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AVERAGE PROPERTIES OF NUCLEAR TEST AREAS AND MEDIA AT THE USERDA NEVADA TEST SITE

L. D. Ramspott and Nancy W. Howard

September 15, 1975

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Prepared for U.S. Energy Research & Development Administration under contract No. W-7405-Eng-48

LAWRENCE LIVERMORE LABORATORY
University of California/Livermore

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy $___*; Microfiche $2.25

*Pages	NTIS Selling Price
1-50	$4.00
51-150	$5.45
151-325	$7.60
326-500	$10.60
501-1000	$13.60

DISTRIBUTION CATEGORY
UC-11

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Contents

Abstract 1

Introduction 1

Description of Test Areas and Meala 2

- Yucca Flat 2
- Pahute Mesa 5
- Rainier Mesa 5
- Climax Stock 5
- Paleozoic Rocks 6

Comments on Data Base 6

- General Comments 6
- Working-Point Parameters 7

Parameters Examined 8

- Density 8
  - Methods of Measurement 8
  - Working-Point Density 8
  - Overburden Density 12
- Seismic Velocity 12
  - Methods of Measurement 12
  - Seismic Velocity in WP Vicinity 16
  - Working Point to Surface Seismic Velocity 19
- Water Content 19
  - Analysis, Sampling, and Error 19
  - The Data 22
- Porosity and Saturation 22
  - Source of Data 22
  - The Data 25

Discussion 31

Summary 35

Acknowledgments 36

References 37

AVERAGE PROPERTIES OF NUCLEAR TEST AREAS AND MEDIA AT THE USERDA NEVADA TEST SITE

Abstract

Data have gradually been accumulated on the physical properties of nuclear test sites at the U.S. Energy Research and Development Administration (USERDA) Navada Test Site (NTS) since underground testing began there in 1957. These data have been stored in the Lawrence Livermore Laboratory (LLL) K-Division Test Effects Data Bank. This report briefly describes the principal test areas (Yucca Flat, Pahute Mesa, and Rainier Mesa) and media (alluvium, tuff, Climax Stock (granite) and Paleozoic rocks) at NTS. Background information is given on the data base and the various methods used to measure geophysical parameters at NTS are described.

The mean, standard deviation, and range of values for each test area and medium are given. However, specific properties for individual sites are not contained in this report. Properties for which averages are given include overburden and working-point density; seismic velocity both near the working point and from the working point to the surface; and water content, porosity, and water saturation of the rocks in the working point vicinity.

Introduction

Nuclear explosives have been tested underground at the USERDA (formerly USAEC) NTS since 1957. Since 1963, when the Limited Test Ban Treaty went into effect, all U.S. testing has been underground. During this time, data have gradually been collected on the physical properties of the test media at NTS test areas. Much of the data has been collected to evaluate specific locations for proposed nuclear tests with respect to containment of radioactivity. However, some of the data is also of interest to workers in the seismic-coupling field. In particular, there is much interest in the low-coupling "dry" alluvium in the Yucca Flat test area.

The purpose of this report is to provide a context for evaluating a given test site in terms of past experience. The mean, standard deviation,* and range of values for test areas or media allow a comparison of specific test sites with documented past experience. Specific properties for individual sites, however, are not given here.

Although it would be desirable to subdivide NTS into more test areas than are presented in this report, there is no basis for doing so. While the mean for a specific property of a particular area subgroup is separated from the mean of another subgroup by a statistically significant amount, the overall quality of the data and scatter within each subgroup makes this difference physically insignificant.

Finally, in presenting this geophysical information, certain cautions about the data are given, property by property. Therefore, the text should be read before attempting to use any of the data.

Description of Test Areas and Media

Statistically significant data bases (i.e., 15 or more sites) exist for only three NTS test areas: Yucca Flat, Rainier Mesa, and Pahute Mesa (Fig. 1). For completeness, available data for the Climax Stock (granite) and Paleozoic rocks are also presented. For more information on NTS geology, consult Ref. 1.

*The formula used for standard deviation throughout this report is

$$s_x = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}} .$$

YUCCA FLAT

Yucca Flat is an intermontane basin measuring about 30 km N-S and about 12 km E-W (Fig. 1). It has interior drainage to Yucca playa at its southern end. Fernald[2,3] has published maps with details of the geology of this area.

The rock sequence, from surface downward, consists of Quaternary alluvial fill, Tertiary volcanic rocks, and Paleozoic sedimentary rocks. Although there are local areas where Quaternary alluvium rests directly on Paleozoic sedimentary rocks, no underground nuclear tests have been conducted in such areas. Four nuclear

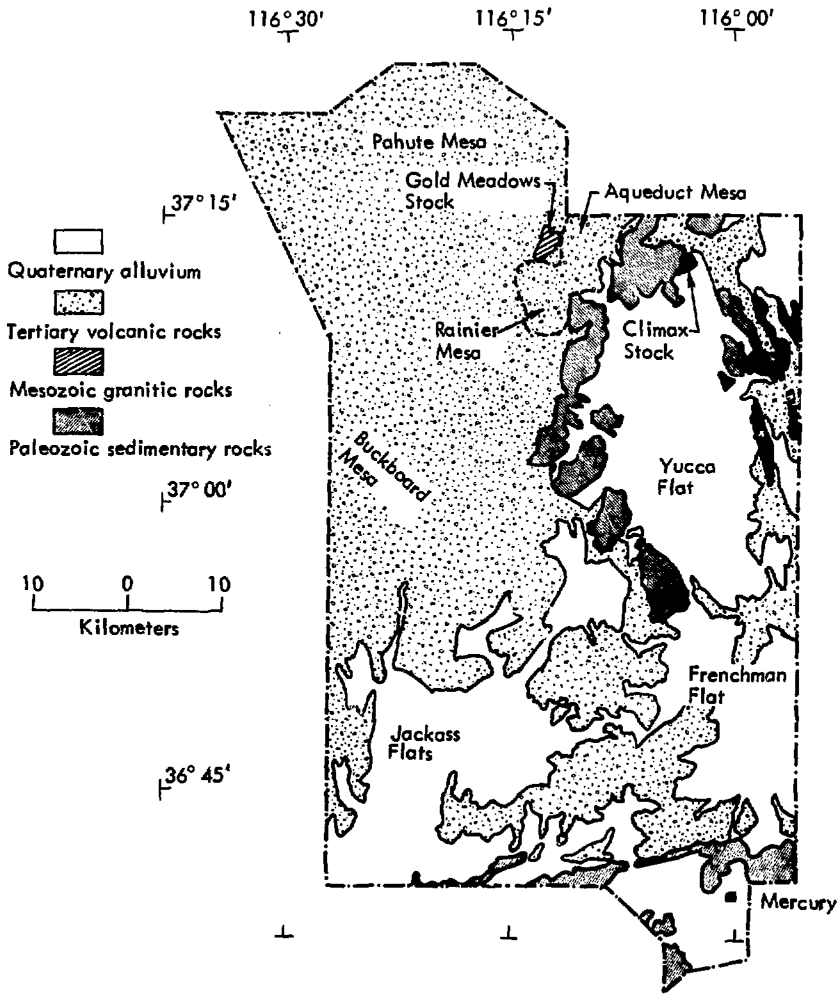

Fig. 1. Map shows principal rock types and test areas at NTS.

tests have been conducted in Paleozoic rock beneath Yucca Flat. These tests are summarized separately here from tests in alluvium or tuff.

The most significant aspect of Yucca Flat geology is the location of the water table, which at all test sites exceeds a depth of 500 m below the surface. The low seismic coupling exhibited by many nuclear explosions in Yucca Flat is a result of testing within this 500-to-600-m-thick sequence of "dry" alluvium and tuff.

Now, if one turns from generalizations to the details of a specific site, geologic complexities arise. For example, the water table may be elevated several hundred metres following a deep explosion near the water table,[4] thus affecting coupling of subsequent nearby explosions. (If the water table lies close enough to the explosion to be within the inelastic zone, it can affect coupling.) Furthermore, there are nearly saturated clay-rich and zeolite-rich rock units lying well above the water table. This means a wide variety of coupling behavior may be expected in Yucca Flat. In general, only explosions detonated at depths less than 425 m below the surface exhibit low coupling behavior.

"Tuff" is treated as a single rock unit in many reports about nuclear explosion phenomenology at NTS. However, tuffs at NTS range from pumice beds with bulk densities around 1.2 Mg/m^3 to densely welded tuffs around 2.4 Mg/m^3 density. These units are interlayered and faulted in the subsurface, are locally only a few tens of metres thick, and are generally difficult to subdivide. As a result, the only commonly used "tuff" subunits are "saturated tuff" and "dry tuff."

Alluvium is commonly distinguished from tuff at NTS, by the presence of fragments of Paleozoic rock. However, "bedded tuff" is simply an old alluvium consisting entirely of tuff fragments. In those areas of Yucca Flat where the upper-most tuff is a welded tuff and the alluvium contains fragments of Paleozoic rock, the alluvium-tuff contact is distinct. In locations where the uppermost tuff is bedded, however, the contact is gradational and the uncertainty of the contact (as determined from drill cuttings) may be as much as 50 m.

Consideration of the material properties alone would not lead to designation of alluvium and tuff as physically distinct test media. Both media have large ranges of properties, with alluvium generally lying within the tuff range for most properties. Nonetheless, both theory and experience lead one to expect different behavior by the media above and below the water table. Thus, the distinction based on water table is more important than the lithologic category for media in Yucca Flat.

PAHUTE MESA

Pahute Mesa, a plateau in the northwest corner of NTS (Fig. 1), is underlain by low-dipping to horizontal volcanic tuffs and lava flows more than 4000 m thick under much of the Mesa.[5] While many stratigraphic units are common to Pahute Mesa, Rainier Mesa, and Yucca Flat, lateral facies* changes and a higher concentration of densely welded tuff and lava flows distinguish Pahute Mesa. This results in generally higher density and seismic compressional velocity and lower porosity at Pahute Mesa sites, compared with Yucca Flat sites in the same unit.

As at Yucca Flat, the water table is deeper than 500 m at all Pahute Mesa test sites.[6] However, because Pahute Mesa has been used primarily for higher-yeild tests, most of the events have been detonated near or below the water table.

RAINIER MESA

Rainier Mesa is a flat-topped volcanic highland between Pahute Mesa and Yucca Flat (Fig. 1). It is underlain by low-dipping to horizontal volcanic rocks that overlie Paleozoic rocks at depths of 600 to 1000 m.[7] The stratigraphic section in the volcanic rocks more closely resembles the Yucca Flat tuffs than the Pahute Mesa section.

Nearly all nuclear testing at Rainier Mesa has been conducted in the lower portion of the volcanic rocks. Although the regional zone of saturation occurs in the underlying Paleozoic sedimentary rocks at depths greater than 1000 m, ground water is perched in fractures in the volcanic rocks. The test media are zeolitized and argillized and have a high water content and water saturation. In addition the area's seismic-coupling characteristics more closely resemble those of Yucca Flat tuff below the water table than Yucca Flat tuff above the water table.

CLIMAX STOCK

The Climax Stock is a small (about 3.5 km^2) outcrop of granodiorite and quartz monzonite at the northern end of Yucca Flat (Fig. 1). Only two nuclear detonations in granitic rock have been conducted at NTS, both in the Climax Stock. The stock intrudes older Paleozoic sedimentary

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*Rocks with a common origin, but having physical differences due to the environment in which they formed.

rocks[8] and is believed to spread to a diameter of 9.6 km at a depth of about 4000 m. The stock contains local perched water at various depths; the regional water table depth is not known.

The stock has been weathered to depths as great as 30 m below the surface. Locally, it is pervasively hydrothermally altered. The rock is strongly jointed at the surface, but less so at depth. It is everywhere broken by fractures, faults, and shear zones, most of which are healed (i.e., cemented by minerals of later origin). Fracture spacing is about 0.3 m or less

Both the pervasive fracturing and the unknown distribution of water-saturated zones above the regional water table could have important effects on containment of radioactivity and seismic coupling

PALEOZOIC ROCKS

Paleozoic (and late-Precambrian) sedimentary rocks outcrop abundantly at NTS.[1] However, the four nuclear detonations in Paleozoic sedimentary rocks at NTS were all conducted in the Yucca Flat area beneath a cover of alluvium and tuff. Three of the four tests were detonated well above the water table, but one (Nash) was near enough to the water table to influence seismic coupling.

Although Paleozoic (and late-Precambrian) rock types range from sandstone through shale to carbonate rocks, all NTS tests in Paleozoic rock have been in carbonate material. Three were in nearly pure limestone or dolomite, and one was in a shaly limestone (CO_2 content about 27 wt%).

Comments on Data Base

GENERAL COMMENTS

Much of the information summarized in this report was developed for presenting proposed nuclear tests to the USERDA Nevada Operations Office Containment Evaluation Panel (CEP). In deriving the average area or media properties presented in this report, site values (themselves averages of many measurements) were averaged. All of the data represent actual test configurations, although nuclear tests have not been conducted at all sites included in the averages.

The data base is stored in the K-Division Test Effects Data Bank at LLL. Data sorting and averaging is done by standard data-bank programs, and it is easy to retrieve information grouped according to geography, test medium, or location with respect to water table.

As noted in the discussions of specific parameters in this report, the data are not of uniform quality. Data sources include a number of organizations, and different measurement and analysis methods have been used within the same organization. However, obviously questionable were not included in the averages presented here.

For nearly all Yucca Flat and Rainier Mesa sites, the data were measured in the emplacement hole or tunnel or in a nearby exploratory hole. In only a few cases, were values extrapolated more than a few hundred feet.

At Pahute Mesa, information was only recently developed by analyzing old logs and core measurements. In some cases, values were extrapolated from holes several thousand feet or more away from the test hole. In our judgement, while the values reported for Pahute Mesa are the best available, the data probably are not as reliable as the values for Yucca Flat and Rainier Mesa.

The values for the Climax stock and the Paleozoic rocks are good measurements, but there is only a small number of sites for each medium. Physical properties in the Climax stock are probably fairly uniform, except for zones of alteration and variations in fracture frequency, and any new sites would be expected to have similar properties. For Paleozoic rocks, however, the reported data represent only detonations in carbonate rock. Sites in other Paleozoic rocks, such as argillite or quartzite, would have different properties.

WORKING-POINT PARAMETERS

Parameters in the vicinity of the working point (WP, the center of explosive energy of the nuclear device) are generally determined over an interval equal to or less than one maximum expected cavity radius above and below the WP. For some tests in northern Yucca Flat, a standard 15-m distance above and below the WP is used. The specific definition of the averaging interval varies from event to event.

In general, variations in the distance interval used for deriving a site average lead to only small (10% or less) variations in mean site values. Although a few sites might have a larger variation, the slight differences in the definition of the averaging interval probably have no effect on the overall area or media averages. This is because the variations, being random, tend to cancel out.

Data are rarely available for a full cavity radius below the WP, but are nearly always available for a full cavity radius above the WP. Although this might be important for an individual test site, there is probably little effect on the overall area averages because of cancelation due to random variation.

Parameters Examined

DENSITY

Methods of Measurement

The sources of density data include: radiation logs, gravity logs, and measurements on core samples. For most of the sites, density was determined from a proximity-corrected gamma-diffusion log. Some holes were logged using a single-scatter gamma tool (the LLL Rugosity Insensitive Density System),[9] others were logged using a borehole gravimeter. Density measurements on core samples were the source of density data for all sites at Rainier Mesa and some of the sites at Pahute Mesa.

All of these methods are capable of reproducibility within ±5%. The quality-control of most of the density logs is good. For any questionable density log during the past five years, independent verification was sought. A substantial number of the sites have two independent density measurements.

For a small number of sites, density was based on projection from holes 300 to 400 m distant from the test hole.

Working-Point Density

Density in the WP vicinity is given in Table 1 for the Climax stock and the Paleozoic rocks and in Table 2 and in Fig. 2 for Yucca Flat, Pahute Mesa, and Rainier Mesa. Comparing Table 1 and 2 shows that "hard-rock" densities are higher than the densities for tuff and alluvium.

In Fig. 2, an envelope is drawn at the limit of one standard deviation of the sample for all sites at Yucca Flat. Within Yucca Flat, all but one subgroup mean and most of the one-standard-deviation bars lie within this envelope. The means for Pahute Mesa volcanic rocks (above the

Table 1. Average geophysical properties for tests in Climax Stock and Paleozoic rocks at NTS.

Test Media	Density (Mg/m^3)		Seismic velocity (m/sec)		Water[a] content (wt%)	Porosity (vol%)	Saturation[b] (vol%)
	WP vicinity	Overburden	WP vicinity	WP to surface			
Climax Stock	2.67	2.66	5700	--	0.3	0.9	89
Paleozoic rocks (Dolomite)	2.79	2.04	5300	2500	0.5	2.5	56

[a]Calculated using assumed saturation.

[b]Assumed saturation.

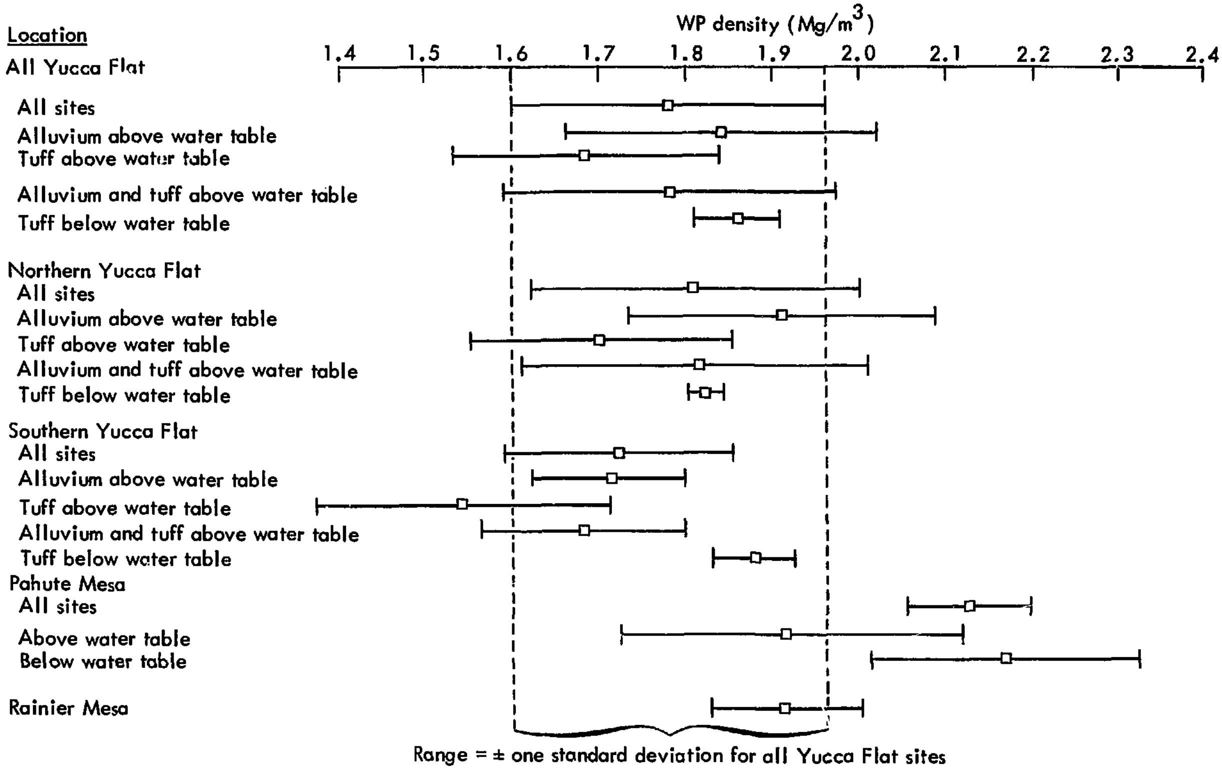

Fig. 2. Plots show means and standard deviations of the sample for WP density.

Table 2. Average WP density at NTS areas.

	Mean density (Mg/m^3)	n[a]	S.D.[b]	Range
<u>All Yucca Flat</u>				
All sites	1.78	144	0.18	1.37-2.20
Alluvium above water table	1.84	80	0.18	1.48-2.20
Tuff above water table	1.68	53	0.15	1.37-2.10
Alluvium and tuff above water table	1.78	133	0.19	1.37-2.20
Tuff below water table	1.86	11	0.05	1.80-1.95
<u>Northern Yucca Flat</u>				
All sites	1.81	104	0.19	1.42-2.20
Alluvium above water table	1.91	52	0.18	1.48-2.20
Tuff above water table	1.70	48	0.15	1.42-2.10
Alluvium and tuff above water table	1.81	100	0.20	1.42-2.20
Tuff below water table	1.82	4	0.02	1.80-1.85
<u>Southern Yucca Flat</u>				
All sites	1.72	40	0.13	1.37-1.95
Alluvium above water table	1.71	28	0.09	1.60-1.90
Tuff above water table	1.54	5	0.17	1.37-1.78
Alluvium and tuff above water table	1.68	33	0.12	1.37-1.90
Tuff below water table	1.88	7	0.05	1.82-1.95
<u>Pahute Mesa</u>				
All sites	2.14	21	0.20	1.71-2.45
Above water table	1.91	3	0.22	1.71-2.15
Below water table	2.18	18	0.17	1.81-2.45
<u>Rainier Mesa</u>	1.90	17	0.09	1.83-2.14

[a]Number of sites averaged

[b]Standard deivation of the sample

water table) and Rainier Mesa volcanic rocks also fall within this one-standard-deviation envelope.

Only the means for southern Yucca Flat tuff above the water table and Pahute Mesa tuff below the water table lie outside one standard deviation about the mean of all sites in Yucca Flat. The Pahute Mesa value is based on a greater number of sites and is further separated from all of the other means than the southern Yucca Flat tuff above the water table. Therefore, the Pahute Mesa volcanic rocks below the water table appear to be a geophysically distinct test medium, as far as density is concerned.

The range and standard deviations of all the groupings in Fig. 2 and Table 2 are large except for Yucca Flat tuff below the water table, which might also quality as a geophysically distinct test medium.

Alluvium above the water table is denser than tuff above the water table at all locations in Yucca Flat. Above the water table, there appears to be generally lower densities in southern versus northern Yucca Flat. However, there is sufficient data scatter to question these being geophysically distinct test media.

Overburden Density

Overburden density is the average rock density from the WP to the surface. Overburden densities for all the sites are given in Tables 1 and 3 and in Fig. 3.

Figures 2 and 3 are quite similar, and most of the general comments in the previous action apply to both. The differences between tuff above and below the water table for all of Yucca Flat are less distinct for overburden density than for WP density.

Because of the great thickness of rocks over which it is averaged, overburden density does not vary as much with individual sites. Also, overburden density tends to increase with depth of burial and to reflect general area characteristics more than WP density. Nevertheless, Pahute Mesa overburden densities are closer to Yucca Flat values than are the WP densities.

SEISMIC VELOCITY

Methods of Measurement

A vibroseis seismic survey (see next paragraph) was made of most sites. For sites below the water table, some type of fluid-coupled acoustic log was run. For sites

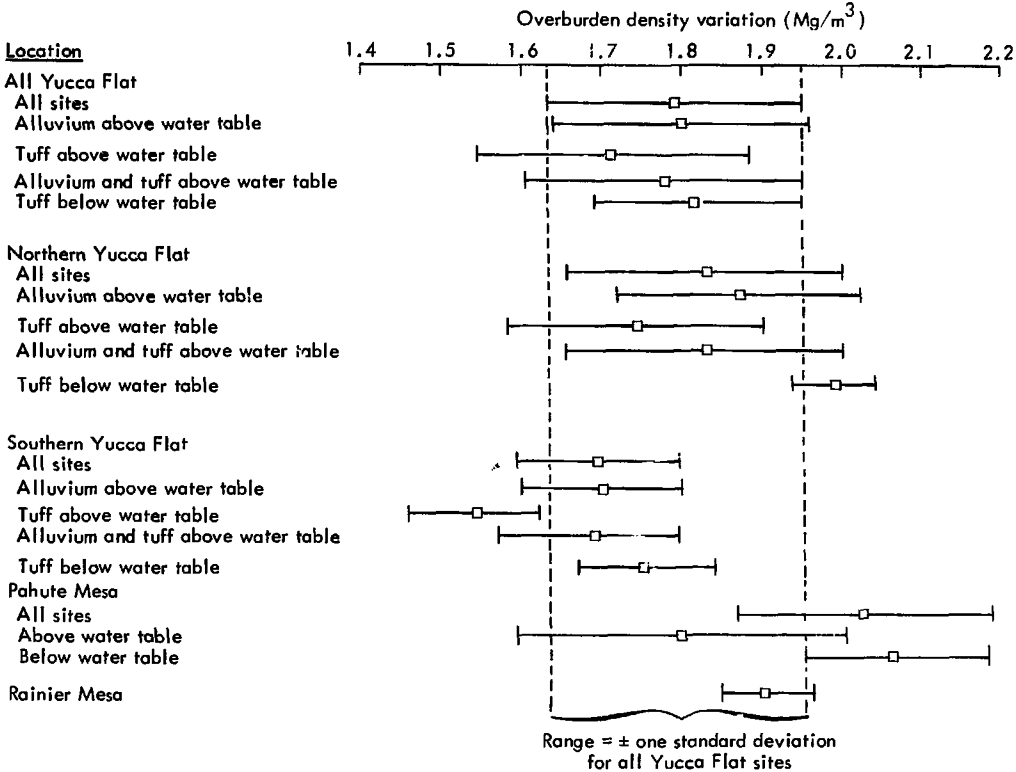

Fig. 3. Plots show means and standard deviations of the sample for overburden density variation.

Table 3. Average overburden density at NTS areas.

	Mean overburden ρ (Mg/m³)	n[a]	S.D.[b]	Range
All Yucca Flat				
All sites	1.79	137	0.16	1.41-2.10
Alluvium above water table	1.80	86	0.16	1.41-2.10
Tuff above water table	1.71	35	0.17	1.45-2.10
Alluvium and tuff above water table	1.78	124	0.17	1.41-2.10
Tuff below water table	1.82	12	0.13	1.64-2.00
Northern Yucca Flat				
All sites	1.83	83	0.17	1.41-2.10
Alluvium above water table	1.87	50	0.15	1.41-2.10
Tuff above water table	1.74	30	0.16	1.50-2.10
Alluvium and tuff above water table	1.83	83	0.17	1.41-2.10
Tuff below water table	1.98	4	0.05	1.90-2.00
Southern Yucca Flat				
All sites	1.69	47	0.10	1.45-1.90
Alluvium above water table	1.70	35	0.10	1.50-1.90
Tuff above water table	1.54	5	0.08	1.45-1.65
Alluvium and tuff above water table	1.68	41	0.11	1.45-1.90
Tuff below water table	1.75	8	0.08	1.64-1.90
Pahute Mesa				
All sites	2.02	19	0.16	1.62-2.24
Above water table	1.79	3	0.21	1.62-2.04
Below water table	2.06	16	0.11	1.89-2.24
Rainier Mesa	1.90	8	0.06	1.84-2.00

[a]Number of sites averaged

[b]Standard deviation of the sample

above the water table, the LLL Dry Hole Acoustic Logger (DHAL)[9] was used. And, for a few sites, a high-resolution explosion seismic survey was conducted.[10] Finally, for a few sites in Rainier and Pahute Mesas, acoustic measurements on core provided the seismic-velocity data.

In a vibroseis survey, a vibrator that repetitively sweeps through a given frequency range is placed at ground surface and signals are recorded at approximately 15-m intervals downhole. The error over any one 15-m interval is dependent on the relation of the timing error to the travel-time difference between stations. For a single 15-m interval, the timing error may be as high as ±50% of the travel time through the interval. For greater distances (200 m or more), the timing error stays constant while the travel time increases, so that the timing error decreases to 5% or less of the travel time through the interval. In some circumstances, the problem becomes one of missing an entire signal cycle due to signal weakness. A missed cycle results in a velocity determination systematically lower than the actual velocity.

Fluid-coupled acoustic logs, quite reliable in normal oil-field operations, encounter some problems at NTS. For example, some rocks at NTS have seismic velocities slower than that of mud or water (i.e., less than 1300 to 1600 m/sec) so fluid-coupled logs cannot be used. Even where this is not a problem, for best results, the mud or fluid should be allowed to de-gas for up to 24 hr before logging. This, however, almost always results in losing most of the fluid due to the high permeability of the rocks at NTS.

Compared to explosion seismic data, the DHAL works quite well in small-diameter (0.35-m) drill holes, attaining a 5% error. In large-diameter (up to 3-m) drill holes, it gives velocities that often are lower than in adjacent small-diameter holes (as much as 40% low in the worst cases).

The uphole or downhole high-resolution explosion seismic surveys are highly accurate, but are expensive and time-consuming. Therefore, they are rarely done.

Core samples are rarely representative of overall average in situ conditions, mainly because of the effects of cracks and fractures in the large-scale in situ condition, but also because of non-representative sampling. Nevertheless, we have no indication of a large (>20%) error from using core data. Therefore, it is included here, wherever no other data were available.

In all cases, the value reported is "effective" seismic velocity as distinguished from "average" seismic velocity. Effective seismic velocity is the reciprocal of an average reciprocal velocity. Effective seismic velocity divided into the interval distance gives the total travel time over the averaging interval, whereas an average of individual seismic-velocity measurements has no analytical relationship to interval travel time. For whatever data source is used, the travel time between two stations is determined. The distance between these stations is then divided by the travel time to give the effective seismic velocity. The reason for this method of analysis is that, in using the data for close-in measurements, one is interested in the travel time to the measurement station.

Seismic Velocity in WP Vicinity

Seismic velocities in the vicinity of the WP are given in Tables 1 and 4 and in Fig. 4. The measurement interval near the WP is much less rigidly defined for seismic velocity than for the other parameters. In some cases, this interval covers several cavity radii above and below the WP. The reason for this approach is the high potential for error (explained earlier) in a vibroseis survey over a small interval. In many cases, the averaging interval is extended until the travel-time interval is great enough to bring the timing error down to less than 20% of the travel time through the interval. The fact that much of the data is not reliable to better than ±20% of the stated value is important because most of the means for the Yucca Flat subgroups in Table 4 and Fig. 4 lie within 20% of the mean value for all Yucca Flat sites.

The seismic-velocity data in Fig. 4 exhibit many of the same trends as density. An envelope of one sample standard deviation for all of Yucca Flat contains most of the means and much of the standard-deviation bars of the Yucca Flat subgroups — with one difference. All of the means for tuff below the water table lie outside the envelope. Although this probably is a real phenomenon, one cannot rule out the possibility that better data exist below the water table due to different logging procedures (i.e., fluid-coupled acoustic logs).

Considering the greater possible velocity errors compared with the density measurements, most of the rest of the Yucca Flat variation in Table 4 is probably insignificant, except

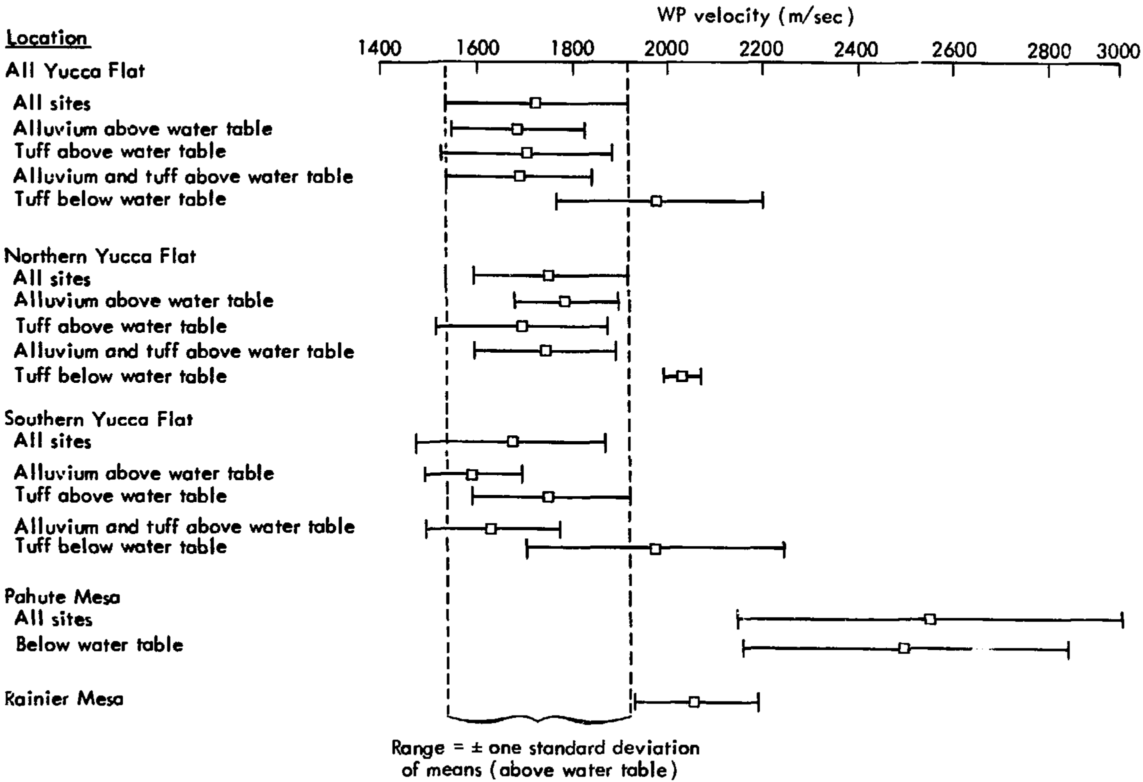

Fig. 4. Plots show means and standard deviations of the sample for WP velocity

Table 4. Average WP seismic velocity at NTS areas.

	Mean velocity (m/sec)	n[a]	S.D.[b]	Range
<u>All Yucca Flat</u>				
All sites	1849	105	364	1190-2840
Alluvium above water table	1789	61	290	1250-2440
Tuff above water table	1805	34	351	1190-2530
Alluvium and tuff above water table	1795	95	311	1190-2530
Tuff below water table	2364	10	442	1200-2840
<u>Northern Yucca Flat</u>				
All sites	1909	65	319	1190-2530
Alluvium above water table	1965	33	220	1520-2350
Tuff above water table	1789	29	357	1190-2530
Alluvium and tuff above water table	1883	62	303	1190-2530
Tuff below water table	2448	3	63	2380-2500
<u>Southern Yucca Flat</u>				
All sites	1752	40	414	1200-2840
Alluvium above water table	1583	28	217	1250-2340
Tuff above water table	1896	5	334	1500-2270
Alluvium and tuff above water table	1630	33	258	1250-2440
Tuff below water table	2328	7	535	1200-2840
<u>Pahute Mesa</u>				
All sites	3490	19	800	1950-5340
Above water table	----	--	---	---------
Below water table	3390	18	690	1950-4675
<u>Rainier Mesa</u>	2500	18	250	1870-2800

[a]Number of sites averaged

[b]Standard deviation of the sample

possibly the difference between alluvium above the water table in northern and southern Yucca Flat.

Overall, it again appears that tuff below the water table at Yucca Flat is the most geophysically distinct test medium and that the other media can be considered as a group.

The Rainier Mesa tuffs, which lie above the regional water table, have seismic velocities similar to Yucca Flat tuffs below the water table. The Pahute Mesa measurements are even higher. From the standpoint of seismic compressional velocity near the WP, there are at least four distinct test media in Table 4 and Fig. 4: Alluvium and tuff above the water table in media in Table 4 and Fig. 4:

- Yucca Flat alluvium and tuff above water table
- Yucca Flat tuff below water table
- Rainier Mesa tuff
- Pahute Mesa volcanic rock below water table.

Although there are few data, Pahute Mesa volcanic rock above the water table might be another geophysically distinct test medium.

Working Point to Surface Seismic Velocity

The effective seismic velocity from the working point to the surface (i.e., distance divided by travel time) is given in Table 5 and Fig. 5. Most of the values are from vibroseis surveys, although some are derived from time-of-arrival data from nuclear tests. A few are derived from evaluating DHAL, fluid-coupled sonic logs, or cores.

The average error here is lower because, over the distances involved, the vibroseis seismic method is capable of ±5% accuracy. All of these values are smaller than the WP values due to the effect of the low-velocity layers found near the surface. A small thickness of low-velocity material will markedly increase travel times. Except for the shift to lower values, these curves are quite similar to those for WP velocity and the same comments generally apply.

WATER CONTENT

Analysis, Sampling, and Error

The water content of a sample is determined by measuring the weight loss of the sample after heating it at 105°C to a stable weight. Values are reported on a wet weight basis (i.e., the weight loss is divided by the original sample weight rather than by the dry-sample weight).

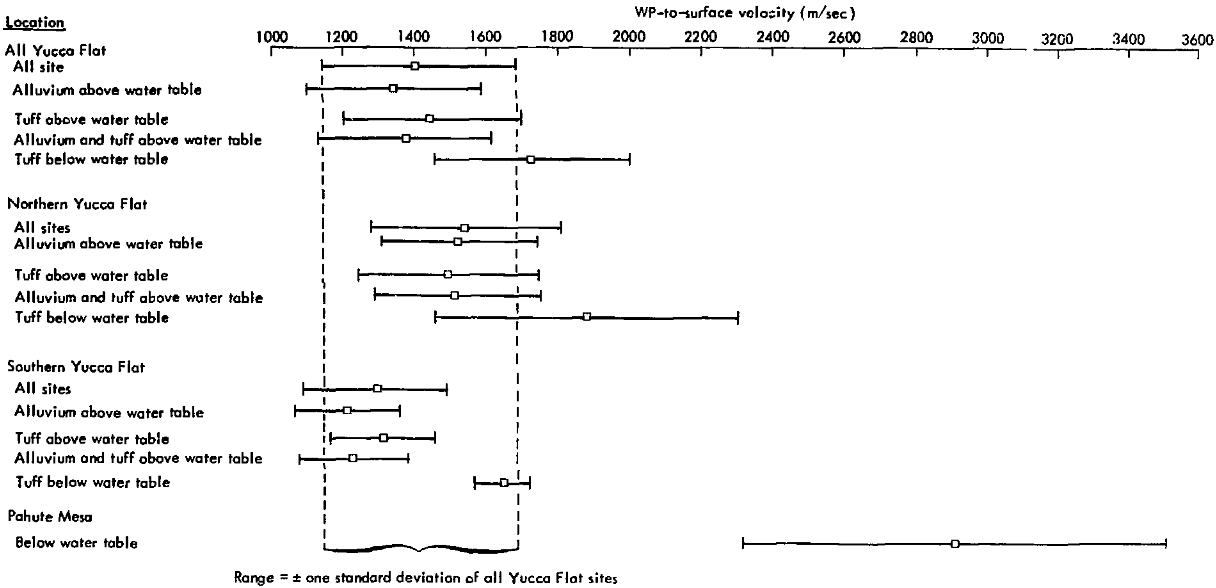

Fig. 5. Plots show means and standard deviations of the sample for WP-to-surface velocity.

Table 5. Average WP to surface seismic velocity at NTS areas.

	Mean WP to surface (m/sec)	n[a]	S.D.[b]	Range
All Yucca Flat				
All sites	1405	100	265	965-2500
Alluvium above water table	1340	66	240	965-2040
Tuff above water table	1440	23	240	1105-1860
Alluvium and tuff above water table	1370	88	240	965-2040
Tuff below water table	1720	11	270	1505-2500
Northern Yucca Flat				
All sites	1535	50	260	1065-2500
Alluvium above water table	1520	29	215	1065-2040
Tuff above water table	1485	17	250	1160-1860
Alluvium and tuff above water table	1510	46	225	1065-2040
Tuff below water table	1875	4	420	1615-2500
Southern Yucca Flat				
All sites	1280	49	200	965-1705
Alluvium above water table	1205	37	145	965-1570
Tuff above water table	1305	6	145	1105-1495
Alluvium and tuff above water table	1220	42	150	965-1570
Tuff below water table	1630	7	75	1510-1705
Pahute Mesa				
All sites	----	--	---	---------
Above water table	----	--	---	---------
Below water table	2910	7	580	2150-3220

[a]Number of sites averaged

[b]Standard deviation of the sample

It is very difficult to obtain a sample undisturbed by the drilling process, and most water values for Yucca Flat events above the water table are too large because they include small (5 to 20%) amounts of water from the drilling fluid.

For a few events in tuff below the water table at Yucca Flat and for all Pahute Mesa events, water content was calculated assuming 100% saturation of the rock sample. In these cases, core samples were available for direct measurement of the porosity.

Easy access afforded by tunnel emplacements at Rainier Mesa allow sampling of undisturbed rock. Therefore, water-content data for Rainier Mesa reflect actual in situ values. Data originally reported on a dry-weight basis have been reclaculated by us on a wet-weight basis.*

In heterogeneous rock such as alluvium, a possible source of error in determining water content is too few samples. The small amount of information available indicates that the error due to estimating the water content of a zone from a single sample is on the order of 10 to 20% of the amount reported. Most sites, however, have five or more samples in the averaging zone. Therefore, the error due to sampling, for most sites, is about 5 to 10%.

Considering the errors introduced by drilling and sampling procedures, the probable water-content error for a single site is on the order of 10 to 20% for most of the data. Thus, small variations in site-subgroup means are not significant.

The Data

Average water content in the vicinity of the WP is given in Tables 1 and 6 and in Fig. 6.

Again one-standard-deviation envelopes about sites above and below the water table are separated (Fig. 6). Considering errors, one cannot conclude that the variations in water content for Yucca Flat subgroups above the water table are significant, but the distinction above and below the water table probably is significant.

POROSITY AND SATURATION

Source of Data

For nearly all sites in Yucca Flat and some sites elsewhere, porosity and saturation values were calculated from measured data using the formulae:

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* $W_w = \frac{Wd}{1+Wd}$

where W_w = wet-weight percent H_2O and W_d = dry-weight percent H_2O.

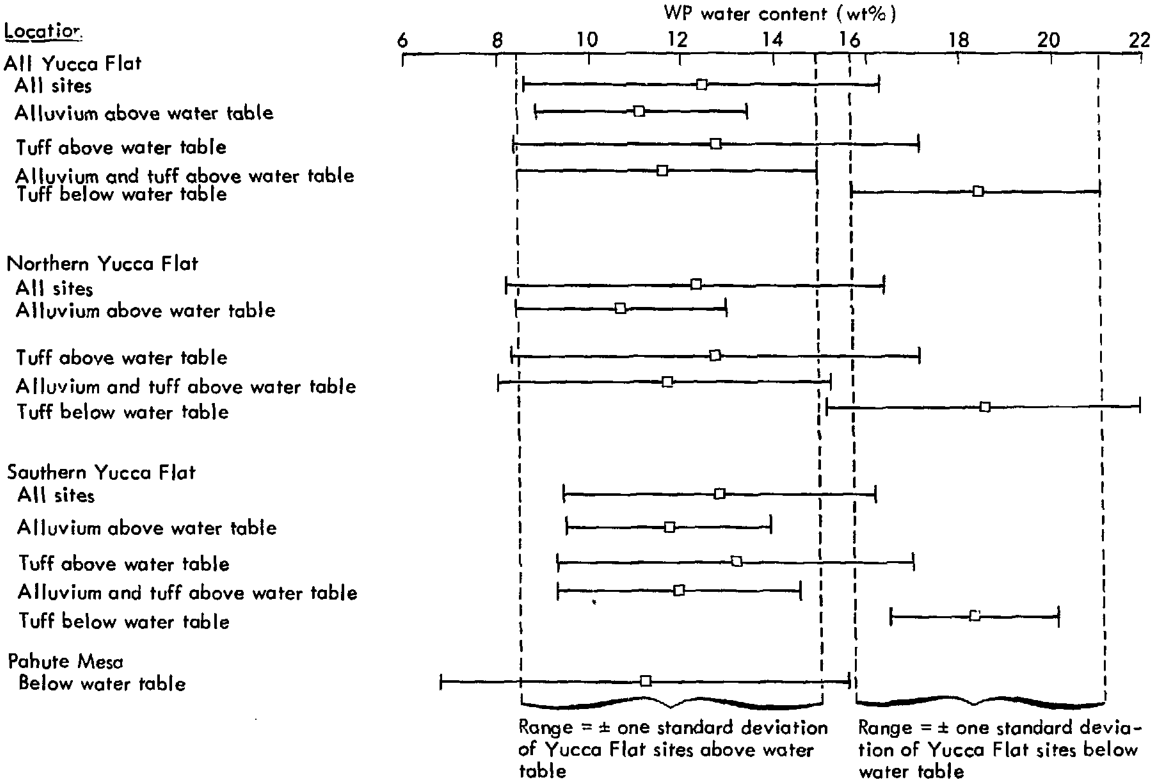

Fig. 6. Plots show means and standard deviations of the sample for WP water content.

Table 6. Average WP water content at NTS areas.

	Mean WP H_2O (wt%)	n[a]	S.D.[b]	Range
<u>All Yucca Flat</u>				
All sites	12.42	127	3.79	3.4-25.0
Alluvium above water table	11.12	74	2.27	6.7-16.0
Tuff above water table	12.74	39	4.34	3.4-25.0
Alluvium and tuff above water table	11.68	113	3.22	3.4-25.0
Tuff below water table	18.38	14	2.66	13.0-22.0
<u>Northern Yucca Flat</u>				
All sites	12.24	75	4.08	3.4-25.0
Alluvium above water table	10.66	36	2.25	7.5-15.7
Tuff above water table	12.64	32	4.46	3.4-25.0
Alluvium and tuff above water table	11.59	68	3.59	3.4-25.0
Tuff below water table	18.50	7	3.42	13.0-22.0
<u>Southern Yucca Flat</u>				
All sites	12.75	51	3.34	6.7-21.3
Alluvium above water table	11.62	37	2.22	6.7-16.0
Tuff above water table	13.19	7	4.02	8.1-18.2
Alluvium and tuff above water table	11.87	44	2.60	6.7-18.2
Tuff below water table	18.26	7	1.88	15.4-21.3
<u>Pahute Mesa</u>				
All sites	-----	--	----	---------
Above water table	-----	--	----	---------
Below water table	11.1	16	4.4	3.0-18.0
<u>Rainier Mesa</u>	17.5	17	3.0	10.6-22.0

[a]Number of sites averaged

[b]Standard deviation of the sample

$$\phi = 1 + \frac{\rho_o(W-1)}{\rho_g} \quad \text{and} \quad S = \frac{\rho_o W}{\phi} ,$$

where ϕ = volume fraction porosity

S = volume fraction saturation

ρ_o = in situ bulk density (Mg/m^3) from geophysical logs

W = weight fraction water in *the in situ rock*

ρ_g = grain (powder) density (Mg/m^3).

In an unpublished error-propagation analysis, Simon,[11] using numerous assumptions, concluded that the average porosities and saturations calculated by the above method might have errors as large as 10 to 30% of reported values for individual events. Given errors of this magnitude, small differences between subgroup porosity and saturation values are meaningless.

For most sites in Rainier Mesa and some at Pahute Mesa, porosity and saturation were determined directly by measurements on core samples. For all sites at Pahute Mesa below the water table, 100% saturation was assumed. This was also done in a few instances at Yucca Flat. Saturation greater than 100% is physically meaningless, although such values do appear in the data because of error propagation. These values have been used, expecting that errors in the other direction will compensate. The existence of average saturation values of 90% below the water table may be due to the occasional use of 100% as an assumed value or upper reporting limit. This **eliminates** values above 100%, which would compensate for erroneously low saturation values.

The Data

Average porosity in the WP vicinity is given in Tables 1 and 7 and in Fig. 7. Average saturation is given in Table 1 and 8 and in Fig. 8.

Yucca Flat alluvium and tuff are highly porous. The mean of all Yucca Flat sites is 36 vol% and the lowest average porosity of any subgroup is 30 vol%. Considering the earlier comments on error magnitude, however, none of the Yucca Flat subgroups appears to constitute geophysically distinct medium. The porosity of Pahute Mesa tuff below the water table, on the other hand, is sufficiently different from Yucca Flat for it to be a geophysically distinct medium. Moreover, this difference is not due to the use of core data because Ranier Mesa porosity, also measured on core, is comparable to Yucca Flat porosity.

In Fig. 8, two envelopes are drawn: one spanning ± one standard deviation about the saturation of all Yucca Flat alluvium and tuff above the water table and the other for

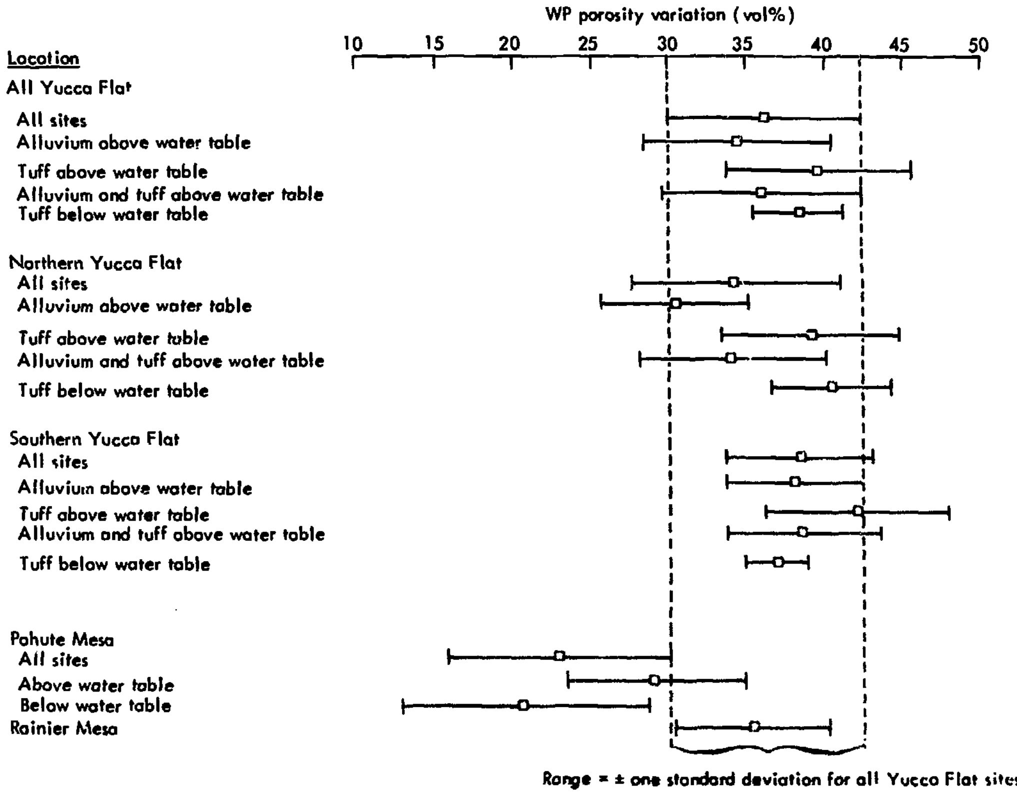

Fig. 7. Plots show means and standard deviations of the sample for WP porosity variation.

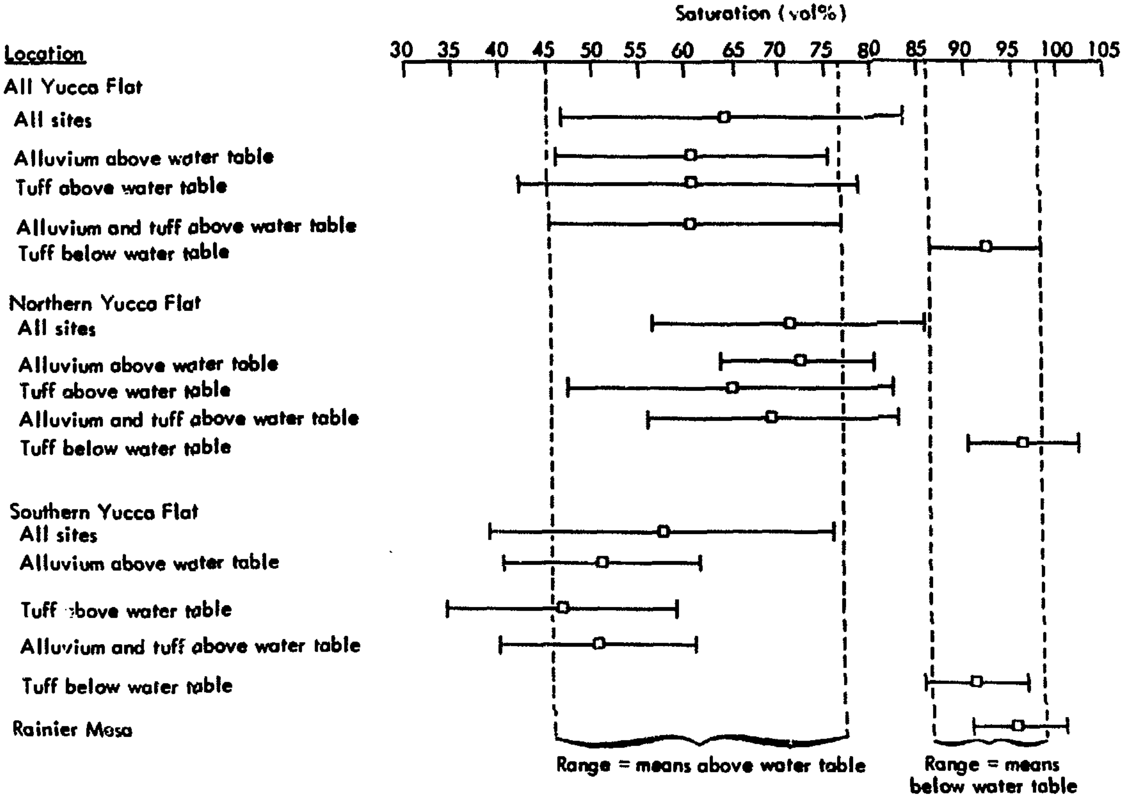

Fig. 8. Plots show means and standard deviations of the sample for saturation.

Table 7. WP porosity variation at Yucca Flat.

	Mean porosity (vol%)	n[a]	S.D.[b]	Range
All Yucca Flat				
All sites	36.0	86	6.2	21-48
Alluvium above water table	34.3	54	6.1	21-46
Tuff above water table	39.4	22	5.9	23-48
Alluvium and tuff above water table	35.8	76	6.4	21-48
Tuff below water table	38.0	10	3.1	33-44
Northern Yucca Flat				
All sites	34.1	45	6.7	21-46
Alluvium above water table	30.2	25	4.8	21-43
Tuff above water table	38.8	17	5.9	23-46
Alluvium and tuff above water table	33.7	42	6.7	21-46
Tuff below water table	40.3	3	4.0	36-44
Southern Yucca Flat				
All sites	38.1	41	4.7	28-48
Alluvium above water table	37.8	29	4.7	28-46
Tuff above water table	41.7	5	6.0	32-48
Alluvium and tuff above water table	38.3	34	5.0	28-48
Tuff below water table	36.7	7	2.1	33-39
Pahute Mesa				
All sites	22.0	22	7.9	8-37
Above water table	28.6	5	5.6	25-37
Below water table	20.0	17	7.6	8-32
Rainier Mesa	35.1	17	4.8	24-44

[a]Number of sites averaged

[b]Standard deviation of the sample

Table 8. WP saturation variation at Yucca Flat.

	Mean saturation (vol%)	n[a]	S.D.[b]	Range[c]
All Yucca Flat				
All sites	64.4	85	18.0	27-111
Alluvium above water table	60.7	53	14.6	27-90
Tuff above water table	60.5	22	18.3	30-111
Alluvium and tuff above water table	60.7	75	15.6	27-111
Tuff below water table	92.0	10	6.0	80.5-100
Northern Yucca Flat				
All sites	70.9	45	14.8	33-111
Alluvium above water table	72.1	25	8.8	57-90
Tuff above water table	64.8	17	17.9	33-111
Alluvium and tuff above water table	69.1	42	13.6	33-111
Tuff below water table	96.0	3	6.1	89-100
Southern Yucca Flat				
All sites	57.0	40	18.6	27-98
Alluvium above water table	50.5	28	10.6	27-70
Tuff above water table	46.2	5	11.9	30-59
Alluvium and tuff above water table	49.9	33	10.7	27-70
Tuff below water table	90.6	7	5.6	80.5-98
Rainier Mesa	95.8	17	5.1	87.9-104.0

[a]Number of sites averaged

[b]Standard deviation of the sample

[c]Values greater than 100 are, of course, not posisble, but are included here to balance errors in the opposite direction.

Table 9. Average WP gas porosity at NTS areas.

	Mean gas porosity (vol%)
<u>All Yucca Flat</u>	
All sites	13
Alluvium above water table	13
Tuff above water table	16
Alluvium and tuff above water table	14
Tuff below water table	3
<u>Northern Yucca Flat</u>	
All sites	10
Alluvium above water table	8
Tuff above water table	14
Alluvium and tuff above water table	10
Tuff below water table	2
<u>Southern Yucca Flat</u>	
All sites	16
Alluvium above water table	19
Tuff above water table	22
Alluvium and tuff above water table	19
Tuff below water table	3
<u>Rainier Mesa</u>	1

all tuff below the water table. As one might expect, there is a distinct separation. This is probably the most significant reported parameter with regard to seismic coupling and is the basis for regarding rocks above and below the water table as two geophysically distinct units.

The data for Rainier Mesa tuffs show a saturation comparable to Yucca Flat tuffs below the water table, which probably accounts for the relatively strong seismic coupling at Rainier Mesa. No values are reported for Pahute Mesa because 100% saturation was assumed below the water table and only one site had natural-state cores above the water table.

Discussion

As noted earlier, averages in this report are based on site averages. For an area such as Yucca Flat, with a large number of events buried fairly randomly throughout the geologic section, the average site properties approximate the average properties of the rock section.* However, for Rainier Mesa where the same stratigraphic horizon is used for most tests and for Pahute Mesa where most tests, because of higher yield, are relatively deeply buried, the average site properties differ from the average properties of the rock section. Properties for the Climax stock are likely representative of that medium due to its homogeneity. Properties for Paleozoic rock are strictly true only for dolomite and limestone, although all Paleozoic rock at NTS is significantly different from tuff and alluvium.

It should be emphasized that this report describes the historical medium properties in various NTS areas, and as such, it is not necessarily predictive. For example, using a different horizon at Rainier Mesa or testing lower-yield explosives well above the water table at Pahute Mesa could lead to significantly different medium properties than those reported here. It is also possible (though not likely) that, if all data for all events were available, the averages given in this report would change significantly. We can only state that

*Germain[12] has made plots on normal probability paper of individual data from hundreds of Yucca Flat samples. Not only did the 50% probability for most parameters have values similar to site means in this report, the plots were also nearly straight-line, indicating a nearly normal distribution.

this is the best information available, and we believe it to be reliable.

It is obvious that, for the areas defined in this report, the "hard rock" areas (Climax Stock and Paleozoic rocks) have physical properties significantly different from the alluvium and tuff areas. However, one might question whether the reported differences among alluvium and tuff areas are significant. Table 10 summarizes the average geophysical properties for areas we regard as geophysically distinct. It also includes gas-filled porosities calculated from the average porosities and saturations in Table 10.

As can be seen in Table 10, no distinction is made between northern and southern Yucca Flat or between tuff and alluvium. For most of the reported properties, the differences between southern and northern Yucca Flat and between tuff and alluvium are not great enough to lie outside the range of possible error. In addition, the possibility of systematic error is introduced by the fact that two different laboratories, using different measurement techniques, gather the data in sourthern versus northern Yucca Flat. Also, there is no seismic evidence that the crude geographic distinction of northern versus southern Yucca Flat is reflected in seismic coupling. Therefore, Yucca Flat is subdivided into only two units, and this distinction, above and below the water table, is based on differences in water content, saturation, and seismic velocity.

Due to the limited number of experiments, there are insufficient data for Pahute Mesa tuff above the water table. Except for saturation, it has mean values similar to Yucca Flat tuff below the water table. The distinction given in Table 10 is therefore inferred from geographic separation and lithologic differences, and not based on measured data.

Rainier Mesa sites have very similar properties (including saturation) to Yucca Flat sites below the water table, although the Rainier Mesa sites all lie above the water table. Again, the distinction is based on geography, as measured data do not separate the two media. Even the distribution on a cumulative-frequency diagram is similar for these two areas (see Figs. 9 and 10).

Pahute Mesa sites below the water table, on the other hand, quite clearly are separated from the other alluvium-tuff media and qualify as being geophysically distinct based entirely on measured data.

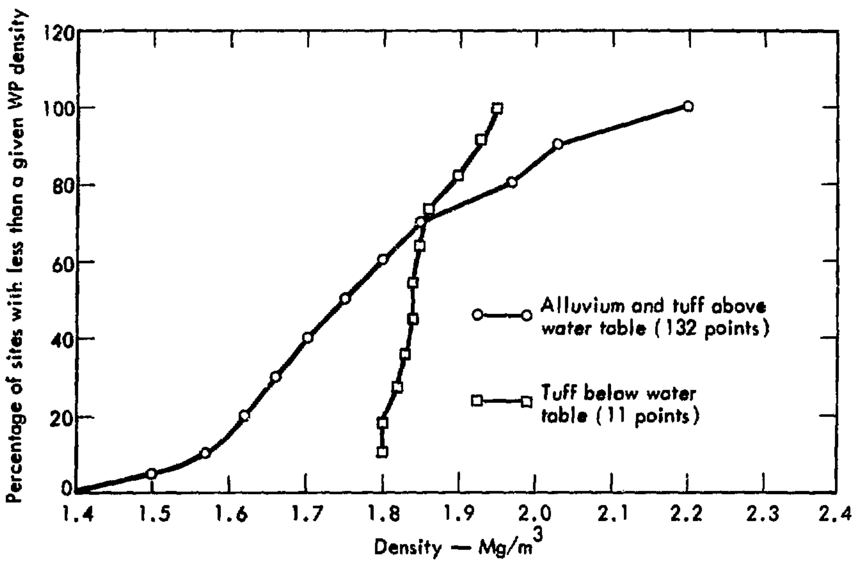

Fig. 9. Cumulative frequency for WP density in Yucca Flat.

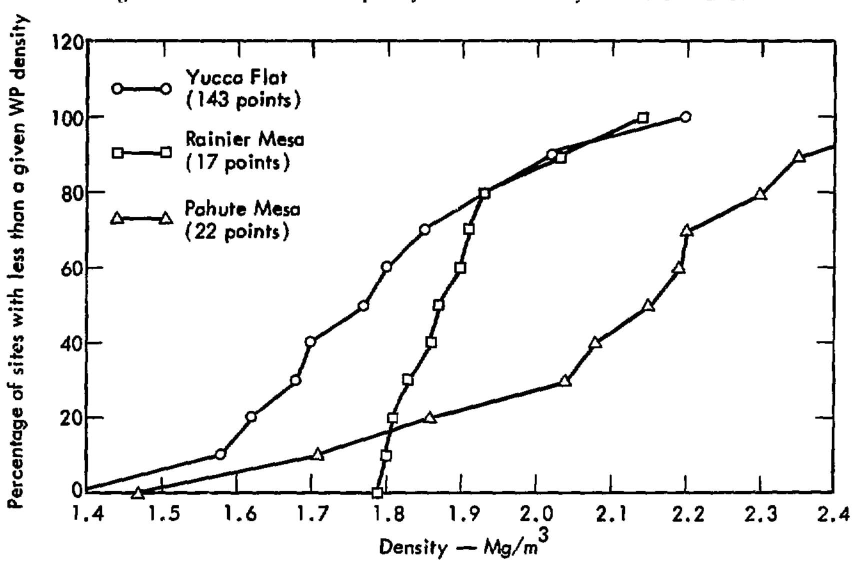

Fig. 10. Cumulative frequency for WP density at NTS.

Table 10. Average geophysical properties for test media at NTS.

Test media	Density (Mg/m³) WP vicinity	Density (Mg/m³) overburden	Seismic velocity (m/sec) WP vicinity	Seismic velocity (m/sec) WP to surface	Water content (wt%)	Porosity (Vol%)	Saturation (Vol%)	Gas porosity (Vol%)
Yucca Flat above water table	1.8	1.8	1800	1400	12	36	61	14
Yucca Flat below water table	1.9	1.8	2400	1700	18	38	92	3
Pahute Mesa above water table	1.9	1.8	----	----	--	29	--	<15
Pahute Mesa below water table	2.2	2.1	3400	2900	11	20	--	~0
Rainier Mesa	1.9	1.9	2500	----	18	35	96	1
Climax Stock	2.7	2.7	5700	----	<0.4	0.9	--	<0.9
Paleozoic rocks	2.8	2.0	5400	2500	<1.0	2.5	--	<2.5

Another point of interest is whether any of the alluvium-tuff areas really qualify as being geophysically distinct in the sense of uniformity. Certainly the range of properties is wide for each of these areas, except for Rainier Mesa tuff and Yucca Flat tuff below the water table (see Figs. 9 and 10). The ranges for Pahute Mesa and Yucca Flat above the water table are particularly large (Figs. 9 and 10). Yet, there are no easily definable, distinctive subdivisions either geographically, lithologically, or by altitude. Pahute Mesa and Yucca Flat above the water table are geophysically distinct areas in spite of their diversity rather than because of their uniformity.

Without considering distinctions of lithology or above and below the water table, Fig. 10 is a cumulative-frequency diagram for WP density comparing Yucca Flat, Rainier Mesa, and Pahute Mesa. This curve well characterizes the three geographic areas. The Rainier Mesa curve is steep, due to uniformity of media. Although both the Yucca Flat and Pahute Mesa curves are similarly flat, their 50th-percentile values are far displaced. Seventy percent of the sites at Pahute Mesa have densities greater than 90% of the Yucca Flat and Rainier Mesa sites.

Summary

Based on past testing history and available data, this report gives the average properties for seven geophysically distinct test media at NTS (see Table 10). Of these areas, two (Yucca Flat above the water table and Pahute Mesa above the water table) have gas-filled porosities greater than 5% and are potential decoupling media. The others all have low (<5%) gas-filled porosities and couple shock energy more strongly.

The Climax Stock and Paleozoic rock sites have significantly higher WP densities and seismic velocities than the other five media. Subdivision beyond these three catagories (alluvium or tuff above the water table, alluvium or tuff below the water table, and "hard rock") is based more on geographic separation than on statistically significant property variations.

Of the various media, Yucca Flat and Pahute Mesa above the water table are the most variable. In these areas, it is possible to find individual past sites with extreme values of reported parameters. The other media are relatively uniform.

All reported geophysical parameters show statistically significant differences for at least one test media. However, the significance (if any) of these differences to underground nuclear explosion phenomenology is not the topic of this report. Rather the averages reported here are representative of the media and are presented to be used as a comparative base for assessing the "normality" of a potential test site with respect to these parameters.

Acknowledgments

This report was compiled from the LLL K-Division Test Effects Data Bank. In addition to the authors, Richard Carlson, John Rambo, Robert Rohrer, Lawrence McKague, Mary Lou Higuera, and Carmela Bell have contributed to the creation and maintenance of the Data Bank. Jerome Richter of EGG-San Ramon is responsible for processing much of the logging data and for creating the system[13] by which it is stored and processed. Richard Carlson and Joseph Hearst have long guided the LLL geophysics program and are largely responsible for the overall system by which much of the data have been obtained in the field, processed, and stored in the office.

Much of the data used to derive Pahute Mesa average site properties came from U.S. Geological Survey measurements on cores samples complied by Evan Jenkins of the Special Projects Branch, U.S. Geological Survey, Denver, Co.

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