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SCALING BEHAVIOR OF GAS PERMEABILITY MEASUREMENTS IN VOLCANIC TUFFS

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ABSTRACT

One of the critical issues facing the Yucca Mountain site characterization and performance assessment programs is the manner in which property scaling is addressed. Property scaling becomes an issue whenever heterogeneous media properties are measured at one scale but applied at another. A research program has been established to challenge current understanding of property scaling with the aim of developing and testing models that describe scaling behavior in a quantitative manner. Scaling of constitutive rock properties is investigated through physical experimentation involving the collection of suites of gas-permeability data measured over a range of discrete scales. The approach is to systematically isolate those factors believed to influence property scaling and investigate their relative contributions to overall scaling behavior. Two blocks of tuff, each exhibiting differing heterogeneity structure, have recently been examined. Results of the investigation show very different scaling behavior, as exhibited by changes in the distribution functions and variograms, for the two tuff samples. Even for the relatively narrow range of measurement scales employed significant changes in the distribution functions, variograms, and summary statistics occurred. Because such data descriptors will likely play an important role in calculating effective media properties, these results demonstrate both the need to understand and accurately model scaling behavior.

I. INTRODUCTION

Performance assessment (PA) calculations aimed at evaluating the suitability of Yucca Mountain as the nation's first high-level radioactive waste repository require detailed information on the geology and material properties of the site. Site characterization is complicated by the fact that many of the important hydraulic, thermal, chemical, and mechanical properties are measured at scales (as limited by current technology) much smaller than can be accommodated in current PA models (computational time limited). In many cases the discrepancy between the analysis and measurement scales is many orders of magnitude on a per volume basis (cm^3 to km^3). It is well established that many properties, particularly constitutive properties, are scale dependent.[1-4] For this reason scaling models are required for transforming information from the scale of the available data to the scale at which PA calculations will ultimately be performed. This raises such questions as:

- do rock properties scale in a predictable and quantifiable manner;
- if so, what is the nature of the scaling behavior;
- how does property heterogeneity influence scaling behavior; and
- how should the characterization of scaling behavior be approached?

A number of theories, representing a wide diversity of approaches, have been proposed for "scaling-up" measurements;[5-12] however, physical data to support these theoretical models are sparse and limited in scope.[13-15] For this reason, a research program founded on systematic physical experimentation has been established to challenge current understanding of property-scaling behavior.[16] The experimental program involves the collection of suites of permeability data at a number of discrete measurement scales, thereby providing a direct means of investigating scaling behavior. Factors influencing scaling behavior (i.e., heterogeneity structure, characteristics of the sampling and analysis program) are varied in a systematic fashion to isolate relative contributions to overall scaling behavior. The data are used to explore potential empirical scaling relationships as well as directly challenge existing scaling theory.

The purpose of this paper is to present the results of recent scaling experiments conducted on two blocks of tuff, one of which was collected from Yucca Mountain. The paper begins with a description of the approach and laboratory method being used to physically measure and quantify scaling behavior. Attention is then turned to describing the tuff samples used in this investigation. Results of the investigation are then discussed, followed by concluding remarks and plans for future work.

II. PHYSICAL INVESTIGATION OF SCALING BEHAVIOR

A. Experimental Approach

The approach taken to investigate and understand property scaling behavior differs from that of other studies in two important ways:

- rock properties are actually measured and compared over a range of discrete measurement scales, and
- factors believed to influence property scaling are investigated in a systematic fashion to isolate relative contributions to overall scaling behavior.

The following paragraphs outline these aspects of the research program in more detail.

Physical investigations aimed at understanding and describing property-scaling behavior require the collection of large suites of data over a range of measurement scales. Furthermore, such measurements must isolate scale effects, which requires that rock property measurements be made in a consistent manner, with consistent physical boundaries and geometry and with a high level of precision. For purposes of this investigation, measurements also need to be rapid, inexpensive, and non-destructive. An instrument meeting these criteria and employed in this investigation is the gas permeameter. Investigations are being performed in the laboratory where measurements are made more accurately, thoroughly, and under a controlled environment. A detailed description of the gas permeameter is given in the following section.

The basic strategy used in capturing scaling behavior calls for the collection of hundreds of gas permeability measurements on a single block face at four or five different measurement scales. As data are collected, efforts are made to distill the information into conceptual scaling models. This involves identifying trends in the data that are diagnostic of scaling behavior. Preliminary analyses focus on trends in the empirical distribution functions and variograms, as well as the associated summary statistics (i.e., mean, variance, skewness, correlation length scale). Characterization of scaling behavior in this manner is of particular importance because such measures (distribution function, etc.) represent the key input required for modeling/simulating heterogeneous property fields. Because these measures may not always provide diagnostic information on scaling behavior, future efforts will explore additional data features (soft geologic information, interconnectivity of high-permeability zones, etc.).

Systematic experimentation is employed to investigate those factors that influence scaling behavior. A preliminary list of these factors is given in Table 1. The work described in this paper focuses on the influence of heterogeneity structure on scaling behavior, which is investigated through the careful selection of rock samples for testing. Here, heterogeneity structure is taken to mean the sum total of the attributes of a rock that define its basic fabric. More specifically, those attributes that govern contrast in the gas permeability field.

Table 1. Factors that Influence Scaling Behavior

1. Heterogeneity Structure:
   - a. nature of heterogeneity (i.e., bedded vs. random),
   - b. scale of heterogeneity (i.e., size),
   - c. intensity of heterogeneity (range in property values),
   - d. frequency of heterogeneity (frequency of pattern recurrence),
   - e. anisotropy.
2. Phenomenological Characteristics:
   - a. transitioning of dominate flow or transport process with a change in scale,
   - b. system dimensionality.
3. Characteristics of the Measurement Scheme:
   - a. scale(s) of measurement,
   - b. sampling resolution (number and separation of measurement sites),
   - c. scale of application (scale at which measured data are used in modeling flow and transport),
   - d. length scale (extent of outcrop or rock block over which measurements are made).

B. Experimental Method

The gas permeameter was originally developed in the petroleum industry for rapid field and laboratory acquisition of gas-permeability data. Since that time, the gas permeameter has found widespread use in the characterization of sandstones,[17,18] welded tuffs,[19] and carbonates.[20] Measurements are made by compressing the permeameter tip-seal against the rock surface and subsequently injecting gas into the rock while measuring the flow rate and gas pressure (from which the gas permeability can be calculated). Of the three basic permeameter designs that exist,[21-23] a system based on steady gas flow and constant injection pressure was adopted for this program. The permeameter consists of four mass-flow meters (0-50, 0-500, 0-2000, and 0-20,000 cm^3 [at standard conditions]), two pressure transducers (0-100, and 0-350 KPa gauge), a barometer, and temperature sensor that are connected to a regulated source of compressed nitrogen. A sequence of specially designed tip seals, the diameter of which defines the scale of measurement, are used to establish a known boundary condition on the rock surface. Thus, by changing the size of the tip seal, the permeameter interrogates volumes of rock ranging in scale from tenths to thousands of cubic centimeters. A soft, durable silicone rubber is used to establish the seal between the injection nozzle and the rock surface.

To improve measurement precision and facilitate data collection, the gas permeameter has been automated for laboratory use.[16] Operation of the electronic permeameter instruments and solenoids (electronic valves) are controlled by specially adapted PC-based software. An x-y positioning system coupled with a pneumatic piston has also been automated for positioning and compressing the permeameter-tip seal against the rock surface. This system allows more than 400 measurements to be made in an eight hour period, unattended.

Gas permeability is calculated directly from information on seal geometry, flow rate, and injection pressure. These calculations are accomplished by means of a modified form of Darcy's Law as developed by Goggin,[24]

$$k = \frac{q \cdot P_O \cdot \mu}{a \cdot G_O \cdot 0.5 \cdot (P^2 - P_O^2)} \qquad (1)$$

where k is gas permeability, q is gas-flow rate, P_O is atmospheric pressure, P is gas injection pressure, μ is gas viscosity, a is internal tip-seal radius, and G_O is a geometric factor. For measurements in a semi-infinite half-space (outcrop or large block measurements), the resulting gas-flow field is hemispherical. By comparing simulations of gas flow in core plugs of different sizes with the semi-infinite half-space condition, Goggin[24] concluded that the effective radius of the resulting gas-flow field is four times the inner tip-seal radius. This implies the effective volume, V, of rock interrogated by the permeameter is,

$$V = 0.66 \cdot \pi \cdot (64 \cdot a^3) \qquad (2)$$

Tip seal sizes commonly employed have inner diameter of 0.31, 0.62, 1.25, 2.54, and 5.08 cm, with an outer diameter measuring twice the inner.

III. SAMPLE SELECTION AND PREPARATION

Two rock samples have recently been collected for investigation. One sample was collected from the crest of Yucca Mountain (Tiva Canyon Member of the Paintbrush Tuff, upper cliff microstratigraphic unit),[25] the other sample, a poorly welded tuff, was collected near Beatty, Nevada. The Tiva Canyon sample (1.3 by 1.3 by 0.6 m) is a welded tuff that has undergone vapor phase alteration. The sample exhibits a clastic fabric; lithic and pumice fragments bound by a fine grain groundmass. The lithics and pumice are subround to angular and vary in size from ~10-50 mm with an average size of ~25 mm. In contrast to the lithics, the pumice fragments are distinctly flattened resulting in a "pancake" appearance. The poorly weleded tuff sample (1.0 by 0.6 by 0.6 m) also exhibits a clastic fabric consisting of abundant pumice fragments. The pumice are subround and relatively uniform in size (~10-15 mm). The pumice content of the sample is also noted to increase from the bottom to the top of the sample giving a faint bedded appearance. Efforts are currently being made to describe quantitatively (i.e., point counting method) the heterogeneity exhibited by each rock sample; the goal being to correlate basic geologic attributes to the scaling behavior measured in the experiments.

Shaping of boulders into blocks is necessary to provide a fresh, flat surface for making gas- permeameter measurements. Blocks are preferred over slabs because, for the tip-seals used in this study, blocks provide a sampling domain that is thick relative to the penetration of the permeameter measurement. Also, the three-dimensionality of the block allows samples with aniostropic heterogeneity structure to be interrogated in three orthogonal orientations. Rock samples are cut using a diamond-impregnated wire line saw. Fresh water is used to lubricate and cool the wire line during cutting as well as to pressure wash the sawn surfaces (to remove cuttings from open rock pores). Orthogonal faces are cut from the boulders along the inferred (from visual inspection) principal permeability axes. The shaped blocks are then transported to Sandia National Laboratories in an enclosed trailer.

Table 2. One-Way Analysis of Variance Data Table[a]

Sample	Tip Size (cm)	Mean Square Between Groups	Mean Square Within Groups	F-value
Tiva Canyon	0.31	2.97	2.07E-2	1.43E2
Tiva Canyon	0.62	8.36	9.21E-5	9.07E4
Tiva Canyon	1.25	6.96	2.96E-4	2.35E4
Tiva Canyon	2.54	12.89	2.15E-1	5.97E1
Poorly welded tuff	0.31	21.55	1.37E-2	1.56E3
Poorly welded tuff	0.62	16.06	2.60E-3	6.16E3
Poorly welded tuff	1.25	17.67	1.11E-3	1.58E4
Poorly welded tuff	2.54	17.68	1.41E-3	1.24E4
Poorly welded tuff	5.08	9.72	2.10E-3	4.62E3

[a] degrees of freedom between groups is 8, degrees of freedom within groups is 27

IV. SCALING INVESTIGATIONS IN VOLCANIC TUFFS

Gas permeability measurements were made on a single face of both the Tiva Canyon and the poorly welded tuff samples. For the Tiva Canyon sample, measurements were made on the face normal to the direction of pumice flattening. Data were collected on a square grid (30 by 30) with 2.54 cm centers. Measurements were made with tip-seals measuring 0.31, 0.62, 1.25, and 2.54 cm in diameter. The largest tip-seal (5.08 cm diameter) could not be used because of a low-frequency surface roughness imparted to the block face by the sawing process. Measurements on the poorly welded tuff sample were collected from a face oriented normal to bedding. Again, a square grid (21 by 36) with 2.54 cm centers was used. For this sample all five tip seals were used. It should be noted that for the 1.25, 2.54, and 5.08 cm tip-seals measurement overlap occurs (see equation 2 above). The acquired data have been reduced via equation 1 and reported in terms of the natural log of gas permeability (m^2).

A one-way analysis of variance (ANOVA) was performed to determine the contribution of measurement error to the observed variability in gas permeability. For each tip-seal and tuff sample, four replicate groups of nine independent measurements were collected for analysis (i.e., a suite of nine measurements at different locations was made then this same suite of measurements was repeated three times). Results of the analysis are given in Table 2. In each case, the ratio of mean square between groups (a measure of the variance due to rock property heterogeneity) to the mean square within groups (a measure of the variance resulting from instrument error), is large, as indicated by the F-value. Because the F-value is much larger than the F-statistic of 2.31 estimated at a significance level of 5%, the null hypothesis that the means of the 9 groups of permeability measurements are equal was rejected. Thus, variance of the data is not related to measurement error of the permeameter, but rather to the variability inherent to the tuff sample. In fact, instrument error is very small in absolute terms, in all but one case less than 1% of the mean permeability. The elevated measurement error in the 2.54 cm data set for the Tiva Canyon sample is likely the result of the low frequency surface roughness described above.

The gas permeability fields measured on the Tiva Canyon sample are presented in Figure 1. The grey-scale plots reproduce in a gross sense the basic fabric of the measured rock face (i.e., dispersed pumice and lithics). Also apparent in these plots is the increased smoothing in the permeability field with increasing measurement scale. Distribution functions and variograms have been calculated to provide a first order approximation of the complex data fields. Comparison of the distribution functions (Figure 2) show a distinct increase in skewness between the 0.31 and 0.62 cm tip-seal measurement scales. This trend appears to be correlated with the size distribution of pumice fragments in the Tiva Canyon sample. At tne 0.31 cm measurement scale, many pumice fragments are large enough to span the permeameter tip seal, hence numerous large permeability zones are measured. However, at the next larger measurement scale fewer pumice fragments span the seal, thus skewing the distribution in the direction of lower permeability. Variogram analysis has been performed on the four data sets with the results given in Figure 3. Overall, the spatial correlation is weak, with a length scale (range) of approximately 7.5 cm. The increase in length scale measured by the 2.54 cm tip-seal is to a large extent due to the overlapping of neighboring measurements (see equation 2 above). In fact, the correlation indicated by the variogram analysis, 10-12 cm, is in exact agreement with the radius of influence for the

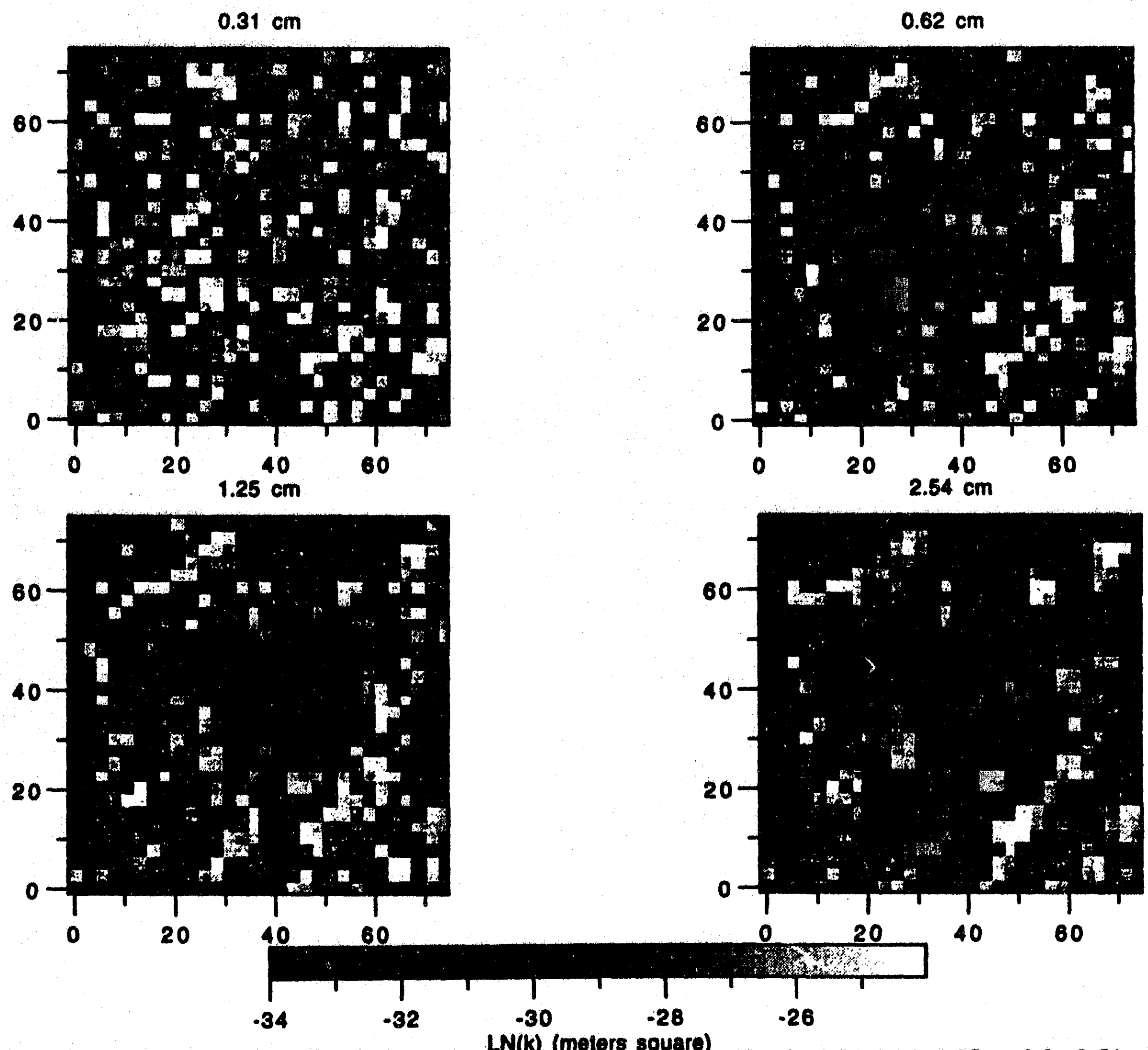


Figure 1. Gas permeability fields for the Tiva Canyon sample, as measured by the 0.31, 0.62, 1.25, and the 2.54 cm tip seals. Data are reported in terms of the natural log of the gas permeability in units of m^2.

2.54 cm tip-seal predicted by Goggin's theory[24](predicted radius of influence is 5 cm, hence measurements must be spaced 10 cm apart to avoid overlap). The information contained in the distribution functions can be further distilled to a suite of key parameters, the statistical moments. These summary statistics provide a simple means of describing the measured permeability fields, and hence are of particular interest here. In reviewing the summary statistics (Table 3) the variance is noted to decrease with increasing measurement scale. However, the mean and the higher order moments do not exhibit such trends. The noted shift in the mean is primarily a reflection of the increase in distribution skewness, while the higher order moments are responding to changes occurring in the tails of the distributions. Inspection of the distribution functions reveals complex behavior in the positive tail of the distributions.

The gas permeability fields measured on the poorly welded tuff sample are illustrated in Figure 4. Again, a distinct smoothing of the permeability field is evident at the larger measurement scales. Corresponding to the visual nature of the tuff sample, faint bedding or layering is evident in the permeability fields measured with the 0.31 and 5.08 cm tip-seals. A comparison of the associated distribution functions is given in Figure 5. In general, as the tip-seal size increases (increasing measurement scale) the distribution functions change from a bimodal to a relatively symmetric unimodal character; however, considerable noise is superimposed on these trends. Based on the precision analyses discussed above this noise appears to be real and not an artifact of the permeameter. A likely reason for this behavior is that the heterogeneity (pumice) is relatively uniform in size and on

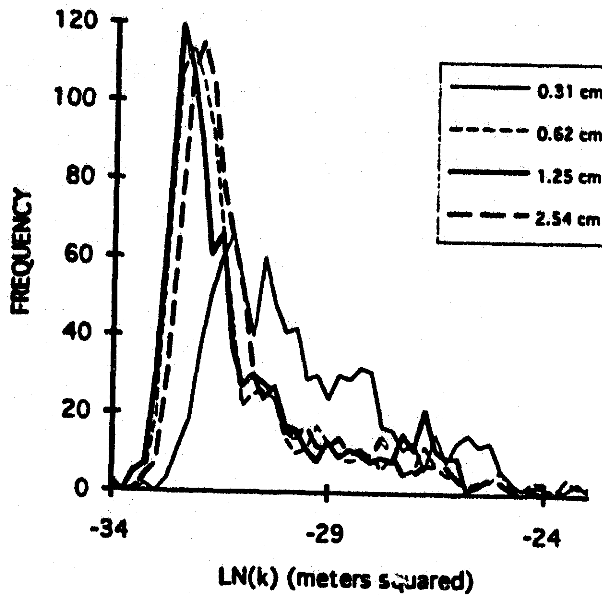


Figure 2. Comparison of distribution functions measured by different tip seals on the Tiva Canyon sample.

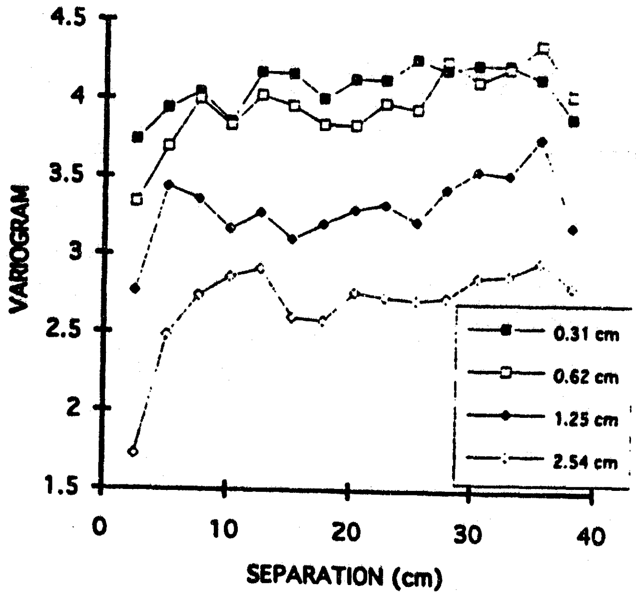


Figure 3. Variogram comparison for the Tiva Canyon sample. Omni-directional variograms are plotted for four different tip seals.

Table 3. Summary Statistics; Tiva Canyon Sample

Statistic	0.31-cm	0.62-cm	1.25-cm	2.54-cm
Mean	-29.47	-30.89	-30.96	-30.85
Variance	3.94	4.00	3.39	2.89
Skewness	0.81	1.79	1.27	1.62
Kurtosis	-0.01	2.88	0.59	2.31
Minimum	-33.05	-33.26	-33.82	-33.20
Maximum	-22.87	-22.70	-25.89	-23.63
Count	900	900	900	900

the order of the smaller measurement scales. It is not until the 5.08 cm tip seal that the measurement scale is sufficiently large to integrate over the sample heterogeneity. Variogram analysis has also been performed for the poorly welded tuff sample (Figure 6). The calculated variograms exhibit both a short range correlation, which is at a scale smaller than the minimum grid spacing, and a longer range correlation, evident from the difference between the variogram sills and the related variance. The longer range correlation is most apparent for the 0.31 cm and 5.08 cm tip-seals, and for orientations parallel to bedding. Short range spatial correlation evident for the 2.54 and 5.08 cm tip-seal is again influenced by overlap in neighboring measurements; however, for this sample considerable anisotropy occurs between the two orthogonal search directions. Inspection of the associated summary statistics reveals poor correlation between the statistical moments and measurement scale (Table 4). Trends might be more apparent if the multiple populations sampled at the smaller measurement scales could be separated and the summary statistics recalculated.

V. CONCLUSIONS

Because many constitutive rock properties must be measured at one scale but applied at another, scaling behavior is an issue facing the Yucca Mountain site characterization and performance assessment programs. The scaling behavior of gas permeability has been investigated on two blocks of volcanic tuff, one from the upper cliff microstratigraphic unit of the Tiva Canyon Member of the Paintbrush Tuff (welded tuff subjected to vapor phase alteration), and the other a poorly welded tuff collected near Beatty, Nevada. The scaling behavior

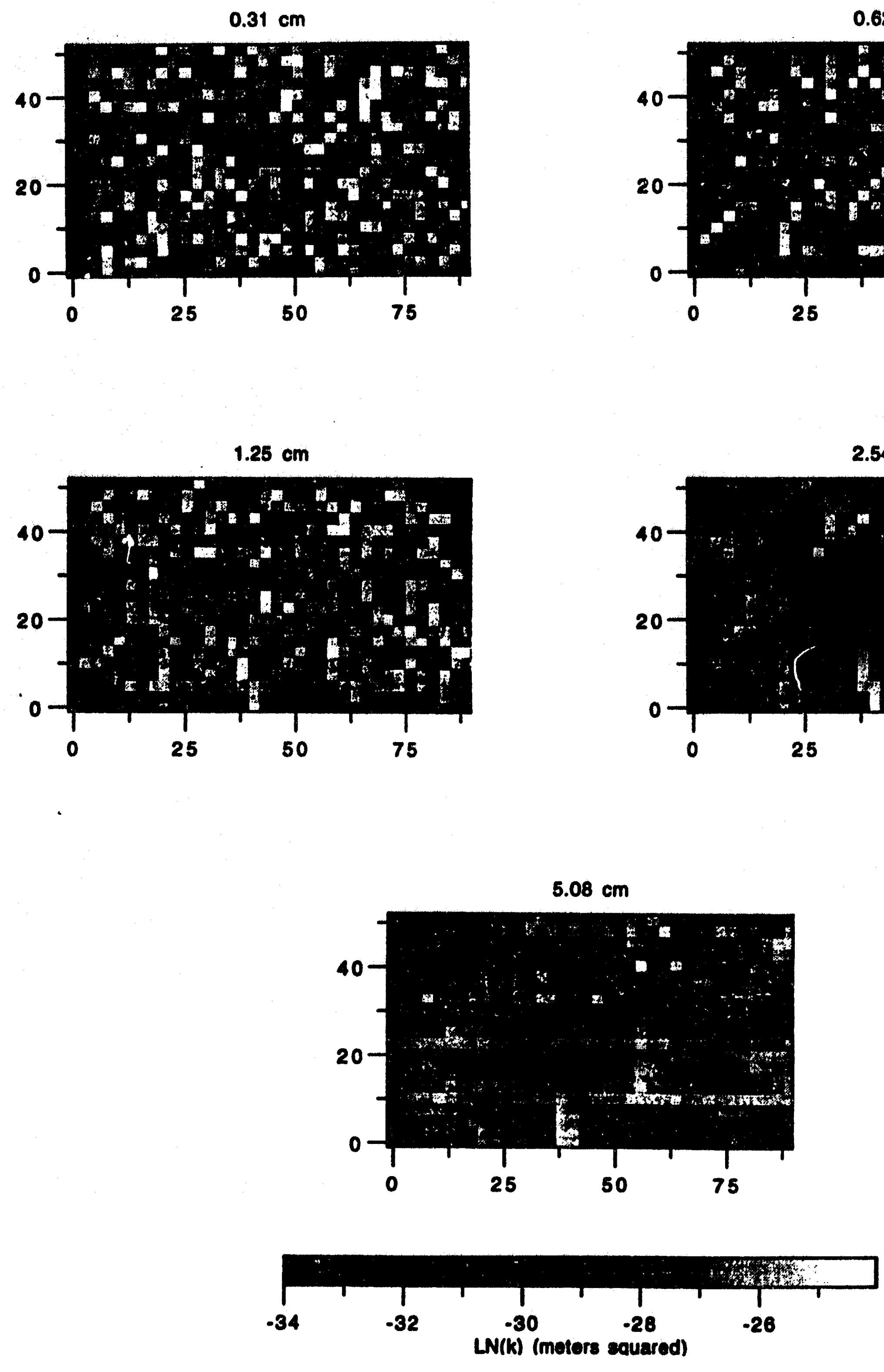
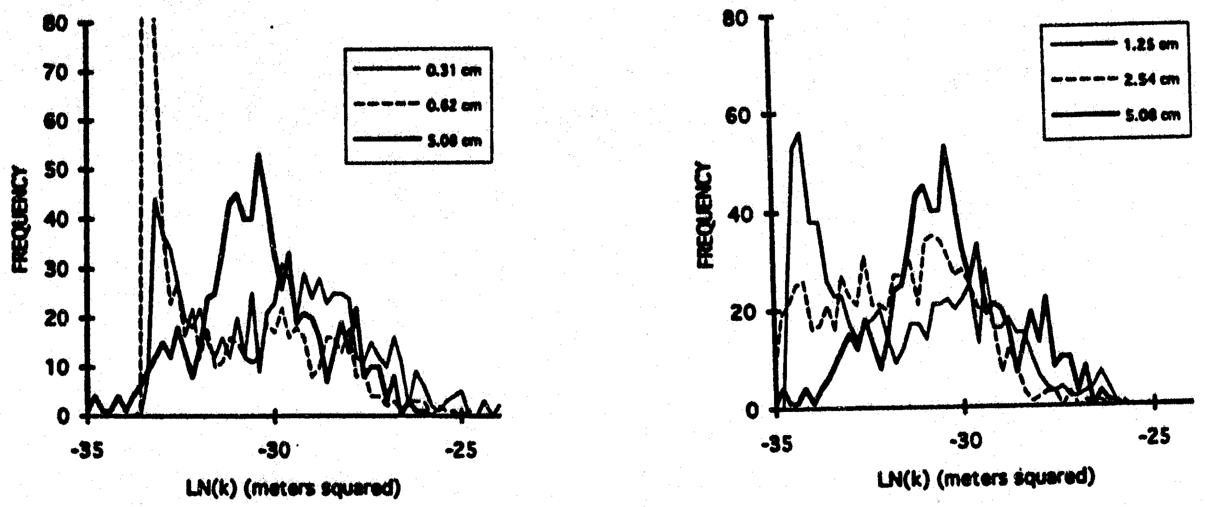
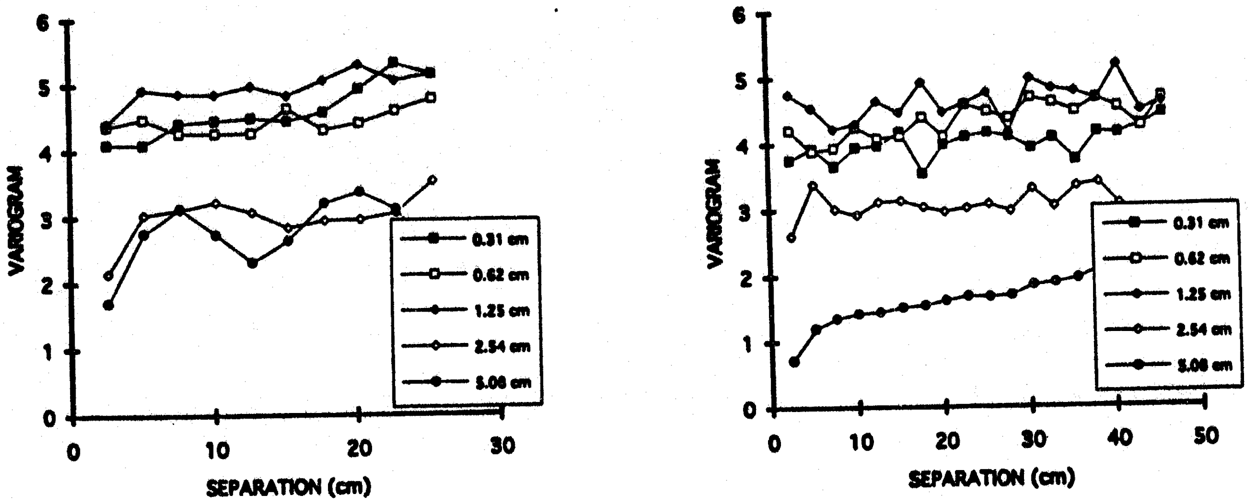


Figure 4. Gas permeability fields for the poorly welded tuff sample, as measured by the 0.31, 0.62, 1.25, 2.54, and 5.08 cm tip seals. Data are reported in terms of the natural log of the gas permeability in units of m^2.



a). b).

Figure 5. Comparison of distribution functions measured by different tip seals on the poorly welded tuff sample. Data for the a) 0.31, 0.62, and 5.08 cm tip-seals, and b) 1.25, 2.54, and 5.08 cm tip-seals are plotted separately to facilitate comparison. For the 0.62 cm tip seal, 197 measurements are associated with the interval -33.5 to -33.3 (data truncated from graph).



a). b).

Figure 6. Variogram comparison for the poorly welded tuff sample. Variograms are provided for orthogonal search directions and different tip seals, a) normal to bedding, b) parallel to bedding.

Table 4. Summary Statistics; Poorly Welded Tuff Sample

Statistics	0.31-cm	0.62-cm	1.25-cm	2.54-cm	5.08-cm
Mean	-29.93	-31.47	-31.57	-31.58	-30.33
Variance	4.81	4.43	5.02	3.29	2.72
Skewness	0.22	0.98	0.40	0.06	0.05
Kurtosis	-0.77	0.08	-0.95	-0.66	-0.09
Minimum	-33.27	-33.41	-34.53	-34.90	-34.94
Maximum	-23.23	-23.69	-25.99	-25.70	-25.96
Count	756	756	756	756	756

exhibited by the two tuff blocks is very different owing to differences in the composition and structure of the rock samples (i.e., heterogeneity structure). The measured scaling behavior is characterized by complex variations in predominately non-Gaussian distribution functions and the variograms. Even for the relatively narrow range of measurement scales employed, which are on the order of the common core sample, significant changes in the distribution functions, variograms, and summary statistics occurred. Because such data descriptors will likely play an important role in calculating effective media properties, these results demonstrate both the need to understand and accurately model scaling behavior.

Additional work is required if quantifiable scaling laws or models are to be developed. Future efforts include investigating the other faces of the Tiva Canyon and poorly welded tuff samples. Six other tuff blocks collected from Yucca Mountain and the surrounding vicinity will likewise be subjected to similar scaling investigations. Efforts are also being made to develop a means of quantitatively describing heterogeneity structure of the tuff samples; the goal being to correlate basic geologic attributes to the scaling behavior measured in the experiments. Once sufficient data are collected, potential empirical scaling laws will be explored and current scaling models will be tested.

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