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Statistical Exploration of Matrix Hydrologic Prope[illegible] for the Bandelier Tuff, Los Alamos, New Mexi[illegible]

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ABSTRACT

The Bandelier Tuff forms the top of the thick vadose zone at Los Alamos National Laboratory (LANL). Subsurface pathway performance or risk assessments at Los Alamos require characterizing the unsaturated hydrologic properties of the Bandelier Tuff. The objective of this study was to analyze available unsaturated zone matrix hydrologic properties data for the Bandelier Tuff from the Los Alamos area for the purpose of developing estimates of properties and parameters for modeling vadose zone flow and transport. The hydrologic properties bulk density, saturated hydraulic conductivity, and the van Genuchten equation parameters, residual and saturated water contents, α, and n, were measured or estimated from measured data. A nonparametric statistical approach was used because of the small sample size leading to nonnormal distribution of the samples. The following differences were investigated: (i) between boreholes for a given unit within a site and (ii) between sites for a given unit. Results for borehole analyses within a location found that properties were different at one location and could be combined at another. The testing between locations found that samples could be readily combined. Linear correlation analyses of the one geologic unit that was the most consistent across the Los Alamos site found that there was essentially no relationship between matrix hydrologic properties or parameters to allow surrogate properties to be used for prediction. This preliminary analysis indicated that investigations at LANL will require more detailed sampling on a site-specific basis because properties cannot be transferred or estimated with any confidence.

Los Alamos National Laboratory (LANL) is located on the Pajarito Plateau in north-central New Mexico. The plateau is bounded on the west by the Jemez Mountains and on the east by the Rio Grande (Fig. 1). Erosion of the plateau has created a number of finger-shaped mesas that trend west to east, and these mesas are separated by steep canyons that contain intermittent and ephemeral streams. The cap rock of the Pajarito Plateau is the Bandelier Tuff that was deposited in a series of eruptions from the Jemez volcanic center, with the last episode occurring approximately 1 Ma (Griggs, 1964). The water table for the regional aquifer beneath mesas at the Laboratory lies at depths ranging from 365 m along the western edge to 183 m along the eastern edge of LANL. This creates a thick vadose zone at LANL that has been used by the Laboratory for disposal of municipal, hazardous, and radioactive wastes, with radioactive waste disposal continuing today. The vadose zone is an important element of the LANL environmental restoration activities because many of the legacy sites are located in the Bandelier Tuff. Knowledge of vadose zone hydrologic properties is critical to assess risks from past, present, and future operations at LANL. In addition, the work at LANL adds to the general knowledge of vadose zone hydrologic response.

The process of describing risks associated with contamination or waste disposal in the vadose zone requires a model to predict travel times of contaminants of concern. The unsaturated zone hydrologic properties required by mathematical models include the water retention curve (water content versus pressure head) and hydraulic conductivity vs. pressure head curve, the saturated hydraulic conductivity (K_s), and porosity. These properties have been shown to be spatially variable (Nielsen et al., 1973)—a property such as K_s can vary by orders of magnitude in a few meters (Koltermann and Gorelick, 1996). Both the water retention and hydraulic conductivity curves are nonlinear, which means that the hydraulic conductivity can vary by several orders of magnitude for a small change in pressure head at low water contents. Unsaturated properties of the soil or rock matrix are derived mostly by laboratory sample analyses; these procedures can be tedious and expensive, so characterizing the variability is important to ensure efficient sampling.

The stratigraphy at LANL by Broxton and Vaniman (2005) shows that the upper units of the vadose zone are in the Bandelier Tuff. Groundwater pathway assessments at Los Alamos focus on the Bandelier Tuff because of its location in the stratigraphic column and because contaminant sources are located on or in the Bandelier Tuff. The Bandelier Tuff is composed of two members: the upper member is the Tshirege and the Otowi is the lower member. The Cerro Toledo interval is a deposition unit formed during the period between the eruptions of the Otowi and Tshirege Members, and it has not been extensively characterized. The Tshirege Member has been divided into cooling units based on lithological analyses, and most sampling for hydrologic properties has used cooling units as an initial classification scheme for sample locations. This is similar to the approach taken by Flint (1998) for Yucca Mountain, Nevada, where initial classification of hydrogeologic units was based on degree of welding.

Risk assessments at LANL for groundwater pathways require statistical analyses of unsaturated zone hydrologic properties because of the limited sampling and large spatial variability in these properties. A number of samples of unsaturated zone hydrologic properties have been collected at Los Alamos National Laboratory over the years as site investigations have progressed.

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Abbreviations: LANL, Los Alamos National Laboratory.

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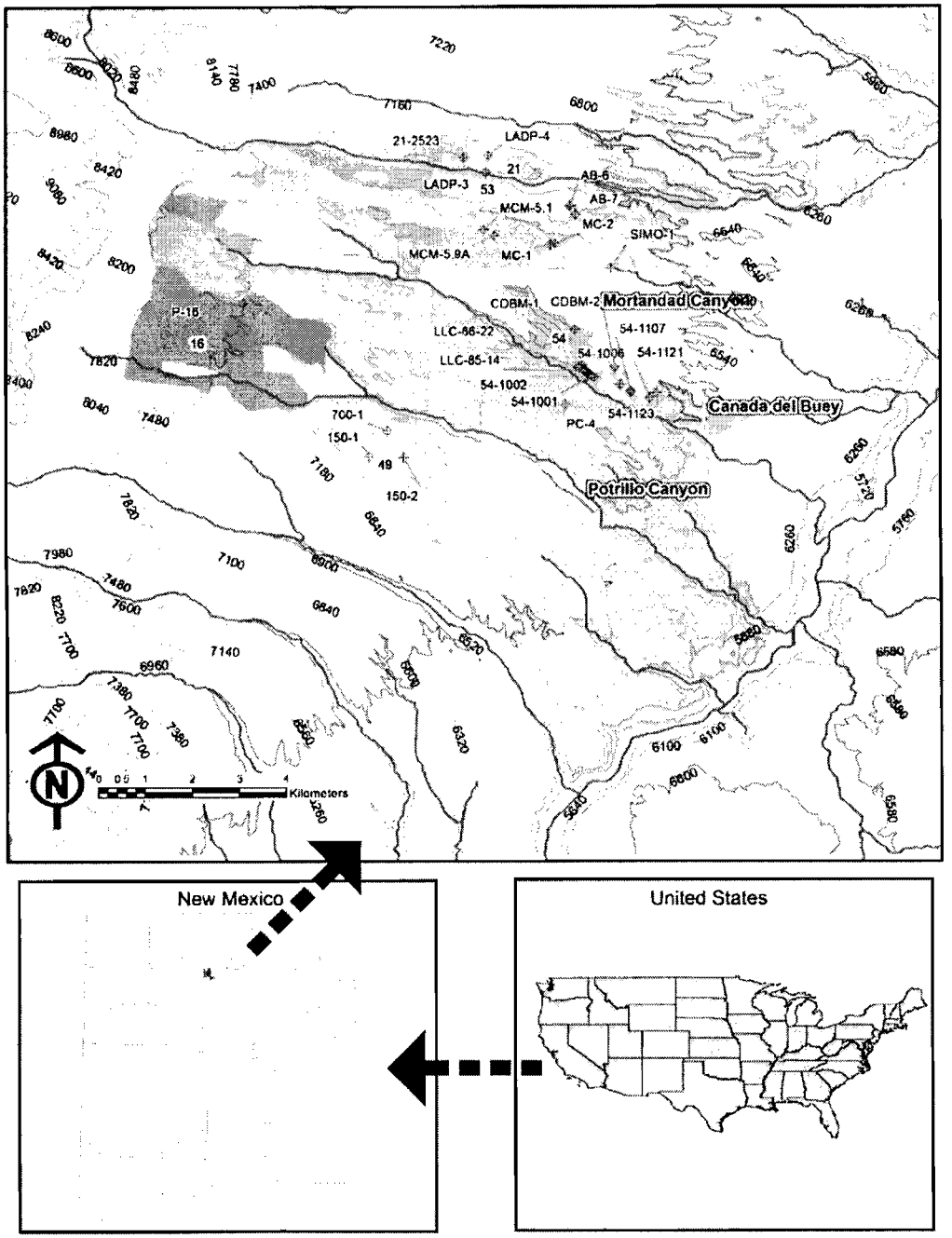

Fig. 1. Map of Los Alamos National Laboratory with the locations of the boreholes used in the unsaturated hydrologic properties analysis.

These samples have been used on a site-specific basis for assessments (Hollis et al., 1997; Birdsell et al., 2000), but no coherent analyses of these samples have been undertaken to examine statistical similarity across LANL. The goal of the unsaturated zone hydrologic parameter estimation project at Los Alamos is the same as that given by Flint (1998): to provide statistical properties of the unsaturated zone properties to support vadose zone modeling. The objective of this study was to analyze the existing data collected from different locations at LANL to determine if more accurate estimates of unsaturated zone matrix properties can be obtained by combining or pooling values from a sample location and across locations.

MATERIALS AND METHODS

Sample Locations

The boreholes from which the samples were collected are listed in Fig. 1. The borehole designator (e.g., 49-2-700) usually indicates in which LANL technical area the borehole is located. Figure 1 shows that most boreholes are located in the eastern and northern parts of the Laboratory where many environmental restoration and waste management activities

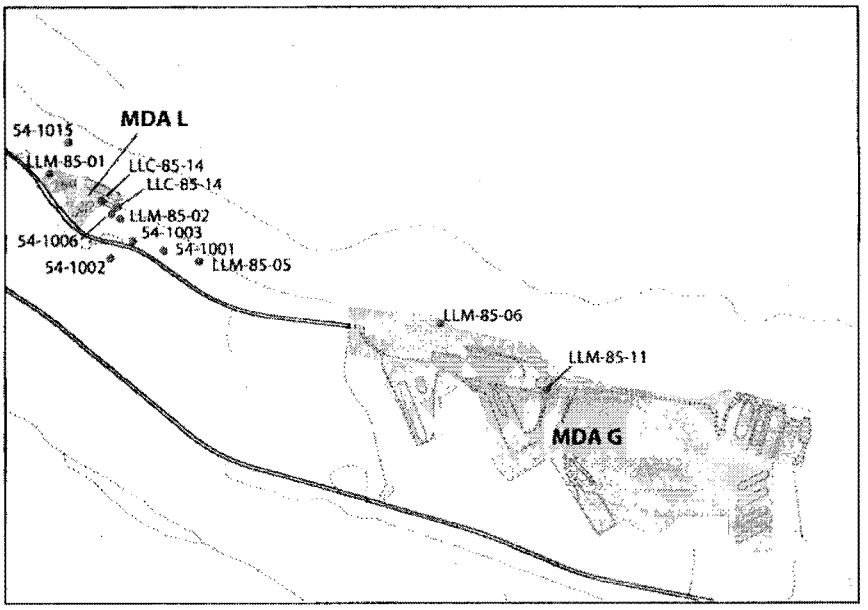

Fig. 2. Map of Los Alamos National Laboratory Technical Area 54 with the locations of the boreholes used in the unsaturated hydrologic properties analysis.

have occurred. A number of boreholes are located at Technical Area 54, and these boreholes are further identified in Fig. 2. Canyons were assumed to represent a different setting for this analysis because of the wetter conditions and reduced stratigraphy that affect weathering of the tuff. Samples from three canyons, Cañada del Buey, Mortandad, and Potrillo, are included in the data set, and these canyons are identified in Fig. 1. Sampling of canyons is not limited to the canyon locations as the LADP-3 borehole from Technical Area 21 is a canyon setting borehole.

Geology

The Bandelier Tuff is composed of the lower Otowi Member, which is a massive pumiceous ash-flow tuff, and the Tshirege Member, which is composed of four ash-flow tuff cooling units (Fig. 3). Because the Cerro Toldeo interval is a volcanoclastic sediment it is not considered part of the Bandelier Tuff. Analyses of hydrologic properties use the basic Tshirege cooling units in Fig. 3 because further delineation for many of the boreholes was not made. Although vertical fractures are present in the Tshirege Member and these fractures can be hydrologically active with clay filling found to a depth of 3 m below the surface (Soll and Birdsell, 1998), this study deals only with matrix hydrologic properties of the Bandelier Tuff. Further description and details on geology and stratigraphy of the Bandelier Tuff can be found in Broxton and Vaniman (2005). The nomenclature in Fig. 3 is used in this paper, so the Tshirege Member is identified with a Qbt and then the cooling unit is designated. For instance, Tshirege Cooling Unit 2 is Qbt 2. The Otowi Member is not differentiated, and it is designated as Qbo.

Sample Characterization

Hydrologic measurements used in this study are basically from three data sources, and a variety of techniques have been used to determine K_s and the moisture characteristic. Nyhan (1979) determined K_s on 12-cm-long cores from Technical Area 21 using constant head methods, and these are designated MDAT in the Appendix. Kearl et al. (1986) measured porosity using helium injection, K_s using nitrogen injection, and moisture retention with a centrifuge on Boreholes LGM-85-06, LLC-85-11, LLC-85-14, LLC-85-15, LLC-86-22, LLM-85-01, LLM-85-02, and LLM-85-05 from Technical Area 54. Samples from the other boreholes listed in the Appendix were characterized by Daniel B. Stephens and Associates in Albuquerque, NM. The methods used by Daniel B. Stephens and Associates varied between samples sets submitted by LANL; the details are too lengthy for this paper. The K_s was measured using both constant head and air injection techniques. Bulk density was obtained from oven-dry analysis of samples and porosity (ϕ) was calculated from ρ_b. The moisture release curve was obtained by pressure plate, submerged pressure outflow cells, or thermocouple psychrometer, depending on the magnitude of the pressure.

Dimensions for the properties are ρ_b (g cm^{-3}), K_s (cm s^{-1}), α (cm^{-1}), and the water content values are (cm^3 cm^{-3}).

Data Analyses

The water content and pressure head data were fitted to the van Genuchten (1980) moisture characteristic equation using the computer code RETC (van Genuchten et al., 1991). The water retention relation is described by

$$S_e = (\theta - \theta_r)/(\theta_s - \theta_r) = 1/[1 + (\alpha h)^n]^m \qquad [1]$$

where S_e is the effective saturation, θ is the volumetric water content (cm^3 cm^{-3}), θ_r is the residual volumetric water content (cm^3 cm^{-3}), θ_s is the saturated volumetric water content (cm^3 cm^{-3}), h is pressure head (cm), α is a fitting parameter (cm^{-1}), and n and m are fitting parameters, with $m = 1 - 1/n$.

The change in hydraulic conductivity with water content is described by the following equation:

$$k(S_e) = K_s S_e^{\ell}[1 - (1 - S_e^{1/m})^m]^2 \qquad [2]$$

where K_s is the saturated hydraulic conductivity (cm s^{-1}), and ℓ is a pore-connectivity parameter (set to 0.5 for these analyses).

van Genuchten and Nielsen (1985) demonstrated the importance of the slope of the water retention curve (Eq. [1]) near saturation on predicted hydraulic conductivity (Eq. [2])

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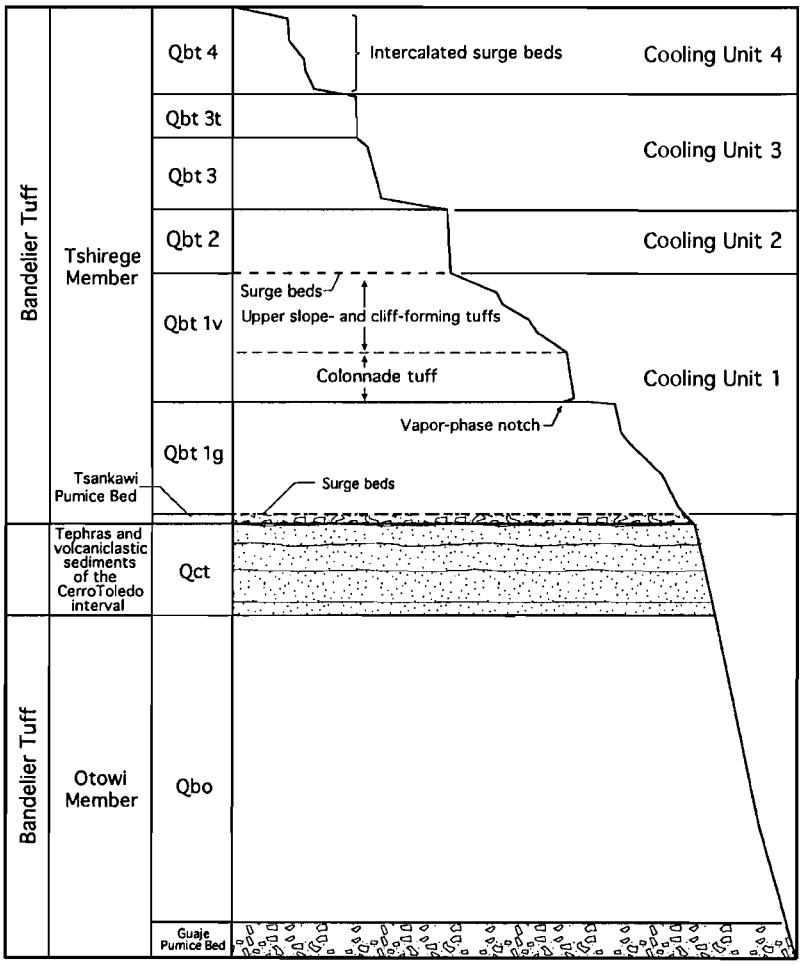

Fig. 3. Stratigraphic nomenclature for the Bandelier Tuff. In this study, the major cooling units such as Qbt 3 in the Tshirege Member were used, and no identification of the subunits was made.

for the entire range of water content values. θ_s can be measured using imbibition, but this approach was not performed with these data. van Genuchten and Nielsen (1985) presented a rationale that any model such as Eq. [1] obscures the description of the water content at saturation, leaving the definition of θ_s model dependent. Springer et al. (2000) found no statistical difference for α and n from Eq. [1] when using a fitted vs. a fixed value such as porosity for θ_s. There were significant differences for θ_r, but these were not viewed as critical because for most cases θ_r is zero.

Rogers and Gallaher (1995) analyzed the Bandelier Tuff data available at that time. They went through each moisture retention data set and censored points that were obvious outliers. The parameters derived by Rogers and Gallaher (1995) were used in this study and are reported in the Appendix.

Statistical Analysis

The statistical analyses used nonparametric methods to test for differences in matrix hydrologic properties between boreholes within a technical area, between technical areas, and between mesa top and canyon settings. For conditions where only two samples were compared, the Mann–Whitney U test was used, and when more than two groups are available, the Kruskal–Wallis analysis of ranks test was used (Sokal and Rohlf, 1969). All statistical analyses were performed using the STATISTICA software (StatSoft, Tulsa, OK; http://www.statsoftinc.com/). A post-hoc analysis of the means for the Kruskal–Wallis test is available to further define differences between the samples (Sokal and Rohlf, 1969).

Although nonparametric tests were used, the values for both K_s and α were transformed using the base 10 logarithm ($\log_{10}$) to reduce the skew of their distribution and to correct for hetroscedasiticity. K_s has been shown to be lognormally distributed (Nielsen et al., 1973).

RESULTS

Sample Size

The number of samples available is critical for determining statistical properties. The number of samples for each cooling unit and technical area for K_s are listed in Table 1. Sample sizes for K_s are the maximum available for all parameters used in the analyses that follow, so K_s represents the best case because there are fewer samples for ρ_b, θ_s, θ_r, n, and α.

Information in Table 1 and Fig. 1 indicate a skewed distribution of samples from the eastern part of LANL. The sums in the last row of Table 1 reveal that more than 60% of the samples for K_s and a similar percentage

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Table 1. The number of samples for each technical area (TA) and unit for $\log_{10}$ saturated hydraulic conductivity (K_s).

Unit	TA-16	TA-21	TA-49	TA-53	TA-54	Mortandad Canyon	Cañada del Buey	Portrillo Canyon	Total for unit
Qbt 4			9						9
Qbt 3	10	36	7						53
Qbt 2		14	13	2	17				46
Qbt 1v		9	2	2	44				57
Qbt 1g		6	5	1	17	11	7	5	52
Qbo		19	3	2		7	12	4	40
Total for site	10	84	39	7	78	18	19	9	

for the other matrix parameters (not shown) come from two locations, Technical Areas 21 and 54. The sampling of these eastern technical areas may bias the estimates of the matrix hydrologic properties if applied to other locations around LANL because distance from the source area, differences in stratigraphy, and weathering affect the hydrologic properties. The data in Table 2 reveal the unequal sampling of Bandelier Tuff cooling units that has occurred. Unit 4 (Qbt4) is sampled only at Technical Area 49 because it is not found to the east. Although better distributed, Qbt3 is sampled at three locations and is not found at Technical Area 54. The last column in Table 1 provides the sample numbers across cooling units, and it appears to be relatively evenly distributed except for Qbt4. There are not a large number of samples in Table 1, nor are these samples well distributed across LANL. Statistical analyses represents a logical approach to determine whether the matrix hydrologic properties from the various locations, or even within a location if there are multiple boreholes, can be combined to estimate hydrologic parameters for modeling assessments.

Residual Water Content

All values for θ_r were estimated with RETC. An alternative approach proposed by Flint (1998) measured θ_r as the differences between over-dry weight at 105°C and weight from drying at 60°C and 65% relative humidity. A total of 200 estimates for θ_r were performed, and 126 (63%) of these were estimated to be zero. The resulting distribution is skewed with zero having a significant finite probability of occurrence. This mixed distribution (Yevjevich, 1972) is difficult to transform, and a more appropriate approach for estimating statistical properties of θ_r is through an empirical cumulative density function. Although results will be reported for θ_r in the following sections, they have to be weighed against its distribution. One option for unsaturated flow modeling of the Bandelier Tuff is to set θ_r to zero given the large number of zero values that were estimated with this data set.

Technical Area Analysis

Within a Technical Area

The initial analysis examined whether the data from boreholes in a given technical area can be pooled. From Table 1, it is readily observed that Technical Areas 21 and 54 have the most samples, and within–technical area analyses were performed for these sites. The samples were sorted by Tshirege cooling units and the Otowi geologic unit, and the applied nonparametric test was dependent on the number of sample locations within the technical area.

The analyses for Technical Area 21 are presented in Table 2. There were a total of four sampling locations at this technical area, three boreholes (LADP-3, LADP-4, and 21-2523) and Nyhan (1979) samples from MDAT. The number of sample locations for any given unit was only two so the Mann–Whitney test was used for analyses.

The $\log_{10}K_s$ values for Tshirege Units 2 and 3 and the Otowi samples were shown to be significantly different (Table 2). The inability to combine the samples of this key flux property, K_s, for a site-wide estimate of this property's distribution indicates that subsurface pathway assessments at Technical Area 21 for Qbt 2, Qbt 3, and Qbo will require either (i) collection of additional samples of K_s or (ii) making additional assumptions about the distribution of this property using these data. The analyses in Table 2 for Qbt 1v and Qbt 1g indicated that matrix hydrologic properties and parameters for these units can be combined for Technical Area 21, but these results must be viewed in relation to the limited sample size, which was 9 for Qbt 1v and 6 for Qbt 1g. In addition to the $\log_{10}K_s$, both ρ_b and θ_s for the Otowi Member tested as different for the two locations. The samples for Obo were obtained from one borehole that was drilled in a mesa top (LADP-4), while LADP-3 is a canyon setting borehole, making this test an initial examination of the differences between these two settings where the canyon settings have higher moisture content because of recharge by streamflow. Summarizing the analysis of Technical Area 21, the matrix hydrologic properties and parameters cannot be readily merged for Tshirege Cooling Units 2 and 3 and the Otowi Member of the Bandelier Tuff, constraining unsaturated zone modeling to a site-specific basis in Technical Area 21 because model parameters are nonuniform.

Analyses of samples from Technical Area 54 are presented by Tshirege Member cooling unit in Tables 3, 4, and 5. From these tables, the larger number of boreholes at Technical Area 54 (17 total) leads to a more limited sample per borehole with only one or two samples per cooling unit as compared with Technical Area 21 (Table 2). The reduced effective sample size per borehole at Technical Area 54 decreases the ability to detect significant differences in matrix properties, especially when variability is large. The only significant difference that was detected for Technical Area 54 was for the van Genuchten n parameter for Unit 1v (Table 4). All remaining parameters for the three units, Qbt 2, Qbt 1V, and Qbt 1g, can be combined into a single sample

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Table 2. Differences between boreholes for matrix hydrologic properties from Technical Area 21 for each cooling unit of the Tshirege and the Otowi Members of the Bandelier Tuff using the Mann–Whitney test (significant if $p \leq 0.05$).

Matrix property	Borehole	Statistics			
		N	Mean	SD	Median
		Qbt3			
ρ_b	MDAT	NA†	NA	NA	NA
	21-2523	NA	NA	NA	NA
θ_s	MDAT	NA	NA	NA	NA
	21-2523	NA	NA	NA	NA
θ_r	MDAT	NA	NA	NA	NA
	21-2523	NA	NA	NA	NA
$\log_{10}\alpha$	MDAT	NA	NA	NA	NA
	21-2523	NA	NA	NA	NA
n	MDAT	NA	NA	NA	NA
	21-2523	NA	NA	NA	NA
$\log_{10}K_s$	MDAT	24	−4.44	0.33	−4.39*
	21-2523	12	−3.67	0.50	−3.72*
		Qbt2			
ρ_b	LADP-4	6	1.63	0.14	1.60
	21-2523	8	1.52	0.11	1.50
θ_s	LADP-4	6	0.33	0.06	0.31
	21-2523	8	0.33	0.04	0.33
θ_r	LADP-4	6	0.009	0.01	0.006
	21-2523	8	0.008	0.01	0.008
$\log_{10}\alpha$	LADP-4	6	−2.61	0.26	−2.66
	21-2523	8	−2.45	0.22	−2.61
n	LADP-4	6	2.11	0.33	2.15
	21-2523	8	2.20	0.37	2.09
$\log_{10} K_s$	LADP-4	6	−4.67	0.43	−4.70*
	21-2523	8	−4.07	0.46	−4.03*
		Qbt1v			
ρ_b	LADP-4	2	1.26	0.04	1.26
	21-2523	7	1.31	0.18	1.40
θ_s	LADP-4	2	0.48	0.10	0.48
	21-2523	7	0.47	0.09	0.44
θ_r	LADP-4	2	0.0	0.0	0.0
	21-2523	7	0.003	0.006	0.0
$\log_{10}\alpha$	LADP-4	2	−2.33	0.18	−2.33
	21-2523	7	−2.17	0.31	−2.10
n	LADP-4	2	1.62	0.32	1.62
	21-2523	7	1.78	0.20	1.82
$\log_{10}K_s$	LADP-4	2	−4.04	0.35	−4.04
	21-2523	7	−3.64	0.35	−3.66
		Qbt 1g			
ρ_b	LADP-4	3	1.20	0.20	1.20
	21-2523	3	1.16	0.09	1.14
θ_s	LADP-4	3	0.52	0.05	0.52
	21-2523	3	0.52	0.09	0.48
θ_r	LADP-4	3	0.0	0.0	0.0
	21-2523	3	0.0	0.0	0.0
$\log_{10}\alpha$	LADP-4	3	−2.10	0.26	−2.25
	21-2523	3	−2.06	0.15	−2.14
n	LADP-4	3	1.56	0.10	1.57
	21-2523	3	1.53	0.09	1.54
$\log_{10}K_s$	LADP-4	3	−3.67	0.20	−3.66
	21-2523	3	−3.51	0.31	−3.52
		Qbo			
ρ_b	LADP-3	6	1.34	0.17	1.29*
	LADP-4	13	1.21	0.10	1.16*
θ_s	LADP-3	6	0.35	0.05	0.36*
	LADP-4	13	0.40	0.03	0.41*
θ_r	LADP-3	6	0.007	0.017	0.0
	LADP-4	13	0.003	0.006	0.0
$\log_{10}\alpha$	LADP-3	6	−2.78	0.35	−2.79
	LADP-4	13	−2.66	0.27	−2.62
n	LADP-3	6	2.17	0.65	1.87
	LADP-4	13	2.23	0.56	2.14
$\log_{10}K_s$	LADP-3	6	−4.83	0.42	−4.68*
	LADP-4	13	−4.59	0.70	−4.48*

* Significant at 0.05 probability level.
† NA, not applicable. Parameters were not available for this unit.

Table 3. Statistics for Bandelier Tuff Tshirege Member Cooling Unit 2 (Qbt 2) for Technical Area 54 by borehole.

Boreholes	Statistics			
	N	Mean	SD	Median
		ρ_b†		
G-5	5	1.42	0.06	1.43
LLC-85-15	1	1.46	0.00	1.46
LLC-85-14	1	1.37	0.00	1.37
54-1006	1	1.28	0.00	1.28
		θ_s		
G-5	5	0.39	0.03	0.38
LLC-85-15	1	0.46	0.00	0.46
LGM-85-06	2	0.41	0.02	0.41
LLC-85-14	1	0.44	0.00	0.44
54-1006	1	0.45	0.00	0.45
		θ_r		
G-5	5	0.009	0.008	0.012
LLC-85-15	1	0.038	0.000	0.038
LLC-85-14	1	0.000	0.000	0.000
54-1006	1	0.000	0.000	0.000
		n		
G-5	5	2.16	0.64	2.19
LLC-85-15	1	2.04	0.00	2.04
LLC-85-14	1	1.89	0.00	1.89
54-1006	1	1.76	0.00	1.76
		$\log_{10}\alpha$‡		
G-5	5	−2.39	0.38	−2.55
LLC-85-15	1	−2.22	0.00	−2.22
LLC-85-14	1	−2.22	0.00	−2.22
54-1006	1	−2.19	0.00	−2.19
		$\log_{10}K_s$§		
LGM-85-11	2	−3.41	0.20	−3.41
LLM-85-02	2	−3.64	0.40	−3.64
G-5	5	−4.21	0.40	−4.40
LLC-85-15	1	−2.80	0.00	−2.80
LLM-85-05	2	−3.45	0.29	−3.45
LGM-85-06	2	−3.70	0.54	−3.70
LLC-85-14	1	−3.38	0.00	−3.38
LLM-85-01	1	−3.96	0.00	−3.96
54-1006	1	−3.39	0.00	−3.39
54-1003	2	−3.41	0.20	−3.41

† Units for ρ_b are g cm^{-3}.
‡ Units for α are cm^{-1}.
§ Units for K_s and cm s^{-1}.

for the data provided. The Otowi Member has not been sampled from a mesa top location at Technical Area 54.

Using Technical Areas 21 and 54 as surrogates for the LANL site because these locations had the largest sample sizes available, it was found that there was a limited ability to combine or pool matrix hydrologic properties by Bandelier Tuff unit for a given technical area. The analyses indicated that the flux parameter, $\log_{10}K_s$ cannot be combined at Technical Area 21, and this presents a major limitation for parameter estimation because vadose zone transport calculations are very sensitive to K_s values. Further analyses by geologic unit across the LANL site are limited by these results.

Comparisons between Technical Areas

The next step of the analysis was to examine the relationships between properties for different technical areas for selected units of the Bandelier Tuff on the basis of the previous analyses. Given the borehole analyses, the ability to pool samples for LANL estimated matrix hydrologic properties from the technical areas is limited. This analysis used the same nonparametric

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Table 4. Statistics for Bandelier Tuff Tshirege Member Cooling Unit 1v (Qbt 1v) for Technical Area 54 by borehole.

Boreholes	N	Mean	SD	Median
		ρ_b†		
LLC-86-22	5	1.18	0.12	1.26
G-5	3	1.17	0.01	1.17
54-1121	5	1.12	0.06	1.09
54-1001	5	1.20	0.03	1.20
G-P38-HH3	6	1.12	0.11	1.08
54-1006	3	1.26	0.03	1.28
54-1002	3	1.23	0.04	1.23
54-1107	5	1.12	0.11	1.16
54-1003	2	1.22	0.00	1.22
		θ_s		
LLC-86-22	5	0.50	0.01	0.51
G-5	3	0.50	0.07	0.48
54-1121	5	0.52	0.03	0.53
54-1001	5	0.47	0.04	0.46
G-P38-HH3	4	0.52	0.03	0.53
54-1006	3	0.45	0.02	0.45
54-1002	3	0.48	0.02	0.49
54-1107	5	0.51	0.04	0.52
LGM-85-06	1	0.53	0.00	0.53
54-1003	1	0.51	0.00	0.51
		θ_r		
LLC-86-22	5	0.02	0.02	0.01
G-5	3	0.00	0.00	0.00
54-1121	5	0.00	0.00	0.00
54-1001	5	0.00	0.00	0.00
G-P38-HH3	4	0.00	0.00	0.00
54-1006	3	0.00	0.00	0.00
54-1002	3	0.01	0.01	0.00
54-1107	5	0.00	0.01	0.00
54-1003	1	0.00	0.00	0.00
		n*		
LLC-86-22	5	1.96	0.33	1.93
G-5	3	1.93	0.15	1.85
54-1121	5	1.54	0.14	1.50
54-1001	5	1.78	0.31	1.78
G-P38-HH3	4	1.67	0.17	1.64
54-1006	3	1.90	0.18	1.88
54-1002	3	1.79	0.41	1.77
54-1107	5	1.41	0.05	1.43
54-1003	1	1.73	0.00	1.73
		$\text{Log}_{10}\alpha$‡		
LLC-86-22	5	−2.54	0.15	−2.59
G-5	3	−2.62	0.29	−2.67
54-1121	5	−2.24	0.19	−2.12
54-1001	5	−2.48	0.10	−2.47
G-P38-HH3	4	−2.42	0.14	−2.39
54-1006	3	−2.61	0.21	−2.52
54-1002	3	−2.41	0.56	−2.51
54-1107	5	−1.92	0.80	−2.22
54-1003	1	−2.52	0.00	−2.52
		$\text{Log}_{10}K_s$§		
LLM-85-01	2	−3.59	0.01	−3.59
LLC-86-22	5	−4.21	0.47	−4.28
G-5	3	−4.05	0.39	−4.06
54-1121	5	−3.84	0.18	−3.79
LLM-85-02	2	−3.89	0.17	−3.89
54-1001	5	−4.08	0.34	−3.96
G-P38-HH3	6	−3.42	0.61	−3.54
LLM-85-05	1	−3.89	0.00	−3.89
54-1006	3	−4.20	0.17	−4.24
54-1002	3	−4.34	0.26	−4.34
54-1107	5	−3.97	0.50	−3.95
LGM-85-11	1	−3.96	0.00	−3.96
LGM-85-06	1	−2.89	0.00	−2.89
54-1003	2	−3.95	0.08	−3.95

* Significant differences from the Kruskal–Wallis nonparametric test are marked for $p \leq 0.05$.
† Units for ρ_b are g cm^{-3}.
‡ Units for α are cm^{-1}.
§ Units for K_s and cm s^{-1}.

Table 5. Statistics for Bandelier Tuff Tshirege Member Cooling Unit 1g (Qbt 1g) for Technical Area 54 by borehole.

Borehole	N	Mean	SD	Median
		ρ_b†		
54-1121	3	1.15	0.02	1.14
G-5	1	1.14	0.00	1.14
54-1107	2	1.14	0.01	1.14
54-1003	4	1.19	0.09	1.16
54-1006	1	1.13	0.00	1.13
54-1002	2	1.15	0.01	1.15
		θ_s		
54-1121	3	0.46	0.03	0.46
G-5	1	0.45	0.00	0.45
54-1107	2	0.51	0.02	0.51
LGM-85-06	1	0.56	0.00	0.56
54-1003	4	0.44	0.03	0.43
54-1006	1	0.53	0.00	0.53
54-1002	2	0.39	0.00	0.39
		θ_r		
54-1121	3	0.020	0.022	0.016
G-5	1	0.008	0.000	0.008
54-1107	2	0.000	0.000	0.000
54-1003	1	0.025	0.000	0.025
54-1002	2	0.000	0.000	0.000
		n		
54-1121	3	1.68	0.11	1.67
G-5	1	2.16	0.00	2.16
54-1107	2	1.89	0.16	1.89
54-1003	1	1.77	0.00	1.77
54-1002	2	1.78	0.05	1.78
		$\text{Log}_{10}\alpha$‡		
54-1121	3	−2.35	0.15	−2.30
G-5	1	−2.59	0.00	−2.59
54-1107	2	−2.46	0.17	−2.46
54-1003	1	−2.40	0.00	−2.40
54-1002	2	−2.29	0.11	−2.29
		$\text{Log}_{10}K_s$§		
54-1121	3	−4.11	0.28	−3.99
G-5	1	−4.51	0.00	−4.51
54-1107	2	−3.71	0.54	−3.71
LGM-85-06	1	−4.04	0.00	−4.04
LGM-85-11	1	−3.74	0.00	−3.74
LLM-85-05	1	−3.80	0.00	−3.80
LLM-85-01	1	−3.66	0.00	−3.66
54-1003	4	−3.72	0.16	−3.70
54-1006	1	−3.92	0.00	−3.92
54-1002	2	−3.98	0.30	−3.98

† Units for ρ_b are g cm^{-3}.
‡ Units for α are cm^{-1}.
§ Units for K_s and cm s^{-1}.

statistical approaches as the analysis within technical areas, except that technical area was the main effect.

Tshirege Unit 3 (Qbt 3). This unit is found at Technical Areas 16, 21, and 49, and Kruskal–Wallis analyses results are presented in Table 6. For Technical Area 21, the properties and parameters other than $\log_{10}K_s$ are from Borehole 21-2523. All properties tested as significantly different for this unit. As noted above, $\log_{10}K_s$ has already tested significantly different for Technical Area 21. Further insight into differences between locations can be obtained from Fig. 4, which contains the median and range for ρ_b (Fig. 4A) and $\log_{10}\alpha$ (Fig. 4B).

The range of ρ_b at Technical Area 16 is large compared with either Technical Area 21 or 49 (Fig. 4A), and this pattern is repeated for the other parameters in this group. Technical Area 16 is the western-most sampled location in Fig. 1, and it is the closest to the

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Table 6. Statistics and Kruskal–Wallis results for Bandelier Tuff Tshirege Member Cooling Unit 3 (Qbt 3) by technical area.

Technical Area	Statistics			
	N	Mean	SD	Median
		ρ_b*†		
16	10	1.47	0.21	1.48
21	12	1.30	0.08	1.27
49	7	1.65	0.05	1.65
		θ_s*		
16	10	0.47	0.08	0.47
21	12	0.36	0.03	0.37
49	7	0.36	0.02	0.36
		θ_r*		
16	4	0.044	0.033	0.050
21	12	0.011	0.007	0.011
49	7	0.000	0.000	0.000
		n*		
16	4	1.88	0.68	1.64
21	12	2.16	0.35	2.12
49	7	1.69	0.18	1.65
		$\text{Log}_{10}\alpha$*‡		
16	4	−2.60	0.28	−2.58
21	12	−2.24	0.09	−2.24
49	7	−2.13	0.12	−2.16
		$\text{Log}_{10}K_s$§		
16	10	−3.86	0.41	−3.75
21	36	−4.18	0.53	−4.29
49	7	−4.31	0.34	−4.24

* Significant differences from the Kruskal–Wallis nonparametric test are marked for $p \leq 0.05$.
† Units for ρ_b are g cm^{-3}.
‡ Units for α are cm^{-1}.
§ Units for K_s and cm s^{-1}.

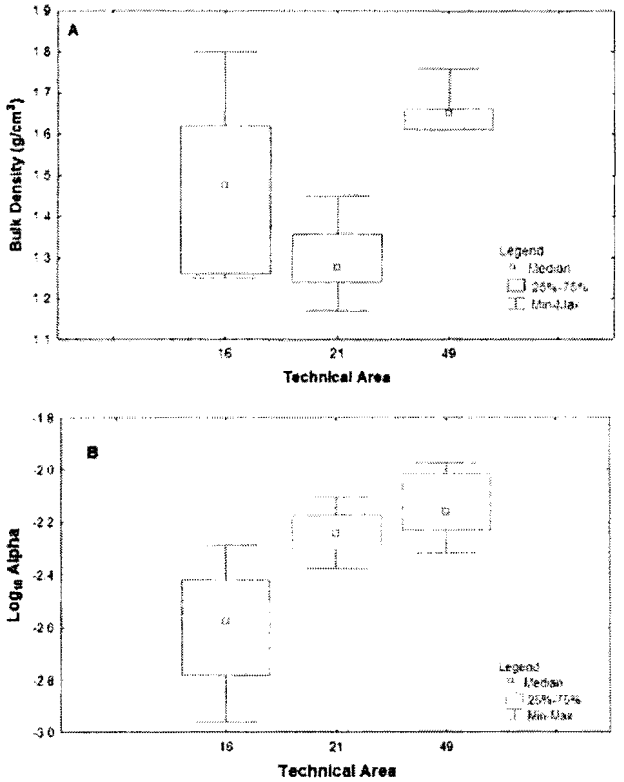

Fig. 4. Box and whiskers plots of the median, 25 to 75% quartile, and range for (A) bulk density (ρ_b) and (B) $\log_{10}\alpha$ from Bandelier Tuff Tshirege Unit 3 (Qbt 3) at designated technical areas of Los Alamos National Laboratory.

volcanic source area of the Bandelier Tuff. Also, at Technical Area 16 additional Tshirege Member cooling units are found above Qbt 3 that will affect its welding, cooling history, and weathering. No overlap exists for ρ_b between Technical Area 21 and 49, and these two locations can be viewed as different. The same description for $\log_{10}\alpha$ (Fig. 4B) reveals a large range for Technical Area 16, but Technical Area 21 and 49 do overlap more that for ρ_b. As observed with the borehole analysis, the unsaturated zone matrix hydrologic properties for Qbt 3 cannot be pooled to create a larger data set.

Tshirege Unit 2 (Qbt 2). Samples for Qbt 2 were from Technical Areas 21, 49, 53, and 54 (Table 1), and, with two samples available from Technical Area 53, this location was eliminated from the analyses. It has already been determined that $\log_{10}K_s$ cannot be pooled (Table 2), so this property was eliminated from the analysis. The Kruskal–Wallis results are presented in Table 7. ρ_b, θ_s, and θ_r are significantly different between technical areas, while the van Genuchten parameters n and $\log_{10}\alpha$ can be pooled for these areas. The median, quartile, and range of ρ_b and $\log_{10}\alpha$ are presented in Fig. 5A and 5B, respectively. For ρ_b that was significant, the range for Technical Area 54 is narrower, and overall values are lower than either Technical Area 21 or 49 (Fig. 5A). For $\log_{10}\alpha$, the ranges at all three technical areas substantially overlap each other (Fig. 5B), providing a basis for combining the values from the technical areas to create a LANL estimated α for unsaturated zone modeling.

Unlike Qbt 3, the van Genuchten parameters for Qbt 2 can be pooled to provide a LANL estimate for these technical areas. It is not possible to extend these LANL estimated parameters to the west of Technical Area 49 without further sampling, but the large region covered by these technical areas provides parameter estimates to a substantial portion of LANL.

Tshirege Unit 1v (Qbt 1v). Technical Areas 21, 49, 53, and 54 (Table 1) were sampled, and only two samples were available from Technical Areas 49 and 53 so these two units were excluded from the analyses even though the statistics for these technical areas are presented in Table 8. A Mann–Whitney test was used rather than the Kruskal–Wallis because only two technical areas were analyzed. The analysis of this unit for Technical Area 54 indicated that the van Genuchten n parameter was significantly different, so this parameter was excluded from the analysis. The statistics and the resulting significant differences are presented in Table 8, with ρ_b and $\log_{10}\alpha$ being statistically different between technical areas. The number of samples from Technical Area 54 was approximately four times larger than from Technical Area 21. This is the first analysis where $\log_{10}K_s$ could be evaluated across technical areas. The plot of $\log_{10}K_s$ in Fig. 6 reveals a two order of magnitude range for the Technical Area 54 $\log_{10}K_s$ values, which is consistent with the extent of this property reported by others (Koltermann and Gorelick, 1996). Also the $\log_{10}K_s$ values for Technical Area 21 are inside the range of the Technical

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Table 7. Statistics and Kruskal–Wallis results for Bandelier Tuff Tshirege Member Cooling Unit 2 (Qbt 2) by technical area.

Technical Area	Statistics			
	N	Mean	SD	Median
		ρ_b*†		
21	14	1.56	0.13	1.52
49	13	1.84	0.14	1.86
53	2	1.36	0.01	1.36
54	8	1.40	0.07	1.40
		θ_s*		
21	14	0.33	0.05	0.33
49	13	0.28	0.05	0.28
53	2	0.47	0.02	0.47
54	10	0.41	0.03	0.41
		θ_r*		
21	14	0.008	0.009	0.008
49	13	0.001	0.002	0.000
53	2	0.061	0.008	0.061
54	8	0.010	0.013	0.006
		n		
21	14	2.16	0.34	2.09
49	13	1.95	0.28	1.92
53	2	2.38	0.38	2.38
54	8	2.06	0.51	1.97
		$\text{Log}_{10}\alpha$‡		
21	14	−2.51	0.24	−2.47
49	13	−2.56	0.27	−2.59
53	2	−2.14	0.07	−2.14
54	8	−2.33	0.30	−2.22
		$\text{Log}_{10}K_s$*§		
21	14	−4.33	0.53	−4.50
49	13	−5.17	0.51	−5.04
53	2	−2.94	0.69	−2.94
54	17	−3.70	0.49	−3.66

* Significant differences from the Kruskal–Wallis nonparametric test are marked for $p \leq 0.05$.
† Units for ρ_b are g cm^{-3}.
‡ Units for α are cm^{-1}.
§ Units for K_s and cm s^{-1}.

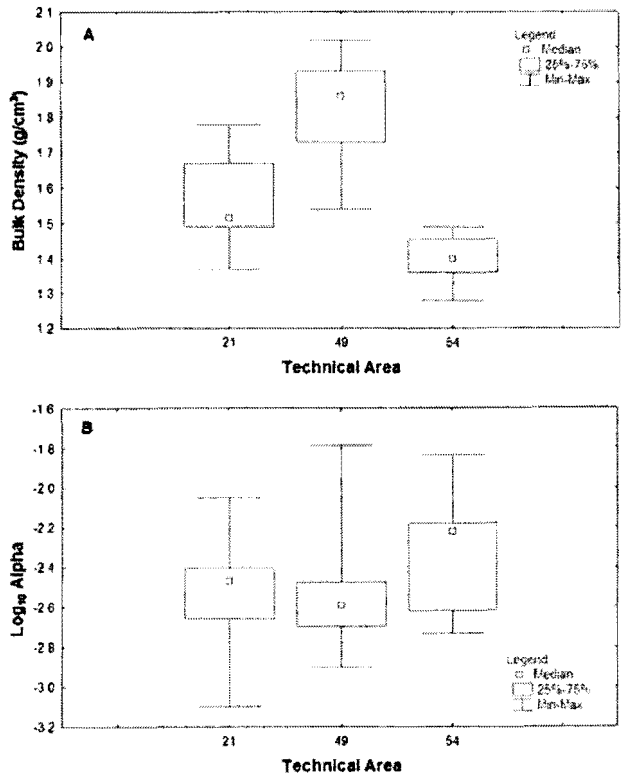

Fig. 5. Box and whiskers plots of the median, 25 to 5% quartile, and range for (A) bulk density (ρ_b) and (B) $\log_{10}\alpha$ from Bandelier Tuff Tshirege Unit 2 (Qbt 2) at designated technical areas of Los Alamos National Laboratory.

Area 54 values supporting the merging of the two samples. A normality analysis using the STATISTICA Shapiro–Wilk W (not shown) of the $\log_{10}K_s$ values indicates that a Gaussian distribution does not describe the $\log_{10}K_s$ values from Technical Area 54, but when the $\log_{10}K_s$ values from Technical Area 21 are included, the $\log_{10}K_s$ values are Gaussian.

Tshirege Cooling Unit 1g (Qbt 1g). There were samples for Unit 1g from Technical Areas 21, 49, 53, 54, Mortandad Canyon, Cañada del Buey, and Portrillo Canyon (Table 1), and with one sample available from Technical Area 53, this area was excluded from the analysis. This was the first unit where the canyon setting became a factor. Canyons at Los Alamos are wetter than the mesa tops, and this may lead to different weathering of the Bandelier Tuff and differences in matrix hydrologic properties. An analysis of the boreholes in Mortandad Canyon indicated that $\log_{10}K_s$ cannot be considered homogeneous, but the other properties and parameters can be. Each canyon was treated as a single technical area for these analyses, even though the boreholes may be spread over considerable distances (Fig. 1).

The statistics by location and Kruskal–Wallis results for Qbt 1g are presented in Table 9. All matrix hydrologic properties except ρ_b are significantly different among locations. Box and whisker plots of $\log_{10}K_s$ and van Genuchten n parameter are presented in Fig. 7 to determine if there are any readily apparent differences between canyon and mesa top settings. For $\log_{10}K_s$ in Fig. 7A, there is overlap, especially for the 25 to 75% quartiles with high median values occurring at a mesa top, Technical Area 21, and a canyon, Cañada del Buey. In Fig. 7B, the 25 to 75% quartiles for the n parameter overlap, except for Technical Area 54, which does have overall larger values for n.

Otowi Member (Qbo). The Otowi Member was sampled at Technical Areas 21, 49, 53, Mortandad Canyon, Cañada del Buey, and Portrillo Canyon (Table 1), and this unit contains both canyon and mesa samples. Table 2 shows that significant differences were found at Technical Area 21 for $\log_{10}K_s$ among boreholes, so this property will not be pooled. Again, canyons were treated as a single technical area for these analyses, consistent with the approach for Qbt 1g.

The Kruskal–Wallis analysis indicated that ρ_b was the only matrix hydrologic property that was not significantly different for the Qbo (Table 10). From a geologic perspective, the Otowi appears to be relatively homogeneous throughout the Los Alamos area, so this result was not expected. The statistics are also provided in Table 10. Technical Area 21 presents a special case in this analysis because samples were obtained from both mesa and canyon settings. Box and whisker plots of $\log_{10}\alpha$ in Fig. 8 show that Technical Area 21 is very different for the Obo than the other locations. Further breakdown

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Table 8. Statistics and Kruskal–Wallis results for Bandelier Tuff Tshirege Member Cooling Unit 1v (Qbt 1v) by technical area.

Technical Area	Statistics			
	N	Mean	SD	Median
		ρ_b*†		
21	9	1.30	0.16	1.28
49	2	1.36	0.06	1.36
53	2	1.37	0.14	1.37
54	37	1.17	0.09	1.18
		θ_s		
21	9	0.47	0.08	0.44
49	2	0.47	0.03	0.47
53	2	0.46	0.04	0.46
54	35	0.50	0.04	0.50
		θ_r		
21	9	0.002	0.005	0.000
49	2	0.000	0.000	0.000
53	1	0.056	0.000	0.056
54	34	0.003	0.009	0.000
		n		
21	9	1.75	0.22	1.82
49	2	1.53	0.31	1.53
53	1	2.21	0.00	2.21
54	34	1.73	0.28	1.70
		$\text{Log}_{10}\alpha$‡		
21	9	−2.20	0.28	−2.10
49	2	−1.95	0.85	−1.95
53	1	−2.54	0.00	−2.54
54	34	−2.38	0.41	−2.46
		$\text{Log}_{10}K_s$§		
21	9	−3.73	0.37	−3.80
49	2	−4.74	0.53	−4.74
53	2	−3.59	0.76	−3.59
54	44	−3.92	0.46	−3.92

* Significant differences from the Kruskal–Wallis nonparametric test are marked for $p \leq 0.05$.
† Units for ρ_b are g cm^{-3}.
‡ Units for α are cm^{-1}.
§ Units for K_s and cm s^{-1}.

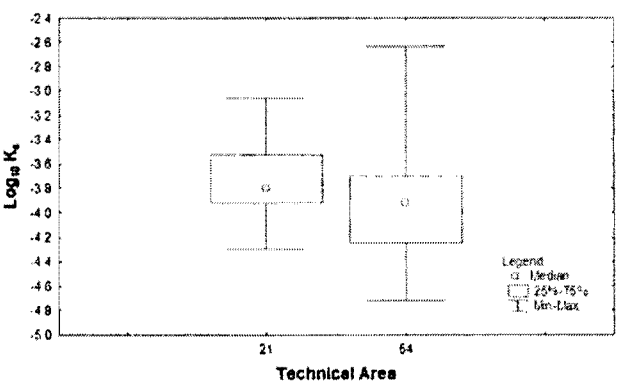

Fig. 6. Box and whiskers plots of the median, 25 to 75% quartile, and range for $\log_{10}K_s$ from Bandelier Tuff Tshirege Unit 1v (Qbt 1v) at designated technical areas of Los Alamos National Laboratory.

in Fig. 9 by separating the Technical Area 21 canyon and mesa samples with the canyon now designated as Los Alamos Canyon indicate that the low values are consistent among the settings and the results presented in Fig. 8 are not necessarily a function of the sampling of the different settings.

Correlation Analysis

Relationships between matrix hydrologic properties and/or parameters make it possible to use a surrogate property or parameter to estimate another more difficult to measure parameter. Table 11 is the correlation matrix for Qbt 1v, which was the only unit where the properties and parameters other than ρ_b were consistent across the site. Significant correlations were found between K_s and both α and $\log_{10}\alpha$, n and $\log_{10}\alpha$ (interestingly not n and α), and the transformations of K_s and α, which are functional in nature. Correlations are introduced by the fitting of Eq. [1] and RETC reports correlations between parameters with high correlations often occurring between α and n. The correlations in Table 10 do not provide any additional capability to predict matrix hydrologic properties for Qbt 1v across the Los

Table 9. Statistics and Kruskal–Wallis results for Bandelier Tuff Tshirege Member cooling unit 1g (Qbt 1g) by technical area.

Technical Area	Statistics			
	N	Mean	SD	Median
		ρ_b†		
21	6	1.18	0.06	1.19
49	5	1.21	0.02	1.21
53	1	1.32	0.00	1.32
54	13	1.16	0.05	1.14
Mortandad Canyon	33	1.16	0.12	1.18
Cañada del Buey	7	1.14	0.11	1.17
Potrillo Canyon	5	1.26	0.14	1.19
		θ_s*		
21	6	0.52	0.06	0.50
49	5	0.50	0.01	0.50
53	1	0.47	0.00	0.47
54	14	0.46	0.05	0.45
Mortandad Canyon	33	0.53	0.05	0.52
Cañada del Buey	7	0.47	0.02	0.46
Potrillo Canyon	5	0.44	0.04	0.45
		θ_r*		
21	6	0.000	0.000	0.000
49	5	0.000	0.000	0.000
53	1	0.057	0.000	0.057
54	9	0.010	0.015	0.000
Mortandad Canyon	9	0.034	0.027	0.040
Cañada del Buey	7	0.012	0.020	0.000
Potrillo Canyon	5	0.030	0.042	0.000
		*n**		
21	6	1.54	0.09	1.56
49	5	1.43	0.04	1.44
53	1	1.82	0.00	1.82
54	9	1.81	0.17	1.77
Mortandad Canyon	9	1.46	0.19	1.47
Cañada del Buey	7	1.67	0.17	1.68
Potrillo Canyon	5	1.55	0.24	1.55
		$\text{Log}_{10}\alpha$*‡		
21	6	−2.08	0.19	−2.15
49	5	−1.80	0.11	−1.77
53	1	−2.64	0.00	−2.64
54	9	−2.39	0.14	−2.37
Mortandad Canyon	9	−1.74	0.52	−1.96
Cañada del Buey	7	−2.19	0.31	−2.26
Potrillo Canyon	5	−2.14	0.31	−2.19
		$\text{Log}_{10}K_s$§		
21	6	−3.59	0.26	−3.59
49	5	−4.23	0.47	−4.20
53	1	−4.21	0.00	−4.21
54	17	−3.90	0.30	−3.89
Mortandad Canyon	11	−3.62	0.49	−3.82
Cañada del Buey	7	−3.67	0.44	−3.66
Potrillo Canyon	5	−4.22	0.50	−4.37

* Significant differences from the Kruskal–Wallis nonparametric test are marked for $p \leq 0.05$.
† Units for ρ_b are g cm^{-3}.
‡ Units for α are cm^{-1}.
§ Units for K_s and cm s^{-1}.

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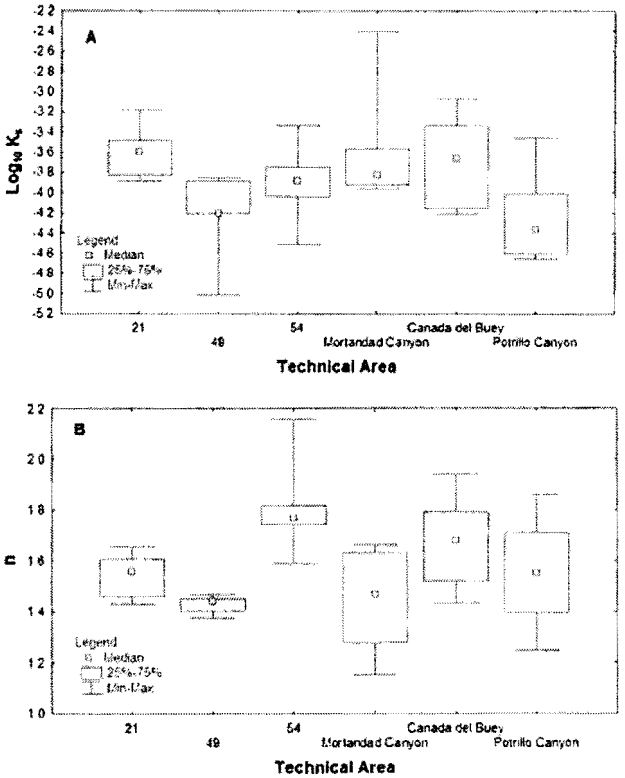

Fig. 7. Box and whiskers plots of the median, 25 to 75% quartile, and range for (A) $\log_{10}K_s$ and (B) van Genuchten n parameter from Bandelier Tuff Tshirege Unit 1g (Qbt 1g) at designated technical areas of Los Alamos National Laboratory.

Alamos area. These results combined with the previous analyses offer no relief in sampling requirements of the Bandelier Tuff at Los Alamos.

DISCUSSION AND CONCLUSIONS

The importance of the Bandelier Tuff at Los Alamos National Laboratory to waste management and environmental remediation means that the unsaturated zone hydrologic properties are critical in defining hydrologic response for either short or long time assessments. Unsaturated zone flow and transport modeling is the most readily available technique to perform required assessments at LANL, but these models require parameters and properties that describe the hydrologic and chemical properties of the geologic material. Bandelier Tuff unsaturated flow properties have been collected at a number of locations within the LANL site, and this study examined the potential of these data being combined using nonparametric statistical analyses to provide the required information at other locations across the LANL site.

Samples were collected and categorized using the geologic nomenclature from Broxton and Vaniman (2005), and this characterization is the starting point for the statistical analysis that was performed. Borehole locations were concentrated in the eastern portion of the LANL site because this is where the majority of the

Table 10. Statistics and Kruskal–Wallis results for Bandelier Tuff Otowi Member (Qbo) by technical area.

Technical Area	N	Statistics: Mean	SD	Median
		ρ_b†		
21	19	1.25	0.13	1.25
49	3	1.21	0.03	1.20
53	2	1.17	0.10	1.17
Mortandad Canyon	14	1.18	0.13	1.16
Cañada del Buey	12	1.20	0.06	1.19
Potrillo Canyon	4	1.16	0.04	1.16
		θ_s*		
21	19	0.39	0.04	0.40
49	3	0.49	0.02	0.50
53	2	0.46	0.00	0.46
Mortandad Canyon	14	0.52	0.05	0.52
Cañada del Buey	12	0.43	0.01	0.44
Potrillo Canyon	4	0.42	0.02	0.41
		θ_r*		
21	19	0.004	0.010	0.000
49	3	0.000	0.000	0.000
53	0			
Mortandad Canyon	5	0.048	0.047	0.028
Cañada del Buey	12	0.019	0.015	0.021
Potrillo Canyon	4	0.018	0.008	0.018
		n*		
21	19	2.21	0.57	2.07
49	3	1.35	0.04	1.35
53	0			
Mortandad Canyon	5	1.58	0.17	1.51
Cañada del Buey	12	1.76	0.25	1.71
Potrillo Canyon	4	1.74	0.08	1.72
		$\log_{10}\alpha$*‡		
21	19	−2.70	0.30	−2.66
49	3	−1.67	0.26	−1.76
53	0			
Mortandad Canyon	5	−2.12	0.23	−2.16
Cañada del Buey	12	−2.23	0.09	−2.23
Potrillo Canyon	4	−2.25	0.10	−2.25
		$\log_{10}K_s$*§		
21	19	−4.67	0.63	−4.51
49	3	−4.17	0.15	−4.25
53	2	−3.71	0.08	−3.71
Mortandad Canyon	7	−3.39	0.89	−3.54
Cañada del Buey	12	−3.64	0.20	−3.66
Potrillo Canyon	4	−3.60	0.36	−3.45

* Significant differences from the Kruskal–Wallis nonparametric test are marked for $p \leq 0.05$.
† Units for ρ_b are g cm^{-3}.
‡ Units for α are cm^{-1}.
§ Units for K_s and cm s^{-1}.

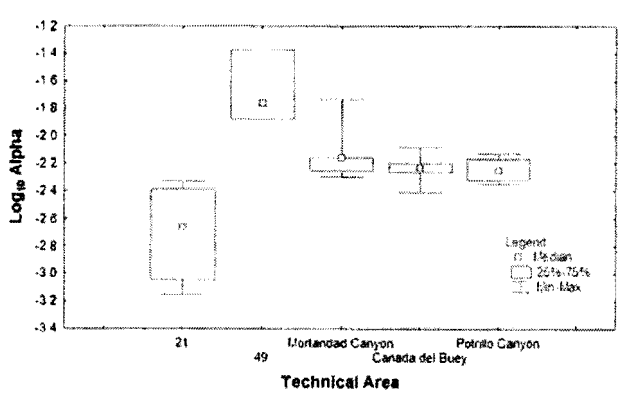

Fig. 8. Box and whiskers plots of the median, 25 to 75% quartile, and range for $\log_{10}\alpha$ from Otowi Member (Qbo) of the Bandelier Tuff at designated technical areas of Los Alamos National Laboratory.

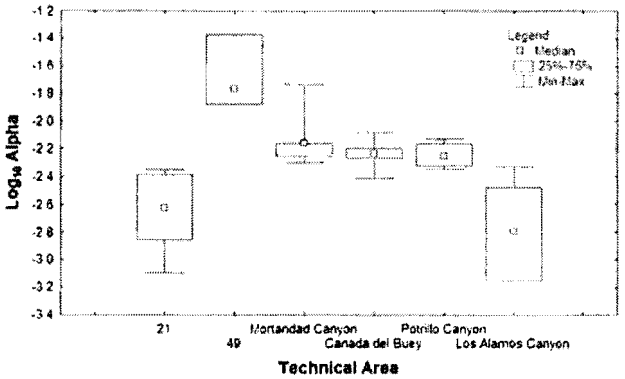

Fig. 9. Box and whiskers plots of the median, 25 to 75% quartile, and range for $\log_{10}\alpha$ from Otowi Member (Qbo) of the Bandelier Tuff at designated technical areas of Los Alamos National Laboratory. The canyon samples from Technical Area 21 are labeled as Los Alamos Canyon.

remediation and waste management activities have occurred. Samples were collected in an ad hoc mode from the boreholes, and there was no attempt at systematic sampling in any location. The uneven distribution in the number of samples per Bandelier Tuff Tshirege Member cooling unit and Otowi Member and the variability limit the conclusions that can be drawn from this study.

The first analyses examined the consistency of matrix hydrologic properties between boreholes in a given technical area. Statistically significant differences were found between boreholes at Technical Area 21, and the key property $\log_{10}K_s$ was found to be significantly different for most geologic units. At a second site, the differences were not as prevalent, but the larger number of boreholes, limited sampling, and variability confounded the analysis. These statistical analyses indicated that the matrix hydrologic properties within a technical area or location are not consistent even for a given geologic unit, and further characterization is required to define model parameters for site vadose zone assessments.

Statistical analyses across technical areas for each Tshirege Member cooling unit and the Otowi Member were performed to examine the potential for pooling data to extend sample size. This analysis revealed that data from technical areas cannot be combined, with only Qbt 1v demonstrating any potential for pooling.

Differences in setting, canyon bottom vs. mesa top, were tested for Tshirege Unit 1g and the Otowi Member. Canyons are wetter than mesas, and matrix hydrologic properties can differ because of the weathering processes that occur with increased saturation. The results from the canyon–mesa comparison did not reveal any significant differences, and if there are, these differences may be masked by those between locations.

This study summarized the statistics for unsaturated matrix hydrologic properties for the Bandelier Tuff at Los Alamos National Laboratory. As indicated above, the sample size in this study was limited, and in many cases <10 samples were available for a geologic unit at a location. If the probability density or cumulative density function must be defined, then at least 30 samples are needed. This is one of the rationales for pooling of the data from different technical areas. What is clear from this study is that one cannot as a general rule combine samples for matrix hydrologic properties from different technical areas at Los Alamos National Laboratory. This means that either more sampling is needed from a technical area to further refine the local distribution function or it is necessary to use the current data with associated uncertainties.

An attempt was made to use a statistical approach to define the hydrogeologic units. The approach proposed by Flint (1998) is more logical when preparing a site investigation. The sampling of basic matrix hydrologic properties at Los Alamos has not focused on obtaining data on a regular or depth or spatial interval to describe the lithostratigraphy. This sampling approach would improve parameterization for flow and transport assessments by (i) better defining hydrogeologic units using an indicator such as porosity, proposed by Flint (1998), and (ii) providing data for geostatistical analyses that will lead to understanding spatial dependencies (in both the lateral and vertical directions).

ACKNOWLEDGMENTS

I especially thank the many people over the years that have collected and characterized data from the Bandelier Tuff because without their efforts, this study would not have been possible. Diana Hollis of the Environmental Restoration Project at Los Alamos provided support for much of this effort. Kay Birdsell has been a catalyst for these efforts to support her vadose zone modeling. Dave Broxton has been a source of insight into the Bandelier Tuff. This manuscript benefited greatly from a review by Phil Stauffer and two anonymous reviewers. Partial support for this paper came from the Los Alamos National Laboratory Directed Research and Development Project, "Computational Models of the Water Cycle in Semi-arid Basins."

Table 11. Correlation matrix for unsaturated zone hydrologic properties from Bandelier Tuff Tshirege cooling unit 1v (Qbt 1v).†

Property	θ_s	K_s	$\log_{10}K_s$	θ_r	n	α	$\log_{10}\alpha$
θ_s	1.00						
K_s	0.05	1.00					
$\log_{10}K_s$	0.16	0.83*	1.00				
θ_r	−0.10	0.05	−0.11	1.00			
n	−0.24	0.07	0.19	0.18	1.00		
α	0.09	0.44*	0.25	0.22	−0.27	1.00	
$\log_{10}\alpha$	0.08	0.44*	0.21	0.09	−0.58*	0.75*	1.00

* Significant at the 0.05 probability level.
† Total N = 46 for this analysis.

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Table A1. Listing of Bandelier Tuff samples and properties used in this study.

Borehole	Technical Area	Unit	Setting	Depth	ρ_b	θ_s	K_s	Log_{10} K_s	θ_r	n	α	Log_{10} α
				m	g/cm$_3$		cm/s				cm^{-1}	
LADP-3	21	Otowi	2	56.5	1.69	0.2570	0.00000220	−5.6576	0.0419	3.1668	0.0007	−3.1549
LADP-3	21	Otowi	2	73.2	1.25	0.3980	0.00003100	−4.5086	0	1.9818	0.0012	−2.9208
LADP-3	21	Otowi	2	83.0	1.30	0.3490	0.00002000	−4.6990	0	1.7494	0.0022	−2.6576
LADP-3	21	Otowi	2	84.0	1.29	0.3920	0.00002300	−4.6383	0	2.8065	0.0007	−3.1549
LADP-3	21	Otowi	2	89.4	1.25	0.3680	0.00001500	−4.8239	0	1.688	0.0033	−2.4815
LADP-3	21	Otowi	2	91.9	1.28	0.3460	0.00002200	−4.6576	0	1.6437	0.0047	−2.3279
LADP-4	21	2	2	4.9	1.49	0.3360	0.00002200	−4.6576	0.0243	1.9272	0.0035	−2.4559
LADP-4	21	2	1	8.3	1.78	0.2640	0.00002500	−4.6021	0.012	2.0162	0.0044	−2.3565
LADP-4	21	2	1	9.3	1.78	0.2820	0.00001800	−4.7447	0.0172	2.5176	0.0026	−2.5850
LADP-4	21	2	1	17.3	1.67	0.2860	0.00000600	−5.2218	0	2.3058	0.0008	−3.0969
LADP-4	21	2	1	21.3	1.51	0.3840	0.00001400	−4.8539	0	1.6076	0.0033	−2.4815
LADP-4	21	2	1	24.5	1.52	0.4060	0.00012000	−3.9208	0	2.2886	0.0022	−2.6576
LADP-4	21	1g	1	49.1	1.19	0.5720	0.00013000	−3.8861	0	1.5712	0.0056	−2.2518
LADP-4	21	1g	1	62.5	1.22	0.4680	0.00022000	−3.6576	0	1.6556	0.0056	−2.2518
LADP-4	21	1g	1	74.9	1.20	0.5220	0.00033000	−3.4815	0	1.4612	0.0156	−1.8069
LADP-4	21	1v	1	31.4	1.28	0.4090	0.00016000	−3.7959	0	1.8463	0.0035	−2.4559
LADP-4	21	1v	1	46.1	1.23	0.5470	0.00005100	−4.2924	0	1.3938	0.0063	−2.2007
LADP-4	21	Otowi	1	94.4	1.16	0.4640	0.00003300	−4.4815	0	2.0705	0.0027	−2.5686
LADP-4	21	Otowi	1	96.7	1.18	0.4000	0.00003200	−4.4949	0	3.1988	0.0008	−3.0969
LADP-4	21	Otowi	1	97.6	1.14	0.4460	0.00004600	−4.3372	0	1.8835	0.0035	−2.4559
LADP-4	21	Otowi	1	100.7	1.14	0.4180	0.00003800	−4.4202	0.01	2.1415	0.0024	−2.6198
LADP-4	21	Otowi	1	103.1	1.11	0.4080	0.00006000	−4.2218	0	3.3755	0.0009	−3.0458
LADP-4	21	Otowi	1	104.5	1.16	0.4160	0.00001800	−4.7447	0	2.3811	0.0019	−2.7212
LADP-4	21	Otowi	1	105.9	1.16	0.4080	0.00002900	−4.5376	0	2.2625	0.0019	−2.7212
LADP-4	21	Otowi	1	107.4	1.15	0.4060	0.00003200	−4.4949	0	2.6222	0.0014	−2.8539
LADP-4	21	Otowi	1	125.4	1.44	0.3980	0.00007100	−4.1487	0.0145	1.7677	0.0041	−2.3872
LADP-4	21	Otowi	1	147.2	1.27	0.4010	0.00009100	−4.0410	0	1.6368	0.0045	−2.3468
LADP-4	21	Otowi	1	151.7	1.29	0.3500	0.00004000	−4.3979	0	1.6421	0.0041	−2.3872
LADP-4	21	Otowi	1	152.4	1.23	0.3810	0.00002900	−4.5376	0.0151	1.7429	0.0041	−2.3872
LADP-4	21	Otowi	1	160.8	1.34	0.3530	0.00000014	−6.8539	0	2.3134	0.0009	−3.0458
MDAT	21	3	1				0.00008100	−4.0915				
MDAT	21	3	1				0.00009400	−4.0269				
MDAT	21	3	1				0.00000830	−5.0809				
MDAT	21	3	1				0.00005000	−4.3010				
MDAT	21	3	1				0.00003900	−4.4089				
MDAT	21	3	1				0.00003100	−4.5086				
MDAT	21	3	1				0.00004200	−4.3768				
MDAT	21	3	1				0.00002200	−4.6576				
MDAT	21	3	1				0.00003600	−4.4437				
MDAT	21	3	1				0.00002800	−4.5528				
MDAT	21	3	1				0.00005000	−4.3010				
MDAT	21	3	1				0.00008600	−4.0655				
MDAT	21	3	1				0.00003300	−4.4815				
MDAT	21	3	1				0.00008100	−4.0915				
MDAT	21	3	1				0.00002500	−4.6021				
MDAT	21	3	1				0.00000830	−5.0809				
MDAT	21	3	1				0.00002500	−4.6021				
MDAT	21	3	1				0.00003600	−4.4437				
MDAT	21	3	1				0.00005300	−4.2757				
MDAT	21	3	1				0.00004200	−4.3768				
MDAT	21	3	1				0.00000560	−5.2518				
MDAT	21	3	1				0.00006700	−4.1739				
MDAT	21	3	1				0.00010000	−4.0000				
MDAT	21	3	1				0.00004400	−4.3565				
21-2523	21	2	1	27.8	1.39	0.3574	0.00024000	−3.6198	0	2.1917	0.0039	−2.4089
21-2523	21	2	1	28.4	1.37	0.3934	0.00046000	−3.3372	0.0084	1.9582	0.0089	−2.0506
21-2523	21	2	1	29.5	1.49	0.3380	0.00009500	−4.0223	0.0128	2.967	0.0051	−2.2924
21-2523	21	2	1	29.9	1.46	0.3170	0.00009000	−4.0458	0.00000	2.0666	0.0021	−2.6778
21-2523	21	2	1	31.9	1.64	0.2690	0.00002100	−4.6778	0.0138	2.5215	0.0029	−2.5376
21-2523	21	2	1	33.4	1.61	0.2839	0.00003400	−4.4685	0.0076	2.1169	0.0036	−2.4437
21-2523	21	2	1	43.9	1.67	0.2843	0.00003000	−4.5229	0.02086	1.89268	0.00393	−2.4056
21-2523	21	2	1	48.6	1.51	0.3640	0.00013000	−3.8861	0	1.8791	0.0018	−2.7447
21-2523	21	3	1	2.0	1.35	0.3121	0.00002400	−4.6198	0.0229	1.9264	0.0042	−2.3768
21-2523	21	3	1	3.8	1.36	0.3249	0.00013000	−3.8861	0.0097	1.8657	0.0069	−2.1612
21-2523	21	3	1	4.4	1.27	0.3360	0.00330000	−2.4815	0	1.7173	0.0079	−2.1024
21-2523	21	3	1	7.7	1.27	0.3300	0.00018000	−3.7447	0.0092	2.0202	0.0066	−2.1805
21-2523	21	3	1	9.8	1.24	0.3520	0.00020000	−3.6990	0.0097	2.1044	0.0079	−2.1024
21-2523	21	3	1	11.7	1.33	0.3878	0.00024000	−3.6198	0.0097	2.1861	0.0051	−2.2924
21-2523	21	3	1	12.6	1.45	0.4090	0.00018000	−3.7447	0.0132	2.1266	0.0065	−2.1871
21-2523	21	3	1	13.6	1.36	0.3773	0.00009800	−4.0088	0.0199	2.4288	0.0049	−2.3098
21-2523	21	3	1	14.4	1.28	0.3960	0.00015000	−3.8239	0.0143	2.5127	0.0051	−2.2924
21-2523	21	3	1	15.1	1.24	0.3840	0.00021000	−3.6778	0.0133	2.8635	0.0044	−2.3565
21-2523	21	3	1	17.1	1.23	0.3808	0.00030000	−3.5229	0.0124	2.4905	0.0064	−2.1938
21-2523	21	3	1	19.4	1.17	0.3670	0.00059000	−3.2291	0	1.7329	0.0051	−2.2924
21-2523	21	1g	1	71.2	1.26	0.6200	0.00065000	−3.1871	0.00000	1.5431	0.0069	−2.1612
21-2523	21	1g	1	77.4	1.08	0.4750	0.00015000	−3.8239	0	1.6074	0.0073	−2.1367
21-2523	21	1g	1	81.9	1.14	0.4670	0.00030000	−3.5229	0	1.4302	0.013	−1.8861

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Table A1. Continued.

Borehole	Technical Area	Unit	Setting	Depth	ρ_b	θ_s	K_s	Log_{10} K_s	θ_r	n	α	Log_{10} α
				m	g/cm$_3$		cm/s				cm^{-1}	
21-2523	21	1v	1	49.4	1.44	0.3770	0.00014000	−3.8539	0	1.5718	0.008	−2.0969
21-2523	21	1v	1	50.0	1.40	0.4150	0.00043000	−3.3665	0.0149	2.0581	0.0065	−2.1871
21-2523	21	1v	1	50.9	1.40	0.4040	0.00022000	−3.6576	0	1.7144	0.0089	−2.0506
21-2523	21	1v	1	56.0	1.09	0.4360	0.00087000	−3.0605	0.0068	1.9019	0.0092	−2.0362
21-2523	21	1v	1	59.0	1.55	0.6280	0.00030000	−3.5229	0	1.8197	0.008	−2.0969
21-2523	21	1v	1	65.3	1.21	0.5250	0.00012000	−3.9208	0	1.9011	0.0015	−2.8239
21-2523	21	1v	1	66.6	1.09	0.4860	0.00008300	−4.0809	0	1.4984	0.0135	−1.8697
P-16	16	3	1	2.4	1.25	0.5180	0.00016000	−3.7959	0.07800	2.87700	0.00250	−2.6021
P-16	16	3	1	3.7	1.26	0.5610	0.00028000	−3.5528				
P-16	16	3	1	5.2	1.27	0.5490	0.00028000	−3.5528				
P-16	16	3	1	6.7	1.25	0.5620	0.00020000	−3.6990				
P-16	16	3	1	7.9	1.38	0.5200	0.00009200	−4.0362				
P-16	16	3	1	11.0	1.61	0.4280	0.00002300	−4.6383				
P-16	16	3	1	13.1	1.62	0.4230	0.00008600	−4.0655				
P-16	16	3	1	18.9	1.70	0.3640	0.00052000	−3.2840	0.06000	1.75900	0.00280	−2.5528
P-16	16	3	1	23.2	1.57	0.4160	0.00023000	−3.6383	0.00000	1.38100	0.00520	−2.2840
P-16	16	3	1	24.7	1.80	0.3460	0.00004400	−4.3565	0.04000	1.51900	0.00110	−2.9586
150-1	49	4	1	5.8	1.23	0.5220	0.00003000	−4.5229	0.00000	1.61875	0.00327	−2.4855
150-1	49	4	1	8.3	1.20	0.5390	0.00006700	−4.1739	0.00000	1.52144	0.00638	−2.1952
150-1	49	4	1	9.0	1.18	0.5460	0.00019000	−3.7212	0.00000	1.54283	0.01059	−1.9751
150-1	49	4	1	16.7	1.40	0.4610	0.00009300	−4.0315	0.00000	1.71136	0.00786	−2.1046
150-2	49	3	1	26.7	1.64	0.3680	0.00010000	−4.0000	0	1.68398	0.00963	−2.0164
150-2	49	3	1	30.3	1.76	0.3190	0.00001300	−4.8861	0	1.58592	0.00587	−2.2314
150-2	49	3	1	34.9	1.61	0.3750	0.00012000	−3.9208	0	1.64087	0.01065	−1.9727
150-2	49	3	1	39.7	1.66	0.3520	0.00003700	−4.4318	0	1.64669	0.0066	−2.1805
150-2	49	4	1	3.4	1.20	0.5380	0.00007400	−4.1308	0	1.4174	0.00419	−2.3778
150-2	49	4	1	4.2	1.12	0.5680	0.00028000	−3.5528	0	1.67705	0.0057	−2.2441
150-2	49	4	1	19.4	1.56	0.3900	0.00000840	−5.0757	0	1.33823	0.01634	−1.7867
150-2	49	4	1	21.0	1.60	0.3780	0.00001400	−4.8539	0	1.62422	0.0046	−2.3372
700-1	49	2	1	59.9	1.86	0.2790	0.00001500	−4.8239	0	1.82518	0.0035	−2.4559
700-1	49	2	1	61.5	2.02	0.2120	0.00000210	−5.6778	0	1.63304	0.00256	−2.5918
700-1	49	2	1	64.5	2.02	0.2120	0.00000059	−6.2291	0.00696	2.37597	0.00126	−2.8996
700-1	49	2	1	68.9	1.93	0.2510	0.00000910	−5.0410	0	1.96029	0.00256	−2.5918
700-1	49	2	1	72.1	1.69	0.3350	0.00000800	−5.0969	0	1.46499	0.01639	−1.7854
700-1	49	2	1	76.6	1.81	0.2950	0.00000760	−5.1192	0	1.7265	0.0036	−2.4437
700-1	49	2	1	79.7	1.89	0.2680	0.00000790	−5.1024	0	1.75281	0.00336	−2.4737
700-1	49	2	1	81.2	1.88	0.2710	0.00001400	−4.8539	0	1.91166	0.00269	−2.5702
700-1	49	2	1	84.3	1.85	0.2770	0.00001200	−4.9208	0	2.33408	0.00202	−2.6946
700-1	49	2	1	87.2	1.93	0.2450	0.00000075	−6.1249	0	1.92509	0.00152	−2.8182
700-1	49	2	1	90.4	1.71	0.3360	0.00001700	−4.7696	0	2.27582	0.00201	−2.6968
700-1	49	2	1	93.3	1.73	0.3220	0.00001200	−4.9208	0	1.92271	0.00222	−2.6536
700-1	49	2	1	95.5	1.54	0.4010	0.00002600	−4.5850	0	2.2116	0.00273	−2.5638
700-1	49	3	1	27.5	1.61	0.3770	0.00007700	−4.1135	0	2.09192	0.00482	−2.3170
700-1	49	3	1	29.2	1.65	0.3580	0.00002800	−4.5528	0	1.66266	0.00696	−2.1574
700-1	49	3	1	36.7	1.65	0.3540	0.00005800	−4.2366	0	1.55129	0.00852	−2.0696
700-1	49	4	1	15.8	1.36	0.4710	0.00007500	−4.1249	0.00000	2.01152	0.00356	−2.4486
700-1	49	1g	1	120.2	1.24	0.5030	0.00000970	−5.0132	0	1.46678	0.01083	−1.9654
700-1	49	1g	1	128.2	1.21	0.4960	0.00013000	−3.8861	0	1.4402	0.02009	−1.6970
700-1	49	1g	1	153.3	1.21	0.4810	0.00006300	−4.2007	0	1.37428	0.01714	−1.7660
700-1	49	1g	1	157.1	1.2	0.4930	0.00014000	−3.8539	0	1.45168	0.01403	−1.8529
700-1	49	1g	1	163.9	1.19	0.5020	0.00006300	−4.2007	0	1.4034	0.01862	−1.7300
700-1	49	1v	1	108.8	1.31	0.4970	0.00004300	−4.3665	0	1.75238	0.00284	−2.5467
700-1	49	1v	1	114.1	1.40	0.4480	0.00000760	−5.1192	0	1.31312	0.04517	−1.3451
700-1	49	Otowi	1	182.8	1.24	0.4740	0.00005600	−4.2518	0.00000	1.38997	0.01327	−1.8771
700-1	49	Otowi	1	184.3	1.19	0.5010	0.00005600	−4.2518	0.00000	1.34955	0.01731	−1.7617
700-1	49	Otowi	1	194.8	1.20	0.5040	0.00010000	−4.0000	0.00000	1.30794	0.04233	−1.3734
AB-6	53	2	1	12.2	1.35	0.4550	0.00037000	−3.4318	0.05500	2.64800	0.00820	−2.0862
AB-6	53	2	1	18.3	1.37	0.4810	0.00350000	−2.4559	0.06700	2.10700	0.00650	−2.1871
AB-6	53	1g	1	45.7	1.32	0.4670	0.00006100	−4.2147	0.05700	1.81600	0.00230	−2.6383
AB-6	53	1v	1	30.5	1.27	0.4850	0.00088000	−3.0555				
AB-6	53	1v	1	33.5	1.47	0.4270	0.00007400	−4.1308	0.05600	2.20800	0.00290	−2.5376
AB-7	53	Otowi	1	21.3	1.24	0.4600	0.00017000	−3.7696				
AB-7	53	Otowi	1	24.4	1.10	0.4620	0.00022000	−3.6576				
54-1001	54	1v	1	20.7	1.20	0.4140	0.00013000	−3.8861	0.00000	1.89400	0.00340	−2.4685
54-1001	54	1v	1	25.3	1.25	0.4600	0.00011000	−3.9586	0.00000	2.22500	0.00220	−2.6576
54-1001	54	1v	1	31.1	1.19	0.5140	0.00016000	−3.7959	0.00000	1.78200	0.00340	−2.4685
54-1001	54	1v	1	37.2	1.18	0.4640	0.00002200	−4.6576	0.00000	1.58300	0.00410	−2.3872
54-1001	54	1v	1	43.3	1.20	0.4820	0.00008200	−4.0862	0.00000	1.42900	0.00370	−2.4318
54-1002	54	1g	1	54.7	1.16	0.3930	0.00006500	−4.1871	0.00000	1.81500	0.00430	−2.3665
54-1002	54	1g	1	74.4	1.14	0.3930	0.00017000	−3.7696	0.00000	1.74500	0.00620	−2.2076
54-1002	54	1v	1	28.2	1.26	0.4600	0.00008100	−4.0915	0.00000	2.21300	0.00120	−2.9208
54-1002	54	1v	1	37.2	1.23	0.4950	0.00004600	−4.3372	0.00000	1.77300	0.00310	−2.5086
54-1002	54	1v	1	43.4	1.19	0.4910	0.00002500	−4.6021	0.01700	1.39300	0.01540	−1.8125
54-1003	54	1g	1	47.9	1.14	0.4320	0.00013000	−3.8861	0.02500	1.76500	0.00400	−2.3979
54-1003	54	1g	1	63.1	1.18	0.4280	0.00015000	−3.8239				
54-1003	54	1g	1	79.6	1.11	0.4880	0.00027000	−3.5686				
54-1003	54	1g	1	82.8	1.31	0.4100	0.00026000	−3.5850				

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Table A1. Continued.

Borehole	Technical Area	Unit	Setting	Depth	ρ_b	θ_s	K_s	Log_{10} K_s	θ_r	n	α	Log_{10} α
				m	g/cm$_3$		cm/s				cm^{-1}	
54-1003	54	1v	1	31.1	1.22	0.5100	0.00013000	−3.8861	0.00000	1.73300	0.00300	−2.5229
54-1003	54	1v	1	36.4	1.22		0.00009900	−4.0044				
54-1006	54	2	1	12.8	1.28	0.4490	0.00041000	−3.3872	0.00000	1.76000	0.00640	−2.1938
54-1006	54	1g	1	49.1	1.13	0.5260	0.00012000	−3.9208				
54-1006	54	1v	1	23.4	1.28	0.4450	0.00009800	−4.0088	0.00000	1.88000	0.00300	−2.5229
54-1006	54	1v	1	37.9	1.22	0.4350	0.00004500	−4.3468	0.00000	1.72100	0.00350	−2.4559
54-1006	54	1v	1	41.7	1.28	0.4720	0.00005700	−4.2441	0.00000	2.08700	0.00140	−2.8539
54-1107	54	1g	1	31.8	1.13	0.4920	0.00008060	−4.0937	0	2.00144	0.00264	−2.5784
54-1107	54	1g	1	33.0	1.15	0.5210	0.00046100	−3.3363	0	1.76976	0.00461	−2.3363
54-1107	54	1v	1	28.4	1.16	0.5490	0.00012900	−3.8894	0	1.47194	0.00602	−2.2204
54-1107	54	1v	1	29.3	1.18	0.5210	0.00011300	−3.9469	0	1.34936	0.00951	−2.0218
54-1107	54	1v	1	29.9	0.93	0.4450	0.00004610	−4.3363	0	1.4326	0.00582	−2.2351
54-1107	54	1v	1	30.2	1.13	0.5210	0.00062500	−3.2041	0.02175	1.35428	0.29698	−0.5273
54-1107	54	1v	1	30.9	1.2	0.5030	0.00003200	−4.4949	0	1.43039	0.00264	−2.5784
54-1121	54	1g	1	24.5	1.18	0.4350	0.00003710	−4.4306	0.04313	1.79672	0.00304	−2.5171
54-1121	54	1g	1	25.2	1.14	0.4980	0.00012200	−3.9136	0.01591	1.58867	0.00594	−2.2262
54-1121	54	1g	1	26.7	1.14	0.4550	0.00010200	−3.9914	0	1.66641	0.00506	−2.2958
54-1121	54	1v	1	19.6	1.09	0.5320	0.00022100	−3.6556	0	1.50077	0.00752	−2.1238
54-1121	54	1v	1	20.7	1.18	0.5440	0.00016400	−3.7852	0	1.69952	0.00404	−2.3936
54-1121	54	1v	1	21.4	1.07	0.5250	0.00014300	−3.8447	0	1.43892	0.00805	−2.0942
54-1121	54	1v	1	22.9	1.2	0.4710	0.00007320	−4.1355	0	1.67761	0.00324	−2.4895
54-1121	54	1v	1	23.7	1.08	0.5390	0.00017100	−3.7670	0	1.38315	0.00816	−2.0883
G-5	54	2	1	2.7	1.35	0.3990	0.00021000	−3.6778	0	1.55762	0.01462	−1.8351
G-5	54	2	1	6.6	1.37	0.4320	0.00013000	−3.8861	0	1.49227	0.00684	−2.1649
G-5	54	2	1	9.9	1.45	0.3670	0.00003100	−4.5086	0.01217	2.63367	0.00285	−2.5452
G-5	54	2	1	13.0	1.49	0.3830	0.00002700	−4.5686	0.01217	2.18579	0.00186	−2.7305
G-5	54	2	1	16.0	1.43	0.3760	0.00004000	−4.3979	0.01853	2.94741	0.00204	−2.6904
G-5	54	1g	1	31.2	1.14	0.4520	0.00003100	−4.5086	0.00825	2.15968	0.0026	−2.5850
G-5	54	1v	1	18.4	1.17	0.5780	0.00022000	−3.6576	0	1.85093	0.00497	−2.3036
G-5	54	1v	1	21.3	1.17	0.4750	0.00008800	−4.0555	0	2.10495	0.00131	−2.8827
G-5	54	1v	1	25.1	1.18	0.4400	0.00003600	−4.4437	0	1.82619	0.00215	−2.6676
G-P38-HH3	54	1v	1	21.4	1.03		0.00162000	−2.7905				
G-P38-HH3	54	1v	1	37.3	1.02		0.00231000	−2.6364				
G-P38-HH3	54	1v	1	39.4	1.32	0.5390	0.00024700	−3.6073	0	1.88591	0.00249	−2.6038
G-P38-HH3	54	1v	1	44.0	1.06	0.5250	0.00034200	−3.4660	0	1.68698	0.00343	−2.4647
G-P38-HH3	54	1v	1	62.3	1.17	0.5300	0.00018200	−3.7399	0	1.49488	0.00484	−2.3152
G-P38-HH3	54	1v	1	78.4	1.09	0.4760	0.00005580	−4.2534	0	1.60049	0.00494	−2.3063
LGM-85-06	54	2	1	8.8		0.4250	0.00048000	−3.3188				
LGM-85-06	54	2	1	15.5		0.4020	0.00008400	−4.0757				
LGM-85-06	54	1g	1	35.1		0.5630	0.00009100	−4.0410				
LGM-85-06	54	1v	1	30.2		0.5260	0.00130000	−2.8861				
LGM-85-11	54	2	1	0.9		0.5400	0.00054000	−3.2676				
LGM-85-11	54	2	1	9.1		0.5150	0.00028000	−3.5528				
LGM-85-11	54	1g	1	35.1		0.6010	0.00018000	−3.7447				
LGM-85-11	54	1v	1	28.7		0.6430	0.00011000	−3.9586				
LLC-85-14	54	2	1	9.1	1.37	0.4410	0.00042000	−3.3768	0.00000	1.89000	0.00600	−2.2218
LLC-85-15	54	2	1	3.2	1.46	0.4640	0.00160000	−2.7959	0.03800	2.04400	0.00600	−2.2218
LLC-86-22	54	1v	1	16.6	1.26	0.5100	0.00005200	−4.2840	0.02000	2.23800	0.00370	−2.4318
LLC-86-22	54	1v	1	16.6	1.26	0.4830	0.00025000	−3.6021	0.00000	1.93200	0.00450	−2.3468
LLC-86-22	54	1v	1	19.8	1.27	0.4870	0.00014000	−3.8539	0.00000	2.34700	0.00260	−2.5850
LLC-86-22	54	1v	1	40.1	1.05	0.5070	0.00001900	−4.7212	0.01200	1.58600	0.00210	−2.6778
LLC-86-22	54	1v	1	40.1	1.05	0.5080	0.00002700	−4.5686	0.04400	1.70900	0.00210	−2.6778
LLM-85-01	54	2	1	9.1		0.3960	0.00011000	−3.9586				
LLM-85-01	54	1g	1	37.8		0.4890	0.00022000	−3.6576				
LLM-85-01	54	1v	1	15.8		0.6440	0.00026000	−3.5850				
LLM-85-01	54	1v	1	30.8		0.6210	0.00025000	−3.6021				
LLM-85-02	54	2	1	2.1		0.4150	0.00044000	−3.3565				
LLM-85-02	54	2	1	11.0		0.4650	0.00012000	−3.9208				
LLM-85-02	54	1v	1	20.4		0.4330	0.00009800	−4.0088				
LLM-85-02	54	1v	1	35.7		0.4850	0.00017000	−3.7696				
LLM-85-05	54	2	1	4.6		0.5260	0.00056000	−3.2518				
LLM-85-05	54	2	1	11.0		0.7360	0.00022000	−3.6576				
LLM-85-05	54	1g	1	37.5		0.6560	0.00016000	−3.7959				
LLM-85-05	54	1v	1	23.2		0.7420	0.00013000	−3.8861				
MCM-5.1	Mortandad	1g	2	13.1	1.19	0.5140						
MCM-5.1	Mortandad	1g	2	13.3	1.16	0.5210	0.00020000	−3.6990	0.05300	1.66100	0.00720	−2.1427
MCM-5.1	Mortandad	1g	2	14.2	0.99	0.5960						
MCM-5.1	Mortandad	1g	2	16.2	1.09	0.5550						
MCM-5.1	Mortandad	1g	2	16.5	1.16	0.4540	0.00015000	−3.8239				
MCM-5.1	Mortandad	1g	2	17.5	1.09	0.5550						
MCM-5.1	Mortandad	1g	2	17.7	1.18	0.5200	0.00018000	−3.7447	0.04000	1.63000	0.00950	−2.0223
MCM-5.1	Mortandad	1g	2	19.2	0.91	0.6290						
MCM-5.1	Mortandad	1g	2	19.5	1.17	0.5320	0.00013000	−3.8861	0.05900	1.64700	0.01260	−1.8996
MCM-5.1	Mortandad	1g	2	20.0	1.20	0.5100						
MCM-5.1	Mortandad	1g	2	20.6	1.15	0.5200	0.00011000	−3.9586	0.03300	1.61400	0.00890	−2.0506
MCM-5.1	Mortandad	1g	2	20.7	1.23	0.4980						
MCM-5.1	Mortandad	1g	2	22.1	1.19	0.5150	0.00014000	−3.8539	0.00300	1.46800	0.01090	−1.9626

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Table A1. Continued.

Borehole	Technical Area	Unit	Setting	Depth	ρ_b	θ_s	K_s	Log_{10} K_s	θ_r	n	α	Log_{10} α
				m	g/cm$_3$		cm/s				cm^{-1}	
MCM-5.1	Mortandad	1g	2	22.3	1.09	0.5550						
MCM-5.1	Mortandad	1g	2	23.0	1.18	0.5180						
MCM-5.1	Mortandad	1g	2	23.8	1.20	0.5100						
MCM-5.1	Mortandad	1g	2	24.5	1.22	0.5020						
MCM-5.1	Mortandad	1g	2	25.1	1.20	0.5890	0.00012000	−3.9208	0.06900	1.27800	0.01350	−1.8697
MCM-5.1	Mortandad	1g	2	25.3	1.18	0.5180						
MCM-5.1	Mortandad	1g	2	26.1	1.19	0.5140						
MCM-5.1	Mortandad	1g	2	26.7	1.09	0.5120	0.00011000	−3.9586	0.00000	1.41000	0.00980	−2.0088
MCM-5.1	Mortandad	1g	2	26.8	1.13	0.5390						
MCM-5.1	Mortandad	1g	2	27.6	1.18	0.5180						
MCM-5.1	Mortandad	1g	2	28.2	1.24	0.4940						
MCM-5.9A	Mortandad	1g	2	25.9	1.00	0.5930						
MCM-5.9A	Mortandad	1g	2	26.2	1.09	0.5550						
MCM-5.9A	Mortandad	1g	2	26.2	1.08	0.6860	0.00390000	−2.4089	0.00000	1.15200	0.23120	−0.6360
MCM-5.9A	Mortandad	1g	2	27.4	0.95	0.6100						
MCM-5.9A	Mortandad	1g	2	29.0	1.35	0.4980	0.00110000	−2.9586	0.05200	1.25800	0.08650	−1.0630
MCM-5.9A	Mortandad	1g	2	29.0	1.52	0.3810						
MCM-5.9A	Mortandad	Otowi	2	36.6	1.11	0.4350	0.00079000	−3.1024	0.00000	1.38800	0.01850	−1.7328
MCM-5.9A	Mortandad	Otowi	2	36.6	1.08	0.5570						
MCM-5.9A	Mortandad	Otowi	2	38.1	1.11	0.5460						
MCM-5.9A	Mortandad	Otowi	2	38.1	1.04	0.5380	0.00028000	−3.5528	0.02500	1.51200	0.00690	−2.1612
MCM-5.9A	Mortandad	Otowi	2	39.6	1.05	0.5700						
MCM-5.9A	Mortandad	Otowi	2	39.6	1.15	0.5190	0.00780000	−2.1079	0.06500	1.82900	0.00560	−2.2518
MCM-5.9A	Mortandad	Otowi	2	45.7	1.30	0.5380	0.00170000	−2.7696	0.02800	1.51200	0.00690	−2.1612
MCM-5.9A	Mortandad	Otowi	2	45.7	1.16	0.5250						
MCM-5.9A	Mortandad	Otowi	2	47.2	1.24	0.4920						
MCM-5.9A	Mortandad	Otowi	2	50.3	1.26	0.4850						
MCM-5.9A	Mortandad	Otowi	2	50.3	1.20	0.4860	0.00029000	−3.5376	0.12000	1.68200	0.00500	−2.3010
SIMO-1	Mortandad	1g	2	6.7	1.19	0.5510						
SIMO-1	Mortandad	1g	2	10.1	1.47	0.4600	0.00027000	−3.5686				
SIMO-1	Mortandad	1g	2	12.5	1.17	0.5600						
SIMO-1	Mortandad	Otowi	2	21.6	1.49	0.4360						
SIMO-1	Mortandad	Otowi	2	26.2	0.98	0.5900	0.00020000	−3.6990				
SIMO-1	Mortandad	Otowi	2	27.4	1.30	0.5010	0.00001100	−4.9586				
CDBM-1	Cañada del Buey	1g	2	7.3	1.17	0.4880	0.00006200	−4.2076	0.00000	1.93900	0.00290	−2.5376
CDBM-1	Cañada del Buey	1g	2	10.4	1.07	0.4620	0.00022000	−3.6576	0.00000	1.63400	0.00550	−2.2596
CDBM-1	Cañada del Buey	1g	2	13.4	1.26	0.4450	0.00007000	−4.1549	0.00000	1.68200	0.00410	−2.3872
CDBM-1	Cañada del Buey	1g	2	16.5	1.09	0.4460	0.00046000	−3.3372	0.00000	1.51900	0.00700	−2.1549
CDBM-1	Cañada del Buey	1g	2	19.5	1.23	0.4510	0.00012000	−3.9208	0.00500	1.72400	0.00530	−2.2757
CDBM-1	Cañada del Buey	Otowi	2	31.7	1.20	0.4460	0.00023000	−3.6383	0.00000	1.48900	0.00640	−2.1938
CDBM-1	Cañada del Buey	Otowi	2	34.7	1.29	0.4510	0.00016000	−3.7959	0.02500	1.77800	0.00450	−2.3468
CDBM-1	Cañada del Buey	Otowi	2	37.8	1.10	0.4370	0.00029000	−3.5376	0.00000	1.44700	0.00820	−2.0862
CDBM-1	Cañada del Buey	Otowi	2	40.8	1.24	0.4470	0.00016000	−3.7959	0.01200	1.64600	0.00570	−2.2441
CDBM-1	Cañada del Buey	Otowi	2	43.9	1.14	0.4280	0.00042000	−3.3768	0.04200	2.30700	0.00550	−2.2596
CDBM-1	Cañada del Buey	Otowi	2	46.9	1.29	0.4100	0.00010000	−4.0000	0.02700	1.89000	0.00390	−2.4089
CDBM-1	Cañada del Buey	Otowi	2	50.0	1.21	0.4360	0.00017000	−3.7696	0.00000	1.48500	0.00610	−2.2147
CDBM-1	Cañada del Buey	Otowi	2	53.0	1.18	0.4120	0.00021000	−3.6778	0.03000	1.89700	0.00530	−2.2757
CDBM-1	Cañada del Buey	Otowi	2	56.1	1.18	0.4320	0.00030000	−3.5229	0.02600	1.89400	0.00620	−2.2076
CDBM-1	Cañada del Buey	Otowi	2	57.6	1.19	0.4300	0.00018000	−3.7447	0.00800	1.64800	0.00570	−2.2441
CDBM-2	Cañada del Buey	1g	2	8.5	1.19	0.4790	0.00085000	−3.0706	0.05100	1.43300	0.02810	−1.5513
CDBM-2	Cañada del Buey	1g	2	11.6	0.94	0.4840	0.00045000	−3.3468	0.02600	1.79100	0.00710	−2.1487
CDBM-2	Cañada del Buey	Otowi	2	20.4	1.16	0.4460	0.00050000	−3.3010	0.01700	1.59800	0.00840	−2.0757
CDBM-2	Cañada del Buey	Otowi	2	20.7	1.22	0.4400	0.00027000	−3.5686	0.03900	1.98700	0.00600	−2.2218
PC-4	Portrillo	1g	2	4.3	1.19	0.4300	0.00004300	−4.3665	0.06600	1.86200	0.00650	−2.1871
PC-4	Portrillo	1g	2	8.8	1.49	0.3820	0.00002500	−4.6021	0.00000	1.24900	0.02330	−1.6326
PC-4	Portrillo	1g	2	18.0	1.29	0.4900	0.00002200	−4.6576	0.08600	1.71100	0.00430	−2.3665
PC-4	Portrillo	1g	2	19.5	1.18	0.4530	0.00009700	−4.0132	0.00000	1.54900	0.00390	−2.4089
PC-4	Portrillo	1g	2	25.6	1.17	0.4500	0.00035000	−3.4559	0.00000	1.39700	0.00790	−2.1024
PC-4	Portrillo	Otowi	2	33.2	1.16	0.4200	0.00039000	−3.4089	0.01500	1.73300	0.00740	−2.1308
PC-4	Portrillo	Otowi	2	36.1	1.12	0.4080	0.00033000	−3.4815	0.02200	1.84800	0.00500	−2.3010
PC-4	Portrillo	Otowi	2	45.4	1.22	0.4030	0.00007500	−4.1249	0.02800	1.71000	0.00450	−2.3468
PC-4	Portrillo	Otowi	2	51.4	1.15	0.4370	0.00043000	−3.3665	0.00900	1.65300	0.00620	−2.2076
Notes		4–Tshirege unit 4 (QBT 4) 3–Qbt 3 2–Qbt 2 1v–Qbt 1v 1g–Qbt 1g	1 = Mesa top 2 = Canyon									

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