U.S. Department of the Interior
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Probability Distributions of Hydraulic Conductivity for the Hydrogeologic Units of the Death Valley Regional Ground-Water Flow System, Nevada and California

Water-Resources Investigations Report 02–4212

Prepared in cooperation with the
U.S. DEPARTMENT OF ENERGY
NATIONAL NUCLEAR SECURITY ADMINISTRATION
NEVADA OPERATIONS OFFICE, under
Interagency Agreement DE-AI08-01NV13944

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(Back of Cover)

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By Wayne R. Belcher, Donald S. Sweetkind, and Peggy E. Elliott

U.S. GEOLOGICAL SURVEY

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Carson City, Nevada
2002

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
CHARLES G. GROAT, Director

For additional information contact:

District Chief
U.S. Geological Survey
333 West Nye Lane, Room 203
Carson City, NV 89706–0866

email: GS-W-NVpublic-info@usgs.gov

URL: http://nevada.usgs.gov

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Multiply	By	To obtain
meter (m)	3.2808	foot
meter per day (m/d)	3.2808	foot per day
square kilometer (km^2)	0.3861	square mile

Temperature: Degrees Celsius (^oC) can be converted to degrees Fahrenheit (^oF) by using the formula $^oF = [1.8(^oC)]+32$.
Degrees Fahrenheit can be converted to degrees Celsius by using the formula $^oC = 0.556(^oF-32)$.

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929, formerly called “Sea-Level Datum of 1929”), which is derived from a general adjustment of the first-order leveling networks of the United States and Canada.

ACRONYMS USED IN THIS REPORT

AA	Alluvial aquifer
ACU	Alluvial confining unit
BRU	Belted Range unit
CFBCU	Crater Flat-Bullfrog confining unit
CFPPA	Crater Flat-Prow Pass aquifer
CFTA	Crater Flat-Tram aquifer
CHVU	Calico Hills volcanic unit
DVRFS	Death Valley regional ground-water flow system
HGU	Hydrogeologic unit
ICU	Intrusive confining unit
LCA	Lower carbonate aquifer
LCCU	Lower clastic confining unit
LFU	Lava flow unit
NTS	Nevada Test Site
OVU	Older volcanics unit
PVA	Paintbrush volcanic aquifer
SCU	Sedimentary confining unit
TMVA	Thirsty Canyon/Timber Mountain volcanic aquifer
TV	Tertiary volcanics
UCA	Upper carbonate aquifer
UCCU	Upper clastic confining unit
VSU	Volcaniclastics and sediments unit
WVU	Wahmonie volcanic unit
YVU	Younger volcanic unit
XCU	Crystalline confining unit

PROBABILITY DISTRIBUTIONS OF HYDRAULIC CONDUCTIVITY FOR THE HYDROGEOLOGIC UNITS OF THE DEATH VALLEY REGIONAL GROUND-WATER FLOW SYSTEM, NEVADA AND CALIFORNIA

By Wayne R. Belcher, Donald S. Sweetkind, and Peggy E. Elliott

ABSTRACT

The use of geologic information such as lithology and rock properties is important to constrain conceptual and numerical hydrogeologic models. This geologic information is difficult to apply explicitly to numerical modeling and analyses because it tends to be qualitative rather than quantitative. This study uses a compilation of hydraulic-conductivity measurements to derive estimates of the probability distributions for several hydrogeologic units within the Death Valley regional ground-water flow system, a geologically and hydrologically complex region underlain by basin-fill sediments, volcanic, intrusive, sedimentary, and metamorphic rocks. Probability distributions of hydraulic conductivity for general rock types have been studied previously; however, this study provides more detailed definition of hydrogeologic units based on lithostratigraphy, lithology, alteration, and fracturing and compares the probability distributions to the aquifer test data. Results suggest that these probability distributions can be used for studies involving, for example, numerical flow modeling, recharge, evapotranspiration, and rainfall runoff. These probability distributions can be used for such studies involving the hydrogeologic units in the region, as well as for similar rock types elsewhere.

Within the study area, fracturing appears to have the greatest influence on the hydraulic conductivity of carbonate bedrock hydrogeologic units. Similar to earlier studies, we find that alteration and welding in the Tertiary volcanic rocks greatly influence hydraulic conductivity. As alteration increases, hydraulic conductivity tends to decrease. Increasing degrees of welding appears to increase hydraulic conductivity because welding increases the brittleness of the volcanic rocks, thus increasing the amount of fracturing.

INTRODUCTION

The U.S. Geological Survey (USGS) is developing a three-dimensional ground-water flow model of the Death Valley regional ground-water flow system (DVRFS). This area lies within the southern Great Basin section of the Basin and Range physiographic province and surrounds both the Nevada Test Site (NTS), where nuclear weapons tests have contaminated the ground water beneath some areas, and Yucca Mountain, which is being investigated for its suitability for permanent storage of high-level nuclear waste in a mined geologic repository. As a result of this area’s importance and intensive studies, an extensive geologic and hydrologic data set exists for a large, regional system.

Bedinger and others (1989) produced a series of probability distributions for rock types common to the Basin and Range physiographic province. Data used to prepare these distributions consisted of published field and laboratory tests within the Basin and Range province, as well as general studies from rocks with similar characteristics from outside the Basin and Range province (Bedinger and others, 1989, p. 18). This work differs in that we use only compiled field data for the rock types found in the region. This study uses the hydrogeologic unit assignments based on Laczniak and others (1996) developed at the NTS, and thus is more detailed than the regional definitions provided by Bedinger and others (1989). Hydrogeologic units are rock units grouped according to their water-storage and transmissive properties (Laczniak and others, 1996). Relations between secondary processes such as fracturing and alteration that affect measured hydraulic conductivity also are examined.

Location

The DVRFS is in southeastern California and Nevada (fig. 1). The DVRFS encompasses about 45,000 km^2 within the Great Basin section of the Basin and Range physiographic province. The area for this study is considerably larger than the DVRFS in order to include areas that contain sites important to defining hydraulic-property estimates for units contained within the DVRFS. The topography typically consists of northerly and northwesterly trending mountain ranges surrounded by broad sediment-filled basins. The Spring Mountains, the highest topographic feature in the area, are about 3,600 m above mean sea level. Other prominent topographic features within the region include the Sheep Range, Pahute Mesa, the Funeral Mountains, and the Panamint Range. Basins generally decrease in altitude from north to south. The lowest altitude at 86 m below sea level in the study area is at Badwater in Death Valley National Park.

Purpose and Scope

The purpose of this report is to present statistical-probability distributions that can be used by hydrologists to constrain hydraulic-conductivity estimates in their studies. These distributions could be useful for hydrologic studies involving numerical simulations of ground water, recharge, rainfall runoff, evapotranspiration, basin analyses, and water budgets. Other uses of the distributions could include contaminant-transport modeling, water-supply issues, and resource protection. The probability distributions also could be used to apply the principle of parsimony (Hill, 1998, p. 35) to simulation efforts. Specifically, the work presented in this report is for use in a transient numerical ground-water flow model of the DVRFS, but because of the diversity of rock types within the study area, these distributions may be useful to flow modelers in other regions and other types of studies for which hydraulic-conductivity information is required.

Limitations

The analyses in this report have several limitations:

1. The hydraulic-conductivity measurements presented in this report are based mostly on the results of field-scale tests and represent a very small part of an overall regional HGU. Lithologic factors that can affect hydraulic conductivity, such as facies changes in sedimentary rock, welding and alteration in volcanic rocks, and degree of fracturing can cause hydraulic properties to vary greatly, even over relatively short distances.

2. Significant spatial bias may exist in the hydraulic-conductivity measurements. Wells tested for aquifer properties were installed to meet the objectives of their parent studies or to provide an adequate water supply, not necessarily to provide adequate spatial coverage for a regional study.

3. Transmissivity measurements from aquifer tests were divided by a thickness value to obtain hydraulic conductivity. The length of the open interval of the well or borehole was used to calculate hydraulic conductivity from this transmissivity. This is a simplistic assumption. If the thickness of the rock or sediment contributing flow is less than the open interval, the hydraulic conductivity will be underestimated, and if the thickness is greater than the open interval, the hydraulic conductivity will be overestimated.

4. Hydraulic-conductivity estimates in heterogeneous aquifers can be biased above the average hydraulic conductivity because many wells are screened preferentially across more productive intervals.

Acknowledgments

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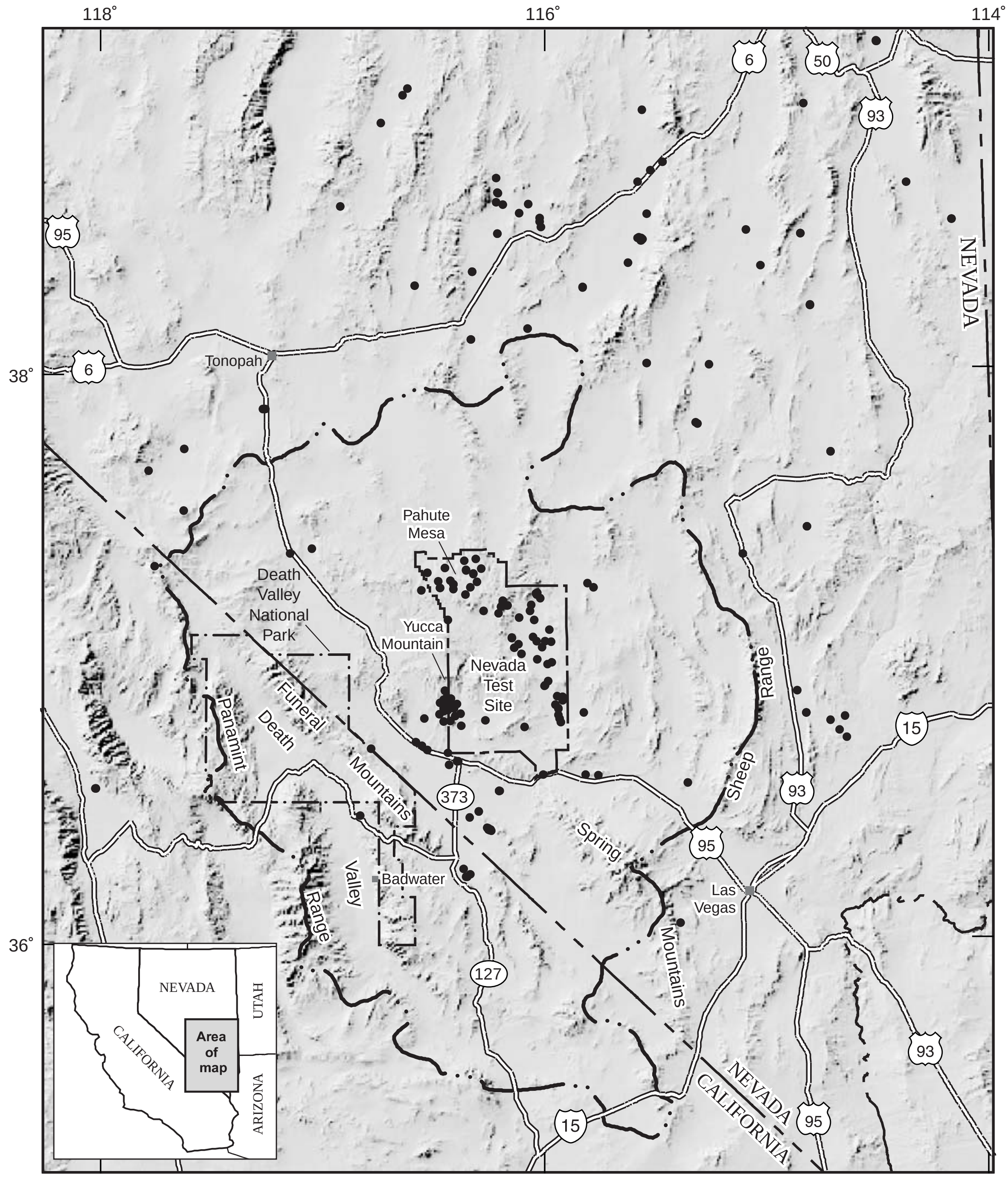

Base from U. S. Geological Survey digital data 1:100,000–scale, 1978–89
Universal Transverse Mercator Projection Zone 11
Shaded relief base from 1:250,000–scale Digital Elevation Model
Sun illumination from northwest at 45 degrees above horizon

0 15 30 60 MILES
0 15 30 60 KILOMETERS

EXPLANATION

— · · — **Boundary of Death Valley Ground-Water System**

● **Well**

Figure 1. Location map of study area.

HYDROGEOLOGIC SETTING

Regional Overview

The study area includes a stratigraphically diverse and structurally complex region in which a thick Tertiary volcanic and sedimentary section unconformably overlies previously deformed Proterozoic through Paleozoic rocks. The stratigraphic framework of the DVRFS consists of a Late Proterozoic through Middle Cambrian wedge of continental siliciclastic rocks, overlain by a thick Middle Cambrian through Middle Devonian carbonate-dominated succession. These carbonate rocks form the major regional carbonate-rock aquifer where ground water flows from central Nevada, through the NTS toward discharge sites in Ash Meadows and Death Valley to the south (Winograd and Thordarson, 1975; Bedinger and others, 1989; Dettinger, 1989). The carbonate sequence is interrupted by Upper Devonian through Mississippian synorogenic clastic and carbonate rocks that form a locally important confining unit near the NTS (Winograd and Thordarson, 1975; Laczniak and others, 1996; D'Agnese and others, 1997). Mesozoic siliciclastic and intrusive rocks are only locally present in the region. Overlying the older rocks are locally thick Oligocene to Pliocene fluvial, paludal, and playa sedimentary rocks, a thick sequence of regionally distributed welded and nonwelded tuffs (which form important bedrock aquifers at the NTS), more locally distributed lava flows with associated intrusive rocks, and overlying Pleistocene to recent alluvium, eolian deposits, and spring discharge deposits (Grose and Smith, 1989, p. 10). All of these rocks have been deformed by complex Neogene extensional normal and strike-slip faults that are superimposed on late Paleozoic to mid-Mesozoic folds and thrusts (Stewart, 1978; Mifflin, 1988). The stratigraphic and structural complexity of the region results in a close spatial relation of diverse rock types and deformational styles; individual HGUs have widely varying physical properties and hydraulic conductivities as a result of variable primary and secondary porosity and permeability.

In the southern Great Basin hydraulic connection between basins is maintained through unconsolidated sediments that were deposited across low topographic divides between the basins and by deep interbasin flow beneath valley floors and adjacent ranges through fractured Paleozoic carbonate rocks (Winograd and Thordarson, 1975; Prudic and others, 1995). Faults and related fractures typically enhance ground-water flow through bedrock aquifers (Faunt, 1997), however, faults also disrupt stratigraphic continuity, which can divert water in regional circulation to local and subregional outlets.

Hydrogeologic Units

The rocks and unconsolidated deposits that form the framework for a ground-water flow system are termed hydrogeologic units (HGUs). HGUs are assigned to a unit that has considerable lateral extent and reasonably distinct hydrologic properties because of its geological and structural characteristics. The distinction between aquifers and confining units in basin-fill sediments is closely related to primary lithologic variations; whereas, the hydraulic properties of competent rocks often are related to observations and assumptions of the degree to which stratigraphic units are fractured. These physical characteristics were used to group geologic formations of hydrologic significance in the vicinity of the NTS into HGUs (Winograd and Thordarson, 1975). Winograd and Thordarson originally defined seven HGUs in the DVRFS region. These assignments formed the basis of HGUs used by subsequent regional modeling studies (D'Agnese and others, 1997; U.S. Department of Energy, 1997). A refinement of the HGU assignments by Laczniak and others (1996) form the basis for the 10 main HGUs (plus several subcategories of these HGUs) used in this report. The geologic units comprising the hydrogeologic units discussed in this report are fully discussed in Belcher and others (2001, table 1).

DATA ANALYSIS AND SYNTHESIS

The 930 hydraulic-conductivity measurements used in this study were compiled by Belcher and others (2001) from published and some previously unpublished hydraulic-property measurements for hydrogeologic units within the study area. Only field-aquifer tests were considered in this compilation, excepting the quartzites of the lower clastic confining unit. The limited number of hydraulic-conductivity estimates from aquifer tests for this particular unit were augmented with estimates from permeameter results.

Estimating Probability Distributions

The logarithmically transformed values of hydraulic conductivity were used for statistical calculations because this parameter tends to be normally distributed (Neuman, 1982). The Cunnane plotting position method was used to assess the normality of the logarithms of hydraulic-conductivity measurements used for each HGU or HGU subcategory (Helsel and Hirsch, 1992, p. 27–29). The assumption of a normal distribution for log-transformed hydraulic conductivity was true. The probability plots for the combined upper and lower clastic confining units and the quartzites of the lower clastic confining unit were influenced by high outliers in the lower clastic confining unit. These data are from rare pumping tests, probably in highly fractured areas with enhanced permeability, and likely atypical. Field tests sample a greater volume of rock types than laboratory tests, thus, these results are more appropriate for application to a regional-scale numerical model. The geometric and arithmetic means, range, and the 95-percent confidence intervals are listed in tables 1 and 2.

To compare the probability distributions of the log hydraulic conductivity for each HGU the data were normalized (Davis, 1986, p. 46–50). To compute the normalized values, the following equation (Davis, 1986, p. 48) was used:

$$Z = \frac{X - \bar{X}}{s} ,$$

where

Z is the normalized value,

X is the observation (in this case log hydraulic conductivity),

$\bar{X}$ is the mean of the log-transformed observations (or the geometric mean), and

s is the standard deviation of the log-transformed observations.

The normalized values represent how many standard deviations particular values of log hydraulic conductivity are away from the geometric mean. The log hydraulic conductivities were plotted as a lognormal distribution by plotting the resulting distributions as a straight-line plot on log-probability coordinates. The distribution for the HGUs (and subcategories) was drawn using the spread plus or minus three standard deviations for log hydraulic-conductivity values reported for each HGU. These values correspond to the spread from 0.1 to 99.9 percentiles of the range of values reported in Belcher and others (2001). The geometric mean of the log hydraulic conductivity is at the 50-percentile value and the majority of the values were included in the range on either side of the mean (plus or minus two standard deviations).

Statistical Hypothesis Testing

Statistical hypothesis testing on the differences of the geometric means between the groupings of HGUs was performed. The large or small sample size with differing variances test was used (as appropriate), with the level of significance being 0.05 (Mendenhall and Sinich, 1988, p. 376–378). The null hypothesis, that there is no difference between the geometric means, and the alternate corollary hypothesis, that a statistically significant difference exists, were tested. The results of the hypothesis testing are listed in tables 3–9.

PROBABILITY DISTRIBUTIONS

Basin-Fill Hydrogeologic Units

The probability distributions of the hydraulic conductivity of the basin-fill hydrogeologic units are shown in figure 2. Units considered include: (1) a coarse, unconsolidated alluvial aquifer (AA), includes the older alluvial and younger alluvial aquifers (Belcher and others, 2001); (2) an alluvial confining unit (ACU) consisting predominantly of silt and clay playa deposits; and (3) undifferentiated basin filling of younger volcanic rocks (YVU) and Tertiary volcaniclastic and sedimentary rocks (VSU) are presented as combined data. The combined YVU/VSU unit shows a distinctly lower distribution of hydraulic conductivity than either the AA or the ACU (fig. 2). This result may be from the unconsolidated nature of the AA which gives it a greater hydraulic conductivity, coupled with a decrease in hydraulic conductivity of the older sedimentary and volcaniclastic rocks due to zeolitic alteration of the volcanic component. The hydraulic-conductivity values for the ACU are problematic, because these values generally are greater than those of the AA. This is probably an indication that the wells in which aquifer tests were performed may be from more permeable parts of the ACU. The ACU as defined by Belcher and others (2001) includes lacustrine carbonates that are locally productive aquifers (Dudley and Larson, 1976). The hypothesis testing confirms that the geometric mean of the ACU is similar to the AA and that the YVU/VSU unit is distinct from both the ACU and the AA (table 3).

Table 1. Horizontal hydraulic-conductivity estimates of hydrogeologic units in the Death Valley regional ground-water flow system

[**Acronyms**: AA, alluvial aquifer; ACU, alluvial confining unit; BRU, Belted Range unit; CFBCU, Crater Flat-Bullfrog confining unit; CFPPA, Crater Flat-Prow Pass aquifer; CFTA, Crater Flat-Tram aquifer; CHVU, Calico Hills volcanic unit; ICU, intrusive confining unit; LCA, lower carbonate aquifer; LCCU, lower clastic confining unit; LFU, lava flow unit;NA, not applicable; OVU, older volcanic rocks unit; PVA, Paintbrush volcanic aquifer; SCU, sedimentary rocks confining unit; TMVA, Thirsty Canyon/Timber Mountain volcanic aquifer; TV, Tertiary volcanic rocks; UCA, upper carbonate aquifer; UCCU, upper clastic confining unit; VSU, volcaniclastic and sedimentary rocks unit; YVU, younger volcanic rocks unit. **Note**: Geometric mean and standard deviation are back-transformed from logarithmic values]

Hydrogeologic unit or subunit	Hydraulic conductivity, in meters per day				95-percent confidence interval	Number of measurements
	Geometric mean	Arithmetic mean	Minimum K	Maximum K		
AA	1.5	10.8	0.00006	130	0.005 - 430	52
ACU	3	10.5	0.003	34	0.02 - 470	15
LFU	NA	NA	0.002	4	NA	2
YVU/VSU	0.06	1.5	0.00004	6	0.00005 - 80	15
TV	0.12	3.9	0.000002	180	0.0002 - 78	172
TMVA	0.01	2	0.0002	20	0.00001 - 18	11
PVA	0.02	4	0.000007	17	0.0000003 - 1,300	9
CHVU	0.2	0.55	0.008	2	0.007 - 5	14
BRU	0.3	1.03	0.01	4	0.006 - 17	6
CFTA	0.05	0.4	0.003	2	0.0004 - 5.3	11
CFBCU	0.4	6.8	0.0003	55	0.0006 - 240	34
CFPPA	0.3	13	0.001	180	0.000006 - 2.4	19
OVU	0.004	0.07	0.000001	1	0.00002 - 5	46
ICU	0.01	0.3	0.0006	1.4	0.00002 - 5	7
SCU	0.002	0.02	0.0002	0.3	0.00004 - 0.09	16
UCA and LCA	2.5	90	0.0001	820	0.0008 - 7,700	53
fractured	19	150	0.01	820	0.03 - 11,000	32
unfractured	0.1	1.6	0.0001	14	0.0002 - 70	21
UCCU and LCCU	0.00002	0.2	0.00000003	5	0.0000000001 - 3	29
shale	0.01	0.07	0.0002	0.4	0.0001 - 1.4	9
quartzite	0.000001	0.24	0.00000003	5	0.0000000001 - 0.006	19

Table 2. Horizontal hydraulic-conductivity estimates of volcanic rock hydrogeologic units in the Death Valley regional ground-water flow system

[Geometric mean and standard deviation are back-transformed from logarithmic values]

Hydrogeologic unit or subunit	Hydraulic conductivity, in meters per day				95-percent confidence interval	Number of measurements
	Geometric mean	Arithmetic mean	Minimum K	Maximum K		
Lava flows	0.13	0.63	0.000007	4	0.0005 - 31	25
Ash-flow tuff	0.12	5.3	0.000002	180	0.0002 - 97	109
Non-welded to partially welded	0.06	6.6	0.0003	180	0.0002 - 24	43
Partially to moderately welded	0.04	1.1	0.000002	19	0.00003 - 50	35
Moderately to densely welded	1.6	13.3	0.02	55	0.005 - 540	7
Tuff breccia	0.31	4.2	0.0008	15	0.0002 - 550	11
Bedded tuff	0.14	2	0.00009	15	0.0003 - 57	14
Unaltered tuffs	0.4	8.1	0.00002	180	0.0006 - 260	71
Altered tuffs	0.04	1.3	0.000002	25	0.0001 - 15	63

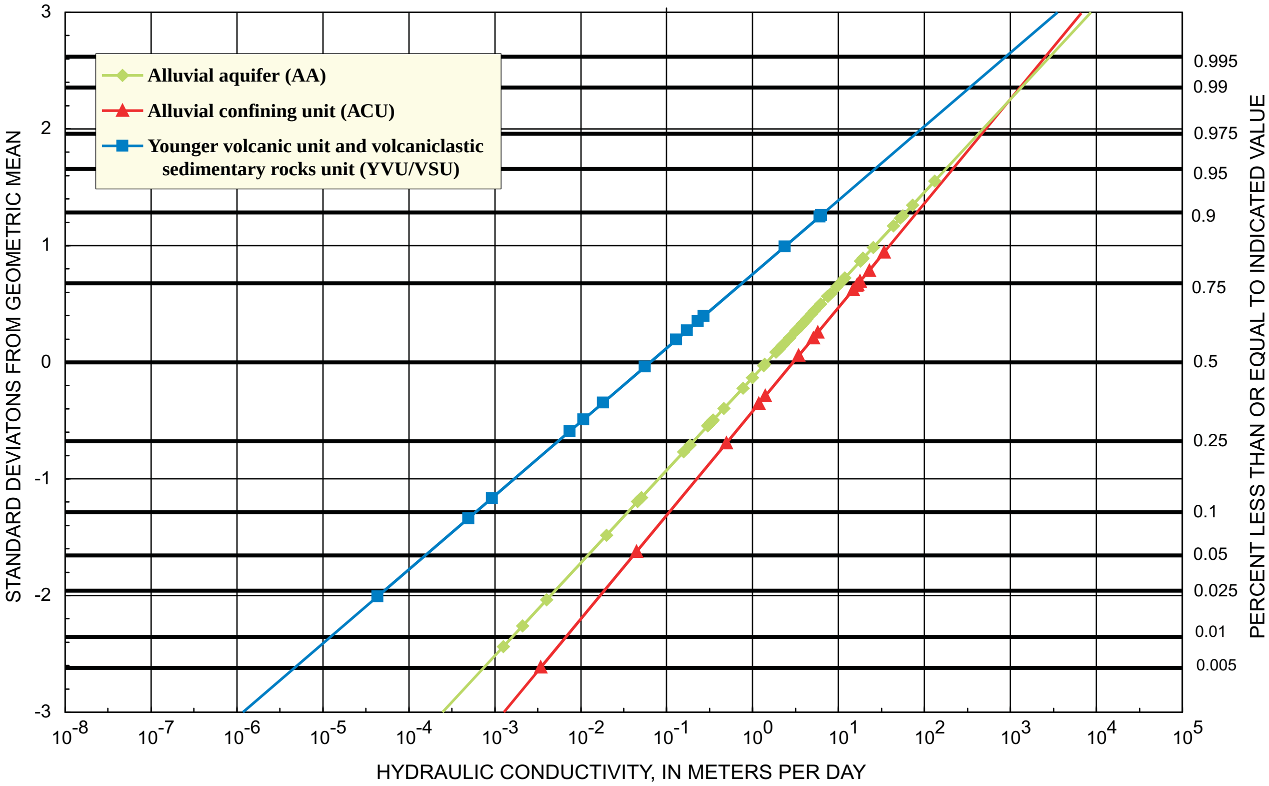

Figure 2. Hydraulic-conductivity distributions for basin-fill hydrogeologic units.

Table 3. Results of hypothesis testing for basin-fill hydrogeologic units

[**Acronyms**: AA, alluvial aquifer; ACU, alluvial confining unit; VSU, volcaniclastic and sedimentary rocks unit; YVU, younger volcanic rocks unit. **Abbreviations**: NR, non-rejection of the null hypothesis; R, rejection of the null hypothesis. **Note**: Hydrogeologic units in column heading are being compared to those in row heading]

Null hypothesis: $\mu_1 - \mu_2 = 0$

Alternate hypothesis: $\mu_1 - \mu_2 \neq 0$

	AA	ACU	YVU/VSU
AA	--	NR	R
ACU	NR	--	R
YVU/VSU	NR	R	--

Bedrock Confining Hydrogeologic Units

Regional bedrock confining units include (1) a lower clastic confining unit (LCCU) of Late Proterozoic through Lower Cambrian fine- to coarse-grained quartzite, siltstone, and conglomeratic sandstone; (2) an upper clastic confining unit (UCCU) consisting of Upper Devonian through Mississippian fine-grained clastic and carbonate rocks; (3) an intrusive confining unit (ICU) consisting of Cretaceous and Tertiary granitic rocks; and (4) a sedimentary rock confining unit (SCU) consisting of Mesozoic cratonic sedimentary rocks (Winograd and Thordarson, 1975; Belcher and others, 2001). The thick, regionally distributed rocks of the LCCU show some of the lowest hydraulic-conductivity measurements (fig. 3). As suggested by the hypothesis testing, the LCCU is distinct from the other confining units. The hydraulic conductivities of the UCCU, SCU, and ICU all have similar distributions (fig. 3), as confirmed by the hypothesis testing (table 4). Greater than expected hydraulic conductivities of the crystalline rocks of the ICU may be due to significant fracture permeability in these granites. Data for the distribution of the crystalline confining unit (XCU) were unavailable (Belcher and others, 2001).

Carbonate Rock Hydrogeologic Units

The distributions for the carbonate rocks, which form a regional aquifer in the DVRFS are shown in figure 4. Outcrop and drill-hole observations and hydraulic-test data indicate that large hydraulic conductivities within the regional carbonate aquifer are often the result of secondary fracturing and dissolution (Winograd and Thordarson, 1975, p. C14–C30). Aquifer-test data from the carbonate rocks were subdivided and statistically summarized to evaluate differences in hydraulic conductivity for rocks with extensive fracturing and rocks without extensive fracturing (fig. 4). These designations were assessed from descriptions given on lithologic logs from wells included in the aquifer tests (fig. 4). Extensive fracturing can increase hydraulic conductivity values in the carbonate rocks. The hypothesis testing confirms that the geometric means of the fractured and unfractured carbonate are not equal; the differences between all carbonates and unfractured carbonates also are not equal (table 5).

Volcanic Rock Hydrogeologic Units

The Tertiary volcanic rocks were divided on the basis of lithostratigraphy (Sawyer and others, 1994; Slate and others, 2000) into the following units: Thirsty Canyon/Timber Mountain volcanic aquifer (TMVA), Paintbrush volcanic aquifer (PVA), Calico Hills volcanic unit (CHVU), Wahmonie volcanic Unit (WVU), Belted Range unit (BRU), Crater Flat-Bullfrog confining unit (CFBCU), Crater Flat-Prow Pass aquifer (CFPPA), Crater Flat-Tram aquifer (CFTA), and older volcanic unit (OVU). Each of these hydrogeologic units constitutes a variety of volcanic rocks with widely differing material properties such as lithology, degree of alteration, and degree of welding that vary both vertically and spatially (Blankennagel and Weir, 1973; Winograd and Thordarson, 1975). The hydraulic-conductivity distributions of these volcanic units overlap (fig. 5), as expected due to variations in lithology, alteration, and welding within individual HGUs. The hypothesis testing indicates that various units appear to have statistically significantly different geometric means while others are not statistically different (table 6). The WVU is not in figure 5 or in table 6, because no aquifer tests were reported for this unit (Belcher and others, 2001).

The Tertiary volcanic rocks were examined for the influence of lithology on hydraulic conductivity (table 2; fig. 6). Four lithologic groups were considered: (1) ash-flow tuffs; (2) lava flows of rhyolite, rhyodacite, and trachyte; (3) tuff breccia; and (4) bedded tuff. The distribution shown in figure 6 suggests that lithology of the Tertiary volcanic units, as defined in lithologic logs, is not an important factor for controlling hydraulic conductivity. The hypothesis testing confirms that the geometric means are not statistically different between any of the lithologies of the Tertiary volcanic rocks (table 7).

Hydraulic-conductivity measurements for ash-flow tuffs were divided into three categories to assess the effect of welding (table 2) based on descriptions from borehole lithologic logs (Warren and others, 1998). These three categories are (1) non-welded to partially welded tuff; (2) partially to moderately welded tuff; and (3) moderately to densely welded tuff. Degrees of welding straddling these categories, such as non-welded to densely welded tuff, were omitted from this analysis. Descriptions of welding including only a single category were placed in the lower category (for example, all intervals described as “partially welded”

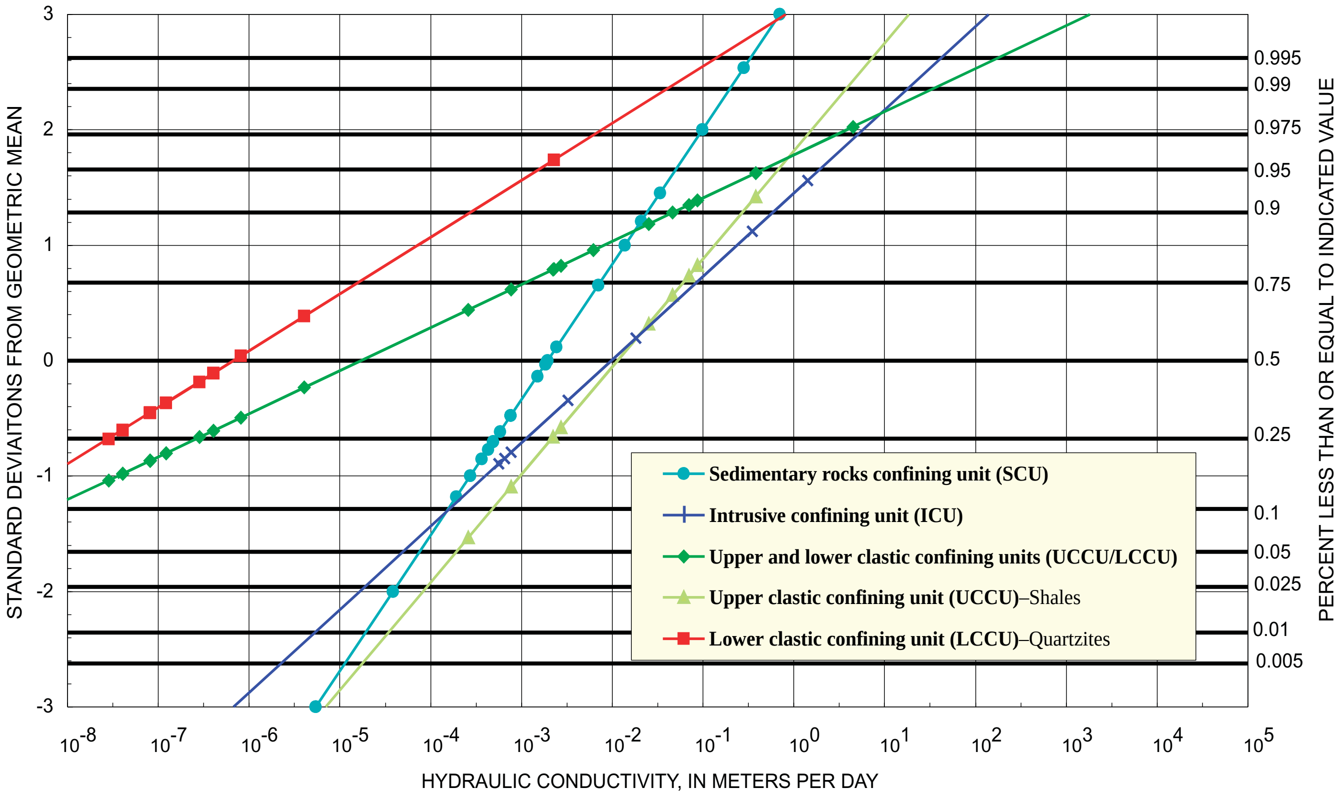

Figure 3. Hydraulic-conductivity distributions for regional bedrock confining hydrogeologic units.

Table 4. Results of hypothesis testing for bedrock confining units

[**Acronyms**: ICU, intrusive confining unit; LCCU, lower clastic confining unit; SCU, sedimentary rocks confining unit; UCCU, upper clastic confining unit. **Abbreviations**: NR, Non-rejection of null hypothesis; R, Rejection of null hypothesis; **Note**: Hydrogeologic units in column heading are being compared to those in row heading]

Null hypothesis: $\mu_1 - \mu_2 = 0$

Alternate hypothesis: $\mu_1 - \mu_2 \neq 0$

	SCU	**ICU**	**UCCU/LCCU**	**UCCU**	**LCCU**
SCU	--	NR	R	NR	R
ICU	NR	--	R	NR	R
UCCU/LCCU	R	R	--	R	R
UCCU	NR	NR	R	--	R
LCCU	R	R	R	R	--

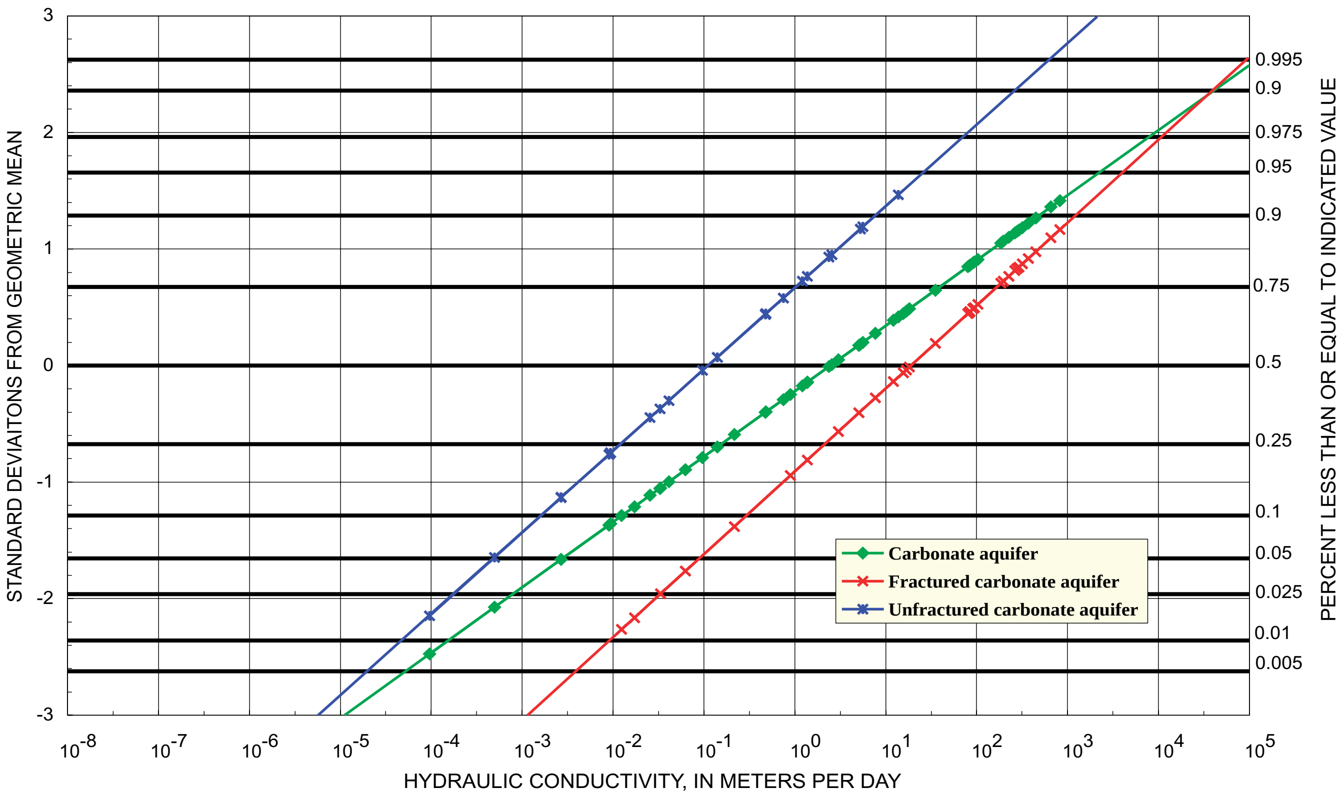

Figure 4. Hydraulic-conductivity distributions for carbonate rock hydrogeologic units.

Table 5. Results of hypothesis testing for carbonate rocks

[**Abbreviations**: NR, non-rejection of the null hypothesis; R, rejection of the null hypothesis.
Note: Hydrogeologic units in column heading are being compared to those in row heading]

Null hypothesis: $\mu_1 - \mu_2 = 0$

Alternate hypothesis: $\mu_1 - \mu_2 \neq 0$

	Carbonate (all)	Fractured carbonates	Unfractured carbonates
Carbonates (all)	--	NR	R
Fractured carbonates	NR	--	R
Unfractured carbonates	NR	R	--

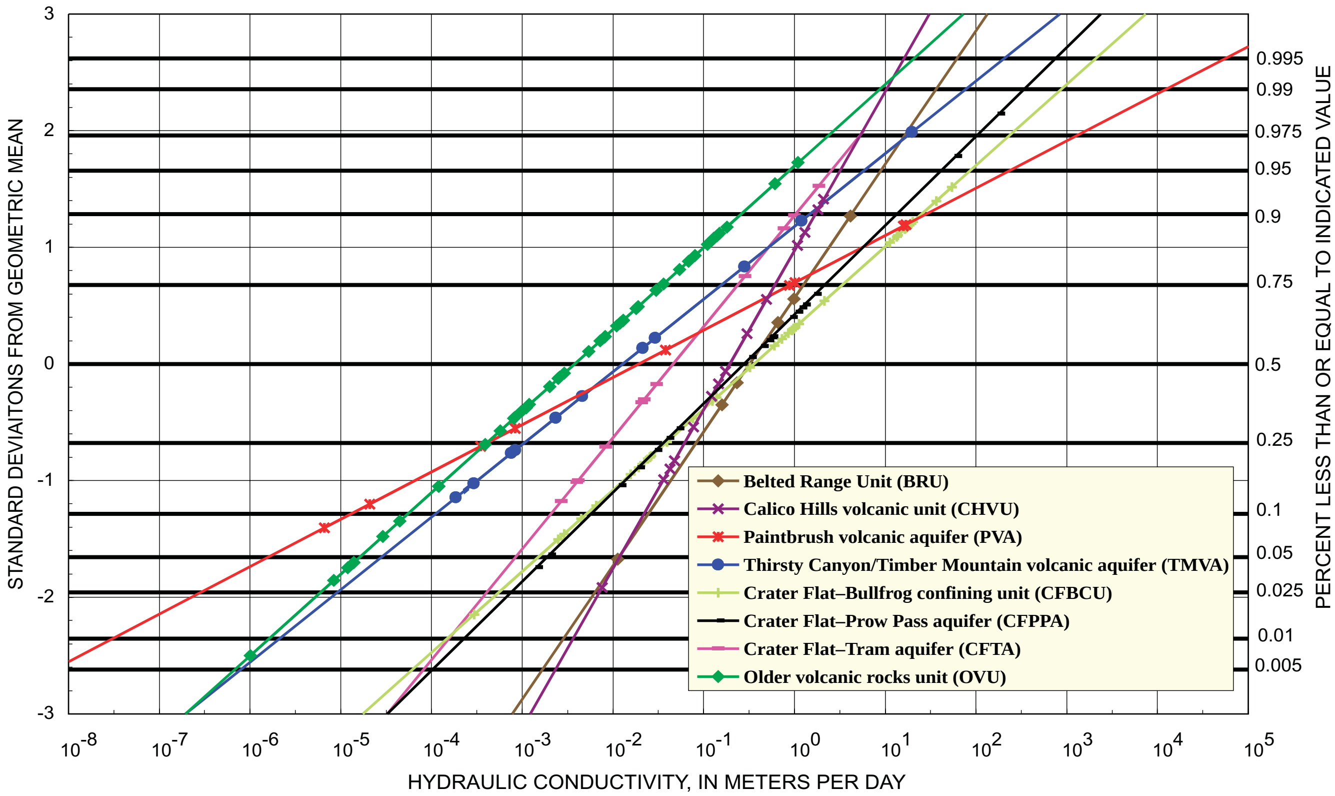

Figure 5. Hydraulic-conductivity distributions for Tertiary volcanic rock hydrogeologic units.

Table 6. Results of hypothesis testing for Tertiary volcanic rock hydrogeologic units

[**Acronyms**: BRU, Belted Range unit; CFBCU, Crater Flat-Bullfrog confining unit; CFPPA, Crater Flat-Prow Pass aquifer; CFTA, Crater Flat-Tram aquifer; CHVU, Calico Hills volcanic unit; OVU, older volcanic rocks unit; PVA, Paintbrush volcanic aquifer; TMVA, Thirsty Canyon/Timber Mountain volcanic aquifer. **Abbreviations**: NR, non-rejection of null hypothesis; R, rejection of null hypothesis. **Note**: Hydrogeologic units in column heading are being compared to those in row heading]

Null hypothesis: $\mu_1 - \mu_2 = 0$

Alternate hypothesis: $\mu_1 - \mu_2 \neq 0$

	BRU	CHVU	PVA	TMVA	CFBCU	CFPPA	CFTA	OVU
BRU	---	NR	NR	R	NR	NR	NR	R
CHVU	NR	---	NR	R	NR	NR	NR	R
PVA	NR	NR	---	NR	NR	NR	NR	NR
TMVA	R	R	NR	---	R	R	NR	NR
CFBCU	NR	NR	NR	R	---	NR	R	R
CFPPA	NR	NR	NR	R	NR	---	NR	R
CFTA	NR	NR	NR	NR	R	NR	---	R
OVU	R	R	NR	NR	R	R	R	---

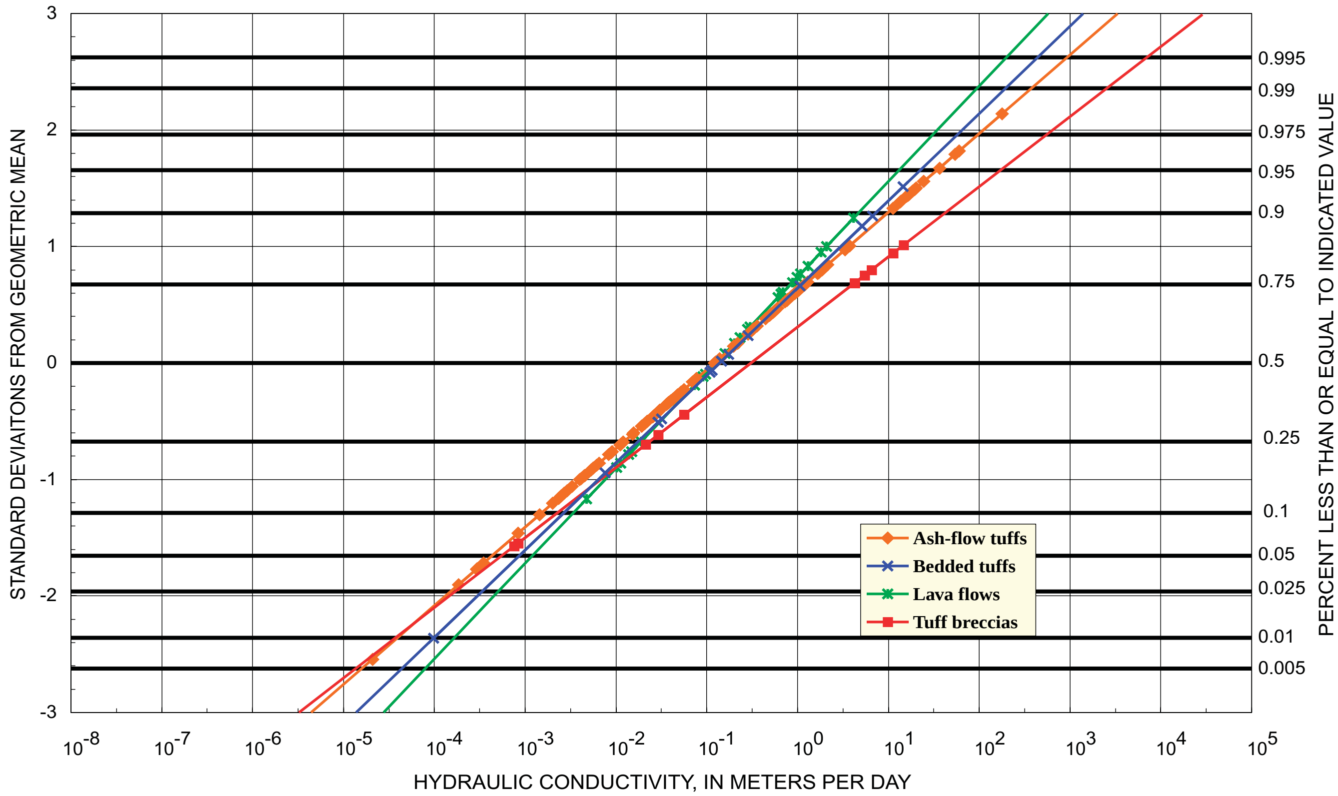

Figure 6. Hydraulic-conductivity distributions for Tertiary volcanic rock lithologies.

Table 7. Results of hypothesis testing for Tertiary volcanic rock lithologies

[**Abbreviation**: NR, non-rejection of the null hypothesis. **Note**: Hydrogeologic units in column heading are being compared to those in row heading]

Null hypothesis: $\mu_1 - \mu_2 = 0$

Alternate hypothesis: $\mu_1 - \mu_2 \neq 0$

	Ash-flow tuffs	**Bedded tuffs**	**Lava flows**	**Tuff breccias**
Ash-flow tuffs	--	NR	NR	NR
Bedded tuffs	NR	--	NR	NR
Lava flows	NR	NR	--	NR
Tuff breccias	NR	NR	NR	--

only were included in the non-welded to partially welded tuff category). The hydraulic conductivity of ash-flow tuffs generally increases as the degree of welding increases (fig. 7). The non-welded to partially welded and the partially welded to moderately welded tuff categories appear to have lower overall values of hydraulic conductivity than the moderately welded to densely welded tuff category. The overlap of the hydraulic conductivity distributions for the two lesser-welded tuff groups may be an artifact of overlaps occurring in the reporting of the degree of welding present in the tested interval of the aquifer tests. Hypothesis testing confirms that the geometric means are not statistically different between the non-welded to partially welded and partially welded to moderately welded tuff categories, but that the geometric mean of the non-welded to partially welded and the partially welded to moderately welded tuff categories are statistically different from the moderately welded to densely welded tuff category (table 8).

Ash-flow tuffs, bedded tuffs, and tuff breccias were divided into two tuff categories, unaltered and altered (zeolitized or argillized), to assess the effect of alteration on hydraulic-conductivity measurements (table 2; fig. 8). Categorization was based on qualitative descriptions in borehole lithologic logs. Intervals of partly altered tuffs were omitted from this analysis. Clay minerals from the alteration of tuff tend to reduce permeability (Flint, 1998). The hydraulic conductivities of altered ash-flow tuffs are less than those for the unaltered tuffs (fig. 8). The geometric mean of the horizontal hydraulic conductivity of the unaltered tuff is greater than altered tuff by about an order of magnitude (table 2). Hypothesis testing of the geometric mean confirms that the unaltered and altered tuffs are distinct from each other (table 9).

Applicability of Distributions to a Regional Model

Values of hydraulic conductivity and transmissivity are dependent on the scale of the tests conducted to obtain these properties (Neuman, 1990). This scale effect generally is attributed to increasing access to a network of conduits for fluid flow as the volume of the medium encompassed by the test increases. In permeameter tests of core samples done in the laboratory, the hydraulic conductivity of the rock matrix is determined, because these tests require unfractured core for successful results. Permeameter-test results generally are not useful for regional-scale ground-water flow models. Thus, results for permeameter tests of core samples are not utilized in the descriptive statistical calculations of the hydraulic parameters (with the exception of the LCCU). If a single-well aquifer test is of short duration, in a formation with low transmissivity, or performed with minimal pumping rates, it typically determines hydraulic properties, only in the near-borehole environment. The accuracy of these tests can be decreased by inefficient borehole construction, convergence of flow lines and related head losses as water flows into or out of sections of perforated casing, and head loss as water moves between the test-interval depth and the pump-intake depth. As such, transmissivity estimates derived from single-well tests tend to be less than those of multiple-well tests. Storage-coefficient estimates from single-hole tests have lesser reliability than those from multiple-well tests. Multiple-well aquifer tests manifest the influence of field-scale features, such as faults and fractures, as well as the water-transmitting properties of the rock matrix.

Because of these variables involving variously scaled tests, how to quantitatively scale the hydraulic-conductivity measurements among permeameter, slug, single-well, and multiple-well aquifer tests is currently unknown; only general comments can be made.

Principle of Parsimony

In the application of numerical flow model calibration, Hill (1998) introduces the concept of “parsimony.” The principle of parsimony (as applied to numerical models of ground-water flow) means to “start simple and add complexity as warranted by the hydrogeology and the inability of the model to reproduce observations” (Hill, 1998, p. 35). The probability distributions presented in this report enable investigators to apply the principle of parsimony. Both statistical hypothesis testing and visual examination of the probability distributions indicate that several of the units in each category can be grouped together. The initial four groups of basin-fill units, bedrock confining units, carbonate rock units, and volcanics represent an initial, practical grouping. Within these groups, the hypothesis testing and probability distributions provide further guidance for adding detail to the flow modeling if

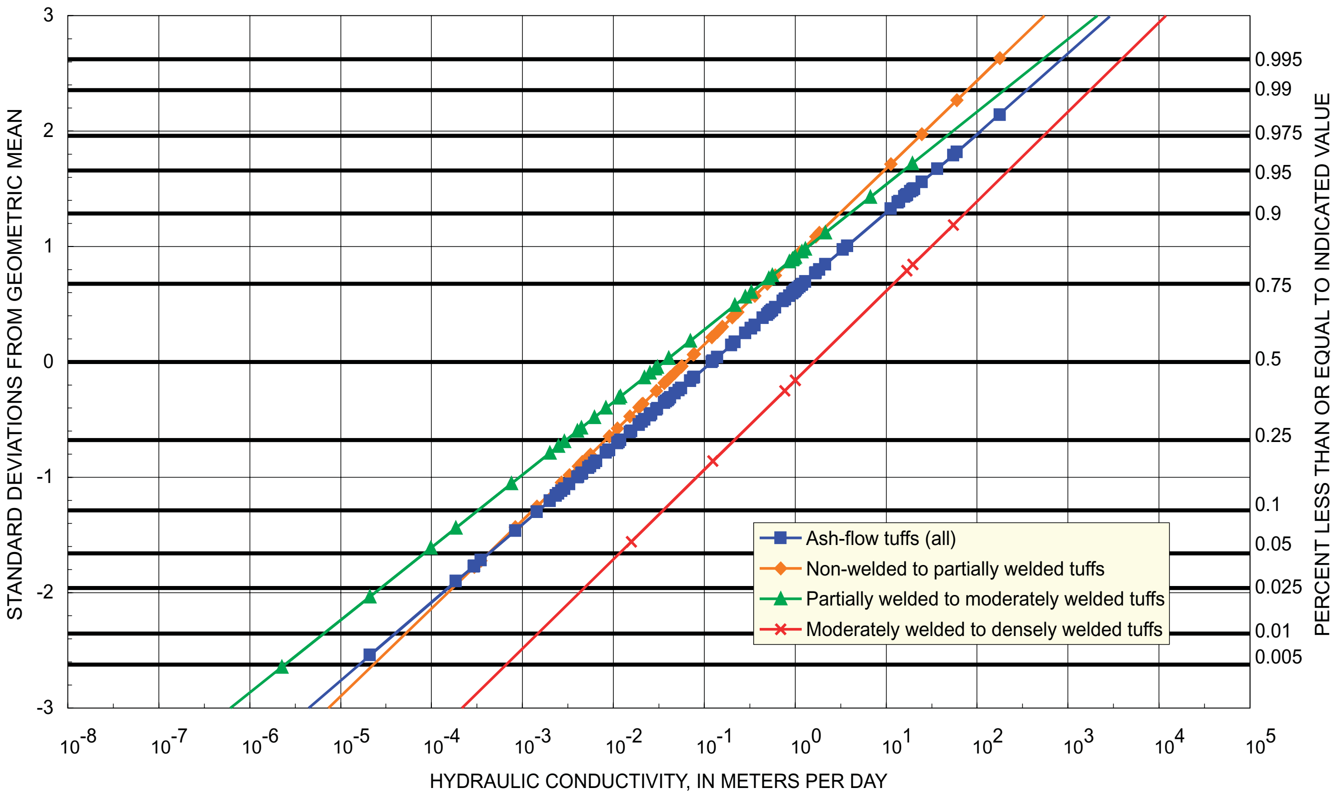

Figure 7. Hydraulic-conductivity distributions for welding in ash-flow tuffs.

Table 8. Results of hypothesis testing for welding in ash-flow tuffs

[**Abbreviations**: DW, densely welded; MW, moderately welded; NR, non-rejection of null hypothesis; NW; non-welded; PW, partially welded; R, rejection of null hypothesis.
Note: Hydrogeologic units in column heading are being compared to those in row heading]

Null hypothesis: $\mu_1 - \mu_2 = 0$

Alternate hypothesis: $\mu_1 - \mu_2 \neq 0$

	NW/PW	PW/MW	MW/DW
NW/PW	--	NR	R
PW/MW	NR	--	R
MW/DW	NR	R	--

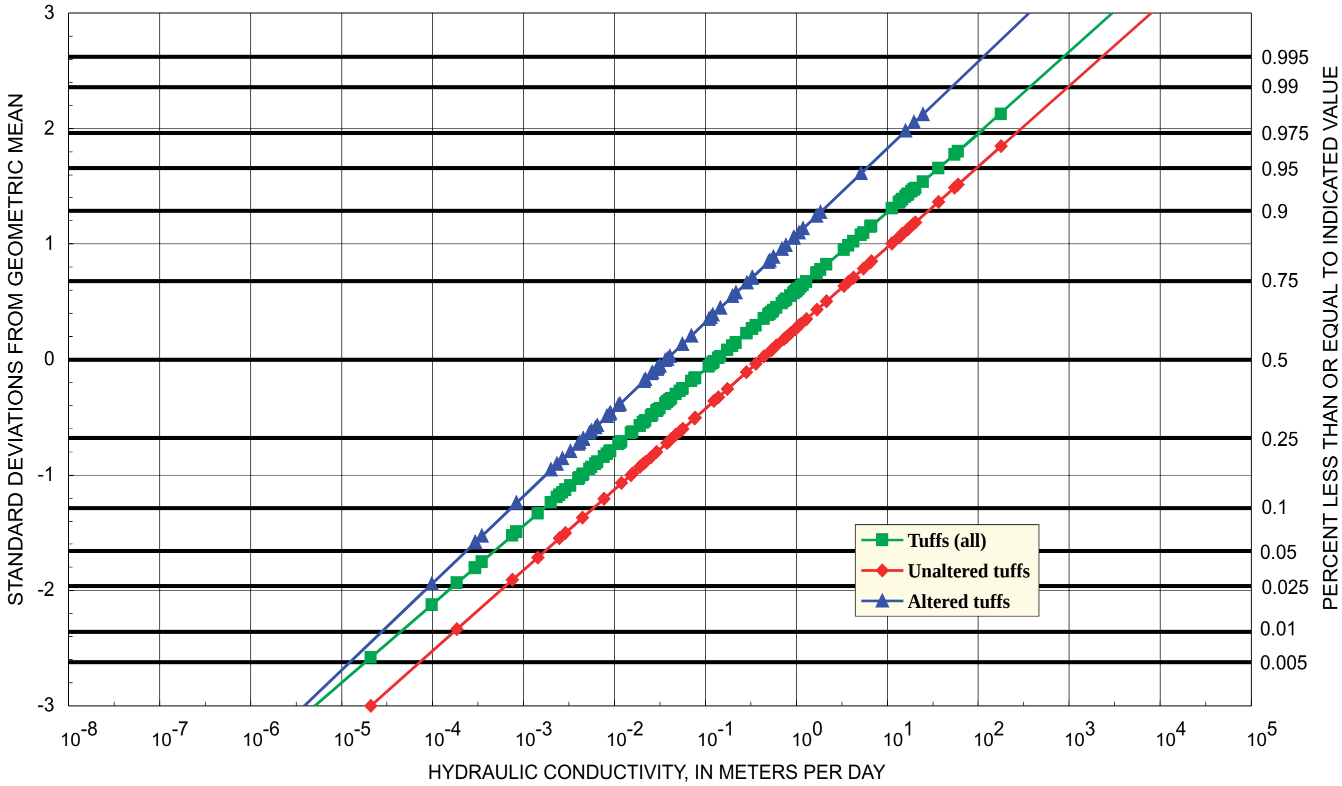

Figure 8. Hydraulic-conductivity distributions for alteration in ash-flow tuffs.

Table 9. Results of hypothesis testing for alteration in tuffs

[**Abbreviation**: R, rejection of null hypothesis. **Note**: Hydrogeologic units in column heading are being compared to those in row heading]

Null hypothesis: $\mu_1 - \mu_2 = 0$

Alternate hypothesis: $\mu_1 - \mu_2 \neq 0$

	Tuffs (all)	Unaltered	Altered
Tuffs (all)	--	R	R
Unaltered	R	--	R
Altered	R	R	--

required during calibration. Within the basin-fill units, the AA and the ACU are similar enough that they initially could be considered the same unit, with the YVU/VSU being distinct. Within the bedrock confining units, the UCCU and the ICU could be combined and the LCCU would exist as a separate unit. Fractured and unfractured carbonates appear to be distinct from one another and could be separated on that basis. The hydrogeologic units of the Tertiary volcanic rocks could be divided into three separate units: (1) TMVA and PVA; (2) BRU, CFBCU, CFPPA, and CFTA; and (3) CHVU and WVU (although no aquifer test data for the WVU exist, it is geologically similar to the CHVU). Alteration of all tuffs and welding in the ash-flow tuffs also appears to be a mechanism for adding complexity to a numerical model.

SUMMARY

The probability distributions of hydraulic conductivity were estimated to support regional-scale simulation of ground-water flow in the Death Valley regional ground-water flow system. Fracturing appears to have the greatest influence on the permeability of bedrock hydrogeologic units, within this region. The degree of alteration and welding in the Tertiary volcanic rocks also influences hydraulic conductivity. As the degree of alteration increases, hydraulic conductivity decreases. Increasing welding appears to increase hydraulic conductivity because degrees of welding increases the brittleness of the volcanic rocks, thus increasing the amount of fracturing.

Probability distributions can be used to apply the principle of parsimony for combining hydrogeologic units. Visual examination of the probability distributions and the use of statistical hypothesis testing allows groupings of the hydrogeologic units to be made, generalizing the units contained within a ground-water flow model. If warranted, complexity can be made by dividing units, either along hydraulic properties (for example welding or alteration in tuffs) or hydrogeologic units.

The hydraulic-conductivity distributions presented in this report have a greater use beyond that associated with the regional ground-water flow model being developed by the USGS. The probability of hydraulic-conductivity distributions could be used for many purposes including contaminant-transport modeling, water-supply issues, and resource protection. The distributions also could be used for similar rock types in areas outside of the southern Great Basin because volcanics, carbonates, and clastics rock types that were analyzed occur worldwide.

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