UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

GEOLOGIC EFFECTS OF THE RAINIER UNDERGROUND NUCLEAR EXPLOSION

(A summary progress report of

U. S. Geological Survey Investigations)

By

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ABSTRACT

This report is a summary of U. S. Geological Survey investigations of the geological effects of the Rainier underground nuclear explosion which was detonated at the Atomic Energy Commission's Nevada Test Site on September 19, 1957. The 1.7 kiloton explosion took place 900 feet below the surface of the ground at the end of a tunnel driven into volcanic tuff of the Oak Spring formation. The rocks close to the explosion point were white to brown pumiceous rhyolitic tuffs that contain phenocrysts of quartz and feldspar biotite and xenoliths of older rocks embedded in a fine-grained matrix of heulandite, clay, β-cristobalite, and amorphous material. Unconnected open vesicles make up to 11.5 percent by volume of the rocks. In the natural state these rocks have an average porosity of 24 percent, a bulk density of 2.0, a water content of 14 percent by weight, an acoustic velocity of 8,300 feet per second, a compressive strength of roughly 4,000 psi at atmospheric pressure, and a tensile strength of roughly 100 psi. Under confining pressures greater than 10,000 psi the tuff will deform at least 20 percent with a consequent increase in density of about 8 percent.

Exploration of the rocks disturbed by the explosion has been carried out by one vertical hole and 3 near-horizontal holes and by tunneling toward the point of the explosion. This exploration has revealed a breccia zone extending 70 feet from the explosion chamber. The breccia contains radioactive glass, angular to subrounded blocks, 0.3 to 3 feet across in a

fine-grained matrix of comminuted tuff. The matrix is characterized by an abundance of hairline fractures which generally do not cross the phenocrysts or xenoliths, thus indicating that most of the deformation was taken up by the soft zeolitized matrix in which the phenocrysts, xenoliths, and glass are suspended.

From the breccia zone to at least 110 feet radially from the explosion chamber the tuffs are minutely fractured. The fractures are not visible megascopically but they are apparent in thin sections of the rock. Some of the fractures especially those near the shear zone are filled with an opaque larger scale non-radioactive material.

The edge of the breccia zone is known only in the Exploratory tunnel and nearby drill holes B, C, and D. Its extent in other directions, is not known. In drilling vertically from the surface a cavity 25 feet deep was encountered about 390 feet above the explosion point, closer to the explosion point the rocks were so friable that only sand was recovered during coring. However, interpretation of this cavity as meaning that the upper limit of the breccia zone is 390 feet above the explosion point is suspect. Natural open joints are common and the recorded cavity may be one of these. Moreover, the rock several hundred feet above the explosion point is naturally so friable that few core samples could be recovered before the explosion; the poor recovery in post-explosion drilling is therefore not meaningly.

Glass produced by the explosion is found in various colors (red, black, clear) and textures (massive, frothy, with and without inclusions) scattered through the breccia zone as fragments, droplets, and as thin coatings on some breccia blocks. The glass contains most of the explosion-produced or induced radioactivity. The glass and the radioactivity are largely confined to the breccia zone. Gamma radiation surveys of the drill holes and mapping in Exploratory tunnel has shown that the distribution of the glass and radioactivity is very irregular within the breccia zone. Most of the radioactivity is present several tens of feet below and to the northwest of the point of detonation.

Fracturing both in the tunnel and on the surface and spalling in the tunnel were observed at greater distances. The tunnel collapsed 200 feet from the explosion chamber. Spalling was severe in the tunnel from 200 to 400 feet radially from the explosion chamber and several new fractures were produced as distant as 1,100 feet. Four inches of movement were observed on a pre-existing fault 1,400 feet from the explosion. The surface effects were confined to small fractures largely along pre-explosion joints and to rock falls along the steep topographic scarp beneath which the explosion was detonated.

Anomalous temperatures measured one year after the explosion are below the boiling point of water as were the temperatures measured by the Lawrence Radiation Laboratory several months after the explosion. A minimum estimate of the fracturing total energy of the explosion remaining in the form of heat is about one-half. The rapid reduction of temperature after the explosion is attributed to heat transport by steam through fractures both natural and explosion-produced. Detectable temperature perturbations (2 degrees centigrade) extend to about 130 feet in the horizontal direction and about 80 feet vertically above the explosion point. The highest temperatures are about 40 feet below the explosion point. The fact that both the temperatures and radioactivity are highest below the explosion point probably indicates that at the time of the explosion a cavity was formed and then collapsed, thus bringing less radioactive and cooler material from above to the explosion point.

As a result of the explosion the rocks adjacent to the chamber were crushed and expanded, resulting in a breccia. Measurement of the changes of some of the physical properties of the rock fragment and matrix that make up the breccia has shown that the porosity increased about 30 percent; the permeability increased; the water saturation decreased about 30 percent; the acoustic velocity decreased about 70 percent; and the compressive strength reduced well over 50 percent. The decrease in water saturation is roughly equal to the increase in porosity, thus suggesting that little water was driven out by the explosion. However, much water was introduced during post-explosion drilling. Because of this and other uncertainties, the meaning of the post-explosion water saturation is not clear.

The highly fractured rocks near the breccia are characterized by low compressive strength, dilatational velocities and high permeability. The strength properties of the rocks increase beyond about 110 feet radially from the explosion chamber.

The Rainier explosion effected the water storage characteristics of the rock for as much as 200 to 400 feet from the explosion point. However because the principal aquifer under Rainier Mesa is more than 400 feet below the explosion point the rate and direction of movement of water and its storage characteristics were not effected.

Seismic effects were measured at distances of 5 to 300 kilometers from the explosion at Geological Survey stations and were recorded by other organizations as far away as Alaska. Ground motion was barely perceptible to observers 2.5 miles from the explosion. From a study of the ground motion caused by Rainier and the underground explosions in Oak Spring formation during Operation Hardtack-Phase II an empirical scaling relation was developed:

$$A = \frac{0.6 \pm 0.5\, W^{0.8 \pm 0.2}}{D^{2 \pm 0.2}}$$

where A is the maximum acceleration in units of gravity caused by an explosion of W kilotons at a distance of D kilometers. The relation applies to the frequency range 1.5 to 20 cycles per second, only to explosions in the bedded tuff of the Oak Spring formation, and only to tests of the same general design as Rainier and the Hardtack-Phase II tests. Factors such as the depth of alluvium at the seismograph stations and the degree of containment of the explosion will vary the maximum acceleration as much as 2 or 3 times.

The effects of the Rainier explosion are very briefly summarized in respect to some possible peacetime uses of underground nuclear explosions.

GEOLOGIC EFFECTS OF THE RAINIER UNDERGROUND EXPLOSION OF SEPTEMBER 19, 1957

(A summary progress report of Geological Survey investigations)

INTRODUCTION

By W. H. Diment

The Rainier explosion on September 19, 1957, was the first contained underground nuclear explosion conducted in the United States. The 1.7 kiloton explosion took place at the end of a tunnel in volcanic tuff 900 feet vertically below the surface of the ground at the Nevada Test Site, Nye County, Nevada. Principal facts are presented in table 2-1. The test was conducted by the Lawrence Radiation Laboratory (Johnson and others, 1958) under the auspicies of the U. S. Atomic Energy Commission.

Scope

This report contains the preliminary results of investigations conducted by the Geological Survey on behalf of the Albuquerque Operations Office of the Atomic Energy Commission for the purpose of providing geological, geochemical, geophysical, and hydrologic information necessary to understand the containment, seismic, and ground water aspects of underground nuclear explosions. Some of

Table 2-1.-- Principal facts concerning the preliminary high explosives and the Rainier tests

	10 ton high explosives test	50 ton high explosives test	Rainier nuclear test, 1.7 kilotons
Date	Feb. 21, 1957	April 5, 1957	Sept. 19, 1957
Time	1401:01 PST	0630:31 PST	0959:59.5 PDT
Latitude	37°12.1'N	37°12.2'N	37°11.7'N
Longitude	116°4.7'W	116°4.6'W	116°12.2'W
Elevation (feet)	5,585	5,585	6,615
Vertical distance to surface (feet)	123	174	900
Minimum distance to surface (feet)	92	165	820
Scale depth* (vertical cover)	570	470	760
Scale depth (minimum cover)	430	450	690
Size of room (feet)	5 x 8 x 8	12 x 12 x 14**	6 x 6 x 7
Average tunnel cross-section (feet)	5 x 7	5 x 7	6 x 7
Type of medium	---------Bedded volcanic tuff (saturated rocks)	(almost dry rocks)	----------------

* Scale depth equals the thickness of the rocks overlying the explosion point in feet divided by the cube root of the yield in kilotons.

**Sandbags reduced the volume of the room to 11 x 11 x 11.

the information is also pertinent to the peaceful uses of underground nuclear explosions.

The results presented are largely restricted to the effects of the Rainier explosion but a few data have been incorporated from the studies of the underground explosions in Operation Hardtack - Phase II. The results of the seismic effects of all the underground nuclear tests to date in the Oak Spring formation have been summarized by Stewart, Roller, and Diment (1959). The surface and underground fracturing caused by the Logan explosion (Operation Hardtack - Phase II) have been reported by McKeown and others (1958). Detailed data on properties of the rock surrounding the explosion chambers of the underground explosions in Hardtack - Phase II have been distributed to interested participants in draft form.

Information on units of the Oak Spring formation not directly affected by the Rainier explosion has been summarily treated or omitted from this report. This information, which is of importance in interpretation of the effects of other underground nuclear explosions, will be presented at a later time, as will the necessary details of experimental and field technique.

The investigations summarized in this report are not complete and many of the conclusions are tentative. Some special studies which may be of significance in the explosion phenomenon have not been included because the data is preliminary or because the interpretation is extremely uncertain. These include:

1) Many samples of glass have been studied, photographed, and analyzed chemically, petrographically and radiometrically. The work is not complete and it is too early to establish relations among the various parameters.

2) Mineralogical investigations of the affected material, particularly by X-ray and infrared techniques, are not complete.

3) Leaching tests are in progress on samples of the affected material, particularly on those of low activity in which explosion-produced glass is not obvious.

Acknowledgements

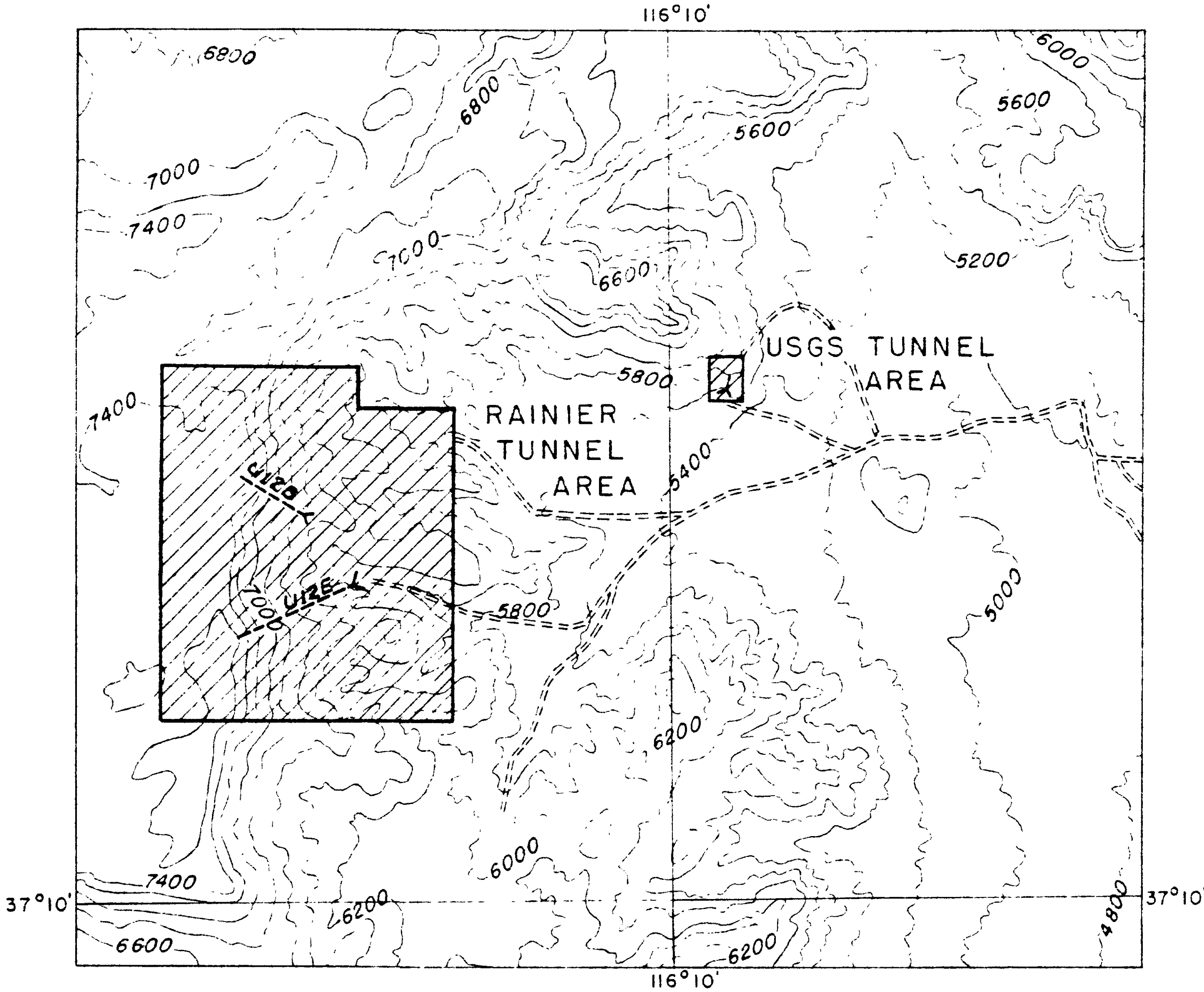
Appreciation is expressed to many members of the Nevada Test Organization whose cooperation, guidance and assistance at a time of considerable operational difficulty facilitated the investigation. The help of M. E. Smith and L. A. Woodruff of the Las Vegas Branch of the AEC, D. T. Schueler, R. G. Preston and D. E. Neilson of the Lawrence Radiation Laboratory and D. McGregor of the Reynolds Electrical and Engineering Company is acknowledged.

The following acknowledgements are made to the Geological Survey personnel not cited in the text: C. H. Sandberg assisted in collection of the temperature data and advised on thermistor calibration and reduction of data. F. E. Currey made many of the gravity observations and assisted in their reduction.

Preliminary high explosives tests

Two high explosives tests, using 10 and 50 tons of 60 percent nitroglycerin gelatin, were conducted by the Geological Survey prior to the Rainier experiment for the purpose of providing scaling and other information that would be needed in designing a contained nuclear explosion. These tests were conducted at the USGS tunnel which is about 3 miles from the Rainier site (figs. 2-1 and 2-3) in rock similar to those in which the Rainier explosion took place. A plan of the USGS tunnel showing the location of the USGS tunnel and the location of the sandbags used to stem the explosion is given in figure 2-3 and the principal facts concerning the explosions are given in table 2-1. A detailed discussion of the design and effects of the high explosives tests can be found in reports by Cattermole (1958), Diment and Dobrovolny (1957) and Hansen and Lamke (1958).

The 10 ton explosion blew out the tunnel by fracturing the rock at the first turn. Spalling was progressively more severe from the portal to station 2+60 (fig. 2-3) but the tunnel could be reentered to station 2+60. Post-shot excavation revealed that the explosion chamber had been enlarged from its original 5 x 8 x 8 feet size to a roughly rectangular cavity 27 feet wide, 45 feet long in a direction parallel to the main tunnel, and 24 feet high above the original floor level. Displacements as much as 2.5 feet



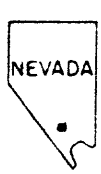


FIGURE 2-1: INDEX MAP SHOWING LOCATION OF RAINIER AND USGS TUNNEL AREAS, NEVADA TEST SITE, NYE COUNTY, NEVADA

1 0 1 MILE

SCALE

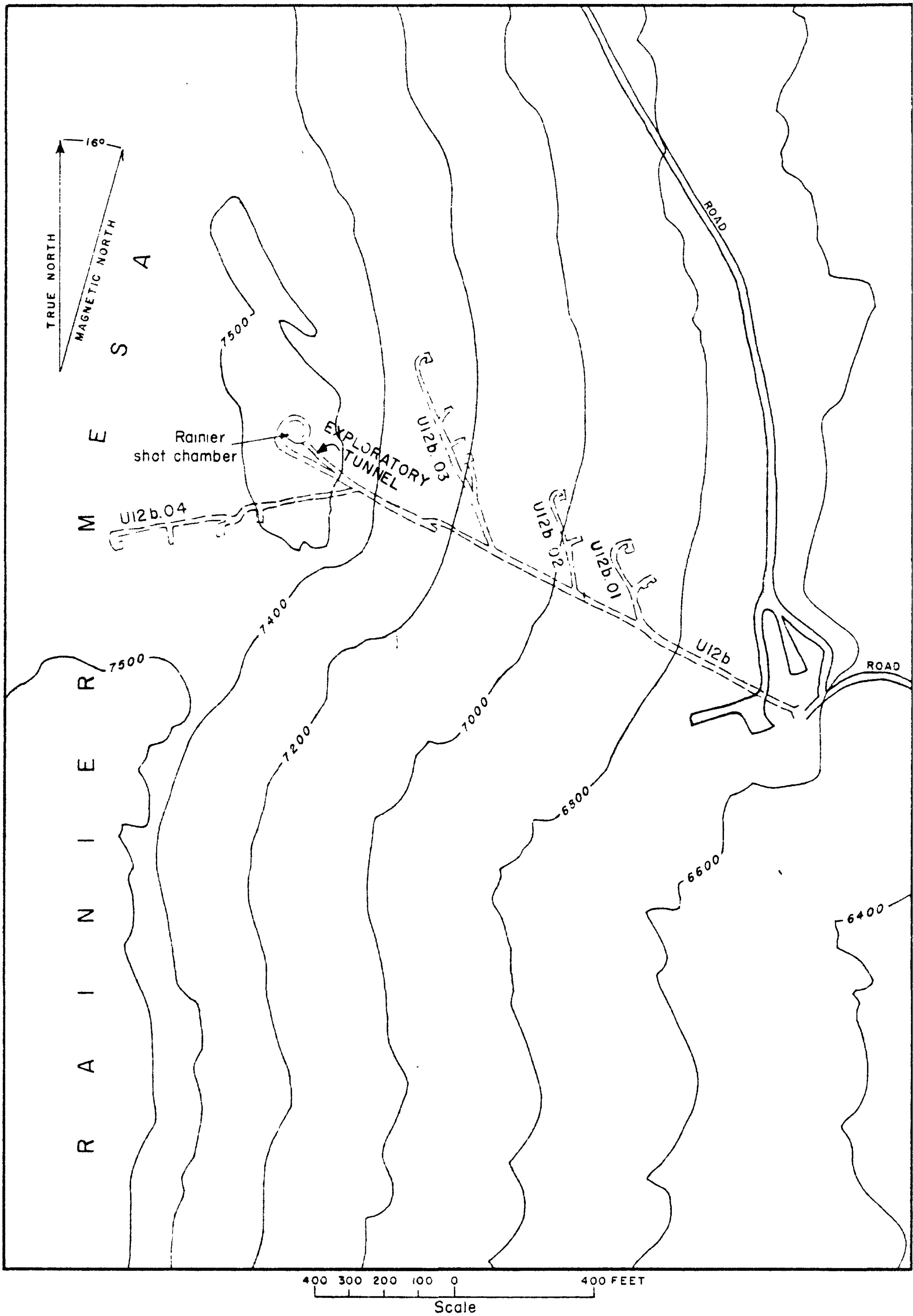


FIGURE 2-2: INDEX MAP SHOWING LOCATION OF RAINIER TUNNEL, RAINIER MESA, NEVADA TEST SITE, NYE COUNTY, NEVADA

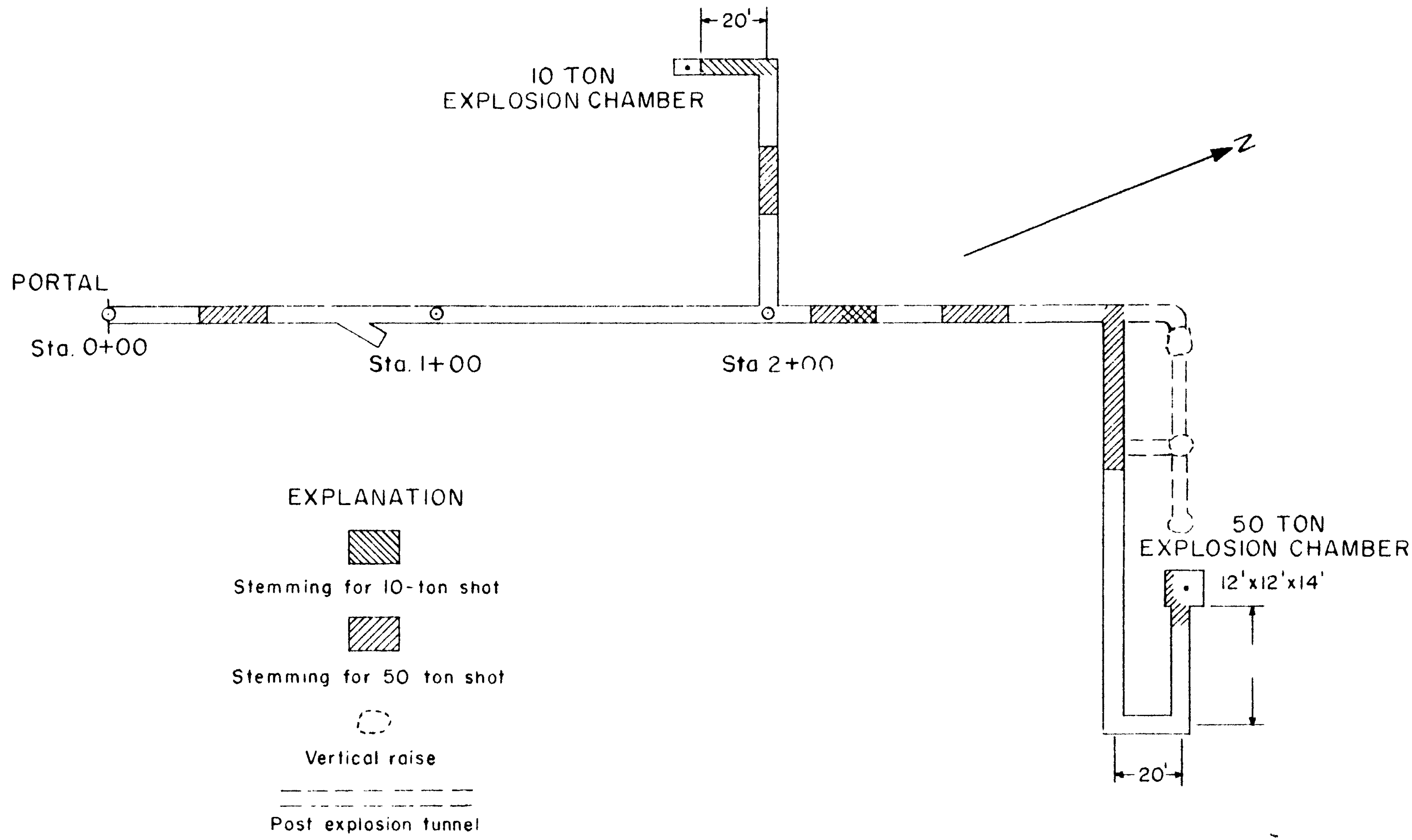


FIGURE 2-3: PLAN OF U.S.G.S. TUNNEL, NEVADA TEST SITE, NYE COUNTY, NEVADA

0 50 100 Feet
Scale

were observed in the roof of the tunnel. Maximum permanent displacements of the surface were slightly more than 1 foot. In addition to the material expelled through the tunnel and out of the portal, gaseous explosion products escaped through the fractures to the surface. Some finely divided solids also escaped because powdered MnO_2 placed in the chamber as a tracer was found on the surface. Severe fracturing and opening of tight joints occurred within a radius of 150 feet of the explosion. Most of the fracturing was along preexisting faults, joints, and bedding planes.

The 50-ton explosion did not blow out through the tunnel, although decomposition products of the explosives were detected on the surface. After the explosion the sandbagged sections near 2+20 and 2+50 were removed; the latter section was squeezed so that its cross sectional area was reduced by one-half. The tunnel was filled with broken rock between the second section of sandbags and the explosion chamber. The tunnel was redriven to station 3+05 after the explosion where the sandbags were so tightly compressed that a new tunnel parallel to, and about 20 feet north of, the preshot tunnel had to be made. The postshot tunnel was driven to within about 20 feet of the explosion point where a zone of explosion-blackened rubble was encountered. Raises from the tunnel (fig. 2-3) at about 50 and 80 feet from the explosion encountered this rubble zone at elevations of 12 and 30 feet above the floor. It is concluded from these facts that the zone of fracturing extends upward from the explosion point at a shallow angle. The surface effects of the 50 ton explosion were much more severe than those of the 10 ton explosion despite the fact that the scale depths are comparable. High speed motion pictures (by Edgerton, Germeshausen and Grier, Inc.) of the shot showed that the maximum transient displacement of the surface was about 20 feet. After the shot, fractures exhibiting displacements as great at 5 feet, widths as much as 2.5 feet and open to depths as great as 30 feet were observed near ground zero.

The high explosives tests indicate that:

1) High explosives at scale depths of 430-450 will fracture the Oak Spring tuff so that gases and finely divided solids will escape to the surface.

2) Most of the explosion-produced fracturing followed pre-existing joints and faults.

3) Improper stemming will permit escape of material through the tunnel.

4) Under conditions existing at the 10 ton shot chamber an open cavity can be sustained in the Oak Spring formation after an explosion.

5) Explosions at approximately the same scale depth in the same medium can produce considerably different degrees of fracturing, depending on many factors, such as differences in topography, differences in faulting, jointing and bedding, size of the explosion chamber, the amount of stemming and the effects of previous nearby explosions.

6) The greater part of the explosion-produced rubble consisted of angular blocks from several inches to as much as several feet across.

Characteristics of the rocks surrounding Rainier chamber

Stratigraphic and structural setting

By V. R. Wilmarth and R. E. Wilcox

The Rainier (U12b) tunnel, the site of the Rainier nuclear explosion, was driven northwestward for about 1,680 feet into Rainier Mesa, a prominent topographic feature of the northwest part of the Nevada Test Site (figs. 2-1 and 2-2). Rainier Mesa is underlain by the Oak Spring formation of Tertiary Age; the Rainier tunnel is entirely within this formation.

The Oak Spring formation in vicinity of the tunnel is about 1,900 feet thick and is composed of welded and nonwelded tuffs. The welded tuffs are hard, resistant rocks that form prominent cliffs or outcrop. The thickest welded tuff unit caps Rainier Mesa. The non-welded tuffaceous rocks are friable, to compact, indurated rocks that crop out on steep slopes. Both the non-welded and welded tuffaceous rocks are rhyolitic in composition.

The tuffaceous rocks of the Oak Spring formation strike N. 55° - 83° E. dip 5° - 28° NW (figs. 2-4 and 3-1). Near the portal of the Rainier tunnel the bedding has an average strike N. 77° E. and dip of 15° NW. Northeast-trending folds, with amplitudes of 50 to 120 feet, and north- to northwest-trending faults, with vertical displacements of as much as 50 feet, cause local deflections in the general structure. Joints are more numerous in the hard, welded tuffs than elsewhere. The two dominant joint sets trend north and northwest and dip steeply.

The Oak Spring formation is underlain, unconformably, by an unknown thickness of Paleozoic sedimentary rocks; the uppermost Paleozoic rocks are

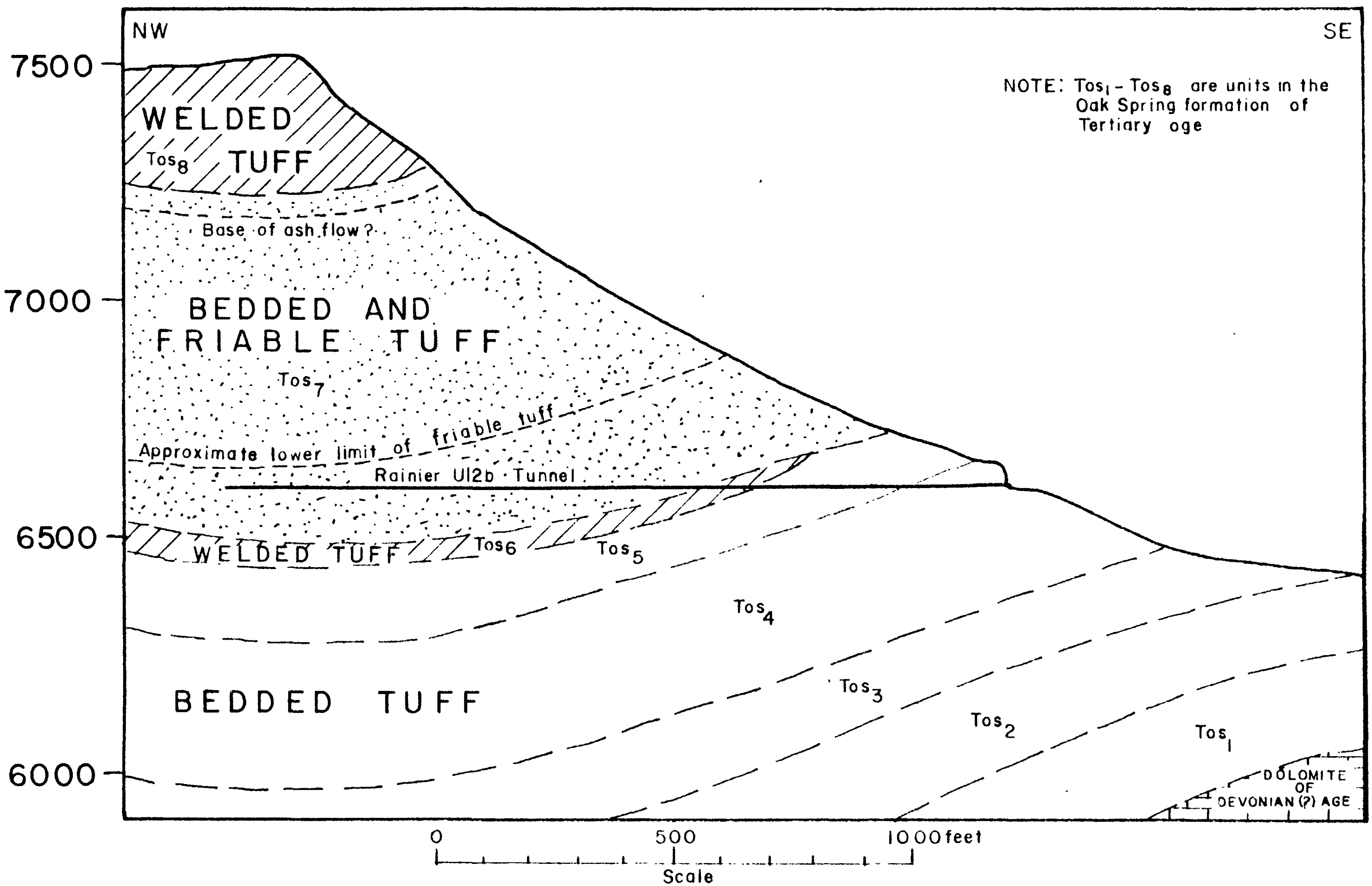


FIGURE ~~5~~ 3-1A - GENERALIZED GEOLOGIC CROSS SECTION ALONG U12b TUNNEL, RAINIER MESA, NYE COUNTY, NEVADA dolomites. These rocks strike N. 10°-63° E. and dips 10°-70° NW. The contact between the Tertiary and Paleozoic rocks on the east side of Rainier Mesa has an average strike of N. 30° E. and dip of 20° NW.; local relief along the contact is about 50 feet. This contact is about 1,200 feet below the Rainier explosion chamber.

The Oak Spring formation

The tuffaceous rocks of the Oak Spring formation in the tunnel area (figs. 2-2 and 2-4) have been divided into eight lithologic units (table 3-1) that are designated, in ascending order--Tos_1 to Tos_8 (Hansen and Lemke, 1958). The rocks composing these units are fine- to coarse-grained, bedded to massive tuffs, welded tuff, tuffaceous sandstones, tuff breccias, and agglomerates. The rocks of the Oak Spring formation are siliceous containing from 65 to 75 percent SiO_2. The tuffs are commonly porphyritic rocks with phenocrysts, principally quartz and feldspar, and lapilli in a fine-grained groundmass containing shards and their alteration products. Heulandite, β-cristobalite, clay minerals and glass are common in the groundmass. Vesicles average 6 percent of the volume of the non-welded tuffs, but only 3.5 percent of the volume of welded tuffs.

The major rock units in the Rainier tunnel area are described in table 3-1; average chemical and mineralogic analyses of the units are in tables 3-2 and 3-3.

Table 3-1.--Generalized stratigraphic section of Oak Spring formation, Rainier Mesa, Nye County, Nevada

Lithologic unit	Thickness (feet)	Description
Tos_8	270	Two ash flows of welded tuff. The lower 130 to 140 feet is quartz latitic tuff; dark gray to gray purple; grades downward into coarse pumiceous nonwelded tuff of Tos_7. The upper part is rhyolitic welded tuff; pale red purple; caps Rainier Mesa. The welded tuffs are resistant to erosion and crop out as cliffs. Near vertical joints are abundant.
Tos_7	720	Tos_7 has been divided into 3 subunits designated from youngest to oldest as a, b, and c. Subunit _a_ is about 50 feet thick; a light brown-gray to orange-brown poorly sorted, massive fine to coarse indurated pumiceous tuff. Subunit _b_ is about 490 feet thick; white, gray, tan to red-brown granular tuff and interbedded gray tuffaceous sandstones; pumice fragments are abundant. The rocks are soft, friable and poor to well bedded; outcrops sparse along the east slope of Rainier Mesa. Subunit _c_ is about 180 feet thick; white-gray locally brown, granular, fine to coarse, indurated tuff. The Rainier explosion chamber and U12b.02, 03 and 04 tunnels are in subunit _c_.
Tos_6	0-75	Olive-brown to purplish red fine to coarse, well-bedded welded rhyolitic tuff; stands in near vertical ledges; unconformably underlies Tos_7.
Tos_5	98-125	Greenish-gray to yellowish-gray fine to coarse, well-bedded pumiceous tuff; forms ledges; unconformably underlies Tos_6.
Tos_4	285	Light gray to green, pale brown to white, in part mottled, fine to medium nonwelded pumiceous tuff in beds from 2 to 15 feet thick; yellow porcelanic beds up to several feet thick forms ledges.
Tos_3	100	Pink, red, purple, light gray to buff nonwelded pumiceous tuff with some tuffaceous sandstones; basal bed is dark red, and forms a blocky outcrop. Most beds are 12 to 35 feet thick. Locally Tos_3 is as much as 170 feet thick.

Table 3-1.--Generalized stratigraphic section of Oak Spring formation, Rainier Mesa, Nye County, Nevada--Continued

Lithologic unit	Thickness (feet)	Description
Tos_2	120	Light gray to buff, locally red to purple, fine to coarse, bedded to massive, nonwelded tuffs; a thick bedded tuffaceous sandstone forms at tops of unit.
Tos_1	210	Purplish to pink, fine, nonwelded tuff, conglomerate as much as 5 feet thick, locally forms base of the unit.
Total thickness	1,803 to 1,905	

Table 3-2. Summary of the average chemical composition (percent by weight) of Oak Spring formation, Nevada Test Site, Nye County, Nevada

Lithologic units	Tos_8	Tos_7 1/ a	Tos_7 1/ b	Tos_7 1/ c	Tos_6	Tos_5	Tos_4	Tos_3	Tos_2	Tos_1
No. of analyses	2			47	2	2	10			
SiO_2	71.4			65.8	74.7	66.5	69.9			
Al_2O_3	14.4			12.5	11.3	13.4	12.3			
Fe_2O_3	1.3			2.4	3.4	2.2	1.4			
FeO	.35			.22	.05	.26	.08			
MgO	.48			1.0	.13	.86	.29			
CaO	1.2			2.4	.29	2.8	1.			
Na_2O	3.8			1.3	4.1	1.9	1.9			
K_2O	4.9			2.3	4.9	2.8	4.5			
H_2O	1.7			11.5	.69	8.8	8.3			
TiO_2	.29			.29	.21	.28	.21			
CO_2	.06			.06	.07	.15	.05			
P_2O_5	.06			.09	.01	.01	.02			
MnO	.06			.14	.15	.04	.05			

1/ Tos_7

A. Upper indurated tuff b. Middle friable tuff c. Lower indurated tuff

Table 3-3.-- Summary of the average mineral composition (percent by volume) of Oak Spring formation, Nevada Test Site, Nye County, Nevada

Lithologic unit	Tos_8	Tos_7 1/ a	b	c	Tos_4
Number of analyses	5			47	4
Phenocrysts	16.4			14.7	14.3
Quartz	4.9			1.5	5.2
Alkali feldspar	7.4			5.0	4.3
Plagioclase	3.8			5.9	4.0
Biotite	.2			1.7	.3
Pyroxene and amphibole	2/			.12	---
Magnetite	.15			.48	.5
Xenoliths	----			4.9	1.6
Shards and lapilli	83.6 3/			74.6	80.7
Heulandite	----			27.0	Nd 4/
Quartz	Dominant			----	Nd
Montmorillonite	----			15.9	Nd
- cristobalite	Present			9.8	Nd
Feldspar	Dominant			----	Nd
Biotite	----			.5	Nd
Amorphous material	Present			21.4	Nd
Vesicles	3.5			5.8	7.9

1/ Tos_7 a. Upper indurated tuff
b. Middle friable tuff
c. Lower indurated tuff

2/ Not present

3/ Quartz and feldspar are the dominant minerals; glass comprises most of the amorphous material.

4/ Nd = not determined

The Rainier tunnel is primarily in unit Tos_7; the outcrop of this unit was divided into three subunits (a, b, c) and, in the detailed mapping of the Rainier tunnel, subunit c was divided into eleven smaller lithologic units designated by letters ranging from A to Z (fig. 3-1). The Rainier chamber is in unit Z, the youngest rock exposed in the tunnel. In post-shot studies, unit V (of Tos_7, subunit c) and other rock units near the chamber, were studied intensively; the results of these investigations are summarized in tables 3-5, 3-6, 3-7, 3-8, and 3-9.

Physical properties of units Tos_1 to Tos_8

By G. V. Keller and E. C. Robertson

Physical properties (average values) of the eight major lithologic units of the Oak Spring formation are summarized in table 3-4. The measurements were made on drill cores and on hand specimens collected from tunnels and from outcrops. The properties measured, with preliminary estimates of the accuracies of the measurements in terms of plus and minus percentages of the average values (table 3-4), are as follows: porosity±25 percent; bulk density±5 percent; water content±15 percent; bulk density±5 percent; grain density±3 percent; permeability±100 percent; velocity±5 percent, thermal measurements± 25 percent, and strengths±40 percent. For example, if the average porosity given is 14 percent, then a true average porosity is probably within the range 14±2.10 percent.

Table 3-5 .--Description of lithologic units near Rainier explosion chamber, Rainier Mesa, Nye Co., Nev.

Unit	Thickness (in feet)	Description	Remarks
S	8 to 9	Reddish-brown and white massive tuff. Color boundaries are irregular and lateral and vertical gradations between brown and white tuff are common. Abundant white, yellow-green, silt-to pebble-size fragments; sand-and granule-size fragments are principally feldspar and lithic fragments. The matrix is pumiceous material that contains red-brown glass.	Exposed in U12b.02 and lateral tunnels.
T	8	Soft white massive tuff. Many rounded dark red and gray metavolcanic(?) rock fragments in a matrix of silt- and clay-size pumiceous material.	Well exposed in U12b.02 and .03 tunnels and in the U12b.02 explosion chamber.
U	16	Interlayered well-bedded reddish-brown and white tuff. disseminated white devitrified pumice fragments as much as one-half inch across; locally abundant granules of dark metavolcanic rock.	Best exposure of unit U is in explosion chambers of U12b.02 and .03 tunnels.
V	30 to 32	Reddish-brown massive to poorly bedded lapilli tuff. Green-white medium to coarse lapilli tuff in irregular beds, as much as 3 feet thick, in the lower and upper parts of unit. Common irregular masses, as much as 5 inches across, of coarse-grained lapilli tuff in the upper part of unit.	Exposed in explosion chambers of U12b.02 and .03 tunnels and throughout all of U12b.04 tunnel. Exploratory tunnel beneath the Rainier chamber is in upper part of this unit.
W	1.5 to 2.5	Grayish-white lapilli tuff. Poorly bedded and contains many granules of metavolcanic rocks and lapilli in a micaceous, clayey matrix.	Only exposed in U12b.03 tunnel.
X	4 to 5	Reddish-brown massive lapilli tuff. Moderately well indurated. Abundant white altered pumice and rock fragments, as much as one-half across, in silt-clay size matrix.	Exposed only in U12b.03 tunnel.

Table 3-5 .--Description of lithologic units near Rainier explosion chamber, Rainier Mesa, Nye Co., Nev. (Cont.)

Unit	Thickness (in feet)	Description	Remarks
Y	2 to 3	Soft white-gray tuff. Abundant granule size lapilli fragments in a clay-like matrix. Unit Y thickens northeastward from Rainier explosion chamber but is absent at end of the Rainier tunnel southwest of the chamber.	Unit Y was well exposed in the Rainier explosion chamber. The only exposures are near alcove 1, in U12b.03 tunnel.
Z	3 (maximum)	Pink-white coarse lapilli tuff with a one foot thick gray tuffaceous sandstone at the base. Rocks of unit Z are soft to poorly indurated.	Rainier explosion chamber was in this unit. Where exposed in U12b.03 tunnel it is 3 feet thick.
Rocks from 0 to 85 feet above Rainier chamber.		Massive to thin-bedded zeolitized tuff. Soft to poorly indurated.	Data obtained from cores from UCRL, drill hole No. 3.

Table 3-6.--Average mineralogic composition of lithologic units near the Rainier Explosion chamber, Rainier Mesa, Nye County, Nevada1/

(in percent by volume)

Lithologic unit	S	T	U	V	W	X	Y	Z	0 to 43 feet above chamber	43 to 85 feet above chamber
no. of analysis	10	3	4	14	3	3	5	2	6	2
Phenocrysts	7.2	1.8	5.4	12.3	29	17	22.5	22.7	5 2/	9
Quartz	.4	.2	.4	.9	2	1.6	1.8	4.7		
Alkali feldspar	4.5	1.6	4.6	3.5	3.4	3.6	9.5	9.1		
Plagioclase	1.3	-	.05	5.9	16.8	9.4	7.1	7.4		
Biotite	.8	-	.1	1.6	5.4	1.7	3.4	.9		
Pyroxene and amphibole	-	-	.05	.2	.1	.1	.2	.2		
Magnetite	.2	-	.2	.2	1.3	.6	.5	.4		
Xenoliths	6.9	4.5	1.4	5.4	3.2	4.7	3.7	9.8	4	6
Shards and lapilli	81.6	87.9	89.9	77.8	63.4	72.4	67.9	56	90	85
Heulandite	22	35	42	24	20	22	28	23	25	
Montmorillonite	10	11	14	14	25	33	15	5	20	35
β-crystobalite	10	8	15	12	12	6	6	10	10	
Biotite	-	-	-	3	1	-	-	-	-	-
Glass 3/										50
Remainder	40	34	19	25	5	12	18	18	35	
Vesicles	4.3	5.8	3.3	4.5	4.4	5.9	5.9	11.5	1	2

1/ Mineralogic determination by E. N. Hinrichs, and R. E. Wilcox. Composition of shards and lapilli by x-ray diffractometer method by T. Botinelly. Percents estimated from peak heights and represent only rough approximations. Remainder comprises quartz, feldspar, crystalline components too small to show by x-ray and amorphous material.

2/ Not determined.

3/ Glass estimated from height of very broad peak extending from 18° to 30° two-theta.

Table 3-7.--Average chemical composition of lithologic units near the Rainier Explosion chamber, Rainier Mesa, Nye County, Nevada.

(in percent by weight)

Lithologic units (thickness in ft.)	S 8	T 8	U 16	V 30	W 2.5	X 5	Y 3	Z 2	Tuff above unit Z 83
Number of analyses	10	3	4	14	3	3	5	2	3
SiO_2	66.4	67.2	64.9	66.7	58.5	62.4	67.5	69.5	69.5
Al_2O_3	12.0	10.2	10.5	11.9	16.4	14.2	12.7	11.9	12.8
Fe_2O_3	2.7	2.0	2.4	2.5	4.0	3.4	1.9	1.5	1.5
FeO	.07	.06	.05	.23	.65	.34	.27	.15	.13
MgO	.8	.85	.8	1.0	1.4	1.4	1.0	1.0	.94
CaO	2.0	2.1	2.0	2.4	3.8	2.9	2.5	2.3	1.8
Na_2O	1.0	.42	.58	1.2	2.3	1.4	1.6	1.0	1.8
K_2O	2.5	2.3	2.2	2.1	1.9	2.3	2.6	2.3	2.6
H_2O+	6.0	7.4	16.2	5.6	4.6	4.8	4.9	5.3	4.7
H_2O-	6.0	7.1		5.7	5.2	6.0	4.5	4.6	3.9
TiO_2	.28	.11	.2	.33	.61	.48	.27	.19	.18
CO_2	.03	0.0	0.0	.07	.21	.10	.10	.05	.01
P_2O_5	.10	.08	.06	.10	.15	.12	.08	.09	.08
MnO	.12	.18	.11	.17	.28	.16	.08	.12	.06
eU	.002	.002	.004	.004	.001	<.001	.001	.002	.002
U	<.001	<.001	.001	.003	<.001	<.001	<.001	<.001	<.001

Samples were air dried before analysis. Analysis by rapid method by Dorothy Powers, P. L. D. Elmore, I. H. Barlow, H. H. Thomas, and Marvin D. Mack. Equivalent and chemical uranium analysis by L. Lee, W. W. Niles, G. T. Burrow, and D. L. Ferguson.

Table 3-9.--Summary of some physical properties of units of the Oak Spring formation near Rainier explosion chamber.

	Rock Units									
	S	T_2 1/	T_3	U_2 1/	U_3	V	W	X	Y	Z
Porosity (percent)										
Arithmetic mean	39.8	39.0	24.9	36.6	23.5	27.0	27.0	23.8	32.3	20.6
1 Standard deviation 2/	--	--	--	±4.2	±3.6	±6.5	--	±3.7	--	--
Number of samples	1	2	5	40	29	32	3	7	2	3
Dry bulk density (g/cc)										
Arithmetic mean	1.41	1.38	1.67	1.42	1.66	1.76	1.71	1.78	1.59	1.78
1 Standard deviation	--	--	--	±0.09	±0.13	±0.15	--	±0.12	--	--
Number of samples	1	2	2	34	12	32	3	7	2	3
Grain density (g/cc)										
Arithmetic mean	2.34	2.25	2.21	2.27	2.26	2.41	2.35	2.40	2.34	2.24
1 Standard deviation	--	--	--	±0.06	±0.08	±0.16	--	±0.11	--	--
Number of samples	1	2	2	34	19	32	3	7	2	3
Water content by weight (percent)										
Arithmetic mean	16.2	22.5	14.7	21.4	15.1	13.0	16.1	14.0	17.3	14.1
1 Standard deviation	--	--	--	±2.8	±3.3	±2.1	±1.7	±1.2	--	--
Number of samples	2	2	2	34	12	26	10	7	2	3
Natural state bulk density (g/cc)										
Arithmetic mean	1.73	1.78	1.95	1.81	1.96	2.02	1.97	2.03	1.86	2.02
1 Standard deviation	--	--	--	±0.07	±0.08	±0.14	--	±0.12	--	--
Number of samples	1	2	2	34	12	24	3	7	2	3

Table 3-9.--Summary of some physical properties of units of the Oak Spring formation near Rainier explosion chamber -- Continued

	Rock Units									
	S	T_2 1/	T_3	U_2 1/	U_3	V	W	X	Y	Z
Water content by volume (in grams/cc of natural-state rock)										
Arithmetic mean	0.389	0.399	0.283	0.388	0.293	0.257	0.301	0.285	0.321	0.284
1 Standard deviation	--	--	--	±0.049	±0.054	±0.039	--	±0.014	--	--
Number of samples	1	2	2	34	12	24	3	7	2	3
Natural temperature of explosion 3/ point (Deg. C).	--	--	--	--	--	--	--	--	--	16.3
Estimated accuracy										±0.2
Temperature gradient at 3/ explosion point (Deg. C/ft).	--	--	--	--	--	--	--	--	--	0.011

1/ Lithologic subunit composed of red-brown tuff

2/ Assuming a normal distribution

3/ Temperature determined by downward extrapolation of 100 feet from drill hole 100 feet west of Rainier ground zero

Unfortunately, not enough samples were available to make a study of each property for each unit, although data are almost complete for the two main varieties of tuff--welded and nonwelded. Despite the lacunae in table 3-4, some generalizations can be made.

1) Each property varies considerably within each of the eight units, hence small differences between the averages in table 3-4 have little significance. The increase in velocity with depth is real, however.

2) The greatest differences are between the welded tuffs of units Tos_6 and Tos_8 and the other units. The welded tuffs have higher strengths, higher elastic moduli, higher velocities (when unfractured), lower porosities, and higher thermal conductivities than the other units.

3) The permeability of samples to fluid is low as compared with that of petroleum reservoir sands. However, the bulk permeability due to fractures in the rock is locally very high.

The porosity of the welded tuff (Tos_8) is only about half that of the bedded friable tuff, but in view of the cementation of the rock, the porosity is surprisingly high (14 percent). Apparently the high porosity is due to unconnected pore space; this is also indicated by the low permeability of the welded tuff. Some units of the friable, non-welded tuff also have surprisingly low permeabilities to brine, which again suggests unconnected pores.

Preliminary interpretations of electric logs suggests that the 15 percent water content determined on the one unit is low; the water content may be nearly 30 percent in most of the unweathered friable tuffs. The dry thermal conductivity of the samples is low but this can be explained by the high values for porosity. Of course, the wet thermal conductivity is higher because conduction is better through the water in the pores than through the rock. The variation in velocity of sound is due to a number of complex factors; these are described in the footnotes to table 3-4.

In strength testing, all deviations and errors in experimental technique tend to decrease the values obtained so that an average figure is not necessarily the most accurate one. That is, the maximum value is more likely to represent the strength of the tuff in place in the ground than is the average value. The average values for strength therefore should be interpreted in terms of the range of measurements. Thus, the most likely value for the compressive strength of tuff in the natural state is 80 percent higher than the average, or 2,200 psi. The most likely values for all other strength determinations are 30 to 50 percent higher than the averages.

Figures for the static elastic moduli, Young's modulus (E), Poisson's ratio (P), and the rigidity modulus (G) are shown under the appropriate tests. Figures are also shown for the dynamic elastic moduli calculated from resonant frequencies of oscillating bars tested by the U. S. Bureau of Mines.

The effect of hydrostatic pressure on the compressive strength was investigated on 25 samples of tuff in the natural state under a hydrostatic pressure of 1,000 psi (table 3-4); and stress-strain curves of a series of 7 tests under various hydrostatic pressures are shown in figure 3-2. The effect of the hydrostatic pressure is to cause an increase of rupture strength; stated roughly, the increase is linear at about 2 to 3 times the hydrostatic pressure.

For hydrostatic pressures above 10,000 psi, the non-welded tuff will deform to strains of at least 20 percent without rupture. The density of samples deformed to 20 percent was increased by 8 percent.

Rocks near the Rainier chamber

By R. E. Wilcox, V. R. Wilmarth, C. C. Hawley, and G. E. Manger

The Rainier explosion affected the rocks in the lithologic units, S to Z, in subunit c of major unit Tos_7 and fairly comprehensive geologic, mineralogic, chemical, and physical investigations were made of the rocks in these units.

Most of the rocks (table 3-5) near the explosion chamber are porphyritic tuffs. However, the amount (expressed in volume percent) of phenocrysts--varies in the different rock units. Phenocrysts make up less than 10 percent of the rocks of units S, T, and U, whereas in the units V, X, Y, and Z (nearer the explosion chamber) they

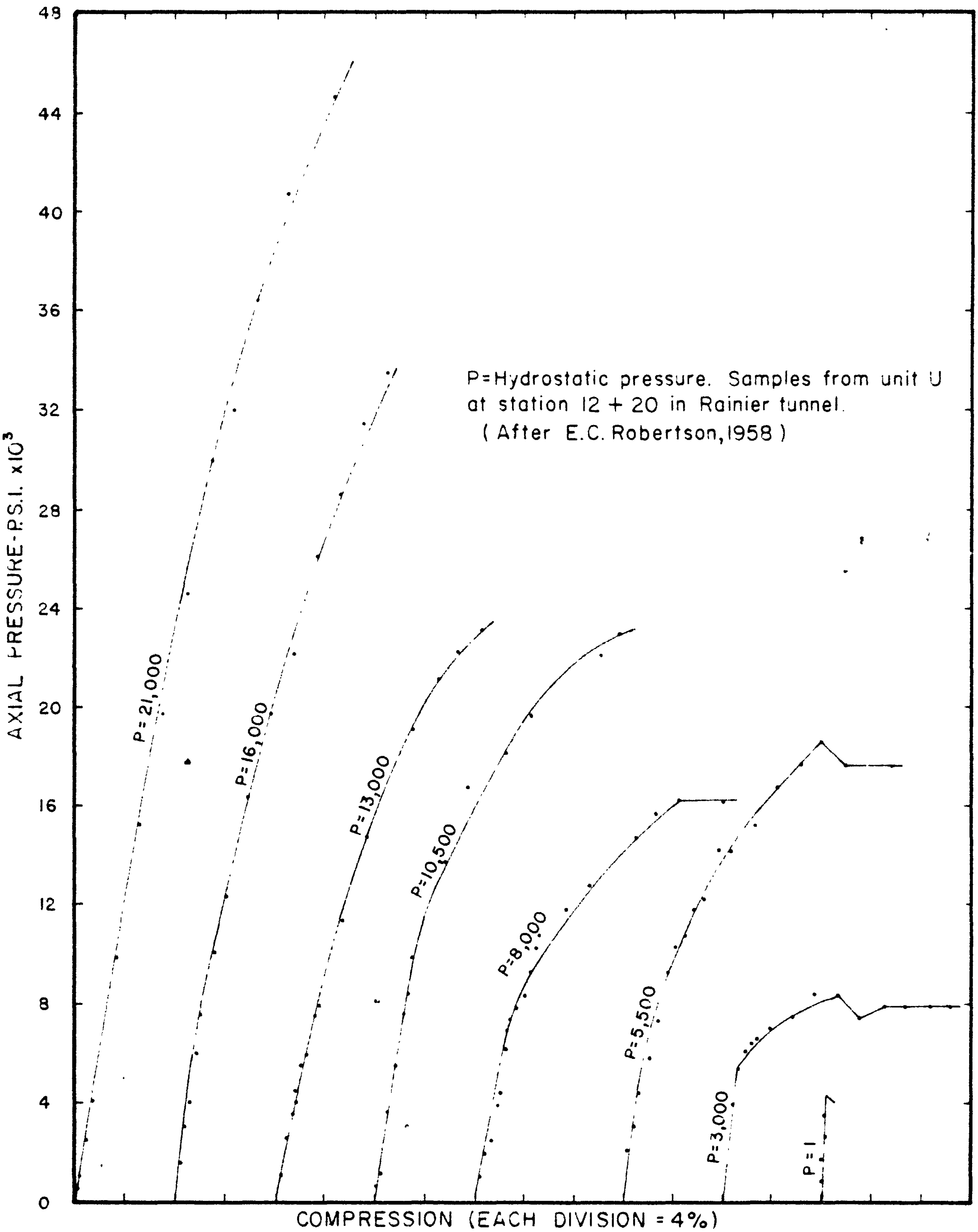


FIGURE 3-2. AXIAL COMPRESSION UNDER HYDROSTATIC PRESSURE OF SAMPLES OF TUFF FROM UNIT U

comprise nearly 20 percent of the rocks. Shards and lapilli occur in the fine-grained matrix of the tuffs and vary inversely to the abundance of phenocrysts. Xenoliths and vesicles also make up considerable, but variable, amounts of the volume of the rocks.

The phenocrysts of the rocks are mainly quartz and feldspar. The mineralogic components (table 3-6) of the matrix vary considerably, but in units S through Z, and in the unlettered beds up to 43 feet vertically above the explosion point, the dominant components are heulandite, montmorillonite, and β-cristobalite. Clay and volcanic glass are more abundant in rocks from 43 to 85 feet above the chamber than they are in units S through Z; heulandite and β-cristobalite are less abundant.

The tuffaceous rocks are generally siliceous (table 3-7) and, in terms of trace elements, are relatively rich in the rare earths (table 3-8). Units W and X are relatively silica poor, containing 58.5 to 62.4 percent SiO_2, respectively, as compared with 65 to 70 percent SiO_2 in other rocks. The decrease in silica in these units is compensated for by an increase in alumina, iron, lime, and soda, and is reflected mineralogically in more abundant plagioclase, biotite, and magnetite. Rare earths such as cerium, lanthanum, neodynium, ytterbium and some of the ytterium earth group are relatively abundant; the amount of niobium is 2 to 3 times the amount found in most granites.

Physical properties of the units near the Rainier chamber are summarized in table 3-9. Porosity ranges from 20.6 to 39.8 and to some extent can be correlated with variation in mineralogy and fabric.

Average composition and properties of tuff close to explosion chamber

Average composition and properties of tuff from a spherical volume around ground zero have been computed (table 3-10). As a basis for the calculations the sphere was assumed to have a radius of 55 feet, corresponding to the spherical void postulated by Johnson and others (1958) to have formed as the result of the explosion. Although the results of the explosion are undoubtedly much different from those postulated from the preliminary study, the spherical void concept at least affords a basis for preliminary calculations. The volume of rocks contained in the postulated void is 523,625 cubic feet and using the average bulk density, their weight is 32,720 tons.

Table 3-10.--Average composition and physical properties of tuff close to Rainier explosion chamber.

Chemical composition (percent by weight)	
SiO_2	66.9
Al_2O_3	12.3
Fe_2O_3	2.2
FeO	.20
MgO	1.01
CaO	2.3
Na_2O	1.3
K_2O	2.2
H_2O+	5.4
H_2O-	5.2
CO_2	.06

Mineral composition (percent by volume)	
Phenocrysts	17.4
Quartz	2.6
Alkali feldspar	6.1
Plagioclase	6.8
Biotite	1.3
Pyroxene & amphibole	.2
Magnetite	.4
Xenoliths	6.7
Shards and lapilli	68.4
Heulandite	23
Montmorillonite	12
β-cristobalite	11
Amorphous material	22
Vesicles	7.5

Physical properties

Natural state bulk density	2.00 g/cc	Porosity	24.41 percent
Bulk density (dry)	1.74 g/cc	Water content by weight	14.27 percent
Grain density	2.32 g/cc	Water content by volume	.282 g/cc

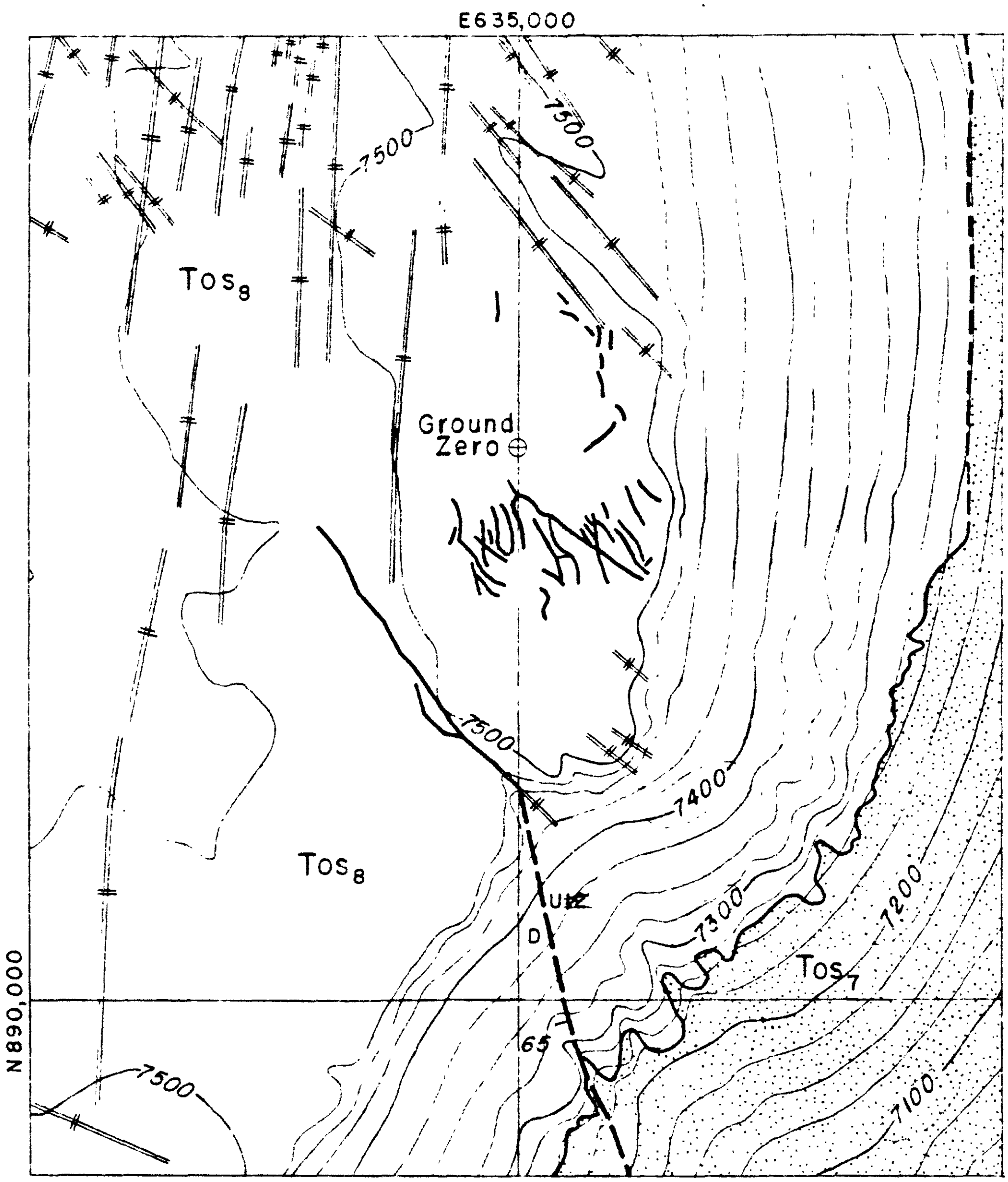
STRUCTURAL CHANGES

By V. R. Wilmarth

Surface effects

The principal surface effects of the Rainier explosion that were observed on the top of Rainier Mesa and on the steep slopes above and near the portal of the Rainier tunnel are rockfalls, rockslides, development of fractures in the welded and nonwelded tuffs, and minor displacement of the surface (Gibbons, 1958). Panoramic photographs of the east slope of Rainier Mesa before, during, and after the explosion clearly indicate that the surface area for approximately one linear mile along the mesa front was affected (Gibbons, 1958). Following the explosion, dust clouds, produced primarily by rockslides and rockfalls, were formed along the slope for as much as 2,100 feet north and 3,500 feet south along the rim of the mesa from ground zero. The rockslides began in the highly fractured, welded tuff along the mesa rim; the largest slide was formed just east of ground zero and extends from the mesa rim downslope about 1,000 feet and is 200 to 300 feet wide. Rockfalls occurred intermittently for several days after the explosion.

Fractures were formed in the welded tuff and soil on top of Rainier Mesa by the explosion (fig. 4-1). Fractures in the welded tuff were as much as 2 inches wide and individuals were traceable along the surface for as much as 300 feet. Fractures in the soil were more abundant but



EXPLANATION

Tos_8	Tos_7

Units of Oak Spring tuff of Tertiary age

Tos_8 : welded tuff

Tos_7 : non-welded tuff

Pre-test lineaments

Post-test fractures

Contact

Dashed where approximately located

U12 D 65

Pre-test fault, showing dip and amount of throw

Dashed where approximately located

Geology by W. R. Hansen and R. W. Lemke. Post-Rainier effects by A. B. Gibbons, J. S. Pomeroy and A. Mason.

FIGURE 4-1. MAP SHOWING FRACTURES FORMED BY THE RAINIER EXPLOSION, NEVADA TEST SITE, NYE COUNTY, NEVADA

200 0 200 FEET

SCALE

they were not as continuous as those in the welded tuff. All of the post-explosion fractures are believed to have formed along pre-existing fractures that strike N. to N. 15° E., and N. 30° to 45° W. The only known post-test fracture along which displacement of rocks could be measured at the surface is a thrust fault just east of the portal of a tunnel approximately 1,400 feet southeast of ground zero. The fault has an average strike of N. 52° E., dips 10° to 15° W., and has been traced along the surface for about 220 feet. The rocks on the hanging wall side of the fault moved eastward about 2 inches as indicated by a small scarp on floor of the tunnel.

Some of the surface effects related to the Rainier explosion are easily observed. The most obvious effects of the Rainier explosion include rockslides and fractures in the rocks. The rockslides formed from the Rainier explosion are clearly visible on photographs taken a year later.

Underground effects

As a result of the Rainier explosion the tuffaceous rocks adjacent to the explosion chamber were brecciated, fractured, and partially melted. Within the Rainier tunnel, the explosion caused rock spalls, new faults and joints, distortion of the tunnel walls and constriction of the tunnel from a point about 210 feet radially from the chamber. The Exploratory tunnel extends from the Rainier tunnel beneath the explosion chamber and in October 1958, the heading was 25 feet below and 48 feet east of the chamber. The radial distance from the explosion chamber is about 52 feet. Anomolous radioactivity was detected in the brecciated and fused tuffs at the west end of the Exploratory tunnel.

Effects in Rainier tunnel

The amount of rock spalled from the tunnel walls and back in the Rainier tunnel increased from the portal inward with the heaviest spalling extending from 13+00 to 14+75; beyond this point the tunnel was inaccessible (fig. 4-2). In addition to spalling, the tuffs were broken by one new fault and 8 new open joints. The new fault, which intersects the tunnel approximately 1,120 feet east of the Rainier chamber, strikes northeast and dips 25° NW., or parallel to the attitude of the beds. The hard, brittle welded tuff of unit Tos_6 on the hanging wall side was pushed eastward about 4 inches over a moderately indurated volcanic breccia. Movement along a pre-explosion fault, 385 feet inward from the portal, was indicated by the walls being moved apart as much as one-half inch. Only a few joints could be proven to have been developed by the Rainier explosion. The 8 post-explosion joints that were found transect the attitude of the bedding and are found in the more indurated tuffaceous sandstones and lapilli tuffs. Near the portal these joints strike

N. 27°-33° E. and dip 60°-54° SE. whereas nearer the explosion chamber they strike N. 19°-50° W. and dip steeply northeast or are vertical.

Detailed cross profiles (fig. 4-3) of the Rainier tunnel were prepared before and after the Rainier explosion to determine the approximate amount of rock deformation. In general the effect of the explosion from about 12+75 inward was to enlarge and deform the cross sectional profile of the tunnel. Within 250 feet of the explosion chamber the tunnel has the shape of a crude parallelogram that is canted to the northeast. Differential movement along shear planes that strike parallel to but dip steeply away from the tunnel accounts for the post-explosion shape of the tunnel (fig. 4-3). A pronounced "arching" of the tunnel was observed near the explosion chamber.

Effects in Exploratory tunnel

The rocks exposed in the Exploratory tunnel (fig. 4-4) are red-brown and white tuff of unit V of Tos_7 plus a new explosion-produced breccia. Bedding in the tuff strikes N. 26° E., and dips 11° NW., approximately the same as the inclination of the tunnel. The white tuff is composed predominantly of pumiceous lapilli and is an irregular bed that thins westward and pinches out just southeast of the breccia. The red-brown tuff makes up most of the upper part of unit V and consists of pumiceous lapilli in a red-brown detrital matrix. Biotite is visible in all of the tuff.

Joints are abundant in the unbrecciated tuff exposed in the Exploratory tunnel. Two sets of about equal magnitude were recognized. They strike N. 4°-33° W., and N. 55°-88° W., and dip steeply northeast to southwest. Comparison of the joint diagrams in figure 3-1 show that the joint sets that were mapped in the Exploratory tunnel, especially in unit V, are present but less well developed in unit V in the lateral tunnels U12b.02, .03, and .04. The force of the Rainier explosion appears to have accentuated these joint patterns but did not develop new ones. Similar diagrams showing dip of the joints also support this conclusion. Extent of the well jointed tuff is unknown but the tuff near the entrance to the Exploratory tunnel, a distance of 220 feet from the chamber is highly fractured.

A 2- to 4-inch shear zone that strikes approximately N. 28° E., and dips 36° NW., separates the breccia and fractured tuff and is at a radial distance of 70 feet from the explosion chamber (fig. 4-4). The rocks for as much as 5 feet west of the shear zone are highly sheared and grade into the highly fractured tuffs within 2 feet. Within the breccia shear planes are common. They strike N. 10°-15° W., and dip steeply northeast and southwest; a few strike N. 20°-30° E., and dip about vertical (fig. 3-1).

The explosion-produced breccia is composed of angular to subrounded fragments of red, brown, gray, and white tuff, and radioactive glass in a fine-grained matrix of comminuted brown to gray-brown tuff. The detailed maps of the tunnel walls portray the relative distribution of the fragments and glass in the matrix (fig. 4-5). The size of the breccia fragments is extremely varied; they range from 0.3 to 3 feet across; smaller fragments as much as 2 inches across are numerous in the matrix. Some of the blocks are angular; most are rounded to subangular. Distribution of the breccia fragments appears to be random as no set pattern of size or degree of angularity or of orientation was noted. The approximate amount of fragments, glass, and matrix of the breccia was determined from measurements of their mapped surface areas as follows:

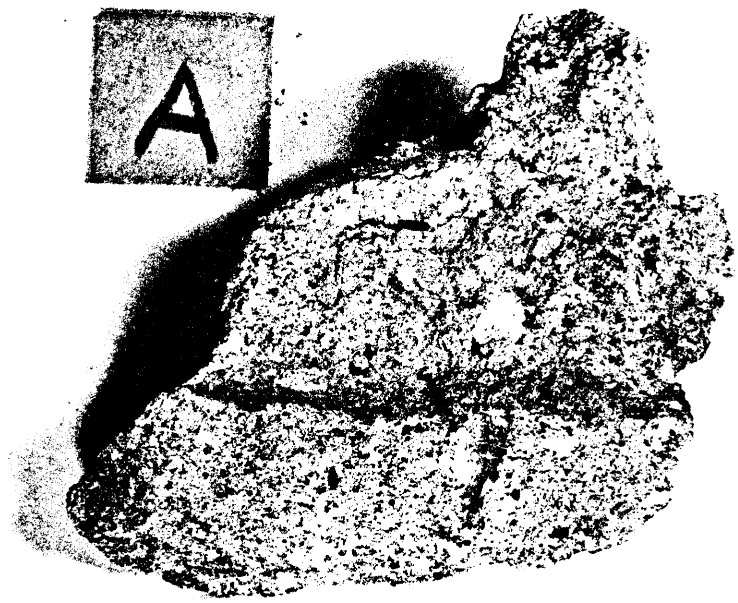
Sketches	Fragments	Radioactive glass	Matrix
1 and 2	40	1	59
3 and 4	25	.5	74.5
5, 6, and 7	33	1.5	65.5

The breccia fragments are presumed to have been derived from the tuff near the Rainier zero point, and they are of diverse composition. Correlation of the individual fragments with the mapped lithologic units is important in determining the extent of the zone of brecciation. Because of the diverse composition of the tuffs, however, further detailed study of the rocks will be required to complete this study. The most abundant blocks are the medium-to coarse-grained biotite-bearing white-gray tuff that forms thick beds in the lithologic units mapped near the Rainier shot chamber. Brown to tan and gray tuff fragments are not common but they have been observed in the heading of the Exploratory tunnel. Possibly they were derived from lithologic units several tens of feet distance from the chamber. The breccia fragments are set in a pale- to dark red-brown fine-grained highly sheared tuff. Shear surfaces are common in the matrix of the breccia and slickensides, where found, indicate some near-horizontal movement.

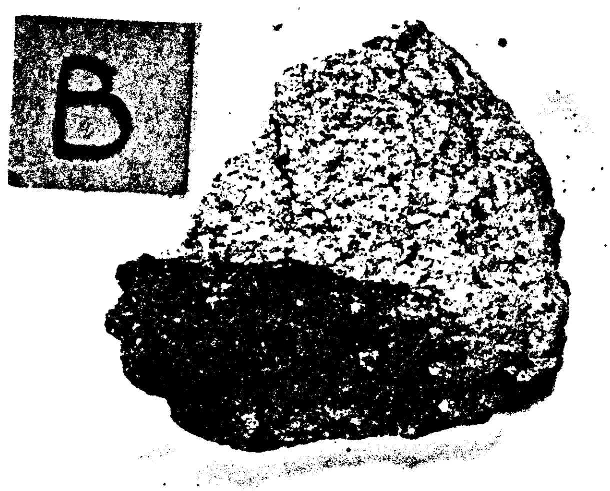
Irregular veinlets as much as 2 inches wide of finely comminuted dark-brown fine-grained, tuffaceous material are common in some of the pale-brown matrix. The contacts between the veinlets and matrix are sharp but highly irregular. Locally the veinlets are parallel to and follow some lithologic contacts but generally they are scattered through the matrix where they appear to cut across textural features. The coarse-grained white-gray tuff of the breccia fragments contain veinlets and irregular masses of dark-gray fine-grained tuff that are locally along the outer edges of the fragments (pls. 1 and 2). Nowhere were the dark-gray and dark-brown veinlets in contact with nor were they observed to grade into one another. Apparently, the composition of the veinlets is related to the enclosing tuff and the breccia fragments. The veinlets are presumed to have formed locally by shearing during formation of the breccia.

Permanent rock deformation

Displacements of survey points within the Rainier tunnel and on the surface above the tunnel were determined by precision surveys made by Holmes and Narver, Inc., of Los Angeles, Calif. The results of the survey before and after the explosion are summarized in tables 4-1 and 4-2 and are shown graphically on figures 4-6, 4-7, and 4-8. The amount of vertical, horizontal, and radial displacement of each survey station

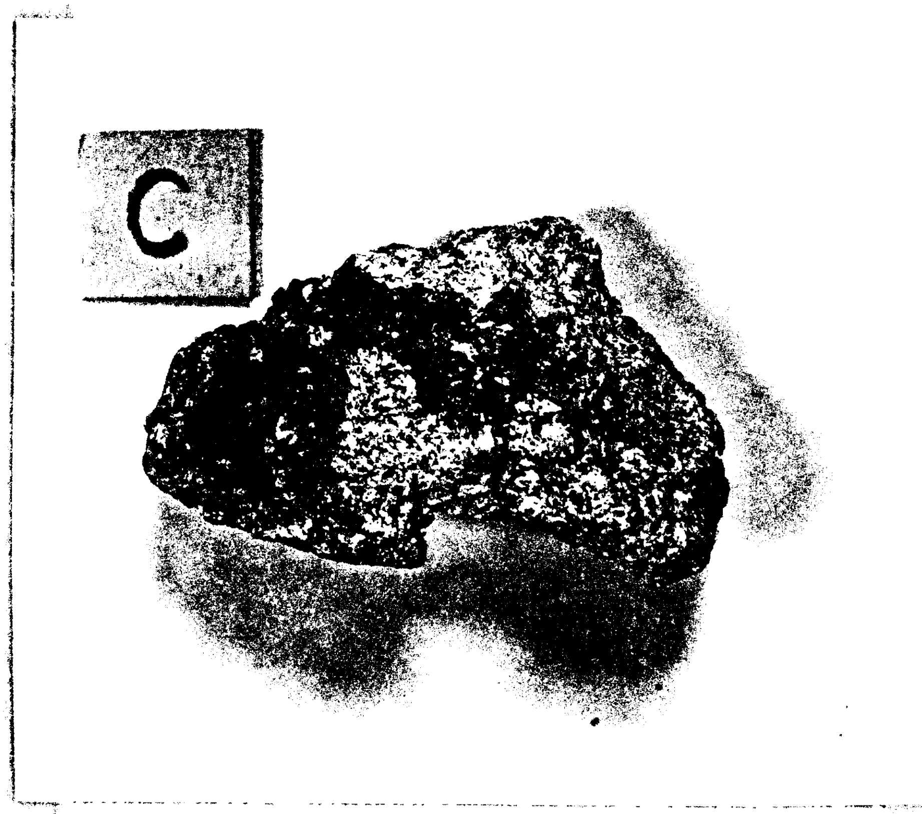


A. Light-gray fine- to coarse-grained tuff with an irregular veinlet of dark-gray tuff. Natural size.



B. Light-gray tuff with a veinlet of dark-gray tuff. Natural size.

Plate 1.--Photograph of tuffs with veinlets from breccia zone, Exploratory tunnel, Rainier Mesa, Nye County, Nevada.



Light-gray breccia fragment in contact with dark-gray very fine grained tuff. Note irregular but sharp contact between the tuffs. Natural size.

Plate 9.--Photograph of tuff from breccia zone, Exploratory tunnel, Rainier Mesa, Nevada Test Site, Nye County, Nevada.

Table 4-1.--Direction and amount of displacement on the surface above Rainier tunnel, Rainier Mesa, Nye County, Nevada (see map, fig. 4-6)

Station	Direction and amount of horizontal displacement (feet)	Vertical displacement[1/] (feet)
1	Not recovered	Not recovered
2	Not recovered	Not recovered
3	.98 south; 2.26 east	+.05
4	Not recovered	Not recovered
5	1.47 south; 3.78 east	-2.21
6	1.30 south; 3.48 east	-1.40
7	1.26 south; 2.86 east	-1.14
8	.36 south; 1.28 east	- .14
9	.25 south; .47 east	+ .10
10	.28 south; .38 east	0.00
11	.35 south; .45 east	- .01
12	.31 south; .10 east	- .06
13	.01 south; .02 east	- .06
14	.20 south; .13 east	- .06
15	.30 south; .32 east	- .07
16	.08 south; .04 east	- .06
17	.20 south; .07 east	- .05
18	.13 south; .16 east	- .04
19	.07 south; .07 east	- .04
20	.08 south; .07 east	- .04

Table 4-1. Direction and amount of displacement on the surface above Rainier tunnel, Rainier Mesa, Nye County, Nevada -- (Cont.)

Station	Direction and amount of horizontal displacement (feet)	Vertical displacement 1/
21	.09 south; .06 west	- .03
22	.04 south; .07 east	- .02
23	.06 south; .07 east	- .03
24	.14 south; .14 east	- .03
25	.11 south; .12 east	- .02

1/ Notation (-) indicates elevation of point was lower (+) indicates point was raised.

Table 4-2.--Direction and amount of displacement in Rainier tunnel, Nye County, Nevada

Station	Direction and amount of horizontal displacement (feet)	Vertical displacement[1/] (feet)
1	.09 north; .84 east	- .087
2	.15 north; .73 east	- .11
3	.13 north; .73 east	- .10
4	.16 north; 1.13 east	+ .10
5	.19 north; 1.29 east	- .01
6	.07 south; 1.23 east	Not determined
7	.04 north; 1.11 east	+ .01
8	.01 north; 1.13 east	+ .01
9	.03 south; 1.18 east	+ .04
10	.07 south; 1.20 east	+ .03
11	.33 north; 1.67 east	+ .02
12	.18 north; 1.59 east	+ .03
13	.21 north; 2.09 east	+ .09
14	.07 north; 1.50 east	+ .12
15	.09 south; 1.62 east	+ .15
16	.17 south; 2.25 east	+ .14
17	.09 south; 1.60 east	+ .16
18	.03 south; 2.03 east	+ .77
19	1.27 south; 2.36 east	+2.24

1/ Notation (-) indicates station lowered; (+) indicates station raised.

is assumed to represent the amount of displacement of the rocks. Results of the surface survey (fig. 4-6) are as follows:

1) The largest vertical and horizontal displacement was measured between stations 3 to 8. The minimum distance to the stations from the explosion chamber is 820 and 980 feet, respectively.

2) The stations were moved horizontally as much as 4.09 feet and vertically 2.21 feet. The horizontal movement was predominantly eastward and downslope.

3) The area of largest horizontal displacement coincides with that of the largest vertical displacement.

4) The soft friable tuff of the middle portion of unit Tos_7 was apparently affected by the Rainier explosion to a greater extent than the rocks of the other units. This amount of surface displacement in the tuff, as shown by the precision survey, may represent an indication of the volume change of the rock between the explosion chamber and the surface from stations 3 to 8. The possibility that this displacement may be a near-surface phenomenon should be considered.

Within the Rainier tunnel, both horizontal and vertical movement decreases rapidly with increase in distance from the explosion chamber. The greatest vertical displacement, 2.24 feet, was measured at station 19 about 200 feet east of the chamber. From this point the amount of displacement decreases rapidly to about 500 feet from the chamber where it is less than 0.1 foot (fig. 4-7). The net horizontal displacement, parallel to strike of the beds, ranges from 0.72 feet near the portal to 2.67 feet at about 200 feet east of the chamber.

The radial component of displacement of the survey stations is plotted as a function of distance from the explosion chamber (fig. 4-8). Points on the graph representing surface stations lie approximately in a vertical plane that includes the tunnel. Those that represent stations in the tunnel indicate the component of displacement in a line connecting the chamber and the survey station. The Rainier tunnel was caved by the explosion at a point about 200 feet from the chamber. Between the distances of 200 and 400 feet from the explosion chamber, the amount of radial displacement within the tunnel decreased from about 2.5 feet to 1 foot (fig. 4-8). Beyond 400 feet the amount of radial displacement is a foot or less (fig. 4-8). The flatness of the curve beyond 400 feet suggests that this point within the tunnel is approximately the outer limit of significant rock deformation. This interpretation is somewhat weakened by scatter of data and the possibility that configuration of the tunnel itself may have had a strong influence on the amount of displacement.

It is evident from figure 4-8 that the rock between 400 to 1,100 feet from the explosion chamber (tunnel data) moved essentially as a unit, because all the stations were displaced radially about one foot. Beyond 1,100 feet the displacement of stations was .6 to .7 foot. This difference (.3 to .4 foot) is corroborated by a new bedding-plane thrust fault that is

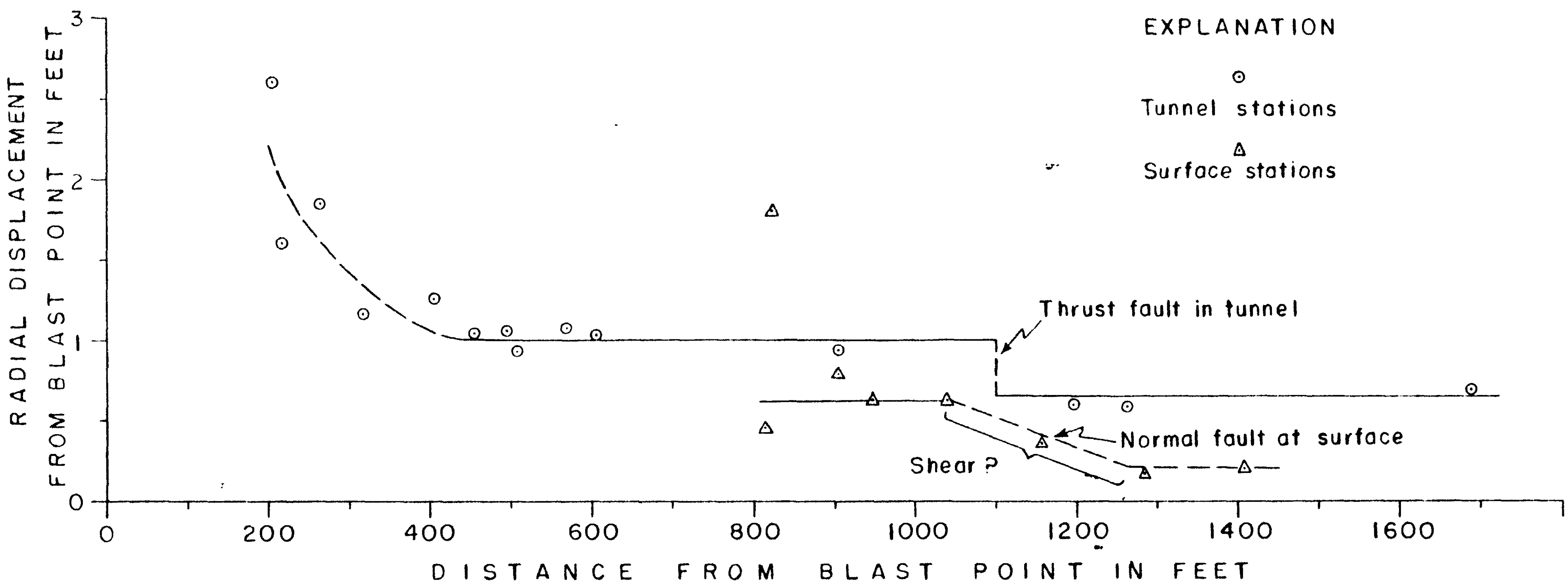


FIGURE 4-8. COMPONENT OF RADIAL DISPLACEMENT OF SURVEY STATIONS FROM BLAST POINT, RAINIER MESA, NYE COUNTY, NEVADA

(Based on survey data by Holmes and Narver, Inc.)

exposed in the floor of the tunnel about 1,100 feet from the explosion chamber and which has a horizontal displacement of about 4 inches (Gibbons, 1958).

Data from surface stations are less meaningful because of the possibility that gravity slumping of the surface rock took place after movement resulting from the blast. This is particularly true of the stations at 820 and 830 feet, which are nearest the point of minimum cover (fig. 4-6). However, the surface data suggest that the survey points between 850 and 1,010 feet from the blast point moved essentially the same distance (about 0.6 foot); that is, they were part of the body of rock that was displaced as a unit. Slope of the curve between 1,000 and 1,300 feet suggest differential movement along fractures, bedding plane partings, and faults. Survey points beyond 1,300 feet moved about 0.2 foot, essentially as a unit.

Resume

As a result of the Rainier explosion the tuffaceous rocks were brecciated, highly fractured, and partly melted. The configuration of the zone of brecciated rock about the explosion chamber is not completely known. The outer limit of brecciated rock was positively determined only in the west end of the Exploratory tunnel where the contact between the breccia, which contains abundant radioactive glass, and fractured tuff is exposed. This contact strikes N. 28° E., dips 36° NW., and is at a radial distance of about 70 feet from the chamber. Examination of the core and drilling records for drill holes B, C, and D provided a few data on the boundaries of the breccia zone. Core recovery from the drill holes was generally poor, especially near the contact of breccia and fractured tuff. In drill hole D, at 95 feet from collar, core fragments contain narrow, dense, fine-grained veinlets similar to those observed in the sheared tuff adjacent to tha breccia in the Exploratory tunnel (see plates 1 and 2). As shown in figure 4-4 the breccia-contact in the tunnel would project up dip with but little change in dip angle and intersect hole D at this point. These veinlets are probably blast-produced along minor fractures and they may or may not represent the breccia-tuff contact. Cores from the other holes were examined but no evidence concerning the contact of breccia and tuff was found.

Some data on the distribution of breccia was obtained from lithologic logs of the drill holes (table 4-3). In these logs the recorded change from tuff to "tuff and sand, sand, or very soft clay" is interpreted as the contact between the breccia and tuff. In drill hole D, the contact is placed at 133 feet, in hole C at about 120 feet, and in hole B at about 95 feet from the collar (fig. 4-4). None of the drill holes penetrated the brecciated rock, thus the data available are pertinent only to the breccia contact on the southwest side of the explosion chamber.

Abnormal radioactivity due to presence of explosion-produced glass is a pronounced feature of the breccia exposed in the Exploratory tunnel. Similar anomalous radioactivity was noted at about 132 feet (fig. 6-1) in drill hole D, indicating that the breccia contact is approximately at this distance from the collar. In holes C and B, the zone of anomalous radioactivity does not coincide with the change in lithology of the core. The

Table 4-3.--Generalized logs of drill holes B, C, and D, near Rainier explosion chamber, Nevada Test Site, Nye Co., Nev. 1/

Distance from collar (feet)	Lithology	Core Recovered (feet)
Drill hole C		
0 - 119	tuff	72
119 - 154.4	very soft clay and sand	28
154.4 - 155	very hard tuff	.5
155 - 167.4	tuff and sand	12
167.4 - 170	firm tuff	3
170 - 284.5	sand and tuff	106.7
284.5 End of hole		
Drill hole B		
0 - 93	tuff	53
93 - 257 (lost water at 182 ft.)	sand	10.5
257 End of hole		
Drill hole D		
0 - 130	tuff	58
130 - 216	sand and tuff	25
216 - 260	soft sand	3
260 - 276	sand and tuff	5
276 - 292	soft sand	4
292 End of hole		

1/ Drilling records courtesy of Longyear Drilling Co.

largest discrepancy was noted in hole B, where the breccia contact based on lithology was placed at 95 feet and point of abnormal radioactivity at 160 feet from the collar. This difference is probably due to inadequate drilling records, and also to the fact that at this point the drill passes from indurated to friable tuff which is difficult to core.

Based on the above data the extent of the explosion-produced breccia zone near the Exploratory tunnel can be determined in part. The approximate contact of the breccia and tuff, and the boundary of abnormal radioactivity are shown on figure 4-4. These boundaries dip steeply toward the explosion chamber but delimit the breccia zone only on the southeast side of the chamber. Considerably more exploration will be required to understand completely the configuration of this zone.

GROUND WATER

By Alfred Clebsch, Jr.

Natural conditions

Prior to the Rainier test the U12b tunnel was virtually dry, except for a small seep from a joint in the back at a point about 1,380 feet from the portal. Laboratory determinations and interpretations of electric logs showed the rock to be saturated with water or nearly so (Keller, 1958b, tables 7 and 8).

The high water content of the rocks appeared inconsistent with the dry condition of the tunnel, so it was suspected that both the high moisture content and any free water might have been introduced artificially during drilling nearby test holes. Information obtained in 1958 has shown that high water content is so common in the tuff that all of this water could not have been introduced artificially. Seeps have appeared in tunnel workings opened in the summer of 1958 at a sufficient number of places to cast doubt on the hypothesis that the water at 1,380 feet was injected into the rock from a drill hole. The seep from the joint at 1,380 feet is explained as local, perhaps temporary, perched water. The individual voids in most of the tuff are very small, and apparently the water is held in them by capillary forces and will not drain out by gravity. Movement of water must take place predominantly through joints, fractures, and faults.

Tunneling operations in the spring and summer of 1958 exposed free ground water at the locations shown on figure 5-1. It may be significant that almost all these seeps are in unit V (fig. 3-1), generally along the strike of the unit. Why this water was not encountered in greater quantity and at more locations in the main Rainier tunnel is not completely understood. It seems possible that water appearing in the U12b.03 and U12b.04 tunnels and at the entrance to the Exploratory tunnel in the spring and summer of 1958 is seepage from snowmelt. (Snow cover in 1957-58 winter was reportedly heavier than the previous winter, but the lag between the time of snowmelt on the surface and the appearance of water in the tunnel possibly could be more than one year.) This interpretation is based largely on the reports of miners working in the U12b.03 tunnel, who stated that the tunnel was dry until several days after the tunnel was driven (July 1958), when the water appeared.

The most prominent seep in the U12b.03 tunnel is at the point where the contact between units V and W intersect the back of the tunnel. Thus, unit V could be the perching (negative confining) bed. However, there are no obvious differences in permeability between the two units and from outward appearances unit W could also be a perching bed. Unit Z appears capable of transmitting some water interstitially, and water may be cascading from a perched zone in this unit or another one higher in the stratigraphic section.

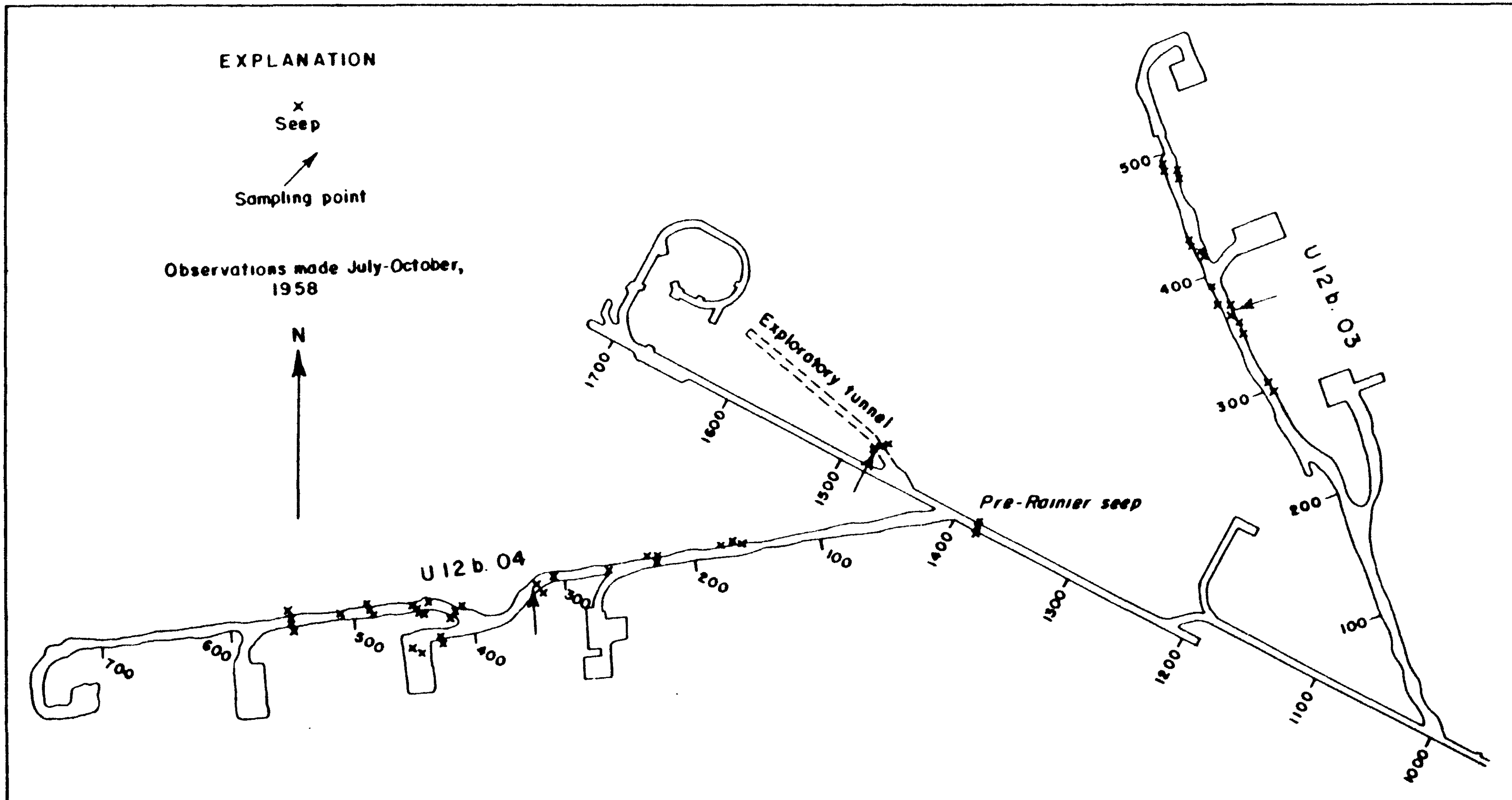


FIGURE 5-1 LOCATION OF SEEPS IN U12b TUNNEL SYSTEM, RAINIER MESA, NEVADA TEST SITE, NYE COUNTY, NEVADA

Virtually all the seeps were very small, yielding only fractions of a gallon per day. In view of the low rate of discharge of the seeps, even from zones that contained open fractures, it is tentatively concluded that the perched water zone is thin. On the basis of the sporadic occurrence of water, it appears that the perched zone is discontinuous.

The scarcity of free water in the Rainier tunnel and information obtained from nearby test holes show that the zones of saturation or perched water tables in the rocks cut by the Rainier tunnel or higher in the Oak Spring stratigraphic section (Tos_7 and Tos_8) are not continuous. The nearest zone in which secondary openings are saturated is 500 to 600 below the level of the Rainier tunnel. This is based on observations of water in unit Tos_3, 0.9 mile south-southeast of the Rainier chamber in another tunnel constructed in the summer of 1958 at an elevation of about 6,100 feet (Clebsch and Winograd, 1958) and on water-level observations in drill hole 10 (the so-called Hagestad deep hole) about 0.8 mile west-southwest of the chamber and near the center of Rainier Mesa (Diment, Gibbons, and Roller, 1958). The elevation of the water level in the drill hole 10 is 6,040 feet. It appears that the water in the drill hole is semiperched, as defined by Meinzer (1923, p. 41), (Clebsch and Winograd, in preparation, 1958).

It is certain that the water in the tunnel at an elevation of 6,100 feet (unit Tos_3) is perched or semiperched. The water table in the perched zone tapped by the tunnel is higher than 6,125 feet;

the exact elevation is uncertain. Whether there is a continuous zone of saturation, or hydraulic continuity, between the two control points is not known, but assuming that these two points of observation are in the same perched aquifer and that there is no ground-water divide between them, there is a westward component to the movement of water. In view of the geologic structure it is unlikely that a divide separates the two points.

Chemical characteristics of water from the two seeps in the U12b tunnel system are shown in table 5-1 and figure 5-2. For comparison figure 5-2 also shows a plot of three analyses of water samples from well 3 (4 miles north of Yucca Pass), which supplied the drilling water for test holes drilled prior to August 1958 in the vicinity of the Rainier tunnel. Some similarities are apparent, but the difference in the concentration of magnesium strongly suggests that the waters are from different sources. The differences in the concentration of fluoride and in the ratios of the concentration of sulfate to chloride may also be significant. If the water from the seeps were drilling water diluted by unmineralized meteoric water, all the lines denoting water from the tunnels would be parallel to the lines denoting water from well 3, taking into account the variation among samples from the same source. Thus, it is concluded that the water in the U12b tunnel system, although similar chemically to the water from well 3, is not water that was injected into the rock through drill holes. It is, ble 5-1.--Chemical analyses of water from U12b tunnel system, Nevada Test Site, Rainier Mesa, Nye County, Nevada

nnel	U12b.03	Exploratory
cation	3+70	14+65
alysis no.	--	2589
hemical components (ppm)		
SiO_2	67	68
Al	.5	.4
Fe[1/]		.00
Fe (total)	.40	.14
Mn	.0	.00
Ca	9.6	13
Mg	1.5	1.9
Na	15	18
K	2.8	2.8
HCO_3	48	74
CO_3	0	0
SO_4	8.2	12
Cl	7.5	5.0
F	.2	.1
NO_3	7.4	2.1
PO_4	.15	.05

the outer limits of complete physical disaggregation and of radiochemical change are within 50 to 100 feet of the blast point.

It is necessary, however, to estimate the outer limit of fracturing because of the possible effect of fractures on the permeability and storage characteristics of the affected rocks.

The only known techniques for measuring these properties are hydraulic; that is, by pumping water from or injecting water into the rock under controlled conditions and observing the head distribution with time. Pumping tests are not feasible because the fractures are not saturated, and post-shot water-injection tests have not been made.

Indirect measurements, such as resistivity determinations and seismic velocity measurements, provide an indication of the radius of rock fracturing, and it is believed that some information on increased storage capacity and permeability might be extracted from the pre- and post-shot survey data. Resistivity anomalies in the U12b.04 tunnel 200 to 260 feet from the blast point have been interprated as indicating the rocks were fractured (this report). Post-shot seismic velocity data indicate that seismic velocities may have been reduced perceptibly for a distance of as much as 500 feet above the blast point (this report). Significant velocity anomalies in the tunnel appear to extend to 200 feet but the interpretation is complicated by the effects of another explosion. This reduction can be ascribed to fracturing of the rock. Additional evidence for an upper limit of fracturing was provided by the post-shot ground zero drill hole (Johnson and others, 1958). A cavity was entered by the drill at a point 386 feet above the blast point and could be interpreted as the upper limit of fracturing of the rock to the extent that it would no longer support its own weight.

Post-shot survey data are available for only two lines: one line about 1,480 feet long extends from the portal of the Rainier tunnel toward the chamber; another is on the surface almost directly above the tunnel (figs. 4-2 and 4-3 and tables 4-1 and 4-2). Stations on both survey lines were displaced generally away from the blast point.

Figure 4-8 shows the component of displacement of surveyed stations radially from the blast point. All points were moved outward, thus indicating that in a vertical plane, which includes the tunnel, the rock moved toward the surface. This is interpreted as indicating an increase in void space, at least in that direction.

It is evident from figure 4-8 that the rock between about 400 and 1,100 feet from the blast point (tunnel data) moved essentially as a unit, because all the stations are displaced nearly an equal distance (about 1 foot). From 1,100 to 1,700 feet from the blast point the displacement of stations also was nearly equal but of lesser magnitude (0.6 to 0.7 foot). This lesser displacement (0.3 to 0.4 foot) is accounted for by the existence of a bedding-place thrust fault, exposed in the floor of the tunnel about 1,100 feet from the blast point, which underwent a horizontal displacement of about 4 inches (Gibbons, 1958).

Between distances of 200 and 400 or 500 feet from the blast point the radial displacement of surveyed stations decreases markedly. The relatively sharp decrease in radial displacement and the flatness of the curve beyond 400 to 500 feet suggest that this is the effective outer limit of significant increase in secondary pore space, although the interpretation is weakened by the scatter of the data and the possibility that configuration of the tunnel itself may have had a strong influence on the nature of the displacement. Beyond a distance of about 500 feet from the blast point the compressional or dilatational effects on the rock mass in the tunnel were negligible.

If the geometric configuration of the outer limit of fracturing and the displacement of the rock mass surrounding this volume were known, it would be possible to compute or approximate the volume of rock affected by the blast, as well as the increase in secondary void space. The simplest geometric model would be a sphere. Assuming a sphere 400 feet in radius, the increase in void volume, $\Delta V = 4/3\ \pi (r+d)^3 - 4/3 \Delta V (r)^3$. Where r = 400 feet and d = 1 foot, $\Delta V = 4.8 \times 10^5$ cubic feet. On the basis of a 500-foot radius and a displacement of 1 foot, $\Delta V = 8 \times 10^5$ cubic feet. The change in void space in the total volume of rock affected by the blast should agree with the volume of the cavity produced by the blast provided rock near the cavity was not compressed. (See the section of this report on post-shot physical properties of the rock.) Johnson and others (1958) computed a volume of 7 x 10^5 cubic feet for the glass-lined cavity that existed momentarily as a result of the blast, also using a spherical model.

It is highly unlikely that the zone of rock in which fracturing took place is spherical. The topographic configuration alone would tend to cause the fractured zone to depart from a spherical model. Fracturing probably would extend farther in the direction of minimum cover than downward or laterally toward the main bulk of the mesa. The fact that the direction of displacement of survey stations was nearly parallel to the strike of the beds suggests that geologic structure exerted a strong influence on the way in which the stresses were relieved. It seems possible that the zone of blast-affected rock may be ellipsoidal having the blast point near one focus, the major axis toward the point of minimum cover, and possibly some elongation parallel to the strike. This is, however, only one of a number of possible interpretations.

Additional survey data would be necessary to determine the increase in void volume accurately and to estimate the shape of the zone in which the volume increased. Complete data from the surveys on the mesa above and west of the blast point are not yet available, but some of the data indicate that the mesa surface subsided a very small amount over a fairly large area. This might reduce the volume computed above by half, again assuming a spherical model.

In view of the agreement between the seismic velocity measurements, the volume of the cavity computed by Johnson and others (1958), and this method of computing the volume of fractured rock, the volume of rock affected by the blast and the increase in void space distributed through it will be used in further discussion of the effects of the blast on ground water, recognizing that the figures are not exact and may be greatly in error.

Effect on storage characteristics

Because the blast effects on storage characteristics of the rock probably were confined principally within a distance of 400 to 500 feet of the blast point and because the only known aquifer is 500 to 600 feet below the level of the blast point, it is tentatively concluded that the Rainier explosion had virtually no effect on the storage characteristics of the principal aquifer beneath the mesa. The probably thin, discontinuous zone of perched water that is supplying the seeps in the tunnel system was undoubtedly altered by the explosion, but inasmuch as the water is perched and the perching bed was ruptured, the ability of this zone to retard the movement of water presumably was reduced rather than increased. The quantity of water involved is insignificant.

Effect on rate and direction of movement

Inasmuch as blast effects of the Rainier explosion apparently did not appreciably change the permeability of the tuff below the principal water table beneath the mesa, there was no direct effect on the rate and direction of movement in that zone of saturation.

Effects of the blast on the rock above the water table could change the rate at which water percolates downward to the water table by changing the vertical permeability of the rock. If the blast-affected rock extended to the surface in such a way that the vertical permeability was increased markedly, recharge in the vicinity of the blast point would be facilitated. In this way a change in the recharge pattern could ensue which inturn would influence the rate and direction of ground-water movement in the zone of saturation. A slight mound might be built up on the water table (possibly only a few inches high over several thousand square feet), thus increasing the water-table gradient and thereby increasing the rate of movement. The mound would affect also the direction of movement, because water would move out radially from it.

Assuming that the radius of effect of the blast on the permeability of the rock was only 400 to 500 feet, there is an additional mass of rock 400 to 500 feet thick above the blast point in which changes in permeability were negligible. Along a radius toward the point of minimum cover (800 feet) on the slope of the mesa there is also a 300- to 400-foot mass of rock in which the permeability was not changed significantly. It is therefore concluded that the Rainier event had virtually no effect on ground-water movement.

Aquifer improvement

The possibilities of using nuclear explosions to improve the productivity of ground-water reservoirs would seem to fall into two major categories: those depending on increasing the storage capacity of the reservoir and those depending on increasing the permeability of the rock. In most applications these probably would be interrelated. For example, usually the purpose of inducing or increasing recharge is to increase the total quantity of water in storage, but commonly this depends on increasing the permeability. Where there is rejected recharge, however, an increase in storage capacity alone might be of value.

The Rainier test was designed to avoid some of the effects that explosions designed to improve aquifers would seek to produce. Inducing or increasing recharge by using excess runoff, for example, depends upon being able to extend open fractures from the blast point to the surface, whereas in the Rainier test this was deliberately prevented. The Rainier test was conducted 500 to 600 feet above the nearest extensive saturated zone and rock breakage probably was well within this distance. Applications for directly increasing the storage capacity and for increasing the permeability of the rocks within an aquifer would have to insure that much of the zone of rock breakage is below the water table. Thus, the Rainier test was not a good experiment from which to draw conclusions regarding the possibilities of hydrologic applications of nuclear explosions.

The increase in rock volume as a result of the Rainier explosion probably was of the order of 10 to 20 acre-feet. It is obvious that a volume change of this magnitude would require very unusual economic conditions for such a small increase in storage to be worth the expense. Much larger devices would be required for applications depending solely on increasing the volume of an underground reservoir. The effect of depth of burial of the Rainier device and the effect of the unique topographic setting on the magnitude of the increase in rock volume are not known. The effects in a different medium, particularly beneath the water table, might be vastly different. Therefore, it would be sheer speculation to attempt to scale the effects of the Rainier test upward to higher yields and to extrapolate to media that are different geologically as well as chemically and physically. It is therefore obvious that additional experiments would be necessary to evaluate the feasibility of hydrologic applications of nuclear blasts.

Some hydrologic applications would require that the explosive energy be carefully controlled insofar as radius of effect is concerned; some would require that the energy be controlled directionally as well. Therefore the need to know the nature of the reaction between the explosive device and the medium within the radius of effects of the blast is essential. Equally important is a better understanding of the possible problem of contamination of water supplies from radioactive material resulting from nuclear blasts. This is very poorly understood and at the present time needs much additional study.

Explosions that would increase the permeability appear to have more promise than those aimed solely at increasing the storage capacity if these explosions are applied to rock aquifers in which the permeability is controlled mainly by secondary openings. The productivity of unconsolidated sand and gravel aquifers might actually be decreased by an explosion, because productivity of such aquifers is controlled by particle size distribution. Blast effects probably would decrease the degree of sorting by rearranging the individual particles thus decreasing the permeability of the aquifer. A blast could also decrease the permeability by disrupting permeable strata and juxtaposing them against less permeable strata. Applications to increase the amount of water in storage by increasing the vertical permeability of rocks between the water table and a source of recharge appear to have considerable promise. This might consist of diverting flood runoff to underground storage, or rupturing perching beds so that perched water could drain into a deeper aquifer. The latter might be done to relieve a water-logged surface condition, or perhaps to dilute deeper water if the perched water were of better quality.

Detailed studies of the geology and hydrology of an area should be made before the feasibility of experiments of this type could be judged.

Hydrologic understanding of an area is frequently a function of previous development of water. Because hydrologic applications of nuclear explosions might necessarily be confined to remote areas extensive test drilling would, in many cases, be required. Thus the cost of preliminary studies to learn hydrologic conditions in an area conceivably could determine the economic feasibility of aquifer improvement experiments.

DISTRIBUTION OF EXPLOSION-PRODUCED GAMMA RADIOACTIVITY

by Carl M. Bunker

The distribution of anomalous gamma-radioactivity resulting from the Rainier explosion was determined in September 1958 by measurements in the underground drill holes near the Rainier chamber and by measurements on both walls and the face of the Exploratory tunnel (fig. 4-4). Natural background gamma-radioactivity was established by measurements along the U12b and U12b.04 tunnels.

Portable survey meters of both scintillation and ionization chamber types were used to determine gamma activity along the tunnel walls. The instrument was held against the rock about half way between the floor and the back of the tunnel. Portable logging equipment of both scintillation and Geiger-Muller types was used to obtain continuous logs of the underground drill holes. A truck-mounted unit with Geiger-Muller and scintillation detectors was used to log holes drilled from the surface. All equipment was calibrated in terms of milliroentgens per hour with a radium-226 standard.

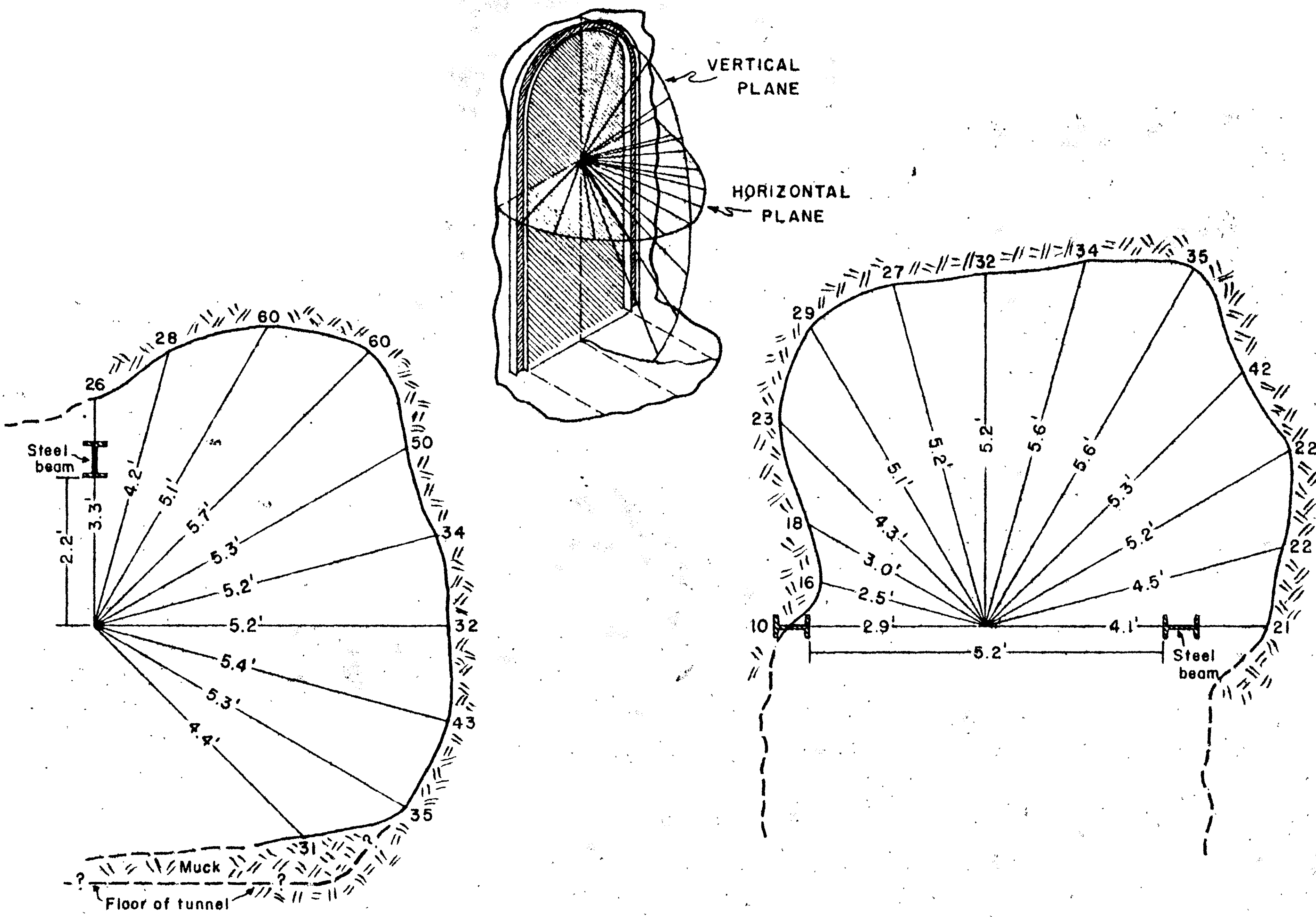
W. A. Bradley and M. D. Shutler assisted in obtaining and evaluating the data.

Results

A gamma-radioactivity survey of the U12b.04 tunnel in the vicinity of the Rainier chamber was made to determine the natural background gamma radioactivity in lithologic units similar to those which would be present in exploratory drill holes (B, C, and D) and in the Exploratory tunnel. The fractured and faulted zones through which radioisotopes might have escaped from the explosion chamber, were carefully examined to determine if they were radioactive. Background gamma-radioactivity of the rocks exposed in U12b.04 and adjacent U12b tunnels (fig. 6-1) ranges from 0.019 to 0.025 milliroentgens per hour; the differences can be related to changes in lithology.

The results of the radiation survey on each wall of the Exploratory tunnel are illustrated in figure 6-1. Although variations in gamma radiation are indicated it is not possible to determine with great accuracy small changes in radioactivity emitted by radioisotopes in the wall rock at a particular location. This is caused by (1) spillage of radioactive materials as they were being taken from the heading of the tunnel and (2) radiation from the walls adjacent to the point of measurement. However, a few general observation can be made. About 15 feet from the heading or about 70 feet radially from the explosion chamber a sharp increase in radioactivity on both sides of the tunnel were measured (fig. 6-1). The radioactivity is due primarily to the explosion-produced glass contained in the breccia that resulted from the Rainier event.

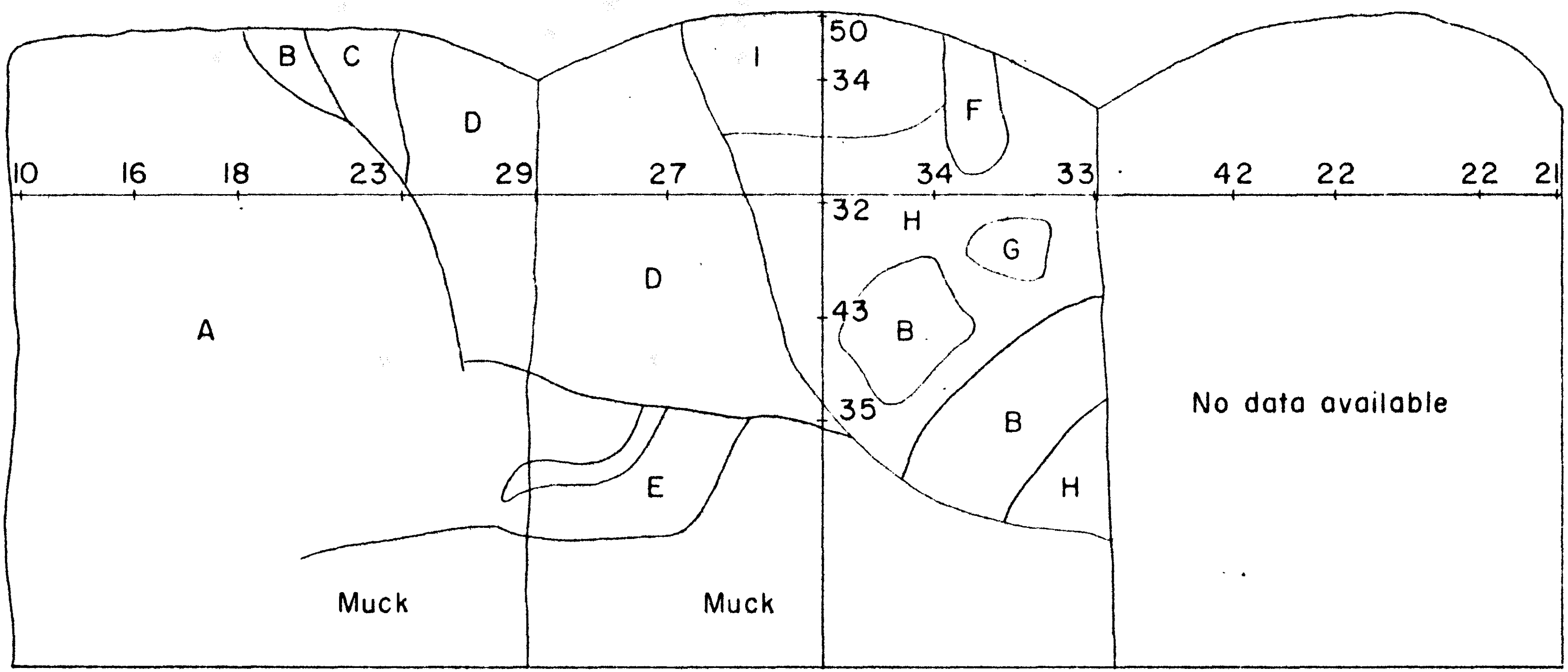
A detailed gamma-radioactivity survey of the heading and walls was made in the Exploratory tunnel when the heading was at 16+23 (63 feet radially from the chamber) (fig. 4-4). Radioactivity values observed during this survey (figs. 6-2, 6-3) range from 10 to 60 milliroentgens per hour. The most radioactive material occurs in discontinuous zones a few inches across



VERTICAL PLANE

HORIZONTAL PLANE

FIGURE 6-2 —RADIOACTIVITY SURVEY AT HEADING, STATION 16+23, EXPLORATORY TUNNEL



EXPLANATION

B

Lithologic unit mapped and decribed by V. R. Wilmarth

32

Radioactivity value in milliroentgens per hour

FIGURE 6-3 —RADIOACTIVITY SURVEY AT HEADING, STATION 16+23, EXPLORATORY TUNNEL in the upper part of the heading and back. These zones apparently have no regular space relation to the point of detonation.

Detailed gamma-radioactivity survey was completed of the walls, heading, and back in the Exploratory tunnel from about 61 to 65 feet radially from the explosion chamber (fig. 6-4). The radioactivity ranges from 12 to 150 milliroentgens per hour. The highest values were found in the central part of the right wall where explosion-produced glass is disseminated in the breccia. The glass is opaque black to translucent tan and generally is associated with white tuff. Lesser amounts of radioactivity were found in the light brown tuff but the dark reddish-brown tuff is generally not radioactive.

Three drill holes, B, C, and D, extending from the entrance of the Exploratory tunnel into the Rainier chamber were logged with continuous recording gamma-ray equipment. One hole drilled into the heading of the Exploratory tunnel was also logged. The interpreted data from the logs are illustrated in figure 6-1.

The radioactivity in the Exploratory tunnel near the heading is greater than that recorded in the hole drilled from the heading because the inhole probe measures radiation from a more confined area than the survey meter placed against the tunnel wall. The inhole probe more accurately defines the magnitudes and location of an anomaly because the rock attenuates radiation from distant points.

A comparison of the drillers' logs* with the gamma-ray logs of the

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*Courtesy of E. J. Longyear Company and the University of California Radiation Laboratory.

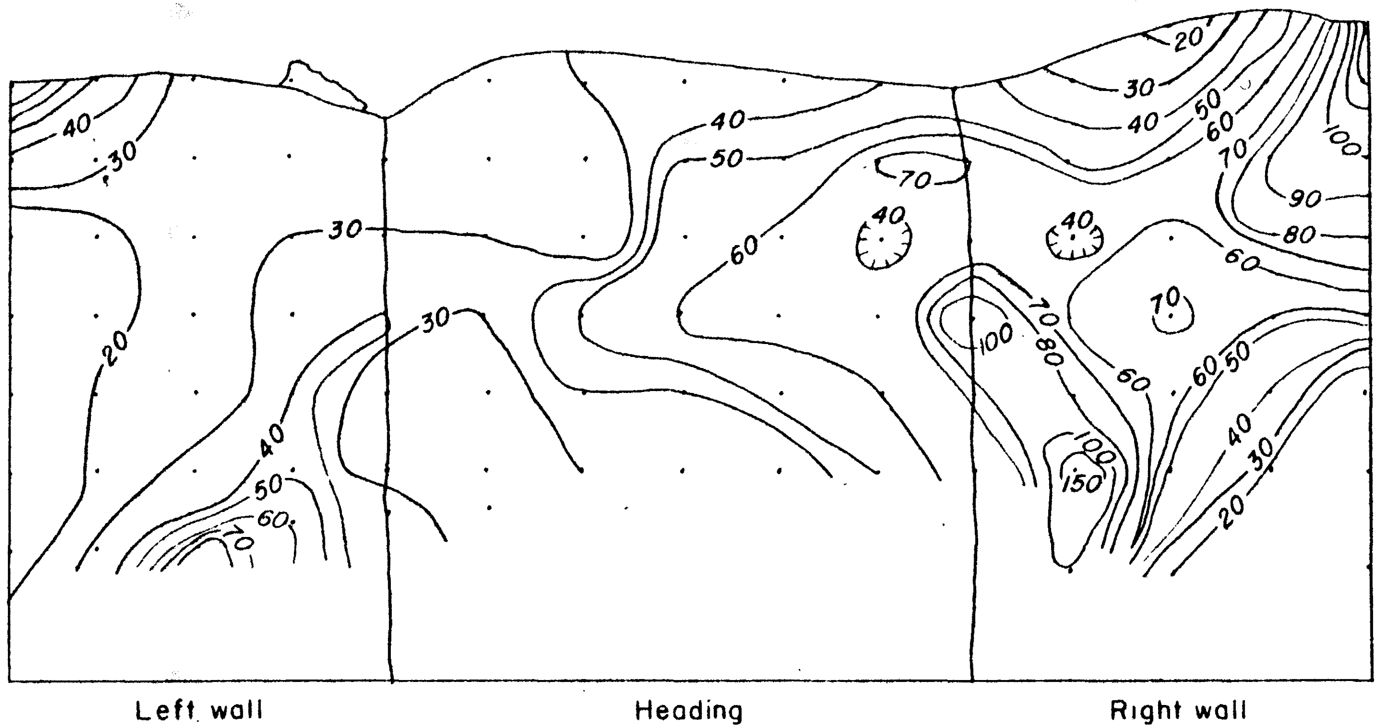

FIGURE 6-4 – CONTOURS OF EQUAL RADIOACTIVITY ON WALLS AND HEADING OF EXPLORATORY TUNNEL

Contour interval 10 milligoentgens per hour explosion point. The highest activities are associated with explosion-produced glass. However, values considerably above background were found where no glass was visible, although microscopic inspection may reveal its presence. The radiation anomalies are not uniformly distributed through the rock at locations which are essentially the same distance from the explosion chamber. Certain rock types exhibit higher gamma-ray anomalies than others, apparently because of variations in the amount of explosion-produced glass. The highest anomalies occur in white tuff; lower anomalies were observed in light brown tuff; and none were observed in dark brown tuff.

(3) The greatest gamma-radioactivity found in the drill holes was about 60 milliroentgens per hour as compared to 137 roentgens per hour detected in February 1958 (Johnson and others, 1958). As shown on figure 6-1, the most radioactive material was encountered in the drill holes below and on the northwest side of the explosion chamber. This nonuniform distribution of radioactive material about the explosion chamber is undoubtedly related to the heterogeneous mixing of rock fragments, molten rock, radioactive materials, and vapor produced by the blast. The influence of the open northeast-trending fault at the end of the Rainier tunnel or distribution of blast products is unknown. However, concentration of the radioactive blast products along the northwest side suggests a channeling of some of these products along this line of structural weakness. The lack of anomalous radioactivity in the vertical drill hole near ground zero about 58 feet above the chamber is evidence that the glassy shell formed by the blast collapsed causing a concentration of radioactive materials in the cavity below the chamber.

TEXTURAL AND CHEMICAL CHANGES

by R. E. Wilcox and V. R. Wilmarth

Specimens of the rocks in the Exploratory tunnel were collected June 6, 1958, by V. R. Wilmarth, F. N. Houser, and E. Dobrovolny at intervals of about 10 feet from about 65 to 210 feet radially from the explosion chamber (fig. 4-4). Twelve channel samples, number I to XII, were collected from the existing heading as shown in figure 4-5. Thin sections of the more radioactive samples were prepared with the help of Dr. Barrie H. Bieler of Dow Chemical Company in the Rocky Flats Plant of the AEC. Radioactivity of the breccia material was investigated by John R. Dooley using the "radioluxograph" technique. X-ray investigations of the samples were carried out by Theodore Botinelly. Specimens (1 to 19) collected from later headings in August and September 1958 (fig. 4-5) were not prepared in time for inclusion in this report.

In specimens from the first 95 feet (14+65 to 15+60) of the Exploratory tunnel the effect of the explosion is indicated by the closer spacing of the joints in the rocks. From 15+60 (120 feet radially from the chamber) toward the face, the rock becomes progressively more friable and much of it can be crushed easily in the hand. On drying in air it becomes somewhat more coherent but disintegrates rapidly upon contact with water. A series of half-inch pieces of the brownish tuff from the samples collected along the tunnel were dried in air and then placed in water. Those pieces from samples obtained between 140 and 210 feet from the chamber showed disintegration only of small masses of white material, that apparently are richer in clay minerals. Those pieces from 75 to 120 feet from the chamber showed progressively more disintegration, and those from 65 to 75 feet disintegrated completely within a few minutes to heaps of granular material, mostly smaller than 1 mm diameter. Similar pieces of air-dried lumps of the white tuff from about 140 feet radially from the chamber all disintegrated rapidly in water, possibly due to higher content of clay.

Thin sections were made from each of the samples collected from the face on June 5, 1958. Most of the samples were fragile or porous and were impregnated with canada balsam or Lakeside-70 to inhibit plucking of harder grains during grinding in kerosene. Several samples of material that had been converted to glass by the explosion could be sectioned without impregnation. Because in general only the more coherent parts of some samples were sectioned the study cannot be regarded as complete.

Under the microscope thin sections of the samples from the interval 140 to 210 feet radially from the chamber do not appear noticeably different from the normal preshot tuff of this portion of the Oak Spring formation. The sample at 15+50 (130 feet from chamber) however, shows a few short irregular hairlike fractures filled with fine-grained opaque material. Specimens taken at points further down the Exploratory tunnel contain similar hairlike cracks in progressively greater abundance, and about 75 feet from the chamber they form a fine anastomosing network of fractures. In many specimens these cracks show no preferred directions, in others a single direction may be dominant. Autoradiographs did not show these fracture networks to be appreciably more radioactive than the intervening rock material. In addition to the hairlike fractures, there are scattered thicker masses of this opaque material in the rock in and near the heading of June 6, 1958. These masses are generally wormlike, up to 1 mm thick, and have blunt or tapering ends. Further investigations of these features are necessary.

Relatively coherent angular masses of white tuff as much as several feet across and scattered small masses of glass were observed in the breccia exposed in the heading on June 6, 1958 (station 16+20). Most of the matrix is a brownish friable material. The radioactivity of the breccia fragments of white tuff is generally low but that of the glassy masses and brownish matrix varied widely. The channel samples collected from the heading and walls (fig. 4-5) includes lumps of granular material from distinct lithologic types of material; a few lumps show contacts between brownish matrix and white tuff. The brown material of some streaks shows appreciably higher radioactivity than the adjacent white tuff and is characteristically less compact. It consists of the usual amount of quartz, feldspar, biotite and magnetite phenocrysts and of aphanitic zeolite and clay minerals. The material is commonly lined parallel to the walls of the contacts; the lineation is visible as a fine fibrous material in plain light and as an oriented birefringence under crossed nicols. Such linear structures have also been observed in the pre-shot rocks.

The biotite phenocrysts of that part of the breccia zone penetrated by the Exploratory tunnel are locally much frayed and split, yet the same degree of disintegration of biotite has been observed in other places in the normal (preshot) Oak Spring tuff, and it cannot be safely concluded that those in the breccia zone have been torn apart to any extent by the explosion. The quartz and feldspar grains likewise are seldom complete crystals, yet again are apparently little, if any, more fragmented than in the beds unaffected by the explosion. No clear evidence was seen of secondary fracturing of the xenoliths of old volcanic rocks and quartzites scattered through the different units of the breccia, and they are unfractured even where the zeolitized lapilli matrix may show many of the microscopic hairlike fractures of the type described above.

Lumps of the masses and streaks of the more radioactive soft brown material from sample III (fig. 4-5) were disintegrated in water, then dried and examined under the binocular microscope. The loose product consists of many grains of materials that are normally present in the tuff, such as phenocryst fragments, xenoliths and lapilli fragments. In addition, there are a few variously shaped masses of glassy material. These are appreciably radioactive and may represent the source of most of the radioactivity of the samples, although the very fine fraction (<0.01 mm) likewise exhibits some radioactivity. Part of sample X is in the form of vesicular glassy blebs up to a centimeter in diameter, and sections of two blebs are more or less radioactive over their whole diameters, as shown by autoradiographs of the sections. A 4- mm-long spindle of glass in a thin section of sample V strongly affected the autoradiograph film.

A very few of the glassy particles of sample III are smooth spheres 0.1 to 0.5 mm diameter, with bubbles and dark streaks visible inside the otherwise clear glass. One nearly perfect sphere 0.4 mm in diameter carries a satellite sphere 0.02 mm diameter. Most of the glassy particles, however, are less regular in shape, with grooved and crenulated surfaces, and carry smaller adherent opaque white particles, apparently of tuffaceous material. Many appear to be fragments of stemlike and even hairlike masses representing a wide range of sizes up to several millimeters length, with longitudinal markings and elongate bubbles and dark streaks. Other masses up to 5 mm diameter appear to be irregularly shaped hubs, from which protuberances and spokes had been freshly broken off.

Distribution, texture, color, and radioactivity of the glass varies markedly. Most of the glass has been found in the matrix, but locally some is at the contacts between the various rocks in the breccia and as thin coatings on the upper sides of some of the breccia fragments. Rarely the glass is found within the breccia fragments. The glass is widely distributed in the matrix as round to subangular masses as much as 2 inches across; in places the glass is in lenticular masses as much as 2 inches wide and 1.5 feet long. The contact of the glass and adjacent rock is sharp and quite regular.

The glass is black, gray, red, or clear and varies from vitreous to dull and massive to frothy. Most of the black glass is vitreous and compact whereas the gray glass is frothy; the clear glass is vitreous. The texture of the glass is variable; some is frothy and some is frothy with discrete schlierenlike masses of black vitreous glass. Some masses of glass are composed of cores of brown clayey material with red vitreous glass enclosed in black vitreous glass. The one specimen of clear glass obtained has a botryoidal surface and is vitreous and dense. It contains some brown inclusions.

Refractive indices were determined for several of the glass fragments and were found to range from about 1.495 to 1.530. Variations exist not only from one particle to another, but also to some extent within the same particle. The glass of one of the blebs of sample X, for instance, shows a range of refractive index from 1.507 to 1.530. Another bleb of sample X was found to range from 1.510 to 1.528. These indices correspond to indices reported for medium to silicic natural glasses.

Four samples of the tuff exposed in the Exploratory tunnel were analyzed by chemical and semiquantitative spectrographic methods to determine if changes in the bulk chemistry of the tuffs were produced by the Rainier Explosion. The principal effects looked for include a change in water and carbon dioxide content, oxidation state of the iron and quantity of soluble salts in the rock contained water. Data on water soluble salts are not yet available. Comparison of the analyses for samples from unit V (table 3-1) with those from unit V (table 7-1) in the Exploratory tunnel shows that the bulk chemical composition of the tuffs has been little affected by the explosion. The ratio Fe_2O_3/FeO varies widely but appears to be not significantly different in samples near the explosion chamber than farther away. No apparent consistent change was noted in the minor element content of the tuffs that were analyzed (table 7-1).

Table 7-1.--Chemical and spectrographic analyses of samples from Exploratory tunnel, Rainier Mesa, Nevada Test Site, Nye County, Nevada

Sample no. 2/	Chemical analysis 1/ (percent)			
	1	2	3	4
SiO_2	67.85	66.00	68.01	69.21
Al_2O_3	11.93	13.01	13.09	11.28
Fe_2O_3	2.67	2.56	2.85	2.23
FeO	.07	.00	.10	.07
MgO	.95	.96	.96	.89
CaO	2.07	2.24	2.16	2.13
Na_2O	1.76	1.59	2.18	1.36
K_2O	3.09	3.21	3.37	2.83
H_2O+	4.10	5.48	3.35	4.86
H_2O-	4.69	4.36	3.62	4.49
TiO_2	.27	.18	.31	.17
P_2O_5	.07	.03	.08	.08
MnO	.08	.08	.10	.07
CO_2	.01	.01	.01	.02
Total	99.61	99.71	100.19	99.69
	Spectrographic analysis 3/ (percent)			
Ba	.03	.07	.07	.03
Be	.0003	.0003	.0003	.0003
Ce	.015	.03	.03	.015
Co	.0003	0. 4/	.0003	0.

Table 7-1.-- Chemical and spectrographic analyses of samples from Exploratory tunnel, Rainier Mesa, Nevada Test Site, Nye County, Nevada--Continued

Sample no. 2/	Spectrographic analysis 3/ (percent)			
	1	2	3	4
Cr	.0003	.00015	.0003	d
Cu	.0007	.0003	.0007	.0003
Ga	.0015	.003	.0015	.0015
La	.007	.015	.015	.007
Nb	.003	.003	.003	.003
Nd	d	.007	.007	d
Ni	.0003	0	0	0
Pb	.0015	.003	.0015	.0015
Sc	.0007	0	.0007	0
Sr	.015	.015	.03	.015
V	.0015	.0007	.0015	d
Y	.003	.003	.003	.003
Yb	.0007	.0007	.0007	.0007
Zr	.03	.07	.03	.07

1/ Analysis by V. C. Smith. All samples were given a preliminary drying at 105°C to remove part of the moisture.

2/ Sample description
1 Brown tuff from point 15+00
2 White-gray tuff from point 15+50
3 Brown tuff from point 15+60
4 Brown tuff from point 16+05

3/ Analysis by R. G. Havens

4/ Looked for but not found

5/ Barely detected; concentration uncertain

X-ray and semiquantitative spectrographic analyses of selected samples of tuff and breccia from the Exploratory tunnel were completed to study further the geologic affects of the Rainier explosion (table 7-2 and 7-3). For the location of samples analyzed see figure 4-4.

Mineralogy of the tuff and brecciated tuff were determined by X-ray diffractometer analyses (table 7-2). The results are believed to be accurate within 10 to 15 percent of the correct value. The principal minerals present are heulandite, clay (mainly montmorillonite), β-cristobalite, mica (mainly biotite) and glass (table 7-2). Although the amounts of these minerals vary from sample to sample, no consistent sequential change in the mineralogic content of the tuffs was noted from the entrance of the tunnel to 16 + 20 about 65 feet radially from the chamber. However, the effect of the explosion may have caused minor changes in the minerals that are not determinable by this method of X-ray analysis. Detailed study of the mineralogy of the altered tuffs is being carried on.

X-ray spectrographic and radiometric analyses of the brown breccia ground mass and dark gray irregular veinlets of tuff that cut the breccia fragments are given in table 7-3. In general, the variations in mineral and minor element content of the veinlets and adjoining rock are small and within the limit of error for the methods of analysis. This suggests that the color difference between the rocks may not be the result of chemical or mineralogic changes but is due primarily to the fine-grained character of the tuff in the veinlets.

Table 7-2.--Representative mineral compositions of tuffs from Exploratory tunnel (percent by volume) 1/

Sample no.		Heulandite	Clay	β-cristobalite	Mica	Remainder 2/
1.	15+30A 3/	35	40	10	-	15
2.	15+30B	35	25	10	-	30
3.	15+90	45	20	10	Tr	25
4.	15+90A	25	15	20	10	30
5.	16+00	45	20	5	-	30
6.	16+05	35	25	10	-	30
7.	16+10	30	25	10	-	35
8.	16+10G	30	40	-	Tr	30
9.	16+12.5	40	40	10	-	10
10.	16+15	40	35	15	-	10
11.	16+20	30	25	10	-	35

1/ X-ray analyses by T. Botinelly. Samples run at scale factor 16, mult. 0.8; time constant 1 sec., goniometer speed 8° 2 theta/min., with CuK radiation at 40 kva, 20 ma. Percents estimated from peak heights and represent only rough approximations accurate within 10 to 15 percent.

2/ Determined by difference; subject to larger errors than other figures.

3/ Sample locations measured from surveyed stations 15+00 and 16+00.

1. Brown coarse pumiceous tuff.
2. White coarse tuff
3. Brown coarse pumiceous tuff
4. Brown coarse pumiceous tuff
5. Brown coarse pumiceous tuff
6. Pale- to dark-brown fine- to medium-grained tuff
7. Pale-brown fine-grained sheared tuff
8. Pale brown-gray fine-grained tuff
9. Pale-brown fine-grained tuff near shear zone
10. Pale-brown fine-grained tuff from breccia
11. Pale-brown fine-grained tuff from breccia

Table 7-3.--Analyses of selected samples of tuff from breccia zone, Exploratory tunnel.

Sample description	X-ray diffractometer analysis in percent 1/						
	Heulandite	Clay	β-cristobalite	Mica	Feldspar	Quartz	Remainder 2/
Pale-brown tuff from breccia groundmass	30	30	- 3/	-	+ 4/	-	40
Pale- to dark-brown tuff from breccia groundmass	30	10	20-25	10-15	+	-	30-40
Light-gray tuff from breccia fragment	25	10	15	5	+	+	45
Dark-gray tuff veinlet in breccia fragment	35	-	20	10	+	-	35

CHANGES IN PHYSICAL PROPERTIES

By G. E. Manger, C. C. Hawley, E. C. Robertson,
G. V. Keller and L. C. Peselnick

Introduction

The rocks around the Rainier chamber were obviously altered and deformed to various degrees by the explosion. Rocks were brecciated for distances 60 - 70 feet from ground zero and they were fractured on a small scale for much greater distances. Although these obvious changes tell us much about the explosion, other less obvious changes, such as measurable physical properties of rocks, may furnish as much information on the nature and total effects of the explosion. The change--or lack of change -- in physical properties should be known to predict effects for future underground explosions and to provide a basis for geophysical study of explosions.

The properties measured were the fabric-dependent properties such as permeability, porosity, grain and bulk density, water content, and electrical resistivity, and the strength properties including compressive strength, elastic moduli, and acoustic velocity.

Changes in these properties were looked for, basically, by comparing properties of post-shot samples near the explosion to the properties of post-shot samples of similar rocks farther from the explosion and presumably unaffected by it. Pre-shot samples of rocks along the line of the exploratory tunnel were not available, of course, because that tunnel was not driven until after the Rainier test.

The results of the studies are not entirely conclusive. It is a definite fact that the physical properties of rocks within the breccia zone differ significantly from those of rocks outside this zone, also that the compressive strength of the rocks within about 110 feet of ground zero has been reduced. However, there are less definite or apparent changes in such factors as porosity and water content in the less altered rocks that cannot be fully evaluated with present knowledge.

Sampling

Two groups of samples were taken: the first group was from the exploratory tunnel; the second group was from the main (U12b) tunnel and the U12b.03 and U12b.04 laterals (figure 8-1). With the exception of the samples from the breccia zone, near the face of the exploratory tunnel, all samples were from lithologically similar, pumiceous tuff of unit V (subunit c, unit Tos_7) of the Oak Spring tuff.

The first group of samples (Exploratory tunnel) are superior in three ways: They are on more closely spaced centers (5 feet); they were collected sooner after mining and more nearly represent the natural state rocks, and third, they are of one stratigraphic interval in unit V. The second group of samples furnish control since they are less apparently affected by the explosion. They are, however, different stratigraphic zones of unit V, so any variations in properties in these samples are more likely to be primary, and due to stratigraphic variations, than are variations in samples from the Exploratory tunnel.

Care was taken to preserve the water in the samples by immediately wrapping them in aluminum foil and then sealing the samples in paraffin. The only samples that indicated appreciable drying were those from the main tunnel (U12b).

Samples were prepared at the Mercury laboratory for measurements at other laboratories. Most measurements were made on one-inch cores of various lengths. So far as possible adjacent segments of core were used for the different measurements, so the results of the different measurements are probably closely comparable.

Samples from the breccia zone (as much as 70 feet from the explosion point) and fractured zone up to 120 feet from the explosion point were physically incoherent due to minute fractures. Those rocks were frozen before coring. The physical incoherence also affected the accuracy of several measurements and it must be considered in interpreting the results of these measurements.

Techniques and calculation of measurements

Water content, grain and bulk density, and porosity (figures 8-1 and 8-2) were determined in one series of operations. To determine the water content the sample was weighed immediately after removal from the foil, then dried for 24 hours at 105°C and reweighed. It is believed that drying at this temperature removes all the pore water, but only a small amount of water contained in the zeolites. The dried sample was placed under a vacuum and then was resaturated with water. The saturated sample was weighed in air, and weighed suspended in water and from these and the original and dry weights all wanted quantities can be computed, in general:

$$\text{Water content (volume percent)} = 100 \times \frac{\text{weight (volume) of water lost in drying}}{\text{volume of sample}}$$

$$\text{Water content (weight percent)} = 100 \times \frac{\text{weight (volume) of water lost in drying}}{\text{weight of sample}}$$

$$\text{Porosity (percent)} = 100 \times \frac{\text{gain in weight in resaturation}}{\text{volume of sample}}$$

$$\text{Bulk density (natural state)} = \frac{\text{Weight of natural state sample}}{\text{Volume of sample}}$$

$$\text{Grain density} = \frac{\text{Weight of dry sample}}{1 - \text{porosity}}$$

Check measurements of grain density were made with a pycnometer with water, tetralin, and alcohol. The pycnometer determinations of grain density and porosity calculated from pycnometer grain densities and known bulk volumes agree in general with those obtained by water saturation (figure 8-2). The pycnometer grain densities are more random and this is probably the result of inherent difficulties in the pycnometer technique.

Fluid permeabilities were measured by Corelabs, Inc., of Denver, Colorado, by the standard technique of measuring the rate of flow of air at a pressure of 1 atmosphere.

Electrical resistivities were measured both on rocks in place in the tunnel and on natural-state cores cut from samples. In place measurements were made with a conventional four-electrode array, (ten-inch span) held against the tunnel wall. In the laboratory, electrical resistivities of cores from natural-state samples were determined on discs 1/4 inch thick by 1-1/2 inches in diameter; brine with a known resistivity was used to calibrate the measurements. Keller (1958) found in a previous investigation of the tuff that the resistivity is a simple function of the water content:

$$\text{Rock resistivity} = (\text{constant})\ (\text{resistivity of pore water})\ (\text{water content})^{-1}$$

Samples for measurements of compressive strength were prepared as cylindrical cores either 1/2 in. diameter by 1 1/2 in. long, or 1 in. by 1 in. Stresses and strains were determined during each test with standard instrumentation, and Young's modulus was calculated from the linear portion of a stress-strain graph. Samples compressed under 1,000 psi hydrostatic pressure were jacketed to exclude the pressure fluid from the rock. An accuracy of about ±40 percent is attached to these data because of inherent variation of the rock and errors with techniques.

Dilatational velocities were measured on 1 in. diameter by 1 in. long cores, both in the natural state samples and after drying. The technique consists merely of measuring the time required for a pulse to travel the length of a core. The pulse is initiated at one end of the sample and picked up at the other end by piezoelectric transducers. The arrival of elastic waves is displayed on an oscilloscope, and the travel time measured. The samples were weak and friable, so the velocities are correct only within ± 20 percent.

Results and Analysis of Measurements

The physical properties of rocks near the Rainier chamber are summarized in figures 8-1 and 8-2 and in tables 8-1 and 8-2. The summarized data, together with other geologic data, such as megascopic and microscopic character of the rocks, indicate explosion-caused differences in certain physical properties, including permeability, porosity, water content, resistivity and strength properties. Since the range in variation in properties in non-deformed rocks is not completely known, some of the interpretations are inconclusive.

The rocks in the breccia zone are more porous, more permeable, contain relatively less water in terms of pore space, and are less dense and weaker than the adjacent less deformed rocks of the exploratory tunnel (tables 8-1 and 8-2). Since the breccia was derived from several rock units, direct comparisons with the immediately adjacent rocks indicate only relative rather than absolute differences in these properties.

The few samples of the breccia zone that were coherent enough to measure indicate that porosity of both matrix and fragments is high. Relativel high porosity may also be inferred from the low resistivity of the rocks (table 8-1), although higher temperatures and permeability also contribute to the low resistivity.

The permeability of rocks in the breccia could not be quantitatively measured because of the friability of the rocks, but in terms of the loss of drilling water it is much greater than in the adjacent fractured rocks. In terms of saturation the water content of the rocks is relatively low,

Table 8-1.--Average textural properties of rocks from the Exploratory tunnel.

Property	Location of samples			
	Breccia zone	Fractured zone		
	60 to 70 feet from explosion point	70-110 feet from explosion point	110-160 feet from explosion point	160-228 feet from explosion point
Porosity	36.7	24.7	25.3	28.1
1 standard deviation	--	±3.0	±4.3	±7.4
Number of samples	4	9	10	15
Dry bulk density	1.49	1.80	1.80	1.72
1 standard deviation	--	±0.02	±0.03	±0.006
Number of samples	3	9	10	15
Natural state bulk density	1.80	2.07	2.10	2.02
1 standard deviation	+	±0.04	±0.02	±0.01
Number of samples	3	9	10	15
Grain density	2.33	2.39	2.41	2.39
1 standard deviation	--	±0.03	±0.04	±0.03
Number of samples	3	9	10	15
Permeability (millidarcies)	--	5.6	1.7	
Apparent saturation (percent)	73	114	111	
Rock resistivities (in place) (ohmmeters)	6	18	18	
Pore water resistivities (ohmmeters)	0.5	0.5	0.5	

Table 8-2.--Average strength and elastic properties of rocks from the Exploratory tunnel

Property	Location of samples		
	Breccia zone	Fractured zone	
	60 to 70 feet from explosion point	70 - 110 feet from explosion point	110-228 feet from explosion point
Compressive strength of natural state samples, no restraining pressure (10^3psi)	< 0.1	0.4	1.3
Compressive strength of natural state samples, 1000 psi hydrostatic pressure (10^3 psi)	*	*	5.8 (x10^3psi)
Young's modulus of natural state samples, no restraining pressures (10^5psi)	0.01	0.2(x10^5psi)	2.5(x10^5psi)
Young's modulus of natural state samples, 1000 psi hydrostatic pressure (10^5psi)	*	*	3.6 (x10^5psi)
Dilatational velocity of natural state samples (km/sec)	1.1 (km/sec)	1.1 (km/sec)	2.6 (km/sec)
Dilatational velocity of dried samples (km/sec)	1.5 (km/sec)	1.8 (km/sec)	2.5 (km/sec)

* Samples were too friable for measurement

Permeability shows a general increase on the graphical plot of data (fig. 8-2) near 75 feet from ground zero; the increase is also reflected in the averages. As in the case of the strength factors the approximately 4-fold increase in permeability (table 8-1) is likely a minimum value. The more fractured rocks did not give good cores for permeability measurements so the increase may be about that of matrix permeability rather than of bulk permeability. Perhaps it may be inferred from the other data that bulk permeability should be relatively high for distances as much as 110 feet from ground zero due to the fracturing.

Rather large variations are found in the physical properties of samples from the U12b tunnel and U12b.03 and U12b.04 laterals. Some average properties are summarized on figure 8-1. With the exception of the rocks in the east part of the U12b.04 lateral which are as close to Rainier as some samples from the Exploratory tunnel, the rocks are not known to have been appreciably fractured by the explosion. In general the rocks are more porous than the rocks of the Exploratory tunnel; they are about as permeable and as strong as in the rocks of the least fractured part of the Exploratory tunnel.

Conclusions

The basic effects of the explosion appear to have been an expansion of the rock mass in the zone nearest to the explosion. This zone of expansion corresponds to the breccia zone which at the level of the Exploratory tunnel extends about 70 feet from the explosion point. The crushing and expansion of the rocks in this zone is reflected by changes in several properties. The compressive strengths, velocities, and Young's modulus are greatly reduced; permeability is increased; and porosity is increased about one half. These changes are minimum ones because many of the samples were too weak to test.

The degree of saturation of the rocks in the breccia zone is less than that in rocks farther from the explosion. However, the total amount of water per unit volume of brecciated rock is roughly the same as in similar unbrecciated rocks. This could be interpreted as meaning that no water was driven from the breccia zone by this explosion; but this is extremely unlikely in view of the rapid cooling of the explosion zone that could only have been caused by transport of heat by steam. Therefore, it is believed that the breccia zone rocks have been in part resaturated by percolating groundwaters and water introduced during the various drilling operations.

The rocks in the Exploratory tunnel from 70 to about 110 feet from the explosion point (outside the breccia zone) were also significantly affected. The compressive strengths are roughly one quarter those of unaffected samples; permeabilities are higher; and velocities are roughly a third of the velocities determined from unaffected samples. Again, these changes are minimum ones because only the stronger samples could be tested.

In the interval between the breccia zone and the region where the rocks are unaffected there is a suggestion that the porosity of the rocks is low (density high) (table 8-1). These low values of porosity may be the result of a net compression of rocks in the minutely fractured zone outside the breccia zone. However, in view of the small change in the porosity of the rocks and the known variation of porosity in the tuff this is only a rather doubtful possibility. However, it is not incompatible with the results of laboratory strength measurements at high confining pressures. Axial compression tests indicate that at hydrostatic pressures greater than 10,000 psi, the tuff can be compressed by about 10 or more percent without breaking apart. Microscopic examination of such compressed samples shows that the deformation resulted in minute fractures. In other words, it appears possible that the density can be increased even though fractures have been developed in the rock mass.

THERMAL EFFECTS

By E. F. Roth and W. H. Diment

Equilibrium earth temperatures were measured before the Rainier explosion in a 800-foot vertical drill hole 100 feet west of Rainier ground zero. Post explosion measurements were made in underground drill holes B, C, and D (September and October, 1958) and in the Rainier ground zero drill hole (February through October, 1958).

Western Electric type 17A bead thermistors individually calibrated and spliced into multiconductor cables were used to make the temperature measurements. The estimated absolute accuracy of the calibrations is one degree centigrade above about 30 degrees and 0.1 degree below 30 degrees.

Contours of equal anomalous temperatures in a vertical plane through the explosion point (figure 9-1) were determined by subtracting the temperatures measured before the explosion from those measured after it. The pre-explosion temperatures were determined to a depth of 820 feet in a drill hole 100 feet west of the Rainier ground zero drill hole. The extrapolated temperature at the Rainier explosion point is 16.3 degrees centigrade and the slope of the extrapolation line is plus 0.012 degrees centigrade per foot of increasing depth. Several comments should be made about the contour map: 1) The underground drill holes are slightly out of the vertical plane, hence the points at which temperatures were measured were rotated into the plane about a vertical line (labeled axis of symmetry in figure 9-1) through the explosion point. 2) Thermal perturbations due to drilling may still be present in the Rainier ground zero drill hole but the temperature change with time is now very small in the lower part of the hole, and it is assumed that the position of the 2 degree contour line is approximately correct at its intersection with the drill hole. 3) It was not possible to contour effects less than 2 degrees because the required accuracy could not be obtained under the operational conditions existing at the time of the measurements.

By assuming the anomalous temperature distribution to be symmetrical about the vertical axis of symmetry a value of 9.4×10^{11} calories was computed for the minimum heat remaining in the rocks. Uniform values for density and specific heat of 1.8 g/cc (density of material in breccia zone) and 0.29 cal/g deg. were used for the computation. The Rainier explosion released a total energy of 1.7×10^{12} calories (Johnson and Violet, 1958). The minimum amount of heat remaining (after one year) in the rocks surrounding the Rainier explosion is, therefore, roughly one half of the total energy released by Rainier. This is a minimum figure for several reasons: 1) Anomalous temperatures less than 2 degrees were ignored because the accuracy of the measurements and drilling perturbations does not allow their inclusion. 2) Symmetry about the Ground Zero drill hole was assumed for the heat content computation, but the data suggest that more heat exists in the half space to the left of the assumed axis of symmetry than in the half space containing the drill holes (figure 9-1). 3) Water percolating downward from the surface or from drilling (over 60,000 gallons were lost in drilling) reduced the temperatures around the explosion point.

There is little difference between the temperatures measured a year after the explosion and those measured 3 to 4 months after the explosion (Johnson et al, 1958). Presumably, the temperature dropped very rapidly (Kennedy and Higgins, 1958) after the explosion by transfer of the heat through natural and or explosion produced fractures. It is clear that to sustain high temperatures about an underground explosion the rocks surrounding the explosion must be dry.

SEISMIC DELINEATION OF THE AFFECTED ZONES

by J. C. Roller, W. H. Jackson, H. W. Oliver, W. H. Diment,
P. E. Byerly and D. R. Mabey

Measurements of the velocities of seismic waves through rock materials in the vicinity of the Rainier detonation point were made to (1) determine the size and shape of the affected zones, and (2) estimate the degree of crushing and fracturing of the material.

Velocities were measured prior to the detonation in a vertical drill hole about 100 feet west of Rainier ground zero and in the U12b tunnel. After the detonation, the velocities of the rocks were measured in the U12b tunnel, the Exploratory tunnel, underground drill holes B and C, and in the Ground Zero vertical drill hole. In addition two reflection survey lines were run on the surface over the Rainier chamber.

The post shot measurements were severely limited by necessary time and access restrictions (two eight hour shifts for the work in the tunnel), poor air in the Exploratory tunnel, limitations on hole depth and charge size (one pound underground, five pounds on the surface) and particularly the continuously high noise level caused by continuous drilling, movement of mine cars, and the general high level of activity in the tunnel. Under ideal conditions results would undoubtedly have been better, particularly those involving wave travel paths more than 100 feet.

Affected zones

The preliminary results obtained by shooting a series of small charges at each end of the Exploratory tunnel (shot points 1 and 2) and recording the travel times to seismometers positioned at intervals of 25 feet in drill holes B and C and at intervals of 20 feet in the ground zero hole are summarized in figure 10-1. The velocities shown are based on straight-line travel paths. The minimum time path may be slightly longer over some of the intervals but it is believed that the velocities in drill holes B and C represent nearly true rock velocities. Straight-line velocities between the shot points and the Ground Zero hole are given for only six of the seismometers. The first energy arriving at other seismometers appear to have travelled up the seismometer cable with a velocity of 4300 - 4600 feet per second.

Figure 10-2 shows graphs of travel time versus distance from shot points in the Exploratory tunnel and the adjacent part of the main U12b tunnel. The inverse slopes of the solid lines are the velocities in the rocks in the tunnel before the Rainier detonation. The dashed lines similarly determine the post-Rainier velocities.

From the data in figures 10-1 and 10-2 and from data obtained by shooting charges near the surface and receiving energy propagated to seismometers positioned in the Ground Zero hole (not illustrated) there appears to be three distinct zones of about 70%, 40% and 10% velocity reduction surrounding the point of detonation. The evidence for and character of these zones are as follows:

Zone 1.--The velocity from the point of detonation to roughly 50 feet, as determined in drill hole C, is 2,300 ft/sec (figure 10-1) or about 6000 ft/sec lower than the preshot value (figure 10-2). This zone compares approximately with the brecciated zone mapped in the Exploratory tunnel. This velocity is about the same as velocities found in inelastic media such as dry sand and alluvium. The change in the "elasticity" (Δe) of this medium is found from the relationship

$$\frac{\Delta e}{e} = \frac{\rho_1 V_1^2 - \rho_2 V_2^2}{\rho_1 V_1^2}$$

where ρ_1, ρ_2, V_1, and V_2 are the pre- and post-Rainier densities and velocities of the media. For values $\rho_1 = 2.1$ g/cc, $\rho_2 = 1.8$ g/cc, $V_1 = 8300$ ft/sec and $V_2 = 2300$ ft/sec., the reduction in the elasticity by the explosion is about 90% which means that the medium is nearly completely disaggregated.

The shape of this brecciated zone is not well defined by the seismic data. However, the low velocities to geophones at depths of 700 to 830 feet in the Ground Zero hole (figure 10-1) suggest an upward flaring out of the zone or possibly a zone of even lower velocity.

Zone 2.-- The velocity from about 50 to 100 feet from the point of detonation along drill hole C is about 4800 ft/sec which is a significant reduction from the 8300 ft/sec preshot velocity. The associated reduction in the elasticity of this zone is about 65% which suggests that it was highly fractured but not disaggregated by the Rainier detonation. This zone compares with approximately the fractured zone mapped in the tunnel. The outer limits both are gradational.

The outer limit of this "fractured" zone was also observed seismically in drill hole B (figure 10-1) and the Exploratory tunnel (figure 10-2) at about the same distance from the point of detonation. The low velocities to geophones in the Ground Zero hole suggest an upward flaring out of zone 2 similiar to zone 1.

Zone 3.--The velocity from about 100 feet outward in drill holes B and C and the tunnel is less than preshot values but the difference is only about 10 percent. Small fractures produced by the explosion are probably responsible for the reduction. Consequently, the rocks are probably slightly more permeable to the passage of the fluids than before the explosion. This inferred increase in permeability is not reflected in the measurement of permeability on samples an inch or so in size. It is assumed, therefore, that the fractures which may cause the reduction in velocity are spaced on the order of several inches or more.

The outer limit of zone 3 is not well defined. The marked reduction in velocity near station 12+00 in the tunnel is thought to be the effect of a high explosive test in a chamber 100 feet north of the main tunnel at station 11+90. Similar reductions in velocity were found in the vicinity of the USGS 10 and 50 ton high-explosive tests.

A perceptible velocity reduction is shown 400-500 feet above the Rainier detonation as determined by shooting charges near the surface and recording the travel time to seismometers positioned in the Ground Zero hole. No information on rock velocities below 400 feet depth was gained from the surface shots because from a depth of 400 to 500 feet the first energy arriving at the seismometers was transmitted down the casing; below 630 feet the first energy to arrive was transmitted down the cable or through the water in the drill hole.

Velocity reductions of less than 10 percent may extend to greater distances than 500 feet as such small differences in velocity approach the accuracy of the method.

CHANGES IN THE GRAVITATIONAL FIELD

by D. L. Healey, M. F. Kane, and W. H. Diment

Gravity stations were established after the Rainier explosion on the surface above the detonation point, in the U12b and Exploratory tunnels, and on the surface directly above the tunnels. No pre-explosion gravity survey was made, although it has been for later underground tests. The gravity observations were made with a meter having a sensitivity of 0.00871 milligals per vernier division. Most of the observations are accurate to 0.02 milligals Most of the gravity measurements were made by F. E. Currey who also assisted in the reduction of the data.

A preliminary interpretation of the results obtained near ground zero revealed no anomalous conditions which could be attributed to the explosion. However, gravity anomalies less than 0.5 milligals would be obscured by limitations in making corrections for the precipitous terrain.

The corrected gravity measurements in the U12b tunnel system are more precise than those made on the surface but they do not indicate any anomalous rock densities that might have been produced by the explosion. Figure 11-1 shows the location of the stations in the tunnels and on the surface directly above the tunnels, and the distribtuion and densities of the different members of the tuff which make up the Rainier Mesa. Figure 11-1B gives the partially corrected gravity data in the tunnel system and the corresponding terrain corrections. The terrain corrections include a factor to correct for small changes in elevation which are beyond the precision of the published tables.

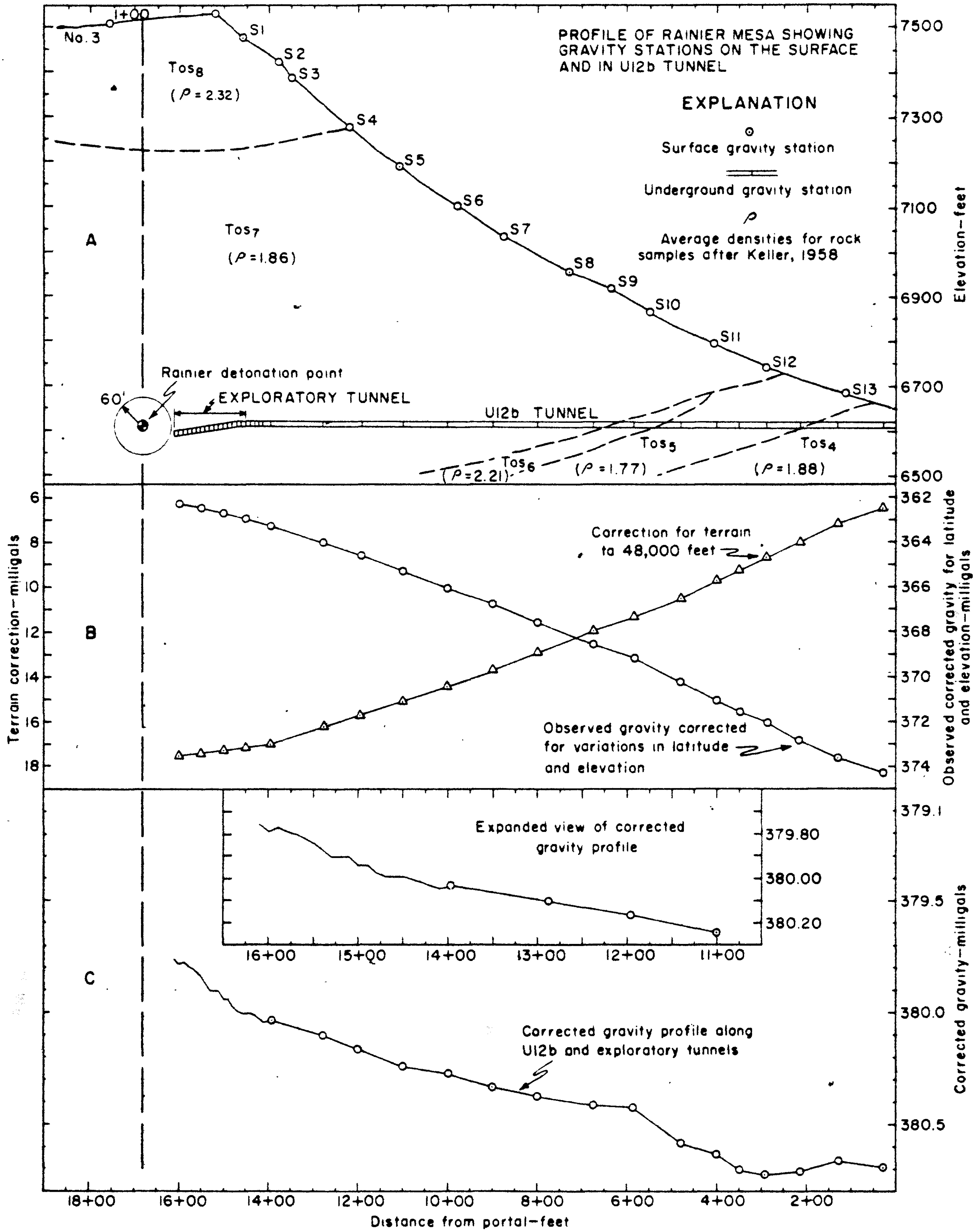

FIGURE II-1 —RESULTS OF GRAVITY SURVEY IN U12b AND EXPLORATORY TUNNELS, NEVADA TEST SITE, NYE COUNTY, NEVADA

Figure 11-1C shows the observed gravity corrected for latitude, the mass of rock removed from the tunnel, the elevation (free air correction and twice the normal Bouguer correction, density 1.86 g/cc*), and the terrain effects (density 1.86 g/cc).

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* The differences in gravity between stations in the tunnel and on the surface above the tunnel provide a means for computing the density of the rocks between the tunnel and the surface. Such a computation of station 36 and the station in the tunnel below it yields a density value of 1.9 which is in close, and perhaps fortuitous, agreement with the average density (wet) of 1.86 for samples taken from unit Tos_7.

The completely corrected gravity profile in the tunnels shows a general decrease in gravity with increasing distance from the portal. This decrease is interpreted as a deepening of the dense dolomite under the less dense tuff as has been indicated by surface observations and drilling. The variations in gravity along the profile between station 0+00 and 8+00 reflect the changes in lithology that are illustrated in figure 11-1A. The effective center of mass of the less dense Tos_5 above the tunnel is at about 3+00. This less dense mass should cause an increase in gravity because of the decrease in the upward attraction of the mass above the point of measurement. Gravity increases at about 3+00. A decrease in gravity should occur at about 5+50 as a result of the combined effects of the more dense Tos_6 above the tunnel and less dense

Tos_5 below the tunnel. The profile shows a decrease between 5+00 and 7+00. At first inspection it would appear that an increase in gravity should be observed over the more dense Tos_6 where it passes below the floor of the tunnel, however, this increase is probably offset by the presence of the less dense Tos_5 underneath Tos_6. From station 8+00 to 14+00 gravity decreases smoothly with no apparent local anomalies.

Gravity in the exploratory tunnel shows an overall decrease with increasing distance along the tunnel. The small fluctuations in the curve can be attributed to inaccuracies in the measurements, and in the correction for the tunnel configuration. The decrease in gravity is opposite to what would be expected if the density of the rocks above the tunnel had been reduced by dissaggregation and fracturing more than those below the tunnel. A decrease could be caused by a relative decrease in density below the explosion point or relative increase in density above it. Little evidence exists to support either of these interpretations. Measurements on samples indicate that the explosion caused a decrease in density by disaggregation and fracturing of the rocks in the breccia zone surrounding the explosion chamber. There are, therefore, two interpretations: the decreases in density above and below the tunnel are so nearly equal that the gravity anomalies caused by the reduction of density cancel each other (the gravity meter measures only the vertical component of gravity). The anomalous mass of low density even if mainly above the tunnel is too small to be detected. The decrease in gravity along the tunnel might best be considered an extension of the normal trend and is attributed to density contrasts at the base of the tuff or to unknown anomalous conditions within the tuff.

The preliminary analyses of the surface and tunnel gravity surveys indicate that no gravitational effects greater than 0.2 milligals were produced by the effects of the Rainier explosion. More detailed corrections and interpretation may reveal significant anomalies resulting from the explosion. The preliminary results indicate that gravity techniques would be of no value in detection inspections except possibly under extremely favorable conditions.

DISTANT SEISMIC EFFECTS

By S. W. Stewart, W. H. Diment and J. C. Roller

The seismic effects of the Rainier event were recorded by many organizations at distances ranging from a few hundred feet to 3600 kilometers (Carder, Cloud, Murphy and Hershberger, 1958). The Coast and Geodetic Survey has assigned to Rainier a Gutenberg-Richter earthquake magnitude of 4.6 from seismic records of the explosion (Carder et al, 1958). A natural crustal earthquake of this magnitude would be perceptible to people several tens of miles from the epicenter but the ground motion produced by Rainier was barely perceptible to people 2.5 miles from the explosion. The difference may be the result of many factors among which are: the nuclear explosion was a point source whereas tectonic earthquakes result from shear movements between large volumes of rock; the explosion was at a shallow depth near a sharp topographic scarp whereas the foci of natural earthquakes are commonly greater than 10 kilometers below the surface.

The maximum accelerations caused by Rainier, as recorded at U. S. Geological Survey three-component seismic stations are plotted in figure 12-1 together with the maximum accelerations caused by Smoky (a 44 kiloton explosion 700 feet above the ground) and an underground explosion of 50 tons of 60 percent nitroglycerin gelatin.[1/] The calibrated frequency range

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1/ The maximum acceleration refers to the largest acceleration determined in any one of the three components -- in other words the maximum single component acceleration.

of the instruments was from about 1.5 to 20 cycles per second. The frequency of the waves producing the maximum acceleration ranged between 2 and 6 cycles per second, the higher frequencies occuring closer to the explosion. The equations shown in the figure are the least squares equations computed on the assumption that the maximum acceleration decreases as the inverse square of the distance.

From the Rainier data, as well as that for the underground explosions in Area 12 during Operation Hardtack -- Phase II, an empirical scaling relation has been developed (Stewart, Roller, and Diment, 1958):

$$A = \frac{0.6 \pm 0.5\, W^{0.8 \pm 0.2}}{D^{2 \pm 0.2}}$$

Where A is the maximum acceleration in units of gravity caused by an explosion of W kilotons yield at a distance of D kilometers. The plus or minus ranges refer to standard deviations based on most of the explosions.

It is important to recognize that these ranges are physically real (at least in part) and not wholly the result of limitations in instrumentation and technique. For example, the maximum accelerations determined for stations on deep alluvium are several times higher than those for stations on tuff or bedrock. Furthermore, factors such as the degree of containment, local topographic and geologic conditions about the explosion, and the size of the explosion chamber may control the amount of seismic energy leaving the shot area.

A graph (figure 12-2) permits an extrapolation to higher yields provided it is recognized that: the scaling relation was developed from

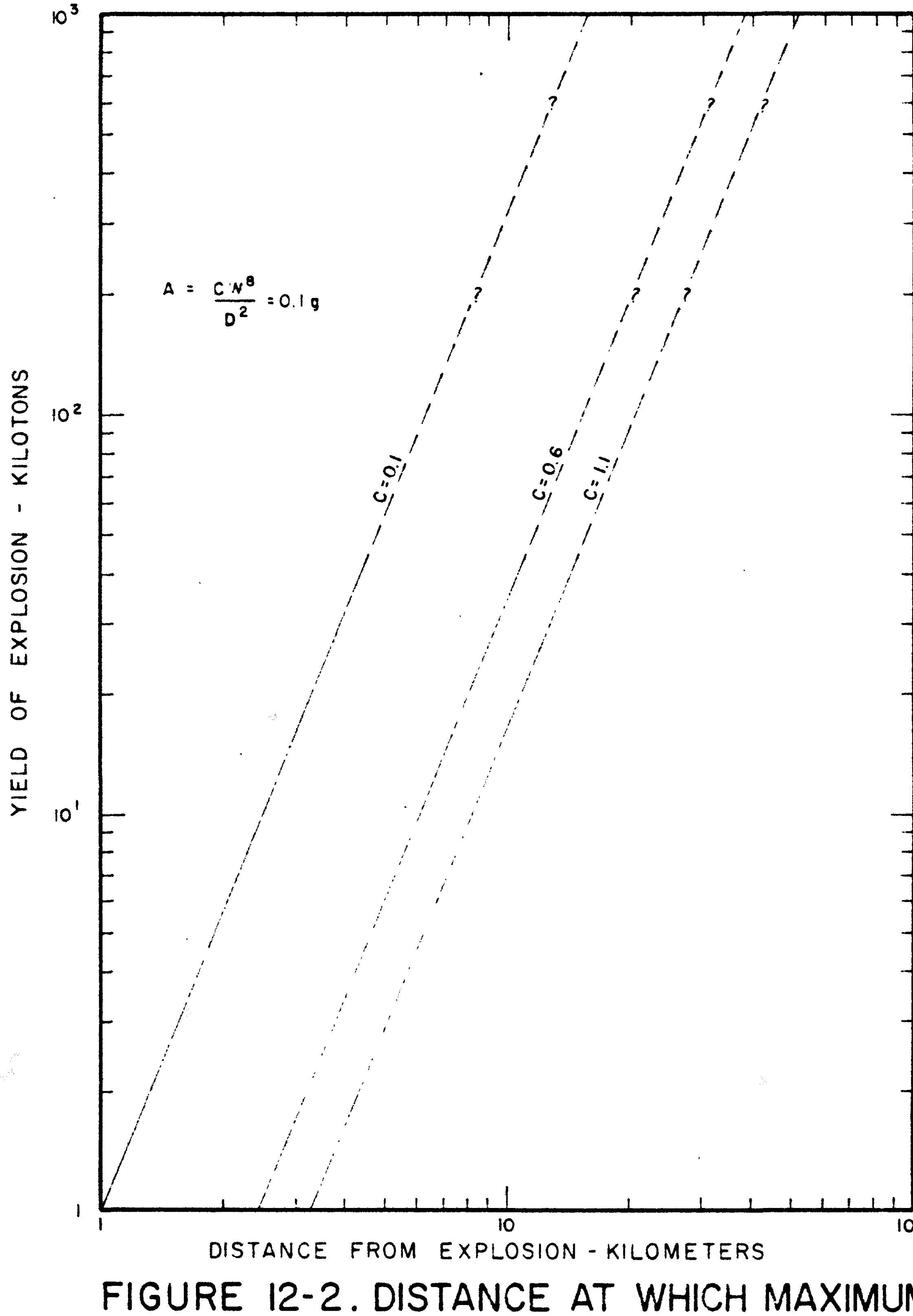

FIGURE 12-2. DISTANCE AT WHICH MAXIMUM ACCELERATION EQUALS 0.1 G VERSUS YIELD OF EXPLOSION

the scaling relation was developed from explosions in bedded tuff and in tunnels of certain design. Marked deviations from these conditions might result in significant differences in the scaling relation. Extrapolation with certainty abbve 100 kilotons is risky because the characteristics of underground explosions as generators of seismic waves may change significantly with yield, although no marked changes have been observed in the preliminary analyses of seismograms from explosions ranging two orders or magnitude in yield. The value of 0.1g was selected because this acceleration is generally accepted as the lower limit of acceleration that will cause damage to weak construction, (Richter, 1958, Thoenen and Windes, 1942).

Preliminary analyses of the ratio of maximum accelerations caused by air and underground shots indicates that the underground shots in Area 12 produce accelerations roughly 10 times those produced by air shots of equivalent yield 500 to 750 feet above the ground. The ratio of the accelerations caused by Rainier and Smoky is several times higher than this average; the exact ratio depends on the yield exponent used to reduce the explosions to the same yield.

Scaled comparison of the maximum accelerations produced by Rainier and the 50 ton high explosives tests indicates that nuclear and high explosives tests of the same yield in the same medium produce roughly the same maximum accelerations. The scatter of data does not permit the establishment of a "HE versus nuclear equivalence" with much precision.

SUMMARY

by W. H. Diment and V. R. Wilmarth

The effects of the Rainier explosion may be grouped according to four somewhat arbitrary zones: 1) the breccia zone in which much of the rock was crushed and blocks of rock were disoriented; 2) a transition zone in which there was considerable fracturing on a microscopic and megascopic scale, but no disorientation of rocks; 3) an outer fracture zone in which displacements and fractures were observed, but in which little or no change occurred in most volume elements smaller than several cubic feet; 4) a distant zone in which there was little or no permanent deformation of the rocks.

In considering these zones it is important to recognize that the information concerning them is limited to a few places within each zone and that the boundaries are not distinct. Furthermore, the assumption of symmetry about the explosion point is probably not valid for most phenomena observed.

Breccia zone

A shear zone was encountered in the Exploratory tunnel at a distance of 70 feet from the explosion point. This shear zone marks the outer limit of the brecciated rock which consists of angular to subrounded fragments of tuff and explosion-produced glass in a matrix of fine-grained comminuted tuff. The size of the breccia fragments varies from 0.3 to 3 feet across and smaller fragments as much as 2 inches across are numerous in the fine-grained matrix. No set pattern of size or degree of angularity was noted. The percentage of fragments, glass, and groundmass exposed in the Exploratory tunnel in the breccia zone is 25 to 40 percent fragments, 0.05 to 3 percent glass, and 60 to 70 percent matrix.

Rock fragments taken from the breccia zone in the Exploratory tunnel revealed the presence of abundant fine microscopic fractures. In many specimens these fractures showed no preferred orientation, but in others a single direction may be dominant. Quartz and feldspar grains, biotite crystals, and xenoliths of old volcanic rocks do not appear to be more broken than in rocks unaffected by the explosion. It is probable, therefore, that much of the deformation of the explosion was taken up in the soft zeolitized matrix in which the phenocrysts and xenoliths were suspended.

Irregular veinlets as much as two inches wide of fine-grained material are found both in the groundmass and in some of the breccia blocks. The veinlets commonly consist of zeolite and clay and the usual amount of phenocrysts and xenoliths, but the material is softer and generally more radioactive than the enclosing rock. The radioactivity is mainly concentrated in small or microscopic pieces of glass.

Explosion-produced radioactive glass was found in the breccia zone in the Exploratory tunnel and in the underground drill holes. The distribution, texture, color, and radioactivity of the glass varies markedly. Most of the glass was found in the matrix, but locally some is at the contacts between rock units or forms a thin coating on the upper side of some breccia blocks. The glass is widely distributed within the groundmass as rounded to subangular masses as much as two inches across. In some places the glass is a lenticular mass as much as two inches wide and 1.5 feet long.

The glass is black, grey, red, or clear, and varies from vitreous to dull and massive to frothy. The black glass is generally vitreous and compact, the grey glass is forthy, and the clear glass vitreous. Some frothy glass contains discrete schlierenlike masses of black vitreous glass, and some masses of glass are composed of a core of brown clayey material with red vitreous glass enclosed in black vitreous glass. Refractive indices of the glass ranges from 1.495 to 1.530. These indices corresponds to medium to silicic natural glass.

The limit of the breccia zone is 70 feet from the explosion point in the Exploratory tunnel. Here the limit of the zone corresponds with the limit of high radioactivity. Gamma intensity surveys, therefore, may be expected to give the limit of the breccia zone in drill holes B, C, and D. Synthesis of this information indicates that the edge of the breccia zone dips west at roughly 60 degrees in this restricted area.

The temperature and gamma intensity anomalies are not symmetrical about a vertical line through the explosion point. The maxima are clearly offset to the west (to the left in the diagrams). Furthermore, the maxima are several tens of feet below the explosion point. The downward displacement of the maxima has been explained on the assumption of the creation of a cavity, the subsequent collapse of which concentrated the radioactive and high temperature materials near the bottom of the cavity below the explosion point (Johnson et al, 1958). The displacement of the maxima to the west is not so easily explained but it should be pointed out that several faults transected the U12b tunnel before the explosion near station 17+00 which is about 30 feet west of the explosion point. One of these faults was open and as much as eight inches wide. Perhaps the faults controlled the shape of the cavity or otherwise influenced the distribution of the high temperature and highly radioactive material.

The extent of the breccia zone above the explosion point is not known. Furthermore, it is unlikely that a well defined edge of the breccia zone exists above the explosion point. It probably dropped with part of the transition zone toward the cavity. The 25-foot deep cavity 390 feet above the explosion point may be the upper limit of the post shot movement toward the cavity. No anomalous gamma radiation was encountered in the ground zero drill hole from the surface to 60 feet above the explosion point. No core could be recovered during the post shot drilling because the rocks were too friable in the interval between the explosion point and 390 feet. However, core recovery in this interval was very poor during pre-shot drilling. Hence, the quantity of core recovered is not a good index in this region of the explosion effects. Further drilling and sampling is required to satisfactorily delineate the zone above the explosion point.

Transition zone

The transition zone extends from the breccia zone to about 110-140 feet from the explosion point in the Exploratory tunnel. The outer limit is gradational. The main effect in this zone is extensive megascopic and microscopic fracturing which increases in severity as the explosion point is approached.

From 120 feet the rock becomes progressively more friable toward the explosion point and much of it can be crushed easily by hand. Samples taken from this zone show microscopic hairlike cracks in progressively greater abundance as the explosion point is approached and at about 75 feet. They form a fine anastomosing network.

Chemical, spectrographic, and X-ray diffractometer analyses of samples from the transition zone indicated a variation in composition and mineral content. However, no consistent sequential change was noted in the tuff from the entrance of the Exploratory tunnel to the breccia zone.

The rock properties in this fractured zone are intermediate between those of the rocks in the breccia zone and those of the unaffected rocks; compressive strengths and dilatational velocities about one third less than the values for unaffected rock; the permeabilities are higher; and the porosities and water contents are about the same.

The porosity of the rocks in the transition zone from 70 to 150 feet from the explosion point are slightly lower (5 percent or less) than the porosity of those to either side. These low values of porosity suggest that the rocks have undergone a net compression. The validity of this suggestion is doubtful because of the natural variation of the porosity within most units of the tuff. However, it is compatible with laboratory compression measurements at high confining pressure. Axial compression tests at confining pressures greater than 10,000 psi indicate that the tuff can be compressed by about 10 or more percent without breaking apart. Microscopic examination of such samples shows many fractures.

Gamma radiation as measured in drill holes B, C, and D is close to natural levels in most of the transition zone. The edge of the breccia zone is marked by a sharp increase in gamma radiation. A few local "hot spots" were found in the transition zone. These might be interpreted as points of intersection with faults containing radioactive material. However, this has not been proved.

Outer fracture zone

Rock falls, rock slides, fractures in the welded and non-welded tuff were observed on the surface mostly near the edge of and on the steep slope of the mesa. The edge of the mesa was affected for a distance of about one mile. Fractures in the welded tuff were as much as two inches wide and some were traceable along the surface as much as 300 feet. Most of the post-explosion fractures formed along pre-existing fractures.

The amount of rock spalled from the tunnel increased from the portal inward to where the tunnel was filled with debris at about 200 feet from the chamber. In general, the effect of the explosion from about 12+75 toward the explosion was to enlarge and deform the cross-sectional profile of the tunnel. Within 250 feet of the explosion chamber the tunnel has the shape of a crude parallelogram that is slanted to the northeast. Eight new joints and one new fault were noted. The fault is about 1,120 feet from the explosion point, has a four inch displacement, dips 25° NW, and is parallel to the attitude of the beds. Movement along a pre-existing fault, 385 feet inward form the portal, was indicated by the walls being moved apart one half inch.

Distant zone

No permanent displacements were observed beyond a distance of about a mile. At this distance the detectable effects were restricted to rock falls from the precipitous edge of the mesa.

Ground motion was barely detectable to observers at a distance of 2.5 miles where the maximum acceleration of the ground motion was measured to be about 0.1 g. This value of acceleration is generally regarded as the lower limit of acceleration that will cause damage to weak construction.

An empirical scaling relation was developed from an investigation of the ground motion caused by Rainier and the underground explosions in Area 12 during Operation Hardtack-Phase II. The applicability of the relation is restricted to explosions in the bedded tuff of the Oak Spring formation and to tests of the same general design as those investigated.

$$A = 0.6 \pm 0.5 \frac{W^{0.8 \pm 0.2}}{D^{2 \pm 0.2}}$$

Where A is the maximum acceleration in units of gravity caused by an explosion of W kilotons yield at a distance of D kilometers. The range in the standard deviations of the constants is at least partially real and reflects the effects of local geologic conditions around the seismic stations and the degree of containment of the explosion. Both factors seem to cause variations of several times in the maximum accelerations.

Underground explosions in the bedded tuff cause accelerations roughly ten times greater than explosions in air 500 to 750 feet above the surface of the ground in the Yucca flat. Comparison of the maximum accelerations caused by the 50 ton high explosives test and the underground nuclear explosions indicates that high explosives and nuclear explosions of equivalent yield produce roughly the same accelerations. However, uncertainties in the scaling constants, variations in the media surrounding the explosion point, and variations in the test design do not permit the establishment of an "HE equivalence."

Peaceful uses of underground nuclear explosions

The Rainier effects are important in evaluating the numerous peaceful applications that have been suggested for underground nuclear explosions (Brown and Johnson, 1958, Teller 1958, Zodtner et al, 1958). The effects that may be of importance in peaceful applications are:

1) Less than a few months after the explosion, temperatures around the explosion had dropped to below the boiling point of water because of transport of heat from the affected zone by steam. Therefore, in order to sustain high

temperatures in the affected zone (as would be desirable for power production) the explosion would have to be fired in dry rocks or some way found to contain the steam. Temperature considerations of this type may also be important in plans for the release of hydrocarbons from oil shales, depleted oil fields, and the like.

2) The residual radioactivity is mostly contained in explosion produced silicate glass and is mostly restricted to the breccia zone. Much of the glass is concentrated several tens of feet below the explosion point but the remainder is erratically distributed. The concentration is attractive for isotope production applications. However, the silicate glass is not easily soluble and other media would be more desirable if recovery by leaching is contemplated.

3) Considerable water was lost during drilling in the zone around the Rainier explosion point, thus indicating a high bulk permeability (the result of natural and explosion produced fractures). Applications that depend on leaching a product from the affected zone should, therefore, be reviewed critically as to if and where the leached produced might be recovered.

4) In regard to improvement of aquifers by underground nuclear explosions, the increase in rock volume as a result of the Rainier explosion was probably of the order of 10 to 20 acre-feet. Such a small increase in storage capacity would not be economical under most conditions. Much larger explosions would be required for applications depending solely on increasing the volume of an underground reservoir. Each aquifer improvement program involving changes in hydrologic conditions is a special case. The Rainier observations cannot be suitably generalized in summary form to cover such applications.

REFERENCES CITED

Brown, H., and Johnson, G. W., 1958, Non-military uses of nuclear explosions: University of California Radiation Laboratory, UCRL-5026, 15 p.

Carder, D. S., Cloud, W. K., Murphy, L. M., and Hershberger, J. M., 1958, Surface motions from an underground explosion: U. S. Dept. of Commerce, Coast and Geodetic Survey, WT-1530, 47 p.

Hansen, W. R., and Lemke, R. W., 1958, Geology of the USGS and Rainier tunnel areas, Nevada Test Site: U. S. Geol. Survey TEI-716, 111 p., open-file report.

Johnson, G. W., Pelsor, G. T., Preston, R. G., and Violet, C. E., 1958, The underground nuclear detonation of Sept. 19, 1957: University of California Radiation Laboratory, UCRL-5124, 27 p.

Johnson, G. W., and Violet, C. E., 1958, Phenomenology of contained nuclear explosions: University of California Lawrence Radiation Laboratory, ITR-1499, 38 p.

Maxey, G. B., and Jameson, C. H., 1948, Geology and water resources of Las Vegas, Pahrump, and Indian Spring Valleys, Clark and Nye Counties, Nevada: Nevada Water Resources Bull. No. 5.

Meinzer, O. E., 1923, Outline of ground-water hydrology, with definitions: U. S. Geol. Survey Water Supply Paper 494.

Richter, C. F., 1958, Elementary seismology: San Francisco, W. H. Freeman and Co., 768 p.

Teller, Edward, 1958, Peaceful uses of fusion: University of California Radiation Laboratory, UCRL-5257, 10 p.

Theonen, and Windes, 1942, Seismic effects of quarry blastings: U. S. Bur. Mines Bull. 442.

Zodtner, Harlan (ed.), 1958, Industrial uses of nuclear explosives: University of California Radiation Laboratory, UCRL-5253, 96 p.