

**A METHODOLOGY FOR THE QUANTIFICATION
OF OUTCROP PERMEABILITY HETEROGENEITIES
THROUGH PROBE PERMEAMETRY**

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ABSTRACT

Outcrops are recognised as an important source of information used to help improve our understanding of permeability heterogeneities within subsurface reservoirs. However, the results of outcrop permeability studies are not having the impact which perhaps they should. From a review of outcrop-based permeability studies published to date the permeability measurement technique and sampling strategies are identified as the main areas requiring improvement. As the probe permeameter is an ideal device for measuring permeability at outcrop the response of this device under outcrop conditions is investigated.

A code of practise for the use of a portable probe permeameter on sedimentary rocks exposed at outcrop is presented here. This code is based on laboratory experiments and the experience gained from several thousand permeability measurements made on a various outcrops. This code of practise is designed to enable the operator to identify and quantify the various sources of error associated with outcrop permeability measurements. Deformation of the probe seal is identified as the greatest source of error but a combination of various other factors (fines, water saturation and so on) can significantly affect the results.

The use of an appropriate sampling scheme is essential in order to minimise bias and maximise information obtained from the results. During sampling, consideration is given to both the statistical variation and spatial distribution of the permeability values. The sampling scheme presented combines an understanding of the geological structure with sampling efficiency to obtain sample data that represent both the variation in permeability and the spatial structure of this variation.

An iterative approach is adopted in the sampling with permeability data collected over successively smaller sample domains. Permeability data are first sampled over the maximum domain size with the minimum sample density. After a combination of geological and statistical (static and spatial) analysis, the domain size is systematically reduced with a corresponding increase in the sample density. The location of each successive sample domain is determined by the spatial statistical variation in the data. The location of sample domains may or may not correspond to the geological structure, but the geological controls on the permeability variation are evaluated simultaneously.

These measurement and sampling techniques are applied in a case study on the White Sandstone in Scotland, interpreted to represent a shallow marine sand shoal. The excellent access provided by mine workings has enabled a very thorough and detailed permeability study. Sample transects, constructed in two orthogonal directions, extend over a horizontal distance up to approximately 500 metres. This study has revealed considerable permeability variation within a sandstone otherwise considered to be 'massive'. However, various statistical and spatial statistical analyses have revealed that the permeability variation has unique fractal characteristics. A Monte Carlo permeability model is presented for 'massive', shallow marine sandstones, based on this outcrop study.

CHAPTER 1 Introduction

Through the exploration, development and production stages of a hydrocarbon reservoir, different forms of data are required; integrating geology, geostatistics, geophysics and petroleum engineering. Aziz et al (1987) have attempted to define these data requirements in order to indicate future directions for research. Included within the suggested requirements are improved reservoir description and stochastic models of reservoir properties. These are required because information about the variations in reservoir characteristics are generally restricted to the borehole with increasing uncertainty with distance away from the control data. Seismic and dynamic well test and production test data do provide some information about reservoir characteristics in the interwell area but this information is rarely detailed enough. It is these variabilities or heterogeneities that determine the storage and flow characteristics of the reservoir.

Pore space heterogeneities occur over a range of scales and they often correlate with depositional structures (Jones et al 1985, Haldorsen 1986, Hearn et al 1986, Stalkup and Ebanks 1986, Weber 1986) and various hierarchical schemes have been proposed for depositional heterogeneities (Lewis 1988, Weber 1986 and others). Consequently, geological models are of particular importance in the prediction of reservoir heterogeneities and these models have been used to guide stochastic reservoir modelling techniques (Weber 1986, Dubrule 1988, Haldorsen and Damsleth 1990).

The effective permeability of a given fluid phase depends on the rock permeability and the rock-fluid interactions. Permeability heterogeneity is one of the more important characteristics of an oil or gas reservoir because it has a major control on where injection fluids will flow and to what extent a reservoir will be contacted and swept by an injection fluid. Whilst geological information provides the key to predicting permeability heterogeneity within the reservoir, it is frequently ignored by those who regard it as non-quantitative and non-portable between formations of the same geological type. This problem may in particular

circumstances be solved through the use of outcrop analyses where permeability data and geological structure are mutually evaluated to develop quantitative reservoir model analogues.

The use of outcrops to investigate permeability variation in sedimentary deposits has been recognised for some years as evidenced by a significant number of published studies on this subject. However, the correlation between efforts placed on research related to reservoir characterisation and improved hydrocarbon recovery shows that this research is not yet having the impact that it should. The implication therefore, is that the information obtained from these studies is either incorrect or inappropriate and two questions arise: first, why are outcrop permeability studies not yet finding sufficient application?, and second, how can this situation be improved?

Whilst outcrop studies can improve our understanding of permeability heterogeneity, application of the resulting models to the reservoir are limited by the capacity of computerised numerical reservoir simulators which are used to predict reservoir performance. It is probably true to say that whilst outcrop permeability studies have attempted to address the problems of reservoir characterisation, the data obtained are often too detailed for practical use in reservoir simulators and suitable averaging procedures are not yet available. This however, may be a question of time. With improved technology the reservoir models obtained from outcrop data should find application as numerical reservoir simulators operate with smaller grid cell sizes and our understanding of permeability averaging improves. The problem is, does an outcrop provide a sufficient analogue and how is the knowledge of permeability heterogeneity obtained from outcrop tuned to a given subsurface reservoir?

Aims and Objectives

As more outcrop studies are completed on different facies types, the reliability of the data base for each facies type can be improved by combining data from independent outcrop studies. This requires compatibility between data from different sources. In the published outcrop permeability studies there is not yet a formalisation of a

standardised method for data collection.

The main aim of this thesis is to improve the information gained from outcrop permeability studies. This is achieved through the development of a code of practise for the use of the portable probe permeameter at outcrop and the development of a standardised method for sampling permeability from outcrop. The code of practise serves to identify the source associated with outcrop permeability measurements and to quantify these errors. The sampling scheme proposed ensure that the permeability data collected are efficient, reliable and appropriate

The organisation of this thesis is shown in Figure 1.1. This thesis is divided into two sections. In the first section, Chapter 2 sets out to define the problem of reservoir characterisation and establishes the role of outcrop permeability studies. Chapter 3 reviews the published outcrop permeability studies, identifying those areas requiring improvement. In effect, Chapter 3 coordinates the aims of the thesis and sets them out in the order in which they are tackled in subsequent Chapters. Chapter 4 investigates the problems associated with permeability measurements made at outcrop through the use of the probe permeameter, and is concluded with a recommended code of practice based on the field experience gained during this research. Having established how to measure permeability, Chapter 5 introduces the different sampling schemes that can be used at outcrop, with methods for estimating the sample error. To illustrate the sampling techniques, two examples of outcrop permeability studies conducted in this research are presented on contrasting lithologies. This Chapter concludes section 1. In section 2 a complete outcrop permeability study on a shallow marine sandstone was conducted and is presented, divided into three Chapters. Chapter 6 describes the geology and depositional environment for the outcrop. This is followed in Chapter 7 by a description of the sampling scheme and analysis of the data. Chapter 8 presents an investigation into the causes of the permeability heterogeneities identified. In Chapter 9, a spatial permeability model is developed for the sandstone and simulated data sets are compared to the original sample data. Section 2 therefore, is effectively a detailed case study, adding further illustration of the application of the sampling methodology outlined in section 1 but also contributing to our understanding of permeability heterogeneities within

this particular lithofacies type. In the discussion in Chapter 10, the findings of this research are drawn together and concluded.

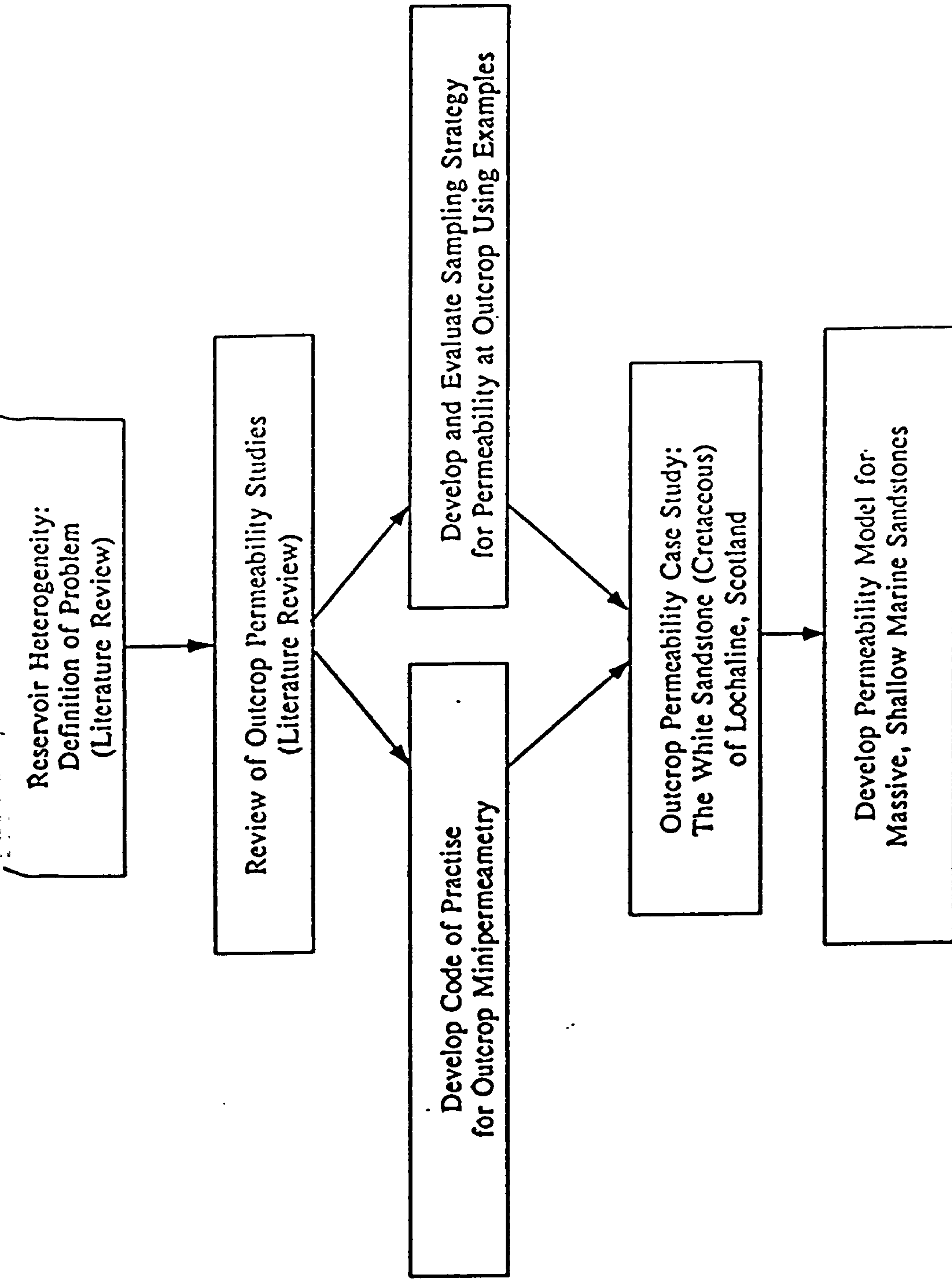


Fig. 1.1 Flow chart showing the organisation of the thesis

CHAPTER 2 Reservoir heterogeneity: cause and effect, modelling and averaging

2.1 Causes of reservoir heterogeneity

From detailed studies of unconsolidated sediments and artificial bead packs (Gratton and Fraser 1935, Beard and Weyl 1973, and others), permeability and porosity have been shown to relate directly to the textural properties of the porous media, including for example, mean grain size, sorting, grain shape and packing. During the process of accumulation, the textural properties of the sediment vary as the controls on the depositional system change such as energy levels, current direction and source material. This results in both vertical and lateral variations in textural characteristics. After burial, the grains selectively undergo compaction, cementation and dissolution. These post-depositional processes are collectively termed diagenesis.

The pore throats and void spaces between grains, and sometimes within the grains, determine the porosity and permeability characteristics of the rock. In addition, the grain surfaces may vary in roughness (often due to selective dissolution) whilst the pore throats may be constricted (by the growth of hairy illites for example). Porosity is the total void volume whilst permeability is dependent on the continuity of the void spaces. Another cause of permeability and porosity is associated with fracturing where fractures may be open or tight.

Various workers (for example, Alpay 1972, Pettijohn et al 1972, Nurmi 1985, Goggin et al 1986, Haldorsen 1986, Lasseter 1986, Weber 1986 and Lewis 1988) have shown that textural heterogeneities can be classified hierarchically. The smallest scale of heterogeneity occurs within or between grains, with successive scales occurring within laminae, cross-beds, coarsening-up sequences, and so on. This concept of hierarchical scales of textural or depositional heterogeneity is based on the discrete nature of bedforms observed in sedimentary rocks. The number of classes may differ therefore between rocks from different depositional environments. This same classification scheme provides a

practical framework for classifying reservoir heterogeneities.

Heterogeneities associated with post-depositional characteristics are more difficult to predict as it is very difficult to unravel the sequence of events to recreate the processes under laboratory conditions. However, variations in permeability and porosity can often be related to the primary depositional characteristics even after post-depositional modification (Polasek and Hutchinson 1967, Dodge et al 1971, Lewis 1988).

2.2 How heterogeneity affects oil recovery

The displacement of oil by water or gas under immiscible conditions occurs at a range of scales as illustrated in Figure 2.1. At the small or microscopic scale (the grain to grain scale), in areas swept by the displacing fluid, trapped or residual oil occurs within small pore spaces where there is a significant contrast in capillary pressure between the pore space and the surrounding porous media. The distribution of this residual oil depends on the viscous, capillary and gravity forces which are influenced by the pore size, pore geometry, wettability and displacement rate. Generally viscous and capillary forces dominate over gravity forces at the microscopic scale which are often regarded as insignificant. Determination of the residual oil saturation is made on core plugs in the laboratory from which the ultimate residual oil saturation, $S_{or}(ULT)$, is determined. This value is then used to calculate the recovery factor. Actually, the core plug volume incorporates many grains and pore spaces, thereby representing a larger scale of heterogeneity, termed the macroscopic scale by Haldorsen (1983).

The large number of pore volumes that sweep a small region during a typical flood often result in the rapid recovery of a significant fraction of the mobile oil and small scale heterogeneities are usually regarded as having only a small effect on recovery efficiency. However, values for $S_{or}(ULT)$ can vary from less than 10% to more than 40% depending on the nature of the microscopic heterogeneities, fluid phases and displacement rate (Archer and Wall 1986).

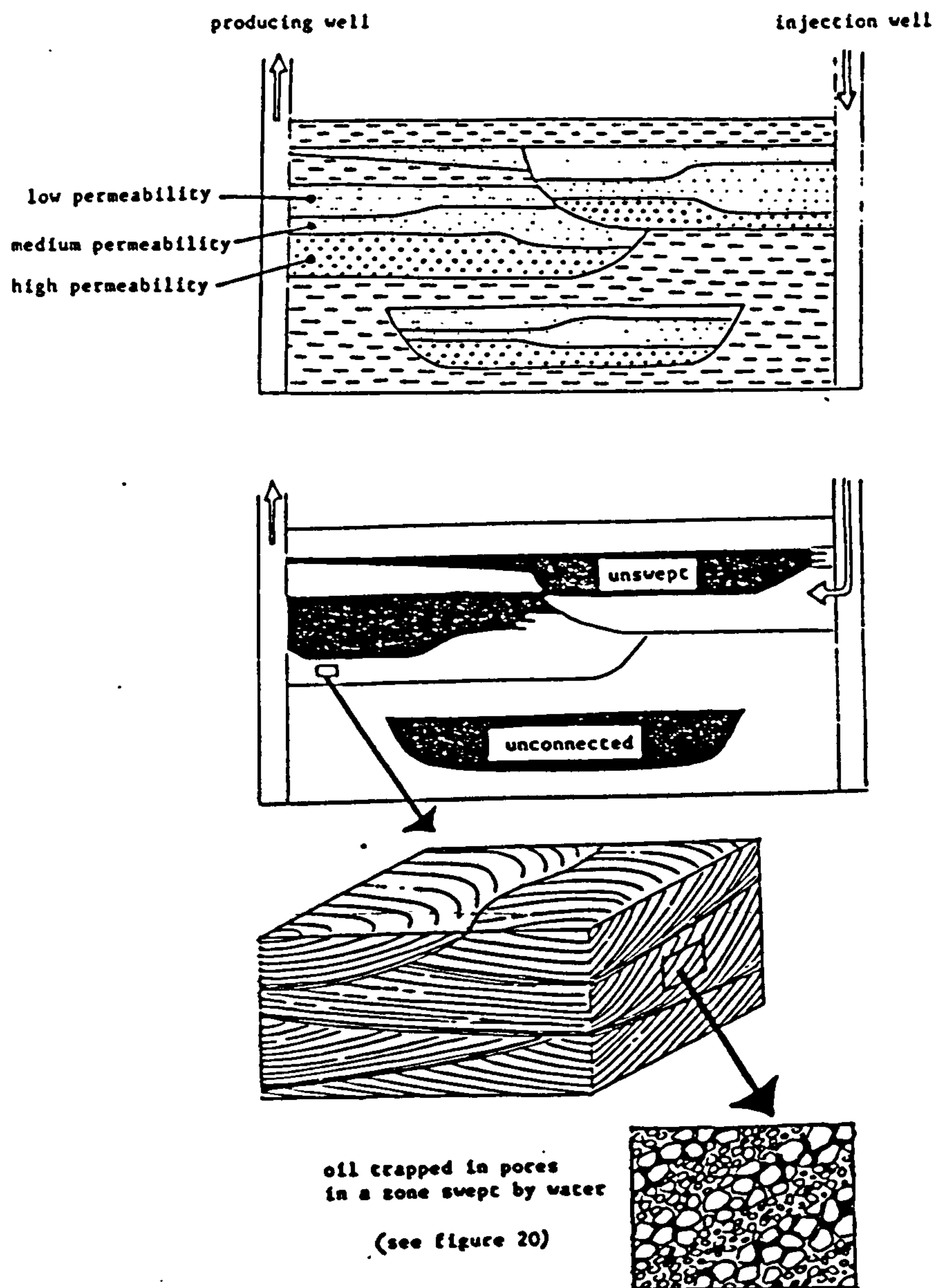


Figure 2.1 The effect of different scales of heterogeneity on residual oil saturation (after Weber, 1986)

At the medium scale (for example, cross-bedding), gravitational forces may be more important and capillary forces less important. As fewer pore volumes sweep the medium scale region relative to the small scale it is generally accepted that heterogeneities have a greater effect on recovery efficiency. Consequently, much attention has been paid to medium scale heterogeneities. Studies such as those of Weber 1982, Kortekaas 1985, and White and Horn 1987, have shown that the correct appreciation of these heterogeneities has an important effect on oil recovery. A typical grid block size used in a reservoir simulator, described as the megascopic scale by Haldorsen (1983), occupies a scale position between the medium and large scale.

At the large scale (synonymous with the interwell scale), the driving force for displacement is represented by the potential pressure gradient between an injection well and a production well. Here, barriers, faults and major permeability contrasts lead to complete or partial bypassing of large regions of the reservoir. The recovery efficiency is represented by the average oil saturation in the reservoir determined by some economic limiting condition. There is a distinction between the average saturation in the swept region, $S_{or}(SWEPT)$, and the average residual oil in the whole reservoir including non-swept regions, S_{or} . The value of S_{or} is used to calculate the relevant recovery factors.

In reservoir analysis, the connectivity between vertically adjacent sands and the degree of contrast in permeability within a given unit are important as they determine any cross-flow between layers. Whilst these factors may be estimated at the well, it is important to be able to predict them away from the well. Routine predictions of cross-flow are made using a combination of core-derived absolute permeabilities, well-test derived effective permeability and the dynamic R.F.T. (Repeat Formation Tester) response. Additional predictions of cross-flow are provided by knowledge of the geometry and continuity of characteristic sand-body types and their effect on displacement. All of this information helps reduce the risk of incorrect or oversimplified averaging procedures which can lead to erroneous predictions of future performance of the reservoir. The information on characteristic sand-body types is available from detailed sedimentological observations

combined with petrophysical and pressure data obtained from outcrop or other reservoirs.

Large scale heterogeneities can have a significant effect on the design of injection schemes. In complex depositional environments, the prediction of effective dynamic compartments in the reservoir is essential as separate injection - production schemes may be required for efficient reservoir management.

Heterogeneities can also control the rate of oil production or injection rate. In homogeneous reservoirs the rate of oil production may not affect the ultimate recoverable volume when the effects of gravitational forces are minimal in comparison to the effects of viscous flow. Reservoirs displaying this type of flow behaviour are likely to have laterally extensive but thin, sheet-like geometries. Gravity drainage mechanisms may be pronounced within thick or steeply dipping homogeneous reservoirs. In heterogeneous reservoirs, recoveries may be lower than expected if the production rate is based on averaged homogeneous reservoir properties. This may be exaggerated by the competing forces of capillarity, gravity and viscous flow. These forces operate over the range of scales from microscopic to interwell and vary depending on the nature of the heterogeneities present and the magnitude of permeability differences.

The correct prediction of reservoir heterogeneities in the interwell region is of paramount importance for oil recovery. A knowledge of the various scales at which reservoir heterogeneities occur may significantly improve averaging procedures and the design of injection and production well location. Thus, an improved understanding of reservoir heterogeneities in terms of their character, spatial disposition and effect on displacement should inevitably lead to improved predictions of oil-in-place and recovery efficiencies.

2.3 Reservoir modelling

A reservoir exists and its characteristics are fixed deterministically, that is, the value for a specific property or feature, for example, porosity or

sediment type, can be measured at all scales and at all points in three-dimensional space. In reality however, due to high drilling costs and limitations imposed by the measuring devices, the knowledge of this system is usually restricted to a few pre-selected boreholes. Whilst individual logs may be run for the entire length of the borehole, composite log suites and core retrieval tends to be restricted to zones of reservoir potential. The reservoir interval is usually sub-sampled for core plugs, either from whole core or from the borehole wall. The sample interval is typically at 1' (0.3 m) intervals. These plugs are used for porosity and permeability measurements, special core analysis (SCAL), and sedimentological analysis. These direct measures of reservoir properties and characteristics (= 'hard' data) are used for the prediction of reservoir heterogeneities into the interwell area.

The validity of predictions of reservoir heterogeneity in the interwell area depends on a number of factors. These factors include the number of wells, the distance between wells, the vertical sample interval within wells, the geological complexity of the reservoir, and the detail of information available from seismic data. Current seismic techniques, whilst often providing excellent two and three dimensional images of the reservoir, are usually of insufficient resolution to correlate features below the scale of major facies changes and stratigraphic horizons (for example, unconformities). To improve reservoir description, some form of modelling that maximises use of the 'hard' data is required. Where observations are correlatable (for example, a shale marker bed), the model is described as deterministic, whereas for correlation obtained through educated aiming (geology, sedimentology) and formalised guesswork the model is described as stochastic (Haldorsen and Damsleth 1990). A deterministic variable is one that, given a set of circumstances, produces the same result. A stochastic variable on the other hand, given a set of circumstances, does not always produce the same result but being confined by statistical regularity is not random.

Few reservoirs can be adequately described using a single deterministic model. This is because reservoir heterogeneities occur over a range of scales where one scale of heterogeneity may be deterministic, for example, the lateral correlation of a deltaic sequence, but other scales of heterogeneity are not, for example, the lateral correlation between

channel facies within the deltaic sequence. Whether a reservoir is modelled deterministically or stochastically therefore depends on the scale at which it is examined. A mixed deterministic - stochastic model may be used to model the entire reservoir.

Laterally discontinuous features are more problematic, and have understandably received more attention. This has resulted in the development of a large number of stochastic modelling techniques. These techniques can be divided into two classes; discrete and continuous (Dubrule 1988, Haldorsen and Damsleth 1990).

2.3.1 Discrete stochastic models

Discrete models are used to describe geologic features of a discrete nature. These are features that have limited and definable characteristics that differentiate the feature from its surrounding medium. Examples of discrete geologic features include sand bodies, shales, facies type and fractures. The discrete stochastic model describes the dimensions and orientation of discrete features. The model also describes the distribution of these features, controlling how each of the discrete features interact.

In the discrete model, rock properties are estimated within assigned classes, such as lithotypes. An example of a discrete stochastic model is the generation of possible channel sand-bodies in cross-section. Assuming the sand bodies are of equal size, the position of each sand body may be generated randomly but controlled by a set of rules. These rules result from an understanding of the geologic processes of channel sand aggradation, accretion and avulsion. For example, one constraint may be that no channel may directly overlie another because observations of differential compaction show a raised surface over channels after burial. This demonstrates the importance of geological guidance in discrete stochastic models. In this example, channel sands may be assigned a permeability value of '1', and interchannel or floodplain deposits assigned a permeability value of '0', as they are comprised mostly of clays and silts.

The example given here represents a very simplistic model for sand body distribution. In reality, the situation is far more complex and sand body dimensions may vary, other heterogeneities may be present (shales and faults for example), and the disposition and connectivity between sand bodies may result from a wide range of processes interacting in a very complex manner. Discrete models are designed to represent these various factors and as a result much work has been done to quantify them (for example Allen (1978), Bridge and Leeder(1979), and Childs et al (1989)). Attempts have since been made to integrate the results of these studies into discrete stochastic reservoir models as demonstrated by Abu-Elbashar et al (1989) and Abu-Elbashar (1990).

Examples of discrete stochastic models are marked point processes including Boolean schemes and random genetic models (Matheron 1975 and Hoiberg et al 1990), Markov fields (Hoiberg et al 1990), truncated random functions (Matheron et al 1987), and two-point histograms (Armitage and Norris 1991).

2.3.1.1 Stochastic shale models

The distribution of shales within sands has received considerable attention because of their affect on fluid flow in the reservoir, for example, gas underrunning, coning protection, and cross-flow. Predicting the shale distribution between wells is problematic because little is known about their lateral dimensions. Correlatable shales can of course be modelled deterministically and are often called marker beds for this reason, but uncorrelatable shales must be modelled stochastically. This requires a statistical description of the vertical and horizontal shale dimensions. Variation in shale thickness can be estimated from core and well-logs (for example, the gamma-ray log) from the reservoir thereby incorporating compaction effects. Variations in shale length and width can be estimated by direct measurement of shales in modern depositional environments (for example, through aerial photography or Landsat imagery) or ancient depositional environments preserved at outcrop. A shale thickness/length/width correlation is required to add length and width to the shales identified in the wells, and to add the appropriate

thickness (considering compaction under reservoir conditions) to the simulated inter-well shales.

In the example given by Haldorsen and Chang (1986), synthetic shale distributions for the reservoir were generated in 2-D using a Monte Carlo simulation, conditioned to the shales observed at the well. This stochastic model generates a random disposition of shales with no correlation between shale size and position. To test whether this synthetic shale distribution was realistic Haldorsen and Chang performed a geostatistical study on the outcrop from which the synthetic shale distribution was generated. This geostatistical study revealed that whilst the disposition of shales may or may not be random, the shale lengths were certainly correlated in space. This comparison between the real and simulated data provides a useful method for evaluating the model. In this case however, the shale model used does not consider the spatial correlation of shale lengths and the use of a discrete Monte Carlo model to generate synthetic shale distributions within sands should perhaps be questioned. Further research may be required into more appropriate modelling techniques for shales such as indicator kriging (Ravenne et al 1987).

Two further assumptions about sand-shale sequences are also required for these shale models. The first assumption is that the shales are impermeable. Begg et al (1985) have shown that in general, shales can be considered impermeable providing the sand permeability, measured on core plugs, is at least 100 times higher than the shale permeability. Given the tabular dimensions assumed for shales, these are likely to have greatest effect on vertical permeability. Where the shales are short (that is, less than the grid block length or width), the shale permeability is probably insignificant if the vertical flow path deviates around the shale margins. Where there is a high pressure differential across the shale (high pressure below and low pressure above), this may be sufficient to cause reservoir fluid to pass through the shale exploiting potential permeability pathways such as burrows and fractures. Where the shales extend over the horizontal dimensions of the grid block, the vertical permeability of the shale may be very significant, especially in thin shales where clay smearing does not seal faults and long, vertical sand-filled burrows (for example, *Skolithos*), grasses and roots perforate the shale.

Permeability measurements may be made on these burrows and plant structures using the probe permeameter (Weber 1982). The second assumption in these shale models is that variation in permeability within the sands can be neglected. In support of this, Desbarats (1987) states that experience with sandstone reservoirs has shown that randomly dispersed low-permeability shales are the single dominant heterogeneity affecting flow behaviour. However, Desbarats does not provide evidence for this assumption. It is probably worthwhile investigating the permeability variation within the sand fraction for different net to gross ratios to examine their influence of this permeability variation on fluid flow behaviour.

In a later study, Hoiberg et al (1990), used two different techniques for modelling shales distributed within sands where the size of the shale units formed two discrete populations. The large shale units were usually intersected by more than one well and were concentrated along time horizons, correlatable between wells (=correlation surfaces). As the disposition of these large shale units along the correlation surface could not be generated using the Monte Carlo approach of Haldorsen and Lake (1984) or Begg et al (1989), a 2-D Markov random field model was used. This model is specified as the conditional probability for shale thickness in an arbitrary location on the correlation surface given the thickness in a defined neighbourhood. The disposition of small shale units was generated using a marked point process which allows random positioning but prevents overlap.

2.3.2 Continuous stochastic models

Continuous models are used to describe phenomena that vary continuously, for example permeability and porosity. Each point in space has its own distinct value for each variable. The model is concerned with the knowledge of how one variable enhances the prediction of the same or a different variable elsewhere. The input parameters include directional trends (especially vertical and horizontal), the variability around the mean, correlation lengths or the similarity of neighbouring variables at different spacings, and the covariance of different variables or the correlation between different variables.

Continuous models all fall within the framework of geostatistics. Examples of continuous models are random functions and random fields, universal and indicator kriging (including co-kriging where more than one variable is used), and fractals. As continuous stochastic models are particularly relevant to outcrop permeability studies with direct measurements of permeability, the geostatistical methods are described in more detail.

2.3.2.1 Geostatistical methods

Geostatistical methods were first used in mining but the formalisation of geostatistics was not developed until Matheron published his 'Traite de Geostatistique Appliquee' in 1962, representing the culmination of many years work on the subject. This was followed by the publication (in English) of the principles of geostatistics (Matheron, 1963), and later the publication of the theory of regionalised variables (Matheron 1971), upon which geostatistical theory is based. The application of geostatistical methods outside the oil industry was first applied to the hydrosciences by Delhomme (1976), but application to the oil industry has been slower. Geostatistical application to the oil industry has received more attention over the last few years with considerable use of the variogram and the development of spatial permeability distributions through conditional kriging (for example, Da Costa E Silva 1985, Gomez-Hernandez and Journel 1990, Rumhy 1990, and Aasum et al 1991).

Geostatistical theory assumes that the variable in question is stationary, that is, all moments of the distribution of the variable are invariant under translation (Armstrong 1990). In reality this is rarely the case and 'weak' or second order stationarity is assumed. In this case, only the first two moments, the mean and covariance, are required to be constant with the difference between two values arranged in space dependent only on distance between the values and direction of one from the other. Where the assumptions of second order stationarity are not satisfied erroneous results can be obtained.

The stationarity of a regionalised variable depends on the size of the

window of observation. With the resolution (or sample size) constant, changing the window size can change the data from non-stationary to stationary and vice versa. For example, a permeability profile for a well obtained from core plug measurements at 1' intervals may be non-stationary over the full cored interval but stationary over part of it. Similarly the data may be stationary over the full cored interval but non-stationary over part of it.

Where the drift in the data sequence responsible for non-stationarity is known this may be removed by fitting a polynomial trend and obtaining the residual values, thereby restoring stationarity. A technique for removing drift with minimal bias when the drift is not known *a priori* involves applying a series of filters, or polynomial trends to the data (Armstrong, 1990). After each filter is applied, the residuals are checked for non-stationarity and an appropriate subsequent filter is applied.

2.3.2.1.1 The variogram

With the assumption that the data are stationary, the spatial correlation of data points can be determined through the use of the variogram (Armstrong 1990, Clark 1979, Journel and Huijbregts 1978). The variogram expresses the similarity, on average, of measurements at increasing distance apart. This relationship between the values of a spatial variable is given by the following equation:-

$$\gamma(h) = \frac{1}{2n} \sum_{i=1}^n [z(x_i) - z(x_i + h)]^2$$

where $\gamma(h)$ = a vector function that varies
with distance and direction

$z(x_i)$ = the measured variate at
position x_i

.....(1)

The spatial covariance between data points are calculated for all possible directions within a defined search ellipse, or tolerance (Figure 2.2). If

this search angle is set at 90^0 all data pairs are included in all possible directions. This produces an omnidirectional variogram. If anisotropic behaviour is suspected where correlation lengths differ in different directions, then directional variograms may be constructed with a specified search angle and tolerance.

The validity of the variogram will depend on the number of data pairs at a given sample spacing, h . To maximise validity of the variogram the sample points are usually arranged in a regular grid format, aligned along the principal axes of interest. For example, where permeabilities are measured from a sequence of parallel bedded rocks, the sample grid may be aligned parallel and perpendicular to the bedding planes, along the directions of the principle permeability tensors, $K_{\text{horizontal}}$ and K_{vertical} .

Most of the problems associated with variography concern sampling. Ideally, variograms of permeability should be constructed from exhaustively-sampled data (=minimum sample interval without overlap of sample volumes). Inexhaustive sampling can result in apparent structures identified by the variogram that correlate with the sample interval and not to the actual permeability structure present. This is because the variogram is sensitive to periodic behaviour where the range may be a multiple of the sample interval. On the other hand, where there is an overlap of the sample volumes the variogram may display a well-defined sill and range. This is because an overlap in the sample volumes will automatically produce similarities in permeability between adjacent samples with a smooth increase in covariance as the sample interval increases.

With increasing distance between sample points fewer sample pairs are available to calculate the average sample variance. As a general rule, the variogram is unreliable beyond $2/3$ of the maximum sample interval. This point is often identified by a characteristic sharp drop in the variogram. To ensure that the maximum correlation length obtained is statistically reliable, the sample domain must be at least one and a half

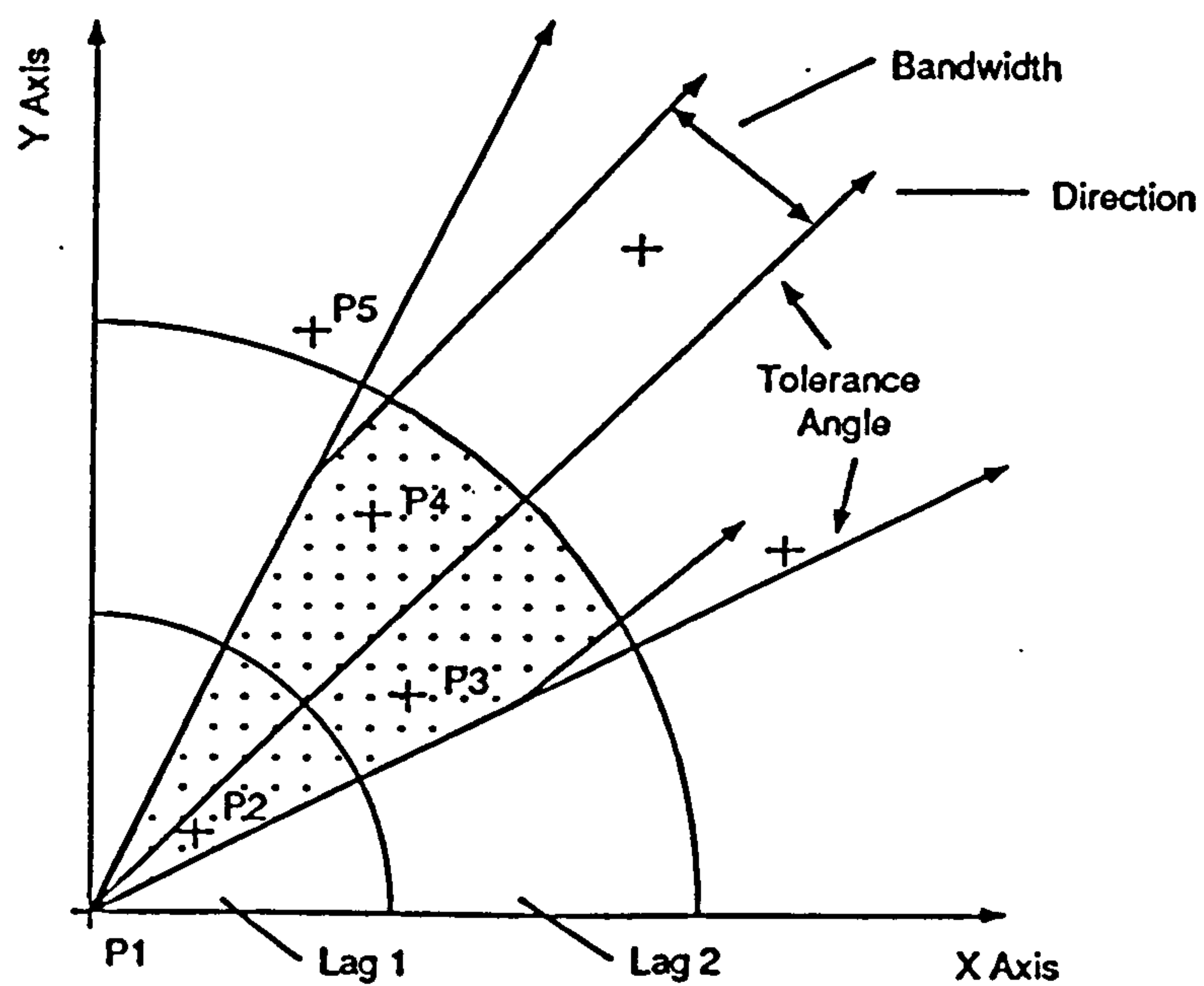


Figure 2.2 The direction, tolerance and bandwidth: parameters used to define the search ellipse used to select data pairs in the variogram calculation.

times this correlation length. To avoid misinterpretation of the variogram therefore, it is helpful to have some prior knowledge of the likely permeability structure and the probable correlation lengths before sampling and constructing the variogram. Although this appears to be a circular argument, the correlations may be validated by extending the sample domain and obtaining infill samples from which a second variogram is constructed. If the correlation lengths are the same for both variograms then they can be regarded as genuine and not sampling-related artefacts.

A particular problem associated with variograms constructed for permeability measurements concern the anisotropy of the measurement itself. Construction of the variogram is based on the assumption that the difference between values is a function of sample spacing only. If the anisotropy of the permeability measurement is unknown (for example, where probe permeameters are used), the variogram may give misleading trends where variation between sample points due to anisotropy is incorrectly modelled as spatial structure. It is important therefore, to know the anisotropy ratio of each permeability measurement thereby allowing variograms to be constructed for permeabilities measured in the same direction.

The variogram, whilst relatively simple to construct and intuitively appealing, could be easily abused and incorrectly interpreted. It is advisable therefore, to use additional techniques such as regression analysis to verify the results and avoid misinterpretation. Usually the worker has some prior understanding of the spatial distribution of the variable under consideration. For example, the thickness of coal seams at short sample spacing is likely to be very consistent and therefore a zero nugget effect would be expected in the variogram model for coal thickness. Channel sand bodies on the other hand, may display fining-up sequences and grain size data from vertical sample transects within these sand bodies are likely to be non-stationary. Some form of filter therefore, will be required to remove this drift before construction of the variogram.

2.3.3 Hybrid or mixed deterministic - stochastic reservoir models

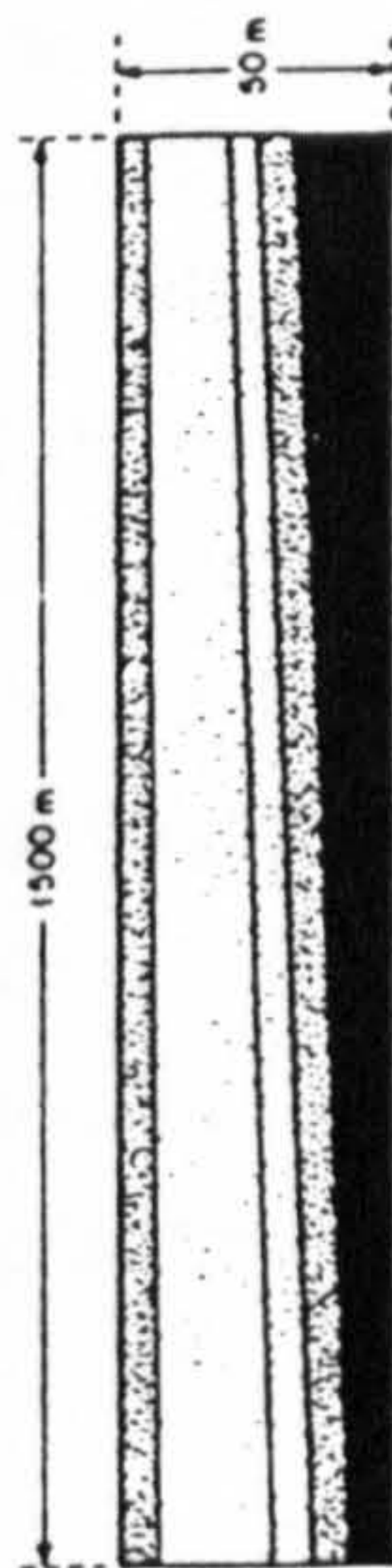
Heterogeneities, such as those associated with the distribution of major facies changes, channel sand bodies and shales, represent geologic features of a discrete nature for which a discrete stochastic model is appropriate. Within these discrete units, the spatial distribution of rock properties or characteristics may vary continuously for which a continuous stochastic model is appropriate. A logical step therefore, is to combine the model types in a two-stage process; first, by developing the discrete stochastic model, and secondly, by refining this model using the appropriate continuous stochastic model for each discrete unit.

2.3.4 Flexible reservoir models

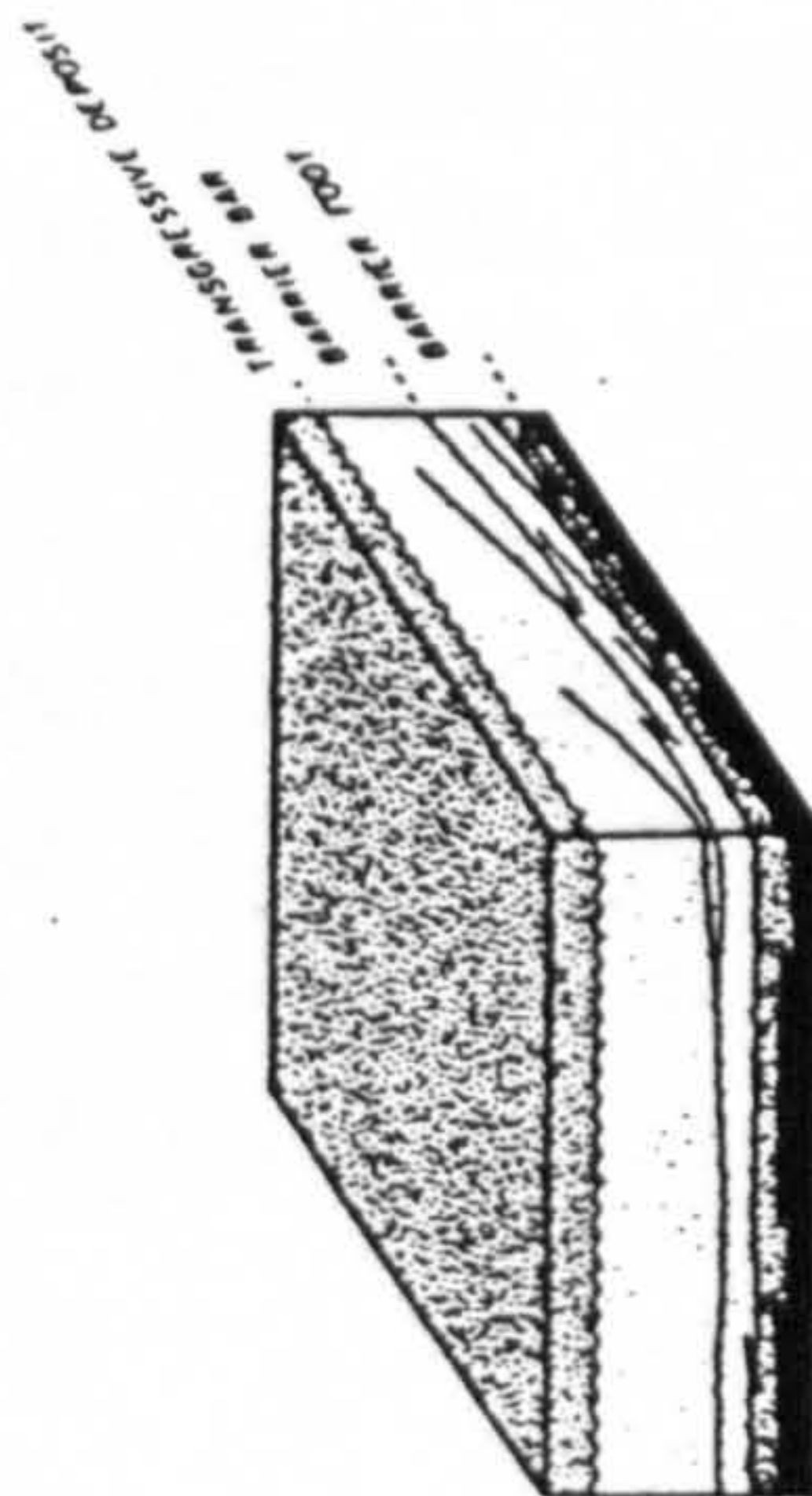
Weber and van Geuns (1989) present a framework for constructing clastic reservoir simulation models from the viewpoint of the geologist. Three basic reservoir types are proposed with increasing complexity; layercake, jigsaw-puzzle, and labyrinth (Figure 2.3). These are thought to be representative of a wide range of reservoir types. A reservoir may be comprised of a combination of types, in which case the reservoir is divided into sub-domains representing these different types. The choice of classification type depends on the well density and the lateral and vertical continuity of discrete units with characteristic properties, for example, sand lenses, and is well suited to the sedimentary genetic unit or building block approach. Such an approach requires an understanding of sedimentary architecture and is therefore most suited to the geologist's appreciation of the reservoir.

The purpose of such a framework for constructing clastic reservoir simulation models is to promote the use of geological information for engineering problems, whilst retaining the integrity of the geologists' and reservoir engineers' interpretation of the reservoir. Having established which model type(s) to apply, the dimensions and petrophysical characteristics of the discrete geological units are defined. The distribution of these discrete units is then determined by the model.

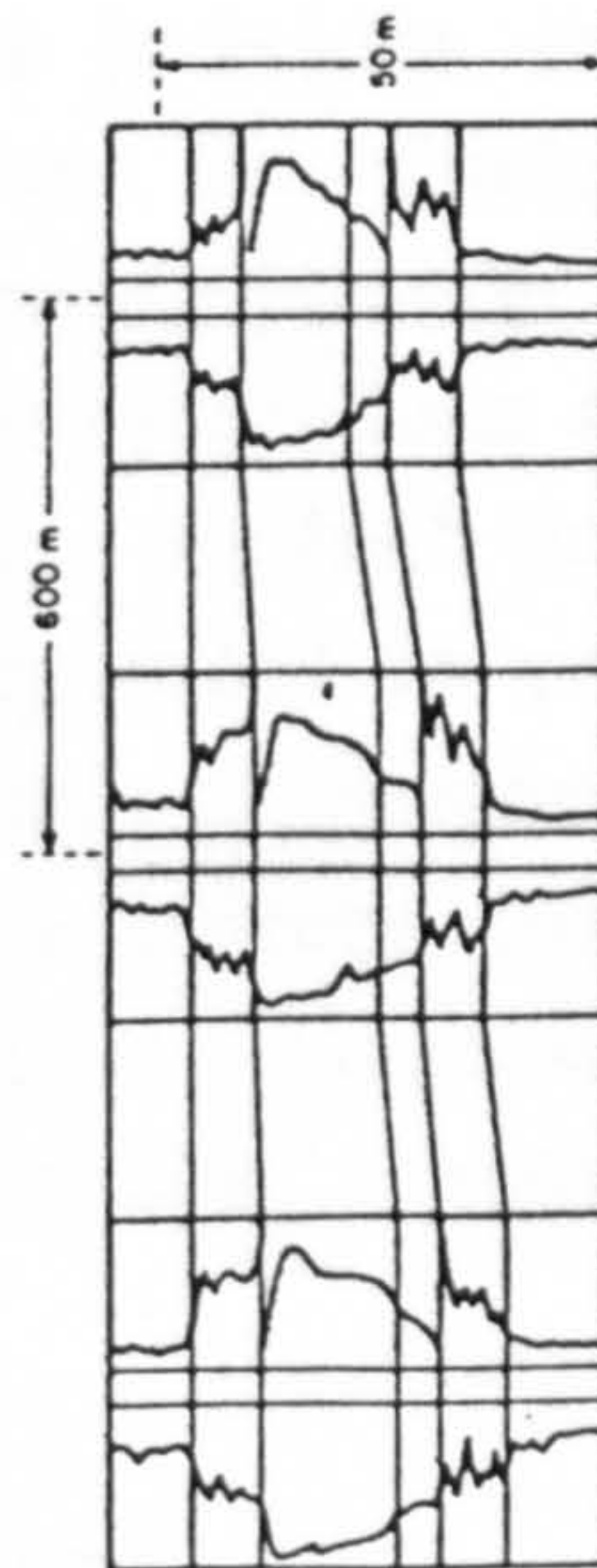
A. LAYER-CAKE RESERVOIR TYPE



a) DISTINCT LAYERING WITH MARKED CONTINUITY AND GRADUAL THICKNESS VARIATION



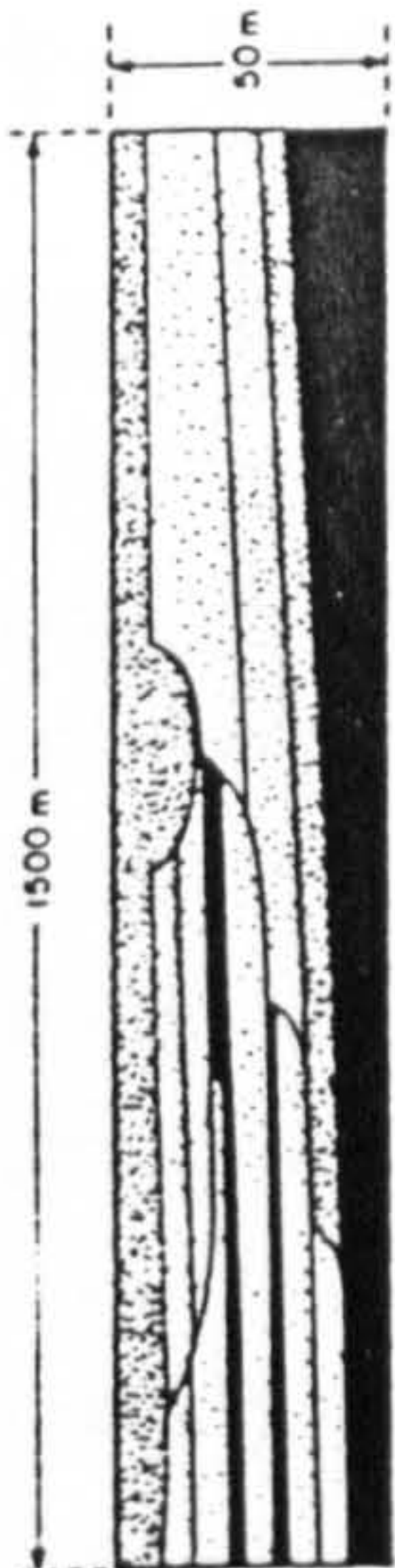
b) LAYERS REPRESENT SANDS DEPOSITED IN SAME ENVIRONMENT OF DEPOSITION



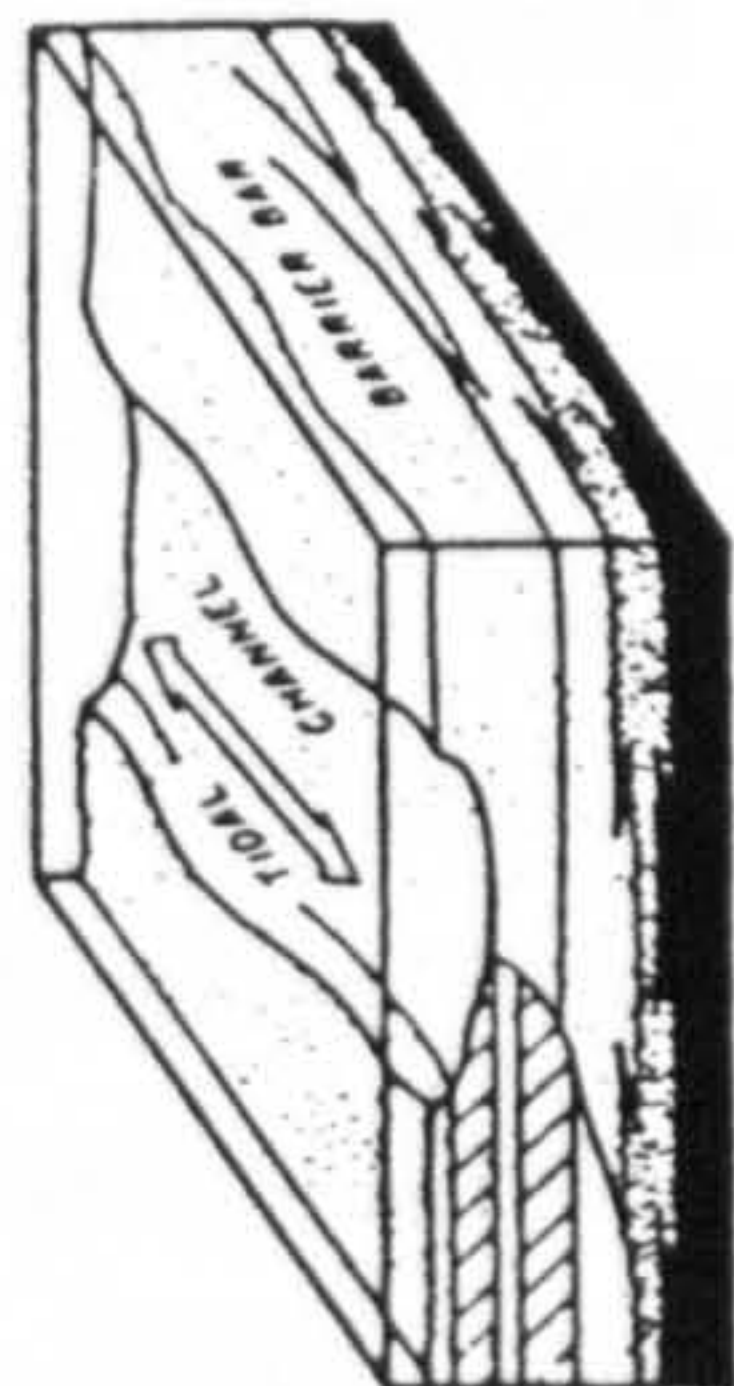
c) EXCELLENT LOG CORRELATION SHOWING GRADUAL LATERAL CHANGES IN THICKNESS AND PROPERTIES

WELL PATTERN	SPACING, m	WELLS/km ²
RECTANGULAR	1000	1
TRIANGULAR	1200	0.8
RANDOM		1.3

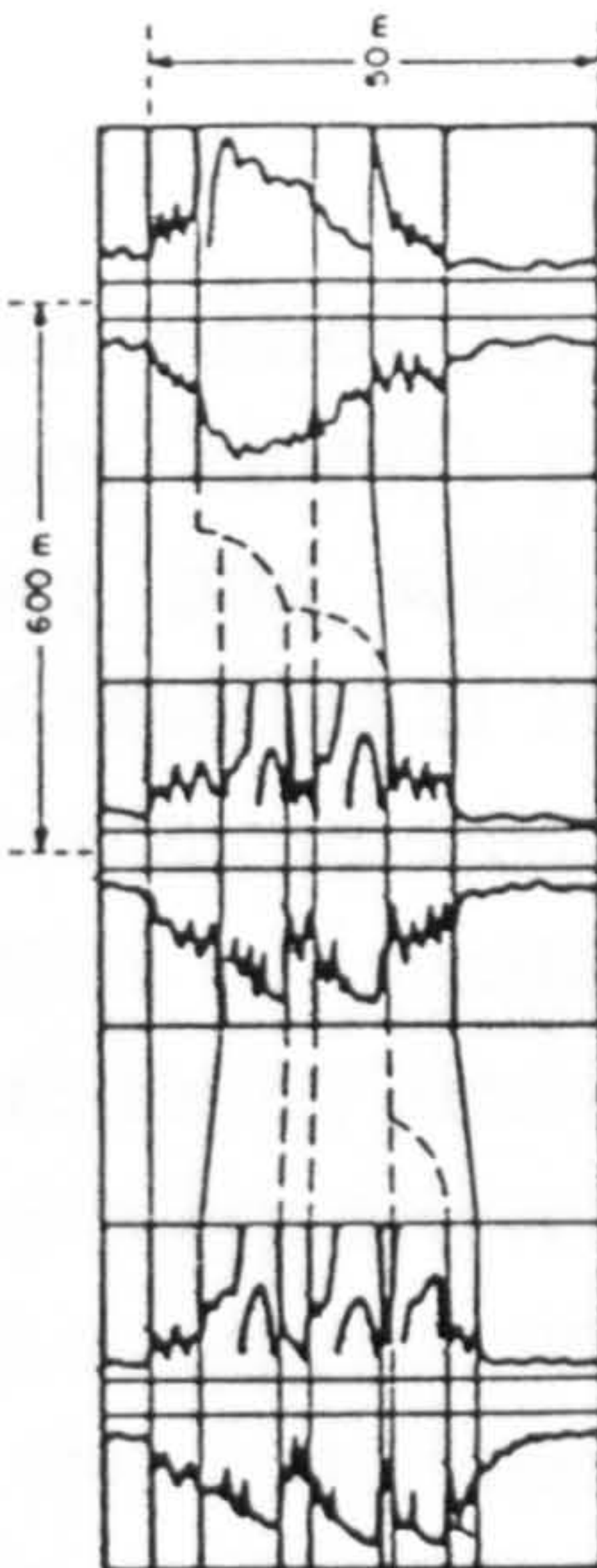
B. JIGSAW PUZZLE RESERVOIR TYPE



a) DIFFERENT SAND BODIES FITTING TOGETHER WITHOUT MAJOR GAPS. OCCASIONAL LOW PERMEABLE ZONES CAN OCCUR LOCALLY BETWEEN ADJACENT OR SUPERIMPOSED SAND BODIES



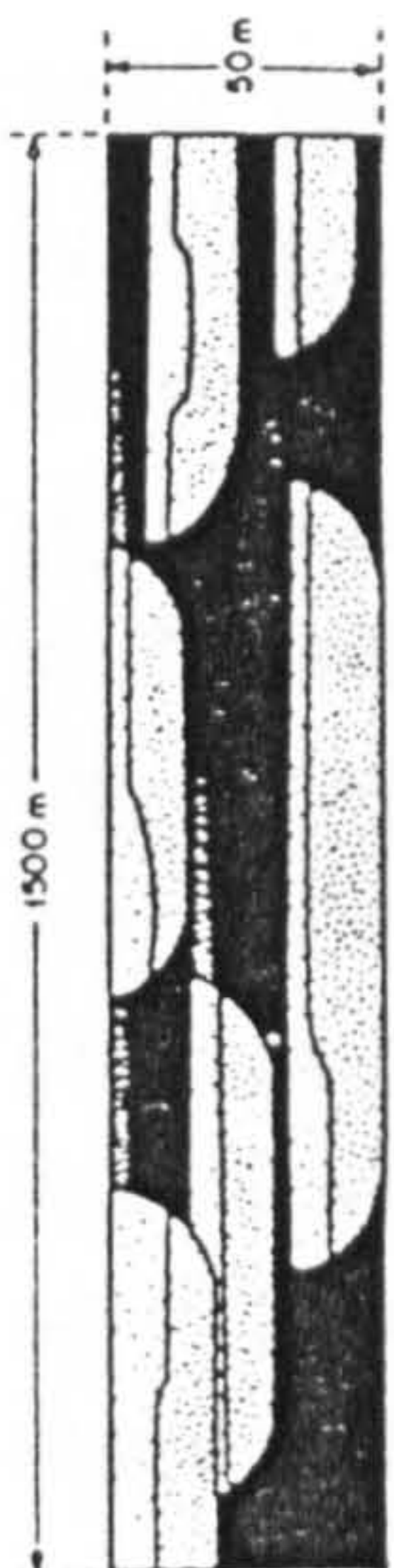
b) RESERVOIR ARCHITECTURE DETERMINATION REQUIRES DETAILED SEDIMENTOLOGICAL ANALYSIS



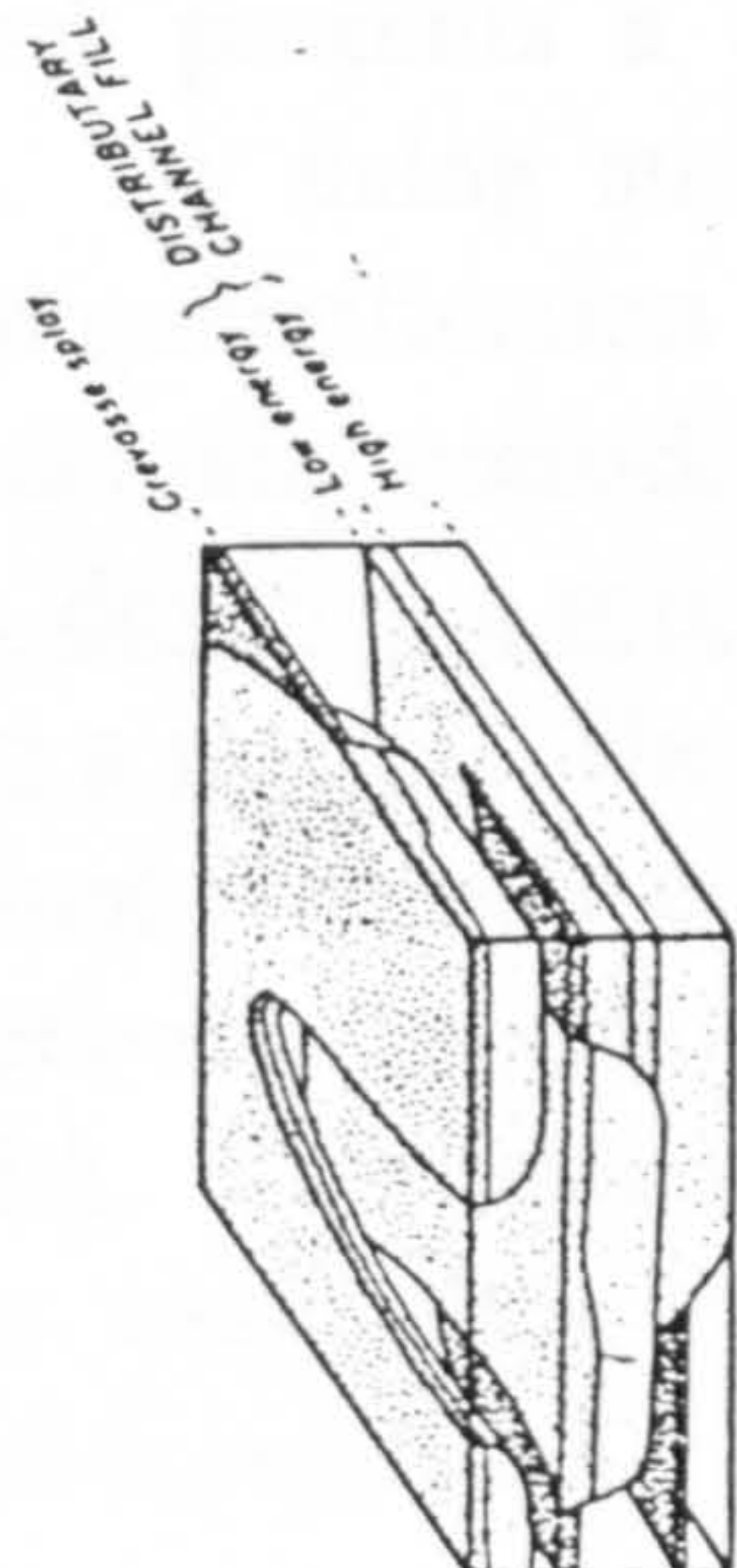
c) ALTHOUGH THE SAND/SHALE RATIO IS HIGH, CORRELATION MAY BE DIFFICULT WITHOUT DETAILED FACIES INTERPRETATION

WELL PATTERN	SPACING, m	WELLS/km ²
RECTANGULAR	600	3
TRIANGULAR	800	2
RANDOM		4

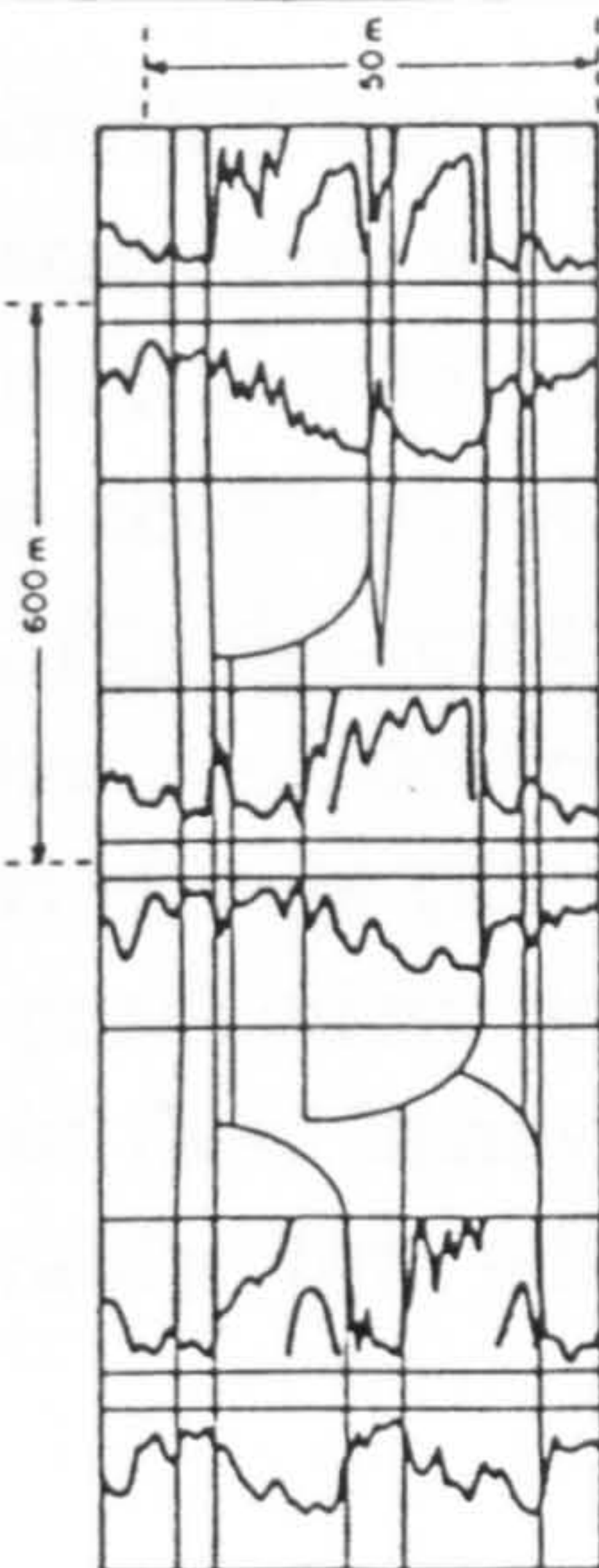
C. LABYRINTH RESERVOIR TYPE



a) COMPLEX ARRANGEMENTS OF SAND PODS AND LENSES OFTEN APPEARING DISCONTINUOUS IN SECTIONS



b) IN 3D INTERCONNECTIONS EXIST LOCALLY BUT IN PART ONLY VIA THIN LOW PERMEABLE SHEET SANDS



c) DIFFICULT LOG CORRELATION EVEN WHEN WELL SPACING IS 400 TO 600 m

WELL PATTERN	SPACING, m	WELLS/km ²
RECTANGULAR	200	25
TRIANGULAR	300	13
RANDOM		32

APPROXIMATE AVERAGE DATA DENSITY REQUIRED FOR DETERMINISTIC CORRELATION OF MAJOR SAND UNITS

Figure 2.3 A framework for constructing clastic reservoir simulation models (after Weber and van Geuns, 1989)

This framework presents a very distilled representation of reservoir heterogeneity. By using such a framework we risk constraining our description and quantification of the reservoir to one of only three model types without actually considering the actual physics of the reservoir. It is desirable to develop a model that fits the reservoir rather than to fit the reservoir to a model. The importance of flexible reservoir models is necessary because reservoir conditions change (for example, the pressure differential between injection and production wells and the type of reservoir fluids). Consequently, fluid flow behaviour within a similar reservoir type may vary considerably for which the appropriate reservoir model is required.

2.4 Permeability averaging

The variety of data sources in reservoir studies (for example, core plugs, whole core, and D.S.T. (Drill Stem Tests)) provide estimates of permeability over different volumes and with different levels of precision and accuracy (Allen 1988, Ahmed et al 1989). For example, a pressure build-up test may have a radius of investigation around the borehole of up to one to two kilometres and containing more than one petrophysical zone. When the permeability derived from this test is compared to the effective phase permeability derived from the core plugs representing the vertical petrophysical zones, the volume of the build-up can be ten billion times larger than the combined volume of the core plugs (Dubrule and Haldorsen 1986). Further complications exist because the pressure build-up test provides an approximation of permeability with assumptions about the thickness and radius of investigation. The core plugs however, provide a direct measure of permeability, usually for air, but approximations are again used when this is converted to liquid permeability. As both precision and accuracy are quantifiable, they can be incorporated in comparisons between different measurements relatively easily. Differences in sample volume or measurement scale however, are more problematic because a change in the volume is often associated with a change in variance and some process of volume averaging or 'normalising' is required.

A commonly used technique for predicting reservoir performance is through computerised numerical reservoir simulation. This technique dates back to the early 1960's and developments through to the present day are summarised by Breitenbach (1991). Due to the running costs and restricted memory of computers, the reservoir is modelled using a limited number of cells or grid blocks. The task of the reservoir engineer is to select the appropriate mathematical model and grid dimensions to predict the reservoir performance under given conditions (for example, water flood). The appropriateness of the model is assessed through history matching (comparing actual results with the predicted results), and the model modified accordingly. The geological model for the reservoir is divided into blocks (typically 100's of metres in the horizontal and 10's of metres in the vertical) which comprise the reservoir model. A single value for each of the various reservoir properties and characteristics are assigned to each block (for example, capillary pressure, porosity, and relative permeability). To determine the value of these parameters, some process of scaling up is required. The grid block size is usually fixed first, the size depending on the geological complexity of the reservoir model.

The scaling up or averaging process for reservoir description comprises two stages. The first stage is the solution of the scale difference between data sources, and the second stage is the assignment of grid block parameters.

2.4.1 The classical statistical approach

In a study of the pressure build-up response for different randomly distributed data sets, seeded from a log-normal distribution using a Monte Carlo approach, Warren and Price (1961) concluded that 'the most probable behaviour of a heterogeneous system approaches that of a homogeneous system with a permeability equal to the geometric mean [average] of the individual properties'. Matheron (1967) found that the effective permeability in an unbound, statistically isotropic medium with a log-normal permeability distribution was also equal to the geometric average, supporting the findings of Warren and Price. In simple systems analysed in linear geometry, the appropriate average is shown to be a

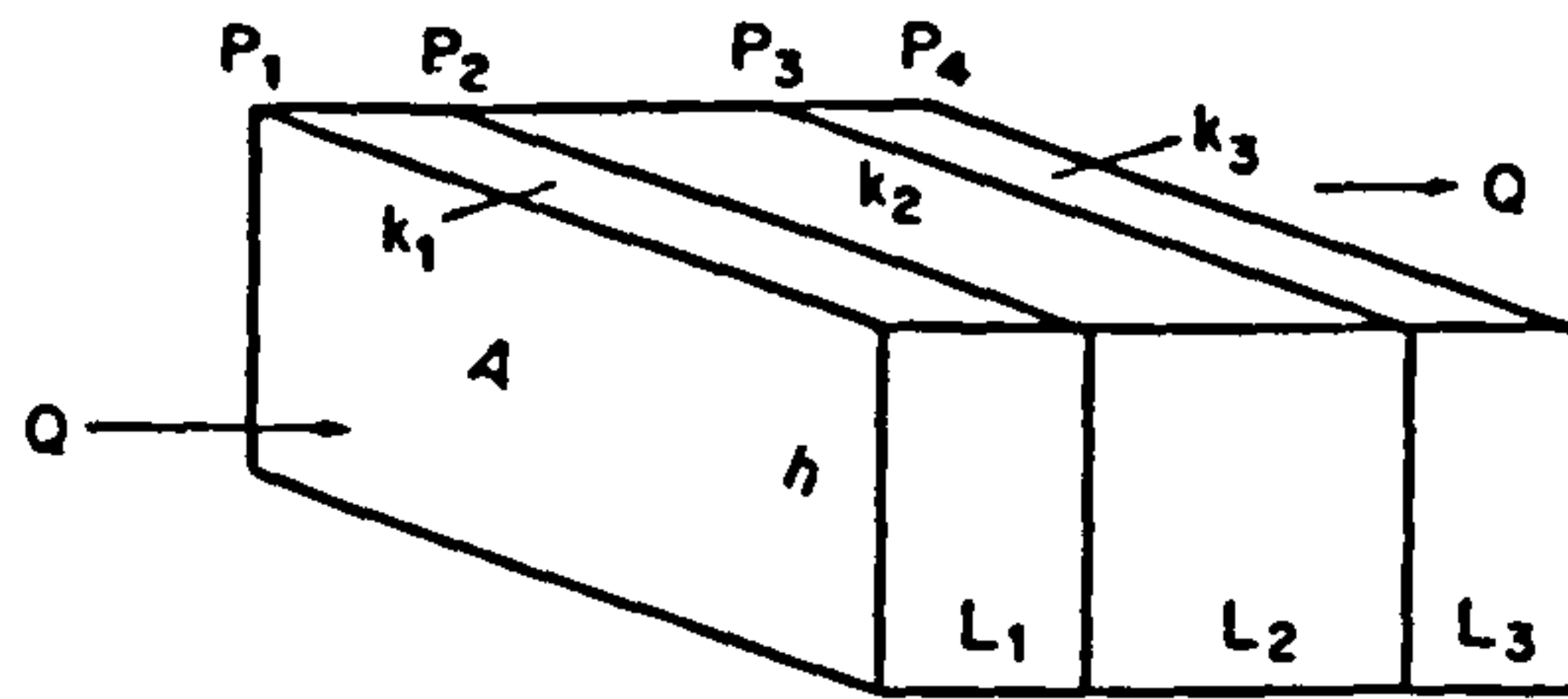
harmonic average for beds in series and an arithmetic average for beds in parallel (Figure 2.4).

Calculation of these averages is based on the assumption that there is no cross-flow between beds, that the beds arranged in series are of equal area, and that the pressure drop across beds arranged in parallel is constant in all beds at equal distances (Archer and Wall 1986). Where the bed thickness varies, the average permeability is thickness-weighted. Thus, a convenient estimate for average permeability is provided for vertical and horizontal permeability. These averaging techniques are based on the following assumptions:-

- 1) That the sample volume is volumetrically representative.
- 2) That the nature of the heterogeneity can be estimated from core data from which the true distribution function for the reservoir can be obtained.
- 3) That random spatial distributions of permeability may exist in reservoirs, that is, vertical and lateral variations may be of the same order of magnitude.

These are very large assumptions and the following criticisms of the statistical approach are made (after Costa da Silva 1984). In the first assumption where the samples are assumed to be volumetrically representative, the relationship between sample size and reservoir is not solved correctly. Where permeabilities are measured on core plugs, this means that the value of permeability for each plug is taken to represent the permeability of whole core with a length equal to the core plug interval. This disregards the effect of heterogeneities over the volume of whole core and assumes that homogenisation of variation is reached at the core plug scale.

Regarding the second assumption, there is no estimate of the degree of error associated with the values generated from the restricted well data. Cardwell and Parsons (1945) suggest that if only 10 to 20 core plugs are used in the permeability estimation for the interval flow-tested, it will often be found that there is no correlation between the results of the flow



Linear beds in series.

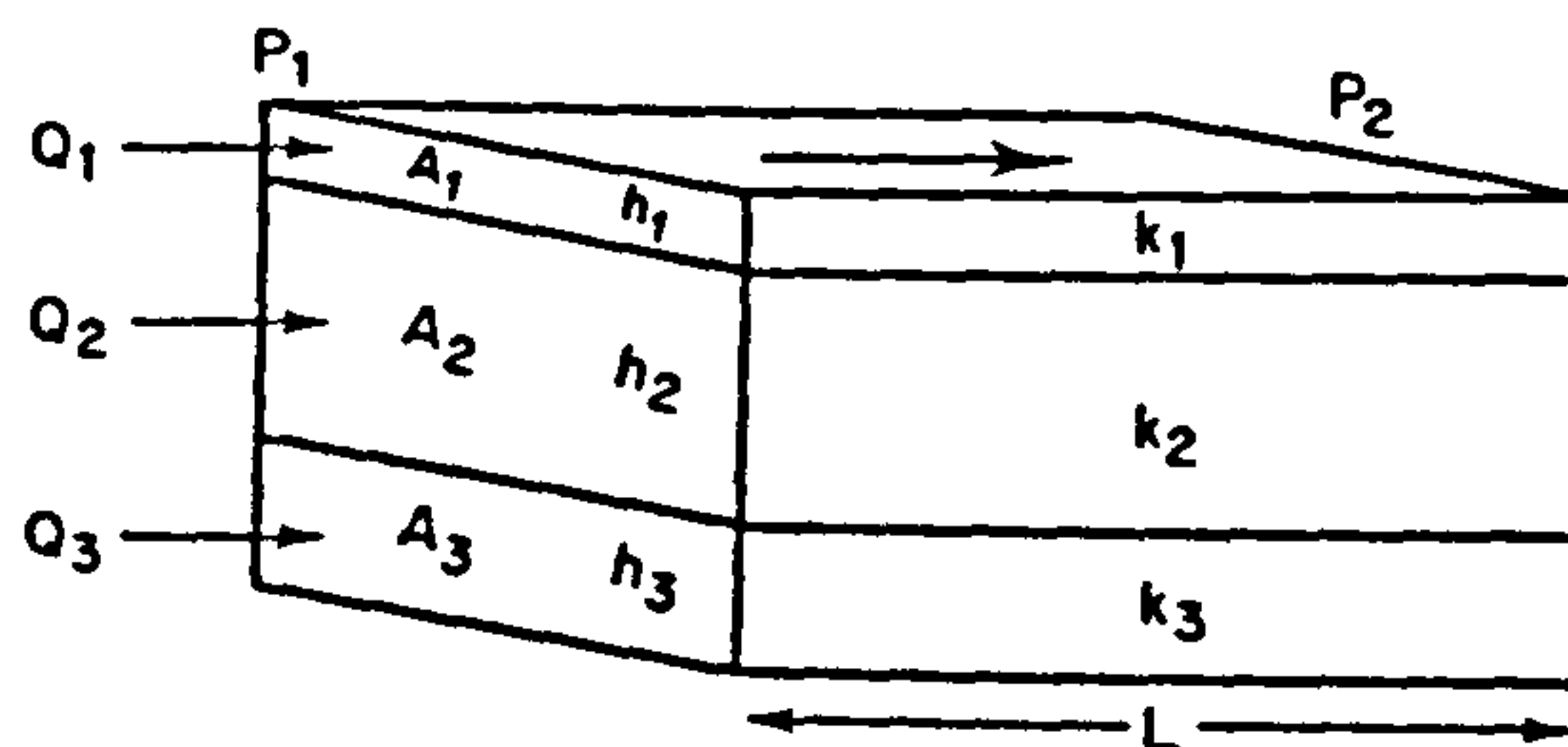
$$(P_1 - P_4) = (P_1 - P_2) + (P_2 - P_3) + (P_3 - P_4)$$

$$\therefore \frac{QL}{\bar{k}A} = \frac{QL_1}{k_1 A_1} + \frac{QL_2}{k_2 A_2} + \frac{QL_3}{k_3 A_3}$$

For equal A then

$$\bar{k} = L / \sum \{L_i / k_i\}$$

The appropriate mean is thus a harmonic average permeability $\bar{k}_H$.



Linear beds in parallel.

$$Q_t = Q_1 + Q_2 + Q_3$$

$$\frac{\bar{k} A (P_1 - P_2)}{\mu L} = \frac{k_1 A_1 (P_1 - P_2)}{\mu L}$$

$$+ \frac{k_2 A_2 (P_1 - P_2)}{\mu L} + \frac{k_3 A_3 (P_1 - P_2)}{\mu L}$$

$$\bar{k} A = k_1 A_1 + k_2 A_2 + k_3 A_3$$

$$\bar{k} = \frac{\sum k_i A_i}{\sum A_i}$$

When all beds are the same width, then $A \propto h$ so $\bar{k}$ is an arithmetic average, $\bar{k}_A$.

$$\bar{k}_A = \frac{\sum k_i h_i}{\sum h_i}$$

Figure 2.4 Diagrammatic illustration of statistical averaging techniques for beds arranged in series (top) and parallel (bottom) (From Archer and Wall, 1986)

tests and the permeability of the analysed plugs. Usually 40 to 50 plugs are required to determine the nature of the heterogeneity (assuming a statistically isotropic medium) and to obtain reasonable results.

The assumption that the true permeability distribution type for the reservoir is represented by core data is based on the further assumption that the true distribution of permeability data is log-normal at all volume-scales. This assumption allows the prediction of the true distribution function for permeability for the reservoir from a sub-sample such as obtained from a set of core plugs. This widely-used assumption is based on the interpretation of work by Law (1944), Warren et al (1961), Bennion (1966), Lambert (1981) and Hoeksema and Kitanidis (1985), but as Jensen (1986) points out, these interpretations are incorrect. Jensen states that none of these workers actually conclude that permeability is log-normally distributed and the present assumption that permeability is log-normally distributed is partly due to a lack of alternatives to the normal and log-normal distribution, with no recognition that there is a continuum of distributions. Jensen also points out that the use of mixed populations to explain deviation from the log-normal distribution (for example, Bennion 1966) should be supported by evidence since a probability distribution function (p.d.f.) can be subdivided into sub-populations with almost any desired function.

In the third assumption, that random spatial distributions of permeability may exist in the reservoir, the position and spatial distribution of the variables is ignored. The spatial correlation structure of permeability is probably one of the most important factors in permeability averaging. This was undoubtedly recognised during development of these statistical averaging techniques but the assumption that permeabilities were uncorrelated was probably due to the absence of quantitative structural information which limited mathematical analysis of it.

It is also assumed in these conventional statistical averaging methods that the permeability tensor will be in the direction of the imposed pressure gradient. Due to the directional nature of permeability, these averaging methods may not give accurate results. A considerable contribution to permeability averaging techniques can therefore be made by quantifying

spatial permeability structures. As Weber and van Geuns (1989) point out, attempts to identify whether some other distribution exists for permeability data are invariably inconclusive because the majority of data sets have too few values. They advocate acceptance of the log-normal distribution with efforts placed on determining the structure of the heterogeneities.

2.4.2 Estimating effective permeability in sand-shale sequences

For rock sequences divisible into discrete permeability classes, such as sand-shale sequences, the traditional statistical permeability averaging techniques are inappropriate because they cannot handle the magnitude of variance, for example, 1 and 0, or the distribution type, for example, bimodal distributions. The most important factor in sand-shale sequences is the spatial connectivity between permeable and impermeable units. A logical approach to estimating effective permeability might be to model the fluid flow behaviour in a reservoir simulator. In some cases, the variation in shale dimensions and shale distribution is very complex, requiring a large number of grid cells in the reservoir model. Such models are impractical for simulation experiments and alternative methods for estimating effective permeability are required.

To solve the averaging problem for sand-shale sequences, two main methods have been developed. The first method, proposed by Haldorsen and Lake (1984), uses an approximate formula based on the stream tube concept which relates effective permeability to the tortuosity of flow paths through the medium. This approach was refined by Begg and King (1985) by incorporating statistics of shale size and abundance into the stream tube formula, thereby removing the need to generate synthetic sand-shale distributions prior to averaging. This relies on a cumulative distribution function for shale length that is obtained from outcrops. Assuming that the shales are randomly distributed within the reservoir, the vertical shale frequency and shale lengths are representative of the shale distribution within the reservoir. Thus, a sample of stream tubes through this well-based shale distribution can be used to estimate the effective vertical permeability (K_{VE}), where K_{VE} is related to the lengths of a sample of streamtubes:

$$\alpha = \left[\frac{K_{VE}}{K} \right] \left[\frac{1 - F_s \times H^2}{N_s} \right] \times \sum_{i=1}^{N_s} \left[\frac{1}{S_i^2} \right]$$

and

$$S_i = H + \sum_{j=1}^{H_s+1} (RN) l_j$$

where α = anisotropy factor $\left(\frac{K_{VE}}{K} \right)$

K_{VE} = Effective vertical permeability

K = Homogeneous vertical sand permeability

F_s = Fraction of shale

H = Thickness of cross-section (metres)

N_s = Number of streamtubes

S_i = Length of i^{th} streamtube

l_j = Length of j^{th} shale from CDF

.....(2)

Finding that the streamtube approach was accurate only for low shale fractions, Desbarats (1987) proposed a second method. This is a numerical procedure based on the pressure-solver approach adopted by Warren and Price (1961) but modified to consider spatial correlation and a binary distribution of permeabilities.

Referring back to section 2.3.1.1, these statistical streamtube permeability averaging techniques rely on the following assumptions: that the sandstones are heterogeneously homogeneous (that is, the value and scale of the heterogeneities are distributed evenly in space) with respect to permeability; that the shales are impermeable under all pressure conditions; and that the distribution of shales within the reservoir is random. These assumptions are unlikely to hold true and the effects this has on the effective permeability needs to be investigated.

2.4.3 Real-space renormalisation

An alternative method for estimating effective permeability based on the field of electrostatics called real-space renormalisation has been developed by King (1988). This technique is based on four-point

(=blocks) resistor networks where the resistance is represented by permeability (Figure 2.5). The permeability variation in a four-point grid is converted to a single value of permeability. In this way, successive calculations of permeability can be used to scale-up fine grid data to a coarser grid. The renormalisation technique can handle zero permeabilities which statistical averaging techniques, notably the geometric average, cannot. The advantage of the renormalisation technique over numerical simulation is that only one input variable (permeability) is required, and is therefore computationally more efficient than numerical simulation. However, with this approach only estimates of single phase average permeability are provided.

A modified form of the renormalisation technique has been used by Abuelbasher (1990a and b) to calculate average permeabilities within complex fluvial reservoirs. In this study the renormalisation technique was modified to incorporate permeability anisotropy at the measurement scale, otherwise assumed to be isotropic. Renormalisation has also been used to calculate effective permeabilities within heterolithic facies in an attempt to define the R.E.V. for different sub-lithofacies (Norris and Lewis 1991). King (1990) used the renormalisation technique to estimate the effective permeability within different realisations of overlapping sand bodies distributed within a shale background.

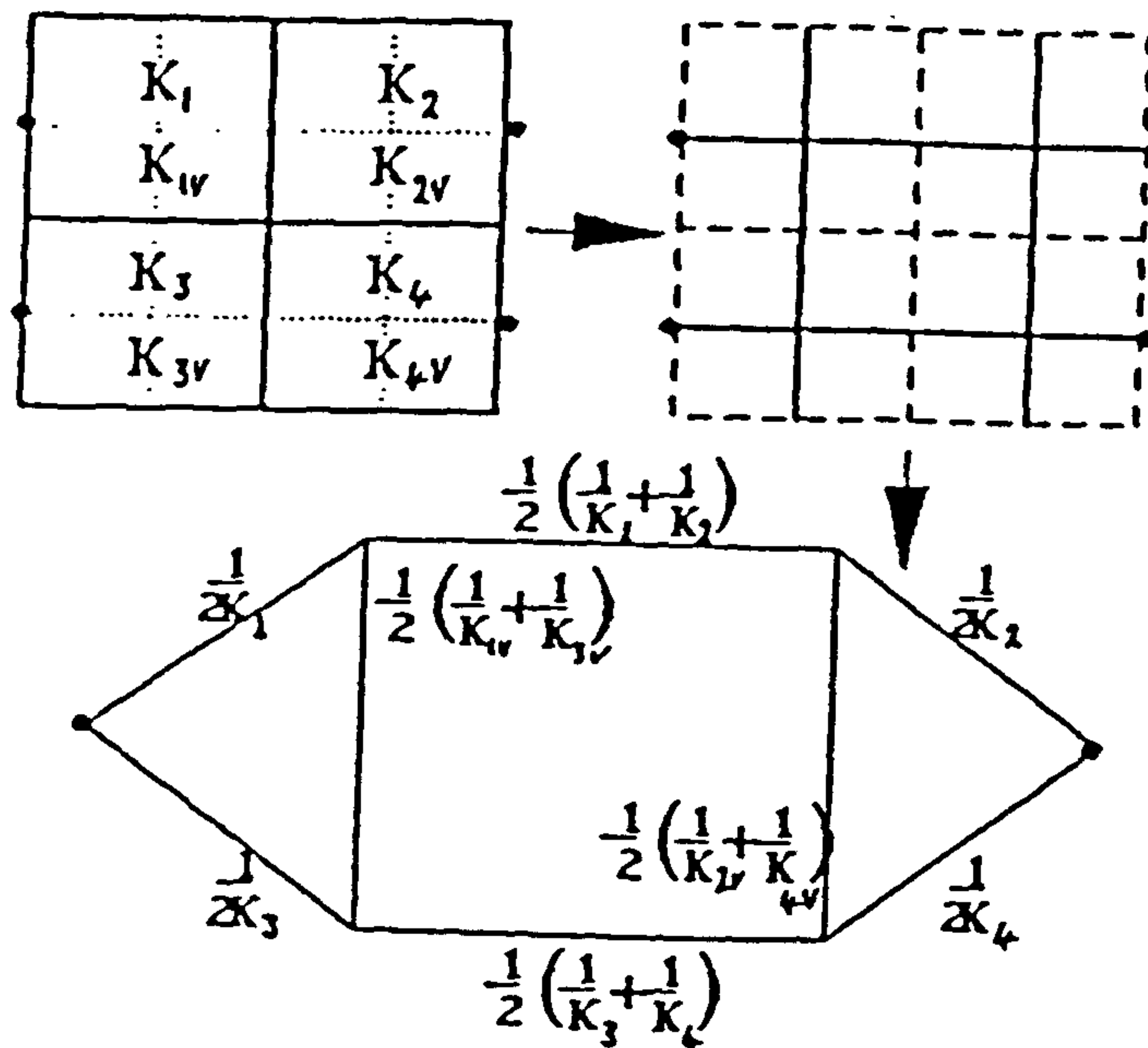


Figure 2.5 A schematic illustration of the renormalisation technique developed by King (1988) to calculate single phase average permeabilities and modified by Abu-Elbashar (1990) to include vertical permeabilities.

2.4.4 Block kriging

Geostatistical block kriging (Armstrong 1990, Davis 1986, Clark 1979, and Journel and Huijbregts 1978) provides an alternative method of averaging that utilises the general structure of the data as defined by the variogram. Thus, the spatial permeability structure is incorporated into the averaging technique. In block kriging, the value of a volume greater than the volume of the point values is estimated by weighting it towards the surrounding point values. It is assumed that there is a direct relationship between variance of the point values and the variance of the kriged block, expressed by the additivity relation:

$$S^2(v|V') = S^2(v|V) + S^2(V|V')$$

Where S^2 = Variance

volume $V' > V > v$

and $v|V'$ = variance v within V'

.....(3)

This additivity relation implies that the value of volume V' can be obtained by the combination of two smaller volumes V and v through some function of integration. This additivity relation applies to extensive properties, or 'measures', but not to intensive properties or 'potentials' (Narasimhan 1983). As permeability is an intensive property it is therefore, non-additive, although capacity functions may be used to volume-normalise intensive properties, thereby converting them to extensive properties (Narasimhan 1983). This is done routinely for porosity where it is expressed as volume percent, but is difficult to apply to permeability. The additivity problem for permeability was avoided by Rumhy (1990) in the development of a conditional kriging technique for permeability by assuming that permeability behaves as a pseudo-additive property when it is normally-distributed although this is generally not proven.

2.4.5 The representative elementary volume (R.E.V.).

Since the transport equations are intrinsically based on the continuum approach, that is, rock volumes associated with a mathematical point are homogeneous (Hubbert 1956), this can be adopted to solve the scale problem statistically, thereby circumventing the problem of describing the exceedingly complex geometry of grains. The task is to determine if and how a rock property or characteristic is a function of the amount of rock-volume associated with a mathematical point or centroid, p . By examining the variation in the measured property or characteristic with increasing sample volume around p , the variation can be plotted as a function of scale (Figure 2.6).

This variation associated with a change in the sample volume can be demonstrated mathematically for porosity by the ratio between the volume of void space and the total volume of the sample:

$$\phi_i = \phi_i(\Delta U_i) = \left[\frac{\Delta U_{v_i}}{\Delta U_i} \right]$$

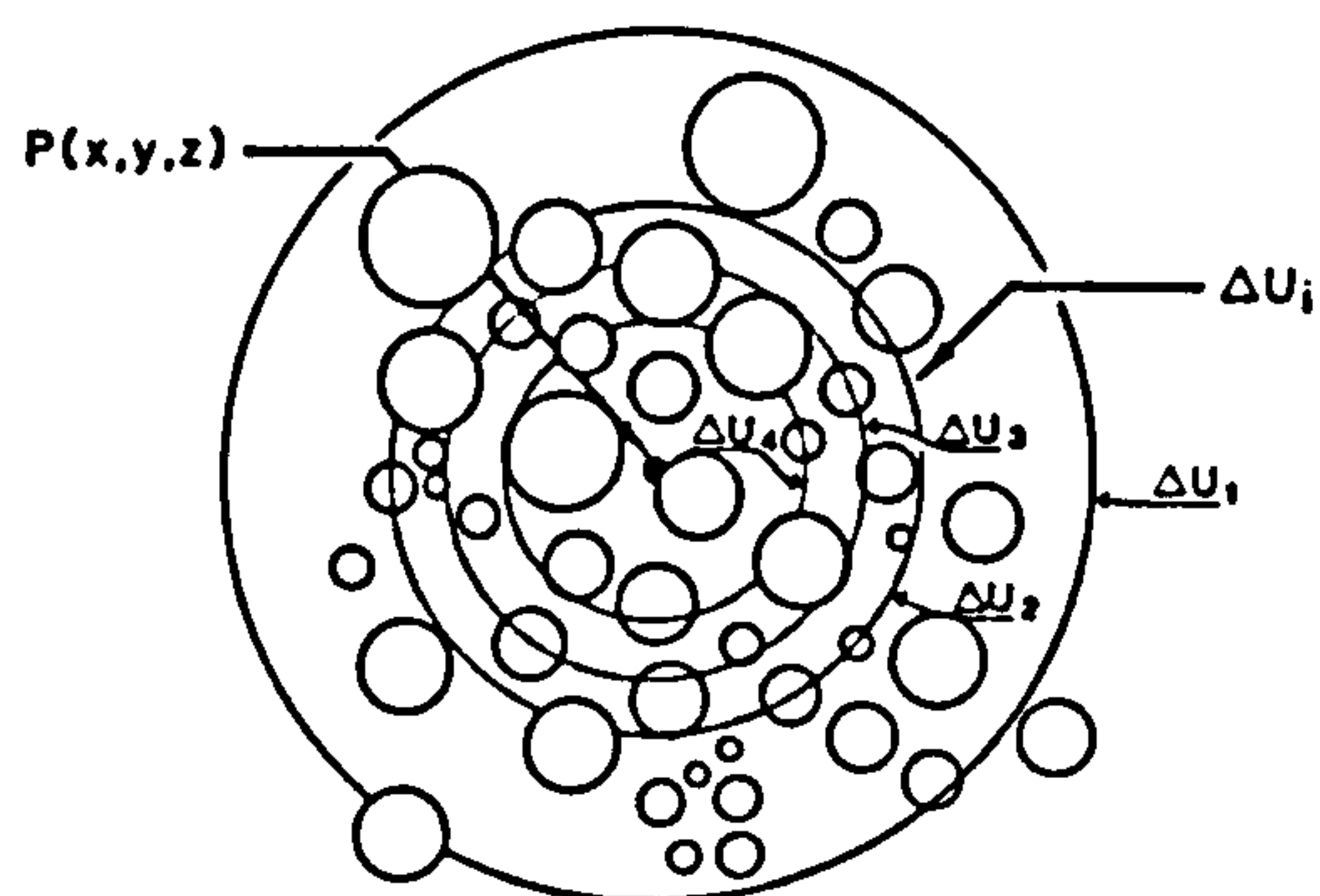
where ϕ_i = porosity fraction associated with sample ΔU_i

ΔU_i = volume of sample associated with the centroid, p

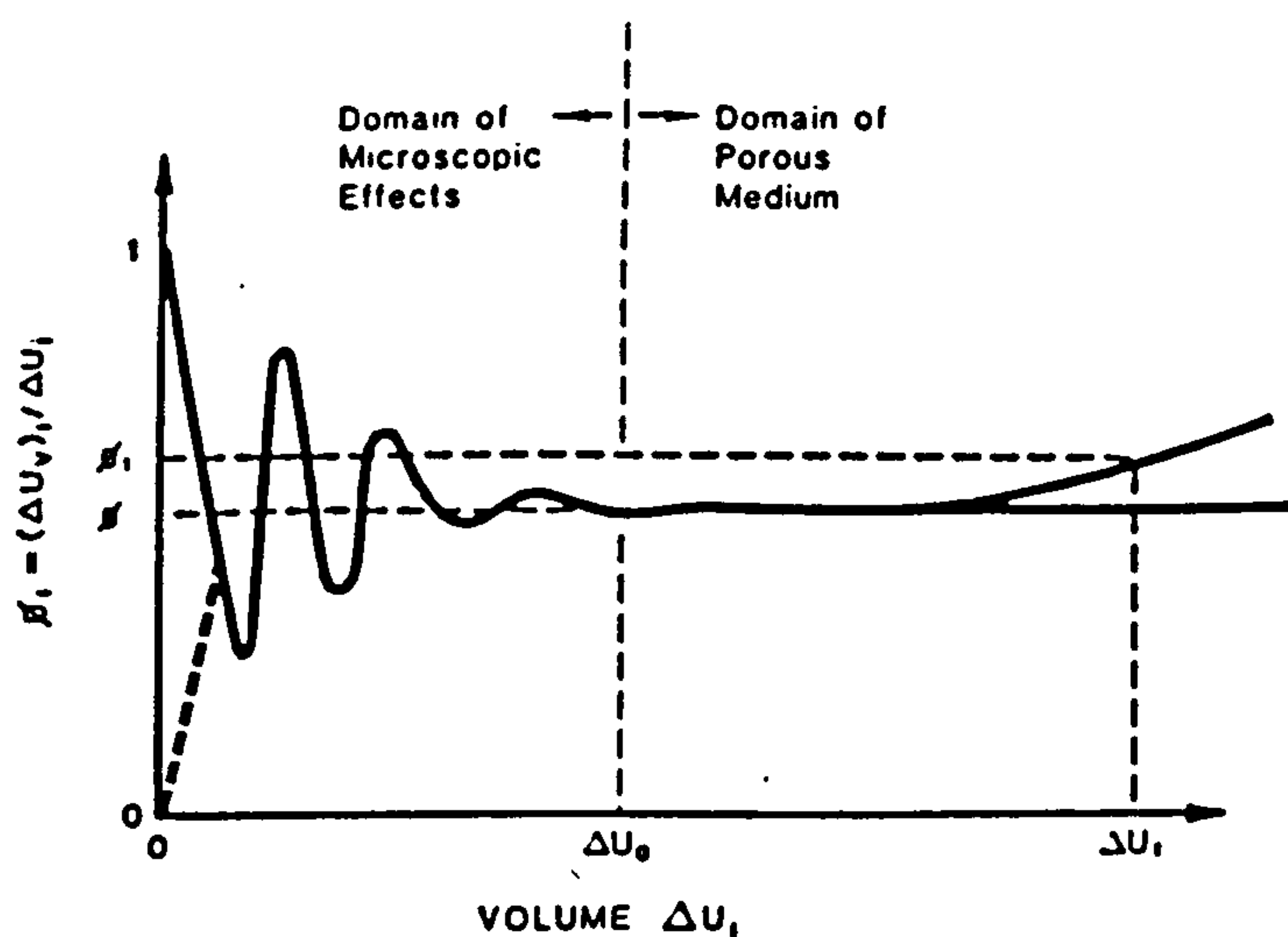
$(\Delta U_v)_i$ = void volume of space within ΔU_i

.....(4)

By repeating the procedure with different sample volumes around the centroid, p , the fluctuations in porosity, ϕ_i , change as a function of volume, ΔU_i . For large sample volumes, the ratio ϕ_i may undergo gradual changes as ΔU_i is reduced, especially if the domain is heterogeneous, associated with layering or banding for example. Below a certain value of ΔU_i , the changes in ϕ_i reduce with only small fluctuations due to random variations in the pore sizes. Where these minimum fluctuations occur this represents the range in sample volume over which the variation in that property, in this case porosity, is heterogeneously homogeneous. Below a smaller value of ΔU_i still, the value of ϕ_i displays large fluctuations as the dimensions of the sample volume, ΔU_i , coincides with either grains or pore spaces. At the central



$P(x,y,z)$ IS THE CENTROID OF ΔU_i . ΔU_i IS A ROCK VOLUME HAVING THE SHAPE OF A SPHERE AROUND $P(x,y,z)$



DEFINITION OF POROSITY AND REPRESENTATIVE ELEMENTARY VOLUME (ΔU_0).

Figure 2.6 Conceptual model for determination of the Representative Elementary Volume for properties of porous media (From Haldorsen, 1986)

point, p , the sample volume will be either within a grain or a pore space. The volume at which individual grains begin to influence the porosity estimate represents the transition from the domain of the porous medium to the domain of microscopic effects. This volume is designated ΔU_0 , and also defines the representative elementary volume. This is actually the lower limit of a range of volumes over which the variation in porosity is at a minimum and from which an R.E.V. may be chosen

Where the sample volume is kept constant, an R.E.A. (representative elementary area) can be defined for a 2-D data set, provided that the average for the property or characteristic is correctly calculated. This requires exhaustive sampling and an appropriate method of averaging. To obtain a global R.E.V. or R.E.A. for rock *per se* is impracticable since it would require incorporation of every rock type everywhere into the sampled rock volume. Thus, some form of rational subdivision for the calculation of R.E.V.'s and R.E.A.'s is required. As hydrocarbon reservoirs are mostly comprised of sedimentary rocks this provides the first division. Further division is conveniently made by dividing depositional rocks into genetic depositional units (bodies of rock that formed under the same depositional processes and environmental conditions). An R.E.V. or R.E.A. is then derived which incorporates these genetic depositional units at a scale appropriate to the geological model and the complexity required for reservoir simulation.

A range of tools are available for the measurement of different rock properties and characteristics over different volumes from which an R.E.V. may be derived. However, these measurements vary in accuracy, precision and volume. Thus, the estimated R.E.V. may have poor reliability. R.E.A.'s on the other hand are easier to calculate where rock properties or characteristics are sampled from outcrop. This technique is particularly suited to outcrops where contrasts in permeability (0, 1 type) are visually apparent, such as within sand-shale sequences. In these cases, exhaustively-sampled data sets can be gathered over large areas of outcrop very quickly from photographs taken at different scales. Of course, any photographic interpretation must be verified by analysis of at least some of the rocks in the sample area. Where differences in permeability are not marked or visually apparent, photographic mapping

cannot be used and direct measures of permeability need to be made.

2.4.6 Pseudofunctions

Pseudofunctions (Kyte and Berry 1975, Lake et al 1990) describe flow through permeable media on a scale that is larger than that measured directly. All permeability averaging techniques, for example the geometric and harmonic means, are therefore, pseudorepresentations. For computerised simulations of flow within the reservoir, several permeable media properties will have to be pseudoised, such as absolute permeability, relative permeability and capillary pressure.

Pseudofunctions enable the different transport properties to be scale-adjusted and combined in a form that can be used easily for reservoir calculations. They are used to model sub-grid block heterogeneities and reduce numerical dispersion in the coarser grid, ensuring that the fluid flow across the grid boundaries for the scaled-up coarse grid will be the same as for the fine grid. One of the purposes of characterising permeability heterogeneities at different scales therefore, is to determine the form of the pseudofunction.

As measures of reservoir characteristics and properties such as permeability and porosity are usually made at the core plug scale, this is taken to be the smallest grid block size within which the effect of heterogeneities on fluid flow are negligible; the block is regarded as homogeneous and a single value of permeability is assigned to it. For permeabilities obtained using the probe permeameter, the theoretical sample volume for this measurement is taken as the smallest grid block size. Relative permeability and capillary pressure curves are obtained for this grid from measurements made on core plugs. Scale-adjusting reservoir properties from this fine grid to a coarser grid can be done numerically (refined simulation), if cross-flow is significant, or it can be done analytically if the reservoir is totally stratified. Whatever the process, all pseudofunctions must be independent of time for practical use, although they can depend on position and must depend on the averaging scale (Lake et al 1990). This scaling-up process may occur over one large step but this is likely to produce inaccuracies between the

fine and coarse grid simulations in more heterogeneous reservoirs. To account for several scales of heterogeneity, which a single scaled-up jump cannot do efficiently, pseudofunctions may be generated in a multi-step process (Lasseter et al 1986 and Kossack et al 1989), as shown in Figure 2.7.

The genetic depositional units used to characterise reservoir heterogeneities can also be used to define each step in the pseudofunction generation process. For a specific depositional environment, the degree of heterogeneity within each genetic unit, for example, laminae, cross-bedding, and coarsening-up sequences, can be used to indicate the importance of each scale of heterogeneity on fluid flow and therefore, the number and size of the steps. As R.E.V.'s are used to describe scaling transitions, they can also be used to define the appropriate number and size of scaling steps for pseudofunctions.

There are, however, two sources of error associated with the pseudofunction approach. Firstly, the pseudofunction for any one scale is assumed to be representative of all positions within the rock. Secondly, the models of reservoir heterogeneities at various scales are generally poor, resulting in oversimplified pseudofunctions. The source of these errors is directly related to the quality of available data and information regarding the variation away from the data source, that is, the well. To reduce these errors, improvements are required in both our understanding of the effect of heterogeneities on oil recovery and in the models used to predict spatial heterogeneities away from the well. Particular attention should be paid to small scale permeability heterogeneities since these have been shown to influence fluid flow and sweep efficiency resulting in an increase in the residual oil saturation and loss of recovery (Kortekaas 1985, Weber 1984). This effect is especially pronounced under conditions of unfavourable mobility ratios.

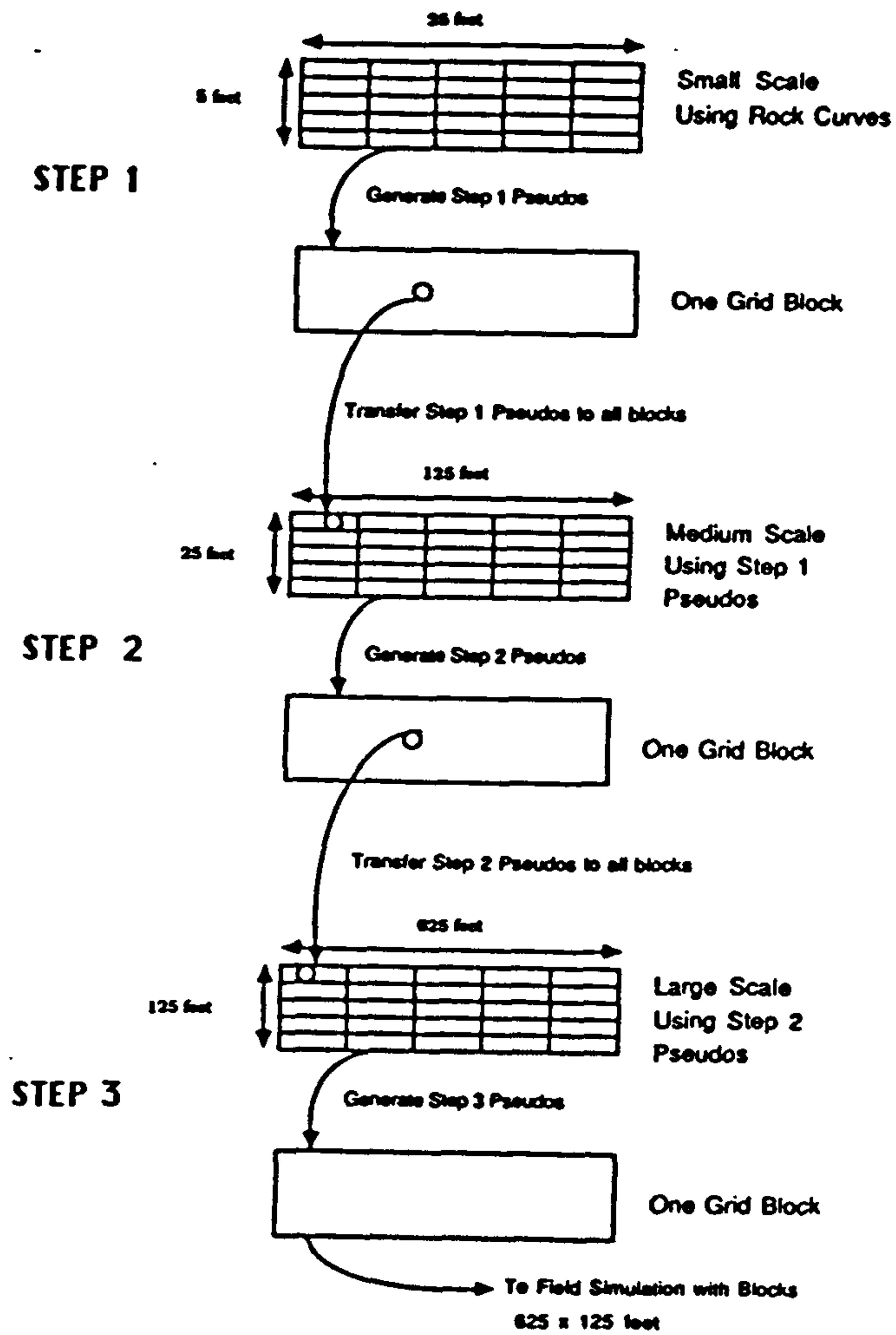


Figure 2.7 Diagrammatic illustration of the multi-step pseudofunction generation process, (From Kossack *et al.* 1989)

2.4.7 Incorporation of non-diagonal tensors

More recently the incorporation of non-diagonal tensors has been a subject of interest in permeability averaging techniques (White and Horne 1987, Kasap and Lake 1989, Samier 1990, and Gomez-Hernandez and Journel 1990). In conventional scaling-up or averaging techniques, the effective permeability for the coarser homogeneous grid block is given symmetric permeability tensors (k_x , k_y and k_z). Where there is heterogeneity and anisotropy at the sub-grid scale, for example, within cross-bedding and burrows, the boundary conditions between blocks will be severely altered. This will also occur when the tensor of the averaged grid block permeability value varies with position, resulting in the incorrect alignment of the grid with the principal directions of the permeability tensor. As a result, the predicted flow paths or pressure differential between block centres will be distorted. A reduction in the grid block size will help solve this problem but will also increase the run-time cost of the simulation. There is a need therefore, to incorporate non-diagonal tensors (for example, k_{xy} , k_{xz} , and k_{yz}) into the averaged grid block.

2.5 Discussion

A quantitative evaluation of spatial permeability heterogeneities is required in order to improve our understanding of their effect on flow within porous media and to improve methods of incorporating these effects into predictions of reservoir performance. As the geological model is used to define the reservoir architecture, depositional heterogeneities provide an appropriate and convenient framework on which to base the quantification of spatial permeability heterogeneities, providing the relationship between depositional and permeability heterogeneity is shown to exist.

The problems of reservoir characterisation presented in this review define the need for outcrop permeability studies as outcrops provide an obvious source of data for quantifying spatial permeability heterogeneities. By sampling permeabilities from outcrop faces, either

through interpretation of photographs or by direct measurement, a 2-D pattern of permeability is obtained. In some cases, 3-D patterns of permeability can be obtained by serial slicing. Having obtained these permeability data, the correlation structure can be quantified and appropriate averaging techniques developed.

2.5 Conclusions

- 1) There is a clear need for improvements in our understanding of spatial reservoir heterogeneities. Of all the reservoir properties and characteristics, permeability is the most significant and attention should be paid by the oil industry to quantifying permeability heterogeneities within different rock types.
- 2) The concept of genetic depositional units offers a logical and convenient framework within which quantification of reservoir heterogeneities can be realistically achieved. The use of such a framework is appropriate since it fits easily into the geological model for the reservoir. Thus, permeability and geological heterogeneities are quantified simultaneously.
- 3) Outcrops provide an obvious source of permeability data for characterisation where they may allow uninterrupted 2-D access over lateral dimensions equivalent to interwell distances. Where outcrop faces are available in more than one direction, reservoir heterogeneities may be modelled in 3-D.
- 4) Outcrop permeability data can be used to improve our understanding of statistical permeability distributions within different lithofacies types. These data may also be used to quantify the representativity of conventional permeability data of both statistical and spatial permeability variation.
- 5) Permeability averaging techniques may be improved through the use of 2-D and 3-D outcrop permeability data. Exhaustively-sampled data can be used to incorporate non-diagonal tensors into averaging techniques.

6) Exhaustively-sampled permeability data from outcrop can be used for calculation of permeability R.E.A.'s and R.E.V.'s. These in turn can be used to determine the grid block size and appropriate pseudofunctions for permeability (their form and number of steps) for numerical reservoir simulation.

Chapter 3 A review of published outcrop permeability studies

3.1 Introduction

There are many outcrop-based studies that describe the geometry and disposition of depositional units (for example, Brown 1969, Campbell 1976, Bridge and Leeder 1979) but relatively few studies provide direct measures of permeability. The main reason for this concerns application of outcrop-derived permeability data to the reservoir. Rather than improve reservoir characterisation, the additional information gained from outcrop permeability studies is often regarded as a complicating factor in reservoir description. In addition to the problem of application, conventional reservoir data from core plugs, whole core measurements, RFT, wireline logs, seismic data and so on are obtained from the reservoir at considerable expense and are themselves often under-used. However, with improved computer capacity and recognition of the importance of geological guidance in reservoir characterisation (Archer and Hancock 1980, Weber and van Geuns 1986, Haldorsen 1986), outcrop-based permeability models and the averaging procedures developed from them are beginning to find application.

The following review of the literature for the last few years reveals a significant increase in published outcrop permeability studies. This influx of outcrop permeability studies also corresponds to more recent emphasis placed on enhanced oil recovery as the importance for maximising oil reserves becomes more apparent. This applies especially to those hydrocarbon producing areas such as the North Sea that are now reaching their mature production phase. This review also shows that the full potential of information gained from such studies is often unrealised because of poor methodology applied to the data collection. Subsequent analyses of these data often produces incorrect or misleading results.

In this review, selected outcrop studies are presented chronologically and summarised in Table 3.1 at the end of this chapter. This table lists the outcrop name, lithofacies type, measured rock characteristics and

properties, permeability measurement technique, sampling scheme, number of samples, domain dimensions, sample interval, any attempts to quantify spatial variations, and the aims of each study. Details of additional published outcrop studies not reviewed here are also included in this table. The conclusions from this review serve to highlight key points regarding sampling methodology from outcrops that warrant further attention. These points are addressed in subsequent chapters.

3.2 A review of published outcrop permeability studies

Identification, classification and prediction of reservoir non-uniformities affecting production operations.

Hutchinson, C.A., Dodge C.F., and Polasek T.L. 1961

Age: Cretaceous

Depositional environment: Shallow marine blanket sands

Outcrop and location: Woodbine Formation, Texas, Gallup Formation, New Mexico, and Dakota Formation, New Mexico. All in the USA.

This is the earliest published outcrop permeability study that aims to describe and quantify reservoir heterogeneities. Both porosity and permeability measurements were made on core plugs sampled from sandstones of shallow marine origin from five different formations within the USA. All of the formations are cretaceous in age. The variety of outcrops and formations allows comparisons to be made between the data sets thereby providing an estimate of the reliability for the observed permeability characteristics within sands from this depositional environment. This is an important point as the 'portability' of outcrop-derived data sets is a key factor for their use in reservoir characterisation.

Hutchinson et al applied the concept that geological variability exerts a strong control on the reservoir heterogeneity by confining both their sampling scheme and analysis of the data to predefined 'geological units of deposition'. The geological unit of deposition is that unit of sediment that is deposited under specific conditions (water depth and current

velocity for example). It is identified by its bedform types, mean grain size, degree of sorting and packing characteristics. A geological unit of deposition therefore, has a specific origin, and is sometimes described as a 'genetic depositional unit' or 'genetic rock unit'. A sandstone formation may be comprised of one or more geological units.

Problems and limitations of the study

Hutchinson et al assume that the geological character (and specifically the grain size) of these depositional units will control the permeability (and porosity) characteristics. To evaluate reservoir heterogeneities, permeability sampling has targeted these units. This sampling technique must be questioned as the data will be biased towards these units before their relationship with permeability is proven. To avoid biasing the data, a randomised sampling scheme should be used first to test any assumptions. Having identified the controls on permeability (bivariate and multi-variate statistics can be employed here), further analyses and subsampling can be conducted on the depositional units should these be shown to have discrete permeability characteristics. It should also be noted that the permeability characteristics include both statistical description and the spatial disposition of permeability.

In the study by Hutchinson et al, virtually all of the core plugs were sampled parallel to the dip of the formation. Permeability anisotropy at the core plug scale will be determined by the orientation of the core plug in relation to the grain fabric and laminae/ bed boundaries. The dip of the formation may bear no relation to the grain fabric and local foreset dip and azimuth, and the variation in permeability between core plugs may be a function of local anisotropy. Consequently, comparisons of core plug permeabilities within and between geological units, outcrops and formations, may be masked by variation due to local anisotropy.

The sampling schemes used are not clearly documented in the report and it is not possible to evaluate the statistical efficiency and suitability of the sampling scheme (given that both the descriptive statistics and spatial disposition of permeability values need to be considered). Hutchinson observed that whilst permeability was controlled by the

sediment texture, the permeability variations were spaced essentially at random. This has important consequences as it implies there is no spatial correlation in permeability within the geological unit *at this sample scale*. The geological unit therefore is homogeneous with respect to permeability. It is unclear however, whether a reduction in the sample interval and the sample volume will reveal a correlation structure otherwise unidentified.

In their analysis of the permeability data, Hutchinson et al used a very qualitative approach. Neither formal tests of significance (for example, the t and F-test and ANOVA) nor trend analyses were performed on the data (although the latter has been performed by Stalkup (1986) in a later study utilising these data). With this qualitative approach, the effects of observed heterogeneities (notably cross-bedding) on the flow characteristics are only described: "from a fluid flow standpoint..... cross-bedded units should be the more unfavourable".

In conclusion, this outcrop permeability study identifies reservoir non-uniformities, but does not adequately classify them, or provide a method for predicting them. There are two reasons for these shortcomings: First, the sampling technique imposes severe limitations on the scales at which permeability heterogeneities are measured. This limits the usefulness of the classification of these heterogeneities. Second, the absence of any quantitative assessment of the permeability variation (the statistical nature and spatial correlation structure) limits the development of models for these heterogeneities.

Permeability distribution in a Holocene distributary channel-fill near Leerdam (the Netherlands).

Weber K.J., Eijpe R., Leijnse D., and Moens C. 1972

Age: Holocene

Depositional environment: Distributary channel-fill sands

Outcrop and location: Leerdam, the Netherlands.

In this study, permeability measurements were taken from borehole cores drilled through a series of stacked festoon cross-beds within a

Holocene distributary channel-fill. The permeability values were analysed in relation to the geometry and depositional character of these cross-beds from which a model was developed for calculating permeability anisotropy and an effective permeability for the sand-body. Numerical estimations for effective permeability using this model were then compared to the results from a flow test performed on the same sand-body. This flow test involved using a series of boreholes as shown in Figure 3.1. Water was injected into a central borehole, whilst the water pressure was monitored in a series of observation boreholes arranged concentrically around the injector borehole. The results from this comparison were very favourable and serve to validate the permeability anisotropy calculations derived from the outcrop study.

Oriented cores from the boreholes (ten in total) were cut in half longitudinally and the sedimentary structures described and quantified (specifically the laminae type, thickness, grain size, and dip angle). Permeability measurements were then made using a probe permeameter which proved an ideal device given the small diameter of the cores.

Problems and limitations of the study

Although reference is made to a separate publication for the technical specifications of the probe permeameter, no documentation is made in the current study regarding the anisotropy of the permeability measurements, the probe tip dimensions or the effects of water saturation.

Weber et al assume that the permeability measurements made using the probe are largely independent of permeability anisotropy, that is, they are isotropic at the measurement scale. This assumption is a very convenient one since it means that the permeability values can be analysed without having to apply corrections for within-sample anisotropy. However, no tests are made to validate this assumption.

The probe tip dimensions are critical in any permeability study since the dimensions will determine the sample volume and therefore the minimum scale of heterogeneity measured. In this study, which investigates the nature of the permeability variation within individual

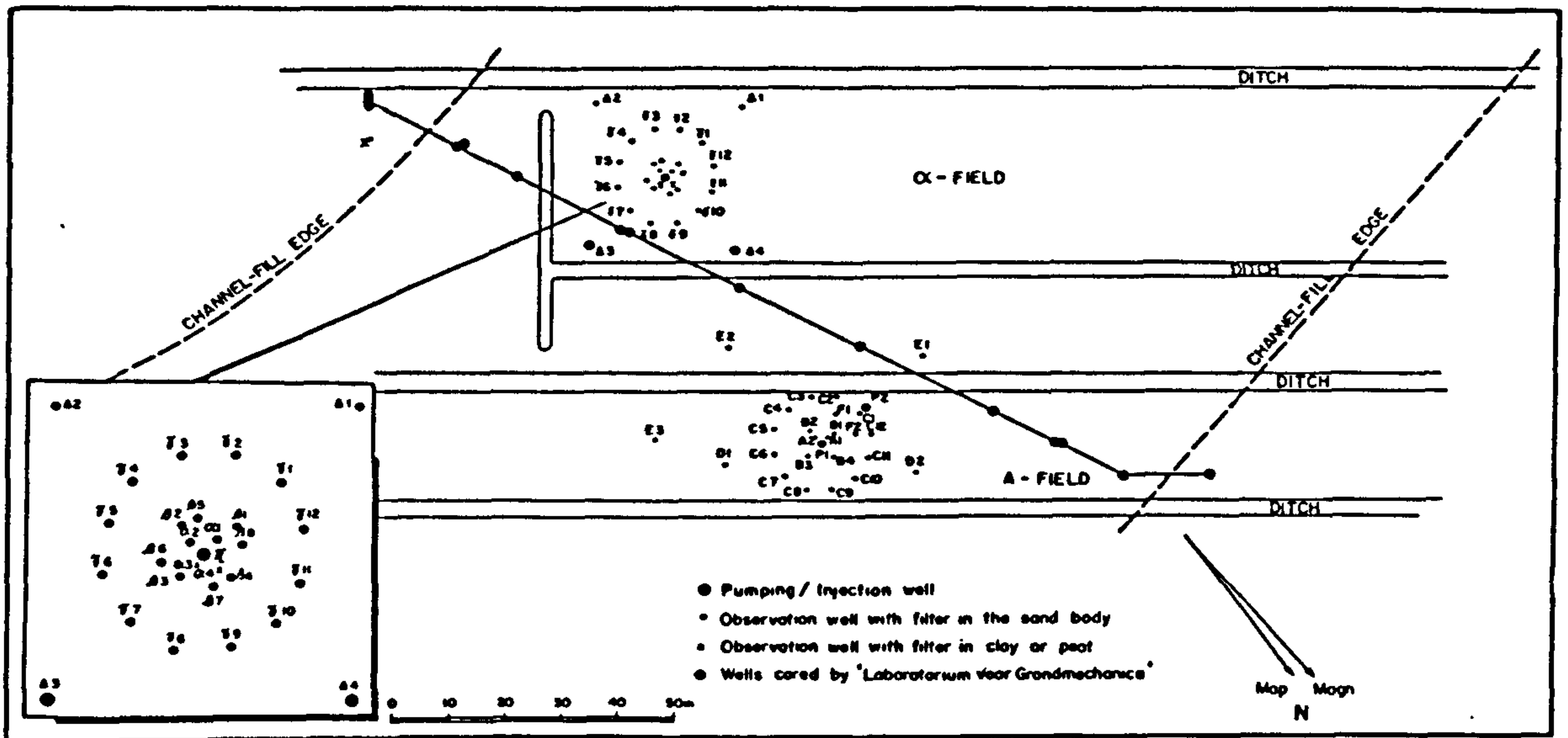


Figure 3.1 Patterns of pumping/injection and observation wells in the test area (after Weber et al 1972)

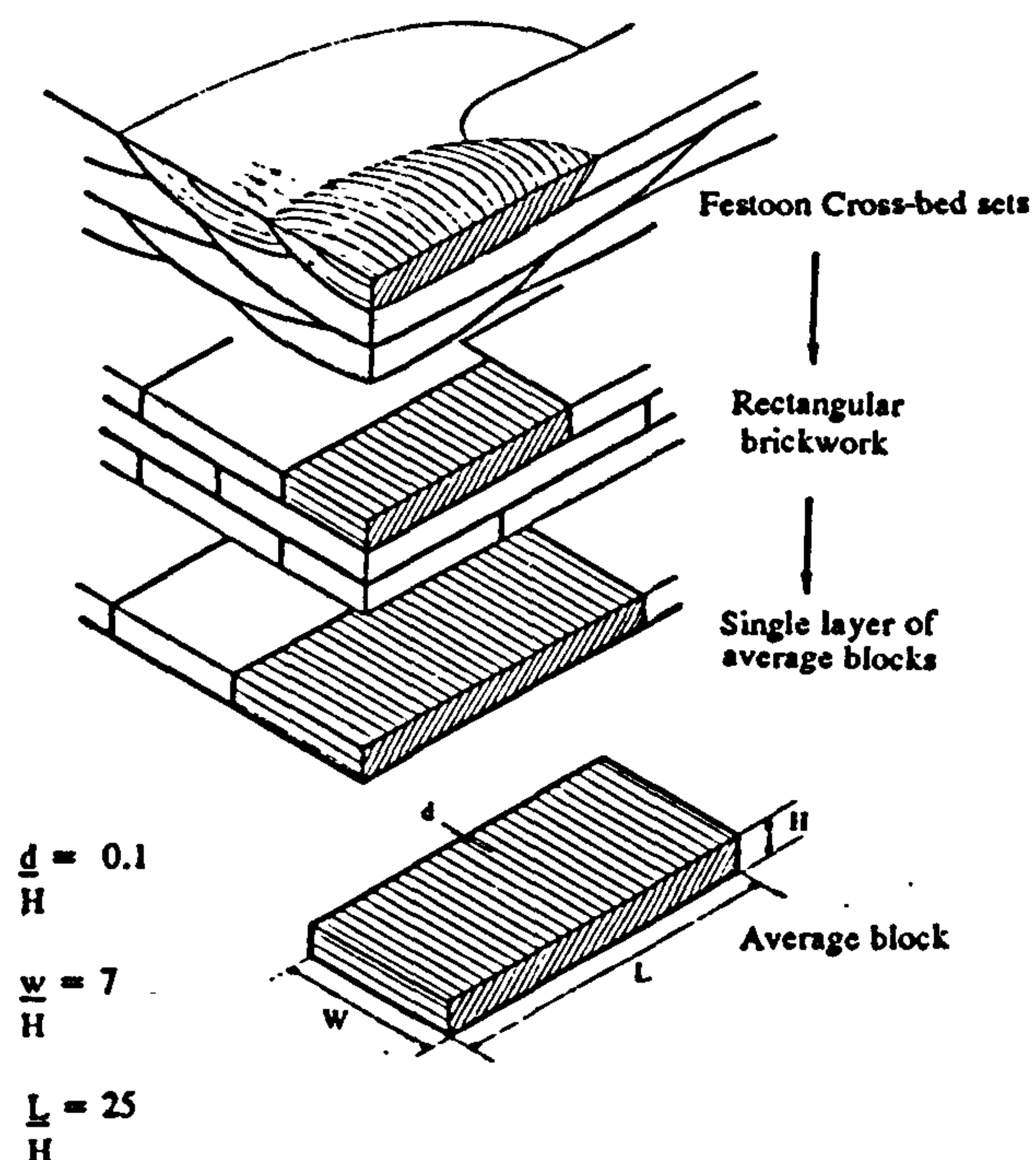


Figure 3.2 Derivation of a model for calculating permeability anisotropy in fluvial sand bodies (after Weber et al 1972)

foreset laminae, the sample volume should be confined to individual laminae. Although Weber et al state that the sample volume is around 1cm^3 and is confined to one or two laminae, neither the probe dimensions nor variation in laminae thickness are documented.

These channel sands are exposed just above the water table (as evidenced by drainage ditches) and measurements of permeability under field conditions are likely to be affected by water saturation. Although permeabilities can be measured on air-dried samples (which presumably is the technique weber et al used in this study), the problem of water saturation on field-derived probe permeability measurements is a practical one and should be addressed. Similarly, the effects of saturation on clays need to be investigated.

Sampling errors are not a problem in this study because the results have been evaluated through comparison with an actual fluid flow test. However, this fluid flow test was performed under single phase conditions using fresh water at surface conditions of temperature and pressure. Under different reservoir conditions (where for example the displacing fluid is water and the displaced fluid is oil, possibly with an unfavourable mobility ratio), the permeability model may need modification; incorporating for example, permeability variations *within* laminae types may have to be incorporated into the model).

From a study of fluvial festoon cross-bed sets in both recent and ancient sediments, the observed consistency in the geometrical ratios of cross-bed sets was used to justify a simplified model. This model consists of a brick-work of rectangular blocks as illustrated in Figure 3.2. Combining the permeability values measured on core with this model, Weber et al derived the following method of calculating horizontal permeability in the direction parallel and perpendicular to the channel axis:

$$K_x = \frac{L}{\frac{d}{K_B} + \frac{L}{K_\alpha}}$$

and

$$K_y = \frac{W}{\frac{d}{K_B} + \frac{W}{K_{||}}}$$

Where:

- K_x = permeability parallel to the channel axis
- K_y = permeability perpendicular to the channel axis
- L = cross-bed set length
- d = bottom set thickness
- w = cross-bed set width
- K_B = average permeability of the bottom sets
- K_α = average permeability in a horizontal direction perpendicular to the foreset strike
- $K_{||}$ = the average permeability parallel to the foreset laminae

.....(5)

Inspection of Figure 3.2 shows that the cross-bed sets form spoon-shaped geometries that pinch out against each other in both the strike and dip directions. Permeability anisotropy at these 'pinch-out' points is likely to be very pronounced where there is a sharp angle of contact between foresets from different cross-bed sets. The juxtaposition of these cross-bed sets is also likely to create bottle-necks in the flow paths which may cause a significant reduction in the average horizontal permeability of the sand-body. Although the flow test performed in the study supported the simplified model, in other cases where the textural character of the laminae within the cross-bed sets differ (for example, where they are finer-grained or contain abundant clay material), this potential bottle-neck effect may become pronounced.

In conclusion, this outcrop permeability study provides an excellent example of a quantitative evaluation of permeability heterogeneity that is used to develop a permeability model. By comparing the estimated

average permeability from the model with that from an actual fluid flow test, both the model and the sampling scheme used to develop it are evaluated. However, the model is a very simplified one and further investigation is required to determine how robust the model is under different reservoir conditions. To this end, additional permeability data are needed in the horizontal direction (both perpendicular and parallel to the channel axis) and spatially within individual laminae. Furthermore, the model is developed from permeability data gathered from one example of a fluvial sand-body. To test and improve the portability of the model, additional permeability data is needed from similar genetic sand-bodies; both ancient and modern.

Permeability variations observed at the faces of cross-bedded sandstone outcrops.

Stalkup, F.I. 1986

Age: Cretaceous

Depositional environment: Shallow marine blanket sands

Outcrop and location: Woodbine Fm., Texas; Gallup Fm., New Mexico; Dakota Fm., New Mexico; all USA.

Stalkup (1986) examined permeability variations within six outcrops containing cross-bedded sandstones. The source of these data was from the study conducted by Hutchinson et al (1961), reviewed earlier in this Chapter. Samples were taken from vertical 'coring stations', representing wells, two to four foot apart over an horizontal distance of 24' to 80'. The study represents a significant advance in outcrop permeability studies where attempts are made to quantify both the statistical character and spatial disposition of permeability values. Statistical methods such as the Kolmogorov-Smirnov and Tukey-Kramer tests were used to identify significant differences in the mean permeability within and between subintervals. The spatial structure of permeability is examined through the use of variograms. A structure of variation emerges that is not random, but is due to small scale permeability layering relating to the alternating laminae of the cross beds. Data from a single 'well' give limited insight into the nature of permeability variation and as such the significance of well data or 'well

representativity' is addressed. The short correlation lengths of the subintervals suggests that a deterministic model for describing these sands would not be possible and Stalkup suggests the use of a stochastic model.

Problems and limitations of the study

The main limitations of this study concern the sample data itself. In order to establish whether vertical permeability trends (from the coring stations) were laterally correlatable, two methods were used: First, intervals of high or low permeability were identified where permeabilities at several points within the interval consistently increased or decreased to a high or low value. This differentiates between regional and single value fluctuations. Second, the trends of permeability profiles from each coring station were compared to establish where similarities existed between these trends.

The identification of intervals in the first method is dependent on the sample density (the sample volume, which is another important factor, remains constant). If intervals of high or low permeability are correctly identified, then a reduction in the sample spacing should confirm their existence where the permeability variation between intervals is greater than within intervals. This was not tested for in the study. In the second method, the identification and comparison of profile trends is based on a visual estimation. Whilst the human eye is very good at pattern recognition, the patterns cannot be quantified and the technique of visual comparison is very subjective. Additional trend analysis techniques such as autocorrelation should be used.

Statistical tests were made to determine whether the subintervals chosen were significantly different. The Kolmogorov test was used to determine the distribution type (whether normal, log-normal or some other type), after which the appropriate statistical tests could be applied. The Tukey Kramer test was used for multiple comparisons of means, and the t-test for two sample comparisons. However, the validity of these tests is dependent on the sample data. As no estimates of sample error were conducted on the sample data and no consideration given to the design of the sampling schemes, the value of conclusions drawn

from these tests is questionable.

To obtain subintervals with statistically-different permeability populations, the sub-interval groupings were altered until the tests showed a significant difference between them. However, the sub-interval boundaries were not changed. This means that the final delineation of subintervals, which would be found eventually, is dependent on the non-quantitative delineation of subintervals in the first instance. With the methodology used to delineate subintervals and the limitations imposed by the sample density, the spatial analysis of these permeability data using variograms (which identify a predominant lack of any correlation structure) must come under scrutiny.

The nature of the permeability variation across the sub-interval boundaries is not addressed. The simplified permeability maps for each outcrop, an example of which is given in Figure 3.3, shows regions with different mean permeabilities that are defined by sharp boundaries (although there are a few exceptions). This implies that there is a sharp change in permeability across the boundary (from 397 mD to 1457 mD for example). This compartmentalisation of the reservoir can have significant implications for fluid flow behaviour, causing, for example, channelised and refracted flow. In recognition of this problem, Stalkup suggests that it may be necessary to increase the sample density at outcrop to obtain a representative standard deviation for each sub-interval; the standard deviation being a measure of the permeability gradient between subintervals and the cells in a reservoir simulator. He also notes that permeability heterogeneity within these subintervals may need to be accounted for given that the influence of different scales of permeability heterogeneity can have a varying influence depending on the displacement process.

This study provides a useful introduction to statistical techniques used to determine whether significant differences exist between permeability populations. However, the guidelines for their application are misleading as the subdivision of the outcrop into areas with different permeability characteristics is biased towards the initial subdivision of subintervals. The significance of the correlation structures obtained through variogram analysis is limited by the sample data which is of

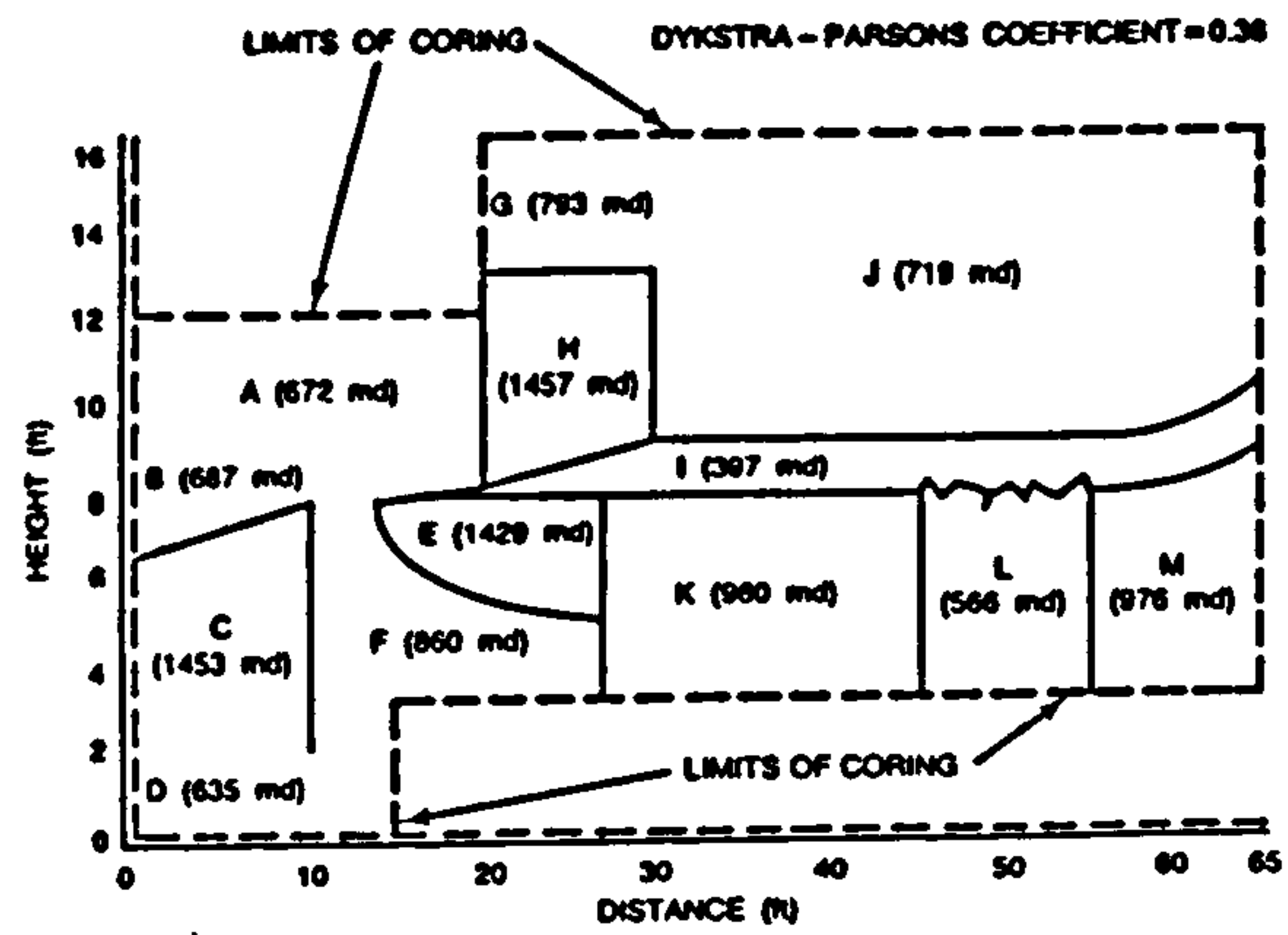


Figure 3.3 Rock Springs outcrop: adjacent layers with statistically different permeabilities (after Stalkup 1986)

low density and does not provide a good case study for this technique. Nevertheless, the importance of identifying and quantifying the spatial disposition of permeability variation is emphasised and provides an important step forward in the contribution of outcrop permeability studies towards our understanding of reservoir heterogeneities.

Geostatistical characterisation and comparison of outcrop and subsurface facies: Shannon shelf sand ridges.

Tomutsa L., Jackson S.R., and Szpakiewicz M. 1986

Age: Cretaceous

Depositional environment: Shallow marine shelf sand-ridge complexes

Outcrop and location: Shannon Fm., Wyoming, USA

In a study of permeability and porosity variation within a subsurface reservoir and its outcropping counterpart, Tomutsa et al (1986) present the first evaluation of the portability of an outcrop-based, quantitative model for permeability heterogeneity to subsurface reservoirs. In this study, permeability and porosity data are analysed from the Shannon Shelf Sand Ridge Sandstone that is exposed at outcrop in the Salt Creek Anticline and forms the Teapot Dome reservoir and the Hartzog Draw field. The permeability and porosity distribution functions, correlation lengths (from variograms), and log permeability - porosity plots are compared for the three sets of data. The study shows that the shape of the permeability distributions are similar for the three sets of data with only porosity showing a slight reduction in the subsurface due to diagenetic alteration. The conclusions drawn from the study are that outcrop permeability and porosity studies are a viable technique for predicting subsurface heterogeneities.

Problems and limitations of the study

As with the previous outcrop permeability studies reviewed here, the justification for, and evaluation of the sampling schemes are only briefly addressed. In this study the outcrop data comprise permeability values from 278 core plugs which are compared to permeability data

from eighteen wells. The outcrop dimensions and sample locations are shown in Figure 3.4. The outcrop measures approximately 900' in length and 17' in height and is divided into facies types recognised as having different porosity and permeability characteristics from analysis of the subsurface reservoir data. These facies types form a tabular, stacked sequence. Due to access difficulties, sampling within the outcrop is confined to four subareas within which core plugs were collected along vertical and lateral profiles. Cores were also drilled along horizontal profiles between these subareas. From Figure 3.4, it is clear that this sampling scheme is not randomised and the closest spaced samples are oriented in the vertical direction. As no justification is given for this sampling scheme the following points require consideration:-

a) The outcrop sample volume (the core plug size), has been determined by the core plug size used in the subsurface reservoirs. This is necessary to allow direct comparison between outcrop and subsurface reservoir permeabilities but consideration must also be given to the importance of within-plug heterogeneities that are averaged out.

b) The orientation of sample profiles should be made relative to a geological datum (for example, a depositional surface) to enable comparison with the reservoir data from cores thereby allowing portability of outcrop-derived permeability models. Whilst the palaeotransport direction for the sand-body is noted in this study, the sample profiles are only loosely described as horizontal and vertical and are not oriented relative to any geological datum.

In this study, the sample data are concentrated along vertical profiles with very few samples in the horizontal direction. The permeability data were then subdivided by facies type. This sample scheme imposes a two-fold bias: first, the vertical sample profiles are likely to enhance any vertical correlation structure that may exist with horizontal correlation structure poorly represented or completely missed; second, the subdivision of the permeability data by facies type is based on the assumption that facies type controls the permeability distribution. This assumption should be evaluated statistically and reassessed as required as part of the sampling process. It is important to ensure that the

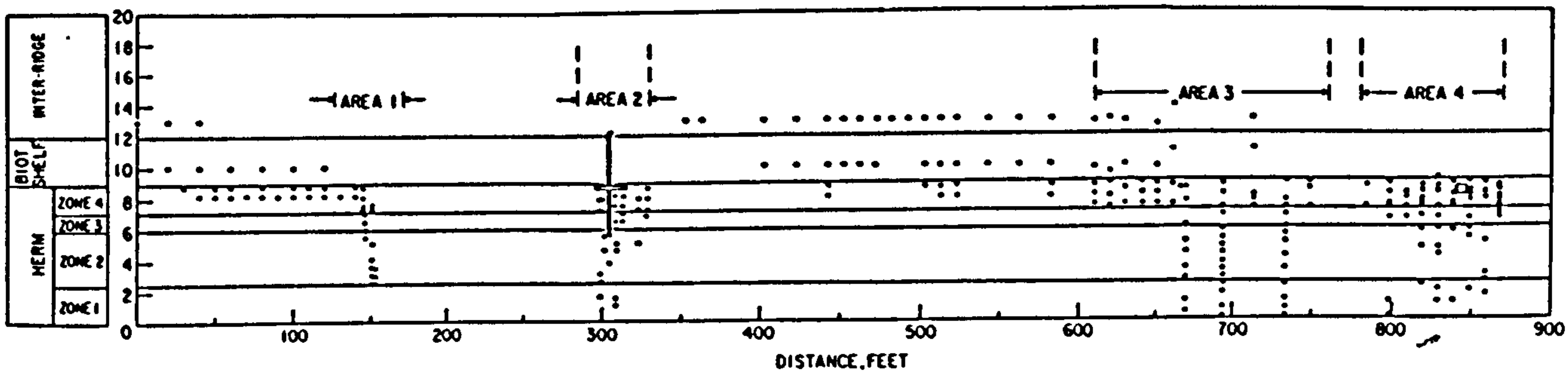


Figure 3.4 Outcrop sample locations: Shannon Shelf Ridge Sandstone, Salt Creek Anticline (after Tomutsa et al 1986)

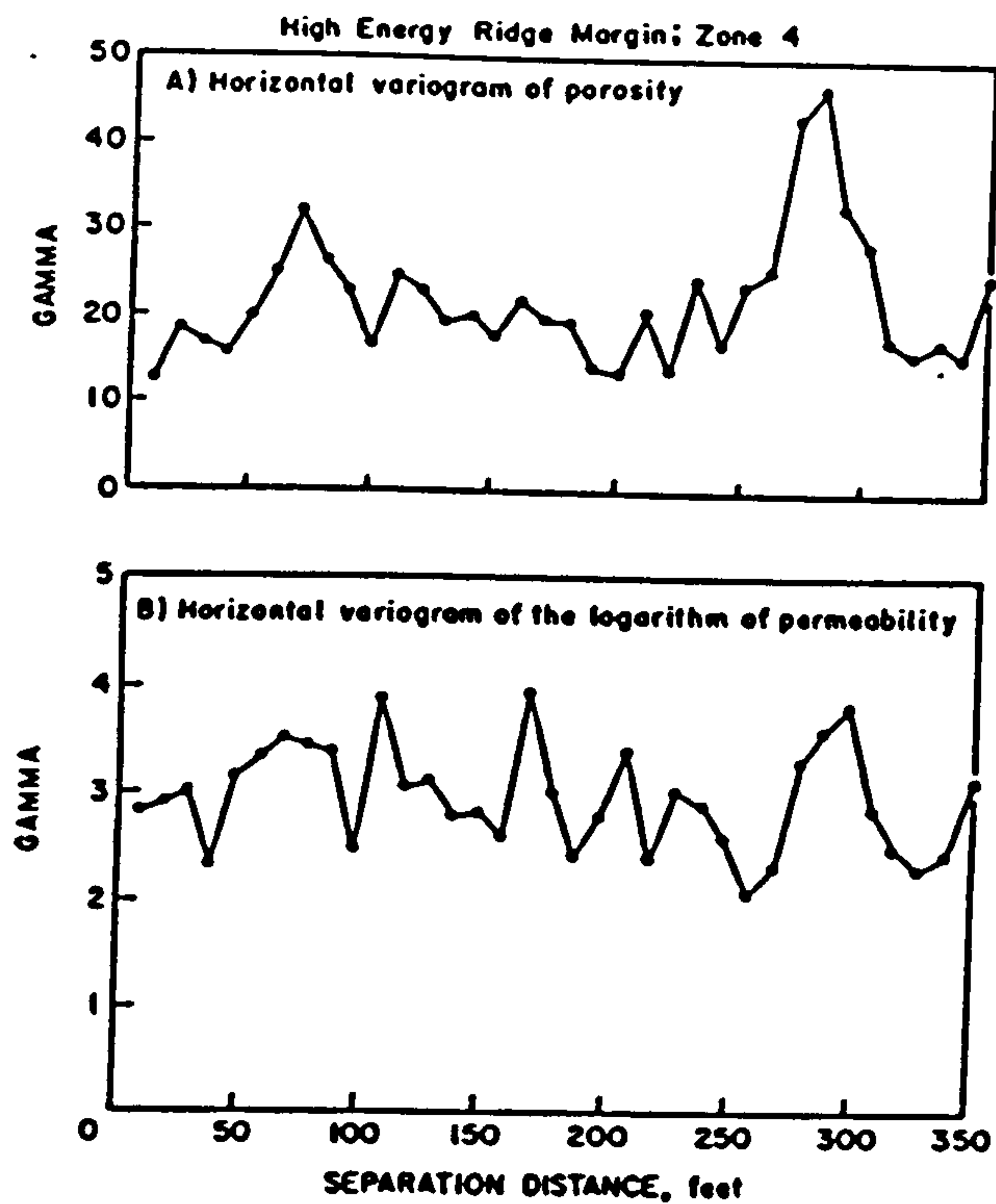


Figure 3.5 Horizontal variograms of the High Energy Ridge Margin facies, Zone 4 (after Tomutsa et al 1986)

permeability data are first sampled in an unbiased manner. Having obtained an unbiased sample (for example, individual samples obtained from randomly distributed locations or on a regular grid), these data can then be divided into regions with statistically different populations and the controls on permeability (e.g. facies type, diagenesis) determined. Having defined statistically different subareas the spatial correlation structure can be measured and interpreted with consideration of these controls.

Inconsistencies in the sampling strategy used by Tomutsa et al become apparent in the permeability correlation lengths derived from the outcrop data. Tomutsa et al identify some short horizontal and vertical correlation structures within variograms for these outcrop data but inspection of their variogram models shown in Figure 3.5 suggests that these structures are very weakly defined and dominated by a pure nugget effect (no apparent correlation structure). This absence of any correlation structure is very likely due to the low sample density; the minimum sample interval in the vertical and horizontal direction is 0.33' (4") and 2' respectively, but in many cases the minimal sample interval is greater than this. As a result, the behaviour of the variogram near the origin (zero sample interval) is poorly represented and difficult to model with confidence. Infill sampling will be required to rectify this.

The apparent absence of correlation structure may also be due to the averaging effect where a single horizontal and vertical variogram is constructed for each facies type. This may result in localised correlation structures being smoothed out. This averaging effect may be important in the High Energy Ridge Margin Facies, which averages 9' thick and extends laterally over 900', for which only one vertical and horizontal variogram was constructed.

In these tabular-form facies, the variation in vertical correlation structure may have a significant effect on fluid flow behaviour within what might otherwise be described as a 'layer-cake' permeability structure. As suggested for the outcrop study by Stalkup (1986), the measurement of permeability across layer boundaries would be useful

for determining appropriate averaging methods. The harmonic average for example, which is commonly used to calculate the vertical permeability for beds arranged in series (Figure 2.4, section 2.4.1), defines permeability at the boundary of adjacent grid blocks. The evaluation of permeability variations across bed boundaries may be used to refine this averaging technique.

Significant improvements can be made in this study by Tomutsa et al by more careful consideration of the sampling strategy. By employing an iterative sampling process, that is: sample - evaluate - sample, to maximise sampling efficiency and to determine the controls on permeability, the effects of sampling on spatial correlation structures and subsequent interpretation of these correlation structures will produce more reliable results.

Patterns of permeability in aeolian deposits (STUDY 1)

Goggin, D.J., Chandler, M.A., Kocurek, G.A., and Lake, L.W. 1986

and,

Permeability transects in aeolian sands and their use in generating random permeability fields (STUDY 2)

Goggin, D.J., Chandler, M.A., Kocurek, G.A., and Lake, L.W. 1989

Age: Cretaceous

Depositional environment: Aeolian dune sandstones

Outcrop and location: Page Sandstone, Arizona; Nugget Sandstone, Utah; Tensleep Fm., Wyoming; all USA.

These studies present the results of an outcrop permeability study on the aeolian Page Sandstone. The first study involved taking 2000 probe permeameter measurements made directly on the outcrop face and on borehole cores from an outcrop of the Page Sandstone, Northern Arizona. The objectives of the study were:-

- 1) to relate permeability variations to primary depositional processes
- 2) to describe the scale dependence of permeability variation

3) to infer the spatial statistics of permeability including its correlation structure and anisotropy.

Four scales of heterogeneity are defined from megascopic to microscopic. The scale dependency of permeability is examined through 'scaling grids', using the coefficient of variance (Cv) as a measure of heterogeneity. Variograms were used to model the spatial permeability structure.

In this initial study, permeability heterogeneity was found to be associated with the arrangement of stratification types, each of which has a unique permeability range. A nested structure comprised of large scale bed to bed permeability variation and within bed permeability variation was identified through variogram analysis. The variogram was also used to define spatial variability as a function of orientation, thus, the scale dependence of anisotropy was also estimated.

In the second study, additional permeability measurements were made on six further outcrops of the Page Sandstone. Added to this data base were permeability measurements made on two subsurface cores from the Nugget Sandstone, Utah, and the Tensleep Sandstone, Wyoming. The complete data base includes a total of 10,000 permeability measurements.

Based on additional permeability measurements from outcrop and subsurface cores, Goggin et al (1989) presented a generalised geostatistical model for aeolian sands. A two-scale variogram model was used, comprising a megascopic between-bed variation and a macroscopic within-bed variation (Figure 3.6). A large scale anisotropic variogram, orientated horizontally, represents permeability variation at the scale of the simulator grid block; the variation resulting from the spatial arrangement of bedding units. A separate, and highly anisotropic variogram orientated parallel to the stratification represents permeability variation at the scale of core plugs; the variation resulting from grain-flow, grain-fall, and wind-ripple deposits. The small scale range ellipses in these variograms have orientations, anisotropy ratios and major axes lengths which change with position in the unit. From core, the range anisotropy ratio is computed by fixing the major axis

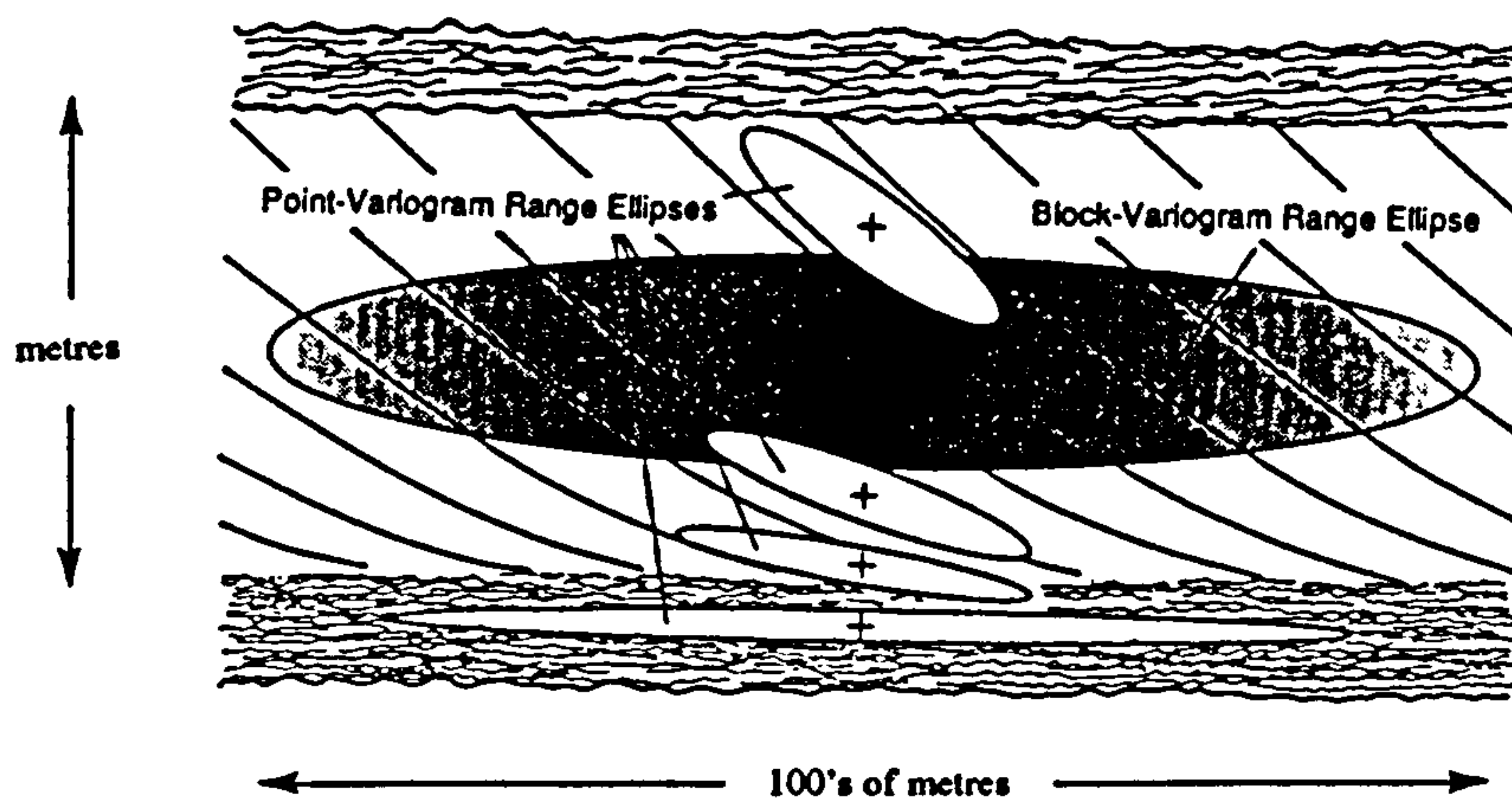


Figure 3.6 Schematic of a generalised geostatistical model for the two volume-scales of permeability variation observed in aeolian deposits. The shaded region represents the range ellipse for a spherical variogram model of block-average permeabilities. The smaller ellipses represent point-variogram models of permeability (after Goggin et al 1989)

length and estimating the minor axis length as a function of the local number of grain-flow/wind-ripple cycles per metre:

$R = 15.0$ metres (fixed). This is the major axis length of the small-scale range ellipse and is obtained directly from outcrop measurements and is a function of the vertical position within the dune unit.

α = Stratification inclination angle. From outcrop measurements this is found to be closely related to the permeability value (essentially a function of grain size) where:

α	$K_{mean} (\mu m^2)$
0	<0.6
$3.143 * K_{mean} - 1.886$	$0.6 \leq K_{mean} \leq 7.6$
22	>7.6

$KR \text{ (anisotropy ratio)} = R * N_{cycles}/metre$

The number of grain-flow/wind-ripple cycles per metre are also found from outcrop observations to be directly related to the permeability value (the frequency and thickness of grain flow tongues, comprised of coarser grains, decreases with height above the dune base) where:

$N_{cycles}/metre$	$K_{mean} (\mu m^2)$
N_{max}	$K_{mean} < K_{min}$
$a + b / (K_{mean} + c)$	$K_{min} \leq K_{mean} \leq K_{max}$
N_{min}	$K_{mean} > K_{max}$

Using the limits of $K_{min} = 0.6 \mu m^2$ and $K_{max} = 7.6 \mu m^2$ used in the estimation of α above, the following values for N are obtained:-

$N_{min} = 50 \text{cycles}/metre$ where $K_{min} = 0.6 \mu m^2$
 $N_{max} = 120 \text{cycles}/metre$ where $K_{min} = 7.6 \mu m^2$
 $a = 40 \text{cycles}/metre$
 $b = 80 \text{cycles}/metre$
 $c = 0.4 \text{cycles}/metre$

Having obtained the range anisotropy ratio for the variogram, the value of the nugget and sill are required. It is assumed that the variograms at both the megascopic and macroscopic scales have no nugget value. This assumption is supported by the close statistical relationship between stratification type and frequency and permeability which implies homogeneity of variance within stratification types as required by a no-nugget variogram. Given that the observed coefficient of variance for permeability remains approximately the same within and between units and with different local mean permeability, the sill value will depend on the mean permeability, where:

$$\text{Sill} = (\text{Cv} * \text{Kmean})^2 \quad \text{.....(6)}$$

Determination of the anisotropy ratio KR is dependent on the appropriate measurement of permeability within stratification types. The individual permeability measurements are probably assumed to be isotropic (although this is not mentioned) otherwise it must be ensured that all measurements are made at a constant orientation with respect to the dip and strike of the stratification. Clearly, careful consideration is also required where there are obvious diagenetic controls on the permeability variation as this may invalidate the permeability model.

The cross-section generation technique for permeability employs a nested geostatistical kriging process. Large scale unit to unit variation is generated first using a cell-kriging process, producing a smooth local permeability surface. Goggin et al (1989) suggest that the horizontally-aligned major ellipse of the variogram, which gives preferential weighting towards interpolated values arranged horizontally in relation to the control data, is consistent with the spatial relationship of permeability within first order bounding surfaces (dune/interdune: Brookfield 1977) in aeolian sequences. Small scale permeability variation associated with cross-bedding is then superimposed onto this large scale variation by means of a second cell-kriging process. The kriged values are not scaled up and so the smoothing effect at this scale of interpolation is less than at the larger scale. The permeability values assigned to each of the cells are interpolated from adjacent cell values using the variogram model obtained from outcrop.

The main limitation of this and other interpolation techniques, is the quality and density of the control data. The influence of these control data on the interpolated values decreases as the distance between the control data and interpolated value increases. Consequently, the confidence limits for interpolated interwell data decreases towards the centre of the cross-section panel. To reduce the effects of this, Goggin et al suggested a method of propagating information from the control data (the wells) into the interwell area thereby increasing the confidence limits of data values within those cells located centrally in the cross-section panel. This method reproduces a realistic sequence of grain-flow and wind-ripple stratification packages in a down-wind direction. In effect, the permeability values for each dune foreset are generated as if the dune was actually being accreted. The method is based on a simple sine-wave model within which the occurrence of grain-flow and wind-ripple stratification types is random:

$$K(x) = K_{mean}[1+Cv_{mix}*\sin(2\pi*N_{cycles})+Cv_{pure}*RN_{g}(0,1)]$$

- Where
- K(x)

= permeability as a function of x

K_{mean}

= the local mean value of permeability

C_v_{mix}

= coefficient of variance for a grain-flow/wind-ripple mixture

C_v_{pure}

= coefficient of variance for a pure grain-flow wind-ripple

N_{cycles}

= number of cross-stratification cycles

RN_g(0,1)

= gaussian random number with zero mean and unit variance
- or

.....(7)

Problems and limitations of the study

Overall, this study presents the most comprehensive data set collected from outcrop rocks of any one depositional environment. The sampling scheme differs from those employed in previous studies and introduces the concept of 'scaling grids'. As with previous studies however, statistical tests of significance have not been applied to these data, either within and between grids at the same outcrop or between outcrops.

The principle of the scaling grid, shown in Figure 3.7, is to identify the scale variation of a property or characteristic by refining the sample point spacing whilst the sample volume is kept constant. These grids are also considered to provide a statistically efficient sample scheme (that is, both the variation in a property or characteristic and the area over which that variation is confined is measured representatively). To allow comparison between permeability values measured over different rock volumes, it was assumed (Goggin et al, 1986) that the grid area is proportional to sample volume and that the sample variance decreases as the grid area (volume) increases. This volume:variance relationship is fundamental to geostatistical block kriging (see section 2.4.4) and R.E.V. theory (the Representative Elementary Volume: see section 2.4.5). In these scaling grids however, the sample volume remains constant, and the change in sample variance is likely to be a function only of sample density and is purely a statistical relationship.

Goggin et al (1986) examined the spatial correlation structure in various directions within these grids through variogram analysis. As the sample interval changes with direction, a modified form of the variogram shown below was used which sorts the sample pair distances into selected distance classes (compare with the standard variogram, equation 1, Section 2.3.2.1.1). This ensures greater statistical reliability in the variogram but the choice of class size is subjective. The value of the variogram will also be an average for each distance class and variation within these classes will be smoothed out. As Goggin *et al* point out, it is important to ensure that the choice of class size does not correspond to some geological phenomena which may cause the variogram to be biased towards this feature. The effect of class size can be assessed by

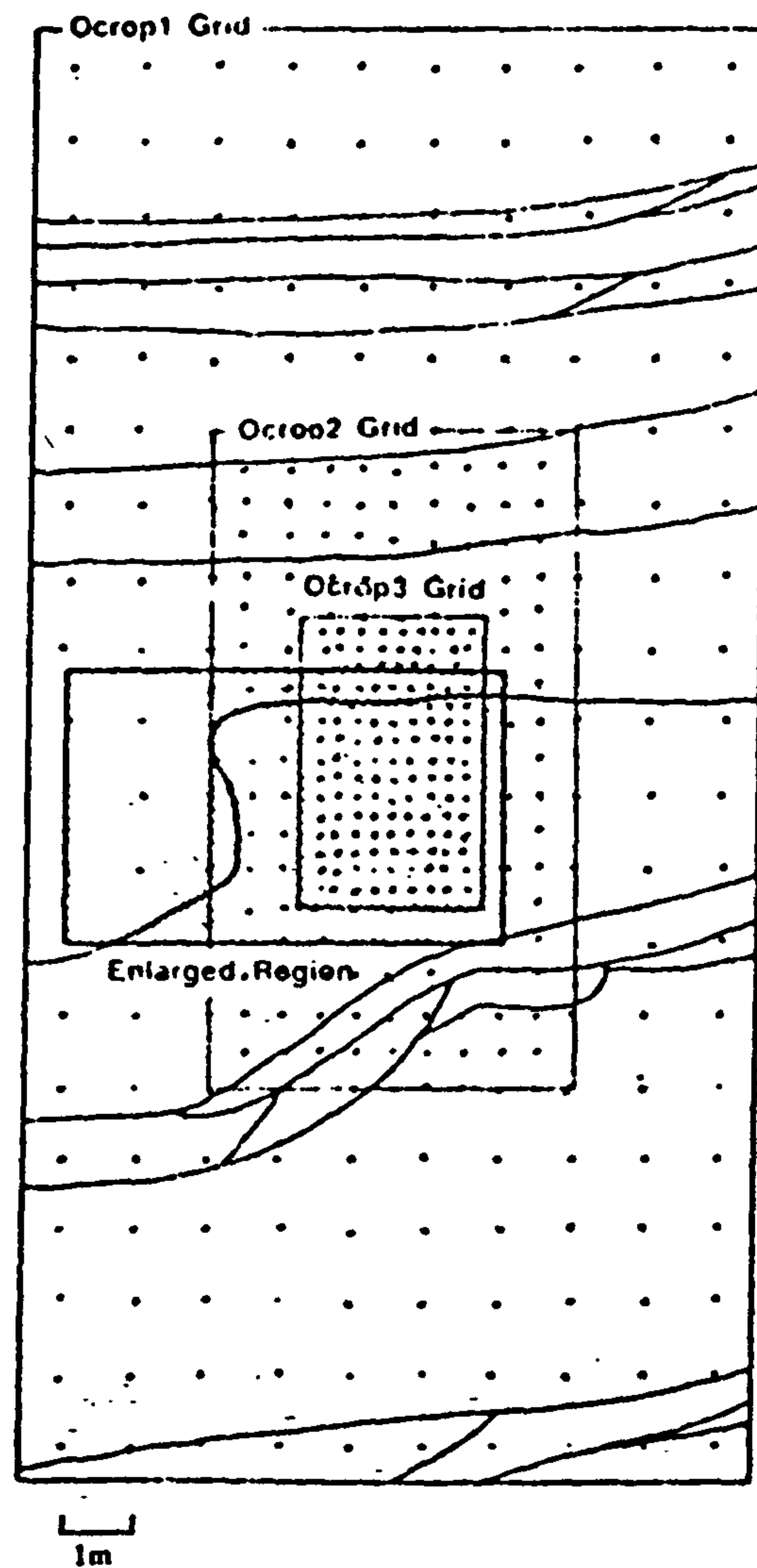


Figure 3.7 Sketch of concentric grid boundaries in relation to stratigraphy (after Goggin et al 1986)

comparing variograms constructed for different class sizes:

$$\gamma(H_K,\delta\pm\delta\Theta)=\left|\frac{\sum_{j=1}^N h_j[f(x_j)-f(x_j+h_j)]^2}{2\sum_{j=1}^N h_j}\right|_{\Theta\pm\delta\Theta}$$

Where

Hk = Class size (metres,feet)

Θ = Direction of variogram relative to horizontal (degrees)

δΘ = Window size or spread of allowable points along Θ, degrees

.....(8)

The estimation of correlation lengths in various directions between the horizontal and vertical (relative to bedding planes) is necessary if permeability variation associated with features such as cross-bedding are to be accounted for.

On examination of the cause of permeability variation, Goggin et al (1986) make an important observation, which is that grain-flow deposits in one unit may be less permeable than wind-ripple deposits of another unit, but grain-flow deposits will be more permeable than the wind-ripple deposits of the same unit. This means that the boundaries of cross-bedded units must be defined (for example, within cored intervals) before predictions of the permeability characteristics based on the stratification type are made. However, no reason for this apparent relationship is given, which is probably associated with selective diagenesis, and it is not clear whether this relationship would persist within subsurface reservoir rocks of aeolian origin that are subject to different processes of diagenesis.

Although several different sources of permeability data were used to develop the model, the effects of diagenesis on permeability, and the robustness of the model are not addressed. It is also unclear as to

whether the model applies to all aeolian dune types or is restricted to a specific type. Further complications regarding application of the model is envisaged where dune development is closely associated with drying-up cycles; influencing the thickness, frequency and ratio of stratification types, and ultimately the grain size distribution and permeability values.

Although the geostatistical model produces a very convincing interwell permeability map that appears to reproduce the permeability variation seen within aeolian dunes, the model has a number of limitations that should be addressed. These limitations are as follows:-

a) The model is based on a number of assumptions regarding the cyclicity of stratification types and the relationship between stratification type and permeability. Although these assumptions are drawn from actual observations made at the outcrops included in the study, possible deviations from these assumptions are not considered. For example, the relative position of the water table to the dune, and the rate and frequency at which this water table fluctuates can have a significant influence on dune morphology, stratification type and accretion rates. One or all of these factors may render the model inaccurate.

b) The model is based on permeability data obtained using a probe permeameter. Where permeabilities are obtained using conventional core plugs, wireline logs or some other form of measurement, the sample volume will invariably be much greater and will probably include several stratification laminae of more than one type. For these data, the model would need to be modified to allow for the reduced variance within samples.

c) The model is dependent on the validity and reliability of the well data but the robustness of this model has not been tested. Further research is needed to test the model using control data of varying validity and reliability and from a variety of aeolian outcrops.

Heterogeneities and geometry of sedimentary bodies in a fluvio-deltaic reservoir (STUDY 1)

Ravenne, C., Eschard, R., Galli, R., Mathieu, Y., Montadert, L., and Rudkiewicz, J.L., 1987

and,

Conditional simulation of the geometry of fluvio-deltaic reservoirs. (STUDY 2)

Matheron, G., De Fouquet, C.H., Beucher, H., Galli, A., Guerillot, D., and Ravenne, C. 1987

Age: Jurassic

Depositional environment: Fluvio-deltaic

Outcrop and location: Ravenscar Gp., Yorkshire, England

This outcrop study and the associated permeability model presented by Matheron et al (1987) is based on a detailed sedimentological and petrophysical investigation of fluvio deltaic deposits; the Ravenscar Group (Middle Jurassic), exposed in a cliff section on the Yorkshire coast. Two types of model are used; at the largest scale, the spatial distribution of facies types is generated using a discrete stochastic model whilst at the smaller scale, permeability values within each of these facies types are generated using a continuous stochastic model.

Detailed areal photography was used to delineate the geometry and distribution of different depositional units, including their internal characteristics and the nature of the contacts between them (Figure 3.8). The characteristics of the depositional units in terms of their lithological and reservoir properties were obtained from detailed description at outcrop and wireline logs obtained from boreholes drilled behind the cliff face. Matheron et al (1987) assigned indicator values to each facies type and modelled their spatial distribution through geostatistical kriging using the variograms shown in Figure 3.9. A significant advantage of this technique over others (for example, boolean sets and random genetic models) is that the facies types do not have to be treated as independent and the position of one facies type may influence the



Figure 3.8 Extract of the digitisation of the cliff over 300m length (after Ravenne et al 1987)

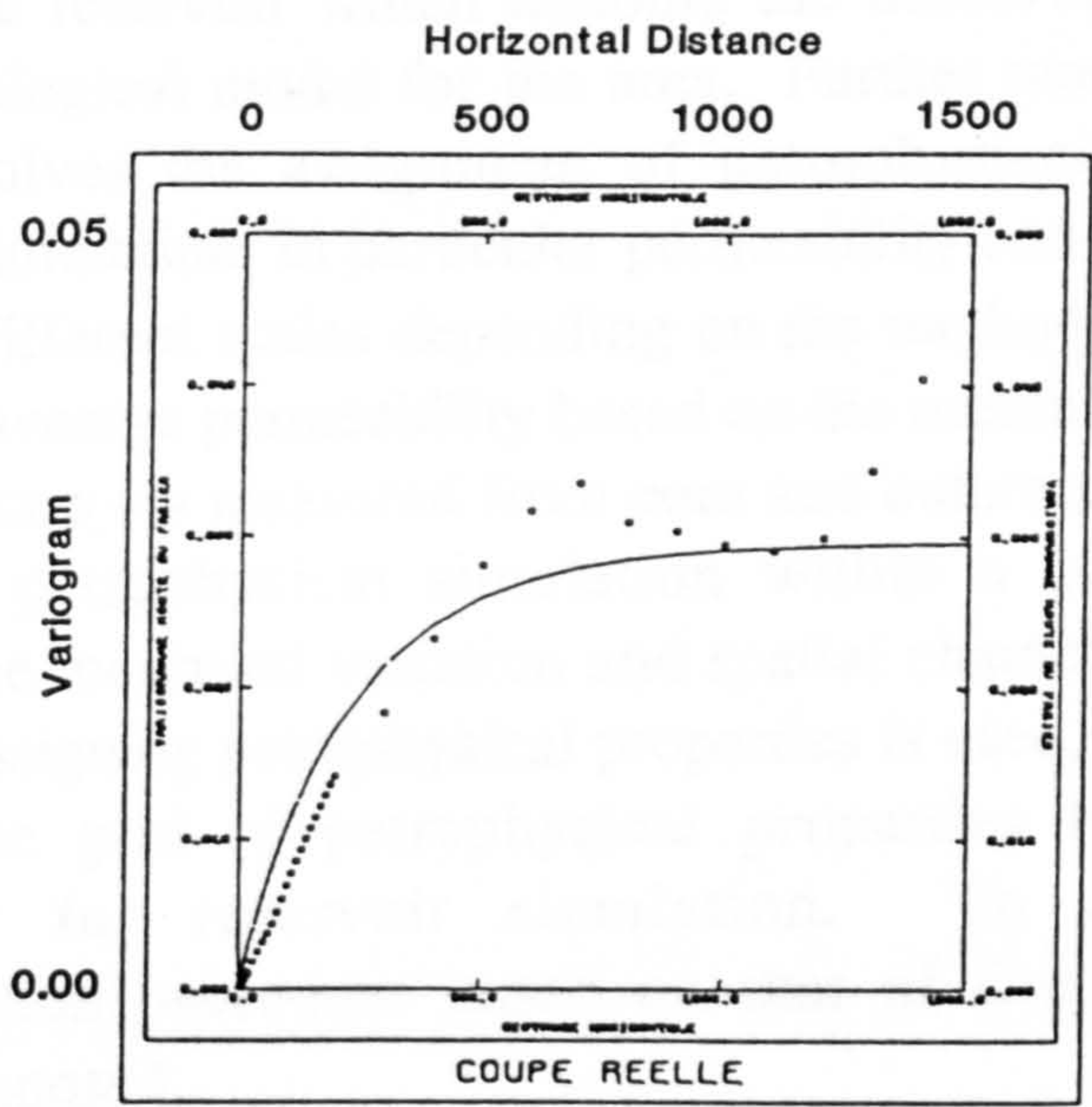


Figure 3.9 Variogram of regularised facies (after Matheron et al 1987)

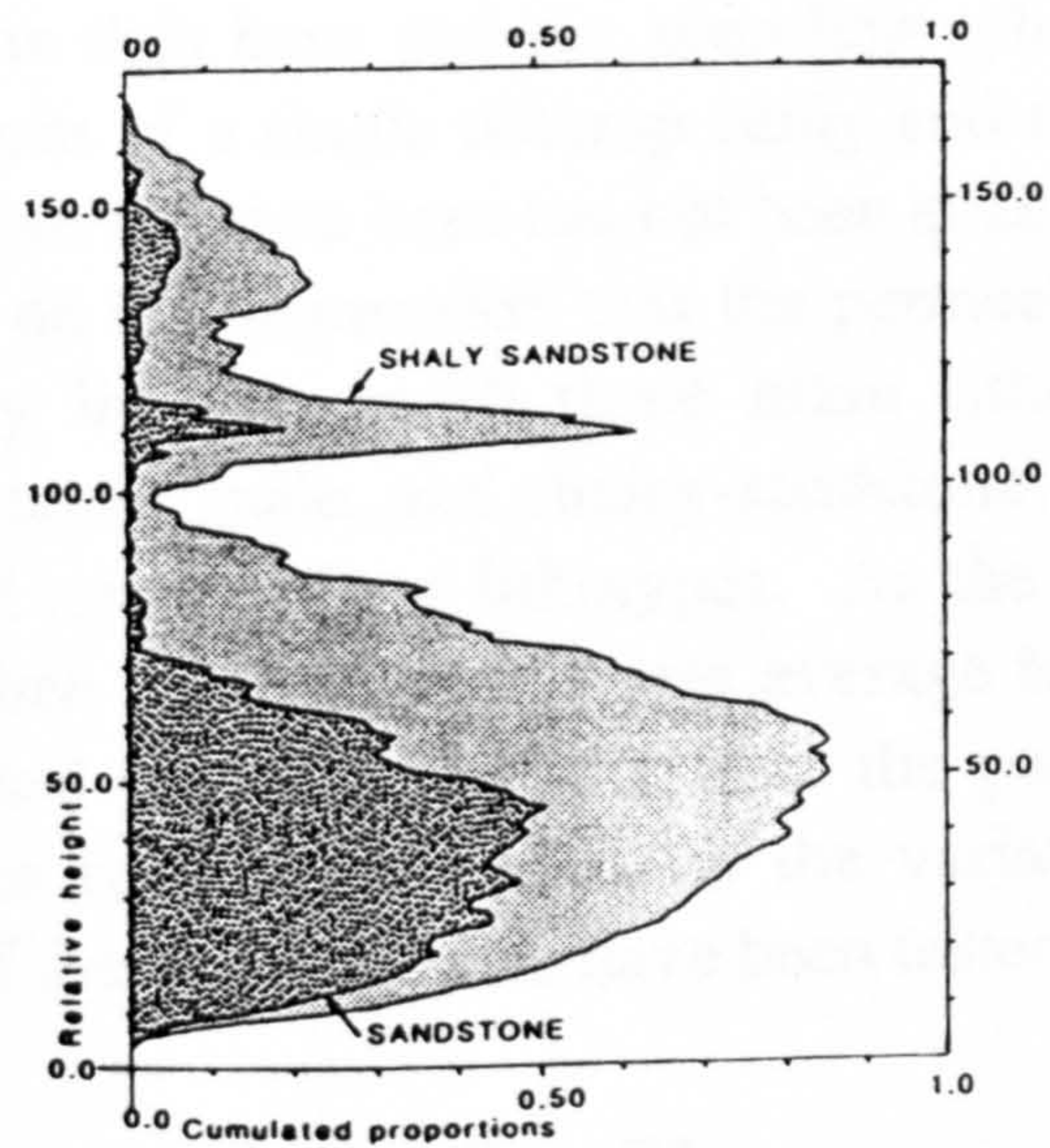


Figure 3.10 Vertical cumulated proportions of sandstone and shaly sandstone (after Ravenne et al 1987)

position of another or the same facies type, governed by some covariance function. The model honours the facies types identified within the wells and those between the wells interpreted from seismic data. In addition, horizontal and vertical facies proportion curves were generated which were used to condition the interpolation process (Figure 3.10).

The resulting simulation of the facies is an equiprobable lithofacies image of the reservoir which honours the observed data and agrees with the geological model for the area. Further work proposed by the authors involves the assignment of petrophysical properties to the lithofacies simulation, in particular permeability and porosity. This can be done at different scales depending on the method used, for example, a statistical average permeability based on the measured variation within a specific facies (as measured from core and outcrop, for example), or a conditional petrophysical simulation within a particular facies to reproduce the measured variation and spatial characteristics. Whatever method of assigning petrophysical properties is used, the final stage is to scale up the grid of petrophysical properties to a grid of cells appropriate for reservoir simulation. To achieve this, an homogenisation procedure based on that of Cardwell and Parsons (1945) is proposed.

Problems and limitations of the study

The main criticism of this study and the model produced is levelled at the validity of the data base and the sampling scheme. The model is based on the results of a single outcrop study and the robustness of the model derived from this data base has not been evaluated. The sampling scheme is based on the assumption that the permeability characteristics are governed by lithology with three main lithotypes; dominantly sandstone, dominantly shale, and shaley-sandstone. Thus the sampling scheme is biased towards these lithotypes. As the disposition of these lithotypes will then be used to calculate average block permeabilities, this must be based on the assumption that the permeability variation within lithofacies types is secondary to the variation between facies types. Neither of these assumptions have been tested.

Studies of reservoir heterogeneity and permeability anisotropy in lithified carbonate sands from the Great Oolite Formation (Middle Jurassic) of southern England.

Lewis, J.J.M., 1987

Age: Jurassic

Depositional environment: Shallow marine carbonate sand shoals

Outcrop and location: Great Oolite Fm., Avon, England

and,

Outcrop-subsurface comparisons of heterogeneity in the San Andres Formation

Kittridge, M.G., Lake., L.W., Lucia., F.J., and Fogg., G.E., 1989

Age: Cretaceous

Depositional environment: Open marine packstones and wackestones

Outcrop and location: San Andros Fm., New Mexico, USA

Carbonate rocks have received considerably less attention in outcrop permeability studies than clastic rocks. There are two main reasons for this; first, the majority of reservoirs are comprised of clastic rocks, and secondly, the problems associated with diagenesis are more acute in carbonate rocks than in clastic rocks.

To date, there are only two significant permeability studies conducted on carbonate rocks; those of Lewis (1987) and Kittridge et al (1989), both of which have focussed on clastic carbonates.

Lewis (1987) investigated permeability and porosity variations within carbonate sand-bodies of the Great Oolite Formation (Jurassic) in south west England. The geometry of these sand-bodies, interpreted as sand shoals, was first described. Permeability measurements were made on core plugs sampled along vertical profiles (vertical with respect to the form of the sand-body) and on scaling grids similar to those used by Goggin et al (1986). The sampling schemes were used for both descriptive and spatial statistical analyses. The number of samples collected was fairly small, probably because of the time and cost

involved in collecting and processing core plugs. A significant contribution by Lewis is provided in the analysis of intra- and inter-partial permeability heterogeneity; highlighting the effect these microscopic-scale heterogeneities may have on hydrocarbon flow and recoverable volume.

In the study by Kittridge et al (1989), a comparison is made between permeability heterogeneities measured at outcrop and in the subsurface on the San Andres Formation (Permian) in Texas. This comparison allowed the evaluation of the effects of diagenesis of permeability characteristics.

The San Andres Formation comprises dolomitised packstones and wackestones which have been interpreted as open marine. These are overlaid by shallow water restricted marine and intertidal carbonate sands. Overlying both of these reservoir units is a dense mudstone and anhydrite which forms the reservoir seal.

Permeability was sampled at outcrop over a grid measuring approximately 100' long and 80' high with a regular sample interval of 10'. The horizontal and vertical axes of this grid were aligned parallel and perpendicular to the bedding planes respectively. Six smaller grids and a vertical transect were placed within this large grid. Sampling within these smaller grids was based on a centric systematic pattern (see section 5.4, Chapter 5), with a minimum sample interval of 0.013m. The sample interval within the vertical transect was 0.051m. All permeabilities were measured using a field portable probe permeameter, but additional core plugs were sampled to provide a calibration for the probe permeameter and to allow comparison with permeabilities measured on core plugs in the subsurface reservoir.

Comparisons between permeability data from outcrop and the subsurface show a general agreement between the statistical properties. The exception to this is the mean permeability which is consistently lower in the subsurface. This reduction in the mean permeability is attributed to an increase in the overburden pressure in the subsurface reservoir. The apparent similarity between outcrop and subsurface permeability variation is encouraging because it implies that the spatial

correlation measured at outcrop can be applied to the subsurface.

The direct comparison between outcrop and subsurface permeabilities is complicated by the differences in sample volume where outcrop permeabilities were measured using a probe permeameter and subsurface permeabilities were measured on core plugs. This problem is recognised by Kittridge et al. (1989) but no solution is suggested.

Particular attention was paid to the effects of fines on the outcrop where these are likely to influence the probe permeability measurements. The face preparation technique used involved grinding the rock face to produce a flat surface. The generation of fines produced through grinding appears to cause a reduction in the variance and mean permeability (Figure 3.11). Kittridge et al argue that these effects on the outcrop permeability values caused by fines do not affect the conclusions regarding the nature of the permeability distribution and how it relates to the geology, nor does it apparently affect the similarity in distribution type and coefficient of variance between the outcrop and subsurface. However, the justification of the face preparation technique here does not justify use of the same technique on different rock types elsewhere.

Variogram analysis was used to determine correlation lengths within the outcrop and subsurface data. Permeability variation was shown to be greater within beds rather than between beds. Different correlation lengths were noted depending on the sample spacing: a correlation length of 0.9-1.5 metres for 0.3 and 0.15 metre sample spacing, and a correlation length of 0.076 metres for the 0.025 and 0.013 metre sample spacing. A sharp drop in the variogram for the vertical transect data from the outcrop is interpreted to be a hole effect, indicating that some pattern of cyclicity exists within these data. However, this 'hole effect' occurs at a lag spacing of 15' which is just short of the transect length of 20' and may be a function of the limited number of sample pairs at this spacing.

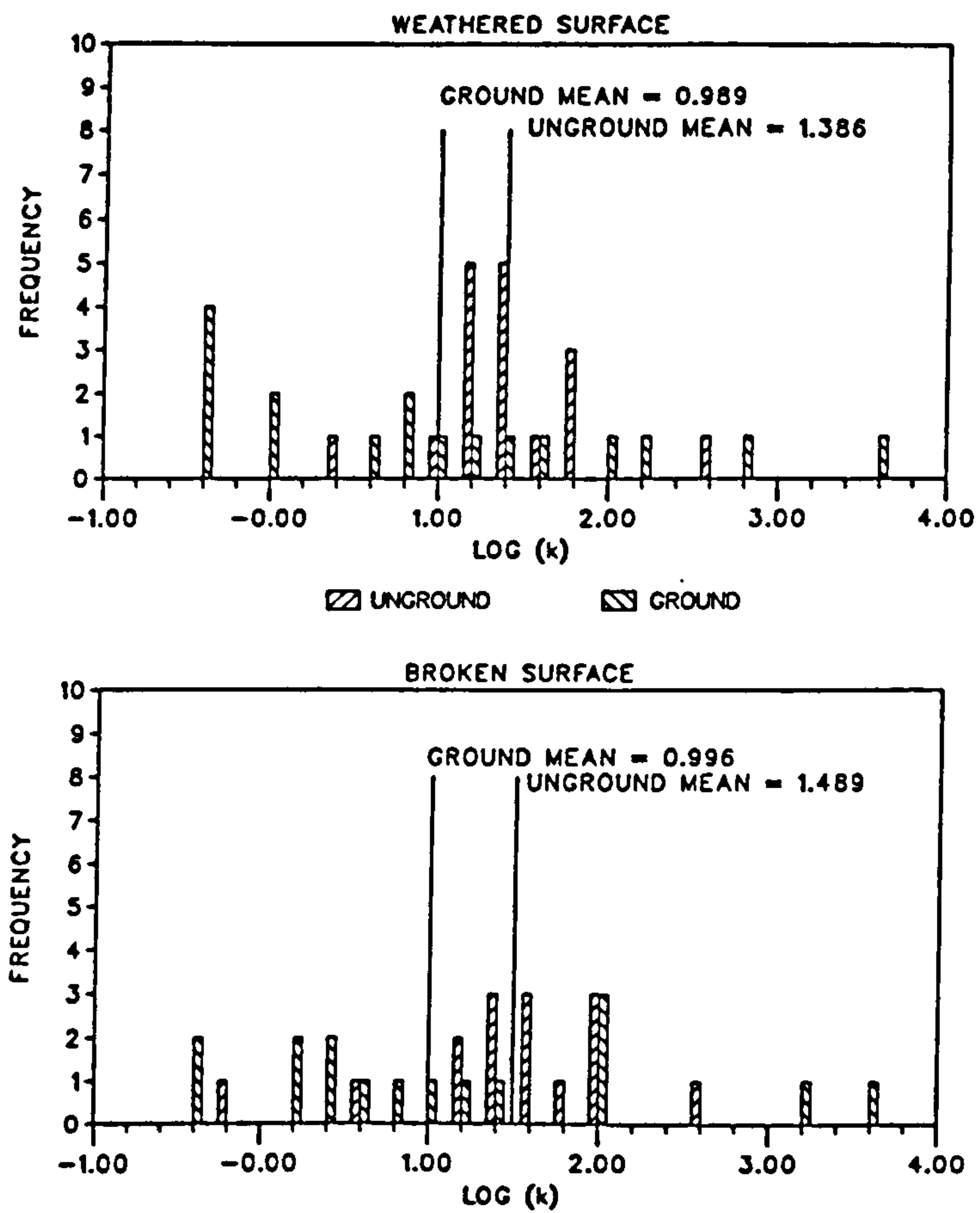


Figure 3.11 Permeability reduction due to grinding process, weathered and broken surfaces (after Kittridge et al 1989)

Problems and limitations of these studies

As noted from previous studies, the position of sample grids, the number of sample grids, and the number of samples within each grid are not justified or validated in either study. In the study by Kittridge et al, the smaller grids were positioned in 'geologically interesting areas and in places which could be sampled easily'. Clearly, this form of sampling will impose a significant bias before the data are analysed and the observed relationships between permeability characteristics and geological variability should be considered in the light of this.

The probe and core plug dimensions are not documented by Kittridge et al and it is not possible to determine what the various sample volumes are likely to be. Although comparison between probe permeability measurements and permeabilities measured on core plugs are used to demonstrate the averaging effect of outcrop samples, this is not quantified.

The importance of intra- and inter-grain permeability heterogeneity identified by Lewis is not addressed by Kittridge et al.

3.3 Discussion

The outcrop studies cited here (summarised in Table 3.1) cover a fairly wide variety of depositional rock types (eolian, fluvial, deltaic and shallow marine). However, only the studies of Dodge et al (1971), Pryor (1973), and Goggin et al (1986 and 1989) investigate permeability variations from different outcrops representing rocks from the same depositional environment. Consequently many of these outcrop studies may be location specific and not portable to the reservoir. The close similarity between the statistical variability and spatial correlation structures within permeability data from the various outcrops in the Dodge et al study is encouraging but perhaps expected since the sandstones were well-sorted, massive blanket sands. Although similarities were observed between the permeability data from different outcrops in the study by Pryor, the results are inconclusive as the

number of data points gathered at each outcrop was small and confused by the incorporation of several scales of heterogeneity.

Those studies that compared permeability data from outcrops and laterally correlatable subsurface reservoirs (for example, Tomutsa et al, 1986 and Kittridge et al, 1989) have shown that the measured variation in permeability displays consistency between samples within which the diagenetic histories differ. These results are important as they demonstrate the portability of permeability models developed from outcrop studies to subsurface reservoir rocks.

There are a number of different measurement techniques for the same property which may complicate the data obtained from outcrop. In the study by Pryor (1973), permeabilities were estimated for eolian dunes using orientated sample tubes, 5.2cm long, within unconsolidated sands. In a later study by Goggin et al (1986 and 1989), permeabilities were collected from outcrop using a probe permeameter. Although these studies might reach similar conclusions about the fluid flow characteristics for the same facies type, the permeability data obtained are not directly comparable because they are measured over different volumes and require appropriate scaling-up. Consequently, combining outcrop-derived permeability data bases is not a simple task. To reduce the problems and errors associated with scaling-up data for comparison between outcrop studies, a logical step is to adopt a standard measurement volume and sample interval for all or part of the data set. These standardised data can then be used to compare results from different outcrop studies with ease and rapidity. As probe permeameters and core plugs are the usual sampling techniques for permeability, then this standard measurement volume will be defined by the probe and core plug dimensions.

Both core plugs and probe permeameter measurements require an evaluation of face preparation before sampling. This is necessary to remove the effects of surface modification caused by a combination of diagenesis, plant growth, and fines. From the published outcrop studies it is apparent that little attention is paid to face preparation, and often only a visual estimation of the depth of surface modification is made prior to sampling. Whilst the results of these outcrop permeability studies often display consistency between statistical and spatial

permeability variation and lithofacies type, permeability variation superimposed through surface modification is rarely quantified. In some cases this modification may be responsible for the apparent correlation with the geology, where, for example the generation of fines and their effect on the measured permeability is lithology-specific.

Probe permeameter measurements are particularly sensitive to surface modification because the measured variation is largely influenced by the fabric at the point of injection. Core plugs on the other hand provide an average permeability over the core plug volume and surface modification at the end on the plug will be less noticeable since it is incorporated in the average value. In those outcrop studies using probe permeameters, face preparation techniques vary greatly. Goggin et al (1986), Kittridge et al (1989), and Dreyer et al (1990) used an angle grinder to obtain a 'fresh', flat face in a desired orientation, whilst Weber et al (1972) simply scraped the surface. The method of face preparation may well introduce its own form of surface modification through the generation of fines or smearing of clays. The prepared surface should be examined closely to ensure that a fresh exposure is obtained with no additional modification of the grain fabric. This has not been documented with sufficient detail in any published outcrop study and emphasises the need for the development of appropriate face preparation techniques that minimise surface modification.

In an attempt to short cut exhaustive sampling which requires considerable effort, various sample schemes have been used. The most commonly used schemes are based on horizontal and vertical transects. These schemes have a practical application because the vertical profiles indicate how and why permeability varies within wells whilst the horizontal profiles can be used to indicate how and why permeability varies between wells. In only a few outcrop studies have tests of reliability been performed on the sample schemes used.

Goggin et al (1986) evaluated their sample scheme by using the model developed from the sample data to reconstruct a map of the permeability heterogeneity. This map was then visually examined to decide whether it reproduced the original data set and looked like a 'realistic dune'. However, this method of evaluating the sampling scheme is somewhat subjective because there is no strict definition for what represents a realistic dune. This method does have the advantage

in that it simultaneously evaluates both the statistical and spatial permeability variation.

A semi-quantitative approach for evaluating the sampling scheme was adopted by Jones et al (1984). In this technique the observed statistical parameters for permeability variations within stratification types was used to predict the stratification type from outcrop permeability data. The predicted types were then compared to the actual types, the accuracy of the prediction being a measure of the validity of the data set and therefore the sample scheme.

However, these techniques employed by Goggin et al and Jones et al use the original sample data to evaluate the sampling scheme used to collect it. This means that the validation is outcrop specific and cannot therefore be generalised to other outcrops.

3.4 Conclusions

From the preceding discussion the following conclusions are drawn:-

- 1) More outcrop permeability studies are required from the same lithofacies to provide more reliable data bases
- 2) A code of practice is required for outcrop permeability measurement. As the probe permeameter is an ideal device for gathering permeability data from outcrop, this code of practice should be applicable to this device. Use of this code of practise should ensure that the errors associated with permeability measurements are minimised and quantified where possible. As a result of this, permeability data collected from different outcrops can be compared more easily
- 3) Outcrop permeability sampling schemes require standardisation in order to achieve the following:-
 - a) improved reliability of the sample data
 - b) maximisation of information with minimal effort (sampling efficiency)

- c) appropriate information
- d) ease of combinability of data from different outcrop studies for the development of 'global' data bases (see 1)

To achieve these, a methodology for sampling permeability at outcrop is required

- 4) Assessment of the portability of outcrop-based permeability models should be made wherever possible by conducting studies on outcrop rocks that also form subsurface reservoirs. In the absence of such outcrops, those outcrops with minimal post-depositional modification should be sought. Modifying processes include diagenesis, igneous activity and tectonic deformation. To evaluate their significance, the role of these processes in determining the measured permeability values should be examined and quantified where possible.

WORKER/DATE	OUTCROP	LITHOFACIES & DEPOSITIONAL ENV.	MEASURED ROCK FEATURES/ CHARACTERISTICS/ PROPERTIES
Hutchinson et al. 1961	Woodbine Fm. Texas USA Picture Cliff, Point Lookout, Gallup & Dakota Fms., all New Mexico, USA	Shallow marine blanket sands	K, ϕ , grain texture, cement %, formation resistivity factor (F)
Dodge et al. 1971	Woodbine & Paluxy Fms., Texas, USA	Shallow marine blanket sands	K, ϕ , grain texture, cement %
Weber et al. 1971	Leerdam, The Netherlands	Distributary channel-fill sands	K
Pryor 1973	Whitewater River, Ohio, Wabash River, Illinois Mississippi River, Louisiana, Sabine Pass, Texas, Ship Island, Mississippi, Louisiana & Santa Rosa Island, Florida, all in USA	Fluvial bar sands, marine beach sands, and aeolian dune sands	K, ϕ , and grain texture
Jones et al. 1984	Mesaverde Group, Colorado, USA	Fluvial meanderbelt sandstone	K and grain texture
Tomlins et al. 1986	Shannon Formation, Wyoming, USA	Shallow marine shelf sand-ridge complexes	K, ϕ
Stallup 1986	As Hutchinson et al. 1961	Shallow marine blanket sandstones	K
Stallup and Ebanks 1986	Ferron Sandstone Member, Utah	Barrier island - tidal channel - tidal delta complex	K
Reverne et al. 1987	Ravenecar Gp., NE England	Fluvio-deltaic	K, ϕ , Spontaneous potential, Gamma Ray Density, Dipmeter and Sonic
Goggin et al. 1986 and 1989	Page Sandstone, N. Arizona, USA Nugget Sandstone, Utah, USA Tensleep Formation, Wyoming, USA	Aeolian dunes	K
Lewis 1988	Great Oolite, S. England	Shallow marine carbonate sand shoals	K, ϕ
Kittridge et al. 1989	San Andres Formation, New Mexico USA	Open marine packstones and wackestones	K, ϕ
Dreyer et al. 1990	Saltwick and Soulby Formations, NE England	Fluvial distributary channels	K

Table 3.1 Summary of published outcrop permeability studies

WORKER/DATE	PERM. MEASUREMENT TECHNIQUE	SAMPLING SCHEME
Hutchinson et al. 1961	Hassler cell-derived permeabilities on core plugs 1' long cut into 1" segments	Core plugs taken parallel to dip within sedimentary units. Several outcrops included in study
Dodge et al. 1971	Utilises data from Hutchinson et al. 1961	Sample grids and vertical transects. Utilises concept of sedimentary units (after Otto, 1938)
Weber et al. 1971	Boreholes (3cm diam.) with probe permeameter measurements on sectioned cores. Draw down fluid tests in boreholes	Vertical transects on borehole cores.
Pryor 1973	Orientated sample tubes 5.2cm long (unconsolidated sands) with permeability measured using a Constant Head-Falling Head Permeameter	Nested sample grids in plan and cross-section, and vertical sample transects
Jones et al. 1984	Core plugs	3 outcrop "complexes" divided into 5 sample "panels" (3 in Upper Strike complex, 1 in Lower Strike complex, and 1 in Dip complex). Sampling targets stratification type with sample no. proportional to frequency of occurrence (utilising concept of sedimentary units). 1 panel in U. Strike complex contains 3 vertical sample transects to represent well data.
Tomutsa et al. 1986	Core plugs (vertical and horizontal)	Outcrop area approx. 900' long by 38' high. Vertical and horizontal sampling concentrated within 4 sampling areas incorporating 3 different facies. Lateral transects located to obtain maximum lateral extent. Location of vertical transects and sampling within them is based on geologic changes.
Stallup 1986	Core plugs 1' long cut into 1" lengths	Six different outcrops with vertical transects spaced 2-4' apart
Stallup and Ebanke 1986	Core plugs 6" long	Fifteen outcrops sampled using vertical transects. Location of transects and sampling within transects is unbiased with respect to geology.
Reverne et al. 1987	Thirty-six boreholes with whole core sub-sampled using core plugs 4cm in length	Two outcrop sites each with a series of cores from boreholes arranged concentrically as square grid with decreased spacing. Boreholes are orientated relative to mean sea level.
Goggin et al. 1986 and 1989	Probe Permeameter and Core Plugs	Seven outcrops and two subsurface reservoirs with horizontal and vertical transects, "scaling" grids (regular grids with decreasing sample interval), and sampling within pre-defined stratification types. Vertical cores are orientated relative to mean sea level.
Lewis 1988	Core Plugs	Vertical transects and "scaling" grids (after Goggin et al. 1986) aligned relative to bedding planes
Kittridge et al. 1989	Probe Permeameter and Core Plugs	"Scaling" grids and horizontal and vertical transects aligned relative to bedding planes
Dreyer et al. 1990	Probe Permeameter	"Scaling" grids after Goggin et al. 1986

Table 3.1 Summary of published outcrop permeability studies

WORKER/DATE	NO OF SAMPLES	MAX. DOMAIN DIMENSIONS (length, x; length, y; height, z)	MIN. SAMPLE INTERVAL (h) & SAMPLE SUPPORT DIAMETER (d)
Hutchinson et al. 1961	?	x = 1000' z = ?	h = ? d = 7/8"
Dodge et al. 1971	1125	x = 800' z = 30'	h = 0.5' d = 7/8"
Weber et al. 1971	c.500	x = 375m y = 75m z = 3.75m	h=3cm d=1cm
Pryor 1973	480 (river bar) 348 (beaches) 164 (aeolian dunes)	River bar: x = 2060' y = 370' z = 20' Beach: x = 1888' y = 150' z = 2.5' Aeolian dunes: x = 2000' y = ? z = 12'	h = <1' d = 2.5cm
Jones et al. 1984	128 from each sample panel	Dim. of Lower Strike Panel: x = 37m z = 3.5m	h = 1' d = ?
Tomutaa et al. 1986	Total of 278 High energy ridge margin = 214 Bioturbated shelf sandstone = 32 Inter-ridge facies = 32	x = 900' z = approx. 30'	h = 0.5' d = 1"
Stallup 1986	?	x = 80' z = 16'	h = 1' d = 1"
Stallup and Ebanks 1986	20 - 25 samples/transect No. transects = ?	x = approx. 1200' z = approx. 15'	h=6" d=1"
Reverne et al. 1987	Total of 54 boreholes Total No. K values = ?	x = 11km y = 11km z = 50m	h = 25cm d = 23mm (borehole dia. = 9.3cm)
Goggin et al. 1986 and 1989	c.10,000	y = 30m z = 60m	h = 13mm d = 13mm
Lewis 1988	?	?	?
Kittridge et al. 1989	1660	x = 100' z = 80'	h = 0.5' d = 1"
Dreyer et al. 1990	537	x = 45m z = 2.4m	h = 10cm d = 0.54cm

Table 3.1 Summary of published outcrop permeability studies

WORKER/DATE	QUANTIFICATION OF SPATIAL K VARIATION?	AIMS
Hutchinson et al. 1961	No	To improve prediction of size, shape and k variation in reservoir non-uniformities
Dodge et al. 1971	No	To improve understanding of sedimentary features and directional parameters that control k and θ
Weber et al. 1971	No	To measure the k distribution in a sand-body from deterministic measures on borehole cores in order to predict the production performance and obtain a method of deriving the spatial permeability distribution from core
Pryor 1973	No	To determine the nature and cause of permeability variations within recent sand-bodies from various depositional environments
Jones et al. 1984	No	To determine the level of detail required for numerical simulation and fluid flow within equivalent reservoir rocks
Tomutsa et al. 1986	Yes, through geostatistical variogram analysis	To relate the observed permeability characteristics to geologic facies To determine whether each facies can be regarded as a flow unit
Stallup 1986	Yes, through geostatistical variogram analysis	To investigate the spatial variability in permeability within cross-bedded sandstones
Stallup and Ebanks 1986	Yes, through geostatistical variogram analysis	To investigate lateral and vertical variation in permeability within sand-bodies from subsurface reservoir core and from the same reservoir exposed at outcrop.
Reverne et al. 1987	Yes, through variogram analysis using indicator geostatistics	To describe and quantify reservoir heterogeneities within fluvio-deltaic rocks to solve predictions of interwell heterogeneities and therefore improve reservoir performance forecasting
Goggin et al. 1986 and 1989	Yes, through variogram analysis and rescaled range (R/S) analysis	To relate permeability variations to their main causes; the primary depositional processes To describe the scale-dependence of permeability variation To infer the spatial statistics of permeability including its correlation structure and the anisotropy therein To investigate the portability of permeability variations (static and spatial) to other aeolian sandstone outcrops To compare outcrop and subsurface distributions of permeability To investigate the use of outcrop-based statistical observations to generate synthetic permeability cross-section maps from well data
Lewis 1988	Yes, through variogram analysis	To develop a classification scheme for reservoir heterogeneities appropriate for carbonate sand-bodies To describe the scale-dependence of permeability heterogeneity and anisotropy
Kittridge et al. 1989	Yes, through variogram analysis	To study areal and vertical permeability heterogeneity within carbonate facies of the San Andres Formation at outcrop and in the subsurface To determine correlation lengths for permeability and porosity To relate the observed permeability characteristics to geological facies To compare outcrop and subsurface results
Dreyer et al. 1990	Yes, through variogram analysis	To relate the observed permeability characteristics to geologic facies To determine whether each facies can be regarded as a flow unit

Table 3.1 Summary of published outcrop permeability studies

Chapter 4 Outcrop probe permeametry

4.1 Introduction

The probe permeameter has the following advantages over core plugs for estimating permeability: 1) The probe permeameter can easily be made portable thereby allowing gas flow rate measurements to be made directly on the outcrop. A simple calibration will provide permeability values, so removing the need for additional sample processing; 2) Probe permeameter-derived permeabilities are significantly cheaper than permeabilities measured on core plugs; 3) As a result of the low cost, large numbers of measurements can be made providing data that are of greater statistical validity than conventional core plug data; 4) The probe permeameter is capable of measuring the permeability of variable rock volumes and can be used to examine small scale variations in permeability (such as within thin beds, clasts and burrows) otherwise averaged out in permeabilities obtained for conventional core plugs. It is for these reasons that the probe permeameter is an ideal device for outcrop permeability studies.

Whereas a general code of practice for probe permeametry has been proposed by Sutherland et al (1991) it has concentrated on application to core measurement and does not adequately address the problems specific to outcrop application. In this Chapter, the physical aspects of the permeability measure obtained using the probe permeameter are described and the performance of the probe permeameter at outcrop evaluated through experimental studies. The results of these studies are used to develop a code of practise for outcrop probe permeametry practice.

The name, 'minipermeameter' and 'probe permeameter' are synonymous with each other. The former name was originally used because the device was first designed to make small volume measurements. However, the probe size may be varied and the permeability measurements are not necessarily 'mini', consequently the latter name has become recognised as standard for this device as it provides a more

accurate description of the measurement.

4.2 Historical background of the probe permeameter

Hassler cell-type permeability measurements made on core plugs are well documented throughout the literature because they are a standard industry measure. probe permeameters on the other hand are not as well known or understood with relatively few publications, although this situation is now changing. The concept of spot permeabilities was first initiated by Dykstra and Parsons (1950) and subsequent publications dealing with the flow characteristics and the technical specifications of the various probe permeameters are given by Eijpe and Weber (1971), Cadman(1984), Hamp (1987), Goggin et al (1988), and Daltaban et al (1989). More recently the specific use of probe permeameters for core analysis has been addressed by Halvorsen and Hurst (1990), Hurst and Rosvoll (1991), and Sutherland et al (1991). Despite the interest in probe permeametry as evidenced by these publications, the use of probe permeameters as a standard industry measure of permeability has yet to find acceptance. However, significant advances are being made towards achieving this goal as evidenced by the success of the first conference dedicated to probe permeametry in reservoir studies, held in Edinburgh in June 1991.

4.3 The physical principles of the probe permeameter

4.3.1 Darcy's Law

The permeability of a rock is a measure of its ability to transmit a fluid or gas through it. The value of permeability represents flow through a series of interconnected tortuous pathways with varying cross-sectional area. Thus this flow is by a complex of accelerations, decelerations, and changes in direction. Navier and Stokes equation provides a fundamental description of these fluid dynamics. Darcy's Law, which is widely used in the oil industry, presents one solution for a given set of conditions.

In 1856, Henri Darcy, a French water engineer, reported his findings of experiments to determine the flow of water through filters. In this study he found that the volume of water flowing through a bed of sand is proportional to the pressure gradient in the bed transversed. This relationship for linear laminar flow, illustrated in Figure 4.1, is given below:-

$$Q = KA((h_1-h_2)/L) = KA(\partial h/\partial L) \quad \text{.....(9)}$$

where Q = flow rate (discharge) (cc/sec.)

K = a coefficient dependent on the nature of the sand

A = the surface area of the filter (the sand bed) (cm^2)

L = the length of the sand column or filter (cm)

h_1 = manometric level at the top of the filter (cm)

h_2 = manometric level at the bottom of the filter (cm)

$\partial h/\partial L$ = the hydraulic gradient expressed in general terms

The relationship between flow rate and head loss, ($Q \sim h_L$), and the relationship between flow rate and flow path length, ($Q \sim 1/L$), is known universally as Darcy's Law, which serves as the basis for the analysis of groundwater movement and fluid dynamics within hydrocarbon reservoirs. It was also found by workers who repeated Darcy's experiment that the difference in manometric level, ∂h , is always the same for a given flow rate and that this law is independent of the direction of flow relative to the earth's gravitational field.

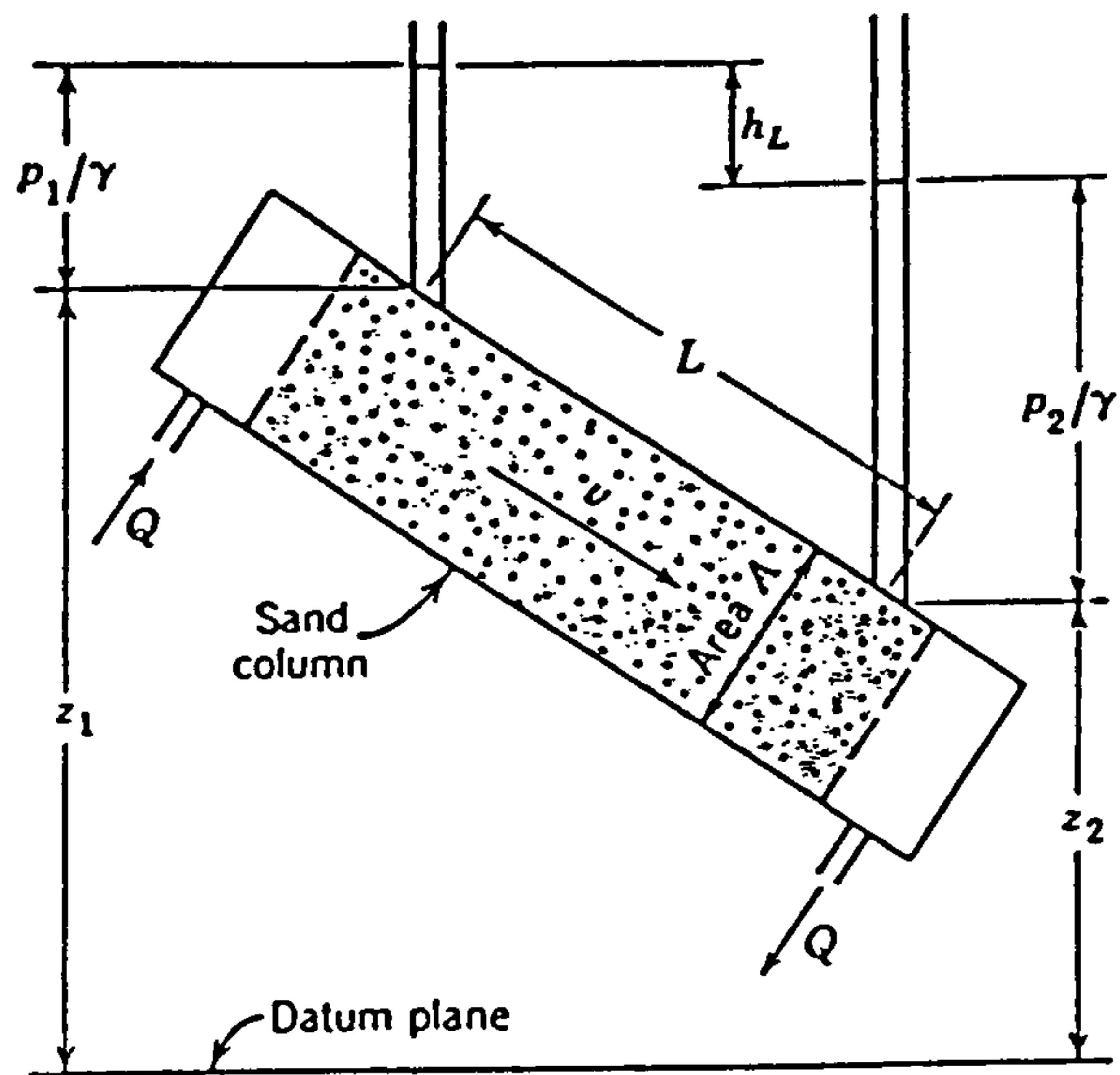


Figure 4.1 Pressure distribution and head loss in flow through a sand column
(from Todd, 1980)

Since Q is the flow rate or discharge, then dividing by the cross-sectional area, A , gives the flow velocity, v , where :-

$$v = Q / A = -K \partial h / \partial L \quad \text{.....(10)}$$

and,

$$K = v (\partial h / \partial L) \quad \text{.....(11)}$$

where v = the Darcy velocity or specific discharge

K = the hydraulic conductivity, a constant representing the permeability

$\partial h / \partial L$ = the hydraulic gradient

The Darcy velocity, v , represents flow through the entire section of the porous media without consideration of the pores and solids. In reality, this flow is confined to the pores only and therefore the value of v will be smaller than the actual velocity which is related to the percentage porosity (Todd, 1980). This actual velocity is the average velocity over the volume, representing the integration of a complex combination of tortuous pathways, accelerations and decelerations and is represented by:-

$$v_{av.} = Q / (\text{porosity} * A) \quad \text{.....(12)}$$

The value of K in Darcy's original equation is more accurately described as the hydraulic conductivity as it refers specifically to the flow of water through a porous media. The intrinsic permeability on the other hand refers to the general ability of a porous media to transmit fluid. To differentiate between the hydraulic conductivity, K , and the intrinsic permeability, k , the density and viscosity of the fluid concerned and a gravitational constant must be incorporated into the Darcy equation. Thus, converting equation 11 for hydraulic conductivity to intrinsic permeability we obtain:-

$$k = v \mu / \rho g (\partial h / \partial L) \quad \text{.....(13)}$$

where k = the intrinsic permeability
 μ = the dynamic viscosity
 ρ = the fluid density
 g = the acceleration due to gravity

which has units of

$$k = (m/s) (kg/ms) / (kg/m^3) (m/s^2) (m/m) = m^2 \quad \text{.....(14)}$$

The intrinsic permeability has units of area which are usually very small and therefore expressed as μm^2 . In the units employed in the oil industry, the Darcy is defined as:-

$$1 \text{ Darcy} = (((1 \text{ centipoise}) (1 cm^3/s)) / 1 cm^2) / (1 \text{ atmosphere} / cm) \quad \text{.....(15)}$$

and

$$1 \text{ Darcy} = 0.987 (\mu m)^2 \quad \text{.....(16)}$$

From Poiseuille's law, velocity in laminar flow is proportional to the first power of the hydraulic gradient. Therefore, from the relationship, $Q \sim \partial h / \partial L$, Darcy's law must be confined to laminar flow. The Reynolds number, N_R , is the dimensionless ratio between inertial and viscous forces and can be used to distinguish between laminar and turbulent flow where:

$$N_R = \text{Inertial Force} / \text{Viscous Force} = 2 \rho r U_{om} / \mu \quad \text{.....(17)}$$

where ρ = fluid density
 r = radius of the pipe
 U_{om} = overall mean velocity
 μ = viscosity of the fluid

When $N_R < 1$, viscous forces dominate over inertial forces under conditions of laminar flow. Where $N_R > 1$, inertial forces dominate over viscous forces under conditions of turbulent flow.

A modified version of the Reynolds number may be used to define the limits of flow within which Darcy's law applies. Experiments show that Darcy's law is valid for $N_R < 1$ and up to $N_R = 10^1$. In most cases of natural underground fluid flow in aquifers and hydrocarbon reservoirs, N_R is usually less than one and very rarely greater than 10. For high velocities where turbulence occurs (within high rate gas wells for example), the resultant pressure drop may be accounted for using the Forcheimer equation (Archer and Wall, 1986) which incorporates the non-Darcy component of inertial resistance, β , into the Darcy equation and describes more realistically the pressure drop relationship $\partial h / \partial L$.

The discrepancy between permeabilities to liquids and gases for rocks of equal permeability was found by Klinkenberg (1941) to be related to the phenomena of slip which itself is closely related to the mean free path of gas molecules. Klinkenberg found that 'gas-slippage' occurred at low pressures where the resultant flow of gas molecules near the capillary walls was higher than expected. From experimental evidence he found that at low mean pressures, the permeability to gas deviated significantly from fluids within an equivalent porous media. As the mean pressure was increased by extrapolation, this difference was reduced until the permeability to gas and fluid coincided. The solution to the problem is to obtain the permeability to gas at infinitely high pressure by plotting the permeability constant against the reciprocal mean pressure. The intersect on the permeability axis is the equivalent liquid permeability for that porous media, which will be constant.

4.3.2 Relating rock flow rates measured using the probe permeameter to intrinsic permeability.

A portable probe permeameter has been developed at Imperial College, London, the main features of which are illustrated in Figure 4.2. This probe permeameter carries its own gas supply and weighs about 21 Kg. Gas flow rates are measured at steady-state through one of four laminar flow elements (L.F.E.'s) that ensure laminar flow from 0-2 cc/min. ($3.33 \times 10^{-8} \text{ m}^3/\text{s}$), 0-20 cc/min. ($3.33 \times 10^{-7} \text{ m}^3/\text{s}$), 0-200 cc/min. ($3.33 \times 10^{-6} \text{ m}^3/\text{s}$), and 0-2000 cc/min. ($3.33 \times 10^{-5} \text{ m}^3/\text{s}$). The measured flow rate is then relayed to a digital display. Injection pressure is measured at the probe tip via a pressure transducer relayed to a L.E.D. digital display. Unconfined flow rates are measured by injecting gas into the surface of the rock through a sealed probe. It is the geometry of the unconfined flow that represents the main difference between permeabilities obtained for conventional core plugs and the probe permeameter. These differences in flow geometry are illustrated in Figure 4.3.

Based on the use of ideal and real gas laws, the probe permeameter provides a flow rate value for a given pressure differential. This flow rate can be related to the Darcy equation for intrinsic permeability. Combining equations (10) and (13), the intrinsic permeability becomes:

$$k = (Q/A) \mu / \rho g (\partial h / \partial L) \quad \text{.....(18)}$$

This relationship applies at a constant temperature since the viscosity and density of the transmitted fluid are temperature dependent.

For the probe permeameter, Q is the measured flow rate in cc/min., P1 is the measured upstream injection pressure and P2 is the downstream pressure. P2 is assumed to be equal to atmospheric pressure where the gas is allowed to escape freely at the rock surface, and $P1 - P2 = \partial h$.

The gravitational constant (g), viscosity (μ) and density (ρ) of the injected gas can be determined, leaving only the surface area (A) and length (∂L) unknown. These unknown values define the flow geometry

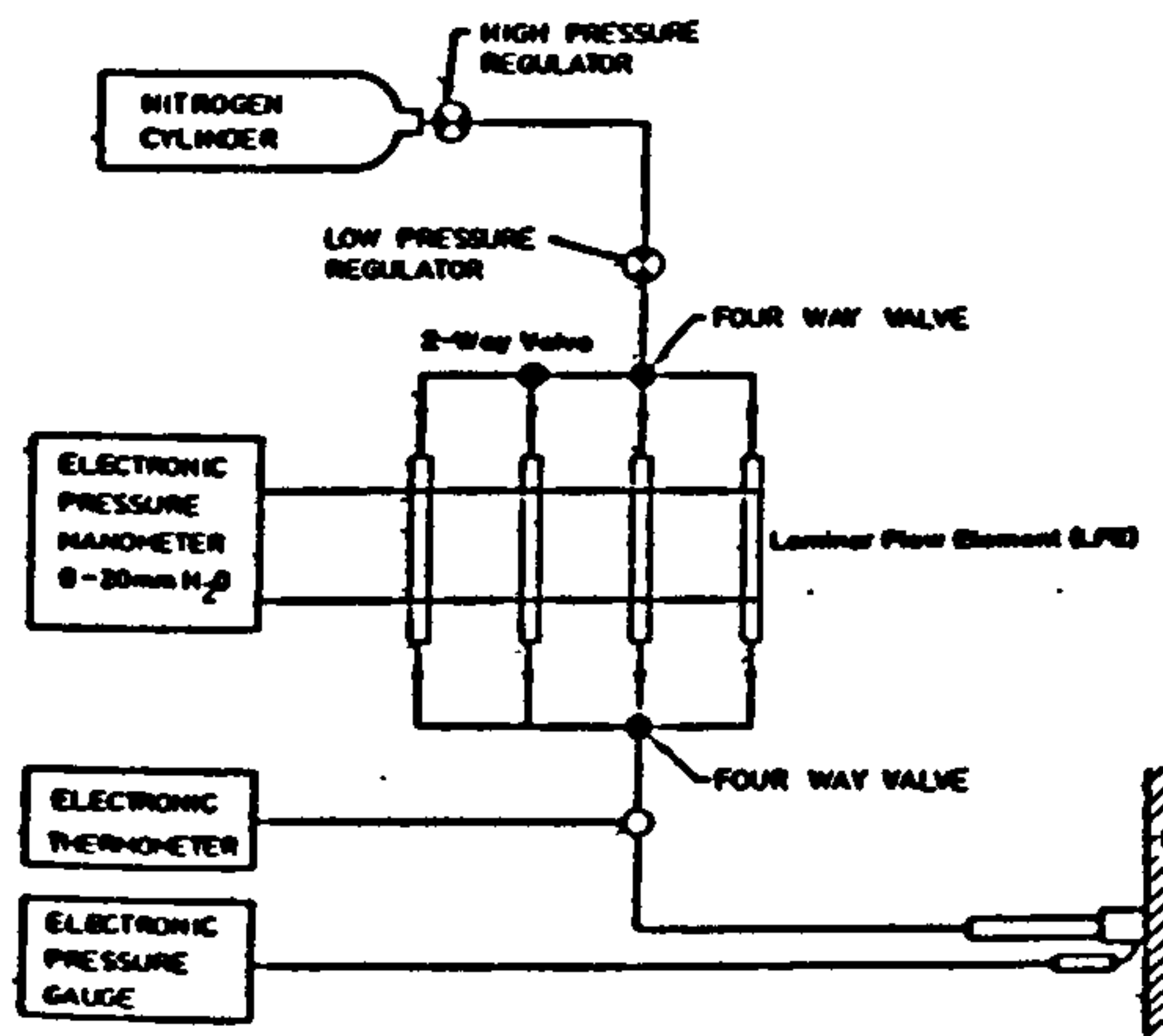


Figure 4.2 The field portable minipermeameter used in this study with a simplified schematic layout showing the basic design features

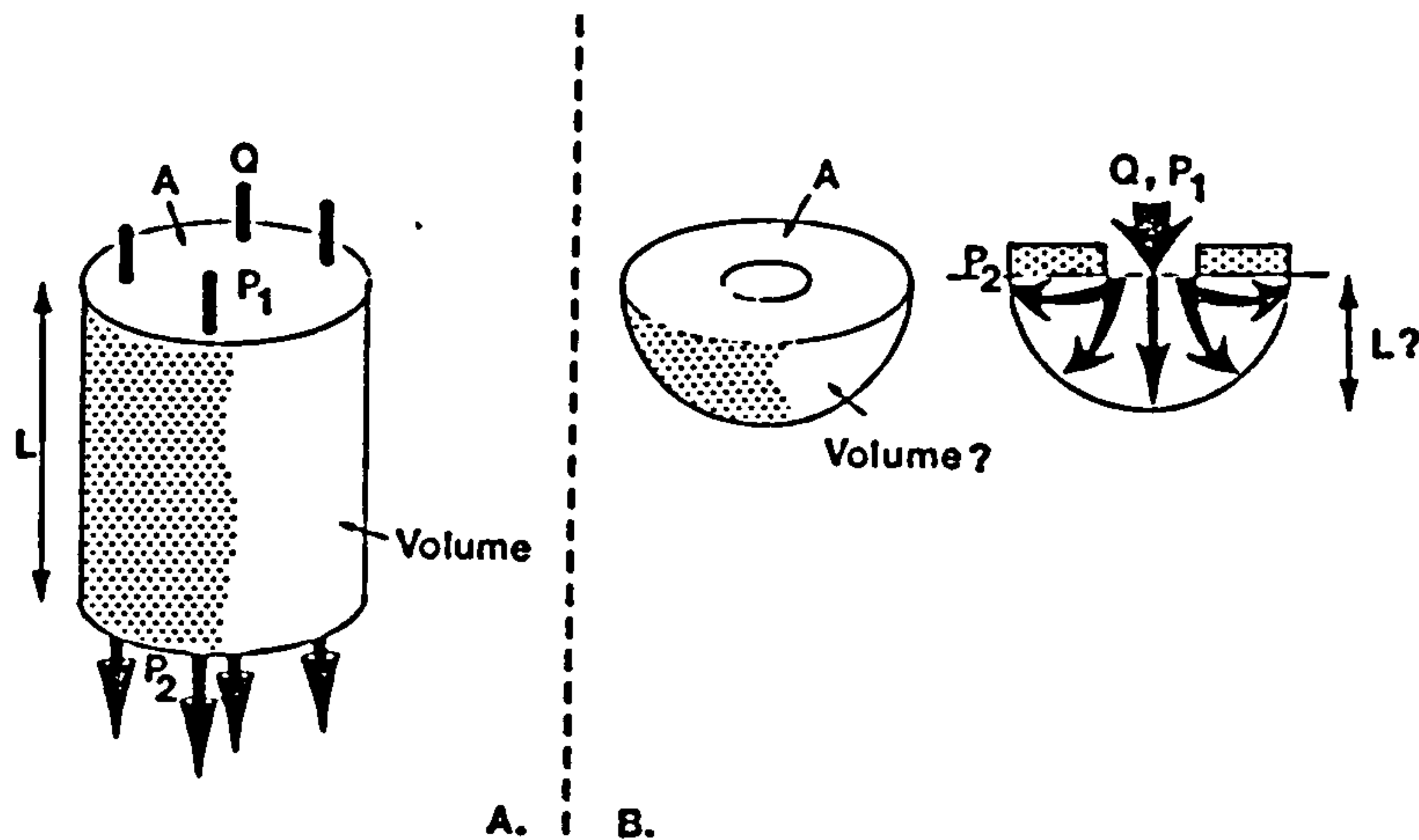


Fig. 4.3 Diagrammatic illustration of the differences in flow geometry between the Hassler cell device (A) and the minipermeameter (B)

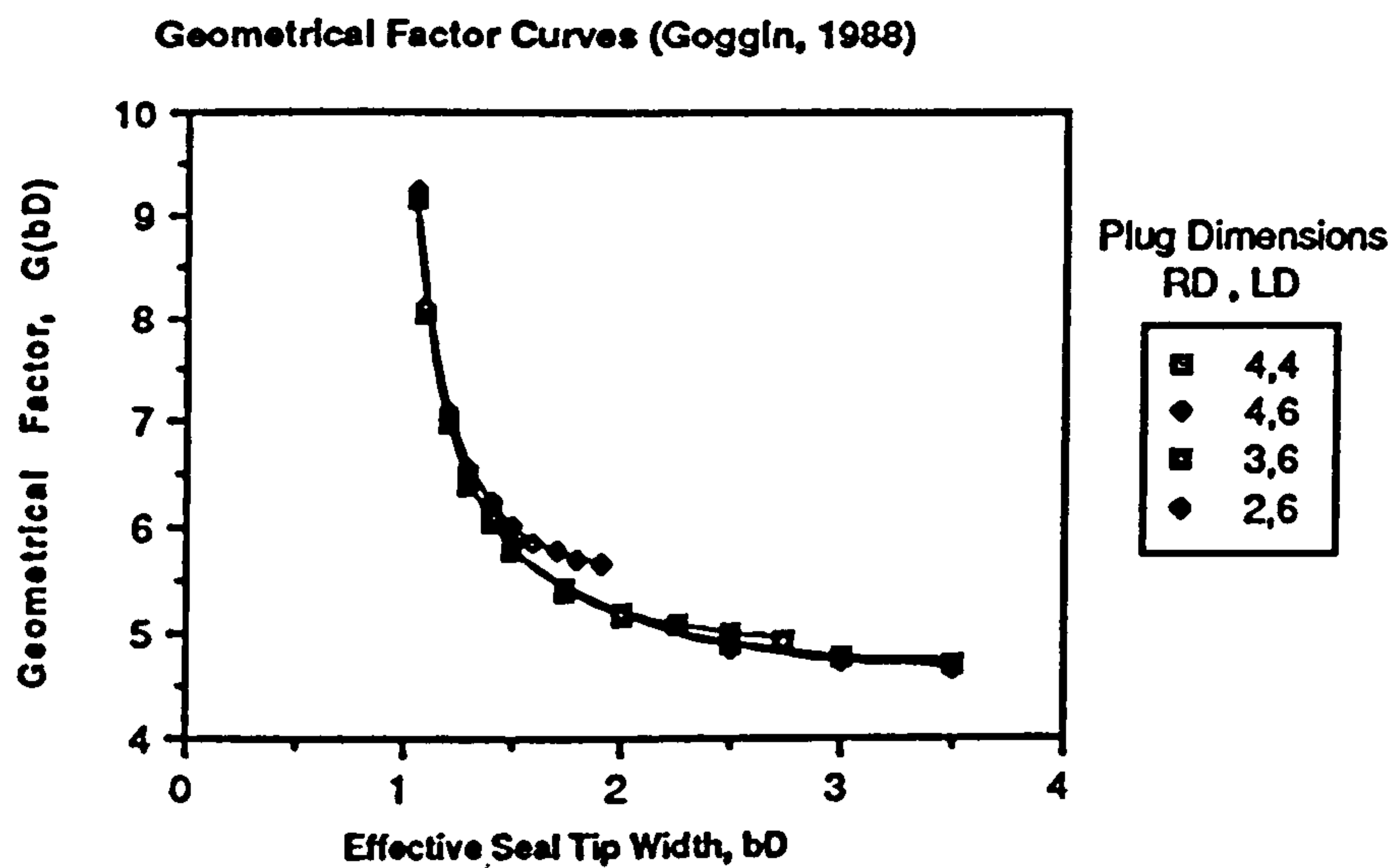


Figure 4.4 Geometric factor curves for different probe seal dimensions (after Goggin et al, 1988)

and there are three methods for determining them as follows:-

- 1) Through empirical calibration relating probe permeameter flow rate at a given injection pressure to intrinsic permeability.
- 2) Through the use of a geometric factor incorporated into the Darcy equation that relates the flow geometry to the injection aperture and seal diameter.
- 3) Through numerical simulation of the gas flow geometry.

4.3.2.1 Empirical calibration

This involves obtaining gas flow rates using the probe permeameter on homogeneous core plugs for which intrinsic permeability is measured by conventional core plug analysis using a Hassler cell device. The use of computer aided tomography (C.A.T.) may be used to select homogeneous core plugs. Probe permeameter flow rates can then be directly related to intrinsic permeability by cross-plotting the two variables. A linear relationship is observed, but the calibration is restricted. Firstly, the empirical relationship applies only to flow rates measured at equivalent injection pressures, and secondly, the empirical relationship only applies to flow rates measured with the same probe seal configuration, that is, the diameter of the external seal and injection aperture. Finding homogeneous core plugs over the range of flow rates measured at outcrop or on core is often difficult and may require extrapolation of the calibration curve to intrinsic permeabilities not represented by actual measurements. This adds a further problem because non-Darcy effects that establish themselves at low permeabilities (for example, gas slippage) and high permeabilities (for example, turbulence) may be incorrectly accounted for. However, where non-darcy effects are incorporated in the calibration, a linear best fit line will reduce these effects providing the calibration line is weighted towards the region where data points comply with Darcy's law. A major advantage of the empirical calibration therefore, is that it provides a relationship between flow rate and permeability with no assumptions made in its determination.

4.3.2.2 Analytical calibration using a geometric factor

To relate gas flow rates obtained by the probe permeameter with intrinsic permeability, Goggin et al (1988) introduced a geometric factor into the Darcy equation which is a non-dimensional representation of the flow geometry produced by varying probe seal geometries. In effect this converts the conventional flow geometry parameters, A and L , representing straight stream lines parallel with the core length, to hemispherical streamlines radiating out from the probe seal. The advantage of a geometric factor is that intrinsic permeability can be obtained for the probe permeameter with any probe tip configuration and injection pressure. However, non-Darcy effects must also be accounted for. This can be done by conventional methods through the use of a Klinkenberg correction to obtain equivalent liquid permeability for gas slippage effects, and the Forcheimer equation to account for pressure loss due to high velocity turbulence effects.

The geometric factor is incorporated to produce a modified form of the Darcy equation. The spatial distribution of pressure (the gas pseudo-potential) around the seal tip was determined by Goggin et al (1988) for a specific combination of seal tip dimensions (I.D. and O.D.) and sample size. This was achieved using the mass conservation equation for a cylindrical coordinate system which was modified for an unconfined flow geometry with radially symmetrical flow:

$$m_o = aGo(b_D, R_D, L_D)K_o^{inf} \Delta m(\Phi) \quad \text{.....(19)}$$

where, m_o = inlet mass rate (m/t)

a = internal tip seal radius (L)

$Go(b_D, R_D, L_D)$ = unconfined core plug flow geometrical factor (no high velocity flow effect)

K_o^{inf} = sample permeability corrected for gas slippage and high velocity flow effects (L^2)

$\Delta m(\Phi)$ = gas pseudo-potential drop (m/t- L^3)

and,

$$K = (q_1 * \mu * P_1) / a * G_o * ((P_1^2 - P_0^2) / 2) \quad \text{.....(20)}$$

where P_0 = atmospheric pressure (outlet pressure)

P_1 = injection pressure at probe seal

q_1 = gas flow rate in cc/min.

μ = gas viscosity

a = radius of injection aperture (internal radius)

b = radius of seal (outer radius)

G_o = geometric factor

Goggin *et al* produced a series of geometric factor curves for different tip seal thicknesses, b_D (where $b_D = b/a$), and different core plug dimensions (Figure 4.4). Each curve represents a series of simulation runs for different (dimensionless) core plug size ratios (diameter versus length). As expected, G_o decreases with increasing b_D where the length of the gas flow path increases whilst the flow rate decreases.

As a general rule, the same geometric factor curve applies to probe permeameter measures where the diameter of the core plug is at least four times the diameter of the injection aperture. This is known as the half space solution curve.

4.3.2.3 Calibration using a computerised numerical simulation

An alternative approach, calibration through numerical simulation, has been developed more recently at Imperial College (Wang 1990, Daltaban *et al* 1989 & 1991). This numerical simulation program (MIN_PER) forms part of a probe permeameter development program, concurrent with the development of the portable probe permeameter used in this study. Numerical simulation has an advantage over the two methods of calibration previously described because the sample can be truly homogeneous and isotropic rather than making assumptions for this. The flow geometry of the probe permeameter can be simulated for different conditions, for example, within a massive, isotropic sand, or a highly stratified, anisotropic sand. Consequently, an appropriate

coordinate system for the flow geometry (for example, spherical or cylindrical) can be chosen depending on the flow nature of the porous media. Computerised numerical simulations can also allow for non-darcy effects by incorporating correction factors for gas slippage and turbulent flow into the program.

4.3.3 Empirical calibration of the field portable probe permeameter used in this study

About 200 core plugs, measuring 1.5" (0.0375m) in diameter and length, were cut from the White Sandstone (Cretaceous). This sandstone represents a very homogeneous, moderate to high permeability sand. A few additional low permeability plugs from another source were also used to examine the correlation at permeabilities lower than represented by the White Sandstone. Gas flow rates were measured using the probe permeameter at three different locations on either end of each core plug. The maximum injection pressure (that is, that pressure assuming zero permeability) was kept constant at 2 psi (0.0123 MPa) for all probe permeameter measurements and the 2 litre LFE was used in all cases. The six measurements on each plug allowed the most homogeneous core plugs to be selected by comparison of the means and variance of values within and between each end of the core plug. This screening process is detailed below:-

1. Select blocks of sandstone with varying permeabilities identified by preliminary investigation using the probe permeameter.
2. Cut plugs (1.5" (0.0375m) diameter & 1.5" length) orientated in three directions; K_x, K_y and K_z
3. Measure flow rate for each plug by taking three probe permeameter measurements at each end, then calculate the geometric mean of each end and the harmonic mean between the ends.
4. Eliminate the most heterogeneous plugs through a two stage process:

- a) reject all plugs where the variance of the values measured on each end of the plug is >5000 cc/min. (>70cc/min.). This is an arbitrary cut-off value that still left >100 acceptable plugs. A minimum of 40 plugs should be used for the calibration (Hamp, 1987)
- b) reject all plugs where the difference in the arithmetic means between each end of the plug is >10% of the arithmetic mean for both ends together (this left >50 plugs).

As a result of this screening, 70 core plugs were retained for conventional air permeability measurement using a Hassler cell device. The cross-plot between flow rate and permeability in milliDarcies, given in Figure 4.5, shows a strong linear relationship between the two parameters with the following relationship:-

$$k \text{ mD} = 2.34 * \frac{\text{probe permeameter flow rate (cc/min.)}}{\text{injection pressure (psi)}} \dots\dots\dots(21)$$

The error estimate for this relationship varies from +/- 700 mD above a measured value of 600 cc/min. psi to +/- 200 mD below this measured value. This variation in the error estimate is related to the heterogeneity of the core plugs where the lower permeability plugs were generally more homogeneous.

It should be stressed that this calibration applies only to flow rates measured at a constant injection pressure. Non-darcy effects in the flow rate are not evident, probably because the maximum permeability is well within the laminar flow capacity of the L.F.E., ensuring laminar flow, and the lowest pressure differential is above the threshold for gas slippage.

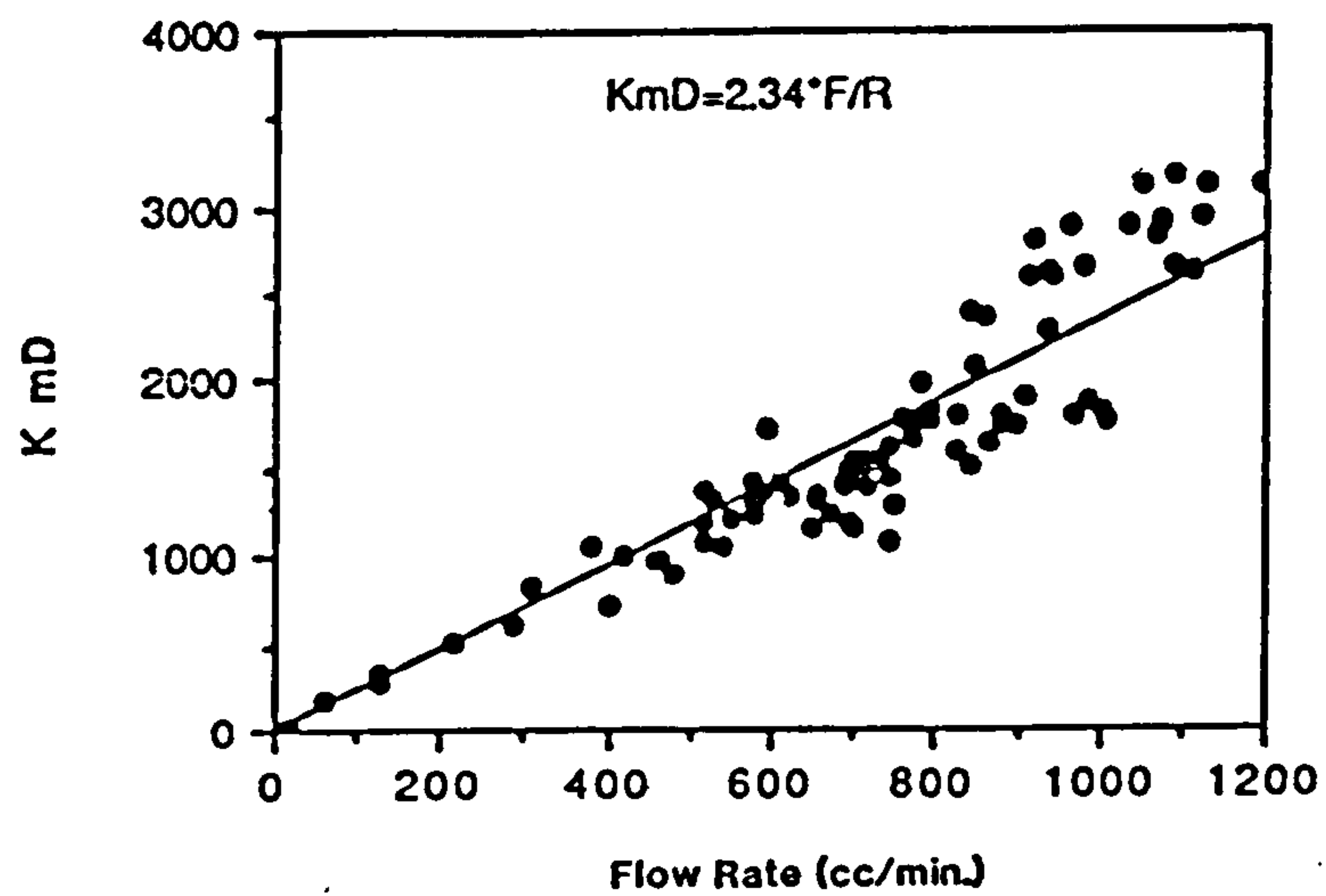


Figure 4.5 Empirical calibration curve for the minipermeameter

4.3.4 Testing the suitability of the geometric factor

In addition to Goggin et al (1988), other workers have observed a good correlation between permeabilities obtained using the geometric factor method and the empirical method (for example, Halvorsen and Hurst 1991). To investigate the suitability of the methods for calibration of the Imperial College probe permeameter, the comparison between the two methods is repeated here.

The probe tip dimensions used were: outer diameter, O.D. = 0.015m and inner diameter, I.D. = 0.004m, producing a bd value of 3.75. The flow rate measurements used are from Hamp (1987) for an earlier version of the probe permeameter used in this study but with essentially the same design features. These measurements were made on core plugs with permeabilities obtained using a conventional Hassler-sleeve device. The dimensions of the core plugs (length = 0.0375m (1.5"), diameter = 0.0375m) are such that the half space solution curve can be used and a geometric factor of 4.5 was obtained for these data.

Between two to four probe permeameter measurements were made on the ends of each core plug with a constant injection pressure of 5psi (0.0345 MPa). To obtain a single flow rate value for each plug, the geometric mean was calculated for each end of the plug and the harmonic mean was calculated from the geometric means of the permeabilities arranged in series. The Hassler-sleeve permeability, probe permeameter-derived flow rates and the estimated permeability using the geometric factor method are shown in Table 4.1 with the cross-plot between measured and estimated permeability shown in Figure 4.6. Comparison between the measured and estimated permeability shows a good correlation. A slight increase in the estimated permeability in low permeable samples is observed which is probably due to gas slippage effects and should be reduced with use of a smaller capacity laminar flow element.

Core Plug No.	Hassler Cell KmD	Minipermeameter cc/min. (Inj. Pressure = 5psi)			Go-Factor KmD (estimated)
		Geo. mean (top)	Geo. mean (bottom)	Harm. mean (both ends)	
1A	647	1027	1324	1162	645
3A	590	1135	1108	1126	620
4A	273	676	586	631	350
5A	170	514	279	360	200
6A	296	514	613	559	310
1B	496	937	757	838	465
2B	520	802	937	856	475
3B	22	180	171	171	95

Table 4.1 Permeability data obtained on core plugs using a Hassler cell device and a minipermeameter using the geometric factor

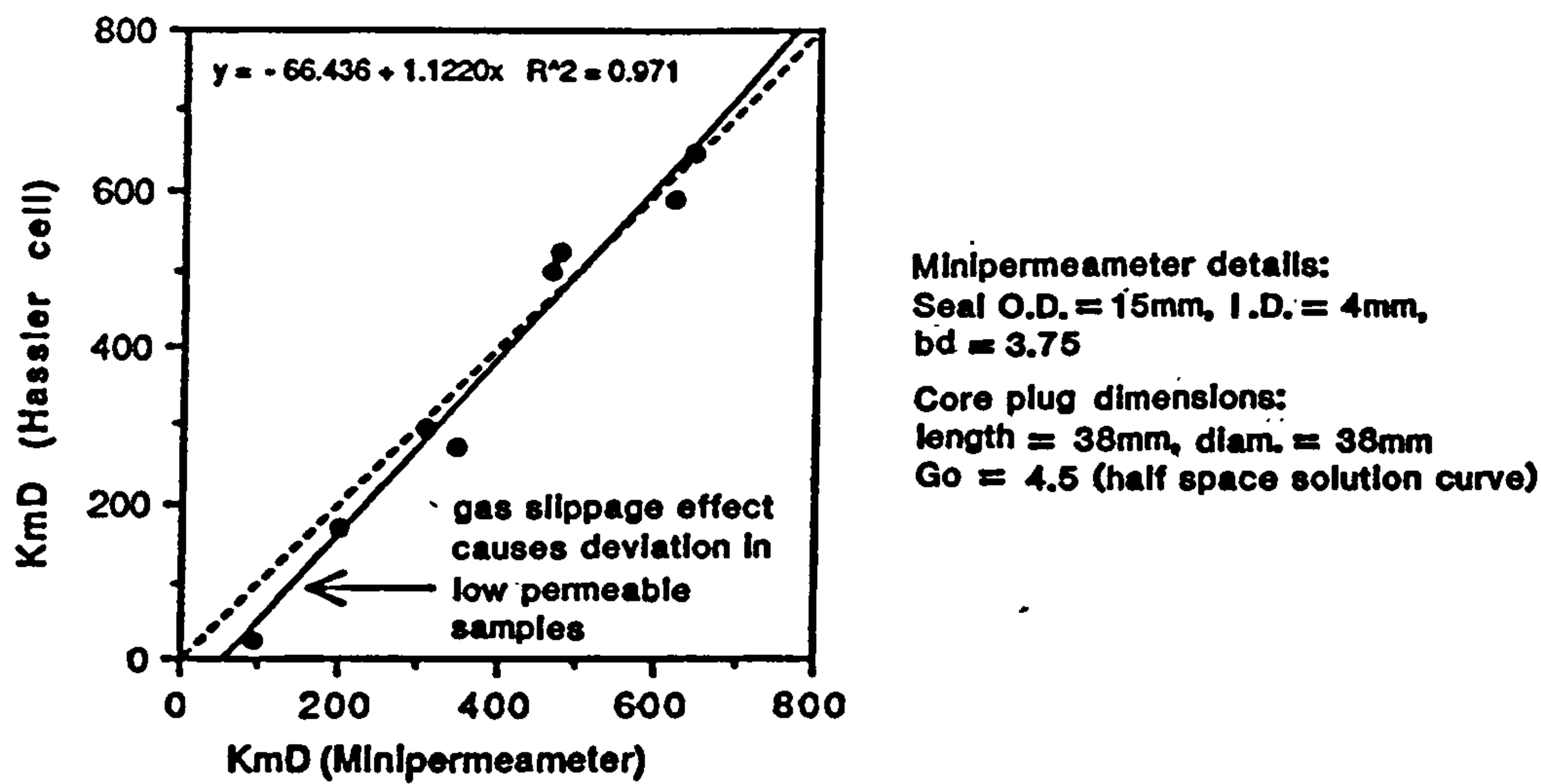


Figure 4.6 Cross-plot of permeability data (given in table 4.1) for core plugs obtained using a Hassler cell device and a minipermeameter using a geometric factor

4.3.5 Identifying non-Darcy effects in the probe permeameter response

Conditions of turbulent flow and gas slippage were identified by Hamp (1987) by cross-plotting flow rate against injection pressure for the 20cc/min., 200cc/min., and 2000cc/min. L.F.E.'s. Hamp identified non-Darcy effects in the deviation from a linear trend between flow rate and injection pressure. Both turbulence and gas slippage were shown to be manifest by an increase in the rate of change in flow rate for a given pressure differential. Turbulence effects were most noticeable in the flow characteristics for the 20cc/min. L.F.E. with possible gas slippage effects identified in the flow characteristics for the 2000cc/min. LFE (Figure 4.7).

The maximum injection pressure required to ensure laminar flow for a given rock permeability can be determined for each L.F.E. by rearranging equation 20:

$$P_1 = \frac{K a G_o ((P_1^2 - P_0^2)/2)}{q_1 \mu} \dots\dots\dots(22)$$

The appropriate values of K , μ , q_1 , a , and G_o are known and can be input this equation. q_1 is the maximum flow capacity of the selected L.F.E. (for example, $q_1=200$ cc/min ($3.33 * 10^{-6}$ m³/s) for the 0-200cc/min L.F.E.). The resultant value, P_1 , is the maximum injection pressure to be used. Injection pressures greater than this will produce turbulent flow.

The minimum injection pressure required, below which gas slippage may occur, can be determined experimentally from response data which are cross-plotted as in Figure 4.7. Where the data deviate from a linear relationship at low injection pressure and a slight increase in flow rate is observed, these measurements are affected by gas slippage. This is the minimum injection pressure required for the L.F.E. used on a rock sample of that permeability. Alternatively, probe permeability data may be corrected for gas slippage effects using correlations reported in the literature, such as the non-Darcy coefficient, β , or using the graphical

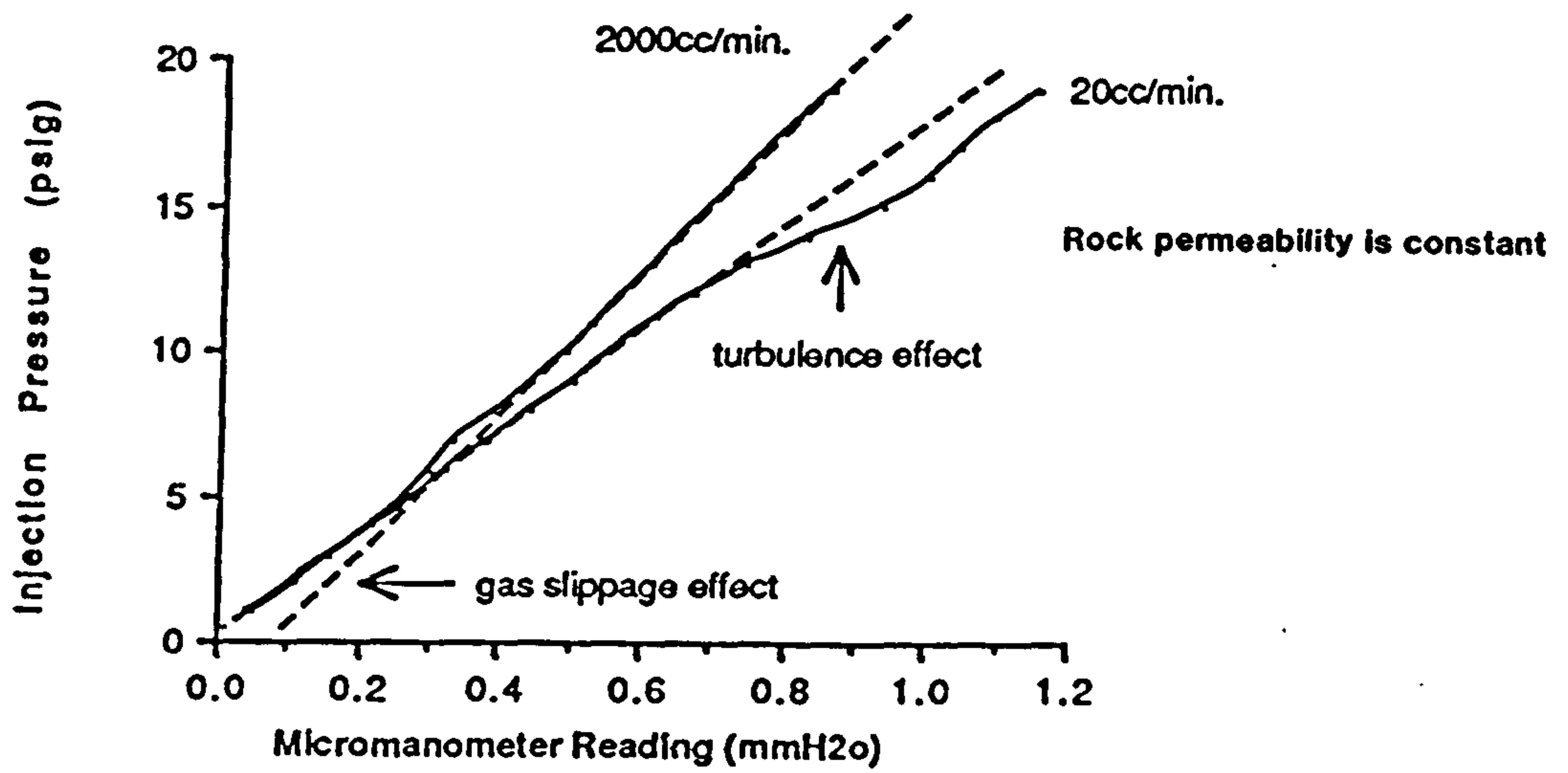


Figure 4.7 Non- Darcy effects in the minipermeameter response (after Hamp, 1987)

technique of Klinkenberg (1941). As reported values of β vary by several orders of magnitude, care must be taken when using these values and use of the Klinkenberg correction is therefore recommended.

4.4 Laboratory studies on probe permeameter response at outcrop

4.4.1 Response associated with the probe seal

In order to effect a seal between the probe permeameter probe and the rock surface some kind of impermeable, deformable compound is required. The deformational or rheological properties of the compound are important since the internal and external dimensions of the seal tip must be maintained. The compound must be soft enough to follow the surface irregularities of the rock surface yet hard enough to resist deformation of the internal and external shape. The ideal compound is deformable in the direction parallel to the application force but undeformable at angles to this so that the chosen seal dimensions do not change.

The importance of seal compound types has been recognised by other workers using probe permeameters (for example, Goggin et al 1988, Hurst and Rosvoll 1991, Halvorsen and Hurst 1990). On slabbed core with flat surfaces, standard 'O'-rings are suitable but these require large application forces. Halvorsen and Hurst (1990) state that an application force of 25 N is required to effect a seal with a soft rubber compound in contrast to a force in excess of 100 N for an equivalent sized 'O'-ring. However, there are no published guidelines for the selection of suitable materials for outcrop permeability studies. The reason for this being that the surface irregularities at outcrop are very variable and the chosen compound is at the discretion of the worker. Guidelines for the selection of seal properties and seal geometries for outcrop application are presented here.

The sealing qualities of different seal compounds were quantified by comparing measured flow rates in cc/minute for the same sample point using different compounds at different application pressures. A press

was constructed using a rigid transparent perspex plate, 15mm thick, bolted at each corner to a rigid wooden plate (Figure 4.8). By compressing various compound types, the resulting deformation could be examined. The change in the size of the injection aperture relative to the seal diameter (the ratio between I.D. and O.D.) was then quantified by comparing measured flow rates (using a known effective seal) for different seal dimensions. The effect of the shape of the injection and seal area was also examined by comparing flow rates for seals cut with different shapes.

4.4.1.1 Sealing quality of different seal compounds

Assuming that there are no fractures, the quality of the seal at the probe tip is determined by the roughness of the rock surface at the outcrop. Surface roughness is due to variations in the grain texture (essentially the grain size and sorting characteristics), mineralogy (where diagenetic modification such as selective grain dissolution may produce a pitted surface), and hardness (caused by cementation). To effect a seal on these surfaces, the seal types used on sawn, flat surfaces such as on slabbed core are not always appropriate. Standard 'O'-rings for example produce an effective seal provided the surface relief is less than the seal thickness and the application force is at 90^0 to the rock surface. Where the rock surface is uneven, 'O'-rings do not provide a reliable seal and alternative seal materials are required that will deform to accommodate roughness caused by the various factors described above.

Four different seal compound types were examined for their suitability as seal material on unsawn rock faces:-

- 1) Hard natural rubber (4mm thick)
- 2) Soft natural rubber (2mm thick)
- 3) Silicone rubber (4mm thick)
- 4) Closed cell neoprene sponge (4mm thick)

A circular seal with O.D.= 20mm and I.D.= 15mm was made from each compound type. A rock sample with a freshly fractured surface was then placed on a set of weighing scales and the gas flow rate measured at

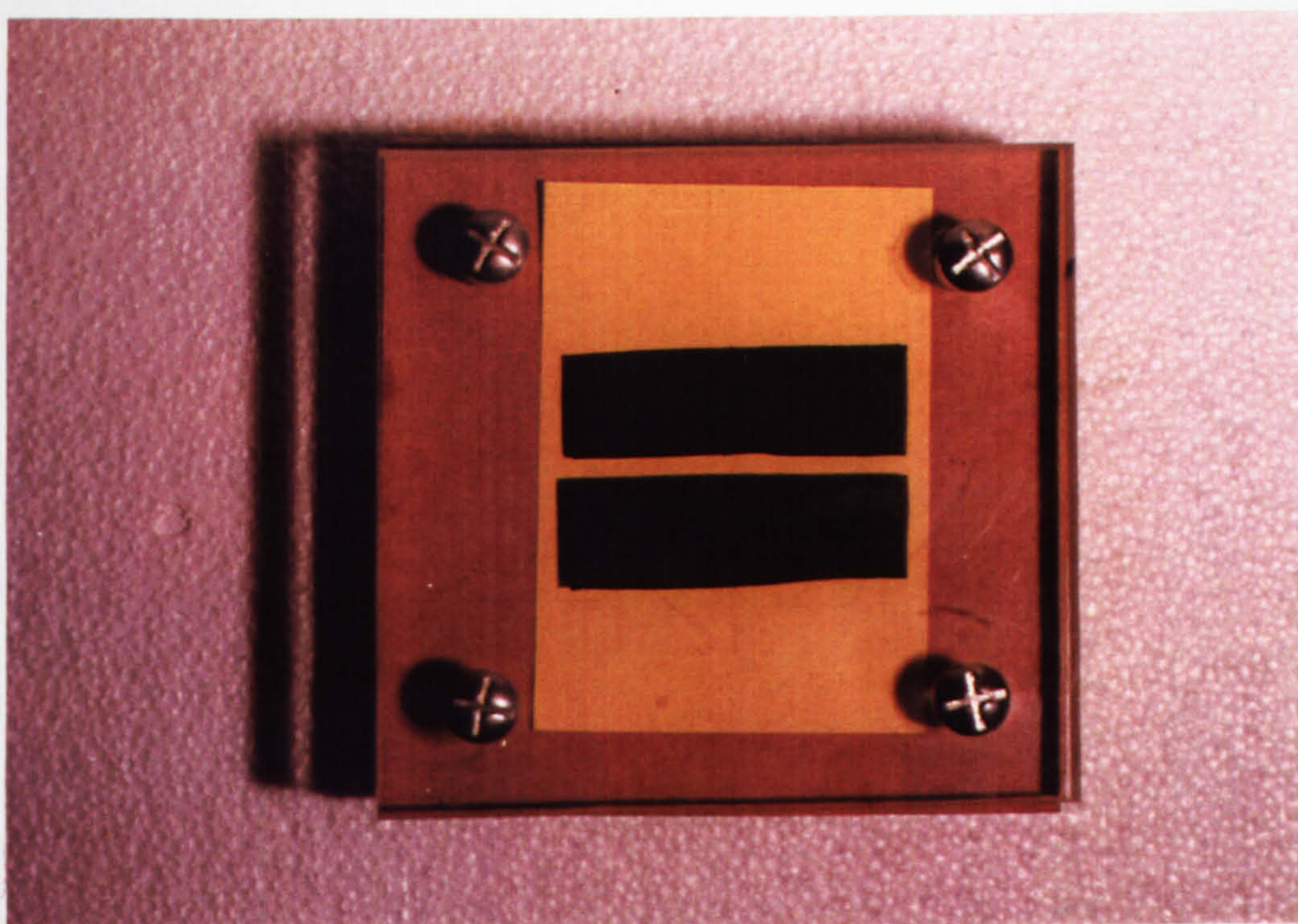
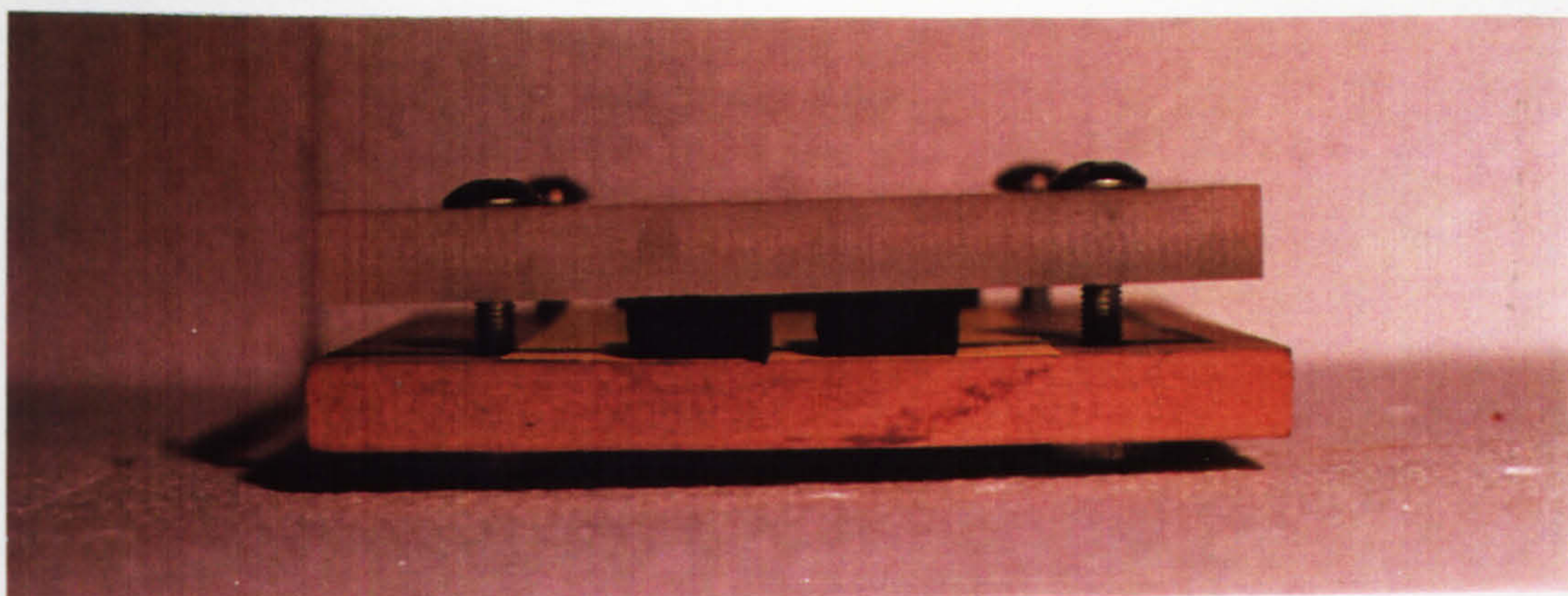


Figure 4.8 Photographic illustration of the press used to examine deformation of the minipermeameter probe seal under application pressure

a series of points using each probe seal compound with increasing application pressure in steps of; 5, 18, 41, 73, 114, 164, and >291 psi (0.034 Mpa to >2 MPa). To minimise flow rate variation caused by sampling slightly different points, the mean flow rate for all of the points sampled was calculated for each application pressure. In the final pressure reading, the spring-loaded probe head was fully compressed with a maximum application force that exceeded the range of the weighing scales.

The gas flow rates for each seal type under different application pressures are shown in Figure 4.9. Of the compound types, the closed cell neoprene sponge provided an effective seal at the lowest application pressure with the silicone and soft natural rubber requiring in excess of 291 psi to effect a seal. Only the hard natural rubber failed to achieve a seal at all.

In a similar investigation into the effect of application pressure on measured gas flow rate, Hamp (1987) found that there was an hysteresis effect in the relationship between application pressure and injection pressure (Figure 4.10). When the application pressure was decreased (downward trend), the injection pressures were consistently higher than those measured at the same application pressure on the upward trend.

Hamp attributed this hysteresis effect to a change in the seal dimensions: With increasing application pressure the injection aperture (I.D.) decreases and the seal diameter (O.D.) increases. This results in an additional increase in the injection pressure over that increase in injection pressure due to the improved effectiveness of the seal. With decreasing application pressure, Hamp suggested that the seal does not return to its original shape, and so for a given application pressure the I.D. is less, and the O.D. is greater than for the upward trend. Consequently the injection pressure is higher as a result of the seal dimensions rather than the effectiveness of the seal.

It is also possible however, that after prolonged application pressure the seal becomes temporarily moulded to the surface irregularities of the rock. This was not considered by Hamp in his study. Once the

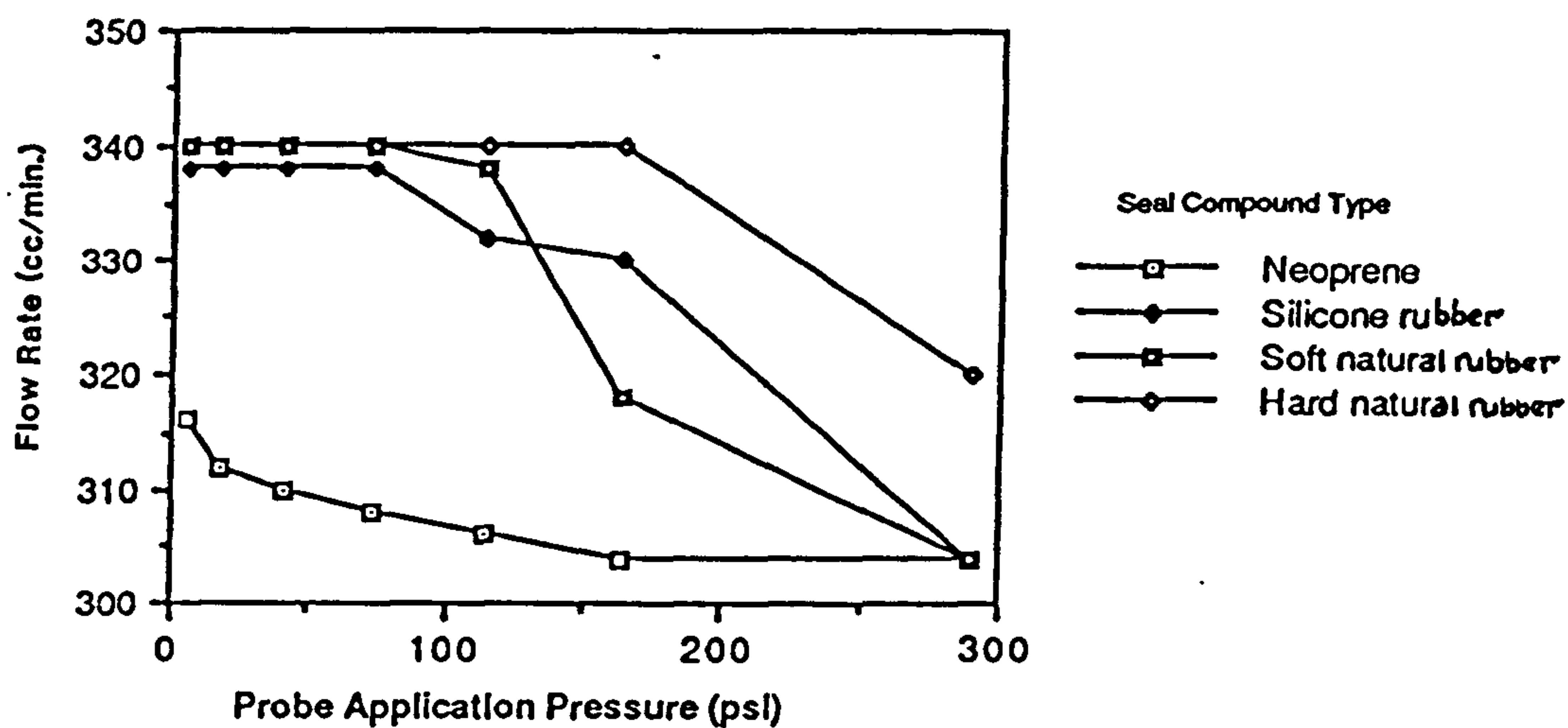


Figure 4.9 Gas flow rates measured at increasing application pressure for different seal compound types

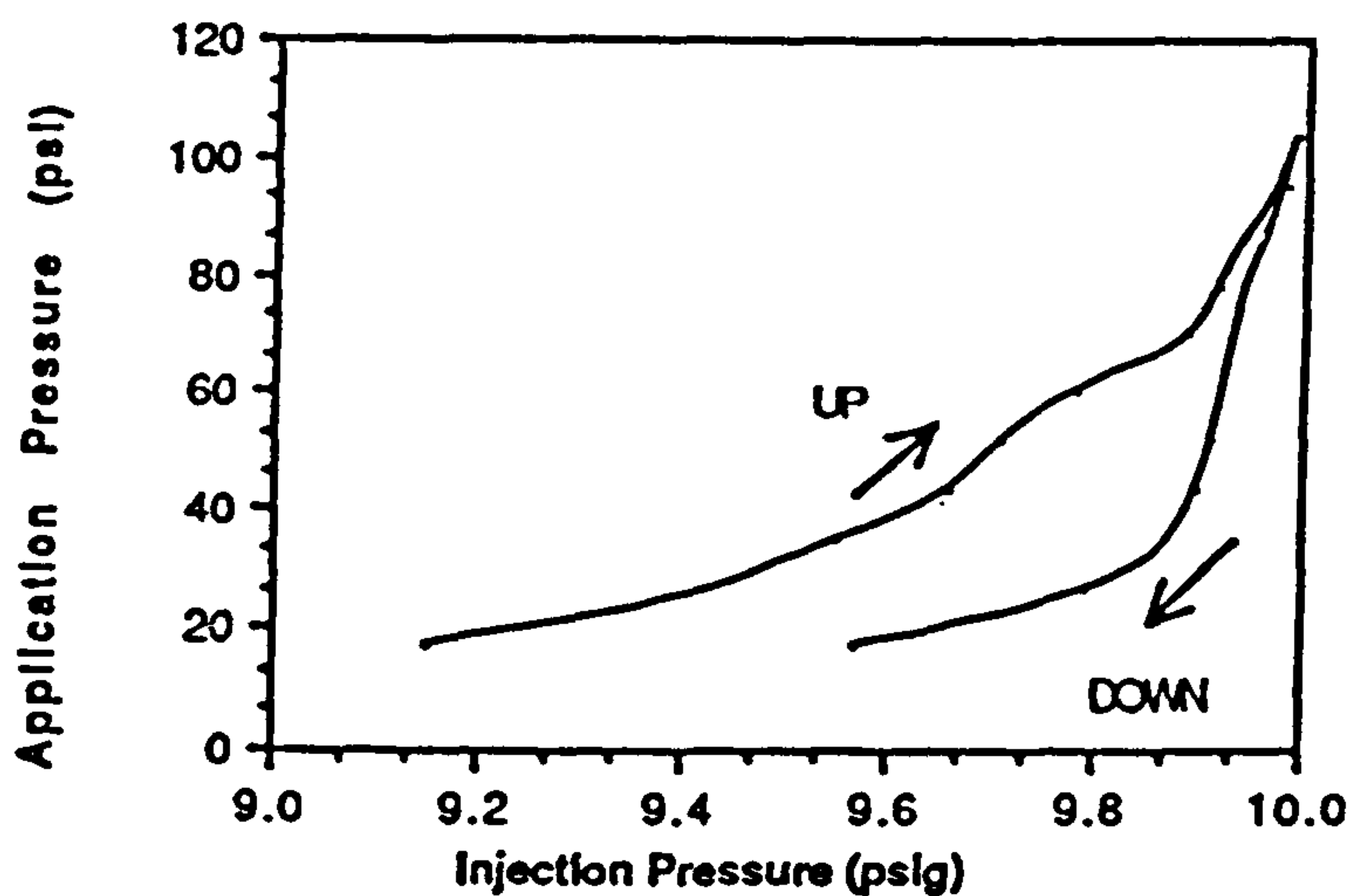


Figure 4.10 Injection pressure response with increasing and decreasing application pressure (after Hamp, 1987)

maximum application pressure has been applied, this moulding effect of the seal would improve the relative effectiveness of the seal with decreasing application pressure.

The probe tip seal can be made up of combined compounds to utilise the rheological properties of each where there is excessive roughness on the rock surface. A soft, highly deformable compound may be used for the seal surface in contact with the rock to provide an effective seal against small scales of relief, and a harder, less deformable compound may be used to provide an effective seal against large scales of relief (Figure 4.11).

4.4.1.2 Seal deformation: changes in seal area.

Since modification of the seal dimensions under application pressure appears to have a marked effect on the injection pressure and measured flow rate, the effects of seal deformation are therefore examined.

Circular shaped seals, each with an O.D. of 20mm (0.02m), and an I.D. of 15mm (0.015m) made from the four different compound types, were compressed to examine the extent of deformation under a force perpendicular to the seal face. The force applied and resultant seal deformation was equivalent to that for normal outcrop measurements. Original and post-deformation of the seal dimensions are summarised in Table 4.2. Increasing the application force results in an increase in the outer diameter of the seal and a decrease in the inner diameter or injection aperture. The minimum change in O.D. and I.D. occurred for the hard natural rubber and the maximum change in O.D. and I.D. occurred for the 8mm thick closed cell neoprene sponge.

From Darcy's law, the flow rate, Q , is directly proportional to the pressure gradient $\partial P/L$, for a homogeneous medium. It follows therefore, that for a constant pressure differential, an increase in the seal width (width = $(O.D. - I.D.)/2$), which is equivalent to an increase in the minimum path length for hemispherical flow, will result in a decrease in the flow rate. Indeed, it is this difference in measured flow rate that

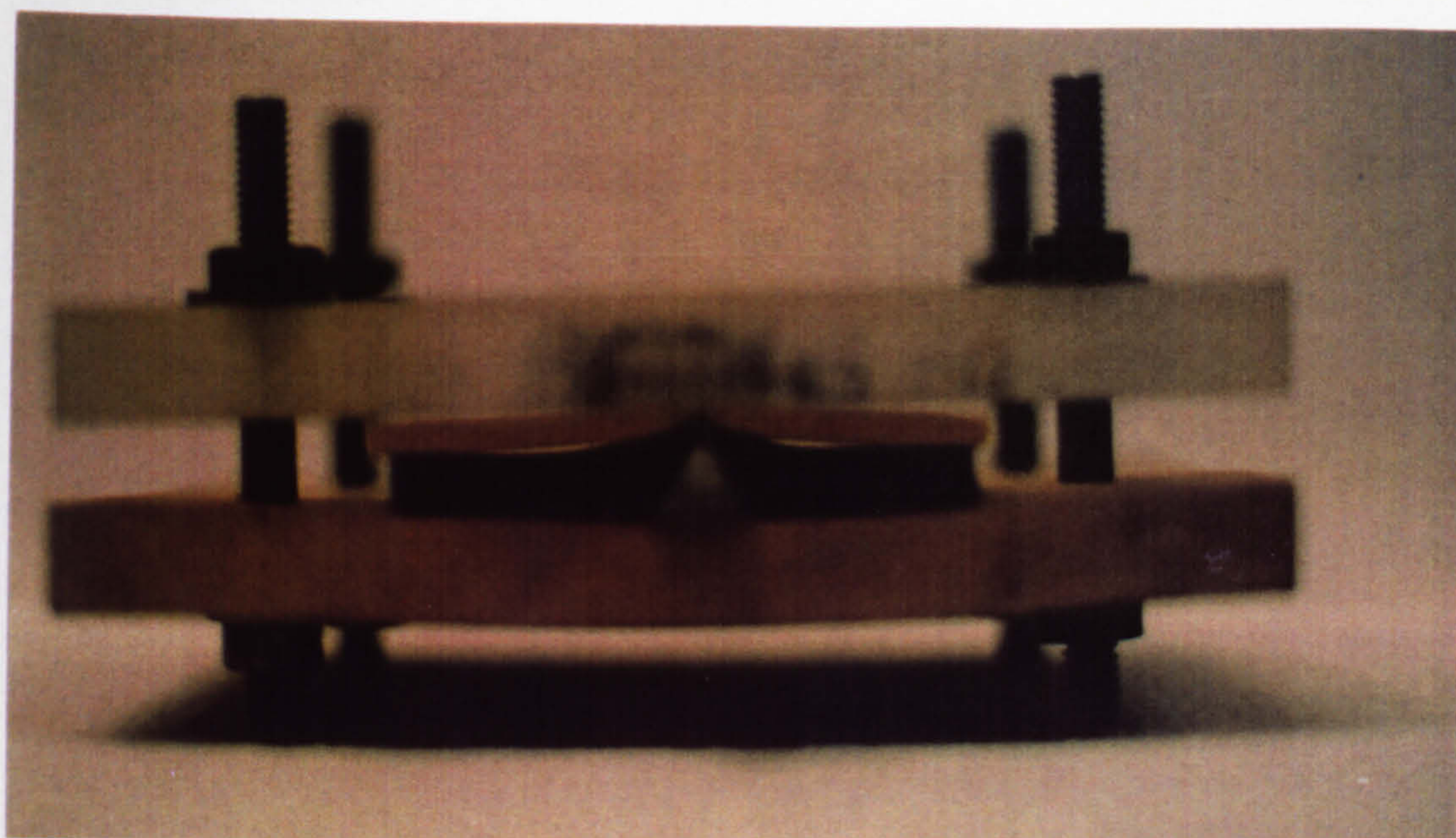


Figure 4.11 Photographic illustration of a multiple compound seal used to produce an effective seal where there is large scale surface roughness

Seal Compound Type	Before Compression		After Compression		Difference	
	O.D. (mm)	I.D. (mm)	O.D. (mm)	I.D. (mm)	O.D. (mm)	I.D. (mm)
Silicone rubber	21	15	23	14	2	- 1
Hard natural rubber	21	15	23	13.5	2	- 1.5
Soft natural rubber	21	15	24	13	3	- 2
Closed cell neoprene (4mm thick)	21	15	25	12	4	- 3
Closed cell neoprene (8mm thick)	21	15	27	9	6	- 6

Table 4.2 Probe seal dimensions before and after compression

necessitates a separate calibration to intrinsic permeability for each seal geometry used. This reduction in the measured flow rate was observed in experimental analysis by Hurst and Rosvoll (1991) and through numerical simulation (Hamp 1987). Thus, changes in the seal dimensions under application pressure may have a significant influence on the measured flow rate.

The experimental analysis of flow rate versus seal geometry was repeated here for the field portable probe permeameter. Flow rates were measured on a sandstone sample using probes made from closed cell neoprene sponge with varying I.D. and O.D. Since it is difficult to repeatedly sample exactly the same point with the probe permeameter probe, flow rates were measured on a series of 31 evenly-spaced points and the average flow rate calculated. It was observed that for a constant O.D. of 20mm (0.02m), an increase in the I.D. from 6mm (0.006m), to 10mm (0.01m), and to 15mm (0.015m), resulted in an increase in the mean flow rate (Table 4.3). This was expected as the minimum path length was reduced. The variance also increased with increasing I.D. (Figure 4.12). This can be explained by the reduction in the number of pores incorporated in the minimum path length. However, it was also observed that for a constant I.D. of 6mm (0.006m), an increase in the O.D. from 20mm (0.02m) to 28mm (0.028m) resulted in an increase in both the mean flow rate and variance (Table 4.3 and Figure 4.12). This response was unexpected since the minimum path length is increased and, in theory, the mean flow rate and variance should decrease.

This increase in flow rate with increasing O.D. was noticed by Hamp (1987) and attributed to gas leakage at the seal. Gas leakage is possible as the force needed to exert a constant pressure at the seal is more than double if the O.D. is increased from 20 (0.02m) to 28mm (0.028m) with a constant I.D. of 6mm (0.006m). Gas leakage would also explain the increase in variance since the rate of leakage is unlikely to be constant.

If gas leakage is the cause of the increase in flow rate and variance with increasing path length then the greatest difference would be expected to occur at sample points with the lowest permeability. This was tested by measuring flow rates using different probe dimensions on a rock with

O.D. (mm)	I.D. (mm)		
	6	10	15
20	373	808	1455
28	440		

n=31

Table 4.3 Mean flow rates measured using seals with varying I.D. and O.D. dimensions

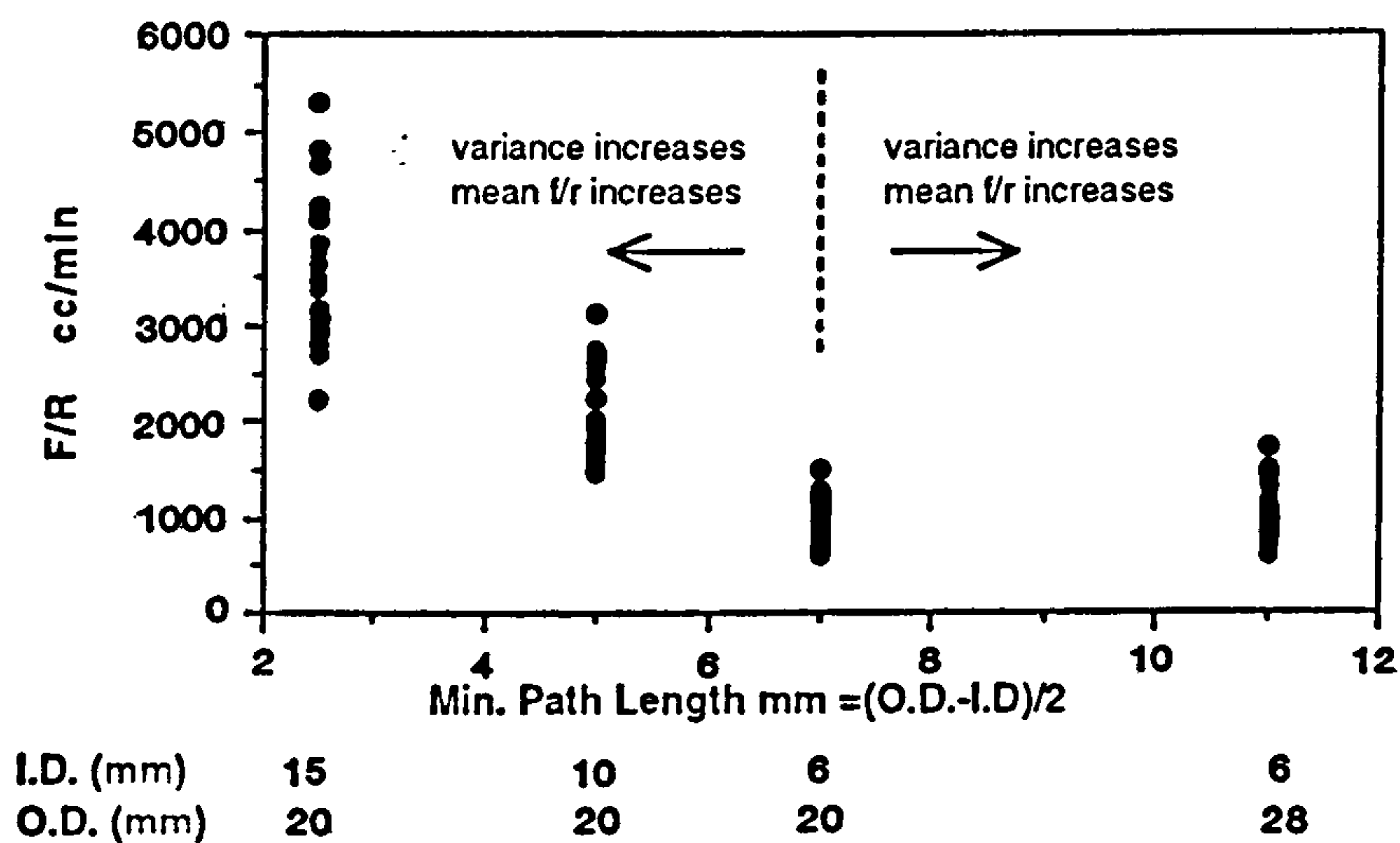


Figure 4.12 Measured flow rate and variance as a function of the minimum path length

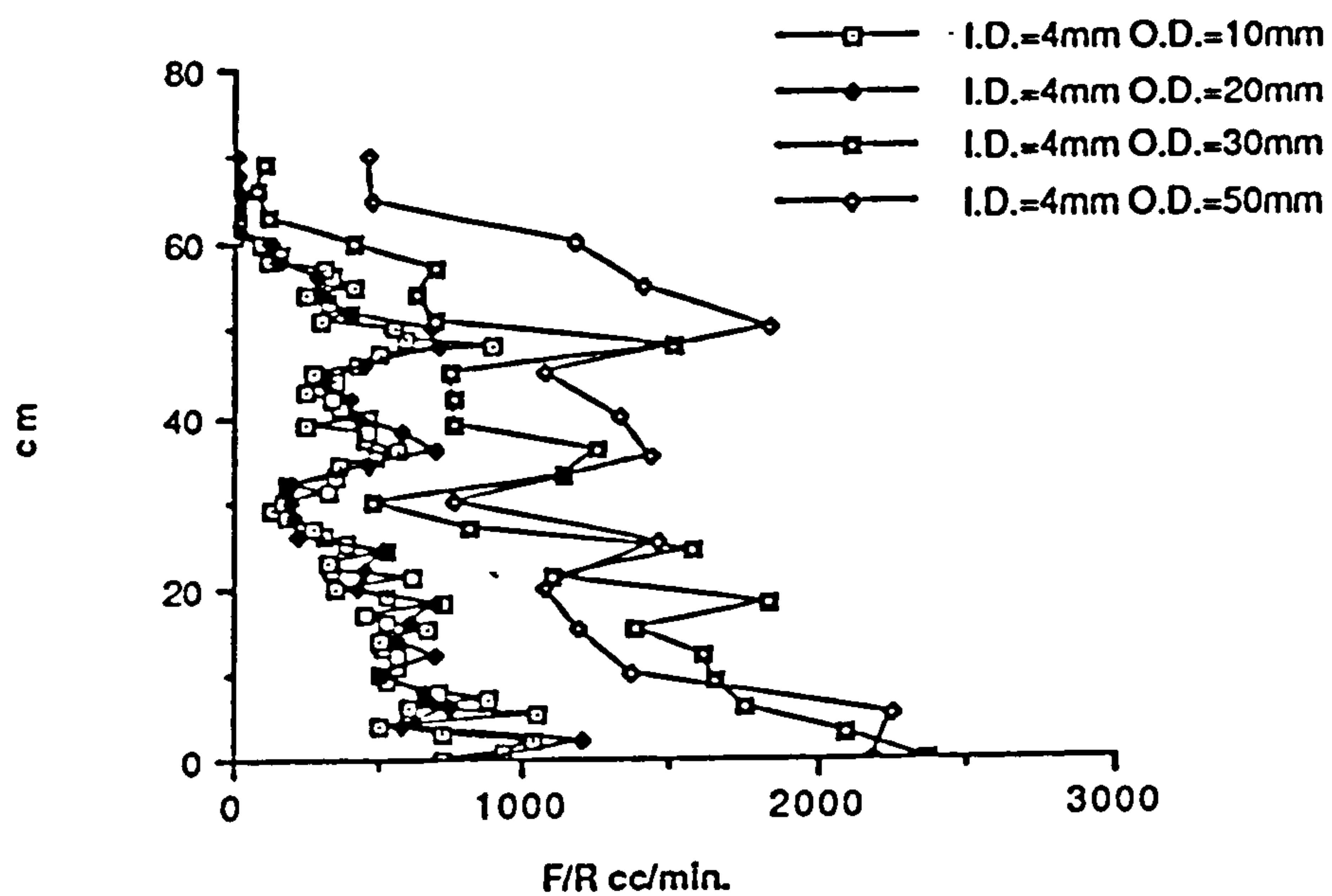


Figure 4.13 Flow rate profiles measured using different O.D. with constant I.D. on rocks with varying permeability

known permeability variation. Figure 4.13 shows the flow rate profiles produced using probes with an I.D. of 4mm (0.004m) and an O.D. of 10, 20, 30 and 50mm (0.01 to 0.05m). Whilst the flow rate and variance increases with an increase in O.D., the amount of increase appears to remain fairly constant even though the rock permeability clearly increases over the sampled section. It is possible that a better seal was effected on the lower permeability sediments where the grain size is smaller and the surface smoother. Whatever the cause (which requires further investigation), this observed relationship between measured flow rate and seal dimensions has important consequences for calibration.

4.4.1.3 Consequences for calibrating flow rates with permeability

Even assuming that there are no leaks at the seal, the change in I.D. and O.D. should be considered since the calibration for flow rate to permeability used for the uncompressed dimensions may differ significantly for the compressed dimensions (see Figure 4.4). For the 8mm-thick neoprene sponge the original seal dimensions of O.D. = 21mm (0.021m) and I.D. = 15mm (0.015m) were changed to O.D. = 27mm (0.027m) and I.D. = 9mm (0.009m) under compression. Assuming an injection pressure of 2psi and a flow rate of 100cc/min., using the geometric factor method, this variation in seal dimensions before and after compression produces permeabilities of 0.9 mD and 1.9 mD. This difference of 1 mD could be very significant under certain reservoir conditions.

If a constant application pressure is applied then an empirical calibration will suffice providing probe permeameter measurements made on the core plugs are taken at the same application pressure. This is easily achieved through the use of a spring-mounted probe tip where the application pressure may be varied by changing the compressive strength of the spring. In practise however, the application pressure required to effect a seal on the outcrop face varies and is impractical to monitor this for every measurement. This points to a major source of uncertainty in the use of hand-held probe permeameters, used either on outcrop faces

or on prepared core surfaces, where the application pressure is not controlled.

Rather than using a constant application pressure, the compressed-state seal dimensions can be measured for a range of application pressures. This information can then be used to obtain the correct geometric factor for each measurement at outcrop for which the application pressure is recorded. The compressed-state seal dimensions should be re-measured if the seal thickness or material is changed. Also, the rheological properties of the seal material may alter with wear and seal tips may need to be replaced periodically.

The conclusions drawn from the relationship between probe size and flow rate for hand held portable probe permeameters concern application practice. For lack of an alternative plausible explanation, it would appear that leaks at the rock - seal interface are responsible for the unconventional response between flow rate and probe size for the hand-held probe permeameter used in this study. It does not seem possible to alleviate this problem with current portable probe technology, so the problem should be allowed for. This can be done by:-

- 1) Ensuring the same probe material and dimensions (O.D., I.D. and thickness) are used throughout the study.
- 2) Ensuring the application pressure is as constant as possible for all measurements, thereby keeping the probe geometry constant.
- 3) Using the same probe dimensions and application pressures on homogeneous core plugs to obtain a calibration specific to the set-up used.

4.4.1.4 Seal deformation: changes in seal shape.

Visual examination of deformation caused by skewing the probe seal against the rock produces a characteristic oval shape (Figure 4.14). Such deformation is likely to occur where the probe seal is applied at an

angle to the rock surface. The softer the seal material the greater the deformation.

The characteristic oval shape produced by skewing the probe tip against the rock surface might reasonably produce a different flow rate from that obtained using a circular seal because the flow geometry is anisotropic. A preferential flow path may also be produced along the minimum path length where the seal width varies. In an homogeneous and isotropic rock, the shape of the injection aperture should have no affect on the flow rate providing the injection area and minimum path length remains constant. This was investigated experimentally on a sample of the White Sandstone.

To take an extreme case of seal deformation, the oval injection aperture was translated to a rectangle with the same area and minimum path length as an undeformed, circular injection aperture. Flow rates were then measured on nine sample points on the White Sandstone sample using different seal shapes; a circular seal with dimensions of I.D. = 15mm (0.015m) and O.D. = 28mm (0.028m), and a rectangular seal with an injection area of 20mm (0.02m) by 9mm (0.009m), and a seal area of 33mm by 22mm (0.033m by 0.022m). Both the circular and rectangular seal have an injection area of approximately 180 mm² (0.00018 m²), and a constant seal thickness of approximately 6.5mm (0.0065m).

Comparison between the flow rates using the different probe shapes are shown in Figure 4.15. There are no significant differences between the flow rates obtained with the different probe shapes which indicates that the permeability at this sample volume is isotropic. If the porous media was divided into well-defined laminae with different permeabilities, orientating the rectangular probe parallel or perpendicular to the laminae is likely to produce different flow rate profiles. A rectangular probe orientated parallel to the laminae would incorporate and average over fewer laminae than if the probe were orientated perpendicular to laminae. This would produce a more variable flow rate profile in the former case and a smoother flow rate profile in the latter case. A circular seal of equivalent dimensions would be expected to produce a flow rate profile lying somewhere between those of the rectangular

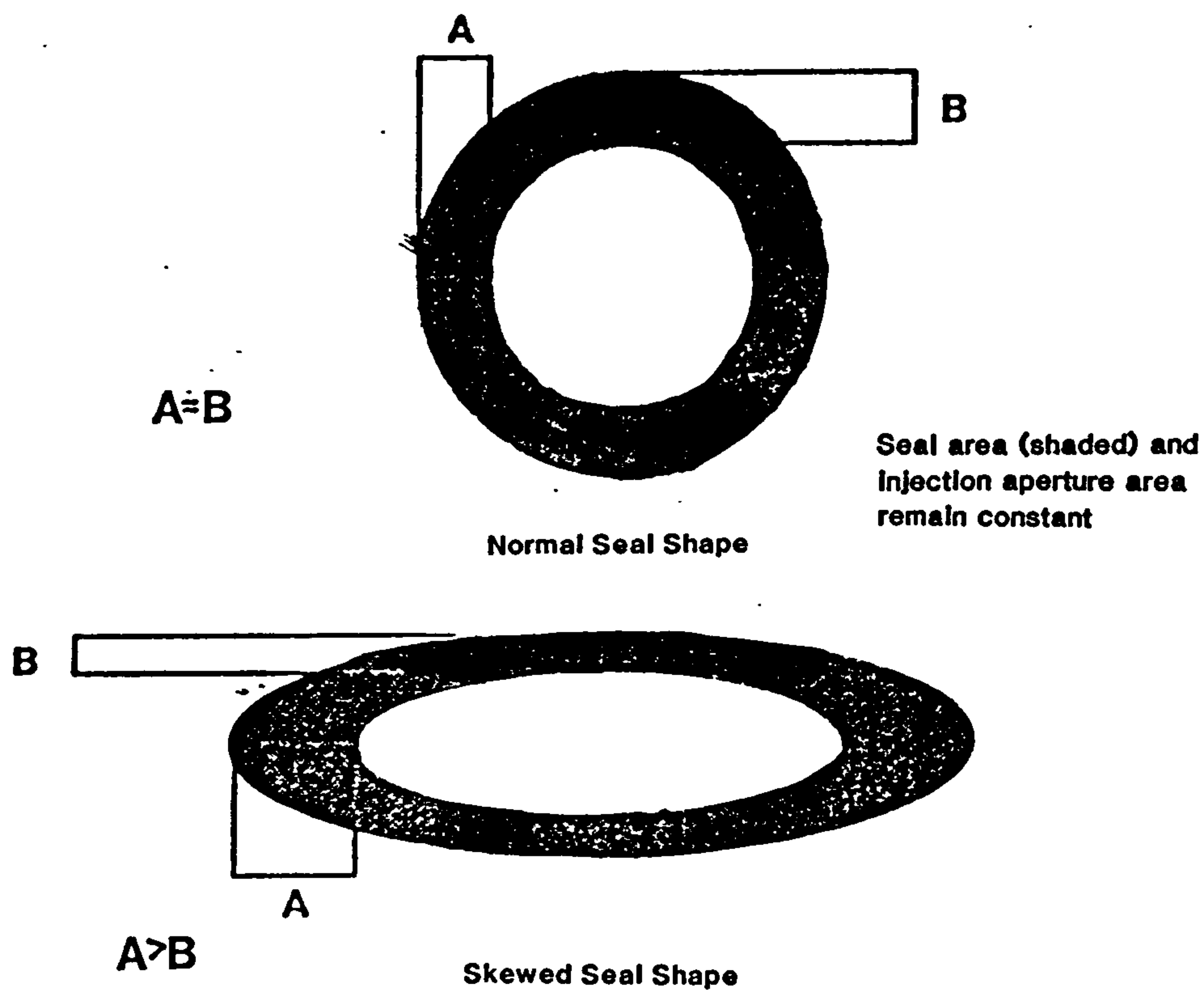


Figure 4.14 Deformation of the probe seal caused by shearing when the probe is applied non-perpendicular to the rock face

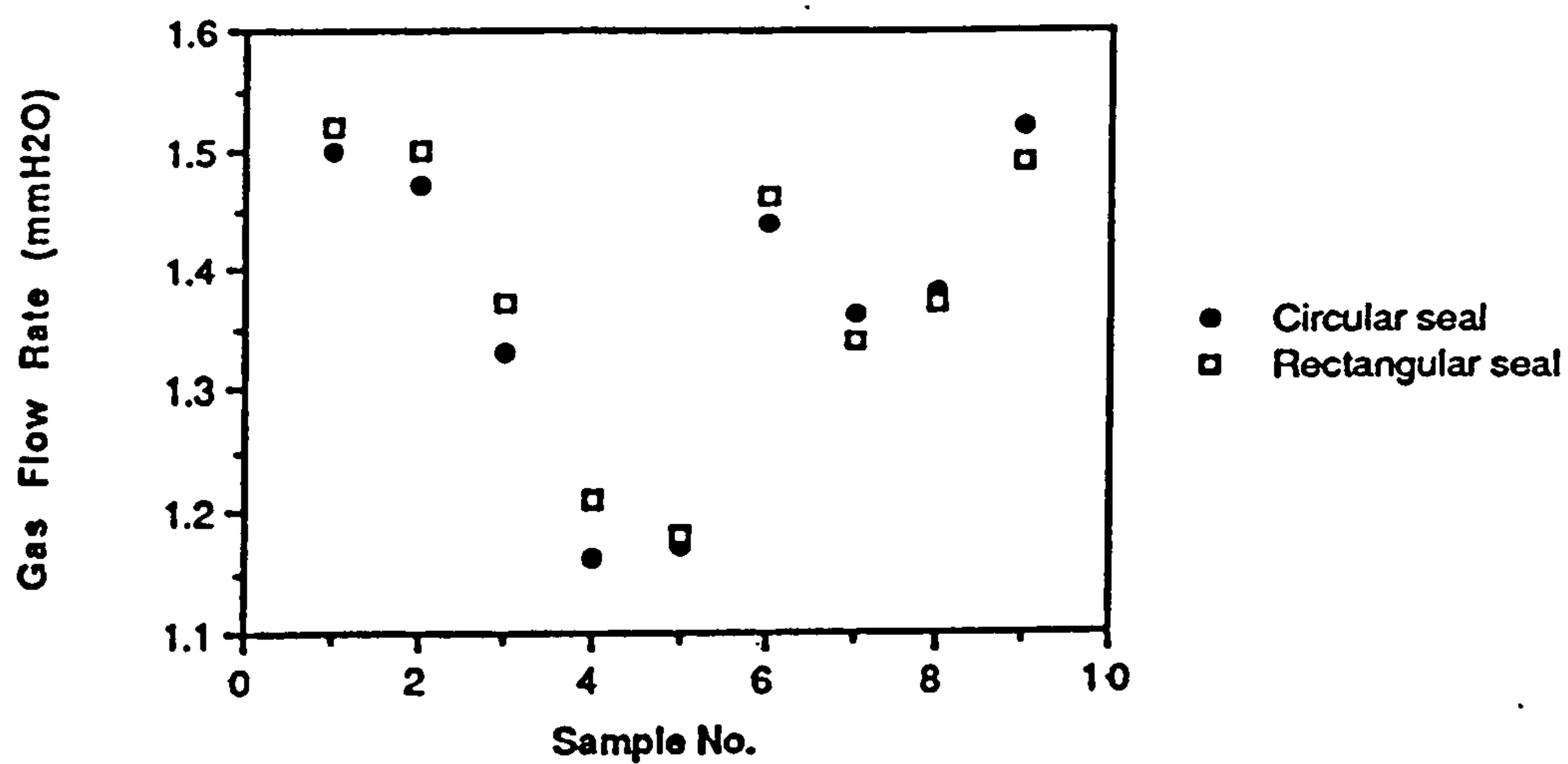


Figure 4.15 Flow rates measured using different probe seal shapes

probe in each orientation. Thus, varying the probe shape is likely to have a very significant effect on the measured permeability and the use of non-circular seals should be treated with caution since they produce biased averaging.

4.4.2 Permeability anisotropy

Unlike conventional permeability experiments on core plugs using a Hassler cell device, the gas flow path for the probe permeameter is allowed to flow freely after injection as there are no constraints on the flow geometry. As the probe permeameter measures flow rate in all directions, it provides some kind of three-dimensional permeability tensor. Permeabilities obtained using probe permeameters often have values between the vertical and horizontal permeabilities measured on orientated core plugs (Gibbons and Halvorsen 1991). In some cases, the orientation of the probe may impose a dominant directional component to the flow rate, parallel with the probe orientation, but generally the pressure differential used in field-portable probe permeameters is so low; usually between 2 - 20 psi, that this directional component is minimal.

As the flow path for the probe permeameter is largely unrestricted the measured permeability will be along the path of least resistance. Assuming this path of least resistance is not at the seal - rock interface, the probe permeameter provides a very useful measure of the permeability variation since it indicates the value of permeability along the most likely path taken by a fluid passing through the rock sample. Permeabilities measured by the probe permeameter automatically integrate the various permeability tensors and therefore provide a more representative and more rapid assessment of permeability variation than core plugs orientated in different directions (usually horizontally and vertically).

Analysis of spatial permeability variation is complicated by anisotropy at the sample scale. If the sample anisotropy is unknown then the spatial variation in permeability may be a function of anisotropy at the

measurement scale rather than true heterogeneity. Where core plugs are used, the permeability can be estimated for a given orientation and assuming that this orientation is kept constant, the measured permeabilities can be directly related to sample interval and direction. For the probe permeameter, controlling the measurement orientation is more difficult because of the hemispherical nature of the flow paths. Correlation between probe permeameter measurements may identify the spatial structure of anisotropy without providing a true representation of heterogeneity.

There are various methods that can be used to investigate whether the value of permeability represented by the flow rate measured using the probe permeameter is isotropic or whether it is biased towards a particular tensorial component (for example, k_x , k_y , k_z , k_{xy} and so on). These methods can be divided into quantitative and qualitative estimations. They are listed below in order of their accuracy (1 being most accurate), according to the type of estimation they provide. References to the technique are given where appropriate.

Quantitative

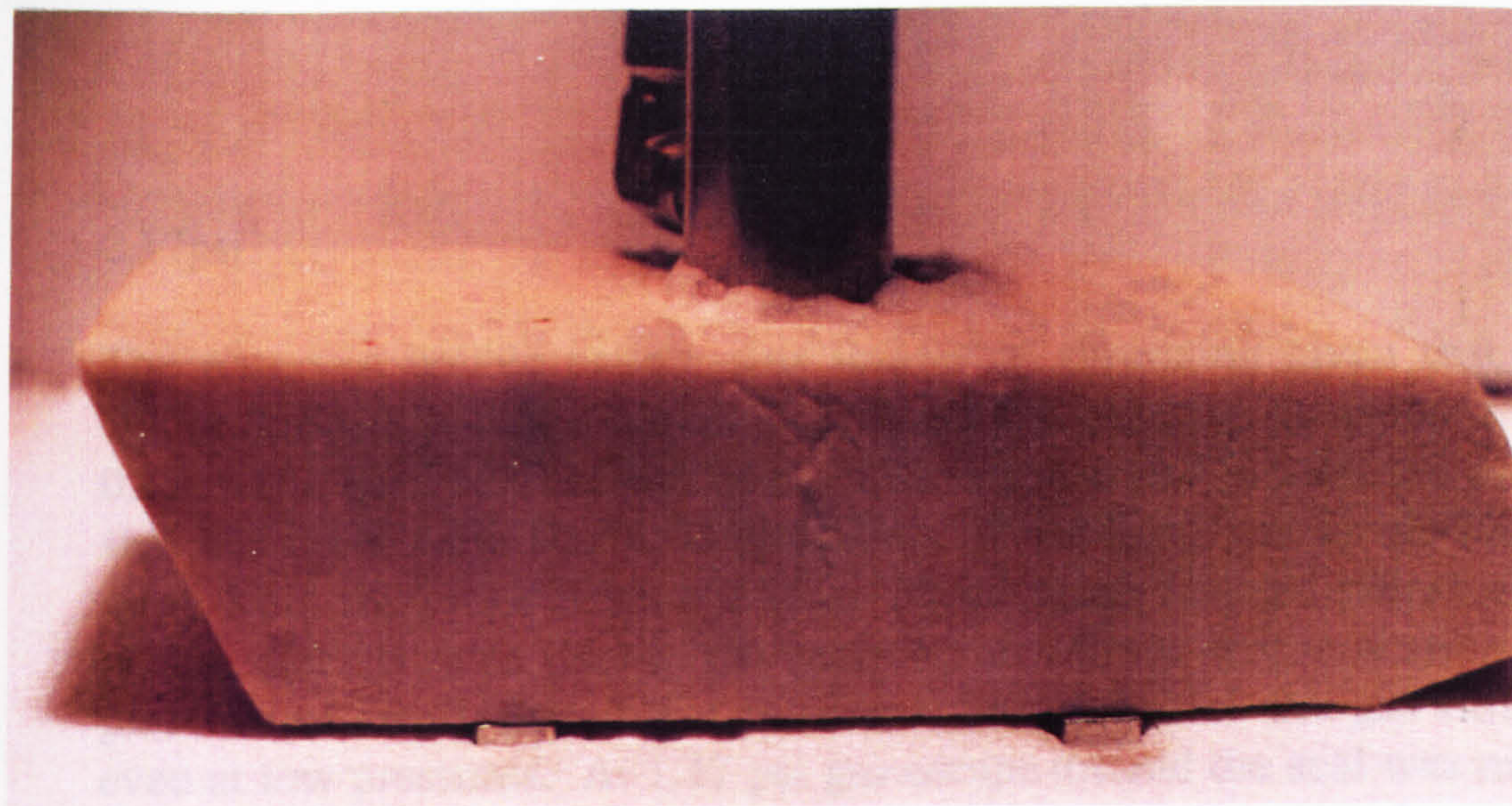
- 1) Measure flow rates on a cubed sample in each direction for which directional permeabilities are known for each orientation (k_x , k_y , & k_z) using a modified Hassler Cell. The dimensions of the cube should be such that the probe permeameter probe avoids edge effects but maximises overlap of the sample volume in different orientations (assuming hemispherical flow).
- 2) Measure flow rates on a cubed sample in each direction with directional permeabilities measured on orientated core plugs. The dimensions of the cube must be sufficient to obtain three core plugs, one in each direction (k_x , k_y & k_z).
- 3) Simulate the flow geometry under isotropic and anisotropic conditions, estimate the permeability in each case and compare these to the measured flow rates (Daltaban et al 1991, Wang 1990).

Qualitative

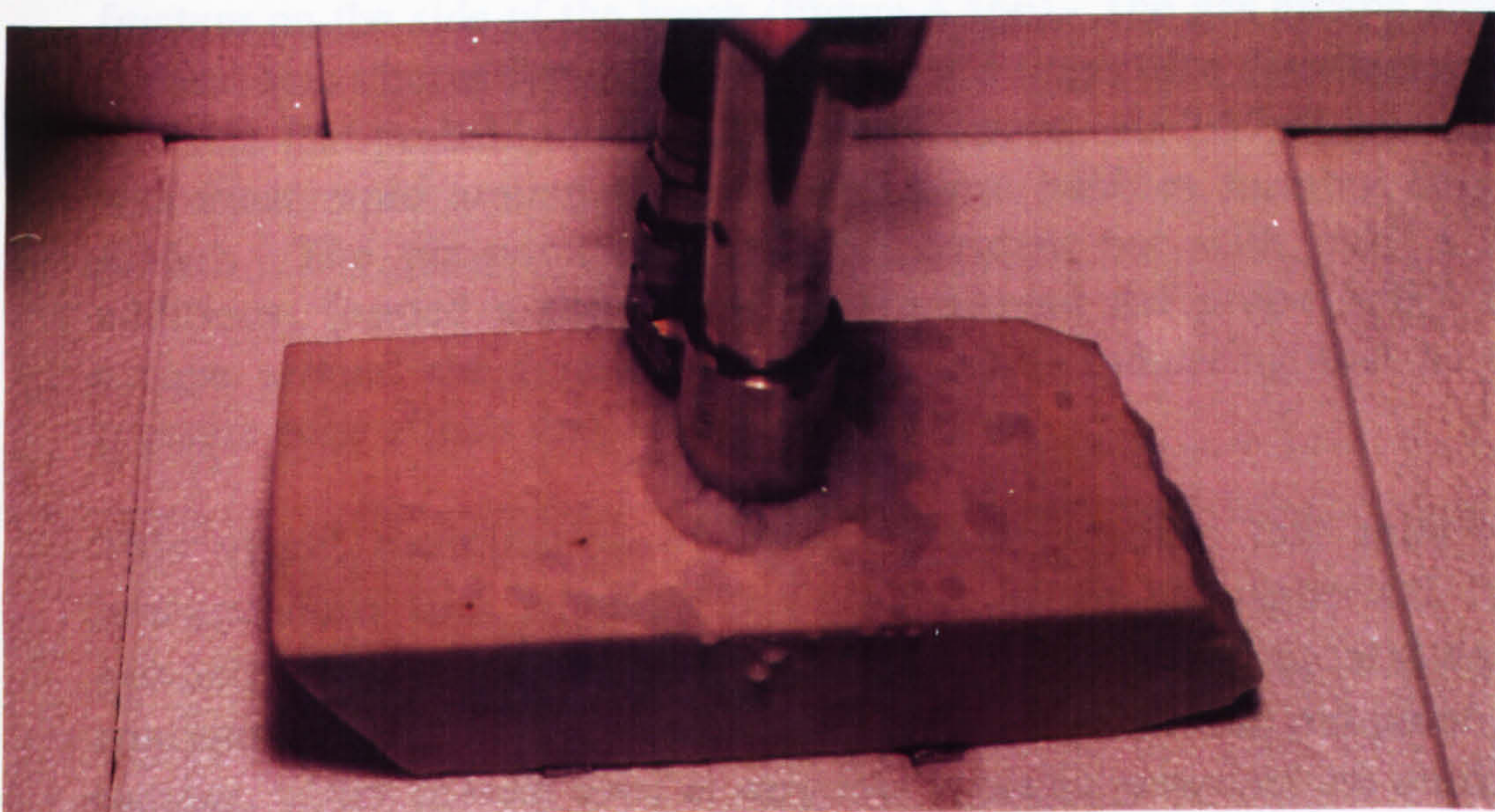
- 1) Obtain a density image in serial sections to visualise heterogeneities using computer aided tomography (CAT) or X-ray techniques (Wellington and Vineger 1987, Hurst and Rosvoll 1991, Halvorsen and Hurst 1990).
- 2) Obtain a 3-D pore cast (Beckett and Sellwood, 1991)
- 3) Obtain a visual image of the flow geometry using water mixed with detergent (this is described in detail later).
- 4) Describe the pore geometry in 2-D thin sections made from a sample cut in different orientations.

The requirement for a computer simulation model and a specially adapted Hassler cell for the quantitative methods 1 and 2 may render these techniques impractical for laboratories that do not possess the necessary equipment and computer software. The specialised equipment required for qualitative method 1 is usually available through hospitals and medical centres where access to this equipment may be made on a rental or service basis. Quantitative method 3 and qualitative methods 2, 3 and 4 are easily performed using a minimum of equipment requirements, all of which should be present in a standard core analysis laboratory. The use of a weak detergent - water mixture in qualitative method 3 was found to be a quick and effective method of visualising the flow pattern and is described in detail here.

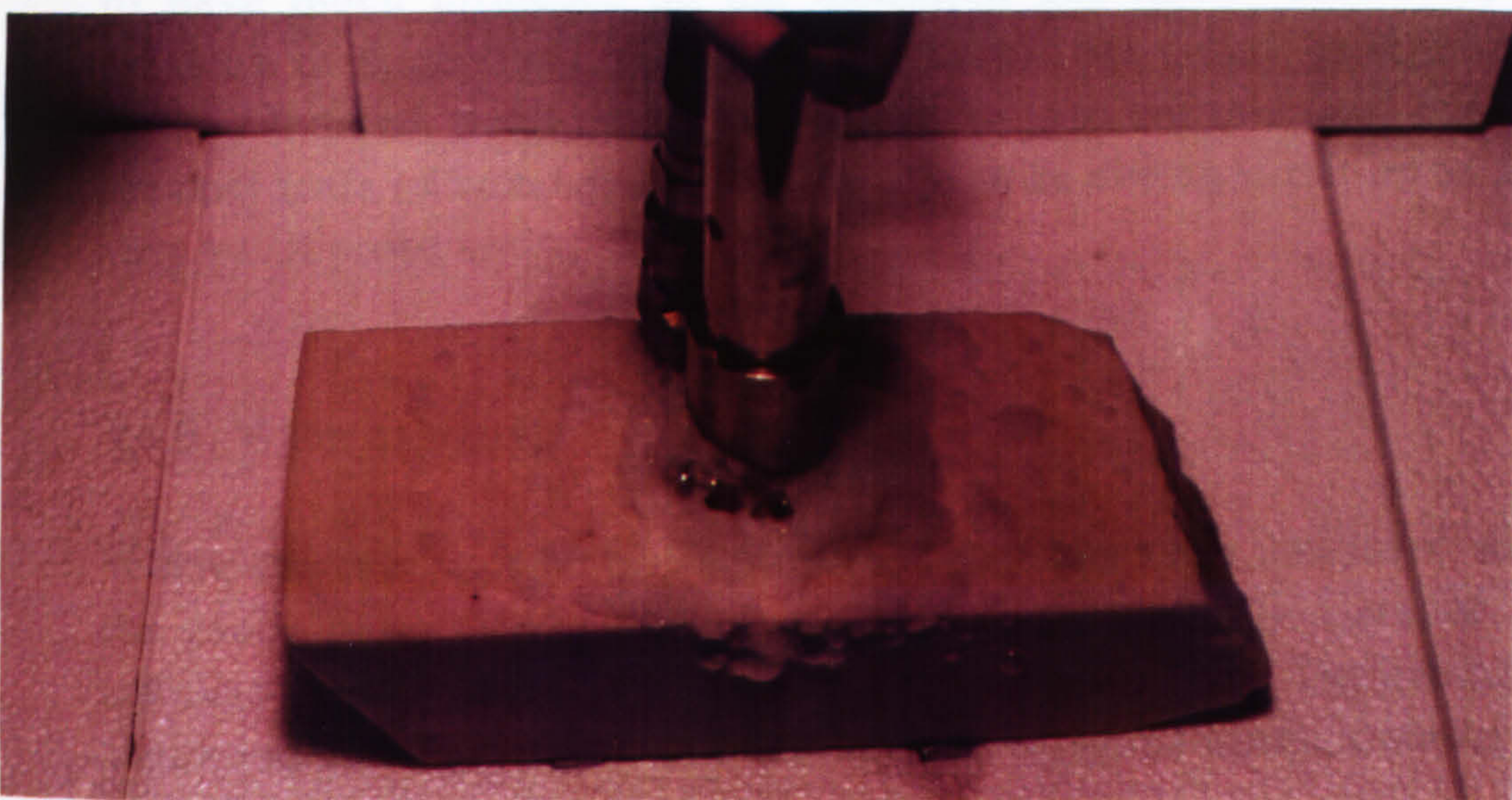
A visual estimation of the flow geometry was performed by saturating a sample of the White Sandstone with water containing a small amount of detergent. The probe seal (O.D. = 20mm, I.D. = 15mm) was first fixed against the rock surface. Saturation of the rock sample was achieved by applying the solution to the upper surface of the sample and allowing the fluid to move downwards through the rock under gravitational forces. The solution was added until it began to puddle on the top surface of the rock. The injection pressure was then increased slowly until the first signs of escaping gas were observed as bubbles appearing on the rock surface (Figure 4.16). This occurred with an injection pressure of 0.17 psi, after which the injection pressure was increased to 1.17psi and



A 0.17psi



B 1.17psi



C 2.17psi

Figure 4.16 The pattern of gas escape around the probe seal identified by bubbles produced by a weak detergent solution

2.17psi.

The observed bubble pattern was somewhat surprising given that the White Sandstone is an extremely well-sorted, massive sandstone. At 0.17psi the escaping gas was seen to be concentrated around the probe seal but there were scattered pin-points of escaping gas up to 70mm away from the probe (Figure 4.16a). These small isolated points were observed at the same time as gas escaping around the seal indicating the presence of small, thread-like pathways through which the gas flowed even at low pressures. At 1.17 psi gas escape around the seal was more noticeable with additional pin-point escapes, especially around a small fracture on the side of the block (Figure 4.16b). The gas escape around the seal was almost symmetrical except for a finger-like development on one side that probably indicates a microfracture. At 2.17psi gas escape was most rapid around the seal with large bubbles forming (Figure 4.16c). The pin-point escapes, still evident but with only a few additions, formed a concentric pattern around the probe seal. Gas escape around the fracture was more rapid, indicating that at this pressure edge effects may be more influential.

This visual examination of flow geometry within this relatively homogeneous rock supports the concept of an hemispherical flow geometry with maximum flow concentrated around the tip seal and a concentric pattern of gas escape away from the seal. The pin-point gas escapes, whilst present even at very low injection pressures are unlikely to have much influence on the measured gas flow. However, the presence of these small, high permeability pathways may be significant as they indicate the presence of a micro to macroscopic (and possible greater) scale of heterogeneity that is otherwise averaged out, even with very small probe seals.

4.4.3 Water saturation

Where the rock is saturated with water, gas flow rates measured using the probe permeameter are initially reduced but slowly increase and stabilise as the water is forced out by the invading gas. The effects of saturation on stabilisation time has been investigated through numerical

simulation (Daltaban et al 1991) where stabilisation times were found to increase by up to 100 times with saturation. The average permeability was calculated from the arithmetic average of at least ten flow rate measurements made on various samples of the White Sandstone using the probe permeameter and converted to Darcy permeability using the calibration described in section 4.4.3. All of the rock samples represented fairly homogeneous rocks with the coefficient of variance (Cv) of permeability less than 0.5 for each rock sample.

Stabilisation times for varying water saturation were determined experimentally for rocks with average permeabilities of approximately 1000 mD, 500 mD and 250 mD. Halvorsen and Hurst (1990) examined the difference in permeabilities measured using a probe permeameter on freshly cut core and the same core left to stand in room conditions for one month. They concluded that the effect of drying was pronounced for the low permeable material (2-20 mD) but no significant effect was seen on material with permeabilities in excess of 100 mD. The stabilisation time was obtained using a probe seal fixed to the rock sample with flow rate measurements taken under dry and saturated conditions. The percentage saturation was not calculated since gravity and capillary effects will modify the saturation at the point of gas injection. Saturated rock conditions are therefore referred to as wet rock, and are obtained by standing the rock in water and allowing capillary forces to draw water into the pore spaces. Flow rates were measured at 5 second intervals and at 1 second intervals for the first 5 seconds on the dry rock where stabilisation times were more rapid. The dry and wet stabilisation times for each rock are shown in Figure 4.17a, b and c.

The dry rock stabilisation times were all below 10 seconds with the 1000 mD sandstone having the most rapid stabilisation time of 1 second. The dry rock stabilisation times for the 500mD sandstone and 250mD sandstone were 5 seconds and 3 seconds respectively which was surprising since dry rock stabilisation times were expected to be inversely proportional to permeability. The reason for this result might be due to the presence of fines in the 500 mD sandstone although this appears cleaner than the other two samples under inspection at low magnification using a hand lense.

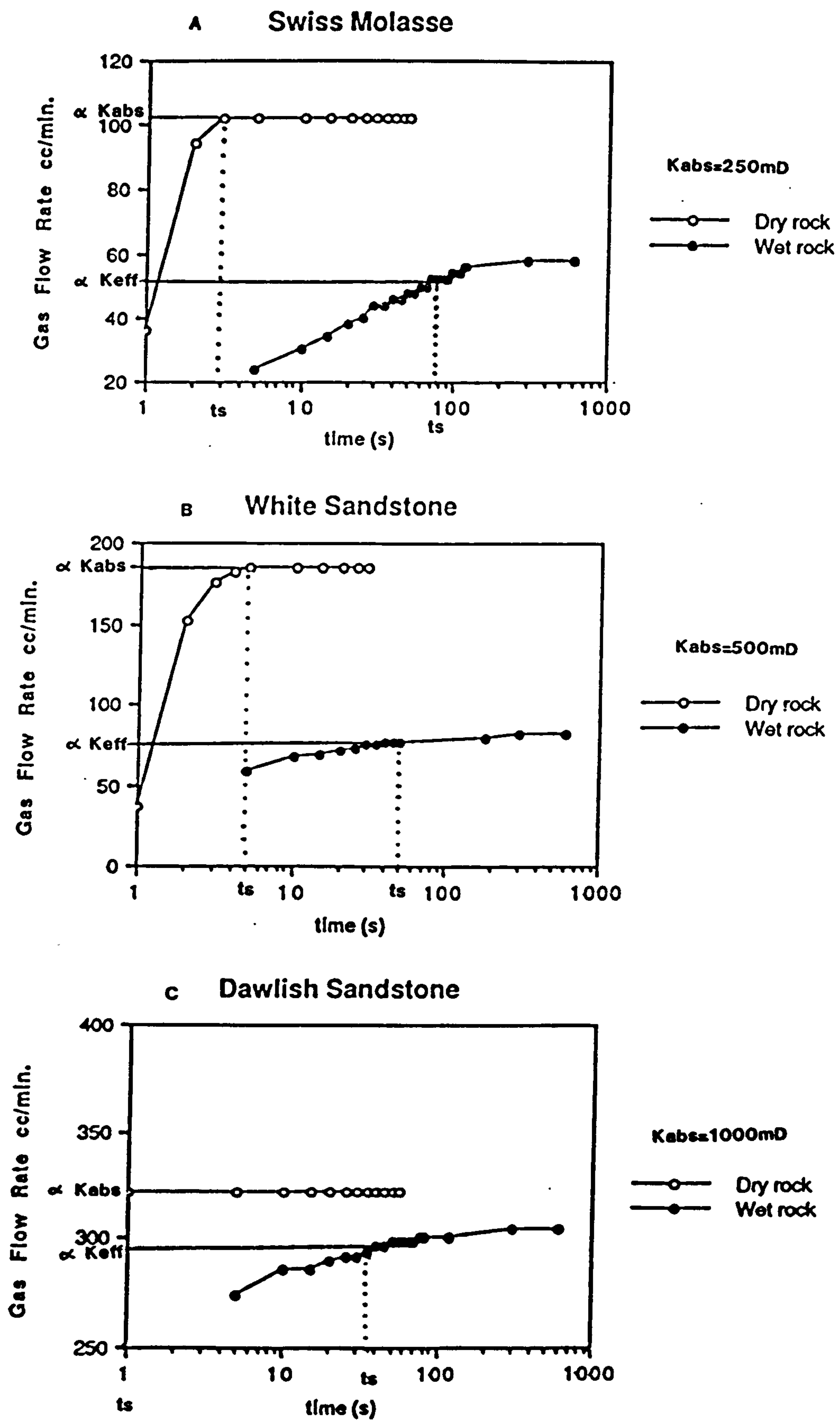


Figure 4.17 Flow rate response on wet and dry rocks with different permeabilities

The wet rock stabilisation times were 35 seconds for the 1000 mD sandstone, 50 seconds for the 500 mD sandstone and 75 seconds for the 250 mD sandstone. These results show that the stabilisation time is inversely proportional to the absolute permeability, K_a , of the rock. However, the stabilised gas flow rates for the wet rock are consistently lower than the stabilised gas flow rates for the dry rock which means that on wet outcrop rocks the probe permeameter provides a measure of the effective phase permeability (K_e) for gas, termed K_g .

For portability, measures of absolute permeability are required from the outcrop and a relationship between absolute and effective permeability must be sought. This relationship can be found by cross-plotting the gas flow rates measured on field samples under field conditions (= wet rock) against gas flow rates measured on the same samples after drying under laboratory conditions (= dry rock). This method of cross-plotting wet and dry rock flow rates is shown in Figure 4.18. A best-fit curve is then found for these cross-plot data where K_g is the dependent variable.

After converting the wet rock flow rates to dry rock flow rates, absolute permeability is estimated using one of the methods of calibration given in section 4.4.2. Since both K_g and K_a are known, the relative permeability, expressed by the relationship; $K_r = K_g/K_a$, is obtained from the slope of the cross-plot ($\partial K_a/\partial K_g$) in Figure 4.18, where $K_r = 1/\text{slope}$.

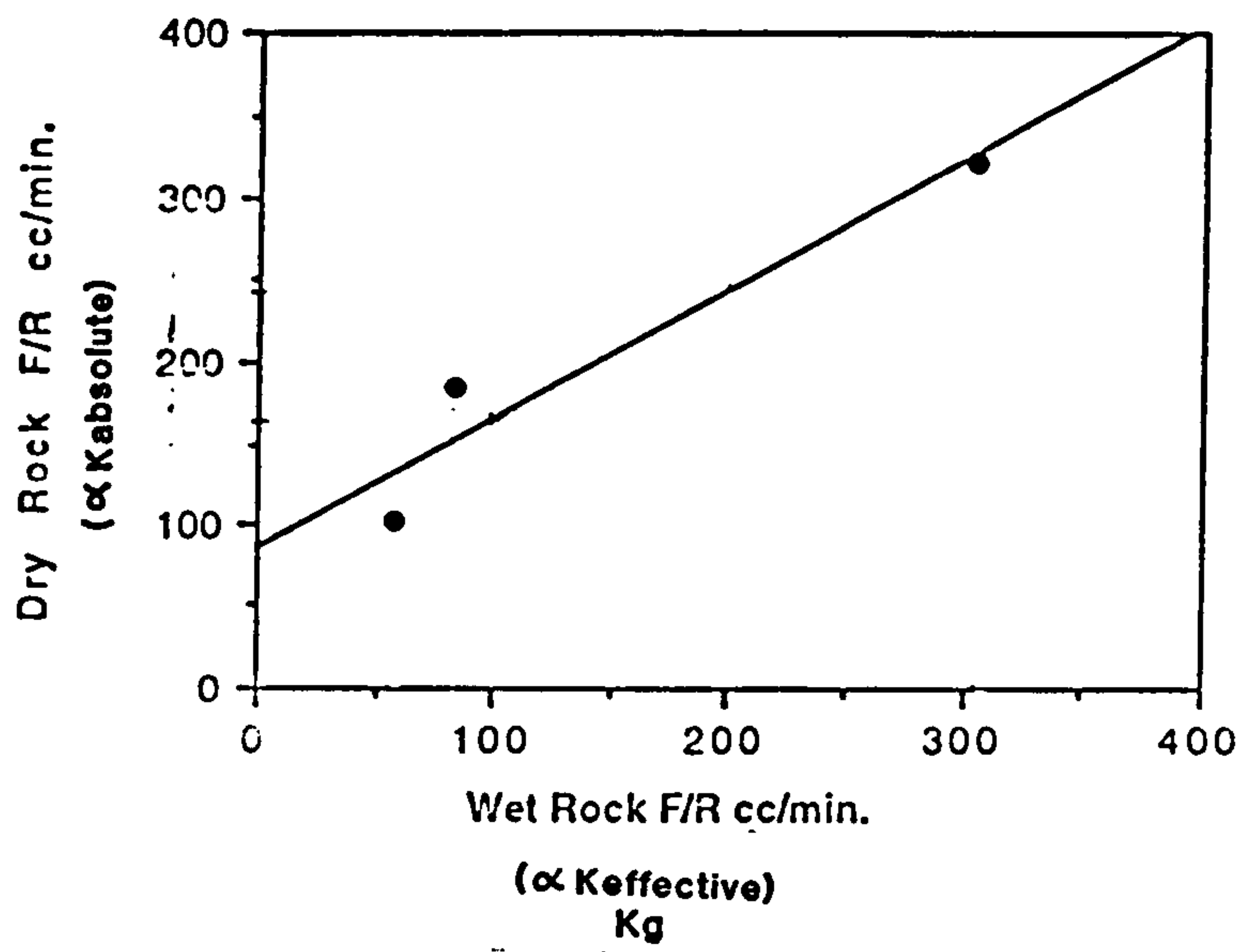


Figure 4.18 Cross-plot of flow rates measured on the same rock under wet and dry rock conditions for determination of absolute permeability

The conclusions drawn from this experimental analysis are:-

- 1) Wet rock stabilisation times are greater than dry rock stabilisation times and inversely proportional to the absolute permeability.
- 2) Flow rates are reduced by water saturation, providing a measure of effective phase permeability. Dry nitrogen gas, whilst drying the rock around the point of injection does not dry the rock sufficiently to provide a measure of absolute permeability, even after prolonged gas flow.
- 3) Measures of effective phase permeability obtained from wet outcrop rocks can be converted to absolute permeability by measuring flow rates on wet and dried samples. A measure of the relative permeability is obtained from the ratio between effective phase and absolute permeability.

4.4.4 Fines

The presence of mobile fines, either on the surface of the rock or within the rock, causes a reduction in the measured flow rate. This reduction is marked by a period of stabilisation in the flow rate and is related to four factors: the proportion of mobile fines, the nature of the fines (for example, platy clay minerals), the permeability of the rock, and the injection pressure used. An advantage of the probe permeameter over conventional core plug analysis is that the pressure differential used in the probe permeameter is much lower and less likely to force mobile fines into pore throats, so reducing the permeability.

Where the grain diameters of surface fines are less or equal to the pore throat diameters the presence of fines on the surface of the rock will have a similar effect on the flow rate as fines within the rock. Surface fines are present on every exposed outcrop face and are frequently the product of diagenesis, for example, the recrystallisation of salts through evaporation. Some surface fines are the formed from wind blown dust or water run-off. Organic fines may also be deposited onto the rock face by both fauna and flora. Dealing with surface fines and diagenetic

modification before making probe permeability measurements is the role of face preparation. This is dealt with later in section 4.5.7.

4.4.5 Temperature

The pressure differential across the laminar flow element in the probe permeameter is dependent on the viscosity of the working fluid. The manufacturers' normal working dynamic viscosity Figure for the laminar flow elements is 18.2 μNsm⁻² for air at 20⁰. Changing either the gas type or gas temperature requires the appropriate coefficient of viscosity to obtain the new differential pressure using the following relation:

$$\text{new } \delta p = \text{given value (mmH}_2\text{O)} * (\text{gas viscosity in centipoise} / 0.0182) \dots\dots\dots(23)$$

The new differential pressure is then converted to flow rate in cc/min. using the appropriate calibration for the laminar flow element. Using Sutherland's constant, the viscosity of a gas at different temperatures can be obtained from:

$$\mu_2 = \mu_1*((T_1+C)/(T_2+C))*(T_2/T_1)^{3/2} \dots\dots\dots(24)$$

where μ2 = required gas viscosity at temperature T2 (in T/K)
μ1 = known gas viscosity at temperature T1
C = Sutherland's constant for that gas

The viscosity of nitrogen gas over the temperature range, 0 to 20⁰C is shown in Table 4.4. A reasonable diurnal variation in the ambient temperature at outcrop might be in the order of 8⁰C, over a range of, say, 12⁰C to 20⁰C. Similar variations in ambient temperature may be experienced between the outcrop and laboratory where core plug measurements are made. Assuming the gas temperature in the probe permeameter equilibrates with the ambient temperature, such temperature variation might have a significant affect on the measured flow rates. Flow rates in cc/min. were calculated for a differential

Gas T/Degrees C	Gas T/k	Nitrogen μ mPa/s
0	273	166.0
1	274	166.5
2	275	166.9
3	276	167.4
4	277	167.9
5	278	168.3
6	279	168.8
7	280	169.3
8	281	169.7
9	282	170.2
10	283	170.7
11	284	171.1
12	285	171.6
13	286	172.1
14	287	172.5
15	288	173.0
16	289	173.4
17	290	173.9
18	291	174.4
19	292	174.8
20	293	175.3
50	323	188.6
100	373	209.5

Table 4.4 The viscosity of nitrogen at different temperatures

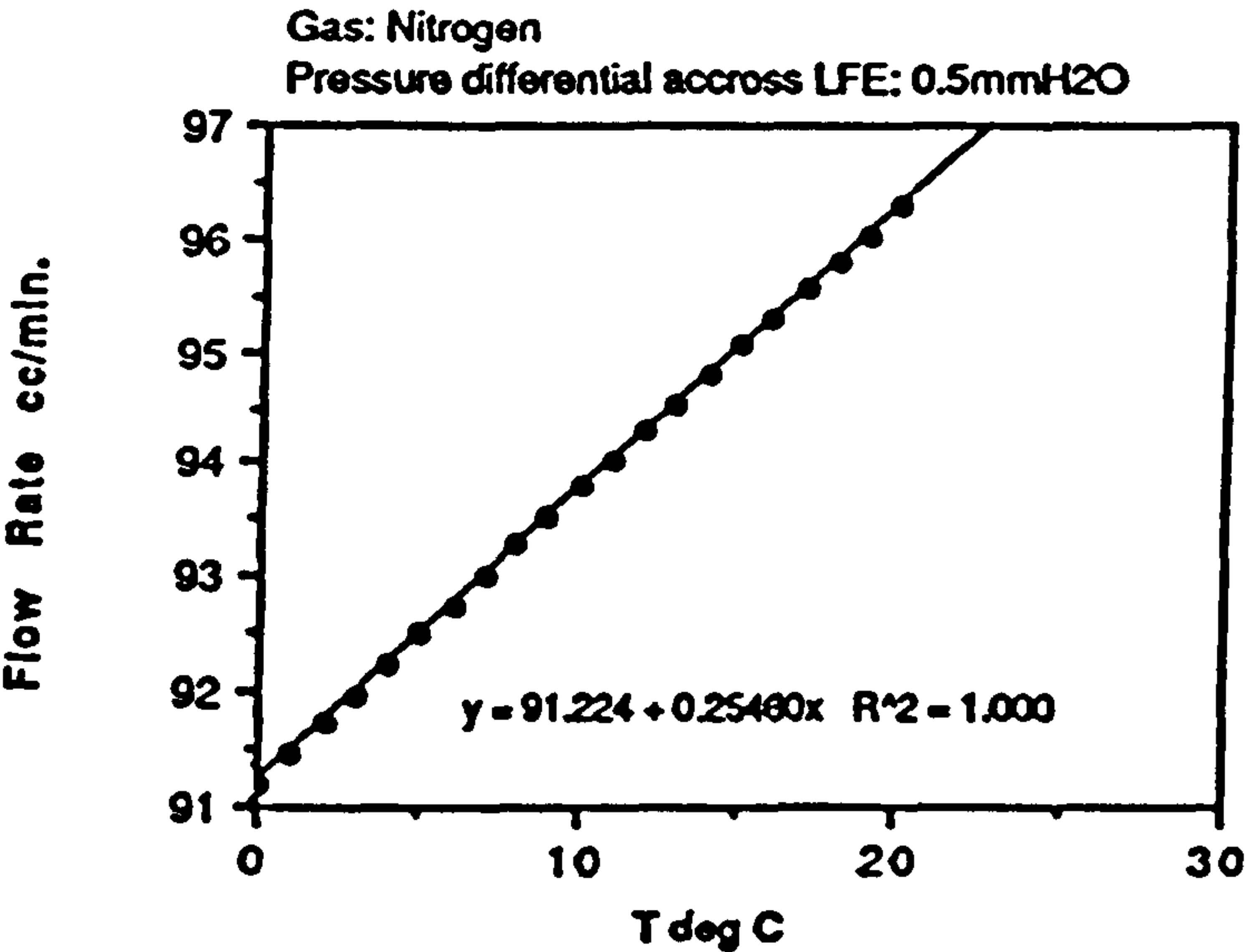


Figure 4.19 Gas flow rate versus gas temperature for a constant pressure differential

pressure of 0.5 mmH₂O using nitrogen gas over a temperature range of 0 to 20°C (Figure 4.19). For a difference in temperature of 1°C, the gas flow rate varies by approximately 0.25 cc/min., and over a temperature range of 8°C, the flow rate varies by 2.03 cc/min. Using an analytical calibration with a geometric factor where $P_1=4$ psi, $bd=4.67$ and $Go=4.2$, this variation in flow rate with temperature is equivalent to 229mD. In virtually all reservoirs this is a significant variation in permeability and it is important therefore, that the gas temperature during each measurement is monitored at outcrop so that the correction can be applied.

The gas temperature is also likely to change as it enters the rock. However, the thermal conductivity of rocks is generally very low, especially where the pore spaces are filled by air, and so the temperature of the invading gas is unlikely to alter significantly between the point of injection and the point of escape around the seal. Similarly, the heating and cooling of the rock surface under normal atmospheric conditions (direct sunlight for example) is unlikely to modify the rock temperature to a depth any greater than the first few grains below the surface. The surface temperature of the rock would, in any case, rapidly equilibrate with the invading gas temperature.

4.4.6 Instrument reliability and precision

The reliability and precision of the probe permeameter depends on a number of factors divisible into those related to the components of the instrument and those related to the interface between the rock and the instrument. The components of the instrument including the laminar flow elements, pressure transducer and associated electrical sensors (micromanometer and digital pressure gauge) are all calibrated individually and the accuracy of each varies.

The digital pressure gauge has a full scale range of 30 psi and a precision of 0.01 psi. The micromanometer has a full scale range of 19.99 mmH₂O and a precision of 0.01 mmH₂O. The combined laminar flow elements have a full scale range of 0.002 ml/min. to 2 l/min.,

provided by four separate flow elements; 0.002 ml/min - 2 ml/min, 0.002 ml/min - 20 ml/min., 0.002 ml/min - 200 ml/min, and 0.002 ml/min - 2 l/min. The precision of each flow element increases as the capacity decreases; the 2 ml/min. LFE has a precision of 0.002 ml/min. over the full scale range, and the 2l/min. LFE has a precision of 0.2 ml/min. over the full scale range.

Assuming 100% accuracy, the probe permeameter has a measurable range in permeability from 0.2 mD to around 50 D, although a realistic accuracy is probably around 3% of the reading over the measurement range. According to the instrument components, and assuming no gas leaks in the instrument or at the probe - rock interface, accuracy is better than 1% for each LFE.

4.4.7 Face preparation

Variation within measured flow rates due to surface fines and diagenetic modification of the rock necessitates the use of some form of face preparation prior to sampling for permeability to minimise these effects. Various face preparation techniques have been used in previous outcrop studies including grinding, washing, sawing and wire brushing (see Chapter 3). The main problem with these techniques is the generation of fines which block pore throats. To avoid this problem, a rotary percussion drilling technique was developed here and has been used on a number of other outcrop studies (for example, Lewis et al 1990).

The drilling technique, now documented in the Recommended Practice for Probe Permeametry (Sutherland et al, 1991), involves drilling out the modified surface using a rotary percussion drill (Figure 4.20). The surface is penetrated to a suitable depth (the modification of permeability can be determined through analysis of rock thin sections and core plugs) and the core plug snapped off leaving a smooth face (in relatively homogeneous sands), in a chosen orientation (to simplify the incorporation of anisotropy), and free of fines. Snapping off the core plug is achieved by placing the end of a cold chisel hard against the base of the plug and applying a sharp tap. This method of chipping out was

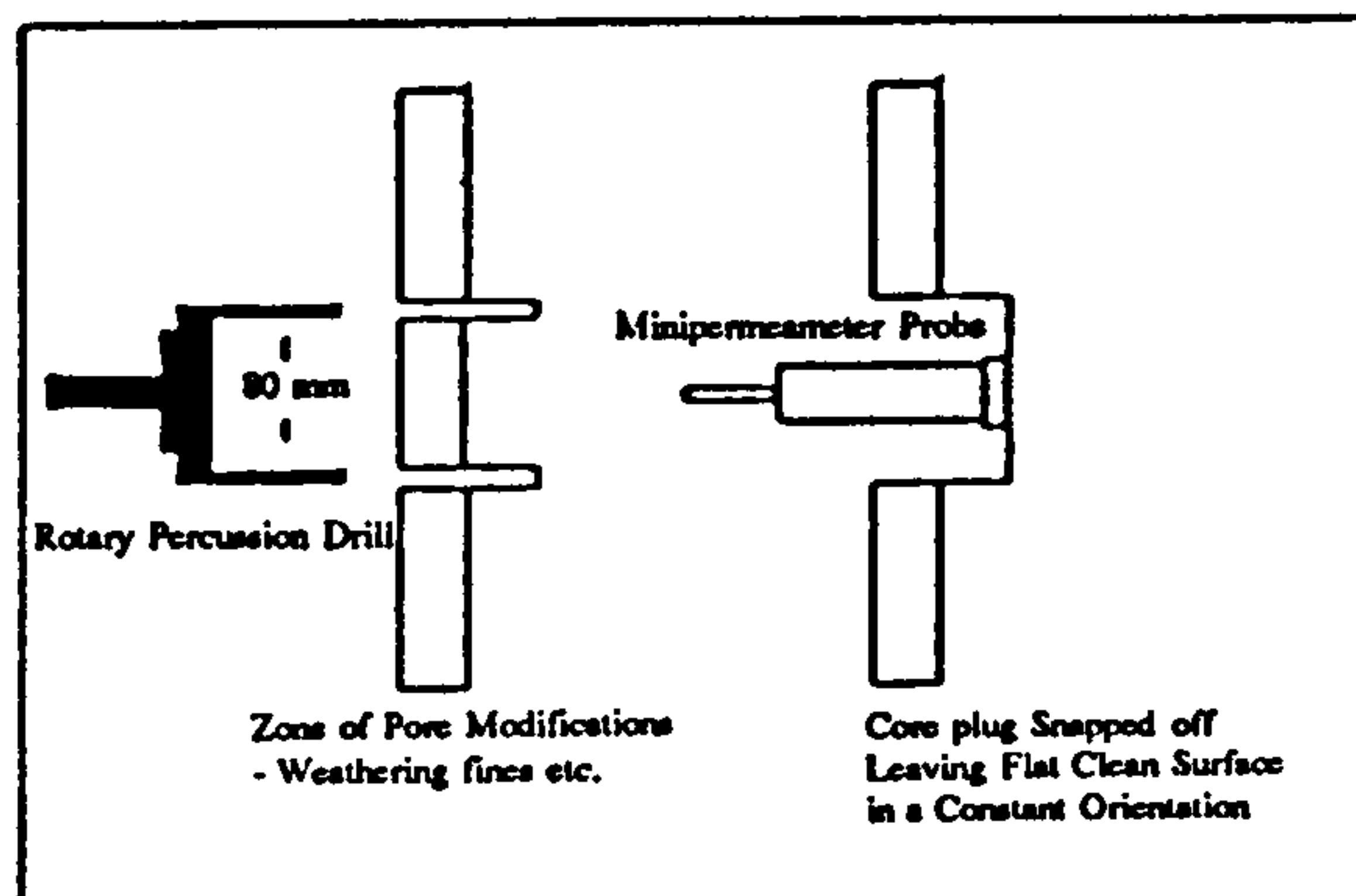


Figure 4.20 Schematic illustration of the method of face preparation

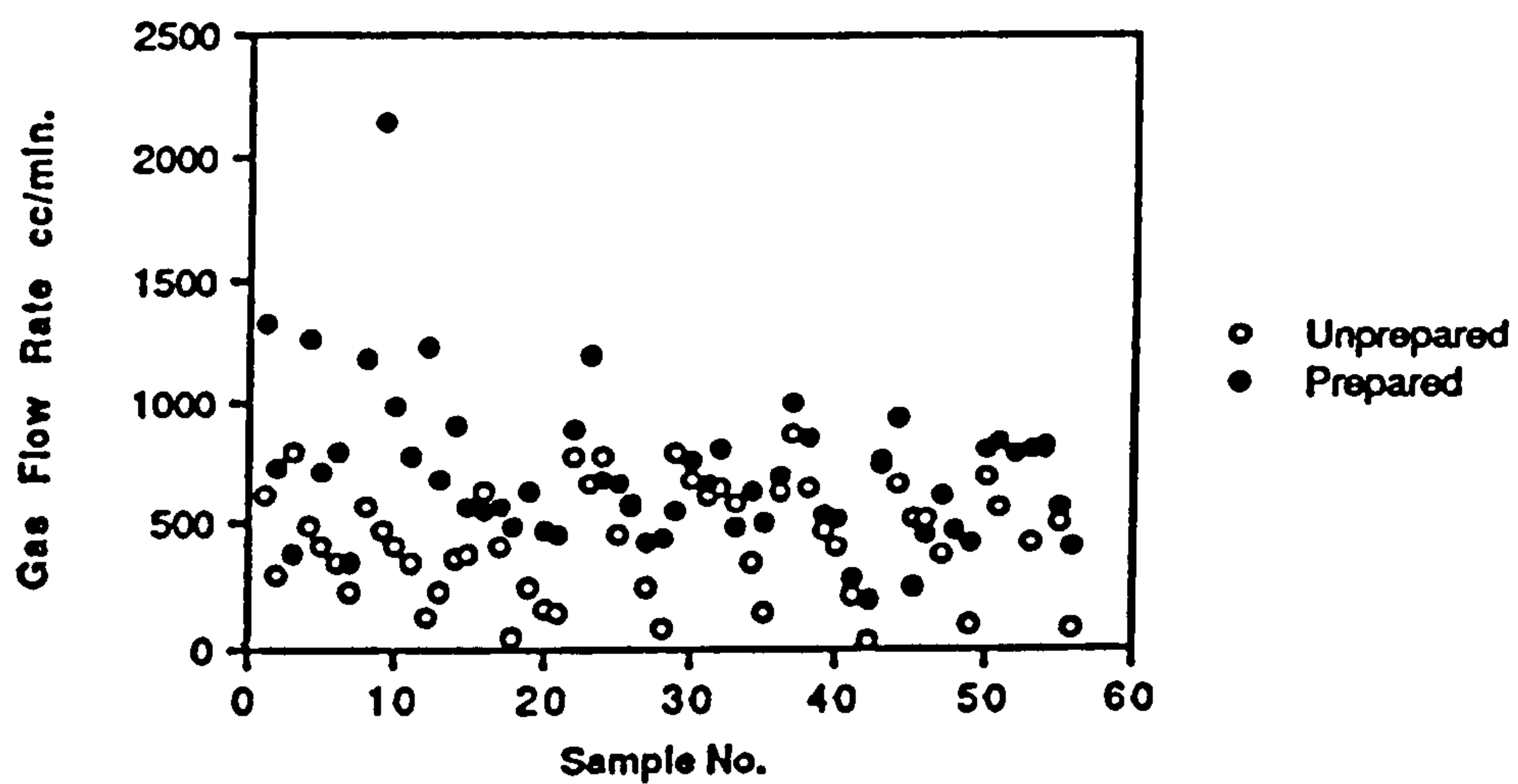
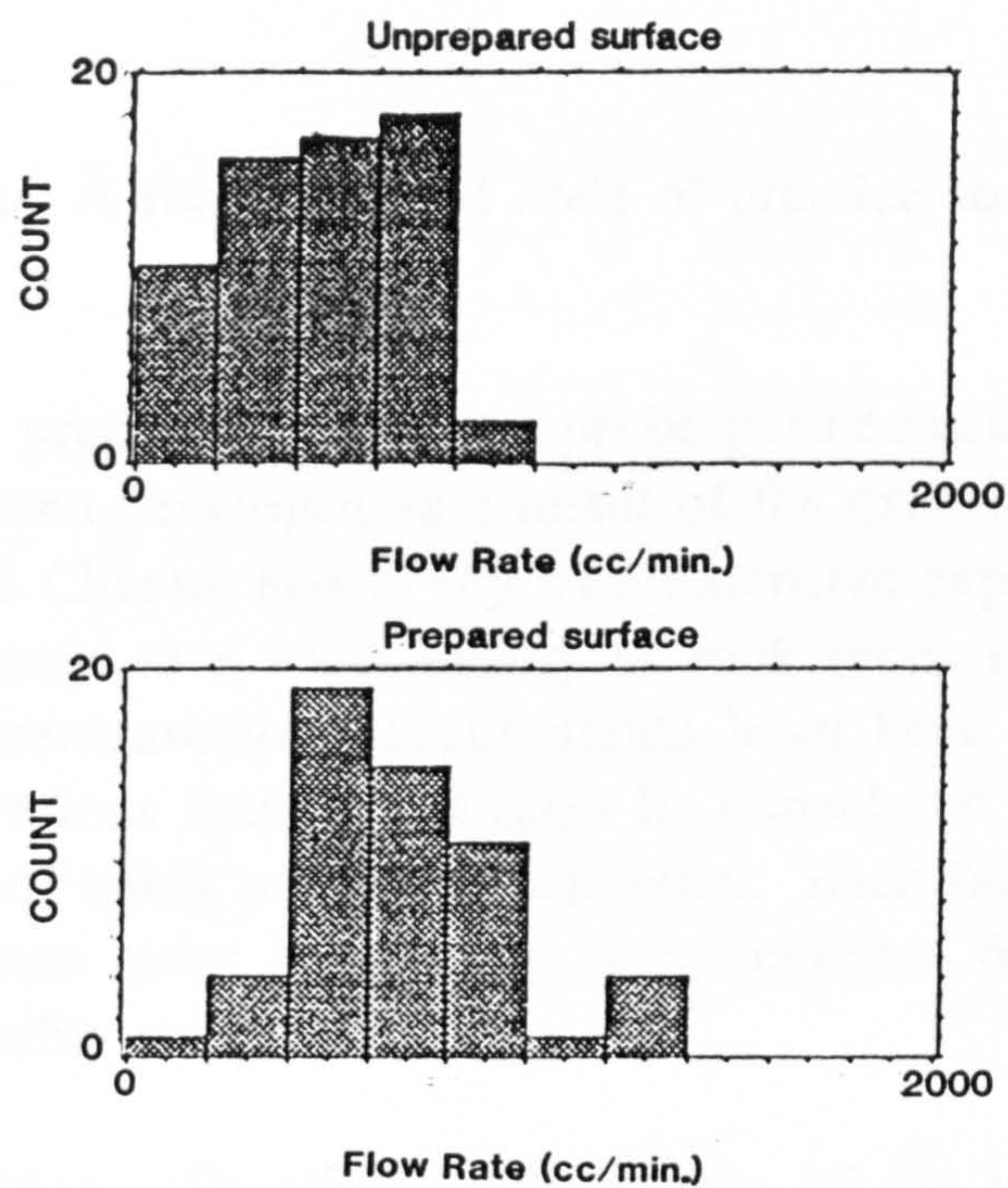


Figure 4.21 Gas flow rate measured on an unprepared and prepared rock surface

found to be remarkably successful for a variety of rock types.

The action of drilling does not appear to deform the sediment structure. A drill diameter of 8 cm was used on the White Sandstone as this was found to leave a sample area that was easily accessible without placing the probe seal against the margins of the cored area. Depending on the friability of the rock, the core plug produced by this process may be retained for further analysis. The face preparation technique described is very destructive and impact on the outcrop from a conservation point of view should be considered. In some cases it may be necessary to replace the plugs into the holes to minimise damage to the outcrop.

To demonstrate the effectiveness of this face preparation technique, a sample grid, containing 56 sample points was placed on an unprepared sandstone surface exposed in an underground sand mine where silica dust and diesel fumes were visible on the rock face. probe permeameter measurements were first made on the unprepared surface which was then prepared by drilling out the outer 2 to 3 cm of rock. Whilst the unprepared and prepared sample points are not in exactly the same position, the average of the grid values provides a good estimate of the difference between flow rates measured on each surface. The difference in permeability values (Figures 4.21 and 4.22), shows the population of unprepared surface data to have a narrower permeability range, a large positive skew (abundance of low flow rates), a lower arithmetic mean, and a conspicuous absence of high permeability values. It was concluded from this that face preparation was necessary and the technique used was appropriate.



X1: Unprepared Surface					
Mean:	Std. Dev.:	Std. Error:	Variance:	Coef. Var.:	Count:
454.429	228.518	30.537	52220.686	50.287	56
Minimum:	Maximum:	Range:	Sum:	Sum Squared:	# Missing:
36	869	833	25448	14436436	0
Kurtosis:	Skewness:				
-.981	-.112				

X2: Prepared Surface					
Mean:	Std. Dev.:	Std. Error:	Variance:	Coef. Var.:	Count:
702.125	321.499	42.962	103361.493	45.789	56
Minimum:	Maximum:	Range:	Sum:	Sum Squared:	# Missing:
187	2138	1951	39319	33291735	0
Kurtosis:	Skewness:				
5.54	1.781				

Figure 4.22 Frequency histograms and descriptive statistics for gas flow rates measured on unprepared and prepared rock surfaces

4.5 Conclusions: A recommended code of practice for outcrop probe permeametry

A new code of practice for outcrop probe permeametry is proposed. This code has been developed as a result of the experimental analysis presented in this Chapter and of my own extensive experience in field probe permeametry on a wide variety of rock types for which some 20,000 probe permeameter measurements have been made. Listed below are the various factors that must be considered in any outcrop permeability study using probe permeameters. Each factor is arranged in the approximate order in which it is encountered during a typical outcrop permeability study.

1) Rock condition. Examine the condition of the rock surface to determine the extent and effect of weathering and fines. Freshly fractured surfaces should be examined in the field to provide comparison with exposed and fresh surfaces. Core plugs should then be taken normal to the rock surface, incorporating the exposed surface. Repeated permeability measures are then made on each core plug over the entire length, then on cut sections of the plug. In this way, the permeability of the exposed rock can be estimated and compared to the permeability of the unexposed rock. Thin sections may also be made from the sectioned plugs to visually examine the rock in more detail. Having determined the depth of surface modification, all probe permeameter measurements should be made at this depth.

2) Face preparation. The use of a hollow core drill allows the modified rock surface to be removed without forcing fines into the pore spaces. In consolidated rocks, a core plug may also be produced which can be retained for other analyses, bearing in mind that this plug will contain modified rock from the exposed surface. After chipping out the core plug, a fresh surface will be produced, the orientation of which depends on the requirements of the study, and can be largely determined by orientating the drill itself. This surface should be examined for surface roughness, fractures, and water saturation. Evidence of new plant roots and staining are good indications of fracturing.

3) Application pressure. As the dimensions of the probe seal can change under pressure, influencing the measured flow rate, it is important to maintain consistency in the probe dimensions between measurements. This can be investigated by practical experiment at the outcrop to determine the maximum application pressure required to effect a seal over the range of surface qualities presented. The probe dimensions under this application pressure should then be measured and this application pressure used for all permeability measurements at the outcrop. This is particularly important for probes with small I.D. and rocks with small permeability contrasts. Changes in the seal dimensions caused by varying the probe application pressure probably represent the greatest source of error associated with hand-held probe permeameters.

4) Seal shape. Changing the orientation of the probe relative to the rock surface can result in distortions in the seal shape which in turn can influence the permeability measurement. It is important to keep the probe orientation constant for all measurements to ensure that the seal shape remains the same.

5) Seal dimensions. To allow direct correlation between permeability values without scaling up, the seal dimensions used should be kept constant. In theory, changing the seal dimensions changes the volume of rock for which permeability is estimated. In heterogeneous rocks therefore, comparisons between permeabilities estimated using different probe dimensions are invalid without appropriate scaling. To allow comparison between permeability data obtained from different outcrop studies, standard seal dimensions should be used, just as standard core plug sizes are also used. Thus, for each outcrop study a reference data set should be obtained at a specific sample interval and within a broadly recognisable geological feature.

6) Water saturation. Water saturation within the outcrop reduces the measured gas flow rate producing a measure of relative permeability that, after stabilisation, represents the permeability at or near irreducible water saturation. An approximate calibration from flow rate to absolute permeability can be made by collecting samples of rock from the outcrop for which gas flow rates have been measured under outcrop conditions. These samples are then dried and the gas flow rates

remeasured. Outcrop flow rates are then converted to dry rock flow rates using a best-fit line obtained from a cross-plot between outcrop measurements and dried rock measurements. These dry rock flow rates are then converted to absolute permeability using the appropriate calibration.

The error associated with this technique will probably be acceptable providing; a) the dried outcrop samples are representative of the variation in water saturation over the entire outcrop sample area, and b) the variation in water saturation is not too great. If the water saturation is suspected to be very variable (and possibly stratified, such as where the sample area crosses the water table) then a separate calibration for dry rock flow rates should be determined for selected ranges of water saturation.

Monitoring the stabilisation time of measurements at outcrop is important as this provides an in-situ indication of the water saturation. As it may be necessary to measure the water saturation of rock samples, these samples should be sealed immediately after they are collected. Consideration should also be given to the effects of drying, especially where clay minerals are present.

7) Fines. The presence of mobile fines within the rock may increase stabilisation times and reduce the measured flow rates, in much the same way as water saturation. Monitoring the stabilisation time of the probe permeameter flow rates is an important part of probe permeameter studies because the presence of fines will be indicated. Differentiating between the effects of water saturation and fines can be achieved by monitoring the stabilisation times for flow rates measured on dried samples. This technique is suitable providing the fines are not modified when the rock is dried, and the presence of clay minerals should be determined beforehand.

As it is difficult to correct for reduced permeability caused by mobile fines, the best solution to this problem is to use a low injection pressure with a short stabilisation time, thereby minimising the movement of fines. Gas slippage effects should also be considered in cases where very low pressure differentials are used.

8) Temperature. The temperature of the gas passing through the laminar flow elements should be measured at intervals to calculate the effect this has on the viscosity. Measured flow rates should then be temperature corrected prior to calibration and analysis through the use of a simple instrumental correction. The variation in temperature and viscosity of the injected gas within the rock itself is negligible and can be safely ignored.

CHAPTER 5 Sampling permeability at outcrop

5.1 Introduction

Having established how to obtain permeability measurements at outcrop using the probe permeameter, the selection of a sampling scheme is discussed. First, the requirements for outcrop selection are defined. Having chosen the outcrop, the geological structure is used to rationalise the sampling schemes. Various sampling schemes are described with statistical tests for estimating sample error and efficiency. Examples are then given of permeability data collected from outcrops with different lithologies. Finally, the limitations of the sample schemes are discussed.

5.2 Selecting the outcrop

The first stage in designing the permeability sampling scheme involves selection of the outcrop itself. A practical starting point is to confine the sampling schemes to rocks from specific depositional environments. Having targeted the depositional environment, a field study is then conducted to identify those outcrops with characteristic facies types.

There is a clear distinction between outcrops used as reservoir analogues and outcrops used to characterise specific depositional environments. In the former case, outcrop selection may be based on a variety of criteria peculiar to the reservoir, such as diagenetic doggers or bioturbated shales, for which an outcrop permeability study may provide a unique solution to that particular reservoir only. In the latter case, rock outcrops are selected as examples of specific depositional environments. These are used to build data bases and to develop generalised models that are applicable to reservoirs comprised of that rock type. Ultimately, permeability data bases should be available for each type of depositional environment. It is the development of these data bases that is the concern of this study.

Once potential outcrops have been found, practical consideration must then be given to the problems and limitations of sampling. To determine whether an outcrop is suitable for a permeability study involves consideration of the following factors:-

1) *Consolidated and unconsolidated rocks.* The consolidation of the rock will determine how the permeability measurement is made. Consolidated rocks allow samples to be measured on core plugs and through the use of probe permeametry. As these rocks cannot be excavated easily, sampling is invariably governed by the available exposure. Unconsolidated rocks on the other hand may be easily excavated to produce the required rock faces.

Consolidated rocks may be sampled for permeability using both core plugs and probe permeametry. The probe permeameter is also an ideal device for measuring permeability on unconsolidated sandstones that are too friable for sampling through the use of conventional core plugs. In addition, the probe permeameter provides a non-destructive measurement of permeability that causes minimal deformation of the grain fabric. In some cases, the permeability of unconsolidated sediments may be beyond the current measurable range of the probe permeameter. An alternative method of measuring the permeability of these sediments is to collect samples of the sediment in tubes with permeability measured using a constant head-falling permeameter (Pryor 1973). Obviously, care must be taken to avoid deformation of the grain fabric when the tube is pushed into the sediment.

2) *The dimensions of the outcrop.* The dimensions of the outcrop should be such that permeabilities can be sampled over realistic interwell distances. The vertical dimension is also important as the data from wells provides information on permeabilities in this direction. Two-dimensional sampling schemes allow comparisons to be made between the spatial variation in permeability measured in different directions. In particular, the observed relationship between permeability variations measured in the vertical direction (relative to modern sea level) and the horizontal direction (relative to some depositional datum) is an important one. This is because there is a need to obtain accurate predictions of permeability in the interwell area.

- 3) *The orientation of samples.* Permeability samples should be orientated relative to a depositional datum (for example, a shale marker bed) to allow portability of the outcrop-based permeability model to the reservoir.
- 4) *Access to the outcrop.* The outcrop should offer unrestricted access to the rock face to minimise bias in the sampling.
- 5) *Outcrop geology.* The geology at outcrop should be well-defined to avoid ambiguities in the interpretation of the depositional environment. For application to the hydrocarbon reservoir the geological interpretation of the outcrop used to obtain the permeability data base must be reliable so that selection of the appropriate outcrop data base is dependent only on the geological interpretation of the reservoir. A solution to this problem is to measure permeability variations within sediments preserved in modern depositional environments in which the processes of deposition are still active or reliably inferred from neighbouring processes. However, modern depositional environments present their own problems for permeability studies. Extensive (and expensive) excavation may be required to obtain suitably sized and orientated sample domains and water saturation may be a serious problem when excavating and sampling from sediments deposited near the water table.
- 6) *Diagenesis and compaction.* Permeability heterogeneities within the outcrop should be attributable to primary rock heterogeneities (heterogeneities associated with depositional features). Permeability heterogeneities may also due to post-depositional processes such as diagenesis, compaction, igneous activity and tectonic deformation and these should be noted, and quantified, where possible. These are termed secondary rock heterogeneities. Clearly, separating permeability heterogeneities due to primary and secondary rock heterogeneities is very difficult and outcrops with minimum post-depositional modification should be sought.

Modern depositional environments are appealing because of the minimal post-depositional modification associated with these sediments. Within

ancient sediments however, diagenetic processes are often governed by primary depositional heterogeneities (Lewis 1987) and outcrop rocks with obvious diagenetic modification may still be suitable for permeability studies.

5.3 Sampling within the outcrop: utilisation of the geological structure

Whether or not a sample will give results that are representative of the whole aggregate depends primarily on whether the errors introduced by the sampling process are sufficiently small not to invalidate the results for the purposes for which they are required. Even if a proper process of selection is employed however, the sample cannot be exactly representative of the whole aggregate. The inevitable errors which then occur are called the random sampling errors of these results. The average magnitude of these random sampling errors depends on the following: the size of the sample, the variability of the material, and the sampling procedure.

Given the high variability and uncertainty in the prediction of point permeability values of natural porous media (rocks), exhaustive sampling would appear to be the only sampling strategy that will ensure that all possible outcomes are represented. In practice, this means that permeability measurements are arranged such that each sample volume touches its neighbour but does not overlap. In reality, exhaustive sampling is very time consuming and costly, especially in those outcrop permeability studies that attempt to sample areas equivalent to interwell areas (10's of metres vertically x 100's of metres horizontally). It is necessary therefore, to utilise the most efficient sample scheme with minimal effort and time.

Faced with the geological complexity of the outcrop, attempting to short cut exhaustive sampling yet end up with the same results might at first appear to be a daunting task. However, assuming that the statistical distributions and spatial disposition of permeabilities are a function of the sedimentary facies and depositional environment, the geological structure provides a convenient framework on which to rationalise the sampling schemes. As there is reasonable evidence to suggest that the

scales of depositional heterogeneities are arranged hierarchically, permeability sampling can be arranged to target each scale. With decreasing scale, there will be a greater number of heterogeneities. The sample scheme therefore, must obtain weighting for the sub-sampled areas proportional to their area or frequency of occurrence.

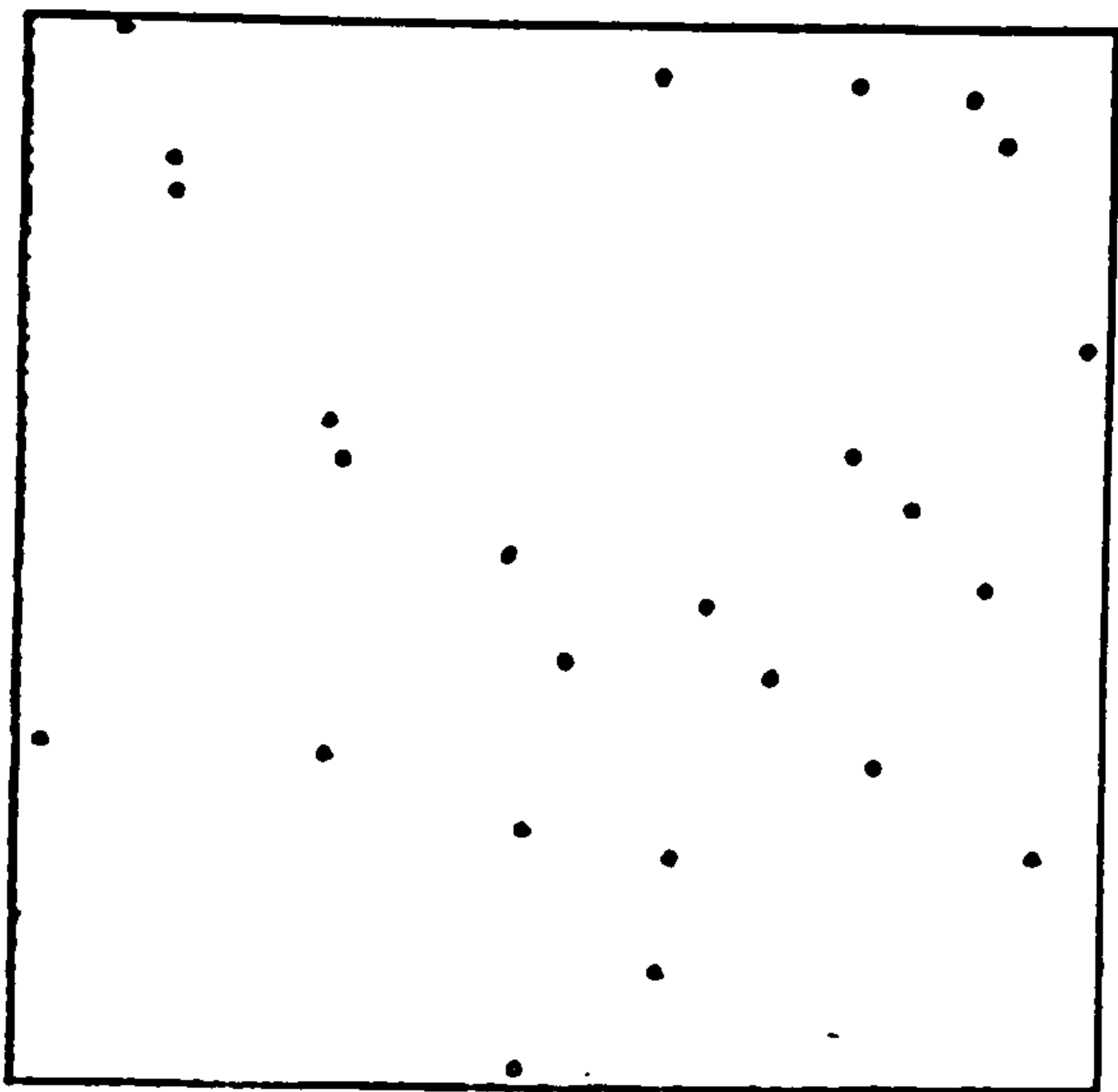
5.4 Sampling schemes

The majority of sampling schemes adopted in previous outcrop permeability studies have been based on transects and grids. Sample transects have been used specifically to identify spatial permeability variation. Vertical transects allow direct comparisons to be made with conventional vertical well data. Horizontal transects are used to quantify long-range correlation lengths for predictions of permeability away from the cored interval. Horizontal transects also allow direct comparisons with horizontal well data which will become more abundant as horizontal drilling technology improves. Sample grids have been used to quantify the spatial permeability structure in two-dimensions and to obtain statistical permeability distributions (pdf's).

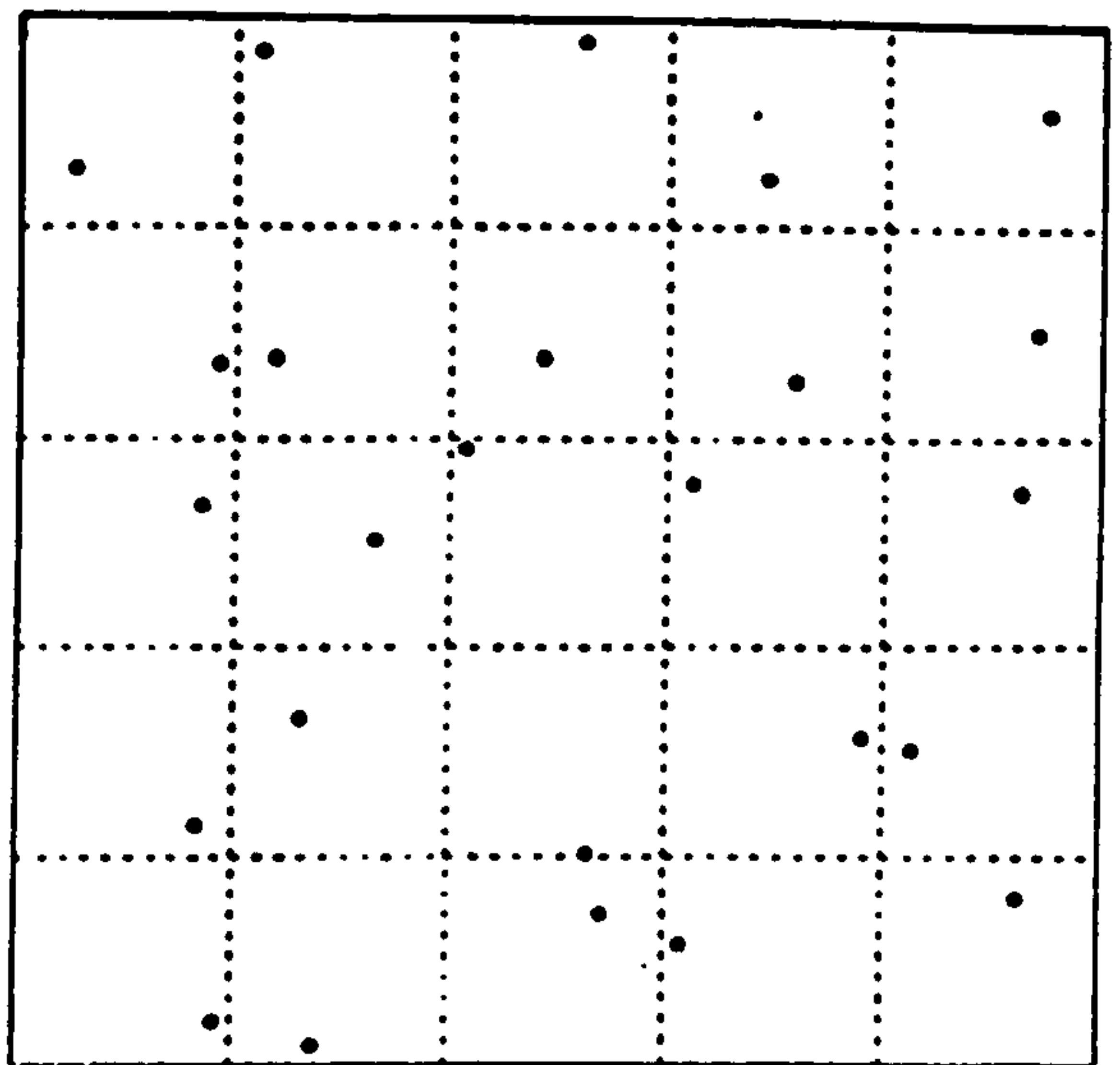
There are specific statistical terms used to describe each sample scheme (Yates 1981, Ripley 1981) and since the chosen sampling scheme can have a significant effect on the validity and interpretation of results it is important to define the sampling scheme correctly. There is a wide range of sampling schemes for spatial variables, but those presented here refer specifically to those schemes appropriate for outcrop permeability studies. These sampling schemes can be divided into two types: random and stratified.

The simplest type of rigorously selected sample is uniform random sampling (Figure 5.1a) and is used in most of the more complex sampling methods. The process of random sampling requires the generation of random numbers which are used to assign coordinates to the sample position. All positions within the sample domain carry equal probability. The number of samples depends on the required accuracy - the greater the accuracy, the greater the number of samples.

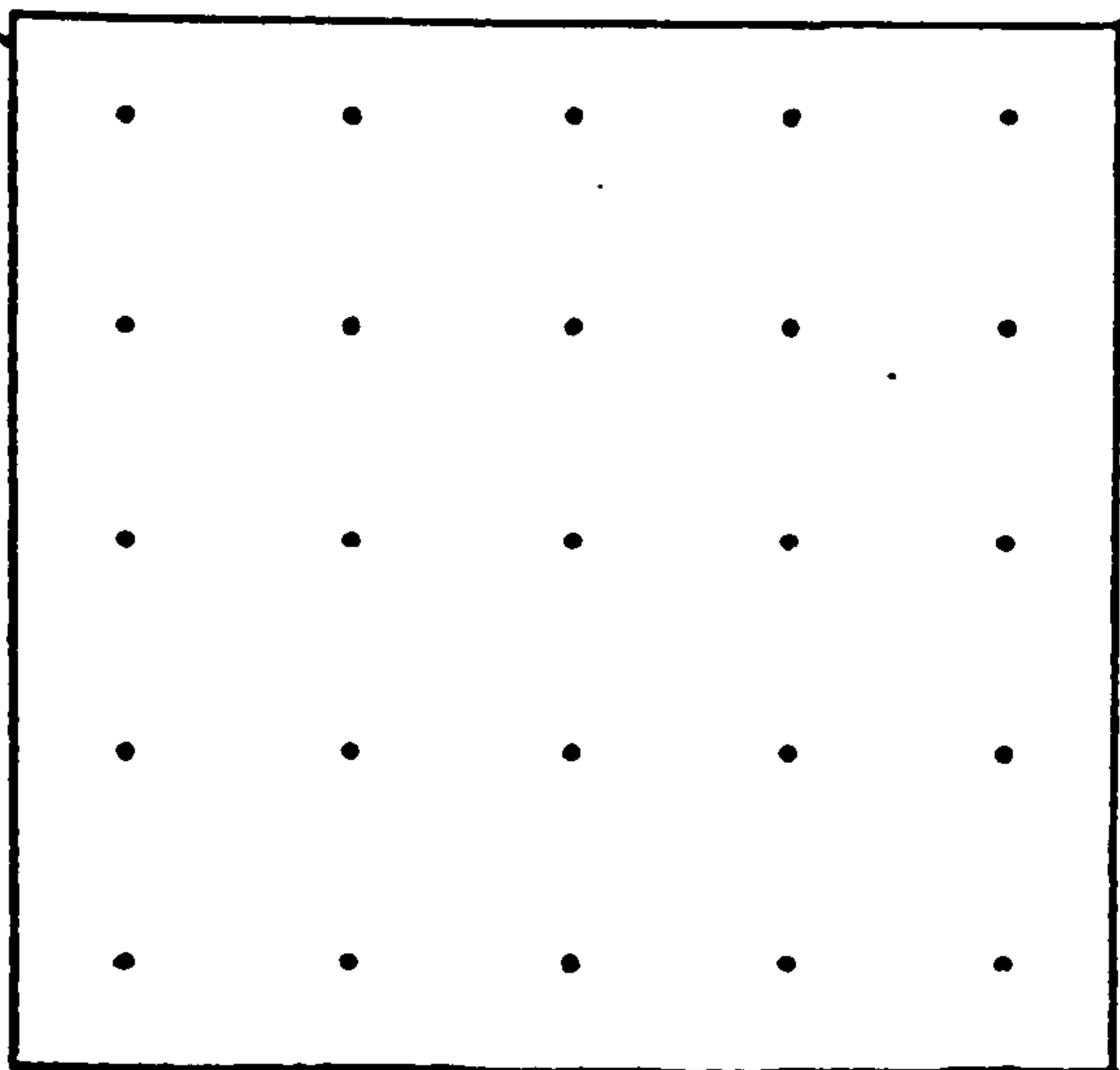
A



B



C



D

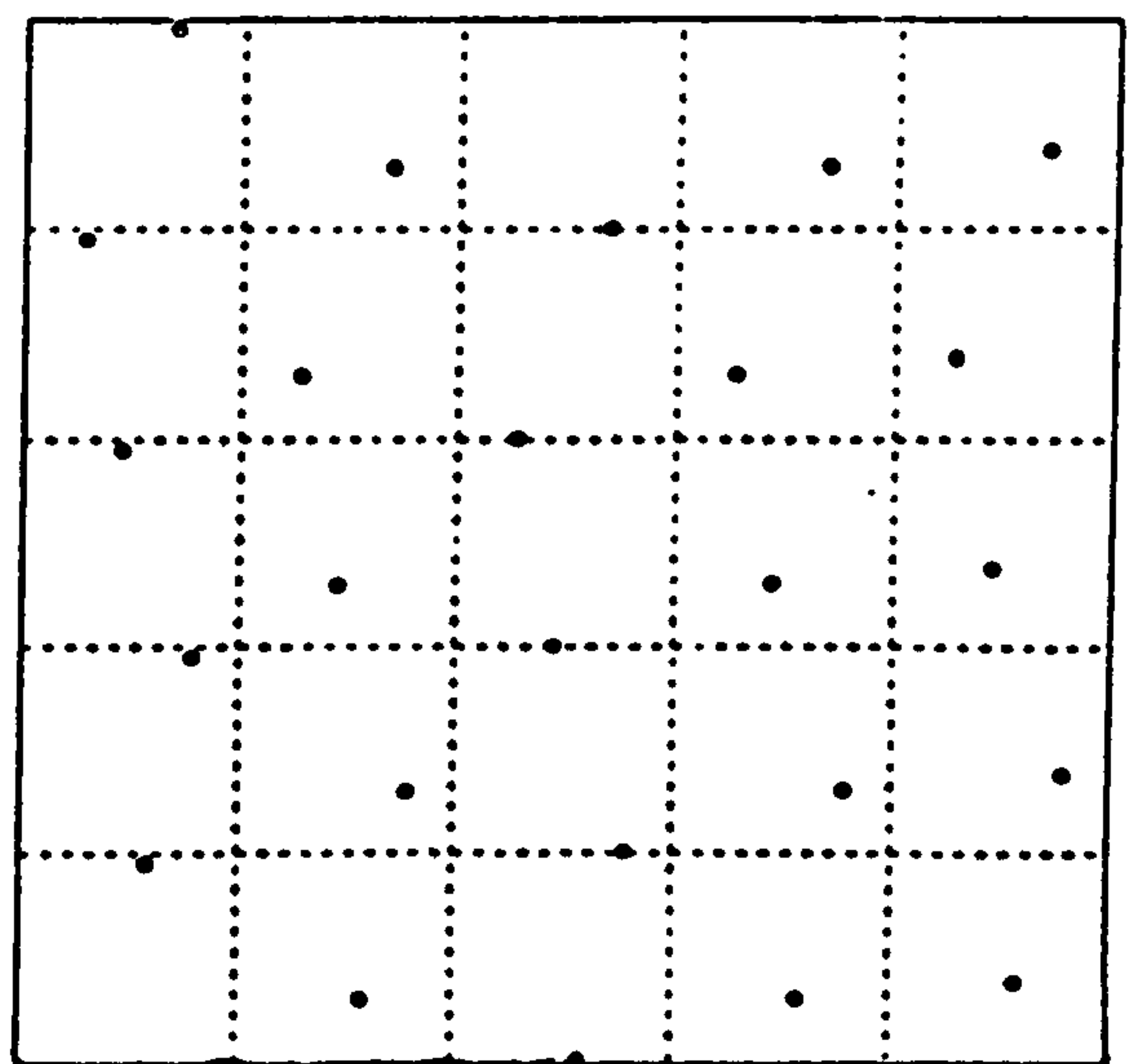


Figure 5.1 Sampling Schemes: a) Uniform random, b) Stratified random, c) Stratified systematic centric, d) Stratified systematic unaligned

Where the domain is divided into areas or strata before selection of the samples this is termed stratified sampling. Square strata are often used but is not necessary. If the position of an equal number of samples from each of n strata are selected randomly with all positions within each strata carrying equal probability this is termed stratified random sampling (Figure 5.1b). If however, samples are taken from the centre of each grid this is termed stratified systematic centric sampling (Figure 5.1c) and is often referred to as 'regular grid' sampling where the strata are equal area squares (Goggin 1986, Lewis 1987). As long as the position of the sample within each strata is constant, it does not have to be centric and the starting position within each row may be randomised. Randomisation may be necessary if there is the possibility that the sample spacing coincides with the correlation structure. In this case the sampling scheme is called stratified systematic aligned. Where the sample positions within the strata are arranged such that they are unaligned in all directions (rows and columns) this is termed stratified systematic unaligned sampling (Figure 5.1d). The unaligned positions of samples are obtained from a randomised selection of position for the first row or column. For the adjacent rows or columns, this randomized sequence of sample locations is repeated but with a new randomized start position.

Transect sampling is essentially a form of 1-D stratified systematic sampling. If the sample interval is kept constant then this is a 1-D stratified systematic centric sampling scheme (Figure 5.2a). If the sample interval changes along the transect (Figure 5.2b) then consideration must be given to the position along the sample transect at which the sample interval changes and the reduction in the sample interval. The sampling scheme is still called stratified because the area of each strata need not change, but the number of samples and therefore, the position of samples within the strata may change. As samples are restricted to lines, the domain lengths can be very great, even for high sample densities, and domain lengths equivalent to interwell distances up to several kilometres are feasible.

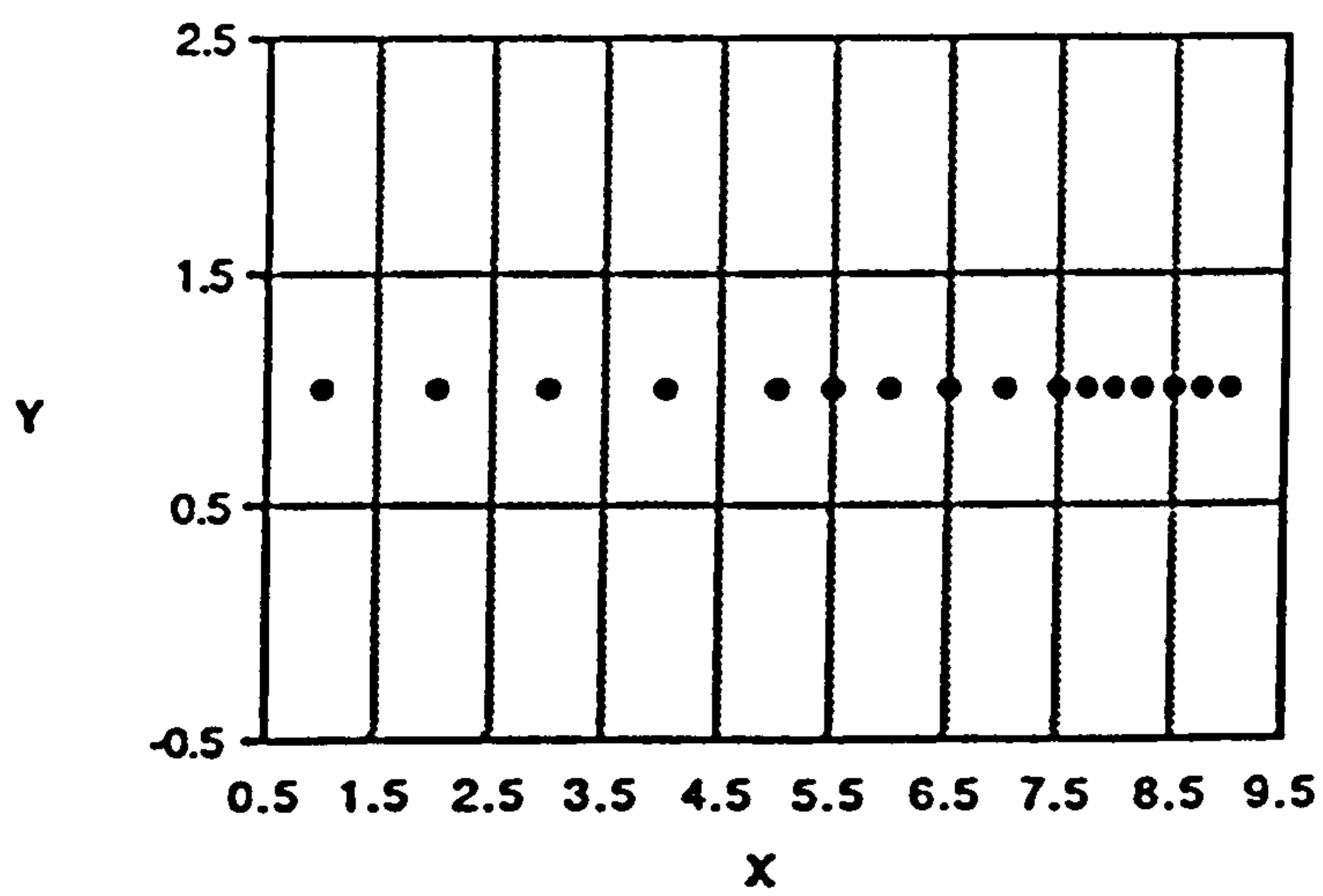
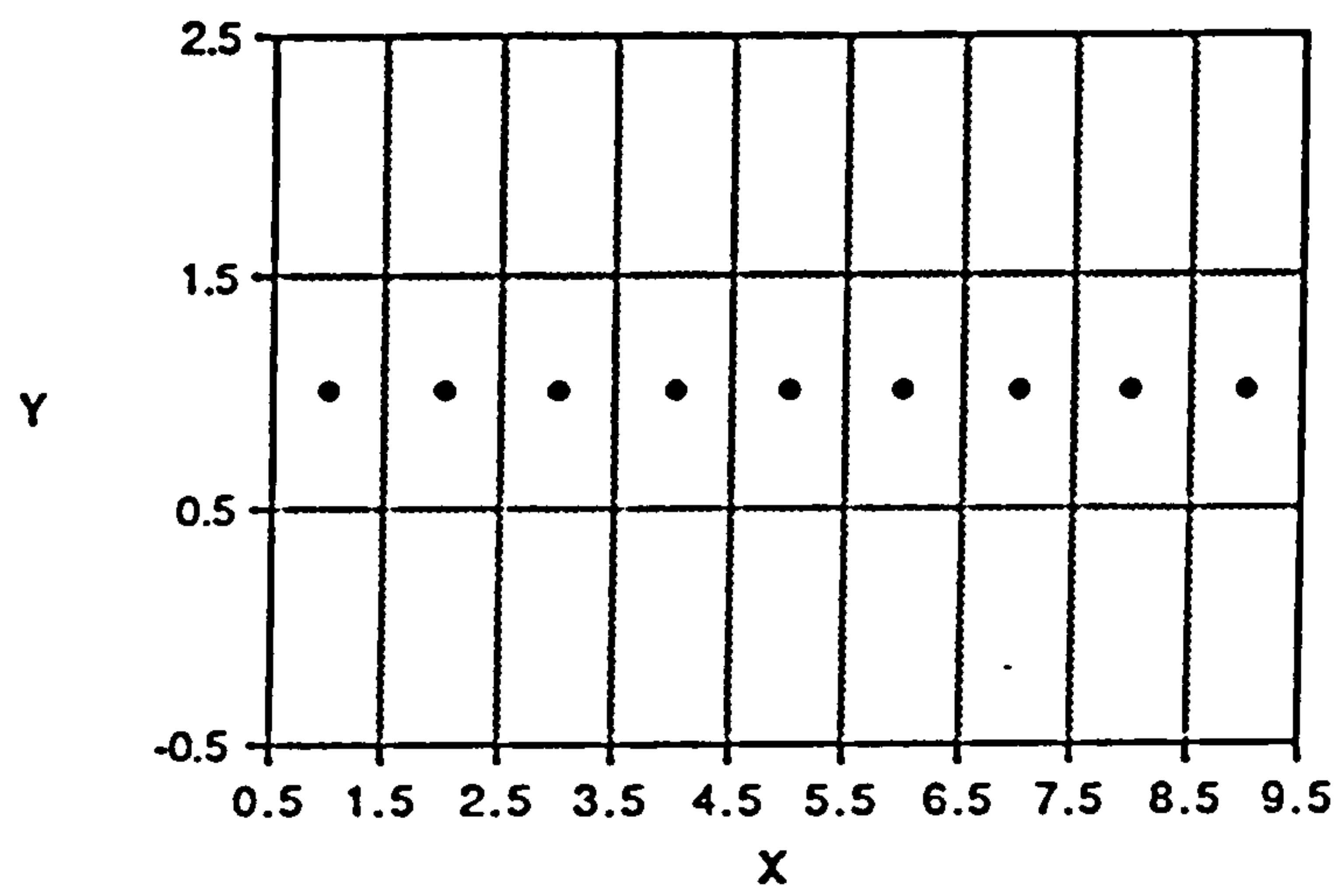


Figure 5.2 Two different types of transect sampling (1-D stratified systematic sampling)

5.5 Definition of support, domain and scale

There are a number of sampling terms that are often used to describe outcrop permeability sampling techniques that are frequently misused. These terms include the sample 'support', the sample 'domain', and the sample 'scale'.

The sample volume or support is very important when sampling for permeability because an increase in the size of the support usually reduces the variance (the 'support effect' in geostatistics - at and below the scale of the R.E.V.). Because of the support effect, it is important that a constant support size is maintained for samples that are to be grouped or correlated. Where permeabilities are measured using varying support sizes, for example, on core plugs and through probe permeametry, the appropriate scaling relationship should be used before comparing or combining the values. This scaling relationship may be obtained by experimental analysis (through the use of different sized Hassler Cells for example), numerical analysis (through the use of stream tubes or the renormalisation technique for example), geostatistical analysis (through the use of the volume:variance relationship) or conventional statistical methods (through the use of arithmetic, geometric and harmonic averages).

The chosen support size depends on the scale of heterogeneity required for investigation. The smallest scale of permeability heterogeneity - the intra or inter-grain scale - can be measured using probe permeameters with small seal dimensions. By increasing the internal injection aperture, larger scale heterogeneities (for example, those associated with individual laminae) may be sampled. The volume of rock contained within a 1" core plug may incorporate several laminae providing a measure of permeability for a larger scale of heterogeneity again (Haldorsen's macroscopic scale). Permeabilities for even larger scales of heterogeneity may be measured using whole core analysis and borehole flooding techniques (Weber et al 1972).

The orientation of the sample is important for incorporation of permeability anisotropy at the scale of the support. Samples can be orientated either locally (for example, the alignment of core plugs parallel to the strike of each individual foreset) or regionally (for

example, the alignment of core plugs parallel to the average foreset strike of the coset). Orientation of the probe permeameter probe is based on the assumption that a tensor for the permeability value lies parallel to the probe. If the tensors of the permeability measurement provided by the probe permeameter are unknown (that is, the injected gas follows a path of least resistance independent of probe orientation), then the orientation of the sample is unimportant.

The sample domain is the length, area, or volume that bounds the samples. Increasing the domain size but retaining the same number of samples will reduce the sample density. For the appropriate weighting of sub-sampled areas, the sample interval should remain constant irrespective of domain size, providing there are sufficient samples for statistical reliability. Thus an increase in domain size will result in an increase in the sample number proportional to the domain size.

In outcrop studies, the orientation of the sample domain is usually determined by the outcrop faces, unless the rock is soft enough to allow faces to be scraped into the desired orientation. To facilitate portability of outcrop-derived permeability data to the reservoir, it is essential that the sample domain(s) are aligned relative to the regional orientation of the sand body and a reliable depositional datum such as an unconformity, continuous shale, hardground surface, or volcanic marker bed should be sought. Where identified, sample domains can also be orientated in relation to the sequence stratigraphy (sea level changes).

In permeability studies, the term 'sample scale' can refer to three different descriptions of the measurement. These are: the volume of the support (which actually refers to the resolution of the sample), the size of the domain (which refers to the window of observation), and the length of the sample interval. These terms are easy to confuse but have very different meanings. When permeability sampling is described as 'large scale', this usually refers to permeabilities sampled over a large domain with a constant support size and constant, or variable, sample interval. However, the term 'large scale' could also imply that a large support size was used. This confusion of the scale term is further

exemplified when compared to its use in cartography. A 'large scale' map is one that contains more detail, that is, the resolution is increased where, for example, pathways and fences are shown. A 'small scale' map on the other hand is one that contains less detail, that is, the resolution is decreased where, for example, only large cities are shown. Generally, small scale maps are used to show variations over large areas on a sheet of paper that is a physically manageable size (for example, a map of the world). This use of the scale term in cartography therefore, contradicts the use of the scale term in some published outcrop permeability studies. By the definition given above, 'small scale' permeability maps should display less detail and be used to show permeability variations over large areas. Conversely, 'large scale' permeability maps should display greater detail and be used to show permeability variations over small areas. The scale term therefore should refer to the sample support size; 'small scale' = 'small support'.

5.6 Evaluating sample error and efficiency in outcrop permeability sampling schemes

The central limit theorem allows us to claim that the estimates of statistics from a group of samples are normally distributed. For an uncorrelated variable, the standard error of the estimate of the mean of a large population from a random sample is inversely proportional to the square root of the number of units, n, in the sample, s (Yates 1981), where,

S.E. (estimate) = (1/sqrt n)*s(25)

In other words, if the samples are unbiased (or independent), the more samples used, the better the estimate of the true median.

In an attempt to determine how many permeability samples are required on core, Hurst and Rosvoll (1991) applied this result and developed the N-Zero statistic which can be used to determine the optimal number of samples required to approximate the true population. To estimate how many measurements are needed (N0) from a sample of a known number of observations (Nx), the following routine is applied:

$$N_0 = ((2 \cdot C_v \cdot 100) / p)^2 \quad \text{.....(26)}$$

where C_v is the coefficient of variance of the sample population and

$$C_v = S / K_{av}$$

where S and K_{av} are the standard deviation and arithmetic average of the sample population respectively.

With the optimal sample number (N_0) known, the optimal sample interval (D_s) may be obtained from

$$D_s (m) = (N_x / N_0) * \text{sample interval (m)} \quad \text{.....(27)}$$

The suitability of the N-Zero test for estimation of the optimal sample density for an uncorrelated data set is easily demonstrated. Consider a regular profile of 100 measurements, representing a normalised random distribution (Figure 5.3). A graph of the mean of sub-sampled data from this parent population plotted against the sample number shows the spread in the mean decreasing as the sample number increases (Figure 5.4). Assuming the mean of the 100 sample points is the true average, then taking a tolerance level of 10% deviation from this mean, the optimal sample number can be estimated. For the data given, with a mean of 4.6 and a standard deviation of 1.04, the optimal sample number is approximately 22. For a tolerance level (p) of 10%, the N-Zero test returns an optimal sample number (N_0) of 21, which is very close to the value of 22 obtained from the graph. Thus, the N-Zero test is shown to be an effective method for estimating the optimal sample number.

Permeability data that are spatially correlated cannot be treated as independent and the N-Zero test is an inappropriate statistic for these data. However, the significance of this assumption of independence in the N-Zero test can be reduced by subdividing the permeability data set into populations representing sub-regions within which the permeability data are assumed to be independent (that is, random or 'heterogeneously homogeneous'). After geological examination the outcrop is divided

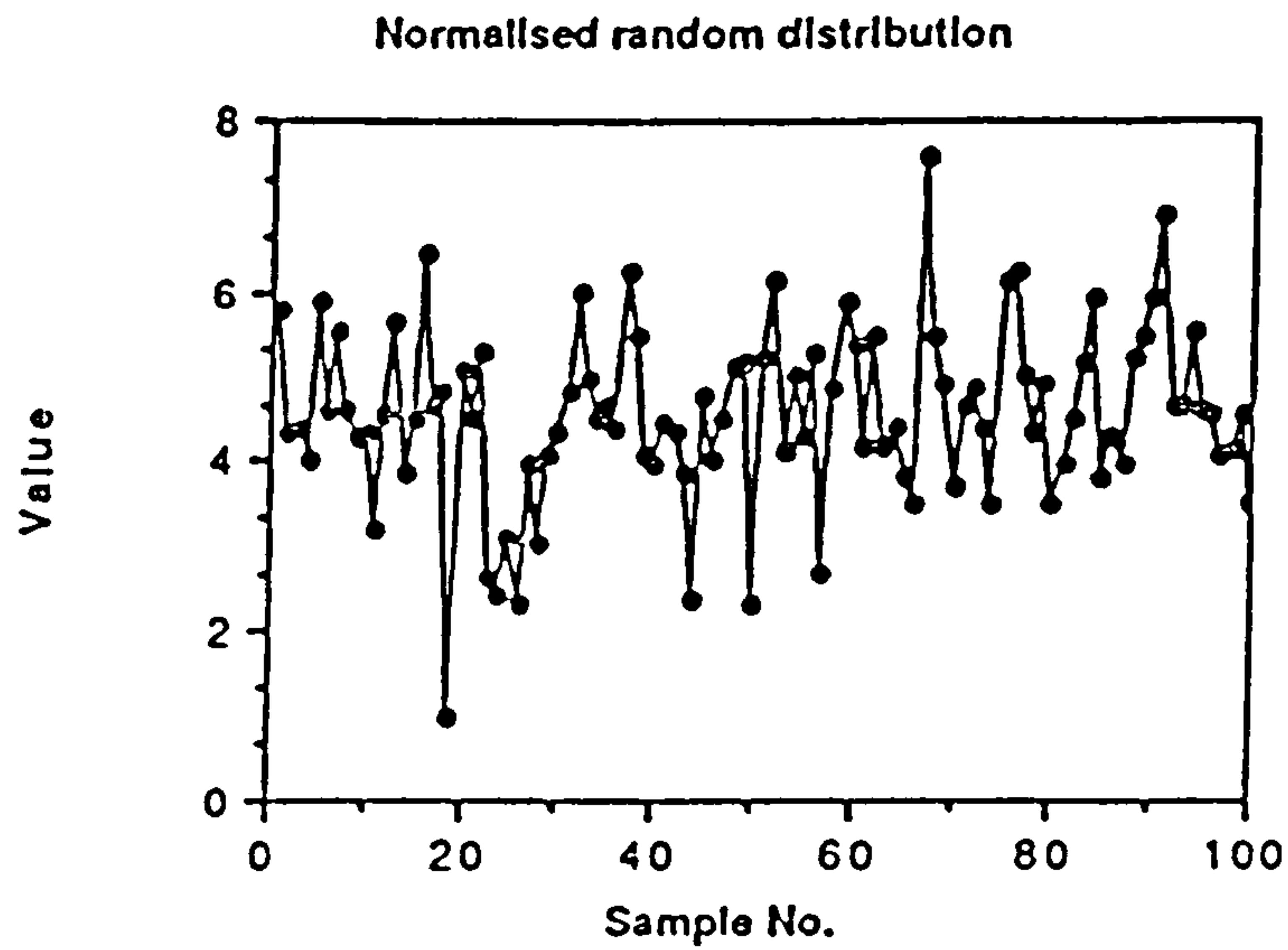


Figure 5.3 A single profile of random values with a normalised random distribution

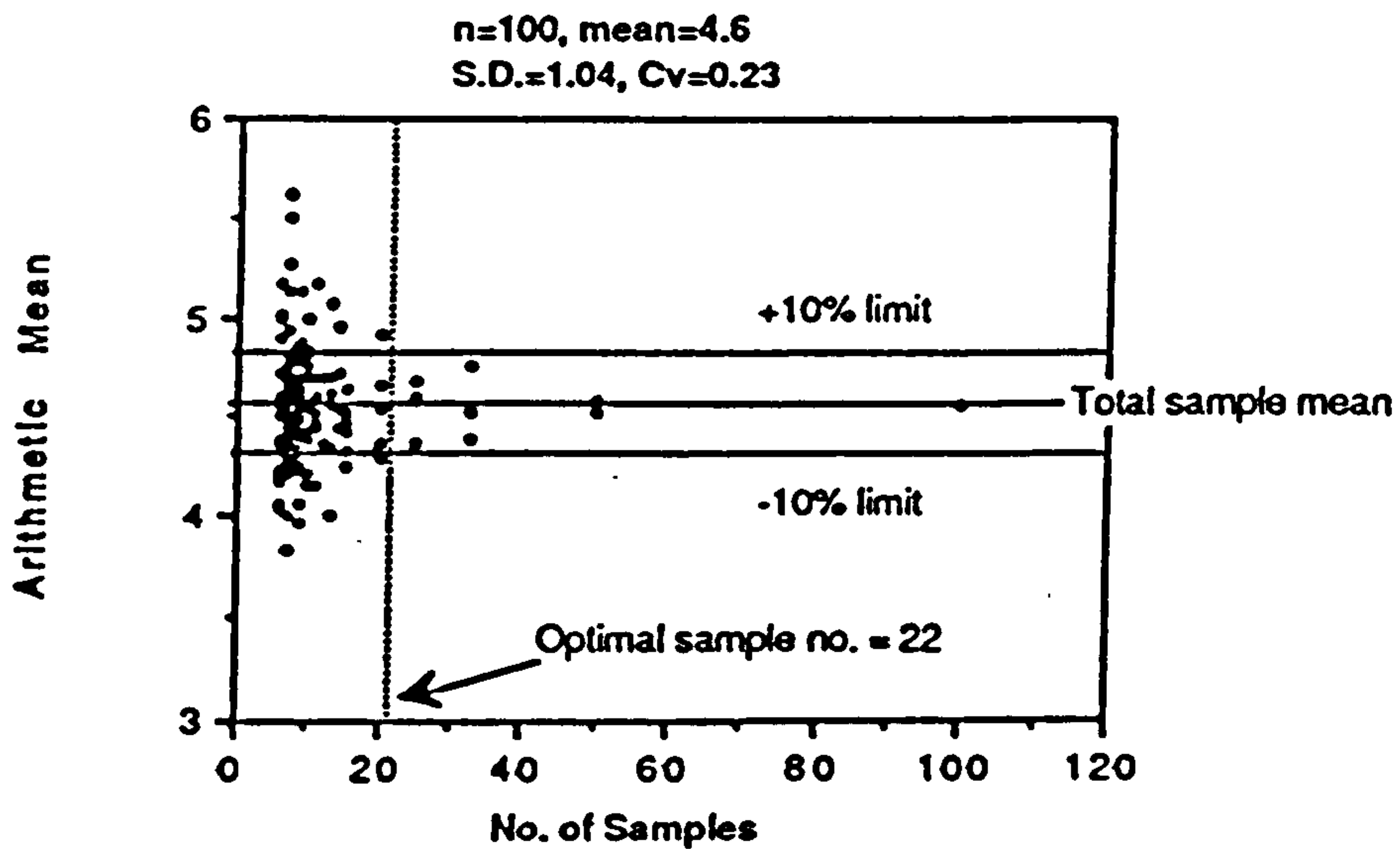


Figure 5.4 Difference from the 'true' population mean with increased sample size. The sample data are shown in figure 5.3.

into sub-regions corresponding to different scales of depositional heterogeneity, for example, coarsening-up sequences, cross-bedded units, and laminae type. The N-Zero test is then applied to each of these sub-regions. All that is required is some measure of the ability of the sample scheme to reproduce the correct sample weights for each sub-region. This method of subdividing the outcrop into regions is demonstrated in the case studies at the end of this Chapter.

In an evaluation of sampling strategies for gravels on a river bar, Wolcott and Church (1991) found that systematic unaligned sampling provided the most efficient sample scheme. Efficiency is defined as the correct sample weight for a given level of effort. They concluded that systematic unaligned sampling performed better than grid sampling (equivalent to stratified systematic centric sampling), but the advantage in ease of navigation for sample location in the latter technique outweighed the performance differences. The use of grid sampling is also convenient because it provides more reliable data for geostatistical analysis. This evaluation of sampling techniques was made using the chi square test and sum of squared deviations, calculated as:

$$\chi^2 = \sum_{i=1}^n \left(\frac{OBS_i - EXP_i}{EXP_i} \right)^2$$

Where OBS_i = No. points falling in the i^{th} facies

EXP_i = Expected no. points based on of the total area occupied by that facies multiplied by the total number of points

.....(28)

and,

$$\text{Sum of Squared Deviations} = \sum_{i=1}^m (x_i - p_i)^2$$

Where m = No. of classes

x_i = Percentage of points occuring in each class

p_i = Actual percentage of total area occupied by the i^{th} class

.....(29)

Using the assumption that the grid sampling strategy will automatically

sample the subareas weighted according to their area, grid sampling can be adopted as a standard sampling technique for permeability at outcrop. It should be noted however, that a limitation of the grid approach is that the objects sampled must not be arranged in an orderly manner which might correspond to the grid spacing. In general, the disposition of permeability data within rocks measured using the probe permeameter or on core plugs is sufficiently irregular for this problem to be avoided, but where there is a periodic distribution of permeability values care should be taken when choosing the sample interval.

Applying the concept of genetic depositional units, the following approach for permeability sampling at outcrop (illustrated in the flow diagram in Figure 5.5) is described:

The outcrop is first described in detail and visible depositional structures corresponding to the various scales of depositional heterogeneity are mapped out. These depositional structures may include facies types, cross-bedded units, bounding surfaces, laminae types and so on. Detailed photographs taken at different scales provide a convenient method of mapping, providing distortion effects are accounted for.

In the first instance, permeability measurements are made over the entire outcrop (or predefined region within the outcrop) on a grid with an arbitrary sample interval. In the studies by Wolcott and Church (1991), the sampling results stabilised at $n=100$, and a sample interval that provides 100 samples is probably sufficient for this first stage.

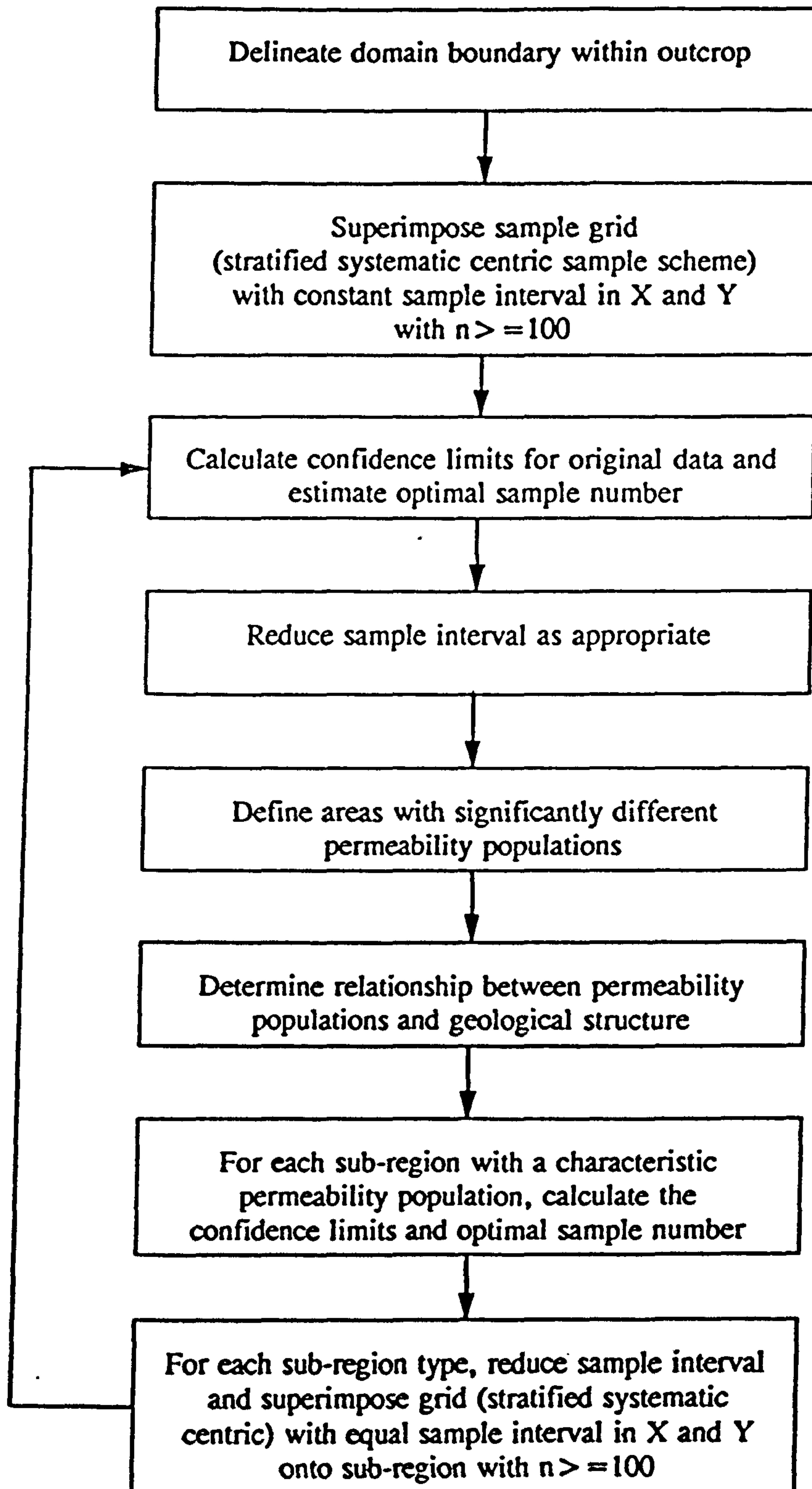


Figure 5.5 Flow chart showing the proposed sampling technique appropriate for permeability studies on outcrop

The optimal sample number is then estimated using the N-Zero test, and the number of permeability measurements increased accordingly. To maintain a constant sample interval the number of samples may have to be increased above that of the optimal number determined by the N-Zero test. If the optimal sample number for the given tolerance is unfeasibly large then the confidence limits for the estimate can be calculated using the following equation:

$$\bar{X} \pm t_{\alpha, n} s / (n)^{1/2}$$

Where $\bar{X}$ = Estimated mean value of the statistic
 t = Student's t from a statistical table based on $1-\alpha$
 n = Sample size
 s = Standard deviation of X

.....(30)

The resultant permeability pattern is then divided into sub-regions that appear to have different permeabilities. Depending on the assumptions made for normality and homogeneity of variance for the sample population, the significance of these sub-regions may be verified using analysis of variance, the Kolmogorov-Smirnov test, or the Tukey-Kramer test, and the sub-regions redefined as appropriate. The formulae for these tests and examples of their application to geological data, including permeability, are given by Davis (1986) and Stalkup (1986). These sub-regions represent the largest scale of permeability heterogeneity within the outcrop, and may correspond to coarsening-up sequences, facies type, cross-bedded units and so on. If necessary, the sample scheme can be evaluated for correct weighting for each sub-region using the chi square test (equation 28) or sum of squared deviations (equation 29) with the number of facies replaced by the number of regions with different permeability characteristics.

Having classified these sub-regions in terms of their mean permeability and/or their variance, refined grids (that is, grids with a reduced sample interval) are then placed within examples of each sub-region, proportional to their frequency of occurrence. The required number of sub-regions can be determined using either the N-Zero test which is applied to the means of each sub-region type, or, if there are

insufficient sub-regions for a valid N-Zero statistic, the confidence limits (equation 30). For each sub-region type, the process of delineating and verifying sub-regions within them is repeated. Thus, the process of permeability sampling is an iterative one, with confidence limits established at each stage. As sampling is based on a grid scheme, it is unbiased and the relationship between depositional heterogeneities and permeability heterogeneities is not predetermined at any stage.

5.7 Spatial statistics

So far the sampling scheme has concentrated on statistical efficiency. Whilst the sampling strategy will represent some quantity (in this case permeability) in the same proportion as the area and frequency of areas characterised by that quantity, it will not necessarily sample all areas. In other words, some areas may be missed altogether. When performing spatial statistical analysis on the data, the correlation structures obtained may be inaccurate. The problem of incomplete areal sampling is particularly apparent where measures or indexes of connectivity (between sand lenses within shales for example) are required. This has significant implications when trying to develop stochastic modelling techniques and appropriate averaging or scaling-up rules for spatial permeability heterogeneities.

An appropriate method for quantifying the spatial correlation structure of permeability over the entire outcrop is to assign indicator values to the permeability classes identified using the sampling technique described earlier. Assuming these classes correspond to identifiable depositional features, the smallest practicable depositional feature (for example, facies type and cosets) can be mapped out over the outcrop through the combined use of photographs and field observations. Indicator geostatistics can then be used to obtain correlation lengths. The resultant permeability model for the outcrop can be evaluated by comparison with the observed permeability variation and disposition of facies types, cross-bed thickness and so on at outcrop.

There may of course be depositional features that cannot be mapped, either because they are too complex or their boundaries are poorly

defined. Within an eolian dune for example, the only division of permeability classes may be between laminae type, for which it would be very time-consuming to map out and assign indicator values. In this case, sample transects are constructed. Geostatistical analysis can then be performed on the transect data. Ideally, exhaustive sampling is used within the transect but some other sample interval may be used depending on the precision required which can be determined using either the N-Zero test or calculation of the confidence limits. For inexhaustive samples it is important to consider the ratio between the sample interval and the expected periodicity in the permeability data. This is necessary to ensure the measured correlation lengths are not a function of the sample interval. It is also important to ensure that the sampled data sequences are stationary as this is an assumption necessary in all time-series procedures (see section 2.3.2.1).

The sample transects should be constructed in directions aligned with the maximum ratio of anisotropy. These directions can be estimated using a combination of geological information (for example, the direction of graded sequences and the orientation of laminae) and the directional correlation of permeability data sampled on a regular grid. The orientation of the transects must also be aligned with some depositional datum to allow portability of measured correlation structures to the reservoir. The location of transects should be guided by the geological structure since it is likely that only a few transects will be available to provide representative correlations. In an elongated sand lense for example, transects may be aligned length-parallel along the three principle axes (X, Y and Z) that define the geometry of the sand-body. The optimal frequency of transects can be estimated by comparing the means of the transects and determining the optimal number using the N-Zero test or confidence limits.

Vertical transects over the entire interval exposed at outcrop also provide a useful comparison with data obtained from vertical wells. Estimates of sampling efficiency can be made through determination of the sample density required within each well and the number of wells required for a given confidence interval.

5.8 Examples of permeability sampling schemes at outcrop

The methodology for permeability sampling at outcrop presented here is demonstrated through two independent outcrop permeability studies on rocks representing different depositional environments. The first example represents a complex arrangement of fluvial facies, and the sampling scheme is based on a coarse grid with localised transects. The second example represents a series of stacked aeolian dunes with clearly defined second order bounding surfaces and cross-beds. In this second study, only vertical and horizontal transects were used.

5.8.1 Study 1: The Sherwood Sandstone, Bawtry, U.K.

5.8.1.1 Introduction

The aim of this outcrop study was to investigate the static and spatial statistical variation in permeability within a sequence of fluvial sediments. A detailed geological investigation was first initiated to define and delimit the different facies types, which were considered to be the most likely source of permeability variation at the largest scale. A regular sample grid (= stratified systematic centric sample scheme) was used to quantify statistically the permeability variation within and between facies types. Having established this, sample transects were then used to quantify the spatial correlation structure of permeability within each facies.

5.8.1.2 Geological setting

The Sherwood Sandstone Formation of eastern England is of Lower Triassic age and comprises a series of continental red beds deposited on the western margin of the southern North Sea basin (Burley, 1984). The predominant deposits are those of low-sinuosity, bed-load fluvial systems and consist of a range of sediments from fine sandstones to coarse pebbly sandstones. No associated eolian deposits are present within the sequences, probably as a result of their erosion and

reworking by the fluvial systems (Bryant and Burley, 1989). Exposures of these sediments may be seen at a number of localities in the Nottinghamshire-Derbyshire area allowing a clear sedimentological model to be built up for the sediments. The main sediment transport direction during deposition was easterly and the dominant structure in the sequence is medium to large-scale tabular cross-bedding. This is interpreted as resulting from downstream migration of large rivers similar to the modern Platte (Smith, 1970) and south Saskatchewan (Cant and Walker, 1978) rivers (Bryant and Burley, 1989). Smaller scale structures are related to modifications of the bar surfaces with planar laminated beds resulting from deposition under higher energy, less channelised flow conditions.

A section of the Sherwood Sandstone exposed at Styrrup Quarry, near Bawtry was chosen for a detailed permeability study. The quarry face is approximately 60 metres long and 5 metres high, exposed in a section transverse to the palaeoflow direction and sediment bedform types. Figure 5.6 shows the section used in the study together with a vertical sedimentological log displaying the main lithological and structural characteristics.

Based on field observations of lithology and sedimentary structures at Styrrup quarry, the sediments have been divided into four lithofacies. Lithofacies 1 is comprised of coarse sands with a high, but variable pebble content. The majority of the sediments possess no structure, although crude horizontal lamination and tabular and trough cross-bedding are visible in places. The base of the bedforms are highly erosive, with at places a high content of large pebbles and clay rip-up clasts. These clay clasts are probably the result of reworking of overbank or floodplain sediments. Lithofacies 1 is interpreted to have been deposited in channels and, therefore, probably represents the highest energy sediments in the section.

Lithofacies 2 consists of horizontal parallel laminated fine sands. the laminae in the beds are approximately 1 to 3mm thick. Thicknesses of the beds themselves are of the order of 30-50cm. The beds have erosional bases but lack a coarse lag. The poorly consolidated nature of the sediment and absence of exposed bedding planes has obscured any

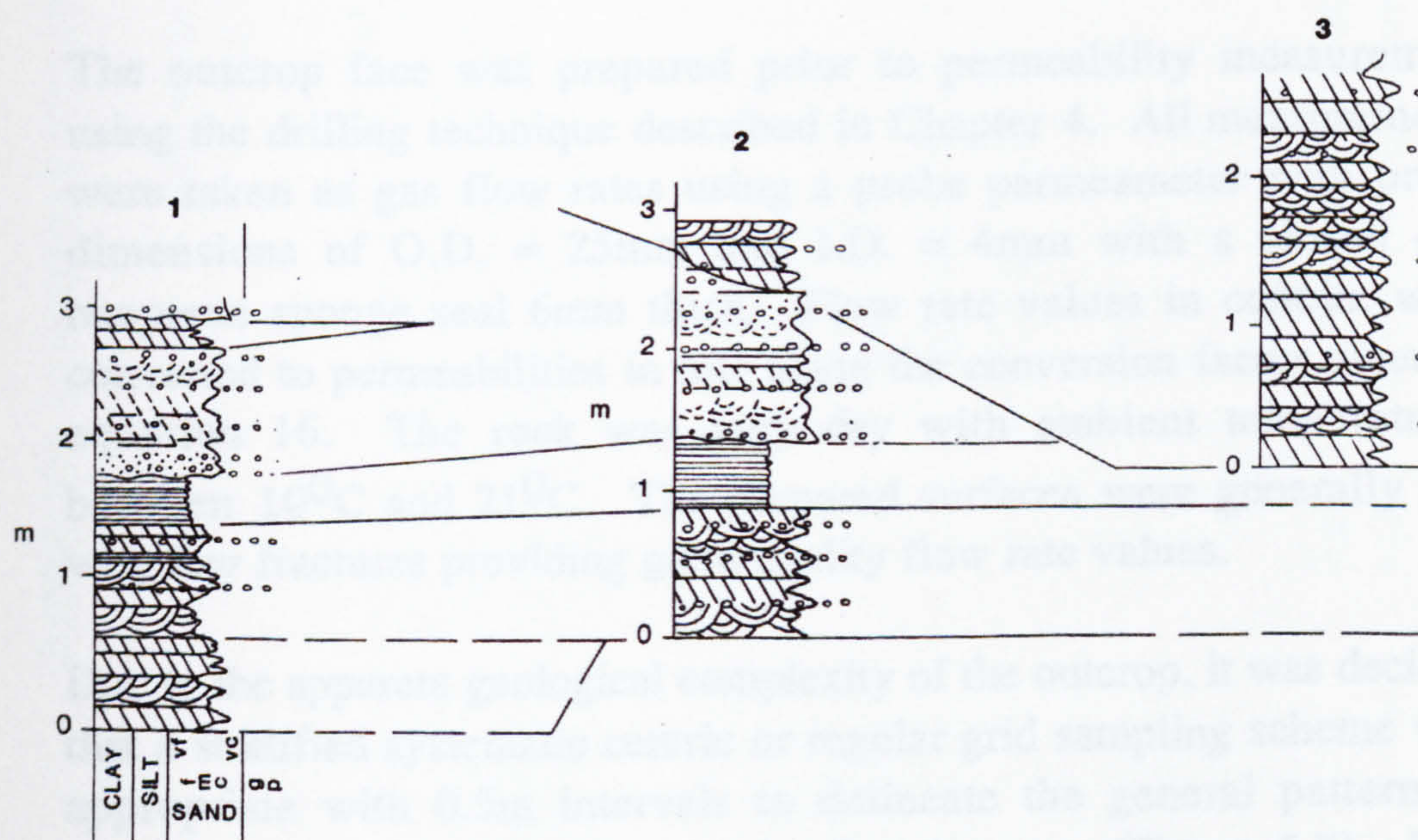


Figure 5.6 Photograph of a section of the Sherwood Sandstone exposed in a quarry at Bawtry that was used for the permeability study. Note person in foreground for scale. Sedimentological log sections are shown below (see Figure 5.7 for log positions).

parting lineation. This lithofacies is interpreted as sheetflood deposits.

Lithofacies 3.1 is typified by fine to coarse sands displaying planar tabular and trough cross-bedding. Pebbles are rare or absent in these deposits, contrasting with lithofacies 1 and 3.2. such deposits are common in braided fluvial systems and are interpreted here as having been deposited as transverse bars between channels.

Lithofacies 3.2 exhibits planar tabular cross-bedding but with a greater pebble content than lithofacies 3.1. It is distinguished from lithofacies 1 by the presence of well defined cross-bedding and from lithofacies 3.1 by a higher pebble content. The division between lithofacies 3.1 and 3.2 is somewhat arbitrary and bedforms can be seen to change laterally from one to the other. This lithofacies is interpreted as having been deposited either in high-energy bars or on the higher energy parts of bars with lithofacies 3.1 sediments being deposited on the lower energy parts.

5.8.1.3 Sampling scheme

The outcrop face was prepared prior to permeability measurement using the drilling technique described in Chapter 4. All measurements were taken as gas flow rates using a probe permeameter with probe dimensions of O.D. = 25mm and I.D. = 4mm with a closed cell neoprene sponge seal 6mm thick. Flow rate values in cc/min. were converted to permeabilities in mD using the conversion factor given in equation 16. The rock was very dry with ambient temperatures between 10⁰C and 21⁰C. The prepared surfaces were generally flat with few fractures providing good quality flow rate values.

Due to the apparent geological complexity of the outcrop, it was decided that a stratified systematic centric or regular grid sampling scheme was appropriate with 0.5m intervals to delineate the general pattern of spatial permeability variation in the first instance (Figure 5.7). The sample points were orientated relative to the sheet flood facies (lithofacies 2) which represents the most reliable depositional datum.

SHERWOOD SANDSTONE (TRIASSIC), STYRRUP QUARRY, BAWTRY, U.K.

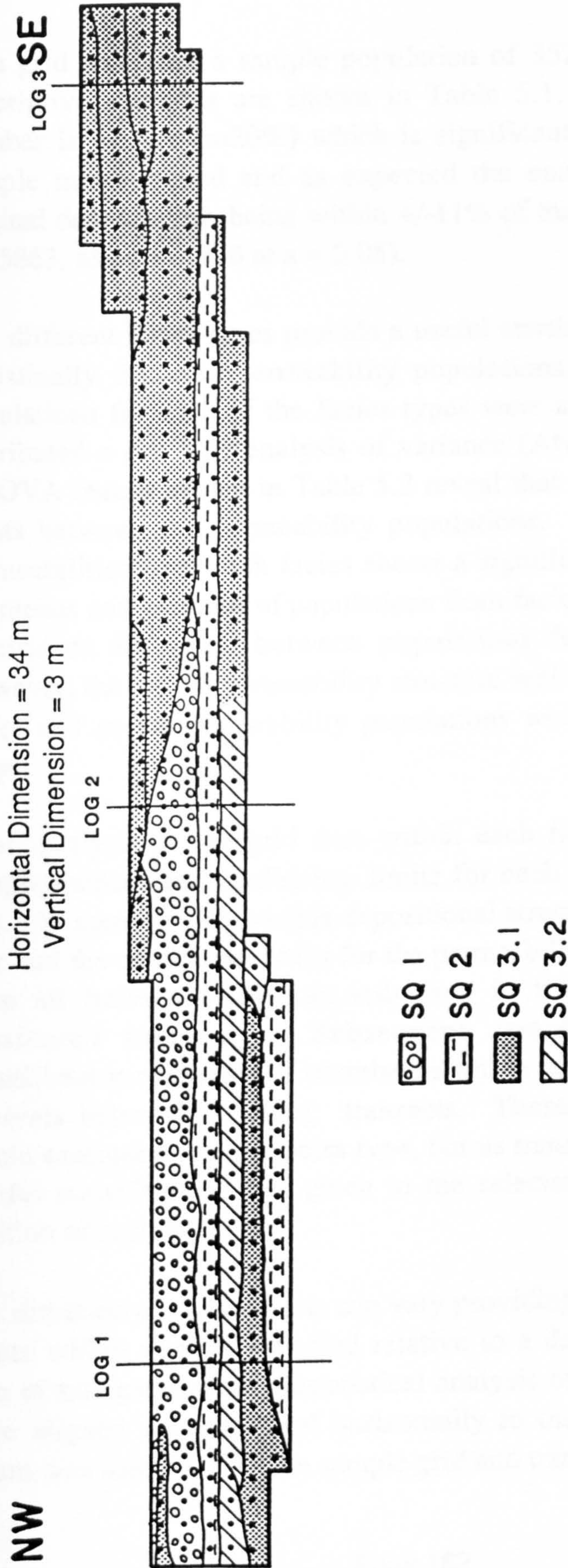


Figure 5.7 Layout of the regular grid sample scheme (sample interval = 0.5m) used on the outcrop of the Sherwood Sandstone.

This grid produced a sample population of 352 values for which the descriptive statistics are shown in Table 5.1. The optimal sample number is 67 (for $p=20\%$) which is significantly less than the actual sample number used and as expected the confidence limits for the original data are low, being within $\pm 11\%$ of the mean (where $n = 352$, $s = 5863$, and $t = 2.576$ at $\alpha = 0.05$).

The different facies types provide a useful starting point for delineating statistically different permeability populations. As the permeability populations for each of the facies types were approximately normally distributed a one way analysis of variance (ANOVA) was used. The ANOVA results shown in Table 5.2 reveal that a significant difference exists between the permeability populations. Comparisons between permeabilities from each facies shows a significant difference between the means and variance of populations from facies 2, 3.1 and 3.2, but no significant difference between populations from facies 1 and 3.2. However, the spatial permeability structure within facies 1 and 3.2 may differ and so the permeability populations were kept separate at this stage.

From analysis of the grid data within each facies type, the optimal sample number and confidence limits for each were calculated (Table 5.3). As there are few visible depositional structures within each facies type and the confidence limits for the permeability data from each facies were all below $\pm 21\%$, no reduction in the sample interval was considered necessary. Subsequent sampling concentrated on quantification of the spatial correlation within each facies type at sample intervals below 0.5m using transects. These transects were placed within examples of each facies type, but as transect samples are biased, careful consideration was given to the selected direction, length and position of each transect.

The direction of the transects can vary providing the position of sample points within them is recorded relative to a depositional datum. For ease of navigation and geostatistical analysis of the data, the transects were aligned vertically and horizontally to the datum. As the same datum was used for both the sample grid and transects, the sample

Name	Sherwood Sstn.
Facies type	Braided Fluvial
Mean KmD	7170
St. Deviation	5863
Cv	0.82
n	352
Conf. Lim. (alpha=0.005)	+/-11%
N0 p=20%	67

Table 5.1 Descriptive statistics for the 0.5m interval grid data

Source:	DF:	Sum Squares:	Mean Square:	F-test:
Between Groups	3	4.3 E9	1.4 E9	64.94
Within Groups	348	7.7 E9	2.2 E7	p=0.0001
Total	351	1.2 E10		

Comparison:	Mean Diff:	Scheffe F-test:	Dunnett t:
1 vs 2	10086	57.05*	13.08
1 vs 3	5203	19.69*	7.69
1 vs 4	1728	1.3	1.97
2 vs 3	-4883	18.63*	7.48
2 vs 4	-8357	31.68*	9.75
3 vs 4	-3475	6.72*	4.49

*Significant @ 95%

Table 5.2 Anova table showing the comparison between permeability populations from the different facies types

Group:	Facies:	n:	Mean KmD:	Std. Dev:	Conf. Lim: (alpha=0.005)	Cv:	N0: p=10%	N0: p=20%
1	1	71	11935	5634	+/-15%	0.47	88	22
2	2	79	1850	1330	+/-21%	0.72	207	52
3	3.1	153	6732	5292	+/-16%	0.79	250	62
4	3.2	49	10207	4823	+/-18%	0.47	88	22

Table 5.3 Optimal sample number and confidence limits for permeability data from each facies type

points within each were aligned parallel to each other.

The spatial correlation structure from the 0.5m interval grid data can be used to determine the appropriate length of the sample transects within each facies type. For the sample grid data from the Sherwood Sandstone variogram analysis was conducted. All variograms for these data (and other data presented in this thesis) were constructed using the MGAP Geostatistical Software Package run on an Apple Macintosh personal computer. Anisotropy in the correlation structure should be noted since the transect length may vary with direction and care is needed where correlation structures are measured from asymmetric domains because this can influence the anisotropy of the correlation structure, especially where a constant sample interval is used in both the vertical and horizontal directions. This is particularly evident in the Sherwood Sandstone where the exposed facies are typically long and thin. All but one of the facies contain, at most, two sample points in the vertical direction. Consequently, vertical correlation structures are unreliable and only horizontal variograms were constructed from the grid data within these facies. As facies 3.1 contains up to 5 data points in the vertical direction, the spatial permeability variation in both the horizontal and vertical were incorporated in a single omnidirectional variogram for these data.

The variograms constructed from the grid data within each facies are shown in Figure 5.8. Point permeabilities within facies 2 and 3.1 are uncorrelated over 0.5m. Consequently a single horizontal transect with a minimum length of 0.5m was considered appropriate for the estimation of the spatial permeability distribution within these facies types. For facies 3.1 which is approximately 3m thick, the omnidirectional variogram indicates that a vertical transect with a minimum length of 0.5m is appropriate. Since facies 2 is approximately 0.5m thick, a single vertical transect 0.5m in length was considered appropriate although no variogram was constructed in this direction from the grid data. For facies 1 and 3.2, where an horizontal correlation structure with a range of 4m and 2.3m is identified respectively, the minimum horizontal transect length should equal this correlation length. Ideally, the length of the horizontal transect would

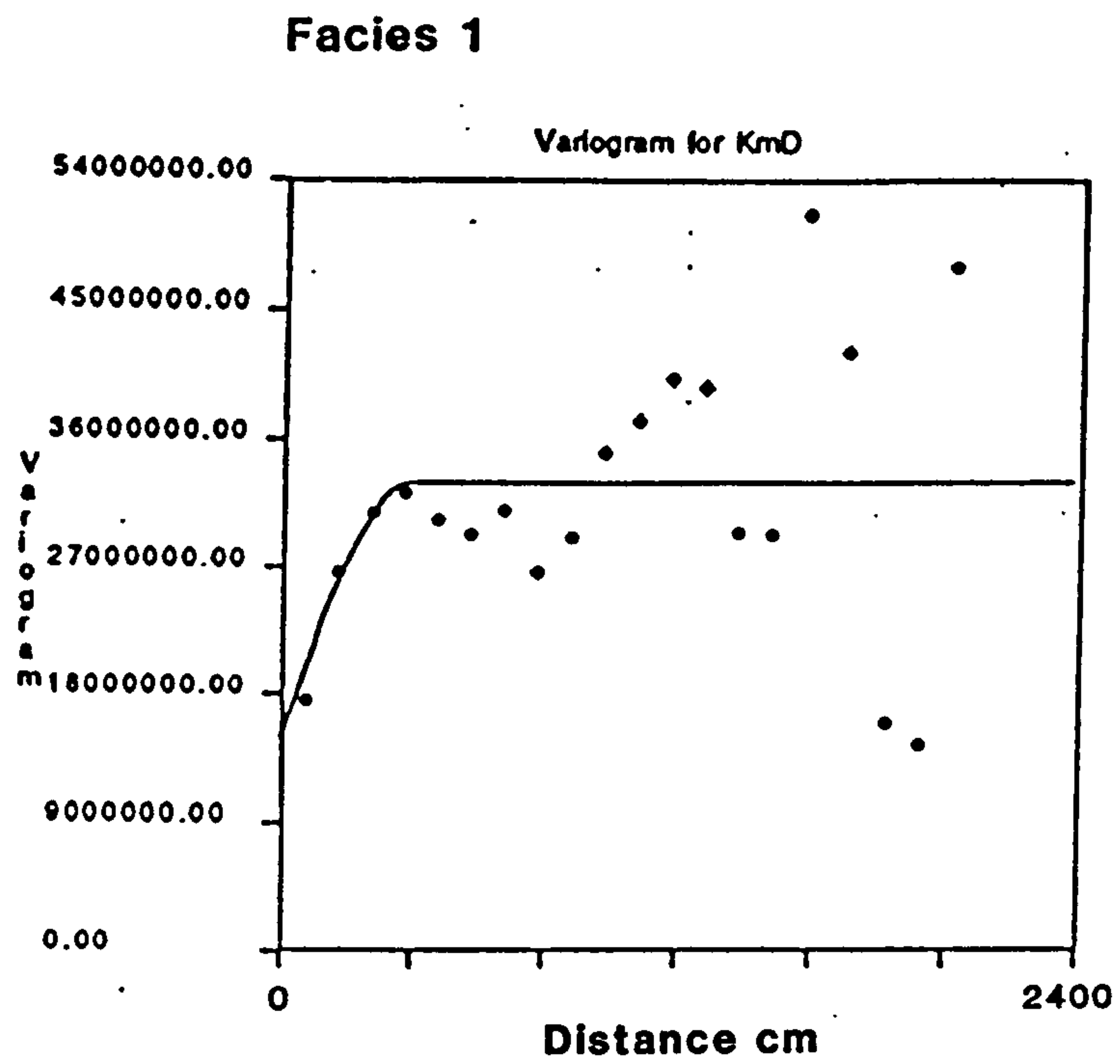


Figure 5.8

Variograms of the permeability data sampled at 0.5m intervals from within each facies type

Facies 2

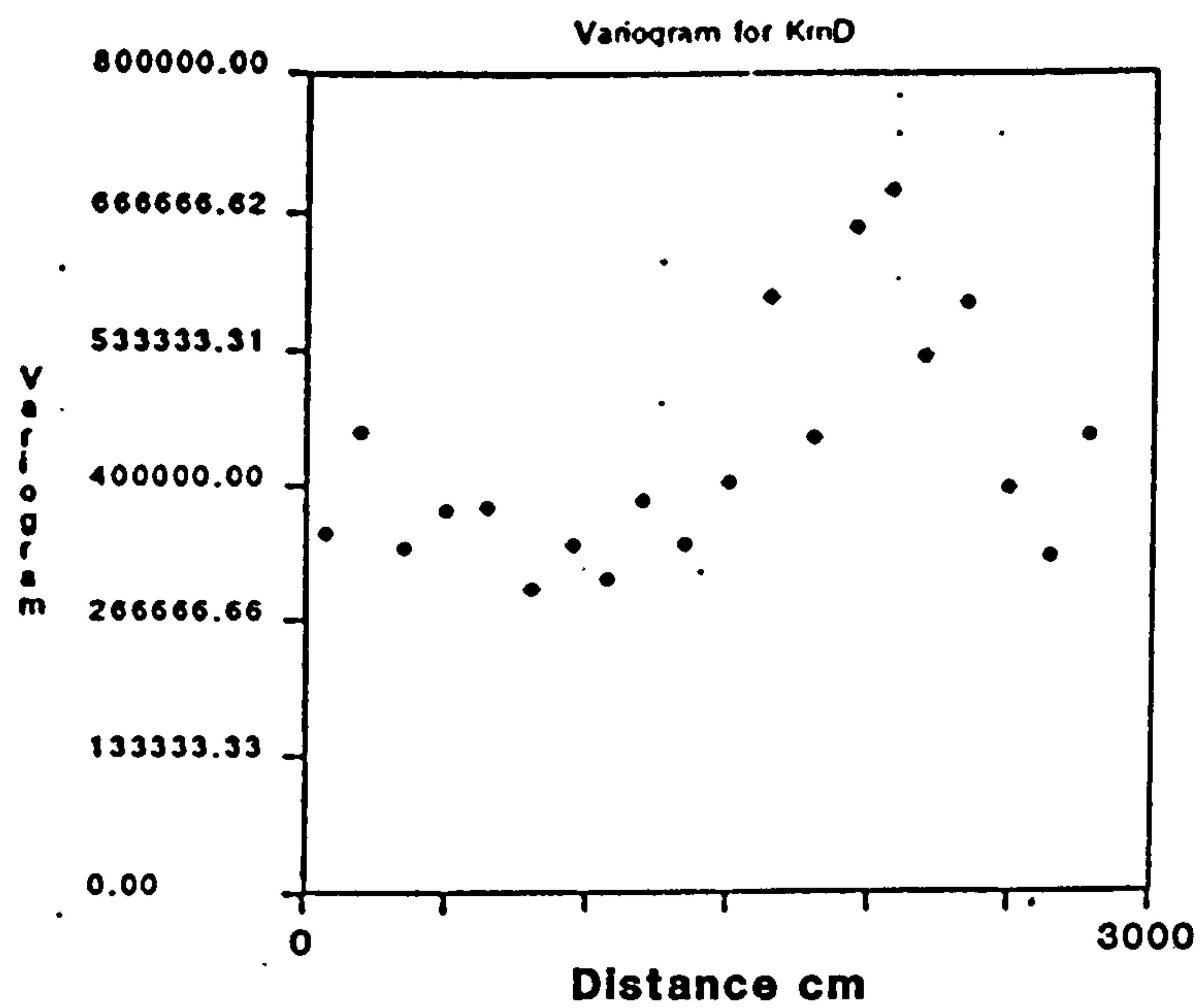


Figure 5.8 (Cont'd) Variograms of the permeability data sampled at 0.5m intervals from within each facies type

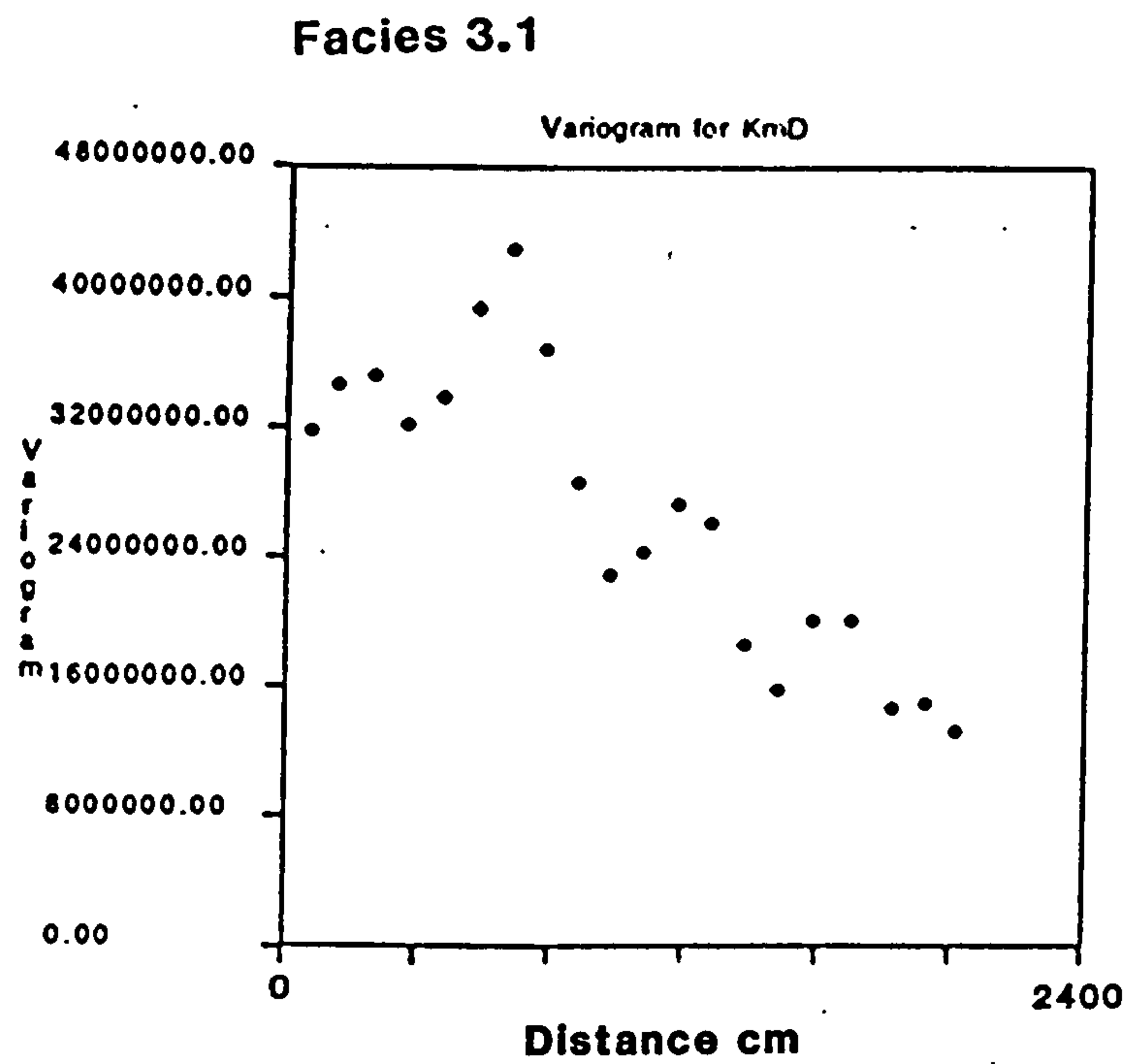


Figure 5.8 (Cont'd) Variograms of the permeability data sampled at 0.5m intervals from within each facies type

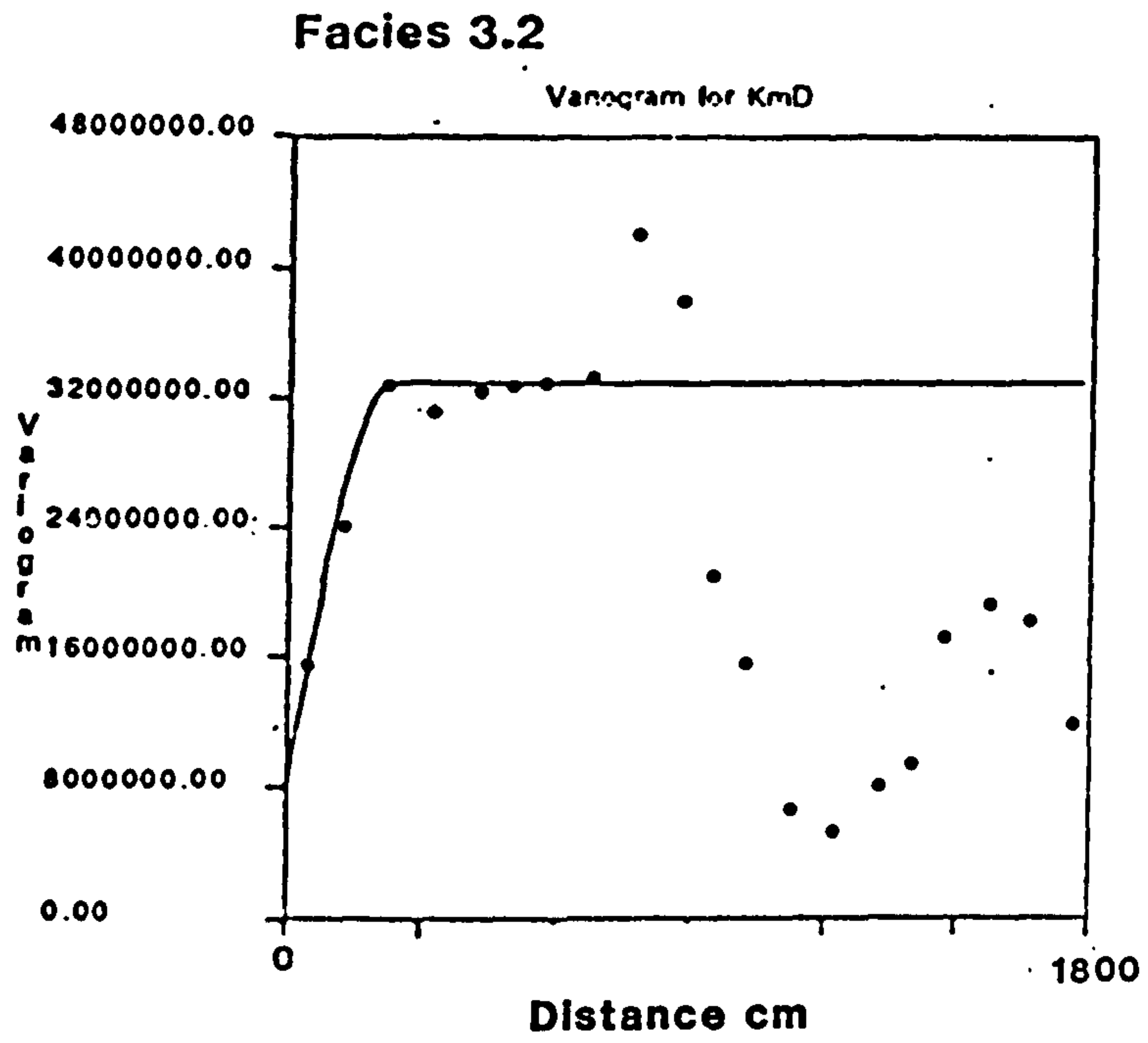


Figure 5.8 (Cont'd) Variograms of the permeability data sampled at 0.5m intervals from within each facies type

be constructed over the entire length of the exposed facies to avoid location dependence of the transect but this was not practicable due to difficult access to the rock face. The appropriate minimum length of vertical transects within facies 1 and 3.2 is equal to the facies thickness which reaches a maximum of 1m and 0.5m respectively.

The position of transects should be arranged so as to minimise bias, that is the transects should be placed at equal intervals over the study area. The number of transects in each direction depends on the required accuracy in the data for which confidence limits can be calculated. The optimal sample number can also be estimated using the N-Zero test although this requires a fairly large number of transects for reasonable accuracy within the statistic itself (usually a number of greater than 50, Hurst and Rosvoll, 1991).

The sample transects should be sampled at an interval that will provide both a statistically representative sample and a measure of the spatial correlation structure. The minimum sample interval used should therefore, be determined through both static and spatial statistical analysis. In the first instance, exhaustively-sampled investigatory transects should be constructed within each facies in areas likely to contain the greatest permeability variation (determined visually and/or from the grid data). From these data, the correlation structure, optimal sample interval and confidence limits can be estimated.

The position of investigatory transects within each facies type from the Sherwood Sandstone, sampled at an interval of 0.02m, are shown in Figure 5.9. Using the N-Zero test the optimal number of samples within each transect was estimated together with the confidence limits for the original data. These results are shown in Table 5.4. Comparing these results with the features of the variograms for each transect shown in Figure 5.10, the following observations are made:

The optimal sample interval within vertical transects from facies 1 and 3.2 and within the horizontal transects from facies 1, 2, 3.1 and 3.2 is significantly greater than that used (0.02m), resulting in high confidence limits, being equal to or less than $\pm 12\%$. For facies 2 the optimal

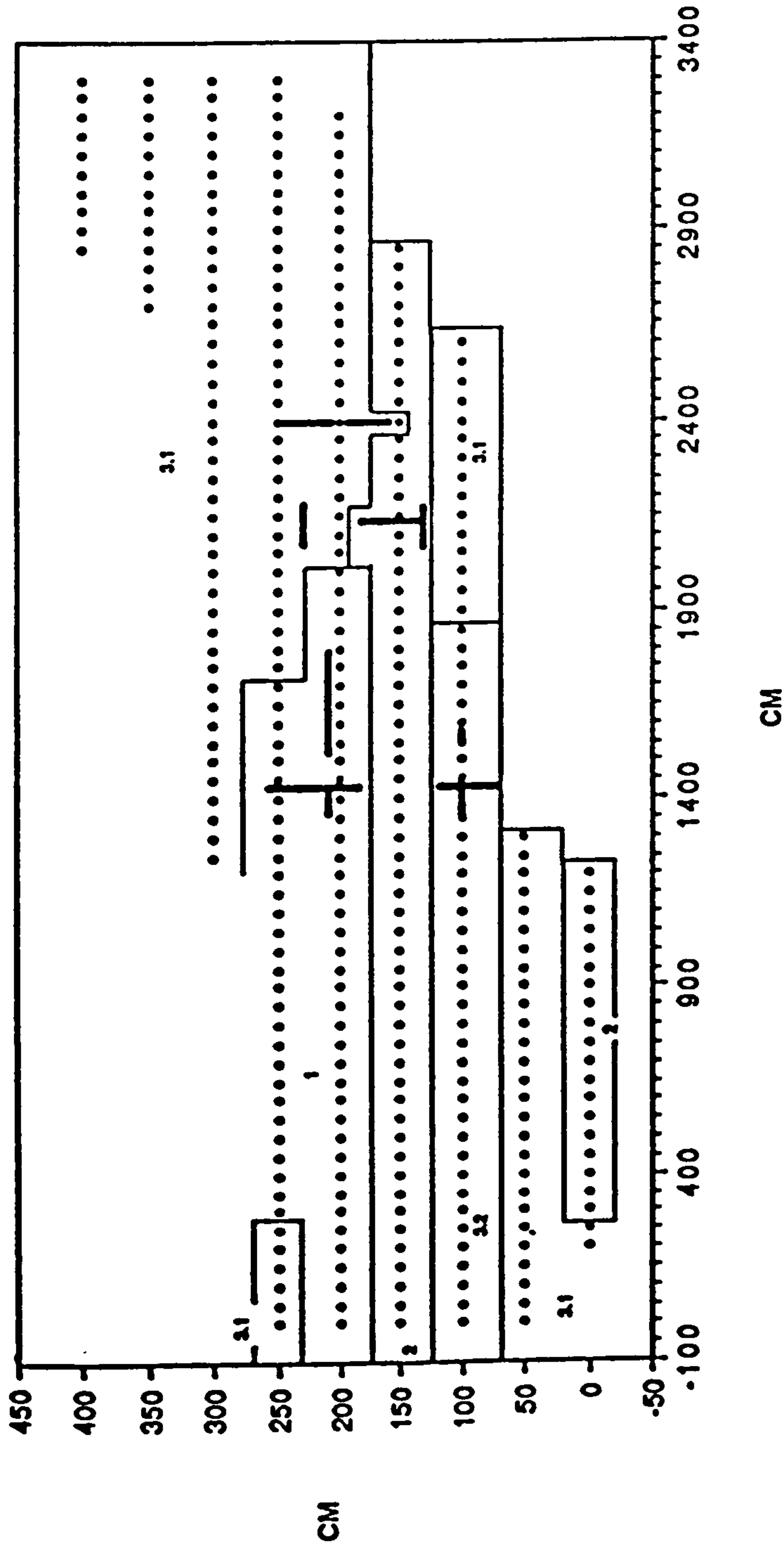


Figure 5.9 Location of sample transects (sample interval = 0.02m) within different facies types

Facies:	Transect Direction:	n:	Sample Interval (m):	Std. Dev:	Mean KmD:	Conf. Lim: (alpha=0.005)	Cv:	N0: p=20%	DS (m): p=20%
1	Horizontal	149	0.02	4471	12104	+/-8%	0.39	16	0.28
	Vertical	35	0.02	3497	16041	+/-10%	0.22	5	0.15
2	Horizontal	51	0.02	707	2125	+/-12%	0.33	11	0.09
	Vertical	23	0.02	822	2119	+/-23%	0.39	15	0.03
3.1	Horizontal	50	0.02	2502	10308	+/-9%	0.24	6	0.18
	Vertical	38	0.02	5187	7651	+/-30%	0.68	46	0.018
3.2	Horizontal	51	0.02	2608	11417	+/-9%	0.23	5	0.43
	Vertical	20	0.02	1897	10298	+/-12%	0.18	3	0.14

Table 5.4 Optimal sample interval and confidence limits for permeability data sampled along the transects within each facies type

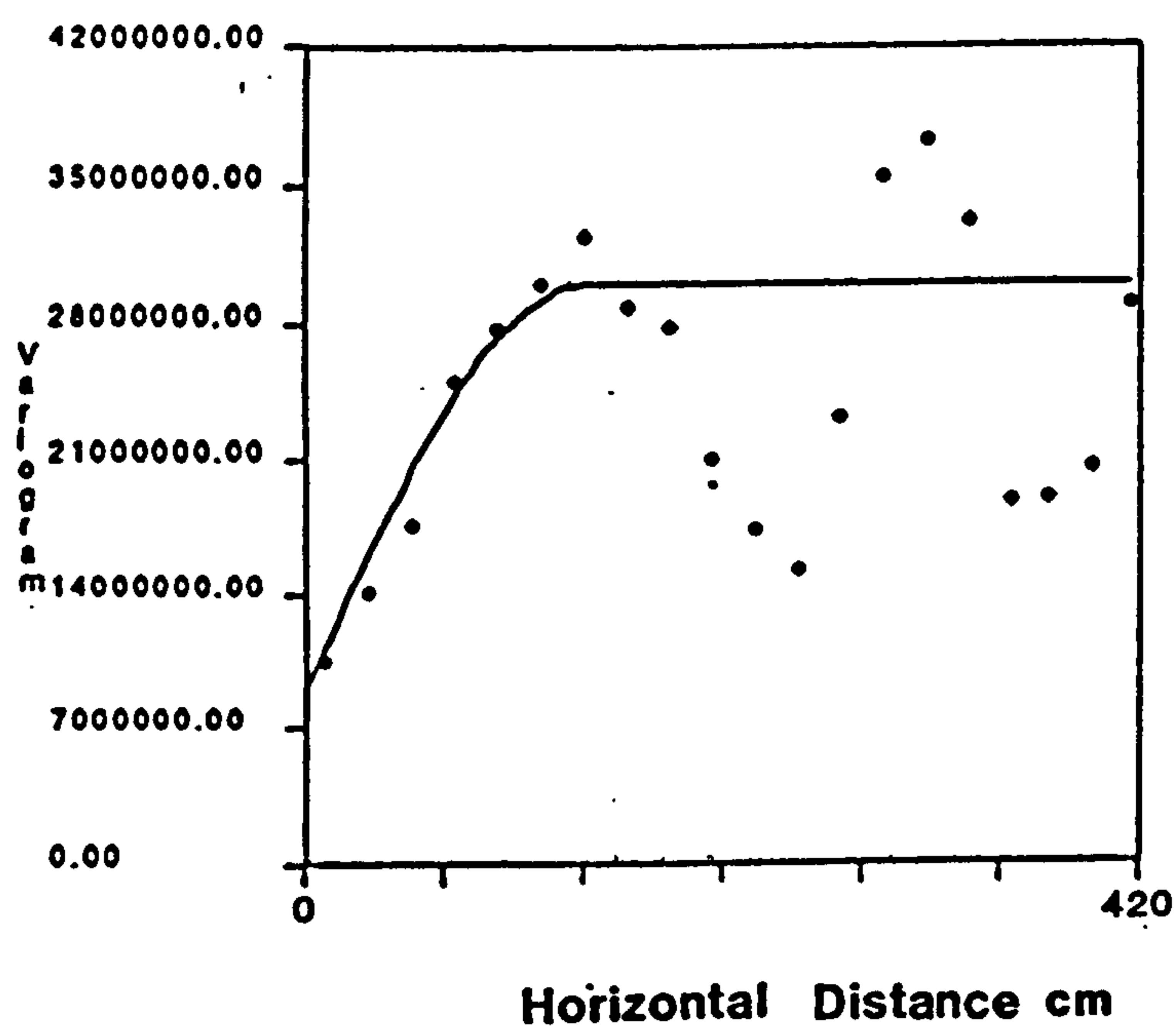
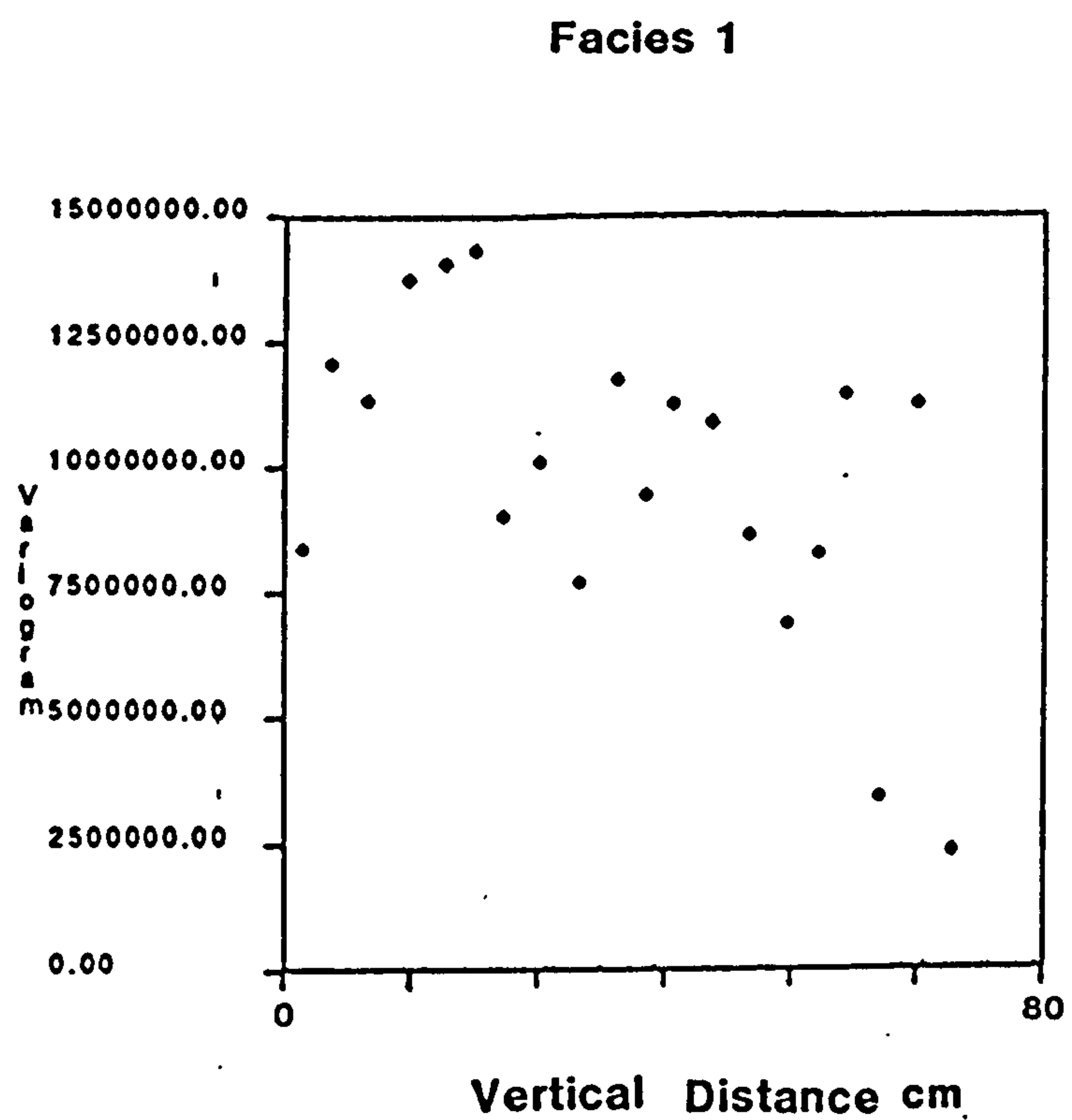


Figure 5.10 : Variograms of the transect data sampled at 0.02m intervals within each facies type

Facies 2

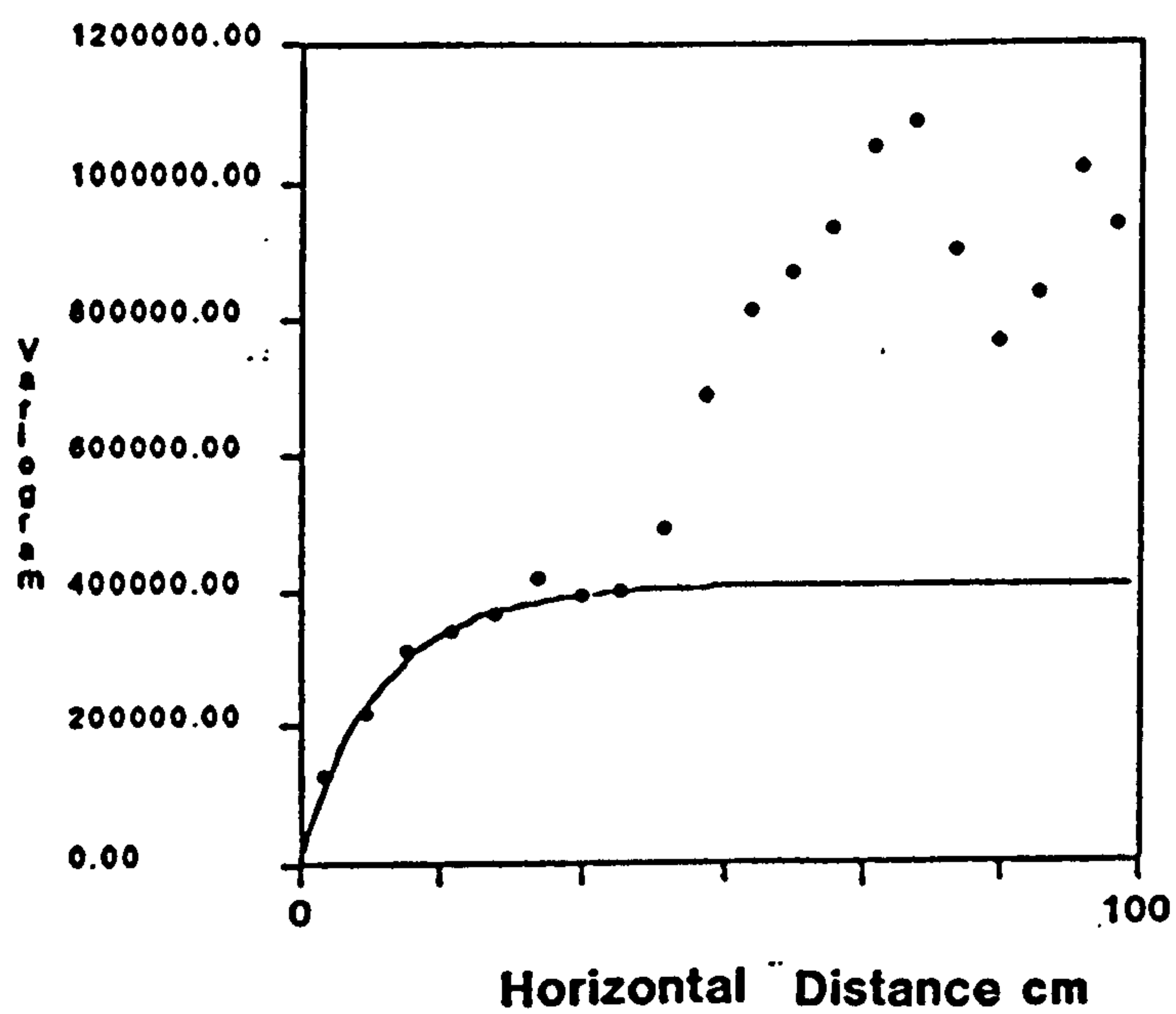
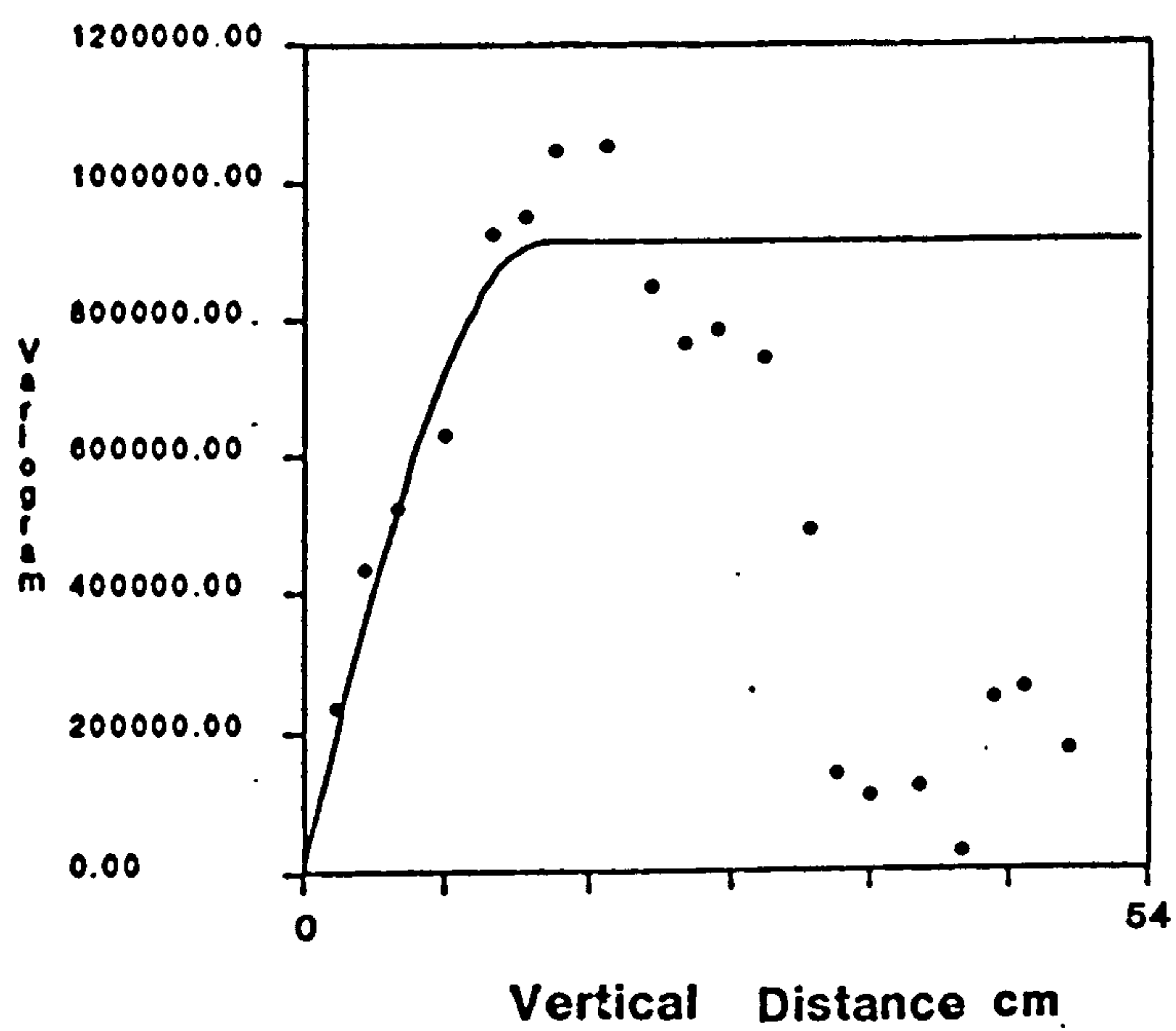


Figure 5.10 (Cont'd) Variograms of the transect data sampled at 0.02m intervals within each facies type

Facies 3.1

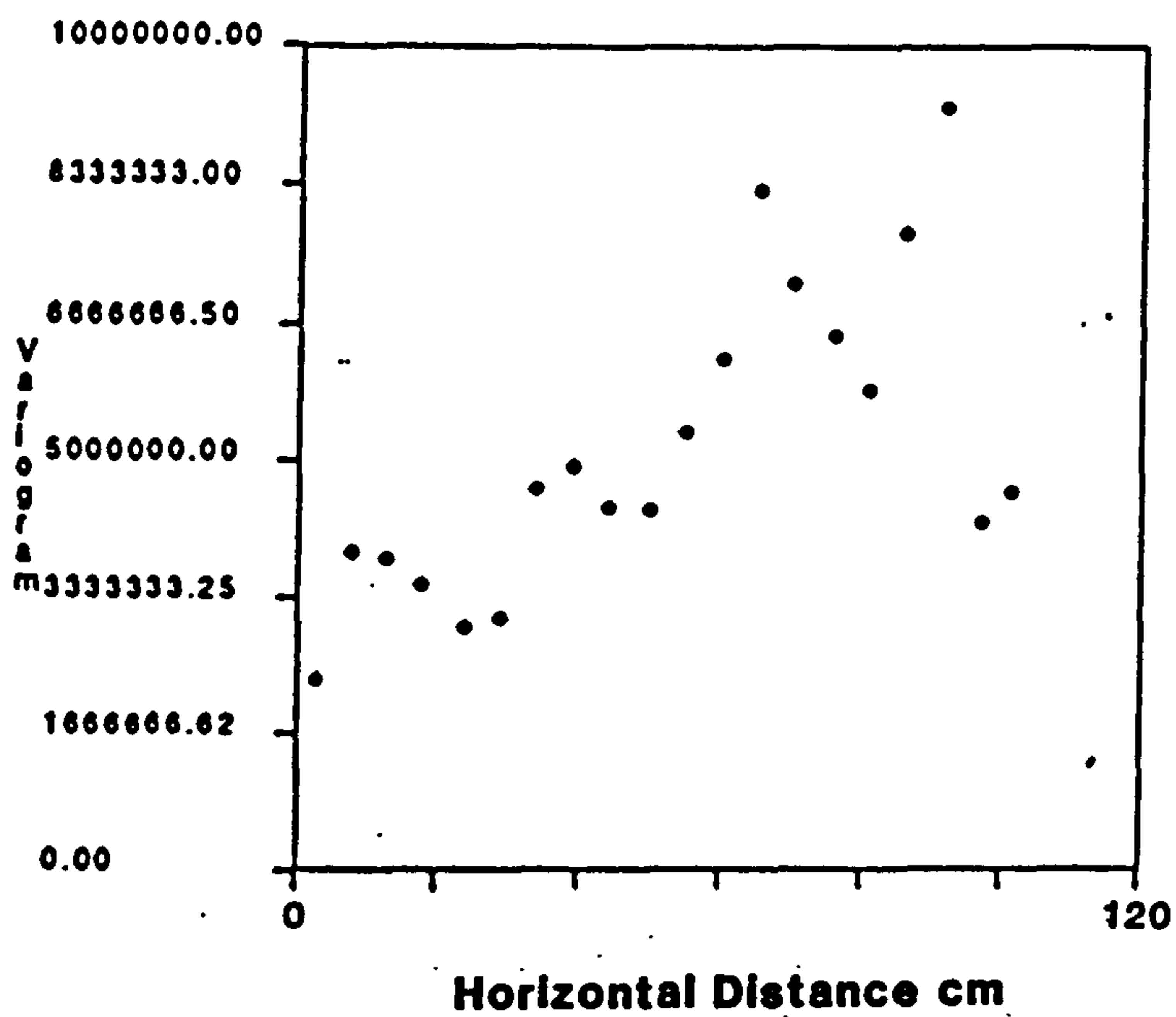
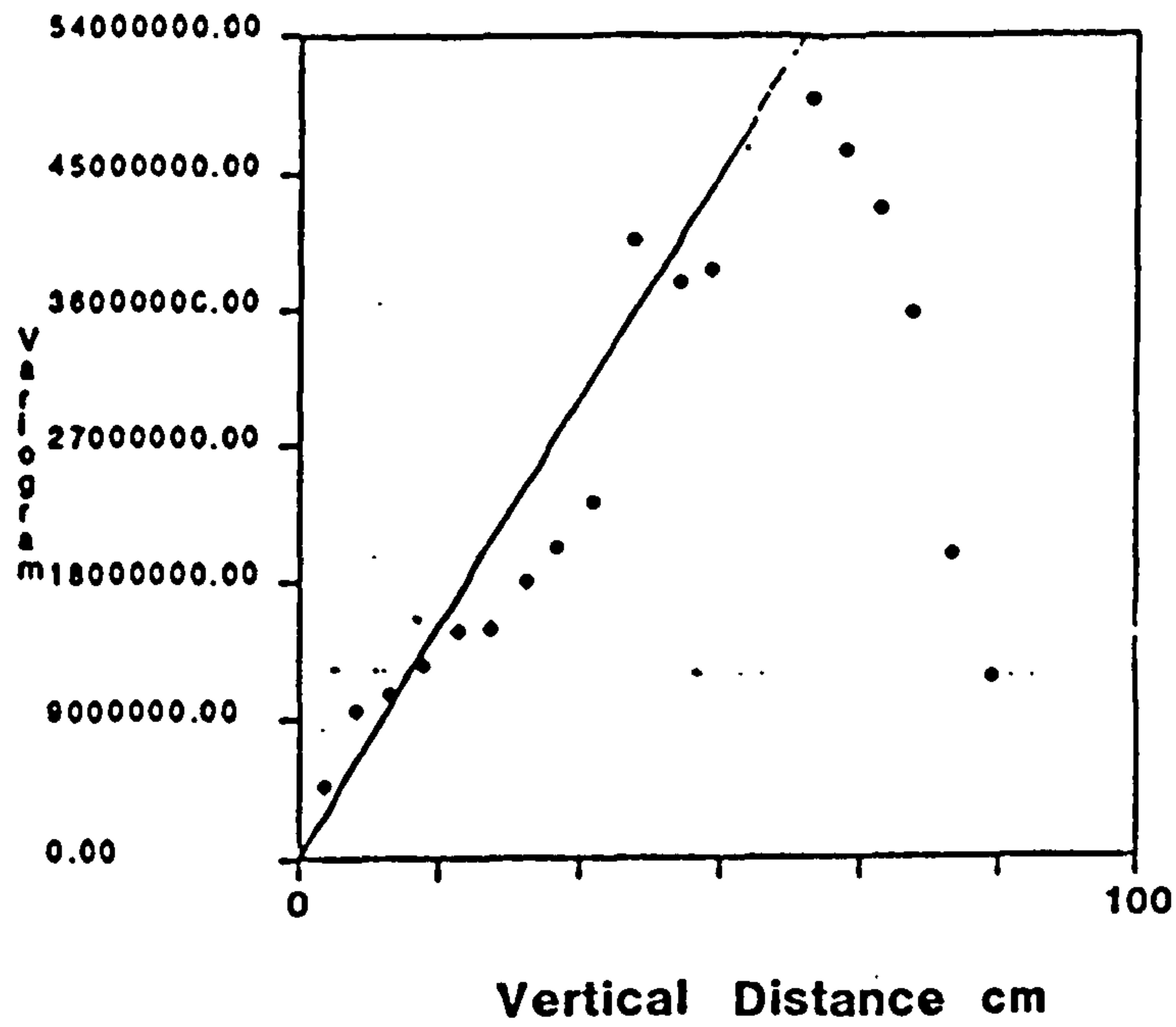


Figure 5.10 (Cont'd) Variograms of the transect data sampled at 0.02m intervals within each facies type

Facies 3.2

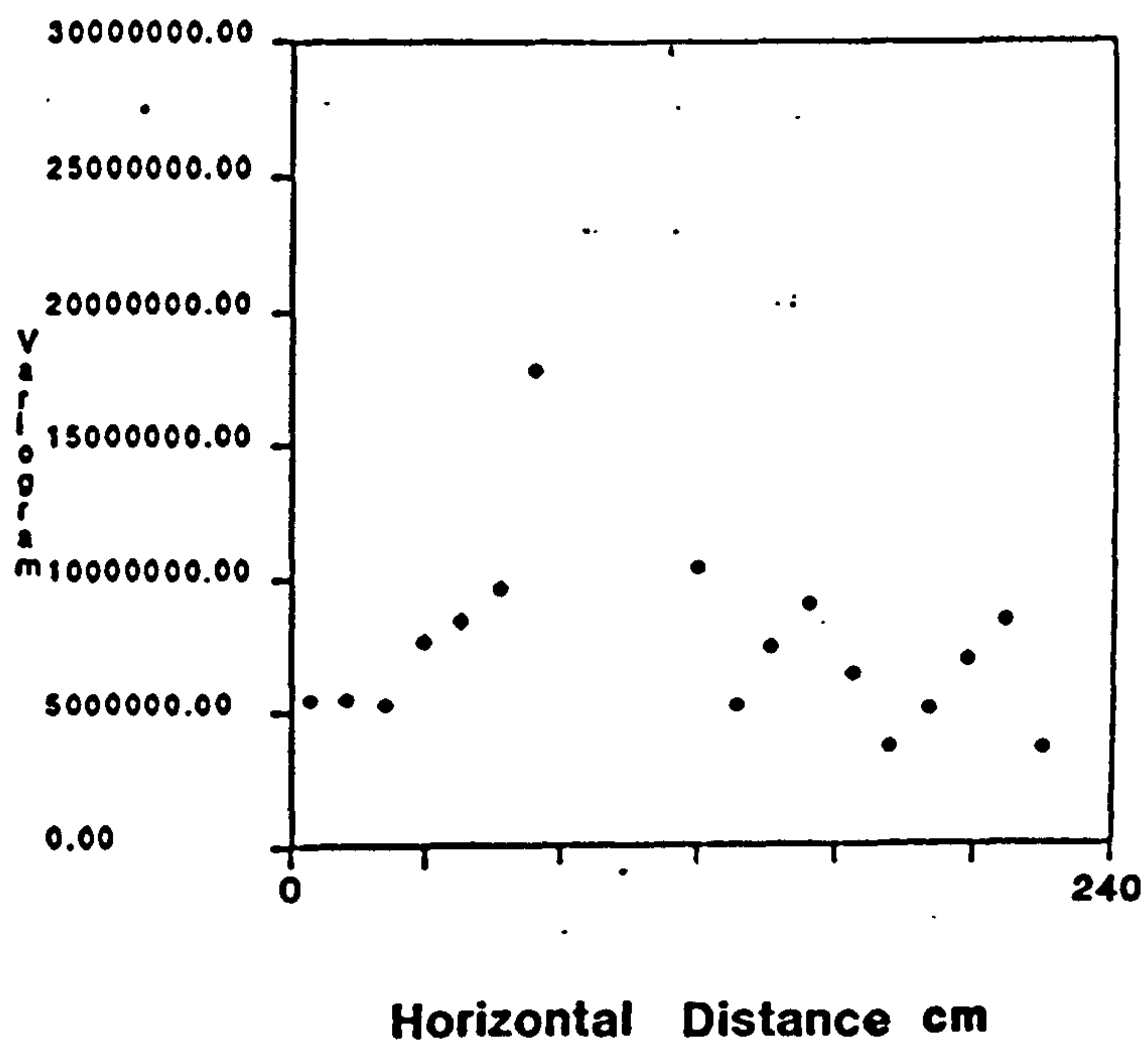
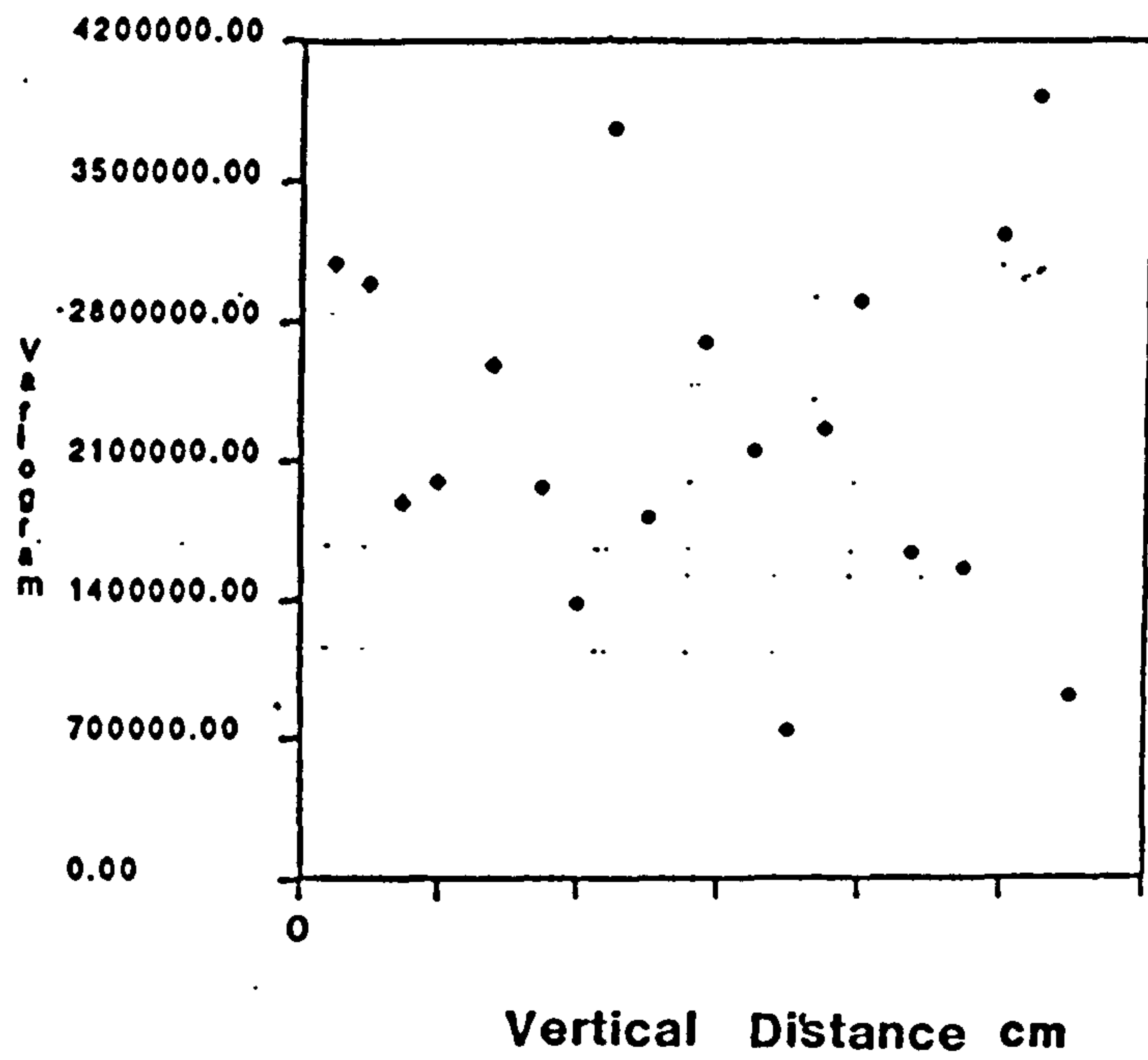


Figure 5.10 (Cont'd): Variograms of the transect data sampled at 0.02m intervals within each facies type

sample interval of 0.03m within the vertical transect is only just greater than that used (0.02m) resulting in the confidence limits being significantly lower at $\pm 23\%$. Only within the vertical transect from facies 3.1 however, is the optimal sample interval of 0.018m less than that used (0.02m). In this case, the confidence limits are lowest at $\pm 30\%$.

For those sample transects within which the permeability data are uncorrelated (that is, those having variograms displaying a pure nugget effect), the optimal sample interval is an appropriate measure of sampling efficiency since the data can be treated as statistically independent. This applies to the vertical transect data from facies 1 and 3.2 and the horizontal transects from facies 3.1 and 3.2. For facies 3.1 a linear or continuous variogram model has been fitted to the vertical transect data which indicates the presence of a drift causing non-stationarity in the data sequence in this direction. A geologically-realistic explanation is required for this drift before removing it to obtain a stationary data sequence. For those sample transects displaying a correlation structure it is important that the sample interval used is less than the correlation length because samples at intervals below this length are statistically dependent. Where a correlation structure was identified in the vertical transects from facies 1 and 2 and the horizontal transect from facies 2, the optimal sample interval is less than the correlation length.

With the exception of the vertical transect data from facies 3.1, it can be concluded that the sample grids and transects provide a reliable estimate of both the static and spatial permeability variation within each facies type. The apparent high degree of permeability variation within the vertical transect data from facies 3.1 is suspect because of the non-stationarity of the data sequence and further investigation of these data is required.

5.8.1.4 Discussion and guidelines for further sampling

Having established the length of transects and the optimal sample interval within transects for each facies, the next task is to place the vertical and horizontal transects at equal intervals over the exposed area of each facies. This is relatively easy to achieve since the 0.5m grid provides a convenient set of marker points for aligning the transects. Ideally, every exposure of the same facies type should be sampled to allow comparison of correlation structure, but as this may involve too many samples, a few or only one example of each facies type can be included.

It is apparent that a major source of permeability heterogeneity exists between the different facies types within the Sherwood Sandstone. The quantification of the spatial disposition of facies types therefore, is necessary in order to develop permeability models at the interwell scale. This can be done relatively easily by assigning indicator values to each facies type which can then be modelled using indicator geostatistics in a fashion similar to that employed by Ravenne et al (1987). Unfortunately, only one or two examples of each facies type exists within this small outcrop and quantification of their disposition is of little use. Whilst exposures of the same sequence are found within outcrops elsewhere, they do not provide the continuous exposure required and cannot be reliably correlated. These other outcrops may be used however, to provide a more accurate description of the facies - permeability relationship, allowing investigation into the role, and perhaps quantification, of the effect of diagenesis on permeability.

The large variation in permeability identified within the various lithofacies types is largely due to the relationship between the sample volume ($\propto$ the probe seal dimensions), the grain size, and the poor sorting character of these rocks (notably the channel facies, SQ1). Given the high permeability values measured within these rocks, and the general lack of correlation structure, the variation identified is likely to be less significant in terms of its impact of reservoir flow characteristics. In view of this, a larger sample volume is more appropriate.

Increasing the sample volume will reduce the permeability variance within each of the lithofacies, thereby reducing the number of samples required. This will improve the accuracy of the sample data and will allow the sample domain sizes and numbers to be increased. This in turn will provide more reliable representations of the permeability variation within and between lithofacies.

By homogenising the variance within lithofacies, comparisons between permeability values measured from equivalent lithofacies in different outcrops are also less likely to be complicated by microscale heterogeneities. Increasing the sample volume therefore, will allow the development of a more reliable permeability model for these fluvio-deltaic deposits.

5.8.2 Study 2: The Dawlish Sandstone, Exeter, UK.

5.8.2.1 Introduction

In this present study the source of permeability variation was determined before sampling through use of the results of an earlier outcrop study by Goggin et al (1986 and 1989). The aim of this present study were specifically to investigate the correlation structure of spot permeability values in the vertical and horizontal direction. The sampling scheme was designed specifically for spatial statistical analysis through the use of sample transects and as a result the sample data are biased.

5.8.2.2 Geological setting

The Dawlish Sandstone (Late Lower Permian) outcrops in south west England and comprises sands, breccias, and the occasional marl. It is interpreted as an aeolian and fluvial sequence lying at the base of an alluvial fan (Edmonds et al., 1975). The sands form the bulk of the formation and are of aeolian and aqueous origin (Lamming, 1954). These aeolian sands are exposed in Bishops Court quarry near Exeter

for which a permeability study using the portable probe permeameter was initiated.

The aeolian sands are bright red in colour, very well sorted with a grain size range between 0.31 mm and 0.25 mm, and well rounded (although some larger grains may display wind-faceted surfaces). Compositionally, these eolian sands are quartz arenites (Lamming, 1954). Sets and cosets 0.5 metre to 5 metres thick are distinguished by large scale cross-bedding with long curved asymptotic foresets. These foresets are identified by pronounced fine to medium and coarse-grained laminae ranging from around 3 mm to 30 mm thick representing wind-ripple and grain-flow laminae respectively.

The grain size distribution parameters of the Dawlish Sandstone compare very closely with that of a modern Libyan desert dune (Lamming, 1954). A combination of the foreset dip angle (mostly below 25 degrees), range of palaeocurrent directions (around 200 degrees), and nature of grain size variation, fabric, and arrangement of strata suggest barchan-type dune forms (Lamming, 1954), although it has been suggested that the sands at Bishops Court may represent a star dune complex (Clarey, 1989*). Bishops Court quarry at Exeter offers excellent access over two faces, orientated north-south and east-west, with each face approximately 100 metres long and 10 metres high.

5.8.2.3 Sampling scheme

The aim of this permeability study was to investigate the lateral continuity of permeability variation within eolian dunes to determine the nature of permeability variation away from the well. Quantification of this variation was made using both static and spatial statistics. By comparing permeability data sampled in the vertical direction with permeability sampled in the horizontal direction, the use of vertical well data (such as conventional core plugs at 1' intervals) to predict permeability values into the interwell area can be evaluated.

* Personal communication

From sedimentological investigation, a series of migrating dune forms were identified at outcrop. On the east-west orientated face, a single horizontal transect was positioned within the second of three stacked dunes, where unhindered access allowed continuous sampling over approximately 85m of the exposed face (Figure 5.11). To the western end of this exposed face, a single vertical profile, orientated relative to an ordnance datum, was constructed over 4.68m incorporating three different dunes (Figure 5.12). Differences in permeability between laminae type within the Dawlish Sandstone was evidenced at outcrop by lichen growth and concentrations of hematite nodules along the coarse-grained grain flow laminae, indicative of a preferential flow of water along the grain fall laminae. Based on this evidence, and on the findings of Goggin et al (1986), the source of permeability variation was assumed to correspond to laminae type. Under consideration of this assumption, sample intervals of 0.2m and 0.02m were used on the horizontal and vertical transects respectively, in order to produce a statistically significant number of samples. This took into account the variation in laminae thickness from 3 to 30mm. All permeability measurements were made using the probe permeameter with seal dimensions of O.D. = 2cm , and I.D. = 4mm and a thickness of 6mm made from closed cell neoprene sponge. The chosen seal tip dimensions were found by repeated sampling at outcrop to provide the most reliable measure with minimum leakage. In addition, these dimensions allowed the probe seal to be placed within individual laminae in most cases (although the injection area of the probe is actually the most critical dimension). The rock face was prepared prior to sampling using the drilling technique described in Chapter 4.

The permeability profile for the horizontal transect is shown in Figure 5.13. The marked variation within the transect produces a very 'spikey' record and is due to the variation in laminae type, where coarser-grained grain flow laminae have higher permeability values than the finer-grained wind-ripple laminae. To the eastern end of the horizontal transect, a sharply-defined region of lower permeability is identified corresponding to the transition over a 3rd order bounding surface.

Statistics for these horizontal transect data are shown in Table 5.5.



Figure 5.11 Photograph showing the horizontal sample transect on the outcrop of the Dawlish Sandstone - Scale bar is 0.5m long (10cm intervals)

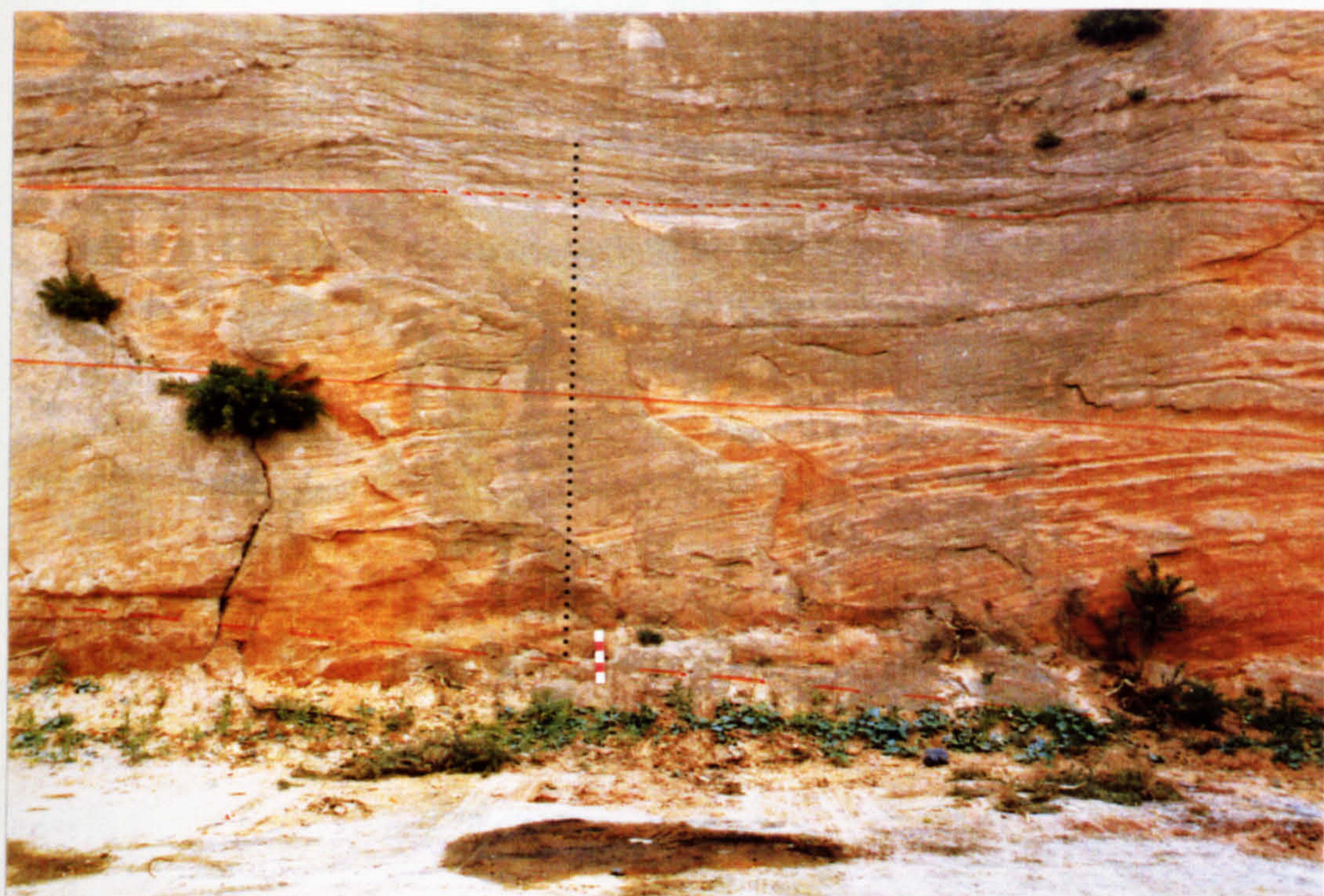


Figure 5.12 Photograph showing the position of the vertical sample transect on the outcrop of the Dawlish Sandstone - Scale bar is 0.5m long (10cm intervals)

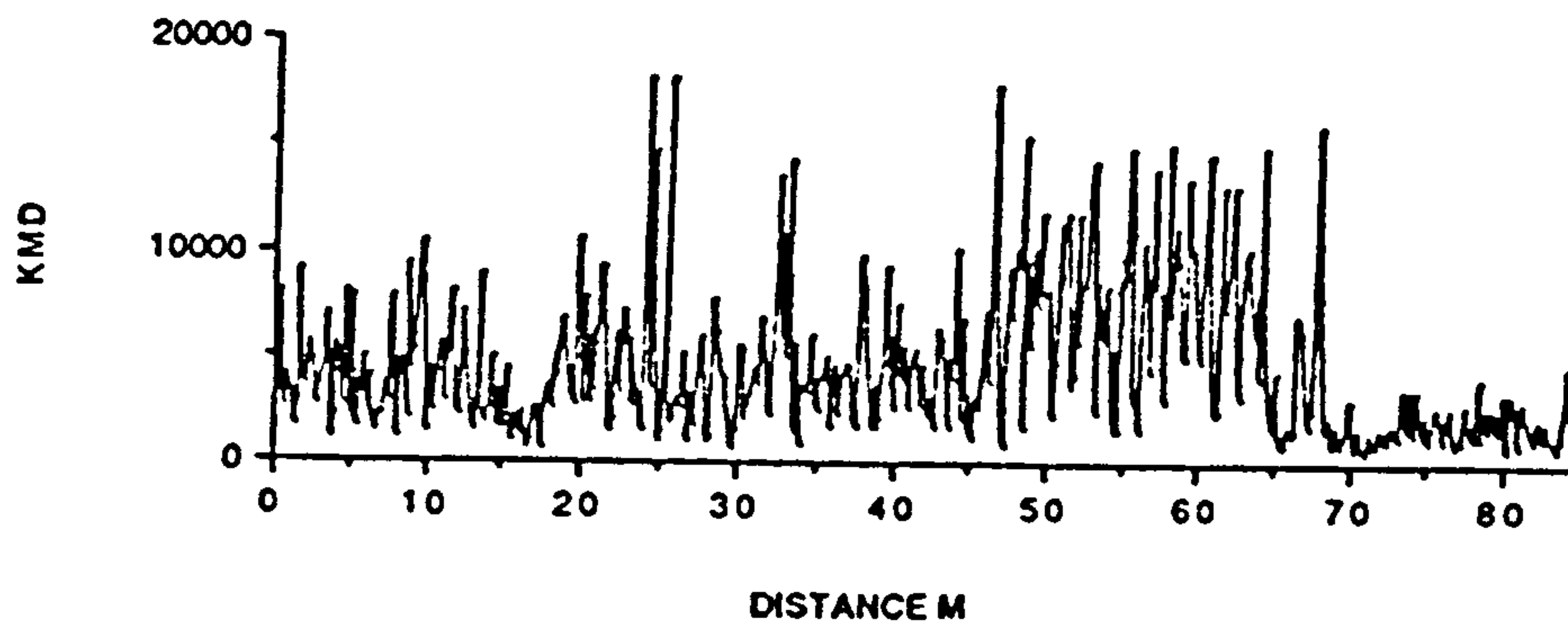


Figure 5.13 Permeability profile from the horizontal transect through the Dawlish Sandstone

Dune:	2
Transect Direction:	Horizontal
Mean kmD:	4489
Std. Dev:	3453
n:	424
Sample Interval (m):	0.2
Conf. Lim. (alpha=0.005):	+/- 10 %
Cv:	0.77
N0 (p=20%):	59
OS (m) (p=20%):	1.4

Table 5.5 Descriptive statistics, optimal sample number and confidence limits for the horizontal transect data

They have a log-normal distribution and are fairly heterogeneous ($C_v=0.77$), but as the optimal sample interval is considerably greater than that used, the confidence limits for permeabilities sampled at 0.2m intervals are low ($\pm 10\%$). Details of the variogram model for these data are shown in Figure 5.14. The correlation length of 18m is greater than the optimal sample interval of 1.4m, and as the nugget effect remains constant for a sample interval from 0.2 to 4m, the optimal sample interval provides an adequate representation of both the static and spatial permeability variation. The size of the nugget effect was larger than expected, indicating a component of random variation within the samples. This suggests that there is a significant variation in permeability within laminae types that is not represented in the variogram models for aeolian dune sands of Goggin et al (1986 and 1989) as discussed in Chapter 3. The cause of this component of random permeability variation within individual laminae types is probably related to localised variations in sorting and grain size, and possibly enhanced by diagenesis.

The permeability profile for the vertical transect is shown in Figure 5.15. The permeability record in this direction is remarkably similar to that in the horizontal direction although the permeability values are generally lower. As for the horizontal data, the high and low permeability values correspond to grain-fall and wind-ripple laminae respectively. Statistics for these vertical transect data are shown in Table 5.6. The vertical permeability data are very variable, returning an optimal sample interval of 0.06m which is close to, but greater than, the actual sample interval of 0.02m. Nevertheless, the confidence limit for the original sample data is still high at $\pm 15\%$. The correlation structure within these data, for which details of the variogram model are given in Figure 5.16, shows a range of 1.2m and a nugget effect that remains constant at a sample interval from 0.02 to 0.2m. The optimal sample interval of 0.06m therefore, provides an adequate representation of both the static and spatial permeability variation. Again, a large nugget effect is observed, although this is smaller than in the horizontal direction. This difference in the nugget values between the horizontal and vertical sample data is surprising since a lower nugget effect might be expected in the horizontal direction where laminae are likely to be of

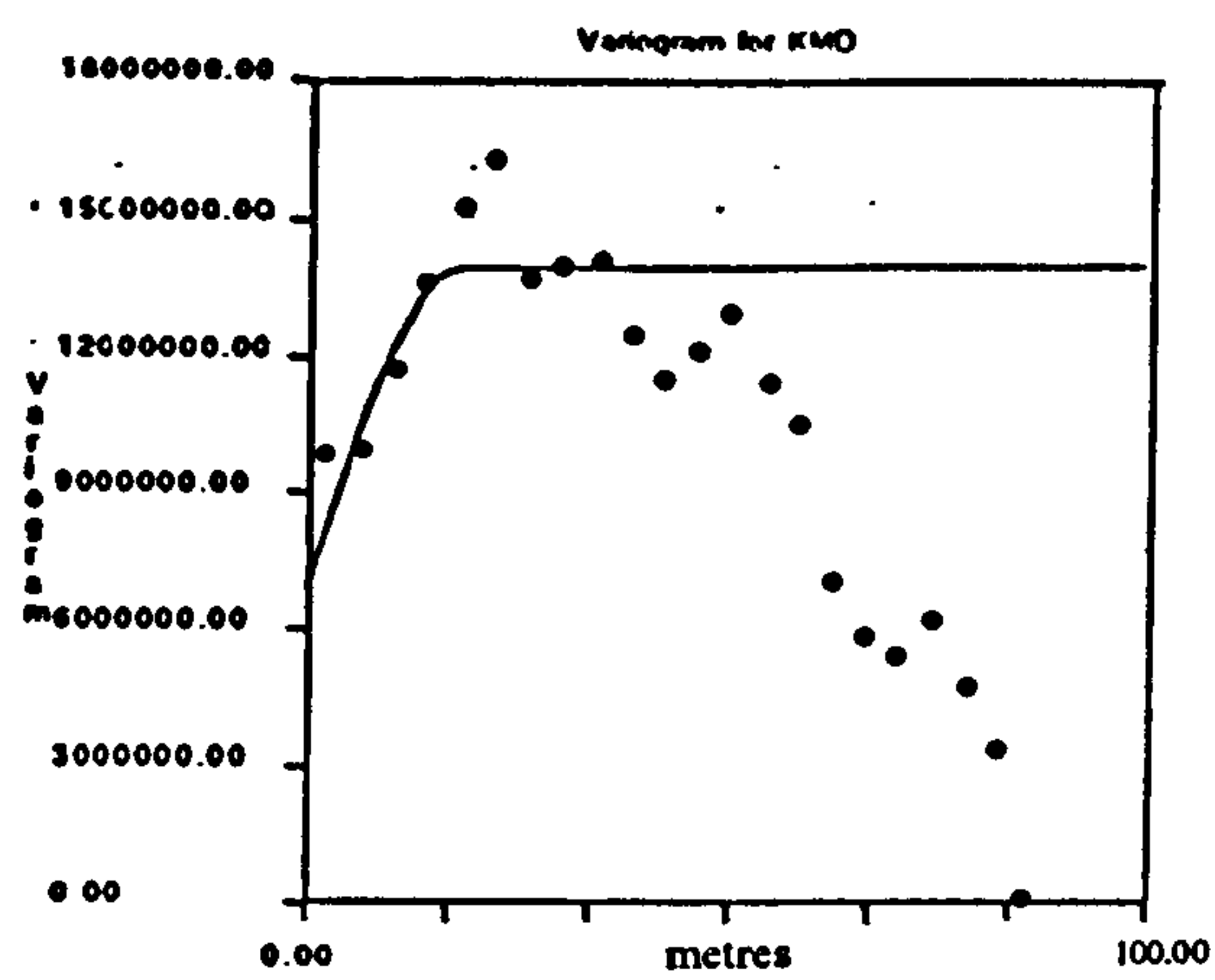


Figure 5.14 Variogram of the horizontal transect permeability data

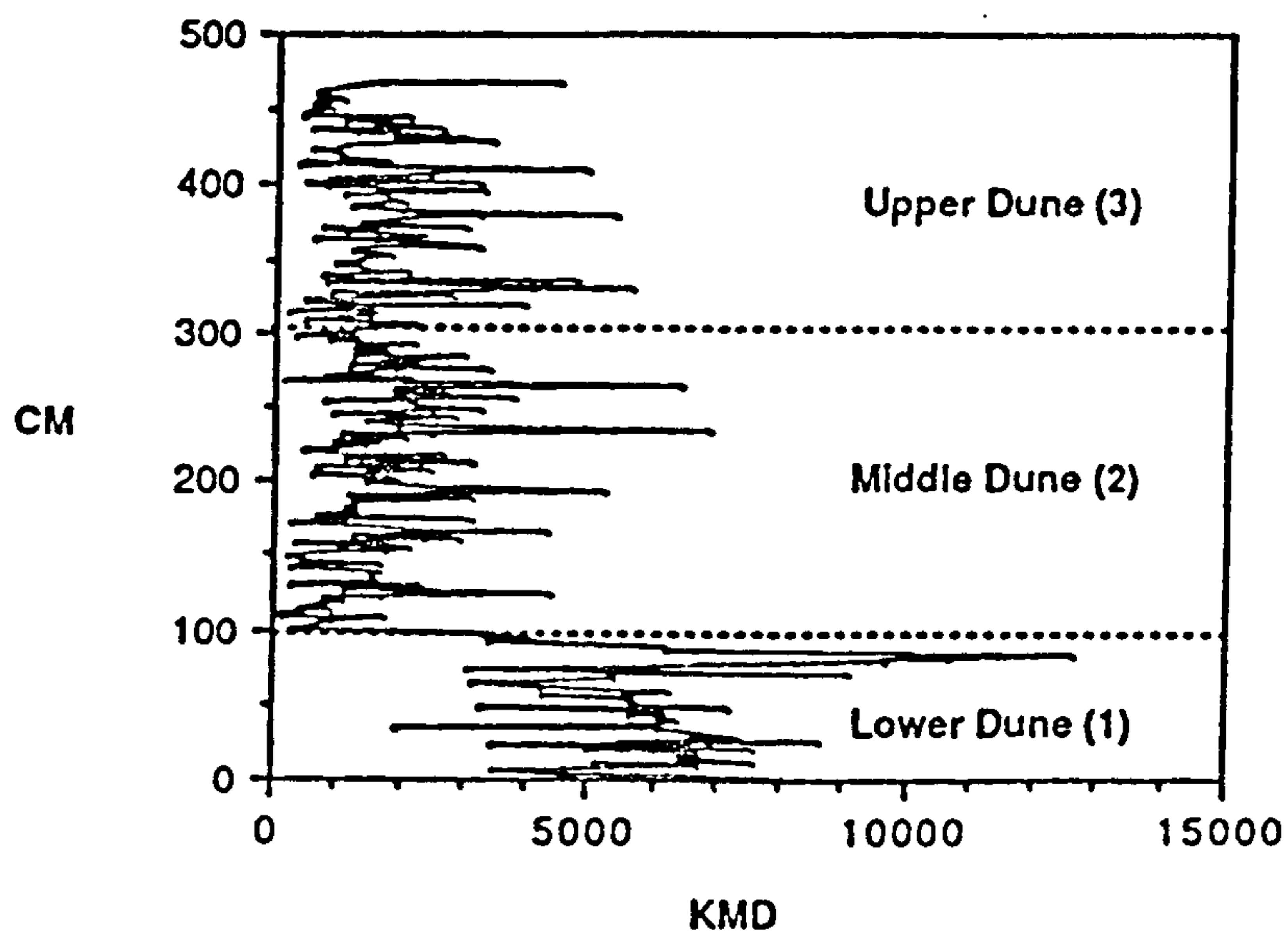


Figure 5.15 Permeability profile from the vertical transect through the Dawlish Sandstone

Dune:	1, 2 & 3
Transect Direction:	Vertical
Mean kmD:	2591
Std. Dev:	2233
n:	234
Sample Interval (m):	0.02
Conf. Lim. (alpha=0.005):	+/- 15%
Cv:	0.86
N0 (p=20%):	74
DS (m) (p=20%):	0.06

Table 5.6 Descriptive statistics, optimal sample number and confidence limits for the vertical transect data

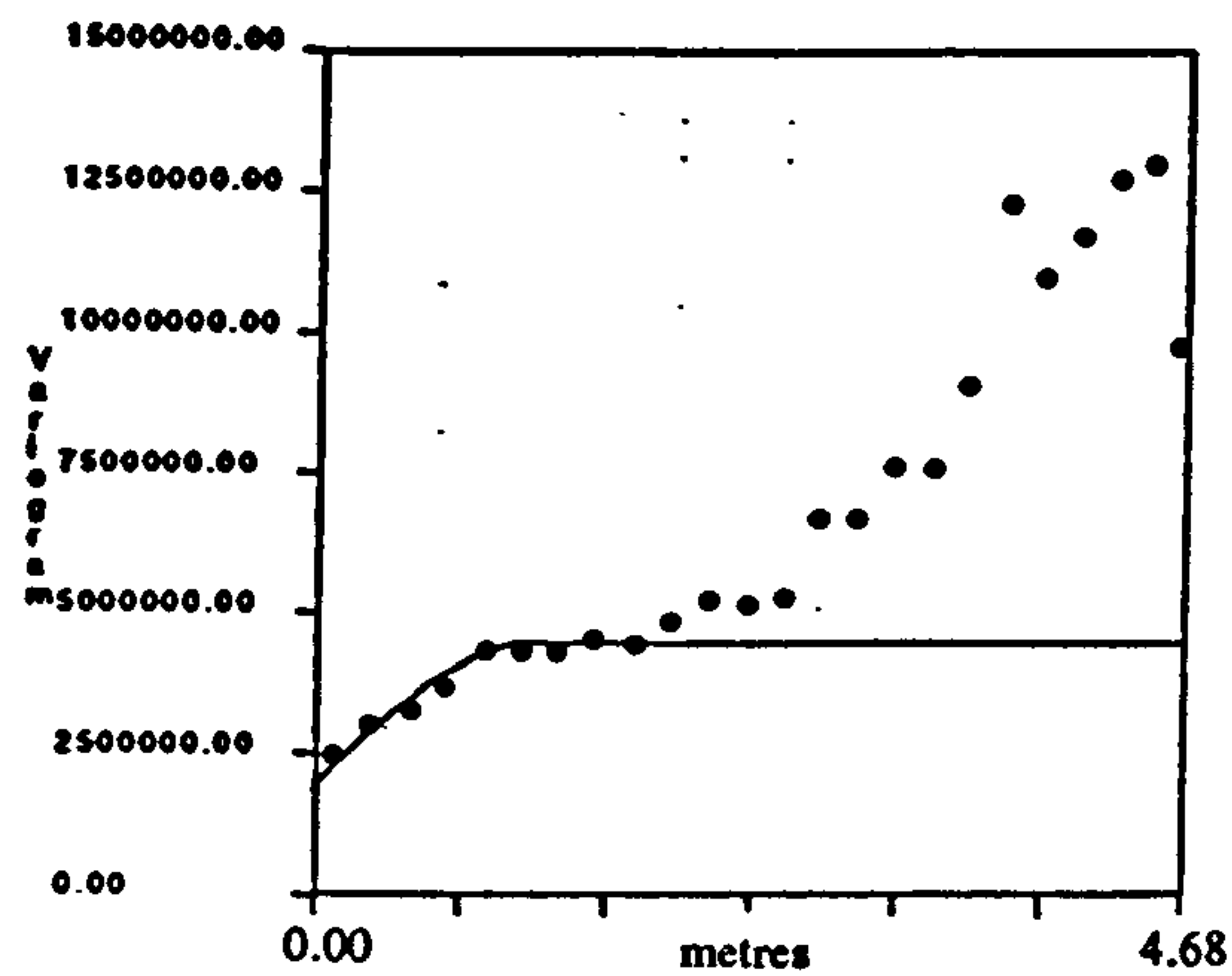


Figure 5.16 Variogram of the permeability data sampled from the vertical transect

Source:	DF:	Sum Squares:	Mean Square:	F-test:
Between Groups	2	6.8 E8	3.4 E8	164.75
Within Groups	231	4.8 E8	2.1 E6	p=0.0001
Total	233	1.2 E9		

Comparison:	Mean Diff:	Scheffe F-test:	Dunnett t:
1 vs 2	4207	141*	16.81
1 vs 3	4189	130*	16.15
2 vs 3	-18	0.004	0.085

*Significant @ 95%

Table 5.7 Anova table showing the comparison between permeability data from within different dunes sampled on the vertical transect

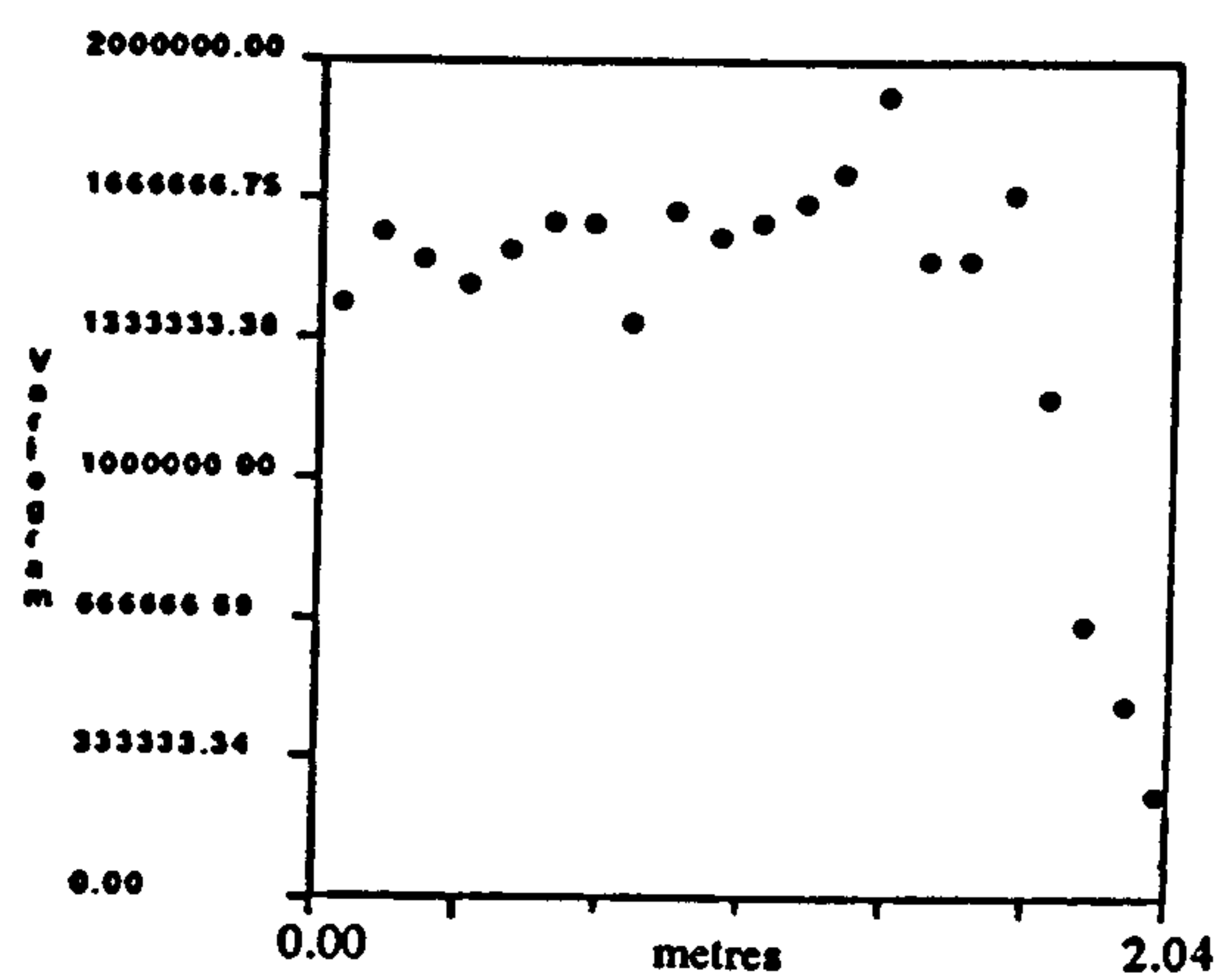


Figure 5.17 Variogram of permeability data from dune 2 sampled from the vertical transect

a similar type where they occupy the same position relative to the dune foreset.

Permeability data from within each dune as identified on the vertical transect were compared using ANOVA (Table 5.7). A significant difference between population means was identified, where the lowermost dune (dune 1) has a significantly higher mean permeability and lower variance than the two overlying dunes. These differences in permeability are probably related to diagenesis. No significant difference was identified between the permeability populations from dunes 2 and 3. As there is no obvious difference in the spatial structure of permeability within dunes 2 and 3, 2nd order bounding surfaces do not provide reliable guidelines for reservoir zonation.

The implication of these results is that within vertical uncored intervals, the interpretations of aeolian dune forms and associated 2nd., 3rd., and 4th. order bounding surfaces (dune boundaries to individual foresets) from wireline log characteristics cannot be extended to provide reliable indicators of permeability heterogeneity without knowledge of the grain size variation within and between individual dunes. It is important therefore that maximum use is made of grain size indicators such as the electrical S.P. logs and high resolution resistivity logs (the SHDT log for example) which should be calibrated using core, side wall cores and ditch cuttings.

In the variogram for the vertical transect data from dune 2, a pure nugget effect is used to model the correlation structure (Figure 5.17). This indicates that these data are completely uncorrelated. This means that permeabilities sampled at the optimal sample interval of 0.04m will provide adequate representation of both the static and spatial permeability variation.

5.8.2.4 Guidelines for further sampling

To complete this outcrop study, further horizontal transects are required within the same dune unit at different levels and from within other dune units. This will enable comparison of static and spatial permeability variation within and between dunes. Additional horizontal transects in different orientations are also required to obtain a quantification of static and spatial permeability variation in 3-D. A detailed investigation of permeability variation laterally over distances up to 1 km within ancient aeolian dunes of the Tensleep Formation (Cretaceous), USA, is currently being undertaken by research staff from Imperial College and Herriot Watt University.

By constructing horizontal transects within dunes 2 and 3, differences in the horizontal correlation structures between the dunes can be established. If the correlation structures differ, this will show that the permeability variation between dunes measured on a vertical transect is statistically indistinguishable, both statically and spatially. This means that permeabilities sampled from vertical transects provide an unreliable indicator of permeability variation away from the well.

The short lateral extent of this outcrop limits application of the horizontal correlation structure for typical interwell distances. Over distances of several hundreds of metres to kilometres, large scale permeability heterogeneities caused by changes in dune morphology and major facies changes (for example, between dune and interdune deposits) will have a significant effect on fluid flow in the reservoir and the accurate prediction of such changes is required. Having evaluated the permeability heterogeneities within this outcrop, the quantification of long-range correlation structures is required from additional outcrops elsewhere.

Investigation into diagenetic and textural variations over the sample domains is also required to explain the observed differences in permeability between dune forms of the same genetic type.

5.10 Conclusions

- 1) Outcrops should be selected to represent rock types from specific depositional environments.**
- 2) The geological structure and depositional model for the outcrop should be well defined and unambiguous.**
- 3) The outcrop should have a reliable depositional datum with measurable palaeocurrent directions.**
- 4) Outcrops should be selected with horizontal dimensions equivalent to well spacing in reservoirs (100's of m to km's). The horizontal dimensions are more important than the vertical dimensions.**
- 5) Depositional and post-depositional characteristics should be easily differentiated in order to establish and quantify the causes of permeability variation.**
- 6) Sampling schemes have two main aims: to obtain probability distribution functions (pdf's) for permeability, and to quantify the spatial disposition of this permeability. Sampling schemes that are used to obtain probability distributions should be unbiased. Sample schemes that are used to quantify the spatial disposition of permeability may be biased provided they are justifiable.**
- 7) The best sampling strategy for permeability at outcrop is a combination of stratified systematic centric ('regular grids') and 1-D stratified systematic aligned sampling ('transects'). Stratified systematic centric sampling is used for both static and spatial statistics. 1-D stratified systematic aligned sampling is used for spatial statistics only.**
- 8) Knowledge of the depositional characteristics provides a rational basis for subsampling. By utilising the concept of genetic depositional units, reliable sampling can be done iteratively at each scale of depositional heterogeneity. By calculating the confidence limits for data at each scale, the reliability of the data base is quantified. Having quantified permeability heterogeneities within genetic depositional units,**

these values can be fitted easily into the geological model for the reservoir.

9) This method of characterising permeability heterogeneities at outcrop is dependent on the existence of a recognisable hierarchy of scales of depositional heterogeneities, corresponding to a similar hierarchy of permeability heterogeneities. Where there is a continuum of depositional heterogeneity, subdivision into classes of permeability heterogeneity may introduce bias.

It is unlikely that all of these conditions required for outcrop permeability studies will be satisfied but providing the limitations of the study are recognised, analysis and interpretation of these data may be conducted in the light of these limitations where the problems and limitations of the study are clearly defined. By doing this, the publication of misleading and ambiguous results can be avoided. Probably the most common problem encountered in outcrop studies is one of accessibility. Invariably the outcrop can be traversed continually with relative ease, even if vegetation, fallen rock debris and soil have to be removed first, but access vertically is usually more difficult. As a result more sample data are often obtained from horizontal transects than vertical ones, and the data are likely to reflect this bias. Analysis and interpretation of these data should therefore consider this bias.

PART 2

Introduction to Part 2

To draw together those factors concerning outcrop permeability studies investigated in part 1 of this thesis, a detailed outcrop permeability study is presented in the second part of this thesis on the White Sandstone; a massive sandstone of shallow marine origin that crops out in the area of Morvern in north west Scotland. This outcrop study serves two purposes; firstly to demonstrate the measurement and sampling methods employed in outcrop permeability studies, and secondly to determine whether the spatial permeability heterogeneities within this massive sandstone are adequately represented by a layer-cake model (see Figure 2.3). The outcrop itself was chosen because of the excellent 3-D exposure afforded by access through a network of mine galleries.

This outcrop case study is presented in four chapters. Chapter 6 describes the geology and depositional environment of the sand body, including a detailed analysis of mineralogical and textural characteristics and depositional bedforms. In chapter 7 the sampling scheme, based around a conceptual geological model for the sandstone, and subsequent data analysis are presented. The sandstone is rather special in that its massive nature makes subdivision into genetic depositional units within the sandstone body difficult to apply and for this reason the sand body is treated as a single genetic unit. Having established the static and spatial variation in permeability, the causes for this measured variation are investigated in chapter 8. Finally, in chapter 9, a permeability model is developed for the sandstone and simulated permeability values are compared with the original data in order to validate the model and assess suitability of a layer-cake model.

CHAPTER 6 The geology and depositional environment of the White Sandstone, Lochaline, Scotland

6.1 The White Sandstone exposures

Movern is one of the few areas on the Northern Scottish mainland where Cretaceous sedimentary rocks are preserved *in situ*. Lochaline (figure 6.1) has the most extensive and best known Cretaceous outcrop, but several other similar Cretaceous sequences are preserved nearby and on western Mull (Judd, 1878; Bailey, 1924; Lee and Pringle, 1932).

On the west side of Lochaline, directly north of the village of Lochaline, approximately 22.5 metres thickness of Cretaceous sequence are preserved, of which approximately 12.1 metres comprise the White Sandstone (Humphries, 1961). This exposure of the White Sandstone is the focus of this study.

6.2 The stratigraphy

Since the work of the Geological Survey during the early part of this century (Bailey, 1924; Lee and Pringle, 1932), only the work of Humphries (1961) has made any contribution to the stratigraphy of the Cretaceous rocks of Morvern. With the exception of one starfish (MacLennan, 1949), the absence of macro- and microfossils make the stratigraphic status of the White Sandstone uncertain. Consequently, the stratigraphy is based on the bounding sequences above and below. The underlying Greensand contains Cenomanian body fossils and recent micropalaeontological investigations (Braley 1990) have confirmed a Cenomanian age. A red mudstone overlies the sandstone which is assumed to be of Tertiary age (Smith, 1989) although there is no palaeontological evidence to support this assumption, and, as a similar claystone is present between the presumed lateral equivalent of the Lochaline Sandstone and a thin sequence of Senonian chalk at Beinn Iadain (figure 6.2) some 11 kilometres north of Lochaline, it is somewhat premature to assume a Tertiary age. Exposures of the

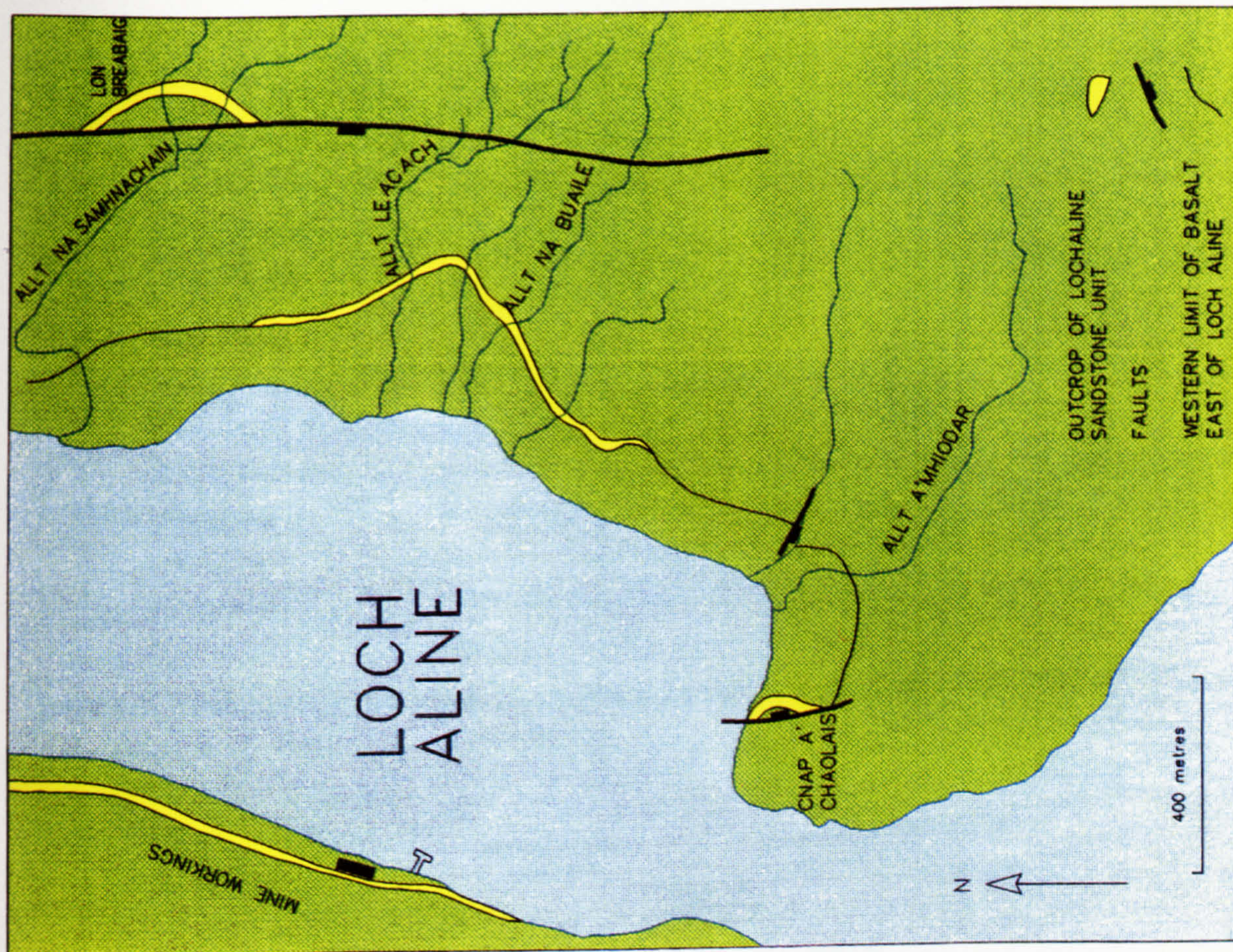
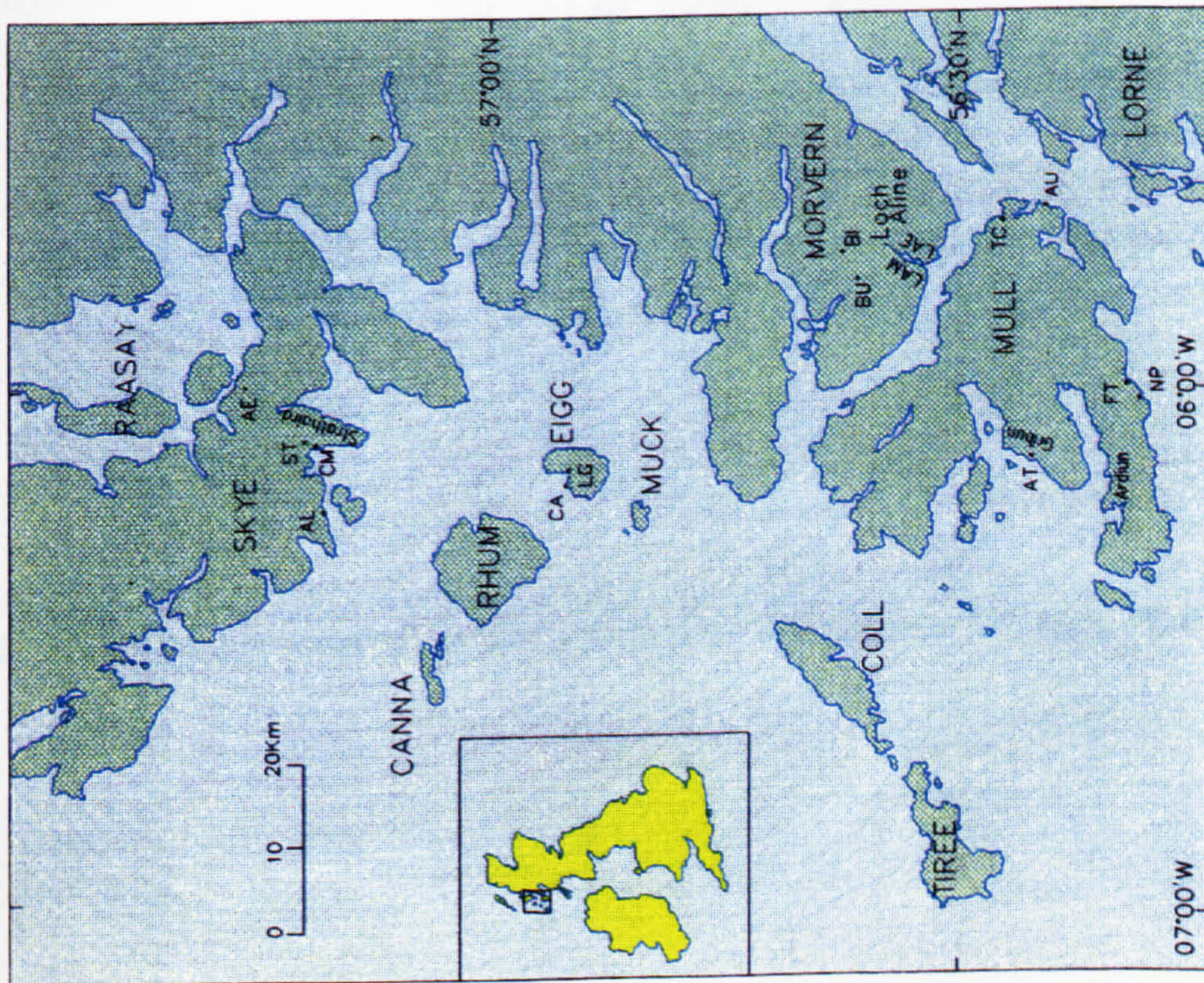


Fig. 6.1 Location of the mine and exposure of the White Sandstone providing the outcrop used in this study

		Ft	In	
(Basalt lava)				
(Red mudstone (altered voic. ash)				
(Sandstone (often discoloured)		4	0	
(Top hard rib of sandstone)	18 in. to ...	2	2	ROOF OF MINE
(White sandstone)		5	0	
(Hard rib of sandstone)		2	0	
(White sandstone)		9	0	
(White sandstone with thin clayey beds)				BASAL DATUM IN THE MINE
(Ribbioned sandstone)	2 in. to ...	0	3	
(White sandstone)	3 ft. to ...	4	0	
Green sandstone				

Table 6.1 Thicknesses of sub-units within White Sandstone as exposed in the mine at Lochaline

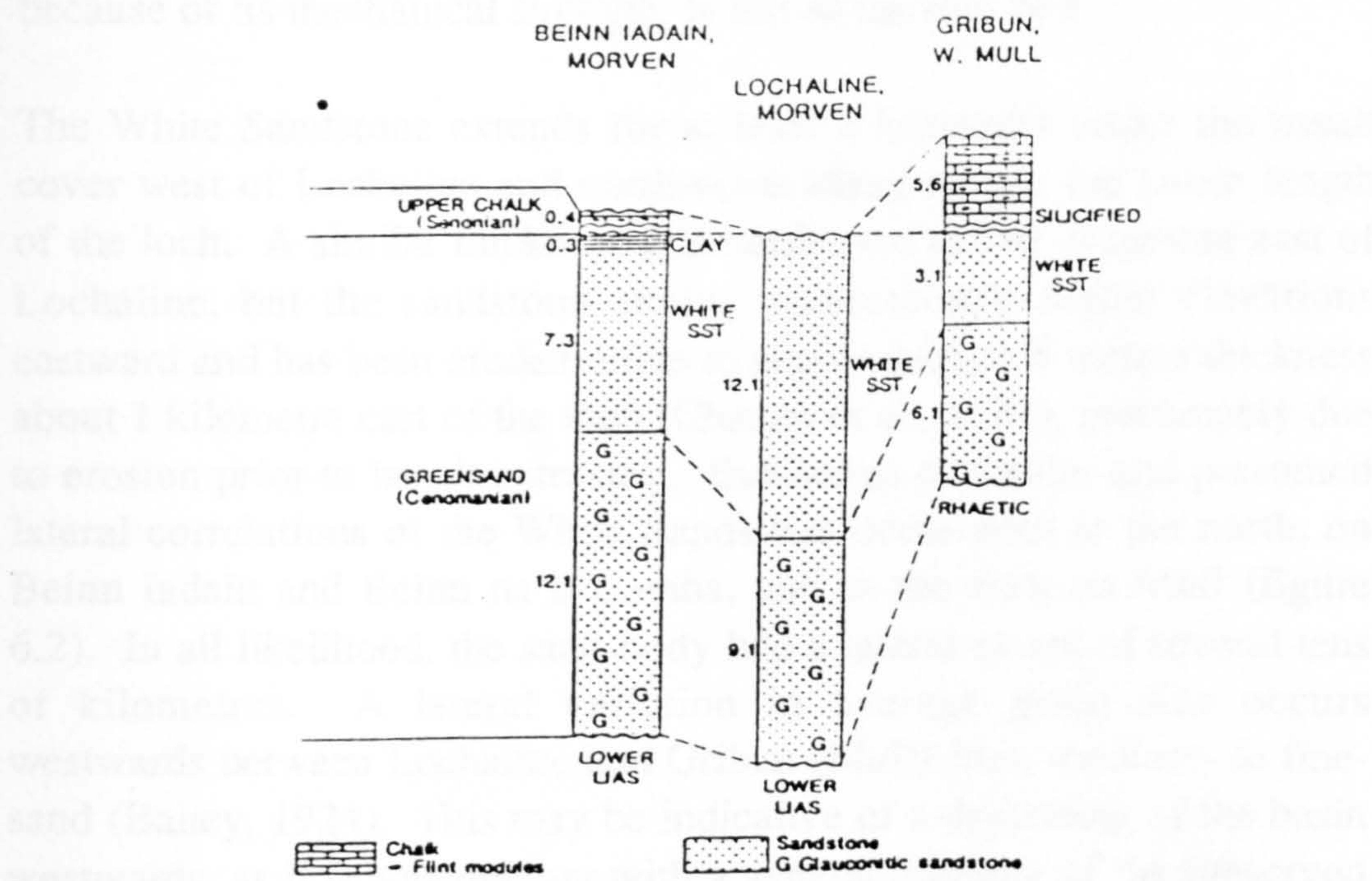


Fig. 6.2 Lateral correlation of the White Sandstone from Morvern (North) to Mull (South)

mudstone in the mine suggest that it has not formed by *in situ* alteration of basalt. A sharp boundary is identified between the basalt and the mudstone, and apparent sedimentary lamination is also present within the mudstone suggesting a depositional origin. If a Tertiary age is attributed to this mudstone then a mixed volcanoclastic - sedimentary origin seems likely. The succession on the west side of Lochaline is summarised in table 6.1.

The White Sandstone has a sharp basal contact with the underlying Greensand and in general, appears remarkably uniform in character. Two layers of 'hard' quartz cemented sandstone (Humphries, 1961) are identified in the upper two to three metres of the sandstone, their precise level varying along the outcrop. Their use as marker horizons is, therefore, limited, though they do identify the top and bottom of the sandstone interval which is extracted in the mine. The upper hard band, because of its mechanical strength, is left as the roof bed.

The White Sandstone extends for at least a kilometre under the basalt cover west of Lochaline and northwards along almost the entire length of the loch. A similar thickness and northward extent is present east of Lochaline, but the sandstone attains progressively higher elevations eastward and has been eroded down to approximately 6 metres thickness about 1 kilometre east of the loch (Chatten et al., 1971), presumably due to erosion prior to basalt extrusion. Exposures of similar and presumed lateral correlations of the White Sandstone occur both to the north, on Beinn Iadain and Beinn na h-Uamha, and to the west on Mull (figure 6.2). In all likelihood, the sand-body had a lateral extent of several tens of kilometres. A lateral variation in average grain size occurs westwards between Lochaline and Gribun (Mull) from medium- to fine-sand (Bailey, 1924). This may be indicative of a deepening of the basin westwards, as it is concomitant with a general thinning of the preserved sequence, though thickness variations may be attributable to pre-Tertiary basalt extrusion erosion.

6.3 The structural geology

The White Sandstone at Lochaline is horizontally bedded with little evidence of regional folding, however, the area around Lochaline is dissected by normal faults, some of which are penetrated by basalt dykes. These fed the extensive Tertiary lava flows extruded onto a surface of eroded sedimentary rocks of Triassic to Tertiary age in the Morvern area. A major series of faults trend approximately north-south, with a second series approximately perpendicular to these (figure 6.3). It is apparent both from figure 6.3 and from outcrops in the mine that the faults often bifurcate and change direction.

Faulting has had a major influence on the Lochaline sandstone both syn- and post- depositionally. On the footwall side of major faults, thicker and better quality sand is present. Smaller scale fault-related variations of thickness and sand quality are also observed, associated at one locality with sediment slumping.

Dykes have intruded along many of the fault planes, with several phases of dyke intrusion as several chilled margins can often be observed within single dykes. Evidence for post-dyke intrusion faulting is abundant. Some faults are extensively sheared, whereas others are truncated. Post-intrusional faulting has in some cases avoided the dykes and it may be inferred that these dykes have annealed the fracture zones. Post-intrusional faulting is clearly visible both at outcrop and within the mine.

6.4 Geological description of the White Sandstone

6.4.1 The mineralogical and textural characteristics

A very detailed mineralogical description of the White Sandstone is given by Humphries (1961), who used a combination of mechanical sieving, electromagnetic separation, and density separation in bromoform. Whilst quartz makes up over 99% of the sand by weight, a small fraction (0.7 grammes from 3.5 kilogrammes of sand collected by

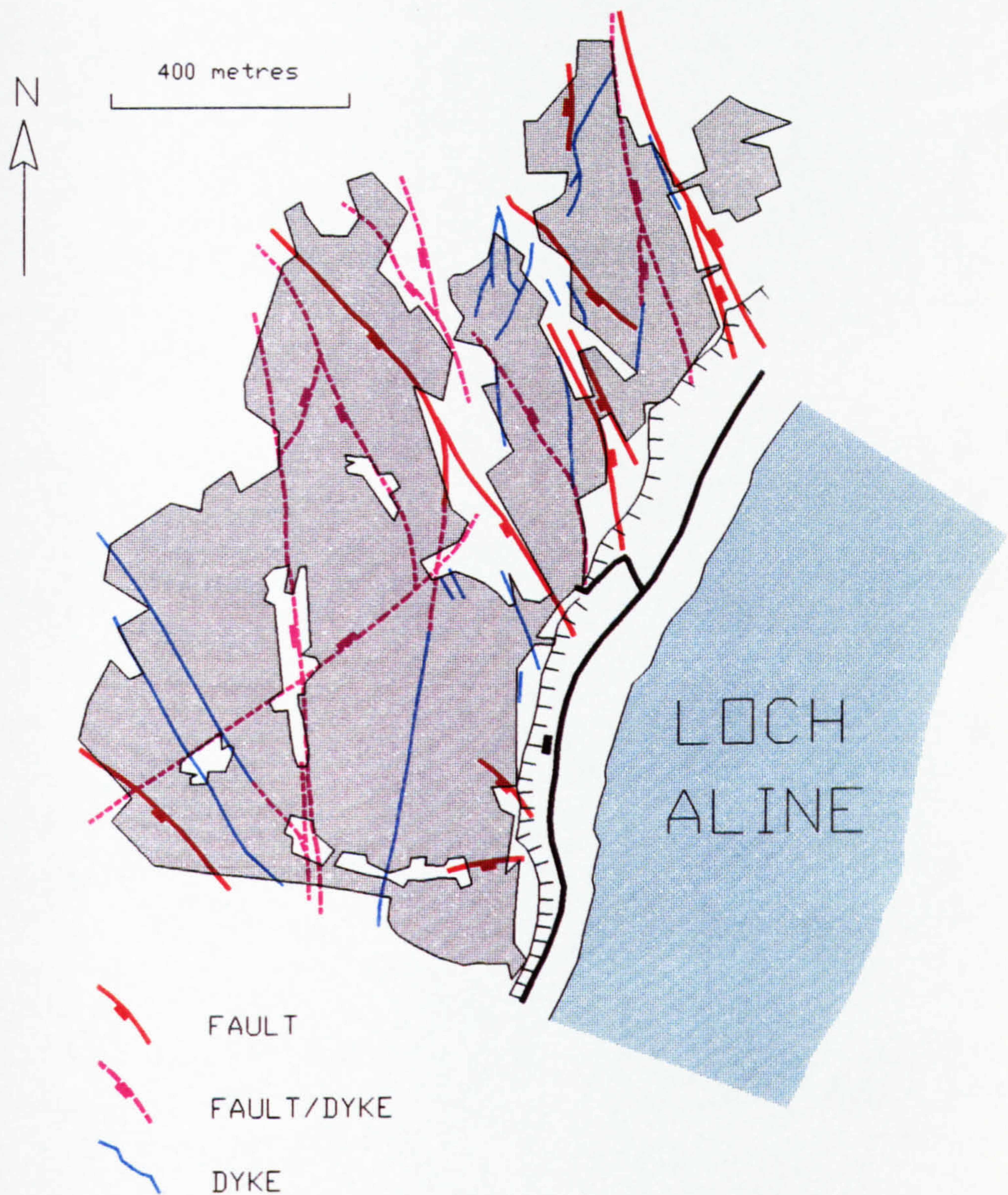


Fig. 6.3 Structural map of the White Sandstone exposed in the mine at Lochaline showing the major faults (thin lines) and dykes (thick lines) - map supplied by Tilcon Mines Ltd. Lochaline

Humphries) consists of accessory minerals (minerals not essential to the definition of the rock). These accessory minerals are subdivided into a heavy and light mineral fraction and then the number of grains are counted. Of the heavy fraction, about half is comprised of opaque minerals (leucoxene, ilmenite, magnetite, goethite, limonite, iron pyrites and chalcopyrites), with the remainder comprising tourmaline (most of which is well-rounded or near spherical), zircon, rutile, garnet, staurolite, epidote, kyanite, sphinel, and sphene in decreasing abundance respectively. The light fraction is comprised of glauconite and clay minerals. The clay minerals occur in pellets of silt-sized quartz grains and aggregates of clay particles (altered feldspar?), both of which are found in the coarser sieve fraction. A trace of kaolin is found in the finest sieve fraction. Micas occur in both the heavy and light fractions and are probably muscovite. This mica is seen to be concentrated in the lower part of the vertical sequence.

A rare, and previously unrecorded, exposure of medium to large, sub-rounded to rounded, pebble-sized quartzose clasts exist at one locality in the roof of the mine. The pebbles appear to be comprised of silicified quartz grains, very similar in appearance to grains from within the White Sandstone itself.

The White Sandstone is a very well sorted, fine to medium-grained sand. Lithological sections, approximately 150 metres apart, orientated north-south, display a coarsening up sequence in which silty, intensely bioturbated sands pass upwards into medium-grained sands (figure 6.4). Visually, this coarsening up transition appears to be variable; in some areas it may occur over the first metre whereas in others it may be over 2 to 3 metres. A vertical sequence of samples were taken at 0.25m intervals, approximately mid-way between the lithological sections shown in figure 6.4. Sieved fractions were examined under the microscope to detect grains with quartz overgrowths but these were very few and had a negligible influence on the grain size results. The frequency histogram for each sample taken from the vertical profile is shown in figure 6.5. The mean grain size increases vertically, corresponding to improved sorting shown by a decrease in the standard deviation. The proportion of fine-grained sands (<0.21mm), whilst

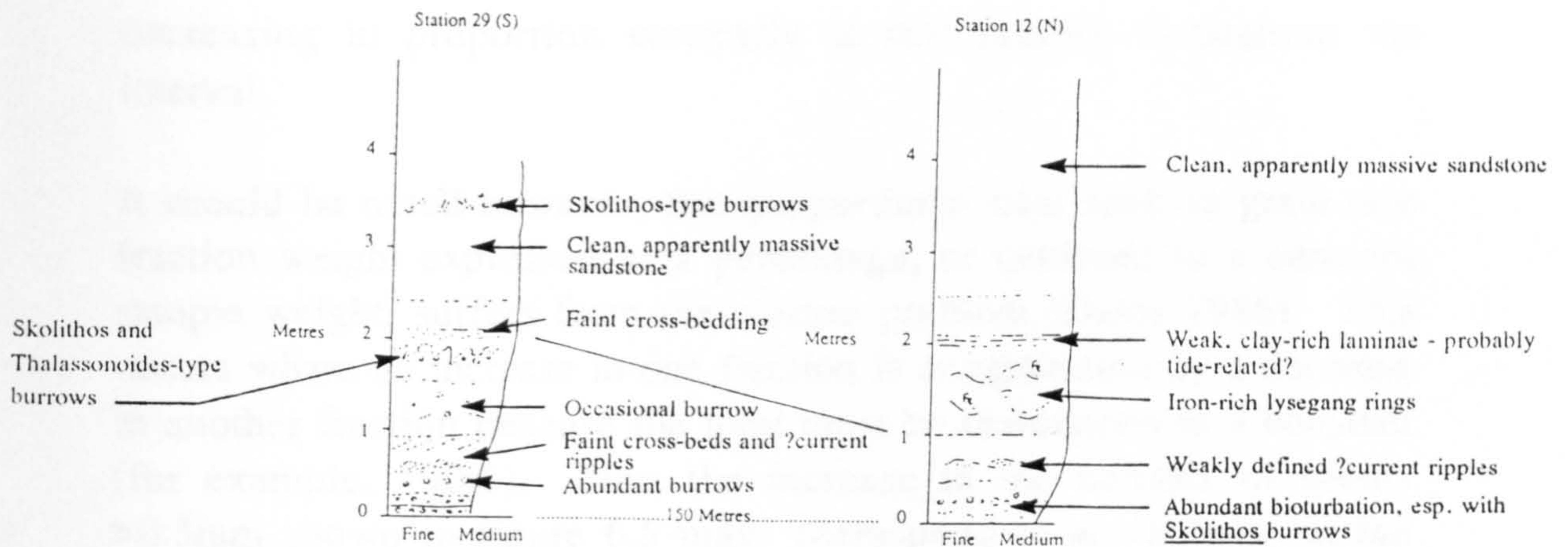


Fig. 6.4 Lithological logs of the White Sandstone from the north-south cross-section

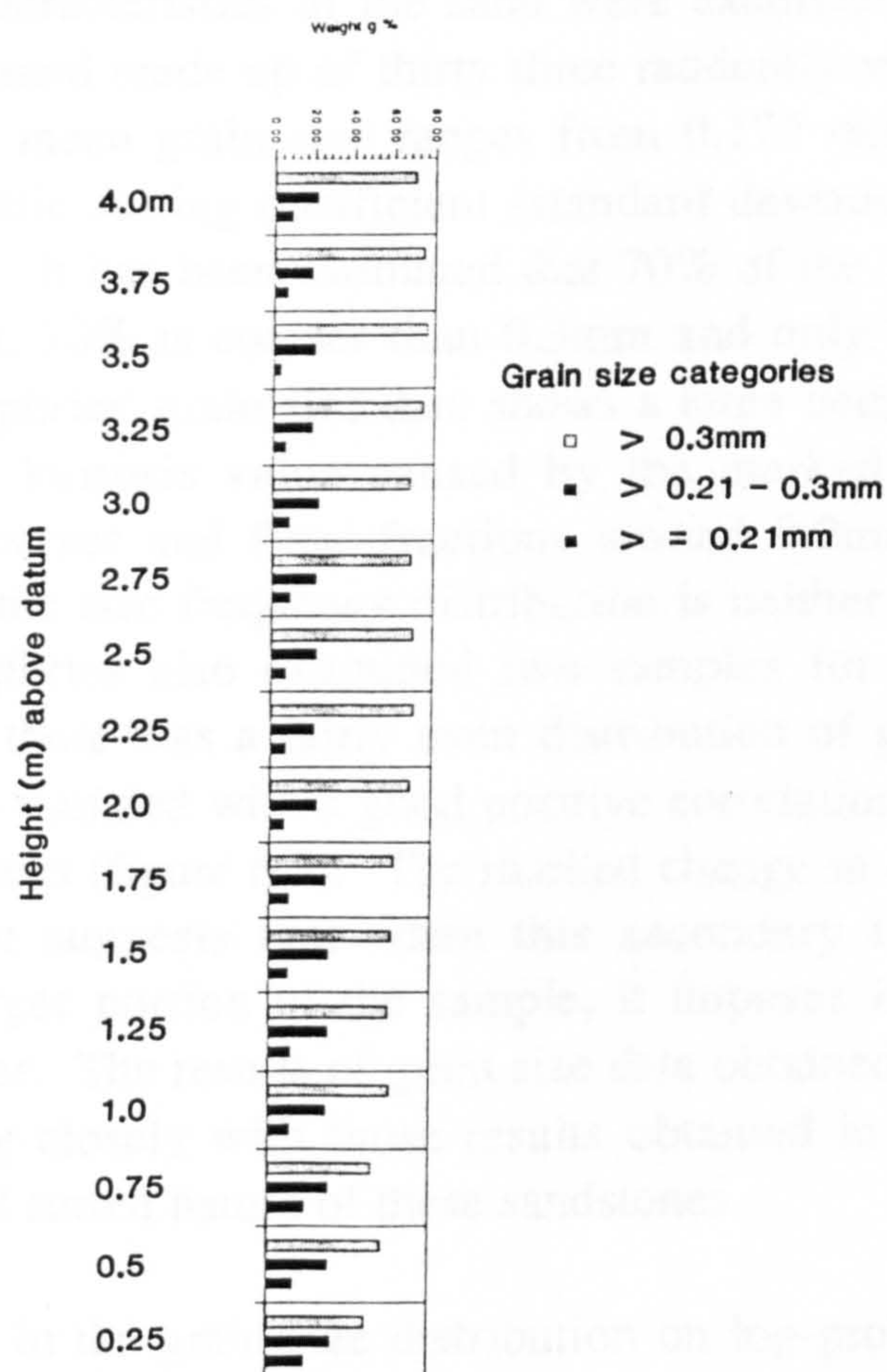


Fig. 6.5 Variation in grain size vertically through the White Sandstone

decreasing in proportion vertically is still present throughout the interval.

It should be noted however, that proportional data such as grain size fraction weight expressed as a percentage, or confined to a constant sample weight, suffers from the closure problem (Davis 1986). This occurs where an increase in one fraction is compensated by a decrease in another fraction because the total must be maintained at a constant (for example, 100%). Thus the increase in the number of grains $>0.3\text{mm}$ shown in figure 6.5 may correspond to an increase in the other fractions but with a lesser rate of increase, and not an apparent decrease in the proportion of finer grained fractions. Nevertheless, the results shown still reflect an increase in mean grain size vertically.

The textural characteristics of the sand were examined by Humphries (1961) from a sand made up of thirty three randomly selected samples. The arithmetic mean grain size ranges from 0.177 mm to 0.244 mm, and the arithmetic sorting coefficient (standard deviation) ranges from 0.368 to 0.817. It has been estimated that 70% of the sand is between 0.2 and 0.3mm, 10% is coarser than 0.3mm and only 3% is less than 0.08mm. Humphries' grain size data shows a large negative skew (fine tail) and large kurtosis value caused by the marked differentiation between the coarser and finer fractions around 0.2mm (figure 6.6), indicating that the size frequency distribution is neither log-normal nor normal. Humphries also examined two samples for roundness and concluded that there was a fairly even distribution of grain roundness from angular to rounded with a good positive correlation between grain size and roundness (figure 6.7). The marked change in the linear slope around 0.2 mm suggests that when this secondary fine population represents a larger portion of the sample, it imposes its own distinct textural character. The results of grain size data obtained by Humphries correspond very closely with those results obtained in this study and confirm the well sorted nature of these sandstones.

Breaks in slope in the grain size distribution on log-probability curves may be used to identify the three different fundamental modes of transport: surface creep, saltation, and suspension (Inman 1949, Visher

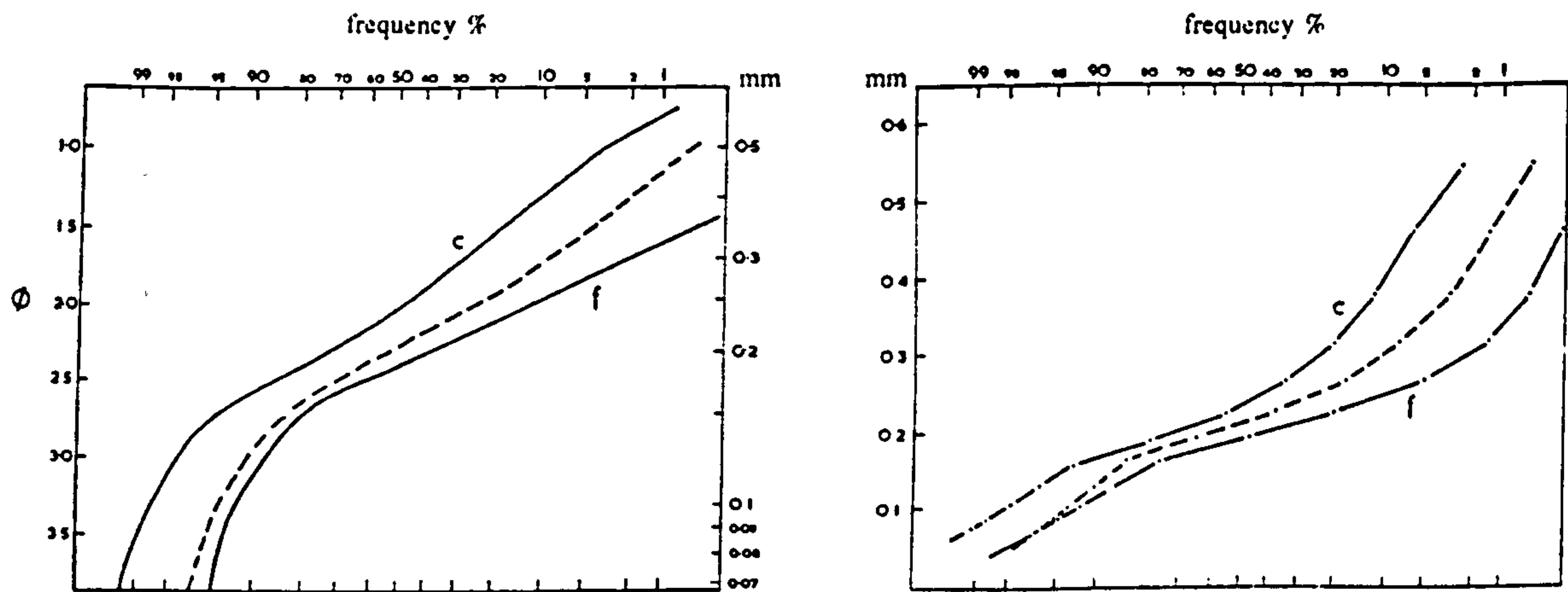


Fig. 6.6 Logarithmic and arithmetic grain size frequency probability curves (after Humphries, 1961)

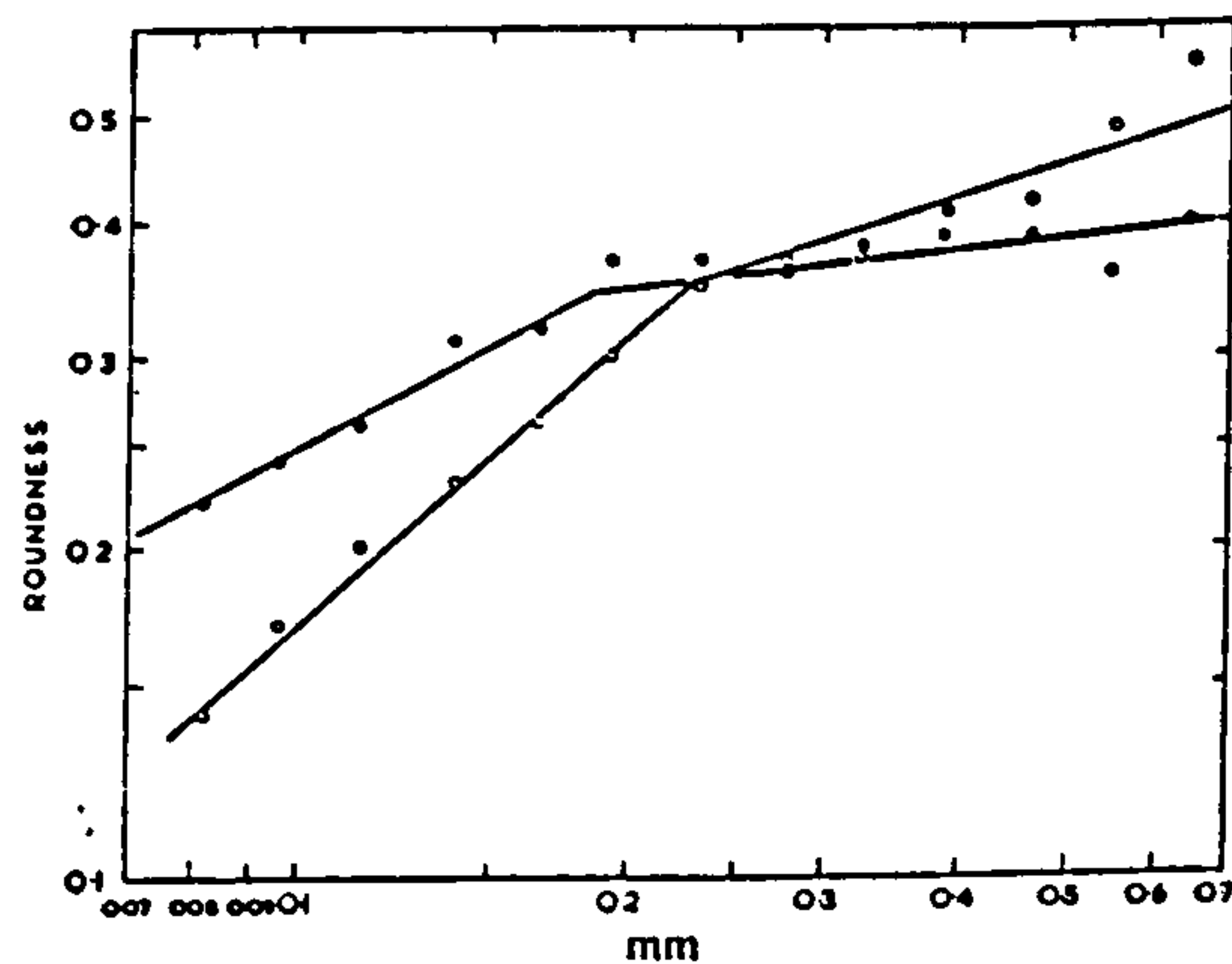


Fig. 6.7 Cross-plot of grain roundness against mean grain size for two sand samples (after Humphries, 1961)

1969). Applying Visher's interpretation to Humphries' grain size probability curves in figure 6.6, a small suspension population below 0.2mm, and an indivisible saltation and surface creep population from 0.2mm to around 0.5mm are identified.

It is interesting to note that if the glauconite is removed from the underlying Greensand, its mineralogical and textural appearance is very similar to the overlying White Sandstone (bearing in mind that decalcification of the White Sandstone may have caused all calcareous material to be leached out as evidenced by the moulds of bivalves that occur in the basal part of the sandstone).

6.4.2 Biogenic and sedimentary structures

Visible bioturbation structures appear to be restricted to the silty horizons at the base of the White Sandstone. The overlying cleaner sands may also be bioturbated but minor variations in grain size and mineralogy render associated structures invisible. Burrow types include *Ophiomorpa* sp., *Skolithos* sp. (*Skolithos nodosa*?) (Martino and Curran, 1990) and *Thalassanoides* sp., with individual *Skolithos*-type burrows extending downwards up to 30 centimetres, often with *spreiten* (layers within the burrow-fill) clearly preserved. A fairly complex tiering system is present in many areas, suggesting varying sedimentation rates and substrate conditions. The upper surfaces of some bioturbated layers are sharply defined and must have been planed down by the next depositional event (figure 6.8). Close examination of these burrows sometimes reveals a lining of clay pellets (*Ophiomorpha*). Within the cleaner sands (those containing fewer fines), the occasional burrow is seen in cross-section producing an oval or circular-shaped structure that may represent the long, vertical U-tubes characteristic of *Skolithos* and possibly indicative of more rapid sedimentation rates. The association of trace fossils and clean, high energy sands make this a good example of the *Skolithos* ichnofacies described by Frey and Pemberton (1984).

Bioturbated layers are only traceable over a few metres laterally, where

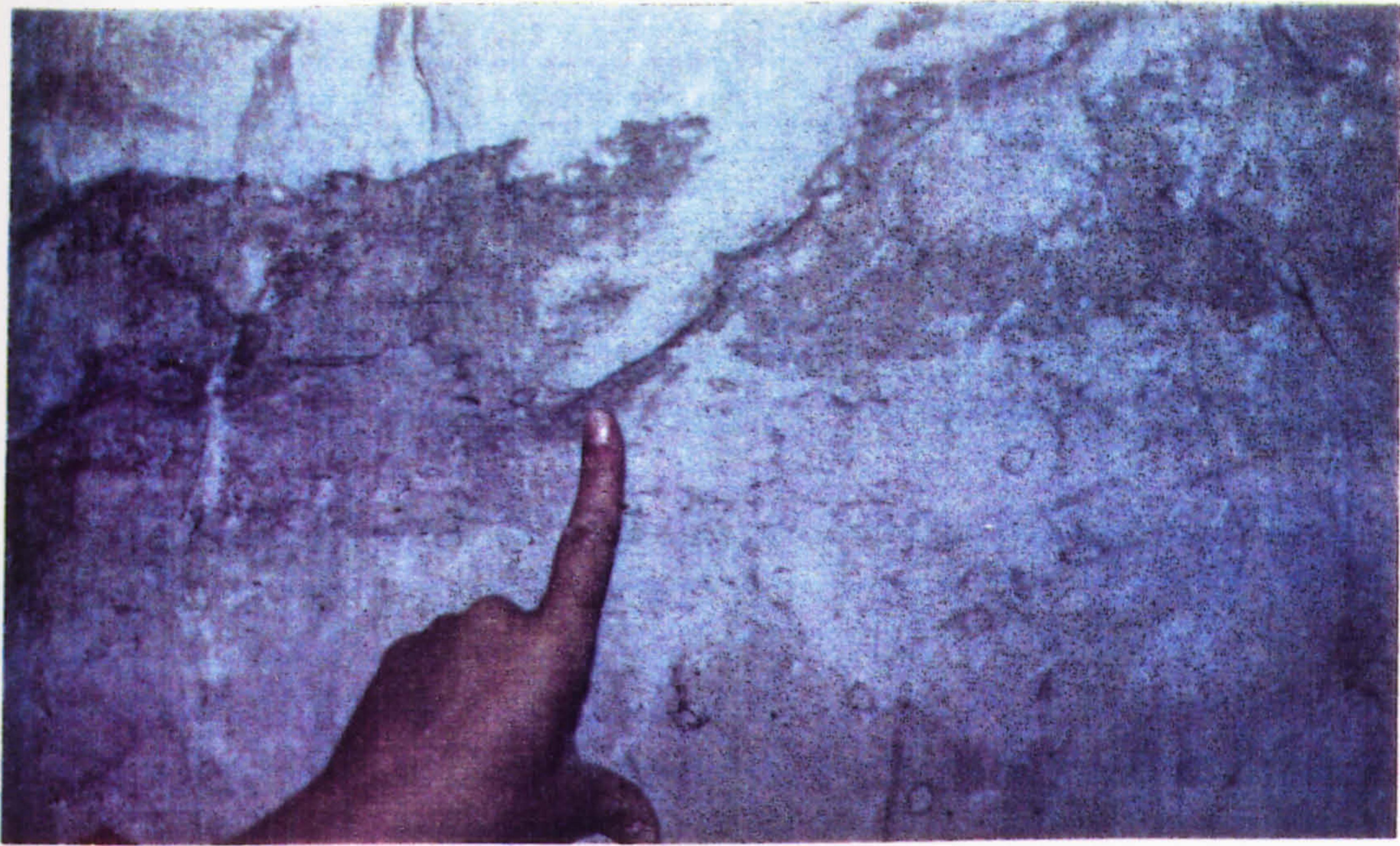


Fig. 6.8 Photograph of bioturbation within the White Sandstone

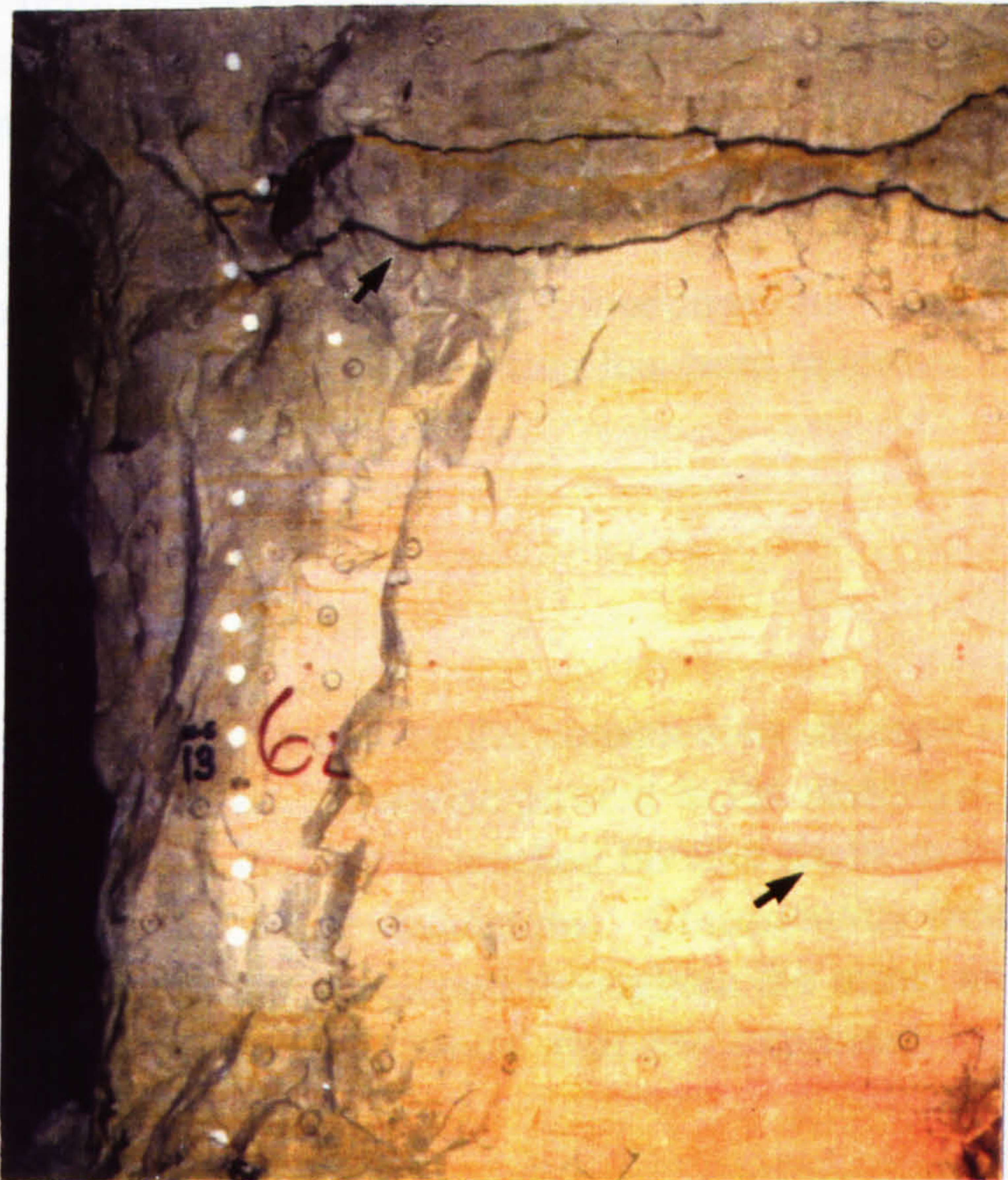


Fig. 6.9 Diagenetic features within the White Sandstone. Silicification (outlined at top) produces discontinuous wavy hard bands. Towards the base of the section, iron staining produces distinct pinkish red lysegang rings

they either disappear or bifurcate. The degree of bioturbation also varies significantly over the area of the mine. This is probably the result of a combination of sediment erosion and patchy faunal activity in low energy areas (hence the association with siltier sands). It is possible that there is a larger regional trend to the bioturbation - silt content over the mine, although this has not been quantified.

Sedimentary structures are difficult to see with the naked eye because of the uniform character of the sand. However, faint cross-beds may be discerned on weathered faces outside the mine where tabular and trough cross-beds form a series of stacked units, each about 0.5 metres thick with a foreset dip angle of approximately 35°. Although there is poor 3-D exposure, a unidirectional foreset orientation towards the north-west is inferred. The boundaries between each cross-bed are sharp and traceable laterally over several metres. As there is no evidence to suggest that these cross-beds pinch out or are truncated, it is possible that these bedforms extend laterally over tens or hundreds of metres. Inside the mine, bedforms are rare, although small current ripples, bundles of silt laminae and gravitational slump structures have been identified. At a few locations within the mine, faint cross-beds may be discernable but these structures are easily confused with non-depositional features produced by concentrations of diagenetic iron oxide. At Beinn Iadain, flaser bedding has been recorded at the base of the White Sandstone (Braley 1990).

6.4.3 Diagenesis

Decalcification is recognised by the conspicuous absence of calcareous macro- and microfossils, otherwise present in the underlying Greensand and evidenced by the moulds of leached bivalve shells in the lowermost silty horizons of the White Sandstone. Conspicuous iron staining is another feature variously developed throughout the mine, and secondary silicification produces 'hard bands' that are exploited to support the mine roof.

The distinct red to orange coloured iron oxide stains form 'lysegang

ring' structures up to a metre or so in height. These are most extensively developed in the lower 2 to 3 metres of the exposed interval although they are occasionally seen higher in the unit (figure 6.9). There is a marked concentration in iron oxide immediately above the silty sands at the base. Different ring structures, identified by their various colours, are seen to cross-cut each other implying different stages of formation. These lysegang rings appear to follow apparent bedding structures in some areas, whilst in other areas they sweep across them. Iron oxide is also concentrated along faults and newly-formed fractures, some of which have been initiated since mining began some 50 years ago.

Silicification is the main diagenetic feature. Many grains have frosted surfaces (Humphries, 1961) which on close examination are seen to be evenly spread over the grain surface in pits and on fractured surfaces. This frosting occurs on grains of all sizes and in some cases grades into sharp, faceted surfaces suggesting that the frosting is a post-depositional chemical dissolution process where the reprecipitation of the silica produces the faceting (figure 6.10). This interpretation is in contrast to other workers (for example, MacLennan, 1949) who have used this frosting on grains as evidence for aeolian abrasion. The development of facets appears to be more marked on the coarser grains suggesting that the precipitation of silica is connected to the radius of curvature of the grain. In extreme cases the grains may be welded together by secondary quartz (figure 6.11). However, silicification has had little effect on cementation elsewhere and samples viewed under high magnification reveals a loosely packed sand (figure 6.12). The sand is held together by its original packing strength, which causes samples to readily disintegrate into loose grains when they are scraped. There is however, a marked variation in the crushing strength (the force applied to an unconfined sample at the point of failure) which is probably caused by minor, localised cementation and/or variations in the grain fabric.

Two hard ribs of sand, forming the roof and about 1.5 metres below the roof of the mine are the product of concentrated silicification. The lower rib varies in thickness from about 0.2 metres to 1 metre thick, whilst the roof-forming rib remains about 1 metre thick over its extent.



Fig. 6.10 Faceting on a quartzose grain caused by the reprecipitation of silica

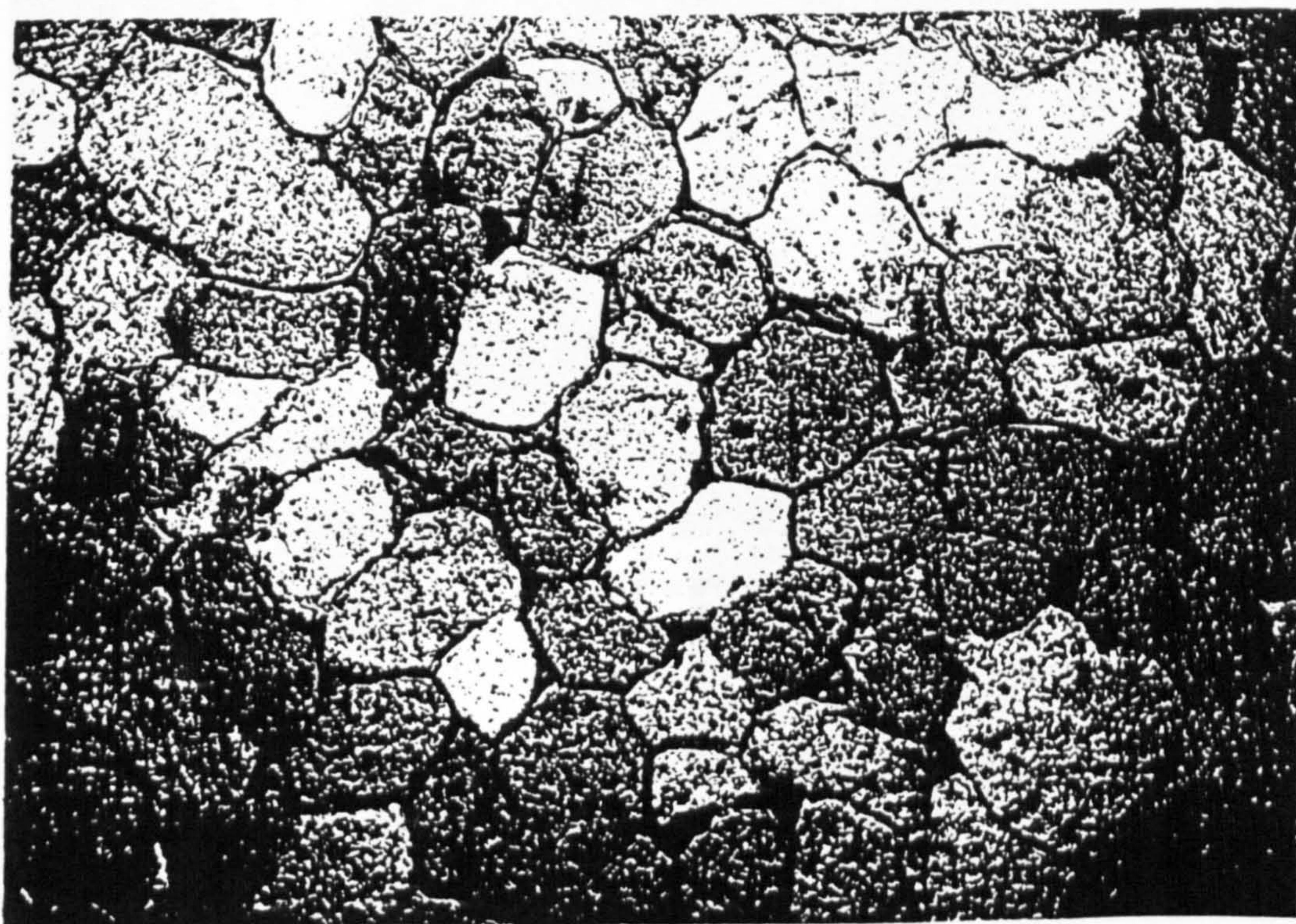


Fig. 6.11 Excessive secondary silicification of the sandstone within a sample from the upper hard band. Field of view is 0.8mm horizontally

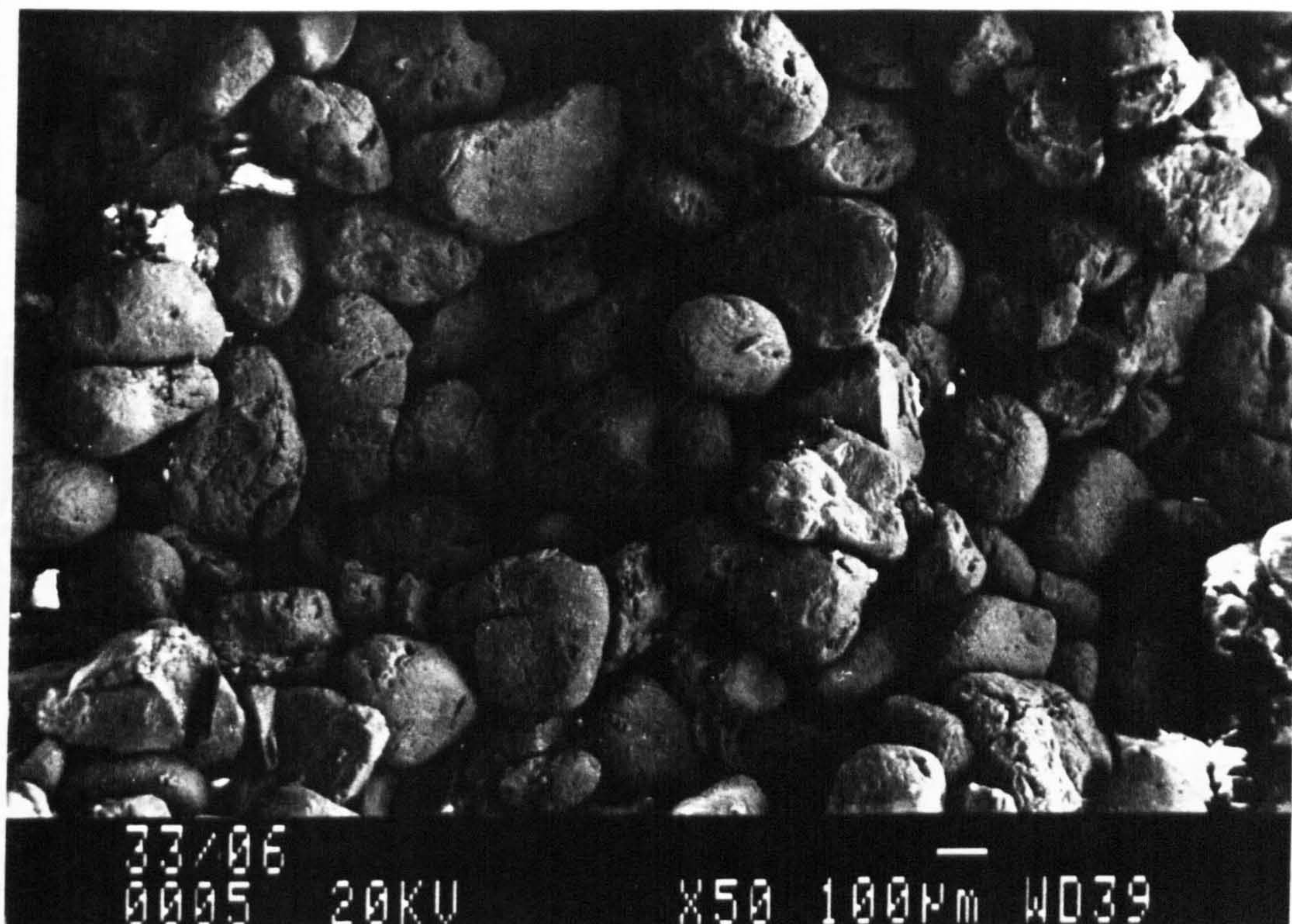


Fig. 6.12 Typical sample of the White Sandstone showing minimal cementation and grain alteration



Fig. 6.13 Rare fractured grains indicating that the sandstone has undergone some slight compaction. There is some evidence for diagenetic clay with boxwork clay coatings seen on the grain surfaces (see middle left)

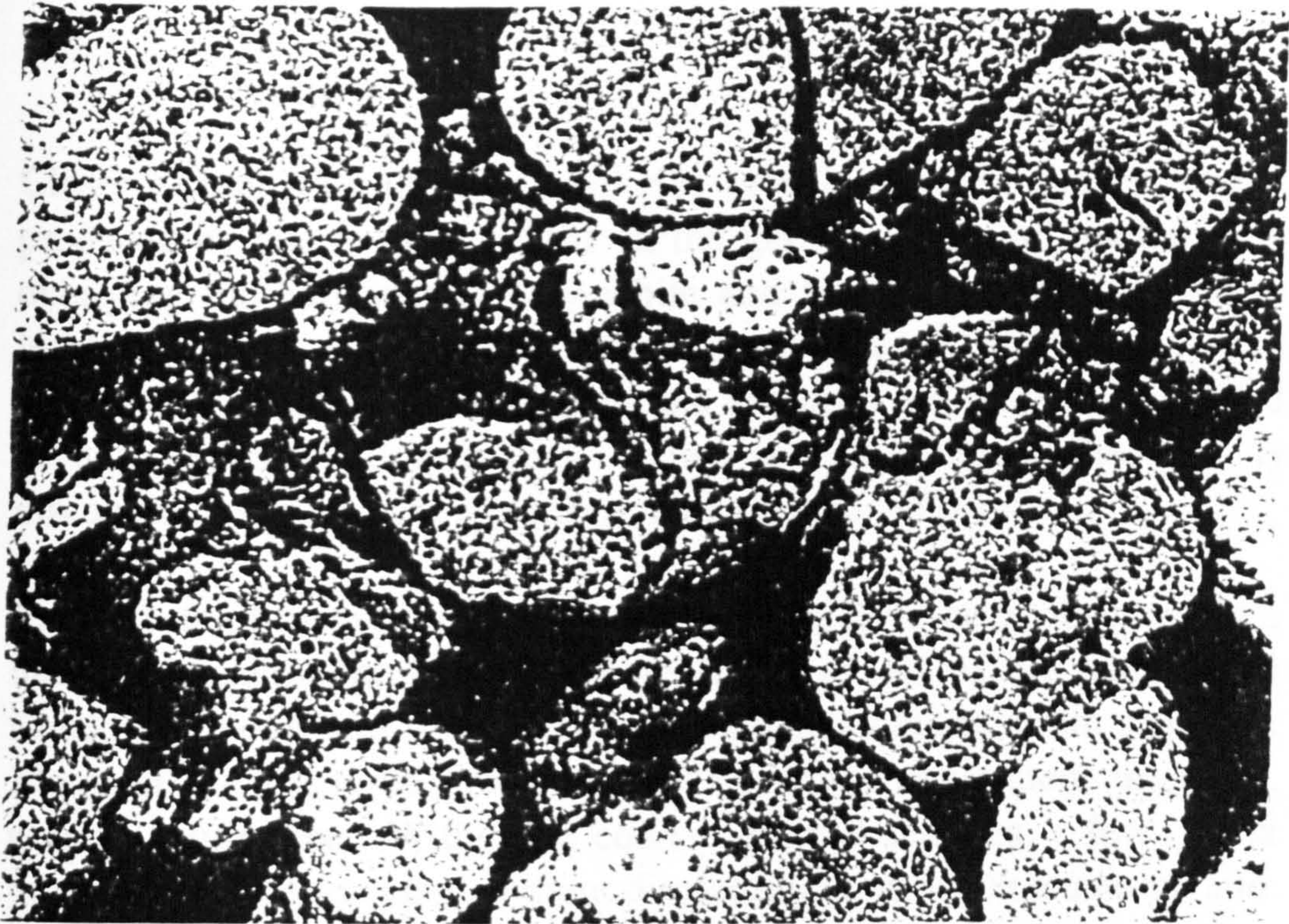


Fig. 6.14 Photograph of a fractured accessory minerals that have been compacted and forced into the adjacent pore space -field of view = 0.5mm horizontally

grains of quartz, feldspar, and mica, which are very fine-grained and have a granular texture. The grains are very small and are often fractured. The fractures are visible as dark, irregular lines separating the mineral fragments. The fractures are visible as dark, irregular lines separating the mineral fragments.

6.5 Textural relationships and the depositional environment

Interpretations of the depositional environment of the White Sandstone vary between authors. Some have considered the White Sandstone to be representative of a marginal marine environment (e.g. Lyster, 1980) or a marginal marine environment (e.g. Lyster, 1980) or a marginal marine environment (e.g. Lyster, 1980).

Thin coal and lignite seams reported by some authors (e.g. Lyster, 1980) of the White Sandstone are interpreted as being deposited in a marginal marine environment. However, the White Sandstone was deposited very close to land. However, neither coal nor lignite was deposited within the sequence of the White Sandstone, indicating a marginal marine environment.

The White Sandstone is composed of quartz, feldspar, and mica, which are very fine-grained and have a granular texture. The grains are very small and are often fractured. The fractures are visible as dark, irregular lines separating the mineral fragments.

Closer examination of these hard ribs reveals a coarse sugary texture produced by quartz overgrowths on the grains. The sand immediately overlying the hard ribs is very white and friable, presumably due to leaching. The silicified rib forming the roof is fairly level and persistent throughout much of the mine and does not seem to be related to any depositional structure. The rib lying below the roof is discontinuous and wavy, often forming lense-shaped pods.

The effects of compaction, although minimal, have been observed in a number of sediment samples where fractured grains are seen to be forced into voids and some quartz grains display slight strain shadows. Many of the fractured grains consist of minor constituent minerals, notably tourmaline. Within the coarser-grained samples, a few quartz grains tend to be fractured without displacement, producing smooth and slightly curved fractures (figure 6.13). Within finer grained samples, the accessory minerals (which are more abundant than in the coarser grained samples) tend to be fractured and displaced (figure 6.14), and grains of mica often display deformation where they are squeezed between more competent grains. Figure 6.13 also shows evidence of minor clay growths on the surfaces of some quartz grains that form a boxwork structure.

6.5 Existing interpretation of the depositional environment

Interpretations of the depositional environment for the White Sandstone vary between authors. Judd (1878) considered the White Sandstone to be representative of a transition from shoreline (the Upper Greensand) to marine (the Upper Chalk), placing it within an estuarine setting.

Thin coal and lignite seams reportedly from within lateral equivalents of the White Sandstone at Beinn-y-Hun are used to support the notion that the White Sandstone was deposited very close to land. However, neither coal nor lignite have been identified within the exposures in the mine or the immediate surrounding area of Lochaline.

The White Sandstone is considered to represent the lateral equivalent of

the Lower and Middle Chalks of central and southern England, with the White Sandstone itself marking the shoreline of the chalk sea at this time. Bailey (1924) examined the textural properties of the White Sandstone and concluded from the exceptional sorting, well rounded nature of the grains and their frosted appearance that they were wind-blown desert sands. As the final deposition of the sands were unquestionably water-lain on the basis of the bounding rocks above and below, Bailey proposed that the White Sandstone was blown into the sea from a desert shoreline somewhere nearby to the north. The purity of the sandstone and of subsequent chalks is attributed to the lack of river-borne detritus into the sea because of the aridity of the land.

According to Bailey, silicification of the sandstone is associated with post-depositional uplift and the generation of silcretes within an arid environment, adding further evidence for a desert environment bordering the chalk seas.

Lee and Pringle (1932), in an account of Mesozoic rocks in Scotland, support Bailey's interpretation for a wind-blown, shallow marine origin in a short appraisal of the White Sandstone rocks, referring to the exceptional purity and wind-polished grains.

Until Humphries (1961) work on the White Sandstone, the origin of the sands from a desert shoreline was generally accepted. However, this interpretation was reached largely on the basis of the regional stratigraphy with no consideration of the evidence that should reflect the final depositional environment; where, for example, is the evidence for a marine reworking after the sands were blown into the sea?

On examination of the mineralogical and textural characteristics of the sandstone, Humphries found that there was an even distribution in grain roundness from angular to rounded, and that the frosting on many of the grain surfaces was due to post depositional dissolution and not abrasion through wind action. Humphries proposed that the White Sandstone gained its mineralogical maturity from the reworking of the Upper Greensand and erosion of the Morvern-Strontian Granite and the Ross of Mull Granite upon which the White Sandstone is seen to rest directly at a few localities in Morvern. After erosion of these source

rocks, Humphries suggests that the sands accumulated within shallow marine sand shoals, deposited in a high energy marine environment surrounding granite islands. The polycyclic origin of the grains and vigorous marine reworking was used to explain the exceptional maturity of the sandstone.

Humphries also considered the silicification of the White Sandstone to have occurred after the chalk was uplifted, probably in association with desert conditions as evidenced by Tertiary sands of supposed desert origin in the surrounding area. This process is in accordance with Bailey (1924), but Humphries does not accept the Tertiary desert as evidence for a Cretaceous desert bordering the chalk sea.

6.6 Discussion

In the following discussion, the origin of the White Sandstone postulated by previous authors is evaluated using the evidence available from the exposures in the mine at Lochaline.

Probably the most convincing evidence for marine deposition within the White Sandstone are the burrows. The trace fossil association seen in the White Sandstone, resembling the *Skolithos* ichnofacies of Frey and Pemberton (1984), represents a high energy shoreface environment. The long vertical *Skolithos* burrows indicate rapid deposition where feeding and living patterns were dominated by a vertical sediment accumulation. The morphology, abundance, diversity, attitude and association of these trace fossils with sedimentary bedforms also indicate periods of slack water and the occasional input of organic material providing a food source.

During quiet periods, bioturbation was probably more intense where the substrate was stable and rich in organic food material, favouring a greater diversity of creatures. The presence of a fine-grained, suspension load throughout the sandstone (see figure 6.5) indicates that fine material was available throughout deposition. During periods of slack water these fines accumulated to form silt drapes as evidenced by the current ripples with silty tops. This fine material was also a rich

food source that encouraged intense bioturbation.

As the energy of the system increased, the grain size of deposited sediment increased and finer material must have remained in suspension as no accumulations of fines are evident. However, this fine material is still found disseminated through the coarser sands and some reason for its preservation is required since fines deposited directly on the sea floor would normally have been reworked and winnowed out. One possible explanation for this is provided by filter feeders. Evidence from the White Sandstone suggests a fairly abundant infaunal community that occupied long vertical burrows. Such burrow types are indicative of high energy, unstable sands, where the animal was able to compensate for changes in the level of the sea floor. Through continued extraction of fines from the surrounding water, a substantial proportion of fines may be incorporated into the substrate. This is further evidenced by the occasional burrow that is lined with clay pellets (*Ophiomorpha* sp.).

Sedimentary bedforms include stacked tabular cross-beds and current ripples and indicate deposition under conditions of unidirectional flow. The 0.5 metre thick cross-beds are laterally extensive and indicate deposition from megaripples formed by unidirectional open-flow rather than channel-confined currents. At one locality within the mine, an apparent rhythmic sequence of silty clay laminae are identified which may indicate tidal influences. The occurrence of syndepositional faults and slump structures suggest that deposition was perhaps at times rapid enough to cause failure of the sediment.

Three gradational energy levels are suggested for the coarsening-up sequence based on the evidence provided by the trace fossil assemblage, depositional bedforms, grain texture and mineralogy. These are as follows:-

- | | |
|------------------|--|
| 2 metres to roof | High energy levels. Clean, intensively reworked sands, with fines winnowed out. Infrequent quiet periods. Filter feeders extract fines from the water and incorporate these into the substrate. Concentration of pebbles in roof represent pebble lag, possibly formed on the exposed surface of a bar or beach. |
| 1-2 metres | Alternating energy levels. Clean sands deposited during high energy events with quieter periods allowing the colonisation of the substrate where fines are used to line burrows. |
| 0-1 metre | Low energy. Silty, grey coloured sands with layers of intense bioturbation reflecting a stable substrate. Some higher energy events erode the sediment surface, but lower energy conditions quickly return and faunal activity is resumed. |

A similar facies to the White Sandstone, is described from the the Um Sahm Formation from Jordan (Selley 1970 and 1972, and Helal 1965), and the Ula Formation from the North Sea (Home 1987). The Um Sahm and Ula Formations are associated with deposition from migrating shoals on an open marine shelf. The characteristic stacked tabular cross-beds described from these formations are reminiscent of those seen in the White Sandstone. The patchy faunal activity observed in the White Sandstone may represent either periods of slack water during the tidal cycle, or areas of slack water such as in sheltered areas on the leeward side of megaripples, on the shoreward side of the shoal, or in deeper, quieter water on the seaward side of the shoal. As the trace fossil assemblage is typical of a high energy shoreface environment, areas with intense bioturbation probably represent periods of quiet water on the shoreward (back-barrier?) side of the sand shoal.

The pebble lag, identified in the roof of the mine, suggests that the sand body may have been above sea level at some period because cementation must have occurred prior to their formation as the pebbles are comprised of material similar in appearance to the White Sandstone

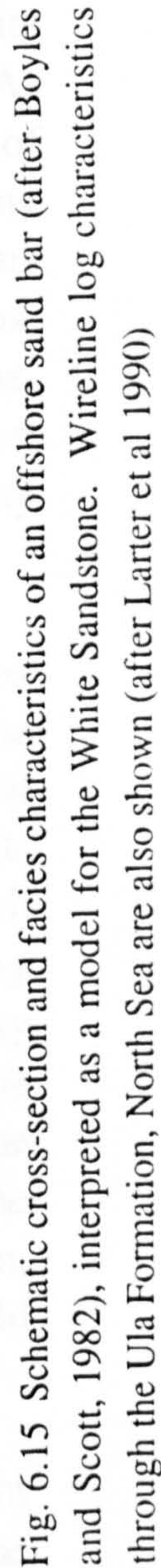
itself. Evidence of wave-generated structures such as symmetrical ripples and hummocky-cross-stratification, which might be expected near the crest of the sand shoal, may be identified but as depositional structures are poorly preserved they provide unreliable indicators of wave activity.

From the evidence available, Humphries' interpretation of the White Sandstone as a prograding shallow marine sand shoal is accepted. Whether deposition was wave or tidally-dominated however, is difficult to ascertain with certainty. A schematic diagram of the possible depositional environment and sand body geometry of the White Sandstone is given in figure 6.15.

6.6.1 Diagenetic history

Both Bailey (1924) and Humphries (1961) suggests that the silicified hard bands are associated with silcretes that formed under hot desert conditions during subaerial exposure of the sands following uplift (Bailey suggests a pre-chalk, ?mid-Cretaceous age whilst Humphries suggests a Tertiary age for these silcretes). If these hard bands are associated with silcretes then they must represent palaeosurfaces which are likely to extend laterally over very large areas. The orientation of these palaeosurfaces are also unlikely to correspond with the orientation of the sand-body or the present day topography. Within the mine however, the hard bands appear to lie parallel with the present sea level and tend to bifurcate and thin rapidly with distance into the mine (that is, away from the loch side). The geometry of these hard bands therefore, suggests that they are probably the product of a more localised and relatively recent process.

Silicified hard bands, similar to those from the White Sandstone, have been described by Thiry et al (1988) from the Oligocene Fontainebleau Sand. The formation of these hard bands is related to fluctuations in the water table during the recent geomorphological evolution of the landscape. Where the position of the water table remains constant for a sufficient period of time, silica, dissolved from the overlying sands by percolation, is reprecipitated at the water table silicifying the sand. This



process produces flat-lying, very tightly cemented sandstones or sedimentary quartzite lenses 2 to 8m thick. This description of the hard bands in the Fontainbleau Sands fits the description of the upper hard band within the White Sandstone that forms the roof of the mine. Contorted quartzites very similar to the lower hard band in the White Sandstone are also described from the Fontainbleau Sandstone by Thiry et al. These are attributed to a falling water table causing the quartzite band to be redissolved, producing the wavy, lense-shaped structure. As silica concentration is low in ground water, very large quantities of silica in solution are needed to provide silica for the cement. This may be achieved where water flow is concentrated at spring outflows, thus silicification would be concentrated on the valley-side of outcrops, pinching out inwards through the sand-body. In the White Sandstone, the maximum development of the hard bands occur in the southern part of the mine towards the loch and do indeed appear to pinch out away from the valley side.

The model for successive stages of quartzite development proposed by Thiry et al is shown in figure 6.16.. On the basis of this model, the relative positions of the two hard bands in the White Sandstone suggest both rises and falls in sea level. The lower hard band, by virtue of its contorted state, must have formed first, after which the water table fell causing dissolution of this hard band. The hard band identified by Humphries (1961) in the lower half of the sandstone interval may represent the position of this low water table. Some time later, the water table must have then risen above the previous level to form the uppermost hard band. As the water table is now below the floor of the mine, all three hard bands are presumably now undergoing dissolution, possibly with a new hard band forming at the present water table should this lie within the sandstone.

The iron staining caused by precipitation of iron oxide is a more recent and ongoing diagenetic process. Recent fractures associated with the mining process occasionally have reddish brown stains visible along the fracture. There is evidence for a number of phases of iron precipitation seen by the cross-cutting relationship of different coloured ring structures. The concentration of iron staining towards the lower

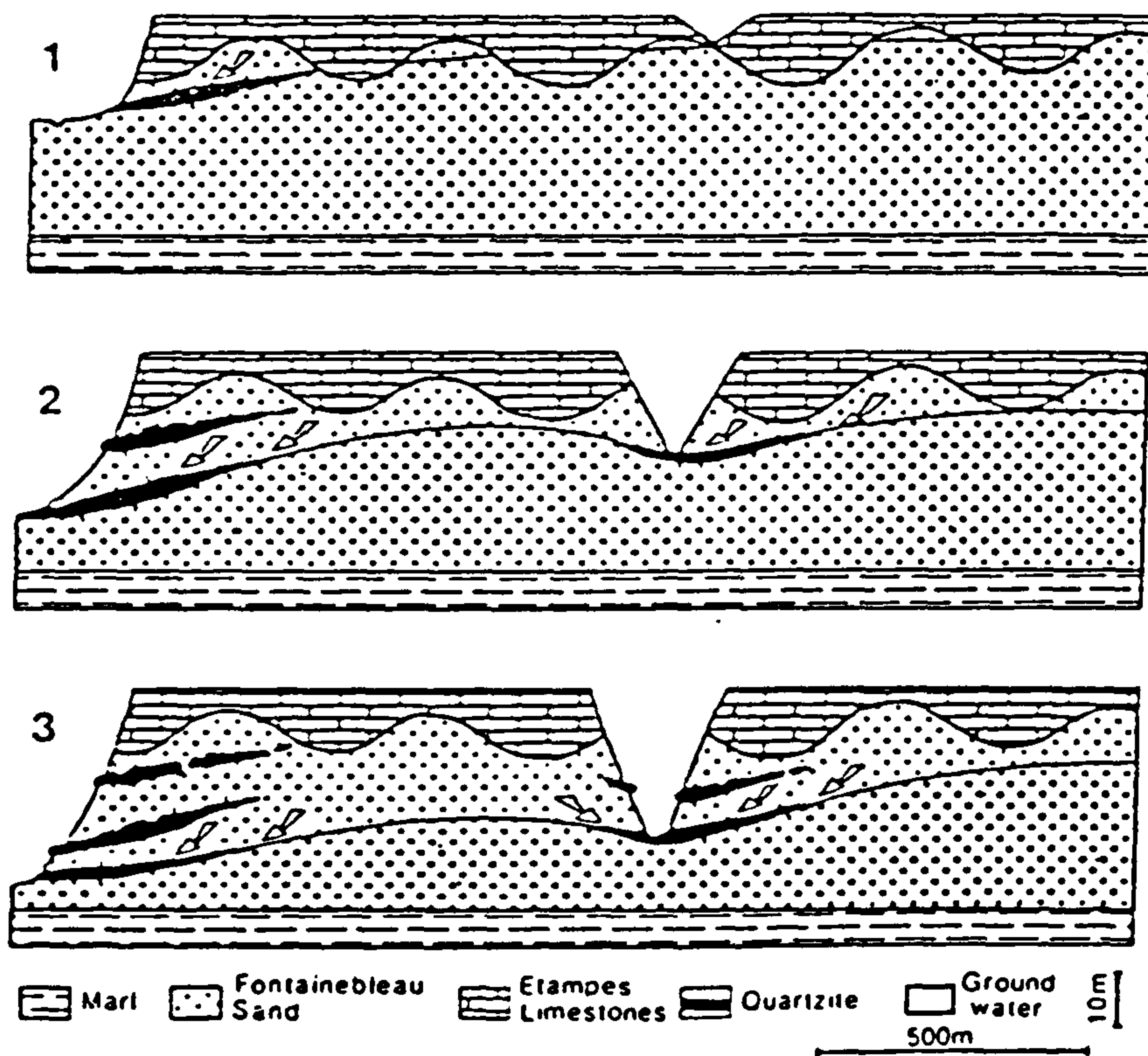


Fig. 6.16 A model for the development of the siliceous hard bands within the White Sandstone (after Thiry et al, 1988)

permeability basal sands suggests that it is produced by the downward percolation of iron-rich ground water, the overlying basalt providing the source for the iron. Free flowing water passing through fractures in the overlying basalt are often associated with newly formed iron oxide staining. Whilst the iron staining is very noticeable, the concentrations of iron are very low (less than 0.3 %), producing very thin rims of iron oxide around the grains.

It is unlikely that the cause of fracturing within grains is through blasting during mining or face preparation prior to permeability sampling because this would fracture grains *in situ* without forcing them into voids. Therefore, the process must be associated with sediment compaction. The degree of compaction is very small however, suggesting that the White Sandstone has been subject to very little tectonic deformation or burial depth. The first burial phase began with the deposition of the chalk, after which the sandstone was uplifted and the chalk removed. The second, and final burial phase, then took place after the Tertiary basalts were extruded above the White Sandstone. Since this time there have been only minor displacements of the sandstone, some of which were probably associated with lateral movement along major faults in the area (for example, the Great Glen and Highland Boundary Faults).

In such mineralogically mature sands, alteration of the primary porosity and permeability will be largely determined by compaction and silicification. Where the hard bands are preserved after burial in the reservoir these would produce effective barriers to vertical flow, compartmentalising the reservoir into layers extending laterally over a few hundred metres. Their orientation and vertical position may bear no relation to the geometry of the sand body except that a topographic low would be expected adjacent to the maximum development of the hard bands. These hard bands may have a very significant effect on the reservoir performance, especially if an injector well is placed within them. As these hard bands are extremely competent and rarely greater than 1m thick, any minor vertical displacement would produce flow paths through them resulting in a significant increase in vertical permeability. The potential effect on compartmentalising the reservoir

and influencing fluid flow may justify further study of these diagenetic features.

6.7 Conclusions

- 1) The White Sandstone is of Cenomanian age, and is described as a massive and mature, fine to medium grained sand.
- 2) The sandstone comprises a coarsening-up sequence within which are a series of stacked cross-beds. Sedimentary structures are generally difficult to see and various concentrations of bioturbation produce the most obvious structures. Palaeocurrent directions indicate a unidirectional flow towards the north-west.
- 3) The White Sandstone is thought to have been deposited under shallow marine conditions within a prograding wave or tide-dominated sand shoal.
- 4) The primary textural characteristics of the sandstone appear to have suffered only minor post-depositional modification. Iron-staining is evident but the concentration of iron is very low. Evidence for compaction is minimal, and with only minor cementation the primary depositional characteristics are well preserved. Any calcareous cement that may have existed appears to have been wholly dissolved and removed. The main diagenetic features are silicified hard bands, thought to have been formed in response to changes in the water table. As these hard bands are easily identified at outcrop their effect on the measured permeability are easily accounted for.

CHAPTER 7 Permeability data collection and analysis from the White Sandstone

7.1 Description of the outcrop

The White Sandstone is extracted at Lochaline for use in glass manufacture because of its high purity. Extraction is made by the pillar and stall, or gallery, method. The mine was chosen for this outcrop study as the galleries afforded excellent access over an area of some 1.3 km² with continuous exposure over distances up to 1.5 km. As the width of each pillar and the space between each pillar is approximately 10 metres, over half of the sand is extracted from the worked interval. The workings may be anything up to 7 metres high, but average approximately 4 metres. Over the last ten years, sand has been extracted progressively further northwards in a network of approximately north-south and east-west passages, although some recent extensions of the workings have been made to the east. During the summer of 1989, a series of dykes and normal faults which downthrow the sandstone to the east-north-east were breached, giving access to a new area of reserves closer to the outcrop along the west side of Lochaline.

7.2 Measurement technique

All permeability measurements at outcrop were made using the field portable minipermeameter developed at Imperial College. The measurement technique followed the code of practice set out at the end of Chapter 4. At all sample points, a smooth, flat face was produced with very good quality flow rate values. Selected core plugs were taken from blocks collected from various positions within the mine in order to represent the range of measured flow rates within the mine. These core plugs were then tested for homogeneity and used to calibrate the minipermeameter in Darcy units of permeability using the empirical calibration shown in equation 21.

7.3 Sampling schemes

Within the White Sandstone, geological structures are poorly defined other than at the scale of the whole sand body which comprises a coarsening-up sequence. For the White Sandstone therefore, the genetic unit approach is limited. The depositional model for the White Sandstone comprises a sequence of unidirectional migrating dunes. These dunes are texturally homogeneous in the horizontal direction but increase in grain size vertically. The concentration of bioturbation decreases upwards but is seen to be variable, although unstructured laterally. From this depositional model, the maximum permeability variation is likely to occur in the vertical direction, with a long range horizontal variation. Sampling, and subsequent analysis was therefore arranged to identify permeability variation perpendicular and parallel to the depositional level. A siltstone, appearing at the base of the mined section, provided a datum to which all of the sampling schemes were aligned (see table 6.1 and figure 6.4).

The sample plans at Lochaline have been determined to a large extent by the spacing of the mine pillars. This has limited the quantification of lateral permeability heterogeneity over intervals from ten to twenty metres. Two types of sampling scheme were used: regular grids (stratified systematic centric with square strata), and transects (1-D stratified systematic centric).

Vertical transects orientated perpendicular to the silt datum were placed at the ends of each pillar along two orthogonal cross-sections, orientated north-south and east-west through the mine, and sampled at an interval of 0.25m (figure 7.1). The combined vertical transects from within each cross-section produce a 2-D stratified systematic centric sample scheme, with domains measuring 4 to 5 metres high and 477 m long in the north - south orientation, and 171 m long in the east - west orientation. Each stratum measures, on average, 9m in length by 0.25m in height (figure 7.2). A unidirectional north-westerly current flow is interpreted from cross-bed foresets exposed at the entrance to the mine, enabling these cross-sections to be orientated in relation to the palaeotransport direction of the sand body.

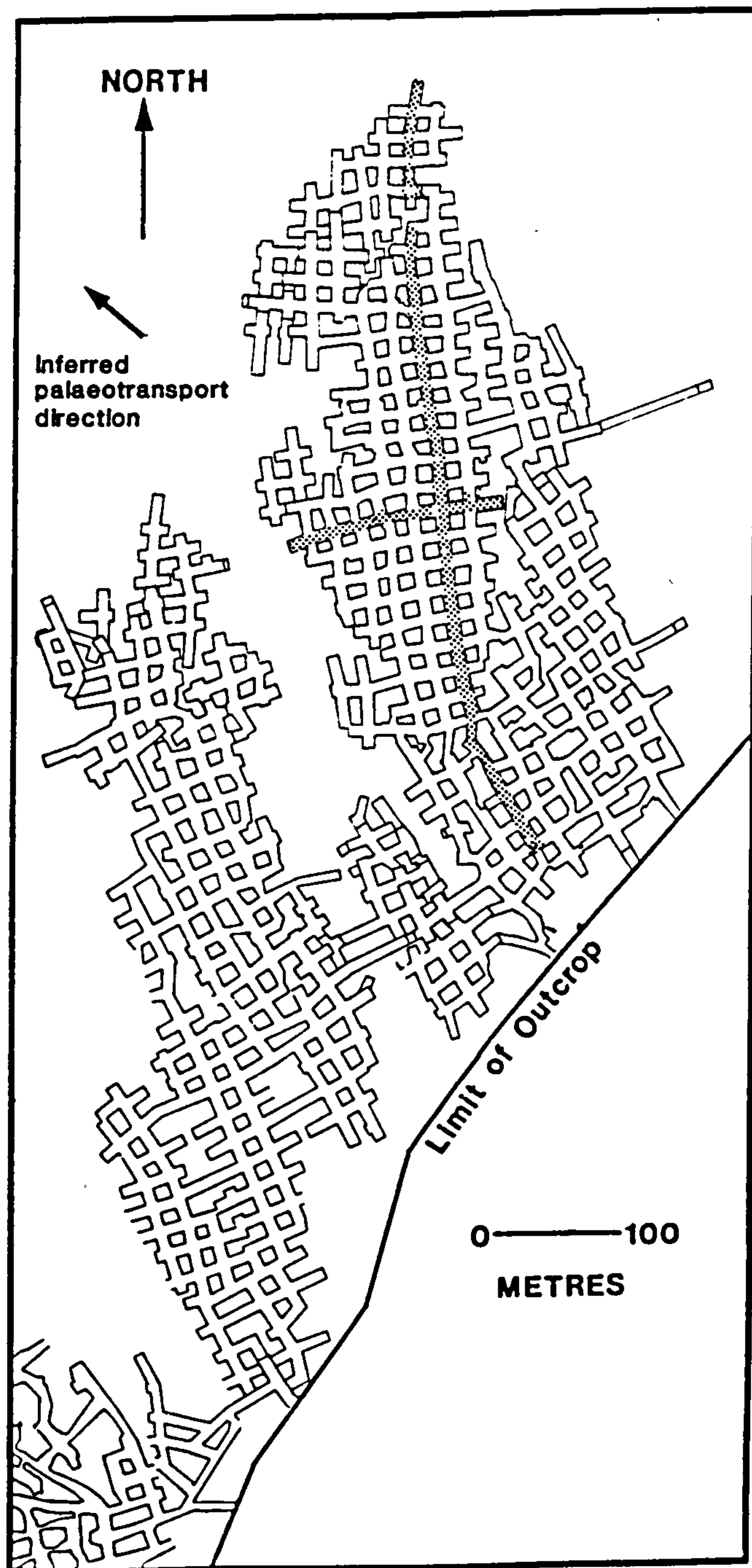


Fig. 7.1 Map of the sandstone mine with the north-south and east-west cross-sections shown (shaded)

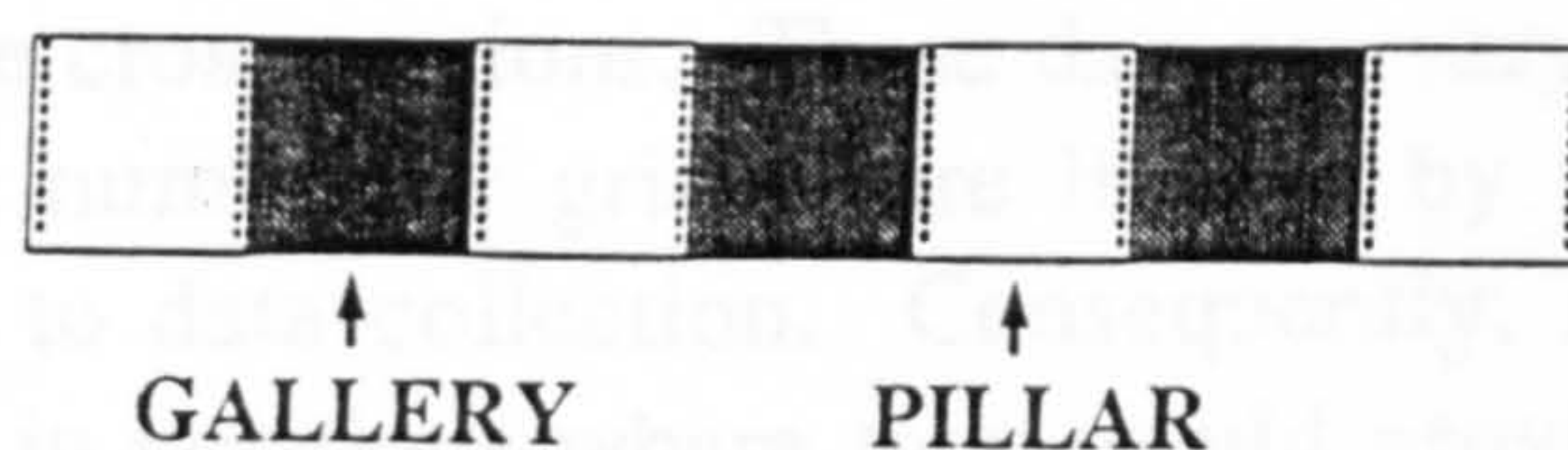
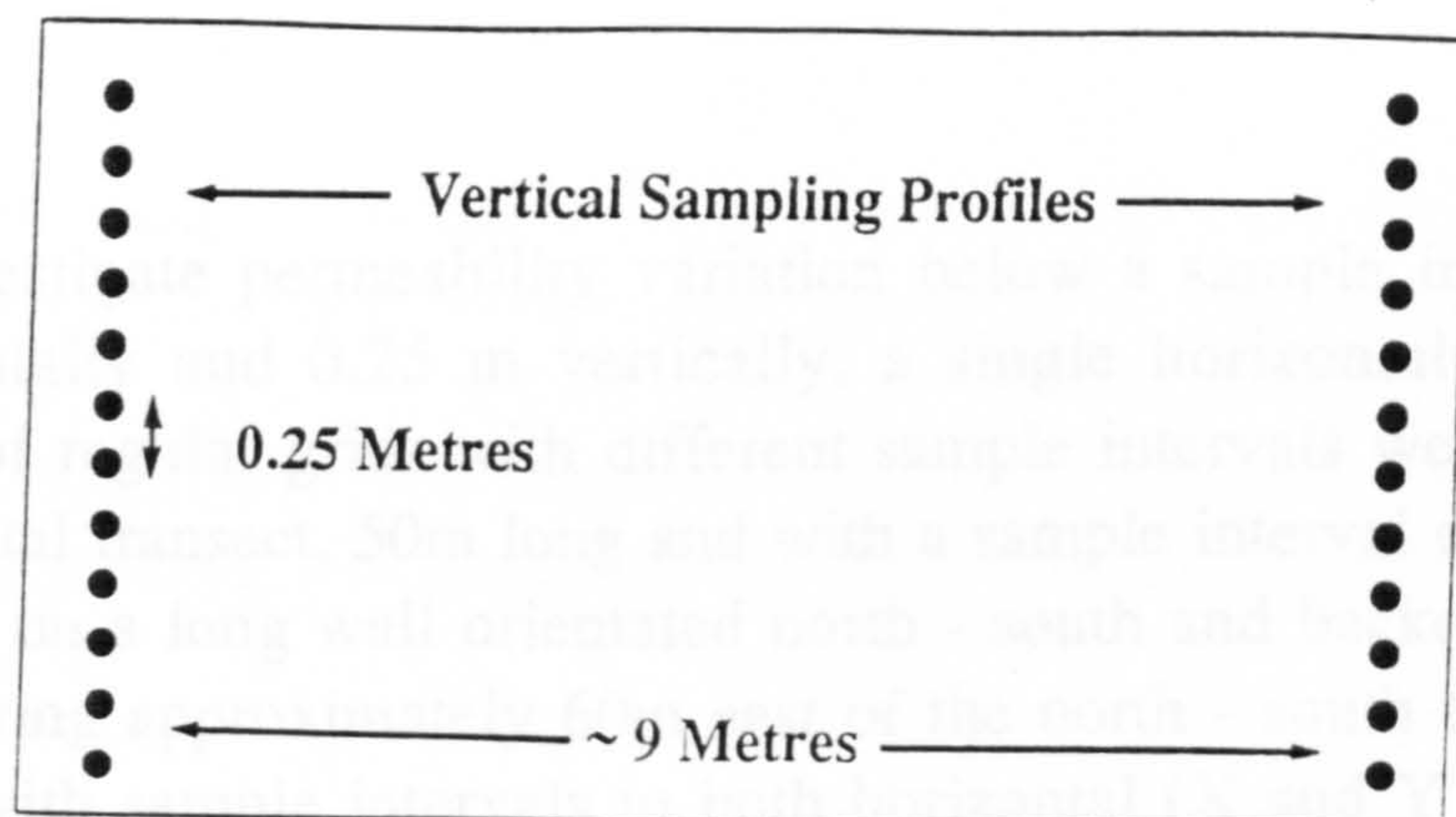


Fig. 7.2 Layout of the sampling scheme within the cross-sections

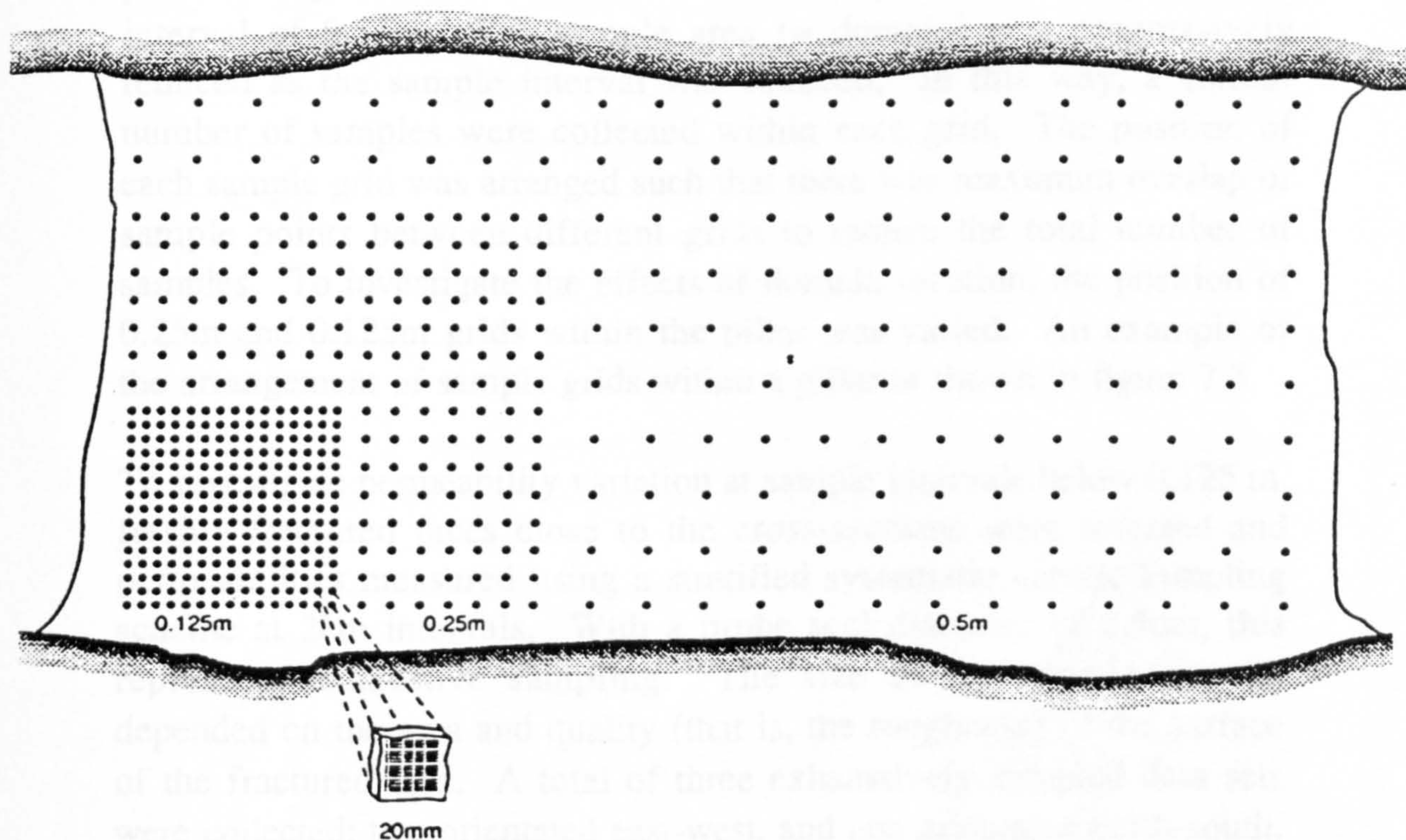


Fig. 7.3 Arrangement of decimetre scale permeability sampling within a single pillar. The photograph shows the sampled pillar at the intersection of the north-south and east-west cross-sections

To investigate permeability variation below a sample interval of 9m horizontally and 0.25 m vertically, a single horizontal transect and series of regular grids with different sample intervals were used. The horizontal transect, 50m long and with a sample interval of 0.25m, was located on a long wall orientated north - south and backed by a major fault, lying approximately 60m east of the north - south transect. The grids, with sample intervals in both horizontal (X and Y) and vertical (Z) directions of 0.5m, 0.25m and 0.125m, were placed within different pillars along the cross-sections. These data are very time consuming to collect and the number of grids were limited by the time frame and costs allocated to data collection. Consequently, it was necessary to place the grids in positions where they would provide a representative sample of the permeability variation. To optimise the location of the grids, the pillar at the intersect between the transects was used since this allowed two sides of a pillar to be sampled. The most variable pillar in the east - west orientation was then identified from the cross-section permeability data. The entire area of each pillar was sampled at an interval of 0.5 m. The sample area (= domain) was progressively reduced as the sample interval was reduced. In this way, a similar number of samples were collected within each grid. The position of each sample grid was arranged such that there was maximum overlap of sample points between different grids to reduce the total number of samples. To investigate the effects of domain location, the position of 0.25m and 0.125m grids within the pillar was varied. An example of the arrangement of sample grids within a pillar is shown in figure 7.3.

To investigate permeability variation at sample intervals below 0.125 m, freshly fractured faces close to the cross-sections were selected and permeabilities measured using a stratified systematic centric sampling scheme at 2cm intervals. With a probe seal diameter of 2.5cm, this represents exhaustive sampling. The size of the sample domain depended on the area and quality (that is, the roughness) of the surface of the fractured face. A total of three exhaustively sampled data sets were collected: two orientated east-west, and one orientated north-south.

In addition to these grids, rock samples were collected from various positions within the cross-sections and measured at sample intervals of

2cm and 4mm. One rock sample was collected from the silty sands at the base of the sequence that was visually heterogeneous due to intense bioturbation. A series of rock samples were also collected from a single vertical sequence. All permeability measurements at 4mm intervals were made using a laboratory-based automated minipermeameter.

7.4 Incorporation of permeability anisotropy at the sample scale

The anisotropy of permeability at the sample scale was examined through a visual inspection of the flow geometry around the probe seal as identified from the pattern of bubbles produced by a weak solution containing detergent (figure 4.16). The bubbles formed a concentric pattern around the probe seal, indicating that the flow geometry was approximately hemispherical. It was assumed from this that all permeability measurements can be treated as isotropic. This simplifies analysis of the outcrop data, and enables direct comparison between permeability values measured in different directions over different sample intervals and domain lengths. This assumption of isotropy is supported by the general absence of visual depositional heterogeneities within the sandstone at the measurement scale, even where bioturbation was evident.

7.5 Analysis of the data

Static statistical analyses used include determination of the permeability probability distribution functions (p.d.f's) and estimation of the coefficient of variance (C_v), a dimensionless measure of variation. These statistical measures were estimated for each data set from each sample domain. The C_v was used in preference to the Dykstra Parsons coefficient (V_{DP}) as it has been shown that the C_v provides a better descriptor of the relationship between rock type and heterogeneity than the V_{DP} (Corbett and Jensen 1992).

Three different techniques were used to investigate and quantify the spatial variation in permeability from the White Sandstone. These include regression analysis, geostatistical variogram analysis, and

rescaled range (R/S) analysis. Data sequences were first examined through regression analysis to identify long range trends. These trends or drifts were then removed and the residual stationary data sequences were examined through variogram analysis to identify structures and quantify correlation lengths. R/S analysis was then applied to these stationary data sequences to determine whether there was any statistical long-range dependence in the data sequences which, it was suspected, had fractal characteristics.

7.5.1 Reliability of measured permeabilities

Before any form of data analysis is carried out, the data should first be checked for reliability to ensure that the measured variation is genuine and not an artifact of the sampling. Permeability data from the White Sandstone were analysed after each stage of collection with repeated sampling where unusual trends or values were identified. The repeated sample values are expected to vary a little since exactly the same point cannot be sampled twice. An example of repeated sampling is illustrated in figure 7.4. Whilst the mean flow rate is slightly higher in the first set of samples, the pattern of spatial permeability variation is very similar. Since these two sets of measurements were made at an interval of months with a different operator, these results show that a high level of confidence can be placed on these data.

7.5.2 Static statistics - Permeability probability distribution functions (p.d.f's)

Permeability is a continuous random variable; that is, the variable can take on a continuum of values (Ostle 1963, Haldorsen and Damsleth 1990). In view of the complexity associated with spatial permeabilities, these data are commonly analysed using a statistical approach. The main tool to describe the variation in a continuous random variable is the probability density function or p.d.f.

Probability is a measure of the likelihood of occurrence of a chance event, allowing the simplification and quantification of complex

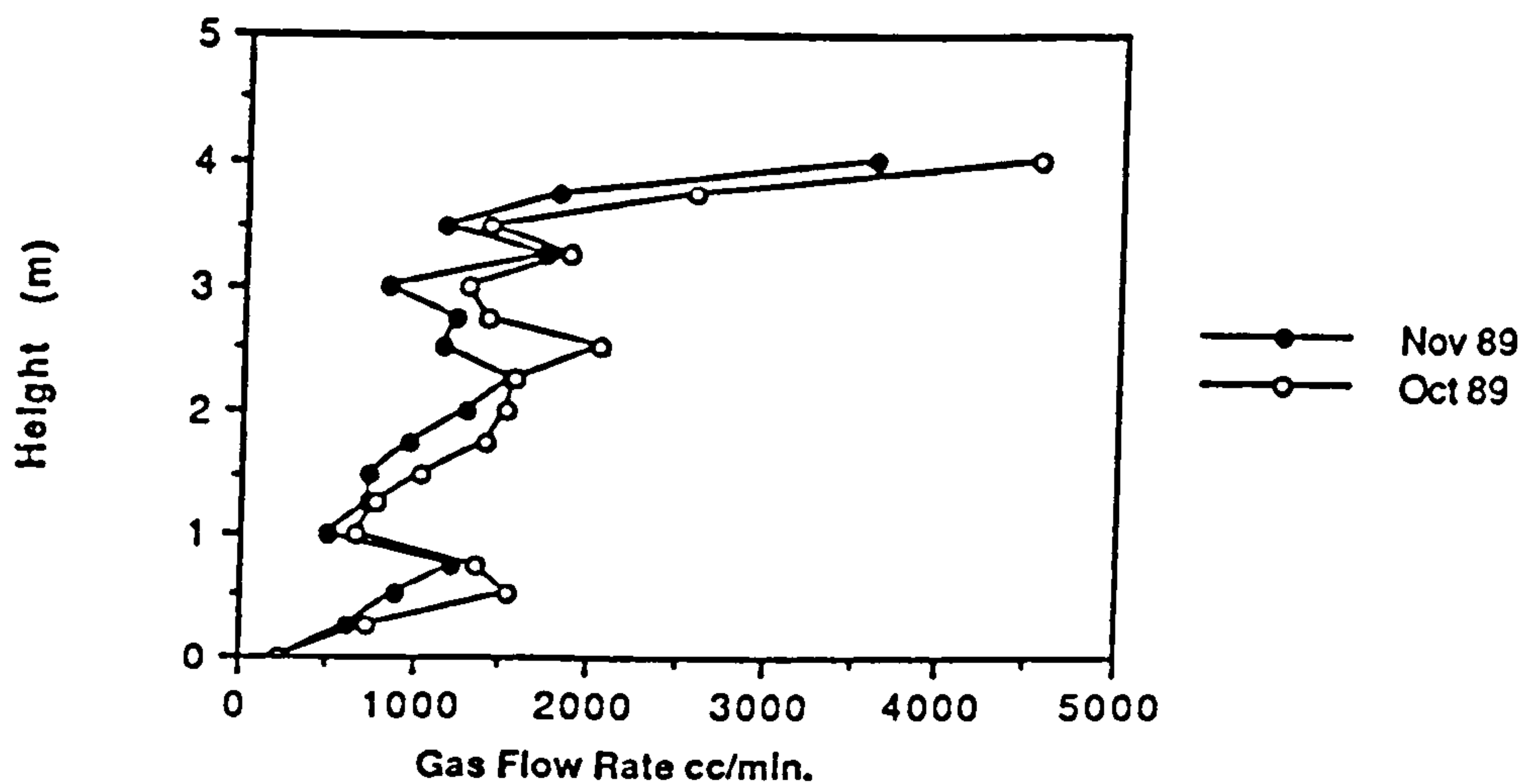


Fig. 7.4 Repeated permeability sampling along a vertical profile indicates only a small sample error due to the measurement.

Domain Dimensions (m)		Data Source:	P-exponent:	Mean Flow Rate c	Std. Dev:	Cv:	n:
Length:	Height:						
170	4.5	E-W XSECT	0.5	715	362	0.51	333
10	4.5	E-W1,0.5	0.5	878	540	0.56	141
8	4	E-W2,0.5	0.5	994	540	0.54	141
3.5	3.5	E-W1,0.25	0.5	828	468	0.57	223
3.5	3.5	E-W2,0.25	0.3	1014	458	0.46	212
1.75	1.75	E-W1,0.125,1	1	743	316	0.43	225
1.75	1.75	E-W1,0.125,2	0.5	1216	647	0.53	225
1.75	1.75	E-W2,0.125	0.5	1049	505	0.48	225
0.26	0.7	E-W1,0.02	1	610	151	0.25	390
0.58	0.58	E-W2,0.02	1	667	247	0.37	900
0.04	3.97	E-WV.PROF,0.02	1	1324	497	0.38	379
477	5	N-S XSECT	0.5	728	455	0.63	899
9	4.5	N-S,0.5	0.5	857	465	0.54	179
3.5	3.5	N-S,0.25	0.5	832	398	0.48	225
48.25	-	N-SH.PROF,0.25	1	248	39	0.16	194
0.24	1.22	N-S,0.02	1	763	188	0.25	806
0.18	0.18	N-S,0.02,BLOCK	1	-	-	0.35	100

Table 7.1 Descriptive statistics for permeability data sampled from each domain with differing sample intervals

variation. The combination of probabilities for a range of characteristics produces a probability distribution. This is often presented in the form of a histogram or cumulative probability plot.

Discrete and continuous variables are represented by a continuum of probability distributions, although certain distributions occur more frequently, for example the normal, binomial and poisson distributions. The description of this distribution is given by the p.d.f.

Permeability p.d.f's for the White Sandstone data were estimated from cumulative probability plots. For a normal distribution the permeability data will plot as a straight line where the permeability values are given on a linear scale. The approximation to a normal distribution can be used as a measure of the p.d.f type. This is done by using a suitable transformation (the p exponent) on the data which produces a straight line plot, or best approximation to a straight line, representing a normal distribution.

Descriptive statistics for permeability distributions from each sample domain within the White Sandstone are given in table 7.1. For each sample population (denoted by its direction, location, vertical and horizontal sample interval; for example, E-W1,0.5,0.5), the maximum horizontal and vertical domain length is given, together with the p exponent, and descriptive statistics for the untransformed data.

Three population distribution types emerge; normal ($p=1$), square-root normal ($p=0.5$) and cubed-root normal ($p=0.3$). Out of seventeen sample populations, nine have square-root distributions, seven have normal distributions, and one has a cubed-root distribution.

There is a close correlation between domain length and direction and distribution type. Permeability data from sample domains less than 1.75m high are normally distributed whereas data sampled over domains greater than 1.75m high are square root normally distributed. This is due to the incorporation of a drift in the data sequence causing a left (positive) skew as the vertical domain length increases. Removal of this drift yields a normally-distributed permeability population for all

sample data, irrespective of the sample interval or domain length. As permeabilities sampled along 1-D horizontal profiles at the same depositional level do not incorporate this vertical drift, they too are normally-distributed irrespective of the sample interval and domain length. Consequently, the p.d.f. remains constant for permeabilities sampled in both the east-west and north-south directions at different densities and over different domain areas (figure 7.5).

From analysis of the permeability probability distribution functions (p.d.f's), the following observations are drawn:-

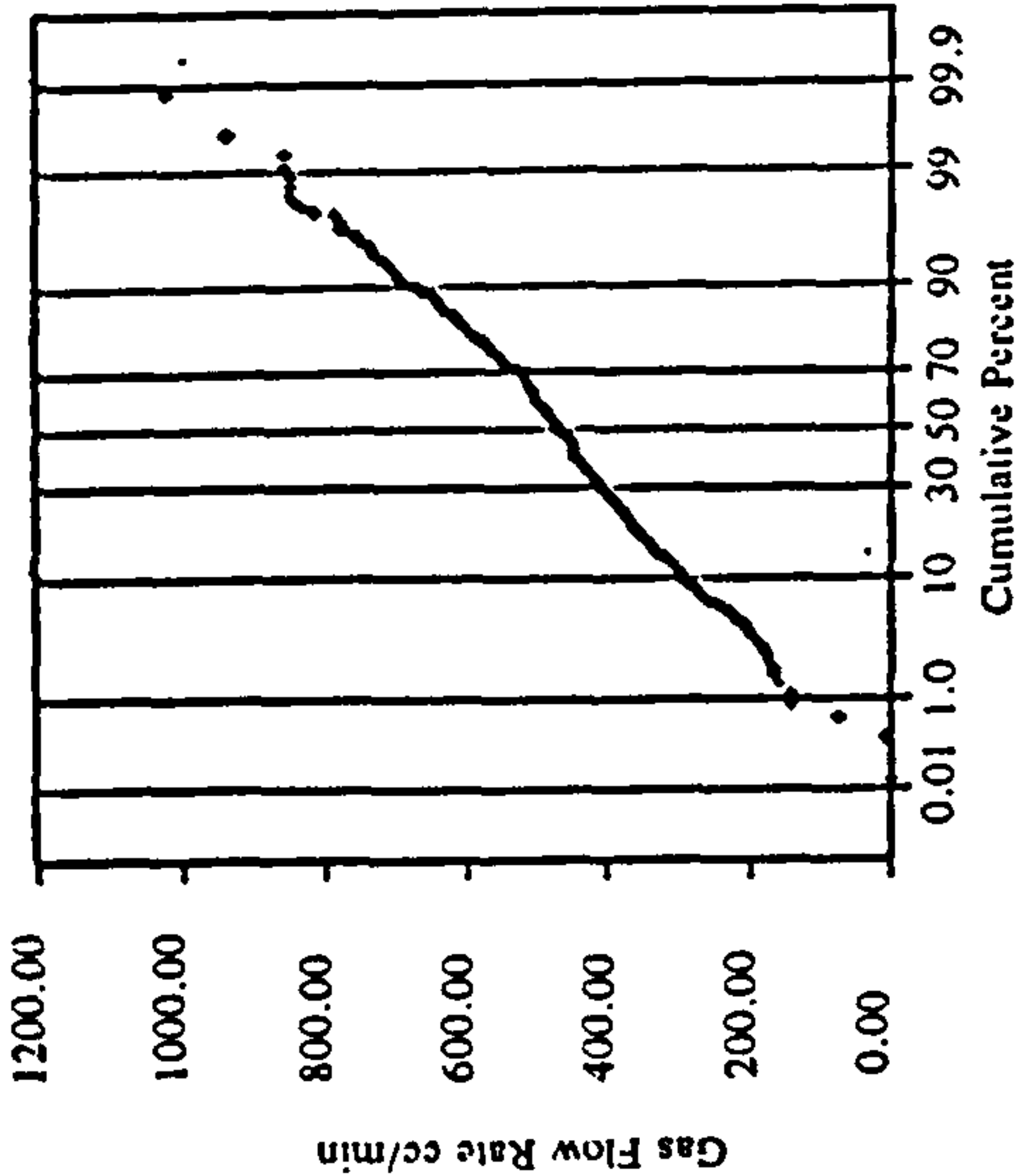
- 1) The p.d.f. for permeability data measured over vertical profiles varies as a function of domain length. As the domain length increases, a vertical drift in the data (upward increase in permeability) is incorporated and the p-exponent changes from 1 to 0.5.
- 2) Permeability is normally distributed (p-exponent=1) at all sample intervals and domain lengths and in both the vertical and horizontal directions after removal of the vertical drift.

7.5.3 Static statistics - Permeability variation within and between cross-sections

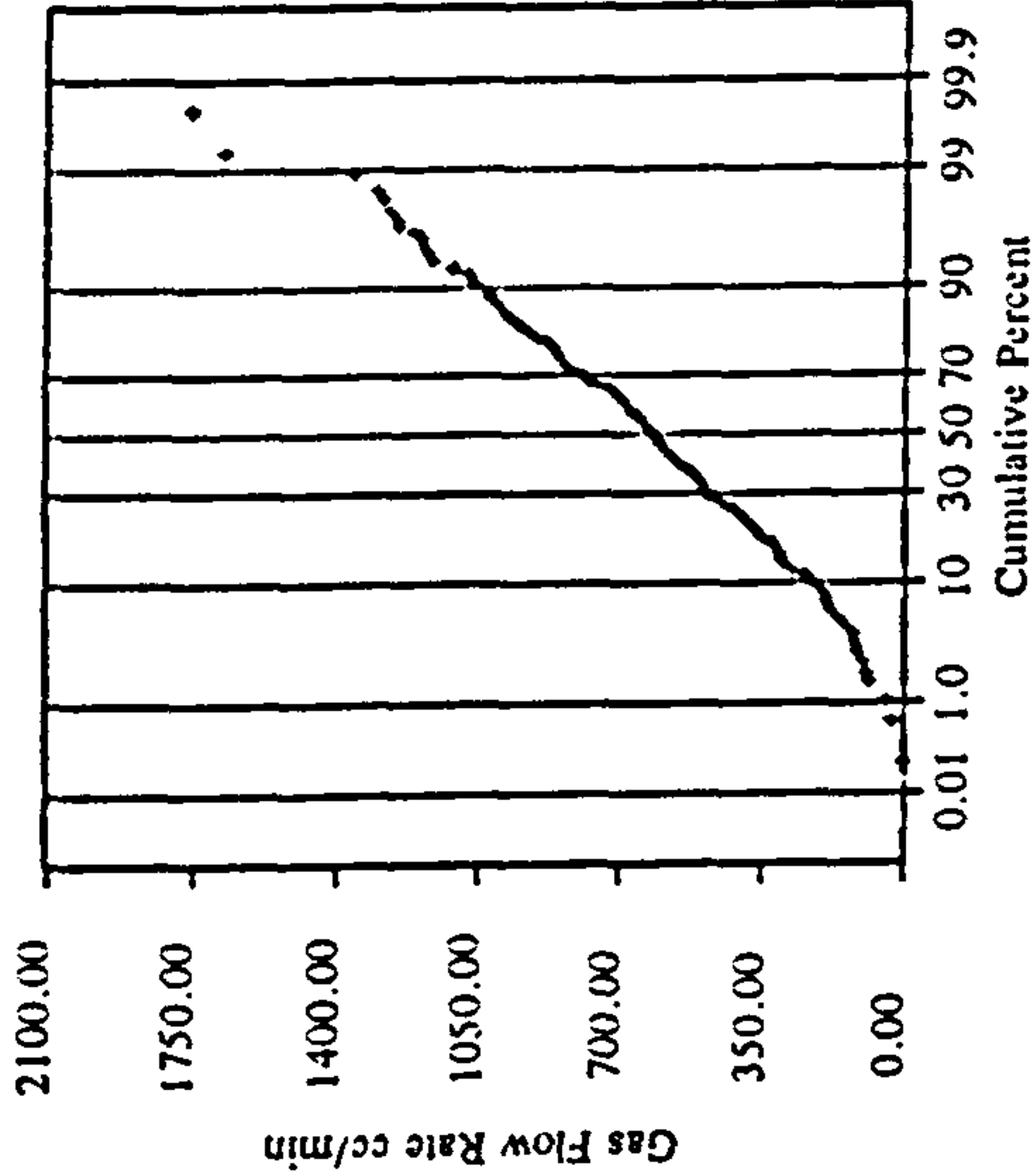
Comparison between permeability populations from vertical transects within each cross-section (figure 7.6a) was made using analysis of variance (anova). The anova results (table 7.2) show that in both the east-west and north-south directions, the variation within vertical transects is greater than the variation between them. This implies some degree of statistical prediction of permeabilities horizontally.

Further comparison using anova was made between permeability populations from horizontal transects at the same depositional level within each cross-section (figure 7.6b). These results are shown in table 7.3. Despite the coarsening-up sequence, the variation within horizontal sequences is greater than between horizontal sequences at different depositional levels, in both the north-south and east-west directions. This is because there is a large random component of variation which

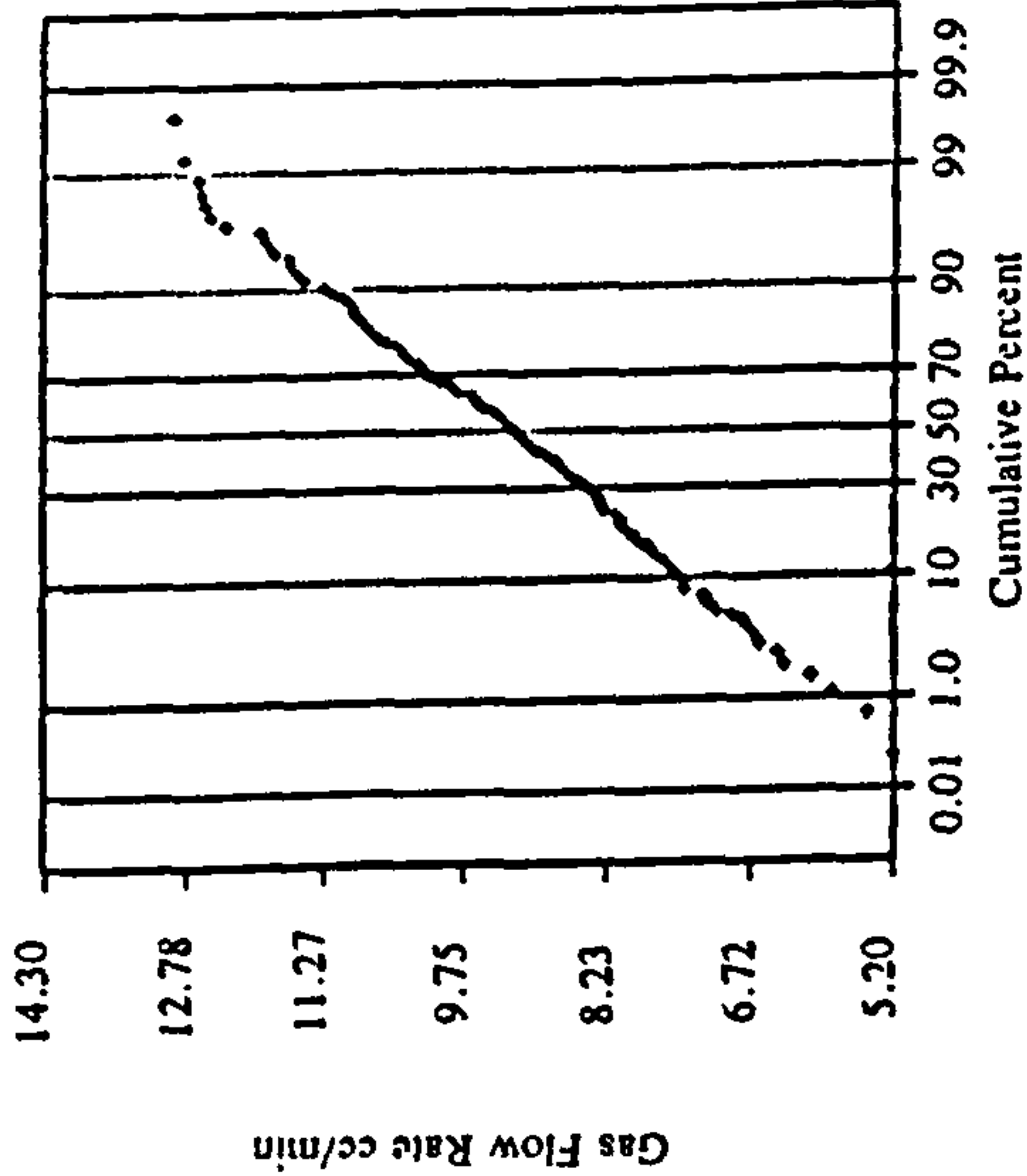
A



B



C



D

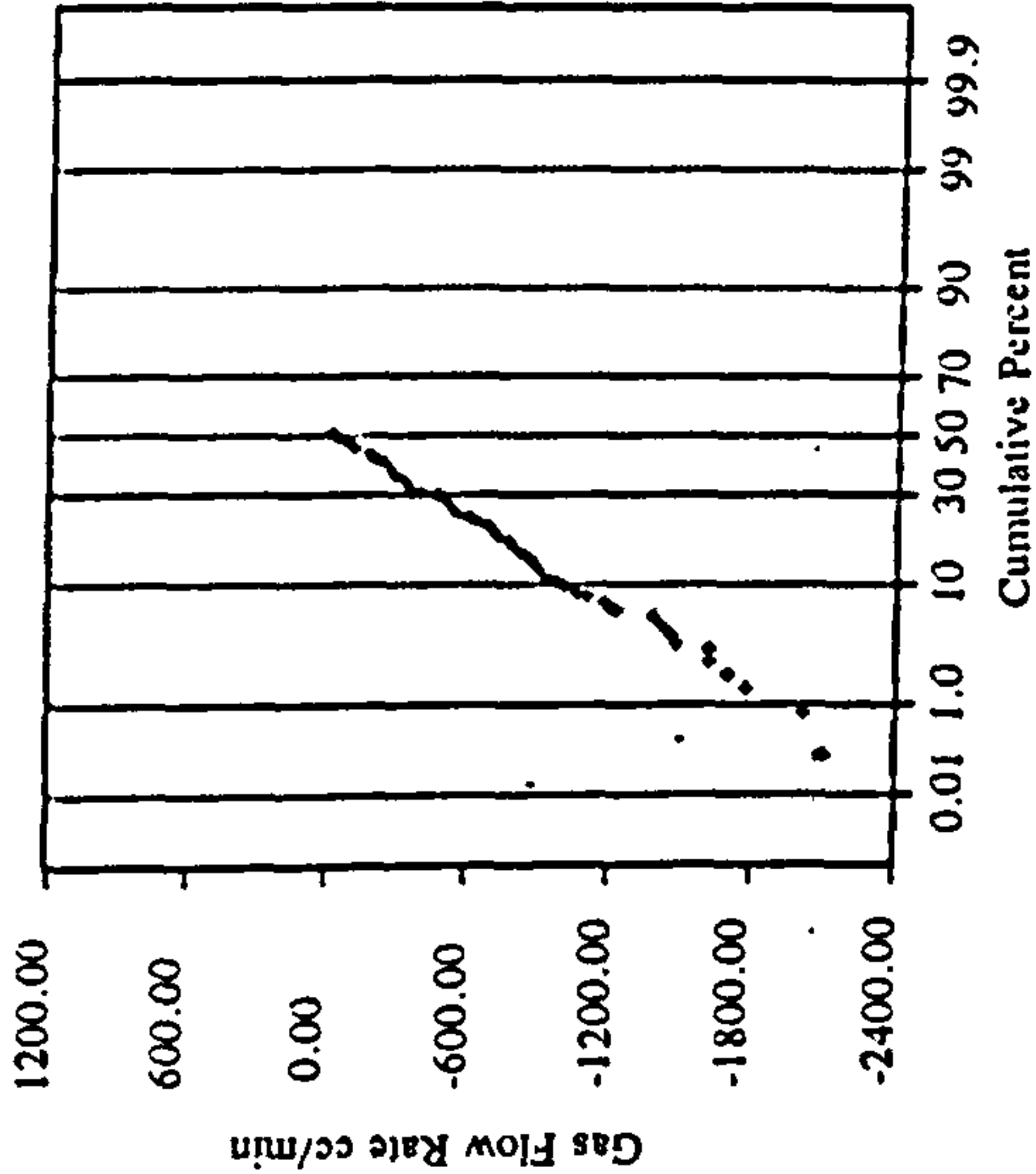


Fig. 7.5 Probability plots for permeability data sampled at different densities with the vertical drift in permeability removed

Min. Sample Interval (m)	Lag Range (m)	Direction	No. Sequences	No. R/S values	Mean	H Value: Std. Dev	Range
0.5	2.0-9.0	Horizontal	19	76	0.74	0.17	0.28-1.03
0.25	1.0-3.5	Horizontal	36	144	0.78	0.19	0.4-1.17
0.125	0.5-1.75	Horizontal	36	144	0.67	0.2	0.26-1.05
0.02	0.08-0.58	Horizontal	39	130	0.78	0.21	0.45-1.2
9	36-477	Horizontal	19	76	0.75	0.16	0.51-1.14
				Mean:	0.74		
0.02	0.1-3.92	Vertical	184	184	0.75	0.16	0.44-1.22
0.125	0.5-1.75	Vertical	100	100	0.68	0.24	0.21-1.24
0.25	1.0-4.5	Vertical	36	36	0.74	0.15	0.52-0.92
				Mean:	0.72		
nd totals & means							
0.02	0.08-477	Horizontal & Vertical	469	220	0.74	0.2	0.21-1.36

Table 7.6 Summary table of the rescaled range analysis results for permeability data from the White Sandstone

Source:	DF:	Sum Squares:	Mean Square:	F-test:
Between Groups	19	5.7 E6	3.0 E5	2.54
Within Groups	311	3.7 E7	1.2 E5	p=0.0005
Total	330	4.2 E7		

East-West Cross-Section

Source:	DF:	Sum Squares:	Mean Square:	F-test:
Between Groups	53	5.3 E7	1.0 E6	6.39
Within Groups	845	1.3 E8	1.6 E5	p=0.0001
Total	898	1.9 E8		

North-South Cross-Section

Table 7.2 Anova table showing the comparison within and between permeability data sampled from vertical transects within the north-south and the east-west cross-sections

Source:	DF:	Sum Squares:	Mean Square:	F-test:
Between Groups	15	1.2 E7	7.7 E5	13.655
Within Groups	290	1.6 E7	5.6 E4	p=0.0001
Total	305	2.8 E8		

Between Depositional Levels: East-West Cross-Section

Source:	DF:	Sum Squares:	Mean Square:	F-test:
Between Groups	15	3.2 E7	2.1 E6	15.482
Within Groups	827	1.1 E8	1.4 E5	p=0.0001
Total	842	1.5 E8		

Between Depositional Levels: North-South Cross-Section

Table 7.3 Anova table showing the comparison within and between permeability data sampled from horizontal transects within the north-south and the east-west cross-sections

Height (m)	Comparison: E-W vs. N-S		F value	Critical F alpha=0.05	t-test (pooled variance)	Critical t alpha=0.05
	E-W n	N-S n				
3.75	14	39	2.082*	2.35		
3.5	15	48	3.916*	2.25		
3.25	19	53	2.950*	2.04		
3	18	54	2.054	2.07	0.75	1.976
2.75	19	54	1.841	2.03	-1.297	1.974
2.5	20	54	2.796*	1.99		
2.25	20	54	2.232*	1.99		
2	20	54	2.376*	1.99		
1.75	20	54	3.715*	1.99		
1.5	20	54	1.734	1.99	0.58	1.973
1.25	20	54	2.888*	1.99		
1	20	54	5.348*	1.99		
0.75	20	54	2.180*	1.99		
0.5	20	54	2.938*	1.99		
0.25	20	54	1.372	1.99	-0.67	1.973
0	20	54	1.3	1.99	-0.1	1.973

Table 7.4 Comparison between permeability data from horizontal transects at equivalent depositional levels from the north-south and east-west cross-sections

implies some degree of statistical prediction of permeability vertically.

Comparison was also made between horizontal transects at the same depositional level from each cross-section (figure 7.6c). As only two sample populations were used in the comparison, the F-test, and where appropriate, the t-test were used. The results are shown in table 7.4. Approximately 30% of the horizontal sequences compared between the cross-sections have equal variance. This implies that there is some degree of statistical prediction of permeabilities in orthogonal horizontal directions. However, there is no consistency in the pattern, that is, it is not possible to predict where in the vertical interval these layers with similar permeability populations occur. For those populations with equal variance, the t-test results showed that in every case there was no significant difference between the means of each population.

7.5.4 Static statistics - Coefficient of variance

The coefficient of variance (standard deviation divided by the mean), or C_v , was used as a measure of the variability in the transformed permeability data. Lower values of C_v indicate a more homogeneous rock with respect to that property. As the C_v is dimensionless, it provides a measure of heterogeneity that is independent of the magnitude of permeability. Such a measure therefore, is portable from the outcrop to the reservoir. By comparing values of C_v for permeability data sampled at different intervals at outcrop we can get an estimate of the degree of heterogeneity at different sample intervals indicative of heterogeneity at different scales.

From figure 7.7 it can be seen that there is an increase in the coefficient of variance for the White Sandstone data as the vertical domain length increases. This is caused by the incorporation of a vertical drift in the permeability data produced by the coarsening-up sequence. If this drift is removed a stationary data sequence is produced. Within these stationary data, the C_v for different vertical sample intervals remains constant irrespective of the length, position or azimuth of the sample

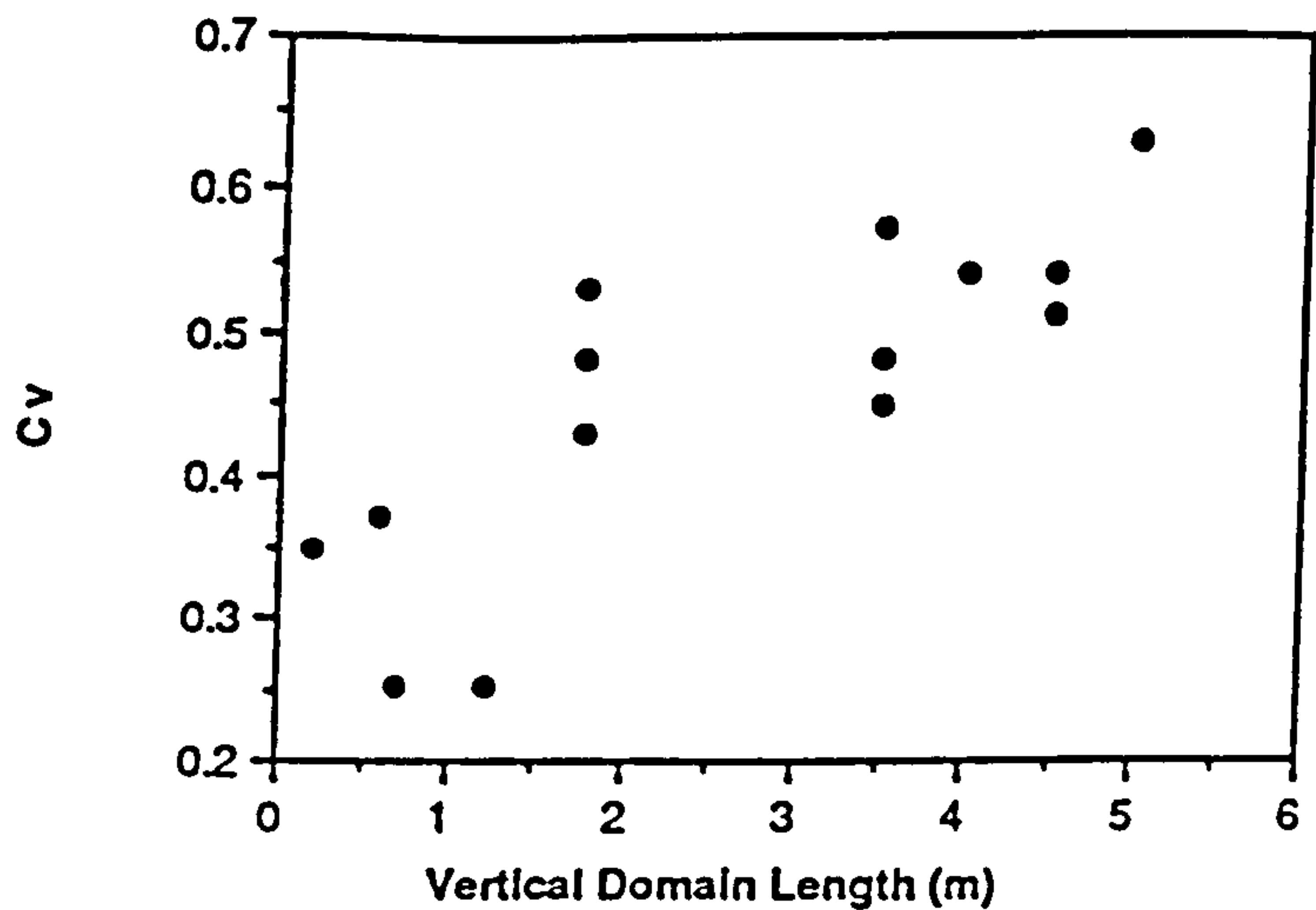


Fig. 7.7 Relationship between the coefficient of variance (Cv) and the vertical domain length

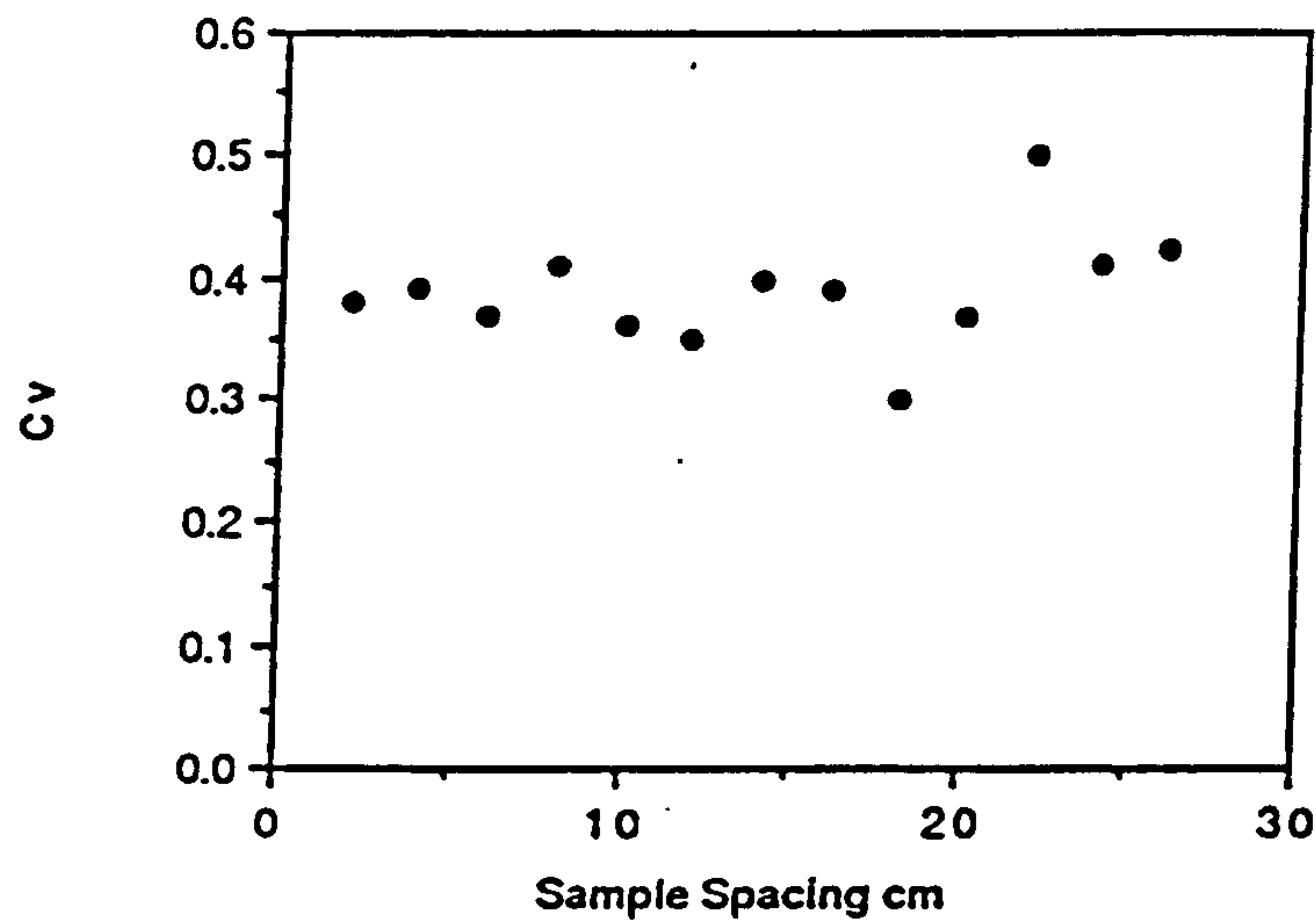


Fig. 7.8 Relationship between the coefficient of variance (Cv) and sample spacing within stationary vertical data sequences

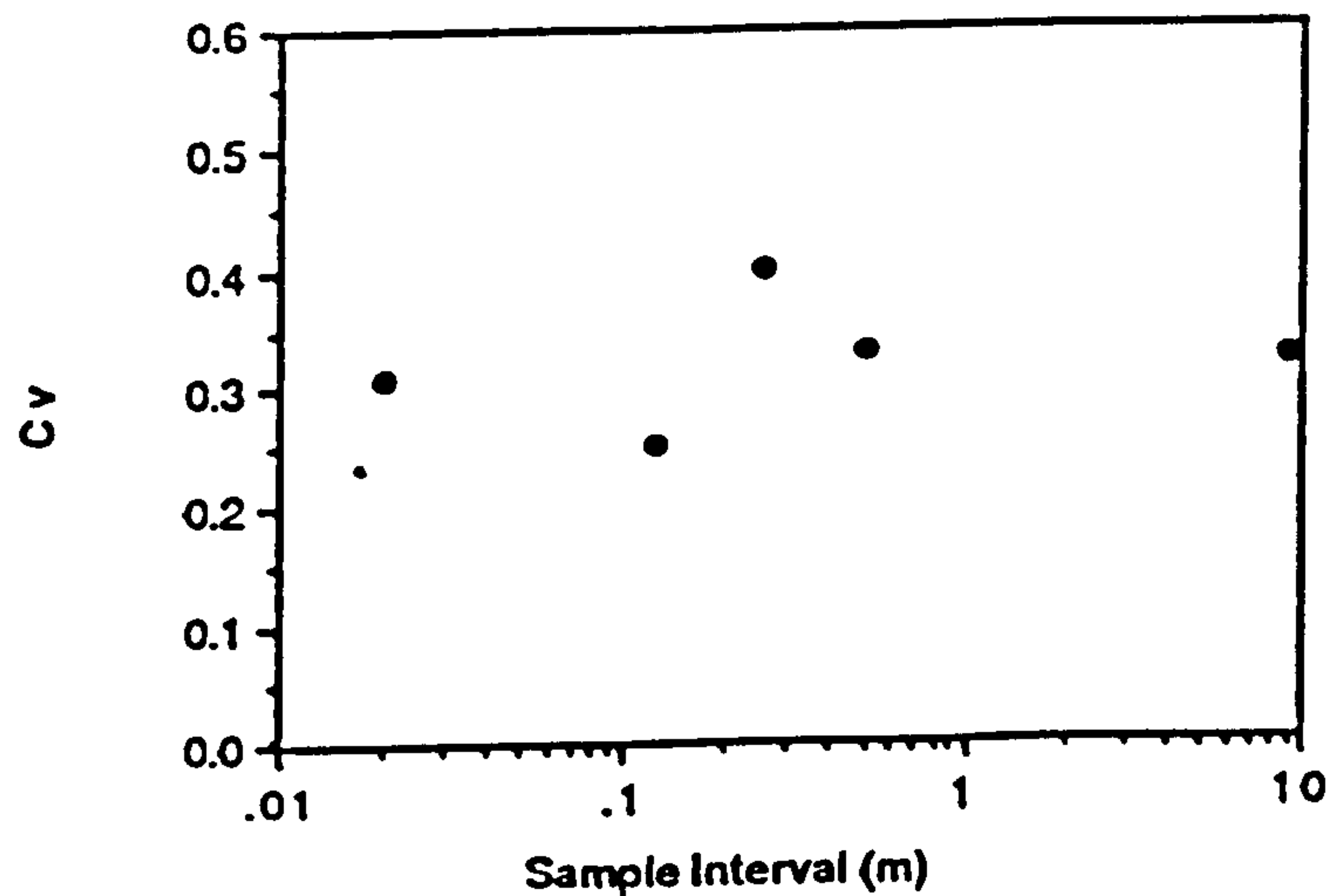


Fig. 7.9 Relationship between the coefficient of variance (Cv) and sample spacing within stationary horizontal data sequences

domain (figure 7.8). This is also shown to be the case for data sequences in the horizontal direction (figure 7.9) which require no adjustment to obtain stationarity. It can also be seen from figures 7.8 and 7.9, that after removal of the vertical drift, the Cv for vertical and horizontal data sequences are very similar.

From the measurements of the coefficient of variance (CV), the following observations have been made:-

- 1) After removal of drifts in data sequences, the Cv for permeability sequences remains similar irrespective of the sample interval, domain position, and direction.
- 2) The Cv for stationary data sequences sampled in the vertical and horizontal directions are similar and indicate isotropic heterogeneity.

7.5.5 Spatial statistics - Regression analysis

In order to estimate the various characteristics of the variation in permeability over the cross-sections, some method of expressing the relationship between observations is required. In a data sequence that contains a drift, the mean does not provide an adequate representation of the data because they are not independent. Rather, a line needs to be constructed that will express the relationship between point permeabilities and distance where deviations from this line are minimised with respect to permeability. This is achieved through regression analysis.

From a visual inspection of permeability trends in the vertical direction, a distinct increase in permeability upwards through the interval was identified (figure 7.10) and a linear model considered appropriate. A linear model was then fitted to each vertical permeability profile from the east-west and north-south cross-sections. Fitted trends with R^2 less than 0.4 were inspected for extreme values (outliers) that may cause a poor fit and deviated slope. The position of these outliers above the datum were found to be random. This justifies removal of these values

from the data set as they are isolated and are unlikely to have a significant effect on fluid flow. Where present, these extreme values were removed and a new linear model fitted to the data. If no extreme values were found, trends with R^2 less than 0.4 were regarded as insignificant and assigned a zero slope.

Figure 7.11a and b shows the slope of the linear models for vertical permeability profiles on the east-west and north-south cross-sections respectively. There is no apparent lateral correlation between slopes in either cross-section where a distinct vertical increase in permeability at one location may pass laterally over 9m into vertical profile with no drift. A test of significance between the slope populations using a one-way analysis of variance shows no significant difference between the mean slope of the drift in the east-west and north-south cross-sections (table 7.5). As a result, the slope populations for each direction can be combined to produce a more reliable measure of slope variability. Slopes that do not contain any significant trend are not included in the combined histogram, but as their frequency in each direction is known they can be quantified separately.

Of the horizontal permeability profiles from the east-west cross-section, 19 display a random scatter of data, and 1 contains a significant trend (figure 7.12). This trend occurs at the base of the cross-section where permeability increases linearly from west to east. As this trend is not repeated through the sandstone interval and is found at the base of the sequence, this increase in permeability may be due to deviation in the sampling level relative to the silt datum. At the western end on the cross-section the lowermost samples on each pillar may extend into the siltier sands, but towards the east the base of vertical sample profiles may start above this silt. As the siltier sand at the base of the section pass gradationally upwards into cleaner sands the silt datum is difficult to define with certainty (to within +/- 0.5m) and the cause of this horizontal permeability trend can only be speculative.

Of the horizontal permeability profiles from the north-south cross-section, 18 display a random scatter of data, and 4 contain a weak 'W'-shaped trend with a wavelength of around 300m (figure 7.13). These profiles are confined within the basal 2.5m of the sandstone interval but

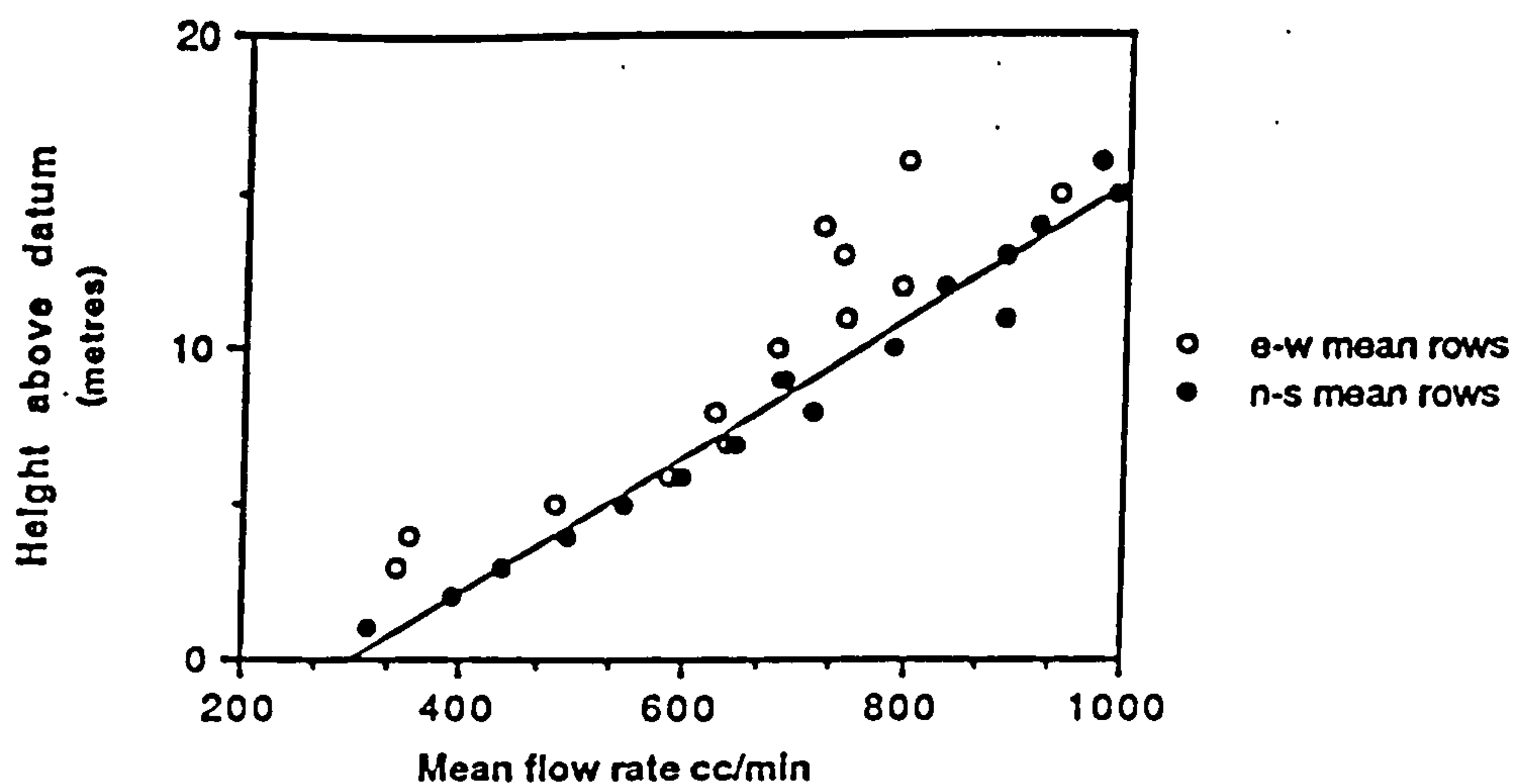


Fig. 7.10 Linear regression model fitted to the vertical trend of mean permeability for samples from the same height above the basal datum

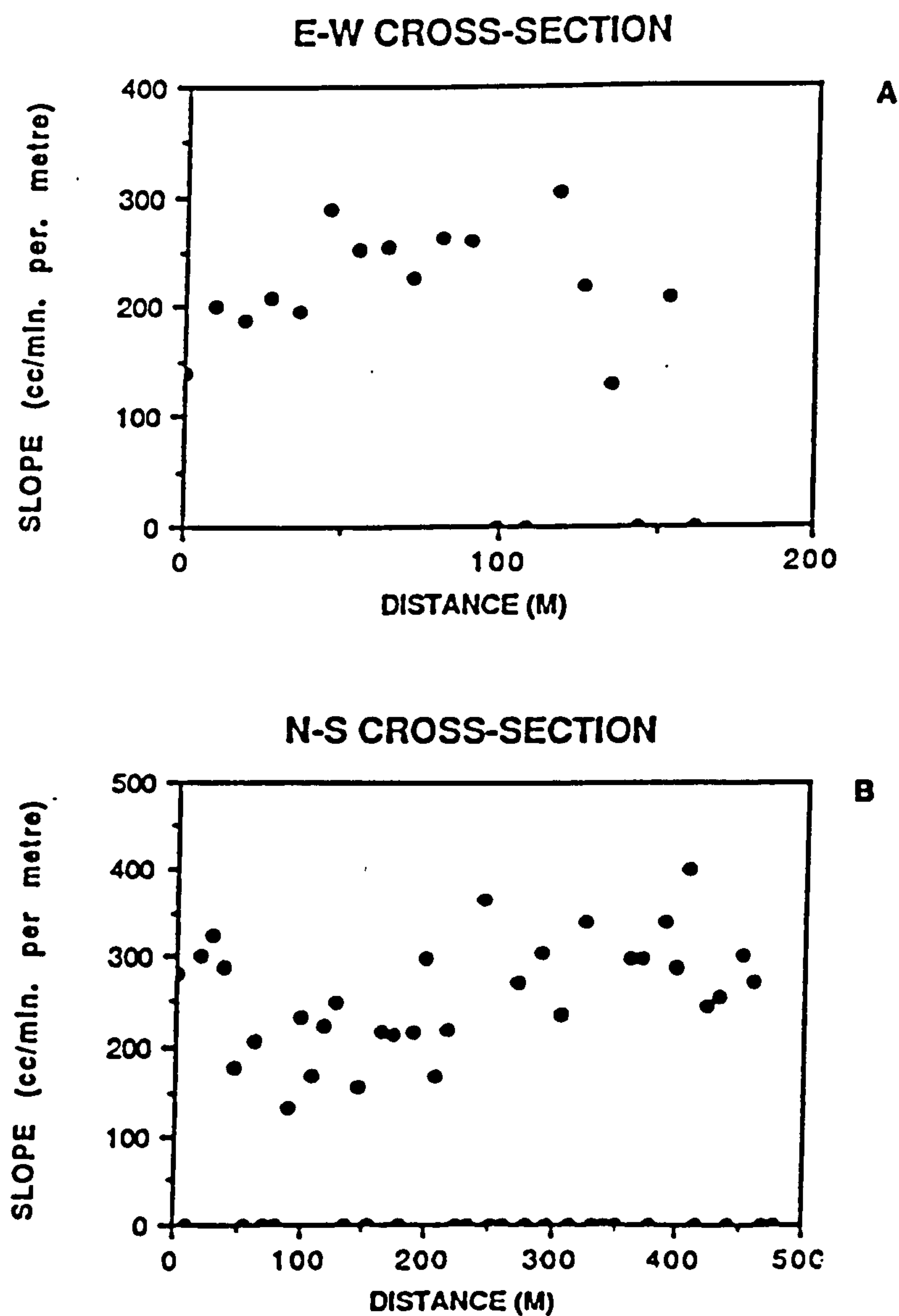


Fig. 7.11 The slope of linear regression models fitted to vertical sample transects for permeability

Source:	DF:	Sum Squares:	Mean Square:	F-test:
Between Groups	1	10509	10509	2.946
Within Groups	45	160506	3567	p=0.0929
Total	46	171015		

Table 7.5 Anova table showing the comparison between the slopes of linear regression models for vertical sample transects for permeability from the north-south and east-west cross-sections

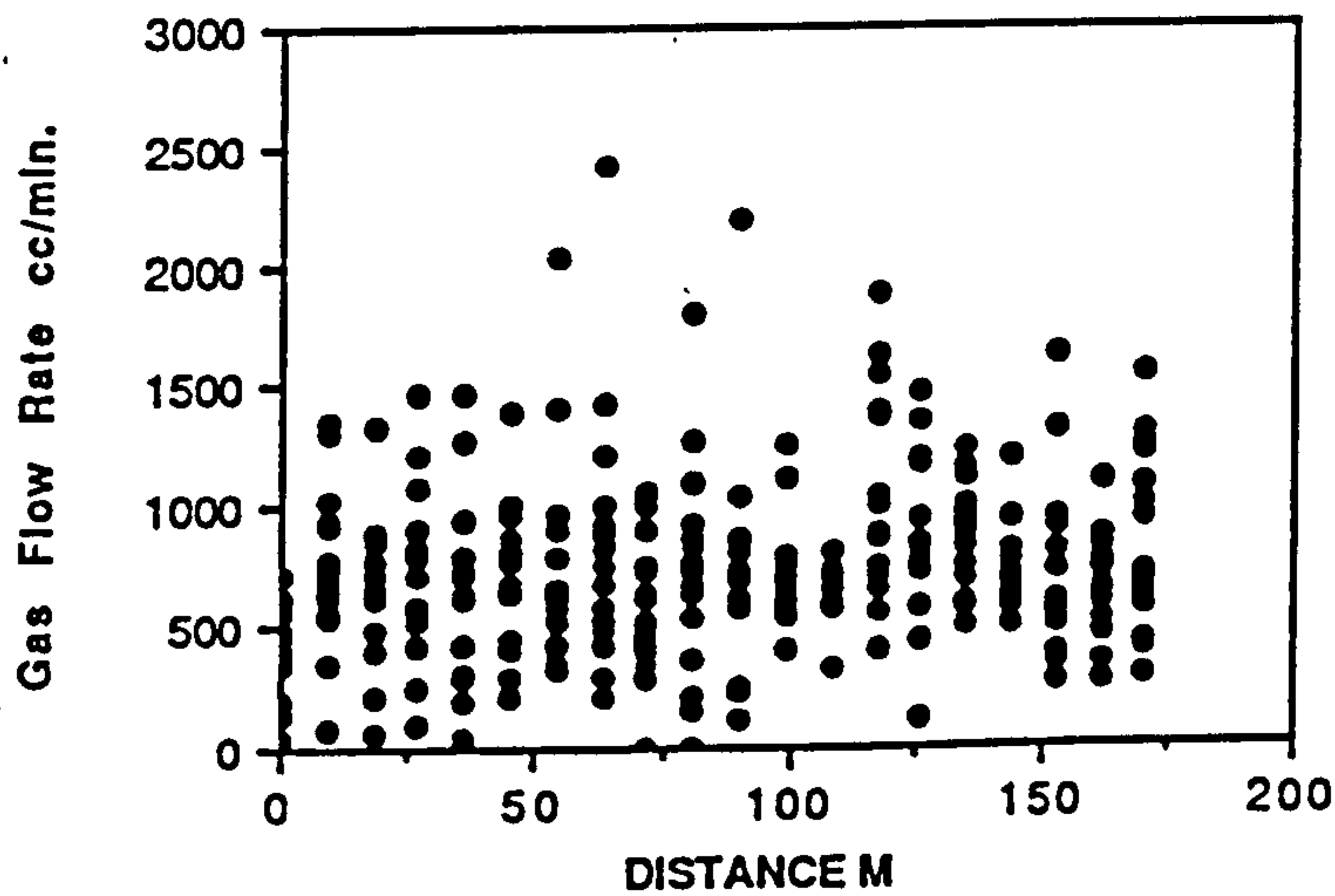


Fig. 7.12 Trends in the horizontal sample data for permeability from the east-west cross-section

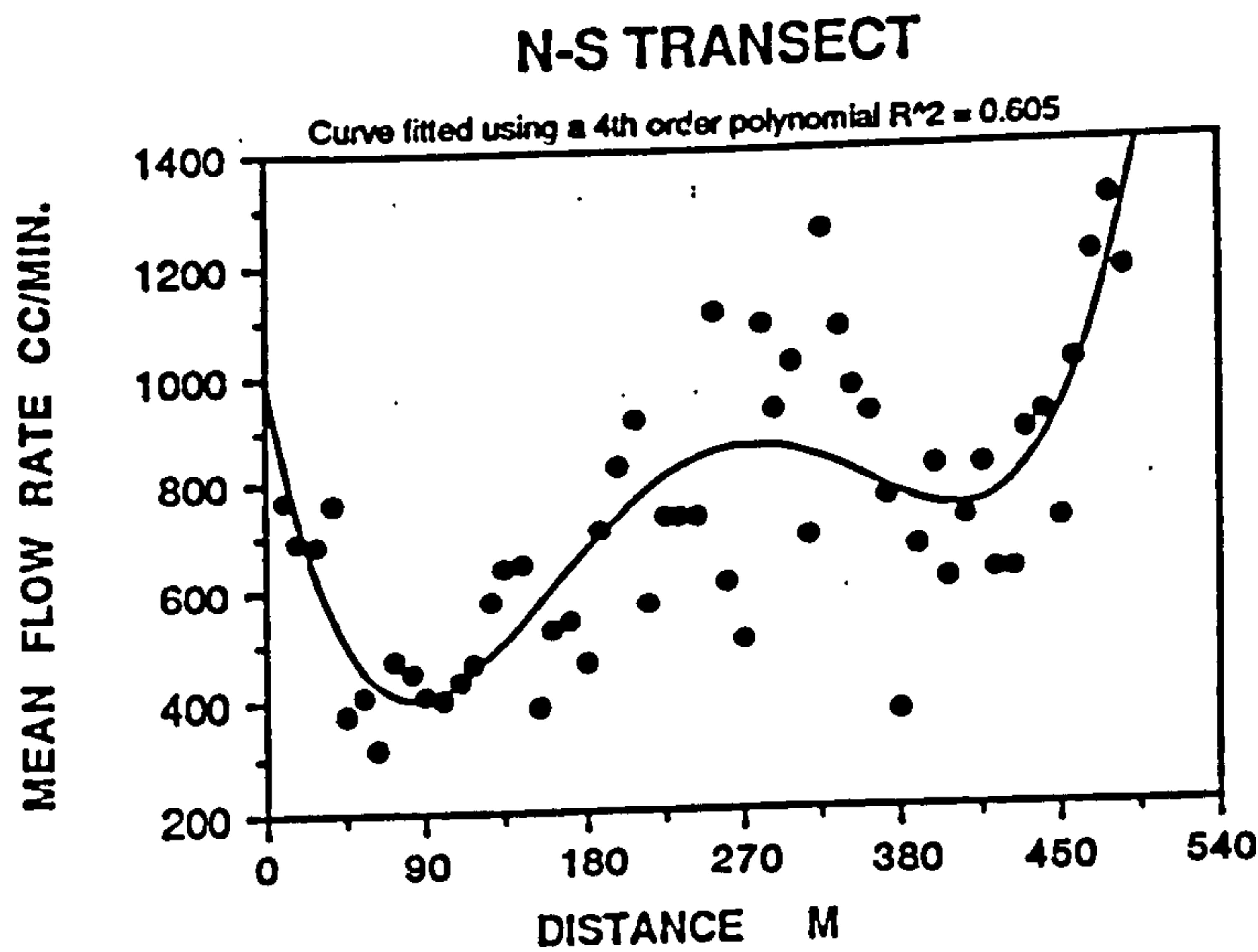


Fig. 7.13 Trends in the horizontal sample data for permeability from the north-south cross-section

there is no pattern to their spatial position. If the horizontal sample level deviated from the silt datum then this trend should occur in the lowermost samples, but would be seen to be lost with an increase in the sample level above the base. Whilst this trend is observed at the lowest sample level it does not disappear at higher levels but is repeated at specific levels. Therefore, deviated sampling from the basal silt datum does not appear to be responsible for this trend. Field inspection of the sandstone in the cross-section using a hand-lense does not reveal any obvious patterns of textural variation or diagenesis. However, this trend may be associated with fracturing, which is often difficult to distinguish because of the uniform appearance of the rock, although greater vertical persistence of the trend might be expected.

From regression analysis the following observations have been made:-

- 1) A distinct increase in permeability upwards through the sandstone is observed throughout each of the sample cross-sections in the mine.
- 1) Vertical permeability trends from both the north-south and east-west cross-sections are appropriately modelled using a linear regression.
- 3) Adjacent vertical sample profiles display no apparent similarity in the slope of the regression lines fitted to the sample data. This applies to vertical profiles from both the east-west and north-south cross-sections.
- 4) No significant difference was identified between the mean slope and slope variance of vertical profile regression slope populations from the east-west and north-south cross-sections.
- 5) Horizontal permeability profiles from the north-south and east-west cross-sections display a predominantly random scatter of permeability values.
- 6) A linear increase in permeability is observed in 1 horizontal profile at the base of the east-west cross-section, and a weak 'W'-shape is observed in 4 horizontal profiles from the north-south cross-section.

The cause of these horizontal trends is unclear but is probably related to faulting.

7.5.6 Spatial statistics - Variogram analysis

Having established the nature of the long-range permeability trends in the vertical and horizontal directions, a measure of the correlation lengths and variability within these trends is required. The variogram, through the successful application of geostatistical modelling to reservoir properties (Costa da Silva 1985 and others), has become an increasingly popular tool for quantifying the spatial correlation of reservoir data. It is however, a technique that requires careful consideration in both the construction of the variogram and its interpretation.

Prior to variogram analysis, the data should be inspected for erroneous values and checked for stationarity. The user should also obtain a 'feel' for the data, that is, what are the expected trends?, how much variation is likely?, and so on. This feel for the data is dependent on the users' understanding of the problem. In many published reservoir and outcrop studies, variograms are constructed from too few data at insufficient density, and the fitted variogram models are often based on intuition with little data control (Aasum et al 1991, Tomutsa et al 1986).

Variogram models may vary considerably for different directions and it is important to differentiate between them. Unless some understanding of the probable spatial disposition of permeability is known *a priori*, omnidirectional variograms should be constructed and the prediction of directional characteristics determined from this.

Geostatistical techniques require that the data is stationary, or at least of second order stationarity. Where there is a drift in the data this must be removed prior to performing geostatistical analysis. From regression analysis of the permeability data, a significant drift was identified in the vertical direction, but the data conformed to weak or second order stationarity in the horizontal direction. Only this vertical drift need be removed before construction of the variograms.

For a 2-D sample domain, a single or average variogram can be constructed from the combined data for a given direction, or a series of variograms can be constructed for each 1-D line of data. Whether multiple or single variograms are used depends on the spatial structure of the variable. If there is little difference in spatial structure within and between sample domains then a single or average variogram constructed from the combined data is adequate, and will also be more reliable since it is constructed from a larger sample. If there are differences in spatial structure, a single variogram may smooth out significant features, or enhance features of less significance. The choice of a single variogram or multiple variograms also depends on the scale of investigation. For fluid flow, where a single low or high permeability layer or band can have a dominating effect on the flow characteristics of the reservoir, accurate modelling of such structures is important. Unless there is reasonable evidence from the geological model to suggest otherwise, multiple variograms should be constructed first to determine whether a single, average variogram is appropriate.

From initial inspection of the White Sandstone permeability data, horizontal permeability variation is fairly consistent between layers. This is particularly evident in the east-west direction, and a single horizontal variogram might be appropriate. In the north-south direction however, a 'W' shaped trend was observed at three different levels above the base. For these data, a series of horizontal variograms may be more appropriate. To enable comparison between horizontal variograms for the the east-west and north-south cross-sections, variograms were constructed for layers 0.5m thick, comprising 3 vertical values, 0.25m apart, in each layer. A total of 6 horizontal variograms were constructed for each cross-section representing layers centred at 0.25m, 1m, 1.75m, 2.5m, 3.25m and 4.5m above the base. As there are few values above 3.5m, a layer thickness of 1.25m was used to increase the sample number.

The greatest permeability variation within the White Sandstone occurs in the vertical direction where the coarsening-up sequence is incorporated. As there is no obvious lateral correlation between the slope of the vertical permeability trends as identified from regression

analysis, individual variograms were constructed for each vertical profile (9m apart on average) from the east-west and north-south cross-sections.

The cross-section data are sampled at intervals of 0.25m vertically and 9m horizontally. To quantify permeability correlation over intervals less than this, closer-spaced samples are required. These data are provided by the sample grids with sample intervals from 0.5 to 0.02m. A separate variogram was constructed for each row and column of data within each sample grid on the north-south and east-west cross-sections. In all, 29 vertical variograms and 60 horizontal variograms were constructed. Examples of variograms representing permeabilities sampled at different intervals shown in figure 7.14.

Vertical correlation structure

Of the eighty nine variograms constructed for a vertical sample interval of 0.25m, only ten display any correlation structure. These variograms have correlation lengths from 0.8m to 2m (figure 7.14a) and display occasional periodic behaviour with wavelengths between 1m and 2m (figure 7.14b). For those variograms displaying correlation structure, the sill values are significantly greater than the nugget value. This indicates that where a correlation structure exists, it is well defined. In general however, the spatial permeability variation over an interval of 0.25m, and up to 4.5m (the domain length), is dominated by uncorrelated structure.

Of the fifteen variograms constructed for a vertical sample interval of 0.125m, only two display any correlation structure. These variograms have correlation lengths from 0.4 to 0.9m (figure 7.14c) with one variogram displaying periodic behaviour with a wavelength of around 0.7m. For those variograms that contain a correlation structure the sill values (the global variance) are at most only twice that of the nugget (the random variance within samples or error-related variance). This indicates that those correlation structures that were identified are weakly defined. Generally, the spatial permeability variation over an interval of 0.125m, and up to 3.5m (the domain length), is dominated

by uncorrelated structure.

Of the nineteen variograms constructed for a vertical sample interval of 0.02m, fourteen indicate the presence of correlation structure in the data with correlation lengths from 0.07 to 1.2m (figure 7.14d). The most frequently occurring correlation length is 0.1m. Periodic behaviour is also seen with a wavelength up to around 0.4m (figure 7.14e). Where a correlation structure is identified, a zero nugget is rare and the size of the sill and nugget are frequently the same order of magnitude, with the sill often only twice that of the nugget. This indicates that whilst correlation structures are common over an interval of 0.02m, and up to 3.97m (the domain length), these structures are again weakly defined. It should also be noted that the correlation length of 1.2m was identified in only one data sequence and was not shown to be repeated.

Horizontal correlation structure

Of the twelve variograms constructed for an horizontal sample interval of 9m, two display a correlation structure. The correlation length for these variograms is 110m, but with the value of the nugget effect similar in size to the value of the sill, these structures are poorly defined (figure 7.14f). In general, the spatial permeability variation is uncorrelated in both the east-west and north-south directions over an interval of 9m, and up to 171m and 477m (the domain length of the east-west and north-south cross-sections respectively).

Of the six variograms constructed for an horizontal sample interval of 0.5m, none display any correlation structure. Three of these variograms are comprised of a pure nugget effect whilst the fourth variogram displays a continuous structure. Thus, over an interval of 0.5m, and up to 10m (the domain length), the correlation structure is dominated entirely by uncorrelated structure in both the north-south and east-west directions.

Of the sixteen variograms constructed for an horizontal sample interval

of 0.25m intervals, only three display any correlation structure (figure 7.14g). This correlation structure is weakly defined in two of these variograms. In general, the spatial permeability variation over an interval of 0.25m, and up to 48m (the domain length), is dominated by uncorrelated structure in both the east-west and north-south directions.

Of the fifteen variograms constructed for an horizontal sample interval of 0.125m, none display any correlation structure. These variograms are comprised of pure nugget effect over an interval of 0.125m, and up to 1.75m (the domain length), in both the east-west and north-south directions.

Of the twenty three variograms constructed for an horizontal sample interval of 0.02m, eight display a correlation structure. Of these eight variograms, five are within one sample domain (N-S(1)0.02m). Correlation lengths range from 0.06m to 0.28m, but the nugget effect is frequently similar in size to the sill value and correlation structures are weakly defined (figure 7.14h). In general, the spatial permeability variation over an interval of 0.02m, and up to 0.58m (the domain length), is dominated by uncorrelated structure. With only three sample domains in total, and one sample domain in the north-south direction, it is not possible to state definitely whether there is a statistically significant difference in correlation structure in the east-west and north-south directions, but in view of the observed variation in depositional structure this is unlikely.

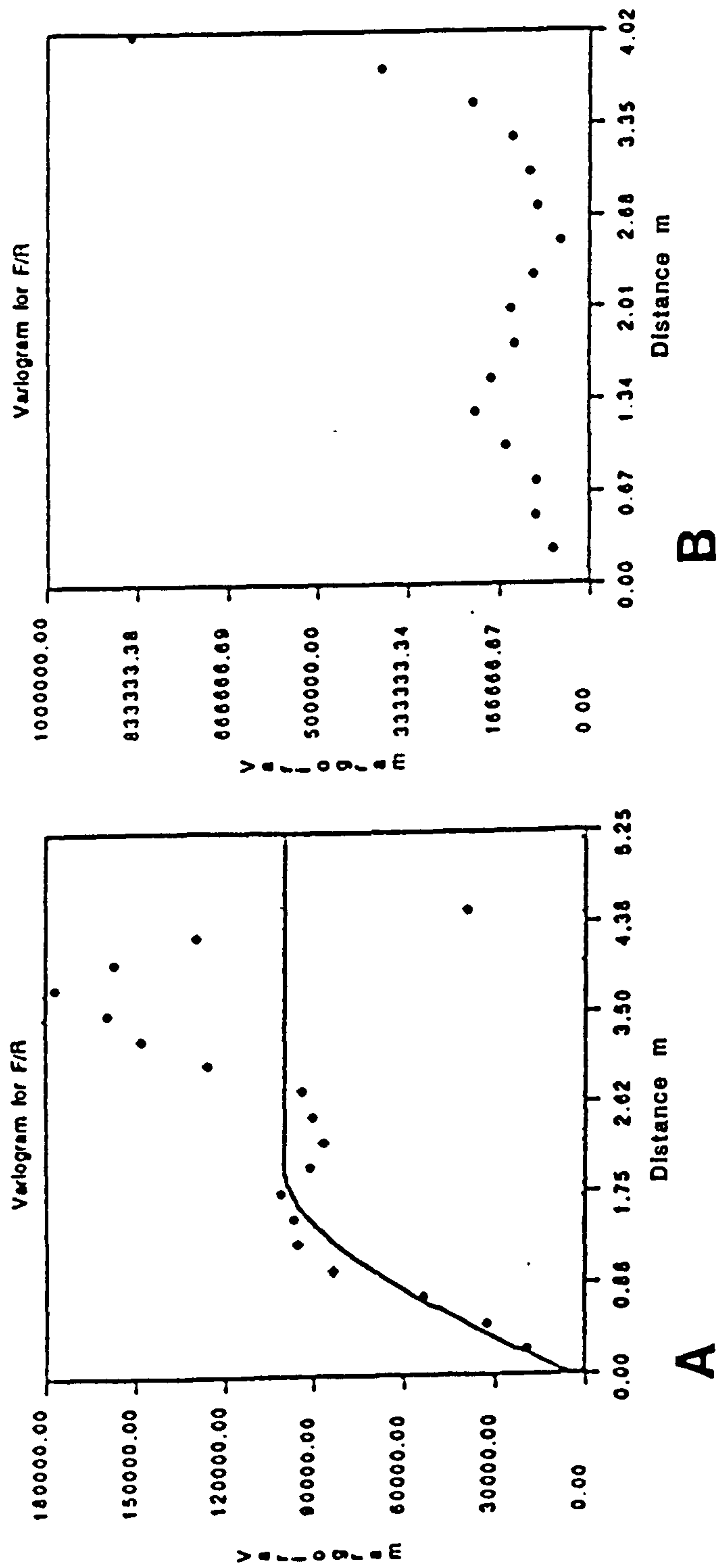


Figure 7.14 Examples of variograms for permeability data sampled from domains with different positions, directions and sample intervals

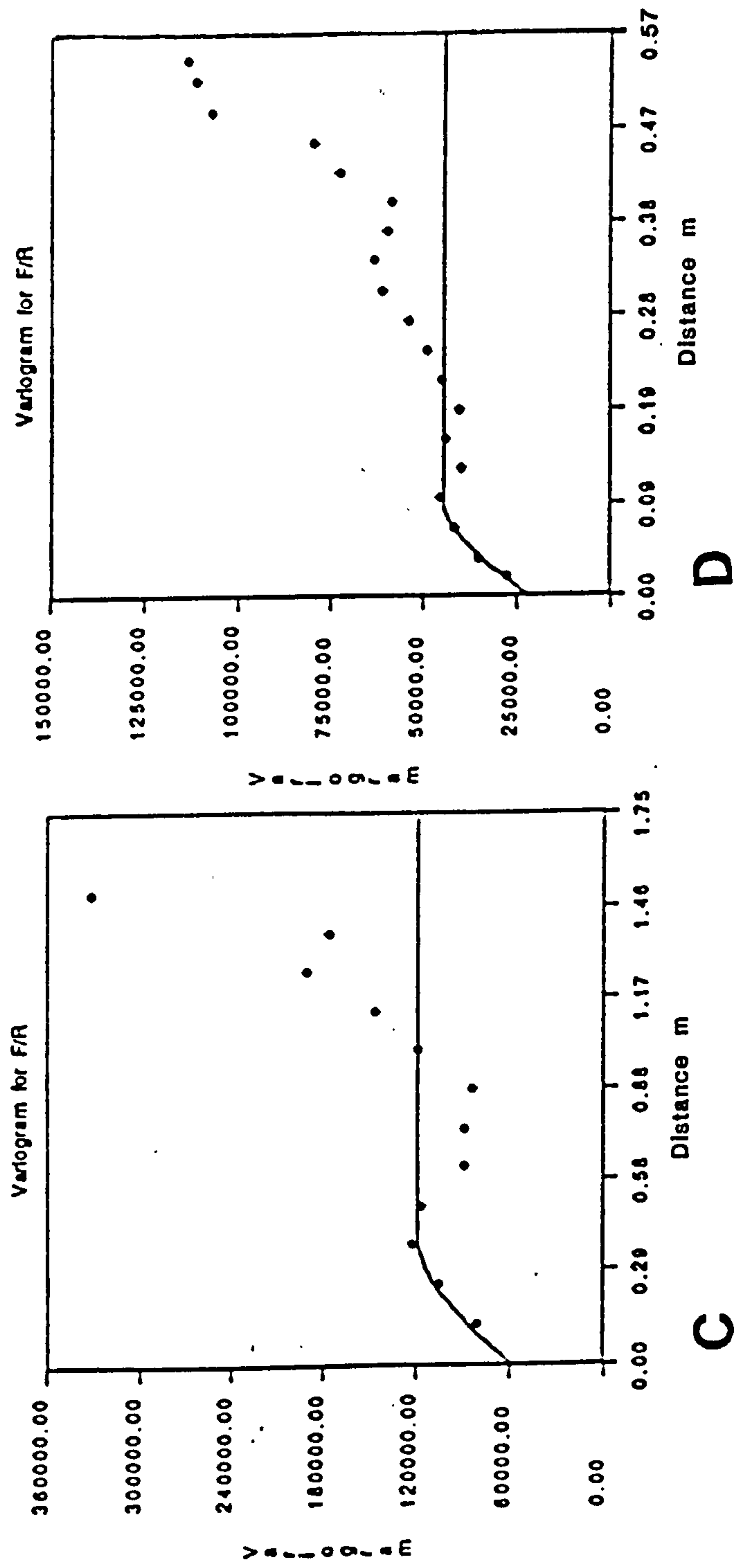
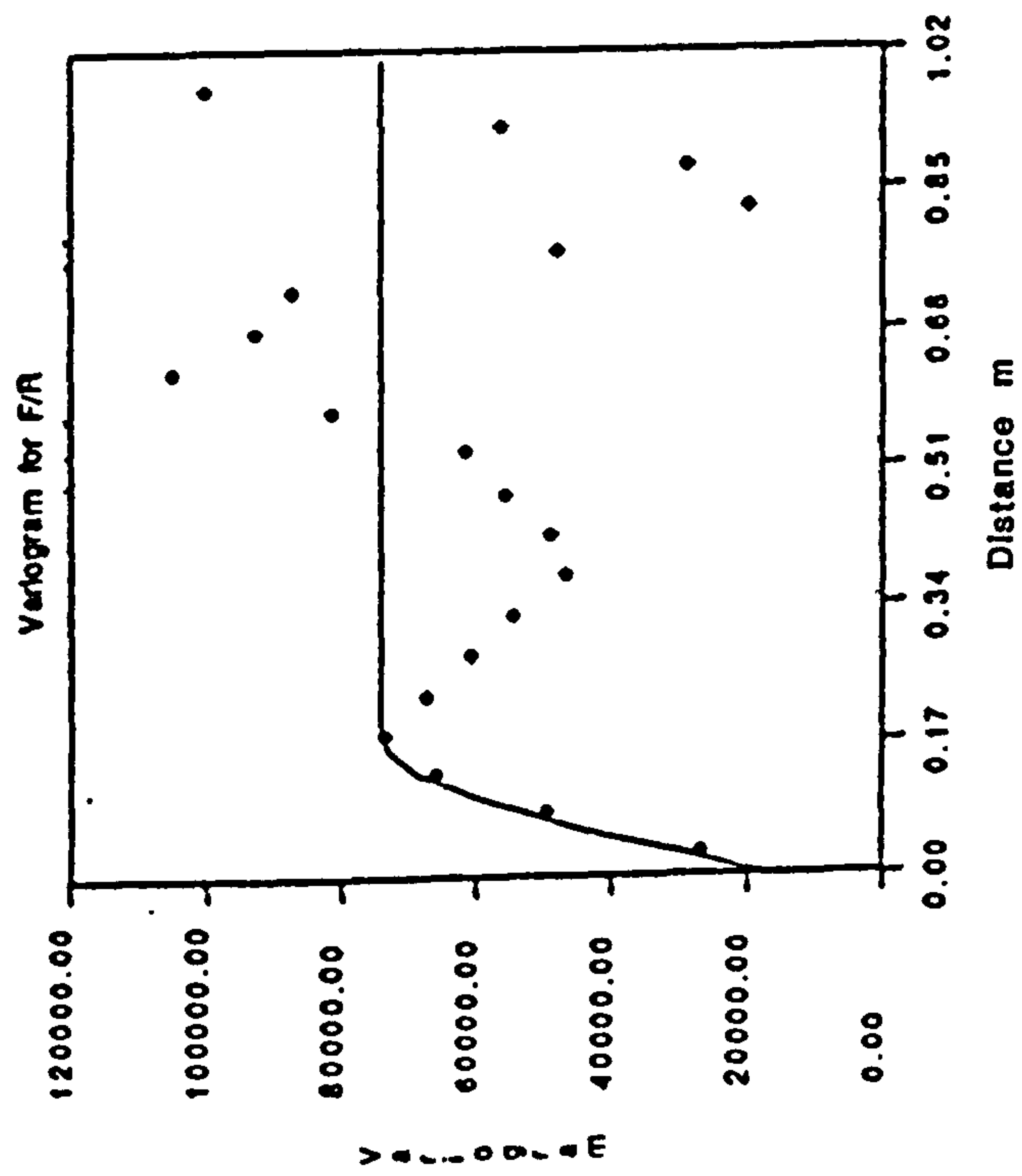
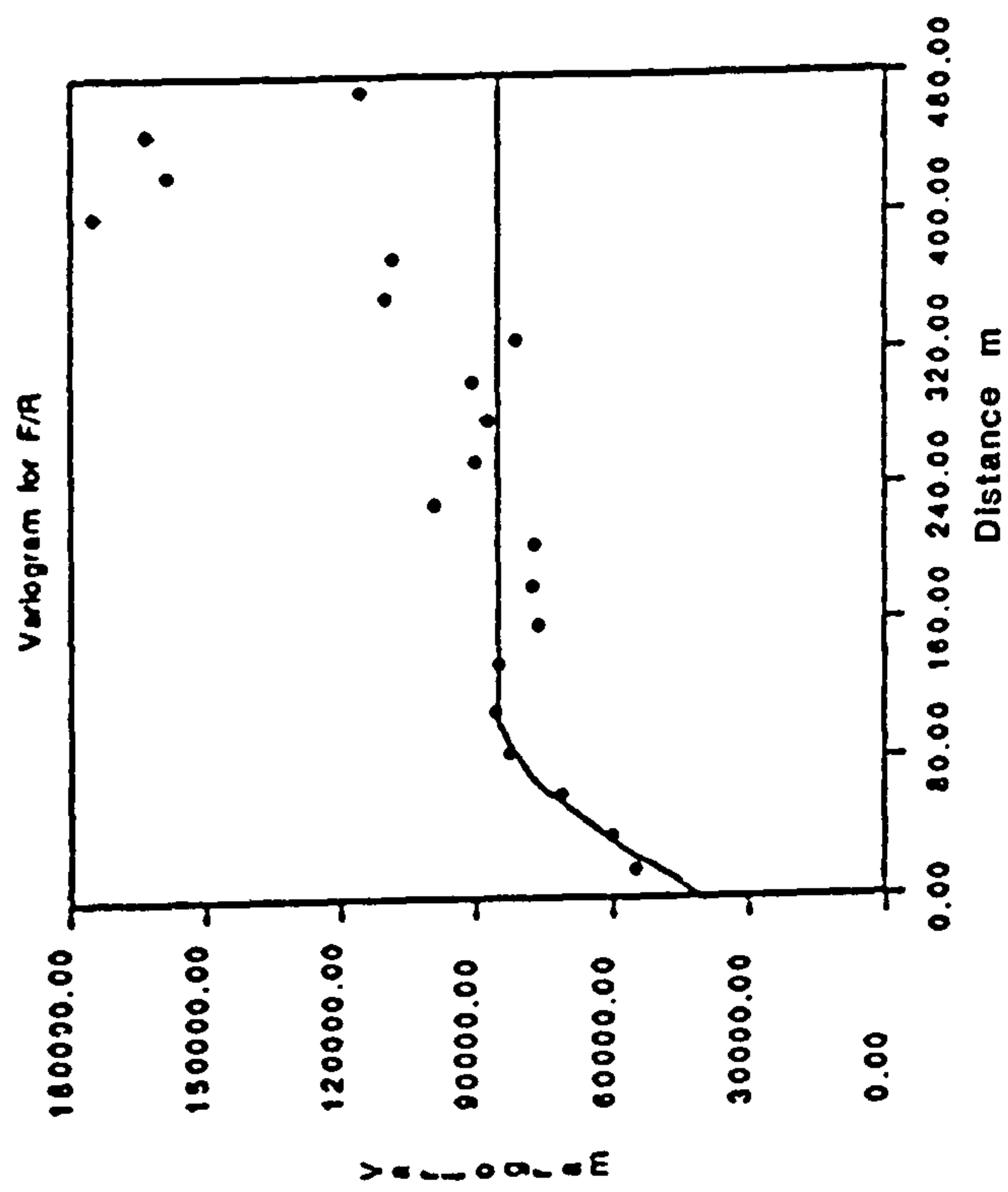


Fig. 7.14 (Cont'd) Examples of variograms for permeability data sampled from domains with different positions, directoins and sample intervals



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F

Fig. 7.14 (Cont'd) Examples of variograms for permeability data sampled from domains with different positions, directoins and sample intervals

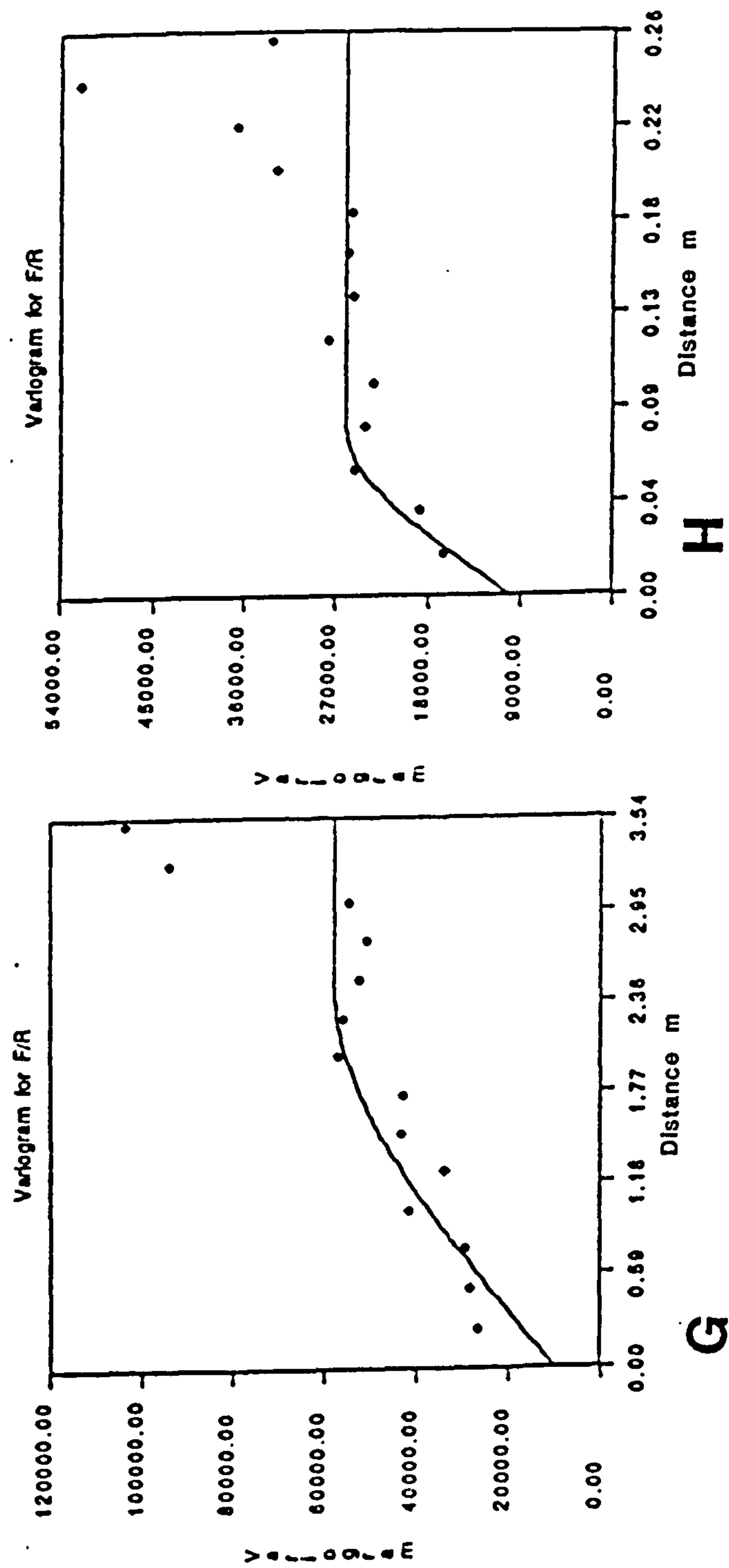


Fig. 7.14 (Cont'd) Examples of variograms for permeability data sampled from domains with different positions, directoins and sample intervals

From variogram analysis the following observations are made:-

- 1) Correlation structure exists within permeability variation in the vertical direction with an average correlation length of 0.24m and a maximum of 2m. Above this interval of 0.24m, permeability variation in the vertical direction is generally uncorrelated.
- 2) A weak correlation structure exists within permeability variation in the horizontal direction with an average correlation length of 0.14m. Above this interval of 0.14m, permeability variation in the horizontal direction is generally uncorrelated.
- 3) There is no significant difference in the horizontal correlation structure within permeabilities sampled in the east-west and north-south directions.

7.5.7 Spatial statistics - Rescaled range (R/S) analysis

Variogram analysis has indicated that the permeability variation within data sequences is largely uncorrelated. As the spatial permeability structure is self-similar over a wide range of sample-intervals this suggests that the spatial permeability variation may display fractal characteristics. This self similarity over different sample intervals is demonstrated in the vertical and horizontal permeability traces from the White Sandstone in figures 7.15 and 7.16. If the permeability data sequences are compressed or expanded, it is possible to generate sequences that are statistically similar to those for smaller and larger sample intervals respectively. This fractal behaviour is also indicated by the similarity in C_v for permeability sequences with different sample intervals; that is, the variation in permeability about the mean remains the same at all sample intervals. This fractal character, if it exists, is a spatial phenomena and is not volumetric and does not imply any fractal scaling-up of permeability.

Spatial fractal permeability characteristics might be expected because permeability is directly related to textural and structural variations in

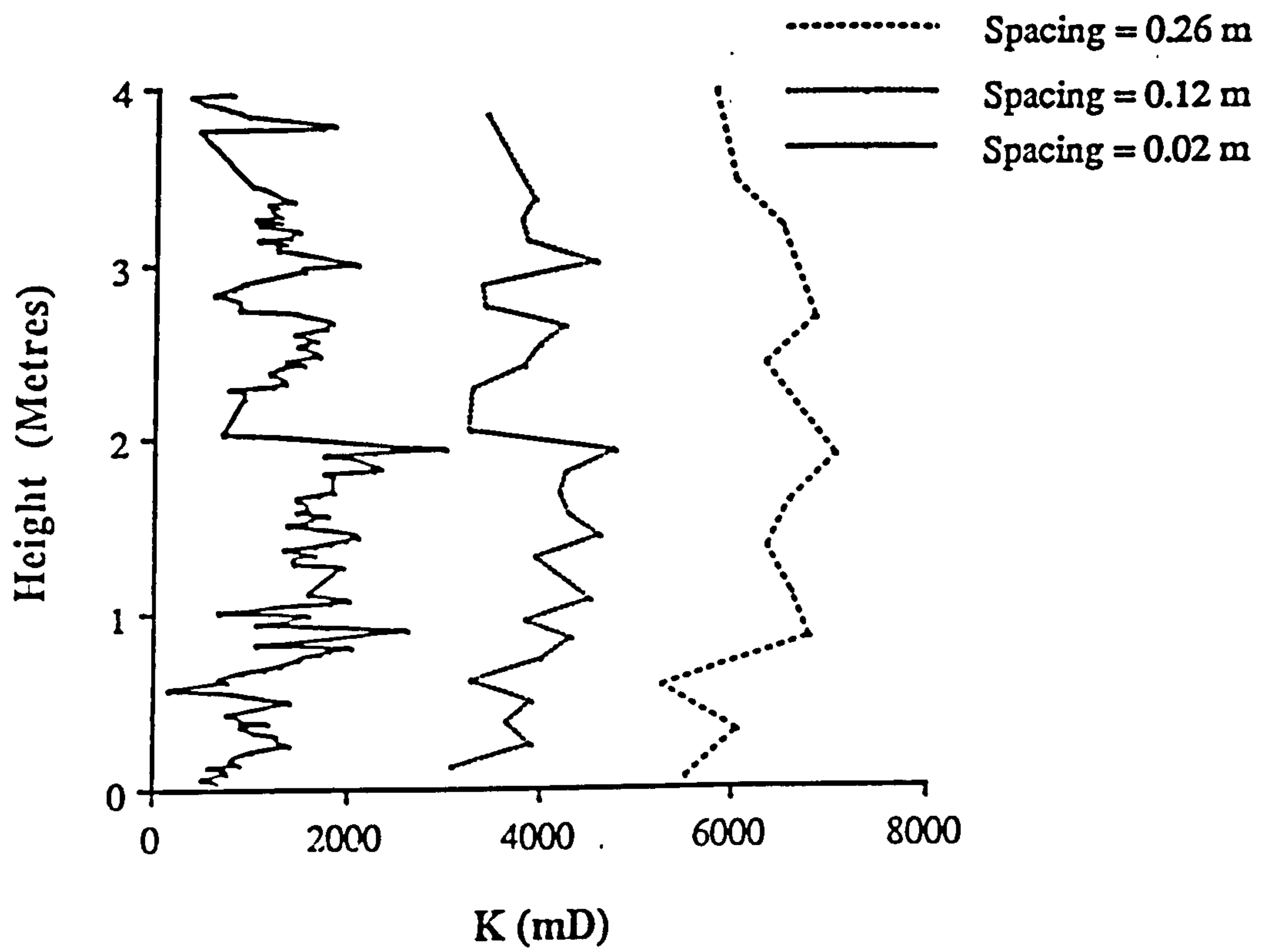


Fig. 7.15 Permeability profiles with different sample intervals for a vertical transect through the White Sandstone

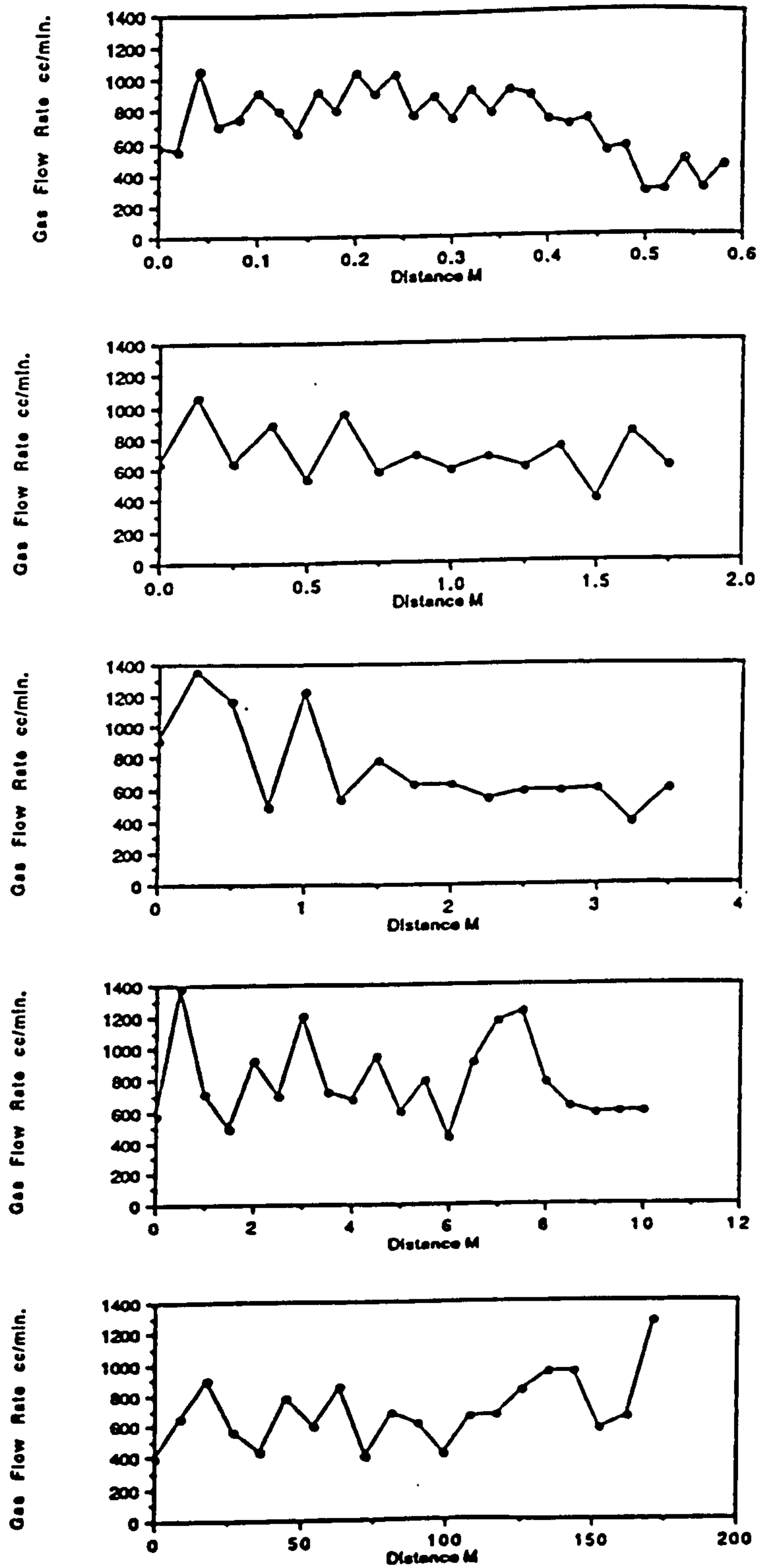


Fig. 7.16 Permeability profiles with different sample intervals for an horizontal transect through the White Sandstone

the sediment body. The processes that combine to form the sediment body such as the detrital input, current velocities, wave height, tidal cycles, biogenic activity and so on are natural phenomena. Spatial variations in permeability are therefore likely to reflect spatial variations in these natural processes. Why natural phenomena should display fractal characteristics appears to be related to the 'memory effect' (Feder 1988). The memory effect describes how an action at one end of a system is felt over time through that system. An example of this occurs in rivers where the fluctuations in discharge within a small tributary stream are felt later within the discharge of a larger river downstream. This is a well known phenomena to people living on low lying floodplains such as the Brahmaputra delta!

Fractal characteristics are quantified using the Hurst coefficient, H (Hurst et al 1965), which can be obtained through rescaled range or R/S analysis. The method of R/S analysis is described in detail by Feder (1988) using an example of river discharge. The method involves calculating the accumulated difference from the mean, X, in the measured variable over time or space (the lag). The range, R, is given by the maximum value of X at a given lag and is calculated by:

$$R(\tau) = \max_{1 \leq t \leq \tau} X(t, \tau) - \min_{1 \leq t \leq \tau} X(t, \tau)$$

where t = time (in this case)(31)

τ = time period or lag

X = accumulated difference from the mean

The range, R, is expected to increase with increasing lag. To compare values of R versus lag for different phenomena, Hurst *et al* used the dimensionless ratio R/S, where S is the standard deviation, thus:

$$S = \left(\frac{1}{\tau} \sum_{t=1}^{\tau} \left\{ \xi(t) - \bar{\xi}_{\tau} \right\}^2 \right)^{\frac{1}{2}}$$

where $\xi(t)$ = value of measured variable at time, t (in this case)

$\bar{\xi}_{\tau}$ = mean value of measured variable of time period or lag, τ

.....(32)

Hurst *et al* found that the observed rescaled range, R/S, for many records in time is very well described by the following relation:

$$R/S = \left(\frac{\tau}{2}\right)^H$$

.....(33)

For natural phenomena, the Hurst component, H, is more or less symmetrically distributed around a mean of 0.73, with a standard deviation of about 0.09. From coin tossing experiments, Hurst *et al* found that random records produce an H value of 0.503 +/- 0.008. From a similar experiment using a 'probability pack of cards', Hurst *et al* found that biased random records produce an H value of 0.714 +/- 0.091, a value that corresponds with the H value for natural phenomena.

In general, records that have H values > 0.5 indicate fractal behaviour, that is, they demonstrate long term dependence or persistence. Records that have H values = 0.5 demonstrate no correlation of the record over time or space, that is, the record is an independent random process. Records that have H values < 0.5 demonstrate antipersistence. In this case, an increasing trend in the past (time or space) implies a decreasing trend in the future and *vice versa*. This is the opposite to the case of records demonstrating persistence.

Values for H were estimated for vertical and horizontal permeability sequences from the White Sandstone. Data sequences that contain a drift were normalised prior to R/S analysis as this drift will produce apparent persistence ($H > 1/2$). As data sequences with different sample intervals are located at various positions within the mine, H values were calculated individually for each sample domain. To obtain a more reliable estimate of H, R/S values for domains sampled with the same interval were averaged producing a single H value for sequences sampled at intervals of 9m, 0.5m, 0.25m, 0.125m and 0.02m.

The R/S analysis results for spatial permeability data within the White Sandstone are summarised in figure 7.17 and table 7.6. Mean values of H are given for each sample interval, estimated from the combined H values for data sequences with that sample interval. Longer records produce more reliable H values whilst short records often produce low

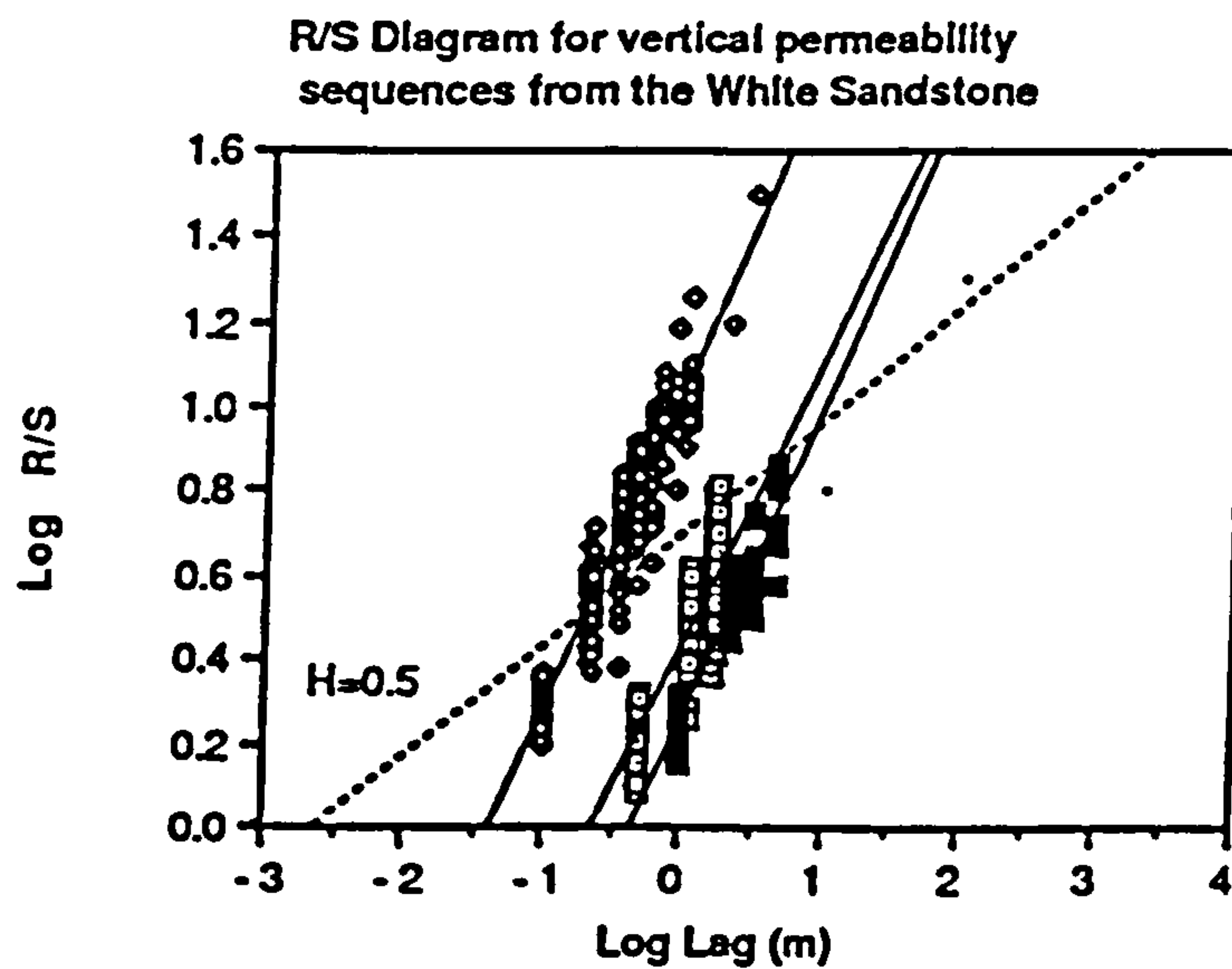
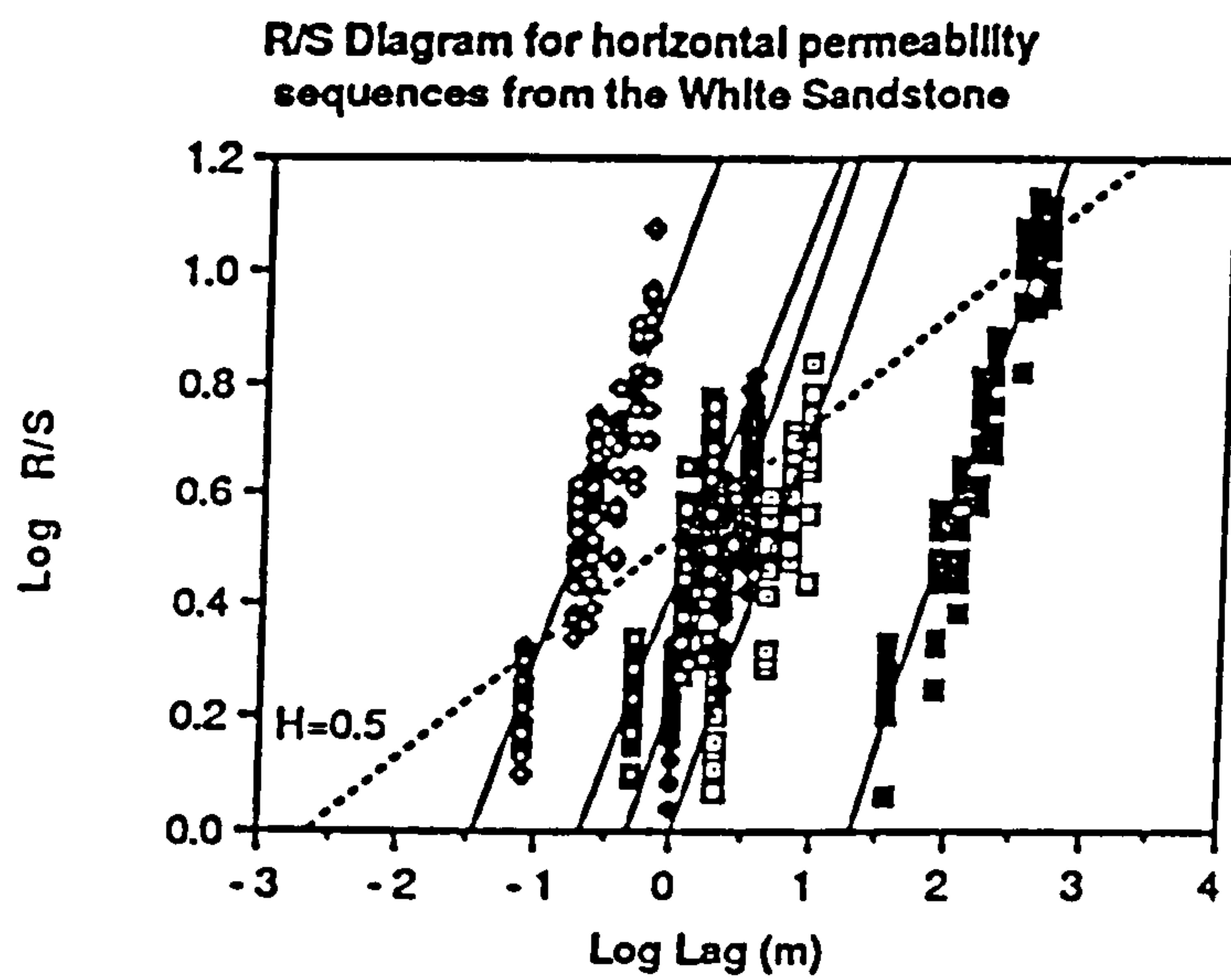


Fig. 7.17 Rescaled range plots for permeability data from horizontal (A) and vertical (B) sequences

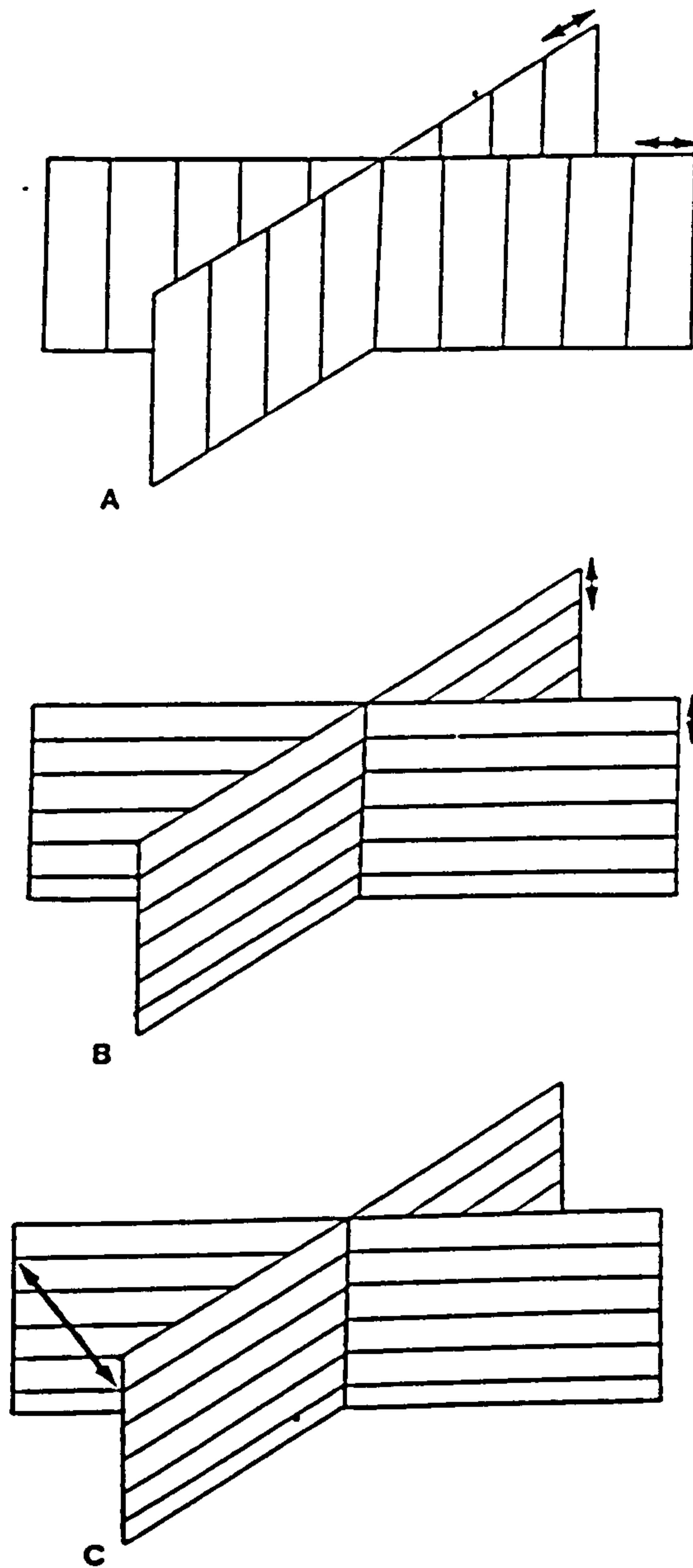


Figure 7.6 Diagrammatic illustration of the various comparisons made between permeability data sampled from the north-south and east-west cross-sections

values of H that are indistinguishable from random records. Therefore, some measure of reliability for the estimated H value is required. This was done by calculating the standard deviation and range of H for data sequences representing each sample interval.

In the horizontal direction, permeability sequences sampled at 0.02, 0.125, 0.25, 0.5 and 9m intervals have H values between 0.67 and 0.78, indicating the presence of long-term dependence over a lag range of 0.08m to 477m (figure 7.17a). For permeabilities sampled at 0.02, 0.25, 0.5 and 9m intervals, the standard deviation for H shows that the 66.6% of H values are significantly greater than 0.5. However, horizontal data sequences sampled at 0.125m, have a mean H value of 0.67 and a standard deviation of 0.2. This means that 33.3% of individual H values lie close to 0.5 which, considering the short length of the domain, are indistinguishable from random records. In horizontal records extending over 477m from the north-south cross-section, the trend of persistence breaks at lags of 390m, beyond which there is random variation and antipersistence up to a lag of 477m. This does not appear to be related to periodic behaviour as identified from regression analysis (the 'W'-shaped trend) since this has a wavelength of about 300m.

In the vertical direction, permeability sequences sampled at 0.02, 0.125 and 0.25m intervals have H values between 0.68 and 0.75, indicating the presence of long-term dependence over a lag range of 0.1m to 4.5m (figure 7.17b). For permeabilities sampled at 0.02m and 0.25m, the standard deviation for H shows that 66.6% of H values are significantly greater than 0.5. Permeabilities sampled in the vertical direction at 0.125m intervals have the lowest mean H value and the highest standard deviation, as identified in horizontal sequences. For these data, 33.3% of individual H values lie close to 0.5, indicating that a significant proportion of vertical permeability sequences are indistinguishable from random records.

The individual values for H for each sample interval and the average value for all intervals are similar for both vertical and horizontal data sequences. The main difference exists between H values for permeabilities sampled at 0.25m intervals.

From rescaled range analysis (R/S) the following observations have been made:-

- 1) Long-term dependence or persistence is identified in permeability sequences with lag spacings from 0.08m to 390m in the horizontal, and with lag spacings from 0.1 to 4.5m in the vertical, in both the north-south and east-west directions
- 2) Statistical independence (random variation) and antipersistence is indicated in north-south orientated horizontal permeability sequences with lags from 390 to 477m
- 3) Permeability sequences sampled at 0.125m intervals in both horizontal and vertical directions contain a significant proportion of records indistinguishable from random records
- 4) Generally, the fractal characteristics for spatial permeability variation in the vertical and horizontal directions are similar.

These conclusions show that the spatial variation in permeability within this shallow marine sand body exhibits remarkably consistent fractal characteristics. This implies that the permeability variation measured at 0.02m sample intervals over a short domain length (2m, for example), in either the vertical or horizontal direction (and probably in any direction) can be used to predict the permeability variation at any chosen interval or position within the sand body. Conversely, the permeability variation measured over large domain lengths (10's to 100's of metres for example) and at large sample intervals (at conventional 1' (0.33m) intervals for example) can be used to predict permeability variation at smaller intervals down to 0.02m. This assumes a sample volume consistent with that volume measured using a probe with O.D. = 0.002m and I.D. = 0.004m (the probe set-up used for this outcrop study).

7.6 Sample error

The variation in permeability, indicated by the coefficient of variance (Cv) within each vertical transect along the north-south and east-west cross-sections is illustrated in figure 7.18. Whilst the permeability variation oscillates, this variation appears to be random over the length of each cross-section. Confidence limits for the original data, together with the optimal sample number and interval are shown in table 7.7.

In the north-south cross-section, the confidence limits are surprisingly low (average= $\pm 44.6\%$) and are reflected in an average optimal sample interval of 0.16m which is less than that used (0.25m). Even to within +1 standard deviation of this average, the optimal sample interval of 0.26m is only just greater than that used.

In the east-west cross-section, the confidence limits are marginally better implying slightly less permeability variation, with the average optimal sample interval of 0.26m being just greater than that used (0.25m).

These results indicate that the vertical sample interval needs to be reduced in many of the transects on both the east-west and north-south cross-sections. This reduction in sample interval is also required for quantification of spatial correlation. Whilst the vertical correlation length is approximately 0.24m, and a sample interval of 0.25m is probably sufficient to identify this correlation structure, a reduced sample interval is required to model behaviour of the spatial permeability variation within this correlation structure.

The permeability variation in the horizontal direction was obtained by calculating the Cv for each horizontal data sequences from the cross-section at different heights above the basal datum. This is shown in figure 7.19. Permeability variation is greatest at the base of the sequence, but stabilises from approximately 1m above the datum. Permeability variation in the horizontal direction also appears to be less in the east-west direction than in the north-south direction. The confidence limits, optimal sample number and optimal sample distance

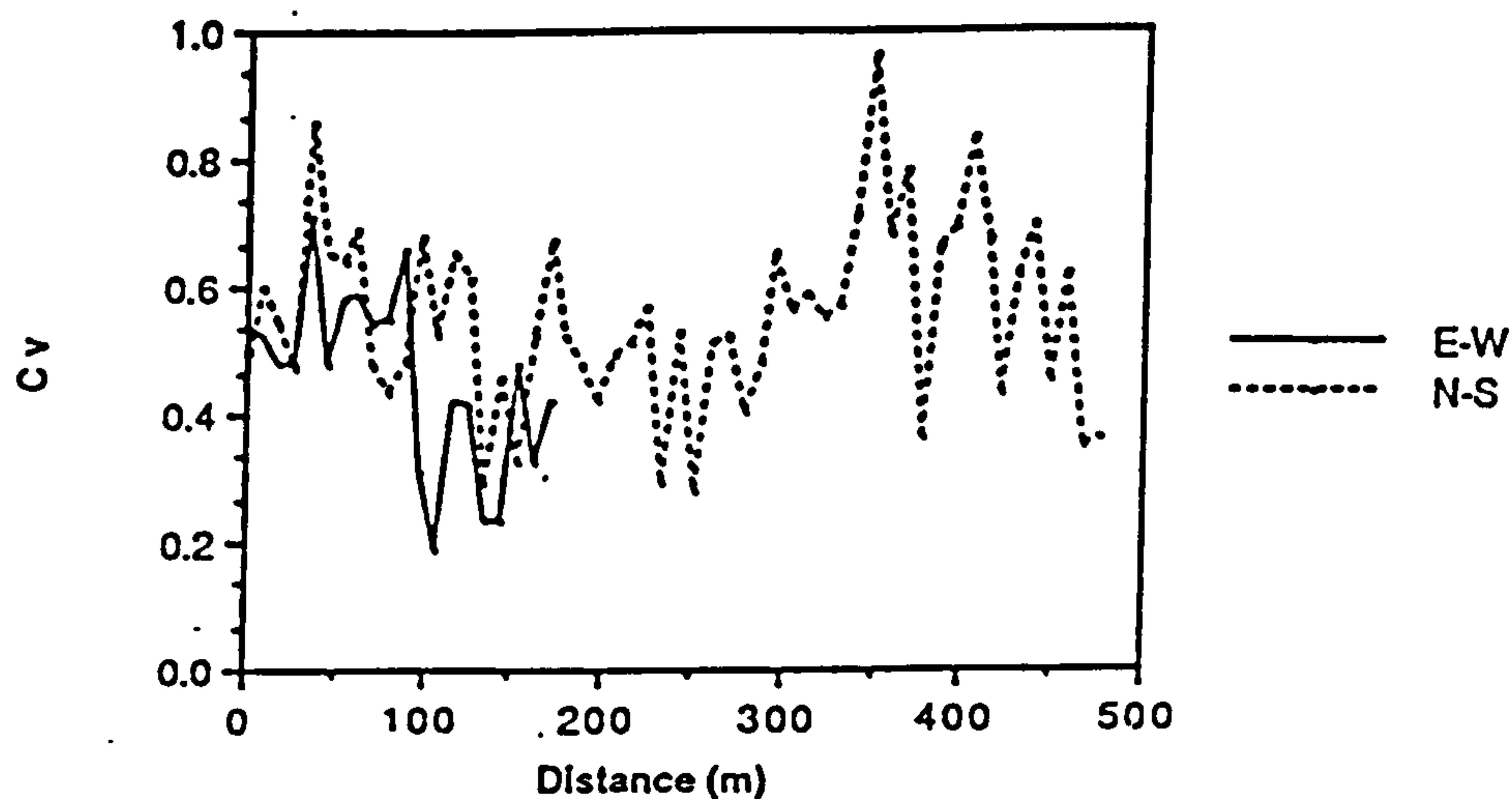


Fig. 7.18 Permeability variation within vertical sample transects along the north-south and east-west cross-sections from the White Sandstone

	Sample Interval (m):	Sample No:	Conf. Limit: (alpha=0.05)	N0:	Ds (m):
Minimin:	0.25	13	+/-22.42%	7.72	0.04
Maximum:	0.25	22	+/-76.28%	92.18	0.52
Mean:	0.25	17	+/-44.6%	32.43	0.16
Std. Dev:	0	2.06	+/-11.73%	16.99	0.10

North-South Cross-Section

	Sample Interval (m):	Sample No:	Conf. Limit: (alpha=0.05)	N0:	Ds (m):
Minimin:	0.25	13	+/-17.24%	3.56	0.08
Maximum:	0.25	19	+/-56.95%	49.80	0.84
Mean:	0.25	16.6	+/-37.17%	22.85	0.26
Std. Dev:	0	1.79	+/-10.92%	12.52	0.22

East-West Cross-Section

Table 7.7 Optimal sample number and confidence limits for permeability data sampled from vertical transects along the north-south and east-west cross-sections

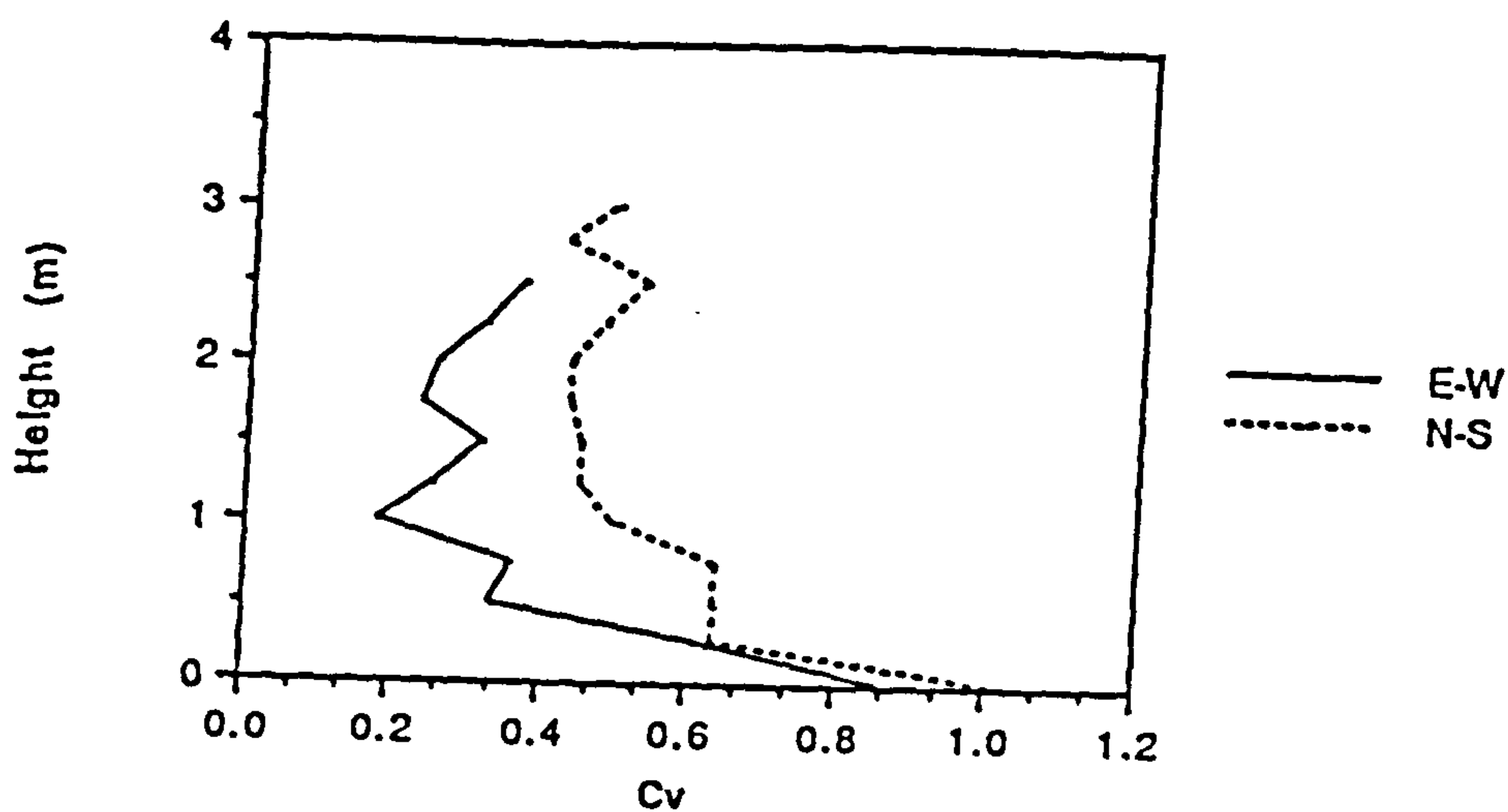


Fig. 7.19 The permeability variation as defined by the coefficient of variance (Cv) within horizontal sample transects along the north-south and east-west cross-sections from the White Sandstone

	Sample Interval (m):	Sample No:	Conf. Limit: (alpha=0.05)	N0:	Ds (m):
Minimin:	9	54	+/-16.34%	17.91	4.65
Maximum:	9	54	+/-39.09%	102.49	26.63
Mean:	9	54	+/-21.15%	32.41	18.50
Std. Dev:	0	0	+/-6.22%	22.77	6.75

North-South Cross-Section

	Sample Interval (m):	Sample No:	Conf. Limit: (alpha=0.05)	N0:	Ds (m):
Minimin:	9	20	+/-11.04%	3.29	2.28
Maximum:	9	20	+/-52.66%	74.90	51.9
Mean:	9	20	+/-22.78%	17.56	19.6
Std. Dev:	0	0	+/-12.02%	21.12	13.82

East-West Cross-Section

Table 7.8 Optimal sample number and confidence limits for permeability data sampled from horizontal transects along the north-south and east-west cross-sections

for these horizontal sequences are summarised in table 7.8. The average confidence limits for data sequences from the east-west and north-south directions are both fairly high ($\pm 23\%$ and $\pm 21\%$ respectively). Consequently, the optimal sample intervals for each direction are similar (19.6 and 18.5m respectively). These values for the optimal sample interval are considerably greater than the interval used (9m on average), the significance being shown by the standard deviation. The optimal sample interval in the east-west direction varies from 5.78m to 33.42m within 1 standard deviation from the mean, therefore, in the majority of cases, the optimal sample interval is equal to or greater than that used at 9m. The optimal sample interval in the north-south direction varies from 11.75m to 25.25m within 1 standard deviation of the mean. Whilst an horizontal sample interval of 9m provides an adequate representation of static permeability variation in this direction, the spatial statistics have shown that there is an horizontal correlation length, albeit weak, of approximately 0.14m. A reduced sample interval therefore, is required.

The vertical and horizontal sample interval was then reduced with sampling concentrated within a series of sample domains placed at various locations along the cross-sections. Confidence limits, optimal sample number and optimal sample distance were estimated for data within each sample domain (table 7.9). With low C_v values, indicating a low degree of permeability heterogeneity within each domain, the actual sample number is consistently greater than the optimal sample number required (at $p=20\%$). Consequently, the confidence limits for the sample data are high, the maximum value being $\pm 21\%$, but more frequently around $\pm 9\%$. The number of sample domains for each sample interval are too few to obtain a reliable estimate of the optimal number of domains required but confidence limits can be estimated. These are shown in table 7.10. As expected the confidence limits of the mean of the domains for each sample interval are low, ranging from $\pm 57\%$ to $\pm 168\%$.

Domain Ref:	Sample Interval (m):	Sample No:	Conf. Limit: (alpha=0.05)	N0:	Ds (m):
E-W1	0.5	180	+/-10.69%	31.02	1.2
E-W2	0.5	141	+/-11.79%	29.51	1.04
E-W1	0.25	223	+/-9.75%	31.95	0.62
E-W2	0.25	212	+/-7.99%	20.41	0.77
E-W1(1)	0.125	225	+/-7.3%	18.09	0.41
E-W1(2)	0.125	225	+/-9.14%	28.31	0.33
E-W2	0.02	225	+/-8.27%	23.18	0.36
E-W1	0.02	390	+/-3.23%	6.13	0.17
E-W2	0.02	900	+/-21.21%	13.71	0.16
E-WVprof	0.5	379	+/-4.57%	11.91	0.12
N-S1	0.5	179	+/-10.45%	29.44	0.17
N-S1	0.25	225	+/-8.22%	22.88	0.73
N-SHprof	0.25	194	+/-2.91%	2.47	19.51
N-S1	0.02	806	+/-2.24%	6.07	0.22

Table 7.9 Optimal sample number and confidence limits for permeability data sampled from domains along the north-south and east-west cross-sections

Domain Dimensions (m)		Max. Domain Area (m^2):	No. Domains:	Conf. Limits: (alpha=0.05)
X:	Z:			
0.58	0.58	0.34	3	+/-80%
0.26	0.70			
0.24	1.22			
1.75	1.75	3.06	3	+/-168%
1.75	1.75			
1.75	1.75			
3.50	3.50	12.25	3	+/-84%
3.50	3.50			
3.50	3.50			
10.00	4.50	45.00	3	+/-57%
8.00	4.00			
9.00	4.50			

Table 7.10 Confidence limits for permeability populations from different sample domains with the same sample interval

7.7 Summary

From the various analyses used on the permeability data from the White Sandstone, the most striking feature is the consistent regularity in both static and spatial variation.

After removal of the linear increase in permeability vertically (associated with the coarsening-up sequence), all data, irrespective of the sample interval, domain size, and direction are normally-distributed and have a similar C_v value. This means that the variation between permeability point values remains constant over intervals from 0.02m up to 477m, irrespective of direction (X, Y or Z). These results are significant because they show that the statistical variation within permeabilities measured in the vertical direction is similar to the statistical variation within permeabilities measured in the horizontal direction. This implies that within similar massive sands of this genetic type, permeabilities sampled in the vertical direction (for example, from vertical well data) may be used to predict the *statistical probability distribution* of permeabilities in the horizontal direction (for example, in the interwell area). This is providing that the permeability variations within the White Sandstone are; a) attributable to primary depositional characteristics, and b) that these results can be applied to similar sand bodies elsewhere where the effects of modifying factors such as diagenesis and reservoir conditions can be quantified.

This isotropic nature of static statistical permeability variation is also identified in the spatial statistics from variogram analysis. The variograms show very few correlation structures, even where permeabilities were measured at 0.02m intervals. Those structures that were identified exist predominantly in the vertical direction and have short correlation lengths around 0.1m. Other correlation structures with varying correlation lengths were identified in both the vertical and horizontal directions but small differences between sill and nugget values indicate that these correlation structures are weakly defined.

R/S analysis provides convincing evidence that the spatial permeability variation has fractal characteristics. The apparent long-range statistical

dependence for permeability within the White Sandstone is remarkably similar in both the vertical and horizontal directions. This implies that within similar massive sand bodies of this genetic type, permeability data sampled in the vertical direction can also be used to predict the spatial statistical distribution of permeability in the horizontal direction, providing the same conditions detailed above are satisfied.

With this low permeability heterogeneity, and generally uncorrelated spatial permeability structure, these permeability data provide a very reliable data base for the quantification of permeability heterogeneity within this sand body type. However, the selection process used to determine the number and position of domains requires a more systematic approach. Whilst it is clear that the sampling scheme used has successfully quantified both the static and spatial permeability variation, the number of domains at each sample interval is not consistent with their area. A reduction in sample interval and domain size must be compensated by an increase in the number of domains. These domains must be distributed in an unbiased fashion, either arranged as a regular grid or arranged randomly.

In this study on the White Sandstone there are too few domains (other than the vertical transects on the cross-sections) to provide a statistically valid estimate of the variation between the domains, even though the geological model would suggest that additional sample domains are unnecessary.

CHAPTER 8 Causes of permeability heterogeneity within the White Sandstone

8.1 Introduction

To obtain a fully portable model for spatial permeability heterogeneities from outcrop, that is, a model that can be used for all reservoirs for which it is an analogue, irrespective of their post depositional histories, it is necessary to understand the cause of these heterogeneities. With the causes known, allowances can be made for permeability variation caused by diagenesis, faults, fractures, and igneous intrusions.

8.2 Relationship with the geological model

Generally, the permeability heterogeneities identified within the White Sandstone conform to the conceptual geological model for the sand-body. The coarsening-up sequence characteristic of marine bars and shoals corresponds to the increase in permeability vertically through the sandstone interval. The absence of well defined and persistent correlation structures over intervals from 0.02m to 500m in either the vertical or horizontal direction reflects the exceptional textural maturity of the sand and the process of homogenisation caused through bioturbation. Over the distances for which permeability samples in this outcrop study were measured, and probably extending over 1000's of metres, the character of the sandstone is unlikely to change. Over greater distances (10's of kilometres) however, there is a decrease in grain size towards the west (Bailey, 1924), possibly associated with a deepening of the basin in this direction, and a corresponding decrease in permeability would be expected.

Vertical correlation structures within permeabilities measured on the sandstone may correspond to textural variation within and between cosets. Considering the apparent lateral continuity of the cross-beds observed outside the mine, the horizontal correlation structures probably relate to permeability variation within cosets. Whether

variation within cosets is attributable to differences in laminae type is not possible to determine but is likely.

It is perhaps surprising that permeabilities measured at 0.02m intervals did not reflect the presence of burrows as these might be expected to produce a marked grain size contrast between the fine-grained burrow-lining and the coarser-grained burrow-fill and surrounding sand. Whilst a patchy distribution of permeability values was observed at this sample interval, convincing patterns resembling burrows were not identified. However, this can be explained by the size or resolution of the sample volume. In this sandstone, burrows are recognised from their lining rather than their fill, where the grade of the burrow-fill is very similar to the grade of the surrounding sand. Thus, a permeability contrast exists between the burrow lining and the sand adjacent to it. Since the burrow lining is, at most, 1mm thick, the minipermeameter with probe dimensions O.D. = 20mm (0.02m) and I.D. = 4mm (0.004m) does not measure the permeability of the lining but the average permeability of the burrow lining and the sand either side. To measure the permeability of the burrow lining, the probe would have to be placed perpendicular to the lining, but as the burrows vary in diameter and are slightly tortuous, longitudinal sections of the burrow are rarely exposed.

Reducing the sample volume and sample interval reveals structures that are otherwise lost as larger sample volumes average them out. A detailed permeability study using the automated minipermeameter provided by Statoil (Halvorsen and Hurst 1991) was used to obtain permeabilities measured using probe dimensions of O.D. = 4mm, and I.D. = 1mm. The resultant permeability maps are shown in figure 8.1. The notion that correlation structures within permeabilities measured at outcrop in this facies type are related to cross-bed and foreset thickness is born out. Due to the well-sorted nature of the sand, permeability contrasts between foresets and cosets are small, and anisotropy ratios for the average permeability over these domains are likely to be low. Distinct burrow patterns are also identified where, as expected, there is a marked decrease in permeability at the margin of the burrow.

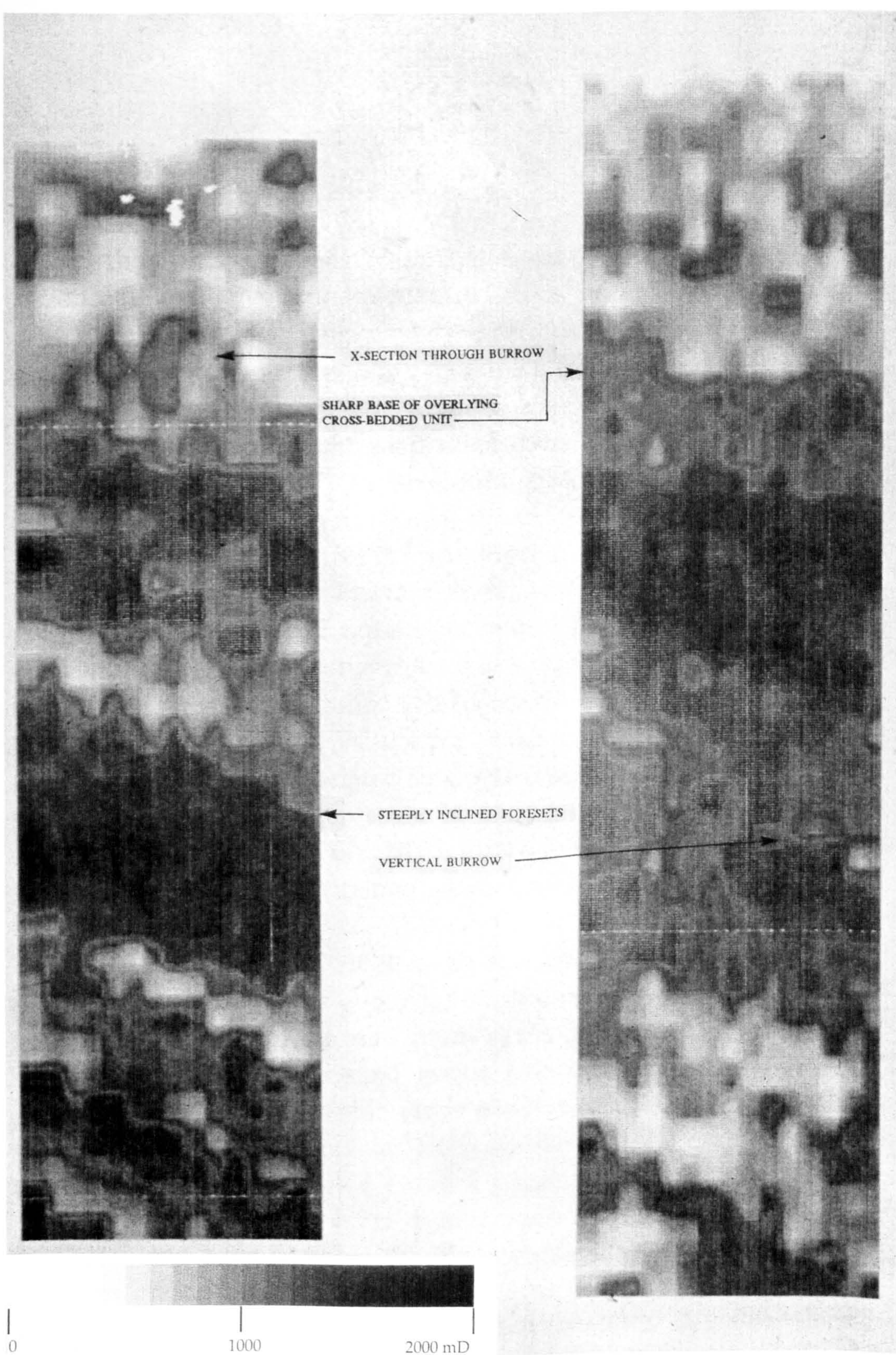


Fig. 8.1 Permeability point maps of the White Sandstone with measurements made at 4mm intervals. The probe seal set-up used was a 4mm outer diameter and 1mm injection diameter. Cross-beds are clearly identified within this otherwise visually massive sandstone. (permeability maps are approximately to scale)

8.3 Post-depositional modification

Microscopic analysis of the White Sandstone has shown that diagenetic modification of the primary texture is minimal except for samples within and immediately adjacent to the hard bands. As these hard bands are easily identified permeability measurements can be located in areas where the rock is unmodified. There is also evidence of variations in the crushing strength of the sand across fault boundaries indicative of variations in cementation. In the eastern area of the mine, where there is a large fault running north-south, the sandstone on the downthrown side is more friable than on the upthrown side. The thickness of the sandstone is also seen to increase on the downthrown side. As these larger faults are easily identified permeability samples can be located away from them, but in some cases faults are difficult to see and some of the measured permeability heterogeneities may be attributable to these (for example, the 'W'-shaped trend on the north-south cross-section). These fault-associated heterogeneities are extremely important as they represent a larger scale of permeability heterogeneity, but unfortunately, due to the difficulty in identifying the faults, quantification of their distribution was not possible in this study.

The basaltic dykes that cut through the sandstone may modify the primary texture through a combination of processes. These processes include compression of the sand grains as the dyke is forced through the sandstone, fusion of the sand grains due to extreme heating, and precipitation of minerals within the sands from volatiles. To investigate the effect of these dykes on permeability within the sandstone, permeabilities were sampled along a transect aligned normal to the plane of the dyke (figure 8.2). Whilst permeabilities were noticeably reduced within a region about 1m wide either side of the dyke and over distances greater than 1m from the dyke, the variation and mean value of the permeabilities were typical of those measured elsewhere in the mine. This narrow zone of modification indicates that the sandstone acted as an effective insulator with volatiles rapidly cooling and crystallising on penetration into the sand.

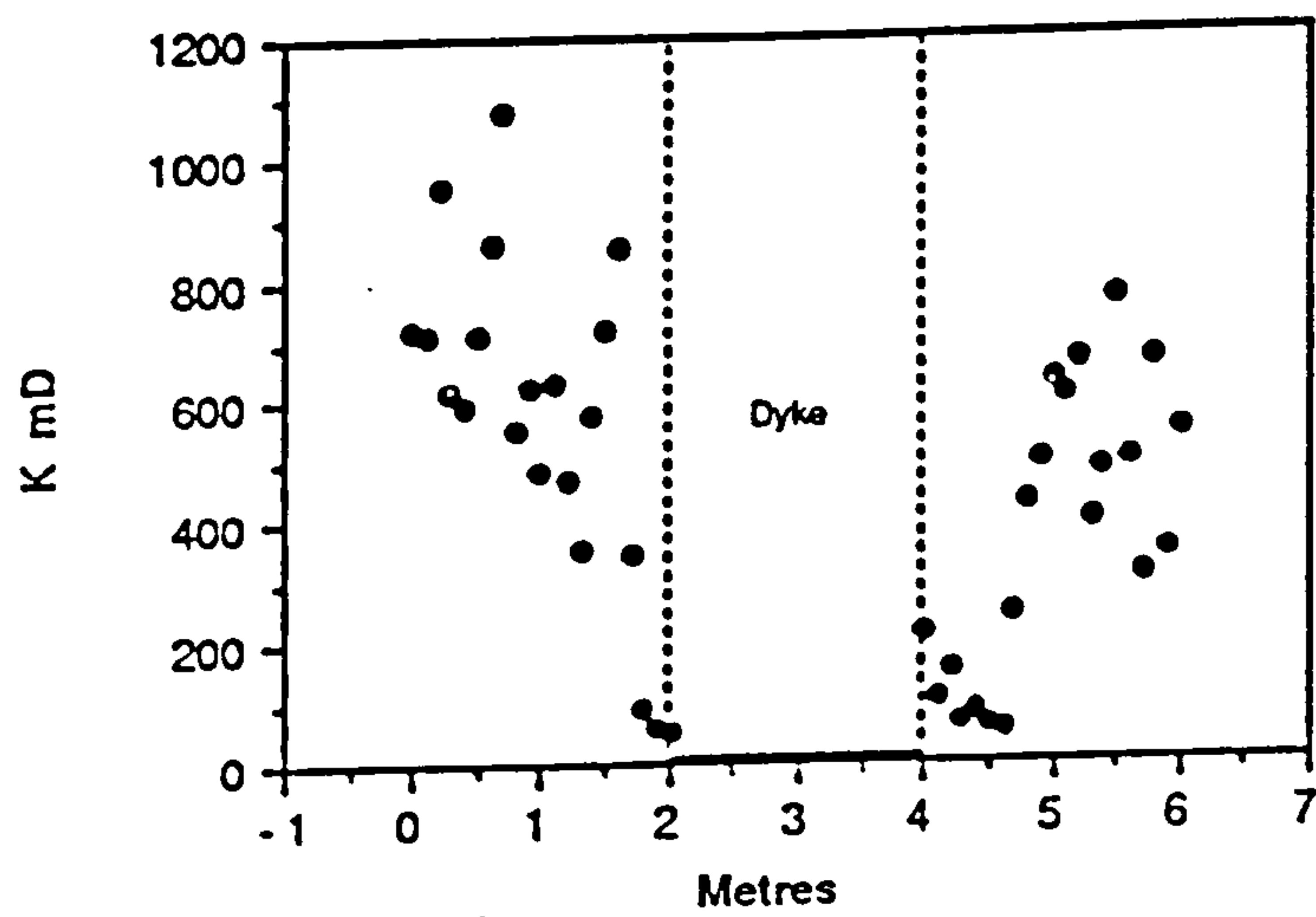


Fig. 8.2 Permeability profile across a basaltic dyke within the White Sandstone exposed in the mine at Lochaline

8.4 Textural controls on permeability

The close correlation between permeability and mean grain size suggests that the permeability values are closely related to textural characteristics. From the classical packing studies (for example, Beard and Weyl 1973), the most important textural properties influencing the permeability and porosity characteristics are grain size, sorting, shape (sphericity), roundness (angularity), and packing. Of these, grain size and sorting are considered to be of major importance. Whilst packing probably has a significant effect on the poroperm characteristics, its influence is uncertain because of the difficulties involved in isolating and quantifying it. The following observations between these textural characteristics and permeability and porosity are summarised below:-

- 1) Porosity increases with improved sorting but is independent of grain size within well-sorted sands. That is, for two sands of equal sorting but different mean grain size, the porosity will remain constant (Rogers and Head 1961, Morrow et al 1969, and Beard and Weyl 1973).
- 2) Permeability increases with improved sorting and with an increase in grain size (Morrow et al 1969 and Beard and Weyl 1973). Thus permeability is often seen to increase with an increase in porosity. However, as grain size may vary with constant sorting, the permeability may show no relation to porosity.
- 3) According to theoretical work (Fraser, 1935, and Tickell and Hiatt, 1938), the packing efficiency is improved with increasing roundness and sphericity. Thus, porosity and permeability will decrease with an increase in angularity and sphericity. In a study by Pryor (1973), little correlation was found between porosity and grain size or sorting and packing was believed to be of major importance. Thus, in some cases the combined effects of roundness, shape and packing efficiency may have a greater influence on permeability and porosity than mean grain size and sorting.

To investigate the relationships between permeability, porosity and grain size, an analysis of the grain size distribution was conducted on

samples for which the values of permeability and porosity were known.

8.4.1 Grain size analysis - methodology

As the White Sandstone is essentially unconsolidated it is easily disaggregated and is ideal for grain size analysis via mechanical sieving. The grain size distribution was determined for samples for which the permeability and porosity were known. These samples were obtained from core plugs used for the calibration of the minipermeameter and the cores produced during the face preparation process. These latter samples, hereafter referred to as hand-samples to avoid confusion with the core plugs, were sampled from a vertical profile. Permeability and porosity were determined for the core plugs and gas flow rates for these hand-samples were measured directly on the rock face behind the hand-sample. Porosity measurements were not made on the hand-samples.

A total of fifteen core plugs were selected from the calibration set covering a range of permeability from 1320 mD to 2830 mD and a range of porosity from 18.1 % to 20.4 %. Grain density was 2.64 g/cc for all the plugs reflecting the very high quartz content. The plugs were selected to give an even spread of permeability values, but additional plugs with similar permeabilities and porosities were included as reliability indicators.

The hand samples, weighing between 34g and 50g, were disaggregated by gently rubbing the samples between the fingers. The loose sand was dried in an oven at 100 degrees centigrade overnight and then split into 34g samples. Each sample was then sieved for ten minutes on a Pascall rotating - tapping machine with ten mesh sizes approximating to half phi intervals. The core plugs were disaggregated in a sonic bath because they were harder to break up. These were then dried and sieved in an identical fashion to the hand samples. Sample weights were between 84g and 103g.

The sieve data was then entered into a computer using the Sahara grain size analysis package (Christiansen and Hartmann, 1988) and the

distribution moments (mean, standard deviation, skewness, kurtosis and median) calculated.

8.4.2 Results

The frequency histograms and moments of each composite grain size distribution for the core plugs and hand samples are shown in figure 8.3 and table 8.1. Both skewness and kurtosis are included because these consider the tails of the distribution that are often ignored. In studies of grain sizes within depositional environments with well-sorted sands that are considered to be texturally indistinguishable (for example, aeolian dunes and beaches), the grain size distribution in the tails has been shown to be a significant diagnostic feature for the depositional environment (Barndorff-Nielsen 1977a, Barndorff-Nielsen et al. 1982 and Vincent 1986). These extreme grain sizes may also have a significant effect on the poroperm characteristics.

The size frequency distributions for the core plugs and the hand samples are very similar. Since the hand samples are taken from a vertical profile at outcrop and the core plugs are cut from blocks distributed around the mine, the composite population of vertical profile samples is believed to be fairly representative of the grain size distribution within the mine (or at least of the area incorporated in the outcrop study).

From the cross-plots between the moments for the grain size distributions shown in figure 8.4 the following observations were made:-

- 1) Sorting improves with an increase in grain size (figure 8.4a).
- 2) Skewness remains unchanged with an increase in grain size, that is, the fine tail is present in all samples (figure 8.4b).
- 3) Kurtosis (or peakedness) increases with an increase in grain size where the sorting in the central portion is improved relative to the tails (figure 8.4c). As kurtosis is an indication of the sorting characteristics, the increase in kurtosis corresponds closely with an improvement in sorting (figure 8.4d).

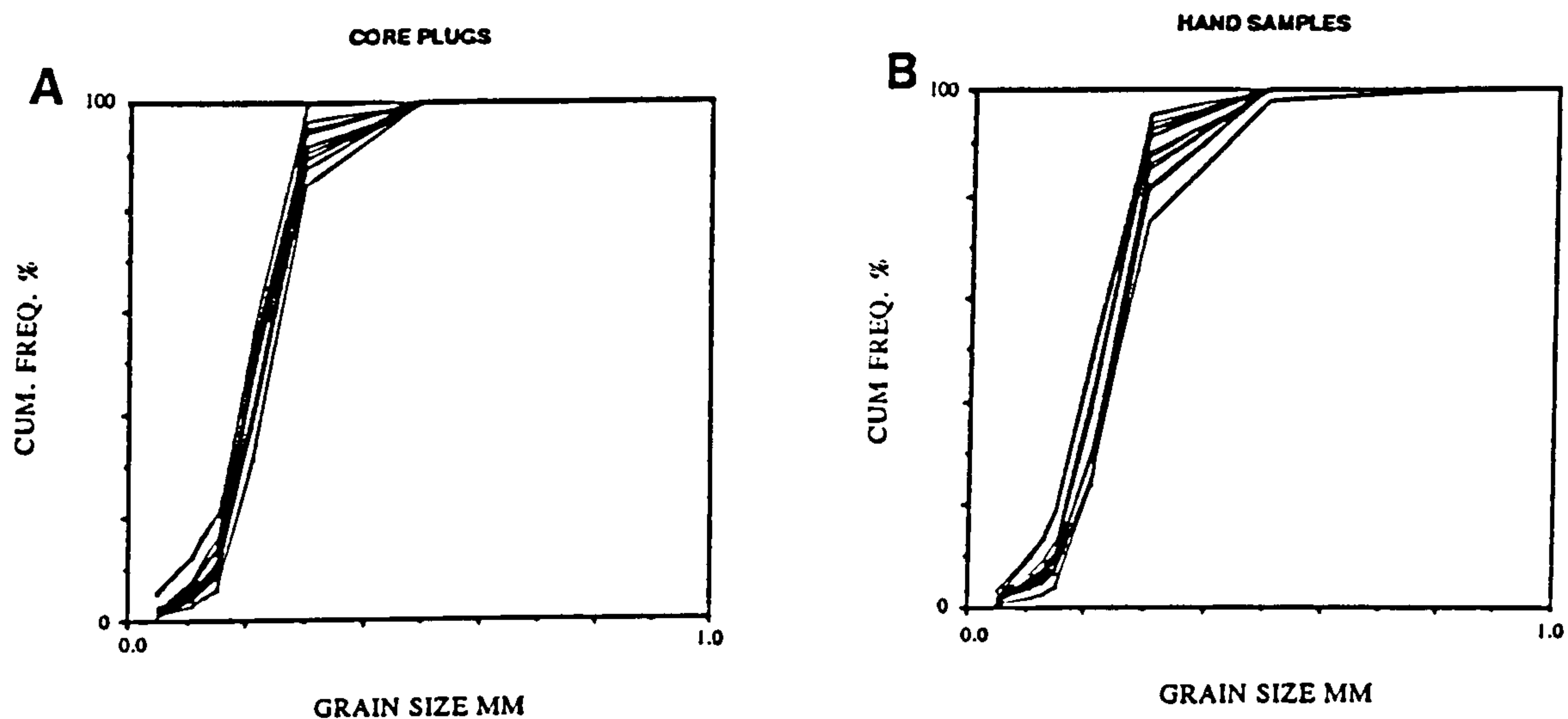


Fig. 8.3 Cumulative grain size frequency distributions for disaggregated core plugs (A) and hand samples adjacent to the probe permeameter sample points (B)

MEAN mm	STD. DEV.	SKEWNESS	KURTOSIS	MEDIAN mm
Hand Samples (Vertical Profile)				
0.179	0.672	-3.37	13.59	0.208
0.198	0.568	-3.84	19.78	0.221
0.190	0.548	-3.22	16.12	0.213
0.206	0.522	-3.96	22.83	0.226
0.206	0.520	-3.99	23.04	0.224
0.208	0.539	-3.98	22.25	0.227
0.212	0.480	-4.06	25.92	0.228
0.225	0.441	-4.01	28.32	0.237
0.228	0.481	-3.97	25.66	0.240
0.225	0.469	-4.22	28.20	0.239
0.221	0.532	-3.94	22.66	0.238
0.221	0.525	-4.09	24.06	0.237
0.244	0.501	-3.38	21.98	0.251
0.239	0.368	-4.38	39.04	0.245
0.237	0.460	-4.02	27.47	0.246
0.228	0.489	-3.65	22.50	0.241
(Distributed Around Mine)				
0.212	0.463	-4.23	28.00	0.228
0.217	0.477	-3.91	25.16	0.230
0.209	0.496	-3.97	24.18	0.226
0.217	0.468	-3.92	25.96	0.229
0.195	0.489	-3.60	21.27	0.212
0.209	0.510	-4.16	24.74	0.227
0.211	0.487	-3.88	24.29	0.225
0.193	0.554	-3.88	20.48	0.213
0.189	0.568	-3.90	19.71	0.211
0.166	0.817	-2.93	8.79	0.204
0.230	0.414	-3.81	28.99	0.239
0.177	0.628	-3.95	17.63	0.200
0.199	0.568	-3.99	21.20	0.217
0.202	0.550	-3.94	21.10	0.223
0.208	0.530	-3.88	22.00	0.226

Table 8.1 Grain size frequency distribution moment values for the hand samples (top) and core plugs (bottom)

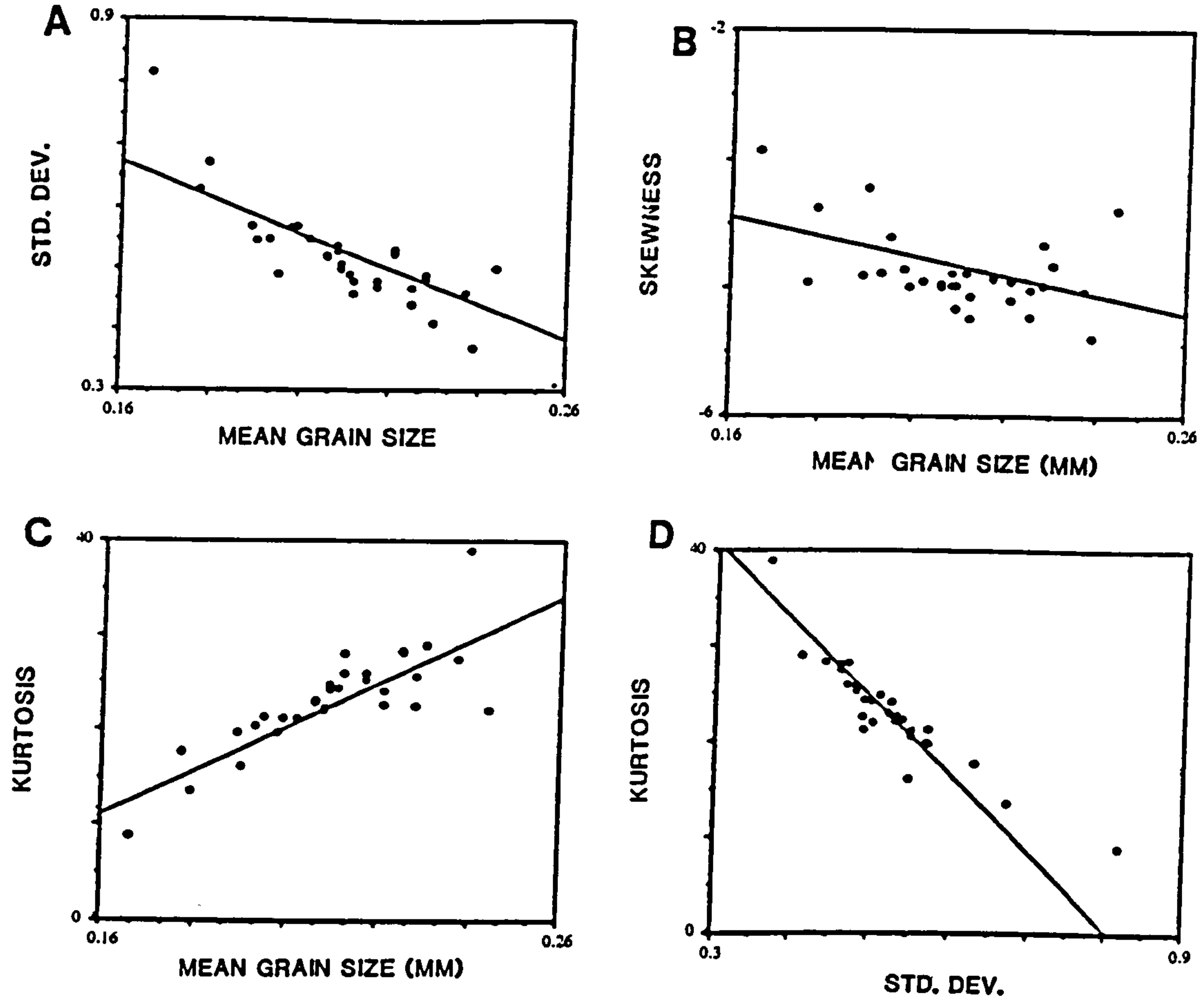


Fig. 8.4 Cross-plots showing the relationships between the four different moments of the grain size frequency distribution for the hand and core plug samples

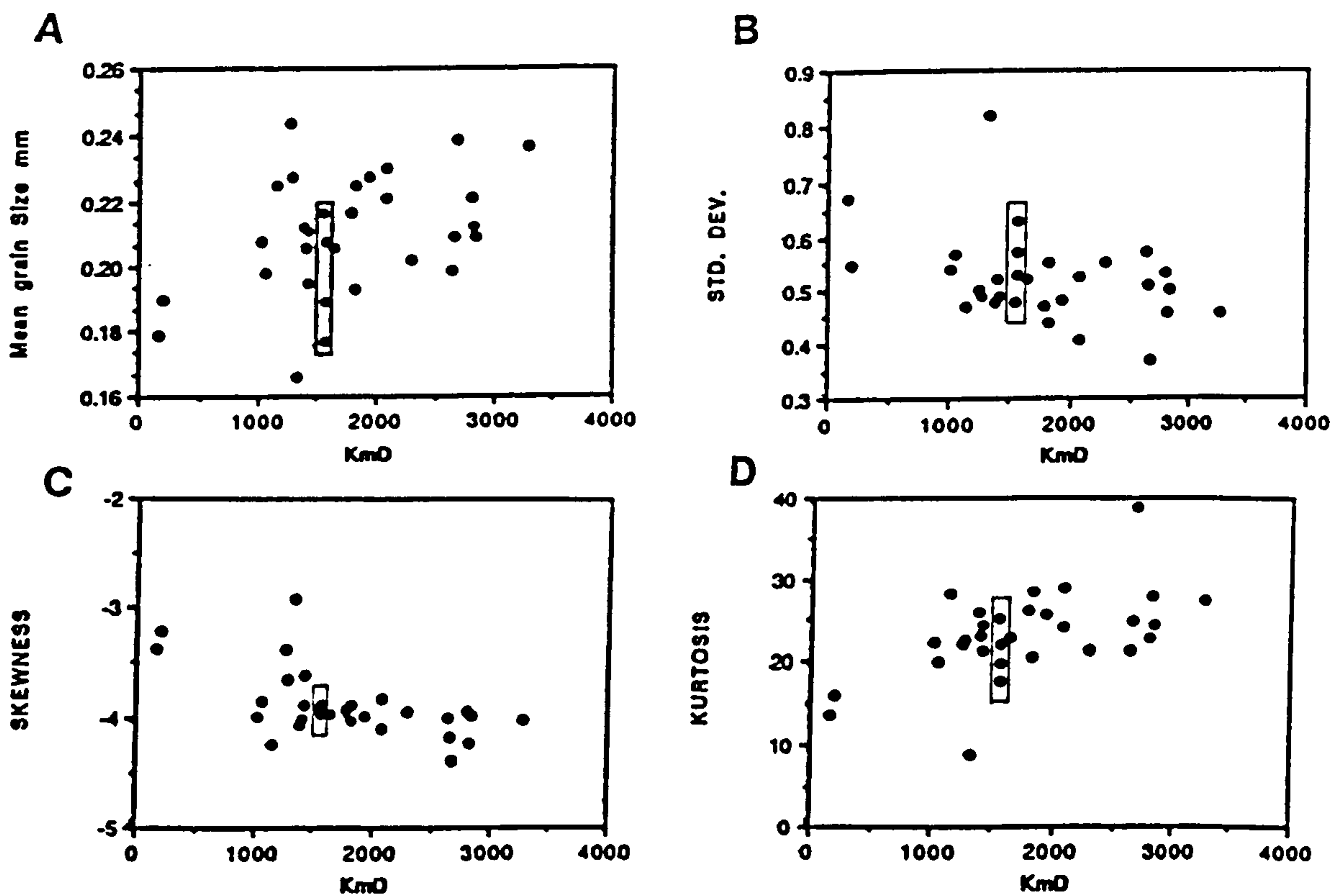


Fig. 8.5 Cross-plots showing the relationships between permeability and the four different moments of the grain size frequency distribution for the hand and core plug samples.

The control data are boxed

8.4.3 The Relationships Between Texture, Permeability and Porosity

Cross-plots for permeability versus the four moments of the grain size distributions are shown in figure 8.5. A good positive correlation exists between permeability and mean grain size (figure 8.5a). However, the control data (boxed) indicates that there is as much variation within the samples as between them. Nevertheless, a trend is shown to exist. No significant relationship was identified between permeability and sorting (figure 8.5b) although a slight increase in permeability may be discerned with improved sorting. This relationship is probably due to the exceptional sorting characteristics of the sandstone where measured permeabilities are insensitive to those small variations in sorting that do exist. As the skewness remained constant in all samples, the lack of any relationship between skewness and permeability (figure 8.5c) was expected. The relationship between permeability and kurtosis (figure 8.5d) is similar, although reversed, to that for permeability and sorting. This is because kurtosis is very closely associated with the sorting characteristics.

The boxwork clay structures identified on the surfaces of some grains (see figure 6.13) may have an effect on permeability. The relief of these clay structures is very small in relation to the pore throat dimensions and the effect of these clay growths on the measured gas permeabilities are likely to be negligible. However, these clays may influence the relative permeability by increasing the wettability and/or irreducible oil saturation within the reservoir.

Cross-plots for porosity versus the four moments of the grain size distributions are shown in figure 8.6. No significant correlations are identified between porosity and mean grain size, sorting or kurtosis (figures 8.6a, b & d). The independence of porosity to grain size was expected considering the well-sorted nature of the sandstone. There is however, a weak relationship between porosity and skewness where porosity increases as the length of the fine-grained tail increases (figure 8.6c), with skewness remaining fairly constant for the control data (boxed). Furnas (1929) showed that porosity on a two component aggregate depends on the size ratio of the particles but is independent of

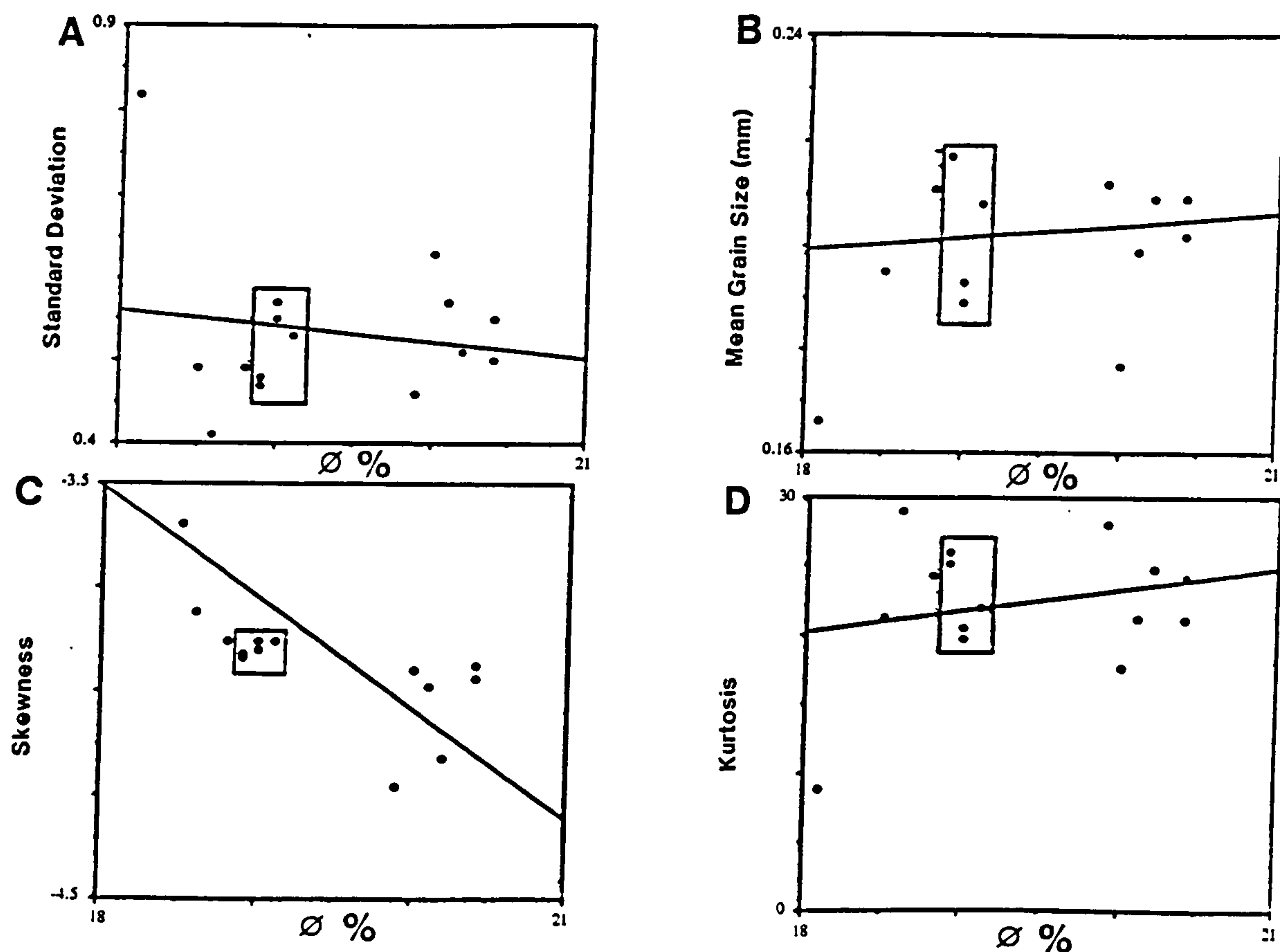


Fig. 8.6 Cross-plots showing the relationships between porosity and the four different moments of the grain size frequency distribution for the hand and core plug samples. The control data are boxed.

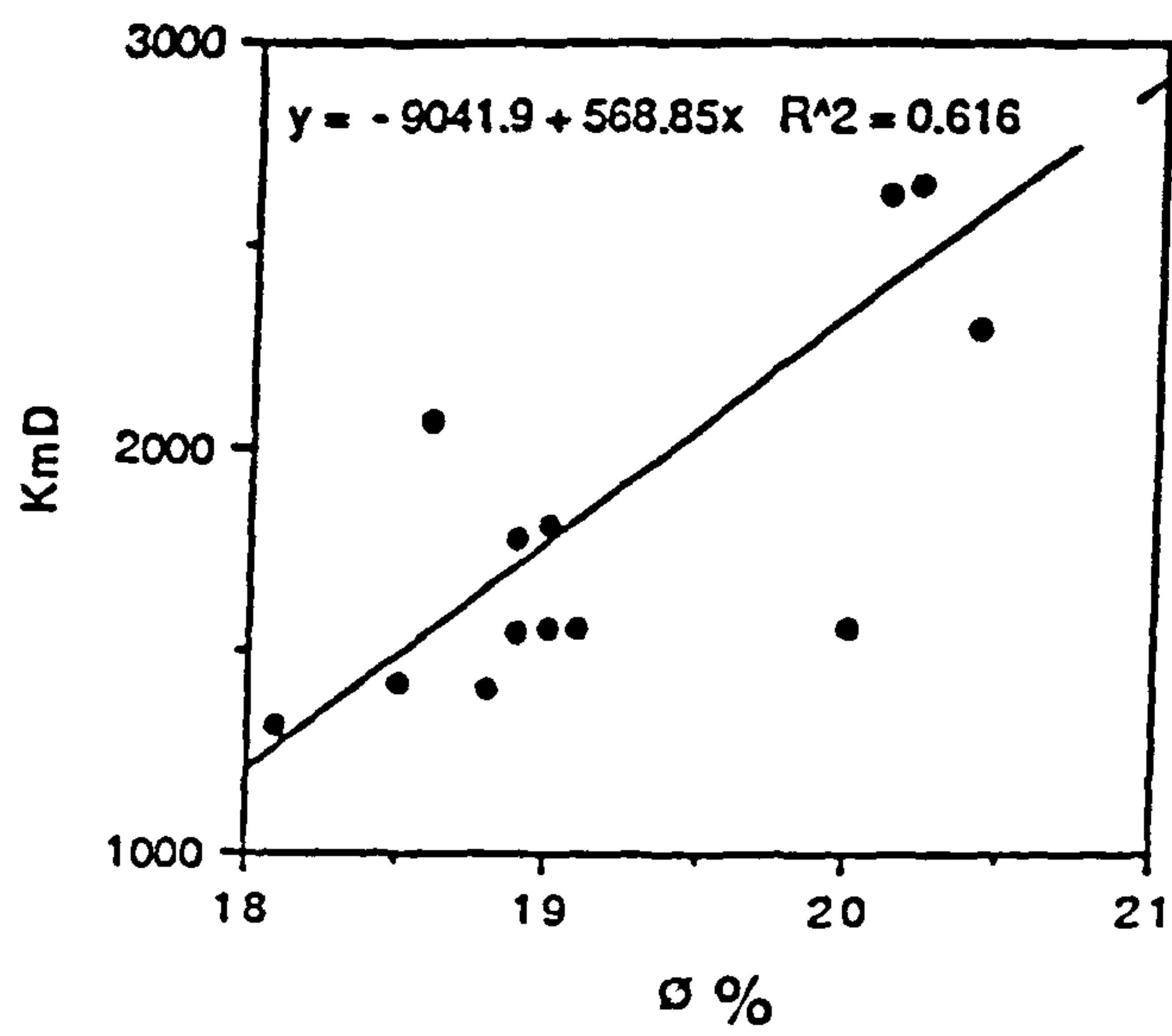


Fig. 8.7 Permeability / porosity cross-plot for the White Sandstone

size alone. As skewness provides a measure of the relative proportion of the fine tail to the coarser grains forming the bulk of the population, it may be an indicator of the size ratio of the particles. If this is the case, it might explain the apparent, albeit weak, relationship between porosity and skewness. The cross-plot between permeability and porosity (figure 8.7), as expected, shows a weak correlation between the two parameters.

8.5 Conclusions

From comparisons between permeability and textural characteristics, permeability heterogeneities within the White Sandstone appear to be controlled predominantly by primary depositional heterogeneities. These depositional heterogeneities exist primarily at the microscopic (grain to grain) scale. This outcrop permeability study therefore, provides a data base that is portable from the outcrop to the reservoir, its application dependent only on recognition of the same facies type in the subsurface. The diagnostic features that comprise this facies type include the following:-

- 1) A coarsening-up sequence (of which there may be several)
- 2) Exceptional textural and mineralogical maturity
- 3) The apparent massive nature of the sandstone as interpreted from core and wireline logs (see figures 6.4 and 6.15)
- 4) A characteristic trace fossil assemblage (dominated by *Skolithos sp.* and *Thalassanoides sp.*)
- 5) A potential areal extent of several square kilometres, with the long axis of the sand body orientated parallel with the direction of net palaeotransport (sand body migration)
- 6) A very high length : thickness and width : thickness ratio
- 7) A lateral facies change from clean, medium-grained, very well sorted sands to siltstones and mudstones. A possible decrease in grain size towards the basin axis within the sand body.

The nature of beds above and below the sand body will help determine the depositional environment. Evidence for marine sediments bounding

the sand body both laterally and vertically should be sought.

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CHAPTER 9 A permeability model for the White Sandstone

9.1 Introduction

The descriptions of static and spatial statistics for flow rate obtained using a probe permeameter (equivalent to permeability) for the White Sandstone have identified and quantified a permeability structure that is highly uncorrelated in both the vertical and horizontal directions. Consequently, the spatial disposition of spot permeabilities within reservoir rocks for which the White Sandstone is an analog should be relatively easy to predict from limited well data using some form of stochastic continuous model.

If the spatial and static permeability distributions within the outcrop have been quantified correctly, it follows that spatial permeabilities generated from a model for the outcrop should provide approximations that are very close to the real case.

9.2 Development of a Monte Carlo permeability model

Simulated data sets were generated using a Monte Carlo approach where values for each location in a 2-D plane (representing a vertical cross-section) were selected randomly from a cumulative distribution function (c.d.f.) for permeability. The method of obtaining a random sample from the c.d.f. is shown diagrammatically in figure 9.1. Since stationary permeability sequences within the White Sandstone display fractal characteristics, it follows that the c.d.f. obtained from permeabilities sampled at one interval, and in one direction, can be used to generate permeabilities at another interval in the same, or another, direction.

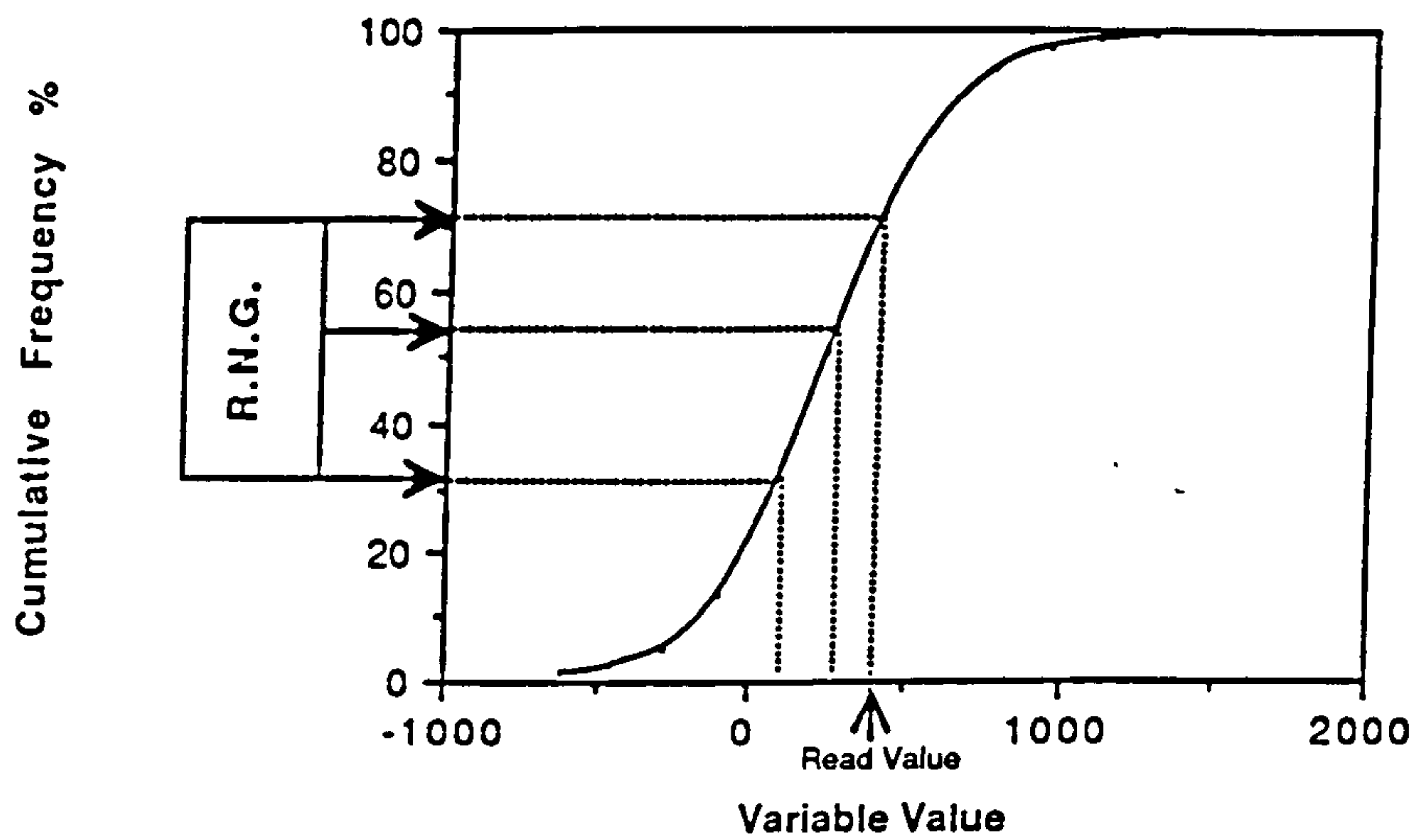


Figure 9.1 Diagrammatic illustration of the method of generating values from a cumulative distribution function. Values from 1 to 100 are obtained from a random number generator (R.N.G.). These values correspond to the cumulative frequency percentage for a given variable (e.g. permeability), for which the cumulative distribution is known. The corresponding variable value is then read off the x-axis for each random value. This method of sampling ensures that the sampled population has the same statistical properties (i.e. mean, standard deviation and range) as the model population

9.2.1 Incorporating the vertical increase in permeability

Where there is a vertical increase in permeability, gravity effects may have a strong influence on fluid flow behaviour causing, for example, the injected water to underrun the oil resulting in early water breakthrough. Particular attention therefore, was paid to modelling the coarsening-up sequence within the White Sandstone. Two methods of incorporating the vertical drift in permeability were used.

In the first method, illustrated in the flow chart shown in figure 9.2, spatial permeabilities are generated using two c.d.f.'s obtained from the outcrop data. The first c.d.f. (figure 9.3) is for non-stationary permeability sequences that contain a vertical drift, generated from normalised, vertical data sequences where the drift is removed. A linear regression was used to estimate the drift. Samples are randomly selected from this c.d.f. to produce vertical data sequences to which the drift is then added. As there is no lateral continuity in the rate of the vertical drift, the variation in slope was obtained by random selection from the second c.d.f which is for slope (figure 9.4). For tilted sandstones, the slopes for the vertical drift should be adjusted accordingly. This requires identification of low energy deposits (from dipmeter analysis for example) from which the tectonic dip can be estimated.

In the second method, illustrated in the flow chart shown in figure 9.5, permeability values are sampled randomly from the c.d.f. for permeability at different levels above the base of the sandstone interval. The cumulative distribution functions for permeability from each layer above a recognised datum (the basal silt) within the White Sandstone are shown in figure 9.6. This method is less complex as it removes the need to add the vertical drift to the simulated data but assumes that permeability values are laterally correlatable between the end wells.

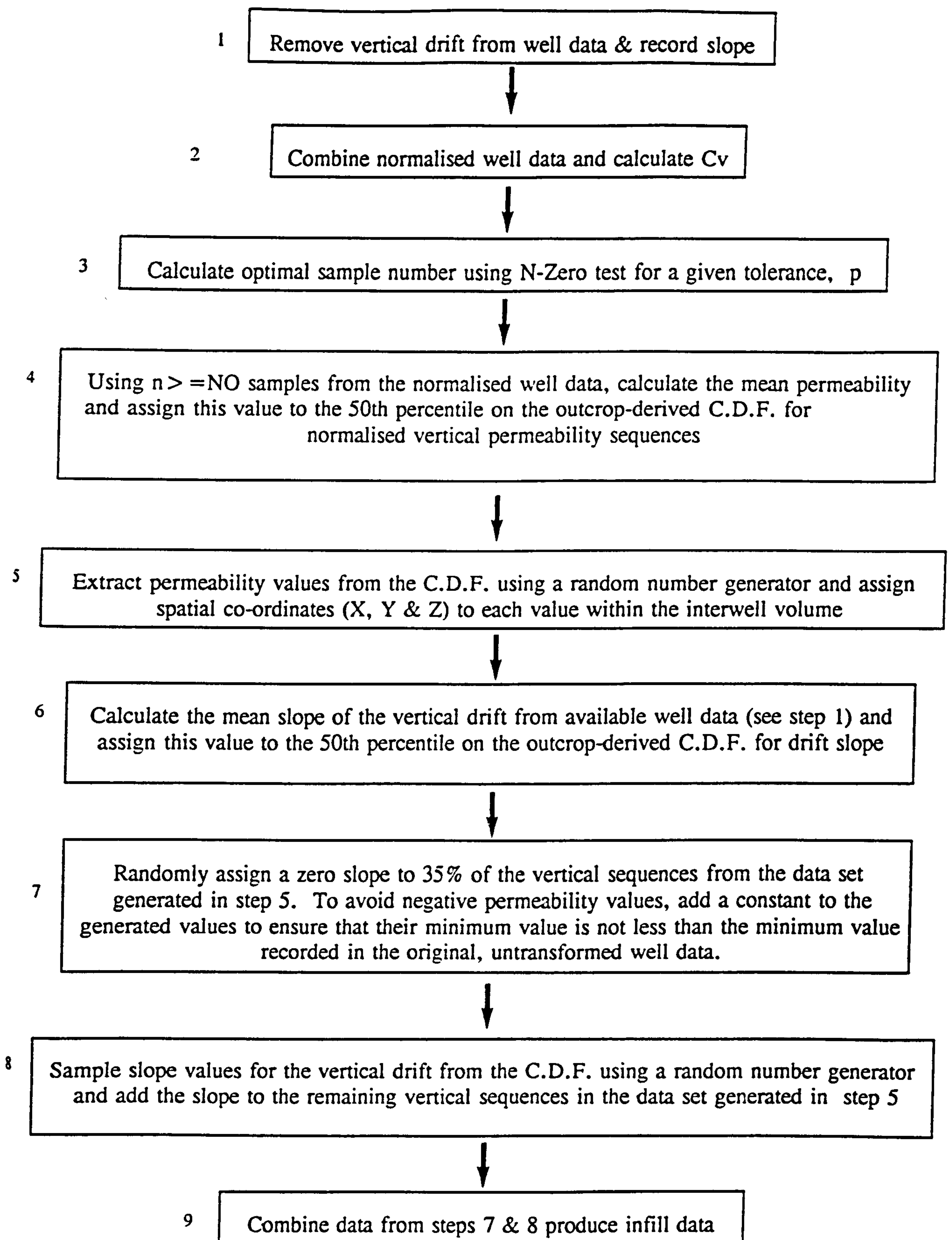


Fig. 9.2 Flow chart showing the first method of generating spatial permeability values for massive shallow marine sandstones developed from the White Sandstone outcrop permeability study. In this method (=method 1), the coarsening-up sequence is honoured using a separate C.D.F. for the slope of the vertical increase in permeability

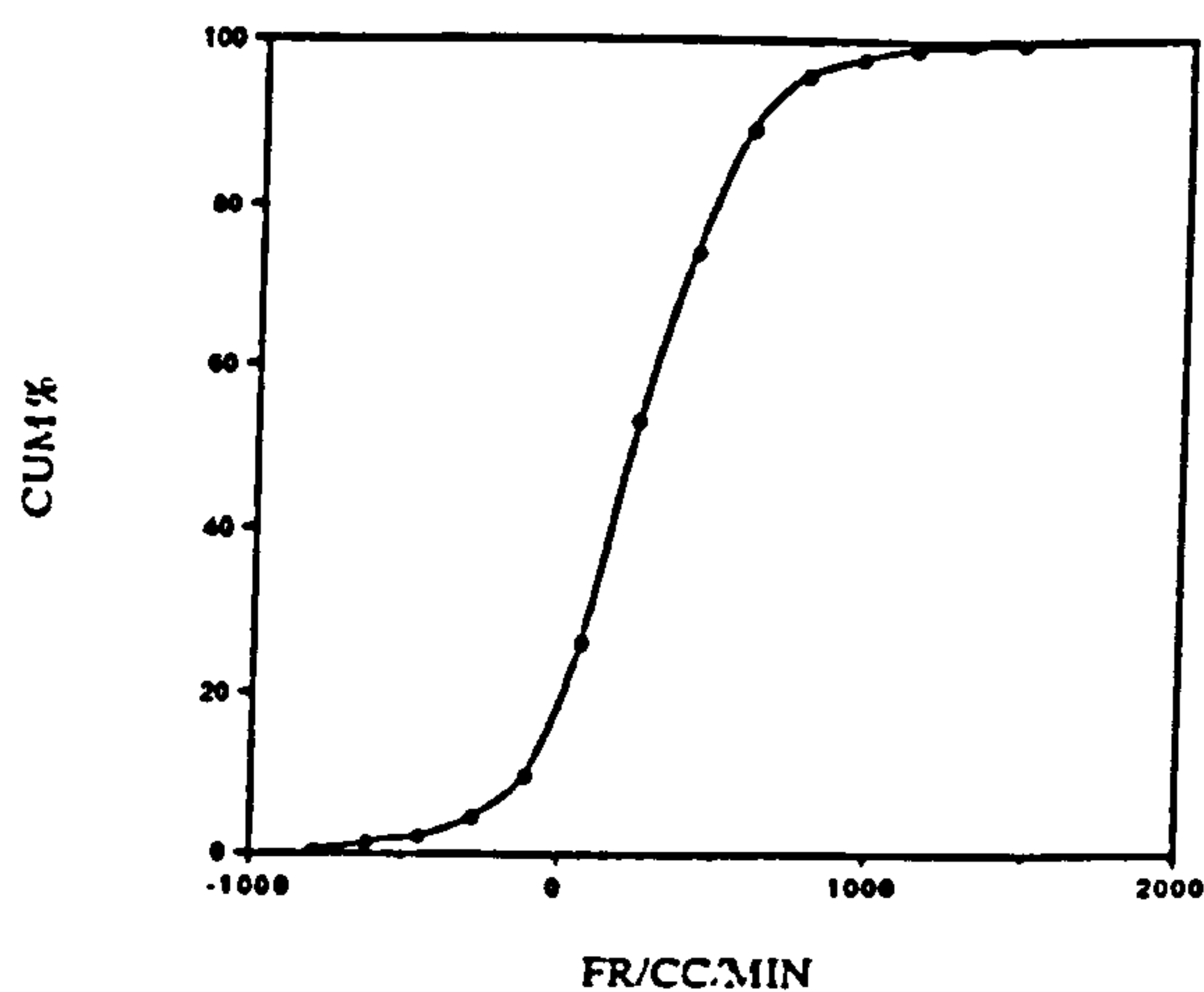


Fig. 9.3 The cumulative distribution function for normalised (stationary) vertical permeability sequences sampled from the White Sandstone

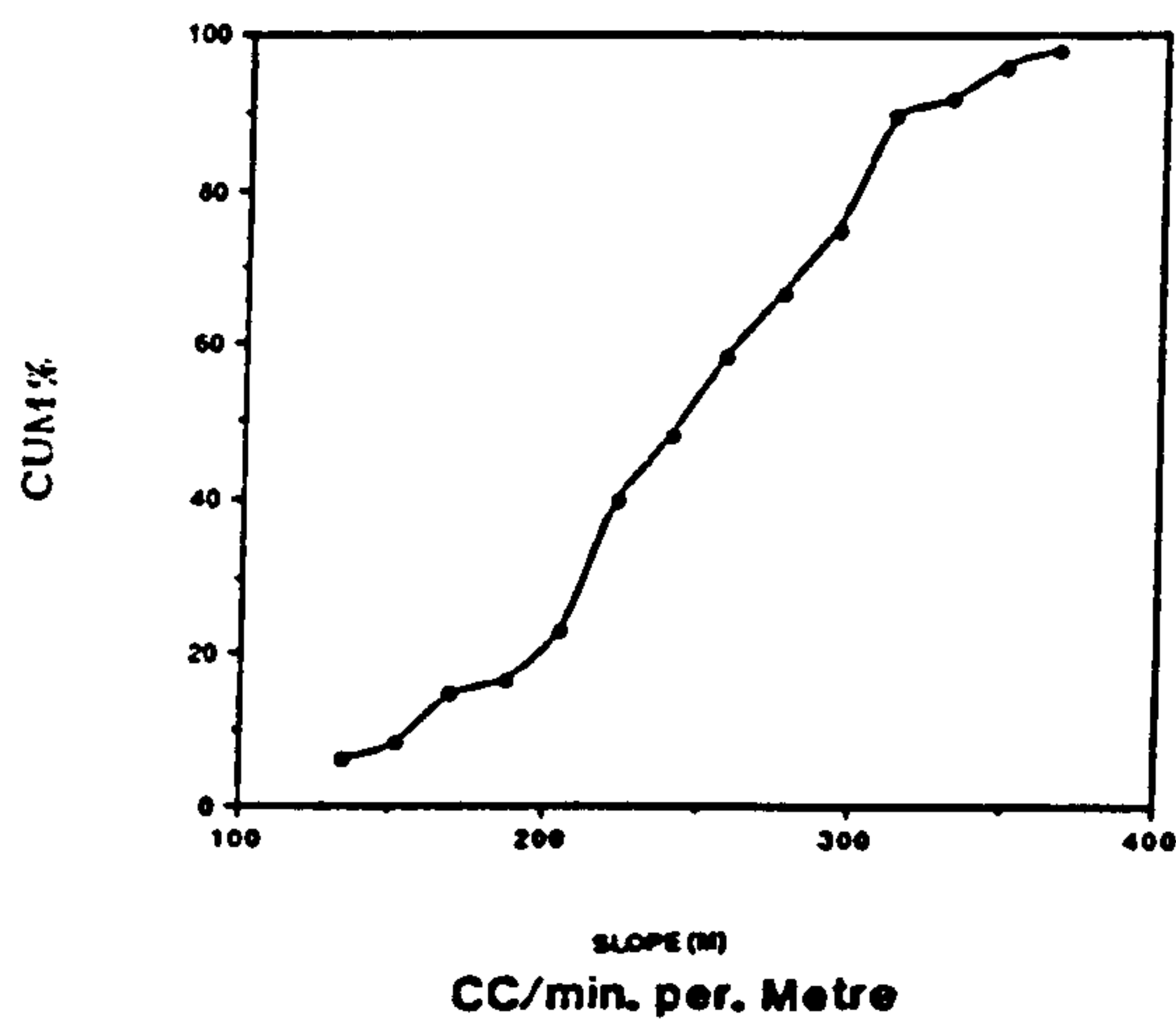
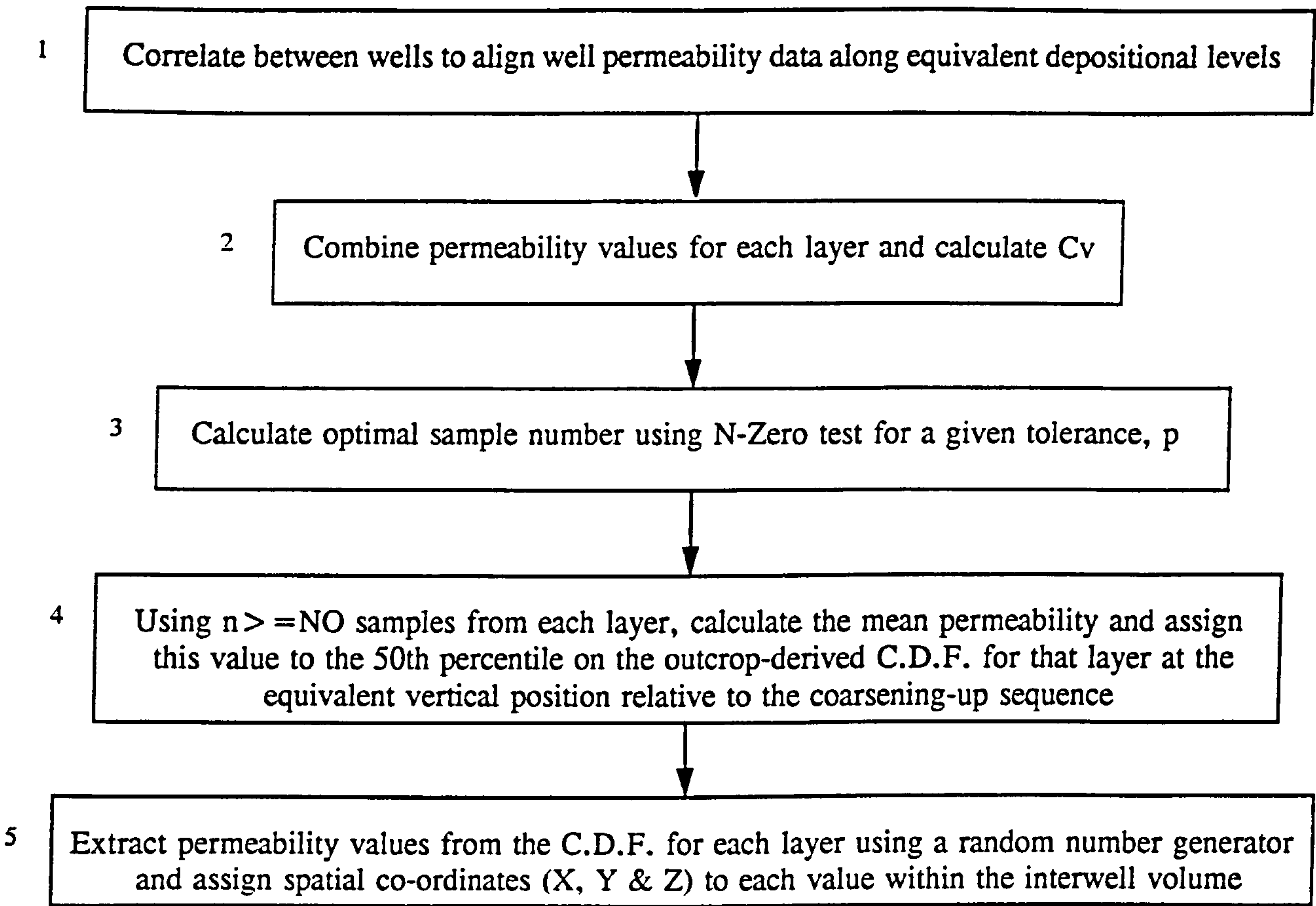


Fig. 9.4 The cumulative distribution function for the slope of the vertical increase in permeability from the White Sandstone (slopes were estimated using a linear regression model)



9.5 Flow chart showing the second method of generating spatial permeability values for massive shallow marine sandstones developed from the White Sandstone outcrop permeability study. In this method (=method 2), the coarsening-up sequence is honoured by using a separate C.D.F. for permeability data from each layer through the sand-body

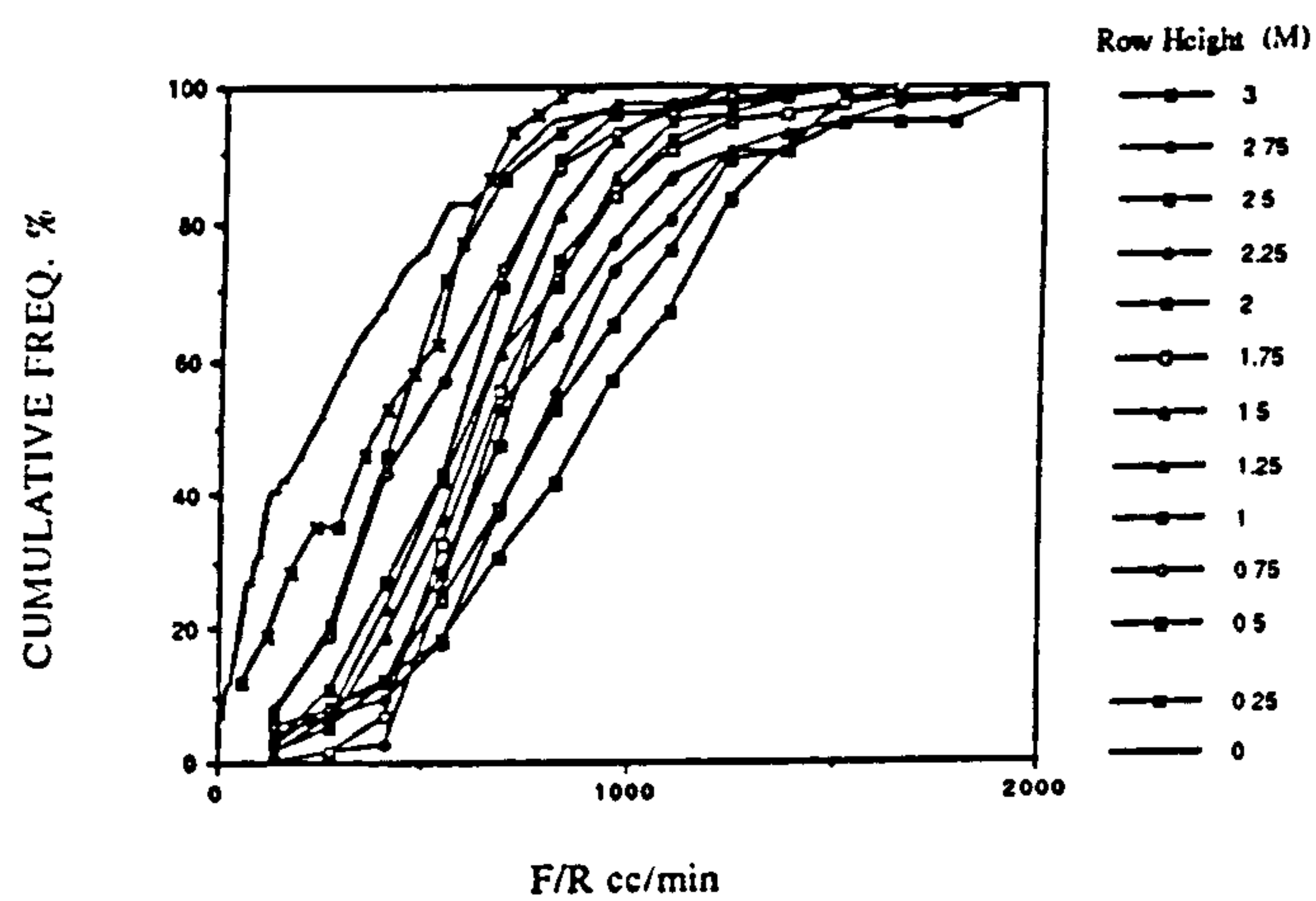


Fig. 9.6 The cumulative distribution functions for permeability sampled from the White Sandstone at the same depositional level above the basal silt datum (through a single coarsening up sequence)

9.2.2 Adjusting the c.d.f.'s using well data

The c.d.f.'s obtained from the White Sandstone must be adjusted to match the range in permeability and slope of the vertical drift for the reservoir. As the adjustment of the permeability c.d.f. is made from vertical well data (although in some cases horizontal well data may be used), it is assumed that the permeability variation in the vertical direction is representative of permeability variation in the horizontal direction. Whilst this assumption is often made in reservoir studies, it is not necessarily true. For the White Sandstone however, this assumption was found to apply where the statistics for permeability variation in the vertical direction were found to be very similar to those for the horizontal direction after removal of the vertical drift.

By using well data to condition the c.d.f.'s there is the additional problem of well representativity. The fewer the wells and number of samples within wells, the less representative the predicted values in the interwell area. For a regionalised variable that is uncorrelated and stationary (such as for permeability within the White Sandstone for sample intervals $>0.1\text{m}$) the number of samples rather than their spatial position will determine how representative the sample is. For such data, the optimal sample number can be estimated using the N-Zero test because the samples can be treated as independent.

The N-Zero test calculates the optimal number of samples (N_0) required to estimate the mean for a given tolerance (P). This mean value can be used to estimate the value of the 50th percentile on the c.d.f., assuming values for the mean and 50th percentile coincide. This assumption is valid if the permeability variation is approximately normally distributed for stationary sequences, which is the case for the White Sandstone.

The method of assigning values to the c.d.f. from well data is given in the following example:

Flow rate values for 'end wells' on the north-south cross-section from the White Sandstone are shown in figure 9.7a. There is a distinct drift in the sequence for the northernmost well, but in the southernmost well the data are approximately stationary. On initial inspection, the two permeability profiles shown in figure 9.7a appear very different and

might be attributed to two different sand bodies. However, we know from the measurements made on the White Sandstone that the permeability variation between wells may be greater than the permeability variation within wells for the same sand body. In fact, permeability profiles similar to those shown in figure 9.7a may be obtained from samples taken between 0.02m to 500m apart laterally within the same sand body. We therefore require information about the likely distribution of the sand bodies before generating infill permeability values between the wells from the model.

To match the well data to the c.d.f. this drift must first be removed (figure 9.7b), after which the data are combined and the C_v is calculated. For a C_v of 0.71, the optimal sample number, calculated for a 30% tolerance, is 23. Since the number of samples from the combined end-wells is 29, the mean of the data set can be estimated without additional samples. The mean value for the normalised end-well flow rates is 754 cc/min., $\pm$ 226 cc/min. (528 cc/min. to 980 cc/min.), for a tolerance level of 30% either side of the mean. This mean value (or any value between 528 and 980) is assigned to the 50th percentile on the c.d.f., with the full range calculated by extrapolation (figure 9.7c)

For the adjustment of the c.d.f. for slope, the N-Zero test is not appropriate since the value of N_0 is proportional to C_v , which in turn is inversely proportional to the mean (for a constant standard deviation). In other words, for distributions with the same standard deviation, N_0 decreases as the mean increases. For permeability, this relationship between N_0 and the C_v is appropriate because the permeability variance in low permeable rocks will be more significant in terms of fluid flow behaviour than the same permeability variance within high permeable rocks. For the rate of drift in a permeability sequence however, the opposite applies and a greater number of samples will be required for sequences with large permeability gradients than for sequences with small permeability gradients. This is because spatial variations in permeability (often associated with coarsening and fining-up sequences) can have a significant impact on fluid flow within the reservoir, causing for example, fluid segregation and early water breakthrough (Archer and Wall, 1986).

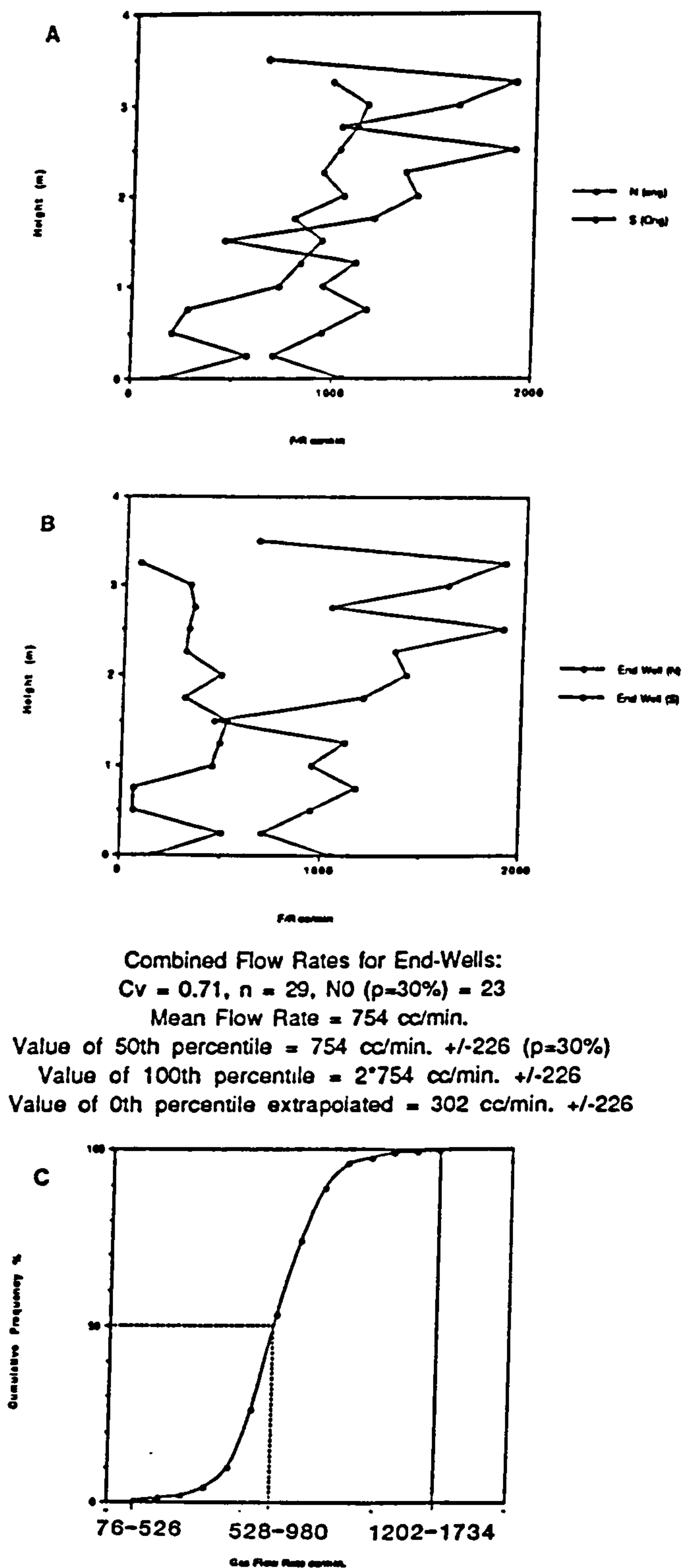


Fig. 9.7 An example of the method employed to condition simulated data generated using cumulative distribution functions by the available well data. A) The original well data. B) The normalised well data after the vertical drift is removed. C) The cumulative distribution function for normalised permeability data from vertical sequences with the scale adjusted to match the available normalised well data

A simple method to determine the reliability of well data for slope estimates is to plot the slope values for wells assumed to represent the 'true' variation in slope and compare these with slopes from sub-sampled wells. Slope estimates for 48 transects from the east-west and north-south cross-sections within the White Sandstone are shown in figure 9.8. For the White Sandstone, individual wells have slopes within $\pm 10\%$ of the mean slope 27% of the time, slopes $>10\%$ of the mean slope 37.5% of the time and slopes $<10\%$ of the mean slope 35.5% of the time. It is apparent from these results that to represent this trend in vertical drift a large number of wells are required. In practise, the required number of wells is probably overestimated but the margin of error can at least be quantified.

In the first method, a single c.d.f. for permeability is used and the available well data can be combined to obtain an approximation for the permeability range for the reservoir. Combining the data maximises the available sample size and increases the reliability of the infill values. In the second method however, the permeability range for each layer will be represented by only a few values (dependent on the number of wells) and the adjusted c.d.f. will be less reliable than in the first method. Although in this second method, the number of values for each layer can be increased by increasing the thickness of the layers and estimating the average c.d.f., this will produce a step-wise vertical drift corresponding to the layer thickness which may have a significant effect on predicted fluid flow behaviour. Furthermore, the second method also relies on the lateral correlation of well permeabilities for the same depositional level in order to adjust the c.d.f. In massive sandstone sequences, there are often few depositional bedforms that provide reliable lateral correlations within the sandstone between wells.

9.2.3 Incorporating short interval correlation structures

In the White Sandstone, short range correlation lengths were identified in the vertical and horizontal directions with an average length of 0.24m and 0.14m respectively. If representation of this correlation structure is required in the model (perhaps fluid flow simulations have indicated

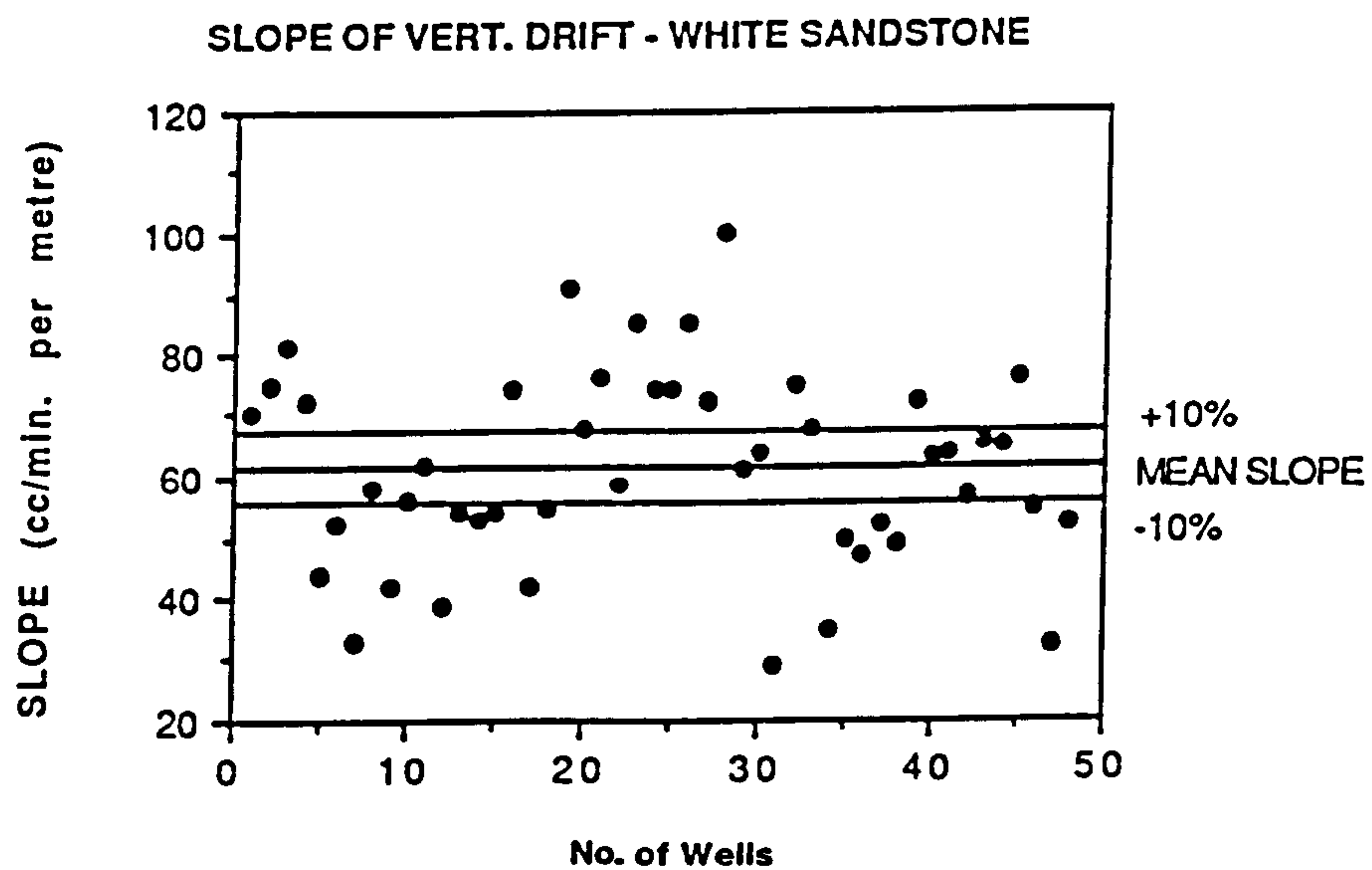


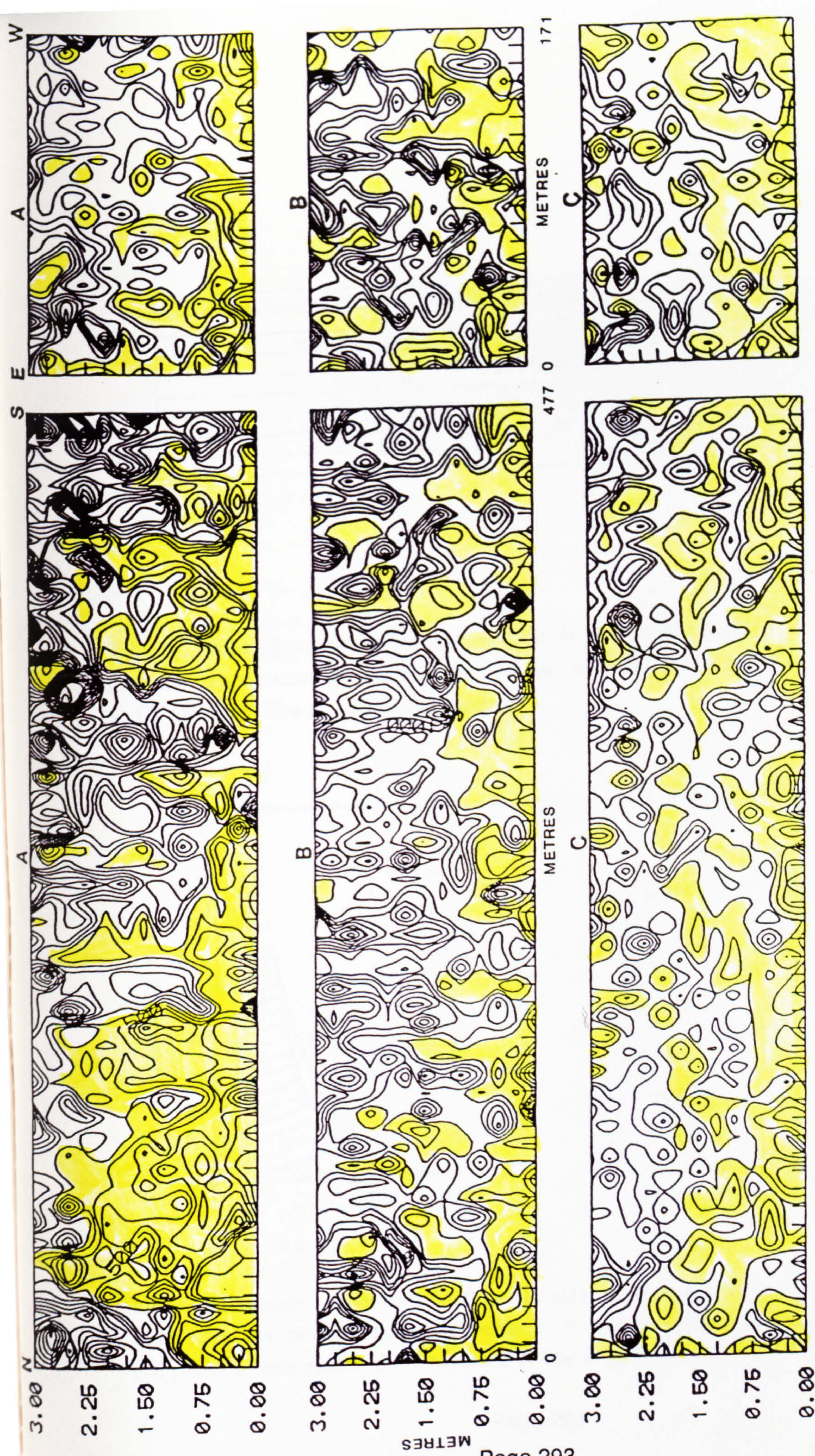
Fig. 9.8 Scatter plot showing the variation in slope between individual vertical permeability sequences compared to the mean slope for all the vertical sequences

that these directional correlation structures have a significant effect), this can be done using conditional point kriging over the appropriate interval. As kriging reduces variation between the interpolated values through smoothing, variation can be superimposed onto the kriged data by adding 'noise'. This noise can be generated randomly, for example, by random sampling from the c.d.f. for permeability variation at the kriged interval. In addition, this noise may be constrained by a fractal dimension where identified (Hewett and Behrens, 1988).

9.3 Evaluating the permeability models

Simulated data sets using the methods described were generated using the c.d.f.'s directly without adjustment for limited well data. These simulations therefore, represent the best cases and can be used to evaluate the model (and therefore, the sampling schemes) by comparing them with the original data. Conditioning the c.d.f.'s to limited well data would simply shift the range of values for the c.d.f., thereby retaining the same variability but with a shift in the mean, the reliability of which depends on the number of wells and sample density within each well. For both simulations, permeabilities were generated at a vertical and horizontal sample interval of 0.25m and 9m. To facilitate comparison, the vertical domain length of simulated data sets was restricted to 3m as the original data sets for the cross-sections contain missing values over vertical domains greater than this. For reference, the data in simulation 1 were generated using c.d.f.'s for both permeability and slope (method 1), and the data for simulation 2 were generated using c.d.f.'s for layer permeabilities (method 2).

Visual comparison between the simulated data sets and original flow rates is provided by the plots shown in figure 9.9. The flow rates for the original data set are shown in figure 9.9a. The 'peaky' nature of the spatial permeability variation and the general increase in permeability vertically through the sandstone interval is clearly represented by both models (figures 9.9b and c). The surface plot for simulation 2 (figure 9.9b) is most similar in appearance to the original data.



Permeability values less than 600mD are denoted by yellow shading

Contour intervals are 100mD for A and B, and 200mD intervals for C

Fig. 9.9 Gas flow rate maps for the White Sandstone. A) The original sample data from this study. B) Flow rate values generated using method 1 (=simulation 1). C) Flow rate values generated using method 2 (=simulation 2).

	A	B	C
Flow Rate cc/min. Statistics	Original Data:	Simulation 1:	Simulation 2:
Mean:	629	813	643
Std. Deviation:	347	460	320
Cv:	0.55	0.57	0.5
Minimum:	0	0	0
Maximum:	2179	2621	1911
Kurtosis:	0.96	0.27	0.92
Skewness:	0.66	0.73	0.61
n	959	962	962

Table 9.1 Descriptive statistics for gas flow rate data for the White Sandstone. A) Original flow rate data measured in this study. B) Simulated flow rate data generated using method 1. C) Simulated flow rate data using method 2

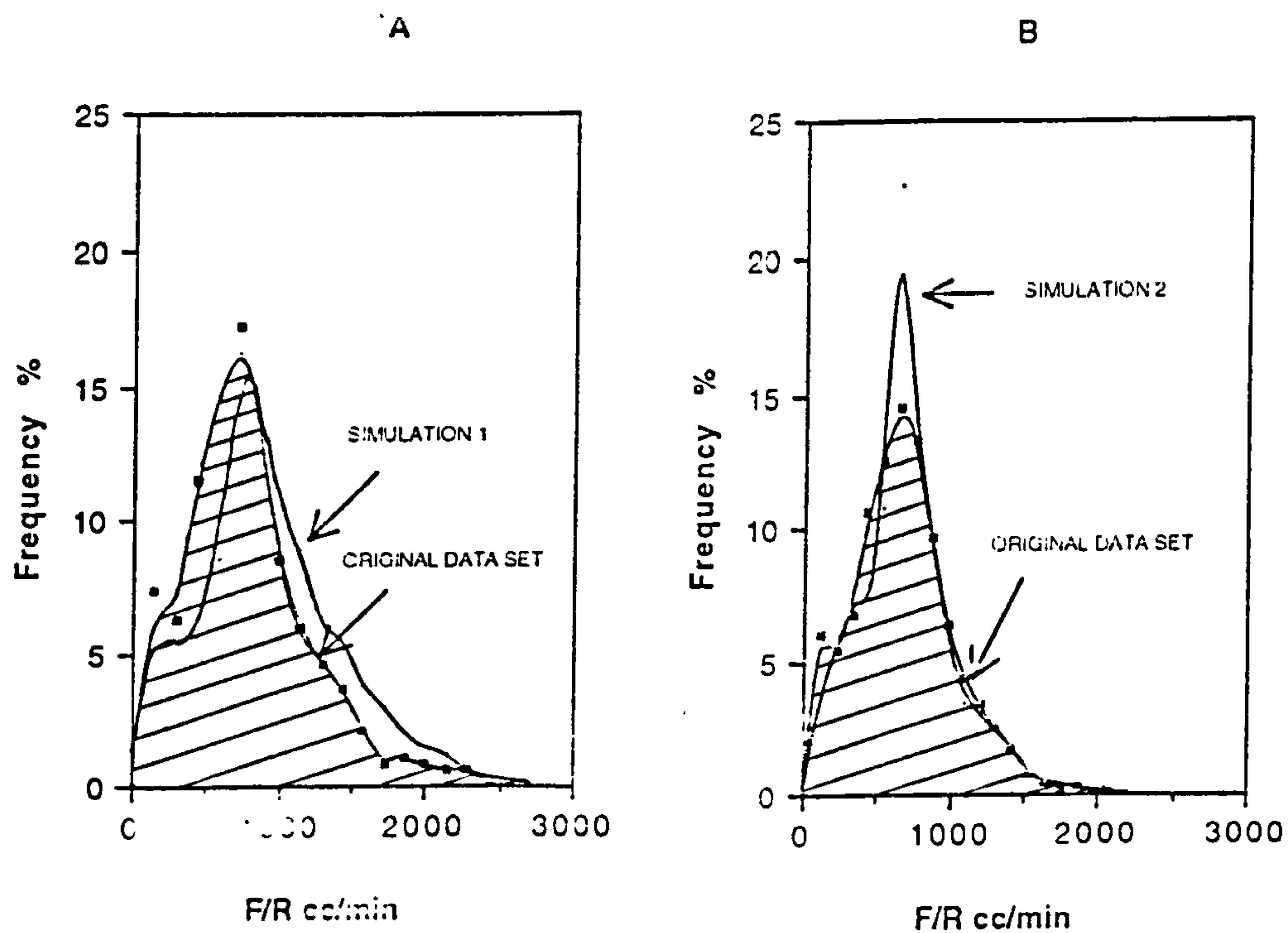


Fig. 9.10 Frequency histograms for flow rate data. A) Comparison between the original sample data and simulated data using method 1. B) Comparison between the original data and simulated data generated using method 2. The original data set is shaded

Source:	DF:	Sum Squares:	Mean Square:	F-test:
Between Groups	2	2.0 E7	2.0 E6	69.067
Within Groups	2880	4.2 E8	1.4 E5	p=0.0001
Total	2882	4.4 E8		

Comparison:	Mean Diff:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Original Data vs Simulation 1	-183.159	34.035*	55.684*	10.553
Original Data vs Simulation 2	-14	34.035	0.325	0.807
Simulation 1 vs Simulation 2	-169.159	34.008*	47.571*	9.754

*Significant at 95%

Table 9.2 Anova table showing the comparison between the populations of gas flow rate for the original sample data from the White Sandstone and the simulated data generated using methods 1 (simulation 1) and 2 (simulation 2)

From the descriptive statistics for the simulated and original data (table 9.1), the statistics for simulation 2 data are very similar to the original data. However, values for simulation 1 data are consistently higher than for the original data and frequency histograms of flow rate (figure 9.10) show a greater proportion of high flow rates in simulation 1 (figure 9.10a) and a greater frequency in the modal flow rate for simulation 2 (figure 9.10b).

To determine how representative each simulation is of the original data, comparisons were made using analysis of variance (table 9.2). At the 95% confidence interval, the F test value indicates a significant difference in variance between the populations of the simulated and original data sets. From the multiple comparison using the Scheffe F-test and Dunnett t-test, it can be concluded that there is no significant difference in the mean or variance between the sample population from simulation 2 and the original population. There is however, a significant difference in both the mean and variance between the sample populations from simulation 1 and the original population.

9.4 Discussion

Visual comparison between 2-D surface plots for the simulated and original permeability data sets have shown that realistic patterns of spatial permeability structure can be generated using the modelling techniques represented by the simulations. There are however, some features that are overemphasised in the simulations. Simulation 1 shows an exaggerated increase in permeability vertically through the sequence. This is probably due to the overestimation of the vertical increase by the linear regression analysis that was used to quantify the rate of increase. This overestimation may be reduced by using the average slope rather than the c.d.f. for slope, or perhaps some other regression type. Simulation 2, whilst very similar in appearance to the original data, tends to exaggerate the 'peakedness'. There is also an apparent, albeit weak, correlation structure in the original data that is not represented in either simulation. Generally however, the permeability models for the White Sandstone (in particular simulation 2) have reproduced the

essential features of the spatial permeability variation.

Comparison of static statistics for the simulated and original data sets through anova have shown that the permeability values from simulation 2 are statistically similar to the original data, whereas the permeability values from simulation 1 are significantly different. This appears to be due to the exaggerated vertical increase in permeability within simulation 1, overestimating both the mean and variance.

Whilst the second model (simulation 2) has reproduced the static and spatial permeability variation better than the first model (simulation 1), the choice of model type used depends on the confidence in lateral correlation between permeability values in each well, and the sample density within each well. Where the lateral correlation between wells is unreliable and the sample data within wells are sparse, the first model is probably a better option than the second model. The importance of representing the permeability trend associated with the coarsening up sequence is also a determining factor in the choice of model type. The first model will produce a more representative, although possibly exaggerated, vertical permeability trend than the second model since it is based on the statistical distribution of vertical trends measured at outcrop.

This permeability study on the White Sandstone has also provided guidelines for scaling up rules and the estimation of the size of appropriate grid blocks for numerical fluid flow simulations. Using a geologically-based grid system superimposed on the detailed permeability model for the reservoir, the average permeability can be calculated for each block. Where the vertical increase in permeability has a significant effect on fluid flow so the sandstone interval must be divided accordingly. If the horizontal variation in permeability is considered insignificant, the reservoir can be divided into layers. The thickness of each layer is weighted towards the rate of vertical increase in permeability (that is, layer thickness is inversely proportional to the vertical rate of increase in permeability). If the horizontal variation in permeability is considered important then each layer may be divided into cells. Taking into account the uncorrelated structure and normal distribution of permeability an arithmetic average permeability can be

used for each cell. The length dimensions of each cell (which would be the same in both the X and Y directions as the permeability structure is isotropic in the horizontal) can vary from around 0.14m to approximately 500m (and possibly extending over the length of the entire sand body) as permeabilities are uncorrelated over this interval. Where the vertical increase in permeability is adequately represented by an anisotropic permeability tensor (where $k_x = k_y > k_z$), assuming no structural or diagenetic modification of permeability, a single grid block can be used with dimensions X and Y = 500m and Z = thickness of single coarsening-up unit (4-5m in the case of the White Sandstone). These horizontal dimensions are determined by the maximum domain length for sampling used on the outcrop of the White Sandstone, and may be greater.

As permeability heterogeneities within these massive sands can be modelled relatively easily using cumulative distribution functions, the accuracy of interwell permeability realisations obtained from limited well data can be defined. If required, the significance of the statistical reliability of the available well data can also be evaluated by performing numerical flow simulations on a range of permeability models covering the error of prediction associated with the available data. Of course the significance of various scales of permeability heterogeneity will depend on a wide variety of factors specific to the reservoir. These factors include the mobility ratio, PVT properties, aquifer strength, oil column, dip, depth, well spacing, completion strategy, and recovery process.

Under certain conditions in the reservoir, the low permeability contrasts measured on this outcrop of the White Sandstone may result in a performance which can be represented by a uniform system having an absolute permeability equal to the arithmetic mean of the individual permeabilities of the heterogeneous system. If however, this permeability contrast is increased or the reservoir conditions altered (for example, to an unfavourable mobility ratio), the accuracy of predicted reservoir performance may become more dependent on the appropriate appreciation of different scales of permeability heterogeneity.

In conclusion, a layer-cake permeability model for reservoirs

comprised of 'massive' sandstones similar in character to those described for the White Sandstone is probably appropriate, but consideration of smaller scales of heterogeneity should be considered under unfavourable reservoir conditions (for example, high mobility ratios).

CHAPTER 10 Discussion and conclusions

As the world-wide demand for oil and natural gas increases the need to produce more hydrocarbons becomes greater. Whilst new reserves of hydrocarbons are being sought, improved secondary recovery from existing reservoirs is also important, especially within oil-producing areas that have reached their mature phase of production such as the North Sea. A greater understanding of reservoir heterogeneities away from areas of data control in the uncored interval and especially in the interwell area is required in order improve recovery efficiency. This is especially important if enhanced oil recovery techniques are used because the recovery mechanisms frequently interact with the reservoir heterogeneities in a complex and often unpredictable manner.

Of the various reservoir properties and characteristics, permeability is one of the most important. Uncertainties exist in the value of permeability within the uncored intervals and interwell areas. As permeability data from reservoirs are generally confined to cored intervals, the quality of the permeability data base for the whole reservoir is dependent on the calibration between 'hard' data (for example, core plugs) and calibrated data (for example, wireline logs and seismic data). With relatively little information about the reservoir provided by the well data, the accurate prediction of permeability heterogeneities away from the control data is dependent on the quality and statistical validity of these control data and our knowledge of the statistical distribution and probable disposition of permeability.

Given that reservoirs are comprised of rock types for which analogues can be found at outcrop, these outcrops provide an obvious source of data with which to both improve our understanding, and the quantification, of spatial permeability heterogeneity. Outcrops allow permeability to be measured in 2 and 3-dimensions, and at levels of detail usually unavailable from conventional core and borehole measurements. These data bases can be used to help evaluate the representativity (statistically and spatially) of vertical well data and to determine how these well data may be used to predict permeability values away from the well bore.

By obtaining permeability data bases for different lithofacies types exposed at outcrop, the permeability models developed for each can be applied to subsurface reservoirs where similar lithofacies types are identified in the geological reservoir model. The selection of the appropriate permeability model is therefore dependent on the correct recognition of lithofacies types in the subsurface. Clearly, it is necessary to separate primary and secondary permeability heterogeneities (for example, depositional and diagenetic heterogeneities) at outcrop in order to develop portable permeability models. Where it is suspected that diagenetic processes have a significant modifying effect on primary depositional heterogeneities within the reservoir, so their effect must be added to the outcrop-based permeability model. The quantification of permeability heterogeneity due to diagenesis, compaction, tectonic deformation (fracturing, faulting and folding) and igneous intrusions (for example, dykes) are important areas for future research. Outcrops can also be used to measure and model reservoir heterogeneities due to these factors.

Although a fairly large number of outcrop permeability studies have been published, more outcrop studies are required to improve the reliability of the data bases for each lithofacies type. To allow combinability of the data bases, standardisation is required in both the permeability measurement technique (especially with regard to probe permeametry) and the sampling scheme.

A new code of practise is proposed here for outcrop-based probe permeametry. By following this code, the reliability of permeability values can be improved with the potential to develop a sample quality index. Whilst both the accuracy and precision of permeabilities measured using the probe permeameter on smooth rock faces is often comparable with that of permeabilities measured on conventional core plugs using an Hassler sleeve device, this accuracy and precision is reduced in the presence of surface fines, formation fluids, seen and unseen fractures, and surface roughness. Such modifying factors are common under outcrop and wellsite conditions and are also encountered on slabbed core.

Improved statistical validity and spatial representation of permeability through increased sample density is often used to promote the use of the probe permeameter, but it is often difficult to determine the level of confidence that should be placed in these values without some measure of their reliability. This level of confidence can be estimated by consideration of each factor presented in the code of practise given here.

All outcrop permeability studies should be constructed with consideration of their global application. In the strictest sense, a global permeability data set is one that may be applied to all reservoirs irrespective of their lithologies or post-depositional history. In order to rationalise the infinite variation of permeability within rocks, outcrop-derived permeability data sets are sampled and classified according to depositional environment and associated scales of depositional heterogeneity.

To obtain a global permeability data base, every possible variable such as lithofacies type, diagenetic history and so on, must be represented by permeability values. This would require exhaustive sampling of all lithofacies types, both modern and ancient. As all sampling techniques are, at some scale, location dependent, it follows therefore, that no permeability data base can ever be truly global and sample-based errors will always be present. However, the significance of these errors will depend on the acceptable recovery factors under certain economic conditions when outcrop-based permeability models are applied to the reservoir. What may be regarded as a definitive or global outcrop-data base under one set of economic conditions may be regarded as a limited or inappropriate data base under a different set of conditions. The term global therefore, has little meaning when applied to outcrop-derived permeability data bases unless quantification of the sample error is qualified by the economic constraints and acceptable reservoir performance figures.

The sampling scheme described relies on the assumption that depositional heterogeneities are arranged hierarchically. This assumption allows rationalisation of the sampling where exhaustive sampling is unfeasible. In deltaic environments for example,

depositional heterogeneities can occur over a wide range of scales resulting from the interaction of fluvial, wave and tide action. Specific bedforms, facies types and sand-body geometries are produced depending on the dominance of one process over the others. Coupled with the variation in sediment supply, these depositional processes can produce sand bodies that vary from homogeneous to heterogeneous within the same general depositional environment. If this range in heterogeneity can be divided into genetic classes, then permeability data bases can be developed for each class. If however, there is no obvious class division, such that there is also a continuum of permeability variation, then the use of a sampling scheme based on genetic depositional heterogeneities cannot be used without introducing potentially significant sample bias (for example, an artificial division of flow units within the sand body). Under certain reservoir conditions, this bias may not be significant, but where it is significant, some other method of permeability sampling will have to be sought.

As an alternative to the hierarchical sampling scheme, the development of representative elementary areas (R.E.A.'s) or representative elementary volumes (R.E.V.'s) may be appropriate where permeability heterogeneities form a continuum. However, the use of outcrop permeability sampling schemes based on recognition of genetic depositional heterogeneities does not preclude the development of R.E.A.'s or R.E.V.'s from the data obtained.

The case study presented on the White Sandstone represents the most detailed quantitative assessment of permeability heterogeneity within shallow marine sand shoal facies to date. In accordance with the geological model, the permeability variation in both the vertical and horizontal directions is largely uncorrelated. A continuous stochastic model using a Monte Carlo approach is appropriate for reproducing both the static and spatial permeability statistics using random sampling from cumulative distribution functions for permeability and the vertical drift in permeability (associated with a characteristic coarsening-up sequence). As the observed permeability variation is controlled by primary depositional characteristics with negligible diagenetic or structural modification, this permeability model is considered to be representative of this lithofacies type and is therefore fully portable

providing the equivalent facies type is identified in the reservoir. Post-depositional heterogeneities specific to the reservoir must then be superimposed on these permeability data generated using this model.

Statistically, the sampling schemes used on the White Sandstone to measure the permeability variation in the horizontal direction over sample intervals less than 9 metres could be improved with more sample domains distributed evenly within the cross-sections. However, considering the remarkable uniformity of the permeability variation, it is unlikely that additional sampling would add further information about the nature of the spatial permeability heterogeneity.

Suggested further research using these data from the White Sandstone outcrop study is to investigate the effects of the measured heterogeneity on fluid flow behaviour through numerical reservoir simulation. Following this investigation, pseudofunctions can be developed and used to scale up the permeability heterogeneities to appropriately-sized grid blocks. This scaling-up technique may then be applied to the reservoir.

The differing nature of permeability heterogeneities identified within the various lithofacies types in the outcrop studies on the Sherwood Sandstone, Dawlish Sandstone and White Sandstone clearly demonstrates that a single permeability model with its associated scaling rules is not appropriate for reservoir rocks comprised of different lithofacies types. To represent permeability heterogeneity more realistically, permeability models are required to represent each lithofacies type. The successful development of 'global' permeability models for different lithofacies types however, is dependent on the degree of variability between outcrops of the same lithofacies type. It is necessary therefore, to attach a value of variability (for example, the coefficient of variance, C_v) and sample error (for example, the optimal sample number, N_0 , or confidence limit) to each data base collected within and between different lithofacies types. With increasing numbers of outcrop permeability studies on different lithofacies types the variability within and between these permeability data bases for lithofacies types should decrease and stabilise. Providing permeability heterogeneity corresponds to lithofacies type, a clear division should become manifest

between different lithofacies types (that is, the variation between is greater than the variation within).

To maximise the information gained from outcrop permeability studies it is necessary to initiate development of non-proprietary permeability data bases. There are practical problems associated with this because outcrop permeability studies are frequently funded by oil companies to solve current, and often very specific, reservoir problems, the results of which are usually confidential. As outcrop permeability studies are generally very time-consuming, they are usually carried out through industry-sponsored research conducted via academic institutions. This provides potential for collaboration between these institutions where the data obtained from outcrop permeability studies can be pooled to provide non-proprietary data bases with confidentiality retained in their interpretation and application to specific reservoir problems. Logically, these permeability data bases should be classified according to lithofacies type. For ease of reference and access to the required parameters, it is suggested that the static statistics (for example, permeability p.d.f's and C_v), spatial statistics (for example, correlation lengths and fractal dimensions) and scaling properties (including anisotropy) are also given. Additional information, including wireline log and seismic characteristics, which would be extremely useful for calibration purposes, may also be included.

A significant contribution of these data bases is that they provide the much-needed step towards the quantification of sedimentary models. As this quantification is based on a geological framework, the geologist's conceptual model of the reservoir remains unchanged, but being accompanied by quantitative permeability data can be utilised more effectively by the reservoir engineer. The quantification of reservoir heterogeneities also provides more convincing evidence for the economic viability of the reservoir.

An obvious limitation and often-quoted criticism of outcrop-derived permeability models is that they are unrepresentative of actual reservoir conditions and diagenetic complexity. However, when considering the large degree of uncertainty in current reservoir models, these predictive and quantifiable models for interwell reservoir heterogeneity can make

a very valuable contribution towards improved recovery. Furthermore, diagenetically simple permeability models are required first to improve our understanding of spatial permeability heterogeneities and to develop scaling-up rules before adding the complexities caused by diagenesis. Once diagenetically-simple permeability models are satisfactorily obtained for specific reservoir rocks, then heterogeneities due to diagenesis can be superimposed on them.

Conclusions:-

- 1) Reservoir heterogeneities can have a very significant effect on oil recovery with large areas of the reservoir often remaining unswept leaving residual oil. In order to design recovery strategies (for example, displacement mechanisms and the design of injection - producer well locations) and to predict recoverable reserves, it is necessary to have a clear understanding of the nature of the spatial heterogeneities within the reservoir. Of the reservoir properties and characteristics, permeability is probably the most important, and an understanding of permeability heterogeneity within the reservoir is essential. Quantification of spatial permeability heterogeneities from rock outcrops can be used to improve our understanding of permeability heterogeneity within the reservoir in both the uncored interval and in the interwell area.
- 2) In a review of the published outcrop permeability studies, key areas for improvement include the permeability measurement technique and the sampling strategies employed.
- 3) A code of practise is presented here for outcrop permeability measurement using the probe permeameter. By following this code of practise, sample errors can be reduced with quantifiable sample quality.
- 4) A sampling scheme is proposed for outcrop permeability studies based on the identification of genetic depositional units. The sampling scheme is an iterative one with repeated sampling as each subsequent and smaller scale of permeability heterogeneity is identified. Techniques for calculating the sample error at each stage are presented. The use of this sampling scheme is demonstrated in two outcrop case

studies representing sediments formed within fluvial and aeolian environments.

5) In an outcrop permeability case study on a 'massive' shallow marine sand body, a persistent although variable coarsening-up sequence is identified producing an upward increase in permeability. Permeability probability distribution functions vary from normal to square root normal. After removal of the vertical drift caused by the coarsening-up sequence all permeabilities are normally distributed irrespective of their sample density or direction. Within the coarsening-up sequence permeability is largely uncorrelated in both the vertical and horizontal directions and a fractal relationship is identified between point permeabilities measured at different sample densities.

6) For this particular shallow marine sand body, the spatial permeability heterogeneities were modelled using a continuous stochastic model. This employs a Monte-Carlo approach with cumulative distribution functions for permeability. Considering the fractal nature of permeability variation, which is similar in both the vertical and horizontal directions, the use of a layer-cake model to represent interwell permeability variation is probably an appropriate technique for reservoirs of this type. Estimates of the validity for end-well values can be made through statistical estimates such as the N-Zero test.

7) To fully utilise outcrop permeability studies and optimise improvements in our understanding of permeability heterogeneity, the data bases from outcrop need to be combinable for similar lithofacies types and placed in the public domain to encourage experimentation in reservoir application. Combinability will be made easier by following the code of practise for outcrop probe permeametry and methodology for sampling presented here.

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