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A Summary and Discussion of Hydrologic Data from the Calico Hills Nonwelded Hydrogeologic Unit at Yucca Mountain, Nevada

HYDROLOGY DOCUMENT NUMBER 710

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NATIONAL LABORATORY

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BRIEF SUMMARY OF DOCUMENT: The Los Alamos report summarizes currently available hydrogeologic data from the Calico Hills unit at Yucca Mountain. Data are presented for 14 wells and boreholes in the vicinity of the site, 10 of which are located within the proposed repository block. The following types of measurements are reported: lab- and field-measured hydraulic conductivity, porosity, saturation, mineralogy, saturation curve fit parameters, and pore-size distribution. The data are shown in tables and figures, and summary statistics are provided. An important conclusion presented in the report is that the Calico Hills unit "does not conform to the concept of a homogeneous porous medium in the classical sense at the scale of curently available measurements."

REASONS WHY A DETAILED TECHNICAL REVIEW IS NOT NEEDED AT THIS TIME: The report is primarily a collection of data derived from other reports, and as such it represents the best available single source of hydrologic information for the Calico Hills unit. The data in the report were analyzed using standard statistical and hydrologic analyses. The conclusions and recommendations presented are reasonably consistent with NRC staff views of unsaturated zone issues.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS vii

LIST OF TABLES viii

ABSTRACT 1

I. INTRODUCTION 2

II. STRATIGRAPHY 3

III. HYDROLOGIC PROPERTIES 11

3.1. Saturated Hydraulic Conductivity 15

3.1.a. Laboratory Measurements 16

3.1.b. Aquifer Tests 26

3.1.c. Discussion 29

3.2. Unsaturated Hydraulic Conductivity 29

3.3. Fluid Potentials and Saturations 34

3.4. Total and Kinematic Porosity 35

3.5. Pore-Size Distribution 37

3.6. Dispersion 39

3.7. Storage Coefficients 40

3.7.a. Specific Storage 40

3.7.b. Capacitance 41

IV. THERMOMECHANICAL PROPERTIES 41

V. CONCLUSIONS AND RECOMMENDATIONS 42

REFERENCES 45

APPENDIX A RELATIVE ABUNDANCE OF MINERALS AND GLASS IN SELECTED WELLS AT YUCCA MOUNTAIN, NEVADA AFTER BISH AND CHIPERA, 1989 54

APPENDIX B HYDROLOGIC DATA 67
DRILL HOLE UE-25 a#1 68
DRILL HOLE UE-25 b#1 72
DRILL HOLE UE-25 p#1 74
DRILL HOLE USW G-1 75
DRILL HOLE USW GU-3 80
DRILL HOLE USW G-4 87
DRILL HOLE USW H-1 97
DRILL HOLE USW H-4 100
DRILL HOLE J-13 101

LIST OF ILLUSTRATIONS

Figure		Page
1.	Index map showing the locations of selected drill holes in the vicinity of Yucca Mountain and the locations of cross-sections shown in Figures 2a and 2b. After U.S. Department of Energy (1988)	4
2a.	North-south stratigraphic correlation between selected drill holes at Yucca Mountain. Vertical:horizontal scale = 2.5:1. After U.S. Department of Energy (1988)	7
2b.	East-west stratigraphic correlation between selected drill holes at Yucca Mountain. Vertical:horizontal scale = 2.5:1. After U.S. Department of Energy (1988).	8
3a.	Sorptive stratigraphy of Yucca Mountain (Bryant and Vaniman, 1984). After Tien et al. (1985)	12
3b.	Sorptive stratigraphy of Yucca Mountain (Bryant and Vaniman, 1984). After Tien et al. (1985)	13
4.	Log-normal probability plot of devitrified, vitric and zeolitic laboratory hydraulic conductivity data	20
5.	Log-normal probability plot of all laboratory hydraulic conductivity data	21
6.	Log-normal probability plot of aquifer test hydraulic conductivity data	28

LIST OF TABLES

Table		Page
1.	Thickness in meters of stratigraphic units included in this report in selected drill holes, in vertical sequence downward. Drill holes are selected for proximity to proposed repository. A hyphen (-) indicates unavailable data	5
2.	Water table location, total Calico Hills nonwelded unit thickness and thickness of unsaturated Calico Hills nonwelded unit	9
3.	Definition of unsaturated-zone hydrogeologic units and correlation with rock-stratigraphic units. After U.S. Department of Energy (1988)	10
4.	Number of measurements on different samples or sub-samples by drill hole	14
5.	Number of samples, dimensions and source of laboratory hydraulic conductivity data from selected drill holes near Yucca Mountain, Nevada	17
6.	Sample statistics of laboratory hydraulic conductivity data for vitric, devitrified and zeolitic tuffs and for lumped data	19
7.	Base-ten logarithm of laboratory hydraulic conductivity (K) measurements for zeolitic tuffs and range, by drill hole. Originally in meters per second. (v)=vertical; (h)=horizontal	23
8.	Sample statistics for aquifer test hydraulic conductivity data	27
9.	Maximum and minimum hydraulic conductivity values and range of base-ten logarithms of aquifer test hydraulic conductivity data, by drill hole	30
10.	Data from laboratory and aquifer testing within selected overlapping intervals	31
11.	Sample statistics of saturation data for vitric, devitrified and zeolitic tuffs in the unsaturated zone.	36
12.	Sample statistics of total porosity data for vitric, devitrified and zeolitic tuffs	38
13.	Property values used to calculate specific storage	41

A Summary and Discussion of Hydrologic Data from the Calico Hills Nonwelded Hydrogeologic Unit at Yucca Mountain, Nevada

by

Colleen Loeven

ABSTRACT

This report is a summary of available hydrologic data from in situ and laboratory testing of the Calico Hills nonwelded hydrogeologic unit, including hydraulic conductivity, porosity, saturation, pore-size distribution and parameters from curve-fits to pressure-saturation data. Sample statistics of hydraulic conductivity, porosity and saturation data for vitric, devitrified and zeolitic tuffs are presented and discussed. While a high degree of variability is observed in both laboratory and in situ hydraulic conductivity measurements, uncertainties arising from differences in size of laboratory test samples, sample handling, test procedures and insufficient number of samples point to the need for additional data of specific types to adequately characterize the unit. Hydrologic issues related to transport analysis in the Calico Hills nonwelded hydrogeologic unit at Yucca Mountain are discussed together with recommendations for future work. The compiled data are included as an appendix.

I. INTRODUCTION

Performance assessment of a high-level radioactive waste repository site will depend in large part on numerical models of water and solute movement. Achieving projections of site containment of radionuclides requires an ability to conceptualize the hydrologic system and estimate the parameters that appear in the models. Unfortunately, our ability to develop sophisticated models exceeds our ability to estimate the parameters in the models. As pointed out by Luckner et al. (1989), this is especially true for the unsaturated hydraulic properties, which are by far the most important parameters affecting the rate at which water and dissolved chemicals move through unsaturated media.

The purpose of this report is to summarize currently available data from the Calico Hills nonwelded unit at Yucca Mountain, Nevada, and to discuss the implications of available data on the direction of future work. Hydrologic data for the Calico Hills nonwelded unit are available in many publications, always as part of a larger data set including stratigraphic units outside the unit of interest in this report. The data are presented in many different measurement units, making comparison difficult, and a number of different systems have been used for categorizing the stratigraphic members listed below. Subsets of the total data set have been used to estimate parameters for input to hydrologic models, but no systematic evaluation of the complete set has been made. This report provides a summary of relevant hydrologic data in a single document for use as a reference in planning and expediting future work in the Calico Hills unit, including evaluation of potential sites for field testing of numerical models and laboratory-derived transport parameters. Graphical summaries of relative abundance of minerals and glass by Bish and Chipera (1989) are included as Appendix A. A listing of the hydrologic data constitutes Appendix B.

Definition of the Calico Hills nonwelded hydrogeologic unit is adopted from Montazer and Wilson (1984). The hydrogeologic unit consists of nonwelded and partially welded ash-flow and bedded tuffs located below the basal vitrophyre of the Topopah Spring Member of the Paintbrush Tuff and above the moderately welded interior of the Bullfrog Member of the Crater Flat Tuff. Members of the hydrogeologic unit include the Lower Topopah Spring Member, the Tuffaceous Beds of the Calico Hills, the Prow Pass Member of the Crater Flat Tuff, the Upper Bullfrog Member and the bedded tuffs between them. It should be noted that in spite of its designation as a nonwelded unit, large sections of this hydrogeologic unit are described in lithologic logs as partially welded. Because the unit directly underlies the proposed repository, hydrologic and transport properties of the

Calico Hills nonwelded unit are of primary importance to radionuclide containment assessment.

The Calico Hills unit is an important natural barrier to radionuclide migration from the proposed repository. Its properties include:

1. **Hydrologic barrier** - the response of nonwelded materials to stress is fundamentally different from that in brittle welded rocks. Failure is distributed over wider zones and faults and fractures are less likely to be discrete and continuous. Healing of fractures in nonwelded tuffs occurs under certain conditions. Nonwelded tuffs are known to contain fewer fractures than the brittle welded zones above and below the Calico Hills nonwelded unit. Also, flow in low permeability unsaturated media under small hydraulic gradients is slow.

2. **Chemical barrier** - as documented in mineralogic summaries (Broxton et al., 1989; Bish and Chipera, 1989; Bish et al., 1984), parts of the unit contain zeolites which are sorptive of certain radionuclides.

3. **Physical barrier** - the total present-day unsaturated thickness of the nonwelded and partially welded units is between 65.2 m (UE-25 b#1) and 244.1 m (USW GU-3) in drill holes in the immediate vicinity of the proposed repository.

Figure 1 shows Yucca Mountain with drill hole locations and the proposed perimeter drift location.

Characteristics of flow and transport in the Calico Hills nonwelded unit have a major impact on estimated ground water travel times and radionuclide transport between the proposed repository and the accessible environment. A comprehensive hydrogeologic study of the nonwelded and partially welded tuffs underlying the proposed repository horizon in the unsaturated zone at Yucca Mountain is planned as part of site characterization.

II. STRATIGRAPHY

The Calico Hills nonwelded unit as defined here includes the following stratigraphic members, listed in vertical sequence downward. Table 1 lists thicknesses of members in selected drill holes as determined from stratigraphic logs. Location of drill holes in northern and southern parts of the exploration block is noted because of the change in degree of zeolitization of the unit from complete in the north to partial in the south.

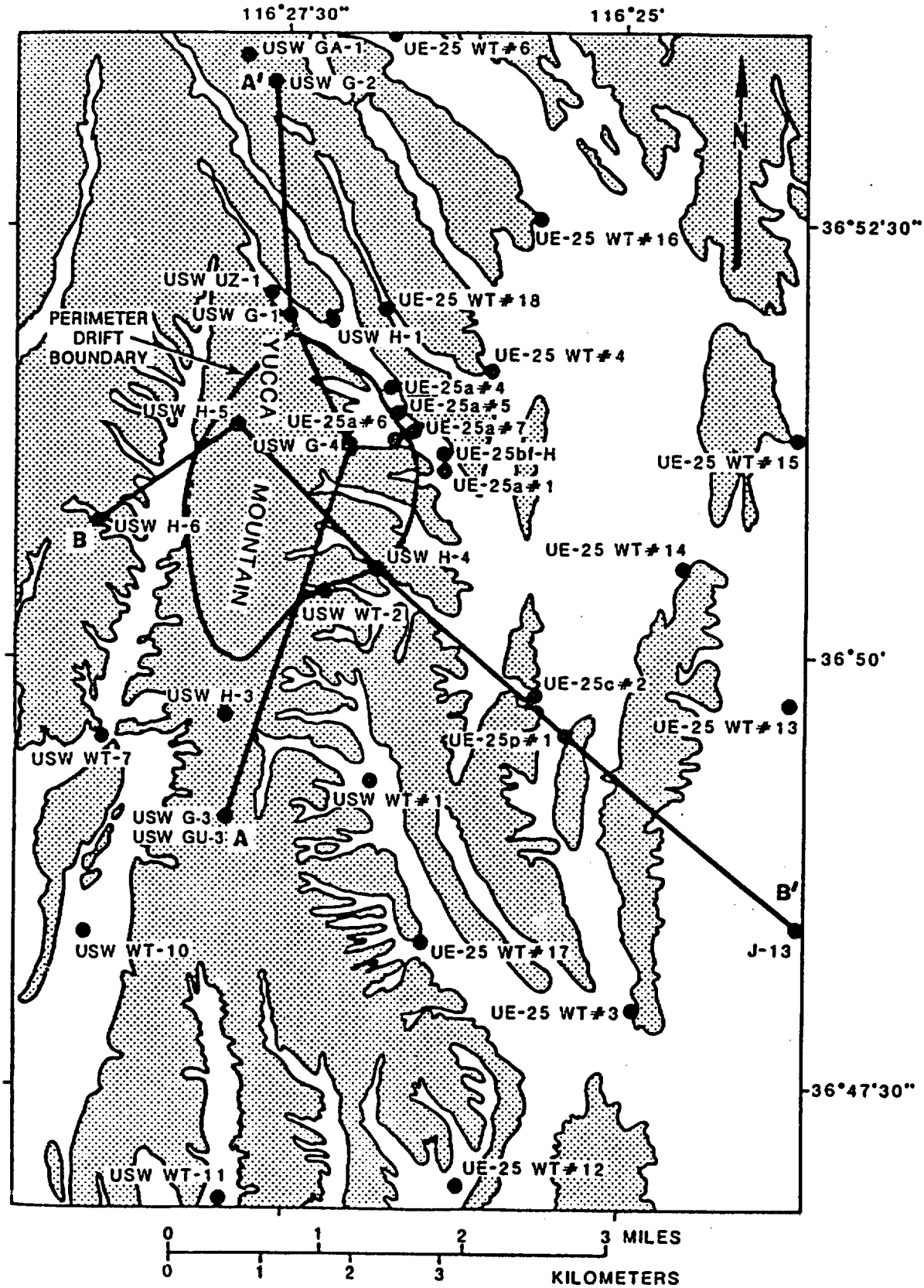


Figure 1. Index map showing the locations of selected drill holes in the vicinity of Yucca Mountain and the locations of cross-sections shown in Figures 2a and 2b. After U.S. Department of Energy (1988).

Table 1. Thickness in meters of stratigraphic units included in this report in selected drill holes, in vertical sequence downward. Drill holes are selected for proximity to proposed repository. A hyphen (-) indicates unavailable data.

Drill Hole	Lower Topopah Spring	Bedded Tuff	Calico Hills	Bedded Tuff	Prow Pass	Bedded Tuff	Upper Bull-frog	Strati-graphy Source
Northern Half of Proposed Repository Block								
UE-25 a#1	13.0	1.2	129.6	14.2	151.6	0.0	51.0±	1
UE-25 b#1	6.1	10.7	138.7	8.8	148.3	1.7	67.7	2
USW G-1	13.2	6.6	94.8	19.8	106.8	6.4	83.5	3
USW G-4	16.2	0.8	90.2	17.0	145.1	2.0	38.4	4
USW H-1	-	5.0	90.0	17.0	135.0	7.0	113.0	5
USW H-5	13.5	3.4	51.8	19.8	89.9	7.0	105.7	6
Southern Half of Proposed Repository Block								
USW GU-3	32.7	2.0	28.6	16.3	131.5	4.0	29.0	7
USW H-3	42.7	0.0	28.9	0.0	125.9	2.2	28.3	8
USW H-4	29.0	0.0	80.2	15.8	193.9	3.6	68.6	9
USW WT-2[a]	-	-	89.0	-	142.0+	-	-	10

[a] Detailed stratigraphic logs unavailable.

Sources:

1. Spengler et al., 1979.
2. Lobmeyer et al., 1983.
3. Spengler et al., 1981.
4. Spengler and Chornack, 1984.
5. Rush et al., 1983.
6. Bentley et al., 1983.
7. Scott and Castellanos, 1984.
8. Thordarson et al., 1984.
9. Whitfield et al., 1984.
10. Muller and Kibler, 1985.

Vitric tuffs are formed when ash-flow deposits cool before crystallization can occur. Devitrified tuffs result from high-temperature crystallization during cooling of an ash-flow sheet, while zeolitic tuffs are the result of low-temperature replacement of glass during secondary alteration. Clinoptilolite is the predominant zeolite at Yucca Mountain, accompanied by varying amounts of mordenite and analcime.

Stratigraphic members of the Calico Hills hydrogeologic unit include the following:

1. **Lower part of Topopah Spring Member** - partially welded grading downward to nonwelded vitric to zeolitic tuffs below the basal vitrophyre.

2. **Bedded ash-fall and reworked tuffs** - between the Topopah Spring Member and the Tuffaceous Beds of the Calico Hills.

3. **Tuffaceous Beds of the Calico Hills** - informal stratigraphic unit consisting of a series of up to 16 relatively massive, homogeneous nonwelded ash-flow tuff units separated by thin (up to 4-m thick) bedded to massive air fall tuffs (Spengler et al., 1979; 1981), zeolitized in the north of the exploration block, vitric to the south.

4. **Bedded ash-fall and reworked tuffs** - separating the Tuffaceous Beds of the Calico Hills from the Prow Pass Member.

5. **Prow Pass Member** - nonwelded to partially welded ash-flow tuff, vitric to zeolitic in upper part, devitrified in central part and zeolitic in lower part (interior moderately welded in places).

6. **Bedded ash-fall and reworked tuffs** - separating the Prow Pass Member from the Bullfrog Member.

7. **Upper part of Bullfrog Member** - nonwelded to partially welded vitric, devitrified and zeolitic tuffs.

Stratigraphy at Yucca Mountain is shown in Figures 2a and 2b; location of the cross-sections is indicated on Figure 1. The unit dips gently to the east and is crossed by the Ghost Dance fault. Table 2 indicates water table location in each of the drill holes listed in Table 1 and the total thickness and total unsaturated thickness of the hydrologic unit in those drill holes.

Table 3 illustrates the correlation between Montazer and Wilson's hydrogeologic units and rock-stratigraphic units.

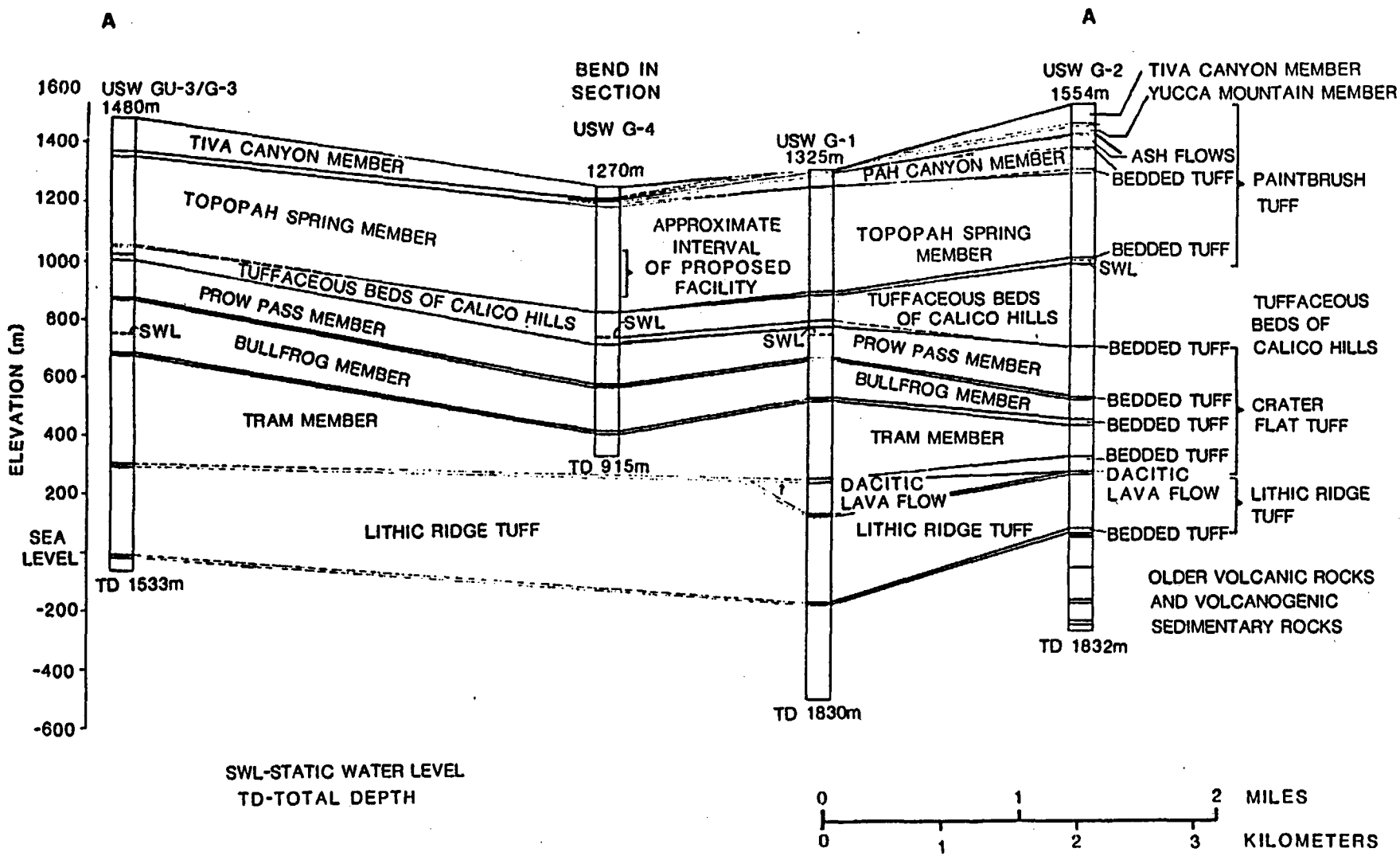
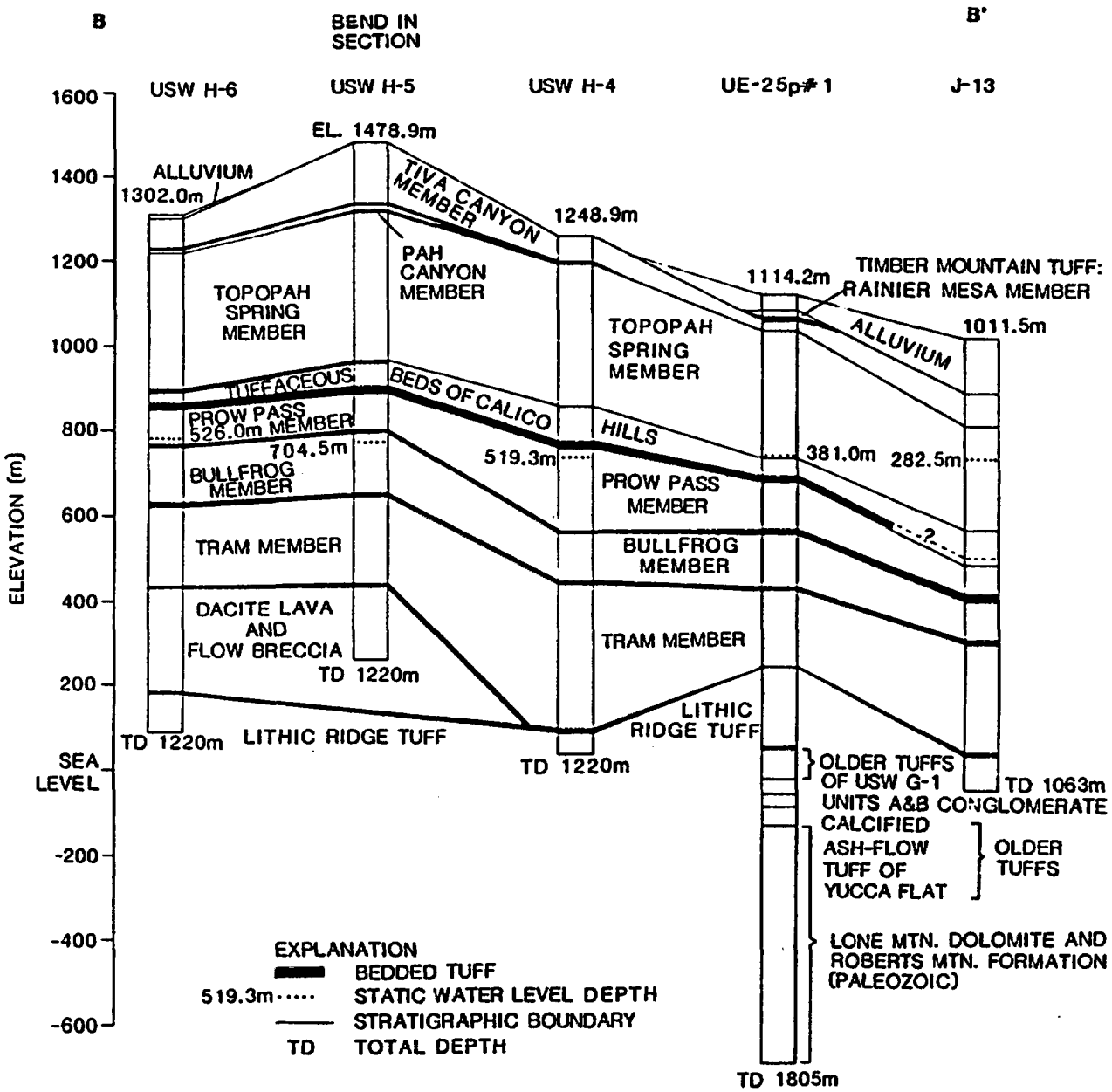


Figure 2a. North-south stratigraphic correlation between selected drill holes at Yucca Mountain. Vertical:horizontal scale = 2.5:1. After U.S. Department of Energy (1988).



REFERENCES

H-6: CRAIG et al. (1983)

H-5: BENTLEY et al. (1983)

H-4: WHITFIELD et al. (1984)

p# 1: CRAIG & JOHNSON (1984)

J-13: THORDARSON (1983)

HORIZONTAL SCALE

0 — 1 MILE

0 — 1 KILOMETER

Figure 2b. East-west stratigraphic correlation between selected drill holes at Yucca Mountain. Vertical:horizontal scale = 2.5:1. After U.S. Department of Energy (1988).

Table 2. Water table location, total Calico Hills nonwelded unit thickness and thickness of unsaturated Calico Hills nonwelded unit[a].

Drill Hole	Stratigraphic Unit	Water Table Location: Depth (m)	Water Table Location: Altitude (m)	Total Thickness Saturated + Unsat. (m)	Total Thickness Unsat. (m)
Northern Half of Proposed Repository Block					
UE-25 a#1	Calico Hills	469.4[b]	728.8	360.6	67.9
UE-25 b#1	Calico Hills	470.6	730.9	382.0	65.2
USW G-1	Prow Pass	571.1	754.2	331.1	157.0
USW G-4	Prow Pass	539.5	730.0	309.7	126.9
USW H-1	Prow Pass	572.1	730.9	367.0	118.1
USW H-5	Bullfrog	704.2	774.7	291.1	199.8
Southern Half of Proposed Repository Block					
USW GU-3	Bullfrog	750.3	730.2	244.1	244.1
USW H-3	Bullfrog	750.8[c]	732.4	228.0	228.0
USW H-4	Prow Pass	518.7	729.8	391.1	147.8
USW WT-2	Prow Pass	571.0	730.3	231.0+	174.0

[a] Water table depths and elevations from U. S. Department of Energy (1988) except where noted. Thickness of units determined from sources indicated in Table 2.
[b] Water level from Spengler et al., 1979. Value represents an average of four measurements.
[c] Water level from Thordarson et al., 1984.

Table 3. Definition of unsaturated-zone hydrogeologic units and correlation with rock-stratigraphic units. After U.S. Department of Energy (1988).

Rock-Stratigraphic Unit		Hydrogeologic Unit[b]	Approximate Range of Thickness (m)	Lithology[c]
Alluvium		QAL	0-30	Irregularly distributed surficial deposits of alluvium and colluvium
Paintbrush Tuff	Tiva Canyon Member	TCw	0-150	Moderately to densely welded, devitrified ash-flow tuff
Paintbrush Tuff	Yucca Mountain Member; Pah Canyon Member	PTn	20-100	Partially welded to nonwelded, vitric and occasionally divitrified tuffs
Paintbrush Tuff	Topopah Spring Member	TSw	290-360	Moderately to densely welded, devitrified ash-flow tuffs that are locally lithophysae-rich in the upper part, includes basal vitrophyre
Tuffaceous beds of Calico Hills		CHn: CHnv / CHnz	100-400	Nonwelded to partially welded ash-flow tuffs: Vitric / Zeolitized
Crater Flat Tuff	Prow Pass Member			
Crater Flat Tuff	Bullfrog Member	CFu	0-200	Undifferentiated, welded and nonwelded, vitric, devitrified, and zeolitized ash-flow and air-fall tuffs

[a]Sources: Montazer and Wilson (1984) except as noted.

[b]QAL = Quaternary Alluvium, TC_w = Tiva Canyon welded unit, PT_n = Paintbrush nonwelded unit, TS_w = Topopah Spring welded unit, CH_n = Calico Hills nonwelded unit, CH_{nv} = Calico Hills nonwelded vitric unit, CH_{nz} = Calico Hills nonwelded zeolitized unit, CF_u = Crater Flat undifferentiated unit.

[c]Lithology summarized from Ortiz et al. (1985).

A geochemical classification based on sorptive units not corresponding to the formal stratigraphic units was described by Bryant and Vaniman (1984). Cross-sections illustrating sorptive stratigraphy of Yucca Mountain are shown in Figures 3a and 3b. Percentages of minerals and glass observed in samples from selected boreholes are summarized graphically in Appendix A. The mineralogic data show that zeolites are present between the proposed repository horizon and the water table to some extent in each of the drill holes included. Thickness and degree of zeolitization varies from complete in the north (USW G-1, USW G-4) and east (UE-25 a#1) to partial in the south (USW H-3, USW GU-3) and minimal in the west (USW H-5, USW H-6). Ability of sorptive intervals to retard downward migration of some radionuclides depends on hydrologic and geochemical processes which are yet to be fully determined.

Fracture information from the Calico Hills nonwelded unit comes from borehole surveys, core samples and surface mapping of outcrops. Analysis of fracture frequency data from three vertical drill holes by Langkopf and Knirk (1986) provided estimates of fracture frequencies ranging from .2 to 2 fractures per cubic meter. They report a fracture frequency of 1.2 fractures per cubic meter in the Tuffaceous Beds of the Calico Hills based on surface mapping in the region known as The Prow.

III. HYDROLOGIC PROPERTIES

A general summary of hydrogeologic characteristics of the unsaturated zone at Yucca Mountain is presented by Montazer and Wilson (1984). The previous authors attribute average parameters and average hydrologic behaviors to the designated hydrologic units. This report includes data which have become available since Montazer and Wilson's report. By making available sample statistics and a listing of the data, researchers are provided an overview of available data which may be useful in assessing current transport analysis strategies and directing those of the future. Appendix B is a listing of compiled data including hydraulic conductivity, porosity, moisture content, saturation, pore-size distribution summary and saturation curve-fitting parameters. The data are generally organized first by drill hole and then by origin. Wherever possible, correlation between sample depth, lithology and alteration was made by referring to well logs and mineralogy available in the literature. Water chemistry data from the unsaturated Calico Hills nonwelded unit do not exist.

Table 4 summarizes the number of data from individual Calico Hills nonwelded unit samples or subsamples for each drill hole included in Appendices A and B (i.e., two porosity measurements on the same sample or subsample are counted as a single data

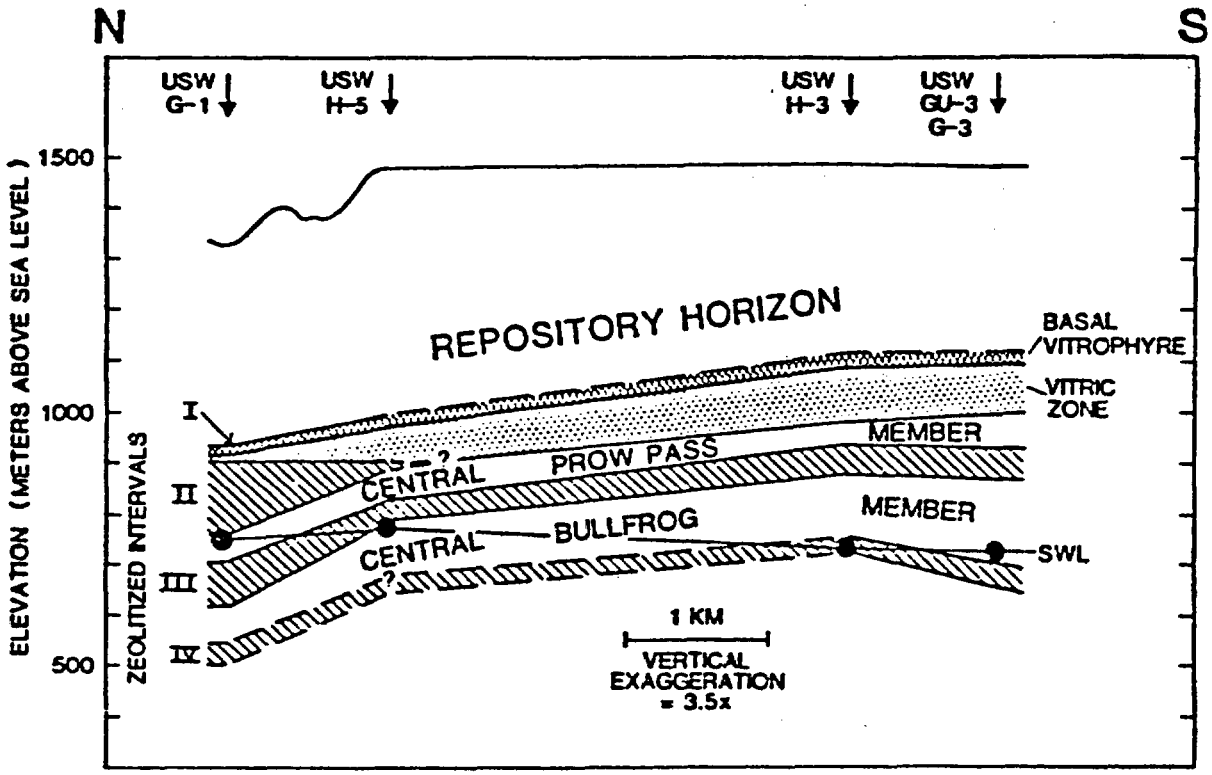
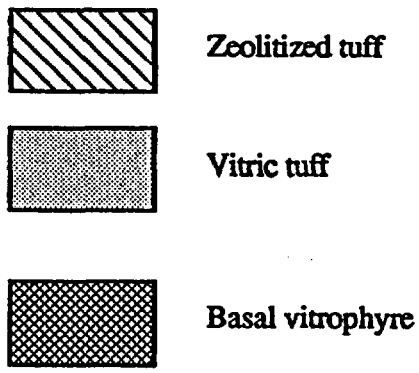


Figure 3a. Sorptive stratigraphy of Yucca Mountain. (Bryant and Vaniman, 1984). After Tien et al. (1985).



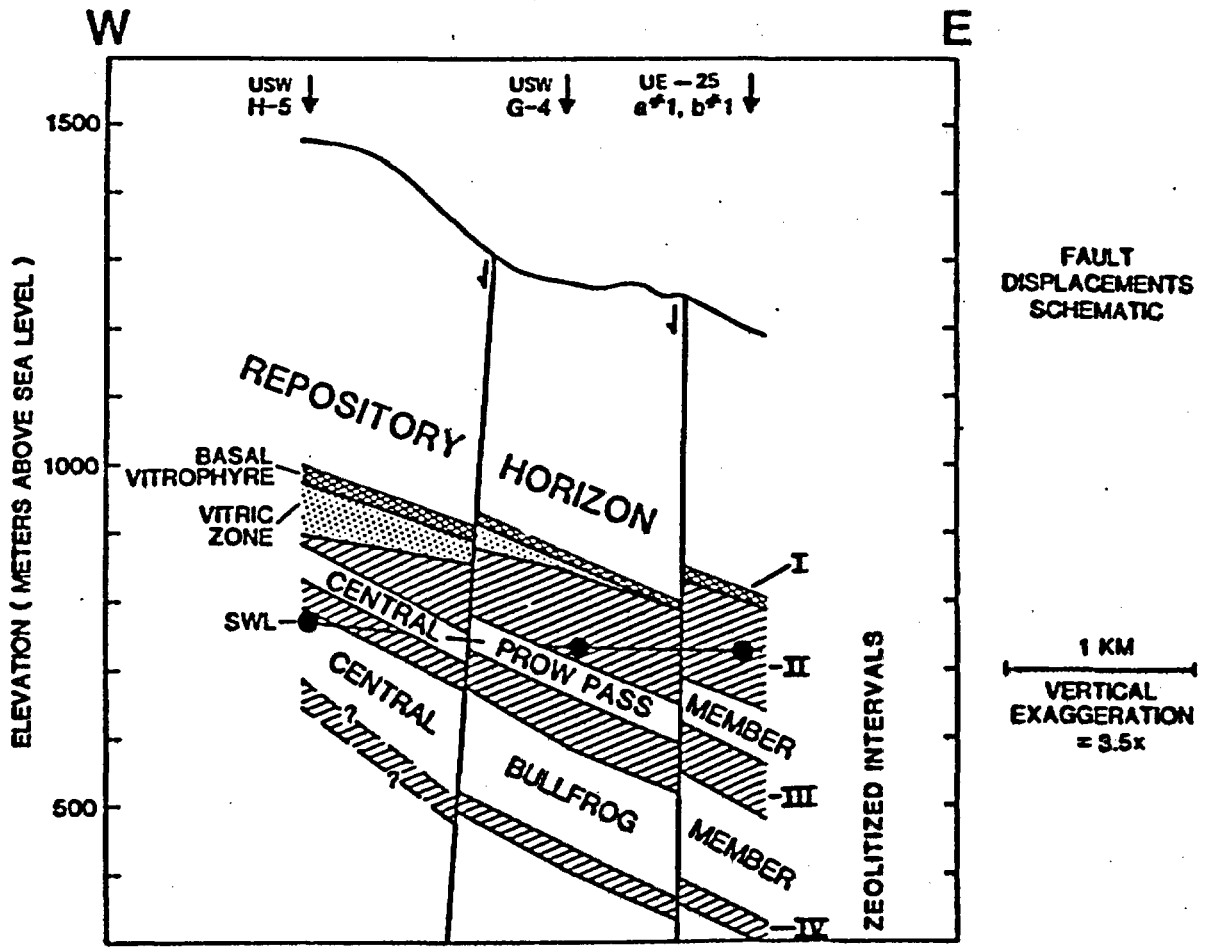


Figure 3b. Sorptive stratigraphy of Yucca Mountain. (Bryant and Vaniman, 1984). After Tien et al. (1985).

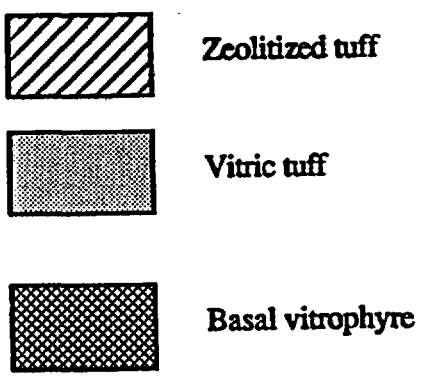


Table 4. Number of measurements on different samples or subsamples by drill hole.

Drill Hole	Hydraulic Conductivity Lab.	Hydraulic Conductivity Field	Porosity	Saturation	Mineralogy	Saturation Curve-Fit Parameters	Pore-Size Dist.
Northern Half of Proposed Repository Block							
UE-25 a#1	18	0	45	42	yes	0	0
UE-25 b#1	5	11	5	5	partial	0	0
USW G-1	19	0	30	22	yes	17	11
USW G-4	56	7	68	23	yes	37	15
USW H-1	12	13	14	14	no	0	0
USW H-5	0	0	0	0	yes	0	0
Southern Half of Proposed Repository Block							
USW GU-3	20	0	36	24	yes	12	9
USW H-3	0	0	0	0	yes	0	0
USW H-4	0	7	0	0	yes	0	0
USW WT-2	0	0	0	0	yes	0	0
Drill Holes Outside Proposed Repository Block							
UE-25 p#1	0	6	0	0	yes	0	0
USW G-2	0	0	0	0	yes	0	0
USW H-6	0	0	0	0	yes	0	0
USW J-13	1	12	3	2	yes	0	0

point, but single porosity measurements from each of two subsamples of the same sample are counted as two data points). Table 4 shows that except for drill hole USW GU-3, located over one and a half kilometers south of the proposed perimeter drift boundary, at this time southern parts of the repository exploration block are poorly represented in terms of hydrologic property measurements.

3.1. Saturated Hydraulic Conductivity

Permeability is a property of a porous medium that characterizes the ability of the medium to transmit a fluid (units L^2). Hydraulic conductivity reflects the ability of a medium to transmit a particular fluid, i.e., properties of the fluid are incorporated into the parameter (units L/t). The relationship between them is expressed as

$$K = \frac{\rho g k}{\mu} \tag{1}$$

where

K = hydraulic conductivity (L/t)
k = permeability (L^2)
ρ = fluid density (M/L^3)
g = acceleration of gravity (L/t^2)
μ = dynamic viscosity (M/Lt)

and

L = length
t = time
M = mass

In this discussion, hydraulic conductivity will always refer to a medium saturated with water (density = 1 g/cm^3) in the standard range of temperature (15°C - 20°C) at atmospheric pressure. Permeability and hydraulic conductivity will be referenced interchangeably.

Numerous studies have led researchers to conclude that hydraulic conductivity in most geologic media is distributed approximately log-normally (Freeze, 1975). For this reason, statistical parameters of hydraulic conductivity data are often determined in log space. Sample statistics of hydraulic conductivity data in both log space and real space are presented here. The geometric mean is generally taken to be a more representative value than the arithmetic mean for use in deterministic calculations, depending on factors including the geometry and dimensionality of the flow field. For a further discussion the reader is referred to de Marsily (1986).

Application of a classical continuum approach to flow in porous media requires the definition of parameters that express the average behavior of a system relative to some property of interest. The continuum approach is fundamentally rooted in the concept of a representative elementary volume (REV). Whether or not laboratory permeability data obtained at the one to six centimeter scale or aquifer test data obtained at the meter to tens of meters scale meet the REV criteria for matrix and fracture-matrix respectively is a critical question that is yet to be answered.

Laboratory samples, at the centimeter scale, are usually homogeneous in the sense that as a rule the physical properties governing fluid flow through the sample do not change substantially within the length scale of the sample. Flow at laboratory scales is assumed to be well approximated as one-dimensional flow. At larger scales, such as those of aquifer tests, flow is more likely to be three-dimensional. Saturated flow measurements obtained at larger scales incorporate a larger range of variability, including both the effects of matrix variability and the influence of fractures and macropores. Field heterogeneities in hydraulic conductivity have been found to play an important role in the dispersion of solutes in porous media. Since it is impossible to know the hydraulic conductivity at every point in space as required by deterministic methods, efforts to describe heterogeneity in porous media have focused on stochastic approaches (Gelhar and Axness, 1983; Neuman, 1987; Dagan 1987). Understanding the effects of that variability on solute transport is essential to the understanding and prediction of field phenomena (Dagan, 1989).

Measurements of saturated hydraulic conductivity in the Calico Hills nonwelded unit from the laboratory and from aquifer tests are summarized in Appendix B. Data are presented in both permeability and hydraulic conductivity units for the convenience of the reader. Lithology of samples was inferred from the drill hole logs referenced in Table 1.

3.1.a. Laboratory Measurements

Laboratory samples were taken from core in both unsaturated and saturated parts of boreholes. Laboratory test data in Appendix B are from cylindrical samples having the dimensions shown in Table 5. Dagan (1986) describes the laboratory scale as between 10^{-1} to 10^{0} m in length. By those criteria, measurements on the samples summarized in Table 5 may be considered to be at sub-laboratory scales. The difference in sample size is related to the low permeability of the rock samples from Yucca Mountain compared with higher permeability in soil cores more typically tested in the laboratory. In both cases, the hydraulic conductivity data obtained in the laboratory represent matrix

Table 5. Number of samples, dimensions and source of laboratory hydraulic conductivity data from selected drill holes near Yucca Mountain, Nevada.

Drill Hole	No. Samples	Dimensions	Source
UE-25 a#1	18	2.54 cm long x 2.54 cm diameter	Anderson 1992[a]
UE-25 b#1	5	?	Lobmeyer et al., 1983[a]
G-1	19	1.2 cm long x 1.5 cm diameter	Site Engineering Properties Data Base
GU-3	12	2.54 cm long x 2.54 cm diameter	Anderson 1992[a]
GU-3	8	5 cm long x 6 cm diameter	Peters et al., 1984.
G-4	23	2.54 cm long x 2.54 cm diameter	Anderson 1992[a]
G-4	37	(32) 1.2 cm long x 1.4 cm diameter (5) 2 cm long x 6 cm diameter	Peters et al., 1984.
G-4	6	1.2 cm long x 1.5 cm diameter	Site Engineering Properties Data Base
H-1	12	1.2 cm long x 1.5 cm diameter	Rush et al., 1983[a]
J-13	1	?	Thordarson, 1983.

[a] Includes measurements of permeability in horizontal and vertical directions from adjacent plugs.

values from samples which may or may not be representative of the medium in a continuum sense. Effects of fractures and other forms of potential fast flow paths are generally not incorporated in the measurements. Likewise, friable media too fragile for sample preparation are not represented by the data. These data may be useful as input parameter guidelines for flow models, but only at saturations where fracture flow does not occur. Also, it should be recognized that omission of friable samples biases the laboratory-scale sample statistics. Friable samples may have higher than average saturated permeabilities and more steeply sloping moisture characteristic curves, with correspondingly lower unsaturated permeabilities over a wide range of moisture contents, than more intact tuffs.

Sample statistics of the laboratory hydraulic conductivities and their base-ten logarithms were determined for vitric tuff, devitrified tuff, zeolitic tuff and the combined data set. Table 6 summarizes the results of the statistical analysis. Data from devitrified, zeolitic sample intervals were included with zeolitic data. Samples from vapor phase tuffs were omitted. Lognormal probability plots of devitrified, vitric and zeolitic data are shown in Figure 4. Figure 5 is a lognormal probability plot of the entire laboratory hydraulic conductivity data set. The Weibull plotting formula was used to determine plotting position or cumulative probability for the probability plots.

The sample statistics in Table 6 show that the geometric mean matrix permeabilities of vitric and devitrified tuffs are close and that both means are nearly two orders of magnitude greater than the geometric mean permeability of zeolitic tuffs. The skewness coefficients indicate that the log permeabilities more closely approximate a normal distribution than do the data in real space. Figure 4 supports these observations. Devitrified and zeolitic data lognormal probability plots are roughly linear. Vitric data plot more erratically, but this may be due to insufficient data points. It should be noted in Figure 4 that while the means of the devitrified and vitric data are very close in log space, the distributions are relatively dissimilar, although again this may result from insufficient vitric data points. The roughly linear lognormal probability plot of the combined data confirms the approximate lognormal distribution of hydraulic conductivity in the Calico Hills nonwelded unit based on this data set, but does not address the question of spatial correlation of the data.

The coefficient of variation suggests that hydraulic conductivity is most variable in the vitric tuffs. However, more data are needed, particularly from the vitric tuffs. Using mineralogy from Appendix A in the sampling intervals, a correlation of -0.613 was found between percent zeolites and log matrix hydraulic conductivity. Correlation between degree of welding and log hydraulic conductivity is 0.428. The vitric tuff

Table 6. Sample statistics of laboratory hydraulic conductivity data for vitric, devitrified and zeolitic tuffs and for lumped data.

Base-Ten Log Hydraulic Conductivity
(originally in m/s)

	Vitric	Devitrified	Zeolitic	All
No. Samples	17	54	83	154
Minimum	-10.70	-9.80	-13.63	-13.63
Maximum	-6.42	-5.65	-8.00	-5.65
Range	4.28	4.16	5.63	7.98
Arith. Mean	-8.40	-8.37	-10.16	-9.34
Median	-8.50	-8.60	-10.30	-9.24
Variance	2.57	0.84	1.43	2.12
Skewness	-0.11	0.77	-0.32	-0.10
C.V.[a]	-0.19	-0.11	-0.12	-0.16

Hydraulic Conductivity in Meters per Second

	Vitric	Devitrified	Zeolitic	All
No. Samples	17	54	83	154
Minimum	1.99e-11	1.57e-10	2.37e-14	2.37e-14
Maximum	3.76e-07	2.25e-06	1.00e-08	2.25e-06
Range	3.76e-07	2.25e-06	1.00e-08	2.25e-06
Arith. Mean	8.80e-08	7.08e-08	8.07e-10	3.50e-08
Geom. Mean	3.95e-09	4.28e-09	6.90e-11	4.59e-10
Median	3.15e-09	2.50e-09	5.06e-11	5.79e-10
Variance	1.73e-14	9.95e-14	3.40e-18	3.77e-14
Skewness	1.18	6.35	3.41	9.98
C.V.[a]	1.49	4.45	2.28	5.55

[a] Coefficient of variation.

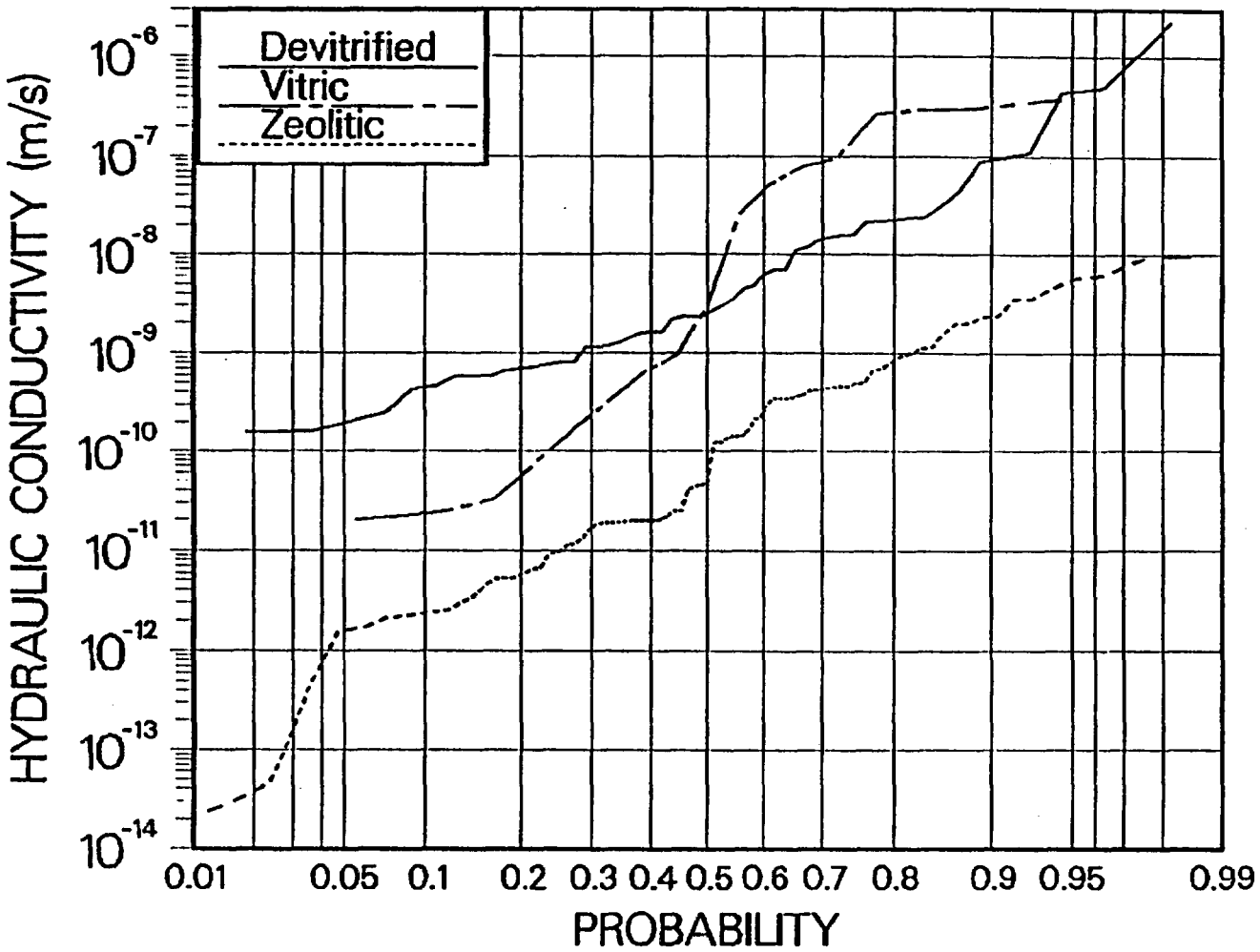


Figure 4. Log-normal probability plot of devitrified, vitric and zeolitic laboratory hydraulic conductivity data.

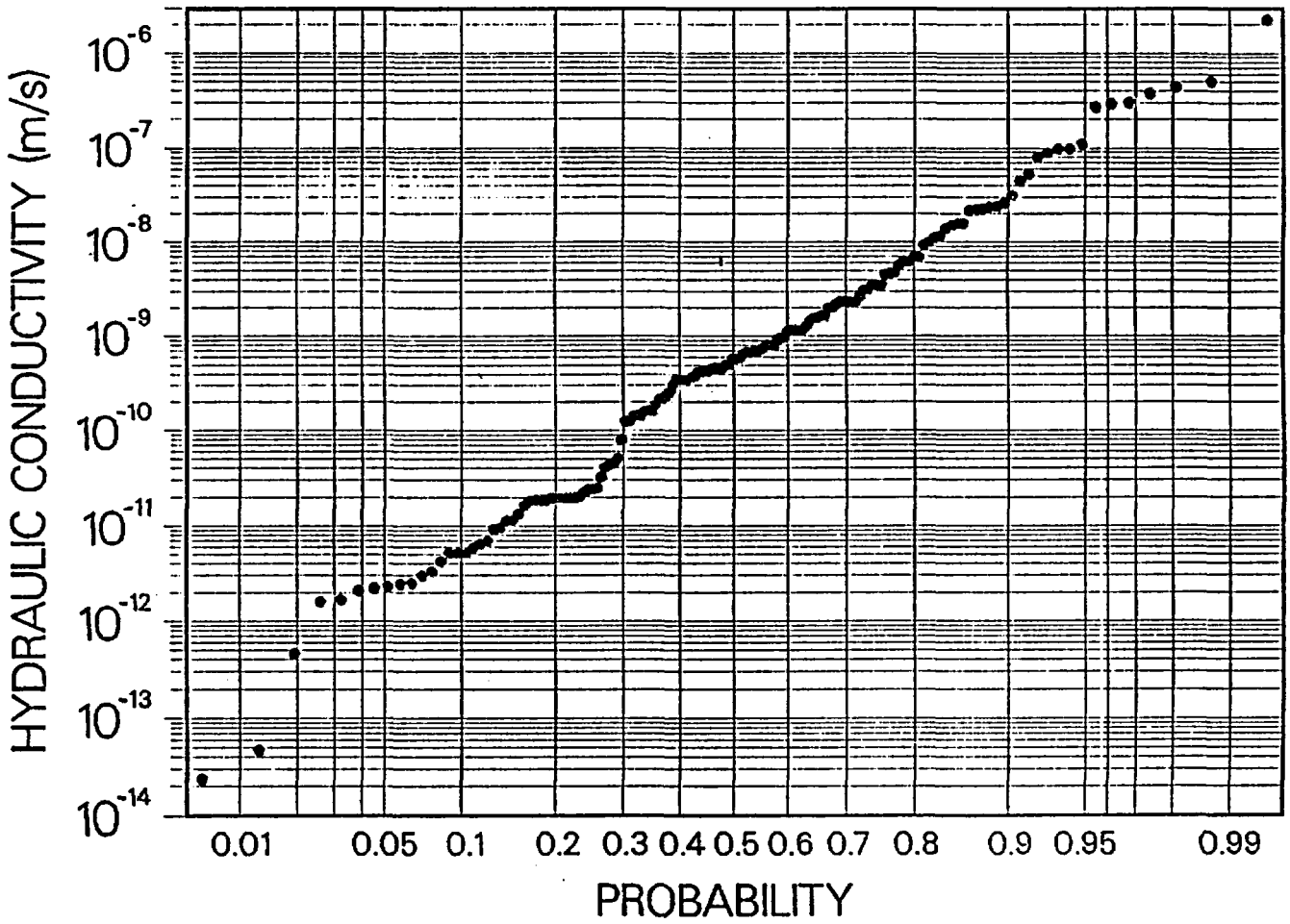


Figure 5. Log-normal probability plot of all laboratory hydraulic conductivity data.

geometric mean hydraulic conductivity, 3.95e-09 m/s, based on 17 samples, is nearly an order of magnitude smaller than that reported by Montazer and Wilson (1984) of 4.62e-08 m/s, based on four samples. Montazer and Wilson (1984) combined data from devitrified tuff and zeolitic tuff and reported a geometric mean hydraulic conductivity value of 9.26e-11 m/s (22 samples), only slightly greater than that reported here for zeolitic tuffs in Table 6, 6.90e-11 m/s.

The implications of the statistics shown in Table 6 are twofold. It is apparent that hydraulic conductivity varies considerably within each of the three groups. Values span between four and six orders of magnitude for the three groups. However, as shown in Table 7 for zeolitic tuffs, variability within individual data sets from each drill hole is considerably smaller, with the exception of the measurements of Peters et al. (1984) in USW G-4. The measurements of Peters et al. (1984) from USW G-4 were obtained using samples of two different sizes and two different testing methods. Reduced variability within drill holes reflects near field correlation of matrix properties relative to the larger repository scale. As a rule, variability increases with separation distance between sampling points. Some part of the observed variability in measured hydraulic conductivity almost surely originates in differences in sample size, sample handling and test methods between researchers. This contribution has not been quantified but most likely has an important but obscured role in the data currently available. Measurements from samples of the same size and handling history obtained by the same methods minimize this added source of variability, but introduce the possibility of bias in the results.

Availability of three sets of data from drill hole USW G-4 allows comparison of values derived by different researchers for the interval of zeolitized Calico Hills nonwelded tuff between about 429 and 520 m depth. The results of a comparison show that values reported by Peters et al. (1984) and in the Site Engineering Properties Data Base (1989) are an average of 2.3 orders of magnitude smaller than those reported by Anderson (1992). While data points are too few in number to draw conclusions, a question is raised regarding the source of the apparent differences in the sets of laboratory hydraulic conductivity values for USW G-4. Similar questions may be asked about the data sets for individual drill holes. How much of the variability is real and how much is an artifact of size, removal, handling and testing procedures? Differences in measured values may be a result of testing sample volumes smaller than a representative elementary volume. The lower size limit of an REV can only be determined by careful testing at different scales. Other sources of differences in reported values may be related to pretest handling of samples, variability in test fluids, or testing methods. The lowest reported permeabilities in USW G-4

Table 7. Base-ten logarithm of laboratory hydraulic conductivity (K) measurements for zeolitic tuffs and range, by drill hole. Originally in meters per second. (v)=vertical; (h)=horizontal.

Depth (m)	Lithology[1]	Log_{10} K	Range Log_{10} K	Source
UE-25 a#1				
462.1	n/dv,z	-9.84466	2.36	Anderson (1981)
477.9	n/dv,z	-8.63451		length = 2.54 cm
499.3	n/dv,z	-8.45346		diameter = 2.54 cm
530.7	n/dvz	-9.29930		volume = 12.84 cm^3
545.9	bt/z	-10.36151		
658.1	p/dv,z	-8.94885		
670.9	p/dv,z	-8.00218		
UE-25 b#1				
479.3	n/z	-9.36856(h)	2.31	Lobmeyer et al. (1983)
479.3	n/z	-8.70553(v)		sample size unknown
679.5	pm/dv,z	-11.01728(h)		
679.5	pm/dv,z	-10.70553(v)		
USW G-1				
457.1	n/dv,z	-10.93554	1.34	Site Engineering
457.1	n/dv,z	-10.73049		Properties Data Base
499.0	n/z	-10.71220		length = 1.2 cm
499.0	n/z	-11.03480		diameter = 1.4 cm
534.0	bt/z,s	-10.94692		volume = 1.85 cm^3
534.0	bt/z,s	-10.78516		
542.4	bt/z,s	-11.65561		
542.4	bt/z,s	-11.68194		
545.5	bt/z,s	-11.28233		
545.5	bt/z,s	-11.28233		
554.9	p/dv,z	-10.39041		
554.9	p/dv,z	-10.34486		
USW H-1				
790.0	nm/dv,z	-9.33442(v)	0.43	Rush et al. (1983)
790.0	nm/dv,z	-9.33442(h)		sample size unknown
791.0	nm/dv,z	-9.03339(v)		
791.0	nm/dv,z	-9.15864(h)		
792.0	nm/dv,z	-9.45967(v)		
792.0	nm/dv,z	-9.09151(h)		

Continued on next page

Table 7., continued
USW G-4

428.2	n/z	-11.52433	4.36	Peters et al. (1984)
471.8	n/z	-11.22915		length = 1.2 cm
471.8	n/z	-10.70553		diameter = 1.4 cm
471.8	n/z	-13.62525*		volume = 1.85 cm^3
472.7	n/z	-10.29585		
472.7	n/z	-10.72584		*length = 2 cm
472.7	n/z	-10.87615		diameter = 6 cm
513.9	n/z	-11.37263		volume = 56.55 cm^3
526.7	bt/z	-10.73049		
526.7	bt/z	-10.61083		
526.7	bt/z	-10.70553		
526.7	bt/z	-13.32883*		
529.4	bt/z	-12.33819		
529.4	bt/z	-10.60555		
529.4	bt/z	-11.79860*		
539.2	n/z	-11.63827		
541.9	n/dv,z	-11.18910		
542.0	n/dv,z	-11.16178		
542.0	n/dv,z	-10.73755		
542.0	n/dv,z	-10.64782		
544.7	n/pa,z	-9.79317		
544.7	n/pa,z	-10.70553		
544.7	n/pa,z	-9.90658		
544.7	n/pa,z	-11.77469*		
611.4	np/z	-10.69250		
640.4	p/dv,z	-9.36051		

USW G-4

460.8	n/z	-8.24260(v)	1.65	Anderson (1992)[2]
511.7	n/z	-9.85387(v)		
602.4	np/z	-8.93930(v)		length = 2.54 cm
602.4	np/z	-9.66959(h)		diameter = 2.54 cm
619.6	np/z	-9.30627(v)		volume = 12.87 cm^3
649.8	p/dv,z	-9.45842(v)		
649.8	p/dv,z	-9.16749(h)		
665.2	p/dv,z	-9.38195(v)		
665.2	p/dv,z	-8.69465(h)		
679.4	n/z,sa	-8.20412(v)		
679.4	n/z,sa	-9.51145(h)		

USW G-4

454.1	n/z	-11.60206	0.33	Site Engineering
486.7	n/z	-11.61439		Properties Data Base
522.6	bt/z	-11.48017		length = 1.2 cm
532.4	bt/z	-11.28483		diameter = 1.5 cm
				volume = 2.12 cm^3

Table 7., continued

USW GU-3

552.9	p/dv,z	-8.81531	1.09	Anderson (1992)
569.2	p/dv,z	-9.42251		
569.2	p/dv,z	-9.44009		length = 2.54 cm
583.1	p/dv,z	-9.90309		diameter = 2.54 cm
597.1	p/dv,z	-9.84164		volume = 12.87 cm^3
612.3	p/z	-9.00218		

[1] Lithology from logs referenced in Table 1.
[2] Vertical and horizontal data from adjacent plugs.

Key to lithology abbreviations:

1. Degree of welding precedes slash.

   n = nonwelded
   p = partially welded
   m = moderately welded
   np = nonwelded to partially welded
   nm = nonwelded to moderately welded
   pm = partially to moderately welded

2. Alteration indicator follows slash.

   v = vitric
   z = zeolitic
   sz = slightly zeolitic
   dv = devitrified
   pdv = partially devitrified
   vp = vapor phase
   a = argillic
   sa = slightly argillic
   pa = partly argillic
   s = silicified
   ps = partly silicified

3. bt = bedded tuff

Example: np/dv,z = sample originates in nonwelded to partially welded interval which is devitrified and zeolitized.

were measured on the largest samples. Sources of field variability include differences in degree of zeolitization, alteration history and the unique circumstances surrounding emplacement and subsequent events at individual sample locations. With this in mind, it is clear that additional work is called for to resolve questions related to existing laboratory permeability data from the Calico Hills nonwelded unit. It is essential to understand exactly what a given data set represents before applying it to a problem. Identification of correlations between properties such as degree of zeolitization and variability of hydraulic conductivity can be important aids in site performance assessment modeling.

The high variability observed in the hydraulic conductivity measurements points to a probable need for a stochastic approach in solute transport analysis in the matrix. Sample statistics also indicate that using matrix hydraulic conductivities of zeolitic tuffs for devitrified tuffs in simulations is not justified. Doing so could result in unrealistically low transport rates at Yucca Mountain when saturations are high and possibly the reverse when saturations are low, depending on the shape of the moisture characteristic curves.

3.1.b. Aquifer Tests

Data in Appendix B from aquifer tests represent intervals of a meter to tens of meters where the units of interest are saturated. Fifty-six data from test intervals in the Calico Hills nonwelded hydrogeologic unit are listed in Appendix B. In addition to length of test interval, volume of rock influenced by aquifer tests varies with test duration, magnitude of induced gradients, effective porosity and hydraulic conductivity. All of the test intervals are in nonwelded to partially welded zeolitic and devitrified tuffs and bedded tuffs, except for a thin, moderately welded interval in USW H-4. None of the aquifer tests were conducted in vitric tuffs. Since many of the intervals spanned multiple horizons, it was not possible to separate data as was done for the laboratory samples. Sample statistics of the aquifer hydraulic conductivity measurements are shown in Table 8. The zero and negative hydraulic conductivity values from drill hole USW H-1 were omitted from the calculations. Figure 6 is a log-normal probability plot of the aquifer test data using the Weibull plotting position.

The aquifer test hydraulic conductivity data show that geometric mean hydraulic conductivity is from two to four orders of magnitude greater at field scales than at laboratory scales in the Calico Hills nonwelded hydrogeologic unit. Figure 6 shows that the data are approximately log-normally distributed. As was the case with the laboratory hydraulic conductivity data, the range of values spans nearly five orders of magnitude.

Table 8. Sample statistics for aquifer test hydraulic conductivity data.

Base-Ten Log Hydraulic Conductivity
(originally in m/s)

No. Samples	56
Minimum	-8.46
Maximum	-3.68
Range	4.78
Arith. Mean	-6.15
Median	-6.36
Variance	0.94
Skewness	0.29
C.V.[a]	-0.16

Hydraulic Conductivity in Meters per Second

No. Samples	56
Minimum	3.47e-09
Maximum	2.08e-04
Range	2.08e-04
Arith. Mean	7.50e-06
Geom. Mean	7.00e-07
Median	4.40e-07
Variance	7.93e-10
Skewness	6.63
C.V.[a]	3.75

[a] Coefficient of variation.

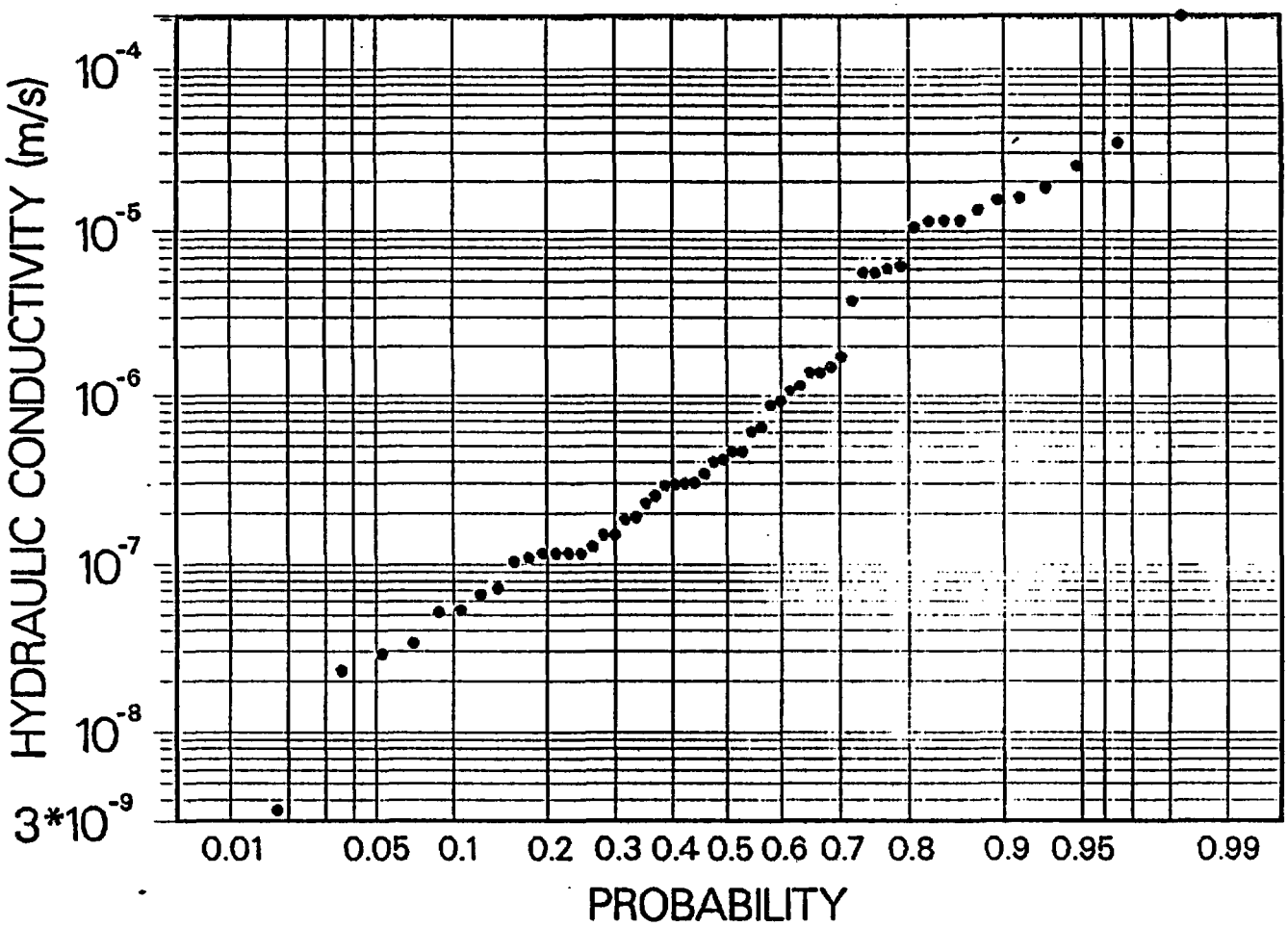


Figure 6. Log-normal probability plot of aquifer test hydraulic conductivity data.

Examination of the data also shows that much of the variability observed in the aquifer test data is the result of data from drill hole USW H-1. Base-ten logs of the range of values from each drill hole for which aquifer test data are included in this report show this in Table 9. The anomalously large range of values in USW H-1 appears to be in part due to a zone of high permeability between 652 and 653 m. A negative value for hydraulic conductivity in drill hole USW H-1 suggests that testing difficulties or a poor match between assumptions of the analysis and in situ conditions may also be factors causing large variance in that particular situation. The degree of variability of hydraulic conductivity should be considered in the application of deterministic and stochastic models in transport analysis.

3.1.c. Discussion

The hydraulic conductivity data illustrate two phenomena that are of importance to transport analysis and prediction. First, at both laboratory and aquifer test scales, permeability in the Calico Hills nonwelded unit is not homogeneous. The dimensions of an REV, if one exists, are unknown. This indicates a need for rigorous testing of the assumptions that are implicit in deterministic large-scale contaminant transport models and development and testing of alternative theory and methods of predicting transport where needed.

The data also illustrate the dependence of permeability measurement results on the volume of medium tested, known as scale-dependence. The highest geometric mean log hydraulic conductivity at laboratory scales is 4.28e-09 m/s, but geometric mean hydraulic conductivity at aquifer test scales is 7.00e-07 m/s. Testing of larger volumes incorporates more of the variability of the medium into the test volume, including fractures and potential fast flow paths of other types. This is clearly shown by comparison of laboratory data and aquifer test data from the same interval, where aquifer test data usually, but not always, indicate higher permeability than do tests on small samples in the laboratory. Table 10 lists laboratory and aquifer test hydraulic conductivity data obtained from overlapping intervals in drill holes USW H-1 and USW G-4. Scale dependence within the laboratory samples is also suggested and should be investigated.

3.2. Unsaturated Hydraulic Conductivity

As a soil desaturates, water is present in only the smaller pores and the cross-sectional area available for flow decreases. This leads to a corresponding decrease in hydraulic conductivity of the soil. The ability of a porous medium to transmit water at a given suction or saturation is known as effective hydraulic

Table 9. Maximum and minimum hydraulic conductivity values and range of base-ten logarithms of aquifer test hydraulic conductivity data, by drill hole.

Drill Hole	Maximum (m/s)	Minimum (m/s)	Log_{10} (max/min)
UE-25 b#1	1.15e-05	2.89e-08	2.60
UE-25 p#1	1.40e-06	2.31e-08	1.78
USW G-4	3.44e-07	5.16e-08	0.82
USW H-1[a]	2.08e-04	3.47e-09	4.78
USW H-4	2.49e-05	4.63e-07	1.73
USW J-13	1.74e-06	3.36e-08	1.71

[a] Zero and negative values omitted.

Table 10. Data from laboratory and aquifer testing within selected overlapping intervals.

Depth (m)	Aquifer Test (m/s)	Laboratory Measurement (m/s)	
USW G-4			
619.6		4.94e-10	vertical
640.4		4.36e-10	
649.8		3.48e-10	vertical
		6.80e-10	horizontal
616.0-655.0	3.44e-07		
USW G-4			
665.2		4.15e-10	vertical
		2.02e-09	horizontal
679.4		6.25e-09	vertical
		3.08e-10	horizontal
700.6		1.58e-08	vertical
		2.23e-08	horizontal
655.0-701.0	1.28e-07		
USW H-1			
640.0		8.10e-10	vertical
		1.16e-09	horizontal
641.0		5.79e-10	vertical
		8.10e-10	horizontal
641.0		5.79e-10	vertical
		6.94e-10	horizontal
616.0-652.0	1.16e-05		
USW H-1			
764.0		3.47e-09	vertical
		1.16e-08	horizontal
772.0		2.31e-09	vertical
		6.94e-09	horizontal
790.0		4.63e-10	vertical
		4.63e-10	horizontal
791.0		6.94e-10	vertical
		9.26e-10	horizontal
792.0		3.47e-10	vertical
		8.10e-10	horizontal
758.0-792.0	3.47e-09		

conductivity, K_{eff}, or effective permeability. Effective hydraulic conductivity is sometimes expressed as

$$K_{eff} = K_{rel} \times K_{sat} \tag{2}$$

where

K_{sat} = saturated hydraulic conductivity

and

$K_{rel} = K_{eff}/K_{sat}$ = relative hydraulic conductivity

Effective hydraulic conductivity is known to be a function of pore-size distribution in the lower suction range and grain surface area in the higher suction range. Determination of effective conductivity relationships requires measurement of fluxes and hydraulic gradients in unsaturated media. This is a difficult and time-consuming task under the best conditions. Field determination of effective hydraulic conductivity in soils is possible, but laboratory measurements are more tractable. Obtaining measurements in unsaturated rock poses major technical challenges, which are currently being addressed. No data from direct determinations of effective permeability in Yucca Mountain tuffs were located.

Theoretical models have been developed to assist in quantifying isotropic effective hydraulic conductivity for modeling purposes (see Mualem, 1986). Many of the models use fluid retention data as a basis for estimating the hydraulic conductivity function in unsaturated media. Widely applied among these are those by Mualem (1976) and Brooks and Corey (1966). Relative hydraulic conductivity curves based on the van Genuchten/Mualem formulation (van Genuchten, 1980) for samples from USW G-4 and USW GU-3 may be found in Peters et al. (1984). The van Genuchten/Mualem formulation expresses relative hydraulic conductivity as

$$K_{rel}(h) = \frac{\{1 - (ah)^{n-1}\,[1 + (ah)^{n}]^{-m}\}^{2}}{[1 + (ah)^{n}]^{m/2}} \tag{3}$$

where

$K_{rel}(h)$ = relative hydraulic conductivity as a function of pressure head
h = suction head (m) (positive)
a = curve fitting parameter (m^{-1})
n = curve fitting parameter
$m = 1 - 1/n$

Sinnock et al. (1986) used the Brooks-Corey function to calculate relative conductivity curves for use in calculational models. The Brooks-Corey exponents, derived by curve fitting to water retention data from USW G-4 and USW GU-3, are listed in Appendix B. Relative hydraulic conductivity is calculated as

$$K_{rel}(S) = \left[\frac{S - S_r}{S_s - S_r}\right]^e \qquad (4)$$

with

S = saturation
S_r = residual saturation
S_s = maximum saturation
e = a soil characteristic parameter = 3 + 2/b
b = negative slope of the log saturation versus log suction curve

It should be emphasized that all of the preceding theoretical hydraulic conductivity models for unsaturated flow were developed for soils and are not tested at the high suction ranges and low unsaturated conductivities found in the Calico Hills unit.

Another issue related to saturation and scale dependence of permeability involves the need to establish a relationship between suction and/or moisture content and effective permeability for fractured, unsaturated porous media. As discussed previously, scale dependence of hydraulic conductivity is attributed to the presence of matrix variability and fractures or macropores in the medium. Large pores are the first to desaturate under negative pressures. Laboratory data used to establish moisture characteristic curves and effective permeability curves are derived from small matrix samples. The data and the hydraulic conductivity models discussed in the preceding paragraph do not incorporate the effects of fractures on permeability at high saturations. Since larger pores desaturate first, permeability at low saturations is not thought to be affected by fractures, although it is possible that fractures may act as barriers to unsaturated flow. Effective permeability curves for fractured media, or composite curves, have been proposed (Wang and Narasimhan, 1986; Klavetter and Peters, 1986; Peters and Klavetter, 1988; Dudley et al., 1988), but no comparison with data has been reported to date. It is not established if, and under what conditions, fracture flow occurs in the Calico Hills nonwelded unit.

A further concern related to effective hydraulic conductivity is the likelihood that anisotropy of unsaturated tuff becomes more pronounced under increasingly unsaturated conditions (Yeh and Gelhar, 1983; Yeh et al., 1985). An increase in the ratio of horizontal to vertical hydraulic conductivity with increased tension has the effect of magnifying the importance of lateral flow above what would be anticipated on the basis of vertical and horizontal saturated permeability measurements. This phenomenon has been observed repeatedly in the field (see discussion in Gelhar et al., 1985) and is a potentially important issue to transport modeling. Studies have

shown that local effective hydraulic conductivity functions are only minimally hysteretic (Luckner et al., 1989), but that under certain circumstances (i.e., stratification) heterogeneity of the medium can cause strongly anisotropic behavior under wetting conditions but not drying (Mantoglou and Gelhar, 1987).

3.3. Fluid Potentials and Saturations

Laboratory measurements of fluid potential as a function of saturation for samples from USW G-4, USW GU-3 and USW G-1 were presented by Peters et al. (1984) and Klavetter and Peters (1987). Accuracy of the thermocouple psychrometer data is reported to be within 10 meters (1 bar) (Peters et al., 1984). Statistical fitting of the van Genuchten curves to the data (Rutherford et al., 1992) resulted in the saturation curve fitting parameters listed in Appendix B. Samples from zeolitized, vitric and devitrified nonwelded and partially welded tuffs and bedded tuffs are included. The van Génuchten formulation relates saturation and suction according to

$$S = (S_s - S_r) \left[\frac{1}{1 + (ah)^n} \right]^m + S_r \qquad (5)$$

with

h = suction head (m) (positive)
S = saturation as a function of suction head
S_s = maximum saturation
S_r = residual saturation
a = curve fit parameter (m^{-1})
n = curve fit parameter
$m = 1 - 1/n$

Variability within the unit is evident in the curves. Data are obtained by drying the samples in steps and measuring suction at each step. The curves are drying curves. Wetting data are not available, and the importance of hysteresis to analysis and prediction of flow in the tuffs is not established at this time. As long as steady state conditions prevail, changes in saturation do not occur and hysteresis is not an issue. Recent work has shown that significant prediction error may result when hysteresis is neglected (Dane and Wierenga, 1975; Hoa et al., 1977; Kaluarachchi and Parker, 1987). Luckner et al. (1989) discuss and present models for direction-dependent (wetting or drying) saturation-suction relationships.

In the absence of thermal and chemical gradients, fluid potentials in unsaturated media are a function of pressure (matric suction) and elevation. In situ measurements of fluid potentials in the Calico Hills nonwelded unit have not been obtained. However, natural bulk density, dry bulk density and

grain density data from cores allow determination of moisture content, porosity and saturation (Hillel, 1980). Saturation data may then be used in conjunction with moisture characteristic curves obtained in the laboratory to estimate a distribution of in situ fluid potentials. Variations in saturation reflect heterogeneities in the moisture characteristic properties of the medium together with spatial variation of fluid potential. As shown in Table 4, saturation data have been included in Appendix B for drill holes UE-25 a#1, UE-25 b#1, G-1, GU-3, G-4, H-1 and J-13. Examination of the data shows that some error is incorporated into the analysis because a few of the calculated saturations exceed one and because saturation values from core extracted below the water table are lower than unity. Some of the error may be due to drying of core during handling (Anderson, 1984). Sources of error in density and porosity measurements are discussed in Schwartz (1990).

Since the data come from different samples it is not possible to combine saturation values directly with moisture characteristic curves to infer in situ fluid potentials. However, it is clear that saturations are generally high in the Calico Hills nonwelded unit. Table 11 summarizes saturation statistics from vitric, zeolitized and devitrified tuff samples obtained above the water table. Mean saturation in vitric tuffs is 80%, in devitrified tuffs is 87%, and in zeolitic tuffs is 92%.

Using available data it is not possible to gain insight into the question of whether or not matric suctions are relatively uniform throughout the unit, as they would be under the unit gradient conditions postulated by Montazer and Wilson (1984), Sinnock et al. (1986), Peters and Klavetter (1988) and others. A statistical study of saturation distribution resulting from unit gradient conditions in the Calico Hills based on the fluid retention curves in Appendix B would be interesting and may help to shed light on the validity of that assumption. Measurements of fluid potentials (matric suctions) in cuttings from the Topopah Spring member of the Paintbrush Tuff in drill hole USW UZ-1 show spatial variations in fluid suction of over an order of magnitude (from -20 to -400 bars) within a vertical distance of 30 meters (Montazer et al., 1988). Equilibrium conditions would dictate approximately a 3-bar difference in fluid suction with a 30 m change in elevation, and unit gradient conditions would dictate no difference in fluid suction with a change in elevation.

3.4. Total and Kinematic Porosity

Total porosity is the ratio of volume occupied by voids to total volume of a sample. Kinematic porosity, or effective porosity, is the ratio of volume of pores that actually

Table 11. Sample statistics of saturation data for vitric, devitrified and zeolitic tuffs in the unsaturated zone.

	Vitric	Devitrified	Zeolitic
No. Samples	14	30	79
Minimum	0.65	0.33	0.47
Maximum	0.97	1.02	1.31
Range	0.32	0.69	0.84
Arith. Mean	0.80	0.87	0.92
Median	0.81	0.90	0.94
Variance	0.009	0.018	0.013
Skewness	0.25	-2.26	-1.49
C.V.[a]	0.12	0.15	0.12

[a] Coefficient of variation.

participate in flow to total volume of saturated medium. This is the porosity that determines the velocity at which a solute moves in porous flow. Total porosity can be considerably greater than kinematic porosity, the difference being determined by the number of dead-end and nonconnected pores and the pore-size distribution. Water molecules in porous media are bound to the solid by molecular forces or free to move in response to fluid gradients. Fine-grained media with small pores and large grain surface areas have a larger percentage of total water adhered to grain surfaces, resulting in a lower kinematic porosity than for larger-grained media. Although kinematic porosity is a function of the magnitude of the hydraulic gradient, it is generally taken to be a constant, usually determined by tracer tests. The reader is referred to de Marsily (1986) for more on this subject.

Total porosity can be measured directly by fluid displacement or can be determined indirectly from measurements of dry bulk and grain density. Table 12 summarizes sample statistics of total porosity data for vitric, devitrified and zeolitic tuffs. Mean total porosity in vitric tuffs is 37%, in devitrified tuffs is 27% and in zeolitic tuffs is 29%. The correlation between porosity and log hydraulic conductivity was found to be 0.265. As was the case with saturation, total porosity shows less variability than does hydraulic conductivity in the unit. Total porosity is the proper parameter for calculation of changes in storage, or capacitance, in unsaturated flow models.

No values of kinematic porosity for the Calico Hills nonwelded unit have been published. Montazer and Wilson (1984) cite a possible value of 0.016 for effective porosity of the vitric facies matrix under saturated conditions, based on pore-size distribution data. The same authors estimated effective porosity of the unit under unsaturated conditions to be around 0.23, with fractures contributing little or nothing under ambient unsaturated conditions.

3.5. Pore-Size Distribution

Mercury intrusion pore-size distribution data from USW G-4, USW GU-3 and USW G-1 samples are included on microfiche in Klavetter and Peters (1987), who evaluated the use of these data for indirect determination of hydrologic properties including saturated hydraulic conductivity and moisture characteristic curves. The previous authors concluded that the approach was probably not sufficiently accurate for many performance-assessment applications since mercury intrusion data produced, at times, physically unrealistic saturation curves.

Table 12. Sample statistics of total porosity data for vitric, devitrified and zeolitic tuffs.

	Vitric	Devitrified	Zeolitic
No. Samples	27	49	129
Minimum	0.169	0.131	0.097
Maximum	0.48	0.397	0.47
Range	0.311	0.266	0.373
Arith. Mean	0.37	0.27	0.29
Median	0.39	0.27	0.30
Variance	0.008	0.004	0.005
Skewness	-0.939	0.141	-0.378
C.V.[a]	0.24	0.22	0.23

[a] Coefficient of variation.

Except for the Montazer and Wilson reference above, no information related to application of pore-size distribution data to determination of kinematic porosity was located. However, these data could provide a means of estimating values for model input until additional data becomes available. Median pore-size data for USW G-1, USW GU-3 and USW G-4 are summarized in Appendix B. It is clear that median pore sizes are extremely small. This is significant because water molecules within 0.1 micron of a particle surface are subjected to adhesive forces of up to several 10^{12} Pa, resulting in increased viscosity and density (de Marsily, 1986). Water molecules within about 0.5 micron of particle surfaces are similarly immobilized and do not move freely. The exact outer limit depends on the nature of the substrate. The result is a reduction in the volume of water that is able to circulate. This reduced area/volume available for flow should be taken into account when calculating velocity in transport models.

3.6. Dispersion

Hydrodynamic dispersion refers to a nonsteady, irreversible spreading of solute beyond the region it is expected to occupy that is observed during flow through a porous medium (Bear, 1972). Characterization of dispersion in saturated and unsaturated Calico Hills nonwelded unit tuffs is required for predictive transport calculations.

Modeling of solute transport with the advection-dispersion equation incorporates a coefficient, analogous to the diffusion coefficient in Fick's Law, to account for dispersion. In the direction parallel to flow, this dispersion coefficient is expressed as

$$D_L = \phi d + \alpha_L U \qquad (6)$$

where

D_L = longitudinal dispersion coefficient
ϕ = total porosity
d = molecular diffusion coefficient in porous media
α_L = longitudinal dispersivity
U = modulus of mean pore velocity

Dispersivity is typically determined from tracer test breakthrough data. No values of dispersivity for tuffs from the Calico Hills nonwelded unit have been reported. Rundberg et al. (1989) reported results of tracer tests in saturated, intact, densely welded Topopah Spring member tuff columns that could not be fit to the classical advection-dispersion equation. Elution

curves from the intact tuff experiments appeared to exhibit time-dependent dispersion at the laboratory scale, but no values for the dispersion coefficients were reported. Dispersivities for tritiated water and pertechnetate in intact tuff were reported to be much greater than dispersivities observed in crushed tuff columns, and dispersivities for sorbing tracers were reported to be significantly greater than dispersivities for tritiated water in the same columns. It was concluded that statistical characterization of the spatial distribution of sorbing minerals and hydraulic conductivity were required for predictive efforts, and that the effects of time-dependent dispersion would be magnified at field and repository scales.

Gelhar et al. (1985) summarized field-scale dispersivities reported in the literature for unsaturated flow in soils. The data are few, but do show an increase of longitudinal dispersivity with scale. Values range from 0.0011 m to 0.7 m. This phenomenon is also observed for transport in saturated media (see Neuman, 1990).

Recent stochastic theories relate dispersive properties of porous and fractured media to the nonuniform velocity field of flow in heterogeneous media. These approaches are based on stochastic analyses of the hydraulic conductivity field. Reductions in uncertainty of predictions are achieved by conditioning on values of hydraulic conductivity, water potential and solute concentration at known points and by the incorporation of inverse methods (Graham and McLaughlin, 1989). Due to the recent development of the theory, the complexity of the problem, the lack of data and the nonlinearity of processes in unsaturated media, extension to the unsaturated zone has yet to be attempted.

3.7. Storage Coefficients

3.7.a. Specific Storage

While no published values for specific storage in the Calico Hills nonwelded unit have been located by this author, it is possible to estimate a value based on the following relationship (Freeze and Cherry, 1979)

$$S_s = \rho g (c_r + \phi c_f) \tag{7}$$

where

S_s = specific storage [1/m]
ρ = fluid density [kg/m^3]
g = acceleration of gravity [m/s^2]
c_r = rock compressibility [1/Pa]

ϕ = total porosity
c_f = fluid compressibility [1/Pa]

Using the values summarized in Table 13 and Equation (7), a specific storage of 5.50×10^{-6} m^{-1} was calculated for vitric tuff and 3.85×10^{-6} m^{-1} was calculated for zeolitic tuff.

3.7.b. Capacitance

Fluid storage in unsaturated media is expressed as capacitance, which is a function of the relationship between suction and water content, water compressibility, bulk rock compressibility and fracture compressibility. Models of capacitance in porous media are discussed by Luckner et al. (1989), Wang and Narasimhan (1986) and Klavetter and Peters (1986). Peters and Klavetter (1988) discuss capacitance models in a fracture-matrix continuum.

IV. THERMOMECHANICAL PROPERTIES

Thermomechanical property data are presented in Nimick (1990), Nimick et al. (1984; 1987, zeolitized bedded tuffs in lower Topopah Spring), Ortiz et al. (1985), Lappin and Nimick (1985), Ogard et al. (1983) and Price and Jones (1982). Grain and bulk density data can be found in Schwartz (1990) and in U.S. Geological Survey reports from individual drill holes.

Maximum vertical stress at the water table was estimated by Peters et al. (1984) to be on the order of 130 bars.

Table 13. Property values used to calculate specific storage.

Fluid density	1000. kg/m^3
Acceleration of gravity	9.81 m/s^2
Rock compressibility[a]	3.98×10^{-10} Pa^{-1} vitric
	2.65×10^{-10} Pa^{-1} zeolitic
Porosity	0.37 vitric
	0.29 zeolitic
Fluid compressibility	4.4×10^{-10} Pa^{-1}

[a] Rock compressibility Nimick et al. (1984).

V. CONCLUSIONS AND RECOMMENDATIONS

This report summarizes hydrologic data from the Calico Hills nonwelded unit, an informal hydrogeologic unit. Hydraulic conductivity data are found to show significant heterogeneity at both laboratory and aquifer test scales. At both scales, reported hydraulic conductivity values range over several orders of magnitude. This is a strong indication that incorporating variability in field and regional scale flow and transport predictions is important. Even the results of long-term field-scale tracer tests will be insufficient to provide adequate information for determining dispersive properties of the Calico Hills nonwelded unit on a scale of kilometers. Theoretical work focused on the characterization of transport at all scales is needed. Development of a plan for collecting data needed for support of theoretical work as well as for use in existing flow and transport models should be a priority.

Analysis suggests that it is necessary to include devitrified tuffs as distinct from zeolitized tuffs in flow and transport models. Other specific issues and needs identified are summarized below.

1. Physical characteristics and measurements of hydrologic parameters show that the Calico Hills nonwelded hydrogeologic unit does not conform to the concept of a homogeneous porous medium in the classical sense at the scale of currently available measurements. The effects of heterogeneities in the Calico Hills on contaminant transport processes and on proper representation of those processes in models are not well understood. Specific areas that require additional research include

    a. Determination of the nature of fracture flow. The conditions under which fracture flow occurs in the Calico Hills nonwelded unit have fundamental implications for the direction of work in modeling, sorption studies and mineralogical characterization.

    b. The question of scale is complicated by the difficulty of obtaining measurements on larger samples or in situ. Relationships between the scale of measurements and the scale of modeling must be determined, particularly for permeability and dispersivity. As these relationships may well be saturation dependent, it is not possible to identify scales most in need of characterization a priori.

c. Investigate possible directional or preferential flow effects due to capillary barrier and/or saturation-dependent anisotropy induced by interlayered bedded tuffs and devitrified tuffs in vitric and zeolitic facies.

d. Evaluate the existence and volume of an REV for matrix and fracture-matrix hydraulic conductivity measurements, for both saturated and unsaturated conditions.

e. Evaluate the effects of variations in sample size, handling and test methods on measured permeabilities as a means of assessing currently available data from Yucca Mountain.

f. Evaluate whether partial welding in tuffs has significant effects on hydrologic processes relative to those in nonwelded tuff.

2. Effective permeability relationships for both liquids and gases in unsaturated vitric, devitrified and zeolitized partially welded and nonwelded tuff are needed.

3. A basis for determining effective cross-sectional area of flow is required for velocity calculations. Kinematic porosity of tuffs from the Calico Hills nonwelded unit has not been characterized. It may be possible to correlate kinematic porosity with pore-size distribution in some cases.

4. Dispersion in saturated and unsaturated vitric, devitrified and zeolitic partially welded and nonwelded tuffs at various scales must be characterized. A plan for systematic sampling of hydraulic conductivity and unsaturated matrix properties is needed to establish a data base for both deterministic and stochastic transport modeling. Traditional and more recent approaches to characterizing dispersion must be tested against field data as a means of testing theory and application to the medium of interest.

5. Cross correlation between hydraulic conductivity and mineralogy should be further investigated. The potential effects of a positive correlation between large hydraulic conductivity and nonsorptive mineralogy have implications for radionuclide transport, as does the reverse situation. Any such correlations will probably be saturation dependent.

6. Models require in situ saturation and suction distribution data for setting initial and boundary conditions in flow and transport models.

7. Techniques for assigning hydraulic conductivities to grid blocks at larger than measurement scales are needed.

8. Research related to quantifying net percolation flux and spatial distribution of flow should be continued.

9. Improved methods for obtaining measurements of all kinds in the unsaturated zone are needed.

Hydrologic and geochemical processes in the unsaturated zone are extremely complex. Interest in unsaturated transport is relatively recent, and understanding of those processes is at an early stage of development. Continued work aimed at characterizing processes important to contaminant transport in unsaturated tuffs, determining parameters quantifying those processes and field testing is needed.

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APPENDIX A

RELATIVE ABUNDANCE OF MINERALS AND GLASS

IN SELECTED WELLS AT YUCCA MOUNTAIN, NEVADA

AFTER BISH AND CHIPERA, 1989

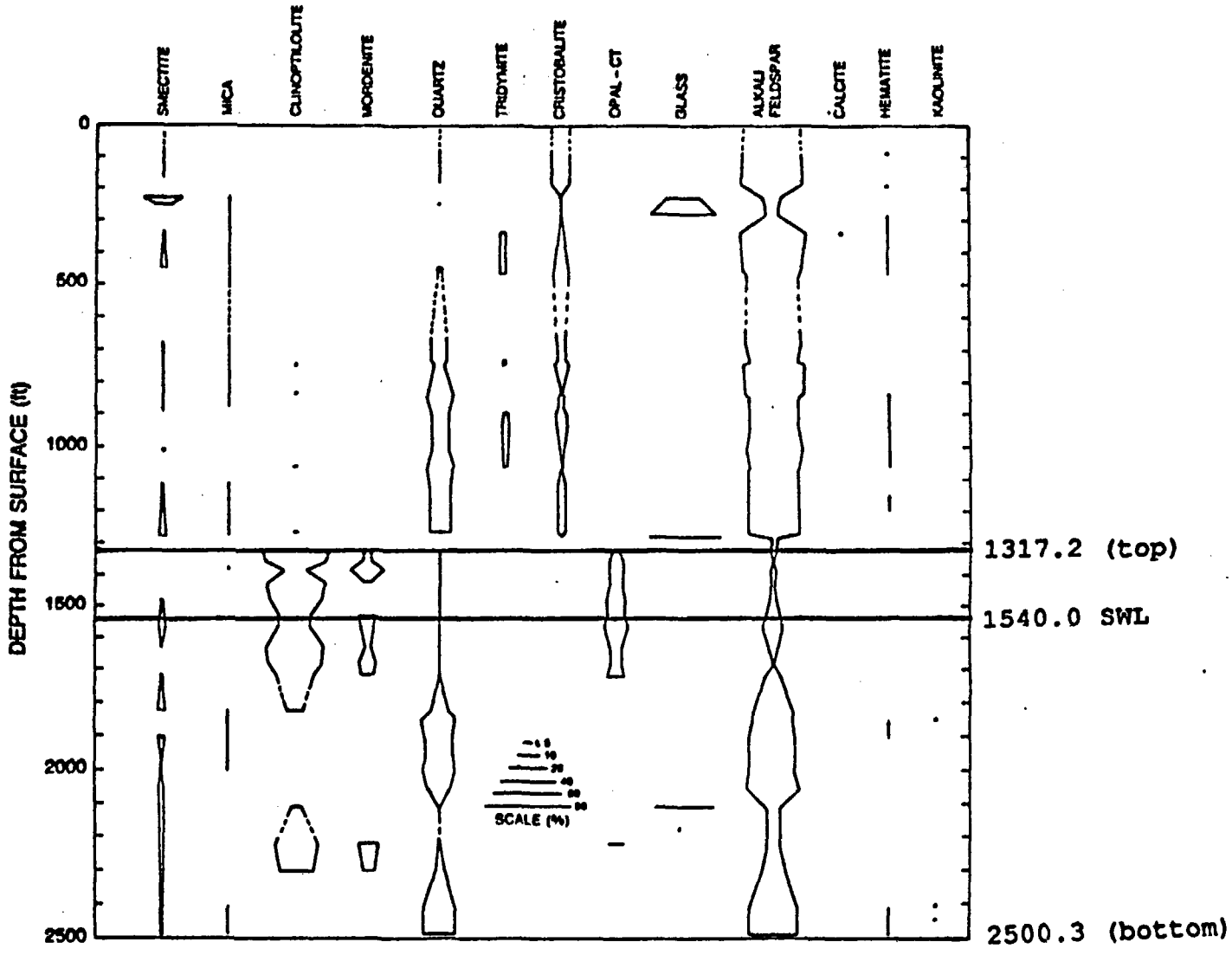

Figure A-1. Relative abundance of minerals and glass in UE-25 a#1 by weight percent. Top and bottom boundaries of Calico Hills nonwelded unit and static water level (SWL) indicated to right (in feet). After Bish and Chipera, 1989.

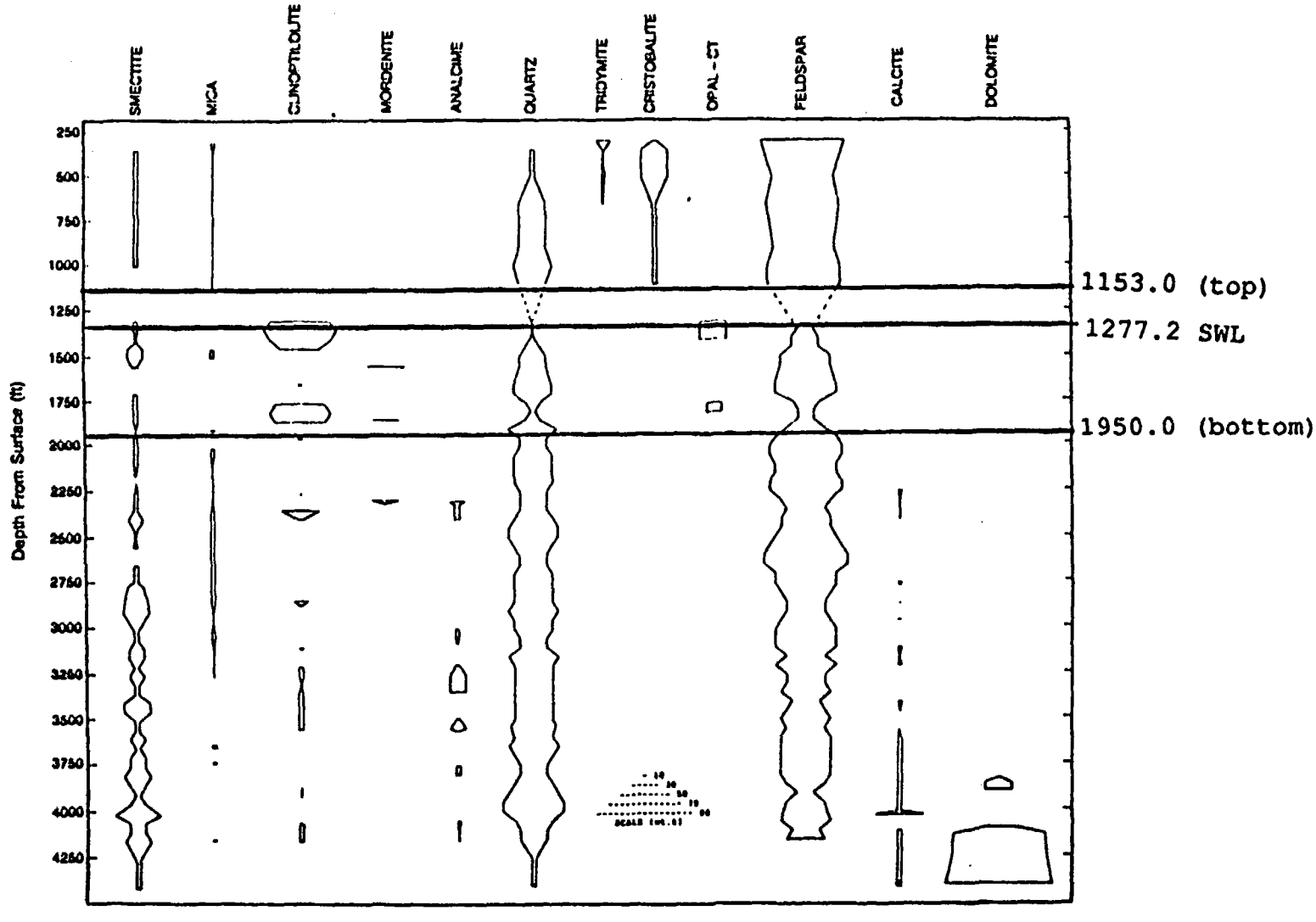

Figure A-2. Relative abundance of minerals and glass in UE-25 p#1 by weight percent. Top and bottom boundaries of Calico Hills nonwelded unit and static water level (SWL) indicated to right (in feet). After Bish and Chipera, 1989.

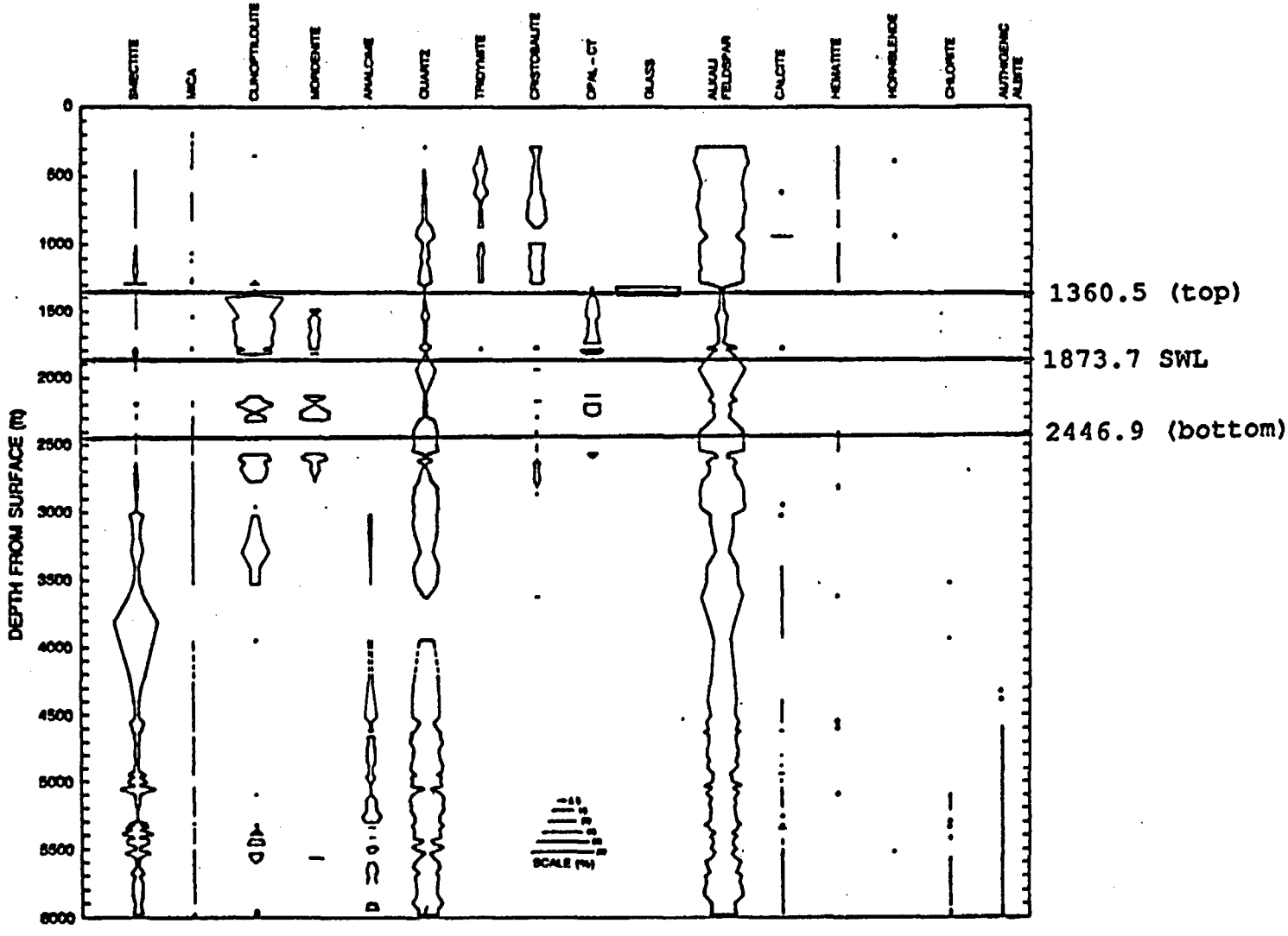

Figure A-3. Relative abundance of minerals and glass in USW G-1 by weight percent. Top and bottom boundaries of Calico Hills nonwelded unit and static water level (SWL) indicated to right (in feet). After Bish and Chipera, 1989.

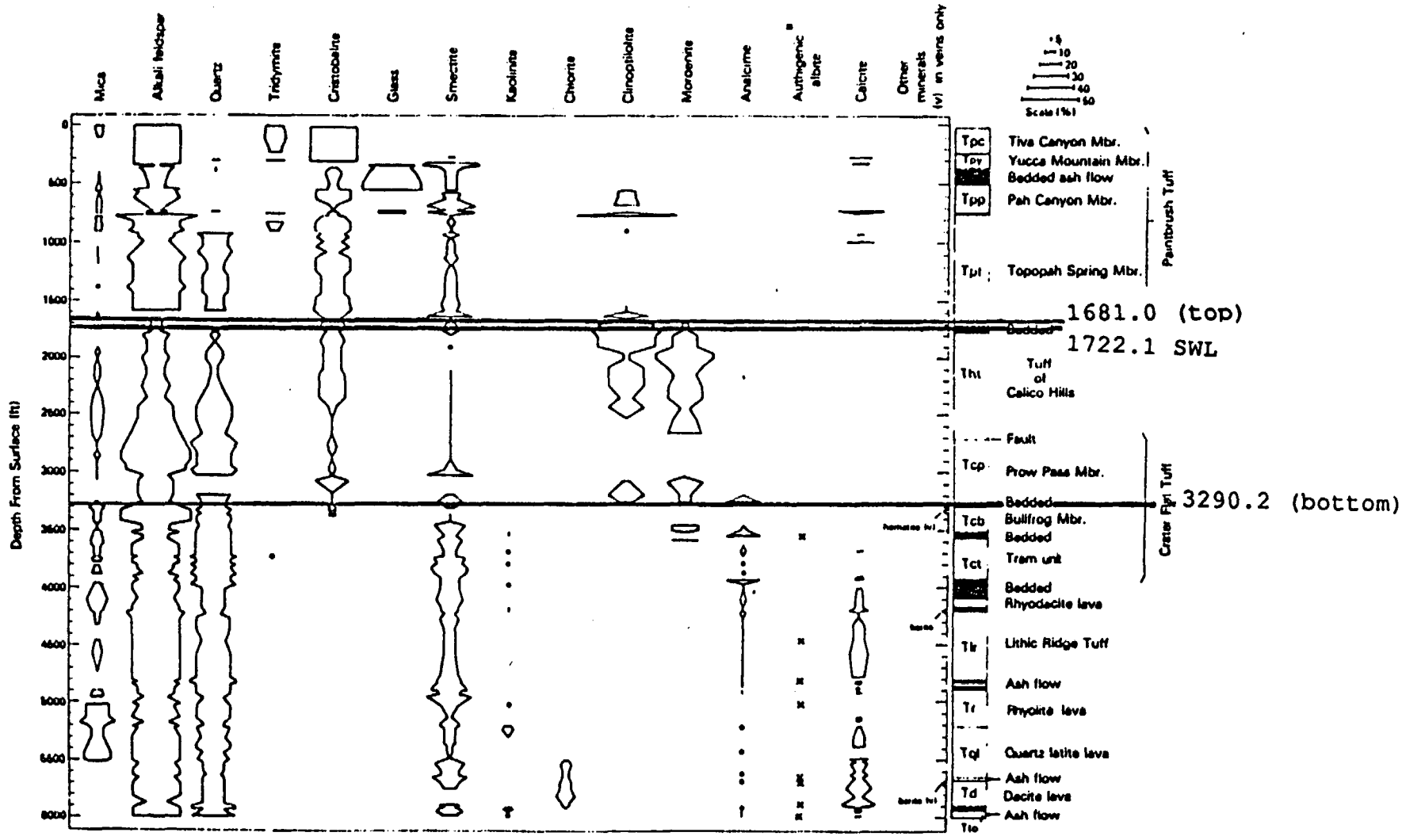

Figure A-4. Relative abundance of minerals and glass in USW G-2 by weight percent. Top and bottom boundaries of Calico Hills nonwelded unit and static water level (SWL) indicated to right (in feet). After Bish and Chipera, 1989.

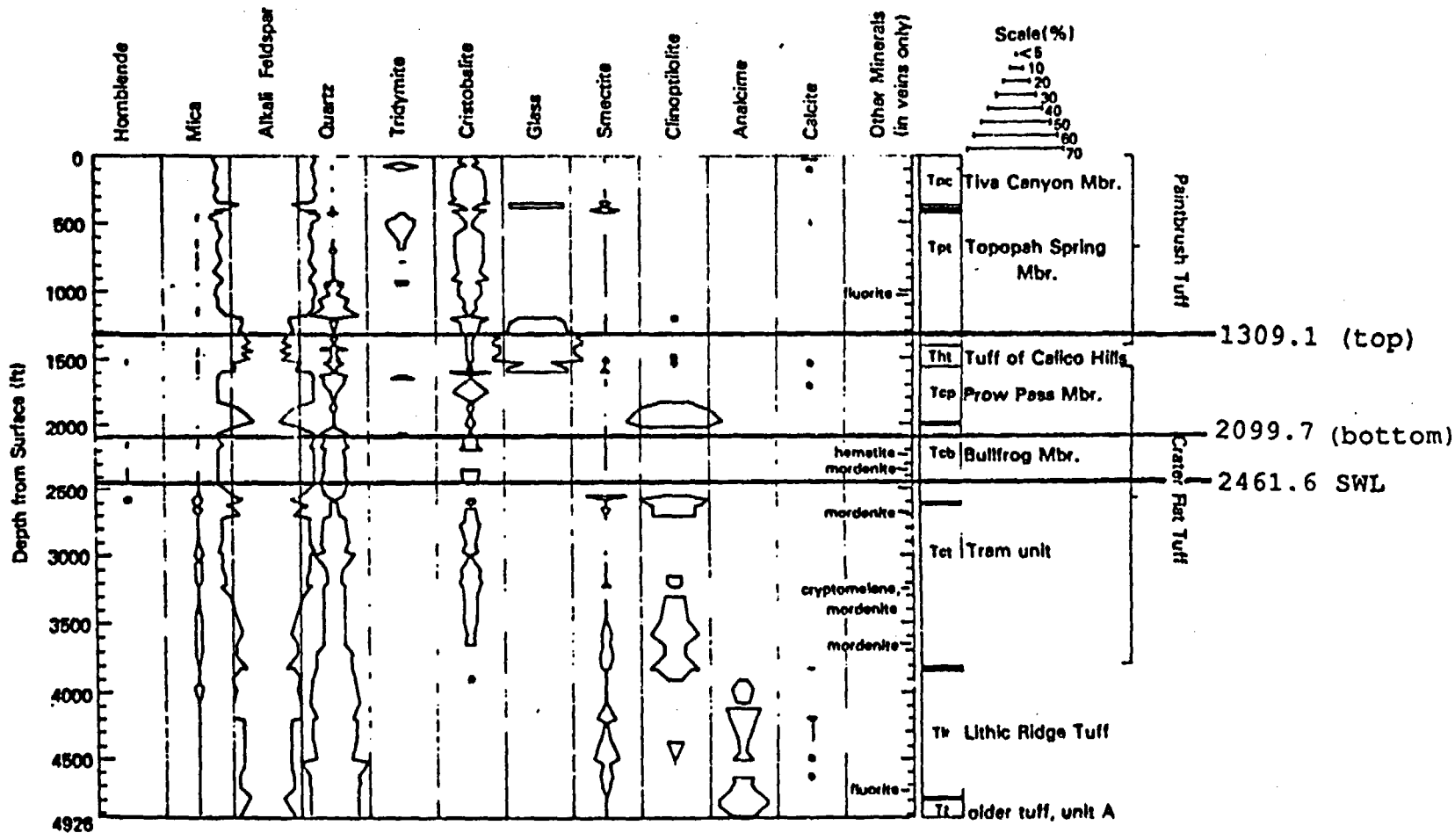

Figure A-5. Relative abundance of minerals and glass in USW GU-3 by weight percent. Top and bottom boundaries of Calico Hills nonwelded unit and static water level (SWL) indicated to right (in feet). After Bish and Chipera, 1989.

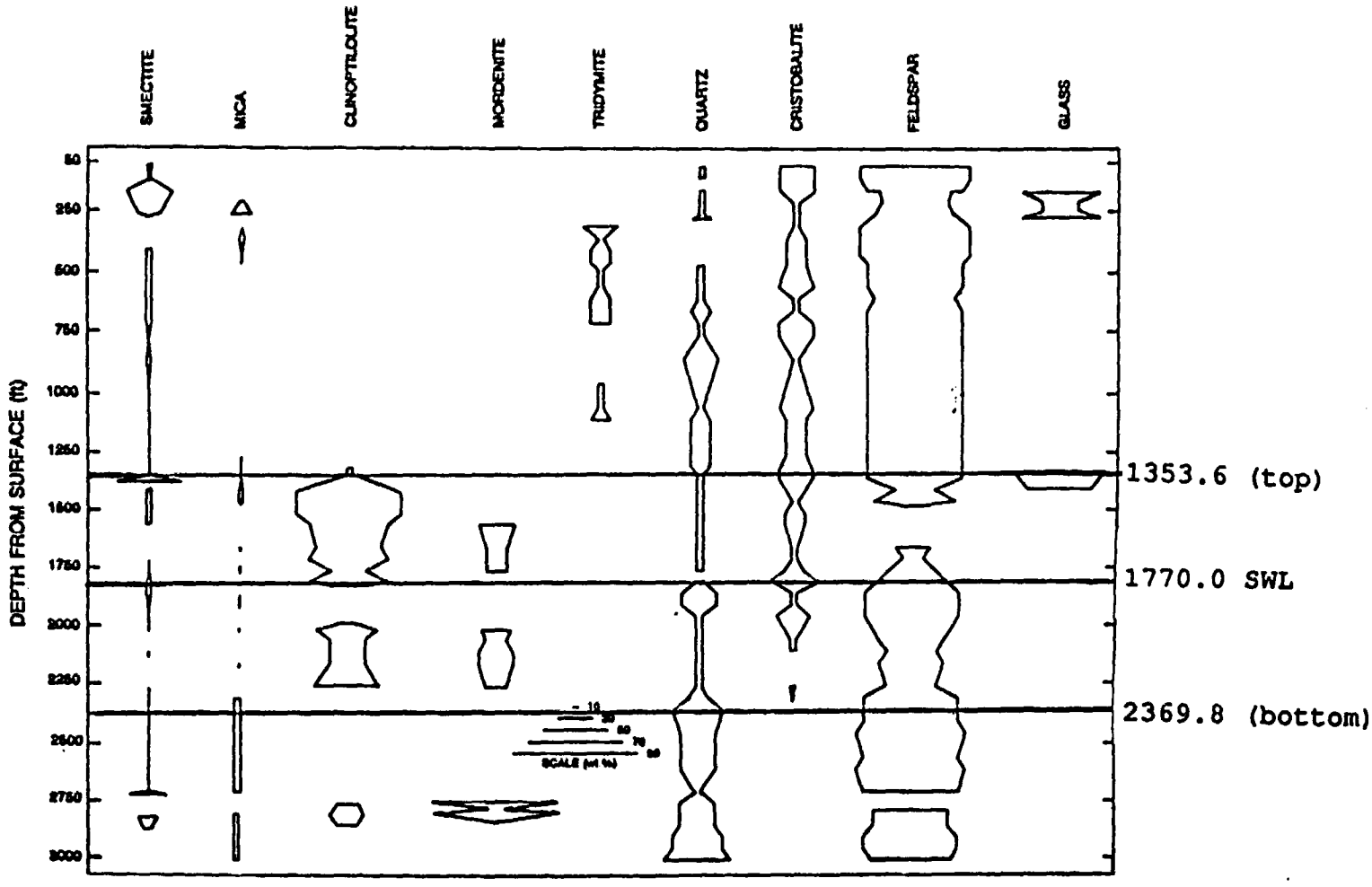

Figure A-6. Relative abundance of minerals and glass in USW G-4 by weight percent. Top and bottom boundaries of Calico Hills nonwelded unit and static water level (SWL) indicated to right (in feet). After Bish and Chipera, 1989.

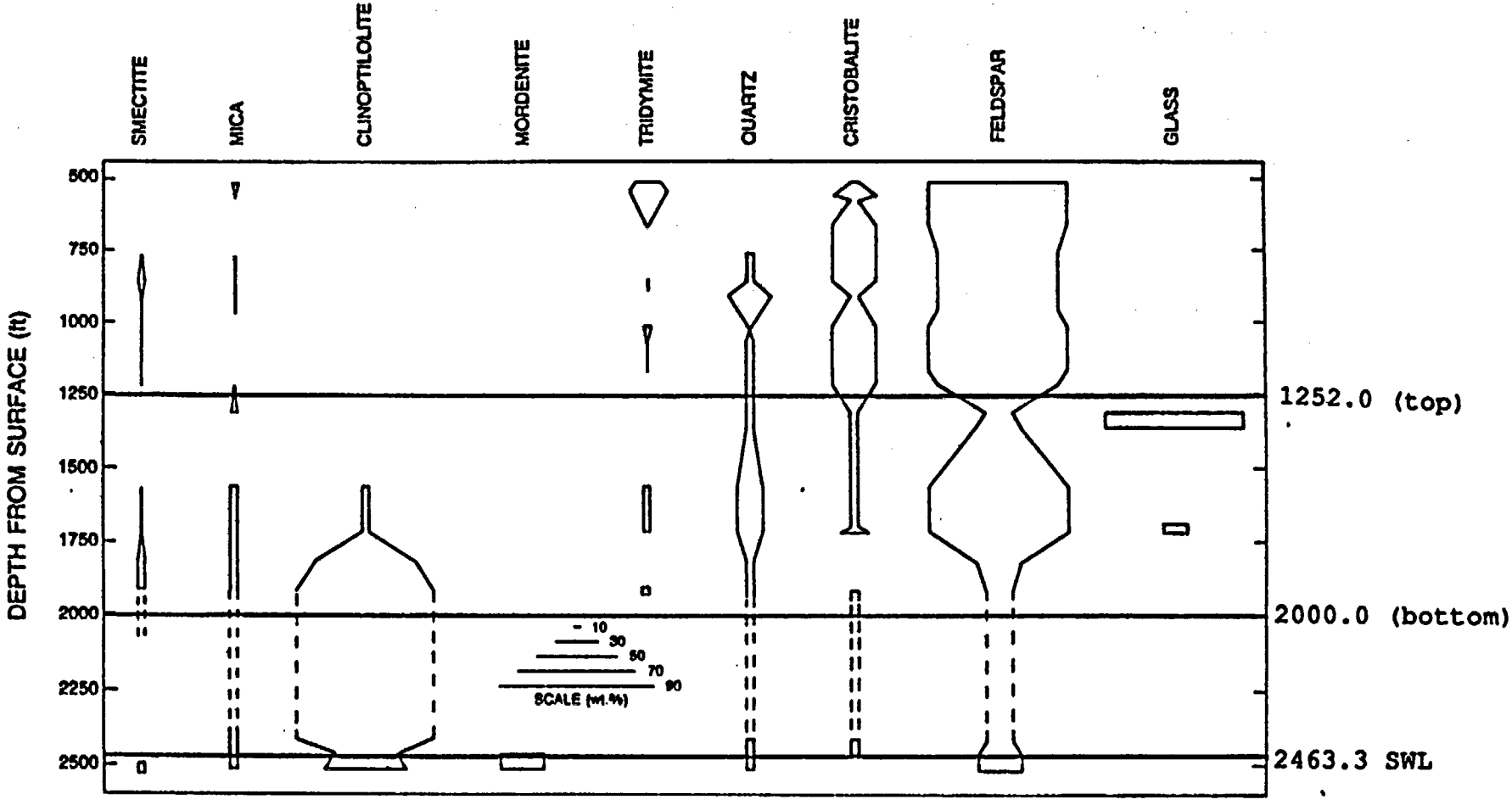

Figure A-7. Relative abundance of minerals and glass in USW H-3 by weight percent. Top and bottom boundaries of Calico Hills nonwelded unit and static water level (SWL) indicated to right (in feet). After Bish and Chipera, 1989.

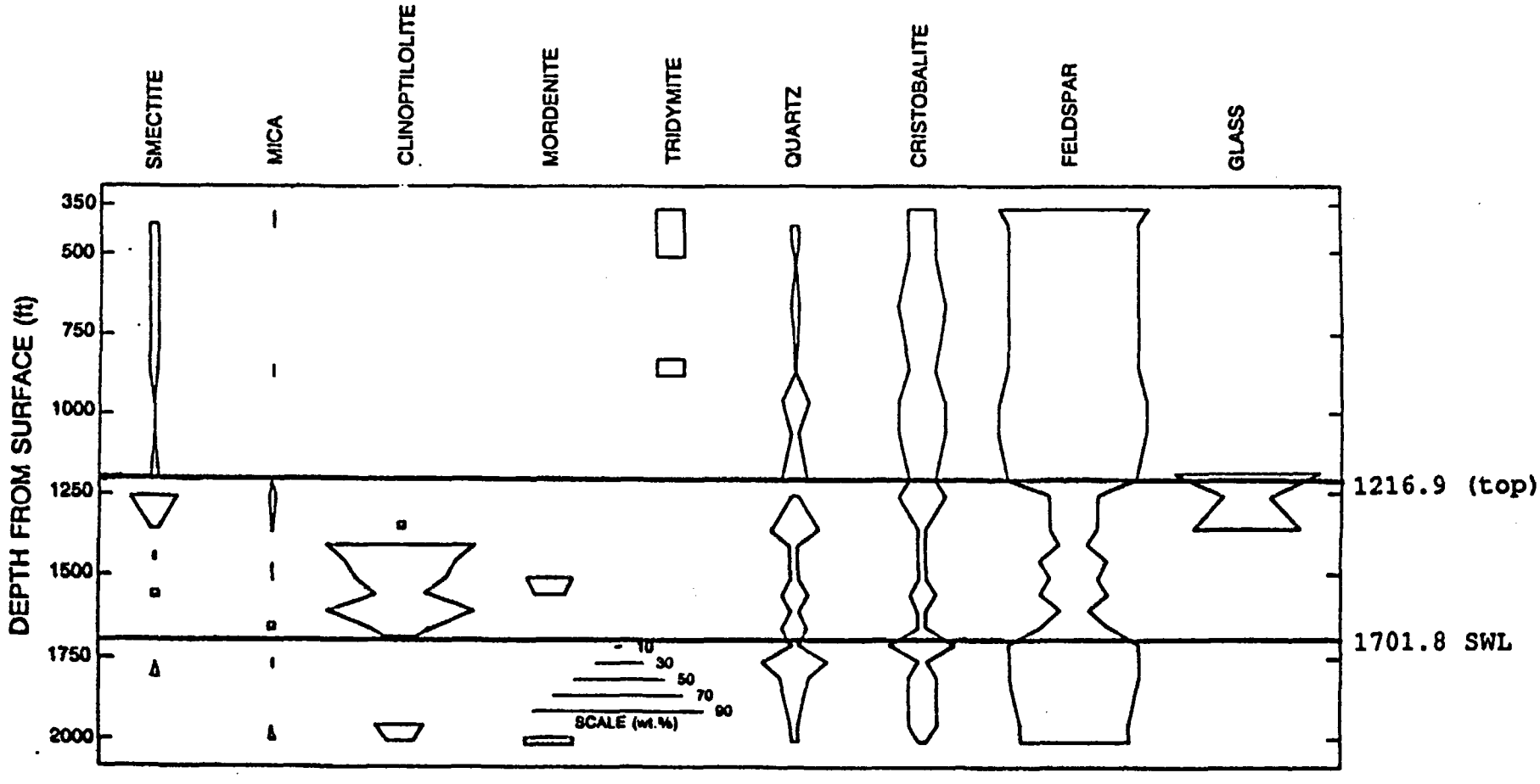

Figure A-8. Relative abundance of minerals and glass in USW H-4 by weight percent. Top and bottom boundaries of Calico Hills nonwelded unit and static water level (SWL) indicated to right (in feet). After Bish and Chipera, 1989.

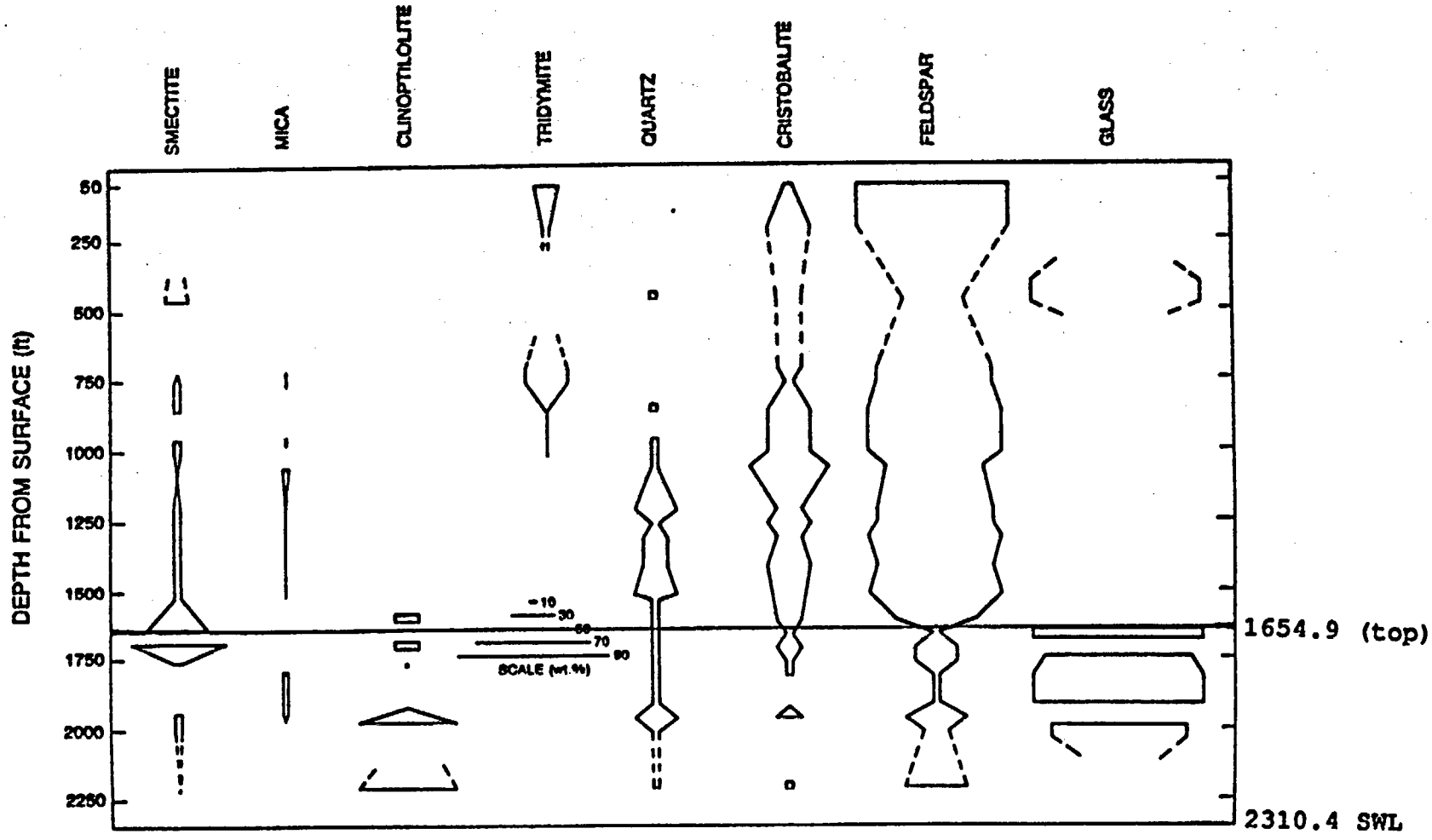

Figure A-9. Relative abundance of minerals and glass in USW H-5 by weight percent. Top and bottom boundaries of Calico Hills nonwelded unit and static water level (SWL) indicated to right (in feet). After Bish and Chipera, 1989.

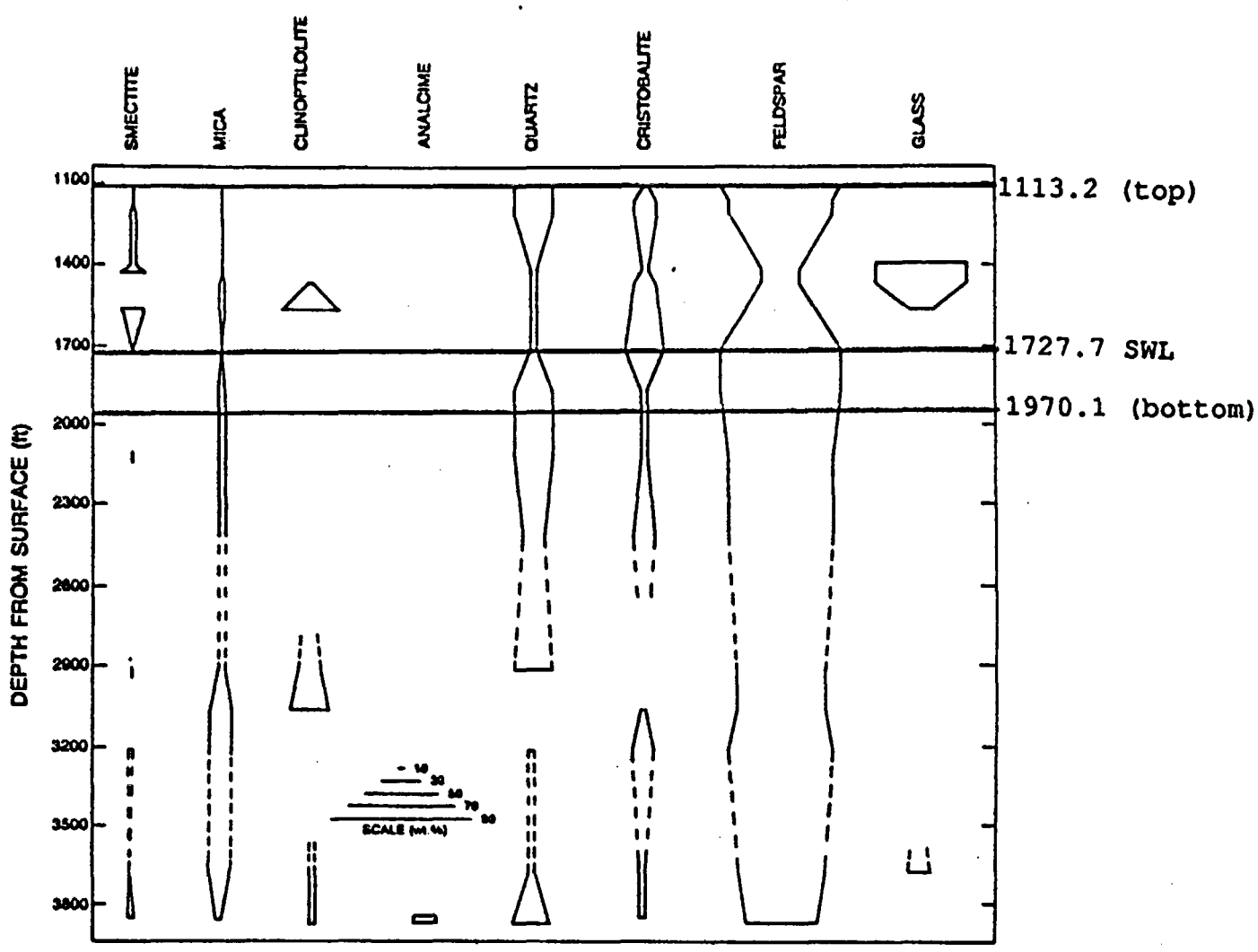

Figure A-10. Relative abundance of minerals and glass in USW H-6 by weight percent. Top and bottom boundaries of Calico Hills nonwelded unit and static water level (SWL) indicated to right (in feet). After Bish and Chipera, 1989.

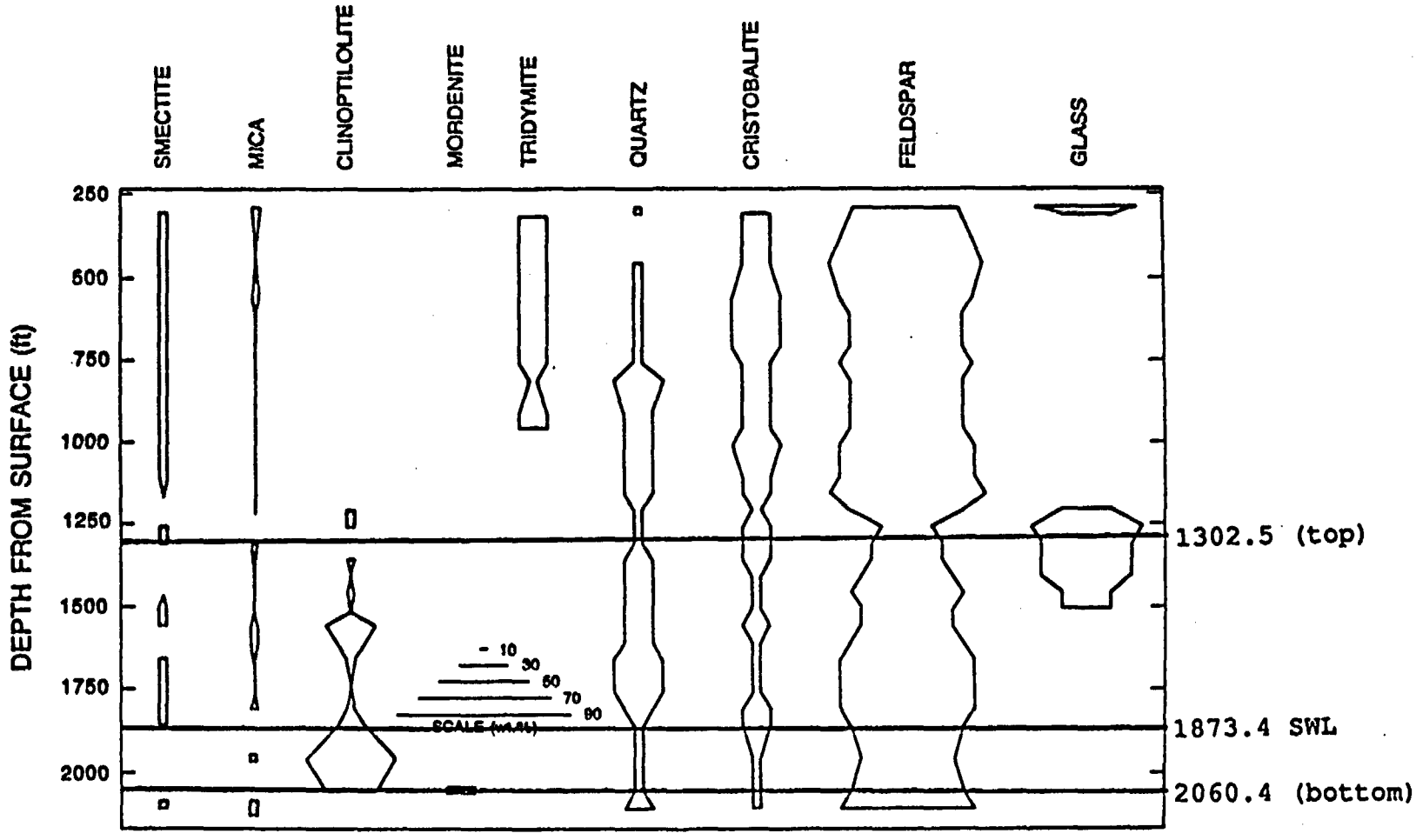

Figure A-11. Relative abundance of minerals and glass in USW WT-2 by weight percent. Top and bottom boundaries of Calico Hills nonwelded unit and static water level (SWL) indicated to right (in feet). After Bish and Chipera, 1989.

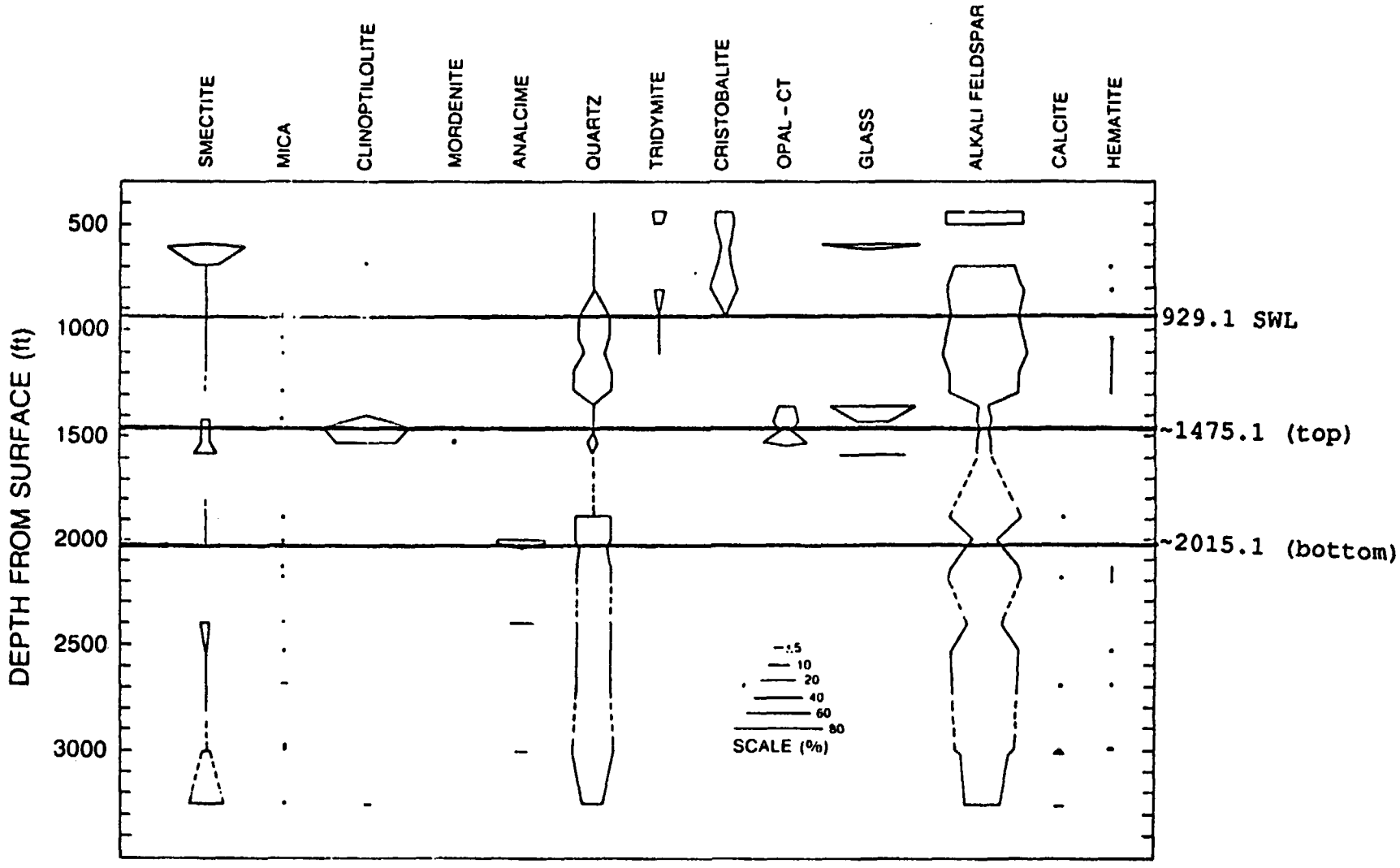

Figure A-12. Relative abundance of minerals and glass in USW J-13 by weight percent. Top and bottom boundaries of Calico Hills nonwelded unit and static water level (SWL) indicated to right (in feet). After Bish and Chipera, 1989.

APPENDIX B

HYDROLOGIC DATA

Key to lithology abbreviations:

1. Degree of welding precedes slash.

   n = nonwelded
   p = partially welded
   m = moderately welded
   np = nonwelded to partially welded
   nm = nonwelded to moderately welded
   pm = partially to moderately welded

2. Alteration indicator follows slash.

   v = vitric
   z = zeolitic
   sz = slightly zeolitic
   dv = devitrified
   pdv = partially devitrified
   vp = vapor phase
   a = argillic
   sa = slightly argillic
   pa = partly argillic
   s = silicified
   ps = partly silicified

3. bt = bedded tuff

Example: np/dv,z = sample originates in nonwelded to partially welded interval that is devitrified and zeolitized.

DRILL HOLE UE-25 a#1 DTW = 469.4 m

Depth (feet)	Depth (meters)	Lithology[a]	Intrinsic Permeability[b] (darcy)	Hydraulic Conductivity[c] (meters/sec)	Porosity[d]	Moisture Content[e] (volume)	Saturation[f]
Lower Topopah Spring Member of Paintbrush Tuff							
1324	403.6	p/z	-	-	0.305	0.27	0.89
1338	407.8	np/dv,z	-	-	0.275	0.24	0.87
1349	411.2	n/z	-	-	0.241	0.24	0.99
Bedded Tuff							
1361	414.8	bt	5.19e-05- 4.06e-05	4.99e-10- 3.90e-10	0.234	0.22	0.94
Tuffaceous Beds of the Calico Hills							
1411	430.1	n/dv,z	-	-	0.300	0.29	0.97
1464	446.2	n/dv,z	-	-	0.281	0.26	0.93
1516	462.1	n/dv,z	1.72e-05- 1.25e-05	1.65e-10- 1.20e-10	0.323	0.30	0.93
1568	477.9	n/dv,z	2.41e-04	2.32e-09	0.291	0.25	0.86
1638	499.3	n/dv,z	3.66e-04	3.52e-09	0.343	0.28	0.82
1686	513.9	n/dv,z	-	-	0.305	0.27	0.89
1741	530.7	n/dv,z	5.22e-05	5.02e-10	0.339	0.31	0.91
Bedded Tuff							
1791	545.9	bt/z	4.52e-06	4.35e-11	0.204	0.20	0.98
1833	558.7	bt/z	-	-	0.206	0.20	0.97

DRILL HOLE UE-25 a#1 DTW = 469.4 m

Depth (feet)	Depth (meters)	Lithology[a]	Intrinsic Permeability[b] (darcy)	Hydraulic Conductivity[c] (meters/sec)	Porosity[d]	Moisture Content[e] (volume)	Saturation[f]
Prow Pass Member of Crater Flat Tuff							
1842	561.4	np/dv	6.13e-05	5.89e-10	0.333	0.31	0.93
1888	575.5	p/dv	1.69e-03- 1.54e-03	1.63e-08- 1.48e-08	0.246	0.21	0.85
1942	591.9	np/dv	7.80e-05- 7.20e-05	7.50e-10- 6.92e-10	0.204	0.17	0.83
1988	605.9	m/dv	1.83e-04- 1.14e-04	1.76e-09- 1.10e-09	0.131	0.09	0.69
2032	619.4	p/pdv	6.07e-05- 2.85e-05	5.84e-10- 2.74e-10	0.224	0.18	0.80
2078	633.4	p/pdv,?	1.37e-04- 5.00e-05	1.32e-09- 4.81e-10	0.196	0.20	1.02
2108	642.5	p/pdv,?	3.11e-04- 2.40e-04	2.99e-09- 2.31e-09	0.222	0.18	0.81
2148	654.7	p/dv,z	-	-	0.225	0.24	1.07
2159	658.1	p/dv,z	1.21e-04- 1.13e-04	1.16e-09- 1.09e-09	0.097	0.09	0.93
2201	670.9	p/dv,z	1.04e-03- 1.03e-03	1.00e-08- 9.90e-09	0.154	0.15	0.98
2247	684.9	p/dv,z	-	-	0.230	0.22	0.96
2300	701.0	np/s,z	-	-	0.183	0.17	0.93
2331	710.5	np/s,z	-	-	0.161	0.15	0.93

DRILL HOLE UE-25 a#1 DTW = 469.4 m

Depth (feet)	Depth (meters)	Lithology[a]	Intrinsic Permeability[b] (darcy)	Hydraulic Conductivity[c] (meters/sec)	Porosity[d]	Moisture Content[e] (volume)	Saturation[f]
Bullfrog Member of Crater Flat Tuff							
2377	724.5	pm/dv	1.57e-03- 1.52e-03	1.51e-08- 1.46e-08	0.238	0.21	0.88
2440	743.7	pm/dv	2.28e-04- 2.19e-04	2.19e-09- 2.11e-09	0.175	0.15	0.86
2495	760.5	pm/dv	4.99e-04- 4.73e-04	4.80e-09- 4.55e-09	0.174	0.15	0.86

[a] From Spengler et al. (1979). Alteration from Spengler et al. (1979) and Bish and Chipera (1989).
[b] Intrinsic permeability from Anderson (1981). Sample size: 2.54-cm long x 2.54-cm diameter.
[c] Hydraulic conductivity calculated from intrinsic permeability data; 1 darcy = 1.04e+05 m/s
[d] Total porosity calculated from dry bulk density (dbd) and grain density (gd) (from Anderson, 1981):

porosity = 1 - dbd/gd

[e] Moisture content calculated from natural bulk density (nbd) and dry bulk density (dbd):

moisture content = nbd - dbd

[f] Saturation calculated from moisture content and porosity:

saturation = moisture content/porosity

DRILL HOLE UE-25 a#1 DTW = 469.4 m

Depth (ft)	(m)	Lithology[a]	Porosity[b]	Moisture Content (volume)[c]	Saturation[d]
Tuffaceous Beds of Calico Hills					
1366.5	416.5	n/dv,z	0.280	-	-
1370.0	417.6	n/dv,z	0.309	0.30	0.97
1381.6	421.1	n/dv,z	0.360	0.34	0.94
1413.8	430.9	n/dv,z	0.309	0.33	1.07
1426.8	434.9	n/dv,z	0.316	0.31	0.98
1448.2	441.4	n/dv,z	0.342	0.33	0.96
1471.9	448.6	n/dv,z	0.329	0.31	0.94
1490.0	454.2	n/dv,z	0.281	0.25	0.89
1547.6	471.7	n/dv,z	0.280	-	-
1555.0	474.0	n/dv,z	0.325	0.28	0.86
1561.0	475.8	n/dv,z	0.335	0.30	0.96
1605.0	489.2	n/dv,z	0.295	0.26	0.88
1662.0	506.6	n/dv,z	0.349	0.32	0.92
1673.3	510.0	n/dv,z	0.388	0.38	0.98
1692.0	515.7	n/dv,z	0.364	0.35	0.96
1718.2	523.7	n/dv,z	0.370	-	-

[a] From Spengler et al. (1979). Alteration from Spengler et al. (1979) and Bish and Chipera (1989).

[b] Total porosity from Schwartz (1990).

[c] Moisture content calculated from natural bulk density (nbd) and dry bulk density (dbd), both from Schwartz, (1990): moisture content = nbd - dbd

[d] Saturation calculated from porosity and moisture content:saturation = moisture content/porosity

DRILL HOLE UE-25 b#1 DTW = 470.6 m

Depth (ft)	Depth (m)	Lithology[a]	Intrinsic Permeability[b] (darcy)	Hydraulic[a] Conductivity (m/s)		Porosity[c]	Moisture Content[d] (volume)	Saturation[e]
Tuffaceous Beds of Calico Hills								
1572	479.3	n/z	4.45e-05	4.28e-10	vertical	0.252,0.281	0.21	0.92
1572			2.05e-04	1.97e-09	horizontal			
Prow Pass Member of Crater Flat Tuff								
2053	625.8	np/pdv	2.17e-05	2.08e-10	vertical	0.238,0.252	0.22	0.92
2053			7.95e-05	7.64e-10	horizontal			
2229	679.5	pm/dv,z	9.99e-07	9.61e-12	vertical	0.101,0.136	0.06	0.59
2229			2.05e-06	1.97e-11	horizontal			
Bullfrog Member of Crater Flat Tuff								
2469	752.7	p/vp	6.02e-04	5.79e-09	vertical	0.230,0.233	0.22	0.96
2469			7.95e-04	7.64e-09	horizontal			
2588	788.9	bt	7.95e-05	7.64e-10	vertical	0.213,0.216	0.20	0.94
2588			8.79e-05	8.45e-10	horizontal			

[a] From Lobmeyer et al. (1983). Alteration from Lobmeyer et al. (1983) and Bish and Chipera (1989).
[b] Back-calculated from hydraulic conductivity: 1 darcy = 1.04e+05 m/s.
[c] Total porosity; first measurement determined with helium pycnometer; second measurement calculated from density. Lahoud et al. (1984); Site Engineering Properties Data Base (SEPDB) DA0003-D.
[d] From Lobmeyer et al. (1983).
[e] Saturation = moisture content/porosity (porosity by helium pycnometer)

AQUIFER TEST HYDRAULIC CONDUCTIVITY MEASUREMENTS[a]

DRILL HOLE UE-25 b#1 Elevation Above Sea Level: 3,939.00 (ft)
Tuffaceous Beds of Calico Hills 422.2 m - 569.7 m[a]
Prow Pass Member of Crater Flat Tuff 569.7 m - 718.0 m
Bedded Tuff 718.0 m - 719.7 m
Bullfrog 719.7 m - 869.5 m

Interval (feet)	(meters)	Test No.	Intrinsic Permeability (darcy)	Hydraulic Conductivity (m/s)	Test Type
Tuffaceous Beds of Calico Hills					
1565-1611	477-491	5	1.44e-01	1.39e-06	packer injection
1611-1657	491-505	4	5.90e-01	5.67e-06	packer injection
1654-1785	504-544	13	4.21e-02	4.05e-07	packer injection
Calico Hills - Prow Pass					
1565-1900	477-579	3	6.50e-01	6.25e-06	packer injection
1657-1900	505-579	2	4.33e-02	4.17e-07	packer injection
1686-1900	514-579	1	9.15e-02	8.80e-07	packer injection
Prow Pass Member of Crater Flat Tuff					
1906-2037	581-621	12	1.11	1.06e-05	packer injection
2037-2169	621-661	14	6.38e-02	6.13e-07	packer injection
Prow Pass - Bedded Tuff - Bullfrog					
2306-2438	703-743	11	5.54e-03	5.32e-08	packer injection
Bullfrog Member of Crater Flat Tuff					
2438-2569	743-783	10	3.01e-03	2.89e-08	packer injection
2556-2687	779-819	9	1.19e-00	1.15e-05	packer injection

[a] From Lahoud et al. (1984); SEPDB DA0003-D.

AQUIFER TEST HYDRAULIC CONDUCTIVITY MEASUREMENTS[a]

DRILL HOLE UE-25 p#1
Top of Casing: 3,654.63 (ft)

Calico Hills 381 m - 422 m[b]
Bedded Tuff 422 m - 436 m
Prow Pass 436 m - 547 m
Bedded Tuff 547 m - 558 m
Bullfrog 558 m - 683 m
Bedded Tuff 683 m - 691 m

Interval (feet)	Interval (meters)	Intrinsic Permeability (darcy)	Hydraulic Conductivity (m/s)	Test Type
Calico Hills - Bedded Tuff - Prow Pass				
1260-1640	384-500	1.46e-01	1.40e-06	pump/borehole flow
Prow Pass Member of Crater Flat Tuff - Bedded Tuff				
1640-1804	500-550	2.40e-03	2.31e-08	packer-injection
1640-1804	500-550	0.0	0.0	pump/borehole flow
Bedded Tuff - Bullfrog				
1804-1969	550-600	6.74e-02	6.48e-07	packer-injection
1804-1969	550-600	1.20e-02	1.16e-07	pump/borehole flow
Prow Pass - Bedded Tuff - Bullfrog - Bedded Tuff				
2100-2264	640-690	2.65e-02	2.55e-07	packer-injection

[a] From Craig and Robison (1984); SEPDB DA0003-G.
[b] Stratigraphy from Carr et al. (1986).

DRILL HOLE USW G-1 DTW = 571.1 m

Sample Size: 1.2 cm long x 1.5 cm diameter

Elevation Above Sea Level: 4,348.60 (ft) Top of Casing: 4,351.80 (ft)

Depth (feet)	Depth (meters)	Sample ID	Lith-ology[a]	Intrinsic Permeability (darcy)	Hydraulic Conductivity[b] (m/sec)	van Genuchten param. a[c] (1/m)	n	S_r
Lower Topopah Spring Member of Paintbrush Tuff								
1386.7	422.7	G1-1387a	np/v	6.70e-05	6.44e-10	0.0197	5.020	0.3418(t)
						0.0002	3.721	0.0477(b)
1386.7	422.7	G1-1387b	np/v	9.94e-05	9.56e-10			
Tuffaceous Beds of Calico Hills								
1499.8	457.1	G1-1500a	n/dv,z	1.21e-06	1.16e-11	0.0048	1.367	0.0
1499.8	457.1	G1-1500b	n/dv,z	1.93e-06	1.86e-11	0.0087	1.324	0.0
1637.0	499.0	G1-1637a	n/z	2.02e-06	1.94e-11	0.0040	1.372	0.0
1637.0	499.0	G1-1637b	n/z	9.60e-07	9.23e-12	0.00189	1.416	0.0
Bedded Tuff								
1752.7	534.0	G1-1753a	bt/z,s	1.18e-06	1.13e-11	0.0020	2.071	0.2157
1752.7	534.0	G1-1753b	bt/z,s	1.71e-06	1.64e-11	0.0020	1.845	0.189
1779.5	542.4	G1-1780a	bt/z,s	2.30e-07	2.21e-12	0.0056	1.357	0.0
1779.5	542.4	G1-1780b	bt/z,s	2.16e-07	2.08e-12	0.0032	1.412	0.0
1789.6	545.5	G1-1790a	bt/z,s	5.43e-07	5.22e-12	0.00171	1.625	0.0
1789.6	545.5	G1-1790b	bt/z,s	5.43e-07	5.22e-12	0.00170	1.591	0.0

DRILL HOLE USW G-1 DTW = 571.1 m

Depth (feet)	Depth (meters)	Sample ID	Lithology[a]	Intrinsic Permeability (darcy)	Hydraulic Conductivity[b] (m/sec)	van Genuchten param. a[c] (1/m)	n	S_r
Prow Pass Member of Crater Flat Tuff								
1820.7	554.9	G1-1821a	p/dv,z	4.23e-06	4.07e-11	0.0061	1.481	0.0
1820.7	554.9	G1-1821b	p/dv,z	4.70e-06	4.52e-11	0.0061	1.467	0.0
1841.1	561.2	G1-1841a	p/dv	1.65e-05	1.59e-10	0.0097	1.427	0.0
1841.1	561.2	G1-1841b	p/dv	1.63e-05	1.57e-10	0.0267	1.386	0.0
1917.4	584.4	G1-1917a	pm/dv	1.70e-04	1.63e-09	0.0131	6.913	0.0726[d]
1917.4	584.4	G1-1917b	pm/dv	1.70e-04	1.63e-09			
1979.3	603.3	G1-1979	p/dv	1.15e-03	1.11e-08			

[a] From Spengler et al. (1981). Alteration from Spengler et al. (1981) and Bish and Chipera (1989).

[b] Site Engineering Properties Data Base product DA0047. All hydraulic conductivity measurements made with liquid permeameter. Intrinsic permeability calculated as: 1 darcy = 1.04e+05 m/s

[c] Saturation curve fit parameters Site Engineering Properties Data Base product DA0047, unless otherwise noted.

[d] Saturation curve fit parameters from Klavetter and Peters (1987).

DRILL HOLE USW G-1 DTW = 571.1 m

Depth (ft)	Depth (m)	Lithology[a]	Porosity[b]	Moisture Content[c] (volume)	Saturation[b]
Lower Topopah Spring Member of Paintbrush Tuff					
1385.2	422.2	np/v	0.33	0.32	0.97
Tuffaceous Beds of Calico Hills					
1470	448.0	n/dv,z	0.37	0.36	0.97
1503	458.1	n/dv,z	0.38	0.32	0.84
1505	458.7	n/dv,z	0.31	0.29	0.94
1515	461.7	n/dv,z	0.33	0.33	1.00
1553	473.4	n/z	0.35	0.27	0.77
1571	478.9	n/z	0.39	0.38	0.97
1606a	489.5a	n/z	0.39	0.35	0.90
1606b	489.5b	n/z	0.31	0.16	0.52
1606c	489.5c	n/z	0.30	0.15	0.50
1606d	489.5d	n/z	0.32	0.24	0.75
1633.5	497.9	n/z	0.335[d]		
1652a	503.5a	n/z	0.36	0.17	0.47
1652b	503.5b	n/z	0.33	0.31	0.94
1664	507.0	n/z	0.33	0.32	0.97
1667	508.1	n/z	0.35	0.34	0.97
1706	519.8	n/z	0.33	0.31	0.94
1722	525.0	n/z	0.36	0.35	0.97
Bedded Tuff					
1785	543.9	bt/z	0.24	0.24	1.00

DRILL HOLE USW G-1 DTW = 571.1 m

Depth (ft)	Depth (m)	Lithology[a]	Porosity[b]	Moisture Content[c] (g/cm^3)	Saturation[b]
Prow Pass Member of Crater Flat Tuff					
1832a	558.4a	p/dv	0.35	0.33	0.94
1832b	558.4b	p/dv	0.36	0.36	1.00
1847a	563.0a	p/dv	0.36	0.35	0.97
1847b	563.0b	p/dv	0.37	0.35	0.95

[a] From Spengler et al. (1981). Alteration from Spengler et al. (1981) and Bish and Chipera (1989).
[b] Total porosity and saturation Lappin et al. (1982) in Tien et al. (1985).
[c] Moisture content calculated as porosity x saturation.
[d] From Schwartz (1989).

DRILL HOLE USW G-1 DTW = 571.1 m Pore-Size Distribution Summaries from Mercury Intrusion[a]

Depth (ft)	Depth (m)	Lithology[b]	Total Intrusion Volume (mL/g)	Total Pore Area (m^2/g)	Median Pore Diameter Volume (microns)	Median Pore Diameter Area (microns)	Average Pore Diameter (4V/A) (microns)
Lower Topopah Spring Member of Paintbrush Tuff							
1362	415.1	np/v	0.1050	21.353	0.2221	0.0049	0.0197
1386.7	422.7	np/v	0.1944	30.762	0.9338	0.0051	0.0253
1392	424.3	np/v	0.1863	26.839	1.0013	0.0049	0.0278
Tuffaceous Beds of Calico Hills							
1499.8	457.1	n/dv,z	0.2007	41.578	0.0367	0.0061	0.0193
1637.0	499.0	n/z	0.1670	34.209	0.0342	0.0077	0.0195
Bedded Tuff							
1752.7	534.0	bt/z,s	0.1555	32.155	0.0283	0.0118	0.0193
1779.5	542.4	bt/z,s	0.1377	21.422	0.1096	0.0079	0.0257
1789.6	545.5	bt/z,s	0.1066	21.559	0.0357	0.0103	0.0198
Prow Pass Member of Crater Flat Tuff							
1820.7	554.9	p/dv,z	0.2198	27.879	0.0630	0.0142	0.0315
1841.1	561.2	p/dv	0.2158	28.848	0.0786	0.0116	0.0299
1917.4	584.4	pm/dv	0.2223	61.058	0.9702	0.0041	0.0146

[a] Data summary from Klavetter and Peters (1987).
[b] From Spengler et al. (1981). Alteration from Spengler et al. (1981) and Bish and Chipera (1989).

DRILL HOLE USW GU-3 DTW = 750.3 m

Depth (ft)	Depth (m)	Lithology[a]	Intrinsic Permeability[b] (darcy)	Hydraulic Conductivity[c] (m/s)	Porosity[c]	van Genuchten Parameters[d] a (1/m)	n	S_r	Brooks-Corey Parameter[e] b
Lower Topopah Spring Member of Paintbrush Tuff									
1311a	399.6	n/v	3.28e-04	3.15e-09	0.27	0.0203	2.475	0.0	2.27
1311b					0.42	0.0152	3.577	0.0	
1331a	405.7	n/v	3.04e-02	2.92e-07	0.45	0.0096	3.733	0.0	3.23
1331b					0.45	0.0067	2.247	0.0	
Tuffaceous Beds of Calico Hills									
1440a	438.9	n/v	2.79e-02	2.68e-07	0.45	0.0162	3.779	0.0	2.86
1440b					0.48	0.0144	3.354	0.0	
1499a	456.9	n/v	2.67e-03	2.57e-08	0.43	0.0326	1.571	0.0	0.59
1499b					0.43	0.0631	1.376	0.0	
Bedded Tuff									
1555	474.0	bt	8.22e-03	7.90e-08	0.47	0.0155	10.137	0.1893	9.09
Prow Pass Member of Crater Flat Tuff									
1628a	496.2	p/dv	7.20e-04	6.92e-09	0.39	0.0144	2.964	0.0180[f]	2.44
1628b					0.39				
1680a	512.1	p/dv	1.33e-04	1.28e-09	0.33	0.0314	3.442	0.0665[f]	2.44
1680b					0.31				
1730a	527.3	p/dv	1.23e-04	1.18e-09	0.24	0.0211	2.851	0.1239[f]	1.85
1730b					0.24				

[a] From Scott and Castellanos (1984). Alteration from Scott and Castellanos (1984) and Bish and Chipera (1989).

[b] Back-calculated from hydraulic conductivity; 1 darcy = 1.04e+05 m/s.
[c] Peters et al. (1984). Sample size: 5 cm long x 6 cm diameter. Total porosity calculated from bulk density and grain density.
[d] Saturation curve fit parameters Site Engineering Properties Data Base product DA0047.
[e] Brooks-Corey parameter from Sinnock et al. (1986). b is the negative of the slope of the log saturation-log suction curve.
[f] Saturation curve fit parameters from Peters et al. (1984).

DRILL HOLE USW GU-3 DTW = 750.3 m

Pore-Size Distribution Summaries from Mercury Intrusion[a]

Depth (ft)	Depth (m)	Lithology[b]	Total Intrusion Volume (mL/g)	Total Pore Area (m^2/g)	Median Pore Diameter Volume (microns)	Median Pore Diameter Area (microns)	Average Pore Diameter (4V/A) (microns)
Lower Topopah Spring Member of Paintbrush Tuff							
1311	399.6	n/v	0.2083	9.986	2.3287	0.0067	0.0834
1331	405.7	n/v	0.3834	22.730	7.6091	0.0050	0.0675
Tuffaceous Beds of Calico Hills							
1440	438.9	n/v	0.3044	12.819	3.7165	0.0068	0.0950
1499	456.9	n/v	0.2406	24.747	3.0851	0.0058	0.0389
Bedded Tuff							
1555(51)	474.0	bt	0.2238	22.553	3.4476	0.0059	0.0397
1555(52)	474.0	bt	0.2594	24.989	3.4698	0.0057	0.0415
Prow Pass Member of Crater Flat Tuff							
1628	496.2	p/dv	0.2847	9.525	2.4278	0.0046	0.1196
1680	512.1	p/dv	0.2120	8.662	1.3956	0.0058	0.0979
1730	527.3	p/dv	0.1329	13.471	0.8354	0.0059	0.0395

[a] Data summary from Klavetter and Peters (1987).
[b] From Scott and Castellanos (1984).

DRILL HOLE USW GU-3 DTW =750.3 m

Depth (ft)	Depth (m)	Lithology[a]	Porosity[b]	Moisture Content (volume)[c]	Saturation[d]
Lower Topopah Spring Member of Paintbrush Tuff					
1330.4-1330.8	405.5-405.6	n/v	0.405	0.35	0.86
1351.3-1351.7	411.9-412.0	n/v	0.398	0.38	0.95
1377.7-1378.1	419.9-420.0	n/v	0.476	0.42	0.88
Tuffaceous Beds of Calico Hills					
1481.9-1482.2	451.7-451.8	n/v	0.392	0.32	0.82
1484.4-1485.1	452.4-452.7	n/v	0.420	0.34	0.81
1490.0-1491.2	454.2-454.5	n/v	0.373	0.32	0.86
1497.2-1497.6	456.4-456.5	n/v	0.394	0.28	0.71
1503.0-1503.3	458.1-458.2	n/v	0.380	0.29	0.76

DRILL HOLE USW GU-3 DTW = 750.3 m

Depth (ft)	Depth (m)	Lithology[a]	Porosity[b]	Moisture Content (volume)[c]	Saturation[d]
Bedded Tuff					
1533.8-1534.2	467.5-467.6	bt	0.343	0.30	0.87
1549.0-1549.4	472.1-472.3	bt	0.406	0.34	0.84

[a] From Scott and Castellanos (1984).

[b] Total porosity from Schwartz (1990).

[c] Moisture content calculated from natural bulk density (nbd) and dry bulk density (dbd) both from Schwartz (1990):

moisture content = nbd - dbd

[d] Saturation calculated from porosity and moisture content:

saturation = moisture content/porosity

DRILL HOLE USW GU-3 DTW = 750.3 m

Depth[b] (feet)	Depth[b] (meters)	Lithology	Intrinsic Permeability[b] (darcy) Vertical	Intrinsic Permeability[b] (darcy) Horizontal	Hydraulic Conductivity[c] (meters/sec) Vertical	Hydraulic Conductivity[c] (meters/sec) Horizontal	Porosity[d]	Moisture Content[e] (volume)	Saturation[f]
Lower Topopah Spring Member of Paintbrush Tuff									
1310.9	399.7	n/v	5.41e-03	1.00e-02	5.20e-08	9.62e-08	0.287	0.23	0.80
Tuffaceous Beds of Calico Hills									
1477.2	450.3	n/v					0.369	0.24	0.65
1501.8	457.9	n/v	3.13e-02	3.92e-02	3.01e-07	3.76e-07	0.343	0.25	0.73
Prow Pass Member of Crater Flat Tuff									
1566.0	477.4	n/v					0.436	0.32	0.73
1637.7	499.3	p/dv	5.20e-02	4.58e-02	5.00e-07	4.40e-07	0.357	0.28	0.78
1666.7	508.1	p/dv	9.15e-03	1.01e-02	8.80e-08	9.71e-08	0.316	0.23	0.73
1706.6	520.3	p/dv	2.44e-03	2.28e-03	2.35e-08	2.19e-08	0.266	0.21	0.79
1779.6	542.6	p/dv	2.35e-01	(-)[e]	2.25e-06	(-)	0.397	0.13	0.33
1813.5	552.9	p/dv,z	1.60e-04	(-)[e]	1.53e-09	(-)	0.361	0.33	0.91
1866.9	569.2	p/dv,z	3.93e-05	3.78e-05	3.78e-10	3.63e-10	0.291	0.38	1.31
1912.7	583.1	p/dv,z	1.30e-05	(-)[e]	1.25e-10	(-)	0.305	0.23	0.75
1958.4	597.1	p/dv,z	1.50e-05	(-)[e]	1.44e-10	(-)	0.343	0.28	0.82
Upper Bullfrog Member of Crater Flat Tuff									
2008.4	612.3	p/z	(-)	1.03e-04	(-)	9.95e-10	0.300	0.26	0.87
2075.0	632.6	p/dv	1.13e-02	(-)	1.09e-07	(-)	0.299	0.22	0.74

[a] From Scott and Castellanos (1984). Alteration from Scott and Castellanos (1984) and Bish and Chipera (1989).

[b] Anderson (1992). From separate adjacent horizontal and vertical plugs. Values reported here are the high end of a range of permeabilities observed in the laboratory. Decreasing permeability with time was attributed to clogging of pores due to grain realignment. Sample size 2.54-cm long x 2.54-cm diameter.
[c] Calculated from intrinsic permeability; 1 darcy = 1.04e+05 m/s.
[d] Porosity from Anderson (1984). Buoyancy method. On core before plugs for permeability measurements were extracted. Porosity, wet and dry bulk density and grain density for the individual plugs can be found in Anderson (1992).
[e] Moisture content determined from density (Anderson, 1984):

moisture content = natural bulk density - dry bulk density

[f] Saturation = moisture content/porosity

- Indicates sample not suitable for measurement.

DRILL HOLE USW G-4 DTW = 539.5 m

Depth (ft)	Depth (m)	Lithology	Intrinsic Permeability[b] (darcy)	Hydraulic Conductivity[c] (m/s)	Porosity[c]	van Genuchten Parameters[d] a (1/m)	n	S_r	Brooks-Corey Parameter[e] b
Lower Topopah Spring Member of Paintbrush Tuff									
1359a	414.2	p/v	3.38e-06	3.25e-11	0.21[f]	0.043	1.651	0.1027	
1359b			2.07e-06	1.99e-11	0.24[f]	0.0212	2.648	0.1315	
1359c			8.35e-06	8.03e-11	0.18[f]				
1405a	428.2	n/z	3.11e-07	2.99e-12	0.41[f]	0.0197	1.254	0.0	0.21
1405b						0.0273	1.249	0.0	
1405c						0.0049	1.343	0.0	
Tuffaceous Beds of Calico Hills									
1548a	471.8	n/z	<1.36e-06	<1.31e-11[g]	0.27	0.0033	1.435	0.0	0.60
1548b			6.13e-07	5.90e-12	0.28	0.0034	1.461	0.0	
1548c			2.05e-06	1.97e-11	0.31	0.0035	1.473	0.0	
			2.46e-09	2.37e-14[h]					
1551a	472.7	n/z	5.26e-06	5.06e-11	0.36[f]	0.0047	1.848	0.1756	
1551b			1.96e-06	1.88e-11	0.32[f]	0.0044	1.782	0.2145	
1551c			1.38e-06	1.33e-11	0.30[f]	0.0035	2.169	0.2300	
1686a	513.9	n/z	4.41e-07	4.24e-12	0.30	0.0100	1.365	0.0	0.45
1686b						0.00512	1.458	0.0	
1686c						0.0035	1.495	0.0	
Bedded Tuff									
1728a	526.7	bt/z	1.93e-06	1.86e-11	0.23	.0007	1.763	0.0	0.70
1728b			2.54e-06	2.45e-11	0.21	.0026	1.398	0.0	
1728c			2.05e-06	1.97e-11	0.21	.0029	1.415	0.0	
			4.88e-09	4.69e-14[h]					

DRILL HOLE USW G-4 DTW = 539.5 m

Depth (ft)	(m)	Lith-ology	Intrinsic Permeability[b] (darcy)	Hydraulic Conductivity[c] (m/s)	Porosity[c]	van Genuchten Parameters[d] a (1/m)	n	S_r	Brooks-Corey Parameter[e] b
1737a	529.4	bt/z	<1.36e-06	<1.31e-11[g]	0.28	0.0037	1.574	0.1880	0.57
1737b			4.77e-08	4.59e-13	0.23	0.00264	1.688	0.1690	
1737c			2.58e-06	2.48e-11	0.23	0.0043	1.446	0.0565	
			1.65e-07	1.59e-12[h]					
Prow Pass Member of Crater Flat Tuff									
1769a	539.2	n/z	2.39e-07	2.30e-12	0.26	0.00064	2.381	0.0	1.50
1769b					0.26	0.00059	2.406	0.0	
1769c					0.27	0.00052	2.671	0.0	
1778a	541.9	n/dv,z	6.73e-07	6.47e-12	0.24	0.0048	1.385	0.0	0.58
1778b					0.27	0.0062	1.381	0.0	
1778c					0.23	0.0040	1.458	0.0	
1778.1a	542.0	n/dv,z	7.17e-07	6.89e-12	0.28	0.0012	3.335	0.2073	
1778.1b			1.90e-06	1.83e-11	0.29	0.00112	3.213	0.1855	
1778.1c			2.34e-06	2.25e-11	0.28	0.00127	3.274	0.1854	
1787a	544.7	n/pa,z	1.67e-05	1.61e-10	0.29	0.0037	1.510	0.0	0.67
1787b			2.05e-06	1.97e-11	0.26	0.0018	1.788	0.0	
1787c			1.29e-05	1.24e-10	0.30	0.0042	1.600	0.0	
			1.75e-07	1.68e-12[h]					
1899a	578.8	p/dv	2.43e-04	2.34e-09	0.25	0.0141	2.639	0.0658[i]	1.61
1899b			1.44e-03	1.38e-08	0.22				
1899c			1.64e-04	1.58e-09	0.25				
			4.64e-04	4.46e-09[g]					
2006a	611.4	np/z	2.11e-06	2.03e-11	0.30	0.00316	2.019	0.1346[i]	1.02
2006b					0.30				
2006c					0.26				

DRILL HOLE USW G-4 DTW = 539.5 m

Depth (ft)	Depth (m)	Lithology	Intrinsic Permeability[b] (darcy)	Hydraulic Conductivity[c] (m/s)	Porosity[c]	van Genuchten Parameters[d] a (1/m)	n	S_r	Brooks-Corey Parameter[e] b
2101a	640.4	p/dv,z	4.53e-05	4.36e-10	0.21	0.00448	1.872	0.3217[i]	0.86
2101b					0.17				
2101c					0.19				
Bullfrog Member of Crater Flat Tuff									
2401a	731.8	p/dv	2.40e-04	2.31e-09	0.24	0.0112	4.148	0.0608[i]	1.21
2401b					0.25				
2401c					0.25				
2407a	733.7	p/dv	6.51e-04	6.26e-09	0.27	0.0293	2.257	0.0559[i]	0.39
2407b					0.27				
2407c					0.27				

[a] From Spengler and Chornack (1984). Alteration from Spengler and Chornack (1984) and Bish and Chipera (1989).
[b] Back-calculated from hydraulic conductivity; 1 darcy = 1.04e+05 m/s.
[c] Peters et al. (1984). Saturated, unconfined, measured with Ruska Permeameter except where noted. Dimensions of Ruska permeameter samples are 1.4 cm x 1.2 cm. Multiple values from subsamples within sample interval. Porosity calculated from bulk density and grain density.
[d] Saturation curve fit parameters from SEPDB unless otherwise noted.
[e] Brooks-Corey parameter from Sinnock et al. (1986).
[f] Text indicates that porosity value listed is an estimate based on the grain density from a nearby sample.
[g] Indicates upper limit.
[h] Measured with large disc. Sample dimensions 6-cm diameter x 2-cm length.
[i] Saturation curve fit parameters from Klavetter and Peters (1987).

DRILL HOLE USW G-4 DTW = 539.5 m

Pore-Size Distribution Summaries from Mercury Intrusion[a]

Depth (ft)	Depth (m)	Lithology[b]	Total Intrusion Volume (mL/g)	Total Pore Area (m^2/g)	Median Pore Diameter Volume (microns)	Median Pore Diameter Area (microns)	Average Pore Diameter (4V/A) (microns)
Lower Topopah Spring Member of Paintbrush Tuff							
1405	428.2	n/z	0.1686	38.1627	0.0234	0.0098	0.0177
Tuffaceous Beds of Calico Hills							
1547	471.5	n/z	0.1768	38.754	0.0294	0.0082	0.0183
1548	471.8	n/z	0.1571	32.7554	0.0308	0.0098	0.0192
1686	513.9	n/z	0.1642	30.2623	0.0528	0.0071	0.0217
Bedded Tuff							
1727	526.4	bt/z	0.1283	21.7169	0.0637	0.0092	0.0236
1736	529.1	bt/z	0.1276	21.320	0.0625	0.0081	0.0239
1736.7	529.3	bt/z	0.1050	21.1806	0.0416	0.0096	0.0198
Prow Pass Member of Crater Flat Tuff							
1769.3	539.3	n/z	0.0968	29.5369	0.0159	0.0067	0.0131
1777.6	541.8	n/dv,z	0.1583	31.2140	0.0290	0.0154	0.0204
1787	544.7	n/pa,z	0.1864	20.5425	0.0779	0.0160	0.0363
1899	578.8	p/dv	0.1271	17.9116	0.8255	0.0050	0.0284
2006	611.4	np/z	0.1991	24.2364	0.0632	0.0182	0.0329
2101	640.4	p/dv,z	0.0885	11.2706	0.0794	0.0112	0.0307

DRILL HOLE USW G-4 DTW = 539.5 m

Depth (ft)	Depth (m)	Lithology[b]	Total Intrusion Volume (mL/g)	Total Pore Area (m^2/g)	Median Pore Diameter Volume (microns)	Median Pore Diameter Area (microns)	Average Pore Diameter (4V/A) (microns)
Bullfrog Member of Crater Flat Tuff							
2401	731.8	p/dv	0.1249	5.1421	0.8943	0.0113	0.0872
2407	733.7	p/dv	0.1316	3.8705	1.0655	0.0176	0.1360

[a] Data summary from Klavetter and Peters (1987).
[b] From Spengler and Chornack (1984). Alteration from Spengler and Chornack (1984) and Bish and Chipera (1989).

DRILL HOLE USW G-4 DTW = 539.5 m

Depth (ft)	Depth (m)	Lithology	Intrinsic Permeability[b] (darcy) Vertical	Intrinsic Permeability[b] (darcy) Horizontal	Hydraulic Conductivity[c] (meters/sec) Vertical	Hydraulic Conductivity[c] (meters/sec) Horizontal	Porosity[d]	Moisture Content[e] (volume)	Saturation[f]
Lower Topopah Spring Member of Paintbrush Tuff									
1361.5	415.1	np/v	2.5e-06	1.91e-05	2.40e-11	1.84e-10	0.169	0.12	0.71
Tuffaceous Beds of Calico Hills									
1431.5	436.3	n/z					0.366	0.37	1.01
1468.2	447.5	n/z					0.321	0.35	1.09
1511.4	460.8	n/z	5.95e-04	(-)[e]	5.72e-09	(-)	0.318	0.33	1.04
1570.3	478.6	n/z					0.358	0.37	1.03
1627.2	496.0	n/z					0.326	0.32	0.98
1678.4	511.7	n/z	1.46e-05	(-)	1.40e-10	(-)	0.343	0.34	0.99
Prow Pass Member of Crater Flat Tuff									
1784.3	543.9	n/dv,z					0.297	0.30	1.01
1822.8	555.7	p/vp	4.19e-03	7.68e-03	4.03e-08	7.38e-08	0.346	0.30	0.87
1870.7	570.3	p/dv,vp	2.48e-03	4.60e-03	2.38e-08	4.42e-08	0.298	0.27	0.91
1915.8	548.1	p/dv,vp	7.00e-05	2.61e-05	6.73e-10	2.51e-10	0.194	0.18	0.93
1976.0	602.4	np/z	1.20e-04	2.23e-05	1.15e-09	2.14e-10	0.325	-	-
2032.4	619.6	np/z	5.14e-05	(-)	4.94e-10	(-)	0.350	0.33	0.94
2072.9	631.8	p/dv,z					0.206	0.21	1.02
2131.2	649.8	p/dv,z	3.62e-05	7.07e-05	3.48e-10	6.80e-10	0.243	0.24	0.99
2181.8	665.2	p/dv,z	4.32e-05	2.10e-04	4.15e-10	2.02e-09	0.292	0.28	0.96
2228.5	679.4	n/z,sa	6.50e-04	3.20e-05	6.25e-09	3.08e-10	0.286	0.29	1.01

DRILL HOLE USW G-4 DTW = 539.5 m

Depth (ft)	Depth (m)	Lithology	Intrinsic Permeability[b] (darcy) Vertical	Intrinsic Permeability[b] (darcy) Horizontal	Hydraulic Conductivity[c] (meters/sec) Vertical	Hydraulic Conductivity[c] (meters/sec) Horizontal	Porosity[d]	Moisture Content[e] (volume)	Saturation[f]
Bullfrog Member of Crater Flat Tuff									
2298.0	700.6	p/dv	1.64e-03	2.31e-03	1.58e-08	2.23e-08	0.248	0.24	0.97
2336.8	712.4	p/dv	2.22e-03	3.21e-03	2.14e-08	3.10e-08	0.244	0.24	0.98

[a] From Spengler and Chornack (1984). Alteration from Spengler and Chornack (1984) and Bish and Chipera (1989).
[b] Anderson (1992). From separate adjacent horizontal and vertical plugs. Values reported here are the high end of a range of permeabilities observed in the laboratory. Decreasing permeability with time was attributed to clogging of pores due to grain realignment. Sample size 2.54-cm long x 2.54-cm diameter.
[c] Calculated from intrinsic permeability. 1 darcy = 1.04e+05 m/s.
[d] Total porosity from Anderson (1984). Sample size: 200-250 cm^3 above 1779.6 ft; 103 - 132 cm^3 below 1779.6 ft. On core before plugs for permeability measurements were extracted. Porosity, wet and dry bulk density and grain density for the individual plugs can be found in Anderson (1992).
[e] Moisture content determined from density data (Anderson, 1984):

moisture content = natural bulk density - dry bulk density

[f] Saturation = moisture content/porosity

- Indicates sample not suitable for measurement.

DRILL HOLE USW G-4 DTW = 539.5 m

Sample Size: 1.2-cm long x 1.5-cm diameter; Gradient = 22.14 m

ELEVATION ABOVE SEA LEVEL: 4,166.90 (ft)

Depth (feet)	Depth (meters)	Sample ID	Lith-ology[a]	Intrinsic Permeability (darcy)	Hydraulic Conductivity[b] (m/sec)	Test Type
Lower Topopah Spring Member of Paintbrush Tuff						
1375.8	419.3	G4-1376	n/v	3.63e-05	3.49e-10	liquid permeameter
Tuffaceous Beds of Calico Hills						
1489.8	454.1	G4-1490	n/z	2.60e-07	2.50e-12	liquid permeameter
1596.8	486.7	G4-1597	n/z	2.53e-07	2.43e-12	liquid permeameter
Bedded Tuff						
1714.5	522.6	G4-1715	bt/z	3.44e-07	3.31e-12	liquid permeameter
1746.8	532.4	G4-1747	bt/z	5.40e-07	5.19e-12	liquid permeameter
Prow Pass Member of Crater Flat Tuff						
1849.0	563.6	G4-1849	p/vp	5.34e-07	5.13e-12	liquid permeameter

[a] From Spengler and Chornack (1984). Alteration from Spengler and Chornack (1984) and Bish and Chipera (1989).
[b] Site Engineering Properties Data Base product DA0047.

DRILL HOLE USW G-4 DTW = 539.5 m

Depth (ft)	Depth (m)	Lithology[a]	Porosity[b]	Moisture Content (volume)[c]	Saturation[d]
1442.5	439.7	n/z	0.375	0.34	0.91
1509.1	460.1	n/z	0.353	0.31	0.88
1572.4	479.3	n/z	0.399	0.35	0.88
1635.9	498.6	n/z	0.346	0.32	0.93
1694.4	516.5	n/z	0.339	0.31	0.91

[a] Fom Spengler and Chornack (1984). Alteration from Spengler and Chornack (1984) and Bish and Chipera (1989).

[b] Total porosity from Schwartz (1990).

[c] Moisture content calculated from natural bulk density (nbd) and dry bulk density (dbd) (both from Schwartz, 1990):

moisture content = nbd - dbd

[d] Saturation calculated from porosity and moisture content:

saturation = moisture content/porosity

AQUIFER TEST HYDRAULIC CONDUCTIVITY MEASUREMENTS[a]

DRILL HOLE USW G-4 DTW = 539.5 m

Elevation Above Sea Level: 4,166.90 (ft)

Prow Pass Member of Crater Flat Tuff 536.9 m - 682.0 m
Bedded Tuff 682.0 m - 684.0 m
Upper Bullfrog 684.0 m - 722.4 m

Interval (feet)	Interval (meters)	Intrinsic Permeability (darcy)	Hydraulic Conductivity (m/s)	Test Type
Prow Pass Member of Crater Flat Tuff				
2021-2149	616-655	3.58e-02	3.44e-07	packer-injection
Prow Pass - Bedded Tuff - Bullfrog				
2149-2300	655-701	1.33e-02	1.28e-07	packer-injection
Bullfrog Member of Crater Flat Tuff				
2290-2369	698-722	5.37e-03	5.16e-08	packer-injection
2369-2451[a]	722-747	3.03e-02	2.92e-07	packer-injection
2451-2598	747-792	3.08e-02	2.96e-07	packer-injection
2598-2749	792-838	1.99e-02	1.91e-07	packer-injection
2631-2710	802-826	3.16e-02	3.04e-07	packer-injection

[a] Lobmeyer (1986); SEPDB DA0030.
[b] Last four intervals in mostly partially to nonwelded tuffs below designated lower boundary of Calico Hills nonwelded unit.

DRILL HOLE USW H-1 DTW = 572.1 m

Sample Size: 1.2-cm long x 1.5-cm diameter (Rush et al., 1983)

ELEVATION ABOVE SEA LEVEL: 4,274.40 (ft) TOP OF CASING: 4,274.55 (ft)

Depth (feet)	Depth (meters)	Sample ID	Lithology[a]	Intrinsic Permeability (darcy)	Hydraulic Conductivity[a] (m/sec)	Porosity[b]	Saturation[c]
Tuffaceous Beds of Calico Hills							
1742	531		n/z	-	-	0.43,0.47	0.96
1749	533		n/z	-	-	0.37,0.44	0.96
Prow Pass Member of Crater Flat Tuff							
2100	640		p/dv	8.43e-05	8.10e-10 vertical	0.28,0.33	0.97
2100	640			1.20e-04	1.16e-09 horizontal		
2103	641	1	p/dv	6.02e-05	5.79e-10 vertical	0.29,0.31	0.96
2103	641	1		8.43e-05	8.10e-10 horizontal		
2103	641	2	p/dv	6.02e-05	5.79e-10 vertical	0.29,0.32	0.95
2103	641	2		7.22e-05	6.94e-10 horizontal		
Bullfrog Member of Crater Flat Tuff							
2326	709	1	nm/dv,z?	2.41e-05	2.31e-10 vertical	0.27,0.33	0.92
2326	709	1		3.61e-05	3.47e-10 horizontal		
2326	709	2	nm/dv,z?	2.41e-04	2.31e-09 vertical	0.32,0.33	0.95
2326	709	2		3.61e-03	3.47e-09 horizontal		
2329	710		nm/dv,z?	4.81e-04	4.63e-09 vertical	0.34,0.38	0.92
2329	710			9.63e-04	9.26e-09 horizontal		

DRILL HOLE USW H-1 DTW = 572.1 m

Depth (feet)	Depth (meters)	Lithology[a]	Intrinsic Permeability (darcy)	Hydraulic Conductivity[a] (m/sec)		Porosity[b]	Saturation[c]
2339	713	nm/dv	4.81e-05	4.63e-10	vertical	0.20,0.19	0.82
2339	713		1.20e-04	1.16e-09	horizontal		
2507	764	nm/dv	3.61e-04	3.47e-09	vertical	- ,0.28	0.87
2507	764		1.20e-03	1.16e-08	horizontal		
2533	772	nm/dv	2.41e-04	2.31e-09	vertical	0.25,0.25	0.94
2533	772		7.22e-04	6.94e-09	horizontal		
2592	790	nm/dv,z	4.81e-05	4.63e-10	vertical	0.19,0.19	0.89
2592	790		4.81e-05	4.63e-10	horizontal		
2595	791	nm/dv,z	7.22e-05	6.94e-10	horizontal	0.20,0.19	0.84
2595	791		9.63e-05	9.26e-10	vertical		
2598	792	nm/dv,z	3.61e-05	3.47e-10	vertical	0.22,0.21	0.89
2598	792		8.43e-05	8.10e-10	horizontal		

[a] From Rush et al. (1983). Alteration from Rush et al. (1983); some mineralogy carried over from USW G-1 in Bish and Chipera (1989).
[b] Total porosity; first porosity value is determined with a helium pycnometer; second is calculated from density. Rush et al. (1983).

[c] Saturation calculated from density data in Rush et al. (1983).

AQUIFER TEST HYDRAULIC CONDUCTIVITY MEASUREMENTS[a]

DRILL HOLE USW H-1 DTW = 572.1 m
Elevation Above Sea Level: 4,274.40 (ft) Top of Casing: 4,274.55 (ft)

Prow Pass Member of Crater Flat Tuff 566 m - 701 m
Bedded Tuff 701 m - 707 m
Bullfrog 707 m - 820 m

Interval (feet)	Interval (meters)	Intrinsic Permeability (darcy)	Hydraulic Conductivity (m/s)	Test Type
Prow Pass Member of Crater Flat Tuff				
1877-1959	572-597	3.61	3.47e-05	pump/radioactive tracer
1877-2257	572-688	1.60	1.54e-05	pump/drawdown
1877-2257	572-688	1.90	1.83e-05	pump/recovery
1959-2021	597-616	1.20	1.16e-05	pump/radioactive tracer
2021-2139	616-652	1.20	1.16e-05	pump/radioactive tracer
2139-2142	652-653	21.7	2.08e-04	pump/radioactive tracer
2142-2257	653-688	4.81e-02	4.63e-07	pump/radioactive tracer
2254-2277	687-694	2.41e-02	2.31e-07	pump/radioactive tracer
2254-2287	687-697	1.20e-02	1.16e-07	injection
Prow Pass - Bedded Tuff - Bullfrog				
2277-2415	694-736	-2.41e-04	-2.31e-09	pump/radioactive tracer
Bullfrog Member of Crater Flat Tuff				
2415-2431	736-741	1.2e-01	1.16e-06	pump/radioactive tracer
2431-2487	741-758	1.2e-02	1.16e-07	pump/radioactive tracer
2487-2598	758-792	3.61e-04	3.47e-09	pump/radioactive tracer

[a] Rush et al. (1984); SEPDB DA0001.

AQUIFER TEST HYDRAULIC CONDUCTIVITY MEASUREMENTS[a]

DRILL HOLE USW H-4 DTW = 518.7
Elevation Above Sea Level: 4,096.50 (ft) Top of Casing: 4,097.10 (ft)

Prow Pass Member of Crater Flat Tuff 496 m - 690 m
Bedded Tuff 690 m - 693 m
Bullfrog 693 - 806 m

Interval (feet)	Interval (meters)	Intrinsic Permeability (darcy)	Hydraulic Conductivity (m/s)	Test Type
Prow Pass Member of Crater Flat Tuff				
1841-1916	561-584	5.90e-01	5.67e-06	pump/radioactive tracer
2044-2096	623-639	1.40	1.34e-05	pump/radioactive tracer
2110-2195	643-669	3.97e-01	3.82e-06	pump/radioactive tracer
Prow Pass - Bedded Tuff - Bullfrog				
2231-2320	680-707	4.18e-02	4.63e-07	pump/radioactive tracer
Bullfrog Member of Crater Flat Tuff				
2320-2405	707-733	2.59	2.49e-05	pump/radioactive tracer
2556-2575	779-785	1.65	1.59e-05	pump/radioactive tracer
2575-2641	785-805	6.26e-01	6.02e-06	pump/radioactive tracer

[a] Whitfield et al. (1985); SEPDB DA0003-C.

DRILL HOLE J-13 DTW = 283.2 m

Depth (feet)	Depth (meters)	Lithology[a]	Intrinsic Permeability[b] (darcy)	Hydraulic Conductivity[c] (meters/sec)	Porosity[d]	Moisture Content (volume)	Saturation[d]
Lower Topopah Spring Member of Paintbrush Tuff							
1407.5	429.0	np	-	-	0.116	0.090	0.769
1416.0	431.6	np	3.64e-07	3.50e-12	0.033[e]	-	-
1445.5	440.6	np	-	-	0.327	0.310	0.946

[a] From Thordarson (1983); SEPDB DA0003-J.
[b] Back-calculated from reported hydraulic conductivity values. 1 darcy = 1.04e+05 m/s.
[c] Thordarson (1983); SEPDB DA0003-J
[d] Porosity and saturation from Thordarson (1983); SEPDB DA0003-J.
[e] Effective porosity, by water saturation method. Thordarson (1983); SEPDB DA0003-J.

AQUIFER TEST HYDRAULIC CONDUCTIVITY MEASUREMENTS[a]

DRILL HOLE J-13 DTW = 283.2 m Elevation Above Sea Level: 3,317.70 (ft)
Tuffaceous Beds of Calico Hills 449.6 m - 530.4 m
Prow Pass 530.4 m - 596.2 m
Bedded Tuff 596.2 m - 614.2 m
Bullfrog 614.2 m - 707.1 m

Interval (feet)	Interval (meters)	Test No	Intrinsic Permeability (darcy)	Hydraulic Conductivity (m/s)	Test Type
Tuffaceous Beds of Calico Hills					
1513-1647	461.2-502.0	19a	1.13e-01	1.09e-06	swab
1546-1647	471.2-502.0	19b	1.56e-01	1.50e-06	swab
1546-1647	471.2-502.0	19	1.81e-01	1.74e-06	injection
Calico Hills - Prow Pass - Bullfrog					
1546-2010	471.2-612.6	4	1.56e-02	1.50e-07	swab
1546-2170	471.2-661.4	6a	1.14e-02	1.10e-07	
Calico Hills - Prow Pass					
1644-1844	501.1-562.1	16	1.56e-02	1.50e-07	injection
1644-1844	501.1-562.1	18	3.13e-02	3.01e-07	swab
1658-1856	505.4-565.7	21	6.86e-03	6.60e-08	injection
1658-1856	505.4-565.7	21	7.46e-03	7.18e-08	swab
Prow Pass - Bedded Tuff - Bullfrog					
1918-2118	584.6-645.6	15	1.08e-02	1.04e-07	injection
Bullfrog Member of Crater Flat Tuff					
2099-2199	639.8-670.3	14	3.49e-03	3.36e-08	injection
2194-2294	668.7-699.2	13	1.93e-02	1.85e-07	injection

[a] Thordarson (1983); SEPDB DA0003-J.

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