Petrophysical Properties, Mineralogy, Fractures, and Flow Tests in 25 Deep Boreholes at Yucca Mountain, Nevada

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U.S. Department of the Interior
U.S. Geological Survey

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By Philip H. Nelson and Joyce E. Kibler

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
barrel (bbl), (petroleum, 1 barrel=42 gal)	0.1590	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
	Pressure	
atmosphere, standard (atm)	101.3	kilopascal (kPa)
bar	100	kilopascal (kPa)
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)
	Density	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)
pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter (g/cm^3)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8

Petrophysical Properties, Mineralogy, Fractures, and Flow Tests in 25 Deep Boreholes at Yucca Mountain, Nevada

By Philip H. Nelson and Joyce E. Kibler

Abstract

As part of a site investigation for the disposal of radioactive waste, numerous boreholes were drilled into a sequence of Miocene pyroclastic flows and related deposits at Yucca Mountain, Nevada. This report contains displays of data from 25 boreholes drilled during 1979–1984, relatively early in the site investigation program. Geophysical logs and hydrological tests were conducted in the boreholes; core and cuttings analyses yielded data on mineralogy, fractures, and physical properties; and geologic descriptions provided lithology boundaries and the degree of welding of the rock units. Porosity and water content were computed from the geophysical logs, and porosity results were combined with mineralogy from x-ray diffraction to provide whole-rock volume fractions. These data were composited on plates and used by project personnel during the 1990s. Improvements in scanning and computer technology now make it possible to publish these displays.

Introduction

Site investigation boreholes at Yucca Mountain penetrate a sequence of ash-flow tuffs and related deposits in a site that was selected as a candidate for the disposal of high-level radioactive waste (fig. 1). The site was systematically investigated by many geologists and hydrologists working from more than 100 study plans, so that the site is said to be “one of the most thoroughly studied geologic features on Earth” (Levich and Stuckless, 2007). The borehole log displays presented in this report represent a large fraction of all drilling at Yucca Mountain and (1) contain information on both the unsaturated and saturated zones above and below the water table, (2) have good geographical distribution over the study area, and (3) summarize a variety of geological and hydrological studies.

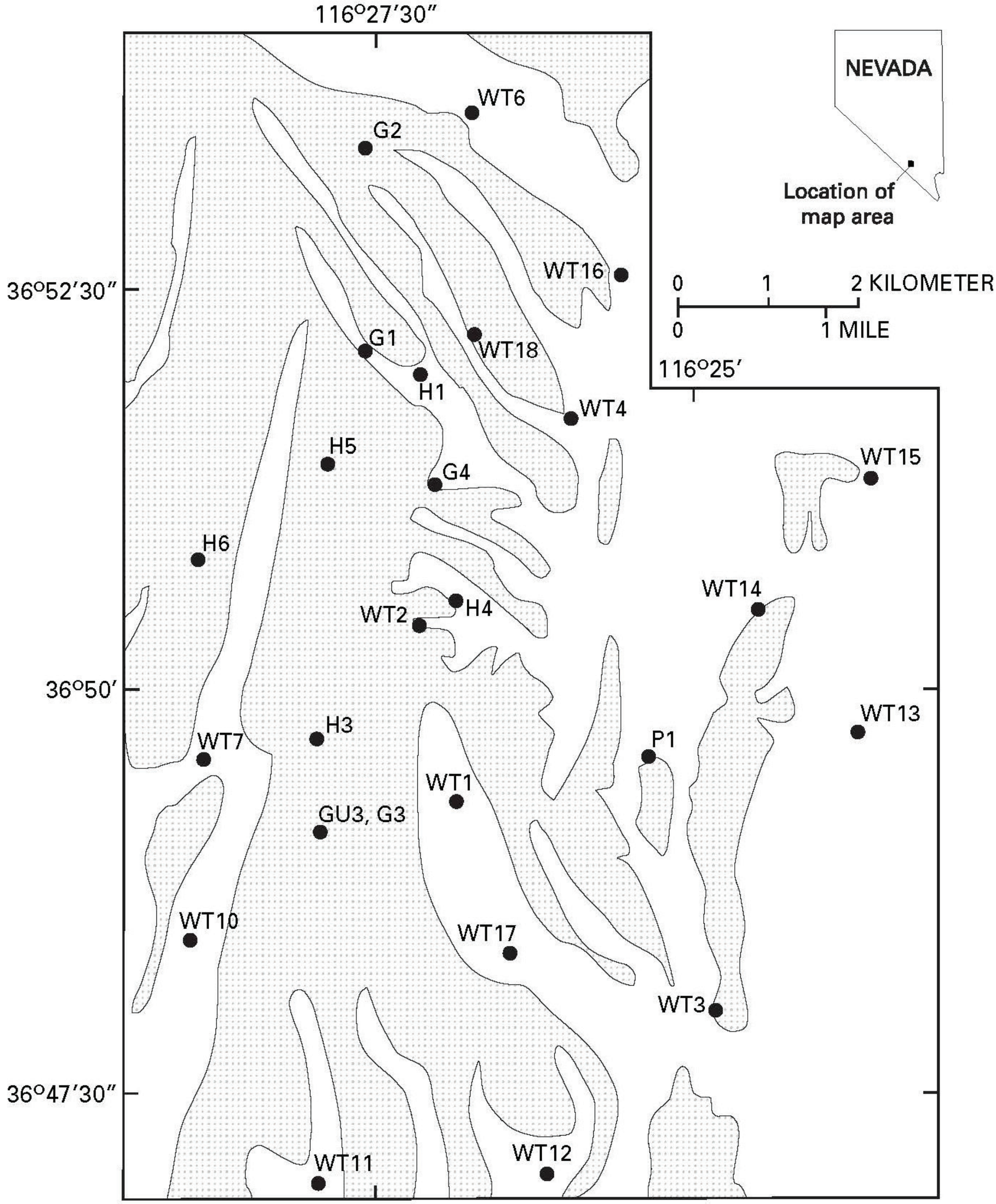


Figure 1. Map showing location of boreholes at Yucca Mountain. Shaded areas represent bedrock exposures, unshaded areas represent Quaternary alluvium in washes. Boreholes H5, H3, and GU-3/G3 are near the crest of Yucca Mountain, and G2 is located at a high elevation north of Yucca Mountain. Boreholes are identified by their short names; corresponding long names are given in table 2.

Geophysical logs and core data acquired between 1979 and 1984 were first published by Nelson and others (1991) along with detailed descriptions of drilling practices, log acquisition, and log characteristics. The goal of the geophysical log analysis and data synthesis was to provide an integrated format for displaying and comparing the disparate data types from individual boreholes. Subsequent work (1) described the petrophysical properties of ash-flow tuff as determined from core measurements (Nelson and Anderson, 1992), (2) examined log-quality issues (Nelson and Schimschal, 1993), (3) derived algorithms for the computation of porosity and water saturation from epithermal neutron and dielectric logs (Nelson, 1993a, 1994), (4) established a methodology for merging log-based porosity with x-ray diffraction-based mineralogy (Nelson, 1993b), and (5) formulated response functions for the different models of density and neutron logging tools (Nelson, 1996). Based on these collective efforts, plots of well logs, core data, derived petrophysical parameters, geologic descriptions, fracture indicators, and flow measurements were composited for 25 boreholes. Thus, 25 plates represent the culmination of a sustained effort to combine the corrected geophysical logs and the log-based computed values of porosity and water saturation with datasets from other investigators. The plates were made available on an informal basis in 1996 to project investigators, but after changes in project direction, the plates went unused and were stored in the author's files. In 2012, the plates were scanned and this report was written to preserve a graphical synthesis of physical property data in ash-flow tuffs.

Parameters provided on the plots include (1) geophysical logs such as caliper, electrical resistivity, and density measurements, (2) porosity and water content, (3) mineralogy and porosity on a volume-fraction basis, (4) degree of welding, (5) presence of lithophysae, and (6) presence of fractures and fracture orientation. Each continuous parameter on the plots, such as a density log, is generically referred to as a curve. Stratigraphic boundaries are shown on the plates and stratigraphic units are listed in table 1 along with representative thicknesses from one of the boreholes (G1). Each plate contains text describing the drilling and log acquisition for that well, followed by one-line summaries of each parameter (curve) and citations for the sources of data. Before discussing the format of the plates, we first explain the naming conventions for the porosity- and water-content curves, while referring to a reproduction of log headings and scales from borehole G1 (fig. 2). This report concludes with a brief discussion of a few outstanding features contained on the plates.

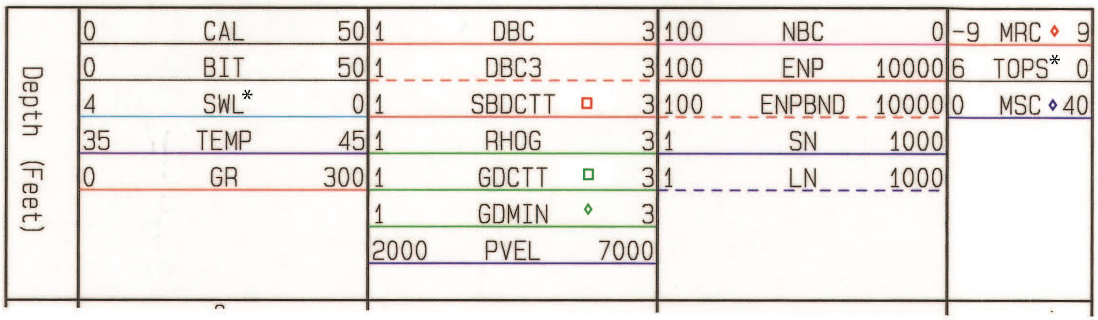
Table 1. Stratigraphic units for which boundaries are shown on the plates. Thickness of units from borehole G1 from Spengler and others (1981).

[ft, feet]

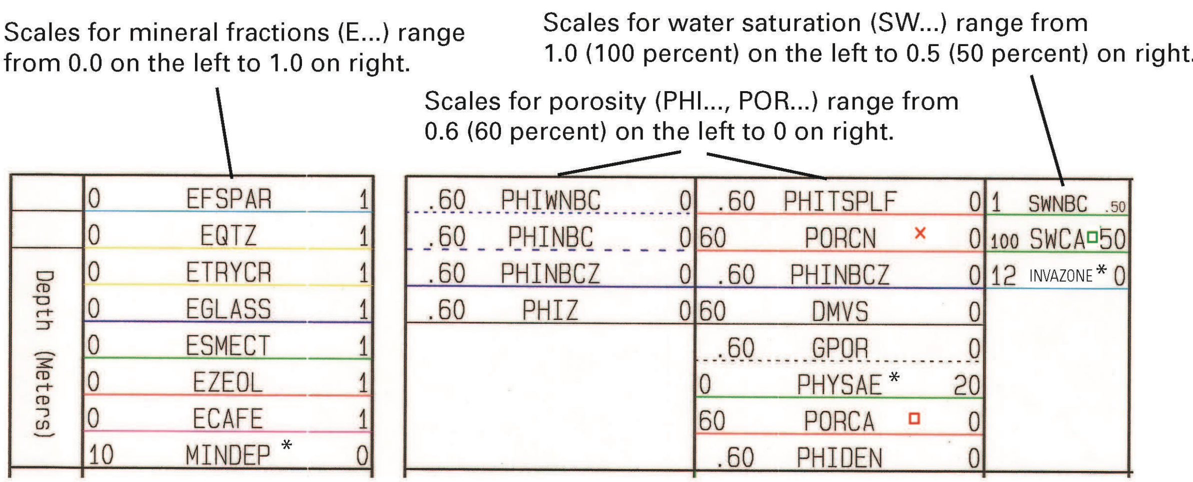
Group	Stratigraphic Unit	Abbreviation used on plates	Thickness in borehole G1 (ft)
Paintbrush	Tiva Canyon Tuff	Tpc	Not present
	Yucca Mountain Tuff	Tpy	40
	Bedded tuff	Tpb	35
	Pah Canyon Tuff	Tpp	100
	Topopah Spring Tuff	Tpt	1,191
	Calico Hills Formation	Tac	376
Crater Flat	Prow Pass Tuff	Tcp	373
	Bullfrog Tuff	Tcb	466
	Tram Tuff	Tct	919
	Flow breccia and lava	Tll	388
	Lithic Ridge Tuff	Tlr	994
	Pre-Lithic Ridge Tuff volcanic rocks	Tt	1,060

A. Original Logs and Core Data

Scales and units for each parameter are described in Explanation of Curves and Symbols. Example: scales for caliper (CAL) and bit size (BIT) range from 0 centimeters (cm) at the left of the column to 50 cm at the right.



B. Mineralogy, Porosity, Water Content



C. Stratigraphy and Fractures

Some parameters, such as TOPS, denote presence or absence and the scale is for display only. Other parameters, such as FRACNO, have a quantitative scale described in text on the right side of each plate.

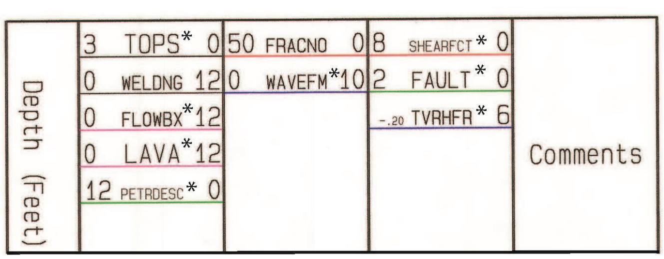


Figure 2. Replicas of log headings from boreholes G1 and G4, with a partial explanation of curve names and scales. Full explanations are given under Explanation of Curves and Symbols in the text column of each plate. Log and core data are scaled in physical units, but numerical values for curves indicated with an asterisk*, such as SWL*, are for scaling only.

Computation of Porosity and Water Content

Porosity and water content were computed from density, neutron, and dielectric logs. Before these computations could be performed, the logs were corrected for borehole effects. The corrections differed among the logging tools and also differed between the saturated and unsaturated zones, requiring special-purpose software to apply the corrections (Nelson, 1996). With corrections applied, the reader of this report can compare the normalized computed values of porosity and water content presented on the plates. The complicated nomenclature of the curve names reflects the need for separate computational algorithms in the unsaturated and saturated zones and the application of two neutron logs and one dielectric log to derive porosity and water content. A further complication arose from the presence of water within mineral grains, referred to as bound water. The defining equations for porosity and water content are given by Nelson (1996). Definitions of well log and computed curves are provided on individual plates. In addition, the following explanation of curve names, in conjunction with figure 2, will help clarify the terminology.

WELDNG. The degree of welding is a primary control on porosity; higher degree of welding reduces porosity. Degree of welding appears on all plates as a stepped curve with a range of values representing (1) bedded tuff, (2) nonwelded tuff, (3) partially welded tuff, (4) moderately welded tuff, (5) densely welded tuff, and (6) vitrophyre (high glass content). WELDNG is scaled from 0 to 12 on the plots so that vitrophyre, with a value of 6, plots at the middle of the column.

PHIT. The prefix PHI represents porosity and the letter T indicates total porosity. In the saturated zone, PHIT is equal to water-filled porosity and can be derived directly from the density log and an estimate of grain density, RHOG. In the unsaturated zone, PHIT equals air-filled plus water-filled porosity; here PHIT requires both density and neutron (or dielectric) logs, and is equivalent to actual total porosity only where zeolite and clay content are negligible. The computed log PHITENP estimates total porosity from the density and epithermal neutron logs. It is accurate where no zeolitic or clay minerals are present, but overestimates total porosity where they are present. Computations of PHIT from the unsaturated and saturated zones are spliced together and filtered to construct PHITSPLF, where SPL denotes spliced and F denotes filtered. PHITSPLF represents the best estimate of total porosity for the entire borehole.

PHIWENP. The prefix PHI represents porosity, the letter W indicates water-filled porosity, and ENP indicates that the water content was measured with the epithermal neutron porosity tool. This curve gives the fractional water content in both the saturated and unsaturated zones.

PHINBC. The prefix PHI represents porosity, and NBC indicates that the water content was measured with a thermal neutron tool designated "neutron, borehole corrected." The NBC tool required a water-filled borehole and hence was not run in the unsaturated zone of the H-boreholes and was not run at all in the WT-boreholes. It was run as conditions permitted in the G-boreholes, which were drilled with drilling mud. The curve PHIWNBC includes a correction to the PHINBC log in the unsaturated zone, providing an improved estimate of water content, and was applied in boreholes G1, G3, and G4.

PHIZ. In this case the prefix PHI represents volume fraction rather than porosity, and the letter Z represents bound water in various minerals. PHIZ is the volume fraction of bound water, computed by summing the volume fraction of each mineral times the fractional bound water of that mineral (Nelson, 1996, p. 20–23) and can be computed only in boreholes with mineralogical data. PHIZ was subtracted from PHIWENP and PHINBC to yield the free water in pore space, PHIWENPZ and PHINBCZ. A good example of the relationships among these curves is shown for borehole G2 (pl. 2, column 6). Note the overlap between PHIWENPZ and PHINBCZ from 1,500 to 1,750 feet (ft).

SWENP, SWNBC. The prefix SW represents water saturation and ENP and NBC represent the neutron curves used to obtain the water content estimates. Water saturation is computed as the dimensionless ratio of water content to porosity and ranges from 0 to 1. Although resistivity logs are used to compute water saturation in oil and gas wells, they were not used for this purpose at Yucca Mountain because of high resistivity values in the unsaturated zone. Water saturation is plotted in the unsaturated zone in most boreholes, as permitted by the availability of porosity and water content estimates.

Core data. A letter "C" is inserted into the curve names for measurements on core samples. For example, GDCN, PORCN, and SWCA are measurements of grain density, porosity, and water saturation from core samples. Trailing letters A and N refer to the sources of data, as referenced in the text on the plates.

Explanation of the Plates

The G, H, and P1 boreholes all penetrated the unsaturated zone and a substantial thickness of the saturated zone. Total depths of boreholes and the correspondence between short and long borehole names are given in table 2. The four G boreholes were continuously cored and the H and P1 boreholes were either partially cored, spot cored, or sidewall cored (table 2). The WT boreholes were drilled for the purpose of monitoring static water levels. The WT boreholes were rotary drilled to a depth ranging from 100 to 200 ft below the static water level, were drilled with air foam consisting of air, detergent, and water, and were not cored. All boreholes presented in this report reach total depth in Tertiary formations, except borehole P1, which penetrates the underlying Paleozoic rocks.

Table 2. List of 25 boreholes with location, surface elevation, and depth. Short names of boreholes are used in the text of this paper; full names appear on the plates. USW prefix applies to boreholes on the western part of the study area, on Bureau of Land Management land. The UE-25 prefix applies to the eastern part of the study area, on Area 25 of the Nevada Test Site. Coordinates (Central Nevada State Coordinate System), surface elevation, and depth of deepest log, all in ft, from Buesch and others (1996) and Nelson and others (1991).

[C, continuously cored; N, not cored; P, partially or spot cored; S, sidewall cored]

Plate	Short name of borehole–this paper	Full name of borehole	Northing	Easting	Surface elevation (ft)	Depth logged (ft)	Cored/ Not cored
1	G1	USW G-1	770500	561000	4,349	6,000	C
2	G2	USW G-2	778824	560504	5,098	6,000	C
3	G3	USW GU-3	752690	558501	4,857	2,664	C
3	G3	USW G-3	752780	558483	4,857	5,031	C
4	G4	USW G-4	765807	563082	4,167	3,000	C
5	H1	USW H-1	770254	562388	4,274	6,000	P
6	H3	USW H-3	756542	558452	4,866	4,000	S
7	H4	USW H-4	761644	563911	4,097	4,000	S
8	H5	USW H-5	766634	558909	4,851	4,000	S
9	H6	USW H-6	763299	554075	4,271	4,000	P
10	P1	UE-25p#1	756171	571485	3,654	5,900	P
11	WT1	USW WT-1	753941	563739	3,942	1,670	N
12	WT2	USW WT-2	760661	561924	4,270	2,050	N
13	WT3	UE-25WT#3	745995	573384	3,380	1,130	N
14	WT4	UE-25WT#4	768512	568040	3,829	1,570	N

Table 2. List of 25 boreholes with location, surface elevation, and depth. Short names of boreholes are used in the text of this paper; full names appear on the plates. USW prefix applies to boreholes on the western part of the study area, on Bureau of Land Management land. The UE-25 prefix applies to the eastern part of the study area, on Area 25 of the Nevada Test Site. Coordinates (Central Nevada State Coordinate System), surface elevation, and depth of deepest log, all in ft, from Buesch and others (1996) and Nelson and others (1991).—Continued

[C, continuously cored; N, not cored; P, partially or spot cored; S, sidewall cored]

Plate	Short name of borehole–this paper	Full name of borehole	Northing	Easting	Surface elevation (ft)	Depth logged (ft)	Cored/ Not cored
15	WT6	UE-25WT#6	780576	564524	4,307	1,240	N
16	WT7	USW WT-7	755570	553891	3,927	1,600	N
17	WT10	USW WT-10	748771	553302	3,686	1,390	N
18	WT11	USW WT-11	739070	558377	3,591	1,440	N
19	WT12	UE-25WT#12	739726	567011	3,527	1,310	N
20	WT13	UE-25WT#13	756715	578757	3,386	1,130	N
21	WT14	UE-25WT#14	761651	575210	3,530	1,300	N
22	WT15	UE-25WT#15	766117	579806	3,553	1,350	N
23	WT16	UE-25WT#16	774420	570395	3,971	1,700	N
24	WT17	UE-25WT#17	748420	566212	3,689	1,390	N
25	WT18	UE-25WT#18	771167	564855	4,383	2,020	N

Because the G boreholes were continuously cored, their plates contain more core data than the other plates. The WT boreholes were logged with a reduced logging program and were not cored, so the plots for the WT boreholes contain less data than the G, H, and P1 boreholes. Consequently, the plots for the G, H, and P1 boreholes are discussed separately from the WT boreholes.

Stratigraphic nomenclature is not consistent among the plates. Units that were previously named formations were raised to group status and ashflows previously named as members were raised to formation rank and given the rank term Tuff (Sawyer and others, 1994). For example, the Tiva Canyon Member of the Paintbrush Tuff was renamed the Tiva Canyon Tuff of the Paintbrush Group by Sawyer and others (1994). The nomenclature of table 1 largely reflects the revisions of Sawyer and others (1994) and is used on the plates for the G and H boreholes. However, plates for the WT boreholes draw from sources that used the earlier (formation/member) nomenclature. As the location names (Tiva Canyon) are unchanged, this inconsistency should not cause confusion. Besides the revisions to stratigraphic nomenclature, lithologic descriptions have also been revised since the plates were composed and printed, and are available in Wood (2007).

On all plots, depth is the measured depth or depth-along-hole, uncorrected for borehole deviation. Hole deviation is discussed in the text on each plate. Depth is scaled in feet, but is also given in meters on the plots. The vertical scale for the shallow WT boreholes is 50 ft per division instead of the 200 ft per division used for the deep G, H, and P1 boreholes, a difference that the user must take into account when comparing results from different boreholes. The horizontal scales for log and core measurements conform with the convention that porosity values increase to the left, and the scales for geophysical logs are arranged accordingly. For example, density, resistivity, and sonic-velocity values all increase to the right because these values increase as porosity decreases.

Plates for the G, H, and P1 Boreholes

Measurements shown on plates 1–10 for the G, H, and P1 boreholes are listed in table 3. In addition, a north-south cross section (pl. 26) displays partial results for boreholes G2, G1, H5, H3, and G3. Except for the gravimeter and magnetic field logs, most well logs were run in each of the boreholes. The porosity logs, prefixed with PHI, and water content logs, prefixed with PHIW and SW, were derived from density and neutron logs (see fig. 2).

Mineralogy determined by x-ray diffraction on core samples or cuttings were performed in all boreholes listed in table 3. Laboratory measurements of bulk density, grain density, and porosity were available for the G boreholes, which were extensively cored, and for borehole P1, which was partially cored. Permeability, sonic velocity, and thermal conductivity were determined for a few boreholes, as listed in table 3.

The static water level was determined in all boreholes, and well tests and flow observations were conducted in all boreholes except G1, G2, and G3. Fault properties and joints could be examined in the cored G boreholes. Televiewer, television, and sonic waveform data were acquired in most boreholes (table 3).

Table 3. Presence (Y) or absence (--) of measurements in the G, H, and P1 boreholes.

Measurement type	Curve name	Borehole identification									
		G1	G2	G3	G4	H1	H3	H4	H5	H6	P1
WELL LOGS											
Caliper	CAL	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Bit size	BIT	Y	Y	Y	--	Y	Y	Y	Y	Y	Y
Gamma ray	GR, TC	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Temperature	TEMP, DTMP	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Density	DBC	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Density, gravimeter	GRAV_SH	--	--	Y	Y	Y	--	--	--	--	Y
Sonic velocity	PVEL	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Neutron	NBC, ENP	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Resistivity	SN, LN, RILD	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Magnetic field	MAGT	--	--	Y	--	Y	Y	Y	Y	Y	Y
Porosity, various	PHI, …	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Water content, various	PHIW, SW, …	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
CORE MEASUREMENTS											
X-ray mineralogy	EFSPAR, …	Y	Y	Y	Y	--	Y	Y	Y	Y	Y
Grain density from mineralogy	GDMIN	Y	Y	Y	Y	--	Y	Y	Y	Y	Y
Bulk density	SBDC, …	Y	Y	Y	Y	--	--	--	--	--	Y
Grain density	GDC, …	Y	Y	Y	Y	Y	--	Y	--	--	Y
Porosity	PORC, …	Y	Y	Y	Y	Y	--	--	--	--	Y
Permeability	PERMH, …	--	--	Y	Y	Y	--	--	--	--	Y
Sonic velocity	VELC, …	--	--	Y	Y	--	--	--	--	--	Y
Magnetic properties	MSC, MRC	Y	Y	Y	--	--	--	--	--	--	Y
Thermal conductivity	THRMCN	--	--	Y	Y	--	--	--	--	--	Y

Table 3. Presence (Y) or absence (--) of measurements in the G, H, and P1 boreholes.—Continued

Measurement type	Curve name	Borehole identification									
		G1	G2	G3	G4	H1	H3	H4	H5	H6	P1
WELL TESTS											
Static water level	SWL	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Hydraulic conductivity	HYDCON	--	--	--	Y	Y	Y	Y	--	Y	Y
Flow log	FLOW	--	--	--	Y	Y	Y	Y	Y	Y	Y
Seepage	SEEP	--	--	--	--	Y	--	--	--	Y	--
GEOLOGIC DESCRIPTION											
Stratigraphic contacts	TOPS	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Degree of welding	WELDNG	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Faults, shear zones	FAULT, SHEAR	Y	Y	Y	Y	--	--	--	--	--	Y
Joints	FRACNO	Y	Y	Y	Y	--	--	--	--	--	--
Fractures from televiewer	TVRFRC, …	Y	Y	Y	--	--	Y	Y	Y	Y	Y
Fractures from television	TVNFRC	--	Y	--	Y	--	Y	Y	Y	Y	Y
Sonic waveform disruptions	WAVEFM	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

The display on each plate is organized into three blocks:

- original logs and core data
- mineralogy, porosity, and water content
- stratigraphy, fractures, and water flow

Original Logs and Core Data

The first block, containing original logs and core data, shows geophysical logs as continuous lines and core data as discrete points. Scales shown at the top of each column refer to full range, in accordance with the standard convention for well log scales. For example, in borehole G1 (pl. 1), the caliper (CAL) ranges from 0 cm at the left edge of the first column to 50 cm at the right edge. Scales change from borehole to borehole to accommodate the data. Most curves represent unprocessed well logs, such as density (DBC), neutron (NBC), short-normal resistivity (SN), or p-wave sonic velocity (PVEL). However, some curves in this block are the result of computational steps devised to obtain estimates of porosity and water content, as explained by Nelson (1996). The segmented curve RHOG represents sequential averages of the available data for grain density from mineralogy (GDMIN) or from core measurements (GDCA). The curve ENPBND is a spline fit to the epithermal neutron curve ENP that removes the effect of rough boreholes in the unsaturated zone—ENPBND can only be seen upon close inspection because it hugs ENP.

Mineralogy, Porosity, and Water Content

The second block contains mineralogy, porosity, and water content. The first column of the second block (column 5 on most plots) contains a whole-rock estimate of mineralogy, in which x-ray diffraction data were converted from weight to volume fraction and then combined with a log-based porosity curve. Short horizontal ticks on the right-hand edge of this column show the locations of samples used for x-ray diffraction analysis. For example, from 450 to 1,250 ft in borehole G1, feldspar is about 0.50, trydimite and cristobalite are about 0.20, porosity (the blank area adjacent to the right-hand scale in column 5) is about 0.25, and other minerals are about 0.05 of rock volume.

Estimates of fractional water content are shown in the second column of the second block (column 6 on most plots), with water content increasing to the left on a scale of 0.0 to 0.6. After correction for borehole effects, the thermal neutron (PHINBC or PHIWNBC) and epithermal neutron (PHIWENP) curves give the total water content as a fraction of total rock volume. An estimate of the fraction of water chemically bound to minerals (PHIZ) is computed from the mineralogical analyses and subtracted from the total water curves, resulting in curves showing the free water fraction (PHINBCZ). Below the water table, porosity is equal to the free-water fraction, but above the water table in the unsaturated zone, part of the pore space is air-filled and the free-water content is less than porosity.

Stratigraphy, Fractures, and Flow

The third block contains stratigraphy, fracture information, welding, and water flow. For each borehole, a geologic report located the formation boundaries and described the degree of welding and other features observed in core and cuttings where core and cuttings were taken. In many boreholes, a complementary hydrologic report documented the results of hydrologic tests undertaken in the borehole. Other specialists reported on the results of televiewer, television, temperature, and sonic-waveform logs. The dip azimuth of fractures (TVRDAZ, TVNDAZ) ranges from 0 to 360 degrees. Undetermined azimuths are plotted in a narrow track to the right of a ZERO line. The small diameter (typically less than 4.25 inches) of the cored G boreholes precluded hydrologic testing; hydrologic tests were carried out in the large diameter (typically 8.75 inches) H and P1 boreholes. Some tests yielded results too complex to show graphically. In these cases, the entries on the plots show only the depth interval of the test (for example, pumping, swabbing, and injection tests in well H3). Some logs can only be run in a water-filled borehole. Thus, there are no sonic (PVEL, SVEL), sonic waveform (WAVEFM), or normal-resistivity (SN, LN) logs available above the top of the static water level (SWL), except in boreholes G1, H1, and GU3 where fluid was added to the borehole to facilitate logging.

Plates for the WT Boreholes

Measurements shown on plates 11–25 for the WT boreholes are listed in table 4. Comparison of table 4 with table 3 shows that the measurement program was more uniform and less comprehensive in the WT boreholes than in the G, H, and P1 boreholes. The dielectric logging tool (DIEL) was the only measurement made in the WT boreholes that was not made in the G, H, and P1 boreholes. A north-south cross section displays partial results for six WT boreholes (pl. 27).

Table 4. Presence (Y) or absence (--) of measurements in the WT boreholes. Column 1 applies to borehole WT1, column 2 to WT2, and so forth.

Measurement type	Curve name	Borehole number for boreholes WT1 through WT18														
		1	2	3	4	6	7	10	11	12	13	14	15	16	17	18
WELL LOGS																
Caliper	CAL	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Bit size	BIT	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Gamma ray	TC	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Density	DBC	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Dielectric	DIEL	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Epithermal Neutron	ENP	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Resistivity	RILD	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Porosity, various	PHI, …	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Water saturation	SW	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
CUTTINGS MEASUREMENTS																
X-ray mineralogy		Y	Y	--	--	--	--	--	--	--	--	--	--	--	--	--
WELL TESTS																
Static water level	SWL	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
GEOLOGIC DESCRIPTION																
Stratigraphic contacts	TOPS	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Degree of welding	WELDNG	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Lithologic description	--	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Fractures from television	TVNFRC	Y	Y	Y	Y	Y	Y	Y	Y	Y	--	Y	Y	Y	Y	Y

The display on each plate for the WT boreholes is organized into three blocks, described as follows.

Original Logs and Fractures

The first block, original logs and fractures, contains geophysical logs that do not require a fluid-filled borehole, namely the caliper, gamma ray, television, density, dielectric, epithermal neutron, and induction resistivity logs. Although core data were lacking for the WT-boreholes, a grain density estimate was required, so the segmented curve RHOG displays values that were assumed based on rock type (Nelson, 1996, p. 20). The curves DBCBND and ENPBND are spline fits to the density and epithermal neutron logs that removes the effect of rough borehole in the unsaturated zone—DBCBND hugs the high side of DBC and ENPBND hugs the low side of ENP.

Porosity and Water Content

The second block displays estimates of water-filled porosity (prefix PHIW), total porosity (prefix PHIT), and water saturation (prefix SW) for the dielectric (suffix DIEL) and epithermal neutron (suffix ENP) logging tools. Plot scales are identical in columns 4 and 5 to facilitate comparison of the two methods of determining porosity and water content. Red and green bars represent interpreted zones of zeolitic alteration (ZEOLZONE) and lithophysae (PHYSZONE), respectively, with each corresponding to the red and green cross hatching between the porosity and water content curves. Mineralogy was determined over parts of boreholes WT1 and WT2 (pls. 11 and 12), but not in any other WT-boreholes.

Stratigraphy

The third block contains graphics for the degree of welding (WELDNG) and number of fractures from the television log (TVNFRC). Geologic descriptions are posted in the right-hand column.

Plates for Two North–South Cross Sections

Selected curves are shown on a north-south cross section that runs along the higher elevation of Yucca Mountain, from five G and H boreholes penetrating both the unsaturated and saturated zone (pl. 26). A second north-south cross section, offset to the east from the first, shows total porosity, water-saturated porosity, and other curves from six WT boreholes that extend to the bottom of the unsaturated zone (pl. 27). Map locations are shown on the plates. Some of the features shown on these cross sections are mentioned in the following discussion.

Outstanding Features

The degree of welding is a primary feature of tuffs, is related to the amount of deformation undergone by a tuff unit during cooling, and is determined by the amount of flattening of pumice fragments. As the degree of welding increases from nonwelded to densely welded, porosity decreases as can be seen by comparing PHITSPLF to WELDNG on the plates. Analysis of the porosity log and degree of welding in borehole G3 determined average porosity values of 40, 30, 19, and 9 percent in nonwelded, poorly welded, moderately welded, and densely welded tuffs, respectively (Nelson, 1993b). In addition, porosity is high in bedded tuffs and low in vitrophyre, with average porosity values of 32 and 7 percent, respectively, for borehole G3 (Nelson, 1993b). Porosity measurements on core samples from boreholes drilled between 1991 and 1998 are tabulated by hydrostratigraphic unit (Flint, 2003) and cannot be compared directly with results on the plates, although the ranges of values are similar.

The degree of welding affected the roughness of the borehole as it was drilled. In particular, the densely welded zone of the Topopah Spring Tuff is brittle, fractured, and has a relatively impermeable matrix so a protective mudcake could not build up. Consequently, this zone produced an especially rough borehole, as can be seen by inspecting the caliper (CAL) log. (Additional details on drilling procedures and their effect on logging are given by Nelson and others (1991)). The density log is susceptible to borehole roughness, especially in an air-filled borehole, as can be seen by the leftward spikes on the density (DBC) logs. Efforts to reduce the rough-borehole effect by bounding and editing the density log were partly successful, but the computed porosity logs in the roughest boreholes (H3, H4, H5, H6, P1, and some WT boreholes) bear the signature of borehole roughness. Consequently, the water-saturation curves, which are computed as the ratio of water content to porosity, also bear the signature of borehole roughness in the densely welded intervals.

In addition to the degree of welding, compaction plays a role in reducing porosity. The depth dependence is best examined in the three deepest boreholes which extend to a total depth of 6,000 ft: borehole G1 (pl. 1), its nearby companion borehole H1 (pl. 5), and borehole G2 (pl. 2). In borehole G1, porosity decreases gradually with depth within the saturated zone, from 30 percent at 2,000 ft in partially to moderately welded tuff, to 5 percent at a depth of 5,800 ft in the pre-Lithic Ridge Tuff (curve PHITSPLF in column 7 of pl. 1). The compaction effect is visible although somewhat less obvious in other boreholes that intersect 4,000 ft or less of tuffs. For example, in borehole P1, porosity decreases from 30 percent at 1,650 ft in unaltered Prow Pass Tuff to 5 percent at 3,720 ft in smectitic, partially welded Tram Tuff (curve PHITENP in column 7 of pl. 10). The effect of compaction on porosity can also be seen in the five-borehole cross section of plate 26.

As expected from the preceding discussion of controls on porosity variations, the logs that respond to porosity are also responding to degree of welding, mineral content, alteration, and depth. Density and sonic-velocity logs, which respond primarily to porosity variations, tend to track variations in the degree of welding. Resistivity is greater in tuffs with a higher degree of welding, but resistivity is also strongly impacted by clays and zeolites, which lower the resistivity. For example, resistivity is less than 10 ohm-m in a high-smectite interval from 3,680 to 3,975 ft in borehole G1 (curves SN and LN in column 3 of pl. 1). The neutron log, as already mentioned, responds to total water content and thus records its highest values in high-porosity zeolitized zones. For example, the highest neutron porosity in borehole G1 is in a highly zeolitized zone at a depth of 1,400–1,750 ft (curve NBC in column 3 of pl. 1).

Lithophysae, which are bubble-like cavities formed by gas expansion in tuff, are a special case of porosity development. In the unsaturated zone, lithophysae are air-filled because their dimensions are too great to hold water by capillary action. Their presence is indicated by “flag” curves from several sources that indicate the presence of lithophysae (for example, LITHPH in G2, PHYSAE in G4, and PHYSZONE in the WT-boreholes). Quantification of porosity contained in lithophysae can be obtained graphically in borehole G4 (column 7 of pl. 4), from 400 to 1,200 ft, by the separation between core porosity (PORCA and PORCN, red squares and red x), which does not sample lithophysal pore space, and total porosity (PHITSPLF, red curve), which does include lithophysal pore space. The separation between the core data and the total porosity curve, which is equivalent to lithophysal porosity, ranges from 5 to 15 percent. Other estimates of lithophysal porosity in borehole G4, from core inspection (DMVS) and the gravimeter (GPOR), range from 5 to 20 percent. In borehole P1 (column 7 of pl. 10), from 330 to 1,000 ft, air-filled porosity is indicated by the green cross hatching between curves PHITENP and PHIWENP. The vertical extent of the lithophysal zones is indicated by the green bars in column 8, and porosity subtended by the green cross hatching is around 10 percent. Similarly, the porosity estimate from the green cross hatching between curves PHITENP and PHIWENP is approximately 10 percent in the upper lithophysal zone of the Topopah Spring Tuff (Tpt) in boreholes H4, H5, and H6 (pls. 7, 8, and 9, respectively), most of which can be attributed to lithophysal pore space. However, air-filled pore space is consistently less than 10 percent in the lower lithophysal zone of the Topopah Spring Tuff, indicating a lesser fraction of lithophysae than in the upper lithophysal zone. A north-south cross section of six boreholes in the unsaturated zone (pl. 27) shows the upper and lower lithophysal zones of the Topopah Spring Tuff to be present throughout much of the site, although the lower zone is not as well defined as the upper zone.

Glass is present in bedded nonwelded tuff units that have not been below water level and altered to zeolites and clays. Zeolitized units are found within the saturated zone or near the top of the static water level (pl. 26). Zeolitized units are characterized by high porosity, total water content greater than porosity, and low resistivity (for example, pl. 6, borehole H3, 1,600–4,000 ft). Vertical red bars on the plates represent intervals interpreted to have substantial fractions of zeolites, based on log response. The spatial relation of glass and zeolite occurrences with the static water level can be examined in the Calico Hills Formation.

The Calico Hills Formation, “a complex series of rhyolitic tuffs and lavas” (Keefer and others, 2007, p. 71), is shown to be vitric (glass) and (or) zeolitic in all boreholes with mineralogical data (for example, see pl. 12, borehole WT2, 1,300–1,600 ft). Inspection of the mineralogy column in the plates shows that glass or zeolite content ranges from 30 to 50 volume percent of rock. Depth ranges, type (glass/zeolitic), and porosity of intervals within the Calico Hills Formation (Tac) were compiled from the plates and posted with water-level elevations for 11 boreholes with mineralogic data (fig. 3). The anomalously high water levels in borehole G2 and nearby WT6 correspond to perched water (LeCain and Stuckless, 2012, p. 46); other water levels in figure 2 represent the static water level. Porosity ranges from 43 to 51 percent in unaltered vitric (glassy) intervals and ranges from 27 to 38 percent in zeolitic intervals (fig. 3), showing that the alteration of glass to zeolite minerals results in a substantial reduction in porosity. The contact between vitric and zeolitic zones in three boreholes—H5, H6, and WT2—lies 300 to 400 ft above the static water level. In other boreholes, with the exception of borehole H4, the base levels of the vitric zones and the tops of the zeolitic intervals are consistent with a vitric-zeolitic contact more than 350 ft above static water level. The vertical extent of the zeolitized interval in borehole G2 reflects an alteration history linked to the presence of perched water. The presence of zeolitic zones hundreds of feet above the present-day water level indicates that water levels at some time in the geologic past were higher than today. This inference is based on the nature of the zeolitization process, as summarized by Keefer and others (2007, p. 64).

> The most extensive post-cooling mineralogic and geochemical change affecting the rocks at Yucca Mountain has been the diagenetic zeolitizaton of nonwelded glassy tuffs. This process involved dissolution of glass shards by groundwater at ambient temperatures (for example, 50°C or lower) and precipitation of clinoptilolite with or without lesser amounts of mordenite, smectite, silica, iron-oxide magnetites and hydroxides, and other minor constituents.

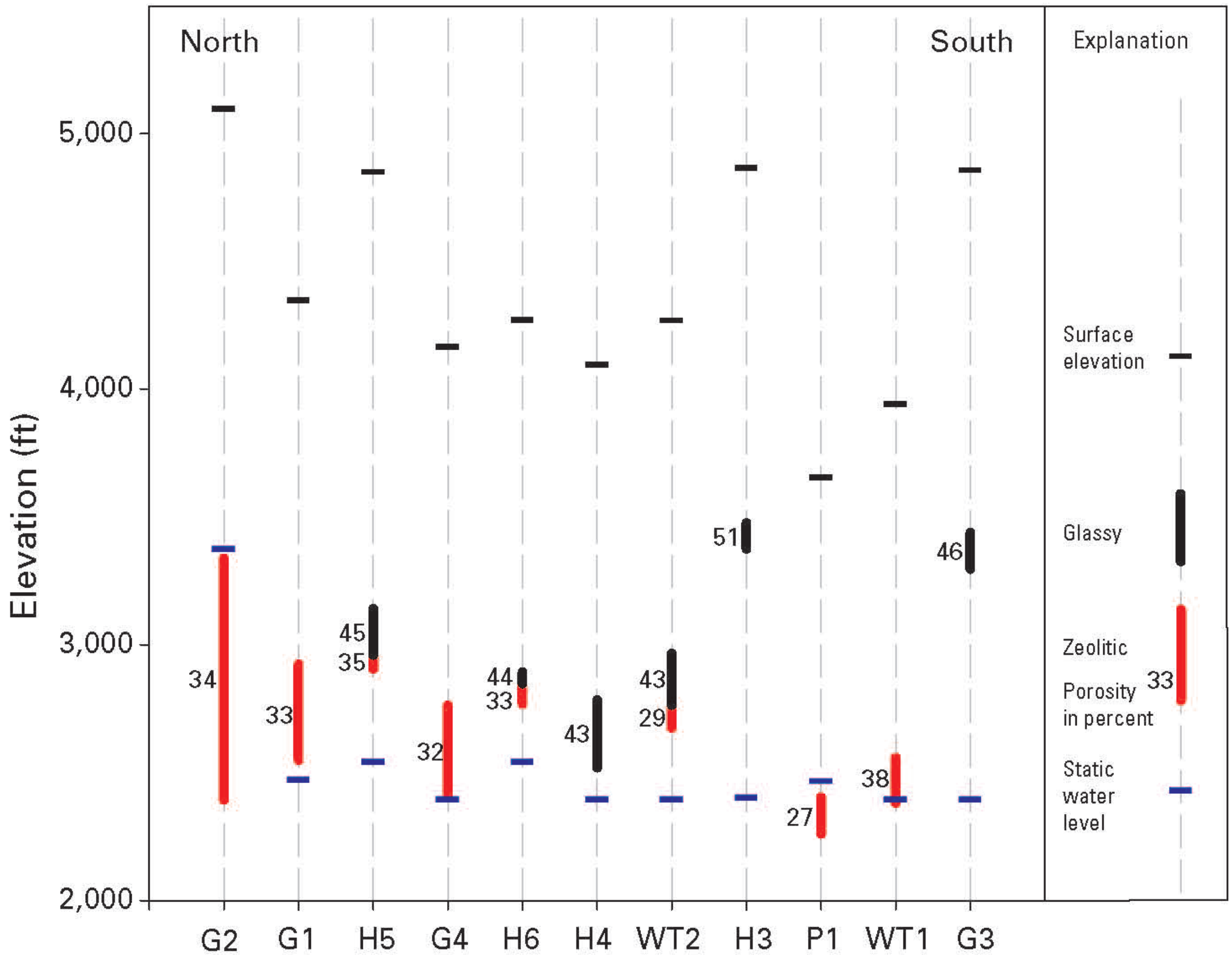


Figure 3. Characteristics of the Calico Hills Formation in 11 boreholes with mineralogical data. Boreholes are ordered from north to south. Borehole G2 is located north of Yucca Mountain and has an anomalously high water level attributed to perched water. Porosity values are higher in tuffs with unaltered glass than in zeolitized zones.

Summary papers on the hydrology of the unsaturated zone (LeCain and Stuckless, 2012) and the saturated zone (Belcher and others, 2012) emphasize the importance of fractures in the movement of water in the subsurface. Those two summary papers, and more detailed studies cited therein, have made use of the hydrologic measurements that are illustrated in the plates of this report. With this perspective, the parameters regarding fractures and water flow listed in tables 3 and 4 and displayed on the plates serve mainly as an index of data gathered in 25 boreholes, and as a visual indicator of planar discontinuities observed in those boreholes. With regard to the latter, fracturing is generally more apparent (longer and throughgoing) in moderately to densely and densely welded zones than in partially welded, nonwelded, or bedded tuffs. Evidence for this comes from the various measures of fracture occurrences, such as fractures observed in core (FRACNO in pl. 3, borehole G3, column 11) and fractures observed in television logs (TVNFRC and TVNDAZ in pl. 7, borehole H4, columns 10 and 11). Fractures appear to be more common within the middle nonlithophysal zone of the Topopah Spring Tuff than in the upper and lower lithophysal zones (pl. 27). There are also many fractures in the lithophysal zones, however, they are not as long or continuous (R. Drake, written commun., 2013). Fractures are also common in the Calico Hills Formation where lavas are present (TVNDAZ and TVNFRC in pl. 23, borehole WT16, columns 1 and 6).

Summary

The primary contribution of this compilation of borehole data is the quantification of porosity and water content on a continuous depth scale, as computed from geophysical logs. These computations depend on logs corrected for calibrations and borehole effects, both of which differ in the saturated and unsaturated zones. Merging of the porosity log with mineralogical data from x-ray diffraction produces a continuous depiction of the volume fractions of mineral composition and porosity. Information from geologic descriptions, fracture-related logs, and well tests were compiled to give a visual inventory of measurements from each of 25 boreholes drilled during the 1979–1984 time period at Yucca Mountain.

An exercise carried out using the data contained in this report demonstrates that meaningful insights can be gained from the plates even though the data are graphical rather than in digital format. A depiction of mineralogy with respect to water-table elevation for the Calico Hills Formation demonstrates the utility of combining disparate datasets (fig. 3). Summary data abstracted from the plates in this report show the spatial relationship of transitions from unaltered to altered tuff with respect to the present-day water levels and allowed inferences to be made concerning diagenesis and past water levels.

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