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INFLUENCE OF DETERMINISTIC GEOLOGIC TRENDS ON SPATIAL VARIABILITY OF HYDROLOGIC PROPERTIES IN VOLCANIC TUFF

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ABSTRACT

Hydrologic properties have been measured on outcrop samples taken from a detailed, two-dimensional grid covering a 1.4 km outcrop exposure of the 10-m thick nonwelded-to-welded, shardy base microstratigraphic unit of the Tiva Canyon Member of the Miocene Paintbrush Tuff at Yucca Mountain, Nevada. These data allow quantification of spatial trends in rock matrix properties that exist in this important hydrologic unit. Geologic investigation, combined with statistical and geostatistical analyses of the numerical data, indicates that spatial variability of matrix properties is related to deterministic geologic processes that operated throughout the region. Linear vertical trends in hydrologic properties are strongly developed in the shardy base microstratigraphic unit, and they are more accurately modeled using the concept of a thickness-normalized stratigraphic elevation within the unit, rather than absolute elevation. Hydrologic properties appear to be correlated over distances of 0.25 to 0.3 of the unit thickness after removing the deterministic vertical trend. The use of stratigraphic elevation allows scaling of identified trends by unit thickness, which may be of particular importance in a basal, topography-blanketing unit such as this one. Horizontal changes in hydrologic properties do not appear to form obvious trends within the limited lateral geographic extent of the ash-flow environment that was examined. Matrix properties appear to be correlated horizontally over distances between 100 and 400 m. The existence and quantitative description of these trends and patterns of vertical spatial continuity should increase confidence in models of hydrologic properties and groundwater flow in this area that may be constructed to support the design of a potential high-level nuclear waste repository at Yucca Mountain.

INTRODUCTION

Volcanic tuffs within the unsaturated zone at Yucca Mountain, Nevada (Figure 1), are being considered for a potential repository for high-level nuclear waste. The infiltration of precipitation and the movement of that water through the materials overlying the potential repository excavations is of considerable interest as part of the repository studies. Recent field studies[1,2] have identified that a marked change in hydrologic properties within the upper portion of the tuff section may have a pronounced effect on the unsaturated flow system and any vertically migrating groundwater at Yucca Mountain. These changes in hydrologic properties appear to be related to a rapid downward change in the basal portion of the Tiva Canyon Member of the Paintbrush Tuff from densely welded to nonwelded tuff. This sequence is above lithologically similar, but somewhat older and depositionally distinct nonwelded tuffs that overlie the densely welded Topopah Spring Member of the Paintbrush Tuff.

This transitional and nonwelded sequence may form a potential capillary barrier or a conductive horizon capable of diverting vertically percolating groundwater laterally.[3] Either effect could profoundly influence the quantity of groundwater reaching the deeper, repository units, as well as affecting the flow paths and travel times for groundwater moving within this system.

In addition, the large lateral extent of the field site, coupled with the requirement to predict hydrologic conditions for 10,000 years, puts considerable emphasis on the three-dimensional site-scale models that will be necessary to construct licensing arguments. More easily described larger scale geologic trends, if correlated with hydrologic parameters, will simplify model construction and execution, reduce errors, and simplify sampling requirements for site characterization.

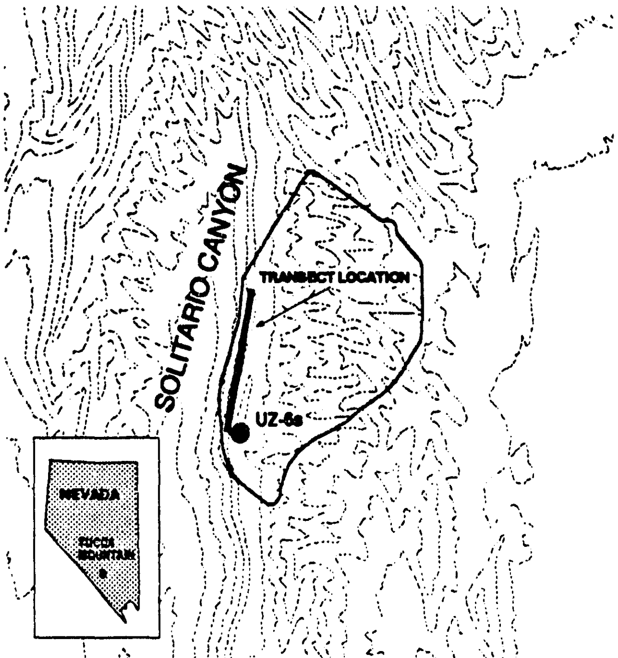

Figure 1. Index map showing location of Yucca Mountain and approximate location of two-dimensional grid sampled for this study.

GEOLOGIC OVERVIEW

Location of the Study Area

Alternating welded and nonwelded ash-flow tuffs at Yucca Mountain have been gently tilted toward the east by Basin-and-Range faulting. The upper portion of the tuff sequence is well exposed by the Solitario Canyon Fault along the west face of Yucca Mountain in Solitario Canyon (Figure 1). Earlier one-dimensional outcrop studies of these tuffs have been expanded into a two-dimensional effort focused on the interval with the most pronounced change in hydrologic properties: the shardy base microstratigraphic unit of the Tiva Canyon Member.[2] We have collected approximately 330 samples along a 1.4 km long north-south exposure of this unit along the western margin of the repository block. The semi-regular vertical grid is approximately aligned with the inferred southerly direction of ash flow transport from a caldera source about 6 km north of the site near present-day Timber Mountain.[4]

Stratigraphy and Lithology

The rocks investigated for this study consist of the lowermost portion of the Tiva Canyon Member of the Miocene Paintbrush Tuff (Figure 2). The base of the interval consists of a pumice-rich air-fall tuff, which overlies a reddish to orangish, weathered (?) zone developed on an underlying, older ash-flow deposit. These pumiceous materials are tentatively inferred to represent the initial stages of the Claim Canyon caldera-collapse sequence, which ultimately produced the 100-meter-thick Tiva Canyon Member.[4] The basal air-fall pumice unit varies markedly in thickness laterally from less than one meter to nearly 3 m. Much of the thickness variation may reflect pre-existing topography. Some exposures have been reworked and indicate a minor hiatus in volcanic activity preceding eruption of the main phase of the Tiva Canyon Member. A weakly developed, iron-stained zone at the top of the pumice unit may indicate incipient development of a weathering profile.

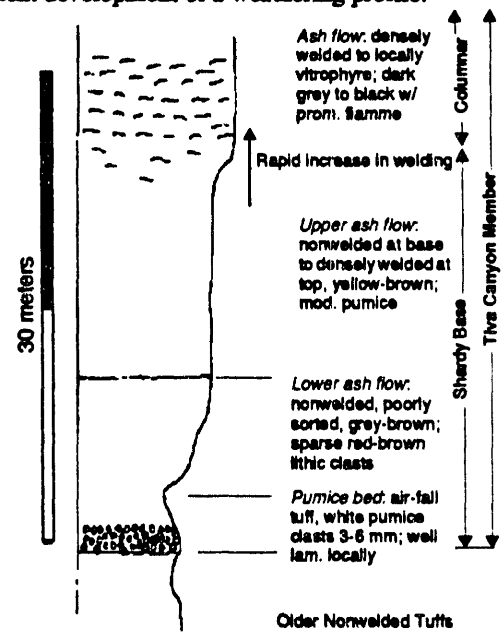

Figure 2. Schematic stratigraphic profile of part of the Paintbrush nonwelded interval in Solitario Canyon showing position of Shardy Base transect lithologic interval near drill hole UZ-6s

The basal pumice unit is overlain by 7.6 to 12 meters (average thickness 9 m) of ash-flow deposits that comprise the bulk of the shardy base microstratigraphic unit. Two subunits appear to be present. The lower ash flow is nonwelded and poorly sorted. Locally, a 20-50 cm zone at the base of the flow may contain large (5-10 cm) whitish pumice blocks that are difficult to distinguish from the remainder of the flow. The upper subunit changes from nonwelded at the base to densely welded at a gradational upper contact with the overlying columnar microstratigraphic unit. Glassy shards are characteristic of the entire shardy base microstratigraphic unit, and the gradational top is essentially defined by the loss of vitric material to devitrification and vapor-phase alteration. The upper limit of the shardy base microstratigraphic unit is selected where the rock becomes devitrified, densely welded tuff. A change in the style of jointing and fracturing also marks the contact with the columnar microstratigraphic unit, which is notable for its distinctive vertical cooling joints. Locally, a densely welded, vertically-jointed vitrophyre forms the lowest portion of the overlying columnar microstratigraphic unit.[5] These flows, together with the overlying welded and devitrified materials, represent products of the on-going, if episodic, eruption and collapse of the Claim Canyon caldera.

METHODS

Field Sampling

Core specimens, nominally 2.5 cm in diameter and 4 to 10 cm in length, were collected from 26 vertical transects along the outcrop exposure using a gasoline-powered, portable core drill. The thickness of the shardy base unit changes along the transect from 7.6 to 12 m and exposures are variable in quality. The vertical spacing between specimens is variable (0.15 m to 3.5 m) and averages 0.76 m. The number of specimens per transect ranges from 10 to 17. Horizontal spacings of individual transects are variable as well, averaging 54 m. Transects are generally closer together in the southern portion of the outcrop belt (as close as 19 m), and are more widely separated (up to 200 m) to the north as the quality of the exposure decreases because of convergence between the floor of Solitario Canyon and the outcrop exposures of the unit.

Locations of core samples were measured in the field as elevation above the base of the lower air-fall pumice bed. The location of each transect was measured relative to an earlier transect taken in the vicinity of drill hole USW UZ-6s, which is located on the crest of Yucca Mountain. Horizontal variation of sample locations for a specific vertical transect is assumed to be negligible, given the distances between transects. This location scheme produces an *x-z* (horizontal distance-elevation) grid (in meters).

It is apparent from the raw data that individual transects vary in thickness, and a transformed, stratigraphic grid was developed that assists in understanding these tuffaceous materials. In place of the absolute elevation, we substitute a normalized stratigraphic elevation, $Elev_{strat}$, which is here defined as

$$Elev_{strat} = 1 - \frac{Elev_{top} - Elev_{sample}}{Elev_{top} - Elev_{bottom}}$$

where $Elev_{top}$ is the elevation of the top of the stratigraphic unit at the transect under consideration, $Elev_{bottom}$ is the elevation of the bottom of the unit, and $Elev_{sample}$ is the elevation of the sample within that unit. $Elev_{strat}$ varies between 0 and 1, for samples located within a particular stratigraphic unit.

Evaluation of the shardy base sample data in terms of stratigraphic elevation suggests that the variability is better defined than when using absolute positions. Stratigraphic elevations are used in the quantitative description of deterministic vertical spatial trends discussed in the remainder of this report.

Laboratory Analyses

Bulk density (ρ_b, in g/cm^3) and porosity (ϕ, expressed as a fraction) were determined using Archimedes' principle. There are two major departures from the classical application of this technique. First, the samples were initially saturated with carbon dioxide gas by introducing the gas into an evacuated bell jar containing the specimens; this step helps avoid air entrapment in small internal pores. The samples were then saturated with deaired distilled water in the conventional fashion. The other difference is that samples were dried in a controlled relative humidity (RH) oven at 60°C and 45-percent RH to preserve water present in the crystal structure of clays and hydrated minerals.[7]

Sorptivity was determined for all suitable core samples. This property represents flow under unsaturated conditions, describing the rate of uptake of water by a porous media without gravitational effects.[8] It is calculated from the early portion of a set of imbibition data using the equation: $I = St^{0.5}$, where I is imbibition (quantity of water, cm^3, imbibed per unit area, cm^2), S is sorptivity (expressed in cm/$t^{0.5}$), and t is time (s).[9,10] Sorptivity was determined as the slope of a line fit through the data which was plotted as I vs. $t^{0.5}$.

Saturated hydraulic conductivity (K_s, in m/s and generally presented as $\log_{10}K_s$ throughout this report) was determined for all suitable core samples. Core samples were encased inside heat-shrink tubing lined with a water resistant sealant to help preserve sample integrity during handling and measurements. Flow measurements were made using a constant-head, steady-state method. Head was induced using a simple water column for most samples. Those specimens that required a head in excess of 1.5 m to produce steady flow (one to three of the more welded samples from each transect) required using pressure to impose a differential hydraulic head across the sample of up to 60 meters. Saturated hydraulic conductivity was computed using Darcy's law with measured sample lengths and cross-sectional areas, and the appropriate flow measurements.

DATA AND RESULTS

Data for porosity (a bulk property) and saturated hydraulic conductivity (a flow property) are presented graphically in approximately their proper spatial context in Figure 3 as grey-scale-coded values. Although significant vertical exaggeration has been incorporated into the figures, this means of representation illustrates the comprehensive, although somewhat biased spatial distribution of the data. The samples are generally systematically spaced, although some notable exceptions due to poor exposure are obvious in some transects (gaps in otherwise more uniform spacing; Figure 3).

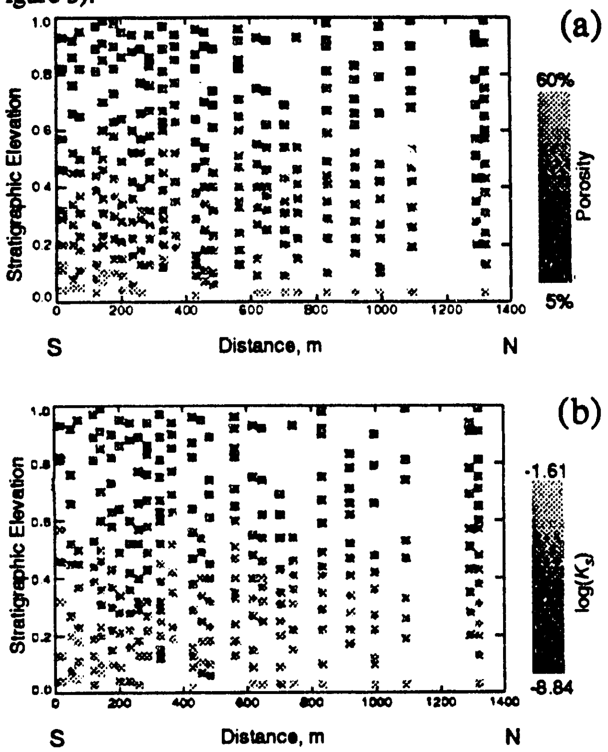

Figure 3. Grey-scale location-value plots of (a) porosity and (b) log saturated hydraulic conductivity showing detailed sampling grid covering the shardy base microstratigraphic unit of the Tiva Canyon Member in Solitario Canyon.

Statistical summaries of the measured properties are presented in Table 1. First, the entire basal nonwelded-to-

Table 1: Summary Descriptive Statistics for Measured Hydraulic Properties, Tiva Canyon Shardy Base Microstratigraphic Unit

	Porosity	Bulk Density	Particle Density	$\log(S)$	$\log(K_s)$
Entire Shardy Base Unit					
Minimum	0.056	0.93	2.21	-5.896	-8.839
Maximum	0.603	2.27	2.57	-2.907	-1.607
Mean	0.329	1.56	2.33	-4.312	-4.933
Variance	0.0202	0.1170	0.0018	0.670	3.6077
C.V.%[a]	43	22	2	19	39
N	306	306	306	290	286

Table 1: Summary Descriptive Statistics for Measured Hydraulic Properties, Tiva Canyon Shardy Base Microstratigraphic Unit

	Porosity	Bulk Density	Particle Density	$\log(S)$	$\log(K_s)$
Basal Pumice Bed Subunit					
Minimum	0.341	0.93	2.31	-4.063	-4.511
Maximum	0.603	1.54	2.39	-2.986	-1.607
Mean	0.520	1.13	2.35	-3.452	-2.862
Variance	0.0042	0.0249	0.0005	0.0699	0.5030
C.V., %	12	14	1	8	25
N	36	36	36	35	33
Lower Ash-Flow Subunit					
Minimum	0.201	1.13	2.23	-5.225	-6.870
Maximum	0.546	1.87	2.49	-2.907	-2.154
Mean	0.403	1.38	2.31	-3.831	-3.826
Variance	0.0023	0.0123	0.0015	0.2296	1.0075
C.V., %	12	8	2	13	26
N	140	140	140	133	133
Upper Ash-Flow Subunit					
Minimum	0.056	1.30	2.21	-5.896	-8.839
Maximum	0.445	2.27	2.57	-3.396	-3.133
Mean	0.195	1.89	2.35	-5.082	-6.728
Variance	0.0099	0.0589	0.0016	0.2631	1.5789
C.V.%	51	13	2	10	19
N	130	130	130	122	120

[a] C.V. is the coefficient of variation, a standardized measure of variability; it is defined as the standard deviation divided by the mean, and typically is expressed in percent

transitionally welded shardy base microstratigraphic unit of the Tiva Canyon Member is considered as a whole. The remainder of the table presents the same summary statistics for the lower air-fall pumice bed and the two identified ash-flow subunits. The material properties of the three subunits are actually quite different from one another. These differences are presented in a slightly different manner through the histograms of Figure 4, which clearly distinguish the two ash-flow subunits from one another. The lower pumice subunit and the lower ash flow resemble each other in their nonwelded character compared with the gradationally welded upper ash-flow subunit. However, even here the porosities of the two lower subunits are substantially different, reflecting differing proportions of fine ashy material. Regardless of the presentation method, the conclusions are essentially the same: each of the three subunits is relatively distinctive in terms of material properties. None of the units appear particularly normal in histogram format (Figure 4).

Despite the differences in properties among the subunits of the shardy base, the histograms of Figure 4 suggest that there is inter-variable correlation between the bulk properties and the flow properties. Summary statistical in-

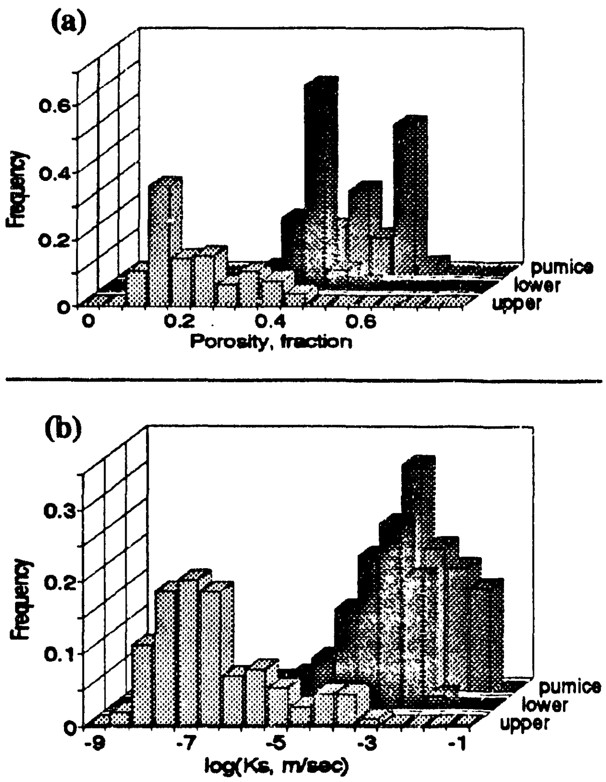

Figure 4. Histograms showing distribution of values for (a) porosity and (b) log saturated hydraulic conductivity for the entire shardy base microstratigraphic unit of the Tiva Canyon Member. "lower" and "upper" correspond to the lower and upper ash-flow subunits, respectively.

formation on these cross variable correlations is presented in Table 2.

Table 2: Regression Summary for Inter-Variable Correlations

Independent Var. Dependent Var.	Cross-Plot Regression Equation	r^2
Porosity log(Sorptivity)	$\log(S) = 5.237\,\phi - 6.040$	0.826
Bulk Density log(Sorptivity)	$\log(S) = -2.176\,\rho_b - 0.912$	0.828
Porosity $\log(K_s)$	$\log(K) - 12.313\,\phi - 9.012$	0.824
Bulk Density $\log(K_s)$	$\log(K) = -5.154\,\rho_b + 3.099$	0.839

Deterministic Spatial Trends

Vertical Trends: The consistent vertical changes in grey-scale intensity of the porosity and hydraulic conductivity data shown in Figure 3 suggest the presence of vertical spatial trends. The existence of strong vertical trends for the several material properties is supported by more detailed analysis. Figure 5 presents the composite porosity

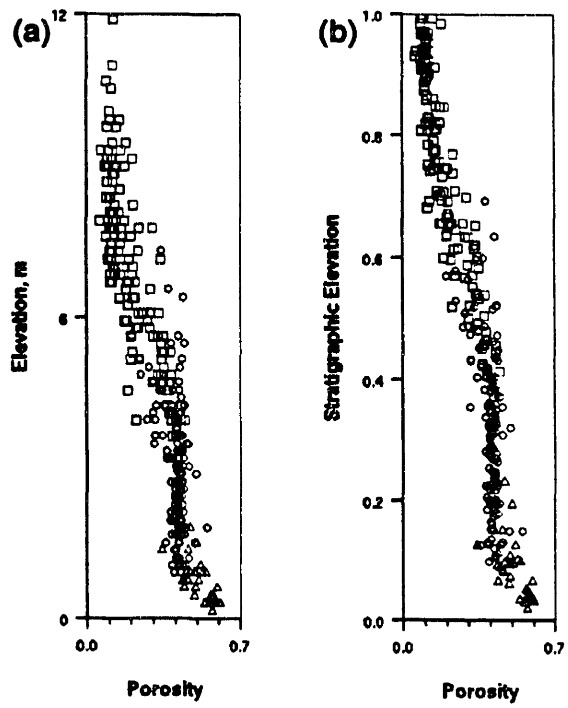

Figure 5. Vertical trend in porosity for shardy base microstratigraphic unit. (a) absolute elevation; (b) stratigraphic elevation. Triangles: pumice subunit; circles: lower ash-flow subunit; squares: upper ash-flow subunit.

data for all transects plotted as a function of absolute elevation above the lower contact of the basal pumice unit (Figure 5a) and as a function of stratigraphic elevation (Figure 5b). The trend is clear: there is a progressive upward decrease in porosity from the basal pumice bed to welded portion of the Tiva Canyon Member. The profile stops at the bottom contact of the densely welded columnar microstratigraphic unit of the Tiva Canyon. The contrast between absolute elevation and stratigraphic elevation shown in Figure 5 is the basis and justification for the stratigraphic-elevation approach described in the section on Field Sampling. As a function of stratigraphic elevation, the data in Figure 5 are much more tightly grouped, and there are fewer apparent outliers.

Stratigraphic elevation is a useful concept in numerous situations,[6] because it allows for scaling of trends by unit thickness. Stratigraphic elevation is applicable when a geologic unit of interest varies in thickness across a region and when the geologic process responsible for a particular feature or property operated throughout the volumetric extent of that unit. In the current instance, the deterministic geologic processes of air-fall and ash-flow deposition and welding took place in a broad region surrounding the Claim Canyon caldera. The resulting ash-flow deposit thins depositionally away from its source, but the general processes of emplacement and welding operated throughout the deposit within the area of interest. Because of this mechanistic control, we are justified in scaling our models of hydrologic properties by the stratigraphic position throughout much of the regional extent of the Tiva Canyon shardy base microstratigraphic unit. By contrast, if the process responsible for changes in thickness across the region of interest was, for example, erosional truncation, such scaling by stratigraphic position would be unlikely to be justified, and more accurate modeling might be obtained by using absolute elevation relative to a basal contact.

The upward gradation in porosity exhibited by this detailed sampling of the shardy base microstratigraphic unit reflects one of the deterministic geologic features described by Rautman and Flint,[2] although it appears that the feature is more complex than originally envisioned. From the detailed porosity (and other) data now available, it appears that the gradational change in porosity is more properly a function of the three subunits identified by this study. The basal air-fall pumice bed is quite porous (52 percent average porosity; Table 1 and Figure 5). The first overlying ash-flow unit is less porous (average about 40 percent), presumably because of the presence of fine-grained ash interstitial to the larger pumice clasts (more poorly sorted). This lower ash-flow subunit appears, however, not to exhibit any welding: the unit maintains an essentially constant porosity throughout its vertical extent (Figure 5). The deterministic welding process is most clearly expressed in the upper of the two ash-flow subunits, and the porosity changes markedly from bottom (about 40 percent) to top (about 5 percent) of this subunit (Figure 5).

Stratigraphic control of porosity, a simple bulk property, is suggested in Figure 5. Evaluation of the porosity and the other hydrologic properties measured for this study indicates that such deterministic geologic trends are meaningful, and can be described quantitatively for use in numerical modeling of geology. The general lithologic description of the shardy base microstratigraphic unit, the simple summary statistics of Table 1, the histograms of Figure 4, and the composite stratigraphic plot of porosity shown in Figure 5 all indicate that this stratigraphic control requires consideration of three separate stratigraphic subunits. However, one of the primary uses of data from Yucca Mountain will be the modeling of a complicated, multi-layer, unsaturated flow system that extends several hundreds of meters from the ground surface to the water table. If, as has been suggested,[2,11] such modeling is to be conducted in a Monte Carlo fashion in order to address characterization uncertainty, the number of distinct layers that must be modeled separately (and repeatedly under the Monte Carlo scenario) must be kept to the minimum necessary to represent *major, flow-controlling features*.[2] It is our suggestion that the shardy base of the Tiva Canyon Member is one such critical unit. Despite additional detail evident in both the geology and hydrologic properties data, we suggest that the unit potentially may be considered as a whole, yielding significant improvements on previous numerical representations of Yucca Mountain, yet without creating an impractical level of detail.

To document quantitatively both the identified deterministic vertical spatial trends and our hypothesis that a simple deterministic model may suffice for some modeling purposes, straightforward linear regressions have been fitted to the hydrologic properties, both as a function of absolute elevation and of stratigraphic elevation. The relevant regression coefficients and the corresponding coefficients of determination are summarized in Table 3. The results of

Table 3: Quantitative Description of Vertical Trends in Hydrologic Properties, Shardy Base of Tiva Canyon Member

Regression Equation	r^2	No. Spls
$\phi = -0.014\,Elev_{sample} + 0.538$	0.823	306
$\phi = -0.470\,Elev_{strat} + 0.550$	0.874	306
$\rho_b = 0.0347\,Elev_{sample} + 1.057$	0.836	306
$\rho_b = 1.139\,Elev_{strat} + 1.029$	0.886	306
$\log(S) = -0.0772\,Elev_{sample} - 3.184$	0.737	290
$\log(S) = -2.555\,Elev_{strat} - 3.115$	0.791	290
$\log(K_s) = -0.183\,Elev_{sample} - 2.262$	0.743	286
$\log(K_s) = -6.091\,Elev_{strat} - 2.091$	0.800	286

these analyses for porosity and log saturated hydraulic conductivity, are presented in Figures 6 and 7. In every case, the r^2 value for the regression against stratigraphic elevation is larger than for the regression against absolute sample position (Table 3). This fact confirms the visual impression that the data points are more tightly clustered around the stratigraphic regression line, and also supports the argument regarding stratigraphic scaling.

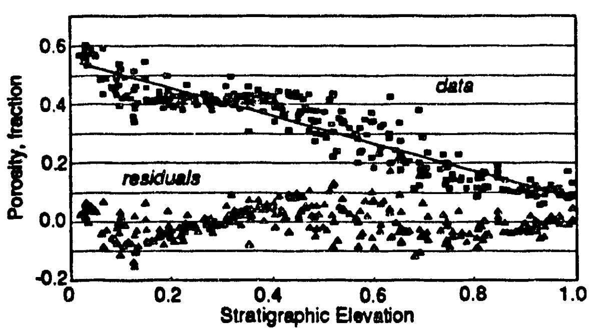

Figure 6. Regression of porosity against stratigraphic elevation. Also shown are residuals from regression described by equation in Table 3.

In addition to the composite data and the fitted regression line, these figures show the residuals computed by subtracting the regression-predicted value from the actual, measured property. In all cases, the residuals have a mean

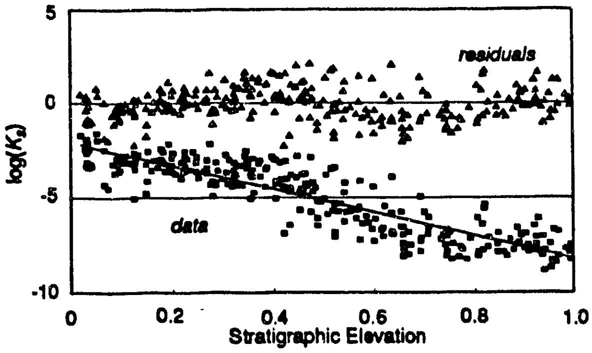

Figure 7. Regression of log saturated hydraulic conductivity against stratigraphic elevation. Also shown are residuals from regression described by equation in Table 3.

of zero, and are fairly tightly clustered around that mean value. The residuals are approximately stationary in space, indicating that the simple linear regression appears to describe adequately the deterministic geologic trend within the shardy base microstratigraphic unit. However, there is some weak non-random component remaining in the plot of the residuals (see especially Figure 6) that appears to be related to the three lithologic subunits present within the shardy base microstratigraphic unit. Residuals from the deterministic-trend regressions are utilized extensively in the geostatistical analysis in a later section.

Horizontal Trends: Evaluation of spatial trends as a function of horizontal position within the shardy base microstratigraphic unit are more difficult. First, sampling has been limited to a two-dimensional pattern, of which only one is horizontal (Figures 1, 3). However, this dimension is located subparallel to the inferred southerly transport direction of the ash-flow tuffs, and should be in an optimal orientation to identify any major deterministic trends related to transport distance.

Changes in the vertically averaged value of several of the hydrologic properties with horizontal transect location have been examined, both for the entire Tiva Canyon shardy base microstratigraphic unit as a whole and for the three subunits identified within it. Illustrative results for porosity and log saturated conductivity for the entire microstratigraphic unit are shown in Figure 8.

There are no statistically significant changes in property values with distance from the northerly source caldera (0.90 confidence or better). However, the changes that do occur are broadly in accord with those that might be expected from the geologic setting. For example, porosity increases from roughly 25 percent in the north near the caldera to some 30 percent to the south. Locally, for portions of the overall transect, this southward increase is even

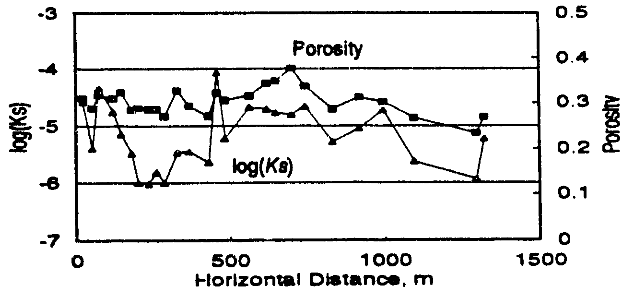

Figure 8. Horizontal variability of vertically averaged values for the 26 transects of the Tiva Canyon Member shardy base microstratigraphic unit. Porosity right scale; log(K_s) left scale.

more pronounced (for example, from northing 1,400 m to about 700 m, porosity changes from 25 to nearly 40 percent). If overall welding is related to proximity to the vent region, these are the general changes that might be expected. Geologic explanations for the observed reversals of "expected" trends (from 700 to 500 m on Figure 8, for example) and for the locally erratic values are less obvious.

Several factors may be affecting the horizontal variability as reflected by simple, vertically averaged hydrologic properties. First, local depositional (pre-depositional) features or processes of the geologic environment may have resulted in the observed small-scale variability (Figure 8). Second, variations in present-day surficial weathering and /or topographic features may have introduced confounding variability of the same magnitude as the actual lateral variability observed in the available outcrops. Third, the vertical-average concept may itself be relatively meaningless in the presence of strong vertical trends (i.e., Figures 5, 6, and 7). Sample spacings within a given transect are variable, and exposures dictated to some extent where samples could be taken. Even slightly biased sampling in the presence of the strong vertical trends observed in the shardy base microstratigraphic unit, and particularly within the upper ash-flow subunit, can induce variability of the magnitude observed in Figure 8. A fourth possibility is that the scale of our sampling of the repository block is simply too restricted (slightly more than 1 km laterally) to identify horizontal trends associated with respect to the volcanic processes responsible for formation of ash-flow sheets that extend 10 to 12 km away from their source.[12] Thus, the evidence for any deterministic horizontal trends is inconclusive at this time.

Geostatistical Description

Variograms have been constructed for the data residuals after removing the deterministic vertical geologic trends described by the regression equations in Table 3. Generally, variograms of residuals from the scaled, stratigraphic-elevation regressions are more interpretable than those using the absolute elevations to describe the deterministic trends. Stratigraphic elevations are used in the variograms discussed below because of the anticipated utility of stratigraphic scaling and the overall improvement in the regression fits presented in Table 3. Horizontal distances were not scaled.

Vertical variograms for residuals from the porosity and log saturated hydraulic conductivity regressions are illustrated in Figure 9. The fitted models indicate a range of correlation of approximately 0.25 to 0.30 of the stratigraphic thickness, depending upon the specific material property considered. The models shown in Figure 9 are spherical models. Gaussian models could be fit to the experimental data as well. However, for each property, the first (shortest separation) gamma value is based upon only 3 pairs of samples. Little credence therefore is placed upon the apparent high degree of continuity and implied nugget effect near the origin of the variogram.

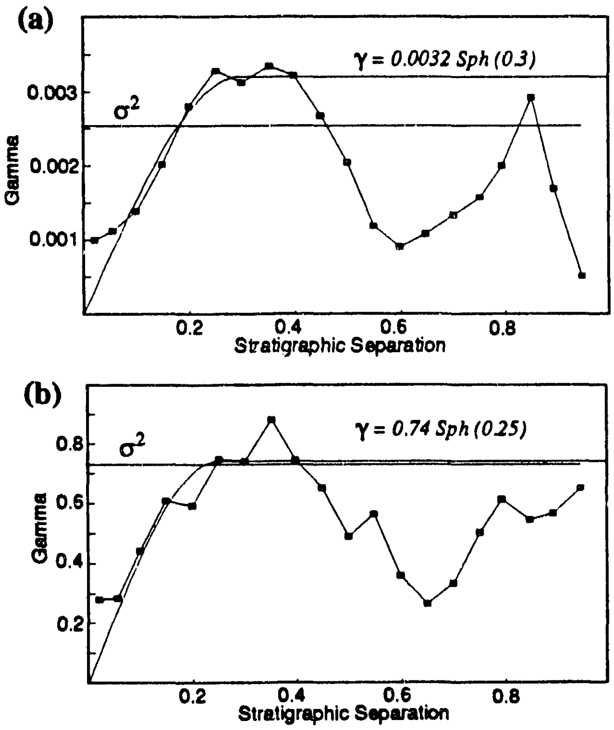

Figure 9. Modeled vertical variograms of regression residuals from shardy base microstratigraphic unit of the Tiva Canyon Member. (a) porosity; (b) log saturated hydraulic conductivity. Class interval: 0.05 stratigraphic elevation.

The pronounced "hole effect," or decrease in the computed values of gamma between roughly 0.4 and 0.8 stratigraphic separation deserves some comment. The classical origin of hole-effect variograms is layered lithology, in which some lag distance eventually starts to compare two like lithologies that are separated by an intervening unlike lithology. Since gamma is based on the squared differences between values a given separation apart, the computed variogram value decreases. A somewhat similar phenomenon is operating in the case of the Tiva Canyon Member shardy base. Here we are dealing with residuals from a regression to describe (remove) a strong vertical trend in the original data. Because we have purposefully simplified[2] the shardy base microstratigraphic unit and treat it as a whole, the less-than-perfect removal of the actual three-part change in hydrologic properties induces a hole-effect-like decrease in variogram value at certain separations. Compare the variogram of Figure 9 with the regression residuals shown in Figures 6 and 7. That the porosity regression does a "poorer" job of removing all of the vertical trend compared with the regression for hydraulic conductivity accounts for the fact that the modeled sill of the porosity variogram (Figure 9a) "overshoots" the theoretically expected sill value of the *a priori* variance of the sample data (σ^2).

Equivalent horizontal variograms for porosity and saturated conductivity are presented in Figure 10. The variograms are remarkably stable, even for the flow property, saturated conductivity (Figure 10b). The range of correlation is modeled as approximately 90 m.

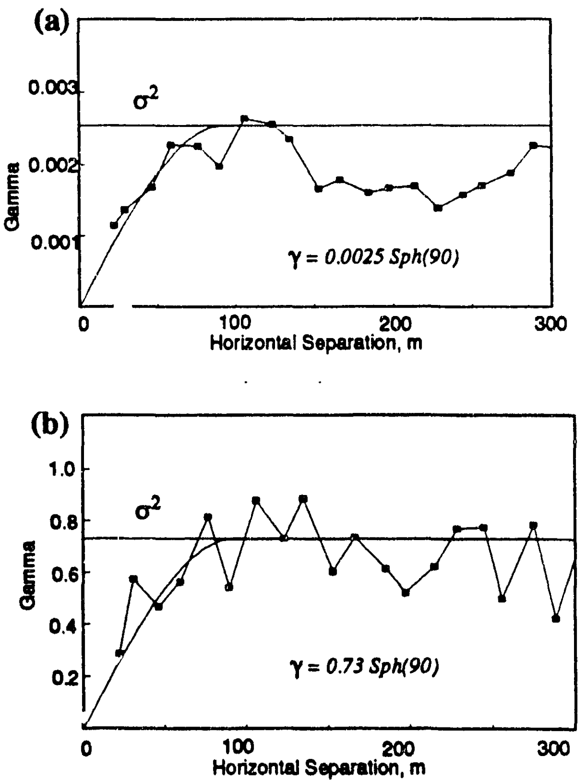

Figure 10. Modeled horizontal variograms of regression residuals from shardy base microstratigraphic unit of the Tiva Canyon Member. (a) porosity; (b) saturated hydraulic conductivity. Class interval 15 m.

Although the results of evaluating horizontal trends in hydrologic properties using vertically averaged values was disappointing, there does appear to be some spatial continuity to the vertical transect-means, however imperfectly computed. Variograms computed in this manner for the basal pumice unit and the lower ash flow appeared to consist of essentially pure nugget effect, indicating no identifiable spatial continuity. In contrast, the upper ash flow yielded interpretable variograms; these patterns of horizontal continuity are illustrated for porosity and log conductivity in Figure 11. The range of correlation suggested by these vertical-average horizontal variograms is approximately one-third greater than that resulting from the variograms of vertical residuals. The significance of this difference is uncertain, but it most likely relates to removal of some longer-range horizontal information through the vertical regression. Both the hole-effect decrease in the computed variogram values at large separations and the mismatch between modeled sill and the *a priori* variance are attributed to the problems associated with the horizontal "trends" discussed previously.

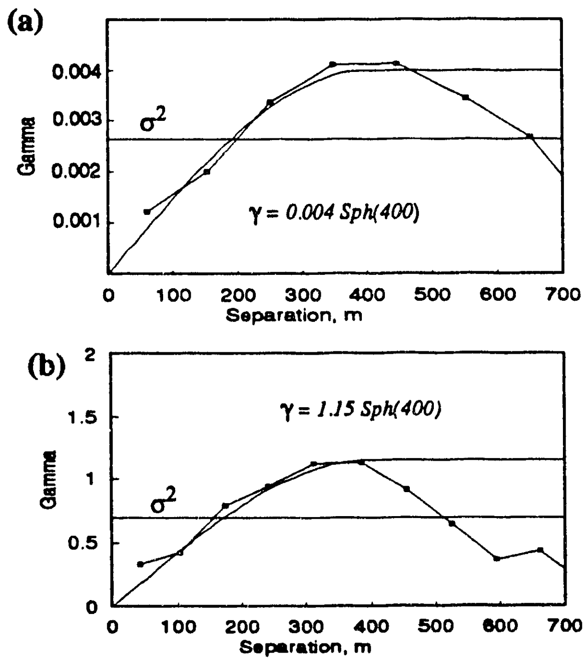

Figure 11. Modeled horizontal variograms of raw hydrologic property values from the upper shardy base ash flow subunit only, vertically averaged by transect. (a) porosity (class interval 100 m); (b) log saturated hydraulic conductivity (class interval 70 m).

APPLICATION OF RESULTS

Statistical models of matrix rock properties are needed for site characterization and performance assessment modeling at Yucca Mountain. The presence of deterministic geologic trends, such as those demonstrated in this study for the shardy base microstratigraphic unit, can simplify the development of these models by providing additional information for use in sampling design, property estimation between boreholes and core samples, and for property simulation. For example, the fitted trends and model variograms presented here can be used, in conjunction with data from existing borehole and outcrop samples, to obtain preliminary estimates for important hydrologic properties for the shardy base unit over the potential repository block. These trends and models can also be used to simulate geologically plausible combinations of rock properties for this unit for use in stochastic water-flow calculations. The inclusion of quantifiable deterministic geologic information provides a rational framework for these procedures, and helps to reduce uncertainty in estimates and simulated values. To the extend that the deterministic geologic features reflect bona fide geologic processes, incorporation of those trends brings a degree of understanding into the modeling process beyond the information contained solely in the numerical values of hydrologic properties.

CONCLUSIONS

Outcrop sampling and laboratory analyses have confirmed the presence of strong vertical trends in rock-matrix properties within the shardy base microstratigraphic unit of the Tiva Canyon Member of the Paintbrush Tuff. This trend is attributed to the occurrence of three progressively less porous subunits: a high-porosity basal air-fall pumice subunit, a lower porosity nonwelded ash-flow subunit, and a third (uppermost) ash flow subunit that changes markedly from nonwelded to densely welded at the top. This trend is best described using stratigraphic elevation, which accounts for variation in unit thickness, and the trend can be expressed quantitatively using a simple, linear model. Sample variograms computed from residuals (after removal of the trend) suggest vertical variation can be described using spherical variogram models with ranges between 0.25 and 0.3 of the unit thickness. Horizontal trends in matrix properties may exist in the shardy base microstratigraphic unit due to varying transport distances from the source caldera; however, no significant north-south trends were observed in these data. Sample variograms computed for regression residuals and for vertically averaged property values suggest that the range of horizontal correlation for matrix hydrologic properties is between 100 and 400 m.

ACKNOWLEDGMENTS

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