PRINCIPLES, PRACTICE AND APPLICATIONS OF LABORATORY MINIPERMEAMETRY

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Abstract Laboratory minipermeametry provides a rapid, non-destructive measurement of permeability which is at least as accurate as conventional Hassler-sleeve measurements and several orders of magnitude cheaper. A high level of experimental precision is attained by automation of all measurement functions including positioning of the minipermeameter probe. Automation gives rapid return on investment in terms of time saved. Conversion of minipermeameter flowrates to mD values is recommended in two ways, by minipermeametry and Hassler-sleeve measurement on standard homogeneous core plugs, and by use of an analytical solution. Core handling procedures can be improved to optimalise conditions for minipermeametry, which at the same time enhance geological description and cause less core damage. Minipermeametry has the potential to supercede 1″ core plugs as the routine method for characterizing permeability in cores. Measurements made on dense sampling grids resolve fine scale heterogeneities not visible on CT-scan images. The low cost and rapidity of minipermeametry permits collection of large numbers of measurements which form statistically significant data sets, and give an accurate impression of reservoir heterogeneity. We believe that improved characterization of core permeability contributes directly to improved reservoir management.

INTRODUCTION

Minipermeametry has been used in the oil industry since the late 1960's (Eijpe and Weber, 1971) without becoming in any way a standard experimental method in core analysis or reservoir characterisation. We will not debate why minipermeametry has not become an industry standard but rather, attempt to document why and how it should become so. We believe that laboratory minipermeametry can make important contributions both as an improved methodology within experimental petrophysics and as a source of data invaluable in routine reservoir characterisation. Probably the two main attractions of minipermeametry in experimental petrophysics are that the measurements are non-destructive and cheap. In this paper we document the optimal conditions for minipermeameter applications and propose several new routines for core handling.

Many of the advantages brought about by optimalising the conditions for minipermeametry have a direct effect on the ultimate usefulness of the data in reservoir characterization. It seems to be accepted that routine core plug measurements are almost certainly not taken at a sampling density appropriate for characterizing permeability distribution (Allen et al., 1988). However, little has been done to investigate what suitable sampling densities are, or, what uncertainty arises from the predictions made about permeability distribution and averaging based on the ″inappropriate″ sampling density of core plug data. We provide examples of the enhancement of reservoir descriptions made possible by obtaining minipermeameter data at higher measurement densities than core plug data and discuss the application of these data for prediction of reservoir behaviour.

Documentation exists of the effects of bioturbation (Weber, 1986) and sedimentary lamination (Hurst and Rosvoll, 1990) on permeability characteristics. Investigation of such features using manual instruments is, however, tedious and prone to error. Automation of minipermeameters makes amenable rigourous investigation of any small-scale heterogeneities present and assessment of their influence on reservoir quality. Within the limits of the continuity of core samples, an approximately continuous log of permeability data can be collected.

Experimental procedures require standardization before minipermeametry to is accepted as a routine method in core analysis. Here, we list the requirements of a successful laboratory minipermeameter and explain how these requirements are attained in practice. In addition, some changes in core handling procedures are proposed which provide optimal conditions for minipermeametry and geological characterization of core material. Finally, some applications of minipermeameter data in reservoir characterization are presented and their advantages discussed.

PRINCIPLES

Minipermeameter Description

In its simplest form, a minipermeameter is no more than a measuring probe which is pressed against the surface of a sample while flowing gas through an aperture into the sample. When gas flowrate and pressure are judged to have reached steady-state, they are recorded and the measurement is complete.

As minipermeameters are both simple and rugged, it possible to develop field-portable systems (Daltaban, et al. 1989; Chandler, et al. 1989) which are capable of operating with a high degree of accuracy. If however, laboratory application is given priority and minipermeameter data are to be regarded as a supplement, or even a replacement, for core plugs, robust precision instrumentation is a requirement. Ultimately, to be regarded as an industry standard a laboratory minipermeameter should be capable of producing permeability data which are at least as precise and accurate as measurements made on core plugs using conventional Hassler-sleeve apparatus. The following requirements are proposed.

1. As the flowrate for a given gas pressure is very sensitive to variations of the internal area of the probe (the cross-sectional area of the aperture through which the gas is flowing adjacent to the sample), the probe must be applied with a constant force and a constant orientation to the sample. The probe tip should be made of material that does not deform appreciably throughout a measurement series. It follows that probe tips should be checked, replaced and recalibrated at regular intervals.

2. Measurement should be non-destructive. Lowering of a probe onto a sample surface should be damped and adjustable over a range of accurately controlled application forces. Variation of probe geometry and application force allows optimal measurement conditions to be defined for samples with all levels of consolidation.

3. As minipermeameter measurement is non-destructive, i.e. makes no hole or other damage to the core, it is possible to collect measurements on very dense sampling grids. Therefore, it is important that a minipermeameter probe can be placed and subsequently re-placed at measuring points with a high degree of precision while being able to record the position of each point. Accurate placement of the probe on measurement points is important for two reasons. Firstly, so that the experimental precision can be evaluated by repeating measurements. Secondly, so that the significance of small-scale geological features can be related to variations in permeability.

4. The same level of accuracy in the measurement of flowrates and pressures is required in minipermeameters as in conventional permeameters. Simple enough if equivalent instrumentation is used.

PRACTICE

Instrumentation

After a period of experience with a laboratory-based manual minipermeameter, it was decided that in order to make further progress with minipermeametry in reservoir characterization applications, and to be able to offer minipermeametry as a service inhouse, it was necessary to develop a fully automatic version.

The Statoil automatic minipermeameter (Figure 1) was designed primarily to accommodate the 1m long sections of centre cut core that come mounted on wood or in aluminum trays. Maximum sample size is 100cm (length) x 25cm (width) x 40cm (height). The sample is secured, if necessary, to an x,y-table (heavy steel construction giving excellent stability). Two heavy duty stepping motors are used to move the table. This gives an accuracy in positioning on the order of 0.01mm, and although this kind of accuracy is not required for routine minipermeametry (1mm is probably sufficient), high accuracy is important in tests involving repeated measurements.

Measurements are made on a regular orthogonal grid. Grid limits and spacing, which can be different in the two directions, are defined at the outset. Practice so far has been to measure at 0.5, 1 and

2 cm intervals along the length of the core, and at 1 or 2 cm intervals across, depending on lithology and physical state of core. An optical sensor is used to detect sample edges, breaks in core and areas with relief likely to inhibit accurate measurement. This ensures that measurements only are performed on undamaged portions of the sample at a pre-specified distance from any edge.

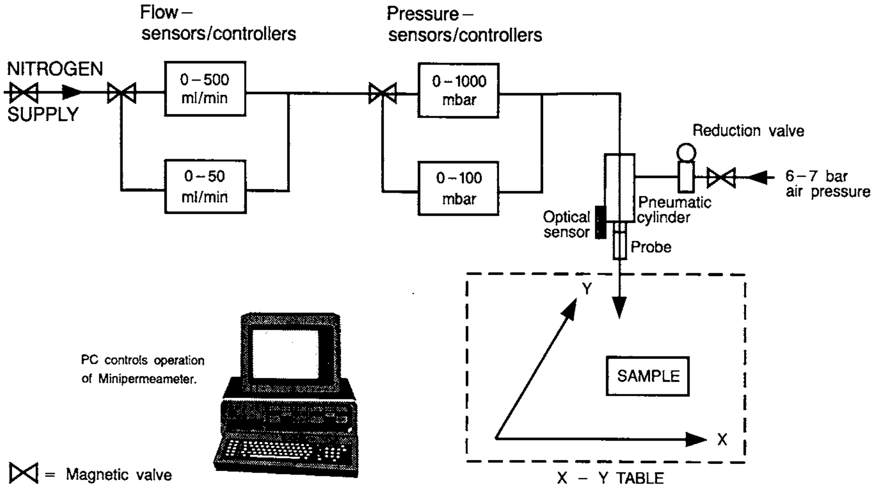

FIGURE 1. Technical layout of automatic laboratory minipermeameter

The probe is forced against the sample by means of a pneumatic cylinder. The cylinder pressure is controlled by a high-grade pressure regulator, while a pressure transducer indicates the actual working pressure. This ensures a repeatable and accurately controlled application force. The tip-seal is made from soft rubber enabling the use of relatively low application forces. A force of approximately 25 N is used with a probe tip with inner diameter 3.4 mm and outer diameter 6.6 mm. Tests have shown this to be more than sufficient force to to ensure a good seal. By comparison, forces of 100 N or more have to be used with "O"-rings of similar size, which may damage poorly consolidated samples.

The measurement itself is made with nitrogen gas at constant pressure. In principle, any combination of flowrate and pressure may be used as long as their relation to permeability is known. However, as this relation may be complicated to define accurately due to factors such as gas slippage, high velocity flow effects, inhomogeneities at the measuring point, and possible fluid saturations, it is recommended that either flowrate or pressure are kept constant and that variations are measured on the other variable. Thereby, at least relative variations in permeability are measured reliably. The main advantage in using constant pressure is that it allows considerably faster measurement than is possible with constant flowrate. At present a measurement takes from thirty to ninety seconds to complete depending on permeability.

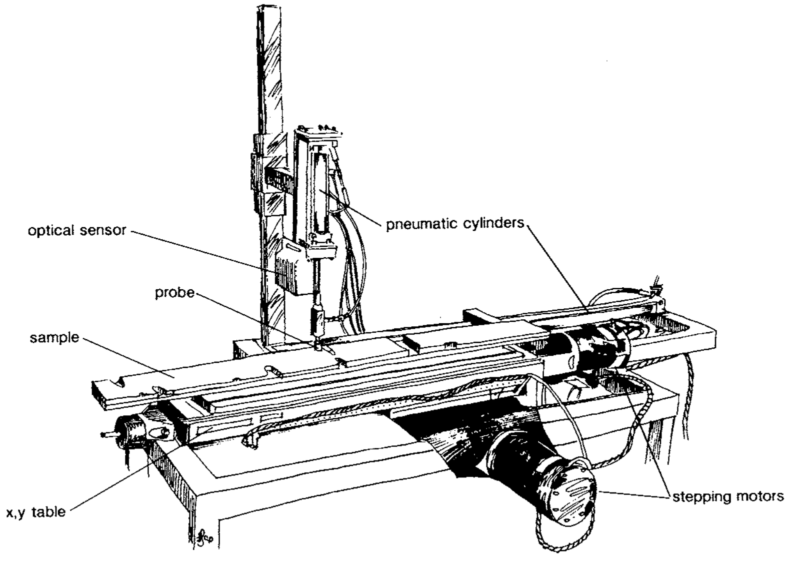

FIGURE 2. Sketch of Statoil's automatic minpermeameter.

In practice, two pressure sensors/controllers are used to supply constant pressure in appropriate steps from 10 to 900 mbars. Two massflow meters/controllers cover the range 0 to 500 cc/min. This corresponds to a measurable range in permeabilities from 1mD to 15 D with the two probes currently in use. Accuracy is dependent on calibration of the sensors, but better than 3% relative uncertainty over most of the measurement range is realistic. Repeatability has been determined to be better than 1%. Flowrate is measured at "steady state," and together with pressure and position, is recorded on disk by the PC (IBM-AT equivalent) that controls operation of the minipermeameter.

The end result (Figure 2) is a fully automatic minipermeameter which, after approximately 20 minutes for mounting the sample and selecting an appropriate probe and measuring conditions, can run, in principle, for days without supervision. So far, the longest continuous run has been about 4000 logged points in 44 hours.

Calibration

Minipermeameter flowrates can be converted into permeabilities in three different ways.

1. Comparison with core plug permeabilities measured on the same interval.
2. Measurement with the minipermeameter on standard ″homogeneous″ core plugs which have known permeabilities and thus, derivation of a relationship between minipermeameter flowrates and permeability.
3. Use of an analytical solution.

Comparison with core plugs

In so far as any routines exist for minipermeametry, comparison between core plug and minipermeameter data measured on the same interval is probably the most common method of calibration. Some problems exist with the method. Firstly, minipermeameter measurements are not made at the positions where core plugs are taken, thus making direct comparison of the measurements of uncertain value. This problem increases proportionally with respect to the degree of heterogeneity of the material. The problem can be overcome if minipermeameter measurement preceeds core plugging, or if minipermeameter measurements are made on the core plugs after cleaning and drying. This last procedure gives in addition an indication of the difference between untreated core and cleaned and dried core. Secondly, the degree of heterogeneity within most core plug samples often gives poor correlation between permeability and flowrate (Figure 3a). If the plugs are reasonably homogeneous a better correlation is obtained (Figure 3b).

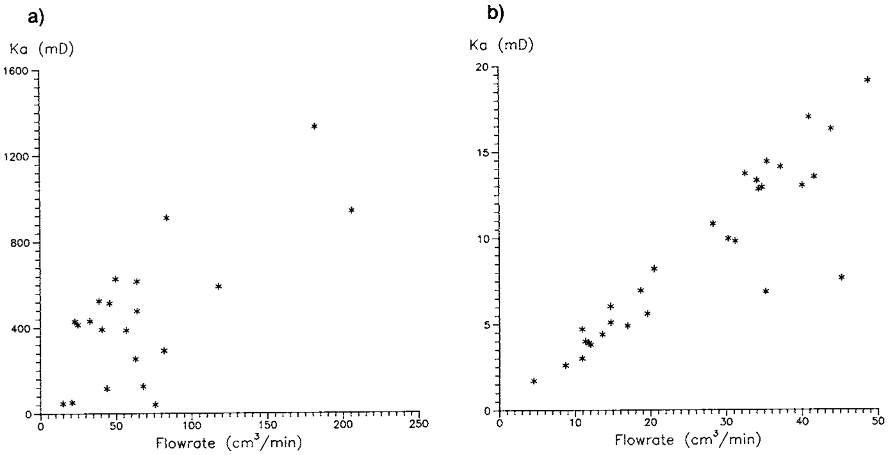

FIGURE 3. Cross-plot of minipermeameter flowrates against Hassler-sleeve data (Ka) for plugs from a heterogeneous reservoir (a), and a homogeneous reservoir (b).

Calibration with homogeneous core plugs

A collection of "homogeneous" core plugs is required which has a wide range of permeabilities. For any lithology a set of optimal measurement conditions (probe geometry, application force, gas pressure) may be defined and the flowrate measured at these conditions on each end of the plug. To get a statistically robust estimate of the average flowrate, (and concurrently a measure of the heterogeneity of the "homogeneous" plug) a number of measurements on each end should be made, for example, 3x3 or 4x4 over the central area of the plug.

Collection of "homogeneous" core plugs is not a trivial task. Hurst and Rosvoll (1990) eliminated heterogeneous samples using CT-scanning. Subsequently, further apparently homogeneous samples were eliminated when average permeabilities ($\overline{k}_{geo}$) measured on each end of core plugs (c.f. Cadman, 1984) proved to be significantly different. Similarity between arithmetic, geometric and harmonic mean values for ends of core plugs is, of course, a good indicator of sample homogeneity with respect to minipermeameter measurements. Examples of calibration measurements on a series of homogeneous plugs are given in Table 1. Typical correlations between flowrate and permeability show the high level of correlation possible using this method (Figure 4).

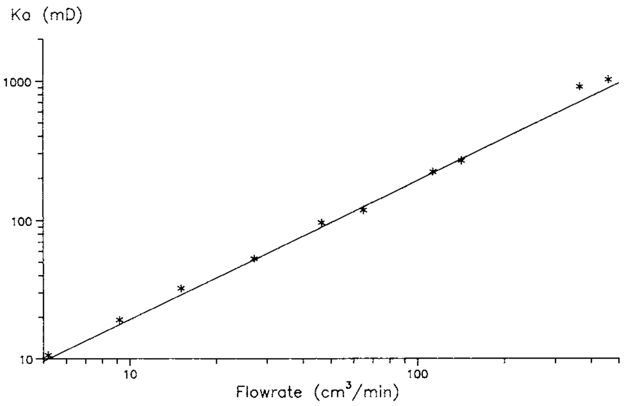

FIGURE 4. Average minipermeameter flowrates plotted against Hassler-sleeve permeability (Ka). The best-fit line is derived from equation (1), K = 1.92 × q.

TABLE 1 Average flowrates measured on homogeneous plug samples. Ka = Hassler-sleeve air permeability; ARIT, GEO, HAR = arithmetic, geometric and harmonic means respectively; G/H = harmonic mean of the geometric means of end A and B.

	END A			END B				
K_a	ARIT	GEO	HAR	ARIT	GEO	HAR	ARIT	G/H
5.9	6.8	6.8	6.7	8.4	8.4	8.3	7.6	7.5
10.6	14.1	14.0	14.0	13.8	13.8	13.8	14.0	13.9
12.1	12.3	12.2	12.2	11.6	11.5	11.5	12.0	11.8
19.1	22.2	22.1	22.0	18.5	18.4	18.3	20.4	20.1
32.3	29.2	28.4	27.5	35.6	35.1	34.6	32.4	31.4
53.0	61.3	61.2	61.2	63.9	63.8	63.8	62.6	62.5
96	108	107	107	105	104	104	107	106
118	161	160	160	156	155	155	159	158
221	239	236	232	239	234	228	239	235
265	272	271	270	311	310	309	292	289

Analytical solutions

An analytical solution for minipermeameter response has been proposed by Goggin et al. (1988). A geometrical factor which is determined from sample dimensions and tip-seal size is introduced into a modified form of Darcy's equation. Neglecting gas slippage and high-velocity flow effects, the permeability measured with a minipermeameter is calculated as:

$$K_{mp}\,(\mathrm{mD}) = \frac{2\,q\,\mu\,P_0 \times 10^3}{a\,G_0\,[P_1^2 - P_0^2]} \qquad (1)$$

where
P_1 = injection pressure (atm)
P_0 = atmospheric pressure (atm)
q = volume flowrate at P_0 (cm^3/s)
μ = gas viscosity (cp)
a = internal tip-seal radius (cm)
G_0 = geometrical factor

G_0 was estimated from Goggin et al. (1988, Figure 5) for the two probes, "small" and "large", (with inner and outer diameters of 3.4mm and 6.6mm and 6.1mm and 10.1mm respectively) currently in use. The average flowrates on both ends of a set of 17 homogeneous plugs were measured, as described above, with both probes at injection pressures of 10, 90 and 400 mbars. K_{mp} was calculated from equation (1) and compared to measured Hassler-sleeve permeabilities, Ka (correcting for gas slippage at P_1 = 400 mbars, and excluding measurements where high-velocity effects might have been present). The following ratios ± one standard deviation were calculated:

K_{mp}/Ka (large probe, P_1 = 400 mbars) = 1.01 ± 0.10 9 samples
K_{mp}/Ka (large probe, P_1 = 90 mbars) = 0.97 ± 0.05 8 samples
K_{mp}/Ka (large probe, P_1 = 10 mbars) = 0.89 ± 0.07 7 samples
K_{mp}/Ka (small probe, P_1 = 400 mbars) = 0.83 ± 0.11 10 samples
K_{mp}/Ka (small probe, P_1 = 90 mbars) = 0.82 ± 0.12 6 samples
K_{mp}/Ka (small probe, P_1 = 10 mbars) = 0.78 ± 0.06 7 samples

Taking into account experimental error in both Ka and K_{mp}, there is good agreement between equation (1) applied to the large probe and the experimental data. Figure 4 shows these data for P_1 = 90 mbars and $K_{mp} = 1.92 \times q$ as calculated from equation (1). High-velocity effects might account for the slight deviation from the straight line seen for the two most permeable plugs.

The situation is different in the case of the small probe, where equation (1) gives permeabilities approximately 20% too low. The only difference in the two experimental situations was the tip-seal dimensions (the application pressure = application force / tip-seal area was roughly equal), and although it is conceivable that this is the source of error, further investigation is necessary. Figure 5 shows experimental data for the small probe at $P_l = 90$ mbars. $K_{mp} = 3.60 \times q$ as calculated from equation (1) is shown together with a weighted ($1/Ka^2$) linear fit giving $K_{mp} = 4.57 \times q$. In addition a second degree polynomial fit (as suggested by Forchheimer, 1901) is shown which gives a better fit at high flowrates.

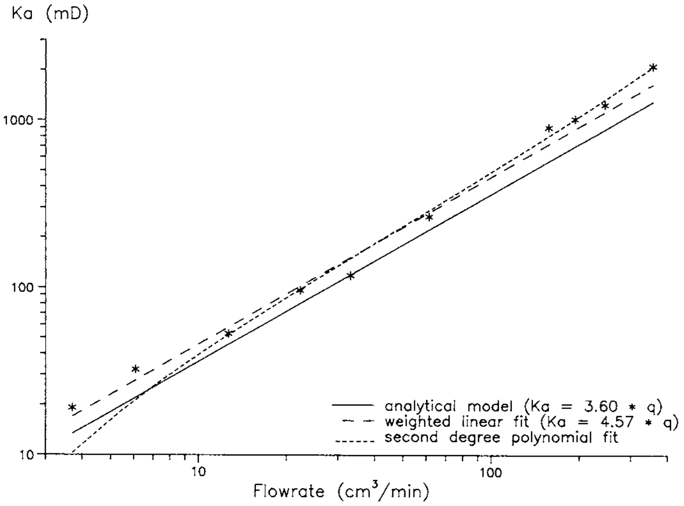

FIGURE 5. Average minipermeameter flowrates plotted against Hassler-sleeve permeability (Ka).

Sample Preparation

Few data regarding sample preparation are published, although several "rules of thumb" seem to be well-known. In general, as little treatment of samples as is possible is recommended prior to measurement. Minipermeameter probes can be used with equal effect on cut and fractured surfaces, provided the fractured surfaces are reasonably flat (c.f. methodology for preparation of rock faces for field minipermeameter measurement (Lewis, et al., in prep.). Indeed probe geometries and rubber seals can be designed to function on a wide variety of irregular and arcuate surfaces.

The effects of residual hydrocarbons on measured flowrates is probably of greatest concern. Cadman (1984) concluded that, "core cleaning increases permeability but the general pattern of permeability variation remains the same." On freshly cut core the effect of partial water saturation should be taken into account. Minipermeameter measurements were performed on 5m of freshly cut core from a North Sea well. Permeabilities derived from minipermeameter measurements (K_{mp}) on fresh core and, the same core after standing in room conditions for 1 month, are plotted against Hassler-sleeve measurements made on core plugs from the same centre-cut section (Figure 6). The effect of drying on permeability is pronounced for the low permeable material (2-20 mD), while no significant effect is seen on the material with a permeability in excess of 100 mD.

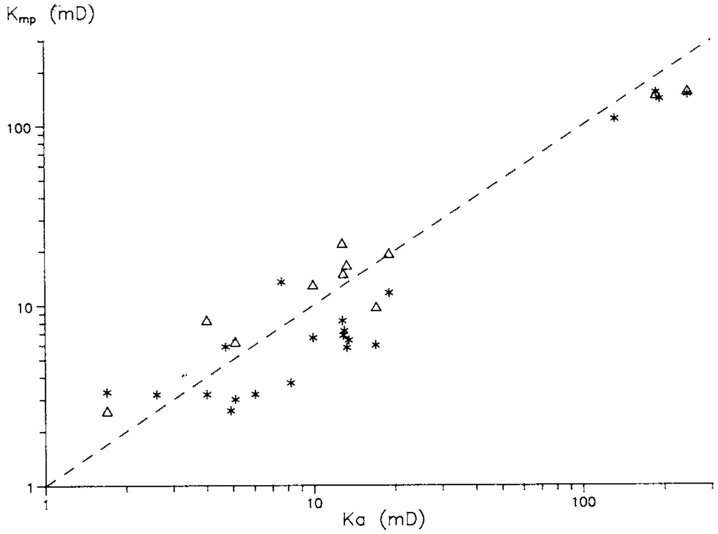

FIGURE 6. Comparison of Hassler-sleeve measurements (Ka) on cleaned core plugs with minipermeameter measurements; first on fresh (*), subsequently dried (△), core.

Effects of sample treatment on permeability measurement is a problem common to conventional methods and minipermeametry, and beyond the scope of this paper. Ultimately, the merits of conventional methods and minipermeametry will not be decided by whether measurements are made are treated or untreated samples, but by the success with which the data are applied in reservoir characterisation.

Experimental Procedure

As laboratory minipermeameters are readily adaptable to measurement on a wide range of materials, experimental procedure is much dependent on the task at hand. If however, minipermeametry is to be applied in a routine manner similar to, or in addition to, present-day practise with core plugs, some guidelines may be defined. Additionally, as minipermeameter studies tend, at present, to be a supplement to conventional routines, measurements are made on cores which are not optimal for minipermeametry.

Although minipermeameter measurements are considerably cheaper and faster than Hassler-sleeve measurements, the main reason for using a minipermeameter should not be cost-reduction. Statoil's initial reason for developing minipermeameters was to examine the significance of sedimentary facies and structures on permeability (Hurst and Rosvoll, 1990), an approach which may allow descriptive geological data to obtain a quantitative significance. Such quantification requires that measurements are collected on dense sampling grids so that sufficient data are available to evaluate the control of sedimentary characteristics on permeability distribution. Results of preliminary work conclude that conventional routines for collection of permeability data from cores provide too little data to assess the significance of sedimentary structures on permeability distribution (Hurst and Rosvoll, 1990).

Regular sample spacing is important if sampling objectivity is to be maintained and statistical manipulation of the data possible (Journel and Huijbregts, 1978). As a standard procedure, it is recommended that minipermeameter data are collected on orthogonal grid patterns with each measurement at 1 or 2cm intervals. Sampling on regular grids is also amenable to automation. If the core is judged to be geologically homogeneous, and is little disturbed by previous sampling (crushed and missing intervals), a 2cm interval is usually acceptable. If the core is in poor condition and/or strongly laminated, a tighter sampling interval is appropriate.

Slabbing, core plugging and storing of core reduces the value of the core for minipermeametry. On a cut surface from a 1 metre length of 10cm diameter core it is in theory possible to make 250 minipermeameter measurements on a 2x2 cm grid (this excludes a 1cm rim around the edge of the sample to avoid the possible effects of leakage during measurement). In practise, sample damage reduces the total possible measurements dramatically (Figure 7). Removal of 1.5″ and 1″ diameter core plugs are all demonstrated to reduce the continuity of core samples.

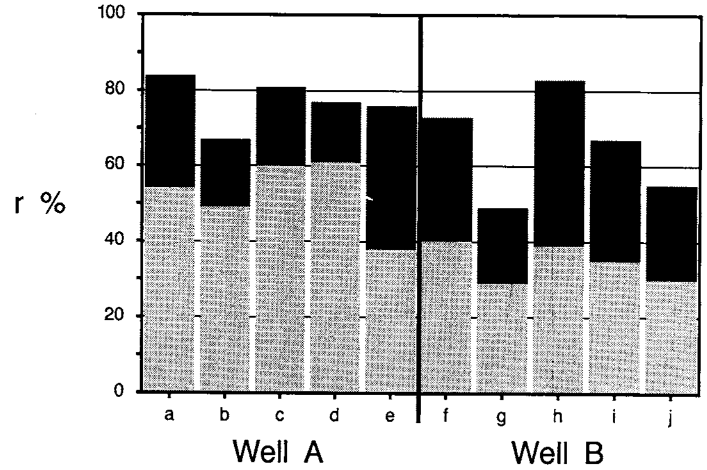

FIGURE 7. Area of core available (r %), on metre lengths of core, for minipermeameter measurement after extraction of 1.5″ diameter core plugs and slabbing (dark hatching), and after extraction of 1.5″ and 1″ diameter core plugs and slabbing (light hatching). Well A is more consolidated and less laminated than Well B.

A further restriction to sampling is the presence of edges and breaks in core. Hurst and Rosvoll (1990) considered that no measurements nearer than 15mm to edges and breaks should be made with the probes then in use. Continued experimental work has shown, however, that measurements considerably closer to a boundary may be made without boundary effects influencing the measurements.

These experimental results confirm the calculations made by Goggin et al. (1988).

For example, in a test using the two probe tips described earlier, measurements were made on the ends of two core plugs, one approximately 50mD, the other approximately 1D. Subsequently, 8-9mm was cut off the end of each plug and the measurements were repeated, first with the back freely exposed to air, then coated with impermeable silicon paste. No significant differences in flowrates were detected. The same kind of experiment was performed with respect to an edge. Again, no effects were measurable with the center of the small probe 4mm from the edge, and likewise for the large probe 8mm from the edge. Even with the large probe 4mm from the edge, i.e. with half the width of the tip-seal over the edge, the measurable effect was less than 5%. Despite the lack of evidence for leakage near sample edges, we choose under normal circumstances, to stop sampling 6-7mm (with respect to the outer rim of the tip-seal) from all edges.

New core handling routines

To optimalise conditions for minipermeameter measurement, and at the same time to fulfill the needs of conventional core analysis, new core handling routines are necessary.

A. If minipermeameter measurements are made circumferentially, removal of drilling mud and areas of drill-damaged core are likely to be the only treatment necessary prior to measurement (Figure 8a), assuming that no solvent treatments are deemed necessary. Following measurement (Figure 8b), core plugging and slabbing of the core can follow established procedure (Figure 8c,d).

B. If minipermeameter measurements are made on a cut surface, which is at present the norm, several changes to routine are recomended. Prior to slabbing, only core plugs used for special core analysis (1.5″ diameter) are taken (Figure 9a). The core is then divided into two almost equal pieces (Figure 9b). Minipermeameter measurements are made on the cut surface of the larger of the two parts (Figure 9c). After measurement, slabbing of core proceeds following normal routines (Figure 9d). The surface on which minipermeameter measurements are made should be preserved as the surface used for geological description. If 1″ diameter core plugs are required they are taken from the remaining half-cut (Figure 9e).

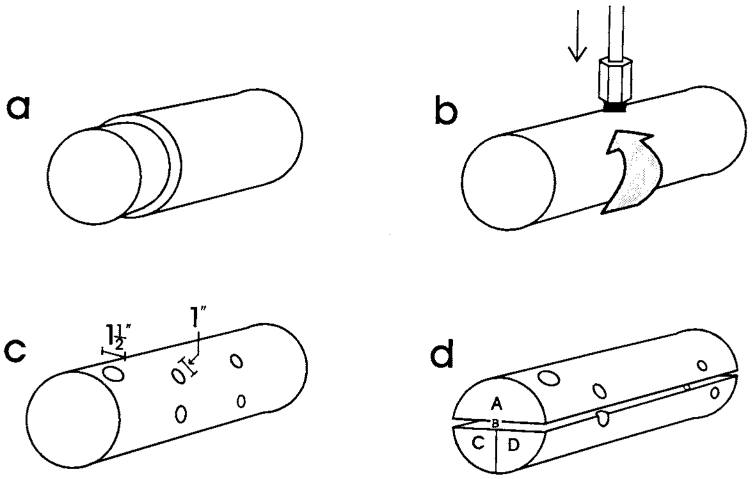

FIGURE 8. Procedure for core handling if minipermeameter measurements are made circumferentialy. a - removal of damaged zone, b - minipermeameter measurement, c - extraction of core plugs, d- core slabbing.

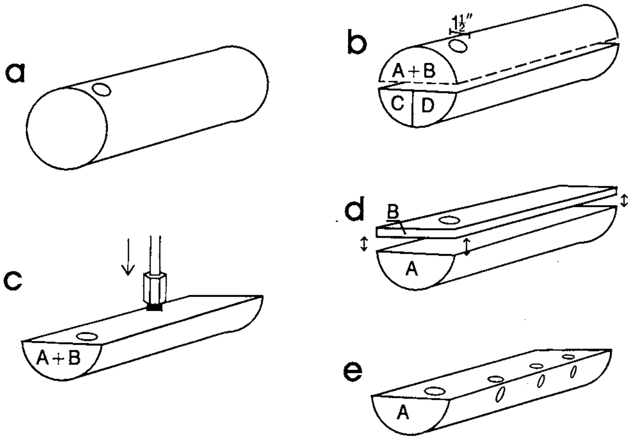

FIGURE 9. Procedure for core handling if minipermeameter measurements are made on a central slabbed surface. a - extraction of 1.5" diameter core plugs, b - slabbing into three core segments A, C and D, c - minipermeameter measurement, d - slabbing of B cut, e - extraction of 1" diameter core plugs.

Procedure ″B″ is not only advantageous for minipermeametry, but, causes less damage to the core prior to permeability measurement and less total damage to the core caused by plugging. Additionally, the preserved surface for geological description is not only the surface on which permeability measurements are made, but, is less disturbed, and therefore more amenable for geological study.

APPLICATIONS

Core analysis

Minipermeameter measurements should initially be regarded as a supplement to conventional core data. However, it is not unreasonable to question to what extent minipermeameter measurements could replace 1″ diameter core plugs as the basic source of core permeability data.

In our experience more than two orders of magnitude as many minipermeameter measurements can be made for the cost of one core plug measurement, if an automated system is used. It would, however, be wrong to give priority to cost-cutting when recommending minipermeametry. Rather, the access to minipermeameter data should be seen as a method for increasing the amount of information available about core permeability without increasing costs. If however, it is possible to reduce the number of permeability measurements on 1″ diameter core plugs by using minipermeametry, both experimental and storage costs may be reduced.

The non-destructive nature of minipermeametry is advantageous in many respects. Better preservation of core is assured. If core plugging is minimised or superceded by minipermeametry, geological core description can be made on undisturbed core surfaces. Equally, better preservation of core means that good quality samples are available for other types of core analysis.

CT-scan images, which are in increasingly common use for special core analysis (Wellington and Vinegar, 1987), provide an interesting comparison with permeability maps constructed from minipermeameter data (Figure 10). Minipermeameter data can be collected at a density comparable to the resolution of a CT-scanner (approximately 2mm) so giving a similar scale of resolution. In the example, the CT-scan images are focussed approximately 1mm from the surface of each cut face, and as expected, reveal similar sedimentary heterogeneities. In fact, the minipermeameter data reveal a greater degree of heterogeneity than the CT-scan images. With calibration, it should be possible to correlate the density/porosity contrasts revealed on CT-scan images with permeability, and so provide an improved link between images of flow experiments performed on CT-scanners and permeability.

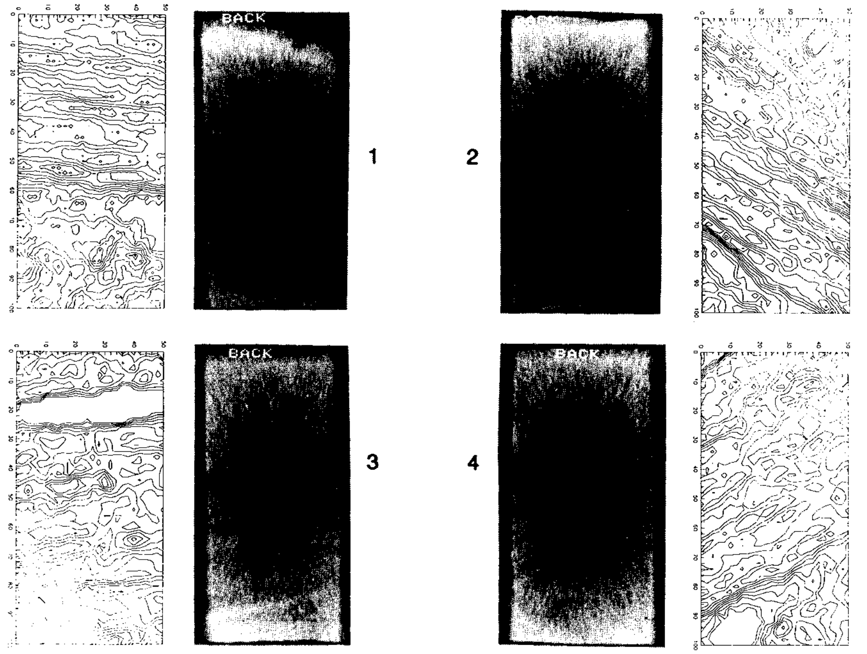

FIGURE 10. Comparison of maps of minipermeameter data from four orthogonal faces with CT-scan images taken from 1-2mm behind the sample surface. Sample dimensions are 10 x 5 cm. A 2mm sampling grid gives a total number of measurements per side = 1326.

Permeability anisotropy can be evaluated either by measurement on the circumference of cores or, by measurement on different slabbed faces (Hurst and Rosvoll, 1990). Of particular interest in this respect, are the markedly different permeabilities present on adjacent orthogonal sections (Figure 11a). Results of ANOVA testing (Davis, 1986) on the same data show that most of the variation in permeability present in the total sample population is attributable to differences between the faces rather than within each face (Figure 11b). These data are all from relatively homogeneous, large-scale cross bedded, quartzose sandstones. Despite their geological homogeneity up to 41% difference in mean permeability ($\bar{k}_g$) is present between adjacent faces (an average difference between adjacent faces of approximately 20%). It is unlikely that the orthogonal faces coincide with maximum and minimum axes of permeability, however, the variation of average permeability caused by sample orientation during measurement is probably of the order of 25%. Intuitively, with increased sample heterogeneity one would expect to find greater variation within each sample surface rather than between sample surfaces.

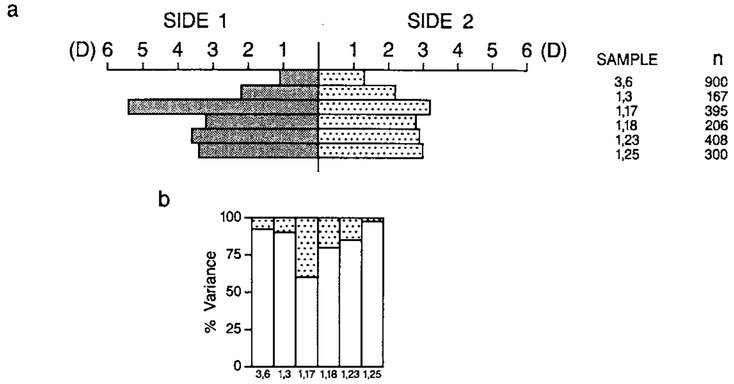

FIGURE 11. Permeability heterogeneity in large-scale cross bedded sandstones. a - variations in mean (geometric) permeabilities between orthogonal faces on the same sample; n = number of measurements approximately equally distributed between faces. b - ANOVA results for comparison of permeability variation between orthogonal faces of the same sample; grey shading denotes variation between faces.

Reservoir Characterisation

Core - wireline log correlation

Correlation of core with wireline log measurements is a major part of reservoir characterisation. Accurate correlation between these data holds the key to successful reservoir zonation and volumetric calculations. Jensen (1990) has shown that even if minipermeameter data give less accurate permeability measurements than core plugs, their greater sampling density gives a more robust correlation with (density) log data. Correlation between minipermeameter and log data is less sensitive to depth shifts than core plug and log data. Jensen's data give considerable cause for optimism with respect to the value of obtaining minipermeameter data rather than relying on plug data, particularly as his minipermeameter data are measurements taken at 10cm vertical intervals. Thus, even with a relatively sparse set of minipermeameter data improvements of core-to-log correlation are possible.

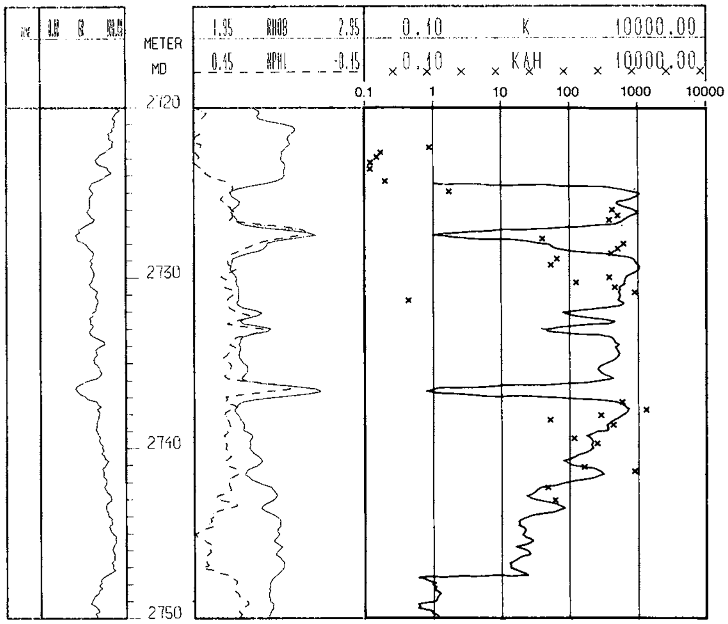

FIGURE 12. Typical core plug / log-derived permeability from a heterogeneous, strongly laminated sandstone reservoir.

Although average permeabilities can often be predicted from logs it is more difficult to detect and predict high and low permeabilities in laminated reservoirs (Figure 12). Definition of net sand is difficult because the logs cannot resolve 1-10 cm thick bedding. Minipermeameter data from the same interval reveal the degree of permeability heterogeneity present, and illustrate the inadequacy of the conventional data for characterising the reservoir (Figure 13a).

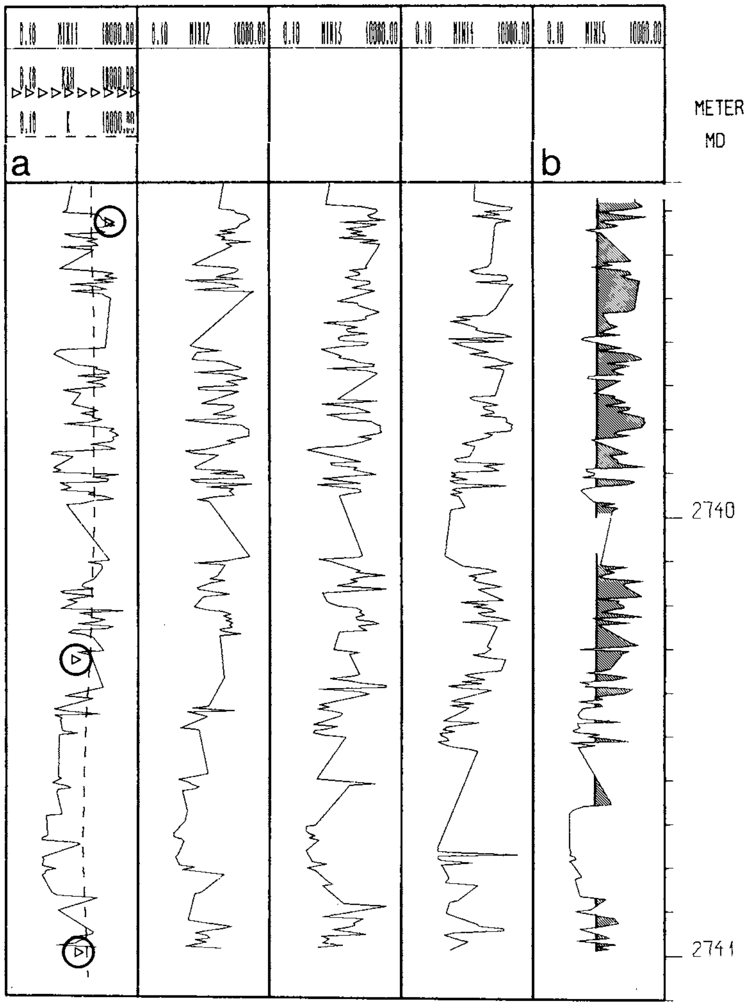

FIGURE 13. Minipermeameter data from part of the interval shown in Figure 12. Five vertical curves are plotted from data collected at 0.5cm vertical intervals. There is a 2cm space between the curves. a - The dashed line is the log-derived permeability curve, and the circles are horizontal plug permeabilities. b - Shaded areas are net sand defined as all intervals where permeability > 20mD.

Few core plug data are available because of the poor consolidation of the interval. Using the minipermeameter data, a value for net sand can be assigned by choosing an appropriate permeability cut-off, in this case 20 mD (Figure 13b). With a cut-off of 20mD a N/G ratio of 0.66 is defined from the average of the five minipermeameter curves as opposed to the value of 1.00, of an albeit shaly sand, from the conventional data. Both core plugs and logs fail completely to detect the 2 to 3 orders of magnitude variations in permeability actually present, and disguise the laminated nature of the reservoir.

In common with high resolution logging tools, minipermeameters enable identification and investigation of thin intervals, or even individual sedimentary structures, which are easily missed by low resolution logs. The potential of defining N/G from microresistivity data is documented (Sallee and Wood, 1984), however, derivation of permeability from the same data seems intangible. With the advent of borehole microscanners, which collect a high density of resistivity measurements from the borehole wall, detailed description of sedimentary layering is often possible (Luthi and Banavar, 1988). Sedimentary structures alone do not control resistivity contrasts and there is considerable potential for calibrating borehole images of resistivity with minipermeameter data (Bourke, et al., in press).

Sampling density

In all correlation procedures it is appropriate to evaluate the significance of the correlation, e.g. correlation coefficients for cross-plots of petrophysical parameters. It is however, unusual to evaluate "how many" data are required to characterize the permeability variation present in reservoirs. It may be that general practice is simply to accept intuitatively that routine core plugs do not provide a satisfactory sampling of permeability variation. However, it is relatively straightforward, using a simple statistical test (N_0, Wonnacott and Wonnacott, 1977) to estimate appropriate sampling densities within pre-defined confidence and tolerance levels. Hurst and Rosvoll (1990) found that even in apparently homogeneous sandstones sampling densities up to five times the experimental sampling density (5mm orthogonal grid) were required. No relationship was found between the average permeability of samples and N_0, although heterogeneous facies require the highest sampling densities.

N_0 values are calculated for a series of cross bedded and massive sandstones (Figure 14) where measurements were made on two orthogonal faces of each sample. From a geological point of view, there is a slightly alarming range of variation within what are visually apparantly homogeneous lithofacies, and also, often considerable variations from side-to-side in individual samples. Optimal sampling densities (d_I) are calculated for the same samples from N_0 such that,

$$d_I = \sqrt{\left(\frac{N_x}{N_0}\right) d_x}$$

where N_x is the number of measurements made and d_x is the measuring grid dimension used for data collection. For the cross bedded and massive sandstones in Figure 14, d_I of 9.7cm and 7.3cm respectively are needed to characterize the permeability variation present to within ±25% of the true permeability variation (Hurst and Rosvoll, 1990). In the light of these data it is unlikely that core plugs taken at single points at 25cm vertical intervals will give a statistically significant impression of the true permeability variation present.

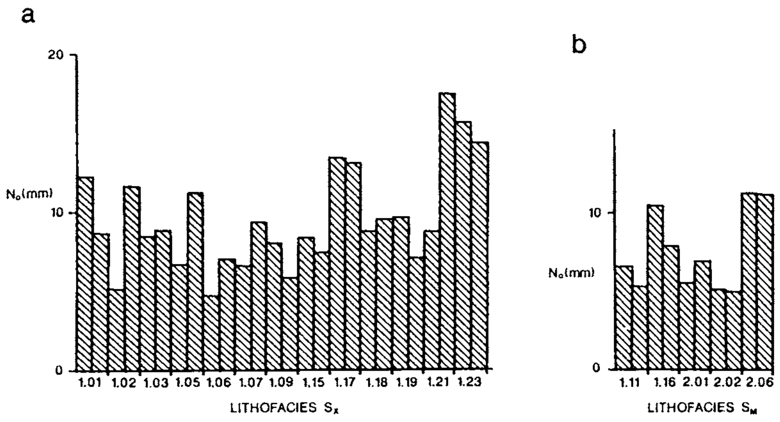

FIGURE 14. Results of N_O tests on measurements from pairs of orthogonal faces in homogeneous sandstones. a - cross bedded sandstones, b - massive sandstones.

N_0 testing assumes that all permeability measurements are independent. This is a simplification that need not be correct. Certainly, if permeability distribution is in some way organised, for example in concordance with sedimentary layering, independency cannot be assumed and a more appropriate statistical test which accommodates directional dependency, perhaps by using variograms, should be applied (Barnes, 1988). N_0 provides, however, a ″quick-look″ method which is probably adequate for examining permeability variation in cores.

DISCUSSION

Automation

Apart from alleviating the boredom associated with manual operation of minipermeameters, automation makes possible both considerable improvement in the control and accuracy of measurement, and cost reduction. Certainly, if digital flow- and pressure-meters/controllers are used, their capacity is only fully utilised if computer controlled. Likewise, accurate placement of the measuring probe and repeated measurements can only be achieved with a satisfactory level of reliability if automated. Direct transfer of flow- and pressure data to disc is not only convenient and not subject to error but, permits the recording of information related to individual measurements, e.g. time used to reach steady-state conditions, changes in conditions while approaching steady-state. Probably the main obstacle to widescale automation of minipermeameters is the tradition that minipermeametry is cheap, thus, the idea of investing in the necessary hardware and software is somewhat incongruous with that preconception. In practice, the investment needed to reach the technical level of Statoil's minipermeameter should easily be covered during the first six months of operation, even with costs per measurement one hundredth lower than Hassler-sleeve measurements.

Permeability Estimation

Our results for the conversion of minipermeameter flowrates/pressures to permeabilities using standard homogeneous core plugs give encouraging support to the validity of the analytical solution of Goggin, et al.(1988). Permeability may be estimated from equation (1) with appropriate corrections for gas slippage and high-velocity flow effects.

As the accuracy of permeabilities calculated from equation (1) are directly dependent on accurate measurements of the absolute values of pressure, flowrate and tip-seal dimensions, it is essential to have a set of standard homogeneous core plugs to use both as a check on equation (1) and as a separate means of calibration, at each set of different measurement conditions. If core treatment and saturation are cause for concern, additional minipermeameter measurements should be made on core plugs from the interval of interest. This will give both an indication of the effect of core treatment on permeability, and allow evaluation of the influence of heterogeneities in the core plugs on their Hassler-sleeve permeabilities.

Reservoir Characterisation

Ultimately, the make-or-break for any new method or data when applied to reservoir characterisation is measured by its effect on the estimation and accuracy of predictions of hydrocarbon recovery. In offshore operations, one of the main problems when making such predictions is the limited amount of well data available. In the North Sea this has resulted in unreliable prediction of key factors such as timing of water breakthrough and well decline, which in turn can give gross under- or over-estimation of recoverable reserves (van Oort, 1988). A frequent problem in measurement of core permeability is that, for a variety of reasons, thin (< 25cm) high and low permeability intervals are rarely characterized adequately. We have shown the capability of minipermeametry for resolving this problem.

Minipermeametry allows statistically significant volumes of permeability data to be collected, without excessive cost. The data improve the understanding of permeability distribution and allow more confident assignment of N/G values and zonation of reservoirs. Additionally, the data enable realistic statistical evaluation of data. For example, for evaluating and optimalising the permeability sampling density of specific geological or reservoir zones.

Minipermeametry has considerable potential for bringing closer the geological and petrophysical characterisation of well data. Indeed, geological description and zonation of core data is essential if evaluation of minipermeameter data is to be optimal. If core handling procedures are modified to enhance their suitability for minipermeametry as we have proposed, the quality of the material available for geological description is improved. On a more fundamental note, the capability of minipermeameters to collect data at a similar scale to that of descriptive geological units (i.e. sedimentary structures) enables the study of the relationships of those units to permeability distribution. This has particular significance with respect to the validity of geologically-defined "flow units" (Hearn, et al., 1984), which are intuitively interpreted to resemble sedimentary facies units in their geometry. Very few quantitative data exist however, to confirm this convenient assumption. In fact, there are many examples where the flow units responsible for establishing water breakthrough represent only small percentages of geological flow units, both with respect to thickness and volume.

CONCLUSIONS

1. Laboratory minipermeameters make non-destructive measurements of permeability which are at least as accurate as Hassler-sleeve measurements, and have a comparable level of precision.

2. Choice of probe geometry, accurate control of probe application force, and use of an appropriate seal on the probe tip, are essential steps for optimalisation of minipermeameter measurements.

3. Automation greatly enhances the use of minipermeametry in core analysis, allows a high level of experimental accuracy to be attained and maintained, and cuts labour costs. The relatively low cost of minipermeametry allows approximately two orders of magnitude more data to be collected than by using conventional methods. This enhances reservoir characterisation, in particular providing possiblities for quantification of geological description.

4. It is recommended that conversion of minipermeameter flowrates to permeabilities be done by calibration with standard homogeneous core plugs, either exclusively or in conjunction with the analytical solution expressed by equation (1).

5. New core handling routines are recommended if minipermeameter studies become commonplace. In particular, slabbing and extraction of 1″ diameter core plugs should be avoided prior to minipermeametry. Modification of core handling procedures benefits both geological description and petrophysical evaluation.

6. Minipermeameter data collected on a regular grid can be used to define net sand. This application is particularly useful in laminated reservoirs where conventional log and core measurements fail to resolve the heterogeneity present. In general, identification of permeability heterogeneity, and their quantification, are enhanced by obtaining minipermeameter data.

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