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The measurement of gas permeability in sediments of the Vryheid Formation

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Synopsis

Excessive build-up of methane and water pressures was identified as the leading cause of some of the roof falls in a coal mine in the eastern Transvaal. In order to characterize the migration of the methane and water into and around the mined coal seam, a laboratory investigation of the permeability of the roof strata was undertaken. The aim of the investigation was to correlate changes in the facies with changes in permeability to enable the prediction of possible zones of pressure build-up.

The tests were carried out on samples from borehole core that had been obtained from the roof strata as part of the mine exploration programme. Permeability measurements were then conducted under atmospheric and triaxial-stress conditions. For the tests under atmospheric conditions, a modified Ohle cell was used and, for the tests under

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Introduction

A coal mine in the eastern Transvaal experienced roof falls as a result of the excessive build-up of methane and water pressure in the roof strata of a mined coal seam. A laboratory-based permeability study was therefore initiated to characterize the migration of methane and water into the mine opening. Samples were obtained from exploration borehole core that had been drilled from the roof strata. The permeability of the samples was tested under atmospheric and triaxial conditions, with methane as the permeating fluid, and the liquid equivalent permeability for each sample was determined by ASTM methods[1]. The liquid equivalent permeabilities were then used as a basis for comparison between the different types of facies. Of the twenty-four facies in the roof strata[2], only eleven were sampled for the tests in this project. For the tests under atmospheric conditions, use was made of a modified Ohle cell[3], and a modified Hoek cell[4] was used for the triaxial tests.

Preparation of the Samples

The core samples were cut into appropriate lengths as required by the different apparatus. The Ohle cell required sample lengths of 12 to 20 mm irrespective of their diameter. The triaxial tests, to reduce 'end' effects, required samples conforming to the 2:1 length-to-diameter ratio proposed by Obert and Duvall[5]. As a result, the samples for these tests were cut into lengths of 100 or 120 mm, depending on the diameter of the core, TNW (54 mm) or NX (60,3 mm). The ends of the samples were ground with carborundum paste until they were parallel and smooth. This was done so that an even load could be applied perpendicular to the long axis of the sample in the triaxial case, and to assure a better seal between the O-rings and the sample when tested in the Ohle cell. The samples were washed so that their pores could be free of grit and paste, which would affect the permeability measurements. The samples were then oven-dried at 100°C to remove all the excess moisture, and were placed in desiccators containing silica gel to keep them free of moisture. Drying over a period of 12 hours was found to be sufficient in most cases for the samples to attain a constant weight, i.e. to be assumed to be moisture-free.

Methodology

Tests with the Ohle Cell

The Ohle cell as described by Ohle[6] and by Chakrabarti and Taylor[7] was modified mainly in relation to the material used for its construction and the sample holder. Brass replaced the stainless steel, because it does not react with any of the fluids used (e.g. it does not rust in tests with water) and is strong enough to withstand the fluid pressures used. The sample holder was modified to allow it to accept a wider range of samples with respect to diameter and length. The seal between the sample and the sample holder is achieved by two rubber O-rings that are pressed against the sample by means of a spacer.

The gas (either nitrogen or methane) was supplied from a commercial gas cylinder that was capable of delivering gas at a pressure of 20 MPa. The pressure was kept constant by means of a regulator, and was measured with a transducer with a digital readout. The flowrates were measured with a stopwatch and a series of bubble flow meters of 25, 100, and 250 cm^3 capacity. Figure 1 shows the different components of the Ohle cell for the tests involving gas as the permeating fluid.

After the sample had been installed in the chamber of the sample holder, the apparatus was assembled, and was sealed with an O-ring compressed against the sample. The effectiveness of the seal was tested by the application of pressure to a steel disc of the same dimensions as the sample inserted in the cell; fluid reaching the bubble flow meter would indicate a defective seal. Once a porous sample had been inserted, a pressure of 150 kPa was applied, and the sample was left to reach equilibrium. Equilibrium is assumed when the measured rate of flow becomes constant, implying that the sample is fully saturated with the testing fluid. The flowrate was then recorded and the gas pressure increased by 50 kPa. The system was again left to reach equilibrium and the flow recorded. This incremental increase in gas pressure was continued until the pressure reached 700 kPa. The permeability at each increment was then calculated from equation [1], which is a derivative of Darcy's Law[8]:

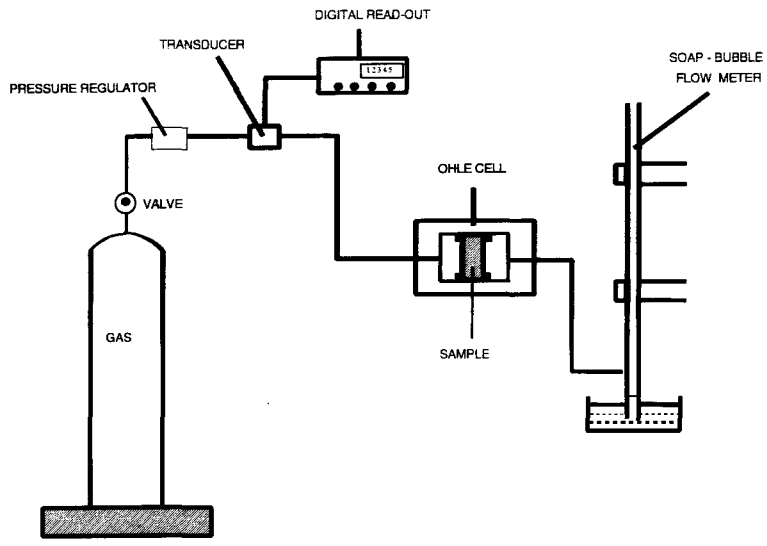

Figure 1—The different components of the Ohle cell used in the tests

triaxial-stress conditions, a modified Hoek cell was used. The liquid equivalent permeabilities of the different samples were obtained by use of ASTM D4525-85, and these were then used as a basis for comparison.

Facies type, i.e. grain size, was found to have an influence on the permeability but, owing to the variable nature of the sediments, a range of permeability rather than a specific permeability value was associated with each type of facies. The measured permeability was found to decrease with an increase in gas pressure. The liquid equivalent permeability was found to increase with an increase in grain size for the coarser-grained facies, and to decrease with an increase in grain size for the finer-grained types. The application of an external stress regime to the sample was found to reduce the permeability, but the amount of the reduction depended on the type of stress. The permeability was also found to depend on the recent stress history of the sample. The authors conclude that the

$$k = \frac{2QP_0\mu L}{(P_1^2 - P_2^2)A}, \qquad [1]$$

where k = permeability in the direction of flow (Darcy)
Q = volumetric rate of flow at inlet pressure (cm^3/s)
P_0 = reference pressure (atm)
μ = viscosity of the fluid (cP)
L = length over which the flow is measured (cm)
P_1 = inlet gas pressure (atm)
P_2 = outlet gas pressure (atm)
A = cross-sectional area across which Q is determined (cm^2).

The reference pressure, P_0, and the outlet pressure, P_2, are usually taken as being equal to each other and to the atmospheric pressure, which is assumed to be 1 atm. A gas pressure of 700 kPa was chosen as the termination point because the initial tests resulted in erratic plots of permeability versus reciprocal mean gas pressure after an inlet pressure of 400 kPa had been reached (Figure 2). This behaviour was thought to be caused by either the Klinkenberg effect[9] or by turbulent flow so that Darcy's Law was no longer valid[10]. Subsequent experiments were continued up to an inlet gas pressure of 700 kPa to ensure that the cause could be identified, as well as providing enough data points for the later statistical manipulations required by the ASTM tests[1].

Generally, for safety reasons, a sample was first tested with nitrogen and then with methane as the permeating fluid. If the seal were defective, there would be less danger from the use of nitrogen than from methane. To change over from one gas to another, the gas pressure was reduced to zero and the pressure released from the system without removing the sample from the cell. The procedure as outlined here was then repeated with the new gas.

Tests with the Hoek Cell

In the tests simulating *in situ* stress conditions, a modified Hoek–Franklin triaxial cell was used[4]. The modifications involved a series of interconnected circular grooves cut into the end platens. The grooves are designed to distribute the fluid over the whole cross-sectional area of the sample at the high-pressure end, and to collect the fluid passed through the sample over the whole cross-sectional area of the sample at the low-pressure end. In the case of coal, it was found that these grooves pressed into the ends of the sample thereby effectively blocking any gas from penetrating the sample. Sintered discs of the same diameter as the platens were used to counteract this.

An axial load was supplied by a hydraulic testing machine capable of applying a load of 1000 kN. The confining stress was supplied by a hydraulic pump that can supply oil pressure up to 50 MPa. The gas was supplied and the flow-rate recorded by the same equipment as described for the tests with the Ohle cell.

Figure 3 shows the different components of the Hoek-cell tests involving methane as the permeating fluid.

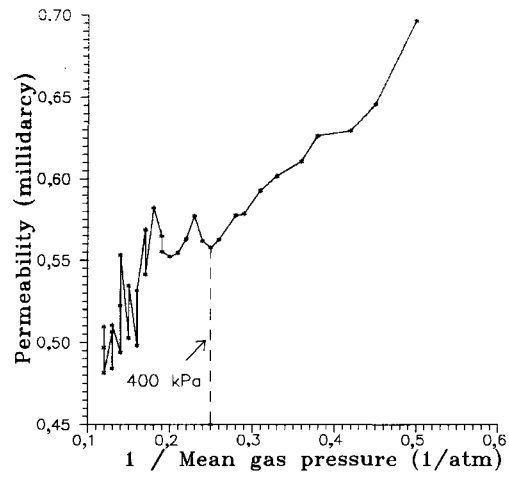

Figure 2—Graph showing the irregular plot for permeability versus reciprocal mean gas pressure beyond 400 kPa

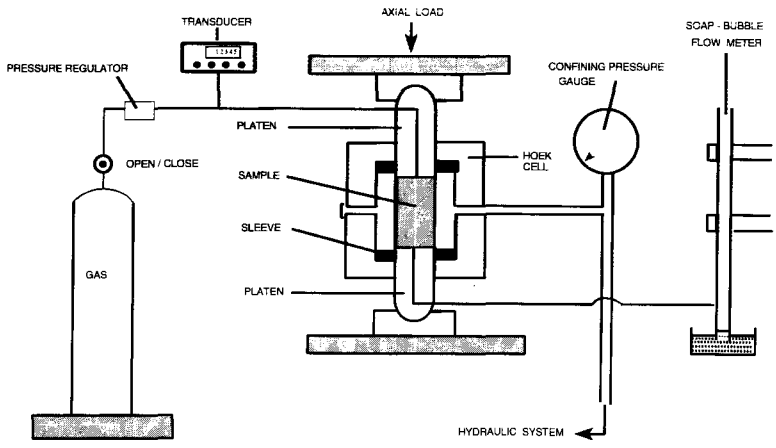

Figure 3—The different components of the Hoek-cell tests

methods described are useful for the correlation of facies type with permeability, but that the results are sensitive to changes in locality.

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Before the sample was placed in the assembled Hoek cell, the annular space between the rubber sleeve and the cell was filled with hydraulic oil. The sample was then placed in the cell, and a hydrostatic stress of 4 MPa was applied. (This was found to be the general stress at which no gas flowed between the sample and the sealing rubber sleeve of any of the samples.) At the outset it was hoped to start the tests at the measured *in situ* stress condition in the mine but, since this stress is estimated to be below 4 MPa, this could not be done. Only tests using methane were carried out: firstly, because of the importance of the methane tests to this study and, secondly, because of the time involved in reaching equilibrium. A full range of tests on one sample could take up to four days to complete. The gas pressure was increased in 50 kPa increments up to 700 kPa at a hydrostatic pressure of 4 MPa, similar to the Ohle tests. From this point, a series of three tests was carried out.

Firstly, the axial stress was increased in intervals of 2 MPa (usually to 20 MPa) while the confining stress was kept at 4 MPa and the gas pressure at 200 kPa. The flowrate was measured after each load interval. Axial load was then decreased in 2 MPa steps until hydrostatic conditions at 4 MPa were again reached.

Secondly, the confining stress was increased in 2 MPa intervals while the gas pressure was kept constant at 200 kPa. This loading was also continued until a load of 20 MPa had been attained, at which time the hydrostatic load was decreased in steps of 4 MPa until the base 4 MPa hydrostatic conditions were again reached.

Thirdly, the hydrostatic stress was increased in 2 MPa intervals while the gas pressure was kept constant at 200 kPa. As in the previous method, the stress was increased until 20 MPa was reached. The confining stress was then relieved until the starting 4 MPa hydrostatic conditions were again attained.

In each of the three cases the procedure was repeated two to three times. The effect of each cycle was determined from measurements of the specific permeability at a series of gas pressures and from the liquid equivalent permeability in each instance.

Results and Discussion

Ohle-cell Tests

When the permeability measured at each inlet-gas pressure was plotted against the reciprocal mean gas pressure (P_m), it was found that the permeability decreased with increasing inlet-gas pressure. In the majority of cases, the nitrogen and methane plots for the sample followed the same pattern (Figure 4). The plot for nitrogen was found to be higher, with steeper slopes than the methane plots. This is as expected since nitrogen has a smaller molecular size than methane. Nearly half of the projected liquid equivalent permeabilities, on the other hand, did not follow this pattern. Theoretically, the difference should be zero[9], and Ohle[6] concluded that the difference can be taken as the experimental error. In the present study, the difference seldom exceeded 10 per cent, and the sample for Figure 4 has a difference of 5 per cent between the two k_{le} values.

Owing to the extreme variability of the sediments tested, even over short distances (centimetre scale) and in the same type of facies, the liquid equivalent values obtained for each facies type is not confined to a single value, but rather to a range of values. This is illustrated in Table I, which shows the ranges obtained from the tests involving methane as the permeating fluid. The relationship between the permeability ranges for the different types of facies is better illustrated by Figure 5.

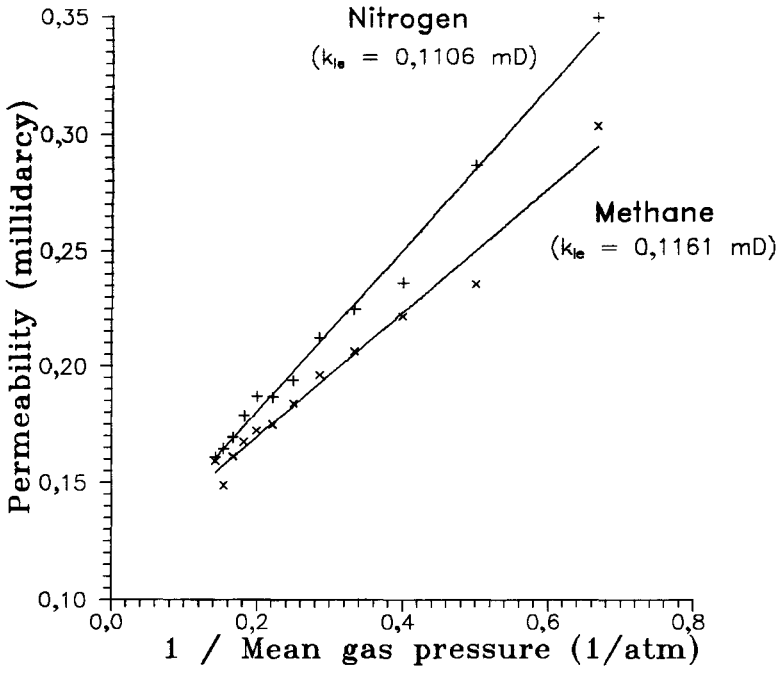

Figure 4—Plot of k_s versus $1/P_m$ for methane and nitrogen for the same sample

Table I

Ranges of liquid equivalent permeability for the facies tested using methane as the permeating fluid

Type and short description of facies	Permeability range, mD			Number tested	Average r^2
	Minimum	Maximum	Average		
2 Lenticular bedded mudrock	0,0057	0,2590	0,1197	4	0,94
3 Alternating layers of medium- and fine-grained sandstone	0,0025	0,6146	0,0808	6	0,77
4 Flaser-bedded fine-grained sandstone	0,0018	0,0040	0,0029	5	0,81
5 Ripple cross-laminated fine-grained sandstone	0,0024	0,0070	0,0026	8	0,78
7 Massive fine-grained feldspathic sandstone	0,0020	0,0247	0,0108	7	0,81
8 Cross-laminated fine-grained feldspathic sandstone	0,0001	0,1161	0,0282	8	0,92
9 Massive medium-grained feldspathic sandstone	0,0213	1,5318	0,2788	22	0,80
10 Cross-laminated medium-grained feldspathic sandstone	0,0128	2,7132	0,4412	103	0,69
11 Massive coarse-grained feldspathic sandstone	0,0681	2,1597	0,3902	34	0,80
12 Cross-laminated coarse-grained feldspathic sandstone	0,1567	3,1960	1,0546	11	0,69

The main objective of this study was to determine whether any correlation could be found between facies type and permeability. As illustrated in Figure 5, a relationship, although not a straightforward one, exists between the facies type and the permeability. In the coarser-grained facies (type 8 and higher) there is an increase of average liquid equivalent permeability with an increase in grain size. For the finer-grained facies (those below facies type 7), the average liquid equivalent permeability was found to decrease with an increase in grain size. This could be the result of many factors but, in the authors' opinion, the factor with the most significant influence is that of the number of samples tested. The more tests done on a specific type of facies, the more statistically representative the range of liquid equivalent permeabilities obtained. The coarser the grain size, the larger the range of liquid equivalent permeabilities because of the larger distribution in grain size of the facies type.

Another very significant factor that could influence the quoted liquid equivalent permeability ranges is the choice of data points used in the extrapolation of the liquid equivalent permeability. The ASTM[1] recommends that a straight line be drawn through at least three data points at the lower values of reciprocal mean gas pressure. This best-fit straight line is then extrapolated to the *y* axis to give the liquid equivalent permeability of the sample. The points chosen for this best-fit straight line may influence the value obtained in the extrapolation and the eventual liquid equivalent permeability ranges obtained. In the present study, all twelve data points were used when the straight line was fitted to give the liquid equivalent permeability.

In some cases (16 per cent of the tests involving nitrogen and 23 per cent of the tests involving methane), the plots of permeability versus reciprocal mean gas pressure had negative slopes for either the methane tests alone (Figures 6 and 7) or for both the methane and the nitrogen tests (Figure 8). Such results were unexpected.

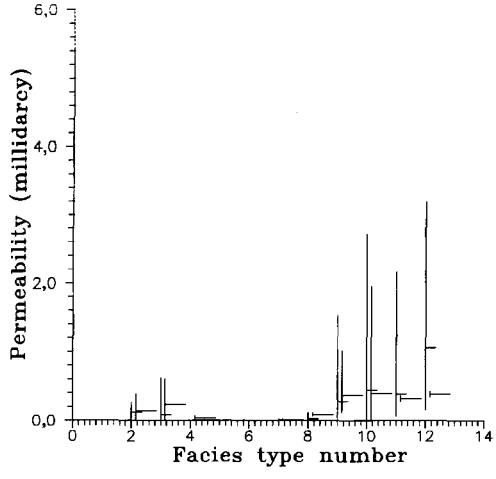

Figure 5—Plot showing the relationship between the k_{10} permeability ranges and the different types of facies in the tests involving methane as the permeating fluid

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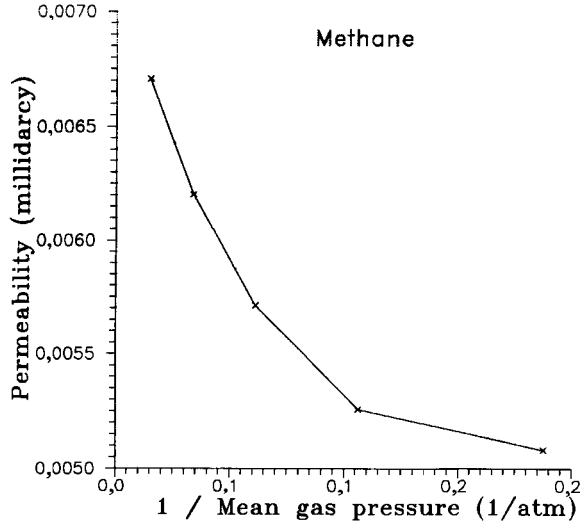

Figure 6—Plot of k_s versus $1/P_m$, showing a negative slope for a test involving methane as the permeating fluid

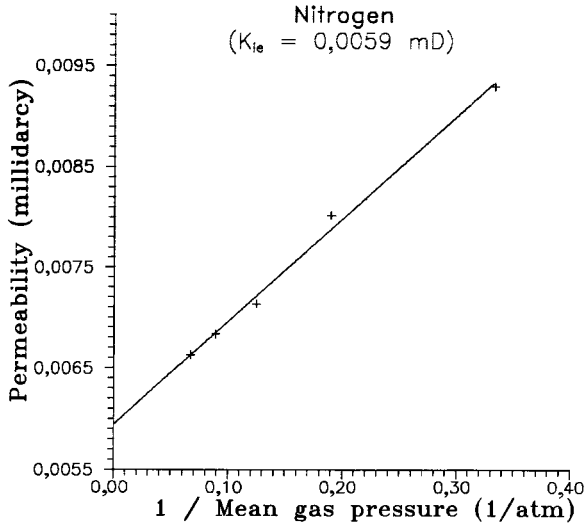

Figure 7—Plot of k_s versus $1/P_m$, showing a positive slope for a test involving nitrogen as the permeating fluid for the same sample as in Figure 4

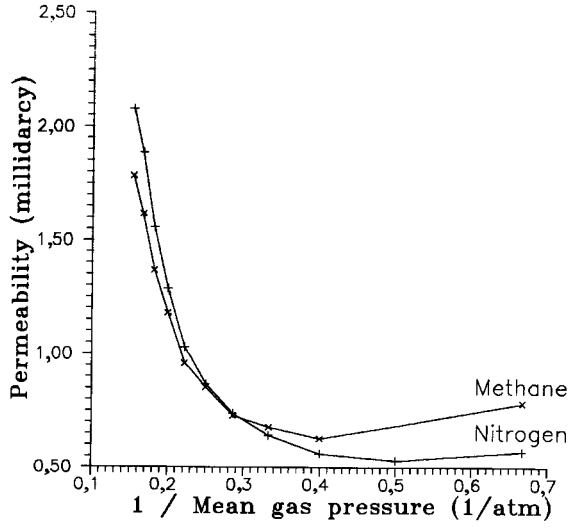

Figure 8—Plot of k_s versus $1/P_m$, showing negative slopes for both the methane and the nitrogen tests on the same sample

The two main phenomena that could be responsible are the Klinkenberg effect and methane adsorption[11]. Klinkenberg's method[9] of analysis (or that of the ASTM[1]) removes the effects of experimental error. If the methane plot has a negative slope but the nitrogen plot for the same sample has a positive slope (Figures 6 and 7), it can be assumed that adsorption is the dominant active phenomenon because methane, and not nitrogen, is reactive towards the samples tested. If both plots result in negative slopes (Figure 8), gas slippage or the Klinkenberg effect must be the dominant mechanism present. In a small number of instances, the extrapolated liquid equivalent permeabilities were found to have negative values, which is a physical impossibility. Scheidegger[12] stated that Darcy's Law represents a straight line between the quantity of flow and the pressure differential and, as such, should result in a line through the origin. Experimental error could thus force the line to intersect the y axis at a negative value.

Both the measured permeability (k_s) and the extrapolated liquid equivalent permeability (k_{le}) were found to vary over very short distances. The plots in Figure 9 represent four samples taken over a distance of 10 cm. They all belong to the same type of facies, but the grain size increases visibly from the medium-grained sample A to the coarser-grained sample D. It can be seen in Figure 9 that k_s and k_{le} increase with increasing grain size. This shows that there must be some relationship between grain size and permeability . The distribution of the data points also becomes less linear as the grain size increases, and the slopes become less steep as the grain size decreases. This means that the gas has a path of larger diameter to flow through, and some turbulent flow (resulting in a non-linear plot) can occur. Figure 9 also illustrates why a range of liquid equivalent permeabilities, rather than single values, were obtained for a specific type of facies.

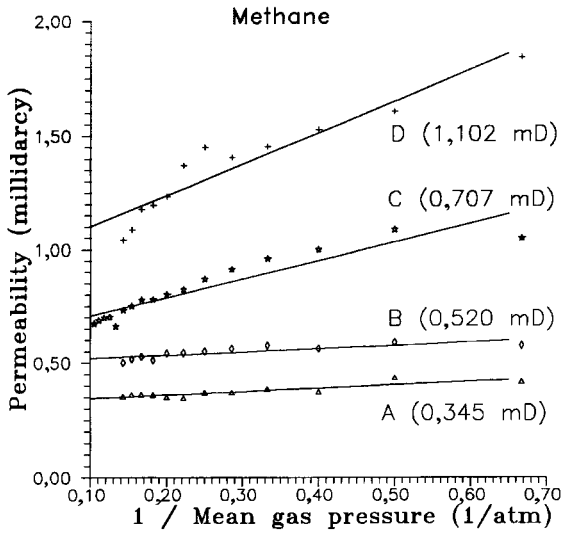

Figure 9—Plot of k_s versus $1/P_m$, showing the variation of permeability over a 10 cm interval. k_{le} is shown in brackets

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Hoek-cell Tests

The time needed for the tests involving methane (or nitrogen) as the permeating fluid to reach equilibrium was approximately 1 hour in the case of the Ohle-cell tests. When a hydrostatic stress of 4 MPa (i.e. $\sigma_1 = \sigma_2 = \sigma_3$) was applied in the Hoek-cell tests, equilibrium was reached only after about 5 hours. The higher the facies number, i.e. the coarser the grain size, the shorter the time needed to reach equilibrium. In order to obtain a basis for comparison with the tests under atmospheric conditions (Ohle cell), a series of permeability measurements at increasing gas pressures were made at different hydrostatic loads. Table II shows the result at 4 MPa. Of the tests, 16 per cent produced plots indicating a deviation from Darcy's Law. The samples in these tests all contained some carbon, indicating that adsorption of methane was the reason for the anomalies.

It was found that an increase in any of the applied stress regimes (axial stress, σ_1; confining stress, σ_3; hydrostatic stress, $\sigma_1 = \sigma_3$) leads to a reduction in permeability. An increase in hydrostatic stress has the largest influence, with confining stress the second largest and axial stress the smallest. Figure 10 shows the influence of a continued increase in confining stress on the permeability. This decrease can be attributed to the closing of the pores under external pressure. The initial decrease, i.e. from 4 to 8 MPa, was found to be the largest in all cases. In some cases, this decrease in permeability was as high as 50 per cent. Subsequent increases produced progressively smaller and smaller decreases in permeability, as can be seen in Figure 10.

Gawuga[11] found that, at some point, there is no further decrease in permeability irrespective of how much the load is increased. The authors could not duplicate this result, but the samples in this study were not subjected to the same number of load cycles as in Gawuga's tests. The decrease was, however, not permanent, and the initial permeability could again be attained after the load had been relieved for a few days. This means that the permeability depends on the stress history of the sample, at least for a while.

Table II

Liquid equivalent permeability ranges for the facies tested with methane as permeating fluid under a hydrostatic pressure of 4 MPa

Type of facies	Permeability range, mD			Number tested	Average r^2
	Minimum	Maximum	Average		
7 Massive fine-grained feldspathic sandstone	0,0061	0,0061	0,0061	1	0,92
8 Cross-laminated, fine-grained feldspathic sandstone	0,0060	0,0666	0,0363	2	0,72
9 Massive medium-grained feldspathic sandstone	0,3492	3,3127	1,3837	3	0,87
10 Cross-laminated medium-grained feldspathic sandstone	0,0096	2,9999	0,5852	14	0,69
12 Cross-laminated coarse-grained feldspathic sandstone	0,5280	0,5280	0,5280	1	0,99
14 Sandstone with carbonaceous drapes and slump structures	0,0075	0,1316	0,0963	4	0,57
22 Mixed dull and bright coal	0,4182	0,4182	0,4182	4	0,67

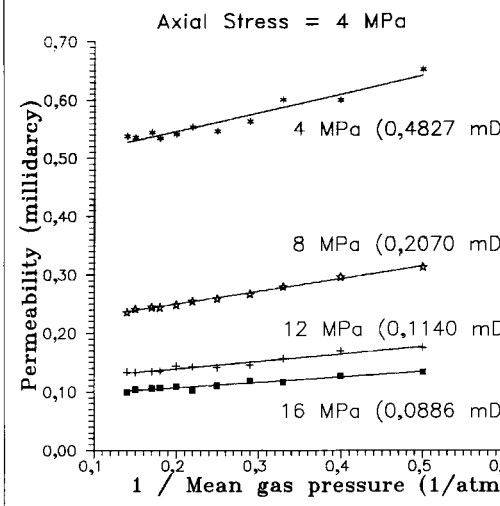

Figure 10—Plot of k_s versus $1/P_m$, showing the decrease in permeability with an increase in confining stress from 4 to 16 MPa for the same sample. k_{le} is shown in brackets

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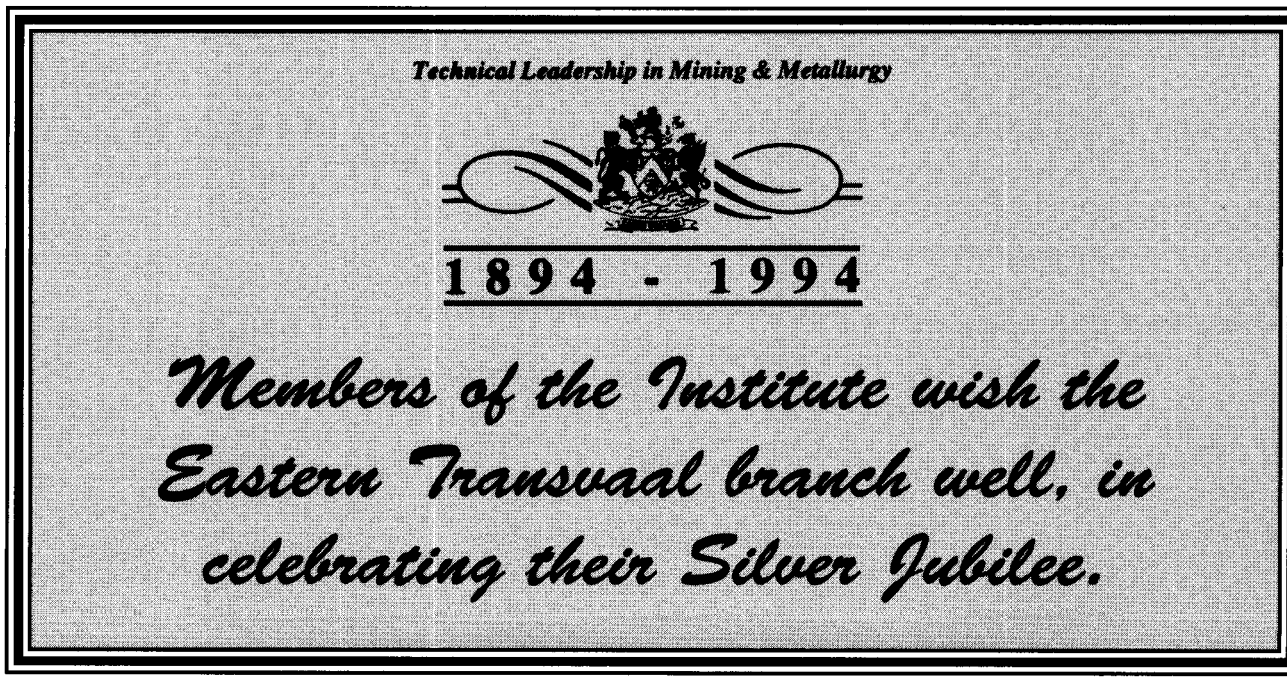
Conclusions

It can be concluded that permeability is a physical property of rock that varies over short distances and is dependent on many internal and external factors. The permeability of a sediment for a gas such as methane or nitrogen decreases with an increase in gas pressure. If carbon in one form or another is present in a sample being tested, it may adsorb methane and yield anomalous plots of permeability versus reciprocal mean gas pressure. This mechanism can, however, be shown to be active rather than due to gas slippage (the Klinkenberg effect) when the sample is tested with both nitrogen and methane, and the resulting plots of permeability versus reciprocal mean gas pressure are compared. Application of an external stress results in a decrease in specific and liquid equivalent permeability. The amount by which the permeability decreases is controlled by the type of external stress applied. The largest decrease occurs when the applied stress is hydrostatic, and the smallest decrease is obtained when the applied stress is axial, with an intermediate decrease for confining stress. Permeability is dependent on the stress history of the sample, but the influence of the stress history decreases with each application of a load cycle. The definition of the lower and upper limits for each range were found to depend on the number of tests carried out on a particular type of facies. Nonetheless, a relationship of increasing permeability with increasing grain size was found in the coarser-grain facies (types 8 and higher). For the finer-grained facies, the permeability was found to decrease with an increase in grain size. This is not detrimental if the results are used as an indicator of a roof-fall hazard or to characterize the flow character for the extraction of coal-bed methane. A graph of permeability versus facies type can be constructed as shown in Figure 4. When a well is to be sunk for the extraction of coal-bed methane or holes are to be drilled in advance of the mining face, one can obtain an idea of the permeability, and therefore the flow character, by identifying the facies type and reading the permeability from the graph.

In general, it can be concluded that the methods discussed can be useful in characterizing the flow in one specific location, but more work is needed to more fully define the relationship between facies type and permeability, especially with reference to the influence of macro-structures such as joints, fractures, and discontinuities. A more detailed microscopic study might delineate the borders between the different types of facies more conclusively, and so enable a better relationship between facies type and permeability to be determined.

Acknowledgements

The authors thank Rand Coal (Pty) Ltd for making the core available and the University of Natal, Durban, for financial support throughout the project. ◆