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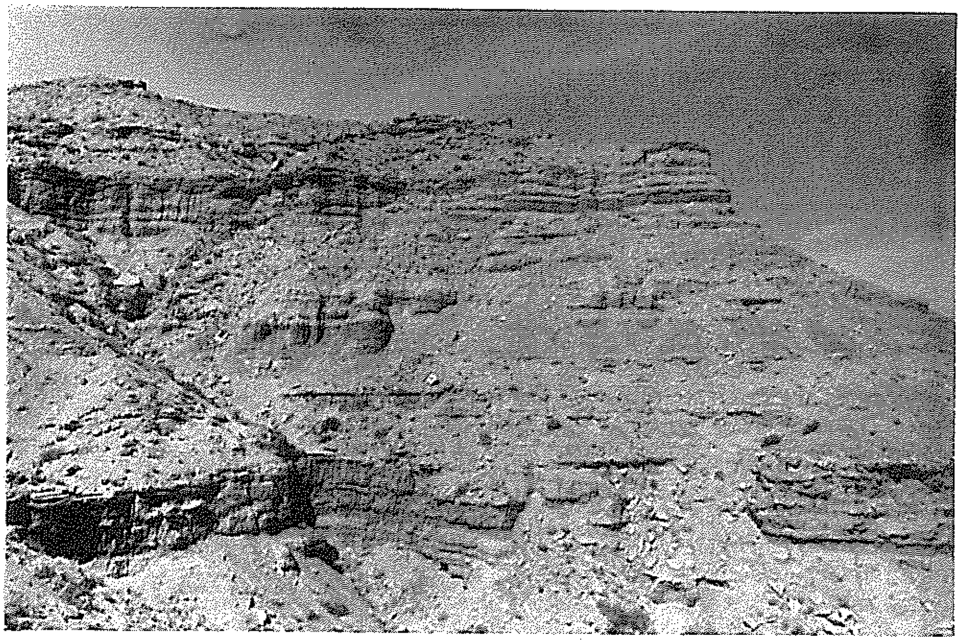

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ALLUVIAL AQUIFER HETEROGENEITIES IN THE RIO GRANDE VALLEY:
IMPLICATIONS FOR GROUND WATER CONTAMINATION

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ABSTRACT

Spatial variation of hydraulic conductivity has been generally recognized as the dominant medium–dependent control on the transport of contaminants in ground water. An empirical study focusing on the relationship between patterns of sedimentology and the distribution of permeability is being conducted at an outcrop of the Pliocene/Pleistocene Sierra Ladrones Formation located in central New Mexico.

Methods of geostatistics and sedimentary basin analysis are employed to study aquifer heterogeneity. An air permeameter provides a means of obtaining extensive field measurements of air–flow–rates through the sediments. These flow rates are subsequently used to characterize the permeability distribution of the outcrop. Both the geologic information and the air–flow–rate data provide the basis for aquifer heterogeneity analysis. Preliminary geologic mapping indicates that sediments in the study area are the products of an arid fluvial/interfluvial depositional environment. Probability distribution analysis of the air–flow–rate data suggests that the permeability of these sediments is log–normally distributed. The air permeability data are used to estimate variograms and correlation ranges in both the horizontal and vertical directions. At the scale of tens of centimeters, the horizontal variograms exhibit either exponential or bell–shaped behavior. Variogram analysis of estimated mean permeability at the scale of meters shows evidence of a nested correlation structure in the horizontal direction and a periodic correlation structure in the vertical direction. Results of this study suggest there is a direct connection between observable geologic structures and permeability statistics.

Key words: aquifer characteristics, hydrogeology, sedimentation, solute transport, stochastic processes

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Introduction

In recent decades, the problem of ground water contamination has emerged as the most serious threat to the nation's supply of potable ground water. Historically, the field of ground water hydrology has focused on water supply, and mathematical formulas have been derived principally to help solve supply problems. As with any engineering problem, simplifying assumptions concerning physical parameters are necessary when deriving and solving the governing ground water flow equations. At the physical scale of the water supply problem, it has been customary to assume the aquifer consists of one or more effectively homogeneous layers. Virtually all water supply problems are solved in two dimensions by averaging aquifer properties over the vertical dimension. Since it is of little concern which parcel of water arrives at the well first, this averaging approach has been fairly successful. As long as a certain number of parcels arrive at the water supply well in a given time interval, the supply problem can be considered solved.

The major challenge facing hydrogeology today is that contamination problems are greatly influenced by small–scale aquifer heterogeneities. Unlike water supply problems, which can be solved by macroscopic averaging of these small–scale heterogeneities, assessment of contamination problems depends on the ability to distinguish between parcels of water at the pore scale. Ground water contamination events occur at spatial scales that are orders of magnitude smaller than those characteristic of water supply problems. Geologically, water supply problems occur at the formation and stratigraphic group level; ground water contamination problems exist at the formation and lithologic facies scale. With respect to water supply problems in alluvial aquifers, hydrogeologists deal with basin fill stratigraphy and in some cases the subsequent structural deformation of that stratigraphy (Meinzer 1923). In the context of ground water contamination problems, hydrogeologists must begin to study how flow and solute transport are controlled by geologic heterogeneity within stratigraphic units. The geologic problem has changed from one of stratigraphy and general basin fill to a sedimentology problem. Therefore, to study a ground water system at the scale at which contamination occurs, it is necessary to investigate the geology in detail.

Mechanisms of solute transport in the subsurface can be broken down into three components: 1)molecular diffusion, 2) advective flux, and 3) mechanical mixing, more commonly known as dispersion. It has been observed since the earliest studies of ground water flow that dispersion can be an important mechanism of subsurface solute transport (Slichter 1899). Molecular diffusion is often insignificant and can be neglected. Advective flux is generally the dominant mode of transport and is controlled by the mean ground water seepage velocity. The dispersive component arises out of mixing processes that occur when fluid elements transported through a heterogeneous aquifer encounter different transport pathways and move at varying velocities. The dispersion mechanism is characterized by a dispersivity coefficient or tensor most often assumed to be spatially invariant.

Recent studies (e.g., Pickens and Grisak 1981a,b) have suggested that the coefficient of dispersivity depends on the distance that solutes are transported through the subsurface. This phenomenon is commonly referred to as scale–dependent dispersion. When considering the geologic heterogeneity of most aquifers, the occurrence of scale dependence is not surprising. As the ground water moves through the aquifer, different water parcels move at different velocities depending on the local hydraulic gradient and conductivity. If the geologic material comprising the aquifer ranges from clays to gravels, then the corresponding velocities will also be highly variable (Schwartz 1977; Smith and Schwartz 1980; Silliman and Simpson 1987). The farther the contaminant plume travels, the greater the number and scale of heterogeneities encountered, and the more the plume becomes subject to dispersive influences. Thus, dispersive controls on contaminant transport are essentially hydraulic in nature, and characterization of aquifer heterogeneities effectively amounts to characterization of the aquifer's solute–transport properties.

The need for quantitative studies of dispersion through heterogeneous porous media and the inability to describe the heterogeneity completely has led researchers to a probabilistic interpretation of the spatial variability of hydraulic conductivity. Studies over the past two decades have interpreted geologic heterogeneity as being a spatially correlated random field or process. These studies in stochastic hydrology have yielded much insight into how a hydrologic system would respond if conductivity is a spatially correlated random process. Works of Bakr et al. (1978), Gutjahr et al. (1978), Gelhar, Gutjahr, and Naff (1979), Gelhar and Axness (1983), and Dagan (1986) address some of the stochastic approach's more theoretical aspects. The papers by Bakr et al. (1978), Gutjahr et al. (1978), and Dagan (1986) primarily discuss the problems of solving the flow equation with a continuum representation of the random hydraulic conductivity field. Dagan (1986) addresses the conceptual relationship between the flow domain scales (pore scale, laboratory scale, formation scale) and the scales of spatial correlation. Gelhar, Gutjahr, and Naff (1979) and Gelhar and Axness (1983) focus on solving the flow and transport equations in stratified and statistically anisotropic porous media, respectfully. Many subsequent works (e.g., Naff and Vecchia 1987; Neuman, Winter, and Newman 1987; Shapiro and Cvetkovic 1988) have focused on various theoretical aspects of the stochastic interpretation of fluid flow and solute transport through porous media. These theoretical investigations have been important in determining the statistical parameters most crucial for the prediction of subsurface flow and contaminant transport.

Some studies have focused on estimating the proper statistical representation of natural geologic material. For example, MacMillan and Gutjahr (1986) studied porosity and permeability in vertical cores of quartzose sandstone and suggest that the average thickness of geologic layering exerts a dominant control on the length over which measurements are correlated statistically. Another study by Goggin et al. (1988a) reports that permeability patterns in eolian deposits are strongly dependent on sedimentary structure. Their study was conducted on the scale of lithologic facies.

To apply classical geostatistics, determination of the necessary statistical parameters may require hundreds to thousands of measurements, depending on the complexity of the geologic system. Such data requirements are clearly prohibitive and still may not completely characterize an extremely complex aquifer. Economic constraints associated with obtaining a data base of this extent have generally resulted in insufficient data. An alternative to this "hard" data approach is to incorporate geologic information which, while more abundant, is subjective and contains a higher degree of uncertainty (e.g., Journel and Alabert 1988; Phillips and Wilson 1989; Phillips, Wilson, and Davis 1989; Anderson 1989). This type of information has been referred to in the literature as "soft" information (Journel and Alabert 1988; Gelhar 1986). The question then becomes: "How can 'soft' geologic information help in supplementing the available data?"

The field of sedimentology offers us an analytical framework to study "soft" geologic information. Lithologic types, their spatial extent, degree of interconnection, and characteristic sedimentary structures are examples of "soft" information. These characteristics of sedimentary deposits vary according to processes that dominated deposition (Galloway and Hobday 1983; Reading 1986). Sedimentology is the study of how depositional processes are related to depositional products and how one can be inferred from the other. It is this process/product relationship that may allow us to estimate the aquifer's hydrologic character and permit us to incorporate "soft" information into the characterization process.

In the past, the geologist's ability to predict the spatial geometric relationships and assemblages of lithologic facies of an aquifer formed in a known depositional environment has been limited. This was not due to an intractable nature of the problem, but rather to the lack of spatially located sedimentological data and an appropriate mathematical framework in which to relate systematically the sedimentological processes to their consequent depositional architecture. In the view of most sedimentologists, permeability distributions in fluvial aquifers are the result of fairly well–understood depositional processes. Such a quantitative framework relating permeability distributions to depositional environments can permit incorporation of "soft" data and a significant reduction in "hard" data requirements. If a quantifiable relation between permeability patterns and geology exists, and if this relation can be systematized into such a mathematical framework, one may be able to predict the permeability patterns of an aquifer based on limited well bore and other "soft" geologic information. Hypothesis refinement and modification may result in methodologies by which the permeability field can be estimated from the observed geologic record.

To arrive at such methodologies, it will be necessary to conduct numerous field investigations that focus on 1) the relation between geologic features and the distribution of permeability, 2) a mathematical description of that relation, and 3) parameterization of the mathematical description based on available information relating to the unique depositional environment under study. Appropriate studies would involve parallel investigation of the permeability field and the spatial configuration of sedimentological units, as well as development of improved models relating depositional environments to observed facies geometries.

This report describes and evaluates a field methodology that addresses the issue of incorporating geologic information into a quantitative description of permeability. Background material on geostatistics and basin analysis is reviewed, serving as a basis for the field methodology presented. Finally, results of the field investigation are presented and discussed.

Sedimentary basin analysis and geostatistics are adopted in this study as analytical methods most useful for characterizing aquifer heterogeneity. The basin analysis techniques presented are dominantly those of fluvial process/product relationships, but the principles of basin analysis should be amenable to other types of deposits. A field site located in the Albuquerque Basin of central New Mexico was chosen to conduct parallel sedimentology and permeability investigations. The site consists of extensive outcrops of the Sierra Ladrones Formation that extend for approximately 15 miles south of Belen, New Mexico. The sediments are largely undisturbed with respect to diagenesis and structural deformation. Under these conditions, permeability is strongly dependent on the depositional environment in which the sediments were formed. The outcrop's large extent and varied exposure offer an excellent opportunity to investigate the three–dimensional character of a fluvial deposit.

The major objectives of this study are:

1) to establish a comprehensive data base for characterizing the permeability distribution of a representative fluvial aquifer,
2) to determine the relationship between the observed geologic record and measured permeability patterns and to infer characteristic styles of heterogeneity from the architecture of the sedimentary units,
3) to investigate methods of incorporating "soft" geologic information into a

quantitative mathematical framework for describing the correlation structure of a heterogeneous permeability field, using known depositional process/product relationships, and to validate the feasibility of this approach by comparing the correlation structure predicted on the basis of "soft" geologic information with that predicted using "hard" permeability data, and

4) to determine the effects of spatial scale on heterogeneity patterns, and to attempt to relate these scales to the architecture of the sedimentary deposits in a systematic manner.

Background

Introduction

This chapter introduces and reviews some of the basic concepts of the two analytical methods we wish to combine: geostatistics and sedimentary basin analysis. The goal of this review is to discuss the key concepts of geostatistics and basin analysis and to relate them to the problem of aquifer characterization.

Geostatistics provides us with a mathematical descriptor to characterize heterogeneity quantitatively. Heterogeneity is, in fact, a deterministic property of the aquifer system. That is, at a given time, the permeability at every location in an aquifer is fixed and theoretically could be described exactly with a deterministic function. The probabilistic interpretation is adopted to account for both measurement uncertainty and uncertainty associated with values at unsampled locations. An implicit assumption in the probabilistic interpretation of heterogeneity is that the spatial distribution of permeability can be modeled mathematically as a random function.

Geology and basin analysis techniques serve as guides to the statistical approach. The main purpose of sedimentary basin analysis is to assimilate a wide variety of geologic information into models of the depositional processes and sedimentary products. These models are manifestations of the concept of process/product relationship, which asserts that depositional environments can be inferred from particular characteristics of the preserved sediments. However, since many sedimentary structures are common to several depositional environments, one must have sufficient geologic information to identify the prevailing depositional regime uniquely.

Sedimentary models and basin analysis are useful in the characterization of aquifer properties in that they allow estimation of the geologic characteristics of an aquifer based on knowledge of the depositional environment. These characteristics focus on lithologic types, spatial relationships of the lithologies, and dimensions of the depositional units that comprise the formation. In the cases of geostatistics and basin analysis, we see an emphasis toward general structural characteristics.

Geostatistics

The most fundamental concept in the application of probabilistic regionalized variables in the description of geologic heterogeneity is spatial correlation. Spatial correlation simply states that values of a random function at two points located near one another are more likely to be similar than values at points spaced far apart.

Estimation of statistical moments.

An underlying assumption of the geostatistical approach is that a continuum of random variables can be represented adequately by the first two moments of their common joint probability density function (Bakr et al. 1978; Journel and Huijbregts 1978). The first moment is the mean of the field and the second moment is the correlation structure, as represented by the variogram. The sample variogram $\gamma(s)$ is calculated as:

$$\gamma(s) = \frac{1}{2N(s)} \sum_{i=1}^{N(s)} [Y(x_i) - Y(x_i + s)]^2 \qquad (1)$$

where: $N(s)$ = the number of pairs of observations separated by a distance s

$Y(x_i)$ = the observed value of the random field at vector location x_i

s = the distance between any two observed values

It is expected that on the order of a hundred permeability measurements will be required to construct meaningful variograms for a given spatial scale of variability, depending on the complexity of the deposits. Not only does this number generally exceed the number of measurements available at a given site, the information supplied by these measurements is usually constrained to a given spatial interval based on the source of the information. For example, if all the data are derived from wells in the form of pump test results or well logs, then the well spacing dictates what scale of variability can be studied with "hard" data alone. In order to supplement the limited "hard" permeability data set and analyze a wide spectrum of spatial scales, we use the techniques of basin analysis to provide additional "soft" geologic information.

Stochastic hydrology.

With the first two moments of the system defined, it is possible to solve the partial differential equations of flow and transport through the field. The methods for solving the equations will not be addressed here in detail. The reader is referred Gutjahr et al. (1978), Bakr et al. (1978), Gelhar, Gutjahr, and Naff (1979), Gelhar and Axness (1983), and Dagan (1989).

Most solutions of the flow and transport equations through the continuum representation require two fundamental assumptions: second–order stationarity and ergodicity. The condition of second–order stationarity states that the first two moments of the joint probability density function, as described by the mean and covariance, are invariant with respect to space. This condition implies that the field exhibits a finite variance and that the covariance approaches a constant value at large separation distances equal to the variance. An alternative to second–order stationarity is to hypothesize that the field is an an intrinsic random field. This condition requires only that the mean and variogram are spatially invariant (Journel and Huijbregts 1978). The intrinsic hypothesis, or the assumption that the field is an intrinsic random field, is usually sufficient for geostatistical operations when dealing with the variogram (Delhomme 1978). When regional variations in the mean and variogram occur, it may be possible to use a moving neighborhood approach where each neighborhood is relatively statistically homogeneous (Journel and Rossi 1989). Ergodicity is also central to the application of geostatistical methods to observed random fields. The ergodic condition asserts that averaging the random property over a single realization of the field is equivalent to averaging all values of the random property that can be assumed at any given point in the field.

Although permeability or hydraulic conductivity have traditionally been the principal aquifer properties studied, aquifer heterogeneity can also be characterized by analyzing a variety of other parameters. For example, Fogg (1989) performed statistical analysis of sand body thicknesses to arrive at sand–body interconnection. Similarly, Journel and Alabert (1988) proposed a method of indicator kriging which analyzes the connectivity of neighboring values of hydraulic conductivity with respect to a threshold value. They maintain this method better simulates the actual continuity that is observed in many geologic deposits than the traditional kriging approach. Johnson and Dreiss (1989) used indicator kriging to describe the degree of interconnection within high– and low–conductivity layers of an alluvial sediment deposit (1989).

These are the analytical methods currently at our disposal. While these methods address many basic issues of geologic and geostatistical importance, it is hoped that the methodology presented in this report will lay the groundwork for the developing alternative methods of analysis that can be used to assess complicated geologic heterogeneities typically encountered in the field.

Basin Analysis

As with the need for understanding the quantitative aspects of characterizing the permeability field, it is also important to investigate methods of geological analysis that will aid us in the final characterization. Although this report addresses the problem of characterizing deposits laid down by fluvial processes, the methodology presented should be amenable to any type of sedimentary deposit.

A sedimentological facies is a body of rock defined and distinguished from others by its geometry, lithology, and sedimentary structures (Selley 1978). Types of sedimentological facies as well as their extent and geometric relationship with respect to one another are critical features of a sedimentary basin. Similarly, the hydrogeologic problem of aquifer characterization is sensitive to the type, extent, and architecture of sedimentological facies.

Analysis of clastic depositional systems relies on models to reconstruct depositional environments. The term model is used here to mean a simplified version of reality that exhibits useful information in the interpretation and prediction of facies assemblages in sedimentary basins. Models of all types have been used to aid sedimentologists in understanding depositional processes and their products. Depositional models serve as reference points for comparison. By comparing and contrasting observed facies assemblages to models that represent a relatively well understood process/product relationship, one can draw conclusions about the prevailing depositional environment and infer the overall character of the deposits at locations where geologic observations are not available. Since most facies architectures are unique to the processes that dominated the depositional environment, different processes are manifested differently in the sedimentary deposits.

Facies models have long been the tool of sedimentologists when analyzing depositional environments. Since well logs have been the primary source of geologic information, vertical facies models have dominated sedimentological studies. According to Miall (1984), "A facies model attempts to provide an interpretation of a particular type of facies assemblage in terms of depositional environment. " The utility of the facies models stems from a conceptual understanding of the relationship between depositional processes and products. Facies models are usually lumped into a depositional model context in which an assemblage of facies is interpreted as resulting from a certain type of depositional environment.

Traditionally, fluvial depositional environments are categorized according to stream morphology. Much effort has focused on delineating between morphologies of braided and meandering streams. Braiding parameters and length of meanders have been used to place modern streams and their associated deposits into a morphological category (Miall 1977). Without such a simplifying scheme, the field of sedimentology would become exceedingly cumbersome.

Based on the limited utility of vertical facies models, Miall (1985) has suggested that facies models should deal with the third dimension whenever possible and characterize the environment in which a deposit was laid down instead of the morphology of the ancient stream. He proposes a method called architectural element analysis, in which the geometric relationships of eight basic sedimentological elements are studied in three dimensions. The eight basic elements, summarized in Table 1 and illustrated in Figure 1, will not be discussed at great length in this report. While admittedly biased toward braided–stream systems, architectural–element classification offers a useful reference for distinguishing among various depositional environments. This study focuses on investigating the characteristics and geometries of the channel and overbank elements of Miall's (1985) classification.

Architectural elements represent the products of different processes acting in a depositional environment. Each element consists of a suite of lithologic sediment types

Table 1.

Miall's (1985) classification of eight basic architectural elements.

Element	Symbol	Principal lithofacies assemblage	Geometry and relations
Channel	CH	Any combination	Finger, lens, of sheet; concave-upward erosional base; scale and shape highly variable; internal secondary erosion surfaces common.
Gravel bars and bed forms	GB	Gm, Gp, Gt	Lens, blanket; usually tabular bodies; commonly interbedded with SB
Sandy bed forms	SB	St, Sp, Sh, Sl, Sr, Se, Ss	Lens, sheet, blanket, wedge; occurs as channel fill, crevasse splays, bar tops, minor bars
Downstream accreting macroform	DA	St, Sp, Sh, Sl, Sr, Se, Ss	Lens lying on flat or channeled base, with covex upward third order internal upper bounding surfaces.
Lateral accretion deposit	LA	St, Sp, Sh, Sl, Sr, Se, Ss, less commonly G and F	Wedge, sheet, lobe; characterized by internal lateral accretion surfaces.
Sediment gravity flow	SG	Gm, Gms	Lobe, sheet; typically interbedded with GB
Laminated sand sheet	LS	Sh, Sl, minor St, Sp, Sr	Sheet, blanket
Overbank fines	OF	Fm, Fl	Thin to thick blankets; commonly interbedded with SB; may fill abandoned channels.

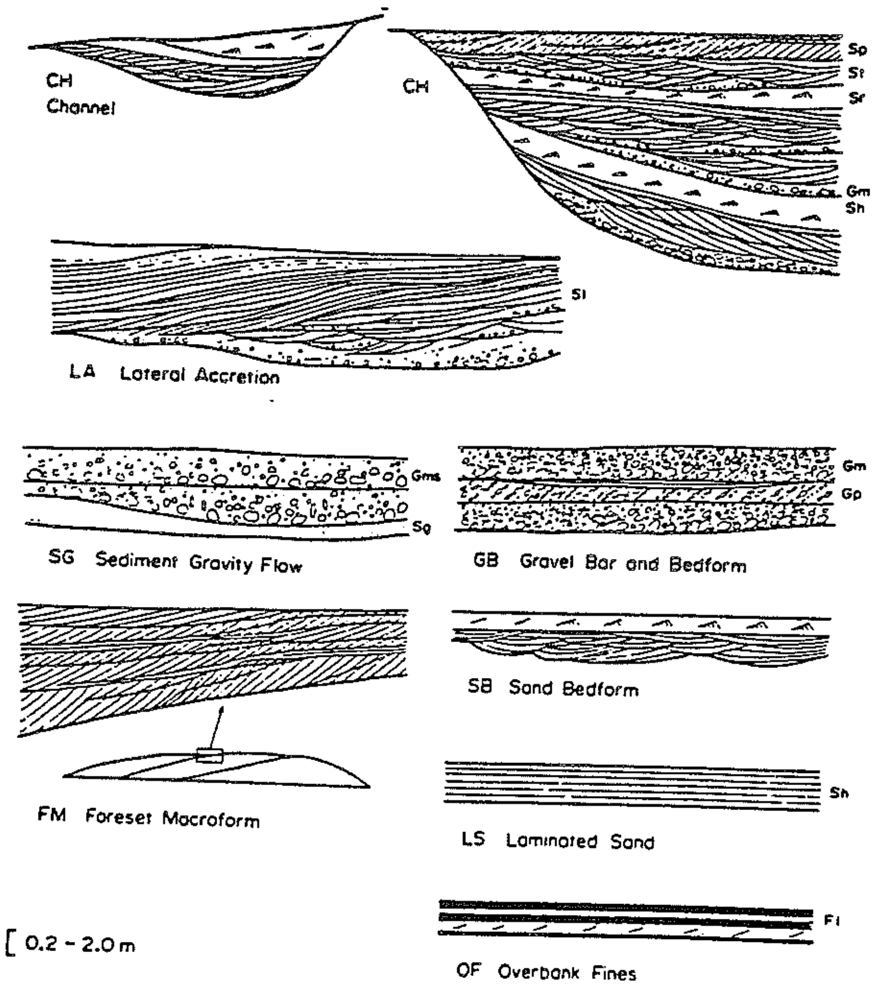


Figure 1. The eight basic architectural elements as defined by Miall (1985). Note the variable scale. (from Miall 1985)

that are associated distinctly with a particular depositional process. The advantage of the architectural element approach in the characterization of aquifer heterogeneities is two–fold. First, the three–dimensional character of the deposit is preserved. Secondly, if architectural elements of the same type exhibit similar permeability patterns, then a statistical representation of the spatial distribution of elements would characterize the aquifer heterogeneity. Sedimentological models of architectural elements and their associated permeability patterns could then be used as a basis for comparison. Similarities in depositional style would result in similar permeability patterns. Likewise, differences between the observed architectural element distributions and architectural element type models would lead to predictable differences in permeability patterns.

Another important concept in fluvial sedimentology is that of cyclicity. Most available generalized facies models consist of vertical assemblages of lithologic facies. Commonly, these assemblages are preserved in vertical sequences which have the same general character but exhibit some variability within a cycle and between cycles. The variability is caused by changes in the depositional processes that generated the deposit, due either to the redistribution of fluvial energy in the basin or to changes in climatic and tectonic regimes.

According to Miall (1980), depositional processes can be broken down into two classes of cyclicity. The first class includes small–scale processes in which the redistribution of energy within the basin results in a cyclic nature of the deposit. This class of processes is termed autocyclic and includes meander translation and enlargement, meander chute and neck cut–off, crevassing, and avulsion. Autocyclic processes contribute largely to the variability within a depositional cycle. The second class of cyclic processes is of a larger scale. Depositional processes that originate outside the sedimentary basin are allocyclic. Changes in climate and tectonic activity are examples of allocyclic controls. The intrabasin manifestation of these large–scale controls are cycles produced by changes in the discharge, variability of discharge, and load and slope of the fluvial transport system. When comparing observed geologic characteristics with type models, the concepts of cyclic processes provide a framework for analyzing variability within and between cycles.

The ideas presented in this section are intended to serve as a brief introduction to the sedimentological concepts and modes of study by which geological information can be incorporated into the characterization of fluvial aquifers. The reader is strongly urged to pursue the references cited to obtain a better understanding of the concepts presented.

Unification of Methods of Geostatistical and Basin Analysis

With respect to the mathematical basis of the aquifer heterogeneity study, we have focused our attention on statistical methods as a means of describing the spatial variability of permeability. Geologically, we have adopted the methods of basin analysis in an attempt to establish an analytical framework in which geologic information can be quantified. The ultimate goal of this research is to arrive at a method of incorporating "soft" geologic information and "hard" permeability data into a characterization of the permeability distribution of an aquifer at a variety of spatial scales. Since a broad range of data types exists, each associated with some uncertainty, it is important that the different kinds of information be incorporated into one mathematically consistent model or set of models.

Statistics and "quantitative" basin analysis have been studied in the past. Some notable examples of basin analysis include the use of Markov chain analysis in the development of preferred facies sequences (e.g., see Cant and Walker 1976, Miall 1973, Reading 1986), and simplified numerical studies on how specific depositional processes control the geometric relationship of sand bodies (e.g., see Allen 1978, Bridge and Leeder 1979).

Other methods of incorporating "soft" information into hydrogeologic problems include 1) Fogg's (1989) simulation of sand thickness and Johnson and Dreiss' (1989) use of indicator kriging to estimate aquifer interconnection, 2) modification of Tetzlaff and Harbaugh's (1989) SEDSIM model to simulate permeability distributions numerically according to basin fill processes and grain size distributions (Koltermann and Gorelick 1990) and use of random–walk techniques for simulating alluvial–fan deposition (Price 1974), and 3) Phillips and Wilson's (1989) application of mean–crossing theory to estimate spatial statistics based on mappable geologic features. Each of these has contributed to a better understanding of how basin fill stratigraphy may be quantified. However, each approach has restrictions or has simply not been adequately field–validated.

There are numerous possibilities for approaching the problem of characterizing aquifer heterogeneity. Characterization must be both geologically reasonable and possess a sufficient level of quantification to allow flow and solute transport problems to be addressed at a quantitative level. Past research has not been oriented toward the investigation of how geologic materials are naturally distributed and what mathematical framework best describes the existing structure. In the Field Methodology section, we present one methodology for implementing the aquifer characterization study.

Heterogeneity and Spatial Scales

Permeability and hydraulic conductivity are by definition averaged properties of the porous medium. Bear (1979) illustrates this with the concept of the representative elementary volume (REV). That is, he hypothesizes that there exists a finite range of volumes for which the parameter being studied does not change appreciably (Figure 2). Below the valid range of volumes, the parameter oscillates due to microscopic effects that are not sufficiently averaged; above the valid range, the parameter begins to incorporate dissimilar material and the averaging process must begin again.

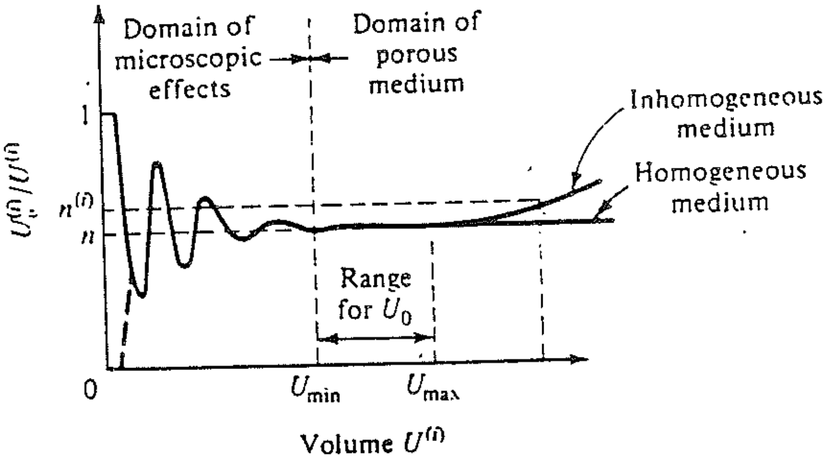


Figure 2. Illustration of the representative elementary volume (REV) concept. (from Bear 1979)

It is common practice in solving ground water flow problems to use effective or equivalent values of hydraulic conductivity in order to simplify the heterogeneity. For example, a heterogeneous layered system can be represented as an equivalent homogeneous, anisotropic porous medium (Freeze and Cherry 1979). Provided the phenomenon under study occurs at a significantly greater scale than some characteristic length of geologic heterogeneity, a properly defined equivalent porous medium will duplicate the hydraulic or solute–transport response of the original heterogeneous system.

However, when dealing with problems of solute transport and ground water contamination in heterogeneous aquifers, solute dispersion depends on the characteristic scale of the heterogeneity. The study of the controlling factors in solute transport is essentially a study of geologic scales and how hydraulic parameters tie into that structure of scales. Weber (1986) breaks geologic scales into five classes (Figure 3). The three largest classes will be the focus of the current and pending investigation.

Figure 4 shows a hypothetical progression of valid REV's in a geologic context in the form of a variogram. The vertical axis represents the variability of hydraulic conductivity and the horizontal axis the scale of the geologic entity. Each sill represents a natural scale at which the permeability field is stationary, with the overall shape of the variogram dependent on the degree to which each natural scale dominates the conductivity field. It is hypothesized that geologic entities such as individual lithofacies, architectural elements, and entire fluvial aquifers possess unique natural scales and can be represented by some equivalent or averaged hydraulic conductivity, giving rise to the hierarchical correlation structure illustrated in Figure 4. While this hypothesis proves to be very useful for conceptualizing hierarchical correlation structure, a given geologic entity may occur over a wide range of spatial scales. For example, architectural elements are composed of lithofacies that can span a wide spectrum of scales, so the elements themselves may cover a broad range of scales in a given de-

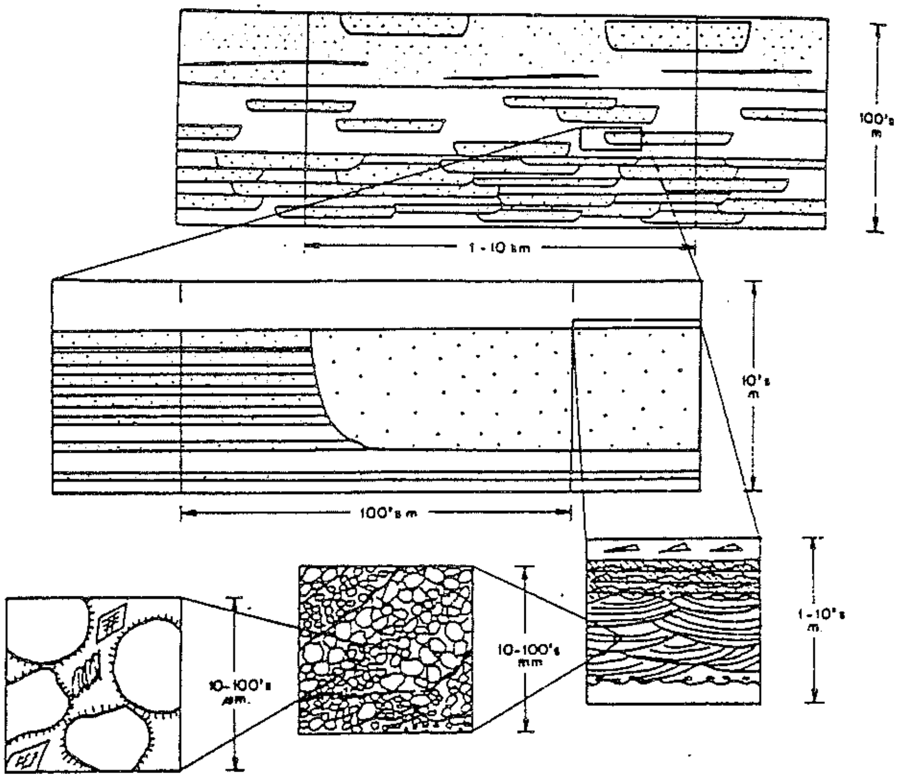


Figure 3. Five–fold breakdown of geologic scales of heterogeneity. (from Weber 1986)

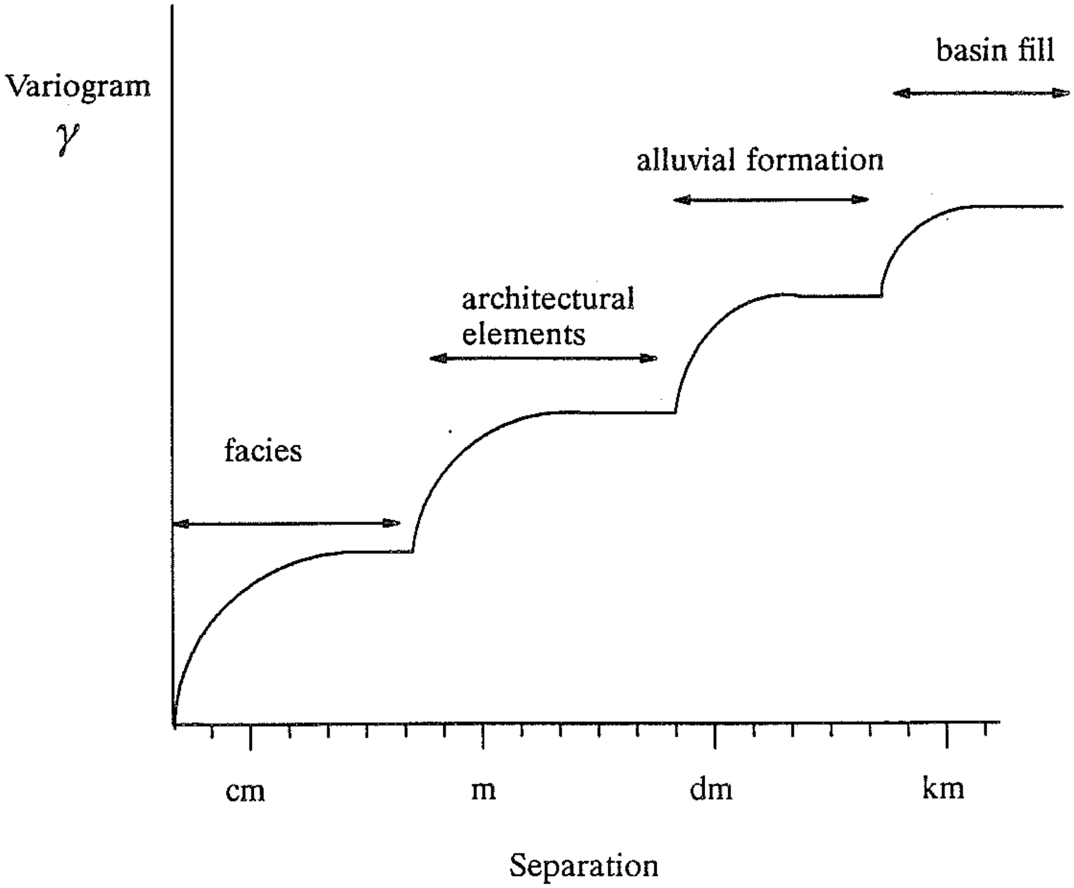


Figure 4. Hypothetical variogram of permeability involving a variety of geologic scales. (modified from Gelhar 1986)

posit. Thus, the natural scales implied by the nested structure may not relate directly to unique geologic entities observed in the field. This lack of a one–to–one relation between natural scale and dimension of geologic units will not materially affect our ability to define the hierarchical structure of the field, which may exist regardless of whether or not we introduce arbitrary classifications of geologic entities. The absence of a unique relationship between observation scale and dimension of geologic units does, however, throw into question the utility of Miall's (1985) geologic classification scheme if geostatistical techniques are to be used for aquifer characterization.

The problem of describing the hierarchy of scales associated with geologic media was recently addressed by Neuman (1990). Using apparent longitudinal dispersivity data estimated from a variety of sites he showed that, in a global sense, logarithmic conductivity follows a random fractal model with homogeneous increments. On that basis, he derived a universal variogram for a continuous hierarchy of scales by superimposing an infinite number of exponential variograms, each representing the correlation structure of logarithmic conductivity at local scales of observation. Since the continuous variogram was derived using data collected from many different sites, each characterized by its own discrete natural scales of heterogeneity and subject to different conditions of transport, the universal scaling rule implied by the variogram cannot generally describe local features of the field, particularly interconnection of high– or low–permeability geologic units (Anderson 1991). Rather, the continuous variogram approximates, in a mean sense, the discrete, stepwise variograms typically obtained when the geologic medium possesses discrete natural scales, as shown in Figure 4 (Neuman 1991). The universal scaling rule, while limited in its applicability to logarithmic conductivity fields that behave as random fractals, represents an important step toward understanding the structure of permeability fields in natural geologic settings. It remains to be seen whether the heterogeneity of Sierra Ladrones Formation deposits can be described, in some average manner, by Neuman's (1990) universal scaling rule.

Field Methodology

Introduction

As discussed previously, in order to relate the geology and the permeability systematically, the two must be studied in parallel. The methodology for such a field study is the topic of this section. While the methodology has been developed for a specific field site, the methods presented are amenable to other sites with little modification. The fluvial deposit chosen to study permeability patterns and sedimentology is the Sierra Ladrones Formation, which crops out extensively along the margin of the Llano de Albuquerque geomorphic surface for approximately 25 kilometers, providing an opportunity to study the problem at a variety of spatial scales (Figure 5). Badlands topography provides good three–dimensional exposure and minimal diagenetic and tectonic effects. The outcrop and field site are described in further detail in the next section.

Some of the field investigation's primary goals are to investigate the relationship between the observed geologic record and patterns of permeability and how depositional processes result in characteristic styles of heterogeneity. Another main objective is to study how heterogeneity changes with variation in spatial scale, and how these scales progress from one to another. To address these questions quantitatively, it is necessary to obtain spatially located information on both permeability and geology at scales of hydrologic importance. Generally, the scales of hydrologic importance depend on the scale of the hydrologic problem under study. For purposes of characterizing aquifer heterogeneity from facies to architectural–element scales, scales of hydrologic significance include the local field and regional scales described by Dagan (1986).

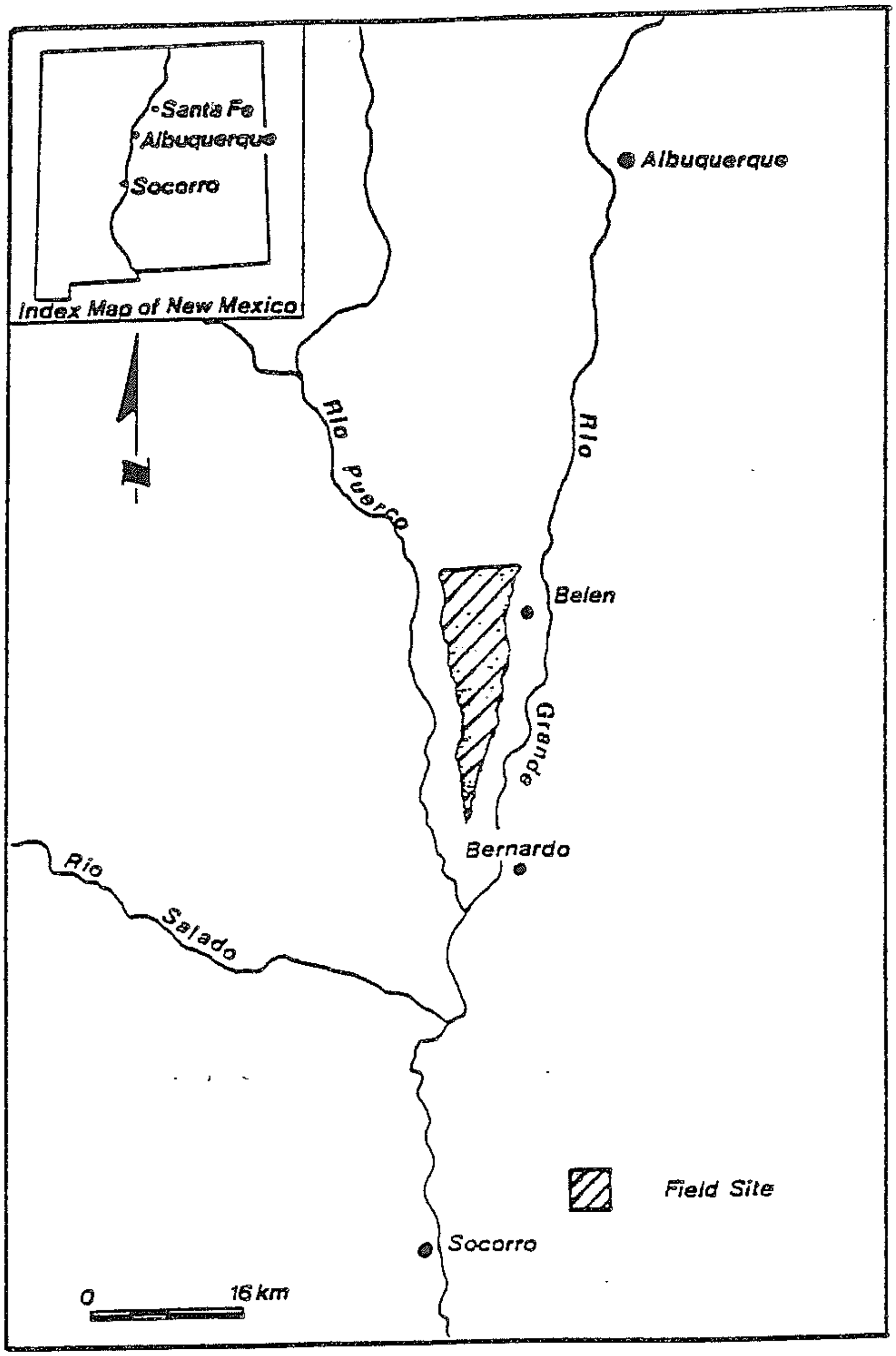


Figure 5. Location map of field site.

Pore and laboratory scales of flow and transport are not considered relevant to the characterization study.

The desired result of this study is a sedimentologically based model of aquifer heterogeneity developed from depositional process–product relationships. No a priori sampling strategy has been employed here. Rather, the approach has been to allow the observations to dictate further sampling strategy, thereby addressing the questions of interest as the study progresses. The primary purposes of the data are three–fold: 1) to serve as a basis for geologic interpretation, 2) to calculate geostatistical parameters on the basis of permeability measurements and, 3) to compare parameters inferred from the geologic record, such as grain sizes, to estimated geostatistical parameters.

Geologic features must be studied in sufficient detail so that the data is adequate for interpretive purposes at small spatial scales. While it is important not to get excessively "lost in the details" on the small scale, the details should be studied so the research can progress along a directed and geologically reasonable path. The uncertainty associated with the geologic record varies according to the scale of observation.

At the level of geologic interpretation and characterization, a clear understanding of geometric assemblages is more important than actual spatial location of the observation in a global coordinate system. However, if the data are to be used in the estimation of statistical parameters for the permeability field, it is necessary to impose adequate control on the spatial coordinates of the geology. Naturally, there exists a question of feasibility. It would not be feasible nor would it be necessary to map the entire escarpment in great detail with highly accurate surveying methods. The question is raised: "At what level of accuracy must the geology and permeability be mapped to obtain a meaningful data set that satisfies the objectives of the study?" The process must clearly be recursive in nature.

This section describes a field methodology that economically fulfills both the geologic and permeability data requirements at all scales of observation. Geologic and permeability data is collected from a base of control survey points. From the control points, the geologic features are mapped and permeability measurements taken. The survey methods vary depending on the scale of interest.

Geologic Mapping

Geologic information serves two purposes. The sediments' lithology and architecture will be used to interpret prevailing depositional processes as well as to estimate permeability–field statistical parameters. The scales of interest can be broken into three general classes, each of which is slightly different in the method of establishing spatial control and the goal of the mapping exercise. Each class of scale is assumed to have an associated geologic entity. Studying all scales in geologic context will lead to a better understanding of the progression of spatial scales with respect to the hierarchy of geologic entities.

Facies scale.

The facies mapping exercises begin with a traditional survey with theodolite and rod. In the survey procedure, it is desired to capture the gross geologic features that are apparent from an initial reconnaissance of the area. Prepared outcrops for permeability measurements are also surveyed. The survey data are then reduced and translated to a two–dimensional representation of the outcrop being studied.

The second phase consists of a more detailed geologic mapping of the outcrop. The surveyed points are supplemented with field sketches of the facies relationships. These field sketches are then transferred to a base map containing the control points. Obviously, at this scale some spatial accuracy is forfeited so that an interpretive level of geologic detail can be incorporated into the study. It is important, however, that there be geologic and hydrologic bases for definition of architectural elements at larger scales.

Major depositional cycle scale.

Another important class of scale is the scale at which depositional cycles vary spatially. This type of variability plays a key role in the large–scale interconnection of architectural elements. Based on preliminary mapping exercises, this scale of variability is estimated to be on the order of several kilometers. A 7.5 minute topographic map enlarged two–and–a–half times is used as a base map. It has yet to be determined what "stratigraphic units" are appropriate for mapping at this scale in our study area.

The major difficulty associated with mapping at the depositional cycle scale lies in the lack of a mappable, laterally persistent transition between two facies. Even though the general trend or package of sediments is laterally continuous, there are subtle changes at the boundary. To further complicate the mapping process, at locations where the outcrop is covered with a thin veneer of colluvium, the procedure must include mapping colluvial cover while occasionally digging through the colluvial cover to confirm the contact.

Element scale.

Finally, the intermediate–scale heterogeneity must also be captured. Since an understanding of element–scale heterogeneity depends to a large degree on an understanding of both facies–scale and depositional–cycle–scale heterogeneity, it is listed as the final scale of aquifer characterization. Once the architectural elements are defined, they can be used to study intermediate scale heterogeneity. Mapping of architectural elements provides the link between the facies–scale mapping and the mapping of larger–scale depositional cycles.

Determining the geometric configuration of architectural elements and of facies within those elements is one of this study's primary objectives. Provided the statistical properties of permeability within architectural elements are distinct and tractable, the statistical parameters of the entire permeability field for the scale of particular interest can be estimated. Since we do not have the method in hand that will allow incorporation of geologic information and permeability data into a quantitative model, the level of accuracy required is, as of yet, unknown.

Collection of Permeability Data

In addition to the geologic information discussed above, spatially located permeability data are necessary for statistical analysis and interpretation of the depositional environment. This section will address the issue of obtaining spatially located permeability measurements.

At this stage of the research, we have chosen to neglect effects of diagenesis, such as cementation. The ideal sampling location is an uncemented fresh deposit. The Sierra Ladrones Formation crops out in a badlands topography for approximately 25 kilometers and the vertical extent of the outcrop varies from several meters to approximately 100 meters. Cementation of the formation occurs locally, usually when a permeable layer overlies a fine–grained unit. However, the majority of the exposure is uncemented, making it easy to obtain core samples for laboratory measurement of permeability. Colluvial cover of the uncemented portion is highly variable, but generally only a few inches need be removed before uncemented, undisturbed deposits are encountered. The preparation of a permeability measurement site has two primary objectives: 1) to remove colluvial cover to expose undisturbed sediment, and 2) to obtain sampling locations that can be located efficiently and accurately.

Air minipermeameter.

To obtain a sufficient number of permeability measurements, a portable air minipermeameter has been developed. The air permeameter is a modification of a device developed by Goggin, Thrasher, and Lake (1988b) and is described fully in Appendix B. It has been calibrated with respect to laboratory measurements of water permeability on core samples. The air permeameter allows rapid, non–destructive sampling of sand–facies permeability. To measure the permeability of the clay and gravel units, new permeameter designs will have to be developed, or at least a methodology adopted that will enable one to estimate the permeability of the extreme value deposits with acceptable accuracy.

Spatially located measurements.

The methodology developed for obtaining spatially located permeability is still in its infancy. It has resulted from a rather substantial set of constraints and it should be noted that the method described here is somewhat site and project specific. Two issues must be addressed: 1) where the measurements are made and 2) how the locations of the measurements are obtained.

The method of locating permeability measurement locations is based on a survey which establishes control points on the outcrop. Outcrops are prepared for permeameter sampling by locally digging away the colluvial cover to obtain a vertical face of undisturbed deposit measuring approximately 3 meters by 1 meter. The outcrop is then photographed so the location of permeability measurements can be recorded. The photograph of the prepared surface, including a scale, serves as a base map on which the locations of measurements are recorded. The sampling locations marked on the photograph are then digitized to obtain a set of "local" coordinates. Also digitized from the photograph are the surveyed control points.

The control points on the photograph allow the transformation of the "local" coordinates into the "global" coordinates of the study area. A similar type of locating scheme is employed to supplement the digout type study. In some locations, small surfaces measuring 15 centimeters by 15 centimeters are prepared and the permeability measurements are performed on a grid of known dimensions. Similarly, these "local" coordinates are then transformed into the "global" system. Figure 6 summarizes the permeability collection scheme.

Sampling of extreme values.

It has been noted in the literature (Journel and Alabert 1988; Silliman and Wright 1988; Fogg 1986, 1989; Desbarats 1990) that ground water flow depends greatly on the spatial distribution and interconnection of the extreme–value permeability units. However, sampling these extreme values remains a major stumbling block for experimental hydrologists. Quick and reasonably accurate measurements of clay and gravel permeability has not been a focus of hydrologic research.

For example, it may be possible to correlate the compaction variables of the low permeability clay to a permeability value (Harrop–Williams 1985). If this can be validated on the specific soils of interest, then permeability may be estimated in the field from a quick consolidation experiment. Another possibility is to perform actual clay permeability tests in the field. A device described by Olson (1966) allows rapid clay–permeability measurement by observing the pressure response due to a given influx of fluid. The problem of obtaining saturated clay samples in the field is still the major factor limiting the device's utility.

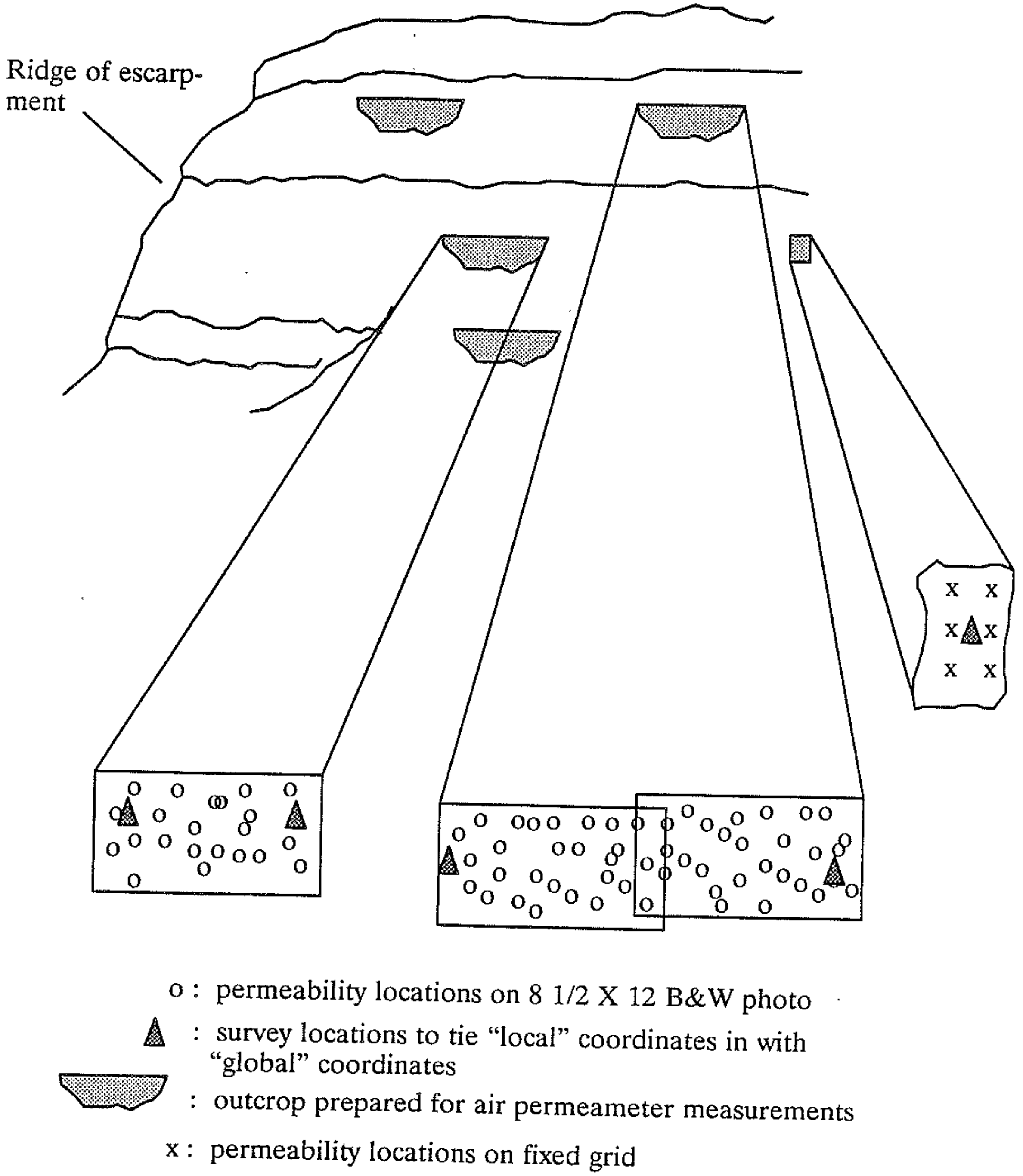


Figure 6. Diagramatic sketch of method used to locate permeability measurements.

Similarly, for the gravel units it may be possible to draw an empirical correlation between type of deposit and permeability based on field permeameter tests. It is most likely that these field tests would require a large volume permeameter to ensure that a sufficient volume of gravel is sampled. The envisioned permeameter consists of a cylindrical water tank, approximately 1 meter in diameter, 0.5 meter in height, and open at the top. With the tank approximately two–thirds full, a 1–liter cylindrical sample of gravel, screened at the bottom and open at the top, is inserted so that there is approximately 1 cm difference between the water level in the tank and the water level in the sample cylinder. Once the system reaches steady state, the difference in head and the flow rate through the sample can be measured. The permeability can then be estimated using Darcy's equation. While some of the gravel deposits in the Sierra Ladrones Formation have undergone diagenetic cementation, the majority of the gravels are uncemented and will be the focus of hydrologic characterization.

The problem of sampling extreme permeability values is an issue not likely to be resolved soon. However, it should be regarded as a serious deficiency that must be investigated. It should also be remembered that it may not be necessary to obtain highly accurate values of permeability for these units of extreme values. It may be sufficient to map their spatial extent and incorporate that "soft" information into the analysis, particularly if they are characterized by much larger or smaller permeabilities than adjacent deposits. The inability to measure clay and gravel permeability need not inhibit the entire aquifer characterization effort.

Implementation of Field Methodology

Introduction

Development of a successful method for incorporating geologic information into the characterization of aquifer heterogeneity requires intensive field effort. The geologic study should be performed on outcrops having sufficient exposure to allow information on both the geology and permeability patterns to be collected. The choice of an appropriate field site to study spatial variability of permeability and to develop sedimentological models of that variability is critical to the success of the aquifer characterization study. The Sierra Ladrones Formation site was chosen primarily for its accessibility, quality of exposure, and workable terrain.

Sierra Ladrones Formation

The Pliocene/Pleistocene Sierra Ladrones Formation crops out along the Llano de Albuquerque geomorphic surface in a badlands topography (Figure 5). The Albuquerque Basin is one of a series of en echelon rift basins that formed along the Rio Grande Rift during late Oligocene and early Miocene (Chapin and Seager 1975). The tectonics of the southwest Albuquerque Basin are fairly well understood at the large scale and less precisely in detail. Lozinsky (1988) summarized the tectonic setting for the Albuquerque Basin as a half–graben dipping eastward in the northern part of the basin and to the west in the south basin. The transition is covered by Santa Fe Group basin fill and is believed to occur along a southwest extension of the Tijeras fault just south of Albuquerque. The structural boundaries of the basin are the San Felipe fault belt in the north, the Joyita uplift in the south, and the Sandia–Manzano–Los Pinos uplift to the east. The western border is less well defined but includes the Lucero and Ladron uplifts.

The Sierra Ladrones Formation is the uppermost formation of the Santa Fe Group and is reported by Machette (1978) to be early Pliocene to middle Pleistocene in age. It consists of two main facies: 1) a piedmont slope facies consisting primarily of alluvial fan and coalescing fan deposits, and 2) a basin floor facies consisting mainly of river sands, gravels, and flood plain deposits. Studies by Young (1982) and Lozinsky (1988) represent the only comprehensive work done on the Sierra Ladrones Section in the area of interest. These studies have focused on much broader geologic aspects of the Formation than are immediately relevant to the aquifer characterization study. However, they may supply valuable information concerning regional characteristics of the Sierra Ladrones Formation. This information can be used to relate site–specific results to other geologically similar sites.

Current Geologic Investigation

The geologic analysis is subdivided into the three scale classes. Each scale class employs a slightly different method of study as well as a slightly different hydrogeologic and sedimentologic focus.

Mapping of major depositional cycles.

The first step in the geologic investigation of the Sierra Ladrones Formation was to become familiar with the overall nature of the deposits. The depositional model of Young (1982) was taken as a basis for analysis and modification.

Based on size of clasts, lack of fine-grained deposits, thick beds and shape of channel, Young (1982) interpreted the depositional environment of the Sierra Ladrones Formation as a complex braided-stream system.

Initial reconnaissance work revealed that lithologic facies in the northern part of the study area west of Belen, New Mexico, were laterally continuous on the scale of tens of meters to a few kilometers. To the south, in areas west of Bosque, New Mexico, more lateral variability in deposits was observed. The reason for the change in lateral variability is still unclear but the possibilities include 1) more of a meandering component to the north and/or 2) the confluence of the ancestral Rio Grande and its tributaries was at one time located to the south.

Similar packages of sediments were observed in both the north and south areas of the field site. Generally, these packages fine upward from coarse sand and gravel to soils and clays. As such, they are believed to represent major cycles of sedimentation. Some are dominated by stacked channels of gravel and coarse sand while others exhibit an abundance of laterally continuous paleosols and overbank material. In an effort to tie the sediments together from north to south, three such packages were noted and mapped on an enlarged topographic map. It is believed that these packages of sediments will aid in the interpretation of the large-scale depositional environment, but this interpretation is beyond the scope of this report.

It is expected that the sedimentological importance of the mappable contacts will reveal itself as a general understanding of the depositional history evolves. Mapping of major breaks in depositional style will continue to be of concern during future research efforts, because it will aid in a better understanding of the processes responsible for the observed sedimentary architecture. Mapping can also be used to determine how depositional processes have affected the large-scale patterns of permeability and interconnection.

To aid in the mapping of large-scale geologic features, two sections were measured at the locations shown on Plate 1. Additionally, in the large-scale investigation it was noted that there are apparently at least three depositional regimes present. By several depositional regimes, it is meant that a single ancient river was not responsible for the entire suite of sediments observed and that more than one mode of deposition was responsible for the formation of the sedimentological units. The geographic location of the site as well as the deposits studied thus far, suggest depositional influences from: 1) the ancestral Rio Grande, 2) the ancestral Rio Puerco/Rio San Jose and, 3) significant debris flows of unknown origin. The ancestral Rio Puerco and Rio San Jose influences are classified together in this study due to a lack of information regarding that regime. It is not apparent whether or not it is necessary or even possible to distinguish between ancestral Rio Puerco and Rio San Jose deposits. However, it is possible to delineate between the drainage from the western tributaries and that of the ancestral Rio Grande. The presence of Grants obsidian derived from Mt. Taylor, New Mexico is an indicator of Rio Puerco/San Jose drainage (Young 1982).

The geographic location of the field site and results of preliminary mapping exercises provide evidence of a multiple depositional regime system. Previous work has suggested that the Rio Puerco, Rio San Jose, and Rio Grande were all active in the Albuquerque Basin during Pliocene/Pleistocene time (Young 1982; Lozinsky 1988). The physical locations of the tributaries and axial drainage system during the depositional history of the basin has not yet been investigated. However, it is reasonable to assume that the field site, which is located in the south–central part of the basin, was influenced by both the ancestral Rio Grande and the tributaries to the Rio Grande. The mapping exercises also show evidence of multiple depositional modes in the area. Mapping on the facies– and depositional–cycle scale suggest a predominantly fluvial depositional environment, possibly from more than one river channel as proposed above.

Additionally, in the southern part of the field site just west of Bosque, New Mexico, a deposit that is several meters thick and extensive laterally for up to a kilometer exhibits features of a large debris flow. Small–scale channel structures with dimensions on the order of centimeters by meters are preserved. Armored mud balls several centimeters in diameter indicate rapid deposition in a high energy environment. Determining this deposit's origin will require mapping its external geometry, as well as analysis of clasts contained in the debris flow.

Soils.

The soils preserved in the Sierra Ladrones Formation may be very useful in the delineation of major depositional cycles for two reasons. They indicate a long hiatus in fluvial deposition and thus may serve as an indicator of relative quiescence. In addition, because they are generally laterally continuous, it may be possible to use the soils as a type of marker bed to map larger scale features. When studying the sedimentology of fluvial systems over distances on the order of kilometers, the paleosols provide a means to correlate different sedimentation cycles (Allen 1974). The correlation of these sedimentation cycles is vital in the reconstruction of a depositional environment. Paleosols can also indicate both paleoclimate and paleogeomorphic conditions. In arid climates it is common to observe well–developed soils that continue laterally for several kilometers. Aridisols in the southwest have been studied thoroughly by Gile, Hawley, and Grossman (1981), Walker (1967), Walker, Waugh, and Grone (1978), and Machette (1985).

Preliminary observations have indicated that soil development results in a reduction of permeability. This is believed to be caused by the introduction of illuvial clays, precipitation of calcium carbonate, and the churning caused by roots and soil fauna. Correlating soil types and patterns of permeability within soils may prove insightful.

Generally, thousands to tens of thousands of years of surface stability are necessary for the development of desert soils; however, since the soil development process can be highly variable, soils are considered to be inadequate for absolute dating of the deposits. Other dating possibilities include using volcanic ashes and mammal fossils. However, as of now, neither of these markers has been observed at the field site.

The issue of diagenesis versus primary depositional process is treated in this study from a hydrological perspective. Since the permeability of these units is distinctly different from other depositional units that were not surficially exposed long enough for soil development, the soils are treated as a distinct depositional process. The term diagenesis in this report is reserved for physical and chemical alteration that occurs after the sedimentary unit is buried. Soil development is thus treated here as a primary depositional process.

Facies– and element–scale mapping.

The facies– and element–scale mapping included both small–scale and intermediate–scale analysis of geology and permeability patterns and will serve as an initial basis for the large–scale study. Once the site for facies–scale mapping was selected, an initial reconnaissance of the outcrop was performed. The nature and locations of the gross geologic features were noted and surveyed. The goal of the facies– and element–scale mapping was to establish "first cut" architectural element definitions and begin to analyze the depositional environment and geologic character of heterogeneity at the element and lithofacies scale.

As discussed above, the large–scale reconnaissance effort indicated that major changes in depositional style occur at certain stratigraphic levels. A package of sediments was chosen to be the initial focus of the facies–scale mapping. The base of the current package under study is a gravelly channel deposit which lies unconformably on what is possibly an alluvial fan deposit. The upper contact is another large unconformity in which a series of stacked channels cut into the sediments under study. The package under study is approximately 25 meters thick at the location of OUTCROP1 shown in Plate 1. This outcrop trends approximately N35E, has an average slope of approximately 45 degrees, and a lateral dimension of approximately 60 meters.

The facies–scale mapping exercise was initiated to begin to define the architectural elements of this particular package. A lithofacies map of OUTCROP1 is presented in Plate 2 and a photograph of the outcrop is shown in Figure 7. Miall's (1978) classification scheme was used as a base for the classification of observed lithofacies. Table 2 summarizes the lithofacies observed during the OUTCROP1 study.

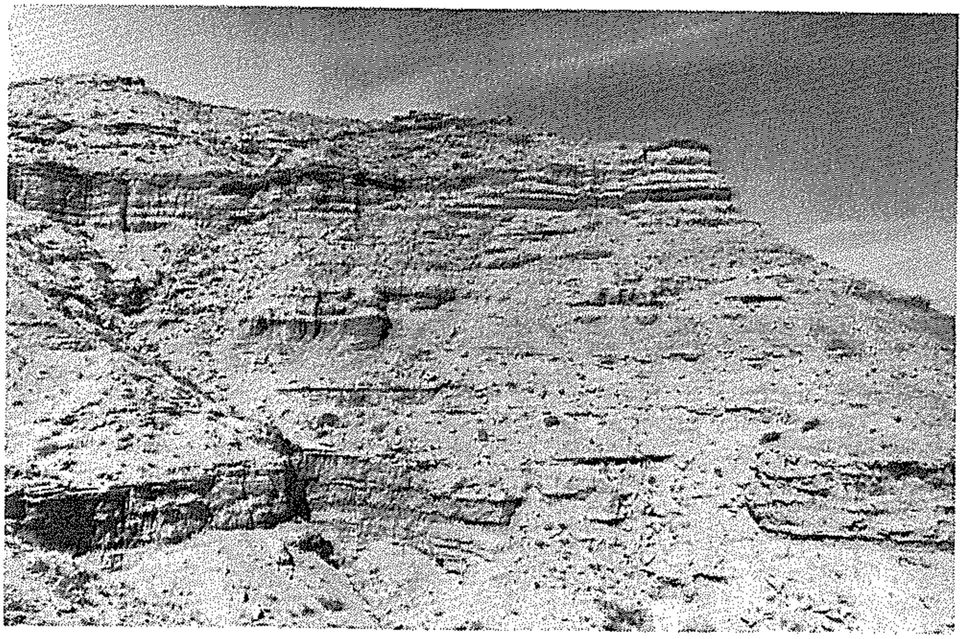


Figure 7. Photograph of OUTCROP1.

Table 2. Lithofacies observed in OUTCROP1 study.

Facies Code	Lithofacies	Sedimentary structure	Interpretation
Gms	massive, matrix supported gravel	none	debris flow deposit
Gm	massive or crudely bedded gravel	horizontal bedding, imbrication	longitudinal bars, lag deposits, seive deposits
Gt	gravel stratified	trough crossbeds	minor channel fills
St	sand, medium to v. coarse, may be pebbly	solitary (theta) or grouped (pi) trough crossbeds	dunes (lower flow regime)
Sp	sand, medium to v. coarse may be pebbl;y	solitary (alpha) or grouped (omikron) planar crossbeds	linguoid, transverse bars, sand waves (lower flow regime
Sr	sand, v. fine to coarse	ripple marks of all types	ripples (lower flow regime)
Sh	sand, v. fine to v. coarse, may be pebbly	horizontal lamination parting or streaming lineation	planar bed flow (l. and u. flow regime)
Sl	sand, fine	low angle (< 10) crossbeds	scour fill
Smb	erosional scours with mud balls	crude crossbedding	scour fill
Sfl	sand, v. coarse to fine	fining upward sand sequence	proximal floodplain
Sm	sand, v. fine to v. coarse, may be pebbly	none	immature soil
Sgm	sand, fine to v. coarse, pebbly	none	slumped bank ?
Fl	sand, silt, mud	fine lamination, very small ripples	overbank or waning flow deposits
Fsc	silt, mud	laminated to massive	overbank deposits
Fm	mud, silt	massive, desiccation cracks	drape deposits
Fr	silt, mud	rootlets	overbank
P	carbonate	pedogenic features	soil

Lithofacies Smb, Sfl, and Sm, were added to Miall's (1978) classification. Facies Smb consists of crudely crossbedded sand, sand–size clay clasts, and armored mud balls. The basal contact of the Smb facies is commonly erosional. The facies Sfl is a fining upward sand facies. The genesis of the Sfl facies is uncertain; however, their occurrence may represent proximal floodplain deposits. The third addition to Miall's (1978) classification is the facies Sm. The Sm facies is a massive sand in which most or all sedimentary structures have been destroyed. This facies is interpreted as an immature soil.

The amount of spatial detail recorded in the facies–scale mapping was restricted principally by the 1:120 scale of the base map. Several lithofacies are actually composites of smaller lithofacies that were lumped together for reasons of feasibility. Those that contain significant sedimentological information have hybrid classifications. For example, the facies denoted Sr/Fm is dominantly a ripple–laminated sand facies that contains several laterally continuous mud drapes. The mud drapes are not only a distinctive sedimentological feature, but undoubtedly play a role in the unit's hydraulic characteristics. This type of small–scale heterogeneity is currently being handled with hybrid facies classification.

Paleosol facies discussed previously occur commonly in the study area. They are generally developed in the non–gravelly type of fabric, and conform to the general diagnostic characteristic of having few if any preserved sedimentary structures, a red coloration, and some degree of calcium carbonate buildup.

Interpretation of Mapping

The geologic interpretation is based on two classes of geologic categorization. The lithologic facies are lumped into architectural elements. The extent and relationships of the elements are then used to interpret the depositional environment. The facies provide within–element characteristics from which primary processes are inferred.

Four elements have been defined based on the facies map of OUTCROP1 (see Plate 2), and are summarized in Table 3. The channel elements can be broken into two types, but more elements may be necessary as the study progresses. Additionally, it is likely that the definitions of the four elements observed will be modified as more information is collected regarding their genetic origin. The two distinct types of channel elements preserved in OUTCROP1 include one that is generally dominated by clean fine–to–coarse grained sandy and gravelly facies, and a second element dominated by sand and sand–size clay clasts. The former can be interpreted as the result of a large, distal, braided or meandering stream environment. The latter element is dominated by a much finer scale heterogeneity. Small–scale (0.1–1 m) scour–fill structures, which suggest a tributary scale channel, have also been observed. The common occurrence of sand–size clay clasts and armored mud balls indicates that hardened mud drapes were ripped up, broken into sand–size clasts, redeposited, and buried in a relatively short distance within the tributary channel. The occurrence of clay clasts and mud balls suggest that the channel was ephemeral in nature, since it is likely that conditions of high fluvial energy would have been required to erode the mud drapes.

The lowermost occurrence of the CH type–II is probably the most difficult to interpret genetically. Two distinct possibilities exist: 1) a preserved bar deposit of a major channel or 2) a deposit that resulted from a large–scale flood event. This CH–II element is dominated by clean planar crossbedded sand with some climbing ripple structures in the lower part and trough cross–lamination and

Table 3. Architectural elements of OUTCROP1.

Element code	Lithofacies present	Description/ Comments
CH–I	Gm, Gt, Sp, St, Sl, Sgm	Channel element consists predominately of gravelly and coarse–sand facies. Much of the element is covered by colluvium and will require further study elsewhere.
CH–II	Gms, St, Sp, Sfl, Sh, Sl, Smb, Fl, Fm, Fsc	Sand and sand–size clay clasts dominate with local lag gravel deposits.
P	P, Sm, Fsc	Soils and stacked soils
OF	Fr, Fm, Fsc, P	Overbank fines

ripple lamination in the upper 10–20 centimeters. The basal contact is erosional, cutting into and locally through an overbank fine deposit. The upper contact is sharp. The uppermost CH–II element is also dominated by planar crossbedded sand, and is grouped here genetically with the lowermost CH–II element.

The other occurrences of CH–II are dominated by small–scale changes in lithology. The abundance of sand–size clay clasts and armored mud balls imply deposition close to the source. Similarly, the common occurrence of laterally extensive mud drapes are evidence of several flow events. It is hypothesized that the middle two CH–II elements were deposited by an ephemeral small–scale channel.

The overbank fine elements (OF) are composed of several distinct overbank deposits. Some of the elements contain weakly to moderately developed, stage I of McGrath and Hawley (1978), soil horizons. The paleosol elements (P) consist of soil horizons that are generally Stage I–II. Reconstruction of the depositional environment entails interpreting the relationships and extents of the elements mapped. The paleosol elements are used here as a basis for that interpretation.

Allen (1974) used pedogenic carbonate units to interpret the depositional environment of the Lower Red Sandstone. He constructed a set of conceptual models based on the observation that soil development requires a "substantial period when its site was denied significant fresh supplies of river–borne clastic sediment" (Allen 1974). As outlined by Allen (1974), the mechanisms of deprivation in a fluvial system include: 1) the migration of the channel away from a site, depriving that site of channel–borne sediment, 2) entrenchment of the channels, depriving sediment to neighboring regions even during large floods, and 3) a

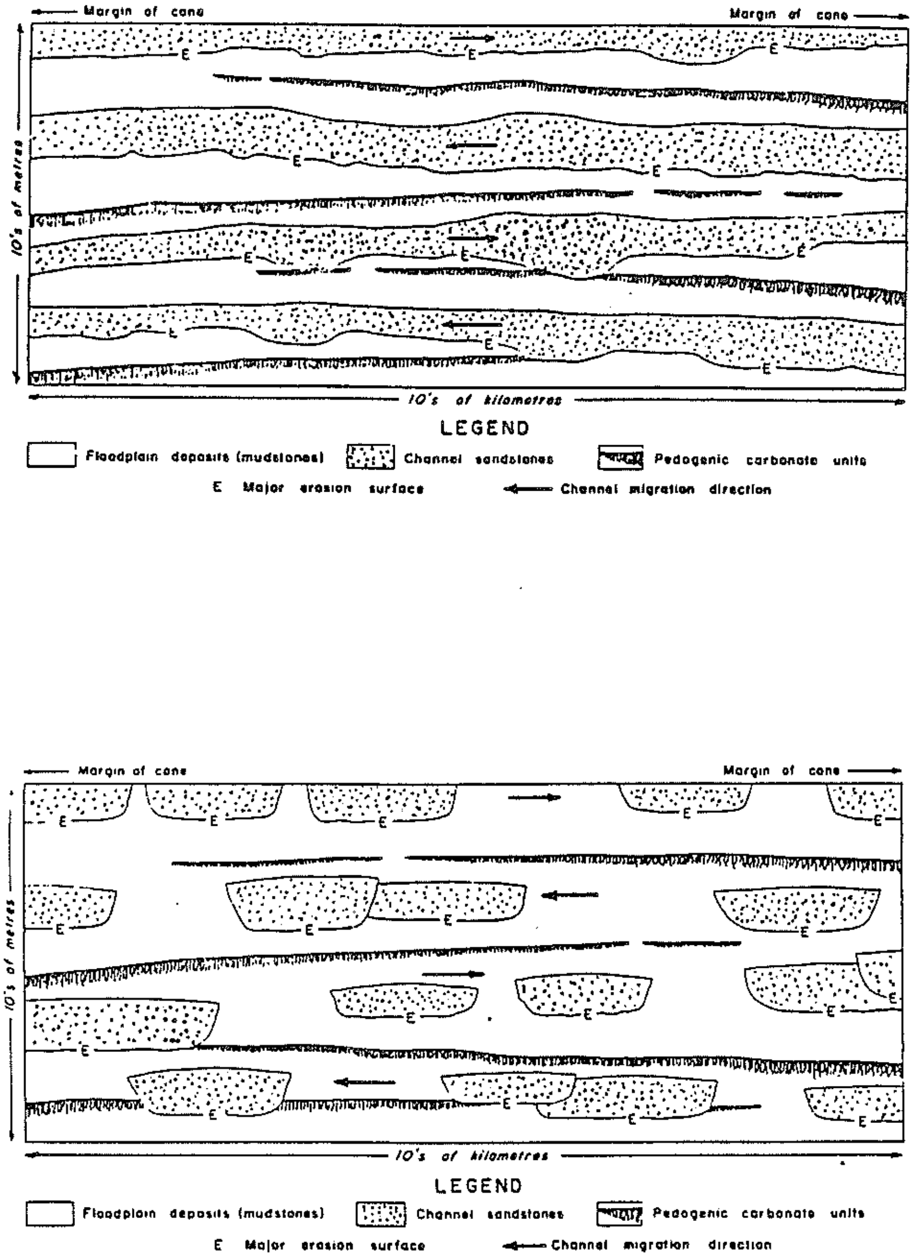


Figure 8. Allen's (1974) depositional models based on pedogenic carbonates. (a) Resulting facies associations from a steady migration of the channel across alluvial plain (cone). (b) Resulting facies associations from an avulsive type of channel migration across the alluvial plain.

combination of (1) and (2). The models of Allen (1974) adopted for this study are those that represent lateral–horizontal migration of the channel. Two such migration patterns are postulated. The first represents a pattern of channel migration in which the channel moves continuously, but not necessarily steadily, perpendicular to its course (Figure 8a). This type of migration is called a combing type of migration because the channel "combs" across the alluvial plain, or cone. The second migration type involves a more sporadic type of channel movement resulting from avulsion events. The hypothetical arrangement of elements resulting from this type of migration is shown in Figure 8b. Differentiation between the two models relies heavily on adequate mapping of profiles normal to the mean paleocurrent direction. At this time, the extent of mapping does not allow this differentiation. Therefore, both models are retained here as equally feasible.

The observed architectural elements and the models of Allen (1974) enable an interpretation of the depositional environment. It is hypothesized that the deposits of at least two types of channels are preserved in the study area. From the models discussed, the occurrence of overbank fines and paleosols between these channel deposits indicate migration of the channel away from its previous position. It is not clear whether the deposits represent an environment in which two distinct types of channels coexisted throughout the depositional history, or one in which the channel character changed in time.

It is clear that the sediments observed in the Sierra Ladrones Formation reflect depositional environments ranging from high–energy channel deposits to low–energy overbank deposits. Thus, the deposits can be considered representative of many heterogeneous alluvial aquifer systems, and the overall approach used to characterize the Sierra Ladrones Formation can be assumed widely applicable to such systems. Continued mapping and interpretation of architectural elements will be necessary to determine more completely the prevailing depositional environment of the Sierra Ladrones Formation sediments. Geologic interpretation and reconstruction of a depositional environment is crucial to the description and prediction of lithologic distributions and, ultimately, to the characterization of aquifer heterogeneity.

Data Analysis and Interpretation

Introduction

As discussed in the preceding section, empirical studies of permeability patterns must be conducted in order to understand and predict heterogeneity of natural geologic material. Two small-scale studies of permeability distributions were conducted at the Sierra Ladrones Formation field site. In addition, an intermediate-scale numerical experiment was performed to evaluate the statistical structure of the heterogeneity using the facies map of OUTCROP1 (Plate 5).

The statistical analysis has four objectives. The first is to estimate empirically the first two moments of the permeability joint probability density function. The second objective is to relate the estimated statistical parameters to the observed geologic features. This is a necessary step to test the hypothesis that statistical can be estimated via "soft" geologic information. The third objective is to assess the statistical parameter's scale dependence by studying heterogeneity and spatial correlation at a variety of scales to determine how multiple correlation structures may be estimated from the dimensions of the geologic entities. Finally, the fourth objective of the statistical analysis is to address the question: "How can geologic information be used to predict quantitatively the spatial statistics of permeability over a broad range of spatial scales?"

The purpose of the statistical analysis is to estimate the statistical properties of a random variable. In this case, the random variable is permeability, as represented by the air–flow–rate surrogate variable. Methods of estimating the first two moments are those commonly employed in geostatistical analysis. That is, the histogram and empirical distribution function are used to estimate the probability distribution of a random variable, and the variogram is used to estimate the correlation structure.

Three data sets are analyzed in this chapter. The first two data sets are the result of heterogeneity studies at the facies scale. They both consist of air–flow–rate data measured with the air–minipermeameter at small outcrops located at the field site. Analysis of the distribution statistics and structural statistics are performed for each separate facies–scale data set. The third data set results from an effort to study the structural statistics of intermediate–scale heterogeneity. The OUTCROP1 facies shown in Plate 2 were divided into four categories on the basis of grain size. Mean permeability was then assigned to each group of facies using estimates provided in the hydrogeologic literature. Directional variograms are then estimated from the mean permeability data.

A common "rule of thumb" in variogram estimation is to rely on variograms for lags of up to approximately half of the sample space dimension (Journel and Huijbregts 1978). Beyond this lag, estimated values of the sample variogram tend to become unreliable because the variogram becomes more a function of correlation between data observed along the edges of the study area. This is, data points located in the interior of the sample domain will not enter into variogram calculations for large lags, and the variogram primarily reflects correlation between relatively few data pairs situated along margins of the study area. The horizontal variograms presented are truncated at lags of approximately three–quarters of the horizontal sample space dimension. Due to the small vertical sample space dimensions, the vertical variograms presented include lags approaching the maximum vertical sample space dimension.

Since the data locations in this study are irregularly spaced, a searching algorithm is involved in the variogram estimation. For regularly spaced data, pairs of measurements are grouped into lag classes if the separation between the measurements is equal to the lag under consideration. For irregularly spaced data, separation between pairs are seldom equal to the lag under consideration. In order to group data into classes based on separation, distance and angle tolerances are used to group measurements whose separation fall within the search window.

An example of the search window is shown in Figure 9. The variogram estimate can depend greatly on the tolerances used in the search for pairings. When setting the angle and distance tolerances, the objective is to use as narrow interval as possible while maintaining an adequate number of pairs per unit lag. The angle and distance tolerances (Δs and $\Delta \phi$) will be given for each variogram estimate presented in this report.

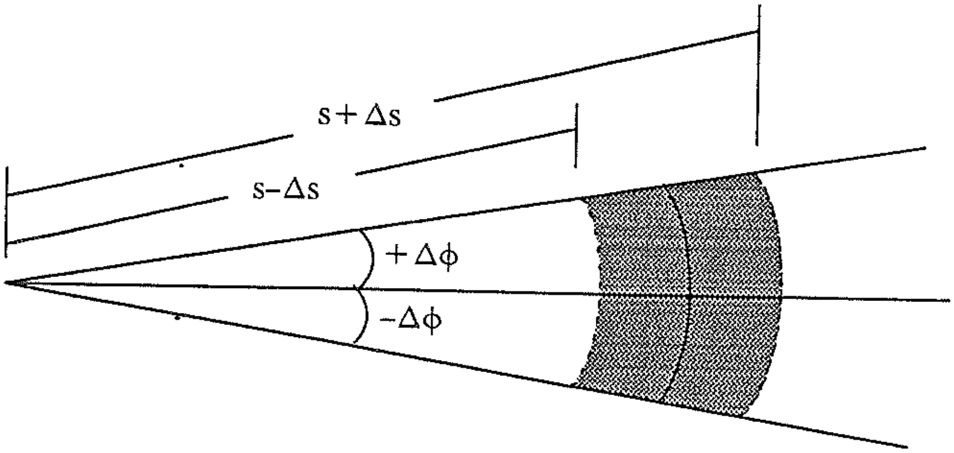


Figure 9. Schematic diagram of search window used in variogram estimation.

Small–Scale Permeability Studies

Permeability study 1 (PS1).

The location referred to as PS1 is located at the Bosque field site. The prepared outcrop is approximately 2 meters wide and 0.8 meter high. Plate 3 illustrates the geologic features and sampling locations. A photograph of the PS1 outcrop is shown in Figure 10.

The PS1 outcrop consists of a fining–upward channel bar deposit. The base of the outcrop is dominated by the major bar form: horizontally laminated coarse– sand. On top of the major bar form, a variety of lithofacies are present. Horizontally laminated fine to medium sands including magnetite and/or illmenite are interbedded with clay drapes, trough cross–laminated sands, and ripple–laminated sands. This upper third of the outcrop is interpreted as representing a period of decreased, periodic flow. Two bioturbated zones which destroy the lateral continuity of the primary deposits were also observed and mapped.

The outcrop studied represents a small percentage of the overall dimensions of the sandy channel deposit. That is, the sample space dimensions are much less than either the vertical of horizontal dimension of the sandy channel. Two–hundred and seventy–seven (277) measurements of air–flow rate were obtained from this outcrop.

A histogram of the PS1 data indicates a skewed right distribution (Figure 11a). After performing a natural logarithm transform of the original data, the logarithmic data appear to be approximately normally distributed (Figure 11b). Applying the Kolmogorov–Smirnov (hereafter referred to as KS) test, the maximum observed difference between the empirical cumulative and the theoretical normal is 0.04. The KS 0.20 tolerance for 277 points is 0.06. The null hypothesis cannot therefore be rejected (Massey 1951).

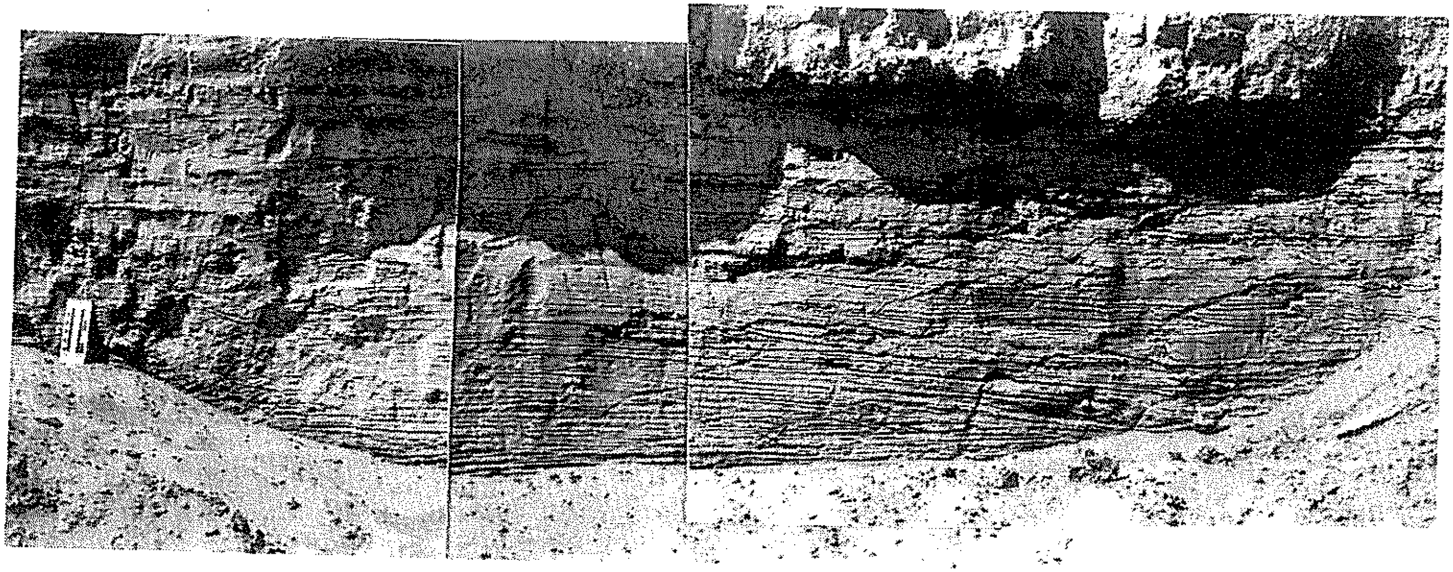
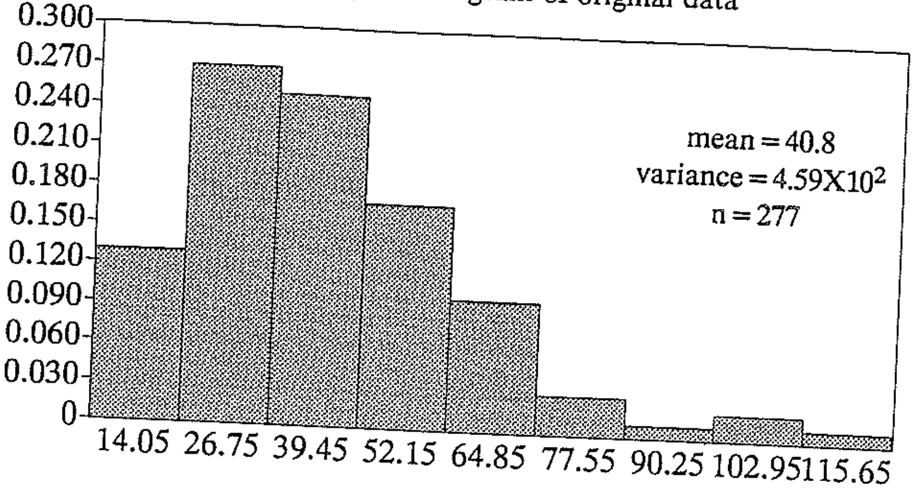


Figure 10. Photograph of PS1 outcrop. Bar scale in photo: DNAG– centimeters on left, inches on right


(a) Histogram of original data

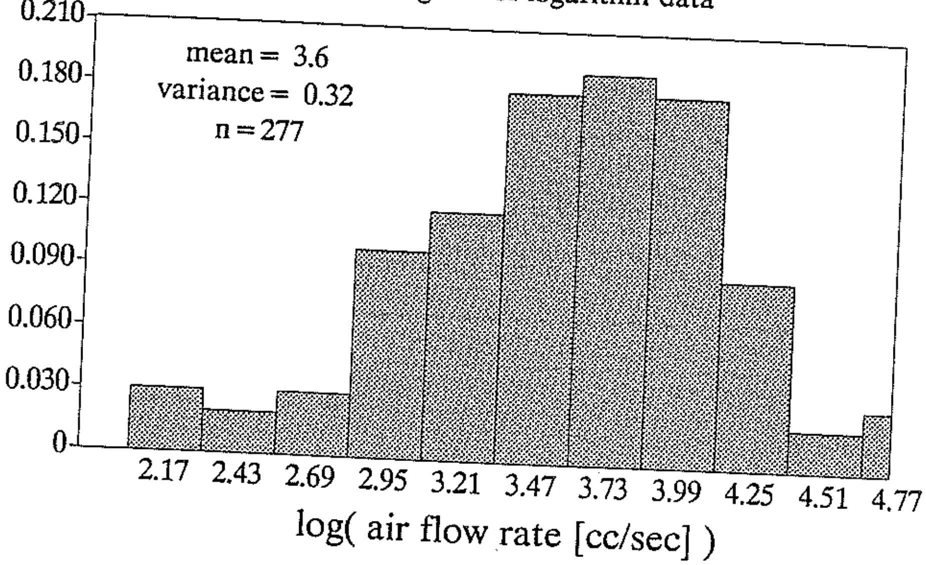

(b) Histogram of logarithm data

Figure 11. Histograms of PS1 air–flow–rate data.
(a) Histogram of original data. (b) Histogram of logarithmic data.

Directional variogram analysis of the PS1 logarithmic air–flow–rate data is presented in Figures 12a and 12b. The horizontal variogram can be modeled with an exponential variogram with a correlation length of 35 centimeters and a sill of 0.31. The estimate of the vertical variogram exhibits quadratic behavior. The fitted models of the original log–air–flow–rate data are:

$$\gamma_h(\xi) = 0.31[1 - exp(- |\xi| /35)]$$

$$\gamma_v(\xi) = 0.21 + 1 \times 10^{-4}\xi^2$$

Quadratic behavior of a variogram is a strong indication that the underlying field is non–stationary and can be an indication of a linear drift in the data mean. The linear drift hypothesis appears valid given that the outcrop is composed of a fining–upward sequence. If in fact a drift in the data is present, the assumption of stationarity is violated. It is common practice in geostatistics to estimate and remove the drift prior to estimating the correlation statistics. The trend removed data can be used for kriging and/or simulation. After kriging and/or simulation of the field has been performed, the drift can be added to obtain the desired estimate.

Several methods of estimating the drift are possible. One method is to perform a linear regression of the log–air–flow–rate data with respect to the hypothetical drift. A complete two–dimensional regression analysis was performed on the data to estimate the best fit plane of the form $z = a + bx + cy + dxy$ to the log–air–flow rate data. The coefficient, c, corresponding to the vertical direction is 0.0146. This value dominates the other coefficients (directions) by more than two orders of magnitude. For this reason, only the vertical drift is treated in this analysis.

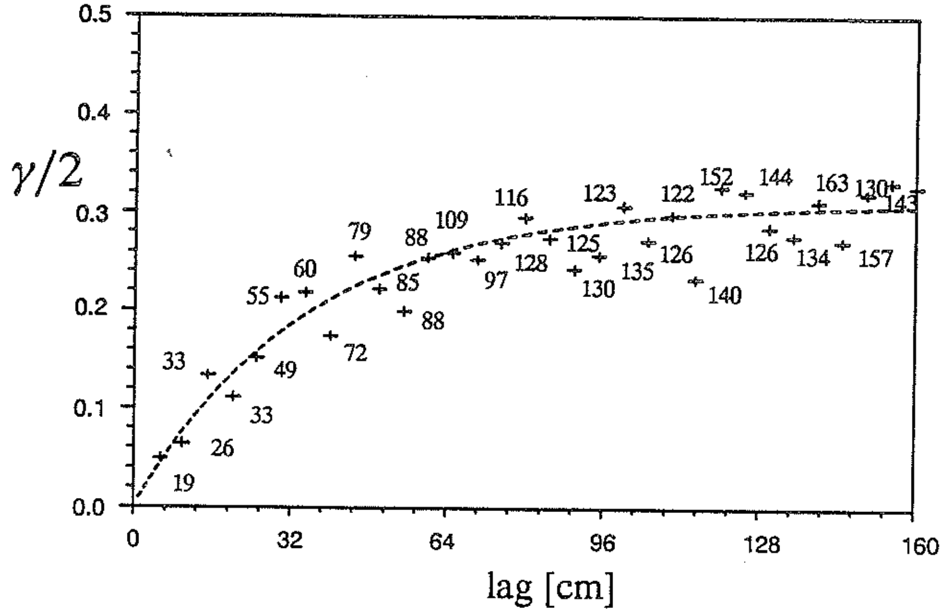


Figure 12a. Fitted horizontal variogram of logarithmic PS1 air-flow-rate data with linear trend present. Number of pairs in variogram calculation shown next to each estimate. (N=277; unit lag=5.0cm; Δs=1.5cm; Δϕ=5°)

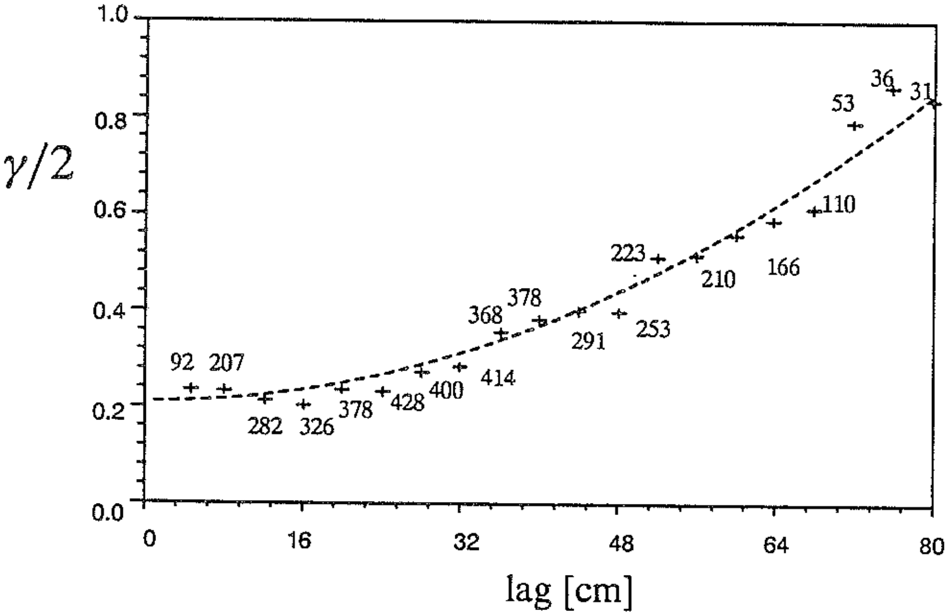


Figure 12b. Fitted vertical variogram of logarithmic PS1 air-flow-rate data with linear trend present. Number of pairs in variogram calculation shown next to each estimate. (N=277; unit lag=4.0cm; Δs=2.0cm; Δϕ=45°).

Starks and Fang (1982) have demonstrated that given a random field Y(x) with variogram $\gamma_Y(\xi)$, a drift in the data of the form $d(x) = a + bx$ results in a biased variogram of the form:

$$\gamma_B(\xi) = \gamma_Y(\xi) + b^2/2$$

where $b^2/2$ represents the bias of the variogram estimate

Applying this model to the case of the PS1 vertical variogram, $\gamma_Y(\xi) = 0.21$ and $b^2/2 = 1.0\text{x}10^{-04}$. If a linear drift is the cause of the quadratic behavior, the slope b can be estimated as 0.0141.

A third method of estimating the drift was to examine a non–kriged contour plot of log–air–flow–rate data. In this case the drift in the vertical direction was estimated to be 0.013. This value is again in close correspondence to the estimates obtained from the other two methods. The estimates from the regression analysis and the contoured data are more reliable since they result from direct observations of the data. While the choice between the drift models obtained from the regression analysis and the contoured data analysis was somewhat arbitrary, the vertical drift from the contoured data analysis was removed from the original log–air–flow–rate data.

Directional variogram estimates of the drift–removed data were then performed. While the horizontal variogram (Figure 13a) of the drift–removed data exhibits the same overall exponential behavior, two differences are apparent. The first is the slight hole effect which manifests itself in the dipping down of the variogram estimate at lags greater than 64 centimeters which approximately corresponds to the separation of the edges of the bioturbation zones. Also, since the overall variability of the data set is reduced by removing the drift, the drift–removed sill value is reduced to 0.21 from the 0.31 value of the original logarithmic data. A cosine–exponential variogram model us fit to the horizontal variogram estimate fo the trend–removed data.

$$\gamma_h(\xi) = 0.21[1 - \cos(0.04\xi)\exp(-|\xi|/35)]$$

The vertical variogram of the PS2 drift–removed logarithmic data (Figure 12b) is modeled with the pure nugget model:

$$\gamma_v(\xi) = 0.21$$

Two interpretations are possible from such a model. The first is that the measurement error overshadows the natural variability, thus the variogram represents pure uncorrelated noise. The analysis of variance performed on the air–permeameter (Appendix A), suggests that the measurement error variance is approximately 0.006. Thus the hypothesis that the nugget is due entirely to measurement error is rejected. The second interpretation is that the natural correlation structure of the field occurs at a higher frequency than is detectable by the sampling frequency. The minimum vertical lag with a sufficient number of pairs is 4.0 centimeters. It is hypothesized that the vertical correlation is less than 4.0 centimeters.

The trend removed log–air–flow–rate data for PS1 can be modeled with an anisotropic variogram model.

$$\gamma(\underline{\xi}) = 0.21[1 - \cos(0.04\xi_h)exp(-(\frac{\xi_h}{35} + \frac{\xi_v}{\lambda_v}))$$

where λ_v is some value less than 4 cm.

Several important conclusions can be drawn from the geostatistical analysis of the PS2 air–flow–rate data. The appear to be log–normally distributed with a variance much less than one. These two features regarding the distribution of permeability are often assumed in the literature. This analysis offers some

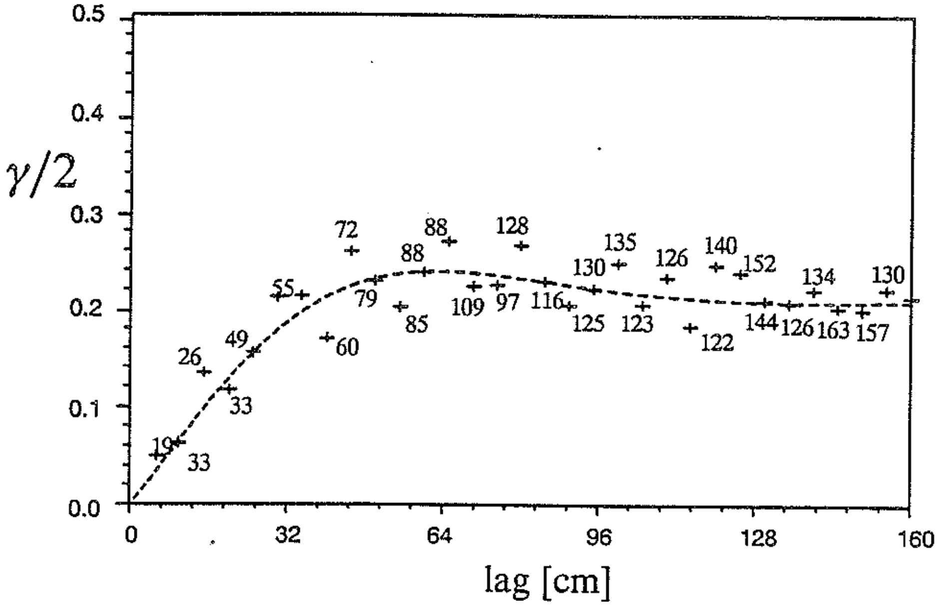


Figure 13a. Fitted horizontal variogram of logarithmic PS1 air-flow-rate data with linear trend removed. Number of pairs in variogram calculation shown next to each estimate. (N = 277; unit lag = 5.0cm; Δs=1.5cm; Δϕ=5°)

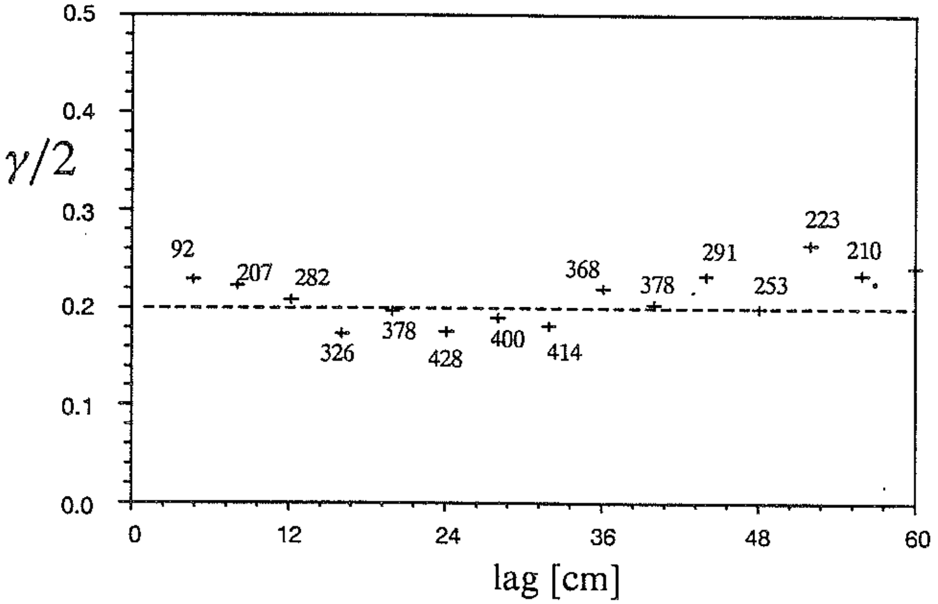


Figure 13b. Fitted vertical variogram of logarithmic PS1 air-flow-rate data with linear drift removed. Number of pairs in variogram calculation shown next to each estimate. (N = 277; unit lag = 4.0cm; Δs=2.0cm; Δϕ=45°).

field validation of these hypotheses although at a very small scale. Also the variogram estimator proved to be a good indicator of the non–stationarity of the log–air–flow–rate data. In this simple case of a linear vertical trend, the actual trend was estimated from the quadratic behavior of the vertical variogram estimate. Removal of the trend and estimation of the structural statistics of the stationary field resulted in an anisotropic variogram model with a much longer correlation length in the horizontal direction than the vertical direction. Both the vertical trend and the anisotropic variogram closely correspond with the geologic observations of a stratified, fining–upward sequence.

Permeability Study 2 (PS2).

The second outcrop studied (PS2) is located in the lower channel element (type CH–I) of Plate 2. PS2 is approximately 1.5 meters wide and 0.75 meters high. The outcrop can be characterized as a high energy channel deposit with crudely stratified to cross–stratified pebbly gravel interbedded with low angle cross–laminated and trough cross–laminated fine to coarse sand (see Plate 4). A zone of ripple laminated sand, representing a decrease in flow energy, occurs at the top of the outcrop. A photograph of the PS2 outcrop is presented in Figure 14.

Unlike the PS1 data set, the PS2 data represent approximately 80 percent of a depositional unit. That is, the spatial dimensions of the sample space approach the spatial dimension of the deposit. Eighty–six (86) measurements of air–flow–rate were obtained from PS2, the locations of which are shown on Plate 4. Again, histogram analysis of the original data indicates a skewed right distribution. When a natural logarithm transformation was applied, an apparently normal distribution resulted (see

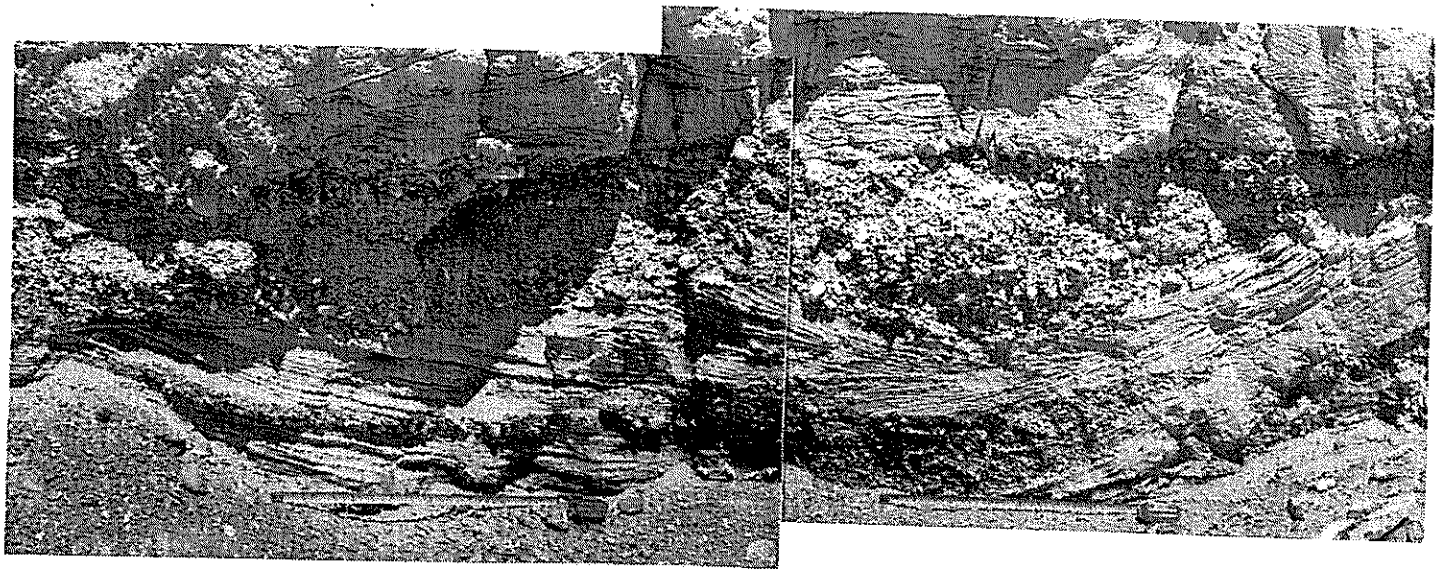


Figure 14. Photograph of PS2 outcrop. Tape measure is extended to 15 inches.

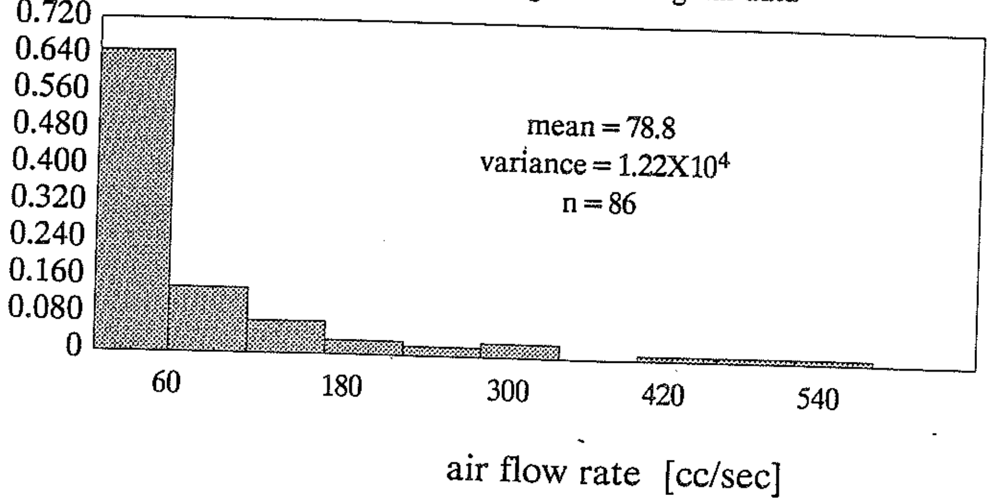
Figures 15a and 15b). As in the case of PS1 air–flow–rate data, the empirical cumulative distribution was compared with the theoretical normal. The maximum observed difference is 0.07. The KS 0.20 tolerance with 86 points is 0.12. The null hypothesis of normality cannot be rejected.

Directional variogram analysis was performed on the logarithmic PS2 data in order to estimate the correlation structure. The variogram estimates are shown in Figures 16a and 17a.

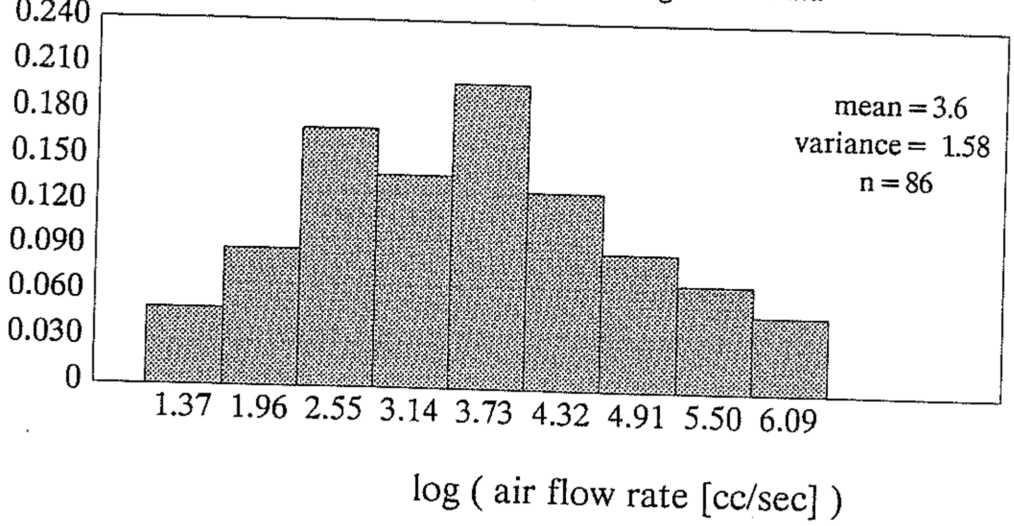
The horizontal variogram estimate is fit with two variogram models. The simple exponential model with as sill of 0.24 and correlation length of 60 centimeters provides a reasonable fit to the estimate (Figure 16a). The second variogram model used to fit the estimate is a nested exponential model. The nested exponential appears to better honor the data particularly the fourth lag estimate which has 113 pairs.

In general, nested structures consist of two or more superimposed variograms each operating over all lags. The nested structures commonly found in geostatistical literature consist of variograms models which all originate at the origin. For example, Journel and Huijbregts (1978) describe nested structures in ore deposits. Variability occurs at a variety of scales due to the variability of parent material and orogenetic processes. Small scale variation in ore grade results in a variogram with a short correlation scale and larger scale variations result in variograms with longer correlation scales. In such cases the composite variogram model consists of the sum of the variograms each representing variability at a given scale.

In the case of the PS2 horizontal variogram, the underlying principle of nested structures is the same. However, only one of the two contributing variograms operates over all lags. The second variogram contribution occurs only for lags greater than 40 centimeters. This is believed to result from

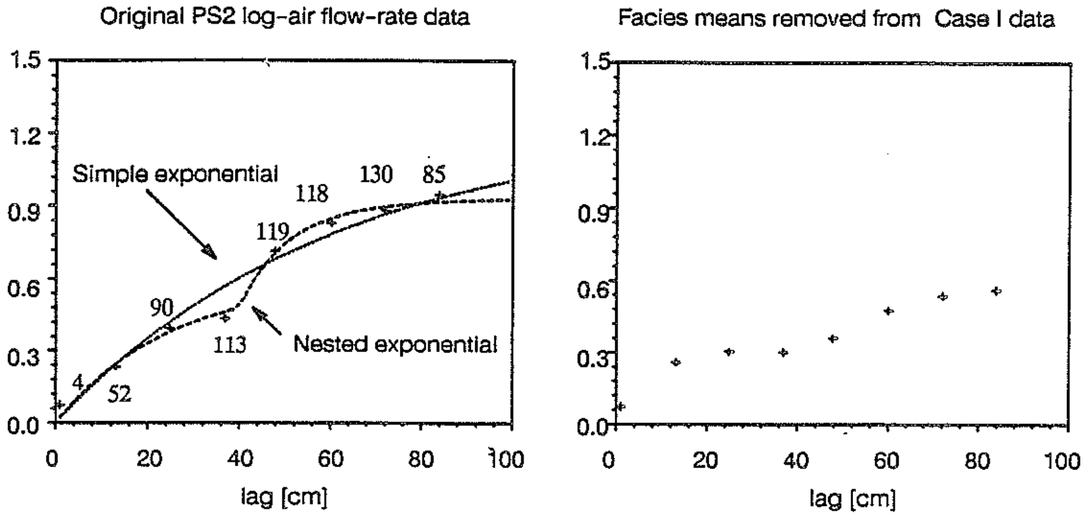


(a) Histogram of original data



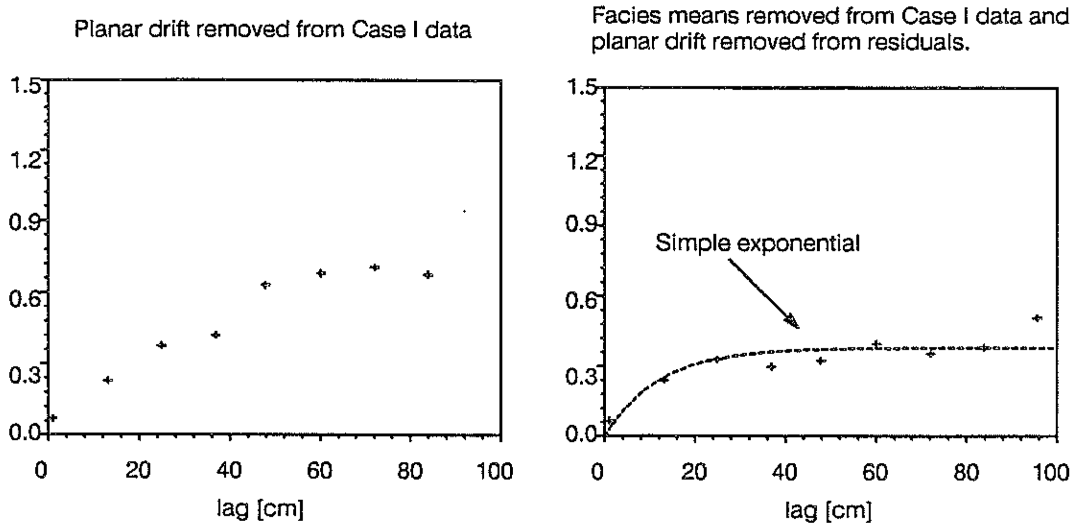
(b) Histogram of logarithm data

Figure 15. Histograms of PS2 air–flow–rate data.
(a) Histogram of original data.
(b) Histogram of logarithmic data.



(a) Horizontal variogram for Case I

(b) Horizontal variogram for Case II



(c) Horizontal variogram for Case III

(d) Horizontal variogram for Case IV

Figure 16. Horizontal variogram estimates of logarithmic PS2 data. (N = 86; unit lag = 12.0cm; $\Delta s = 6.0$cm; $\Delta\phi = 10°$).

discrete style of heterogeneity of the PS2 outcrop. That is, three different facies are present at PS2 each of which exhibit different mean log–air–flow–rates. The boundaries between the facies are sharp resulting in heterogeneity which is composed of small scale variations within each facies and variation across facies boundaries at the facies scale. It is hypothesized that the combination of continuous variability at the sub–facies scale and the discrete variability at the facies scale is the cause of the nested structure. The two models used to fit the horizontal variogram estimate of the original log–air–flow–rate data are given by:

$$\gamma_{Hexp.}(\xi) = 1.24[1 - \exp(-\,|\xi|/60)]$$

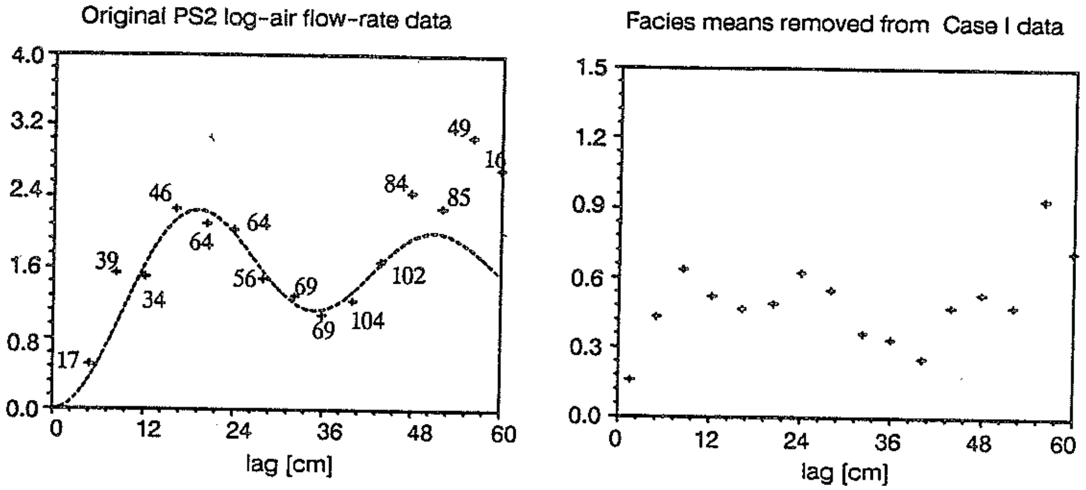
$$\gamma_{Hnested}(\xi) = \begin{cases} 0.5[1 - exp(|\xi|/25)] & \text{for } \xi < 40 \text{ cm.} \\ 0.5[1 - exp(|\xi|/25)] \\ \quad + 0.34[1 - exp(-\,|\xi - 40|/9)] & \text{for } \xi \geq 40 \text{ cm.} \end{cases}$$

The vertical variogram of the logarithmic PS2 data (Figure 16a) is periodic; the fitted model is a Bessel variogram.

$$\gamma_V(\xi) = 1.6[1 - J_0(\frac{|\xi|}{5})]$$

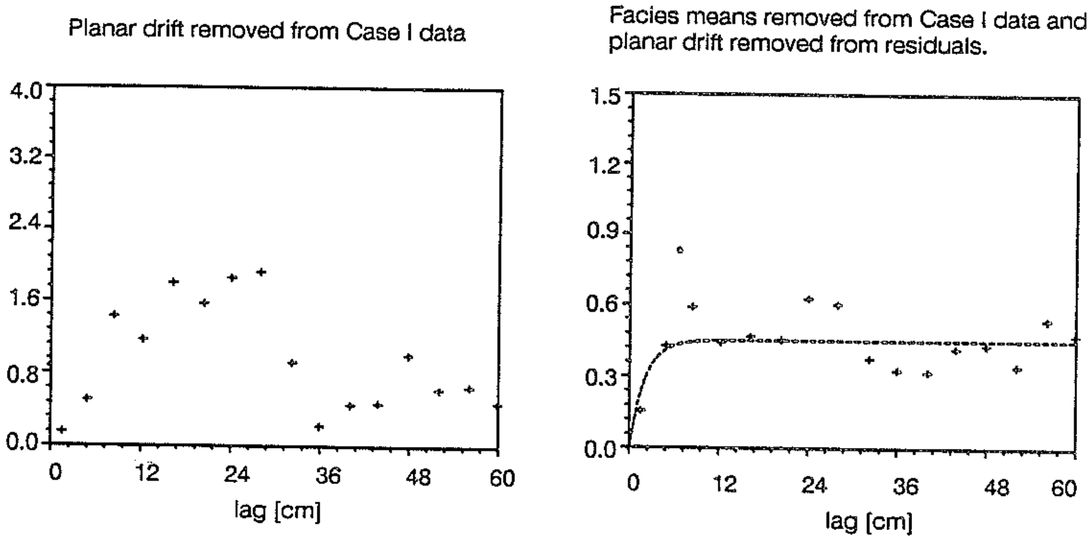
The periodic structure is consistent with the layering of the deposit. The strong hole in the variogram estimate at 36 centimeters corresponds roughly to the average distance between the middles of similar units.

The sill of the vertical variogram is estimated to be 1.24 and the sill of the vertical variogram is estimated to be 1.6 representing non–stationarity. If the sill values of the horizontal and vertical variograms are equal, the two directional variograms can be represented as one anisotropic variogram.



(a) Vertical variogram for Case I

(b) Vertical variogram for Case II



(c) Vertical variogram for Case III

(d) Vertical variogram for Case IV

Figure 17. Vertical variogram estimates of logarithmic PS2 data. (N=86; unit lag=4.0cm; $\Delta s=2.0$cm; $\Delta\phi=45°$)

$$\gamma(\underline{\xi}) = \sigma^2\left[1 - \exp\left(-\left(\frac{\xi_h}{60} + \frac{\xi_v}{10^4}\right)\right) J_0\left(\frac{\xi_h}{10^4} + \frac{\xi_v}{5}\right)\right]$$

Note that the large coefficients in the anisotropic model correspond to the directions which do not exhibit exponential (vertical) and periodic (horizontal) behavior. If the anisotropic model is adopted the geostatistical analysis can be considered complete. However, the nested horizontal model appears to better honor the data, especially the fourth lag which is based on 113 pairs.

The choice between the two may at first seem somewhat arbitrary and of little consequence. Many workers (Journel and Huijbregts 1978; Fogg, 1989) have shown that subtle differences in variogram models lead to insignificant differences in kriged and simulated fields. This conclusion is based on comparison of two similar admissible variogram models. Depending on the lag at which nesting begins (40 centimeters for PS2), the corresponding covariance ($C(\xi) = \text{sill} - \gamma$) may not be be semi–positive definite. Thus the model may not be admissible. The subtle difference in the two variogram models presented may be the difference in a model that is admissible and one that is not.

Along these same lines, the goal of the geostatistical analysis has been to estimate the properties of the underlying random field. The properties can then be used to estimate values of the random field where no data is present (via kriging and /or simulation). It is imperative that the properties estimated from the geostatistical analysis adequately represent the underlying random field.

A common assumption in stochastic hydrology literature is that the underlying random field can be represented as a continuous Gaussian process. When such fields are simulated with the Fast Fourier Transform (Gutjahr, 1989) or the Turning Bands Method (Montaglou and Wilson, 1982) the resulting fields approximate a continuous process. Extreme values of the random field cannot be adjacent. The reader is referred to Tompson and Gelhar (1990) for an example of a continuous random field with an exponential variogram model. A direct comparison between the field presented by Tompson and Gelhar (1990) and the PS2 model is hampered by the isotropy of the Tompson and Gelhar field and the anisotropy of the PS2 data. The anisotropic Bessel–exponential variogram model would result in a much more layered field. While the layering may closely resemble the overall appearance of the PS2 permeability field, the sharp boundaries between the facies are smoothed due the continuous random field approach.

An alternative would be to analyze the data as a composite of separate regions with different means and analyze the data as non–stationary. As with PS1, the drift of the means must be estimated and removed from the original log–air–flow–rate data.

The form of the drift is hypothesized to consist of two parts: 1) regions with different means, and 2) planar drift. First, the means of the three facies are estimated by dividing the 86 measurements into three classes corresponding to the facies from which the measurements were obtained. The estimated means and variances of the three classes are presented in Table 4.

The hypothesis that the measurements taken in different facies are from different populations with different means is evaluated with the student's t–test (Davis 1986). The assumption is made that the data are independent of one another. The validity of this assumption will be assessed once the trends are

Table 4. Statistics of different lithologic facies observed at PS2 outcrop.

	Gt	St	Sr
N	29	30	27
mean	4.82	3.54	2.26
variance	0.723	0.519	0.400
t values	6.25	7.09	
		12.71	

removed and the spatial correlation structure estimated. The t–values of the three possible combinations are shown in Table 4 and each value exceeds the critical value for the 0.1 significance level by a factor of at least two. Provided that the assumption of independence is valid, the hypothesis that the measurements came from populations with different means cannot be rejected.

The facies means are removed (Case II) from the original (Case I) data and the directional variograms are shown in Figures 15b and 16b. The assumption of independence appears valid since the correlation lengths of the facies–mean–removed data appear to be much less that the average dimensions of the facies.

A planar drift is also believed to contribute to the non–stationarity of the data. The planar drift of the original log–air–flow–rate data is estimated and removed (Case III). The corresponding directional variograms are shown in Figures 15c and 16c. The planar drift alone appears to have little influence on either the horizontal nested or the vertical periodic correlation structure. A planar drift is also estimated from the residuals of the facies means removed data (Case II). The resulting directional variograms are presented in Figures 15d and 16d. The horizontal variogram is now modeled with a simple exponential variogram with a sill of 0.36 and correlation length of 12.0

centimeters. The vertical variogram estimate is also modeled with a simple exponential variogram with a sill of 0.45 and a correlation length of 4.0 centimeters. As with the PS1 trend removed log–air–flow–rate data, the PS2 trend removed log–air–flow–rate data is exhibits statistical anisotropy. Unlike the PS1 analysis however, the PS2 trend removed structural statistics cannot be combined into a single anisotropic variogram model because the sill differ in the horizontal and vertical directions.

The statistical analysis of the PS2 log–air–flow–rate data offers two possible interpretations. The first interpretation is that the field can adequately be described by an anisotropic Bessel–exponential variogram model. While the difference in sill values in the two principle directions implies non–stationarity, the general structural behavior of layering is preserved. The second interpretation is that the field can be described by an underlying anisotropic exponential variogram and detailed information regarding the spatial dimensions and relative locations of the lithologic facies.

Each interpretation has certain advantages and disadvantages. If the first interpretation is adopted and the classical geostatistical assumption of a continuous random field employed, a false degree of smoothness is manifested in any simulation of the deposit. However the methods of simulation and analysis are well documented in the geostatistical and stochastic literature. If the second interpretation is adopted, the discrete nature of the deposits is preserved. However detailed information regarding means and spatial dimension of facies must be incorporated. Methods of incorporating such geologic information are an area of active research. Development of such methods may enable utilizing "soft" geologic information in the characterization process thus better preserving the discrete nature of the deposits.

Distribution studies.

In addition to studying the distributions of each sample set as a whole populations (PS1 and PS2) and populations based on lithology, distributional analysis has also been conducted based on grain–size classes within sample sets. Each sample set consists of four distinct grain–size classes. The PS1 study was conducted in what is believed to be a channel bar deposit; the observed grain–size classes are fine, medium, and coarse grained (see Plate 3). The fourth grain–size category, which will not be analyzed in detail here, is that of the bioturbated sands comprised of a mixture of several different grain sizes. Distributional analysis of the air–flow–rate data for each of the three principle grain–size classes reveals that each class is approximately log–normal and exhibits distinctively different means. The results of the distribution analyses are summarized in Table 4 and presented in Figure 17.

The PS2 study was conducted in a channel deposit consisting of grain sizes that range from fine to pebbly sands with some gravels. The four principle grain sizes were fine, medium, coarse, and pebbly. As discussed earlier, the clast–supported gravels cannot be sampled with the air permeameter. As such, they were not included in the set of permeability measurements and therefore are not included in the grain–size analysis. Distributional analysis of the air–flow–rate data for each PS2 grain–size class is summarized in Table 4 and presented in Figure 18.

While delineating permeability according to grain size is common in the hydrologic sciences (Carmen 1939; Freeze and Cherry, 1979; Milne–Home and Schwartz 1989), investigation of permeability distributions according to grain–size classification may contribute additional proxy information in estimating perme-

Table 5. Summary of permeability distribution statistics for populations based on grain–size classifications.

PS1		Statistical Moments				Kolmogorov – Smirnov Stats	
Grain size	n	mean	variance	kurtosis	skewness	max|diff|	Tolerance
fine	5	2.172	$1.41X10^{-2}$	-1.820	0.2015	0.1806	0.6082
medium	128	3.351	0.1574	-0.240	$-1.067X10^{-2}$	$3.71X10^{-2}$	0.1202
coarse	126	3.956	0.1307	0.1511	0.2053	$6.05X10^{-2}$	0.1202
burrowed	18	2.811	0.3451	-1.407	0.2650	0.2029	0.3206

PS2		Statistical Moments				Kolomogorov – Smirnov Stats	
Grain size	n	mean	variance	kurtosis	skewness	max|diff|	Tolerance
fine	31	2.303	0.3675	$-9.33X10^{-3}$	$6.487X10^{-2}$	0.0845	0.2443
medium	16	3.467	0.3037	-0.9840	0.3234	0.09843	0.3400
coarse	11	4.015	0.4561	-1.333	0.3483	0.1567	0.4101
pebbly	28	4.820	0.7258	-1.220	0.1048	0.1022	0.2570

Mean flow rate values for different grain size classifications

Data Set	fine	burrowed	medium	coarse	pebbly
PS1	2.172	2.811	3.351	3.956	***
PS2	2.303	***	3.467	4.015	4.820
PS1 & PS2	2.285	2.811	3.365	3.961	4.820

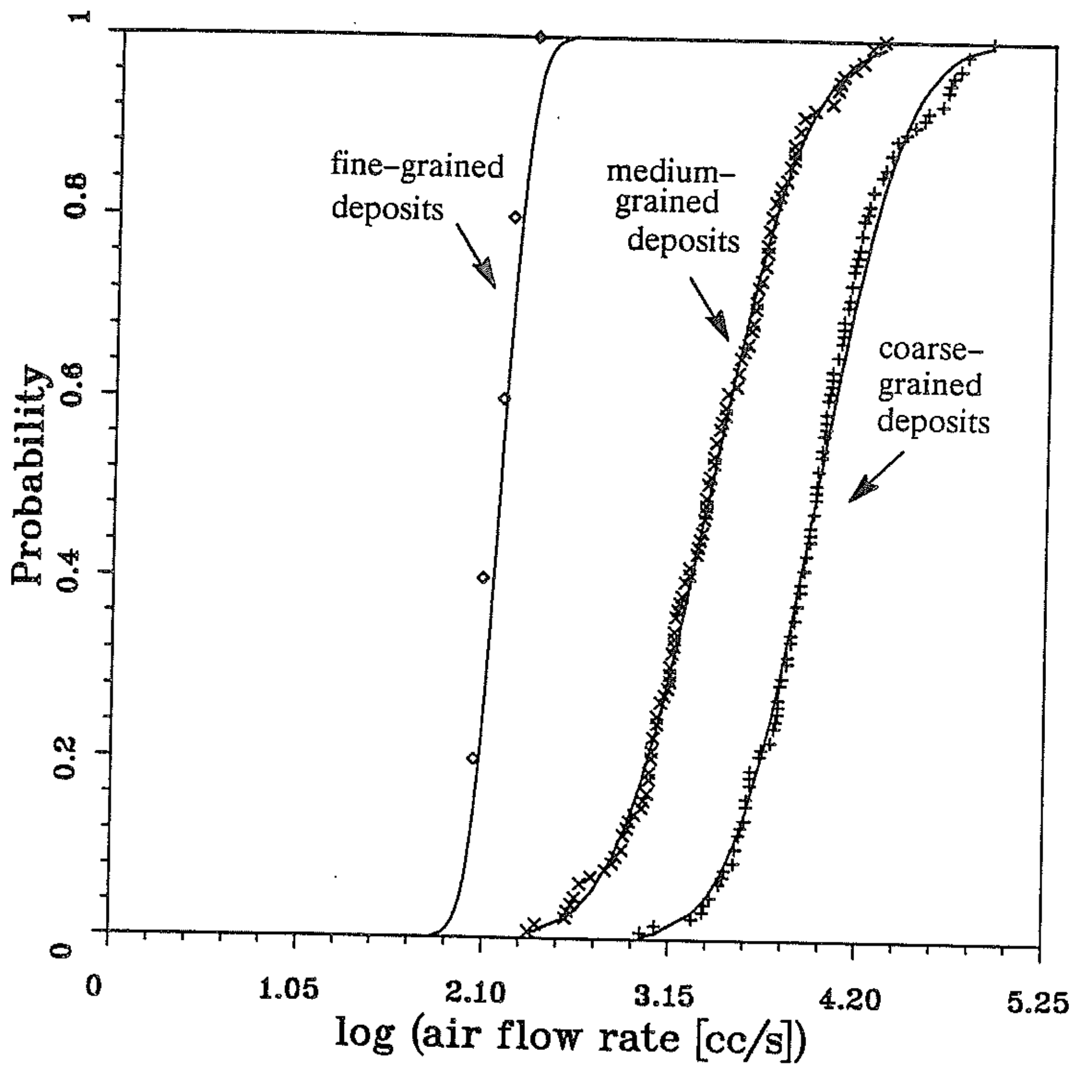


Figure 18. Comparison of empirical distributions with theoretical normal for PS1 logarithmic air-flow-rate data based on grain-size classification.

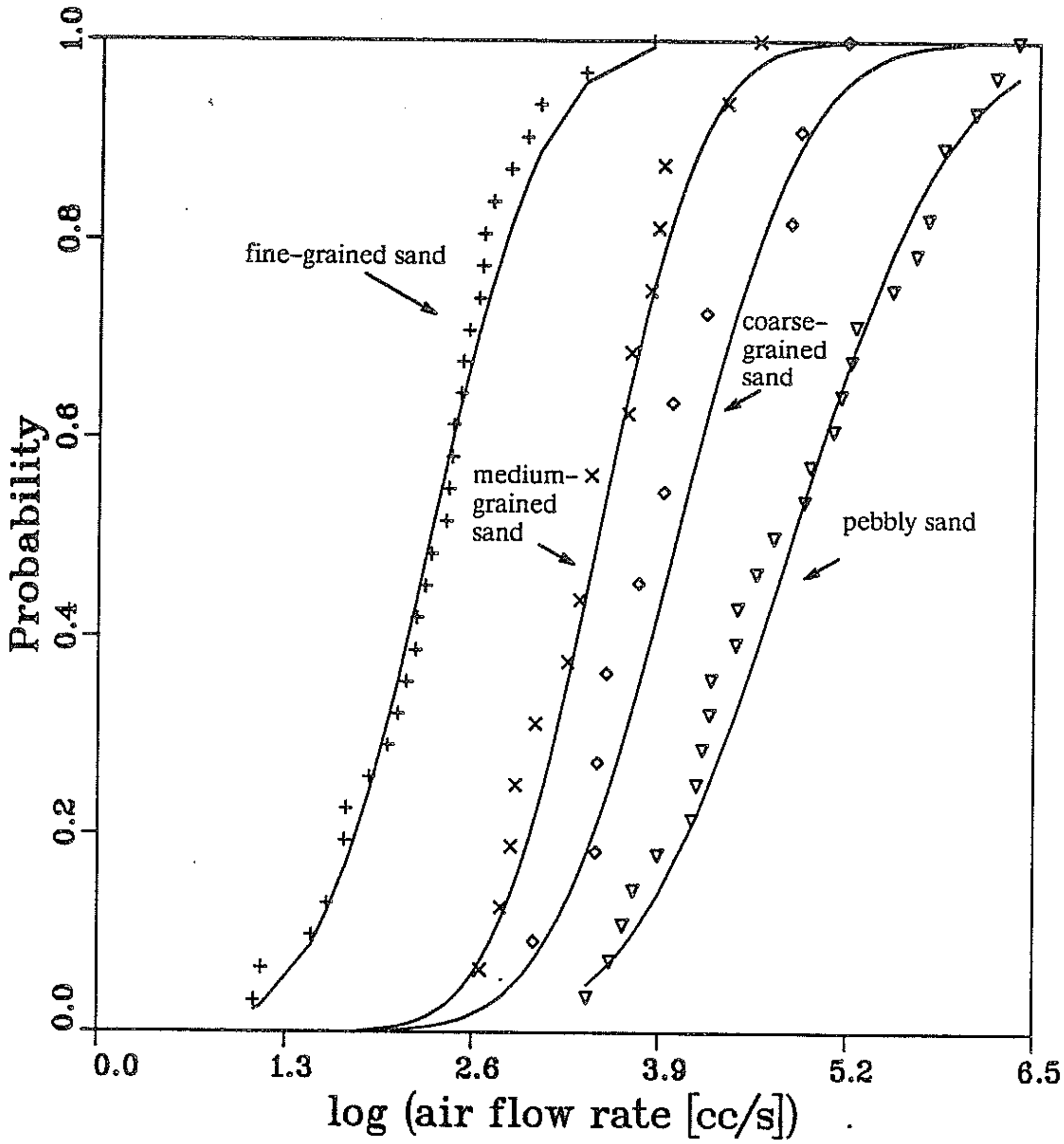


Figure 19. Comparison of empirical distributions with theoretical normal for PS2 logarithmic air-flow-rate data based on grain-size classification.

ability of natural geologic material. Recall that the primary goal is to supplement "hard" permeability measurements with "soft" geologic information. Grain size is, strictly speaking, a quantitative geologic descriptor. However, its visual estimation in the field constitutes a qualitative type of measure, and can be considered an example of "soft" information.

One possibility for incorporating grain–size information into the statistical analysis is to use permeability distributions based on grain size to supplement "hard" permeability data from a region. Using an indicator approach, it is possible to incorporate prior information such as cumulative distribution functions of grain size into the estimation of permeability (Journel 1989). Another possibility may be to incorporate geologic information on how different grain sizes are spatially distributed throughout a deposit to improve the estimate of mean permeability behavior. Knowledge of the spatial distribution of permeability for a given grain size may enable us to discriminate between a trend in the mean and random fluctuations about the mean. Say, for instance, a variogram estimate is desired for a fining–upward sequence, as we encountered with the PS1 and PS2 studies. Knowledge of the spatial distribution of grain sizes in a deposit will enhance our understanding of the mean's spatial distribution. When performing trend analysis on data, it is always important to have a physical justification for the fitted trend model. Further study of how permeability is related to grain size, as well as the degree to which grain size and spatial patterns of grain size in sedimentary deposits reflect spatial permeability trends, will enhance our ability to incorporate "soft" data into the statistical analysis.

Intermediate–Scale Permeability Studies

In addition to the two small–scale permeability studies, a study was conducted using the OUTCROP1 facies map shown in Plate 2 to estimate the spatial statistics of permeability at a larger scale by maintaining the lithofacies' distinction as a basis of analysis. Conceptually, the study entailed performance of a numerical experiment that helped to characterize the spatial distribution of mean lithofacies permeability. The utility of such an experiment lies in the ability to obtain large numbers of measurements so a structural analysis can be performed. This experiment is not intended to replace a study using actual measured values, but rather to help direct the investigation and give a preview of what one may expect to see at the larger scale.

The lithofacies observed at OUTCROP1 were lumped into four classes based on lithology and representative permeability. Rather than collect exhaustive air–flow–rate data from all facies in OUTCROP1, representative permeabilities were assigned to each facies class on the basis of information obtained from hydrogeologic literature. The permeability estimates of Freeze and Cherry (1979) were used to assign mean log–permeability of the observed lithologies. The resulting categories are shown in Table 5. There was no attempt to lump the facies into distinct architectural elements, although ultimately such grouping will be performed to characterize the structure of intermediate–scale heterogeneity as more data become available and distinct elements can be delineated. The purpose of the numerical experiment was not to quantify the structure of within–element heterogeneity, but rather to determine how the structure of facies assemblages observed at the intermediate scale are manifested in directional variograms.

The facies map presented in Plate 2 was analyzed on a 60 centimeter by 60 centimeter grid (map scale). For each of the 2159 digitized locations, the facies type at the location was recorded and an approximate log permeability value assigned from Table 5.

Table 5. Mean log–permeability estimates used in intermediate–scale study.

Lithofacies	Approximate mean permeability [darcy]	log(k)
Gms Gm Sgm	10^3	3
Sp Sl St Sh	10	1
Sr Sr/Fm Sm P	10^{-1}	–1
P(clay) Fl Fsc Fr Fm	10^{-3}	–3

Plate 5 shows the distribution of assigned mean log permeabilities of the lumped facies. Variogram analysis of the location and approximate log permeability values was then performed. Although the sample variograms are not based on actual air–flow–rate measurements or permeability, they do reflect the overall correlation structure of the permeability field at the intermediate scale. The results of the horizontal and vertical directional variograms from the numerical study are presented in Figure 20. Both directional variograms exhibit a hole effect, which represents a negative correlation at some finite distance.

The vertical variogram appears to be strongly periodic (Figure 20a). As such, a trigonometric function was used to model the vertical variogram. The fitted function is:

$$\gamma(\xi) = \begin{cases} a|\xi| & \text{for } \xi < 2.45 \text{ meters} \\ 2.5 + 0.65cos(\pi + \xi) & \text{for } \xi \geq 2.45 \text{ meters} \end{cases}$$

The wavelength of the variogram model is 2π (6.28) meters, which appears to correspond to the average repeatability of the grouped facies in the vertical dimension.

The horizontal variogram estimate (Figure 20b), while exhibiting a slight hole effect, also conforms to the properties of an exponential model. After Journel and Huijbregts (1978), the theoretical variogram model for the horizontal variogram is based on the product of the exponential and cosine covariance functions. A nested structure is also apparent in the horizontal variogram. This is modeled by appending an additional variogram model to the original one for all lags greater than the break at a lag of 17.5 meters. The resulting model is:

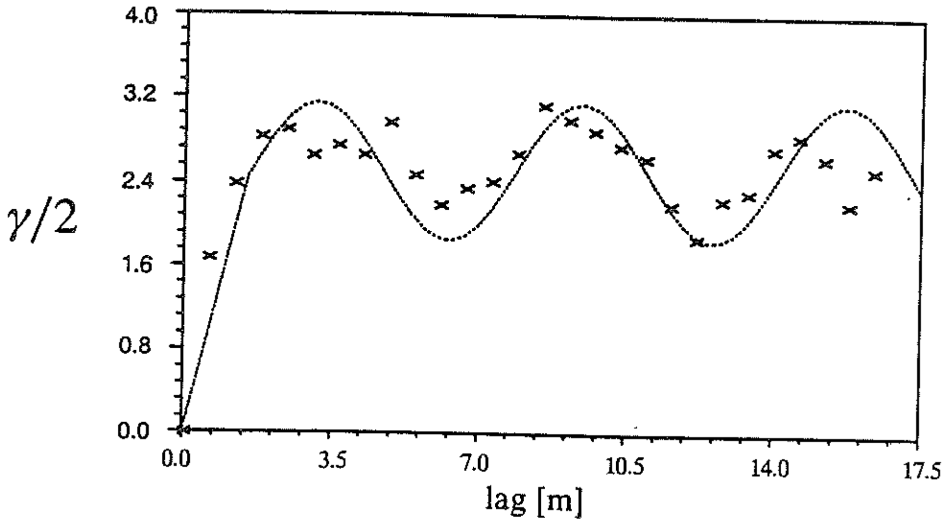


Figure 20a. Fitted vertical variogram estimate of intermediate-scale study. (unit lag=0.6m; $\Delta s = 0.25m$; $\Delta\phi = 1°$)

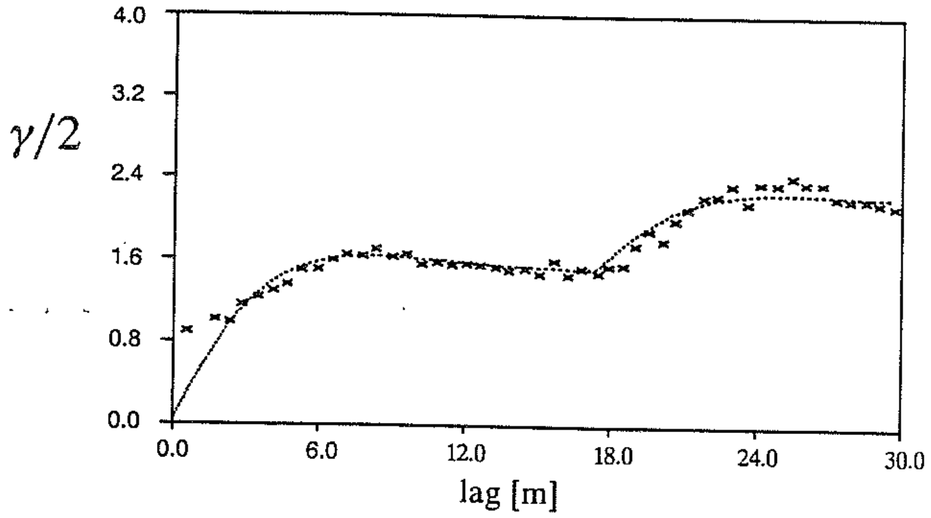


Figure 20b. Fitted horizontal variogram estimate of intermediate-scale study. (unit lag=0.6m; $\Delta s = 0.25m$; $\Delta\phi = 1°$)

$$\gamma(\xi) = \begin{cases} \gamma_1(\xi) & \text{for } \xi < 17.5 \text{ meters} \\ \gamma_2(\xi) & \text{for } \xi \geq 17.5 \text{ meters} \end{cases}$$

where

$$\gamma_1(\xi) = 1.5[1 - e^{-\xi/3.3}\cos(0.3\xi)]$$
$$\gamma_2(\xi) = \gamma_1 + 0.7\gamma_1(\xi - 17.5)$$

The ranges associated with the horizontal variogram models are approximately 17.5 meters for the first (γ_1) structure and 25.1 meters for the second (γ_2) structure (Journel and Huijbregts 1979). Since the lumped facies map of OUTCROP1 (Plate 5) shows that most facies extend horizontally across the entire length of the cross section, one would expect that the associated horizontal variograms would exhibit a single correlation range. However, the variogram reflects the average correlation structure over the entire cross–section, and thus includes the effects of facies that pinch out. The first range of 17.5 meters, therefore, represents the average lateral dimension of the facies over the entire cross–section. The second contribution to the variogram is hypothesized to reflect the discrete lateral changes from on lithofacies to another. Since the data consists of estimated mean values only, it is not possible to analyze the mean–removed data as with the PS2 study. The possibility that the observed nesting is the result of the search window used in the variogram estimation cannot be ruled out. However, the window width for the one degree angle tolerance used is plus–or–minus 0.31 meters for a lag of 18 meters and 0.43 meters for a lag of 25 meters.

The derivation of admissible variograms from observed and mean permeability values suggests that permeability, at least in a local sense, is described by an intrinsic random field, and that the correlation structure of small–scale heterogeneity can be completely described by the variogram. This particular property of the random permeability field may facilitate further geostatistical analysis. Collection of additional air–flow–rate measurements at progressively larger scales will help to resolve the issue of whether the permeability field, when viewed simultaneously at all scales of hydrologic significance, fits a random fractal model as suggested by Neuman (1990).

Development of a Quantitative Description for Heterogeneity

Developing a method to determine the statistical characteristics of aquifer properties addresses only part of the aquifer characterization study. Quantitative description of heterogeneity is also necessary so that ground water flow and solute transport through the heterogeneous aquifer medium can be predicted. The statistical representation of hydraulic conductivity is one approach to characterizing realistically the spatial variation of flow and transport properties of an aquifer system. With the statistical representation, two methods of solving the flow and transport equations are available.

The first approach to characterizing the effects of permeability variations on flow and transport, which is here referred to as the stochastic analytic approach, uses the perturbation method to solve the governing equations of flow and transport analytically (e.g. see Bakr et al. 1978; Gutjahr et al. 1978; Gelhar, Gutjahr, and Naff 1979). The random hydraulic conductivity field, however, generally exhibits properties that prevent solving the partial differential equations that govern flow and transport. Numerical solutions are often employed under such complex conditions as an alternative approach to solving stochastic flow and transport equations analytically. The problem of predicting flow and transport in a heterogeneous aquifer thus reduces to generation of a realistic permeability field that can be used to obtain these numerical solutions.

Traditionally, geostatistics offers two methods of generating realizations of fields that exhibit certain statistical characteristics. The first is to determine a best linear unbiased estimator (BLUE). The field is then estimated with the linear interpolator from the data. Commonly referred to as kriging, this method greatly smooths the fluctuations that actually exist.

The second method of producing a realization of a random function is the method of simulation. Simulation differs from kriging in that the small–scale fluctuations about the mean are preserved in accordance with the correlation structure. Two classes of simulation are possible. Unconditional simulation preserves only the distribution function and covariance or variogram. The result is a field that honors only the data's statistical properties. Alternatively, known data values can be used, along with the statistical properties of a field, to perform conditional simulation. The conditional simulation method honors not only the statistical properties of the field but also the known values of the random field. Conditioning on known data restricts the realizations of the random function to those that honor the data. The primary disadvantage of simulation is that it produces a maximum entropy field, thus potentially destroying certain aspects of the geologic continuity actually present in the field (Journel 1989). Geologic continuity is preserved only to the extent that the generated random field honors the variogram and the observed data. In applications of kriging and conditional simulation, additional data provide narrower confidence intervals by reducing the estimation variance, thereby minimizing the loss of observed geologic continuity.

In a discussion of geostatistics mining applications, Journel and Huijbregts (1978) state: “The estimation curve is preferable to locate and estimate reserves, while the simulation curve is preferred for studying the dispersion of the characteristics of these reserves.” Given the two methods of producing realizations of random functions and assessing what we know regarding geologic heterogeneity, it seems feasible that a hybrid method of simulation be investigated. Such a method would use kriging to estimate location and extent of architectural elements. Subsequently, the within–element permeability field would be conditionally simulated using a characteristic variogram for that particular type of architectural element, as well as “hard” and “soft” data, thereby preserving the variability or “dispersion” of the permeability field within the element. Interconnection probabilities based on conditional simulation of joint probabilities of facies connections might be used to maintain observed geologic continuity within the element (Fogg 1989).

Following generation of architectural element location, extent, and permeability distribution, the effective permeability of the element would be estimated by imposing a known hydraulic gradient across the element, simulating flow through the element using numerical methods, and dividing the Darcy flux by the magnitude of the imposed gradient. The principal directions of permeability could then be estimated by imposing the known gradients in a number of directions, and an effective permeability tensor calculated accordingly. This effective permeability tensor would represent an average, or upscaled, version of the detailed permeability field within the element. Definition of an effective permeability tensor for each element will make it possible to design finite–element flow and transport models in which each finite element corresponds to a particular architectural element of the Sierra Ladrones Formation deposits.

Successful prediction of ground water flow and contaminant transport in fluvial deposits depends on the degree to which geologic information can be used to help generate realizations of the permeability field. Geologic information in the form of depositional process/product relations has been suggested as a quantifiable form of "soft" information. This includes information on both the spatial association and distribution of architectural elements. Statistical characteristics and patterns of permeability distributions within facies and elements can be arrived at through variogram analysis of "hard" measured and possibly "soft" estimated permeabilities. There are essentially an infinite number of regionalized variables that can be used as proxies in the aquifer characterization process. One of the goals of the study is to investigate a variety of them and choose those that best estimate the aquifer's hydraulic properties.

Summary and Conclusions

Summary

Successful solution of aquifer contamination problems requires that the heterogeneities of the contaminated aquifer be characterized at the scale of the contamination problem. Since the exact characteristics of an aquifer can never be entirely determined, a probabalistic interpretation of aquifer properties has been proposed. If there does exist a quantifiable relationship between permeability patterns and geology, it has been suggested that realistic characterization of aquifer heterogeneities may be accomplished by incorporating "soft" geologic information into this probabilistic interpretation. Methods of sedimentary basin analysis allow systematic characterization of lithology, extent, connectivity, and architecture of sedimentary structures, and have been adopted as a means of incorporating "soft" information into the aquifer characterization process. Miall's (1985) architectural element analysis seems particularly well suited to the problem of relating correlation ranges of permeability fields to the scales of the underlying sedimentary structure.

Concepts of basin analysis and geostatistics have been discussed in the hope that they provide quantifiable parameters for incorporating "soft" geologic information into the probabilistic framework. The method of variogram analysis has been discussed and employed as a means to estimate the correlation structure of specific permeability fields. Preliminary analysis of the methods used and data collected has highlighted the strengths and weaknesses of the current methodology.

Among the strengths of the adopted methodology is the air permeameter, a device that enables rapid, inexpensive measurement of air–flow rates. In addition, the method of locating measurements that has been developed for data collection is efficient and economical. Mapping lithofacies has enabled us to define architectural elements and begin to interpret the depositional environment of the Sierra Ladrones Formation in the context of the associated permeability field.

Shortcomings of the current approach include the inability to sample permeability of the extreme value deposits, such as those comprised of clays and gravels. Since extreme–value units play a key role in the determination of contaminant migration pathways, methods of estimating the permeabilities of these units need to be developed. In addition, a method for relating the progression of scales of sedimentary structures to the anticipated nested hierarchy of correlation scales may prove to be elusive due to the wide range in spatial dimensions for any given class of sedimentary structures. Neuman's (1990) universal random fractal model may offer an alternative means of describing the permeability field, at least in a global sense.

Until an adequate theoretical model is developed to describe the hierarchy of sedimentary and permeability structures, the traditional approach of removing trends in the data is necessary. Practical means of defining and removing trends from the permeability data which incorporate geologic information such as grain–size and dimensions geologic units (lithofacies and/or architectural elements) should be developed to maintain an intrinsic permeability field and to justify using most geostatistical techniques.

Results of the geostatistical analysis appear to substantiate the hypothesis that, although the sample variogram is not an intrinsic property of the geologic system and is somewhat subjectively-based, there does exist a quantifiable relationship between observed geologic structure and the statistical parameters of permeability fields. Future variogram analysis must address the issue of the effect of search window geometry and size on the estimated sample variogram.

An important implication of the statistical analysis of the air-flow-rate data is that the distribution of air-flow rate as a surrogate to permeability approximates a log-normal distribution in the deposits studied thus far. While this is a fundamental assumption in geostatistics, it has been made time and time again in studies of stochastic hydrology, but in most cases has not received proper field validation. Although there is no physical basis for postulating that all permeability measurements are log-normally distributed at any scale, log-transformed permeability data generally approximate a normal distribution to a much greater degree than untransformed permeability data (Freeze 1975). Further work is necessary to see if this underlying probability distribution holds true for element- and formation-scale heterogeneities as well.

Another implication of the statistical analysis is that observed and quantifiable geologic features, such as cross-bedding, lateral and vertical changes in lithofacies, and changes in grain size appear to be strongly related to the estimated statistical parameters of a particular deposit. Specifically, correlation ranges estimated from "hard" data obtained at the facies scale agree reasonably well with the average dimensions of lithologic facies observed in outcrop. While geostatisticians may deem this result trivial, it verifies a critically important hypothesis that will enable us to estimate spatial statistical parameters from geologic observations with relatively little "hard" data.

Conclusions

While it is not the purpose of this report to draw final conclusions on the research described, several fundamentally important conclusions can be made. It has been shown that geostatistical parameters such as correlation range agree well with those that can be inferred from geologic observations. The extent of the agreement has yet to be determined rigorously. However, it appears the practice of studying geologic features in parallel with structural statistics is viable, warranted, and necessary for accurate and practical characterization of aquifer heterogeneities. It is clear that much more research should be devoted to 1) developing methods of obtaining field permeability measurements/estimates of the gravels and clays, 2) conducting experiments with various structural estimators to determine the best method for removing trends and for optimizing the data, and 3) determining how the geostatistics of nested structures and the rather evasive hierarchy of sedimentary bedding surfaces are interrelated.

This report has presented some of the fundamental concepts of geostatistics and sedimentary basin analysis. Some preliminary data analysis has lead us to refine and to some degree validate our hypotheses. The work presented here is not intended to be the final chapter on the incorporation of geologic information into the characterization of aquifer heterogeneity. The purpose has been to evaluate the methods and delineate the major issues facing the aquifer characterization process.

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Appendix A

Glossary of Terms

Actualistic models– A subset of depositional type models based on an actual study of an actual suite of sediments and geologic interpretation. The facies assemblages are generally distilled down to the basic essence of the deposit. (see Reading 1986)

Allocyclic depositional controls– Cyclic controls on depositional style resulting from variations in discharge, load and slope, which originate outside the sedimentary basin ultimately through tectonic or climatic changes. (Miall 1980)

Alluvial– Pertaining to or composed of loose material deposited by streams on river beds, flood plains, and alluvial fans.

Autocyclic depositional controls– Cyclic controls on depositional style which arise from energy distributions within the sedimentary basin, including meander translation and enlargement, meander chute and neck cut–off, crevassing and avulsion. (Miall 1980)

Bioturbated zones– Regions of a sedimentary deposit that have been churned and stirred by plant and/or animal organisms.

Conceptual facies models– A subset of depositional type models derived from a conceptualization of how sedimentological facies would be associated for a given set of depositional processes.

Correlation length– A physical length over which data points are correlated.

Covariance– A statistical measure of data similarity. In this report, the emphasis is on similarity with respect to physical separation between data points.

Cycle of sedimentation– A sequence of related processes and conditions, repeated in the same order, that is recorded in a sedimentary deposit.

Cyclothem– A sequence of sedimentary deposits. The general character is cyclic and controlled by allocyclic processes.

Diagenesis– The physical and chemical alteration that occurs after a sedimentary deposit is buried. Soil development is not considered here a diagenetic process.

Illuvial– The accumulation, in a lower soil horizon, of material that was transported by ground water percolation (especially colloidal material). (Bates and Jackson 1984)

Facies– A body of rock which can be defined and distinguised from others by its geometry, lithology, and sedimentary structures. (Selley 1978) syn: lithofacies, sedimentological facies

Facies assemblages– A group of facies that occur together and are considered to be genetically or environmentally related.

Lag– A physical length separating a pair (or pairs) of data points.

Lithologic distribution– The spatial distribution of genetically related or environmentally related lithologies. Differs from facies assemblage in that: 1) general lithologies (sand, gravel, fines) are studied rather than well defined facies (St, Sh, Gt) and 2) added emphasis is placed on spatial relationships.

Log–normal distribution– A sample set whose logarithmic transform (natural or base 10) is normally distributed.

Model (geologic)– A simplified version of reality that exhibits useful information in the interpretation and prediction of lithologic distributions and/or facies assemblages. Examples include mathematical models and type models.

Model (variogram)– A function fitted to an estimated variogram that is presumed to represent the underlying statistical structure.

Paleosol– A buried soil; soil of the past. (Bates and Jackson 1984)

Pedogenic– Pertaining to the development of soils.

Type model (depositional)– A simplified version of facies assemblages that indicate a certain depositional environment. Type models serve as a basis by which to compare and contrast observed facies assemblages. Depositional type models are a subset of geologic models.

Variogram– Similar to *covariance*, however the variogram is a measure of dissimilarity of values that are separated by a *lag* distance.

Appendix B

Air Permeameter

Introduction

Obtaining large numbers of permeability measurements has been a goal and area of active research in the petroleum industry for some time. To achieve this goal, gas has commonly been used as the fluid due to its low viscosity thus enabling steady state conditions much more quickly than water.

Eijpe and Weber (1971) developed one of the first air–permeameters by which the air permeability of consolidated and unconsolidated sands could be measured quickly and nondestructively either in situ or in the form of samples. Goggin, Thrasher, and Lake (1988b), of the University of Texas at Austin, constructed a more portable air–permeameter, hereafter referred to as the UT device, and developed a theoretical framework to calculate permeability based on specific flow geometry. The UT device applies a constant pressure from a tank of compressed nitrogen to the outcrop through a tip seal. Steady state is achieved and the resulting flow is measured with a series of rotameters. With a constant pressure and flow rate, the permeability can be calculated for the resulting flow geometry. The reader is referred to Goggin, Thrasher, and Lake (1988b) for details pertaining to design and operation of the UT device.

The great utility of the UT analysis is that the theoretical development is valid for any system that utilizes a constant pressure to achieve steady flow through a specific flow geometry. The flow geometry is radially symmetric with a vertical component, as illustrated in Figure B–1. For this geometry, perme-

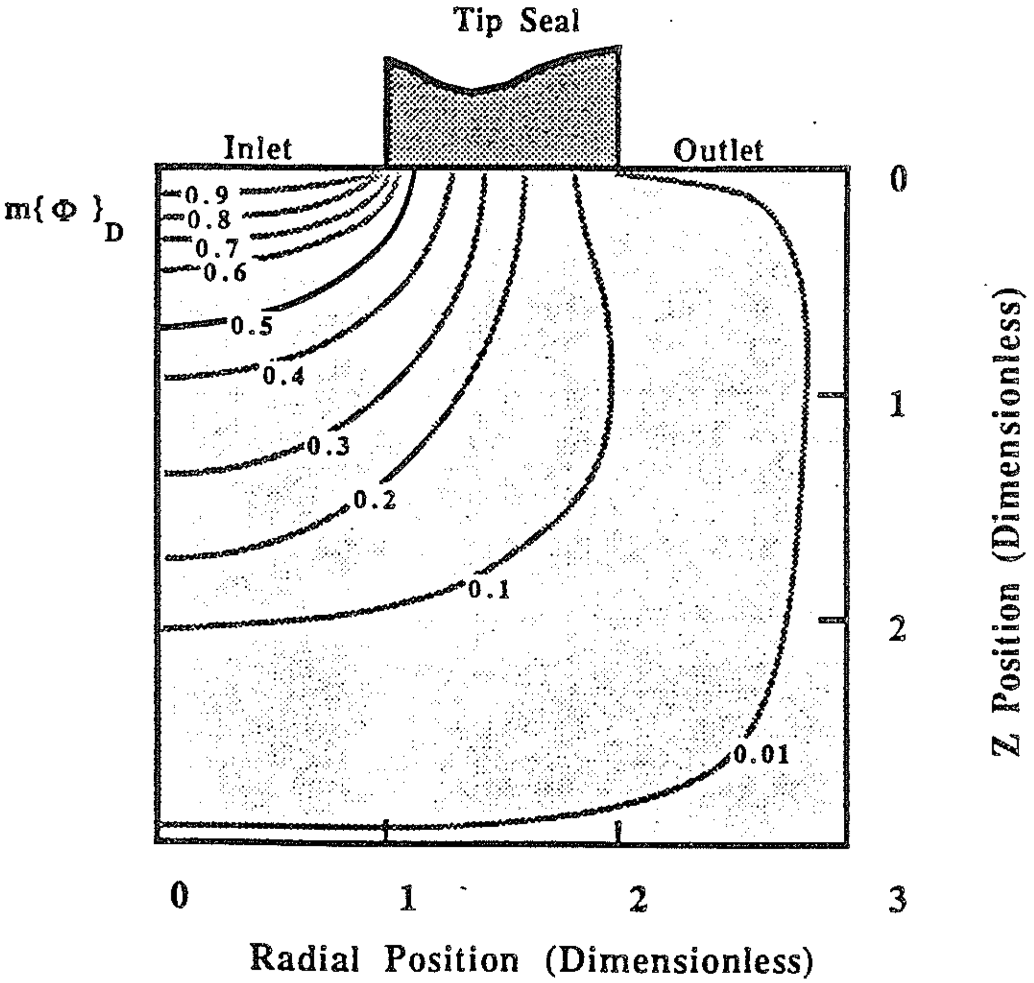


Figure B-1. Pseudo-potential contours illustrating air permeameter flow geometry. (Goggin, Thrasher, and Lake 1988b) ability can be calculated via the equation:

$$k = \frac{q_1 \mu P_1}{a G_0(b_D^{\infty}) \frac{P_1^2 - P_0^2}{2}} \tag{B1}$$

where:

P_0 = atmospheric pressure
P_1 = tip–seal injection pressure
q_1 = air–flow–rate
μ = dynamic viscosity of air at atmospheric conditions
a = internal radius of tip–seal
$G(b_D^{\infty})$ = geometric factor determined graphically from Goggin, Thrasher, and Lake (1988b)

The ability to obtain rapid, nondestructive permeability measurements in situ was necessary for successful characterization of permeability distributions in fluvial deposits. Our design is based on that of the UT device, but with a new set of constraints regarding sampling medium and portability. Since the current field site consists of primarily unconsolidated material, it was necessary to apply a very small, yet accurately measurable, pressure. To honor the pressure constraint and increase portability, another type of device based on the permeameter developed by Heller (1988) was investigated. Heller has developed an air–permeameter that uses a pistón/cylinder apparatus, which is referred to here as the Heller Piston Device (HPD). The piston applies a constant pressure and a seal is maintained between the piston and cylinder using a latex prophylactic. The flow rate is then calculated by timing the rate at which the piston falls. The device presented in this report is somewhat of a hybrid between the the UT and HPD devices. The tip seal governing flow geometry is similar to the UT device, while the air–supply portion is a modified HPD.

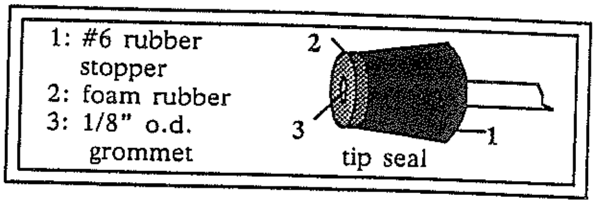
Permeameter Design

Figure B–2 presents the basic design of the air permeameter developed in this report. A Becton–Dickenson® 100cc ground glass syringe was ground further with fine grit corundum to provide a fairly frictionless contact while maintaining an adequate seal between the piston and the syringe casing. The flow rate is obtained by electronically timing displacement of a known volume. This is achieved with a stopwatch, a set of photoresistors, and lamps (Figure B–3).

The primary differences between the device described here and the UT device are the manner in which: 1) the pressure is applied 2) the applied pressure is measured, and 3) the resulting flow rate is measured. The UT device applies pressure to the outcrop with a compressed air source requiring pressure guages to measure the applied pressure and flow meters to measure the resulting flow. The device described here accomplishes all three functions (apply pressure, measure pressure, and measure flow rate) with the glass syringe. Pressure is applied with a "free–falling" piston; the mass and area of the piston are known resulting in a known pressure. The flow rate is measured as the time which is required for the piston the displace a known fixed volume.

The tip seal is the part of the apparatus that governs the flow geometry at the permeameter/outcrop interface. The UT design was modified so the same flow geometry could be obtained on unconsolidated samples. The modifi-

1: 100cc syringe
2: lamps (#222)
3: circuit board
4: photoresistors
5: stopwatch
6: lamp switch
7: circuit board switch
8: stopwatch switch
9: stopwatch reset
10: battery pack (4 'c' cells)
11: outlet to tip seal


1: #6 rubber stopper
2: foam rubber
3: 1/8" o.d. grommet

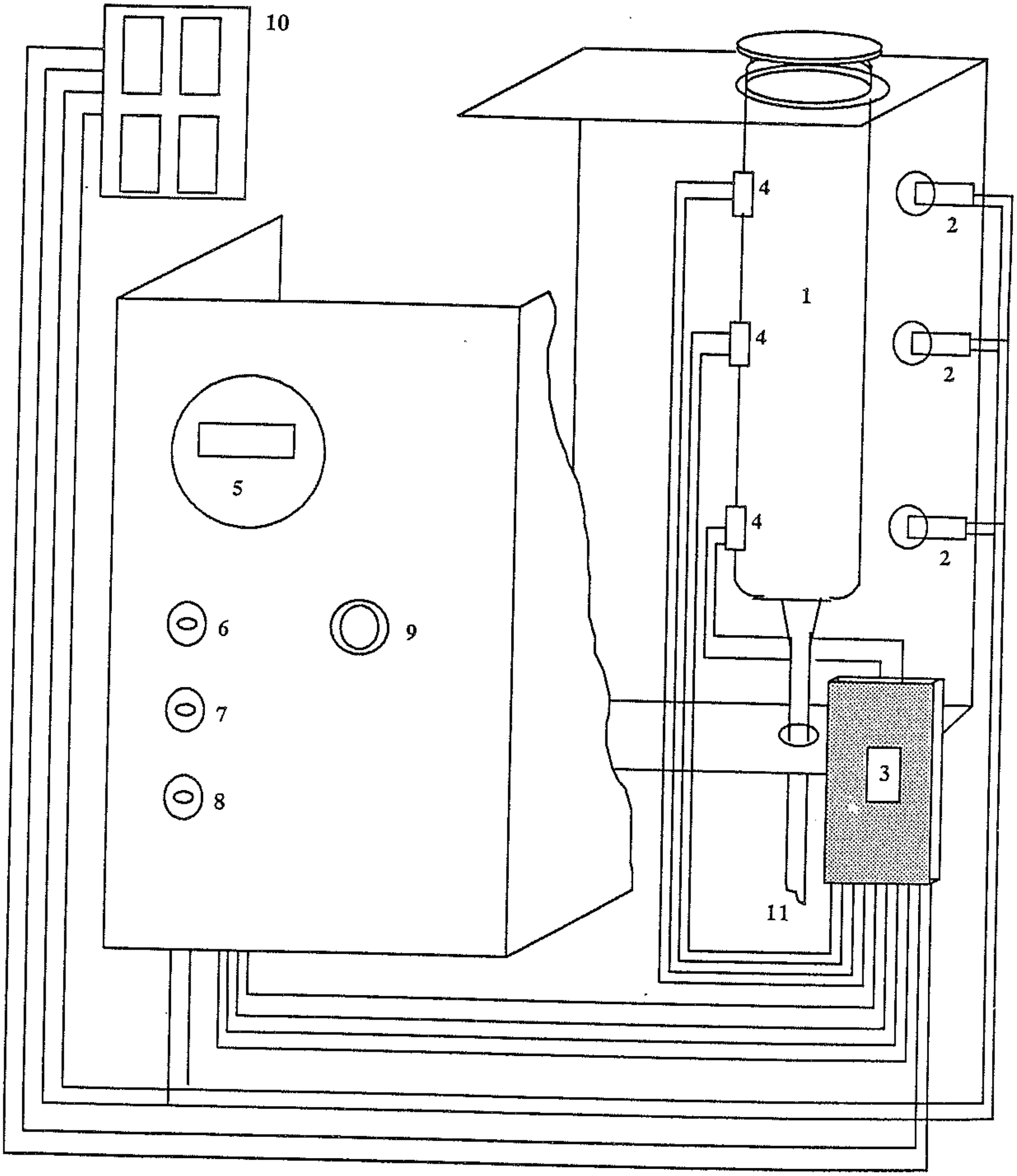
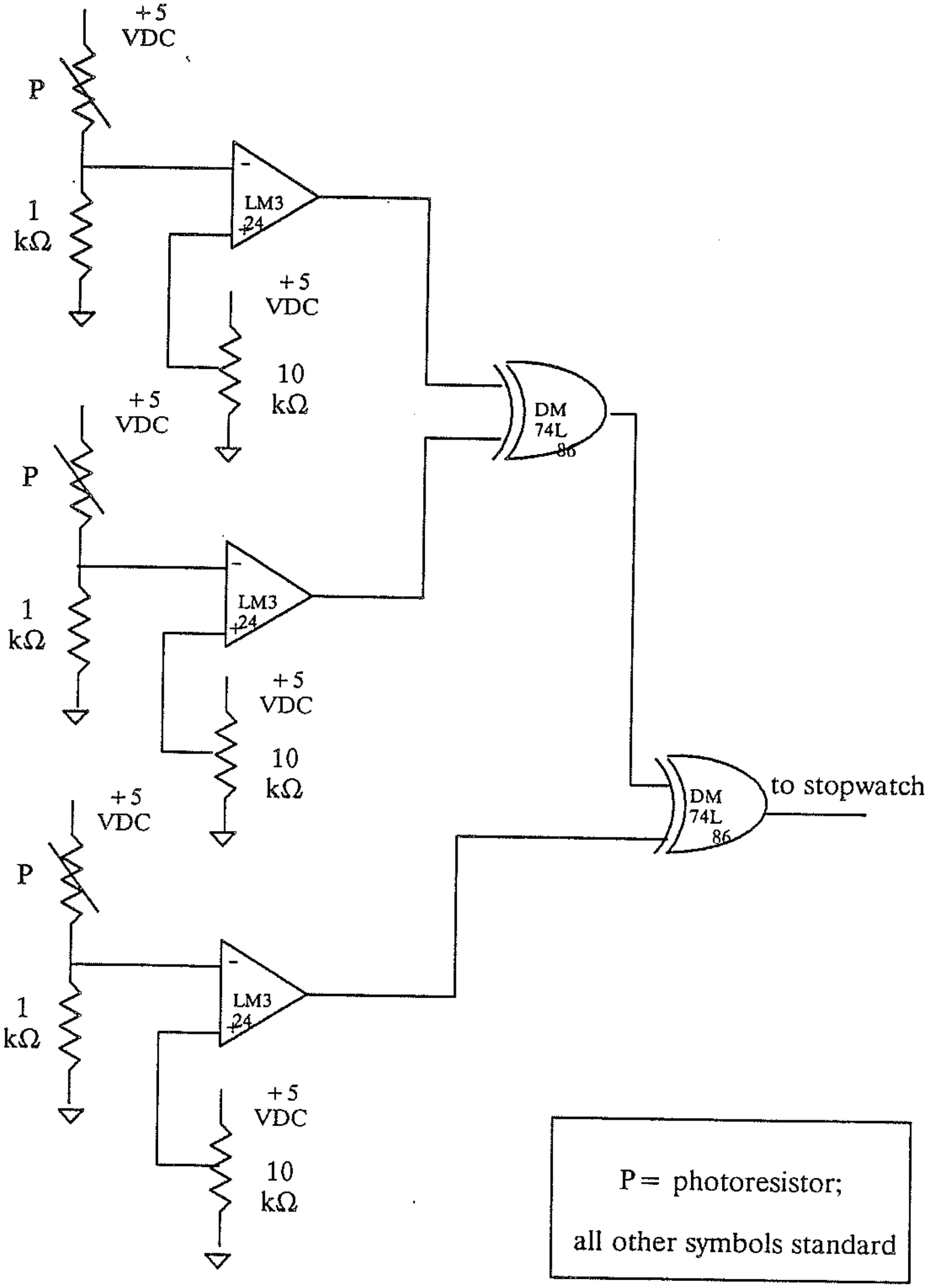


Figure B-2. Schematic diagram of air permeameter



P= photoresistor;

all other symbols standard

Figure B-3. Wiring diagram of electronic timing device.

cation entails an increase in the outer diameter of the tip seal in order to provide structural stability when applied to an unconsolidated outcrop.

Calibration

Efforts to calibrate the air–permeameter have focused on comparing the intrinsic permeability derived from a constant–head water permeameter with air permeability calculated from equation B1. Calibration results are shown in Figure B–4. It was difficult to obtain a one–to–one correlation between air– and water– permeameter results due to the drastic difference in volumes sampled. Based on a tip–seal diameter of 1/8–inch, the air–permeameter is estimated to have a radius of investigation on the order of one centimeter, thus sampling approximately a 1cc. volume. On the other hand, the soil ring samples used in the water–permeameter are 5 centimeters in diameter and 5 centimeters in length, a volume of approximately 100cc. A one–to–one correlation of permeability measured from two such vastly different volumes should not necessarily be expected. While the calibration thus far has not resulted in a highly accurate relationship between permeability derived from the constant head apparatus and air–permeability, the results are encouraging because the linear correlation coefficient estimated from the air– and water–permeameter data sets is equal to 0.86.

Analysis of Measurement Error

An analysis of variance (ANOVA) was performed on a set of logarithmic air–flow rates measured at 25 different locations to determine if variation of flow rates observed at these different locations could be attributed to permea-

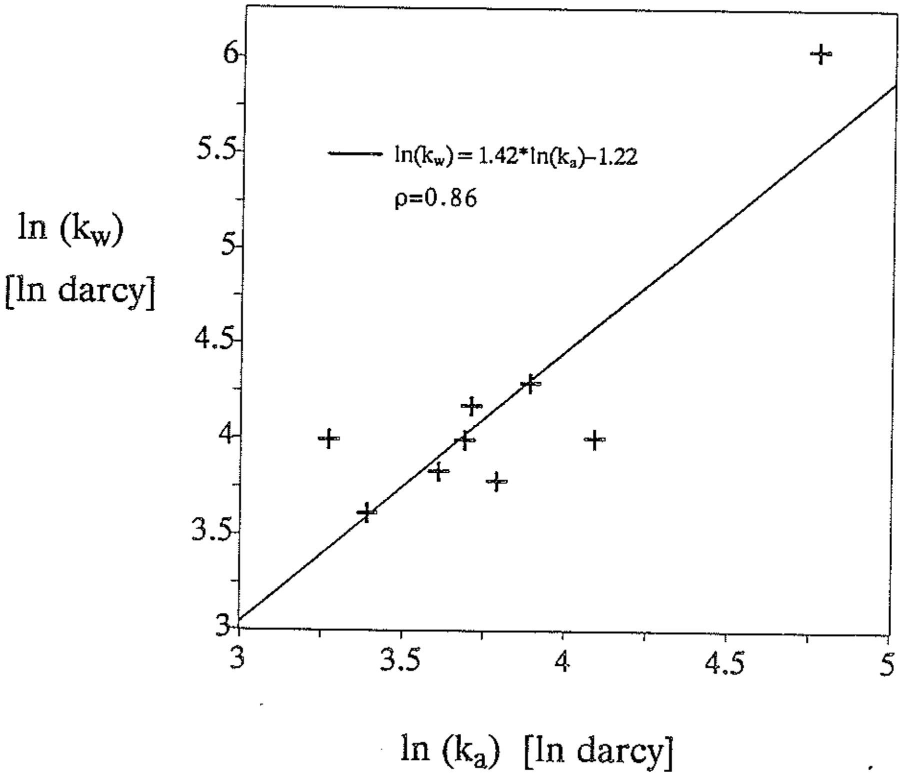


Figure B–4. Comparison of log–permeabilities derived from air permeameter (k_a) and constant–head water permeameter (k_w).

meter measurement error rather than to actual variation in the properties of the sampled geologic material. The data set was comprised of 25 groups of data, each of which contained 2 or 3 logarithmic air–flow–rate measurements observed at the same location. The variance of measurements within each group was compared to the variance of measurements between groups. This was done to determine whether the total variance of the logarithmic data set could be explained as the result of true variation in geologic materials or might instead be caused by an inability of the permeameter to replicate measurements collected from a homogeneous outcrop. A dominance of within–group variance with respect to between–group variance would suggest that the flow–rate variance was largely due to variance inherent to the permeameter, while dominance of between–group variance would imply that changes in the flow rates from location to location are related to changes in the geology of the outcrop rather than to any instrument limitations.

Table B–1 presents results of the analysis of variance. The mean square within groups, or the 'average' variation within groups (MSW), was estimated to be equal to 0.006, while the 'average' variation between groups (MSB) was calculated to be 1.183. The F–value, determined as the ratio MSB/MSW, was equal to 171.45, indicating that between–group variance was more than 2 orders of magnitude greater than within–group variance and likely not due to permeameter error. Since this value is much larger than the F–statistic of 1.79 estimated at a significance level of 5 percent, the null hypothesis that the means of the 25 groups of logarithmic flow rates are equal was rejected. Thus, variance of the data can not be related to random fluctuations in the response of the permeameter, but can be attributed to variation in the sampled geologic materials.

Table B-1.

Results of ANOVA for 25 groups of logarithmic air-flow-rate data.

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)
Between Groups	28.39	24	1.183
Within Groups	0.25	42	0.006
Total	28.65	66	0.434

The absence of significant nugget effects in the sample variograms presented in the report further substantiates that random measurement error is small relative to the inherent variability of the sediments. Results of the ANOVA confirm that the air permeameter is a reliable means of characterizing the structure of permeability variations in the Sierra Ladrones Formation fluvial deposits.

Discussion

As the calibration process continues, other issues inherent with gas permeability will need to be addressed. For instance, at low pressures, the Klinkenburg effect is commonly observed; at higher pressures non–Darcy flow effects result in the underestimations of permeability (Katz et al. 1959). These issues as well as soil moisture effects will be investigated as the study of geologic heterogeneity continues.