POROPERM EVALUATION IN RELATION TO APPLIED STRESS STATES FOR A GAS RESERVOIR

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Abstract The results of a study conducted on sandstone samples from a North Sea gas reservoir, indicate that the response of a core plug subjected to a laboratory stress, can be influenced not only by the stress state imposed on the sample but also by its rock type.

Changes in equivalent liquid permeability with increasing stress can be seen to be influenced by rock type and to a limited extent by the stress state. Changes in Helium porosity due to a stress increase is observed to be strongly influenced by the stress state imposed and is quite independent of the rock type. The majority of the permeability and porosity reduction is shown to occur during the initial 1500 psi of stress application.

The permeability data from several producing wells were used to calculate psuedo-stress permeability averages, and these are in better agreement with calculated drill stem test permeabilities than those derived from conventional core analysis data.

The study suggests that caution should be employed when core analysis data generated under different stress conditions, particularly at low values of stress, are compared. Consideration of the permeability/stress response of the rock types encountered in a reservoir should be used in the compilation of core analysis studies.

INTRODUCTION

Porosity and permeability data derived from conventional core analysis can be a valuable source of information during field appraisal and development leading to production from hydrocarbon resevoirs. Such measurements on core samples may not be indicative of features controlling fluid flow and hydrocarbon storage on a macroscopic scale in the way that drill stem test (D.S.T.) permeabilities are, but rather, are related to microscopic properties. Thus core analysis provides an independent factor during the evaluation of hydrocarbon reservoirs and is useful when combined with other evaluation techniques, such as wireline logs.

For core analysis to be successful, the data generated should be an accurate and representative measure of the property being evaluated. Measurements of porosity and permeability are often performed under conditions which are not representative of the insitu reservoir. This has prompted much work over the past 35 years and has led to the examination of the behaviour of porous rocks when subjected to a laboratory load. The main findings from this previous work can be summarised as follows:

1. Both porosity and permeability are subject to initially rapid reductions, followed by a slower asymptotic decrease with increasing stress.
2. The majority of porosity and permeability reduction takes place during the first 3000 psi of stress application.
3. Permeability undergoes a greater range of reduction than porosity. Permeability reduction can vary from 10% of the initial value to nearly 100%. Porosity reduction, in competent consolidated rocks, is rarely in excess of 20% of the initial value.
4. Low permeability and porosity rocks generally exhibit a greater percentage reduction than those with higher permeability and porosities.
5. Many sedimentary rocks exhibit a degree of porosity and permeability hysteresis with stress cycling.

6. Permeability and porosity change is controlled by an effective stress law, which may be unique to each particular case.

The state of stress in crustal rocks is poorly understood and difficult to accurately measure. As the character of reservoir rocks and insitu reservoir conditions vary around the world it would be naive to expect the rocks of every formation to respond to the effects of stress in a similar manner. Indeed work has shown that for both consolidated and unconsolidated sands both compositional and textural characteristics can influence the sample's response to stress (Hossain, 1990).

There are no standard confining conditions used for conventional core analysis and data generated at various conditions is often used interchangeably with the assumption that differences in effects due to stress application are negligible.

This study investigates the influence of applied laboratory stress conditions on porosity and permeability measurements of reservoir core samples. Equipment has been designed to allow a variety of stress states to be applied to core plugs while monitoring porosity and permeability changes due to increasing stress.

Lithic and sublithic arenite, reservoir sandstones from permian Rotliegendes aeolian, fluvial and lake margin depositional environments have been tested.

This paper presents preliminary results based on the two most commonly encountered stress-states in core analysis. Samples were subject to an increasing stress cycle from 500 psi to 4000 psi (reservoir pressure), with porosity and permeability being determined at specific stress levels. The implications of the findings to core analysis measurements are also discussed.

STRESS STATES IN LABORATORY TESTING

The state of stress acting at a subsurface point is assumed to be caused by a complex combination of gravitational forces, those acting on pore spaces from interstitial fluids, and other induced forces of a mechanical or chemical origin. Changes in these forces at any time will result in changes to the stress state.

Actual stress states are poorly understood due both to their complexity and to the fact that a satisfactory technique to measure stress in crustal rocks does not at present exist.

The simplest case to consider is the stress due to the action of gravity acting on a column of overburden of unit area. If the density, D, is considered to be variable, then stress due to gravity (Sg) is equal to the weight of the column.

$$Sg = \int_0^Z D.G.\ dZ \quad ......(1)$$

A common assumption in rock mechanics is that stresses are the same in all directions and are due to the effect of gravity alone. This state of stress is termed the lithostatic stress state and the assumption that this case prevails is termed Heims rule. Jaeger and Cook (1979,Chpt.14) state that since stress in sediments is lithostatic throughout their formation, then the final stress state should also be lithostatic.

By convention the stress acting at a point is often considered in terms of three mutually perpendicular principal stress directions (Figure 1).

The vertical stress is taken to be S_z and the horizontal or lateral stresses to be S_x and S_y.

The horizontal stress due to the action of gravity on an column of overburden ($S_z = S_g$) can be calculated from stress-strain relations by the following expression where V is Poissons ratio.

$$Sx = Sy = \frac{V}{1-V}\ Sz \quad ......(2)$$

$$\text{or} \quad Sx = Sy = KS_z \quad ......(3)$$

The derivation assumes no horizontal displacement takes place. Poissons ratio for sedimentary rocks is typically taken to be 0.2 or 0.25; resulting in values of K of 0.25 and 0.33.

Elastic theory gives no indication as to what actual horizontal stresses should be. Jaeger and Cook (1979 Chpt.11) show that for a viscoelastic material of Maxwell or Brughers type, when there is no lateral movement, stresses do tend to lithostatic.

The simple cases discussed above are only concerned with a flat lying surface at rest. This is rarely the case as topography, tectonic and thermal forces complicate the structure. Measurements indicate that horizontal stresses are often of the same order as the vertical stresses and are frequently higher. This is a strong indication that even if virgin stresses were lithostatic (as given in Equation (1)), they do not remain so over geologic time. Stress measurements in hydrocarbon reservoirs are becoming more common, but are not generally available when conventional core analyses are undertaken. The application of an appropriate stress state in the laboratory is therefore difficult to define. Several stress states are commonly used in laboratory testing based on the simplistic assumptions in Equations (1) and (2).

The hydrostatic stress state satisfies the conditions for lithostatic stresses, i.e. stresses are equal in all directions and this is commonly used in core analysis. However, the most common core analysis stress state is the biaxial condition where stresses are applied equally in two directions only by confining the sample in a rubber sleeve, the stress in the remaining direction is zero. This could be considered to represent the stress at the well bore where stress relaxation in a lateral direction exists, but it is used more because of its ease of use and the simplified design requirements than for its technical merit.

The triaxial stress state satisfies Equation (2) and is more commonly used in rock mechanics to establish strength criteria for rocks. It is considered by many to be a more representative stress state, but the problem of which value of K to use still exists.

The uniaxial stress state is the simplest to consider, but its application is generally limited to uniaxial compressive strength tests. A modified form can be used, where lateral strain is restricted and is used to model changes brought about by the production of hydrocarbons.

The core holder designed for this study can apply four stress states, which are illustrated in Figure 2. Stresses are applied by two means, force transmitted to a piston in contact with the flat ends of the sample generates the axial stress, while stresses applied to the curved surface by a rubber sleeve are termed radial stress. By necessity the two principal stresses in the radial direction must be equal.

LITHOLOGY

Petrographic analysis of the reservoir sandstones used in this study reveal the bulk to be lithic arenites and the remainder to be sublithic arenites. The sandstone classification chart modified from Dott by Pettijohn et al is shown in Figure 3. The following facies breakdown has been used.

1.aeolian dune
2.fluvial channel
3.lake margin

These have been further divided into a number of facies types which are described in Table 1.

Although facies type refers to a depositional environment, it has been used in this study as being synonymous with rock type and examination of samples in hand specimen tends to support this approach.

SAMPLE PREPARATION

All of the samples used in this study were cut from preserved whole core. Samples were drilled using synthetic formation brine (SFB) as the coolant/ lubricant to produce 3.8 cm diameter right circular cylinders. A trimsaw core holder ensured that parallel ends were cut, by gently confining the sample during trimming. It also permitted SFB to flow through the core, removing fines at the cut face during trimming. The length to diameter ratio of the samples was maintained as near to two as was possible, though the nature of the rocks tended to make this difficult. Jaeger and Cook (1979,pp.144) recommend a length to diameter ratio, between 2 and 2.5 to minimise non-uniform stress distribution through the sample.

The samples were cleaned using a mild miscible solvent flushing technique. SFB was flowed through the sample followed by a mixture of methanol and SFB (50/50). Methanol alone was then flushed through the core to remove all traces of SFB, completion of this was confirmed by a negative result for the silver chloride test for soluble chloride. The temperature of the flushing fluids was maintained at 35°C.

The cleaned samples were dried in a relative humidity oven at conditions of 60°C and 40% relative humidity in order to minimise possible damage to any clay structures. (Bush and Jenkins, 1970, McPhee, Pers comm). Prior to testing, samples were removed from the oven and allowed to cool to room temperature in a desiccator.

EXPERIMENTAL PROCEDURE

The following describes the experimental procedure.

1.When the sample had cooled to room temperature, it was weighed and dimensioned using digital calipers.

2.Ambient condition porosity was determined using Boyles law grain volume and a bulk volume calculated from the calipered dimensions. For grain volume measurement, the sample was held in a grain matrix cup and was thus unconfined.

3.(i)The sample was then mounted in the core holder and confined biaxially at 500 psi, to provide porosity and permeability values under conditions comparable with conventional core analysis measurements.

(ii)Gas permeability was then measured over a range of mean flowing pressures to enable Klinkenberg equivalent liquid permeability to be calculated (Klinkenberg, 1941).

(iii)Porosity was calculated using values of Boyles Law pore volume and Boyles Law grain volume measured previously.

4.If a stress-state other than biaxial was to be examined, the confining conditions would be altered maintaining a 500 psi maximum principal stress. Then permeability and porosity were redetermined.

5.Measurements were repeated at 1000 psi, 1500 psi, 2000 psi, 3000 psi and 4000 psi.

6.The samples were returned to the relative humidity oven for storage after testing.

The samples were allowed to remain at each confining pressure for 30 minutes to allow instantaneous and short term deformation to settle. Experiments on rocks including sandstones indicates that time dependant deformation is small compared to the instantaneous response.

Klinkenberg permeability was calculated to allow comparisons of results as it would have been impractical to measure gas permeability at the same mean pressure for each sample. Darcy's Law is only valid for conditions of laminar flow and inclusion of gas permeability data measured under non-laminar conditions can introduce a significant error into the extrapolated Klinkenberg permeability. Numerical or graphical techniques, described by Dranchuck and Kolada (1967,1968) should be used to calculate Klinkenberg permeability. These techniques allow non laminar data to be excluded from the analysis, (using the graphical technique) or use of a modified Forchheimer equation which accounts for slip, (using the numerical technique). In this study a commercial software package which provides the numerical analysis was used to check for significant non laminar contribution to flow. Porosity was calculated using bulk volumes calculated from pore volume and grain volumes as this has been shown to be more accurate than using those calculated from calipered dimensions.

(Unalmiser & Stewart, 1989). This does assume however that grain compressibility is negligibly small as the unconfined grain volume is used throughout.

EQUIPMENT

Permeameter

A modified commercial steady state nitrogen permeameter was used.
Upstream pressure was controlled by a pressure regulating valve, and measured using a pressure transducer with a digital display. Two differential pressure transducers, 0-100 psid,0-5 psid also digitally displayed, measure the pressure drop across the core, Where possible the latter is used as it is more accurate. Flow rate is sensed as a pressure drop across one of three calibrated flow tubes by a differential pressure transmitter, and displayed as a percentage of the maximum flow. The flow tubes have the following ranges, 0-25 cc/sec, 0-200 cc/sec and 0-2000 cc/sec. Temperature can be measured using thermocouples sited upstream and downstream of a micrometer valve which can be brought into line before the flow tubes to exert a back pressure. This can offer greater flexibility over flow rate and pressure control, particularly for high permeability samples. Data is recorded and processed by a computer.

Porosimeter

A Boyles Law helium porosimeter was converted from a commercially available model to permit not only grain volume determinations in an unconfined sample cup, but also pore volume measurements on samples confined in a suitably calibrated core holder. Gas pressure is sensed by a pressure transducer and displayed as a digital output. A sensitive pressure regulator allows reference pressures to be set with precision and a variety of reference volumes allow a wide range of sample types to be accommodated. A storage tank allows the helium to come to temperature equilibrium while the temperature inside the porosimeter is set using a sensitive controller. Gas expansion through the system is controlled by solenoid valves allowing fully automated measurements. The porosimeter doubles as an unsteady state permeameter.

Core Holder

The triaxial core holder shown in Figure 4 was specifically designed for the study to enable rapid sample mounting and removal. This is achieved by a novel end piece design which enables a typical sample mounting in seconds as no end piece or threaded joints have to be dismantled. Axial stress can be provided by either a hand pump or a computer controlled constant pressure pump acting on a piston in one end. Radial stress is provided by the same means acting on a 3mm thick nitrile rubber sleeve. By various combinations of these stresses, uniaxial, biaxial, hydrostatic and triaxial stress states can be simulated.

Fluid flow through the core holder is in the axial direction, via small diameter channels drilled through the end pieces.

The equipment is shown schematically in Figure 5.

RESULTS

The effect of increasing stress on porosity and permeability is shown in Tables 2 and 4, for a maximum principal stress of 4000 psi. The change in porosity and permeability is expressed as the ratio of the value of the parameter at 4000 psi and the value at 1000 psi, as a fraction. The Tables are arranged in decreasing order of parameter change. The value at 1000 psi is used as a basis for comparison to avoid influence due to sleeve compliance and stress relaxation cracks which could predominate at lower confining levels.

The range of parameter change exhibited by each facies type is shown graphically in Figures 6 and 10. Crossplots shown in Figures 8,9,12 and 13 illustrate the influence of initial values of porosity and permeability on the results. Tables 5 and 6 show the fractional change in porosity and permeability which occurs between 500 psi and 1500 psi for a 500 psi to 4000 psi stress application.

In order to calculate psuedo-stress permeabilities from conventional core analysis data, a conversion factor for each facies type was taken as the mid value of the range of permeability change observed from the experiments on horizontal samples. Table 7 shows the comparison of average permeabilities, for the DST intervals calculated from both conventional and pseudo-stress data, with permeabilities calculated from the DST itself.

A few facies were tested which had not been studied; these were arbitrarily assigned a 50% reduction. In order to examine whether any change was purely due to the action of reducing the air permeability values an arbitrarily adjusted psuedo-stress value was calculated using a 50% reduction factor for all facies types.

DISCUSSION

The Effect of Stress on Porosity

The results presented in Table 2 and Figure 6 show that porosity has been reduced by up to 18.5% of the value at 1000 psi for some samples. The majority of the samples exhibit reductions of less than 10%, and two samples were studied where the porosity increased (permeability however decreased). Typical porosity reduction of these samples is shown on Figure 7, for hydrostatically and biaxially loaded samples. The results suggest that hydrostatically loaded samples are subject to greater porosity reductions than biaxially loaded samples, apparently independent of rock type. No strong influence of initial porosity and permeability on the results was observed. Typical crossplots are shown on Figure 8 and 9. Within facies types C1,C2,A1 and A2, the lower porosity and permeability samples were subject to greater reductions than the higher porosity, more permeable samples.

Table 3 shows a comparison of the data at conditions of similar mean stress. Hydrostatic conditions at 3000 psi gives the closest (but lower) mean stress to biaxial conditions at 5000 psi. This might suggest that the direction of loading is more significant than the magnitude of the mean stress.

The lower porosity reduction of the biaxially loaded samples may be due to a greater connectively being maintained in the axial direction, since in the loading configuration used this is the direction of zero stress application. Further, since it is effective porosity which is being measured, and the direction of fluid flow in the core holder is also axial, this seems all the more reasonable. The relationship between reduction and permeability within some of the facies types might suggest that it is the amount of effective porosity rather than simple volume reduction which is the controlling factor. If this were the case, then the actual pore volume reduction could be less than that indicated by effective porosity measurements, since closed off pores will be interpreted as volume reduction.

The Effect of Stress on Permeability

Permeability reduction with increasing stress ranges from over 15% to nearly 70% of the value at 1000 psi (table 2). Examination of table 2 and figure 10 (which shows the range of change for each facies type) shows a tendancy for samples to cluster in relation to facies types. Facies C1,A2 and A1, and A3 and B2 tend to cluster together. The greatest variability is exhibited by facies A3, which covers a wide range but in general shows the greatest permeability reductions alongside facies B2. Facies C1 forms a fairly distinct group, as the samples undergoing the least change, whereas facies A2 dominates the middle of the range. Facies C2 reminds us that this method of classifying rock type has only a general application. However, the tendancy to cluster around facies type would certainly appear to exist. Samples which cluster together in general show similarities in rock type when examined in hard specimen, supporting in this case the use of facies type as a guide to rock type. Pore image analysis, thin section or mechanical strength characteristics may be a more appropriate if somewhat less routine method of classification.

In general, no complex relationship with reduction and initial porosity and permeability exists, other than that the lowest porosity and permeability samples undergo greater permeability reductions and the higher porosity and permeability samples (eg facies C1) reduce the least (Figures 12 and 13).

Within facies types C1 and A2 there is an indication that biaxially loaded samples are reduced to a lesser extent than hydrostatically loaded samples. Triaxially and biaxially loaded samples from facies B2 do show greater reductions than hydrostatically loaded horizontal and vertical plug samples.

The effect of mean stress on the results was examined, but as with porosity, suggested that stress direction is more important than magnitude.

These data indicate that rock type can influence the response of the samples to imposed stresses, and in addition the directional characteristics of the applied load, i.e. the stress state are influential in relation to the rock type.

Stress Sensitivity

Examination of Tables 5 and 6 show that the majority of the porosity and permeability reduction for a 500 psi to 4000 psi loading cycle, takes place during the initial 500-1500 psi stress increment. This does not appear to be influenced by rock type or stress state, suggesting that other factors may be dominant over this stress increment. These factors may be sleeve compliance effects or the closure of stress relief cracks. Hence data taken at low confining stresses may not be accurate for a given rock type or stress state. This suggests that the use of a higher initial stress levels is likely to result in more representative data and that caution is required when comparing data generated under non-similar loading conditions especially at low confining stresses.

Application to Conventional Core Analysis

An illustration of a practical application of this type of study is a comparison of permeability averages for producing reservoir intervals calculated using core analysis data and DST data, shown on Table 7. For the intervals in which conventional core analysis permeability averages are lower it seems that the psuedo-stress values are a better indication of reservoir permeability. The arbitrarily reduced averages suggest that this is not necessarily only due to the method of calculation used. It was observed that often only one or two of the facies encountered in an interval significantly control the resulting averages, therefore reasonable consideration of the response of those rock types to an imposed stress improved the overall results.

For comparison, one interval is included where the DST permeability is higher than that derived from core analysis. This shows that the core data does not always represent the reservoir on a macroscopic scale and that some other feature is contributing to the reservoir permeability eg a fracture(s).

It is not suggested that stress accounts completely for the difference between conventional core analysis data and DST data as irreducible water saturation, the effect of clay minerals, sample preparation etc, will all undoubtedly have some effect. It does however show that using good experimental data can increase confidence in the interpretation used when mapping reservoir permeability.

The study suggests that caution should be exerted when using conventional core analysis data which has been generated under non-similar stress conditions, particularly at low stress levels, when samples are at their most stress sensitive. It indicates that establishing the permeability/stress response of a rock type can improve the understanding of core data and how it should be analysed. If for example a particular rock type was found to be relatively insensitive to stress increase at reservoir pressures, then further elevated stress tests need not be considered. This would then allow more resources to establish the behavior of more sensitive rock types. If the response of a particular rock type to increasing stress were found to be well established throughout a formation, it would permit stress-permeability correlations to be used with greater confidence.

CONCLUSIONS

1.The results of this experimental work confirm the findings of previous workers regarding the effect of increasing stress on porosity and permeability i.e.
(i)Porosity is reduced to a lesser extent than permeability.
(ii)Lower permeability and porosity rocks are generally subject to greater reductions in porosity, than higher porosity/permeability samples.
(iii)The nature of the change is an initial rapid reduction followed by a slower asymptotic decrease.
2.The reduction in porosity with increasing stress is influenced by the stress-state used; hydrostatically loaded samples are subject to a greater porosity reduction than biaxially loaded samples. This effect is apparently independent of rock type.
3.Permeability reduction with increasing stress can be influenced by rock type and to a lesser extent by stress state.
4.The majority of porosity and permeability reduction occurs during the initial 1500 psi of stress application and may be due in part to features which are not related to the rock type, e.g. sleeve compliance and stress relief cracks.
5.Conventional core analysis permeability data can be adjusted using conversion factors generated from permeability/stress experiments to calculate producing reservoir interval average permeabilities that are in better agreement with DST permeability than untreated data.

ACKNOWLEDGEMENTS

The authors extend their appreciation to Phillips petroleum Company (UK) Limited and the Science and Engineering Research Council for the funding of this project and the permission to publish these results.

We extend our thanks to the following for their contributions; Dr. A.C. Todd and Mr. J.A. Tweedie of Heriot-watt University for their academic guidance, Mr. C.A. McPhee and all at Edinburgh Petroleum Services Ltd. (Core Systems) for the technical advice and in particular the donation of equipment designs and software essential to the completion of this work. Thanks are also due to Mesbahul Hossain who significantly contributed to the experimental work.

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NOMENCLATURE

D = Density of rock
Z = Depth Equation (1)
G = Gravitational constant
Sg = Stress due to gravity alone
Sz = Vertical stress Figure (1)
Sx = Horizontal stresses Figure (1)
Sy
V = Poissons ratio
Equations (2)&(3)
$K = \frac{V}{1-V}$ or a constant

TABLE 2 THE EFFECTS OF STRESS ON POROSITY

STRESS STATE	FACIES	POROSITY CHANGE	POROSITY 1000 (%)	PERM(Kl) 1000 (md)
H	C2	.815	12.24	0.06
H	A2	.816	19.03	0.20
H	B2	.900	16.47	0.29+
H	A3	.949	14.77	0.86
H	C1	.952	12.44	4.96
H	A1	.953	16.34	0.36
H	C1	.967	15.79	4.25
H	A1	.975	21.58	1.57
B	A3	.975	14.96	0.08
B	C2	.984	18.49	1.45
B	C1	.985	19.35	5.31
B	A3	.988	11.69	0.18
B	C1	1.02	20.28	12.66
B	B2	1.10	8.90	0.22

H- HYDROSTATIC STRESS
B- BIAXIAL STRESS
+ VERTICAL PLUG
POROSITY CHANGE = POR 4000/POR 1000psi

TABLE 3 COMPARISON OF BIAXIAL AND HYDROSTATIC STRESS STATES AT SIMILAR MEAN STRESS

FACIES	STRESS STATE	FRACTIONAL CHANGE (%)
C2	H	.818
A2	H	.853
B2	H	.941+
A3	H	.957
C1	H	.964
A1	H	.966
A3	B	.967
A1	H	.968
C1	H	.975
C2	B	.982
C1	B	.983
A3	B	.988
B2	B	.990
C1	B	1.01

MEAN STRESS = Sz+Sx+Sy/3
B - BIAXIAL (MEAN STRESS = 3333)
H - HYDROSTATIC (MEAN STRESS = 3000)
\+ VERTICAL PLUG

TABLE 4 THE EFFECT OF STRESS ON KLINKENBERG EQUIVALENT PERMEABILITY

FACIES	STRESS STATE	FRACTIONAL CHANGE	POROSITY 1000 (%)	PERM(Kl) 1000 (md)
A3	T	.244	-	0.01
A3	H	.288	-	0.02+
B2	B	.311	16.12	2.20+
A3	B	.319	11.69	0.18
A3	U	.352	-	18.39
B2	T	.386	17.47	0.36+
C2	H	.424	12.24	0.06
B2	T	.439	-	6.83
A2	H	.500	19.03	0.20
A3	H	.510	14.77	0.86
B2	B	.519	8.90	0.22
A2	U	.622	14.95	0.27+
B2	H	.648	16.47	0.29+
A2	H	.654	-	0.48
A2	H	.690	-	5.08
A1	H	.691	21.58	1.57
A2	B	.705	-	1.50
A3	B	.709	14.96	0.08
A1	H	.732	16.34	0.36
C1	H	.736	15.79	4.25
C1	H	.742	12.44	4.96
C1	B	.823	19.35	5.31
C2	B	.840	18.49	1.45
C1	B	.840	20.28	12.66

+ VERTICAL PLUG
B - BIAXIAL
H - HYDROSTATIC
T - TRIAXIAL
U - UNIAXIAL
FRACTIONAL CHANGE = PERM 4000/1000 psi

TABLE 5 POROSITY REDUCTION BETWEEN 500-1500 PSI

FACIES	STRESS STATE	FRACTIONAL REDUCTION %
C2	H	.361
B2	H	.372+
A3	H	.473
C1	H	.552
C1	H	.561
A3	B	.563
A2	H	.568
C1	B	.606
A1	H	.615
C2	B	.629
A3	B	.769
A1	H	.949

\+ VERTICAL PLUGS
B - BIAXIAL
H - HYDROSTATIC
FRACTIONAL REDUCTION
IS
POR 500-1500/500-4000 psi

TABLE 6 KLINKENBERG PERMEABILITY BETWEEN 500 -1500 PSI

FACIES	STRESS STATE	FRACTIONAL REDUCTION (%)
B2	T	.322+
B2	H	.468+
C1	B	.635+
A2	U	.637
C1	H	.664
A3	H	.692
A2	H	.695
A2	H	.707
A3	B	.712
A1	H	.723
B2	T	.745
A2	B	.751
C2	B	.780
C1	B	.796
A1	H	.812
C1	H	.818
A2	H	.859
C2	H	.879
A3	B	.923
B2	B	

+ VERTICAL PLUG
B - BIAXIAL
H - HYDROSTATIC
T - TRIAXIAL
U - UNIAXIAL
FRACTIONAL REDUCTION IS
PERM 500-1500/500-4000 psi

TABLE 7 COMPARISON OF PERMEABILITY AVERAGES

WELL	ZONE	Ka (md)	Ka′ (md)	Ka" (md)	K DST (md)
1	A	12.5	6.22	6.22	6.0
	B	14.77	4.93	7.39	6.0
2	A	35.3	12.38	17.24	44.5
	B	9.43	3.98	4.96	2.2
3	A	17.4	7.32	8.65	5.0
	B	22.0	7.58	10.64	5.0

ZONE A ARE LAKE MARGIN SANDS
ZONE B ARE FLUVIAL SANDS
Ka - CONVENTIONAL CA AVERAGE
Ka′- PSUEDO STRESS AVERAGE
Ka" - ARBITARY PSUEDO STRESS AVERAGE (50%)

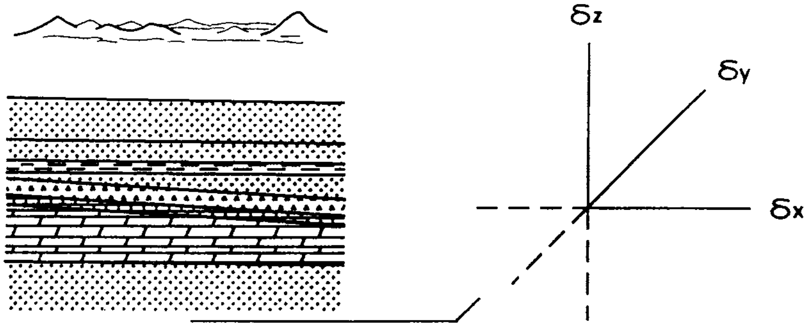
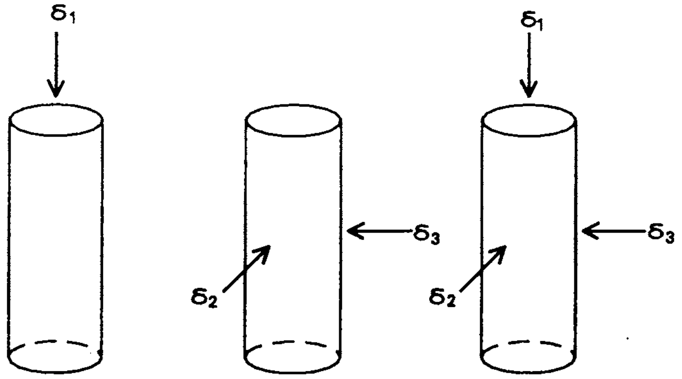


FIGURE 1 Mutually Perpendicular Stress Directions



	UNIAXIAL	BIAXIAL	(i) HYDROSTATIC (ii) TRIAXIAL
HORIZONTAL PLUGS	$\delta_1 = \delta_x$ $\delta_z = \delta_y = 0$	$\delta_2 = \delta_3 = \delta_z = \delta_y$ $\delta_x = 0$	(i) $\delta_z = \delta_x = \delta_y$ (ii) $\delta_2 = \delta_3 = \delta_z = \delta_y$ $\delta_1 = \delta_x = K\delta_z$, $K = 0.25 \rightarrow 0.33$
VERTICAL PLUGS	$\delta_1 = \delta_z$ $\delta_x = \delta_y = 0$	$\delta_2 = \delta_3 = \delta_x = \delta_y$ $\delta_z = 0$	(i) $\delta_z = \delta_x = \delta_y$ (ii) $\delta_1 = \delta_z$, $\delta_2 = \delta_3 = \delta_x = \delta_y = K\delta_z$ $K = 0.25 \rightarrow 0.33$

FIGURE 2 Experimental Stress States

TABLE 1 Facies Associations and Facies Types

	GRAIN SIZE	SORTING	ROUNDING	ARGILLACEOUS CONTENT	STRUCTURE
Aeolian Dune					
Sediments					
(i) Dune Top Sandstone	Fine to	Moderately	Sub Angular to	Rare	Laminated
(A1)	Coarse	Well	Well Rounded		
(ii) Dune Base Sandstone	Fine to	Moderate to	Sub Angular to	Very	Laminated
(A2)	Coarse	Moderately Well	Rounded	Slight	
(iii) Inter Dune Sandstone	Very Fine to	Moderate to	Sub Angular to	Argillaceous	Massive or
(A3)	Medium	Moderately Poor	Well Rounded		Laminated/Disrupted
Fluvial Sediments					
(i) Prolonged Stream Flow	Fine to	Moderate	Sub Angular to	Very	Laminated
Channel all Sandstones	Medium		Rounded	Argillaceous	
(B2)					
Lake Margin					
Sediments					
(i) Sand-Rich	Very Fine to	Moderately	Sub Angular to	Argillaceous	Massive or
(C1)	Coarse	Poor	Rounded		Laminated/Disrupted
(ii) Sheet Floot & Minor Fluvial	Very Fine to	Moderate	Sub Angular to	Argillaceous	Laminated or
Channel Sandstones	Medium		Rounded		Laminated/Disrupted
(C2)					

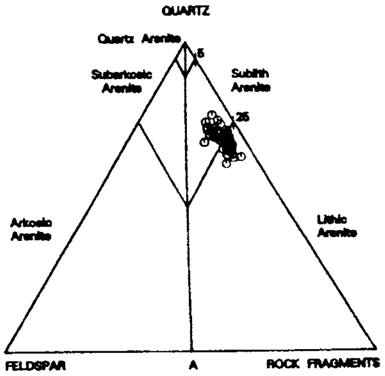


FIGURE 3 Sandstone Classification (Dott, Petijohn) Matrix <15% (After Lowrey et al)

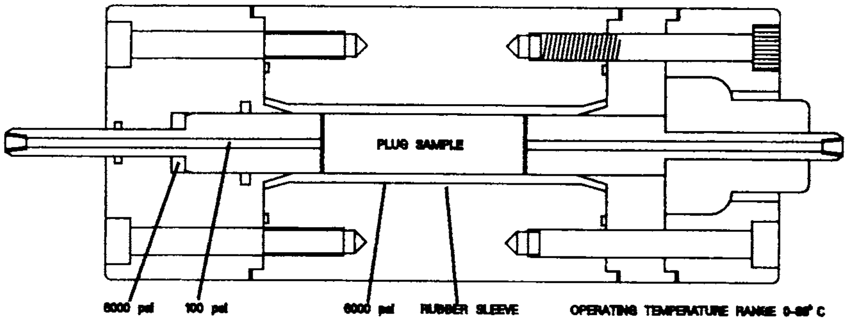


FIGURE 4 Triaxial Core Holder

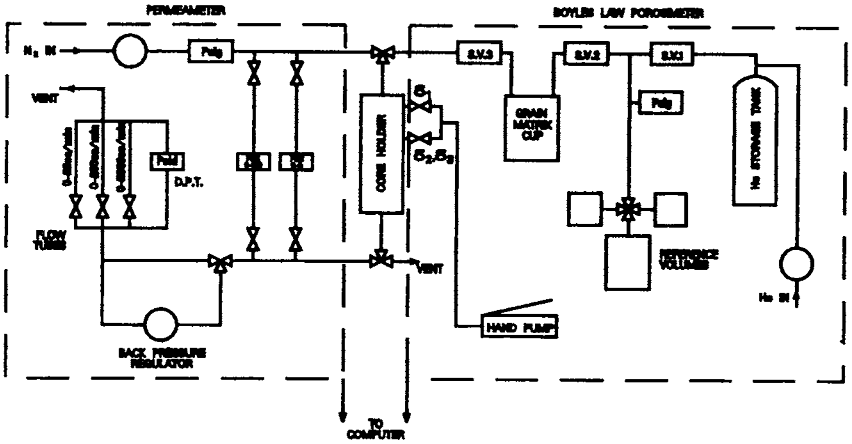


FIGURE 5 Schematic of Experimental Equipment

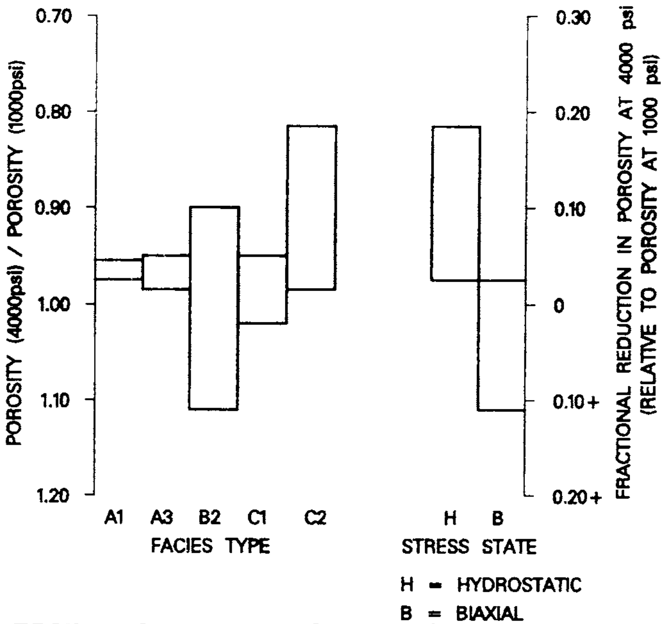


FIGURE 6 Range of Porosity Change at 4000 psi

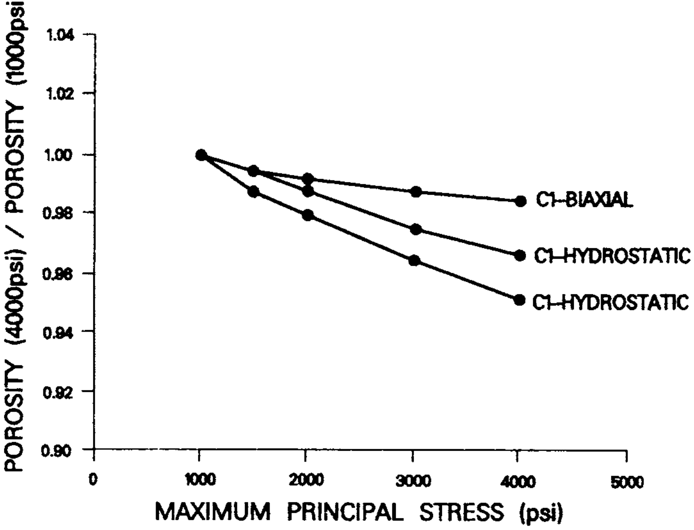


FIGURE 7 Effect of Stress on Porosity (Facies C1)

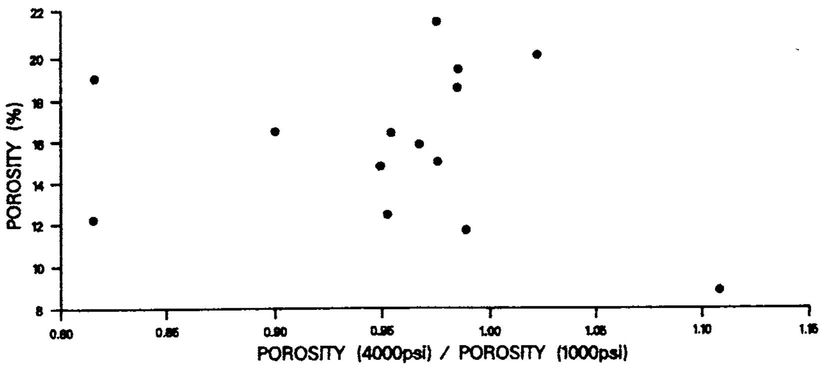


FIGURE 8 Porosity at 1000 psi v Porosity Change at 4000 psi

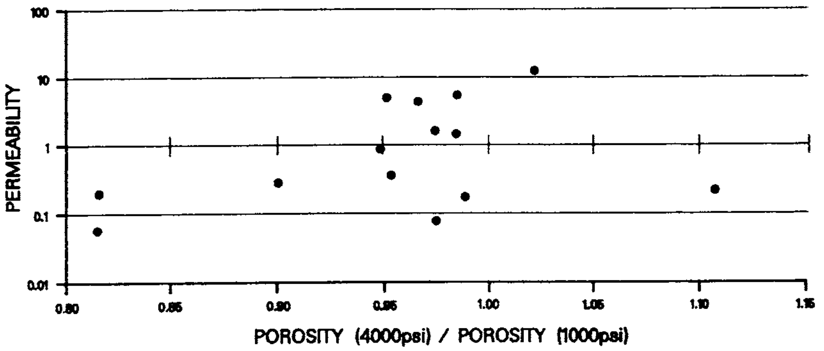


FIGURE 9 Klinkenberg Permeability at 1000 psi v Porosity Change at 4000 psi

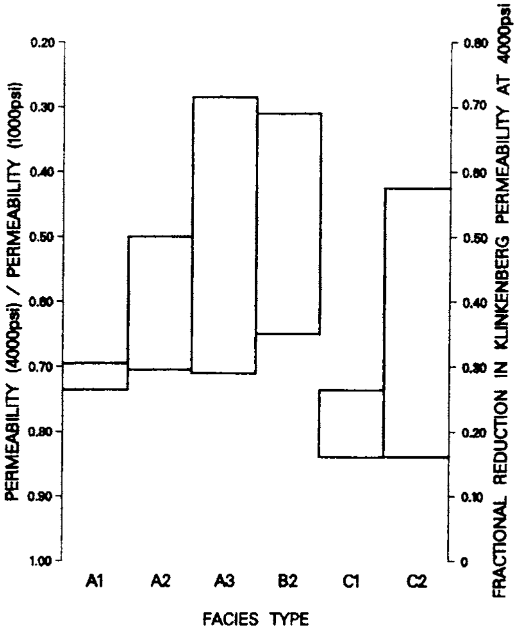


FIGURE 10 Klinkenberg Permeability Change at 4000 psi

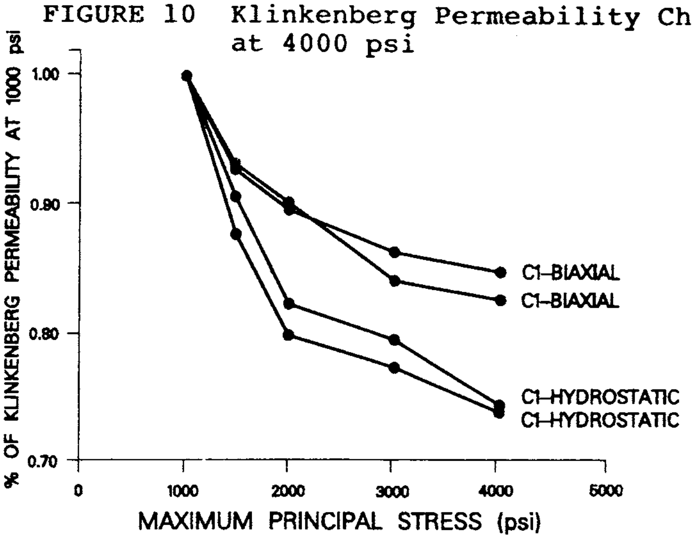


FIGURE 11 Effects of Stress on Permeability (Facies C1)

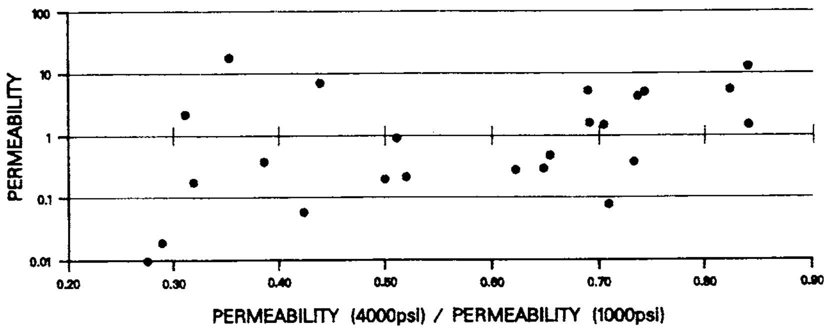


FIGURE 12 Klinkenberg Permeability Change at 1000 v 4000 psi

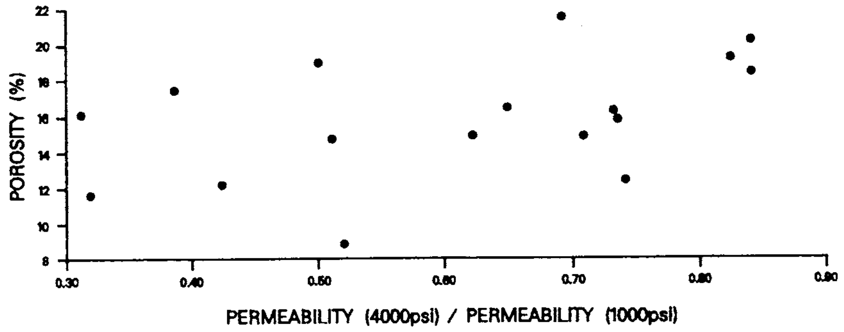


FIGURE 13 Porosity at 1000 psi v Klinkenberg Permeability Change at 4000 psi

EUROPEAN CORE ANALYSIS SYMPOSIUM
LONDON
21-23 MAY 1990

A FRESH LOOK AT PREDICTIVE EQUATIONS FOR COMPRESSIONAL WAVE VELOCITY - POROSITY

by
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