UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

PERCHED GROUND WATER IN ZEOLITIZED-BEDDED TUFF, RAINIER MESA AND VICINITY, NEVADA TEST SITE, NEVADA*

By

William Thordarson

1965

Report TEI-862

This report is preliminary
and has not been edited for
conformity with Geological
Survey format and nomenclature.

*Prepared on behalf of the U.S. Atomic Energy Commission.

CONTENTS

CONTENTS--Continued

ILLUSTRATIONS

TABLES

PERCHED GROUND WATER IN ZEOLITIZED BEDDED TUFF, RAINIER MESA AND VICINITY, NEVADA TEST SITE, NEVADA

By

William Thordarson

ABSTRACT

Rainier Mesa--site of the first series of underground nuclear detonations--is the highest of a group of ridges and mesas within the Nevada Test Site. The mesa is about 9.5 square miles in area and reaches a maximum altitude of 7,679 feet. The mesa is underlain by welded tuff, friable-bedded tuff, and zeolitized-bedded tuff of the Piapi Canyon Group and the Indian Trail Formation of Tertiary age. The tuff--2,000 to 5,000 feet thick--rests unconformably upon thrust-faulted miogeosynclinal rocks of Paleozoic age.

Zeolitic-bedded tuff at the base of the tuff sequence controls the recharge rate of ground water to the underlying and more permeable Paleozoic aquifers. The zeolitic tuff--600 to 800 feet thick--is a fractured aquitard with high interstitial porosity, but with very low interstitial permeability and fracture transmissibility. The interstitial porosity ranges from 25 to 38 percent, the interstitial permeability is generally less than 0.005 gpd/ft^2, and the fracture transmissibility ranges from 10 to 100 gpd/ft for 500 feet of saturated rock. The tuff is generally fully saturated interstitially hundreds of feet above the regional water table, yet no appreciable volume of water moves through the interstices because of the very low permeability. The only freely moving water observed in miles of underground workings occurred in fractures, usually fault zones.

This water is perched by the poor interconnection of the fractures themselves. The top of the zone of fracture saturation is irregular but usually lies near the top of the zeolitic tuff strata at an altitude within a few hundred feet of 6,000 feet.

The movement of the perched water is slowly downward along steeply dipping fractures to discharge points within the underlying more permeable Paleozoic strata. This downward movement was suggested by measured declines in head with depth in test wells. The head measurements made at different depths in two wells suggest vertical hydraulic gradients ranging from 0.3 to 1.0 foot per foot. Movement of water from shallow water-bearing fractures into deeper but empty fractures may account for some of the head changes observed in other wells.

A marked difference in the salinity of the interstitial and fracture water is suggested by study of electric logs and by chemical analyses of the fracture water. The specific conductance of the interstitial water is apparently 25 to 35 times greater than the specific conductance of water perched in the fractures. The difference may be related to the addition of ions to the pore water by ionization of clay particles, to differences in the residence time of the interstitial and fracture water, or to salinity of the interstitial water at the time of its introduction into the bedded tuff.

INTRODUCTION

Purpose and scope

This report describes the occurrence, movement, and discharge of perched ground water in tuffaceous rocks that cap and underlie Rainier Mesa--the site of the first series of underground nuclear detonations made by the Atomic Energy Commission at the Nevada Test Site. It also briefly describes the occurrence of ground water in other rock types adjacent to and beneath Rainier Mesa. The report is one of several prepared, or in preparation, by the Geological Survey to document the geologic, hydrologic, and geophysical setting of the nuclear detonations beneath Rainier Mesa in the northwestern part of the Nevada Test Site (fig. 1).

The objectives of the study and report were two-fold. First, a basic knowledge of the occurrence of ground water in the tuffaceous rocks beneath Rainier Mesa was necessary for an evaluation of the potential contamination, however slight, of ground water by the underground testing program. Second, observations in the tunnels afforded a rare opportunity for a 3-dimensional study of a bedded-tuff aquitard, which is also found deeply buried beneath Yucca Flat and which plays an important role in the regional movement of ground water beneath that valley. An understanding of the movement of water through the bedded tuff beneath Yucca Flat was thus obtained through observation of water occurrence in, and movement through, identical strata beneath Rainier Mesa. This report does not comment directly upon the first objective because that objective has already

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

PREPARED ON BEHALF OF THE
U.S. ATOMIC ENERGY COMMISSION
TEI-862

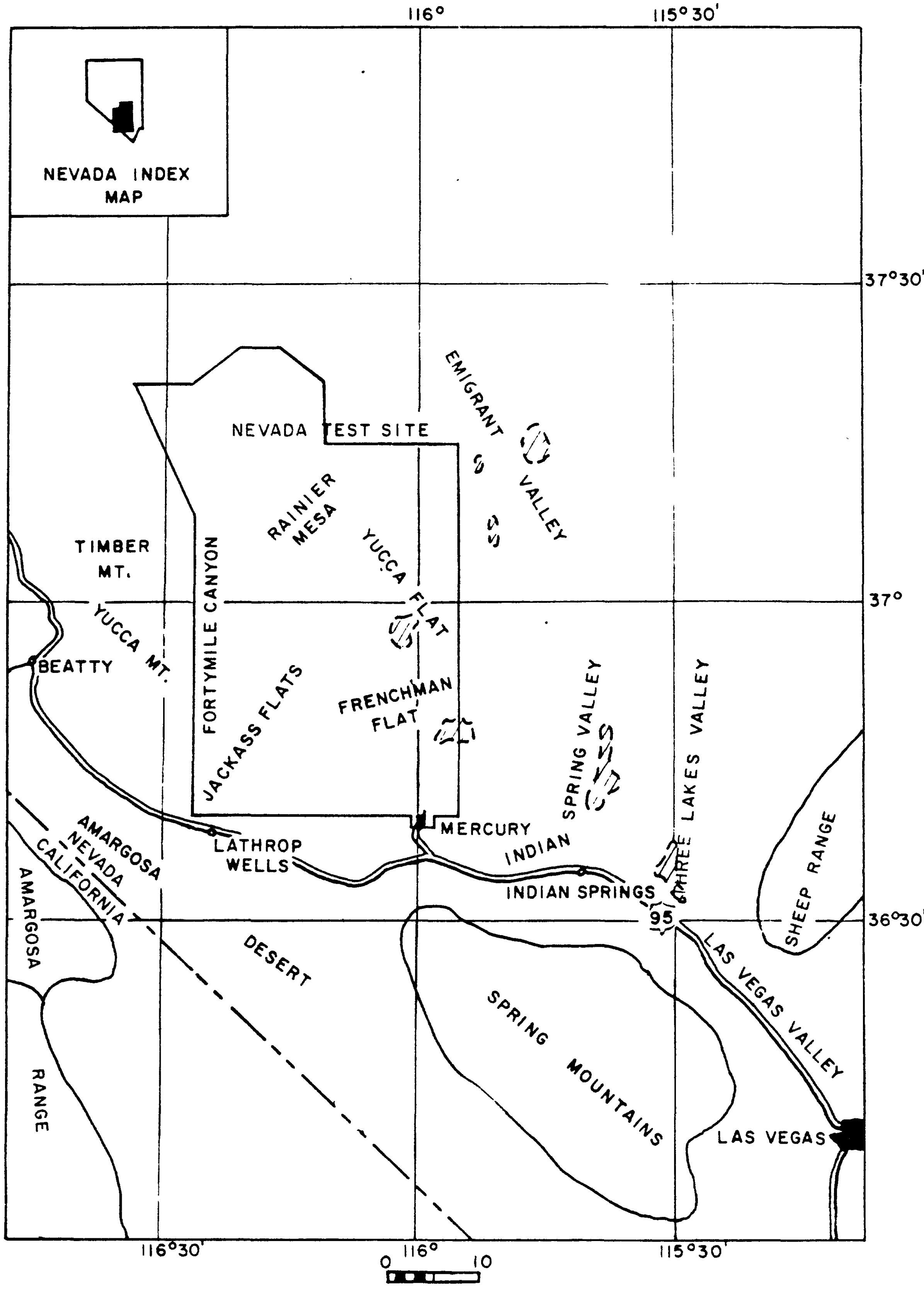


Figure 1.--Index map showing location of the Nevada Test Site and Rainier Mesa, Nye County, Nevada

been discussed briefly by Clebsch (1960), and it is the subject matter of other reports in preparation. A description of the hydrogeology of the tuffaceous rocks--the second objective of the study--is the prime purpose of this report.

Studies of the ground-water regimen of the Rainier Mesa area were begun in 1958 and were continued intermittently through 1961. Report preparation was delayed by other commitments until 1964. The interpretations presented in this report are based primarily on observations of ground-water occurrence in several miles of underground workings and on hydraulic data obtained from six deep test holes. Also utilized were laboratory determinations of the porosity, permeability, and water content of cores and chunk samples of the tuffaceous strata.

Geography

The Nevada Test Site of the Atomic Energy Commission is in south-central Nevada, about 70 miles northwest of Las Vegas (fig. 1). The Test Site is in the Great Basin section of the Basin and Range physiographic province. Rainier Mesa is in the north-central part of the Test Site. A generalized 7½-minute topographic map of Rainier Mesa and surrounding areas is presented in figure 2. The study area of this report corresponds to the 60-square-mile area within the borders of this 7½-minute quadrangle (fig. 2), and this region will be referred to henceforth as the "Rainier Mesa area" or "Rainier Mesa and vicinity." The term "Rainier Mesa" or simply "mesa" will henceforth be utilized specifically to describe topics associated with the major topographic feature of the quadrangle, Rainier Mesa.

Rainier Mesa is the highest of a group of mesas, ridges, and low mountains that border the northwestern part of Yucca Flat, a large intermontane basin (fig. 1). The mesa trends north-south, is about 3 miles long, 1.5 miles wide, and includes 4.4 square miles within the area of its caprock. The mesa rises 200 to more than 700 feet above the nearby highlands, and about 2,500 to 3,500 feet above nearby intermontane basins. The altitude of the volcanic caprock of the mesa ranges from 7,400 to 7,679 feet. By contrast, the maximum altitude of Yucca Flat, about 5,000 feet, is attained about 3 miles east of Rainier Mesa. The mesa is part of a drainage divide that separates westerly drainage to the Fortymile Canyon area from easterly drainage to Yucca Flat.

The Nevada Test Site is characterized by low precipitation, low relative humidity, and large daily variations in temperature. Average annual precipitation on Rainier Mesa was 7.5 inches per year during the 5-year period of record between 1959 and 1964. By contrast, in the nearby intermontane basins, the average annual precipitation in northern Yucca Flat was 4.5 inches for a 3-year period of record and in northern Fortymile Canyon was 5.4 inches for a 3-year period of record. The precipitation record admittedly is short and does not reflect the very irregular precipitation in desert regions; however, the short-term precipitation record does indicate a marked difference between precipitation on the mesa and that on the nearby valley floor.

The varieties and the amounts of vegetation in the Rainier Mesa area differ from the vegetation in Yucca Flat. The vegetation on Rainier Mesa consists of open stands of pinyon pine and juniper trees, whereas that in Yucca Flat consists of desert shrubs. Between the mesa and Yucca Flat, the rocky slopes of the ridges and low mountains support only a scanty vegetative cover of shrubs and small plants.

Tunnels and drill holes

Most of the data used in this report were obtained from tunnels and drill holes, projections of which are shown on the generalized topographic map of the Rainier Mesa area (fig. 2). The major tunnels, which are actually adits, were driven westward into Rainier Mesa. Several smaller tunnels were driven into hills northeast of Rainier Mesa. Most of the drill holes mentioned in this report were drilled from the surface, but the U12e.M-1 hole and the U12e.03-1 hole were drilled vertically downward from within the U12e tunnel system.

Previous investigations

Detailed geologic mapping of the Rainier Mesa area was done by Gibbons and others (1963) and was published in the U.S. Geological Survey map series. The strata of greatest hydrologic interest in this area--the Tertiary tuff and the Paleozoic dolomite--are described in reports by Hinrichs and Orkild (1961), Poole and McKeown (1962), Dickey and McKeown (1959), and by Orkild (1964).

The geology in the U12a, U12b, U12e, and other tunnel systems in the Rainier Mesa area has been mapped and described. Selected references are Cattermole and Hansen (1962), Hansen and others (1963), Diment and others (1958a and 1958b), McKeown and Dickey (1961), Dickey and Emerick (1961), Emerick (1962), Emerick and Dickey (1962), and Laraway and Houser (1962).

The ground-water hydrology of the Rainier Mesa area and the physical properties of the tuffaceous rocks have been described briefly by Clebsch and Winograd in Diment and others (1958a), Clebsch in Diment and others (1958b), Clebsch (1960), and Keller (1960). The chemistry of ground water in the tuff has been discussed by Schoff and Moore (1964).

GENERAL GEOLOGY

The geology of Rainier Mesa and surrounding areas has been described in detail in the numerous reports previously cited. A brief description of the geologic setting is presented herein for a more complete understanding of the hydrology. A generalized geologic map is presented in figure 3.

The rocks exposed in the Rainier Mesa area are of sedimentary and igneous origin and range in age from late Precambrian to Recent. The oldest rocks exposed are quartzite and argillite of late Precambrian and Paleozoic age and dolomite of Paleozoic age. These sedimentary strata have been subjected to at least two periods of deformation and consequently are folded, faulted, and highly fractured. These strata, aggregating more than 9,000 feet in thickness, are most prominently exposed in the Eleana Range, a prominent ridge southeast of Rainier Mesa, and in the foothills immediately east of Rainier Mesa (fig. 3). Small outcrops of late Precambrian and Lower Paleozoic quartzite also are found in Gold Meadows immediately north of Rainier Mesa. Although dolomite, argillite, and quartzite are presently exposed only in portions of the region, test drilling data and the geology of adjacent regions indicate that these rocks underlie the entire Rainier Mesa region.

A quartz monzonite stock is the only rock of Mesozoic age found in the region. The stock, which crops out in Gold Meadows north of Rainier Mesa, intruded late Precambrian and Cambrian quartzite and argillite. Gibbons (1963) believes it is Jurassic or Cretaceous in age. No sedimentary or volcanic rocks of Mesozoic age are present in the Rainier Mesa area, or for that matter elsewhere at the Nevada Test Site.

Volcanic rocks of Tertiary age are the strata most widely exposed in the area. They cover about two-thirds of the Rainier Mesa area. These volcanic rocks include bedded ash-fall tuff, welded tuff, and to a lesser degree, rhyolite. The bedded and welded tuffs beneath Rainier Mesa range from 2,000 to about 5,000 feet in thickness. The thickness of the rhyolite is unknown. Unlike the late Precambrian and Paleozoic strata, which are steeply tilted and locally overturned, the bedded and the welded tuffs are relatively flat lying with dips seldom exceeding 25°.

The bedded tuff--oldest of the tuffaceous strata--was deposited upon an erosional surface of low to moderate relief (Houser and Poole, 1960) developed upon the Paleozoic and late Precambrian sedimentary rocks. The dip of the tuff, therefore, largely reflects the pre-Tertiary topography because these strata were virtually draped over the then present hills and ridges much as snow mantles hills as well as valleys. Houser and Poole (1960) have shown that, as a consequence, the major primary fold axes in the tuffaceous strata are subparallel to the trends of the pre-Tertiary valleys. Successive ash-fall deposits subdued the pre-Tertiary relief by filling the valleys cut into the Paleozoic strata. As a consequence, the youngest volcanic strata are almost flat lying, except where tilted by post mid-Tertiary block faulting. Beginning in Miocene(?) time and continuing into the Pliocene, the Rainier Mesa region was subjected to the block faulting, characteristic of the Basin and Range province. As a result of this faulting, the Yucca Flat area east of Rainier Mesa and the Fortymile Canyon area to the west were depressed relative to the mesa. Rainier Mesa may thus be considered as a prominent erosional remnant of a widespread tuff-capped plateau that probably existed in the area prior to the block faulting.

MAJOR HYDROLOGIC UNITS

Numerous geologic formations ranging in age from late Precambrian to Recent and containing diverse lithologic types have been mapped within the region (Gibbons and others, 1963). For a discussion of the perched ground water within the Tertiary tuff, it is advantageous to group these various formations into seven major hydrologic units or sequences on the basis of differences in gross lithology and transmissibility of the formations. The seven hydrologic units in order of decreasing age are: (a) quartzite and argillite of late

Precambrian and Paleozoic age; (b) dolomite of Paleozoic age; (c) quartz monzonite of Mesozoic age; (d) zeolitic-bedded tuff of Tertiary age; (e) friable-bedded tuff of Tertiary age; (f) welded and partially welded tuff of Tertiary age; and (g) alluvium and colluvium of Quaternary age.

The formal geologic names of the formations composing these seven hydrologic units, the thicknesses of the major lithologies of each group, and their water-bearing characteristics are outlined in succeeding paragraphs.

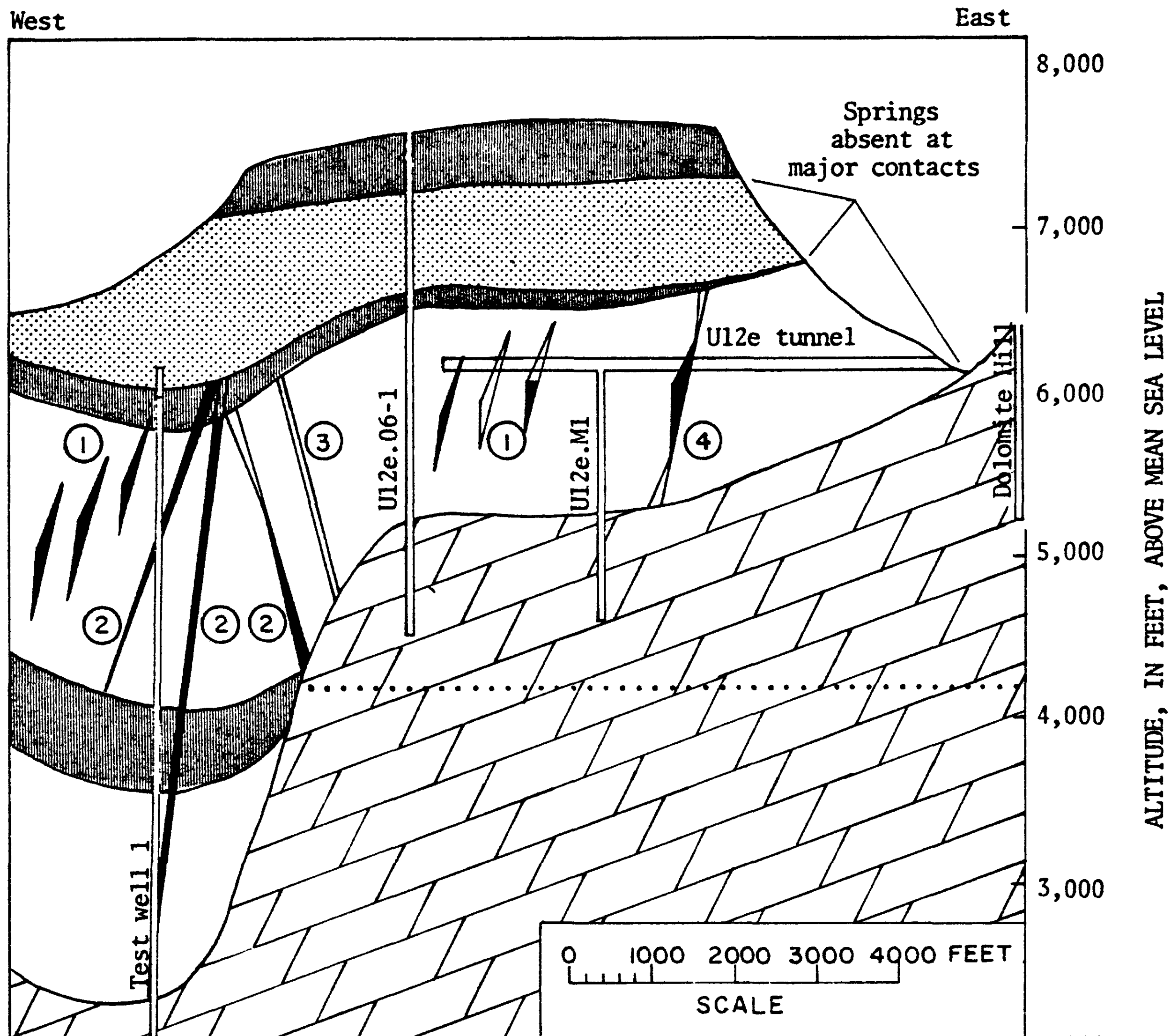
The geologic relationship of hydrologic units b, d, e, and f beneath southern Rainier Mesa is shown in cross section in figure 4. Some further subdivision of the Tertiary tuff--the major subject matter of this report--is presented in table 1.

Quartzite and argillite

Quartzite and argillite are present in each of two formations--the Wood Canyon Formation and Sterling Quartzite, undivided, of Cambrian and late Precambrian age, and the Eleana Formation of Mississippian and Pennsylvanian age. The Wood Canyon Formation and Sterling Quartzite crop out in a small area in the northwestern part of the Rainier Mesa quadrangle (fig. 3). The Eleana Formation crops out in the Eleana Range in the southeastern part of the area and in a few hills in the northeastern part of the area (fig. 3).

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

PREPARED ON BEHALF OF THE
U.S. ATOMIC ENERGY COMMISSION
TEI-862



EXPLANATION

Welded tuff: vertical line pattern
Friable tuff: stippled pattern
Zeolitic bedded tuff: no pattern
Dolomite: rhombohedral pattern
Test hole: open vertical lines
Perched water: black
Water table in dolomite: horizontal dots

Fracture types: 1 - en echelon joints or faults, some containing water, others empty; 2 - faults, all closed above contact with dolomite, fully and partly saturated; 3 - fault, open at bottom and top, and dry; 4 - fault with pinch-and-swell structure, partly saturated.

Figure 4.--Diagrammatic cross section of the southern part of Rainier Mesa showing geology, drill holes, and hypothetical fractures.

The Wood Canyon Formation and Sterling Quartzite contain brown and gray quartzite and argillite in thin to thick beds. The exposed thickness of the Wood Canyon Formation and Sterling Quartzite is about 1,000 feet (Gibbons and others, 1963).

The Eleana Formation contains brown fine-grained to conglomeratic quartzite and argillite in thin to thick beds. Limestone is present in this formation on the east flank of the Eleana Range. The exposed thickness of the Eleana Formation in this area is about 5,000 feet (Gibbons and others, 1963).

In the subsurface below the northwestern half of Rainier Mesa, the Exploratory 1 and U12q drill holes (fig. 2) penetrated quartzite, and the Hagestad 1 drill hole in the central part of the mesa penetrated argillite. This quartzite and argillite may be a subsurface extension of the outcrop of the Wood Canyon Formation and Sterling Quartzite north of the mesa in Gold Meadows (F. M. Byers, oral communication).

No hydraulic data were obtainable from the stratigraphic test holes that penetrated the quartzite and argillite beneath Rainier Mesa. Hydraulic tests of drill holes penetrating quartzite and argillite in other parts of the Nevada Test Site indicate that ground water moves through these rocks primarily in fractures and that the fracture transmissibility is very low.

Dolomite

In the Rainier Mesa quadrangle, dolomite crops out in several low hills immediately east of Rainier Mesa (fig. 3). Data from drill holes U12e.M-1 and U12e.03-1 in the tunnels, drill holes U12e.06-1 and U12b.07-2 on top of the mesa, and test well 1 just south of the mesa show that the dolomite also underlies the eastern and southern half of the mesa.

The dolomite is dark gray, thin to thick bedded, and is of Ordovician to Devonian age (Gibbons and others, 1963). Immediately east of the mesa, in the vicinity of Dolomite Hill (fig. 2), the beds strike N. to N. 25° E. and dip 10° to 25° W. to NW. The exposed but incomplete thickness of dolomite in the vicinity of Dolomite Hill measured about 1,460 feet (Dickey and McKeown, 1959, p. 6).

The dolomite contains abundant faults, joints, and folds. Exposures in the vicinity of Dolomite Hill show steeply dipping, northeast-trending, faults with vertical displacements of 5 to 80 feet. Many of the fault zones contain quartz veins (Dickey and McKeown, 1959, p. 12). Joints in surface exposures and in cores dip at angles greater than 50°. Cores from a test hole drilled on Dolomite Hill were examined by the author; only a small percentage of the fractured core contained openings or vugs. However, because the core recovery was poor, many open fractures in the rock may have been destroyed by the coring operation. Most of the fractures were filled with calcite, quartz, or iron oxide. The structural features of the Paleozoic carbonate rocks beneath Rainier Mesa probably are similar to those found at the Dolomite Hill site.

The effective porosity, and consequently the permeability, of the dolomite near and beneath Rainier Mesa seems to be entirely due to secondary porosity developed along fractures. The porosity of the dolomite was calculated by C. H. Roach (Schoff and Winograd, 1961, p. 26) from both geophysical logs and cores of the test hole drilled atop Dolomite Hill. From resistivity logs, he calculated that the average total formation porosity ranges from 3 to 3.5 percent, but in places ranges from 4 to 7.5 percent. By contrast, from laboratory analyses of 16 cored samples, he determined that the average interstitial porosity was only 0.6 percent. In addition to Roach's work, the author carefully selected for analysis four cores from among dozens available from the holes drilled at Dolomite Hill and at the U12e.06-1 and U12b.07-2 sites on Rainier Mesa (fig. 2). These cores were selected because visual inspection with hand lens suggested that they had above average interstitial porosity. Laboratory determinations of the effective porosity of these four cores ranged from 0.6 to 1.1 percent. The interstitial permeability of these cores, to water, ranged from 0.0002 to 0.00007 gpd/ft^2 (gallons per day per square foot).

The preceding measurements, visual inspection of hundreds of cores, and laboratory measurements of dolomite samples from other parts of the Nevada Test Site, indicate that ground water within the dolomite must move principally through the secondary porosity developed along fractures. Core examination has shown that in places these fractures are enlarged by solution; nevertheless, evidence of large solution cavities is absent both in cores and in outcrop.

Quartz monzonite

Quartz monzonite of Jurassic(?) or Cretaceous age crops out in Gold Meadows. This granitic rock intruded the late Precambrian and Paleozoic rocks and is overlain by tuff. Although the thickness and the subsurface extent of this body are unknown, the U12r drill hole (fig. 2) shows that the intrusive mass extends beneath the northwestern part of Rainier Mesa. In the Exploratory 1 drill hole, cores of the Wood Canyon Formation contain a thin granitic dike, which indicates the proximity of an intrusive mass. This suggests that the intrusive body extends at least a mile south of its southernmost exposure.

No hydraulic tests were made in the quartz monzonite, because no wells have been drilled into it. Nevertheless, its hydraulic properties probably are similar to those of the Climax stock, a granitic intrusive about 7.5 miles east of the Gold Meadows intrusive mass. Ground water in the Climax stock occurs only locally in poorly connected fractures. Test holes penetrating that stock showed no extensive zone of saturation and showed an erratic range in static fluid levels (Walker, 1962, p. 36). Hydraulic tests in selected test holes drilled into the Climax stock showed that some of the holes were "dry". In holes that contained water, the fracture permeability was extremely low (Walker, 1962, p. 36); most of the test holes were dry or could have been bailed or swabbed dry.

Table 1.--Summary of the hydraulic properties and lithology of tuff underlying Rainier Mesa

Hydrologic unit of this report	Formal geologic name: Formation	Formal geologic name: Member	Lithology	Thickness (feet)	Interstitial permeability (gpd/ft²) 1/: Number of samples	Interstitial permeability: Average	Interstitial permeability: Range	Interstitial porosity (percent): Number of samples	Interstitial porosity: Average	Maximum specific capacity 2/	Effective permeability 3/
Welded or partially welded tuff	Timber Mountain Tuff	Rainier Mesa	Welded and partially welded tuff (caprock of Rainier Mesa)	270-550	6 (10)	0.01 (0.006)	0.0002-0.03 (0.00002-1.1)	37	14	--	Fracture
Friable-bedded tuff	Paintbrush Tuff	Tiva Canyon	Welded and partially welded tuff	0-about 80	--	--	--	--	--	--	Fracture
Zeolitic-bedded tuff	Paintbrush Tuff	Stockade Wash	Nonwelded to partially welded pumiceous tuff, base locally zeolitic	0-about 230	--	--	--	--	--	--	Fracture
Welded or partially welded tuff	Paintbrush Tuff	Bedded tuff (informal local unit) 4/	Bedded-friable vitric tuff	100-1,000	2 5/	3.7 0.46	3.3-4.1 0.22-0.89	8	40	--	Interstitial
			Zeolitic tuff in lower 150 feet on east side of Rainier Mesa		11 (5)	0.2 (0.03)	0.0003-1.0 (0.002-0.49)	319	30	--	Fracture
	Indian Trail	Grouse Canyon, upper part	Welded tuff, lenticular and local	0-70	1	0.0006	--	4	19	--	Fracture
Friable-bedded tuff		Grouse Canyon, lower part	Friable vitric tuff in upper portion, zeolitic tuff in lower portion	45-120	(9)	(0.21)	(0.07-1.1)	40	40	--	Fracture
Welded or partially welded tuff		Tub Spring	Welded tuff	0-about 400	--	--	--	--	--	--	Fracture
Zeolitic-bedded tuff		Informal local units (includes Tunnel Beds 1-4 or $Tiit_1$-$Tiit_4$) 6/	Zeolitic-bedded tuff ($Tiit_4$)	265-375	2 (9)	0.02 (0.002)	0.0003-0.03 (0.00009-0.3)	166	38	--	Fracture
			Zeolitic-bedded tuff ($Tiit_3$)	100-200	42 (4)	0.003 (0.0007)	0.00008-0.04 (0.00001-0.004)	142	35	0.04	Fracture
			Zeolitic-bedded tuff, contains pisolite beds and locally a welded tuff at the top ($Tiit_2$)	120	(12)	(0.0004)	(0.0007-0.03)	28	32	0.02	Fracture
			Zeolitic-bedded tuff ($Tiit_1$)	200-210	(3)	(0.001)	(0.0005-0.004)	31	25	0.01	Fracture

1/ Permeability, in Geological Survey units, gallons per day per square foot (gpd/ft²); this unit is approximately equivalent to 55 millidarcies. Permeability to fresh water by U. S. Geological Survey, Denver, Colorado; permeability to brine (in parentheses) by Core Labs, Inc., Denver, Colorado.

2/ Specific capacity unit is gallons per minute per foot of drawdown (gpm/ft). The specific capacity data cited are maximum values because bailing was of short duration and fraction of water bailed was taken from storage in the bore. See table 3.

3/ Effective permeability is defined as the permeability, either interstitial (primary) or fracture (secondary), that is dominant in transmitting ground water to wells, or tunnels.

4/ This unit is equivalent to the Survey Butte Member of Poole and McKeown (1962).

5/ Gas permeability for sample of 5.

6/ These informal units are equivalent to the Tunnel Beds of Hansen and others (1963), and to the Lower Member of Poole and McKeown (1962).

Tuff

Rainier Mesa is underlain by the Indian Trail Formation, and by the Piapi Canyon Group, which includes the Paintbrush Tuff and the Timber Mountain Tuff. Beneath the mesa, these tuffs aggregate to 2,000 to 5,000 feet in total thickness. The older Indian Trail Formation includes in ascending order local informal units of bedded tuff, the Tub Spring Member, and the Grouse Canyon Member. The Paintbrush Tuff includes in ascending order bedded tuff, the Stockade Wash Member, and the Tiva Canyon Member. The Timber Mountain Tuff is represented by the Rainier Mesa Member. The stratigraphy and lithology of these tuff units are summarized in table 1.

Structurally, the tuff beneath Rainier Mesa forms a broad curving syncline whose limbs dip 2° to 12° (fig. 3). The limbs of this syncline contain minor anticlinal and synclinal structures. In general, these folds were formed by the draping of the ash-fall tuff over the irregular topography of the underlying Paleozoic rocks. Faults and joints are abundant in the tuff. The faults and joints dominantly strike northwest and northeast and dip 70° to 90°. The joints generally parallel the attitudes of the faults. Most faults have little or no stratigraphic displacements, but a few are displaced several tens of feet. Details on the geology of the volcanic rocks in the vicinity of Rainier Mesa can be found in Poole and McKeown (1962), Hinrichs and Orkild (1961), and in Gibbons and others (1963).

In this hydrologic study, the tuff is subdivided into three types: (a) zeolitic-bedded tuff, (b) friable-bedded tuff, and (c) welded and partially welded tuff. The hydraulic characteristics of these units and the formal geologic names are summarized in table 1; their geologic relationship is illustrated in figure 4. In general, the effective porosity and the permeability of the zeolitic and welded tuff are situated within and are controlled by fractures; and the effective porosity and the permeability of the friable tuff are controlled by interstices. Evidence for the dominance of fracture permeability in the zeolitic and welded tuff is shown by the hydrologic data collected from the tunnels, test wells, springs, and from laboratory analyses of cores and chunk samples. This evidence is presented in the following sections of the report.

Zeolitic-bedded tuff

The zeolitic-bedded tuff is present in the lower half of the tuff section exposed at Rainier Mesa. This tuff comprises local informal units, the lower part of the Grouse Canyon Member of the Indian Trail Formation, and bedded tuff of the Paintbrush Tuff (table 1). These units generally aggregate about 800 to 1,200 feet in thickness. In the tunnels, the local informal units in the Indian Trail Formation are subdivided into four so-called Tunnel Beds designated $Tilt_1$ to $Tilt_4$ (table 1) or simply as Tunnel Beds 1-4.

The zeolitic-bedded tuff was deposited by the fall of volcanic ash, which consisted predominantly of pumice and glass shards. The pumice and glass shards of these ash-fall tuffs were later massively altered, predominantly to the zeolite minerals clinoptilolite, mordenite, and analcime. The zeolitic tuff also contains minor amounts of clay as well as some silica and hematite as cement. Within the zeolitic tuff there are some thin silicified beds, and in places there are some thin clayey beds. A thick clayey bed was penetrated at the base of the tuff in test well 1 south of the mesa. Nonzeolitic constituents, generally amounting to 5 to 30 percent of the zeolitic-bedded tuff, are small crystals of quartz, feldspar, biotite, and dense lithic fragments. These unaltered constituents are nearly impermeable to water, and are surrounded by a slightly permeable zeolitic matrix.

Many samples of the zeolitized tuff were analyzed for interstitial porosity, interstitial permeability, and percent saturation of the interstitial pore spaces. These samples were taken from both the U12e and U12b tunnel systems; the analyses of samples from these tunnel systems are described separately below, and, in part, are summarized in table 1.

Chunk samples were taken in the U12e tunnel complex from Tunnel Beds 1-4 ($Tilt_1$-$Tilt_4$) of the Indian Trail Formation. These samples were collected in or just above the top of the main zone of fracture saturation discussed below. The average interstitial porosity of the zeolitic tuff in the Tunnel Beds ranges from 25 to 38 percent, whereas the average interstitial permeability of the tuff ranges from 0.0004 to 0.02 gpd/ft^2, which is very low (table 1). The values of interstitial porosity, which are high for consolidated rock, and of permeability, which are extremely small, are probably due to abundant microscopic pore spaces. No relation between porosity, permeability, and grain size of the zeolitic tuff was noted.

The natural moisture content of the samples collected in the U12e tunnels was determined by sealing chunk samples in aluminum foil and paraffin immediately after collection. The water saturation of the pore space in these "natural-state" samples was generally close to 100 percent (Byers, 1961). Analyses of electrical logs also indicate that the zeolitic tuff is fully saturated (Keller, 1960 and 1962). An exception was found in Tunnel Bed ($Tilt_1$) in the U12e tunnel complex in which only 70 percent of the pore space was saturated, possibly because it was sampled close to the portal of the tunnel and therefore was exposed to more evaporation. Byers (1961, p. 20 and 26) states that at greater depths Tunnel Bed 1 probably would be completely saturated.

Samples were also taken in the U12b tunnel system from the zeolitized bedded tuff in the lower informal unit of the Paintbrush Tuff. The U12b tunnel was driven above the main zone of saturation, which contains the water-bearing fractures. In three drifts in the U12b tunnel--U12b.01, U12b.03 and U12b.04--the average interstitial porosity of the zeolitic tuff ranges from 27 to 29 percent (Diment and others, 1959a and 1959b). The average interstitial permeability to fresh water was 0.2 gpd/ft^2, but to brine was only 0.03 gpd/ft^2. The porosity values are comparable to the values for the zeolitic-bedded tuff in the U12e tunnel system; the permeability values, however, are somewhat greater than those for the zeolitic-bedded tuff.

Natural-state samples, samples containing the naturally occurring interstitial water, were collected from the zeolitized tuff in the U12b.01, U12b.03, and U12b.04 drifts. The samples from the U12b.01

drift showed only 62 percent water saturation, whereas the samples from the U12b.03 and U12b.04 drifts showed 100 percent water saturation. Perhaps the samples from U12b.01 drift are relatively less saturated because they were closer to the surface outcrop and were subjected to relatively more evaporation in the zone of aeration.

The specific yield of the zeolitic-bedded tuff is not known. Nevertheless, the general absence of water on the walls of the tunnels indicates that the interstitial water in these strata is strongly held by capillary forces. Possibly, the general absence of interstitial water leaking from the zeolitic tuff into the tunnels is due to evaporation of the small amount of water as it reaches the tunnel walls.

The extremely low interstitial permeability of the interstitially saturated zeolitized tuff and the abundant water in some fractures in the tunnels indicate that the movement of ground water through the zeolitic-bedded tuff is principally through open fractures. Some water may move through interstices in the zeolitized tuff, but it is a very minor amount when compared to the amount of water that moves through fractures.

The fracture permeability of these strata--more properly termed fracture transmissibility--is also extremely small. The specific capacity of several hundred feet of these strata in bore holes is usually less than 0.05 gpm/ft (gallons per minute per foot of drawdown), suggesting transmissibilities less than 100 gpd/ft. Additional discussion of the fracture transmissibility and the movement of ground water through fractures in these strata is presented elsewhere in this report.

Friable-bedded tuff

Friable vitric-bedded tuff comprises the lower part of the Grouse Canyon Member, and most of the bedded tuff in the Paintbrush Tuff (table 1). The friable vitric-bedded tuff is a prominent light-gray, slope-forming unit, which underlies the caprock of Rainier Mesa. The friable-bedded tuff was deposited as ash-fall, but, in contrast to the zeolitic-bedded tuff, the pumice and glass shards are generally unaltered; that is, they retain their glassy or vitric appearance. The absence of zeolitic or other cement makes this tuff very friable.

The interstitial porosity and the permeability of the friable-vitric tuff are generally relatively high compared to the other types of tuff at the Nevada Test Site. The average interstitial porosity for eight samples of friable-vitric tuff from the U12b.08 tunnel beneath Rainier Mesa is 40 percent (table 1; Emerick and Houser, 1962, p. 14). The interstial permeabilities to water of two samples taken from the surface outcrop are 3.3 and 4.1 gpd/ft^2 (table 1), the highest interstitial permeabilities measured from tuff at the Nevada Test Site. The interstitial permeabilities to air of five samples of friable-vitric tuff taken from the U12i.01 drill hole at the U12i tunnel site range from 0.2 to 0.9 gpd/ft^2 and average 0.5 gpd/ft^2 (Bowers, 1963). Data presented by Keller (1960, table 183.1) suggest that the interstitial permeability of tuff to air is about 2 to 20 times greater than the interstitial permeability to water.

Natural state samples of the friable-vitric tuff collected from the U12b.08 drift show that the interstitial pore space averages about 64 percent in water saturation (Emerick and Houser, 1962, p. 14). This interstitial water probably is mostly held by capillary forces and is not available as free water; that is, it will not move into a tunnel or bore in response to gravity.

No data are available on the fracture transmissibility of these strata. However, the extremely friable nature of the vitric-bedded tuff suggests that open fractures are rarely preserved in these rocks. Fractures that have been observed in outcrops are filled with a clayey gouge-like deposit. Some evidence on the occurrence of open fractures is available from drill holes and geologic mapping in the U12j tunnel. Drilling records of five test holes drilled over the U12b.04 (Evans) explosion chamber show that circulation was lost only locally during drilling through the friable-bedded tuff of the Paintbrush Tuff (Poole and Roller, 1959, p. 28). By comparison, circulation was lost several times during drilling in the overlying, highly fractured, welded tuff of the Rainier Mesa Member. Apparently, the friable tuff penetrated by the test holes contained no open fractures. Faults in the friable tuff mapped in the U12j tunnel were generally closed and some were filled with clay gouge (Laraway and Houser, 1962). These sealed faults obviously have low permeability. Joints are abundant in places, but apparently they are also tightly closed.

Welded and partially welded tuff

Welded and partially welded tuff compose the Tub Spring and Grouse Canyon Members of the Indian Trail Formation, the Stockade Wash and Tiva Canyon Members of the Paintbrush Tuff, and the Rainier Mesa Member of the Timber Mountain Tuff. The welded and partially welded tuffs were deposited as ash flows of incandescent tuffaceous particles, which were subsequently densely welded together by their own heat and weight. Superficially these rocks resemble rhyolites; however, their origin and emplacement differs greatly from rhyolites. Some of the welded tuffs have friable partially welded or nonwelded basal units, which may grade indistinctly into bedded tuffs. The genesis of these unusual lava flows has been described in detail by Ross and Smith (1961). Fractures caused by cooling as well as structural deformation are abundant in the welded tuff. The density of fractures is greatest in densely welded tuff and is least in the partially welded or incipiently welded tuff.

The interstitial porosities of the welded tuff in the Rainier Mesa and in the upper Grouse Canyon Members average 14 and 19 percent, respectively. The interstitial permeability of the Rainier Mesa Member averages 0.01 gpd/ft^2 to water and 0.006 gpd/ft^2 to brine (table 1). These are the lowest values of interstitial porosity and among the lowest values of interstitial permeability that were measured in the tuffaceous strata beneath Rainier Mesa.

Five pre-shot drill holes over the U12b.04 (Evans) explosion chamber show that lost circulation was appreciable during drilling through the Rainier Mesa Member at intervals where fractures were indicated on sonic logs (Poole and Roller, 1959, p. 28). This lost circulation and the fact that the interstitial permeability is very low clearly indicate that fracture porosity controls the flow of ground water through the welded tuff.

A measure of the fracture transmissibility of the welded tuff in the Rainier Mesa area was determined in only one test hole--test well 1, which is south of the mesa--because in other test holes in the area these strata occur well above the saturated zone. Test well 1 penetrated an unidentified welded tuff at a depth of 1,910-2,480 feet. The specific capacity of the test hole in this tuff interval, determined from several short pumping tests, ranges from 0.1 to 1.7 gpm/ft. This marked range was due to intermittent plugging of casing perforations or the pump intake screen by lost circulation materials used during drilling of the test hole. Four days of pumping failed to eliminate the plugging. Consequently, the specific capacity of the test hole in this welded tuff may be as great as 1.7 gpm/ft, and might indeed be much larger.

Drill stem and pumping tests of fractured-welded tuffs in other parts of the Nevada Test Site indicate that locally these strata have high fracture transmissibility. For example, the specific capacity of these strata ranges from 2 to 60 gpm/ft in 3 water wells in Jackass Flats, in the southwestern part of the Nevada Test Site. At Pahute Mesa, northwest of Rainier Mesa, ten drill-stem tests of welded tuff indicated specific capacities in the range of 0.0 to 0.5 gpm/ft (R. K. Blankennagel, oral communication, 1964). In both these areas the welded tuff transmits water chiefly through fractures.

Alluvium and colluvium

Unconsolidated rocks of Quaternary age compose the talus, landslide deposits, alluvial fan deposits along the mountain fronts, and alluvium in the washes. These unconsolidated deposits range in grain size from silt to boulder. In most of the area, the alluvium is less than 100 to 200 feet thick. However, beneath the large alluvial fans fronting the Eleana Range, the alluvial deposits probably are several hundred feet thick. Neither porosity nor permeability data are available for these deposits in the vicinity of Rainier Mesa. Three water wells tapping 200 to 500 feet of similar strata in Yucca and Frenchman Flat have specific capacities ranging from 2 to 5 gpm/ft.

GROUND WATER

Beneath Rainier Mesa, ground water is perched in fractures in the zeolitic-bedded tuff of the Indian Trail Formation; however, the regional zone of saturation occurs in the Paleozoic strata several thousand feet beneath the surface of the mesa. No water is known to occur in alluvium in this area. Generally, the movement of water is vertically downward from the recharge area at the top of the mesa into the welded tuff caprock (Rainier Mesa Member) and thence into and through the underlying friable vitric-bedded tuff of the Paintbrush Tuff (fig. 4). Vertical movement of water through these units probably is rapid owing to their relatively high transmissibility. The downward passage of vadose water, however, is retarded when it reaches the relatively impermeable zeolitic-bedded tuff. There, the water accumulates in poorly connected fractures creating the perched zone of saturation observed in tunnels and tapped by numerous drill holes. Vertical movement through the zeolitic tuff into the underlying Paleozoic strata continues but at a very slow rate. Once in the Paleozoic strata, particularly the dolomite, the water again moves through a zone of aeration before it reaches the regional water table in those strata, fully 3,300 feet beneath the surface of the mesa. A relatively minor amount of the perched water does not reach the main zone of saturation and is discharged by a few small springs.

The evidence for the occurrence, movement, and discharge of ground water in the Rainier Mesa area was obtained primarily from observations in tunnels, hydraulic tests of wells, and visits to springs. This evidence is presented in the following paragraphs. The formations are discussed from younger to older because, in general, water moves downward through the formations in that order.

Water in alluvium and colluvium

No water was found in four test holes (Effinger 1-4) (fig. 2) that penetrated the alluvium on the eastern side of Rainier Mesa in Tongue Wash and at the mouth of the main wash leading into Yucca Flat (Moore, 1961, table 2). These test holes were drilled in selected parts of the washes where geophysical seismic profiles indicated that the alluvium was thickest. The holes--drilled in an attempt to locate a shallow ground water supply--penetrated 40 to 190 feet of alluvium, and each hole bottomed in the underlying bedrock of the Eleana Formation.

The absence of water in these test holes and the absence of phreatophyte vegetation where the alluvium is thin indicate that no ground water is being carried away from the principal recharge area, Rainier Mesa, through the alluvium.

Water in tuff

Ground water is perched in poorly connected fractures in the zeolitic-bedded tuff in the Tunnel Beds of the Indian Trail Formation comprising the lower half of Rainier Mesa (fig. 4). The zeolitic-bedded tuff generally has very low interstitial permeability and fracture transmissibility and can best be described as a fractured aquitard in which the interstices are all nearly saturated. Water that will flow into a borehole or tunnel occurs only in fractures in this aquitard. The top of the zone of water in the fractures, herein called the top of the zone of fracture saturation, is near the top of the zeolitized-bedded tuff at an altitude between 6,033 and 6,184 feet in the east-central part of the mesa, and at an altitude of 5,746 feet in the southern part of the mesa. Interstitially, the tuff is nearly saturated not only within the zone of fracture saturation but also hundreds of feet above the zone of fracture saturation, as shown by the saturated chunk samples collected in the U12b tunnel; this tunnel is at an altitude of 6,600 feet, or about 400 feet higher than the top of the saturated zone within the fractures tapped in the U12e tunnel complex.

Evidence from tunnels

Since 1958, several major tunnel systems consisting of adits and drifts have been driven into tuff in the Rainier Mesa area (fig. 2). Of these tunnels, four were driven into the mesa and four were driven into hills northeast of the mesa. All the tunnels are nearly horizontal and penetrate tuff from older strata to younger strata in a downdip direction. Table 2 shows the tuff strata penetrated, the altitude of the portal, and the relative amounts of water that were found in these tunnels. The tunnels that yielded the most perched ground water were those driven into the zeolitic-bedded tuff of the Tunnel Beds of the Indian Trail Formation (table 2). Tunnels driven into the friable-bedded tuff of the Paintbrush Tuff yielded no water.

The U12e tunnel complex (figs. 2 and 5) is the longest of the tunnels at Rainier Mesa, and it also contained the most water. Much of the evidence bearing upon the occurrence of the perched water has been compiled from that tunnel; the following paragraphs present this evidence. The U12e tunnel penetrated only the Tunnel Beds of the Indian Trail Formation, which within the tunnel consists largely of zeolitic-bedded tuff and some interbedded thin clayey tuff.

Table 2.--Data on major tunnel systems in the Rainier Mesa area

Area	Tunnel system	Altitude of portal	Tuff strata penetrated	Occurrence of water
Rainier Mesa	U12b	6,606	Lower Grouse Canyon Member to Paintbrush Tuff	A few small seeps
	U12e	6,115	Tunnel Beds 1-4	Many small seeps and many moderate to large flows in excess of 20 gpm
	U12g	6,115	Tunnel Beds 2-4	A few small seeps
	U12n	6,024	Tunnel Beds 2-3	Many seeps and many moderate flows up to 20 gpm
Hills northeast of Rainier Mesa	USGS (U12a)	5,585	Tunnel Beds 3-4	One small seep
	U12i	5,635	Lower Grouse Canyon Member to Paintbrush Tuff	None
	U12j	5,635	Lower Grouse Canyon Member to Paintbrush Tuff	None
	U12k	5,635	Lower Grouse Canyon Member to Paintbrush Tuff	None

Nature of fractures in tunnels.--In the U12e tunnel, ground water occurs in normal faults and in joints that are parallel to and probably genetically related to the faults (Diment and others, 1959b, p. 28). The faults and joints strike northeast and northwest and are steep to vertical in dip. The faults, compared to the more abundant joints, are relatively scarce. Tunnel drifts that were driven northwestward intersected more northeast-striking faults, and drifts that were driven southwestward penetrated more northwest-striking faults (fig. 5).

Three factors, all highly variable, seem to determine the water-bearing ability and potential storage capacity of any individual fracture; namely, (a) the extent of the fracture, (b) the width of the fracture opening, and (c) the degree to which the fracture is sealed along its strike and in its lower extremities.

Differences in extent of fractures are well illustrated by the faults and joints in the U12e tunnel complex (fig. 5). Most of the faults in this tunnel seem to be minor normal faults that have stratigraphic displacements measured in inches. Comparison of faults in the U12e.05 drift with faults in the flanking drifts indicates that the faults in the U12e.05 drift extend less than 100 to 300 feet (fig. 5). Only a few of the faults in the U12e.05 drift seem to extend across the flanking drifts. The faults are of relatively short extent in the U12e.05 drift, possibly because some are discontinuous en echelon faults.

Intense fracturing occurs in the welded tuffs in several of the tunnels, possibly because the more competent welded tuff could not absorb the tectonic stresses as well as the less competent zeolitic tuff. However, marked differences in the competency in the zeolitic tuff of U12e tunnel were not apparent and therefore the large differences in density of fractures in adjacent drifts is apparently not controlled by differences in the competency of those beds; moreover, the same beds occur in the U12e, U12e.03, and U12e.05 drifts.

The widths of openings in faults and joints also vary considerably. Some faults are open as much as 6 inches, whereas other faults are nearly sealed with fault gouge. The joints generally are closed, but in places some are open as much as several inches. Some fractures, open several inches at one point, are tightly closed within just a few feet along their strike.

For fractures to perch the vertically percolating water, they must be closed or nearly closed along their strike and in their lower extremities or at some point vertically along the fracture. Evidence from the tunnels indicates that the fractures become closed or nearly closed in places for several reasons. First, irregular opening and closing along some fractures may be attributed to pinches and swells associated with faulting. Second, some fractures appear to be somewhat more open in the massive zeolitic beds than in the thin clayey bedded tuff. For example, fractures that extend downward from relatively competent zeolitic strata into the thin tuff strata containing abundant clay appear to close almost completely, or perhaps do not even extend through the clayey strata. Other possibilities are faults closed by clayey fault gouge or faults and joints that have been filled by silt and clay particles, possibly carried downward by percolating water. Some fractures may have been partly closed by the precipitation of minerals such as manganese oxide.

In summary, the extent and width (openness) of fractures in the zeolitic-bedded tuff of the U12e tunnel complex are highly variable even within relatively small areas encompassing a single lithology. Causes for the marked changes in density of fracturing within these tuff strata are not known with certainty. As might be expected, the occurrence of ground water reflects the differences in fracture characteristics.

Occurrence of fracture water in tunnels.--All the ground water observed in the tunnels came from fractures in the zeolitic-bedded tuff; this water is best described as fracture water. The tunnels acted as a drain for the water-bearing fractures that they intersected. The draining of individual fractures after they were penetrated by the tunnels was characterized by a maximum initial discharge that decreased gradually until in a few days the discharge was only a small seep or drip. Most of the fractures drained completely within a few weeks or months, but water dripped from some fractures for 2 years or more (Clebsch, 1960).

The close relationship between the occurrence of ground water and faults is well illustrated in the U12e tunnel (fig. 5). In this tunnel, about half the occurrences of water are in or near faults, and, more important, most of the flows of fracture water that initially amounted to more than 5 gallons per minute came directly from faults. By contrast, the dryest parts of the tunnel system, the U12e.01 and U12e.07 drifts, contained only a few faults. The U12e.01 and U12e.07 drifts may have been dry also in part because the fractures in these drifts probably were above the top of the zone of fracture saturation, as will be shown below in the section on test wells.

The distribution of the perched fracture water in the zeolitic tuff is, as mentioned previously, directly related to the extent, interconnection, and openness of fractures, and may therefore be expected to be erratic. Evidence for erratic occurrence of ground water in the tunnels is shown by the following: (a) differences in occurrence of water in relation to the types, the strike directions, and the intensity of fracturing; (b) extreme differences in volume and duration of discharge from the fractures; and (c) range in temperature of fracture water.

The occurrence of water in relation to the types of fractures was observed in the approximately 19,000 feet of drifts in the U12e tunnel system. Although about 110 faults and an estimated 5,000 joints were mapped, 50 to 60 percent of the faults yielded most of the fracture water; but no more than 2 percent of the joints yielded only a minor part of the total fracture water. Moreover, tens of open-though-dry fractures are interspersed among the water-bearing fractures. The open-but-empty fractures in the tunnels may be without water for several reasons. Some may be dry because they are open below and are drained easily to the regional water table (fig. 4) or some may be empty because they are poorly connected to fractures that receive recharge.

Locally, fracture water occurred primarily in joints having certain strike directions. For example, in the U12e main drift, in the range of distance 3,000 to 3,500 feet from the portal, water occurred only in the northeast-striking joints, and in the U12e.03b drift water occurred in the northwest-striking joints. In both of these drifts, northeast- and northwest-striking joints occur also, but the water-bearing joints comprised more than two-thirds of the total number of joints. This suggests a poor hydraulic connection between the fractures composing a joint set.

The erratic occurrence of fracture water may be related also to intensity of fracturing. For example, faulting and jointing is more extensive in U12g tunnel than in the U12e tunnel. Although the U12g tunnel is at the same elevation as the U12e tunnel, most of the fractures in the U12g tunnel were dry. By comparison, fractures in the U12e tunnel contained large quantities of ground water. The fractures in U12g tunnel apparently persist to depth and therefore cannot hold water at the same altitude as fractures in the U12e tunnel; nevertheless, fractures cutting the U12g tunnel may perch water at some depth below the tunnel floor.

Extreme variations in discharge rate with time, observed during the drilling of the U12e tunnel system, also illustrate the erratic occurrence or poor interconnection of the fractures carrying water. As mentioned previously, every discharge of water from fractures was characterized by an initial maximum rate of discharge that rapidly decreased to a fraction of the original discharge rate. This behavior is best illustrated by a drawing (fig. 6) and description given by Clebsch (1960, p. 13). He states:

> "Figure 4 shows the cumulative length of tunnel beyond the 1,900-foot point and variations in discharge of water with time during the period Aug. 22 through Oct. 16, 1958. The zero point on the lower graph is the 1,900-foot point in the main tunnel. The points on the graph show the total length of tunnel beyond that point, or the length of drain, and represent the combined

> lengths of the Logan and Blanca tunnels[1], which branched from the main tunnel at about 2,000 feet from the portal. The discharge measurements, shown on the upper graph, were made by several observers using various methods and are approximate only. However, increased accuracy would not have changed the jagged appearance, which is the important feature of the curve and is in marked contrast to the steady trend of the lower curve, because it illustrates the variations in water-bearing characteristics of the rock being drained by this system of tunnels. Discharge increased as more permeable zones were penetrated and decreased as these zones were dewatered. The highest peak on the curve (Sept. 12) results from inflow of water from intensely jointed and faulted tuff of unit Tcs_3 (Tunnel Bed 3) penetrated by the Blanca drift. The succeeding peaks resulted from discharge from fractures in the rock penetrated by the Logan drift. It was not practicable at all times to measure separately the discharge of Logan and Blanca drifts, but on October 6 the discharge from the Blanca drift was measured at 20 to 25 gpm. At the time of the last discharge estimate, made on October 11, most of the flow was from the Logan drift. About 30 acre-feet (about 10 million gallons) drained out before the Logan explosion."

Clebsch's observations were confirmed dozens of times in other portions of the U12e and other tunnel complexes.

The rapid decrease in discharge rate described above must reflect the poor hydraulic connection of the water-bearing fractures in the zeolitic-bedded tuff. First, if the fractures had been well connected the discharge rate probably would not have declined as markedly as described, nor would certain fractures have completely dried up in short time intervals. Second, and of greater importance, the fact that water-bearing zones were continually penetrated during

---

[1] The Logan and Blanca tunnels of Clebsch are synonymous with the U12e.02 and U12e.05 drifts of this report. Figure 6 of this report is a reproduction of Figure 4 of Clebsch.

new tunneling indicates that the previously drained or partly drained fractures were not well connected to the water-bearing fractures eventually reached by tunneling.

The poor hydraulic connection of fractures in the U12e tunnel system is also suggested to a lesser degree by the range in temperature of water flowing into the tunnel from fractures at 11 measuring points (fig. 5). The depth of overburden is about the same for all temperature measurement points, except the two measuring points in the U12e.02 and U12e.05 drifts and the measuring point close to the portal of the U12e main drift. The water temperature at points having about the same amounts of overburden ranges from 60° to 67° F.

The range in temperature cited above may reflect differences in thermal conductivity, geothermal gradient, residence time of ground water in the tuff (that is, variations in rate by recharge to various fractures), or the height above the tunnel from which the water came. Because the physical properties of the bedded tuff are fairly uniform and the area involved is a small one, the influences of thermal conductivity and geothermal gradient probably can be neglected.

Usually, the temperature of ground water within a small horizontal and vertical segment of aquifer is uniform; the variations measured in the tunnels therefore suggest either variations in residence time in the rock or water derived from different vertical heights above the tunnel. Thus the coolest water could represent either water from a fracture that was recently recharged by precipitation or water draining from a fracture that is open several hundred feet above the U12e tunnel level. The difference in residence time seems to be the more logical explanation because the U12e tunnel is near the top of the zone of saturated fractures. Both interpretations suggest that the hydraulic connection of the water-bearing fractures is poor.

Water-level data from test holes and shafts, presented later in the report, offer further evidence of poor hydraulic connection of the water-bearing fractures.

Occurrence of interstitial water in tunnels.--Seepage of water from interstices in the zeolitic tuff was observed locally as moist spots on the walls of the U12e tunnel; no interstitial water was observed dripping from the tunnel walls or back (ceiling). Locally, seepage from interstices formed moist walls over distances of 10 feet or less; the seepage discharge observed undoubtedly was less than one-hundredth gallon per minute. These seeps may have been controlled by very thin perching beds composed of clayey tuff, very densely zeolitized tuff, or silicified tuff. Seepage of water from interstices was not observed in any other tunnel.

Although the interstices of the zeolitic tuff are almost 100 percent saturated, the small amount of interstitial seepage in the tunnel indicates that nearly all the interstitial water is retained by capillary forces. The extremely low interstitial permeability of the zeolitic tuff (table 1) suggests further that the yield of interstitial water will be extremely slow, even when the rock is subjected to an hydraulic gradient of hundreds of feet per foot. The general dryness of most of the tunnel walls probably reflects the extremely slow rate, if a rate does indeed exist, at which the zeolitic tuff yields interstitial water under the force of gravity. However, the air circulated by the ventilating systems may evaporate interstitial water as fast as it reaches the tunnel walls.

Further evidence that the specific yield of the zeolitic tuff is extremely small--or conversely that the capillary attraction is large--was obtained from observation of several horizontal holes that were drilled from the U12e main drift. These horizontal holes were dry for a period of many months after their completion. Evaporation rates in the drill holes probably were small compared with the evaporation rates in the open tunnel. Therefore, the absence of seepage from these holes indicates that the specific yield of the zeolitic tuff under the force of gravity is extremely small, if it indeed yields any water at all.

Observations in U12e tunnel indicate that stratification does not control the movement of any appreciable amount of interstitial water. If stratification in any way controlled water movement, water would be expected to concentrate along the bottom of the prominent syncline in the U12e tunnel, the axial trace of which intersects the U12e.06, U12e main, and U12e.03 drifts (fig. 5). However, only minor seeps of water were seen at the axial trace of the syncline, and those seeps were from fractures and not from interstices.

Thus, movement of interstitial water along bedding in the zeolitic tuff is negligible when compared with the movement of water along fractures.

Discharge from the U12e tunnel complex.--About 10 million gallons of water was discharged from the U12e.05 and U12e.02 drifts during August, September, and October 1958 (fig. 6). The volume of water discharged from the remainder of the U12e tunnel complex in the 3-year period December 1958 to December 1961 amounted to about 15 to 30 million gallons at an average discharge rate, measured at the portal, of 10 to 20 gpm (gallons per minute). During the subsequent 2-year period, December 1961 to December 1963, perhaps as much as 5 to 10 gpm discharged from the portal for an estimated total of 5 to 10 million gallons. Most of this discharge probably came from the U12e.03 and the U12e.06 drifts. Thus the total discharge from the U12e tunnel complex may have amounted to about 30 to 50 million gallons, or 90 to 150 acre-feet from August 1958 through December 1963. Although no estimates are available for the discharge from the other tunnel complexes, spot observations establish that the total discharge from those tunnels was only a fraction of that from the U12e complex.

Evidence from test wells

Hydraulic tests of the zeolitic-bedded tuff were made in the Hagestad 1 drill hole, test well 1, two deep core holes in the U12e tunnel, and several 100-foot holes that were drilled for seismic work in the U12e.03 drift. The locations of all but the 100-foot holes, are shown in figures 2 and 5. The hydraulic data obtained from these test wells are summarized in table 3.

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

PREPARED ON BEHALF OF THE U.S. ATOMIC ENERGY COMMISSION
TEI-862

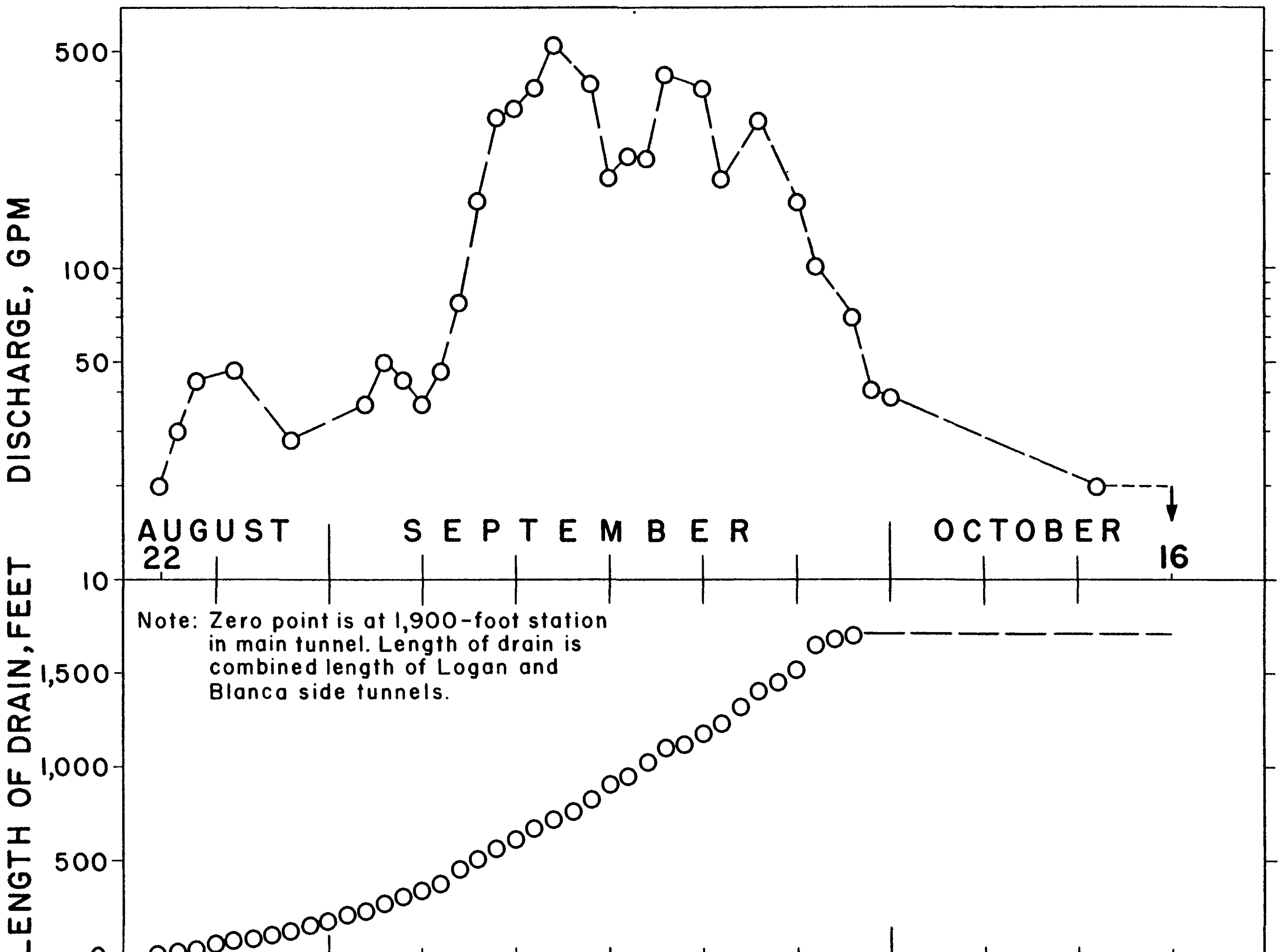


Figure 6.--Discharge of water from the U12e.02 and U12e.05 drifts, Aug. 22 - Oct. 16, 1958 (after Figure 4 in Clebsch, 1960)

Table 3.--Hydraulic data from test holes in the Rainier Mesa area

Test hole: U12e.03-1 Location: Nevada State coordinates (Central Zone), N.888,264; E.634,169; hole is in U12e.03 personnel tunnel at station 11 + 86 feet Altitude: 6,150 feet

Date of test (1959)	Hole depth (feet)	Interval tested (feet)	Rock at hole bottom[1]	Depth to static water level (feet)[2]	Maximum specific capacity[3] (gpm/ft)	Remarks
July 2	29	9- 29	Tilt3	5.4	--	Surface casing, 0-9.5 ft. NX core hole (3.63 in. dia.).
July 6	82	9- 82	do	+ .7	0.02	First detection of appreciable water. Flowing.
Do	82	9- 82	do	+ .7	.01	
July 7	122	71-122	do	+ .5	.04	Packer set at 71 ft., may have leaked. Water level rising.
Do	142	9-142	do	+ 1.1	--	Flowing.
Do	150	9-150	Tilt2	+ 1.1	.02	Packer set at 120 ft., may have leaked.
July 8	211	9-211	do	+ 1.1	--	Flowing at 0.06 gpm.
Do	232	9-232	do	+ 1.1	--	Flowing at 0.2 gpm.
July 9	252	9-252	do	+ 1.1	--	Flowing at 0.2 gpm.

See footnotes at end of table, p. 57.

Table 3.--Hydraulic data from test holes in the Rainier Mesa area--Continued

Date of test (1959)	Hole depth (feet)	Interval tested (feet)	Rock at hole bottom[1]	Depth to static water level (feet)[2]	Maximum specific capacity[3] (gpm/ft)	Remarks
July 9	330	9-330	$Tilt_2$	+ 1.1	--	Flowing at 0.05 gpm.
Do	340	9-340	$Tilt_1$	+ 1.1	--	Flowing at 0.08 gpm.
Do	352	291-352	do	+ 1.1	.01	Packer at 291 held. Flowing at 0.2 gpm.
Do	352	291-352	do	+ 1.1	<0.00	Started test with water at 35 ft. Water temp. 71.3°F.
July 12	430	9-430	do	+17.3	--	Static level from pressure gage shut in for 47 hours.
July 15	478	18-478	do	+ 2.5	.01	NX surface casing, 0-19 ft.
Do	478	18-478	do	+ 2.5	<.00	Water temp. 69.9°F.
Do	478	332-478	do	>226 <272	--	Packer set at 332 ft. held.
July 17	632	18-632	do	45	.01	Water levels meas. for 44.2 hrs. 45 ft. of fill in hole bottom.
July 21	682	478-682	Basal breccia	>484	--	Packers set at 478 ft. and held.

See footnotes at end of table, p. 57.

Table 3.--Hydraulic data from test holes in the Rainier Mesa area--Continued

Date of test (1959)	Hole depth (feet)	Interval tested (feet)	Rock at hole bottom[1]	Depth to static water level (feet)[2]	Maximum specific capacity[3] (gpm/ft)	Remarks
Sept 19	833	4-508	$Tilt_1$	+0.8	--	Casing in hole: 6 in. from 0-5 ft.; 4 in. from 0-509 ft.; 3 in. 0-702 ft. (cemented in). Flowing at 0.25 gpm between 4- and 6-inch casing.
Sept 30	834	701-834	Dolomite	>710.0 and possibly above 768	--	Dolomite may be "dry".

See footnotes at end of table, p. 57.

Table 3.--Hydraulic data from test holes in the Rainier Mesa area--Continued

Test hole: U12e.M-1 Location: N.886,644; E. 633,532; hole is in maindrift of U12e tunnel at station 46 + 76 feet Altitude: 6,158 feet

Date of test (1959-60)	Hole depth (feet)	Interval tested (feet)	Rock at hole bottom[1]	Depth to static water level (feet)[2]	Maximum specific capacity[3] (gpm/ft)	Remarks
Oct. 13	19	9- 19	$Tilt_4$	+ 0.8	--	Surface casing, 0-9 ft. NX core hole (3.63 in. diam.).
Oct. 15	101	9-101	do	+ .1	--	First detection of appreciable water. Water level rising.
Oct. 16	199	9-199	$Tilt_3$	+ .3	--	Water level rising.
Oct. 21	314	9-314	do	+ 1.9	--	Flowing at 0.3 gpm.
Oct. 22	435	9-435	$Tilt_2$	+ 1.9	--	Flowing at 0.1 gpm.
Oct. 24	554	9-554	$Tilt_1$	+ 1.9	--	Flowing at 0.3 gpm.
Oct. 27	631	9-631	do	+ 1.9	--	Do
Do	631	9-631	do	+26.3	--	Level from pressure gage shut in for 1.5 hrs; pressure still rising.
Nov. 1	777	9-777	do	53.6	--	Static level measured 48.5 hours after drilling stopped.

See footnotes at end of table, p. 57.

Table 3.--Hydraulic data from test holes in the Rainier Mesa area--Continued

Date of test (1959-60)	Hole depth (feet)	Interval tested (feet)	Rock at hole bottom[1]	Depth to static water level (feet)[2]	Maximum specific capacity[3] (gpm/ft)	Remarks
Nov. 4	844	9-650	Basal breccia	+ 18.4	--	Packer set at 650 ft. Static level from pressure gage shut in for 11.3 hrs.
Do	844	650-844	do	>389 and possibly <513 feet	--	Packer set at 650 ft.
Nov. 21	866	854-866	do	> 814	--	NX casing cemented in at 854 ft.
Nov. 22	866	854-866	do	> 819	--	Water level falling.
Dec. 27	1,125	854-1,125	Dolomite	> 975	--	Water level falling.
Feb. 12	1,501	854-1,501	do	>1,452	--	Water level falling; dolomite probably unsaturated.
Feb. 25	1,501	854-1,501	do	>1,485	--	Do

See footnotes at end of table, p. 57.

Table 3.--Hydraulic data from test holes in the Rainier Mesa area--Continued

Test hole: Hagestad No. 1 Location: N. 889,190; E. 631,132; hole on top of Rainier Mesa in north-central part Altitude: 7,485 feet

Date of test (1957-58)	Hole depth (feet)	Interval tested (feet)	Rock at hole bottom[1]	Depth to static water level (feet)[2]	Maximum specific capacity[3] (gpm/ft)	Remarks
Aug. 8	--	664- 674	--	--	--	Hole cased to 1,932, cemented, and gun perforated; cement plug, 1,932-1,941 feet; "dry" during drill-stem test.
Sept. 7	--	1,874-1,904	$Tilt_1$ (?)	1,567±	--	
Sept. 13	1,941	1,600-1,620 1,750-1,770 1,874-1,904	$Tilt_4$ (?) $Tilt_3$ (?) $Tilt_1$ (?)	1,446±	0.03	Additional intervals gun perforated as shown; bailing test.
Sept. 15	1,941	1,600-1,620 1,750-1,770 1,874-1,904	$Tilt_4$ (?) $Tilt_3$ (?) $Tilt_1$ (?)	1,446	.02	Bailing test.
Sept. 16	1,941	1,600-1,620 1,750-1,770 1,874-1,904	$Tilt_4$ (?) $Tilt_3$ (?) $Tilt_1$ (?)	1,446	.03	Do
Sept. 18	1,941	1,600-1,620 1,750-1,770 1,874-1,904	$Tilt_4$ (?) $Tilt_3$ (?) $Tilt_1$ (?)	1,446	.03	Bailing test, see figure 7 for hydrograph

See footnotes at end of table, p. 57.

Table 3.--Hydraulic data from test holes in the Rainier Mesa area--Continued

Test hole: U12e.06-1 Location: N. 885,038; E. 631,776; hole on top of Rainier Mesa and penetrates U12e tunnel level about 100 feet northwest of U12e.06 drift Altitude: 7,573 feet

Date of test (1962)	Hole depth (feet)	Interval tested (feet)	Rock at hole bottom[1]	Depth to static water level (feet)[2]	Maximum specific capacity[3] (gpm/ft)	Remarks
Feb. 16	3,114	0-3,114	Dolomite	>2,927.3	--	Slotted BX tubing to 3,114 ft.; not cemented in place.
May 23	3,114	0-3,114	do	>2,929.9	--	Dolomite "dry"; only residual drilling fluid left.

Test hole: Dolomite Hill hole Location: N.886,712; E. 638,632; hole is on top of Dolomite Hill east of Rainier Mesa Altitude: 6,399 feet

Date of test (1959-60)	Hole depth (feet)	Interval tested (feet)	Rock at hole bottom[1]	Depth to static water level (feet)[2]	Maximum specific capacity[3] (gpm/ft)	Remarks
April 8	--	0- 681	Dolomite	--	--	Dolomite bailed "dry"; bailing recovered drilling fluid only.
April 10	--	0- 775	do	--	--	Nearly bailed dry; bailing recovered drilling fluid only.

See footnotes at end of table, p. 57.

Table 3.--Hydraulic data from test holes in the Rainier Mesa area--Continued

Date of test (1959-60)	Hole depth (feet)	Interval tested (feet)	Rock at hole bottom[1]	Depth to static water level (feet)[2]	Maximum specific capacity[3] (gpm/ft)	Remarks
June 4	--	0-1,200	Dolomite	--	--	Nearly bailed dry; Bailing recovered drilling fluid only.
June 30	--	0-1,200	do	[4] >1,111	--	Dolomite "dry"; only residual bentonitic drilling fluid removed by bailing.
Aug. 20	--	0-1,200	do	[4] >1,117	--	Do
Jan. 29	--	0-1,200	do	[4] >1,124	--	Do

See footnotes at end of table, p. 57.

Table 3.--Hydraulic data from test holes in the Rainier Mesa area--Continued

Test hole: Test well 1 Location: N. 876,855; E. 629,310; hole in Stockade Wash immediately south of Rainier Mesa Altitude: 6,156 feet

Date of test (1960-62)	Hole depth (feet)	Interval tested (feet)	Rock at hole bottom[1]	Depth to static water level (feet)[2]	Maximum specific capacity[3] (gpm/ft)	Remarks
9-30-60	560	0- 560	Zeolitized tuff	411	--	Water first hit at depth of 560 ft. rose to 410 ft.
11-18-60	1,615	0-1,615	do	416	0.7	Bailing test.
2-21-61	1,840	1,615-1,840	do	1,024	--	Hole cased to 1,615 feet and cemented.
8-16-62	4,195	1,615-3,300 (?) (probably test of interval 1,910-2,480 ft.)	do (Welded tuff 1,910-2,480 ft.)	1,441	>.1-1.7+	Casing perforated 1,910-2,430 ft. Pumping test; lost circulation material clogged perforations or pump screen; test results questionable.
6-9-61	3,731	3,700-3,731	Dolomite	1,993±	--	Drill-stem test.
8-10-62	4,195	3,700-4,206	do	1,967	0.75	Hole cased 1,615-3,700 ft. Bottom of casing cemented. Pumping test.

See footnotes at end of table, p. 57.

[1] See table 1 for identification of tuff units $Tilt_1$-$Tilt_3$.

[2] Plus sign indicates that water level is above floor of tunnel and that water was either flowing or rising to top of casing. All measurements from ground level or floor of tunnel.

[3] Specific capacity--in units of gallons per minute per foot of drawdown (gpm/ft)--was determined by bailing or swabbing. Values tabulated are maximum possible for interval tested because bailing and swabbing was of short duration, and much of water removed was taken from storage in hole rather than from the bedrock.

[4] Fluid level declining; probably represents residual drilling mud. Dolomite not believed saturated.

Top of the zone of fracture saturation in the zeolitic-bedded tuff.--The highest water levels measured in the test wells and in two shafts that were sunk below the tunnels suggest that the top of the zone of saturation of fractures in the zeolitic tuff is irregular but is within a few hundred feet of an altitude of 6,000 feet (table 4). The seemingly irregular top of the zone of saturation probably reflects the poor interconnection of the water-bearing fractures discussed in previous sections of this report. The top of the zone of fracture saturation occurs within the uppermost zeolitic-bedded tuff in Tunnel Bed 3 or Tunnel Bed 4 ($Tilt_3$ and $Tilt_4$ of figure 5).

Table 4.--Altitudes of highest water levels measured in test wells and shafts

	Name	Altitude of highest water level (feet)	Tunnel Bed at highest water level
Test wells	U12e.M-1 (in U12e tunnel)	6,184	$Tilt_4$
	U12e.03-1 (in U12e tunnel)	6,167	Top of $Tilt_3$
	Hagestad 1	6,046	$Tilt_4$
	Test well 1	5,746	$Tilt_4$
Shafts	Shaft in U12e.07 drift	6,033	$Tilt_4$
	Shaft in U12b.07 drift	6,147	Top of $Tilt_3$

Only one of the water levels cited in table 4, that in test well 1, is a static water level representative of the top of the zone of saturation. However, the levels at which the first occurrences of fracture water were noted in the shafts in the U12e and U12b tunnels probably are also close to the static water levels. On the other hand, water levels in the test holes in the U12e tunnel were measured with pressure gages after surrounding fractures were drained by the tunnels; therefore these levels probably are below the levels that existed before the tunnels were driven. The water-level altitudes for these wells represent shut-in pressures obtained after the test holes began to flow water. The water level cited for the Hagestad 1 drill hole (table 4) represents only the composite "static" water level of two perforated intervals in the cemented casing. If the casing had been perforated at higher intervals, the static water level might have risen to a still higher level as will be explained in a subsequent section of this report.

The top of the zone of fracture saturation beneath Rainier Mesa has undoubtedly been lowered over the tunnels that drained the intersected fractures. An example of the possible magnitude of the lowering of the top of the zone of saturation due to tunneling is illustrated by the decline of water level in the Hagestad 1 test hole, which followed driving of the U12e.07 shaft and U12e.07a drift. A hydrograph of water levels in this hole for the period 1958-63 is presented in figure 7. Between May 1960 and June 1961 the water level in Hagestad 1 declined about 10 feet; during the previous record (September 1958 to April 1960) it fluctuated less than 10 feet. Between May 1962 and September 1963 the water level dropped about 120 feet. The 10-foot drop occurred after water was first found in the U12e.07 shaft; in fact, the level in the bore declined to about the level in the shaft. The shaft and the hole are about 600 feet apart. The 120-foot decline occurred after the U12e.07a drift was driven toward the Hagestad hole from the shaft. At its closest point, the drift was roughly 100 feet from the test hole.

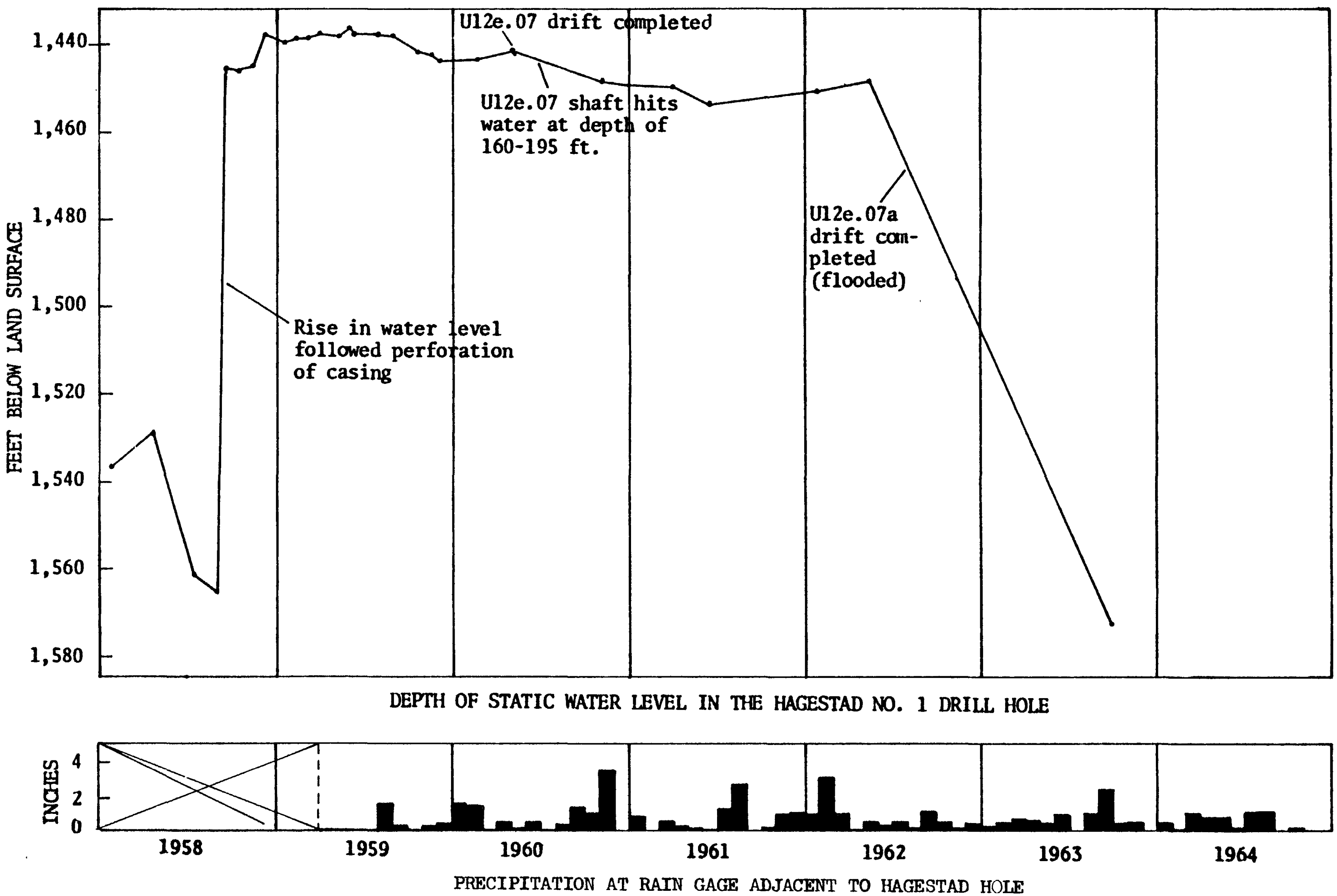


Figure 7.--Hydrograph of Hagestad No. 1 drill hole and monthly precipitation data for the period 1958-1964

The water-level decline may have been also due to below-average precipitation, but no apparent relationship is seen between the hydrograph of the Hagestad well and precipitation data (fig. 7). Although a lag period of several years might exist between precipitation on the mesa and water-level changes in this hole, the general appearance of the hydrograph argues against a decline due to below-average precipitation, particularly the 120-foot water-level drop that occurred in 1962. If this decline was due to deficient recharge, the rate of drop should have decreased gradually (as perhaps for the period May 1960 to May 1961); the 120-foot decline, however, cannot readily be ascribed to precipitation deficiency. Recent studies of aquifer response to nuclear detonations suggest that this drop in water level is not due to underground nuclear detonations. W. E. Hale and M. S. Garber (written communication, 1964) have shown that water levels in zeolitic tuff beneath both Rainier Mesa and Yucca Flat typically rise in response to nearby detonations and, moreover, decline very slowly thereafter. Thus the 120-foot drop in water level and possibly also the 10-foot decline in the Hagestad hole were caused by draining of water-bearing fractures tapped by the U12e.07a drift and U12e.07 shaft.

Above the top of the zone of fracture saturation, the zeolitic-bedded tuff in the lower part of the Paintbrush Tuff in the U12b tunnel complex is also usually saturated interstitially. Several small seeps of water were found in fractures of the U12b tunnel system in saturated zeolitic-bedded tuff, which is about 150 feet thick at the base of the Paintbrush Tuff. This tunnel is at an altitude of about 6,600 feet, about 400 to 600 feet above the zone of fracture saturation in the zeolitic tuff. The seeps in the U12b tunnel probably represent vadose water moving downward into the underlying zeolitic tuff of the Indian Trail Formation.

Rises of water levels during initial drilling of test wells.--The first appreciable ground water found in several of the test wells was characterized by a rather abrupt entry of water into the hole. Prior to this entry, no water was reported by the drillers. The sudden entry of water into the holes probably was due to the initial penetration and draining of a water-bearing fracture.

Three of the test wells in the tunnels, the U12e.M-1, U12e.03-1 (figs. 2 and 5), and U12e.03 "hobo" hole 22 (not shown on figs. 2 or 5), became flowing wells after they first penetrated water at depths ranging from 19 to 82 feet below the tunnel floors (table 3). The U12e.03 "hobo" hole 22 is of special interest because it was only 106 feet deep; the natural flow from this hole declined gradually from about 20 gpm (gallons per minute) to 1 gpm in only a few weeks. This decline in discharge may be compared to the decline in flow rate in short periods of time from the water-bearing fractures penetrated by the tunnels.

The abrupt rise of water level in these test wells and the sharp decline in discharge in the U12e.03 "hobo" hole 22 indicate that the water entering the test wells is fracture water rather than interstitial water. The rapid decline of flow in hole 22 indicates that the fractures tapped by this hole were emptied quickly, which in turn indicates poor hydraulic connection of the water-bearing fractures.

No marked rises in head were noticed during the subsequent deepening of the test wells into the zone of fracture saturation. Because of the extremely low fracture transmissibility of the tuff, head increases would not have been reflected by marked increases in discharge. Packer tests to measure head increases with depth were not made.

Declines in head during deepening of test wells.--Declines in head were observed in test holes U12e.M-1 and U12e.03-1 as they were deepened into the zone of saturation in the zeolitic tuff (table 3). Most of the head measurements tabulated in table 3 represent composite water levels from several intervals in the tuff and do not necessarily represent the heads of individual fractures. The composite heads represent the hydraulic adjustment of all water-bearing fractures penetrated by the bore. Packer tests in the U12e.03-1 and U12e.M-1 holes indicate that when the holes were deepened into the bedded tuff the wells were still flowing at the surface; however, the head in the lower part of the holes, determined by packer testing, was hundreds of feet below the surface. This means that prominent fractures (probably mostly faults) in the upper parts of the composite intervals tested produced enough water to maintain flow even though zones of lower head existed in deeper parts of the wells.

The few packer tests in the U12e.03-1 and U12e.M-1 holes suggest that the greatest declines in head are in the basal zeolitic tuff of Tunnel Bed 1 ($Tilt_1$) and in the basal breccia underlying that bed. Additional packer tests might have shown that the decline in the heads of individual water-bearing fractures was more or less gradual and that it ranged from heads above the tunnel floor in the upper part of the bedded-tuff sequence to zero heads at the tuff-dolomite contact. Some of the head declines could also be due to the penetration of open-but-unsaturated fractures.

Data from Hagestad 1 drill hole and test well 1 also indicate marked decline in head with increasing depth (table 3). In the Hagestad hole, the decline was indicated by the water levels measured before and after perforation of the cemented casing. The perforated interval (1,874 to 1,904 feet) at the bottom of the tuff section produced water that stood at a depth of about 1,567 feet below land surface. Later, after perforation of other intervals several hundred feet higher, the water level rose to about 1,446 feet below land surface (fig. 7). If the casing, which was cemented in place, were perforated at still higher intervals, the water level might rise further; but the water level of about 1,446 feet is at an altitude of 6,046 feet and is probably at or near the top of the irregular zone of saturation in the zeolitic tuff.

The head in test well 1, immediately south of the mesa (fig. 2), declined at a more or less gradual rate during the deepening of the hole through the tuff (table 3). After the dolomite was penetrated, the head of the regional water table in that rock was found at a depth of 1,967 feet, or at an altitude of 4,189 feet. This depth is about 1,900 feet lower than the 1,446-foot water level in the Hagestad hole.

In addition to the decline in head with increasing depth within the tuff, the hydraulic tests in the U12e.M-1 and U12e.03 test holes showed that dolomite immediately underlying the zeolitic tuff beneath the U12e tunnel is not saturated. Data from test well 1 indicate that the zone of saturation within the dolomite is at least 1,100 feet below the base of the tuff at the U12e.M-1 site.

The decline in head with increasing depth indicates that ground water perched within the zeolitic tuff is draining downward into the underlying Paleozoic strata, chiefly dolomite, through steeply dipping to nearly vertical fractures. The virtual absence of springs along the flanks of the mesa, of along the contact of the tuff and dolomite immediately east of the mesa (fig. 4), also supports this concept. Further indication that the movement must be predominately downward along fractures is the absence of any evidence of bedding plane control of water movement.

Hydraulic gradients.--The declines in head in several of the test wells can be used to obtain a rough approximation of the downward directed hydraulic gradient in the zeolitic-bedded tuff. In figure 8 the average heads of packed-off or otherwise isolated intervals are plotted against hole depth for test holes U12e.03-1, U12e.M-1, Hagestad 1, and test well 1. The range in hydraulic gradients is 0.3 to 2.5 feet per foot; the range is decreased further if the questionable gradients for test holes U12e.03-1 and U12e.M-1 are discarded. Owing to the drain conditions imposed by the tunnels, some of the static water-level measurements for test holes U12e.03 and U12e.M-1 may not have been at static pressure. Moreover, leakage around the packers may have influenced the head; that is, the level may have represented composite zones rather than

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

PREPARED ON BEHALF OF THE
U.S. ATOMIC ENERGY COMMISSION
TEI-862

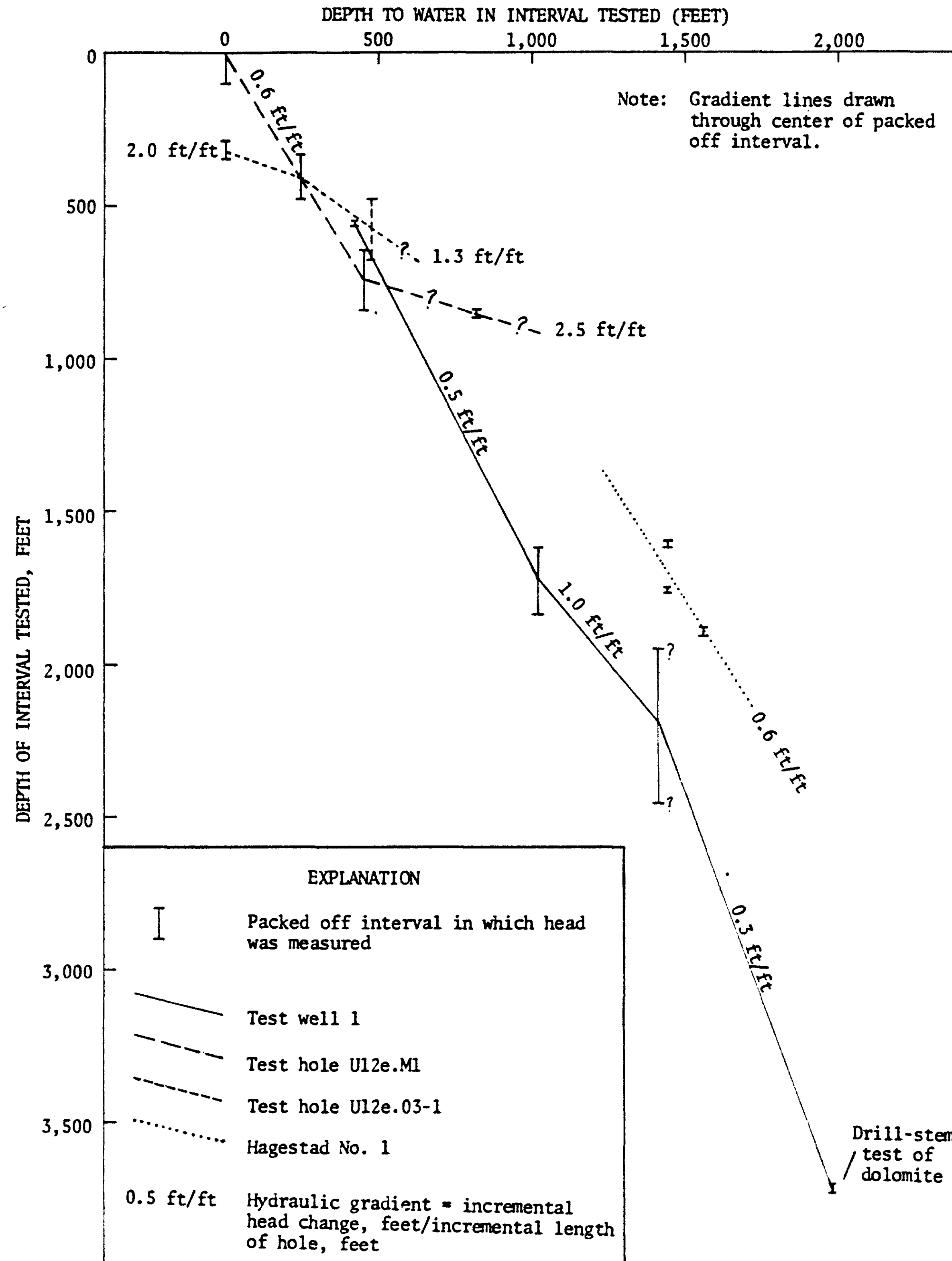


Figure 8. Estimated vertical hydraulic gradients in zeolitic-bedded tuff in four test wells

the zone within the packed-off intervals. Accordingly, gradients would be different from those shown in figure 8. On the other hand, measurements made in the test well 1 and probably in Hagestad 1 were static levels and, owing to the mode of construction of these wells, very likely represented the intervals shown on figure 8.

Perhaps the major question on the validity of the hydraulic gradients concerns the effect of unsaturated fractures upon the gradient. If the measured head drop with increasing depth reflects in part the intersection of unsaturated fractures by the bore, or their presence near the bore, then a meaningful hydraulic gradient has not been measured between the top of the zone of fracture saturation and the base of the bedded tuff.

Aquifer tests.--Tests to determine the specific capacity of the tuff aquifer were made by bailing or swabbing fluid out of selected wells and then measuring the recovery of water level. The wells so tested were the Hagestad 1 hole, test well 1, and the U12e.03-1 hole. Hole U12e.03-1 was drilled with water to a depth of 706 feet by the rotary method, and test well 1 was drilled to 1,840 feet with natural formation water by the cable-tool method. Therefore, the fractures in the tuff penetrated by these holes probably were not plugged with drilling mud. The Hagestad hole was drilled with mud, cased, and cemented; it was then gun perforated in a few intervals (table 3). Thus, the test results from the Hagestad hole probably are representative only of a small percentage of the aquifer thickness.

The specific-capacity values listed in table 3 are maximum values, because during the tests much of the water removed was from storage in the bore and because the maximum drawdown could not be measured owing to the time lag between the last bailer coming out of the hole and the lowering of the water-level measuring device for the first measurement. If these two factors could be more closely controlled, the specific-capacity values cited probably would be much lower. Only the specific-capacity value of test well 1 was corrected for the amount removed from storage in the bore by using a geophysical caliper log of hole diameter. The correction amounted to only 5 percent of the total. The amount of water stored in the other wells tested was not computed because caliper logs were not made in those holes.

The aquifer tests of the U12e.03-1 hole were generally additive in nature; that is, the successive tests made as the hole was deepened also sampled all the intervals previously tested. In addition, several bailing tests of packed-off intervals were also made. The tests made in Hagestad 1 and test well 1 were of small intervals of hole isolated from adjacent intervals by cemented casing.

The tests of the U12e.03-1 hole indicate that the specific capacity of a 600-foot well tapping a fractured zeolitic-bedded tuff is less than 0.05 gallon per minute per foot of drawdown. In contrast, the tests of test well 1 indicate that the specific capacity of a fractured interval of zeolitic tuff can be as high as 0.6 gpm per foot. Data from dozens of tests of zeolitic-bedded tuff in other parts of the Nevada Test Site indicate that the specific capacity of 500-foot thick intervals of zeolitic tuff is usually less than 0.05 gpm per foot of drawdown, although locally, where these strata are highly fractured, the specific capacity may exceed 0.1 gpm per foot. The specific capacities obtained from tests of the U12e.03-1 hole and the Hagestad hole, rather than data from test well 1, are considered representative of the average yield of these strata in the Rainier Mesa area.

The values of specific capacity are predominately measurements of fracture transmissibility because, as shown previously, strong capillary forces prevent interstitial water from flowing into a well bore. The extremely low specific capacity suggests a fracture transmissibility that ranges from 10 to 100 gpd per foot for a 500-foot-thick section of rock.

Refinements in the computations of the coefficients of transmissibility were not considered justifiable. The description of the fractured zeolitic tuff presented earlier shows that the basic assumptions of the Theis recovery formula (Theis, 1935)--used for the computation of the coefficient of transmissibility in homogeneous aquifers--are not applicable to the zeolitic tuff "aquifer". These assumptions state that an aquifer should be isotropic and of infinite areal extent in which the transmissibility is constant at all times and in all places and in which unconfined water bodies discharge water to the well instantaneously with fall in the water table. In addition, Theis states also that the well should penetrate the entire thickness of the aquifer and flow should be radial to the well.

Because of the limited storage capacity of the water-bearing fractures and because of the poor connection between fractures, most wells in the zeolitic tuff probably would be pumped dry after a short period of time. In other words, pumping the wells probably would drain the fracture water in a manner similar to the way the tunnels drained the fractures that were intersected by the tunnels.

Evidence from springs

Water perched in the zeolitic-bedded tuff in Rainier Mesa area is not being discharged in large quantities through springs or by evapotranspiration. This conclusion follows from consideration of a small amount of discharge from the springs, from the absence of a spring line at the contact of the friable tuff and the relatively impermeable zeolitic tuff along the slopes of the mesa, and from the absence of phreatophytes.

Two springs and one seep occur in the lower part of the zeolitic-bedded tuff of the Indian Trail Formation at Rainier Mesa (fig. 2 and 3; and Moore, 1961, table 2). The two springs are topographically and hydrologically separate from Rainier Mesa. They are Whiterock Spring, having a maximum discharge of 1 to 2 gpm, and Captain Jack Spring, having a discharge of about 0.2 gpm. The seep, called "Rainier Spring", is at the foot of Rainier Mesa, and its discharge ranges from 0 to 0.1 gpm; in recent years it has not flowed, although grass grows in the damp soil near it.

Flow from the springs and the seep comes from fractures. The water is perched in a few hundred feet of zeolitized tuff above the tuff-Paleozoic rock contact. The water probably moves laterally along fractures toward the springs.

Local precipitation recharges the springs at an apparently rapid rate. Data from a water-level recorder installed in a shallow well about 300 feet up-slope from Whiterock Spring and observations at the spring show that the water level rose rapidly and the flow of the spring increased very soon after precipitation. The rapid increase in discharge could be due to either a pressure pulse following a build-up in head at some distance from the spring or an actual movement of precipitation into, and rapid discharge from, the tuff. Because the catchment area of the spring is limited (see geologic map of Gibbons and others, 1963) and the nearly vertical fractures in the zeolitized-bedded tuff are poorly connected, the increased discharge probably represents local movement of precipitation through the tuff.

All four of the other known springs in the Yucca Flat basin also discharge from zeolitic tuff of the lower part of the Indian Trail Formation. Thus, these widespread tuffs probably perch small quantities of ground water throughout the Nevada Test Site.

Recharge

The mean annual precipitation on the caprock of Rainier Mesa is 7.5 inches for the 5-year period of record (1959-64), at a weather station at the center of the mesa adjacent to the Hagestad well (fig. 2). A hydrograph of monthly precipitation for this station is shown in figure 7. An estimated 6 inches of precipitation falls on the slopes of the mesa. The total annual precipitation of the caprock's 4.4-square miles area is about 1,800 acre-feet, and the estimated precipitation on the slopes of the mesa's 5.1-square miles area is about 1,600 acre-feet. The total average annual precipitation on the mesa and its slopes is roughly 3,400 acre-feet.

Probably only a small part of the total precipitation recharges the perched zone of saturation in the zeolitized tuff because of the return of moisture to the atmosphere through evaporation, transpiration by vegetation, rapid runoff, or retention in the soil zone. Abrahams and others (1961, p. 142) found that the soil overlying welded tuff on the Pajarito Plateau in New Mexico completely trapped downward percolating water in the C-zone due to abundant clay in this zone. He concluded that where the normal surface cover on top of the Pajarito Plateau is undisturbed, there is little or no recharge to the zone of saturation. This conclusion may also apply to Rainier Mesa, although the soil cover on Rainier Mesa is undoubtedly thinner and less widespread than that on the Pajarito Plateau.

Estimates of the percentage of the precipitation that recharges the zone of saturation in the bedded tuff were made for Rainier Mesa using a method described by Eakin (1962) for Ralston Valley about 60 miles northwest of the mesa. He estimates (p. 11) that for areas between altitudes of 6,000 and 7,000 feet the annual precipitation is about 8 to 12 inches; and the amount recharged is roughly 1 percent. For areas between altitudes of 7,000 and 8,000 feet, the annual precipitation is about 12 to 15 inches; and the amount recharged is roughly 7 percent. For Rainier Mesa, the recharge area above the perched water in the bedded tuff includes the area of the mesa and the area of the slopes surrounding the mesa, a total of about 9.5 square miles. This area lies between altitudes of about 6,100 and 7,680 feet. For this range in altitude, the amount of precipitation reaching the water table is about 4 percent, the average of 1 and 7 percent. The calculated amount of recharge on the mesa and its slopes is thus about 140 acre-feet per year.

A measure of the average vertical permeability of the zeolitized-bedded tuff can be obtained utilizing the estimated recharge (140 acre-feet per year or 125,000 gallons per day), the apparent vertical hydraulic gradient through the zeolitized tuff (0.3 to 1.0 foot per foot), and the area of the mesa and its slopes (9.5 square miles). Using the familiar underflow equation, Q = PIA (flow rate in gallons per day = permeability in gallons per day per square foot x hydraulic gradient in feet per foot x area in square feet), the values of average vertical permeability are about 0.0005 and 0.002 gpd per square foot for respective hydraulic gradients of 1.0 and 0.3 foot/foot.

An independent estimate of the tranmissibility of a horizontal strip of tuff may be made from the vertical permeability values by multiplying the permeability by the length of the mesa (about 3.8 miles or 20,000 feet). This calculated transmissibility ranges from about 10 to 40 gpd per foot for a hydraulic gradient of 1.0 and 0.3 foot per foot, respectively. This range of values compares resonably well with the transmissibility determined from the swabbing and bailing tests (see page 50).

A minor and new source of recharge to the tuff is the fluid lost during drilling operations. In the months starting in September 1961, many holes were drilled into Rainier Mesa. These holes have lost relatively large amounts of drilling fluid, an estimated total of more than 10 million gallons, prior to 1964.

Tritium age of water

The age of the water in fractures in the zeolitic tuff in the U12e tunnel system was estimated from one sample by the tritium concentration method. The age of the water was estimated to be in the range greater than 0.8 year but less than 6 years (Clebsch, 1961, p. 124). (The sample was collected in September 1958.) By contrast, the tritium-age of ground water from the regional zone of saturation in other parts of the Nevada Test Site is greater than 50 years (Clebsch, 1961, p. 124). The much younger residence age of water in the zeolitic tuff of Rainier Mesa confirms that this water is in transit to the regional water table.

The tritium sampling point in the U12e tunnel was a fault zone in the U12e.05 drift about 500 feet vertically below the east slope of the mesa and about 1,300 feet diagonally below the caprock. If the water sampled was about 1 year old, the apparent water velocity from recharge to sampling point is 500 to 1,300 feet per year, depending upon whether the water originated from recharge on the slope or on the caprock. If the water was more nearly 6 years old, the apparent velocity is about 80 to 200 feet annually. Because the U12e tunnel complex is near the top of the zone of fracture saturation (table 4), the apparent velocities represent rates of movement through the vadose zone; strictly then, these velocities should not be used to estimate movement of ground water through fractures within the zone of saturation. The apparent velocity suggested for movement from caprock to the sampling point, 200 to 1,300 feet per year, seems too high because such recharge would have to move interstitially through 600 to 800 feet of highly porous vitric-bedded ruff (average porosity, 40 percent) prior to reaching fractures in the zeolitized-bedded tuff. Conversely, the velocity suggested for movement from the slope of the mesa 500 feet vertically above the sampling point, 80 to 500 feet per year, seems somewhat more reasonable because this movement would be predominately through the effective fracture porosity of the zeolitized tuff; this porosity is estimated to be a fraction of 1 percent.

Whiterock Spring (fig. 2) was also sampled for tritium analysis in August 1958. The age of that water was estimated to be also in the range of greater than 0.8 year but less than 6 years; however, the rapid response of the spring flow to precipitation and the limited catchment area of the spring suggest that the residence age of this water is closer to 1 year.

Salinity of interstitial and fracture water

The geochemistry of ground water in the tuff aquifers has been discussed in some detail by Schoff and Moore (1964). Their discussion is devoted both to ground water occurring in tuff aquifers beneath the regional water table and to the perched fracture water in the tunnels or discharged by springs. They did not discuss the chemical character of the interstitial water in the zeolitic-bedded tuff because, as mentioned earlier, this water will not flow into a bore or tunnel and, hence, cannot readily be sampled. Utilizing the electric-log analyses of Keller (1960 and 1962), however, it is possible to compare the salinity of the interstitial and fracture waters. A discussion of this comparison follows.

Utilizing electric log interpretive techniques and laboratory measurements of cores saturated with water of different resistivities, Keller (1960 and 1962) concludes that the resistivity of the interstitial water in the zeolitic and other tuff beneath Rainier Mesa averages 1.6 ohm-meters. This corresponds to a specific conductance of about 6,800 micromhos at 25°C[a].

The specific conductance of ground water perched in fractures within the zeolitic-bedded tuff in the tunnels and at spring sites is summarized in table 5, as is the specific conductance of water from tuff aquifers beneath the regional water table under the valleys.

The specific conductance of the interstitial water, as calculated by Keller, is 25 to 35 times as great as that of the water perched in fractures; it is about 15 times greater than that of the water from the deep tuff aquifers. The dissolved-solids content, or salinity, of the interstitial water probably ranges from 3,700 to 5,100 ppm (parts per million).[3] This salinity is roughly 18 to 30 times that of the perched water and 10 to 15 times that of the ground water from the regional zone of saturation.

---

[a] Keller does not give a reference temperature with his resistivity data. Commonly, though, log analysts report their data at 20°C. At this temperature the specific conductance would be about 6,200 micromhos.

[3] Hem (1959, p. 40) states that the dissolved-solids content of water is usually 0.55 to 0.75 times the measured specific conductance (in micromhos at 25°C). The ratio of dissolved-solids content to specific conductance of the fracture water is given in table 5.

Keller (1962) recognized that his calculated resistivity of the formation water was much smaller--or conversely the specific conductance was much greater--than the resistivity of the water sampled from fractures in the tunnels. He explained the difference as follows:

> "The ground-water resistivity calculated in this way is equivalent to a salinity far greater than that observed for water flowing from the Oak Spring formation. This discrepancy is always found between values of water salinity determined from resistivity measurements and those determined directly on produced-water samples. The difference is caused by the addition of ions to pore water by ionization of clay particles in the rock. These ions are weakly bound to the clay, and remain in the rock when the water is driven from it."

The apparent difference in specific conductance of the pore and fracture water may be due to not only the mechanism suggested by Keller but also the residence time of the water in the zeolitized tuff.

Because of the extremely low interstitial permeability of the zeolitized tuff, ground water probably moves through the interstices at a fraction of the rate that it moves through fractures; in fact, the presence of fully saturated interstices hundreds of feet above the regional zone of saturation in the dolomite suggests that movement of the interstitial water may be governed more by electrochemical forces than by hydraulic forces. Thus, the markedly greater specific conductance of the pore water may be due to, at least in part, a marked difference in age or residence time.

A possible indication of the effect of residence time upon specific conductance of water is offered by a comparison of the specific conductance of water from fractures in bedded tuff from the tunnels with fracture water samples from tuff strata deeply buried beneath Yucca, Frenchman, and Jackass Flats (table 5). The specific conductance of water in the deeply buried tuff strata--three of which are zeolitized-bedded tuff aquitards--is more than double that of the tunnel water; on the basis of tritium determinations, Clebsch (1961) reported that the age of water from beneath the valleys was in excess of 50 years; in comparison, Clebsch reported that the age of samples from the U12e tunnel and from Whiterock Spring ranged from about 1 to 6 years. Comparison of specific conductance of the fracture water from the two sources is valid, however, only if it is assumed that the higher conductance of the deeply buried water is not due to its former passage through the overlying valley fill aquifer.

Another hypothesis for the apparent difference in resistivity of the pore and fracture water involves speculation about the geologic history of the water. This hypothesis states that the water was relatively saline at the time it entered the bedded tuff and that its entrapment resulted from a marked decrease in interstitial permeability, which may have followed the massive zeolitization of the bedded tuff. If the water is related to the zeolitization, it may be as old as late Pliocene or early Pleistocene.

In summary, several questions remain to be answered on the relationship of the interstitial to the fracture water in the zeolitized-bedded tuff. These are: Is the difference in conductivity of water from the two sources real or apparent? How much older is the water in the interstices than that in the fractures? Was the interstitial water moderately saline at the time of its

Table 5.--Specific conductance and dissolved-solids content of ground water in tuff

Source	Number of sampling points	Specific conductance (micromhos per cm at 25°C)		Dissolved-solids content (ppm)[1]		Ratio dissolved solids-content to specific conductance
		Average	Range	Average	Range	
Water from fractures in zeolitic-bedded tuff in tunnel complexes	25	190	98-351	[2] 166	96-314	0.87
Springs emerging from zeolitic-bedded tuff[3]	8	258	188-414	207	168-293	.80
Deep wells tapping tuff strata beneath regional water table[4]	10	486	265-1,196	350	200-880	.72

[1] Calculated.

[2] Sample of 23.

[3] Of the eight springs sampled, one emerges from rhyolite and one from tuff breccia; the remaining six are from zeolitic-bedded tuff.

[4] Only 3 of the 10 sampling points represent water from zeolitic-bedded tuff; the specific conductance of these samples ranges from 358 to 492 micromhos, and the dissolved-solids content from 263 to 327 ppm. Of the remaining 7 sampling points, 3 represent water from welded-tuff aquifers; the type of tuff tapped by the four remaining wells is not known.

introduction into the tuff? A related question pertains to the role of ground water, if any, in the genesis of the massive zeolitization of the bedded tuff of the Indian Trail Formation.

Partial answers to these questions undoubtedly lie in the chemistry of the interstitial water. The author suggests that this water somehow be extracted and analyzed chemically by those interested in the paleohydrology of the region and in the cause of the massive zeolitization of the older bedded tuff.

Water in dolomite

The occurrence of water in the dolomite of Paleozoic age has been determined almost entirely from test wells in the southern half of the Rainier Mesa area (figs. 2 and 3). The dolomite immediately below the tuff is unsaturated in the southeastern half of the mesa (fig. 4). This is indicated by evidence from the U12e.M-1, U12e.06-1, and the Dolomite Hill holes. These holes bottomed in dolomite at altitudes between 4,643 and 5,199 feet above mean sea level. When drilling was completed, the fluid level in all three holes was within the bottom 85 feet of each hole. These fluid levels generally declined very slowly over a period of many months and were declining when last measured. Not all the bentonitic drilling fluid used to drill the holes was removed after the holes were completed. Therefore, the fluid levels measured probably represent the slow draining of the residual drilling mud from the drill holes. Further evidence that the dolomite is unsaturated to the depth penetrated in these holes is the position of the regional water table in dolomite in test well 1; there the water level is at an altitude of 4,189 feet, which is far below the fluid levels in the three holes mentioned above.

South of the mesa in the vicinity of test well 1 the dolomite underlying the tuff is fully saturated (fig. 4). The dolomite-tuff contact at this location is at an altitude of about 2,450 feet or about 2,800 feet lower than the tuff-dolomite contact in the U12e.M-1 hole. Hence, at test well 1 the tuff-dolomite contact lies well below the regional water level in dolomite (altitude 4,189 feet), whereas in the vicinity of the U12e tunnel complex the dolomite-tuff contact is well above the regional water level. In other words, at test well 1 the ground water occurs under confined conditions, whereas toward the north and east the same aquifer is unconfined. The marked difference in the altitude of the tuff-dolomite contact reflects the moderate relief of the pre-Tertiary topography developed on the Paleozoic strata.

A pumping test of the dolomite in test well 1 showed that it had a specific capacity of 0.75 gpm per foot of drawdown. This specific capacity is substantially higher than the average specific capacities of zeolitized tuff and shows that the dolomite is much more permeable than the tuff, as does examination of outcrops and cores. Data from 9 wells drilled into carbonate strata at the Nevada Test Site confirm this conclusion. The specific capacities of those wells, including test well 1, range from 0.3 to 450 gpm per foot of drawdown and have a median value of 4.4 gpm per foot (Winograd, 1963).

Because the fractures in the dolomite are relatively well connected, water from the overlying tuff is transmitted directly downward to the regional water level. For this reason little or no water is perched in the dolomite in those areas where the tuff-dolomite contact is above the regional water level.

The depth to water in the dolomite aquifer tapped by test well 1 is 1,967 feet (altitude 4,189 feet above mean sea level). This altitude is considered representative of the regional piezometric surface within the Paleozoic dolomite underlying Rainier Mesa and exposed east of it. This level is about 1,800 feet higher than the piezometric surface in similar rocks in Yucca Flat and suggests that one or more prominent hydraulic barriers separate the carbonate aquifers in both areas. The Eleana Formation, which underlies the dolomite east of the mesa and aggregates about 5,000 feet in thickness, is considered to be such a barrier.

The regional direction of ground water movement in dolomite beneath the Rainier Mesa area cannot be determined from measurement of the piezometric level in a single well. Considerations of the hydrology of surrounding area suggests that the water in the dolomite may perhaps be moving principally southwestward.

Water in argillite, quartzite, and quartz monzonite

Although argillite, quartzite, and quartz monzonite were penetrated in four stratigraphic test holes beneath the central and northwestern parts of Rainier Mesa, no hydraulic tests were made in them. However, in other parts of the Nevada Test Site these rocks have much lower fracture-transmissibility than the dolomite (Winograd, 1963). The argillite and quartz monzonite, in fact, may be as impermeable as the zeolitic-bedded tuff. Owing to the generally low fracture transmissibility of these rocks, they may in places perch ground water in a manner similar to that described for the zeolitic-bedded tuff. In addition, because of their low transmissibility, the regional piezometric surface in these strata that underlie northern Rainier Mesa may be several hundred feet higher than that within the permeable dolomite beneath the southern part of the mesa. Further, water in tuff that overlies argillite or quartz monzonite possibly does not move primarily downward but rather laterally, roughly paralleling the tuff-argillite or tuff-quartz monzonite contact. The quartzites probably are somewhat more permeable than the bedded tuff but evidence is lacking.

SUMMARY OF OCCURRENCE AND MOVEMENT OF PERCHED GROUND WATER IN TUFF

Ground water in tuff of the Rainier Mesa area occurs only in zeolitic-bedded tuff in the lower part of the Indian Trail Formation. The younger welded and the vitric-bedded tuff of the Paintbrush Tuff are partly saturated interstitially. The zeolitic-bedded tuff is usually 100 percent saturated interstitially hundreds of feet above the regional water table, yet no appreciable movement of water occurs through interstices because the permeability of the tuff is extremely low. The bulk of the water moves through fractures in the tuff. Because the fractures are poorly connected, only a small percentage contain water; and most of the water occurs in faults. The zeolitic-bedded tuff is best described as a fractured aquitard.

In the zeolitic tuff, the fracture water is perched by the fractures themselves above underlying and generally more permeable Paleozoic carbonate rocks. The top of the zone of saturation of fractures is irregular, but it lies within the top part of the zeolitic-bedded tuff sequence within a few hundred feet of an altitude of 6,000 feet. The irregularity in the top of the zone of saturation reflects the poor hydraulic connection of the water-bearing fractures.

The movement of the perched water in the tuff is slowly downward along steeply dipping fractures to discharge points within the underlying Paleozoic rocks. This downward movement was suggested by declines in head with depth in test wells tapping the tuff. The head measurements made at different depths in two wells suggest vertical hydraulic gradients in the range from 0.3 to 1.0 foot per foot. Some of the head declines observed in other test wells may be due in part to movement of water from upper water-bearing fractures into lower empty fractures.

The occurrence and movement of ground water through fractures in the zeolitic tuff are summarized in a diagrammatic fashion in figure 4; the actual details of the occurrence and movement are much more complex.

Wells tapping the zeolitic tuff have very low specific capacities, generally less than 0.05 gpm per foot of drawdown for several hundred feet of penetration. These low values of specific capacity imply that the fracture transmissibility probably ranges from 10 to 100 gpd per foot. Because of the limited storage capacity of the poorly connected or nearly isolated fractures, wells developed in the zeolitic tuff can be pumped dry in relatively short periods of time.

A marked difference in the salinity of the interstitial and fracture water is suggested by electric logs and by chemical analyses of the fracture water. The specific conductance of the interstitial water is about 25 to 35 times greater than that of water perched in the fractures. The difference may be related to the addition of ions to the pore water by ionization of clay particles, to differences in the residence time of the interstitial and fracture water, or to salinity of the interstitial water at the time of its introduction into the bedded tuff.

REFERENCES

Abrahams, J. H., Jr., Weir, J. E., and Purtymun, W. D., 1961, Distribution of moisture in soil and near-surface tuff in the Pajarito Plateau, Los Alamos County, New Mexico: U.S. Geol. Survey Prof. Paper 424-D, p. D142-D145.

Bowers, W. E., 1963, Outline of the geology of the U12i and U12i.01 tunnels and lithology of the U12i.01 drill hole, Nevada Test Site: U.S. Geol. Survey TEI-842, open-file report, 23 p.

Byers, F. M., Jr., 1961, Porosity, density, and water content data on tuff of the Oak Spring Formation from U12e tunnel system, Nevada Test Site, Nye County, Nevada: U.S. Geol. Survey TEI-811, open-file report, 28 p.

Cattermole, J. M., and Hansen, W. R., 1962, Geologic effects of the high-explosive tests in the USGS tunnel area, Nevada Test Site: U.S. Geol. Survey Prof. Paper 382-B, p. B1-B31.

Clebsch, Alfred, Jr., 1958, Ground water, in Geologic effects of the Rainier underground nuclear explosion: a summary progress report of the U.S. Geological Survey Investigations: U.S. Geol. Survey TEI-355, open-file report, 134 p.

______1960, Ground water in the Oak Spring Formation and hydrologic effects of underground nuclear explosions at the Nevada Test Site: U.S. Geol. Survey TEI-759, open-file report, 29 p.

______1961, Tritium age of ground water at the Nevada Test Site, Nye County, Nevada: U.S. Geol. Survey Prof. Paper 424-C, p. C122-C125.

Clebsch, Alfred, Jr., and Barker, F. B., 1960, Analyses of ground water from Rainier Mesa, Nevada Test Site, Nye County, Nevada: U.S. Geol. Survey TEI-763, open-file report, 22 p.

Clebsch, Alfred, Jr., and Winograd, I. J., 1958, Geological Survey investigations in the U12e.02 tunnel, Nevada Test Site: Part IV. Ground water: U.S. Geol. Survey TEM-728 (Preliminary draft), p. 23-30, 31-36.

Dickey, D. D., and Emerick, W. L., 1961, Interim report on geologic investigations of the U12b tunnel system, Nevada Test Site, Nye County, Nevada: U.S. Geol. Survey TEI-799, open-file report, 13 p.

Dickey, D. D., and McKeown, F. A., 1959, Geology of Dolomite Hill, Nevada Test Site, Nye County, Nevada: U.S. Geol. Survey TEI-755, open-file report, 64 p.

Diment, W. H., and others, 1958a, Geological Survey investigations in the U12e.02 tunnel, Nevada Test Site: U.S. Geol. Survey TEM-728, open-file report, 37 p.

______1958b, Geologic effects of the Rainier underground nuclear explosion, a summary progress report of the U.S. Geological Survey Investigations: U.S. Geol. Survey TEI-355, open-file report, 134 p.

______1959a, Geological Survey Investigations in the U12b.01 tunnel, Nevada Test Site: U.S. Geol. Survey TEM-998, open-file report, 39 p.

______1959b, Geological Survey Investigations in the U12b.03 and U12b.04 tunnels, Nevada Test Site: U.S. Geol. Survey TEM-996, open-file report, 75 p.

Eakin, T. E., 1962, Ground-water appraisal of Ralston and Stonecabin Valleys, Nye County, Nevada: Nevada State Engineer Ground-Water Resources Reconn. Ser. Rept. 12, 32 p.

Emerick, W. L., 1962, Interim geological investigations in the U12e.06 tunnel, Nevada Test Site, Nye County, Nevada: U.S. Geol. Survey TEI-773, open-file report, 38 p.

Emerick, W. L., and Dickey, D. D., 1962, Interim geological investigations in the U12e.03a and U12e.03b tunnels, Nevada Test Site, Nye County, Nevada: U.S. Geol. Survey TEI-806, open-file report, 26 p.

Emerick, W. L., and Houser, F. N., 1962, Interim Geological investigations in the U12b.08 tunnel, Nevada Test Site, Nye County, Nevada: U.S. Geol. Survey TEI-814, open-file report, 23 p.

Gibbons, A. B., and others, 1963, Geology of the Rainier Mesa quadrangle, Nye County, Nevada: U.S. Geol. Survey Geol. Quad. Map GQ-215.

Hansen, W. R., and others, 1963, Stratigraphy and structure of the Rainier and USGS Tunnel areas, Nevada Test Site: U.S. Geol. Survey Prof. Paper 382-A, 47 p.

Hem, J. D., 1959, Study and interpretation of the chemical characteristics of natural water: U.S. Geol. Survey, Water-Supply Paper 1473, 269 p.

Hinrichs, E. N., and Orkild, P. P., 1961, Eight members of the Oak Spring Formation, Nevada Test Site and vicinity, Nye and Lincoln Counties, Nevada: U.S. Geol. Survey Prof. Paper 424-D, p. D96-D103.

Houser, F. N., and Poole, F. G., 1960, Structural features of pyroclastic rocks of the Oak Spring Formation at the Nevada Test Site: U.S. Geol. Survey Prof. Paper 400-B, p. B266-B268.

Keller, G. V., 1960, Physical properties of the Oak Spring Formation, Nevada: U.S. Geol. Survey Prof. Paper 400-B, p. B396-B400.

______1962, Electrical resistivity of rocks in the Area 12 tunnels, Nevada Test Site, Nye County, Nevada: Geophysics, v. 27, no. 2, p. 242-252.

Laraway, W. H., and Houser, F. N., 1962, Outline of geology of the U12j and U12j.01 tunnels, Nevada Test Site: U.S. Geol. Survey TEI-828, open-file report, 12 p.

McKeown, F. A., and Dickey, D. D., 1961, Interim report on geologic investigations of the U12e tunnel system, Nevada Test Site, Nye County, Nevada: U.S. Geol. Survey TEI-772, open-file report, 17 p.

Moore, J. E., 1961, Records of wells, test holes, and springs in the Nevada Test Site and surrounding area: U.S. Geol. Survey TEI-781, open-file report, 22 p.

Orkild, P. P., 1964, Paintbrush Tuff and Timber Mountain Tuff of Nye County, Nevada: U.S. Geol. Survey Bull. (in press).

Poole, F. G., and McKeown, F. A., 1962, Oak Spring Group of the Nevada Test Site and vicinity, Nevada: U.S. Geol. Survey Prof. Paper 450-C, p. C60-C62.

Poole, F. G., and Rooler, J. C., 1959, Summary of some physical data from five vertical drill holes over the U12b.04 (Evans) explosion chamber, Nevada Test Site, Nye County, Nevada: U.S. Geol. Survey TEI-762, open-file report, 32 p.

Ross, C. S., and Smith, R. L., 1961, Ash-flow tuffs: Their origin, geologic relations, and identification: U.S. Geol. Survey Prof. Paper 366.

Schoff, S. L., and Moore, J. E., 1964, Chemistry and movement of ground water, Nevada Test Site: U.S. Geol. Survey TEI-838, open-file report, 75 p.

Schoff, S. L., and Winograd, I. J., 1961, Hydrologic significance of six core holes in carbonate rocks of the Nevada Test Site: U.S. Geol. Survey TEI-787, open-file report, 97 p.

Theis, C. V., 1935, The relation between the lowering of the piezio-metric surface and the rate and duration of discharge of a well using ground-water storage: Am. Geophys. Union Trans., pt. 2, p. 519-524.

______1938, The significance and nature of the cone of depression in ground-water bodies: Econ. Geology, v. 33, no. 8, p. 889-902.

Walker, G. E., 1962, Ground water in the Climax Stock, Nevada Test Site, Nye County, Nevada: U.S. Geol. Survey TEI-813, 48 p.

Winograd, I. J., 1963, A summary of the ground-water hydrology of the area between the Las Vegas Valley and the Amargosa Desert, Nevada: U.S. Geol. Survey TEI-840, open-file report, 79 p.

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

PREPARED ON BEHALF OF THE U.S. ATOMIC ENERGY COMMISSION
TEI-862

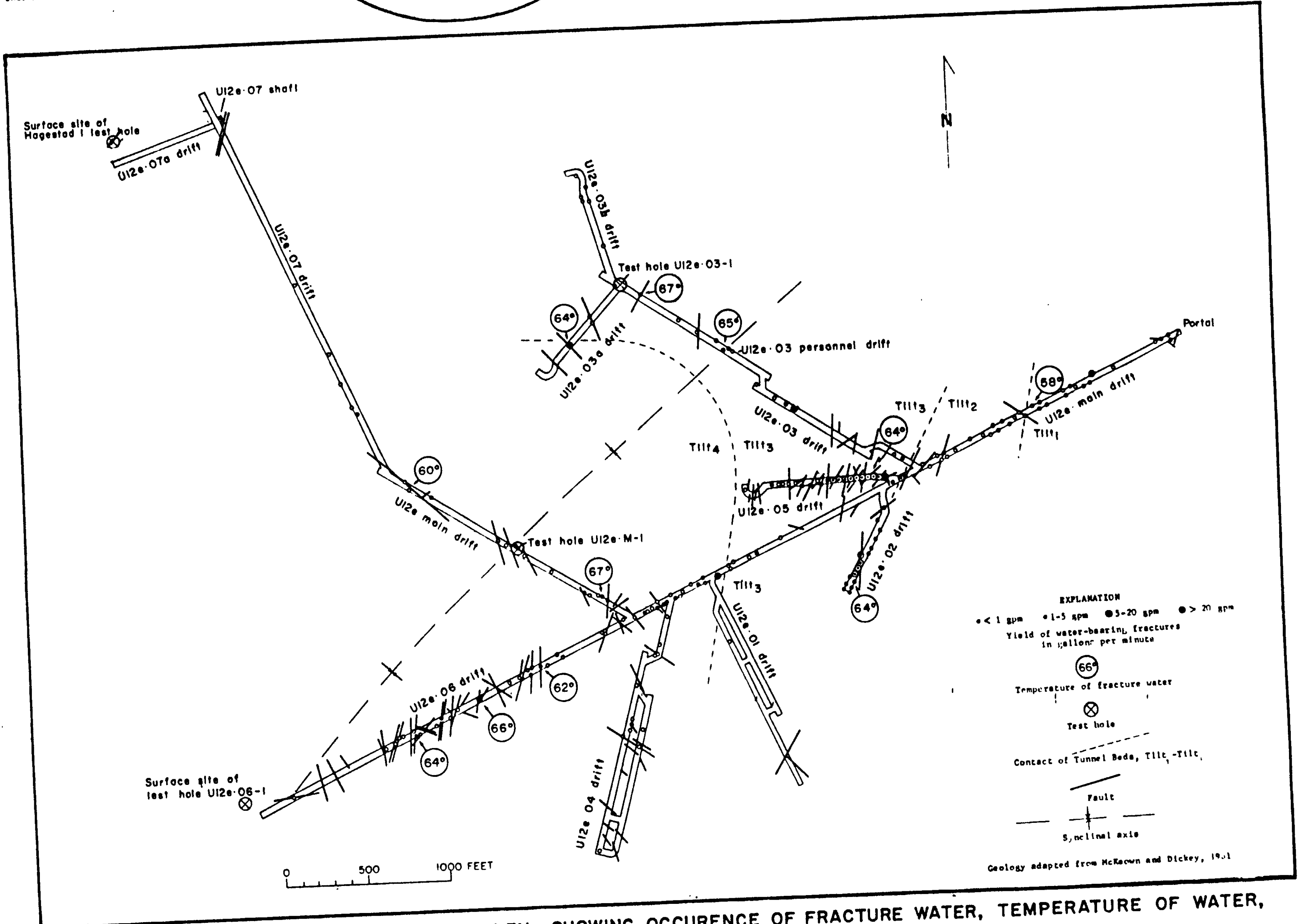


FIGURE 5. PLAN OF THE U12e TUNNEL COMPLEX, SHOWING OCCURENCE OF FRACTURE WATER, TEMPERATURE OF WATER, TEST WELLS, AND GEOLOGY

PLEASE REPLACE IN POCKET
IN BACK OF BOUND VOLUME

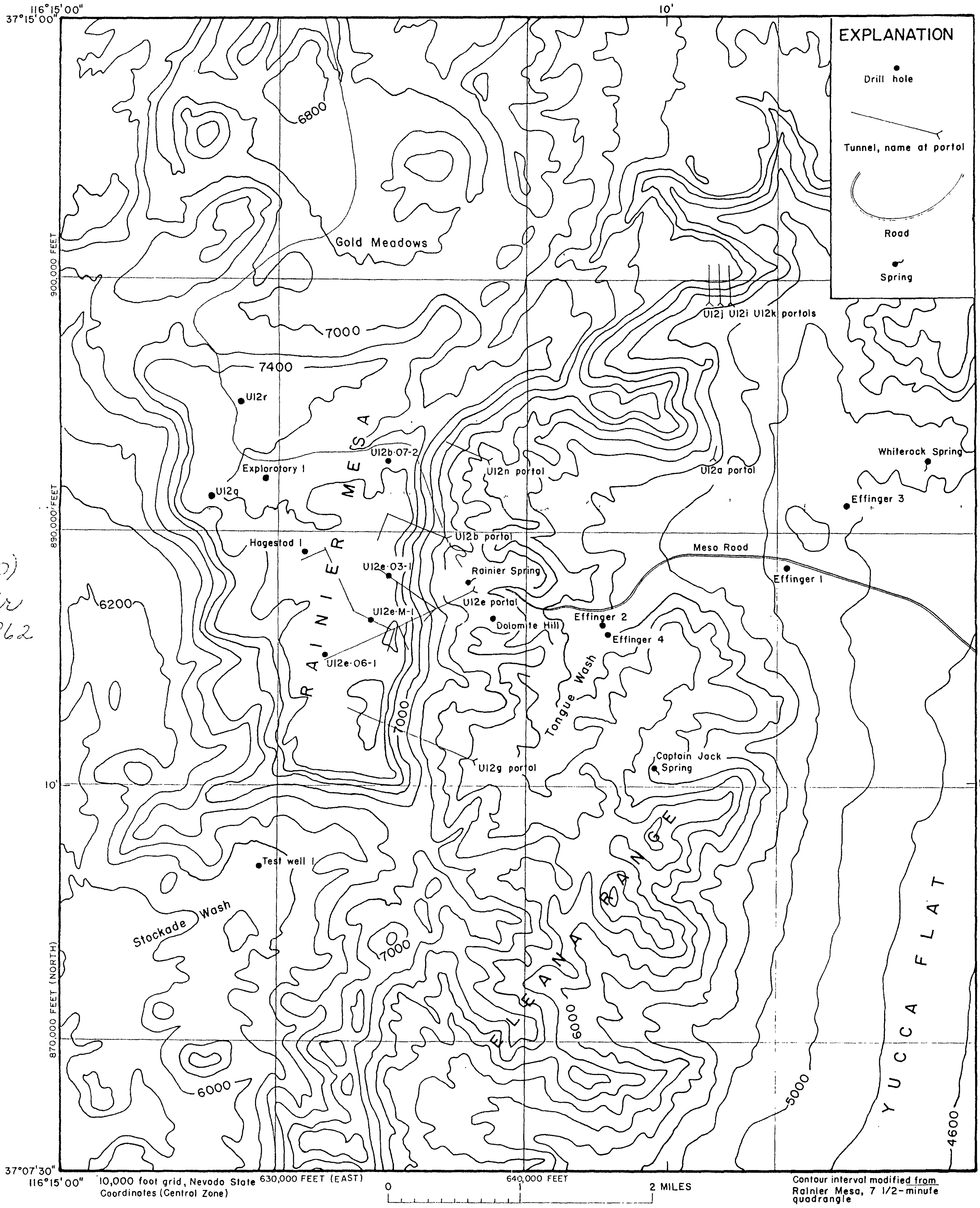


FIGURE 2. GENERALIZED TOPOGRAPHIC MAP OF THE RAINIER MESA QUADRANGLE, SHOWING LOCATIONS OF SPRINGS, TUNNELS, AND DRILL HOLES

PLEASE REPLACE IN POCKET
IN BACK OF BOUND VOLUME

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

PREPARED ON BEHALF OF THE U.S. ATOMIC ENERGY COMMISSION
TEI-862

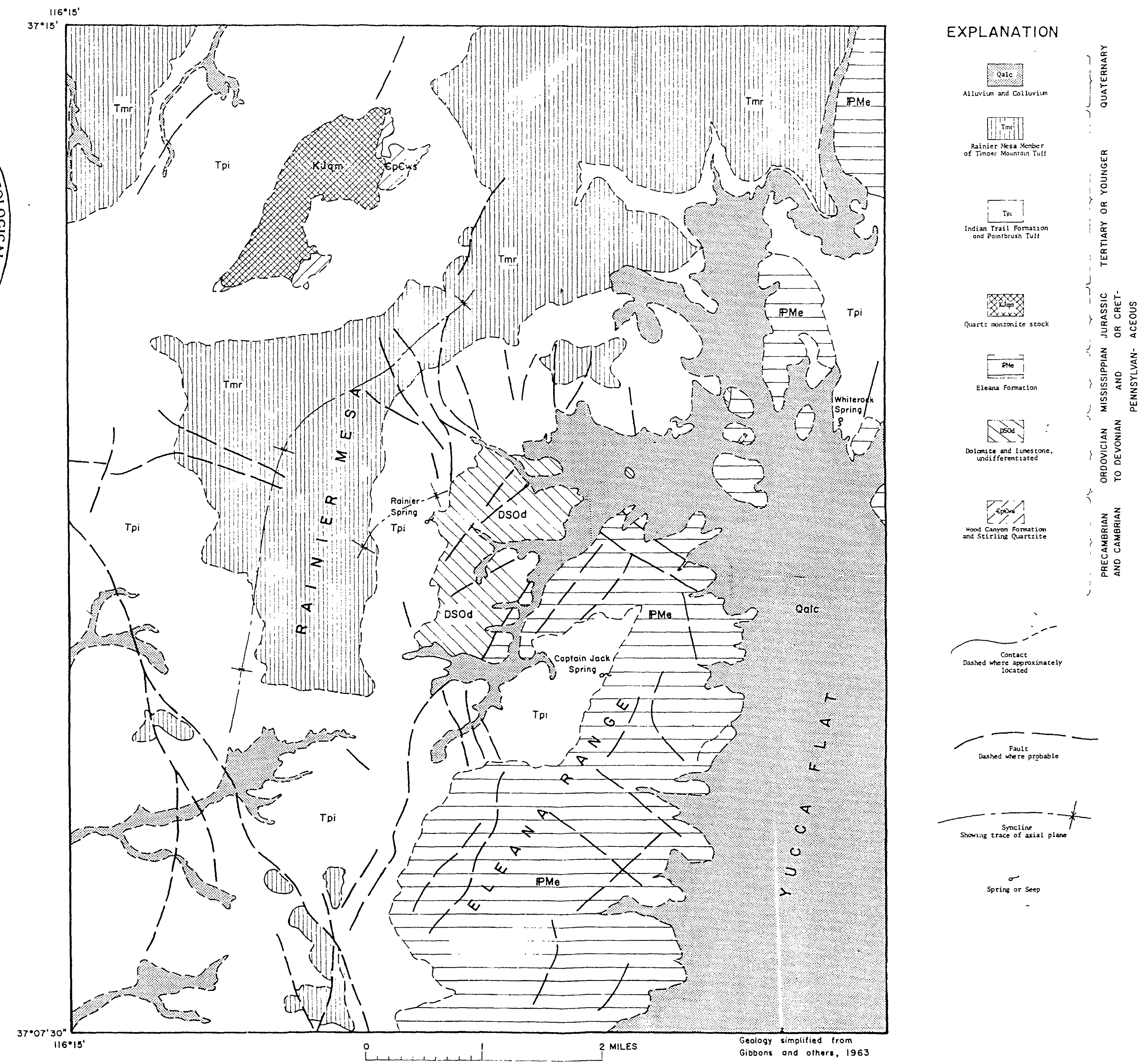


FIGURE 3. GENERALIZED GEOLOGIC MAP OF THE RAINIER MESA QUADRANGLE

66-139

Table 1.--Summary of the hydraulic properties and lithology of tuff underlying Rainier Mesa

Hydrologic unit of this report	Formal geologic name: Formation	Formal geologic name: Member	Lithology	Thickness (feet)	Interstitial permeability (gpd/ft²)1/: Number of samples	Interstitial permeability (gpd/ft²)1/: Average	Interstitial permeability (gpd/ft²)1/: Range	Interstitial porosity (percent): Number of samples	Interstitial porosity (percent): Average	Maximum specific capacity2/	Effective permeability3/
Welded or partially welded tuff	Timber Mountain Tuff	Rainier Mesa	Welded and partially welded tuff (caprock of Rainier Mesa)	270-550	6 (10)	0.01 (0.006)	0.0002-0.03 (0.00002-1.1)	37	14	--	Fracture
Friable-bedded tuff	Paintbrush Tuff	Tiva Canyon	Welded and partially welded tuff	0-about 80	--	--	--	--	--	--	Fracture
Zeolitic-bedded tuff		Stockade Wash	Nonwelded to partially welded pumiceous tuff, base locally zeolitic	0-about 230	--	--	--	--	--	--	Fracture
Welded or partially welded tuff		Bedded tuff (informal local unit)4/	Bedded-friable vitric tuff	100-1,000	2 5 5/	3.7 0.46	3.3-4.1 0.22-0.89	8	40	--	Interstitial
			Zeolitic tuff in lower 150 feet on east side of Rainier Mesa		11 (5)	0.2 (0.03)	0.0003-1.0 (0.002-0.49)	319	30	--	Fracture
		Grouse Canyon, upper part	Welded tuff, lenticular and local	0-70	1	0.0006	--	4	19	--	Fracture
Friable-bedded tuff		Grouse Canyon, lower part	Friable vitric tuff in upper portion, zeolitic tuff in lower portion	45-120	(9)	(0.21)	(0.07-1.1)	40	40	--	Fracture
Welded or partially welded tuff		Tub Spring	Welded tuff	0-about 400	--	--	--	--	--	--	Fracture
Zeolitic-bedded tuff	Indian Trail	Informal local units (includes Tunnel Beds 1-4, or $Tilt_1$-$Tilt_4$) 6/	Zeolitic-bedded tuff ($Tilt_4$)	265-375	2 (9)	0.02 (0.002)	0.0003-0.03 (0.00009-0.3)	166	38	--	Fracture
			Zeolitic-bedded tuff ($Tilt_3$)	100-200	42 (4)	0.003 (0.0007)	0.00008-0.04 (0.00001-0.004)	142	35	0.04	Fracture
			Zeolitic-bedded tuff, contains pisolite beds and locally a welded tuff at the top ($Tilt_2$)	120	(12)	(0.0004)	(0.0007-0.03)	28	32	0.02	Fracture
			Zeolitic-bedded tuff ($Tilt_1$)	200-210	(3)	(0.001)	(0.0005-0.004)	31	25	0.01	Fracture

1/ Permeability, in Geological Survey units, gallons per day per square foot (gpd/ft²); this unit is approximately equivalent to 55 millidarcies. Permeability to fresh water by U. S. Geological Survey, Denver, Colorado; permeability to brine (in parentheses) by Core Labs, Inc., Denver, Colorado.

2/ Specific capacity unit is gallons per minute per foot of drawdown (gpm/ft). The specific capacity data cited are maximum values because bailing was of short duration and fraction of water bailed was taken from storage in the bore. See table 3.

3/ Effective permeability is defined as the permeability, either interstitial (primary) or fracture (secondary), that is dominant in transmitting ground water to wells, or tunnels.

4/ This unit is equivalent to the Survey Butte Member of Poole and McKeown (1962).

5/ Gas permeability for sample of 5.

6/ These informal units are equivalent to the Tunnel Beds of Hansen and others (1963), and to the Lower Member of Poole and McKeown (1962).