The Operating Characteristics of Minipermeameter and
Its Ability to Investigate The Small Scale
Permeability Heterogeneity

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Dedicated to my parents
The heterogeneity of a reservoir is one of the most important characteristics that influences the oil recovery. These variations exist at all scales, ranging from formation level to scale of few pores. The most important aspect of reservoir heterogeneity is the permeability variations which influences the performance of the displacement process.

The minipermeameter is used for measurement of permeability both in the laboratory and field application where localized measurements are needed to characterize the spatial distribution of permeability. The operating characteristics of the minipermeameter are studied. The size and shape of the region measured by the minipermeameter is found experimentally, to show the magnitude of the spatial range of measurement of the instrument with real rock.

The influence on measured value of permeability by using different tip sizes at the same surface location of a sample is also studied. In addition to the magnitude and occurrence of natural variability in the rock, several instrumental sources of measurement variability are studied.

Once the operating conditions of the minipermeameter are known, the capability of the device to obtain permeability measurement on a very small scale is investigated. The heterogeneity within reservoir core sample is measured with precision at the very small measurement intervals of \(1.25 \times 10^{-3}\) inch. The small scale permeability minipermeameter measurements made in this study at a close spacing over the surface of many samples revealed that most reservoir rocks
exhibits significant heterogeneity.

The vertical heterogeneity of permeability in a core was also investigated in this thesis. There was no trend of permeability, however the limiting variances for each layer vary significantly.
INTRODUCTION

The knowledge of permeability variations in reservoir rock is a very important, if not the most important, reservoir property for obtaining optimum recovery in the exploitation of reserves. An objective of this work is to examine the small-scale heterogeneity of an apparently uniform rock sample by measuring permeability and using an automatic minipermeameter. A further objective is to define the operating characteristics of the minipermeameter itself.

For enhanced oil recovery, detailed information about the permeability of a reservoir is an important characteristic that affects oil recovery. Permeability of a heterogeneous reservoir should be precisely determined to show how fluids are moving in the reservoir to help design highly efficient enhanced oil recovery projects. Reservoir heterogeneities, such as fractures, channels, and high permeability streaks, can cause early breakthrough of injected water or gas, which will have an adverse effect on oil recovery. An apparatus for measuring local permeabilities of consolidated reservoir samples was described in 1950 by Dykstra and Parsons using the principle of steady-state flow through the rock. This was the first form of minipermeameter.
Dykstra and Parsons measured local permeability at the surface of core samples taken from a sandstone oil reservoir and examined the effect of local permeability variations on the recovery of oil by waterflood. They investigated the distribution of permeability of the end face of a core plug, finding significant variability even on this relatively small area, and noticeable correlation between uniformity of the core and effectiveness of oil recovery by waterflood.

Later, Eijpe and Weber (1971) and Chandler et al. (1986) constructed and used minipermeameters for laboratory use and field measurements of permeability manually. In these measurements, the air flow rate is measured by a rotameter and the permeability of the sample rock is derived from this flow rate and applied pressure. Daltaban et al. (1989) developed an electronic field minipermeameter in which the flow rate is determined using a series of laminar flow elements and a macromanometer. The injection pressure is measured using an electronic pressure transducer positioned at the injection tip. For a given laminar flow element and a given pressure differential, the drop in pressure along the flow element is proportional to the flow rate. Using this relationship, the gas law and an experimentally derived calibration of macromanometer reading permeability values are calculated. Halvorson and Hurst (1990) constructed an automatic minipermeameter to perform permeability measurements on center-cut cores.

A completely computer controlled automatic scanning minipermeameter was developed at the Petroleum Recovery Research Center (PRRC), which is used in this study of small-scale permeability heterogeneity (Heller, 1992). For this apparatus, the time is measured
for a known volume of air to flow into and through the rock through a small tip at a
known, constant pressure.

The distinguishing feature of minipermeameters is the geometry of the flow—air flows
out through a small tip into the rock directly below the tip and out again through the
same slabbed surface at various distances from the tip Fig 1.1. Although the
permeability of the rock is expected to be proportional to the ratio of the flow rate to the
pressure function, the value of proportionality constant is not evident in this nonlinear
geometry. Goggin (1988) used a numerical simulation technique to compute the
geometric factor that should be substituted into a modified form of Darcy law to allow
computation of permeability from a steady-state measurement of gas/flow rate and
injection pressure. This geometrical factor G is defined in Goggin’s work for placement
of the tip in the center of one face of a conventional cylindrical core. Under these
circumstances, G is primarily a function of b_D, (ratio of the outside to the inside radii
of the tip) and to some extent as a function of the dimensionless core sample length and
the dimensionless core sample radius.

Chen (1992) further developed the above work to measure not only the local permeability
but also the porosity at approximately the same location of the rock. The permeability
measurement is done under a steady-state flow and the porosity is determined under a
transient flow. Chen treated the dimensionless length and radius (that is distance of the
tip from outside boundary) to be large enough so that the difference between the values
of $G$ computed for these conditions is less than 0.2%. In this the case the geometric factor $G$ only depends on the dimensionless tip-seal radii.

The numerical computations by Goggin and by Chen involved solution of the partial differential equation for flow of an ideal gas in the characteristic geometry of the minipermeameter. The differential equation was derived from the Darcy's Law, and is based on the usual assumption that both rock and fluid are mathematically continuous and devoid of internal structure, and that the porous sample is homogeneous in its properties within the region of investigation. In the usual use of Darcy's Law for the measurement of permeability in a sample cut into a right circular cylinder, the 'region of investigation' is clearly defined. For the minipermeameter, on the other hand, this region is not immediately evident. It is one of the purposes of this work to define at least the 'practical limits' of this region.

Information on permeability variability in a heterogeneous reservoir evaluated on a core is best obtained by minipermeameter, which gives a rapid localized nondestructive measurement with a high resolution. It can be used to supplement conventional core plug measurements of permeability, which are generally analyzed by Hassler/Sleeve measurements that provide overall average permeability measurements for the core.

Customary core analyses generally represent measurement of only one small sample from each foot of core. Instead of such a limited number of measurements, an approximately continuous log of permeability data can be collected by using the minipermeameter,
which can give more information about core permeability without increasing the cost. It is difficult to detect high and low permeabilities in a laminated reservoir using conventional methods. Minipermeameter data can be used to evaluate the degree of permeability heterogeneity present and show when conventional data might be sufficient for characterization of a reservoir. The automatic minipermeameter allows high volumes of permeability data to be collected without an increase in cost. This data improves the understanding of permeability distribution, the zonation of a reservoir, and can help in the accurate small scale characterization of a reservoir.

The minipermeameter measurements made in this and other studies at a close spacing over the surfaces of many samples have revealed that most reservoir rock exhibits
Fig 1.1  Minipermeameter Flow Geometry And Gas Streamlines
significant heterogeneity. This study continues the collection of such data, and also describes the capability of the minipermeameter to perform permeability measurements on a very small scale to investigate heterogeneity within reservoir core samples. Permeability measurements carried out for identification of this heterogeneity are constrained by the flow geometry of injected air in the sample rock. In this investigation, the size and shape of the region measured by the minipermeameter is investigated. The experimental study is hampered by the presence of heterogeneities even in the very small volume of rock directly below the tip and in the surrounding rock outside and below the main region of investigation for even apparently uniform rock. For instance, regularly spaced permeability measurements taken on Berea core along a diameter line of 0.5 inch, with increments of only $1.25 \times 10^{-3}$ inch, show a permeability variation from 434 to 1400 md.

In addition to the magnitude and occurrence of natural variability in the rock, several instrumental sources of measurement variability are studied in this thesis.

Another instrument variation is caused by the proximity of the tip to the edge of the core. The influence of this, and of the type of boundary condition (free flow or no-flow) are examined. The general question of the size and shape of the region which is examined by the minipermeameter is also studied both experimentally and computationally. Although the former of these is made uncertain by the lack of any perfectly uniform rock samples, it was possible in both cases to consider the apparent permeability of structures
consisting of two layers, of different permeabilities and thickness, and to use this effect to estimate the 'depth of investigation' below the tip.

The measurements taken by an automatic minipermeameter help to accurately determine a quantitative small scale description of permeability distribution in a reservoir rock.
CHAPTER 2

LITERATURE REVIEW

In 1856, Darcy studied the vertical flow of water through packed sand filter beds and found that the volumetric flow rate of water was directly proportional to the head of water above the outlet pipe at the base of the filter.

A schematic drawing of the equipment used is shown in Fig 2.

Fig 2.1 Darcy's fluid flow apparatus
The original Darcy equation with no units specified is

\[ q_w = c \frac{A \Delta h_w}{L} \]  

(2.1)

where

- \( q_w \) = volumetric flow rate of water
- \( A \) = cross-sectional area of filter bed
- \( \Delta h_w \) = vertical head of water above the outlet pipe
- \( L \) = vertical height of the filter bed
- \( c \) = proportionality constant

The direct proportionality between the volumetric flow rate and head proved valid for other fluids; however, the constant \( c \) was found to be a function of the fluid as well as the porous medium.

Further experimentation showed that the flow rate was directly proportional to the fluid density \( (\rho) \) and inversely proportional to the fluid viscosity \( (\mu) \). The Darcy equation for the one-dimensional flow of any incompressible fluid in such a vertical configuration is

\[ q = K \frac{A \rho \Delta h}{\mu L} \]  

(2.2)

where

- \( g \rho \Delta h \) = pressure drop across the system—atmospheres
By including the acceleration of gravity in the pressure drop term $g\rho \Delta h$, the proportionality constant ($K$) is, to first approximation, a function of the porous medium only and is termed the permeability of the medium. The unit of permeability, the darcy, is defined by the sentence "A porous medium with a superficial cross-section area of $1 \text{ cm}^2$ and a length of one cm has a permeability of one darcy if fluid of one cp viscosity flows at the rate of one cc per second under a pressure drop of one atmosphere." The permeability, $K$, as it appears in Eq. (2.2) is the absolute permeability, measured when only one fluid is present in the porous medium. Eq. (2.2) was developed for the gravity flow of fluid through a vertical porous medium, where the gravity factor $g\rho \Delta h$ represents the pressure drop in the direction of flow. During fluid flow problems that are encountered in reservoir engineering, the flowing pressure gradient can be in any direction. If gravity forces are important, the force causing flow in a vertical direction is the vector sum of the pressure imposed gradient and gravity forces. This resultant force is often called the flow potential ($\Phi$). If the flow is in a level system and gravity is not important, we can use the externally imposed pressure for flow potentials.

The Darcy law, for the flow of an incompressible fluid, in terms of pressure at the inlet and outlet ends of the system, is

$$q = K \frac{A(p_o - p_L)}{\mu L}$$

(2.3)

where

$q = \text{flow rate in cc/sec}$

$\mu = \text{viscosity in cp.}$
\[ p_o = \text{the pressure at the inlet end—atmospheres} \]
\[ p_L = \text{the pressure at the outlet end—atmospheres} \]
\[ L = \text{length of core in cm}. \]

In contrast to that for a liquid the gas volumetric flow rate varies with pressure and the value for \( q \) at average pressure in the core must be used in Eq. (2.3). To convert gas volumes at the mean pressure to gas volumes at a given base pressure \( P_b \), and the term \( Q \) is introduced for gas flow rate in \( \text{cm}^3/\text{sec} \) of pressure, \( P_b \).

\[
\frac{Q}{q} = \frac{(p_o + p_L)}{2P_b} \quad (2.4)
\]

Substituting this in Eq. (2.3)

\[
Q = \frac{KA}{2L\mu P_b} (p_o^2 - p_L^2)
\]

or \( K = \frac{2QL\mu P_b}{A (p_o^2 - p_L^2)} \) \quad (2.5)

where

\( K \) = permeability of rock sample in darcies

The darcy law gives average value of permeability \( K \) in the region under examination. Reservoirs have complicated shapes and nonuniform permeabilities and porosities. Most reservoirs are deposited from water (although some are buried sand dunes or Eolian deposits) and are layered because of variations that existed in the depositional
environment. Slow moving water deposits mostly small-grain particles at specific locations, but when the water is moving much faster, only relatively large particles are deposited at the same place. This results in a vertical series of dissimilar units called strata. Conditions also vary from one location to another at the same time during deposition, resulting in lateral as well as vertical changes within the rock unit. Both vertical and lateral changes in rock properties result in variations in porosity fluid distribution, and permeability to fluids.

Cardwell and Parsons (1944) estimated a single equivalent permeability for a heterogeneous oil reservoir, or a portion thereof, whose actual permeability varies in an irregular manner. The equivalent permeability lies between the harmonic and arithmetic-volume average of the actual permeabilities. The effective permeability of the formation around a wellbore lies between a volume-harmonic and volume-arithmetic average of the core-sample permeabilities. When the permeability variations away from a well are unknown, it is reasonable to assume that the equivalent permeability of a heterogeneous oil reservoir lies between the harmonic-depth average and the arithmetic-depth average of the core-sample permeabilities.

Greenkorn and Johnson (1960) analyzed natural sandstone reservoir cores and showed that thickness, permeability, and porosity can have large variations over a relatively small area. The variation of permeability changes extremely with in small areas. The variations are quite large, both areally and vertically. Also variation of porosity is
significant within small areas. Change in variation of porosity, both areally and vertically is also significant.

Knutson (1961) coordinated a logging-coring program which yielded significant formation characterization data for the San Miguel sandstone reservoir. He showed that good evaluation of core measurement deviations are required to determine the well drainage area and field variations.

Warren, Skiba, and Price (1961) compared core-analysis permeabilities to those determined from a pressure buildup test. The results showed that the permeability measurements are significant in the qualitative determination of the nature of the heterogeneity that exists in a reservoir. More accurate core data, improved pressure buildup testing, and independent determination of anisotropy are needed to obtain a better reservoir description.

Warren and Price (1961) studied the effect of the disposition of heterogeneous permeabilities on a single-phase flow for a known permeability-distribution function and attempted to infer the presence and probable configuration of heterogeneities from core analysis and pressure buildup data. A three-dimensional model was used in which the block permeabilities were randomly arranged. The flow equations were solved numerically and the results were interpreted statistically. They concluded that the most probable behavior of a heterogeneous system approaches that of a homogenous system with a permeability equal to the geometric mean of individual permeabilities. Also, a
qualitative measure of the degree of heterogeneity and its spatial configuration are obtained from a comparative study of core analysis and pressure build-up data.

Burns (1969) showed that a vertical test can determine the in-situ vertical and horizontal permeabilities of tested zones and the effectiveness of tight zones as a barrier to vertical flow can also be determined directly by the harmonic average across layers of different permeabilities of actual vertical permeability of each layer. The measured value of vertical permeability can appear to be low if the well has skin damage or if partial shale barriers are present in the tested interval, and can be higher in case of a poor cement job behind the casing.

Kamal (1979) discussed the use of pressure transient tests to obtain quantitative reservoir description for homogenous and heterogeneous reservoirs. He recommended the use of the parameter estimation technique to analyze pressure-transient data from a heterogeneous system.

Weber (1982) collected data on shale continuity as a function of the environment of deposition and used four methods for determining the effective vertical permeability of a distribution of shale in porous media, and achieved consistent results in similar models both in two and three dimensions.

Begg and King (1985) demonstrated that the effective vertical permeability is strongly dependent on shale dimension, shale density, and facies thickness.
Giordano et al. (1985) showed that a finite difference simulator can accurately model the qualitative behavior of non-steady flows if the permeability distribution, and viscosity behavior of the process are properly accounted for. Their work suggests that qualitative agreement could be obtained if the permeability distribution on a finer scale could be measured.

Weber (1986) determined that the key to the analysis of heterogeneity is the correct identification of the environment of deposition and digenetic history. The author suggests that information for quantification of heterogeneity can be obtained with the aid of cores, logs, analogue models, conceptual modeling and reservoir production tests. The enhanced oil recovery projects have shown that heterogeneities cannot be neglected and simple averaging procedures rarely lead to the expected results.

Goggin et al. (1986) described the minipermeameter as an excellent field device for the detailed sampling of large outcrops and showed that the mean permeability is a strong function of three stratification types—grainflow, wind-ripple, and interdune—in eolian deposits.

Lewis (1988) indicated that the reservoir data obtained from cores are insufficient in most cases for accurate prediction and quantification of reservoir heterogeneity. In order to understand the scale and magnitude of reservoir heterogeneity, it should be quantified in large two-dimensional, and preferably three-dimensional, exposed outcrops of analogous
sediments. A minipermeameter was used for taking the permeability measurements of outcrops in their studies.

Martin and Evans (1988), while investigating permeability distributions in Rotliegentes sandstone, found that plug measurements were incapable of adequately describing permeability variations.

Robertson and McPhee (1990) made a comparison of permeability distribution in a heterogeneous reservoir using conventional core-plug data and the automatic minipermeameter data and found that the minipermeameter can provide a more accurate estimate of core heterogeneity and can identify very thin permeability zones which cannot be identified by core plug measurements alone.

Bahralolom (1991) Investigated the variability of rock properties at small scale using computerized imaging techniques. The comparison of spatial variability of field and laboratory permeability measurements to find the relationship of small to large scale permeability heterogeneity, suggested that the variograms made from large scale data includes the small scale variability as a major component.

Bahralolom and Heller (1992) discussed the implication of small-scale heterogeneities on displacement, or coreflood experiments. In addition to measuring the permeability and porosity variations by a variety of ways, they calculated the apparent dispersion that
would be observed in a miscible flood of a rock containing permeability heterogeneities correlated along the length of a flow sample.

Ghori and Heller's (1992) experimental work used a minipermeameter to measure areal permeability on grid points. Rock sample permeability was measured at the top and bottom surfaces of a block of sandstone using the minipermeameter. A tracer experiment was performed and tracer output curves were obtained at the outlet of the rock sample. The minipermeameter data was used in the numerical simulation. The tracer curves obtained from simulations were compared with experimental ones and good agreement between the two showed that the flow of tracer was mainly affected by permeability variations. This experiment showed that reliable permeability data can be obtained by the minipermeameter.

Ghori (1992) describe a basis on which well-to-well tracer tests can be used to obtain quantitative information about the geostatistical parameters (variance and correlation length) of permeability. One of his conclusion is that a comparison of the numerical and experimental tracer curves indicates that the tracer output curves are affected mainly by permeability variation.

Jones (1992) designed a new fast minipermeameter for measurement of permeability in a range from 0.001 to 20,000 md. This instrument is modified to reduce the permeability measurement time by removing the flow controller and using reservoirs of different calibrated volumes. The time rate of pressure decay as nitrogen flows from any
one or all of these reservoirs through the probe and into the sample yielded a direct measure of the sample's permeability. It reduced the time required for the low permeability samples from 20 minutes to 20 seconds and the uncertainty of all measurements was reduced to ±5%.

Heller (1992) introduced the PRRC automatic scanning minipermeameter. For this instrument, both the air supply and the means for flow measurement are achieved by the use of a simple glass syringe and pressure is calculated based on the weight on the syringe plunger. All other minipermeameters use a compressed gas source and flow meters to determine the flow rate, q, and pressure transducers or mechanical gauges to measure the pressure difference, Δp. The PRRC automatic scanning minipermeameter is simple and more economical than similar devices that are commercially available and used in other laboratories.

Chen, Mclemore and Heller (1993) developed the Minipurpermeameter for simultaneous measurement of permeability and porosity. The capability of minipermeameter is further expanded to measure porosity as well. Immediately after calculation of the permeability, and under defined conditions, a precise value of the porosity at same portion of rock is computed from the transient pressure change that is observed at the probe-tip after cutting off air supply into the rock from the probe.
CHAPTER 3

CHARACTERISTICS OF THE PRRC AUTOMATIC MINIPERMEAMETER

In this chapter, characteristics of the minipermeameter are described. The accuracy of the measurement and the size and shape of the region measured by the minipermeameter are investigated. The minipermeameter can perform permeability measurements on very small and large areas of rock samples with high measurement density, precision, and accuracy. An air-permeameter is also briefly described, which is used to determine the permeability of packed glass beads, that are used in an auxiliary experiment.

3.1 MINIPERMEAMETER DEVICE

The minipermeameter used in this study is a completely computer controlled automatic scanning minipermeameter which was designed by Dr. John Heller of New Mexico Tech’s Petroleum Recovery Research Center (Heller, 1992). In this device, both the air supply and the means for flow measurements are achieved by the use of an ordinary glass syringe (an air pump is used to fill the syringe prior to measurement) with a weighted plunger. The syringe minipermeameter is mounted on a movable instrument carriage that scans over a table holding the rock sample. The table is also movable in a direction at right angles to the direction in which the instrument carriage moves. The maximum scan area is 22 x 22 inches. Measurements can be taken at minimum spacing of $1.25 \times 10^{-3}$ inch in X-direction and $1 \times 10^{-3}$ inch in Y-direction.
The device is computer controlled. Sensors and actuators are mounted with the probe and syringe on the instrument carriage, and a digital control card is located inside the computer. The program to control the operation of the device is written in Turbo Pascal.

The minipermeameter has a vertically moving probe with an interchangeable silicone rubber tip that is pressed against the face of the rock surface to measure permeability. One of the parameters that affects the permeability measurement is the quality of the seal between the injection tip and the rock surface. To provide a good seal between the rock surface and the tip, an optimum weight is placed on the probe to press it against the rock surface. The optimum weight depends not only on the tip size and the ratio of outer to inner radii (that is, on the area of the rubber in contact with the rock), but also on the permeability of the rock. Ali (1993) determined optimum weights for earlier version of tip design. The total time interval (T) that is required to inject the fixed volume of air is a characteristic of the permeability of that portion of the rock sample underneath the injection tip.
Fig 3.1 PRRC Automatic Scanning Minipermeameter.
Figure 3.1 Shows the parts of PRRC minipermeameter.

A: Complete setup of PRRC minipermeameter along with control box and the computer.

B: A close up of minipermeameter.

C: Syringe, plunger and the weights on the plunger.

1. Aluminum frame
2. Steel table
3. Long screw to move the steel table
4. Diaphragm air pump
5. Stepping motors
6. Probe
7. Silicone rubber tip
8. Slotted weights
9. Glass syringe
10. Weights on the syringe plunger
11. Slot detector
12. Photographic film
3.2 FLOW ANALYSIS OF MINIPERMEAMETER.

To obtain accurate measurement of permeability it is critical to achieve a steady state condition for flow of gas/air in the porous rock. The steady state condition can be affected by the non-steady, vertical movement of the plunger. The leakage that may occur between the interface of the syringe and plunger, and between the rubber tip seal and the rock surface can void an assumption that air flows only through the rock. In addition, the time required for the air flow to reach steady state condition needs to be determined.

In absence of any leak between the syringe and the plunger, the flow rate could be calculated as follows:

\[ q = \frac{\pi r_{syringe}^2 \Delta h_{syringe}}{T} \]  

(3.1)

In a core test for a homogeneous rock sample, the Darcy streamlines are considered to be straight lines parallel to the axis of the core, and the permeability is calculated by a simple application of the compressible gas form of Darcy law.

\[ K = \frac{2QL\mu P_b}{A(p_o^2 - p_L^2)} \]  

(3.2)

It is convenient to refer to the quantity \( 2P_L/(P_o^2 - P_L^2) \) as the pressure function. In the minipermeameter and as verified by the Darcy Law solutions of Goggin and Chen, streamlines are curved even in a perfectly uniform rock as indicated in Fig 1.1 This is because the cross-section for the flow changes from one part of the sample to another,
crowding together streamlines in those parts of the rock near the tip. This means, incidently that the measured value will therefore depend much more on the permeability in that region than elsewhere. The dimensionless ratio of tips outer to inner radii, $b_D = b/a$, determines the shape of the practical outer boundary of the air flow pattern, where as the volume enclosed within it can be expected to be proportional to the third power of the tip radius. Although the permeability of the rock is proportional to the ratio of the flow rate to the pressure function, the value of proportionality constant is not evident in this nonlinear geometry. Goggin (1988) used a numerical simulation technique to compute the geometric factor that should be substituted into a modified form of Darcy law to allow computation of permeability from a steady-state measurement of gas/flow rate and injection pressure. It is not really a constant except for a particular tip, but depends on the value of the radius ratio, $b_D$. Chen (1992) calculated the value of $G$ as a function of $b_D$. Fig 3.2 is a graph of values for Goggin geometrical factor as calculated by Chen.

Suboor and Heller (1994) pointed out that the curve given in Fig. 3.2 showing the variation of the Goggin factor $G$ with radius ratio $b_D$ (or $b/a$), has an important implication for tip design. It is to be noted that the negative slope of this curve is much larger at small values of the tip ratio. Consequently, the error in the permeability measurement that is due to uncertainty in the precise value of the ratio is much greater if the tip design is such that $b/a$ is small. Because the material of the tip is necessarily a soft rubber, the shape is easily distorted and both outer and inner radii are subject to
change when the tip is pressed against the sample. There has even been a tendency, in
the manufacture of commercial minipermeameters, to use "O-Rings" as the tip seal.
Suboor and Heller (1994) see this as an unfortunate design choice, since with it, the
actual seal with the rock sample cannot be made unless the outer radius (of rubber in
contact with the rock) is increased and the inner radius decreased simultaneously by the
pressure of the tip against the sample. Unless this pressure is very accurately maintained,
from one measurement to next, there will be significant uncertainty in the value of \( b/a \),
and therefore in \( G \), to be used in the permeability calculation. This will cause the same
relative error on the measured permeability.

The permeability calculated by the modified form of Darcy law is

\[
K = \frac{2Q\mu P_s}{aG(P_s^2 - P_a^2)}
\]

\[
= \frac{Q\mu}{aG} \cdot \frac{1}{\Gamma P_g}
\]

(3.3)

where

\[
P_g = P_s - P_Q
\]

\[
\Gamma = \left[ \frac{1 + P_g/P_a}{1 + P_g/2P_a} \right]
\]

\( G \) = Goggin geometric factor

\( P_s \) = Absolute value of pressure

\( P_a \) = The atmospheric pressure

\( P_g \) = Gauge pressure
Fig 3.2 Goggin Geometrical Factor calculated by Chen (1992)
It is almost impossible to avoid any leakage between the syringe and plunger in this type of minipermeameter. Heller (1992) presented an analysis of the syringe minipermeameter with air leaking in the system. He showed that there are two flow rates that contribute to the total flow rate, $Q$, which can be written as a sum:

$$Q = q_{darcy} + q_{leak}$$

$$q_{darcy} = \frac{A\Delta h}{t} = \frac{k_a G \rho g}{\mu}$$  \hspace{1cm} (3.4)

The leakage along the sides of the syringe plunger can also be presumed to be proportional to the same function of the pressure and can be written as

$$q_{leak} = \frac{A\Delta x}{t_{lk}} = c_{lk} \Gamma \rho g$$  \hspace{1cm} (3.5)

$$c_{lk} = \frac{A\Delta x}{\Gamma \rho g t_{lk}}$$  \hspace{1cm} (3.6)

where

$c_{lk} = \text{conductivity of the leak}$

$t_{lk} = \text{time interval in which the syringe plunger will move downwards by the distance } \Delta x \text{ in the absence of flow into the rock}$

$A = \text{cross-sectional area of the syringe}$
\[ \Delta x = \text{distance the plunger moved from } X_1 \text{ to } X_2 \]

\[ P_g = \text{gauge pressure inside the syringe} \]

Heller (1992) showed a good approximation for the actual situation of the minipermeameter based on the assumption that the influence of friction is negligible, and that \( P_g \) is small, as follows:

\[
K = \frac{\mu A \Delta x}{a G T P_g} \left[ \frac{1}{T} - \frac{1}{t_{tk}} \right]
\]  \hspace{1cm} (3.7)

where

\[ a = \text{Inner radius of tip} \]

\[ \mu = \text{Viscosity of air} \]

\[ T = \text{The time interval for syringe plunger to sink from } X_1 \text{ to } X_2 \]

Heller assumed that the distance between \( X_0 \) and \( X_1 \) is large enough so that the limiting velocity has been attained, where \( X_0 \) is the position at which the plunger motion starts before it arrives at the first mark, \( X_1 \), from which the travelling time will be counted. These distances are indicated in Fig 3.3.

The equations used for permeability measurements are derived on the assumption that the core sample (or rock within range of minipermeameter) is absolutely uniform. Because this assumption is never strictly true, variability is expected in measurements on real rock.
M = total mass on the syringe plunger.

x is measured downward from an arbitrary zero.

\( P_g \) is the gauge pressure inside the syringe during the experiment (the more correct form with \( (P^2 - P_{\text{atm}}) \) must be used if \( P >> P_{\text{atm}} \)).

\( r_{\text{syringe}} \) is the radius of the syringe plunger.

\[ a_2 = 2\pi r_{\text{syringe}} (h + x) \] is the area on the outside surface of the syringe plunger, that is in contact with the inside of the syringe cylinder.

\[ A = \pi r_{\text{syringe}}^2 \]

Fig 3.3  The Syringe Minipermeameter.
The equation for the flow of compressible fluids should have a squared pressure term. When the pressure difference is small, this can be approximated as shown because the factor $C$ (or $\Gamma$) varies only very slowly with pressure if $(P_g/P_a - 1)$ is small Eq (3.7) is the formula for computing permeability values from the minipermeameter used in this study. If $\mu$ is in centipoise, $Q$ and $\Delta x$ are in centimeters, $A$ is in centimeters squared, and $P_g$ is in fractions of a standard atmosphere, then permeability, $K$, will be in darcies. The Goggin geometric factor, $G$, and the pressure correction factor, $\Gamma$, are dimensionless.

3.3 PARAMETERS FOR CALCULATING PERMEABILITY

The parameters which remain unchanged during the operation of the minipermeameter are used as constants in the computer program which controls the operation of the minipermeameter. These constants are the weight on the syringe plunger in grams, the syringe area in cm$^2$, the altitude of Socorro in ft, the standard sea level atmospheric pressure in Pascals, the acceleration due to gravity cm/sec$^2$, the viscosity of air in cp, the number of stripes to count on the interrupter mask, total number of dark stripes in 1.2 inches of the mask, and the distance increments to be taken by the X and Y stepping motor/pulses between the measurements.

The variables used by the computer program are: the travelling time, $T$ (which is corrected for leak time $t_{lk}$), the ID of the tip, $a$, and the Goggin geometric factor, $G$. The measured value of travelling time, $T$, for the syringe to move from mark $X_1$ to $X_2$ includes both leakage and the flow through the rock. The actual permeability of the rock
sample is calculated by taking into account the leak time ($t_{lk}$). $t_{lk}$ is the time for the syringe plunger to move from $X_1$ to $X_2$ in absence of flow into the rock sample. Leak time is determined during the operation of the minipermeameter. The tip of the minipermeameter is moved occasionally to the leak pads, which are made with a perfectly smooth plastic surface. The pressure on the tip should be enough to provide a good seal between the tip and the sample’s surface. If the pressure is less, than there will be a leak directly between the sample and the tip. Giving a higher value of $t_{lk}$ and a lower value of $T$. The measured value of permeability in this case would not be representative of the actual permeability in that case.

3.4 OPTIMUM WEIGHT ON THE TIP

The quality of sealing between the injection tip and rock surface is one of the important parameters that affects measured values of permeability. The quality of the seal depends on both the softness of the rubber used in the tip and the surface of the rock on the pressure applied on tip. The pressure on the tip should be enough so that there is no leakage between the tip and the rock surface. If the pressure on the tip is too large the geometry of the tip is distorted, which results in impeding the flow. The Goggin geometric factor would also become invalid for the tip in use if its shape were distorted as tip geometry might no longer be circular due to excess pressure on the tip. Calculated permeability values would then be incorrect and not representative of the assumed rock region. On the other hand, if pressure is not great enough on the tip, then the air will leak directly along the surface of the rock, resulting in erroneously high permeability
values. In this automatic scanning minipermeameter, pressure on the tip is obtained by placing weights on the probe.

An optimum weight for each tip for Berea sandstone has been determined by performing ten single permeability tests on the same spot for each tip, for different values of weight on the tip. The Figs 3.6 to 3.9 show plots of the data for each tip, giving the measured value of permeability, at a particular place on a Berea core, for different weights on the tip. The conditions under which air might leak or not leak, for an early tip design, leak are shown in Fig 3.4. Based on these results the optimal weight, above which the permeability do not vary significantly, is determined. The dimensions and optimum weight for each tip are given in Table 3.1. It appears that there is a linear relation between the optimal weight and tip area, see Fig 3.5.

An additional factor involved in the quality of seal is the smoothness of the rock sample surface. This, in turn, depends on the fineness of the teeth of the saw with which it was cut. All of the experiments described below were performed on Berea sandstone, the surface of which were cut with a fine diamond saw in the Core Preparation Laboratory at the Petroleum Recovery Research Center.

Although it does not concern surface smoothness, it may be appropriate here also to note, on sample preparation procedure, that for minipermeameter measurements it is especially important that the surface not be contaminated by dust or fine particles which may have been forced into the surface pores by the cutting operation. A standard technique to
prevent this difficulty has been to use circulating water or brine as a cutting lubricant, and to brush the surface of the rock lightly after oven drying.

**TABLE 3.1**

Optimum weight for each tip

<table>
<thead>
<tr>
<th>Tip</th>
<th>OD (inches)</th>
<th>ID (inches)</th>
<th>Optimum Weight</th>
<th>Tip Area sq cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>2A</td>
<td>0.25&quot;</td>
<td>0.056&quot;</td>
<td>1000 grams</td>
<td>0.3008</td>
</tr>
<tr>
<td>2B</td>
<td>0.25&quot;</td>
<td>0.067&quot;</td>
<td>950 grams</td>
<td>0.2939</td>
</tr>
<tr>
<td>2C</td>
<td>0.25&quot;</td>
<td>0.083&quot;</td>
<td>900 grams</td>
<td>0.2818</td>
</tr>
<tr>
<td>2D</td>
<td>0.25&quot;</td>
<td>0.125&quot;</td>
<td>800 grams</td>
<td>0.2315</td>
</tr>
<tr>
<td>3A</td>
<td>0.375&quot;</td>
<td>0.083&quot;</td>
<td>2125 grams</td>
<td>0.6777</td>
</tr>
<tr>
<td>3B</td>
<td>0.375&quot;</td>
<td>0.100&quot;</td>
<td>2000 grams</td>
<td>0.6619</td>
</tr>
<tr>
<td>3C</td>
<td>0.375&quot;</td>
<td>0.125&quot;</td>
<td>2050 grams</td>
<td>0.6334</td>
</tr>
<tr>
<td>3D</td>
<td>0.375&quot;</td>
<td>0.1875&quot;</td>
<td>1750 grams</td>
<td>0.5344</td>
</tr>
</tbody>
</table>
Fig 3.4  A: Weight on tip is insufficient. Leakage at contact.

B: Weight on tip is too large. Both ID. and OD. of tip distorted.

C: Weight on probe is correct (optimum weight)
Fig 3.5  Optimum Weight vs Tip Area for Berea Sandstone
Fig 3.6 Optimum weight for tips 2A and 2B
Fig 3.7 Optimum weight for tips 2C and 2D
Fig 3.8 Optimum weight for tips 3A and 3D
Fig 3.9 Optimum weight for tips 3C and 3D
3.5 REPEATABILITY IN PERMEABILITY MEASUREMENTS

The precision of the permeability measurements calculated by the minipermeameter was determined by conducting a test to measure the permeability at the same location on a Berea core sample. A total of 500 permeability measurements were taken at the same location. The results of the calculated permeability show a very good repeatability. The arithmetic mean of the measurements was 0.6767 Darcy and the variation in measured values was within a standard deviation of 0.0036. Fig 3.10 shows the permeability measurements taken at the same spot. It is to be noted that the zero has been suppressed in order to make visible small variations from one reading to next. The accuracy in readings using an earlier version of this device was studied by Maqsood (1993).

A comparison of PRRC minipermeameter readings with both the permeability of standard plugs and with minipermeameter readings by a commercial instrument was conducted by Lambert (1993).

A second test was performed in this work to investigate the reliability of minipermeameter measurements with the latest version of the device. The permeability measurements were taken across the diameter of the core. These measurements show significant variation of permeability from place to place. Two sets of permeability data were recorded. The first set of measurements were performed across the diameter of the core which was 1.5" long (single line), with increments between intervals of $5 \times 10^3$ inch in each measurement. The second test was a repeat section on part of the same line, without disturbing the location of the core sample on the minipermeameter. The repeat
section covered only 0.5 inch (from 0.5 to 1 inch of the 1st set of readings) with increments in measurement distance for this case of only .00125 inch. Fig 3.11 shows a plot of the permeability measurements across the diameter of the core, and also of its repeat section. By overlaying the repeat section on the main section of permeability plot, it can be seen that an excellent repetition of permeability values have been attained. Even with different increments in the measurement distance, the calculated values of permeability were almost the same. This test provides strong evidence that the indicated permeability variation is indeed real, not an artifact of the method.
Fig 3.10 Repeated measurement of permeability at the same location.
Fig 3.11 Permeability Measurements taken at two different scales of measurements show very close repetition of permeability values.
CHAPTER 4

INVESTIGATION OF FLOW GEOMETRY FOR THE MINIPERMEAMETER

In this chapter an attempt is made to define more precisely the size and the shape of the region of the rock under the probe-tip, in which the permeability is measured. The Darcy-law, numerical treatments of Goggin (1988) and of Chen (1993) of course predict a non-zero, although infinitesimally small, flow even at great distances away from the probe, suggesting that the permeability of all parts of the rock contribute to some extent to the measurement. The treatment here will consider instead the practical limits on the measured region, outside of which the rock permeability contributes less than a fraction of a percent to the measurements and is thus undetectable with precision observed in previous chapter.

4.1 RADIUS OF INVESTIGATION LATERALLY FROM THE TIP

To determine the lateral radius of investigation of the minipermeameter, the following method was employed. Permeability measurements were taken across a core of Berea sandstone in a straight line over the length of 0.485 inches from near its center to the edge of the core. The measurements along the line were made with increments of 1.25 x 10^-3 inch. The experiment was repeated after pasting modeling clay onto an open edge
of the core so that no air would flow out, thus changing the boundary condition from free
flow to no flow. Modeling clay was carefully pressed onto the side of the core without
disturbing the core's position on the minipermeameter table. With tip 2A the effect of
the type of boundary conditions was observed up to 0.145 inch from the edge of the
core.

Plots of both sets of permeability data with and without the no flow boundary condition,
and of the difference between the two measurements versus distance along the line
indicated that permeability measurements repeated the same (within 0.5 %) up to a
distance of 0.34 inch. At this distance the permeability data started deviating, indicating
the difference between the flow the no flow boundary (Fig 4.1a). The permeability
measurements were taken on a Berea core length of 0.485 inch. The effect of the
boundary condition was observed beginning at 0.34 inch and continued to edge of the
core which was located at 0.484 inch. The boundary condition effect was thus observed
with this tip, up to a distance of 0.145 inch from the edge.

The tip used in these permeability measurements was 2A, with an outside diameter of
0.25 inch and inside diameter of 0.056 inch. For this tip with the dimensionless ratio of
tip outer diameter to inside diameter, \( b_D = 4.5 \) the effect of boundary conditions is
observed when tip is less than 0.145 inch from the edge.

Calculations of radius of investigation for \( b_D = 4.5 \)

\[
\begin{align*}
0.145 / 0.028_{\text{tip internal radius}} &= 5.18 \\
0.145 / 0.125_{\text{tip outer radius}} &= 1.16
\end{align*}
\]
Based on these experiments it is determined that the for tips with \( b_D = 4.5 \), the radius of investigation is about 5.2 times the internal radius of the tip used, or 1.16 times the outside radius.

A second test was conducted using tip 3D, and the procedure as described above was repeated. The tip 3D has an outside diameter of 0.375 inch, inside diameter of 0.1875 inch, and the dimensionless tip ratio \( b_D = 2 \). In this case the effect of boundary condition are observed from 0.23 inch and continued up to the edge of the core at 0.5 inch. The boundary condition effect is thus observed when the tip is closer than 0.27 inch, from the edge.

Calculations of radius of investigations for \( b_d = 2 \)

\[
0.27/0.09375_{\text{(tip internal radius)}} = 2.88
\]

\[
0.27/0.1875_{\text{(tip outside radius)}} = 1.44
\]

Therefore for tips with \( b_D = 2 \) the radius of investigation is about 2.88 times the internal radius of the tip used, or 1.44 times the outside radius.

Although no such experiments were performed with other from the eight available tips listed in table 3.1 it can be presumed that the dimensionless lateral radii of investigation are functions of the dimensionless number \( b_D \) (the radius of outer to inner radius of the tip). A two point indication is shown of this functional relationship in Fig 4.2.
Fig 4.1 Plot for lateral radius of investigation
Fig 4.2 Functional Relationship (lateral radius of investigation)
4.2 Air-Permeameter Device

To study the effect of depth of investigation of minipermeameter tip composite packs were used, composed of a rigid but thin disc of Berea at top glass beads packs. The permeability of unconsolidated packs of glass beads was determined by using an air-permeameter (Fig 4.3) at the PRRC. The air-permeameter uses compressed nitrogen/air supply, a manometer to record pressure drop across the pack of glass beads or core, and a bubble marker used to detect and measure air flow. The latter could be used to measure the time for a known amount of nitrogen/air to pass through the pack of glass beads or core by recording travel time of soap bubble.

The details of use of these glass beads in determining the depth of investigation is explained in the next section.

The glass beads were first sieved to separate them according to grain sizes and the permeability measurements of cylindrical packs of beads were then performed. The air-permeameter derived permeability values will be used to find the depth of investigation underneath the tip of minipermeameter.

Packs of glass beads were made by packing them in plastic tubes. Ordinary filter paper was used on both ends of the tube to allow for the flow of air through the pack. The pressure gradient was generated across the pack of glass beads and the rate of the
air flow through the sample was recorded. The permeability of the glass beads was
determined by using the following equation (Steven, 1954):

$$K_{\text{air}} = \frac{L}{\Delta t \Delta P A} \frac{8.231 \times 10^8}{1769 + \Delta P} \quad (4.1)$$

where

- $L = \text{length of the pack of glass beads in cm}$
- $\Delta P = \text{pressure drop cm H}_2\text{O}$
- $\Delta t = \text{time in seconds (for 25 cc of air to pass through pack of glass beads)}$
- $A = \text{area of cross-section of the pack of glass beads}$

Table 4.1 gives the permeability values of glass beads obtained by using this air-
permeameter. The relation between the measured permeability values and beads radius
is shown in Fig 4.4. It is expected that if the pore-space in all the packs are
geometrically similar, and proportional in size to the mean bead size in the pack, that the
permeabilities should be proportional to the square of the beads size. This expectation
was borne out by the slope of approximately 2 on the best straight line on the log-log
graph Fig 4.4
Fig 4.3 A set-up for air-permeameter.
# Table 4.1

Air-permeameter permeability data for glass beads

<table>
<thead>
<tr>
<th>US Sieve No.</th>
<th>Sieve Opening (microns)</th>
<th>Permeability of Glass Beads (Darcies)</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>105</td>
<td>14.5</td>
</tr>
<tr>
<td>170</td>
<td>88</td>
<td>6.8</td>
</tr>
<tr>
<td>200</td>
<td>75</td>
<td>3.7</td>
</tr>
<tr>
<td>230</td>
<td>63</td>
<td>2.4</td>
</tr>
<tr>
<td>270</td>
<td>53</td>
<td>no sample</td>
</tr>
<tr>
<td>325</td>
<td>45</td>
<td>1.53</td>
</tr>
<tr>
<td>400</td>
<td>38</td>
<td>1.256</td>
</tr>
</tbody>
</table>
Fig 4.4 Permeability of Pack of Glass Beads measured by Air-Permeameter.
4.3 DEPTH OF INVESTIGATION OF MINIPERMEAMETER

Reservoir structure contains different scale of heterogeneities. As pointed out in numerous experiments and in the introduction of this thesis, most rocks are not homogeneous. Given this fact, the main use of the minipermeameter is seen to be the examination of the local variation of permeability between one region and another. For its effective application to this problem, the spatial limits of a minipermeameter measurements must be studied. Minipermeameter depth of investigation, that is the depth in the rock below which its permeability makes no essential difference to the reading, was investigated by using two techniques. These experimental and computational approaches are discussed in the next paragraph.

Slices of varying thickness of Berea sandstone rock of known permeability values were placed on top of relatively deep packs of glass beads having known, well sorted grain size. The apparent permeability of these assemblies were measured using the minipermeameter. The permeabilities at many points on the surface of each rock are measured prior to the cutting of each slice from the rock. The measured permeability of the slice would not be the same as that of the rock, the slice would seem more permeable than the rock it self, because the slices were thin enough for air to escape from lower surface as well as the top. The slices are cut in an increasing order of thickness, from 0.095 to 0.22 inch.
The permeability of packs of glass beads were also measured separately using an air-permeameter as described in the previous section. Glass beads of the same grain size were used below the slices of Berea rock in the sequence of measurements made with the minipermeameter and described below.

The air that flows from the minipermeameter tip would go first into the slice and then into glass beads and then back into the slice and out the surface. Therefore the measured permeability is a combination of the permeabilities of slice and glass beads. During these permeability measurements the air coming out from tip enters the slice first then the glass beads and back out to surface. In each of the different experiments with a particular bead pack the thickness of the slices is increased gradually. There will be a point where measured permeability will be equal within the precision of reading to the permeability of rock. At this stage it can be said that most of the air flowing from the tip into the slice will flow out again through the surface of slice without entering the glass beads, and the practical "depth of investigation" (for the given tip size) has been reached.

Generally we expected that measured permeabilities $K_m$ would lie between the permeability of glass beads $K_b$ and the permeability of the rock $K_r$. (It was further expected that the ratio $K_m/K_r$ would approach unity for thickness of slices large enough in comparison to the tip dimensions.) At this point the measured permeability would be essentially equal to that of the rock. At the other end of the sequence, the measured permeability $K_m$ would become equivalent to the permeability of the glass beads $K_b$ for extremely thin slices.
The following experiments were performed to find the depth of investigation of minipermeameter tip.

Permeability measurements were made on a rock of Berea sandstone in a grid of size 0.5 x 0.5 inch with increments in measurements of 0.05 inch. As would be expected, there was a considerable variation among the different measurements. For each of the experiments, a region was selected on the rock before it was cut, which was surrounded by permeabilities with similar values. The coordinates of that point were saved so that after the slice was cut, the experiments described above were made in that region.

A first slice 0.095 inch thick was cut from the core. After cutting, the core and slice were dried for 24 hrs in oven at 68⁰ C. The same procedure was repeated to obtain three more slices of 0.11, 0.126, and 0.22 inch thick. The Berea core was carefully marked such that it was placed in the same position on the minipermeameter table after a slice was cut, to make next set of permeability measurements. Before cutting the slice the starting position of tip was marked on the slice and to be used as a reference point for these measurements to be made with the slice on top of the glass beads. Permeability measurements were taken for glass beads of six different grain sizes. The slice of Berea sandstone was placed on top of the glass beads to take the minipermeameter reading. The tip of the minipermeameter was moved starting with the reference starting point marked on the slice on the region of rock which was surrounded by permeabilities of similar values.
This experiment was repeated for each of four slices using four different tips. Table 4.2 summarizes the dimensions of tips used in these experiments. The thickness of each slice and permeability of the nearly uniform region is given in Table 4.3. In each case it was possible to choose a region in which the pre-sliced permeability was the same.

**TABLE 4.2**

Dimension of tips used in experiment.

<table>
<thead>
<tr>
<th>Tip</th>
<th>$b_D$</th>
<th>Outside diameter (inches)</th>
<th>Inside Diameter (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2A</td>
<td>4.5</td>
<td>0.25</td>
<td>0.056</td>
</tr>
<tr>
<td>3A</td>
<td>4.5</td>
<td>0.375</td>
<td>0.083</td>
</tr>
<tr>
<td>2D</td>
<td>2</td>
<td>0.25</td>
<td>0.125</td>
</tr>
<tr>
<td>3D</td>
<td>2</td>
<td>0.375</td>
<td>0.1875</td>
</tr>
</tbody>
</table>
Tables 4.4 and 4.5 summarize the permeabilities $K_b$ of the glass beads in packs obtained by using the air-permeameter, and the measured permeabilities $K_m$ of the assemblies of slices and glass beads. The measured permeability $K$ is plotted against the dimensionless number $D$ defined as the ratio of thickness of rock slice "$d" to the internal diameter of that tip that is $d/2a$.

$$D = \frac{d}{2a} \quad (4.2)$$

Plots of measured permeability $K_m$ vs $D$ with permeability plotted on log scale are shown on Figs 4.7 to 4.10.

The dimensionless ratio of the slice thickness to tips inner and outer radii is given by

$$D_{inner} = \frac{d}{a} \quad (4.3)$$

$$D_{outer} = \frac{d}{b} \quad (4.4)$$

where

$a = \text{tip inner radius}$

$b = \text{tip outer radius}$

Thus $D_{in} - b_D D_{out}$
An analysis of the plots indicated that in all the cases, the permeability measurements made on the four assemblies with the slices of increasing thickness showed values close to that of the rock permeability. Table 4.7 gives the summary of depth of investigation for the tips with two $b_D$ values and obtained by using slices of Berea rock on top of different sizes of glass beads.

The tip used in these experiments has a dimensionless ratio of outside to inside radii $b_D = 4.5$ and $2.0$.

The depth of investigation for tip with $b_D = 4.5$

Analysis of plots on Fig 4.7 and 4.8 shows that $K_{\text{max}}$ does not change for $D > 3.63$, which is $D_{\text{in}} > 7.26$ or $D_{\text{outer}} > = 1.63$

The depth of investigation for tip with $b_D = 2$

Analysis of plots on Fig 4.9 and 4.10 shows that $K_{\text{max}}$ does not change for $D > 1.75$ which is $D_{\text{in}} > 3.5$ or $D_{\text{outer}} > = 1.75$.

All the 12 plots on Fig 4.7 - 4.10 show that a permeability point on the thickest slice gives a higher value of permeability when measurements are made with a tip having larger outer diameter. The following paragraph describes the reason for this high value of permeability.

In the thickest slice the region of permeability of 0.645 darcy,(the value of permeability picked in other 3 slices also) was very small and it was surrounded by regions of higher permeabilities. The permeability measurements made using the larger outer radius tips
on this slice averaged a higher value of permeability. Because for each permeability measurement, minipermeameter samples the volume of rock directly below the tip and in the surrounding rock. The lateral radius of investigation for these tips is therefore more. Thus when the measurement point is surrounded by the a region of higher permeability average value of permeability is higher. But in the case of tips with smaller outer diameter the lateral radius of investigation is also short. Therefore for the thickest slice when permeability measurement are made using tips with small outer diameter the permeability value is close to 0.645 darcy, The affect of higher permeability region surrounding the selected region of 0.645 darcy permeability is not reflected in these measurements.

Also the weight used on the larger outer diameter tip is about 120 grams less than optimum weight to avoid breaking of slice due to excess weight, that could have contributed to some error in measured value of permeability.

4.4 THE PRACTICAL LIMITS OF MEASUREMENT FOR DIFFERENT TIPS:
The vertical and the horizontal dimension of the "practical limits of measurements for different tip radius ratios b_D are obtained from results of two experiments described in previous sections. The lateral limit and the depth limit of minipermeameter tip measurement are summarized as follows.

i) Tip with b_D = 4.5

Lateral limit R_lateral / b = 1.16

Depth limit D_out = 1.63
ii) Tip with $b_D = 2$

Lateral limit $R_{\text{lateral}} / b = 1.44$

Depth limit $D_{\text{out}} = 1.75$

As described earlier for the case of lateral radii of investigation, similarly it can be presumed also that the dimensionless depths of investigation are function of the dimensionless number $b_D$ (the radius of outer to inner radius of the tip). A two point indication is shown of this functional relationship in Fig 4.5. Practical limits of measurement for tips with $b_D = 4.5$ & 2 are shown in Fig 4.6.

With these measurements of the practical limits of the region in which the sample’s permeability is observed, one could also ask "How closely are we approaching the actual porous structure of the rock?", or more particularly, "How many discrete pores are contained in this region?" This question is discussed more fully in Suboor and Heller (1994): suffice it to say here merely that calculations indicate that for Berea rock, the "practical limits" region under the smallest probe used in this study contains more than one million pores, and that therefore that the merely statistical variation of permeability, from one such region to the next, can be expected to be on the order of one part in one thousand. In the next chapter, the actual magnitude of the variation will be seen to be greater than this. This in turn suggests that the sedimentation process was not strictly random, and that there were real spatial variations in the environmental and geological conditions under which the deposit was laid and modified.
Fig 4.5 Functional Relationship (depth of investigation)

The ratio of the radius of outer to inner radius of the tip

$\frac{b_d}{b} = \frac{b}{a}$
Fig 4.6 Practical limits of measurements for tip ratios $b_B = 4.5, 2$
TABLE 4.3
Permeability of slices of Berea

<table>
<thead>
<tr>
<th>Slice Thickness &quot;d&quot; inch</th>
<th>Permeability of Rock (region of similar Perm.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.095</td>
<td>0.645</td>
</tr>
<tr>
<td>0.11</td>
<td>0.645</td>
</tr>
<tr>
<td>0.126</td>
<td>0.645</td>
</tr>
<tr>
<td>0.22</td>
<td>0.645</td>
</tr>
</tbody>
</table>
TABLE 4.4

Measured permeability values for two layers

(Slice of Berea on top and Glass beads below).

Tips used have $b_D = 4.5$

(dimensionsless ratio of tips outer and inner diameter)

<table>
<thead>
<tr>
<th>Glass beads</th>
<th>105 microns</th>
<th>88 microns</th>
<th>75 microns</th>
<th>63 microns</th>
<th>45 microns</th>
<th>38 microns</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{IN}$</td>
<td>$D_{OUT}$</td>
<td>$D$</td>
<td>$K_b = 14.5$</td>
<td>$K_b = 6.8d$</td>
<td>$K_b = 3.7d$</td>
<td>$K_b = 2.4d$</td>
</tr>
<tr>
<td>2.3</td>
<td>0.51</td>
<td>1.14</td>
<td>1.2907</td>
<td>1.1969</td>
<td>1.2185</td>
<td>1.1189</td>
</tr>
<tr>
<td>2.7</td>
<td>0.59</td>
<td>1.33</td>
<td>1.0910</td>
<td>1.038</td>
<td>1.1305</td>
<td>1.0940</td>
</tr>
<tr>
<td>3.1</td>
<td>0.67</td>
<td>1.52</td>
<td>0.9966</td>
<td>0.8792</td>
<td>1.0047</td>
<td>0.9619</td>
</tr>
<tr>
<td>3.4</td>
<td>0.76</td>
<td>1.7</td>
<td>1.205</td>
<td>0.966</td>
<td>0.9116</td>
<td>0.861</td>
</tr>
<tr>
<td>3.9</td>
<td>0.88</td>
<td>1.96</td>
<td>0.9769</td>
<td>0.883</td>
<td>0.8682</td>
<td>0.7947</td>
</tr>
<tr>
<td>4.5</td>
<td>1.01</td>
<td>2.25</td>
<td>0.8635</td>
<td>0.761</td>
<td>0.7869</td>
<td>0.7003</td>
</tr>
<tr>
<td>5.3</td>
<td>1.17</td>
<td>2.65</td>
<td>0.8865</td>
<td>0.8215</td>
<td>0.9095</td>
<td>0.8555</td>
</tr>
<tr>
<td>7.9</td>
<td>1.76</td>
<td>3.93</td>
<td>0.7300</td>
<td>0.6835</td>
<td>0.7586</td>
<td>0.6465</td>
</tr>
</tbody>
</table>
**TABLE 4.5**

Measured permeability values for two layers

(Slice of Berea on top and Glass beads below).

Tips used have $b_D = 2$

(dimensionless ratio of tips outer and inner diameter)

<table>
<thead>
<tr>
<th>Glass beads</th>
<th>$D_{in}$</th>
<th>$D_{out}$</th>
<th>$D$</th>
<th>$K_b = 14.5d$</th>
<th>$K_b = 6.8d$</th>
<th>$K_b = 3.7d$</th>
<th>$K_b = 2.4d$</th>
<th>$K_b = 1.53$</th>
<th>$K_b = 1.26$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.12 0.51 0.51</td>
<td>1.78</td>
<td>1.382</td>
<td>1.1991</td>
<td>1.1968</td>
<td>1.1763</td>
<td>1.1484</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.16 0.59 0.59</td>
<td>1.589</td>
<td>1.2735</td>
<td>1.1594</td>
<td>1.1042</td>
<td>1.1228</td>
<td>1.0899</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.25 0.67 0.67</td>
<td>1.23</td>
<td>1.1388</td>
<td>1.1226</td>
<td>1.0037</td>
<td>1.0336</td>
<td>0.9861</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.52 0.76 0.76</td>
<td>1.09</td>
<td>0.9597</td>
<td>0.8150</td>
<td>0.8020</td>
<td>0.7465</td>
<td>0.7220</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.76 0.88 0.88</td>
<td>0.9204</td>
<td>0.7976</td>
<td>0.7617</td>
<td>0.7119</td>
<td>0.7147</td>
<td>0.6866</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.02 1.01 1.01</td>
<td>0.833</td>
<td>0.7676</td>
<td>0.7007</td>
<td>0.7093</td>
<td>0.7053</td>
<td>0.6591</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.35 1.17 1.17</td>
<td>1.04</td>
<td>0.9885</td>
<td>0.9519</td>
<td>0.9437</td>
<td>0.9892</td>
<td>0.93773</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.52 1.76 1.76</td>
<td>0.656</td>
<td>0.6562</td>
<td>0.6760</td>
<td>0.6693</td>
<td>0.6019</td>
<td>0.5989</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4.6
The depth of investigation using different glass beads below the slices of Berea Sandstone.

<table>
<thead>
<tr>
<th>Glass Beads Size (microns)</th>
<th>Tips with $b_D = 4.5$ Depth of Investigation obtained from plot</th>
<th>Tips with $b_D = 2$ Depth of Investigation obtained from plots</th>
</tr>
</thead>
<tbody>
<tr>
<td>38</td>
<td>3.4</td>
<td>1.75</td>
</tr>
<tr>
<td>48</td>
<td>3.63</td>
<td>1.79</td>
</tr>
<tr>
<td>63</td>
<td>3.68</td>
<td>1.65</td>
</tr>
<tr>
<td>75</td>
<td>3.68</td>
<td>1.74</td>
</tr>
<tr>
<td>88</td>
<td>3.68</td>
<td>1.75</td>
</tr>
<tr>
<td>105</td>
<td>3.73</td>
<td>1.84</td>
</tr>
</tbody>
</table>
Fig 4.7 Dimensionless Depth of Investigation of Minipermeameter
(for glass beads of 38, 45, and 63 microns using tips 2A & 3A)
Fig 4.8  Dimensionless Depth of Investigation of Minipermeameter
(for glass beads of 75, 88 and 105 microns using tips 2A & 3A)
Fig 4.9 Dimensionless Depth of Investigation of Minipermeameter
(for glass beads of 38, 45 and 63 microns using tips 2D and 3D)
Fig 10 Dimensionless Depth of Investigation of Minipermeameter
(for glass beads of 75, 88 and 105 microns using tips 2D & 3D)
4.5 COMPUTATION OF FLOW GEOMETRY.

The flow geometry for two layers with two different values of permeability near the surface and below it is calculated using a computer program developed by Chen (1992). Computer runs were made for two layers. Layer representing the rock that have a permeability $K_r = 0.645$ Darcy and the lower layer representing the glass beads. The permeability of two different sizes of glass beads are given in the table 4.7.

<table>
<thead>
<tr>
<th>Glass Beads Size (microns)</th>
<th>Permeability (Darcy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>38</td>
<td>1.3</td>
</tr>
<tr>
<td>63</td>
<td>2.4</td>
</tr>
</tbody>
</table>

The tips 2A and 2D with dimensionless ratio of outside to inside diameter $b_D = 4.5$ and $b_D = 2$ were used. As described in the introduction $b_D$ is used to calculate the Goggin Geometric factor which is used in the calculation of permeability.
The calculated geometrical factor $G = 4.76$ for tip 2A, $b_D = 4.5$ was calculated by Chen's program using Simpson rule. Also program calculated geometrical factor for same $b_D$ by using Trapezoidal rule, which is $G = 4.79$

The calculated geometrical factor $G = 5.29$ $b_D = 2$ was calculated by Chens program using Simpson rule. Also program calculated geometrical factor for same $b_D$ by using Trapezoidal rule, which is $G = 5.33$

The pressure distribution obtained with tip 2A with $b_D = 4.5$ and a slice 0.095 inch thick having a permeability of 645 md, and glass beads having permeability 1300 md is presented on grayscale map in Fig 4.11a

Similar pressure distribution for $b_D = 2$ and the same conditions described above are shown in Fig 4.11b
Fig 4.11 Grayscale plot of pressure distribution

computed by Chens program

a) Tip 2A $b_d=4.5$

b) Tip 2D $b_d=2$
CHAPTER 5

INVESTIGATION OF SMALL SCALE HETEROGENEITY

The measurements reported in this chapter have all been on samples of Berea sandstone. Even though Berea is markedly different from many oil and gas reservoir rocks, this quarried, porous rock has been used in many laboratories for various flow displacement studies and has acquired in the minds of many the ‘standard porous medium’. Despite the difference between Berea and many other sandstones and all carbonate rocks, it is not felt that the choice of this material for the tests reported here places any limitations on the validity of the experiments. In fact these Berea samples show heterogeneity, it would seem likely that most reservoir rocks are even more heterogeneous, and that spatial non-uniformity of permeability is widespread in nature.

Most samples of Berea sandstone although consisting predominately of silicon dioxide granules, are rich in clays. The silica grains are moderately well-sorted, with mean diameters of about 150 microns. The cementation is mostly crystal overgrowth, providing pore spaces with average diameter of about 30 microns. Porosities run from 25 to 29 %, and permeabilities from 50 md to 800 md. As has been noted, the surfaces of samples used in these experiments are as left by the water-lubricated, diamond saw cuts made in the core preparation laboratory at PRRC.
5.1 SMALL SCALE PERMEABILITY HETEROGENEITY

With the background provided by the previous section it is possible to deal more completely the other objective of this study to investigate small scale heterogeneity of apparently uniform rock. As the size of the sample of porous media increases, most of the heterogeneity details which might appear at a smaller sample size are usually overlooked.

Permeability measurements obtained by minipermeameter at smaller measurement spacing gives more information on permeability heterogeneity. Our previous results gave confidence to the assertion that these small variations are real, and many times the measurement errors. The earlier also make it possible to envisage the shapes and the sizes of the regions of the sample investigated.

The heterogeneity of the reservoir is one of the most important characteristics that influences oil recovery. The description and quantification of the spatial distribution of permeability in a hydrocarbon reservoir is the most challenging problem in success of enhanced oil recovery projects.

The knowledge of small scale permeability heterogeneity can be used with geostatistical techniques to predict permeability spatial distribution. Measurements made by PRRC Automatic Scanning Minipermeameter give the same measured value of permeability when measurements are repeated on the same points of rock sample, within standard deviation of the order of 0.5 %.
The measurements obtained by minipermeameter at different locations on the same rock can reflect variation far above this value, as a result of variation in the measurement interval and to some extent in the size of tip in use.

5.2 INFLUENCE OF MEASUREMENT SPACING ON MEASURED VALUE OF PERMEABILITY

Closely spaced measurements with small tip size give extensive permeability information. These detailed and accurate permeability measurements will provide a better small scale characterization of reservoir.

On a Berea sandstone sample core more than 3000 permeability measurements were made by minipermeameter in a square of 0.5 x 0.5 inch. Two sets of permeability measurements were made on the surface of this sample. The first set of value were made with a measurement spacing of 0.01 inch so that a total of 2601 permeability values were recorded. The second set of measurements were obtained without disturbing the position of the sample on the minipermeameter table with a spacing of 0.025 inch so that a total of only 441 measurements made over the same area. The tip 2A with OD 0.25 inch and ID 0.056 inch was used to take both sets of measurements, optimum weight was used on tip to provide a good seal between sample rock and tip. The table 5.1 summaries the measured permeability details for the obtained data where M is defined as the mean value given by following equation.
\[ M = \frac{\sum m_i}{n} \quad (5.1) \]

and the error \( \Delta M \) is defined as the difference between the total mean \( M \) and the partial mean \( m_i \)

\[ \Delta M = \frac{|M - m_i|}{m} \cdot 100 \quad (5.2) \]

Permeability measurements of Berea core with different measurement spacing.

Table 5.1

<table>
<thead>
<tr>
<th>No. of data Points</th>
<th>Spacing inch.</th>
<th>Mean &quot;m&quot; K (Darcy)</th>
<th>&quot;( \Delta M )&quot; %</th>
<th>Minimum K (Darcy)</th>
<th>Maximum (Darcy)</th>
<th>Variance ( \sigma^2 ) (darcy$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2601</td>
<td>0.01</td>
<td>0.485</td>
<td>1.13</td>
<td>0.18</td>
<td>0.86</td>
<td>0.0107</td>
</tr>
<tr>
<td>441</td>
<td>0.025</td>
<td>0.474</td>
<td>1.16</td>
<td>0.19</td>
<td>0.73</td>
<td>0.0109</td>
</tr>
</tbody>
</table>
As would be expected the mean and variance of the measured permeability shows good agreement for both dense and coarse spacing.

The variograms of the two sets of data are shown in Fig 5.2. The two variograms are similar, with almost the same correlation length of 0.075 inch on this scale of .5 inch. It is apparent that with measurement points spaced as described, only a small fraction of the points in either measurements set were at the same locations as any other set. Thus one would expect appreciable statistical variation between the variograms. Grayscale maps of permeability data obtained with 0.01 inch measurement spacing and 0.025 inch measurement spacing are shown in Fig 5.3 and Fig 5.4 respectively. Although the spacing used in both maps is quite different, the main features such as the low permeability region in the left top corner is present in both maps.

The histograms of two permeability data sets are shown in Fig 5.5 and as expected they are almost the same. The dense spacing provided almost 6 times as many permeability values as the coarse spacing. It is interesting to notice that the univariate statistics (mean, variance, histogram) as well as spatial correlation (variogram) can be well obtained with a coarse spacing. Furthermore the permeability data obtained at dense spacing of 0.01 inch was averaged to a coarse spacing of .025 and .05 inch, grid. All the permeability data points in a square of 0.025 inch which were obtained at a dense spacing of .01" were averaged to get a single permeability point, thus 2601 data points were reduced to 441 points taking averages in a square of .025". The arithmetic, geometric and harmonic mean were used for averaging. Similarly these 2601 data points were reduced 100 points in the spacing of 0.05".
Table 5.2 gives the computed values of permeability.

<table>
<thead>
<tr>
<th>No. of reduced data points by avg.</th>
<th>Spacing (inch)</th>
<th>Arithmetic mean (Darcy)</th>
<th>Geometric mean (Darcy)</th>
<th>Harmonic mean (Darcy)</th>
<th>Variance $\sigma^2$ (Darcy$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>441</td>
<td>0.025</td>
<td>0.4771</td>
<td>0.4753</td>
<td>0.4753</td>
<td>$8.3 \times 10^{-3}$</td>
</tr>
<tr>
<td>100</td>
<td>0.05</td>
<td>0.498</td>
<td>0.4881</td>
<td>0.4854</td>
<td>$6.5 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Permeability values at the coarse spacings of .025 and 0.05 inch are computed from the experimentally obtained permeability values at dense scale of .01 inch.

The variogram for the computed values of permeability at coarse scale (Fig 5.2) showed that the correlation length (0.075") remains the same as in the actual permeability measurements. The variance in the coarse spacing of .025 inch is reduced from 0.0082 to 0.0065 in further coarse spacing of 0.05 inch. The decrease in the variability is expected with the increase in the scale. At coarse scale, we are sampling less data points and the number of values is limited which gives less variance. On a dense scale the number of data points is larger and the variance also is increased.
Fig 5.1  Variograms of permeability measurements for experimental values of dense and coarse spacing (0.01 and 0.025 inch)
Fig 5.2 Variogram of computed permeability values at coarse measurement spacing of 0.025 and 0.05 inch obtained from experimental permeability values of dense spacing.
Fig 5.3 Grayscale plot of Permeability in darcy for Berea core with dense measurements spacing of 0.01 inch.
Fig 5.4 Grayscale plot of permeability in darcy for Berea core with coarse measurement spacing of 0.025 inch.
a. Histogram of Berea core with dense measurement spacing of 0.01 inch

b. Histogram of Berea core with coarse measurement spacing of 0.025 inch

Fig 5.5 Histogram of measured permeability values
a dense and coarse spacing
5.3 INVESTIGATION OF VERTICAL HETEROGENEITY OF PERMEABILITY:

The permeability near the surface of the core represent only a fraction of core below the measured surface. The variation in permeability observed on a cross section would almost certainly not remain the same along the entire depth of the core. As a result there would be a change in the pattern of heterogeneity. To investigate permeability heterogeneity across the depth of the core below the measured surface an experiment has been conducted on a core of Berea sandstone. Permeability measurements were made at 441 evenly spaced locations on a sample rock in a grid of 0.5 x 0.5 inch. (ie with spacing in both X and Y direction of 0.025 inch)

After taking the measurements, a layer of core 0.13 inch thick was cut using a circular diamond saw, expecting a new surface. The thickness of the saw is about 0.068 inch. Each set of 441 permeability measurement were made at a vertical distance of 0.2 inch below the previously measured surface of rock. A total of 12 equal thickness layers were cut and permeability measurements were made at the same scale on each layer before it was cut. The sample rock was placed in the same orientation on the minipermeameter table for each measurement. After cutting each layer the core was dried in oven at a temperature of 68° C for 24 hrs before taking the next set of measurements.
The arithmetic mean \( m_i \) of the 441 values of permeability is defined for each layer, and the total mean \( M \) for all the layers is simply the mean of the twelve \( m_i \). Similarly the variance of all values of the 12 layers is defined as \( \Sigma^2 \)

For each layer \( \Delta M_i \) is defined as

\[
\Delta M = \frac{|M - m_i|}{M} (100) \quad (5.3)
\]

\( \Delta M_i \) represent the difference between the mean \( m_i \) of each layer and the mean \( M \) of all the layers.

The percentage error for variance \( \Delta \sigma^2 \) is calculated in the same way.

\[
\Delta \sigma_i^2 = \frac{\left| \Sigma \sigma_i^2 - \sigma_i^2 \right|}{\Sigma \sigma_i^2} (100) \quad (5.4)
\]

In this series of experiments a total of 5292 permeability measurements were made.

The permeability value of these measurements have a mean \( M = 0.79 \) Darcy and a Variance \( \Sigma^2 = 0.023 \) Darcy\(^2 \).

Analysis of the permeability data obtained from each layer indicated that the mean differed little from one layer to another (Table 5.3). There was also no trend of permeability with vertical depth at this scale.
The mean of each layer \( m_i \) is close to the total mean \( M \) of all layers. The mean \( m_i \) for the first layer is very low in comparison to other layers. Possibly the first layer surface might have been filled with crushed sand particles while initially cutting this core from a block of Berea sandstone in our core preparation. Fig 5.6 gives mean minimum and maximum for all layers. The variance for layer 6 is the highest \( \sigma^2_6 = 0.0189 \). Based on the mean value, a small sample (one layer) is representative of the whole core. However the limiting variances for each layer vary significantly. Considerable changes occur from one layer to another as shown in Table 5.3. This change in variance affect the spatial distribution for each layer which has a different sill from one layer to another (Figs 5.7 - 5.8) which leads to different variograms. However the correlation length remains almost the same for all the layers (about 0.1 inch). This is expected since all the data collected represent the same scale. After the correlation length of 0.1 inch no correlation is observed and there is no specific trend at this scale of 0.5 inch. However layers 4 and 12 show a slight hole effect in the variogram (Figs 5.7 - 5.8) but no apparent periodic trend appears on the grayscale maps (Figs 5.9 - 5.14). Histograms of all the layers look similar with a slight difference in the minimum and maximum values (Figs 5.15 - 5.16).

The particularly low permeabilities in the first of the layers may well be correlated with the fact that the surface on which these readings were taken had been cut at quarries, and was the surface of one of the blocks that had been shipped to the PRRC. Thus the low values may be an indication of surface damage due to extra accumulation of fine particles at and just below this surface.
### TABLE 5.3

Permeability data of Berea layers

<table>
<thead>
<tr>
<th>LAYER i</th>
<th>Mean $m_i$ K (Darcy)</th>
<th>$\Delta M$</th>
<th>Variance $\sigma^2_i$</th>
<th>$\Delta \sigma^2_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.65</td>
<td>18.24</td>
<td>0.0129</td>
<td>44.64</td>
</tr>
<tr>
<td>2</td>
<td>0.9</td>
<td>13.21</td>
<td>0.0181</td>
<td>22.32</td>
</tr>
<tr>
<td>3</td>
<td>0.76</td>
<td>4.4</td>
<td>0.0169</td>
<td>27.47</td>
</tr>
<tr>
<td>4</td>
<td>0.79</td>
<td>0.63</td>
<td>0.0239</td>
<td>2.58</td>
</tr>
<tr>
<td>5</td>
<td>0.81</td>
<td>1.8</td>
<td>0.017</td>
<td>27.04</td>
</tr>
<tr>
<td>6</td>
<td>0.82</td>
<td>3.1</td>
<td>0.0189</td>
<td>18.88</td>
</tr>
<tr>
<td>7</td>
<td>0.78</td>
<td>1.9</td>
<td>0.0168</td>
<td>27.9</td>
</tr>
<tr>
<td>8</td>
<td>0.76</td>
<td>4.4</td>
<td>0.064</td>
<td>29.61</td>
</tr>
<tr>
<td>9</td>
<td>0.73</td>
<td>8.2</td>
<td>0.0149</td>
<td>36.05</td>
</tr>
<tr>
<td>10</td>
<td>0.95</td>
<td>19.5</td>
<td>0.025</td>
<td>11.16</td>
</tr>
</tbody>
</table>
Fig 5.6 Permeability data of Berea layers.
Fig 5.7 Variogram for layer 1 to 6
Fig 5.8 Variogram for layer 6 to 12
a. 1st Berea Layer.

b. 2nd Berea Layer.

Fig 5.9 Grayscale plot for Permeability of 1st and 2nd Layer
a. 3rd Berea Layer

b. 4th Berea Layer.

Fig 5.10 Gray scale plot for Permeability of 3rd and 4th layers
b. 6th Berea Layer

Fig 5.11 Gray scale plot for Permeability of 5th and 6th layers
Fig 5.12 Gray scale plot for Permeability of 7th and 8th layers
a. 9th Berea Layer

b. 10th Berea Layer

Fig 5.13 Gray scale plot for Permeability of 9th and 10th layers
b. 12th Berea Layer

Fig 5.14 Gray scale plot for Permeability of 11th and 12th layers
Fig 5.15 Histogram for Berea Layers 1 - 7 cut from a core to investigate vertical heterogeneity of permeability
Fig 5.16 Histogram for Berea Layers 7 - 12 cut from a core to investigate vertical heterogeneity of permeability
A constant concern in this thesis is to find the optimum number of measurements representative of the statistics. For each layer 441 permeability values were measured.

The question is how many values will lead to almost the same statistics. To answer this question, for each layer, N values were selected randomly out of 441 available permeability values. For each set of N values, the mean, and the resulting variance were computed. The number of values N was N = 330, 220, 110 and 55. For each set of data the error between the reduced mean and variance was compared to the statistics obtained with 441 permeability values (Tables 5.4 -5.7). It appears again that a good estimation of the mean can be found with 4 times less data. However, a small reduction in the number of data can induce 8 % error in the variance. As a result we see that the minipermeameter can be a useful measurement tool when accurate statistics are desired.
### TABLE 5.4

The effect for statistics after reducing the number of data points in the 1st layer

**1st LAYER** (total permeability points 441)

<table>
<thead>
<tr>
<th>Points Picked</th>
<th>Mean $m_i$ (Darcy)</th>
<th>$\Delta M$ (error of mean)</th>
<th>Variance $\sigma^2$ (error of $\sigma^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>330</td>
<td>0.67</td>
<td>3 %</td>
<td>$1.2 \times 10^{-2}$</td>
</tr>
<tr>
<td>220</td>
<td>0.65</td>
<td>0 %</td>
<td>$1.4 \times 10^{-2}$</td>
</tr>
<tr>
<td>110</td>
<td>0.63</td>
<td>3 %</td>
<td>$1.2 \times 10^{-2}$</td>
</tr>
<tr>
<td>55</td>
<td>0.61</td>
<td>6 %</td>
<td>$9.7 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

### TABLE 5.5

The effect for statistics after reducing the number of data points in the 3rd layer

**3rd LAYER** (total permeability points 441)

<table>
<thead>
<tr>
<th>Points Picked</th>
<th>Mean $m_i$ (Darcy)</th>
<th>$\Delta M$ (error in mean)</th>
<th>Variance $\sigma^2$ (error in $\sigma^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>330</td>
<td>0.786</td>
<td>1.1 %</td>
<td>$1.6 \times 10^{-2}$</td>
</tr>
<tr>
<td>220</td>
<td>0.756</td>
<td>0.5 %</td>
<td>$1.5 \times 10^{-2}$</td>
</tr>
<tr>
<td>110</td>
<td>0.792</td>
<td>4.2 %</td>
<td>$1.68 \times 10^{-2}$</td>
</tr>
<tr>
<td>55</td>
<td>0.772</td>
<td>1.6 %</td>
<td>$8.1 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
TABLE 5.6

The effect for statistics after reducing the number of data points in the 9th layer

9th LAYER (total permeability points 441)

<table>
<thead>
<tr>
<th>Points Picked</th>
<th>Mean $m_{i}$ (Darcy)</th>
<th>$\Delta M$ (error of mean)</th>
<th>Variance $\sigma^2$</th>
<th>$\Delta \sigma^2$ (error of $\sigma^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>330</td>
<td>0.75</td>
<td>2.7 %</td>
<td>$1.5 \times 10^{-2}$</td>
<td>2 %</td>
</tr>
<tr>
<td>220</td>
<td>0.74</td>
<td>0 %</td>
<td>$1.3 \times 10^{-2}$</td>
<td>12.7 %</td>
</tr>
<tr>
<td>110</td>
<td>0.73</td>
<td>3.9 %</td>
<td>$1.68 \times 10^{-2}$</td>
<td>12.8 %</td>
</tr>
<tr>
<td>55</td>
<td>0.74</td>
<td>1.5 %</td>
<td>$9.7 \times 10^{-2}$</td>
<td>12.8 %</td>
</tr>
</tbody>
</table>

TABLE 5.7

The effect for statistics after reducing the number of data points in the 12th layer

12th LAYER (total permeability points 441)

<table>
<thead>
<tr>
<th>Points Picked</th>
<th>Mean $m_{i}$ (Darcy)</th>
<th>$\Delta M$ (error in mean)</th>
<th>Variance $\sigma^2$</th>
<th>$\Delta \sigma^2$ (error in $\sigma^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>330</td>
<td>0.82</td>
<td>0 %</td>
<td>$1.6 \times 10^{-2}$</td>
<td>9.2 %</td>
</tr>
<tr>
<td>220</td>
<td>0.81</td>
<td>1.2 %</td>
<td>$1.5 \times 10^{-2}$</td>
<td>18.5%</td>
</tr>
<tr>
<td>110</td>
<td>0.80</td>
<td>2.4 %</td>
<td>$2 \times 10^{-2}$</td>
<td>29.3 %</td>
</tr>
<tr>
<td>55</td>
<td>0.81</td>
<td>1.2 %</td>
<td>$9.7 \times 10^{-2}$</td>
<td>1.1 %</td>
</tr>
</tbody>
</table>
CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS.

This study is mainly concerned with the examination of small scale heterogeneity of an apparently uniform rock sample by measuring permeability and using an automatic minipermeameter.

The operating characteristics of PRRC automatic scanning minipermeameter have also been explored.

6.1 CONCLUSIONS

The conclusions and observations drawn out of this study are presented below.

1. The minipermeameter is a very useful device in the study of rock heterogeneity and spatial distribution of permeability.

2. A procedure has been developed to correctly simulate the radius of investigation and depth of investigation of minipermeameter.

3. The radius of investigation laterally from tip, and depth of investigation depends on tip ratio $b_D$. (The ratio of tip outer radius to inner radius $b/a$).
i) The lateral radius of investigation laterally from tip were measured to be:
   for tips with $b_D$ (tip radius ratio $b/a) = 4.5$ is $1.16 \times b_{(tip \ outer\ radius)}$
   for tips with $b_D$ (tip radius ratio $b/a) = 2.0$ is $1.44 \times b_{(tip \ outer\ radius)}$

ii). The depths of investigation were measured as:
   for tips with $b_D$ (tip radius ratio $b/a) = 4.5$ is $1.63 \times b_{(tip \ outer\ radius)}$
   for tips with $b_D$ (tip radius ratio $b/a) = 2.0$ is $1.75 \times b_{(tip \ outer\ radius)}$

4. The permeability measurements obtained by minipermeameter readings at smaller measurement spacing gives more information on permeability heterogeneity, as compared to measurements obtained from larger measurement spacing.

5. The variance of permeability measurement increases by 0.5% when the density of measurement increases by a factor of 2.5. The spatial correlation expressed in variograms remains almost the same.

6. There was no apparent trend of vertical heterogeneity in the permeability measured in 12 layers of a vertical core 4" long. However, significant changes can be found in the spatial statistics of each layer. The changes in variance do not affect the correlation length. For the 12 layers the correlation length was about 0.1 inch.
6.2 RECOMMENDATIONS.

The tip size to be used for permeability measurements should have \( b_D \geq 2 \) as observed during experiments on flow geometry and calculated by Chen (1992) the value of Geometric factor "G" increases sharply for \( b_D < 2 \) and becomes almost asymptotic for \( b_D < 1.2 \).

If the \( b_D \) is less than 1.2 calculated value of permeability will be extremely dependent on the exact value of this ratio, which can not be precisely measured.

Because, the "O" rings values are generally low and unpredictable they should not be used as the tip seal in minipermeameter.

Two other recommendations, given in retrospect, concerns sample preparations. The surface on which the minipermeameter reading is made should be cut by a fine-tooth diamond saw that does not pluck large groups of grains from the surface. Such pits would make it difficult to obtain a good seal with the tip weights that were satisfactory for the experiments reported here.

Second it is recommended that a good surface cleaning be performed to avoid excessive accumulation of fines in the near-surface pores after cutting and oven drying. To remove the cutting fines, it would be wise to brush the surface with a moderately soft, fine-bristle brush, or even to use a vacuum cleaner on the surface.

While these requirements can be met more easily in laboratory minipermeameter use as has been described here, it is noted that many minipermeameter measurements are made
with portable instrument in the field. In such case, it is often not possible to find a suitably flat surface on which to press the probe, and it would be very worthwhile to investigate separately the optimum tip design and surface preparation measures that can be taken, in order to optimize measurement precision and accuracy.
NOMENCLATURE

\( A \) = Cross-sectional area.
\( a \) = Inner radius of tip.
\( b \) = Outer radius of tip.
\( b_D \) = Tip radius ratio \( b/a \) (outer radius to inner radius)
\( c \) = Constant of proportionality.
\( C_{lk} \) = Conductivity of the leak.
\( D \) = Dimensionless number (ratio of thickness of rock slice to internal diameter of tip)
\( d \) = Thickness of rock slice.
\( G \) = Goggin geometric factor.
\( g \) = Gravity
\( \Delta h_w \) = Vertical head of water above the outlet pipe.
\( K \) = Permeability in darcies.
\( K_b \) = Glass beads permeability.
\( K_m \) = Measured value of permeability (Slice and glass beads)
\( K_r \) = Rock permeability.
\( L \) = Length of core or vertical head of water above the outlet pipe.
\( P_a \) = Atmospheric pressure.
\( P_b \) = Base pressure.
\( P_g \) = Gauge pressure.
\( P_L \) = Pressure at outlet.
\( P_0 \) = The pressure at in let.

\( P_s \) = Absolute value of pressure.

\( \Delta P \) = Pressure drop cm H\(_2\)O

\( Q \) = Gas flow rate in cm\(^2\)/sec

\( T \) = Time interval for syringe plunger to sink from \( X_1 \) to \( X_2 \).

\( \Delta t \) = Time in second (for 25 cc of air to pass through pack of glass beads)

\( t_{\text{tik}} \) = Time interval in which the syringe plunger will move down wards by the distance \( \Delta X \) in absence of flow into the rock.

\( M \) = Total mass on the syringe plunger.

\( r_{\text{syringe}} \) = The radius of syringe plunger.

\( \Delta X \) = Distance the plunger moved from \( X_1 \) to \( X_2 \).

\( \Gamma \) = Correction factor

\( \rho \) = Density.

\( \mu \) = Viscosity.
REFERENCES


This thesis is accepted on behalf of the faculty of the Institute by the following committee:

[Signatures]

March 30, 1994
Date

I release this document to New Mexico Institute of Mining and Technology.

[Signature]

March 30, 1994
Students Signature
Date