QUANTIFICATION OF PERMEABILITY VARIATIONS ACROSS THIN LAMINAE IN CROSS BEDDED SANDSTONE

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Abstract An automated precision probe permeameter has been used to investigate the influence on the flow properties of thin laminae in cross bedded sandstone. The material analysed is characterized by lamination, some easily visible and shown to have high permeability contrasts between laminae, but also more subtle lamination in material appearing virtually massive.

Because of the unconfined flowgeometry of the probe permeameter, the permeability of low-permeable laminae thinner than the diameter of the probe tip-seal will be overestimated. This is shown by having cubes cut parallel to the laminae. The permeability in three orthogonal directions have been measured conventionally in a core-holder and compared to probe permeameter measurements on the sides of the cubes. This method has also demonstrated and quantified permeability anisotropy on a scale smaller than the dimensions of the probe.

Probe measurements on plugs show that horizontal (Kh) and vertical (Kv) conventional plug permeabilities may give reliable information about the higher contrast lamination. With lower contrast lamination, local variations in permeability shown by the probe permeameter to exist even in visually very homogeneous material, make conclusions drawn from Kv and Kh more uncertain.

The results from the small-scale measurements have been combined with probe measurements on a 7 m interval of tabular crossbedded sandstone to estimate a probable permeability interval for the unit. Comparison of the permeability estimated from the core data with well test permeability shows reasonable agreement.

INTRODUCTION

Fluvial deposits are characterized by heterogeneities on several scales (Figure 1). A hierarchical classification of a fluvial reservoir, based on lithostraligraphic and sedimentological principles, provides a basis for a quantitative description of sand body geometry on different scales. In addition, this principle also gives the potential for an improved and simplified permeability characterization of the reservoir.

The aim of this study has primarily been permeability characterization on the lamina and facies level using a probe permeameter, while assessing the performance and resolution of the probe permeameter when measuring on laminated material. These measurements have been supported by conventional measurements on core plugs and a few measurements on core cubes. Finally, comparisons were made with well test data.

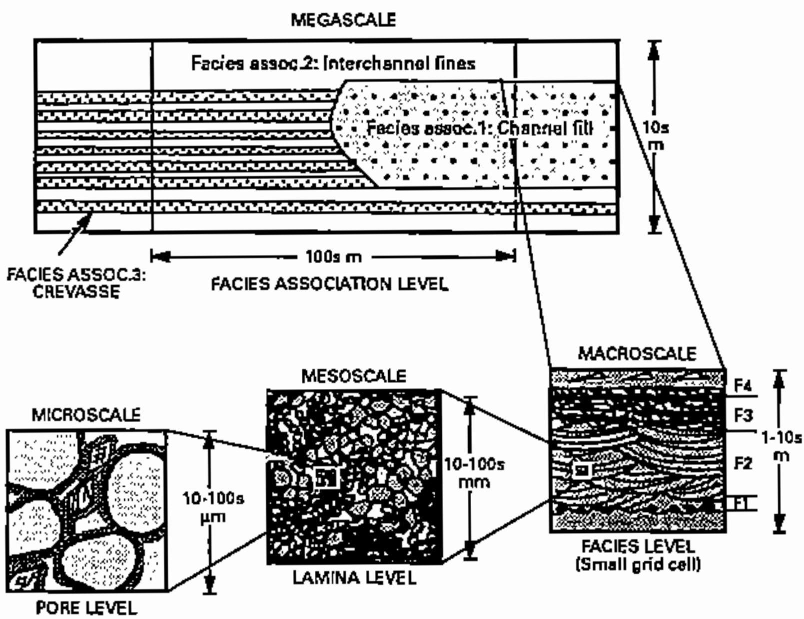

FIGURE 1 Levels of reservoir heterogeneity. Example is from a fluvial reservoir. Modified from Dreyer et.al. 1990.

The selected core material was from two wells in the late Triassic to early Jurassic Statfjord Formation of the Gullfaks Sør Field, a formation representing a braided fluvial environment (Steel and Ryseth, 1992).

The permeability analysis has been performed on lamina level both on distinctly laminated, and on more homogeneous material. In addition, permeability has been measured on a seven meter thick, tabular cross bedded sandstone unit (Figure 2). The tabular crossbeds were probably produced by downstream foreset accretion of a transverse bar, or a similar depositional macroform, corresponding to the architectural element "Downstream accreting macroform" as defined by Miall (1988). This type of sand body is classified as a macroscale unit (Figure 1). The unit chosen is interpreted to represent a downward accreting macroform, and is bounded at the top and bottom by low-permeable channel fill sediments. The well was tested by a perforation interval covering the tabular crossbedded sandstone unit.

One important characteristic of flow in crossbedded sandstones is the permeability anisotropy in the horizontal directions, parallel and normal to laminae. This anisotropy effect has been discussed by Weber (1972) for trough crossbedded sandstone.

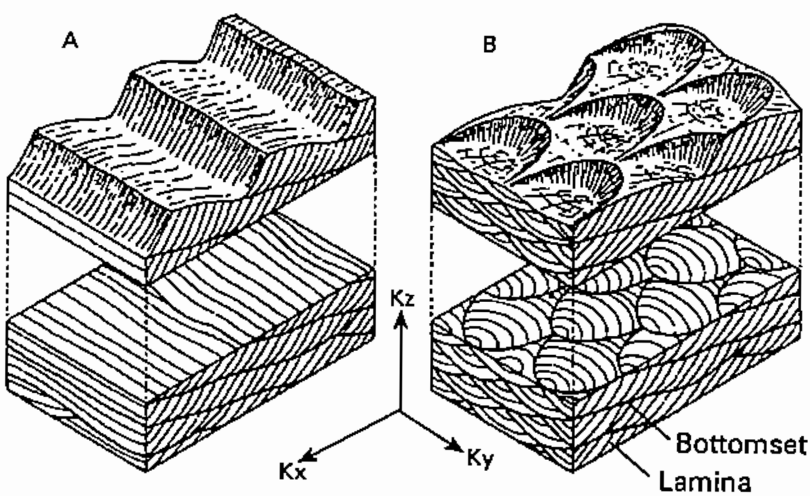

FIGURE 2 Block diagram showing tabular and trough crossbedding (Redrawn from Allen, 1984).

A similar anisotropy is also found in tabular crossbedded sandstone, where flow parallel to laminae is concentrated in permeable laminae, while flow in a direction normal to laminae must go through the fine grained low permeability laminae (Figure 2). Characterization of representative laminae is therefore important.

Individual tabular crossbeds are separated by low permeability bottomsets which act as vertical permeability barriers. Bottomsets in trough crossbeds are present only in the lower part of the trough, and therefore, do not act as vertical permeability barriers as in tabular crossbedded sandstone.

EXPERIMENTAL METHODS AND RESULTS

A fully automated probe permeameter was used for the series of measurements (Halvorsen and Hurst, 1990). For many of these measurements the probe permeameter was measuring either parallel or normal to low-permeable, thin laminae (Figure 3). The spatial resolution of the probe is determined by the size of the probe tip-seal which for these measurements had an inner diameter (id) of approximately 3.5 mm and an outer diameter (od) of approximately 7.0 mm (Figure 3a).

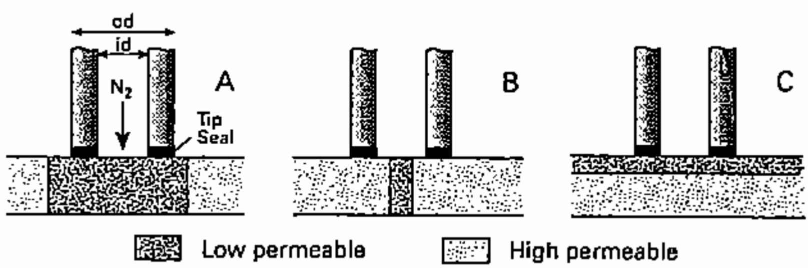

FIGURE 3 Probe measuring on thin, low-permeable lamina.

Figure 3a shows the calibration or normal geometry. Experiments (Halvorsen and Hurst, 1990) have shown that the lamina boundary may be quite close to the outer edge of the tip-seal without affecting the measured response. The geometry in Figure 3c is close to 3a. The flow must pass through low-permeable material, but for a shorter distance and partially in series with the high-permeable material. The probe response should be a harmonic mean of the two permeabilities modified by a geometric factor. In Figure 3b the geometry is closer to flow through parallel layers, and the probe response should be a modified arithmetic mean. In both cases the permeability of the low-permeable lamina will be overestimated by the probe permeameter.

Fine Grids

A series of regular orthogonal "fine grids" on uncleaned, half- or quarter-cut core were measured to determine the permeability variation in various lithofacies in the two selected wells. A fine grid typically had a size of 2-6 cm horizontally and 6-12 cm vertically, with a spacing between gridpoints in both directions of 1-4 mm.

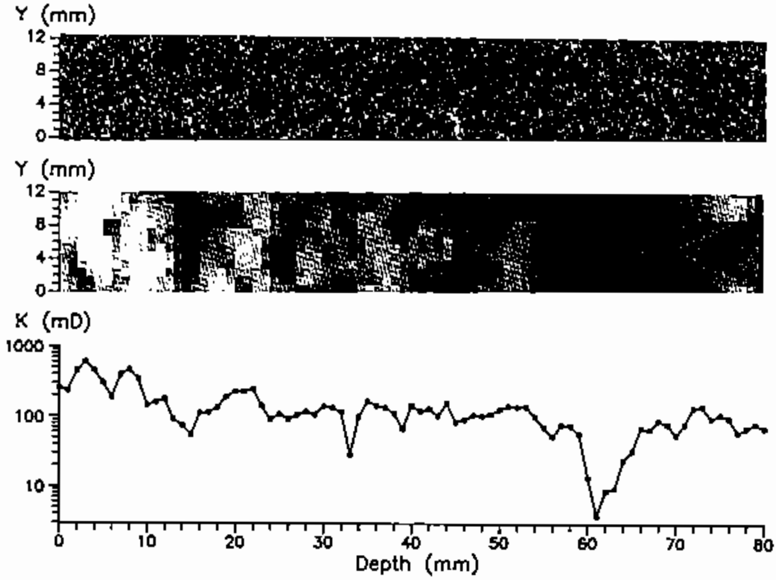

FIGURE 4 Example of permeability variation in a visually homogeneous sandstone. A density plot shows the spatial variation. Greyscale is proportional to log(K). Gridpoint spacing is 1 mm. A cross section taken at Y=6 shows magnitude of variation.

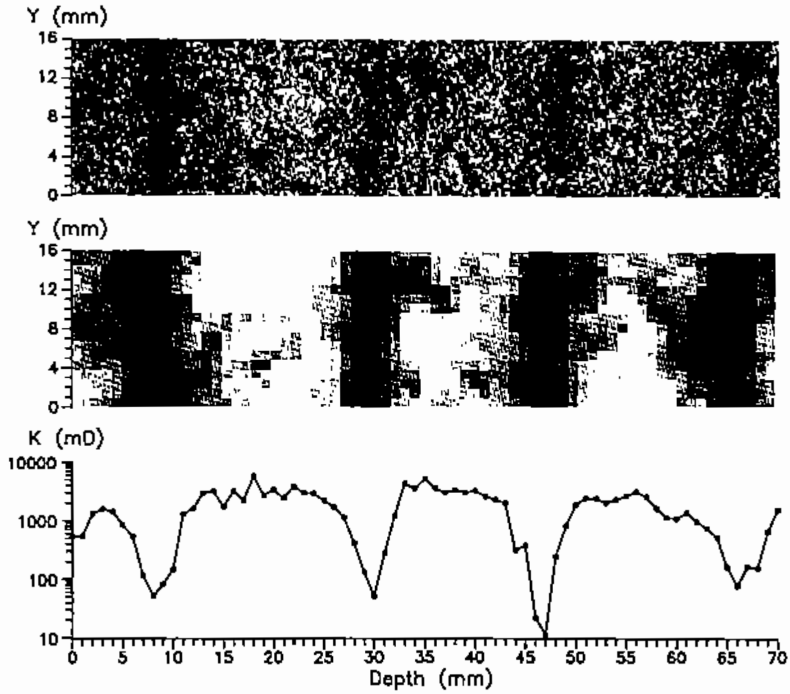

FIGURE 5 Example of permeability variation in a laminated sandstone. A density plot and cross section (Y=9) is shown.

Figure 4 shows more than two orders of magnitude variation in permeability over a distance of 8 cm in what visually is a homogeneous sandstone. Figure 5 shows an example of fine grid measurements on a well laminated sandstone. The presence of very fine grained, low-permeable laminae produces rapid, local permeability variations of about 2 orders of magnitude.

Probe Measurements on Core Plugs

The laminated sandstone shown in Figure 5 came from a 7 m interval of tabular crossbedded sandstone. The routine 1″ core plugs from this interval are approximately cut either parallel with (Kh, 23 plugs) or normal to bedding (Kv, 27 plugs). Applying

Darcy's law to beds in parallel or series, leads to the expectation that the arithmetic and harmonic mean of the probe measurements on the core plugs will give the best fit to Kh and Kv respectively. The plugs were measured with the probe permeameter at two points on each end-face, in addition to two measurements every 4 mm along the sides of the plugs; 12-14 measurements in all per plug.

The arithmetic, geometric and harmonic means of the probe measurements on each plug was calculated and the correlation coefficient for a linear fit between the set of each of these mean values and the set of conventionally measured permeabilities for the horizontal (Kh) and vertical (Kv) plugs respectively was determined (c.f. Halvorsen and Hurst, 1990). In addition, the mean value of the ratio (plug value)/(probe mean) was calculated for the horizontal plugs for each of the three mean values mentioned above. Likewise for the vertical plugs (Table 1).

The difference between the probe and plug permeability values is substantially greater for the vertical plugs compared to the horizontal. The greatest errors (an order of magnitude or more) occurred in five plugs each containing one or two very fine grained laminae, typically 2-4 mm thick, running through the plugs normal to the direction of flow. Suspecting overestimation of the permeability of these thin laminae, the five plugs were taken out of the data set for Kv, and R^2 (Kv) and Kv/probe recalculated for the harmonic average (Table 1).

The probe response across thin, fine grained laminae was further investigated by measuring along the length of the plugs with sampling points at a spacing of 1 mm. Figure 6 shows two examples of the results.

TABLE 1 Correlation plug - probe. R^2 is for the linear fit between averaged probe permeameter data and plug permeabilities. Plug/probe is the mean value of this ratio for each set of plugs.

Data set	Averaging method		
	ARIT	GEO	HAR
R^2 (Kh)	0.91	0.82	0.47
Kh/probe	1.09	1.64	3.26
R^2 (Kv)	0.46	0.67	0.89 (0.93)
Kv/probe	0.15	0.30	0.59 (0.96)

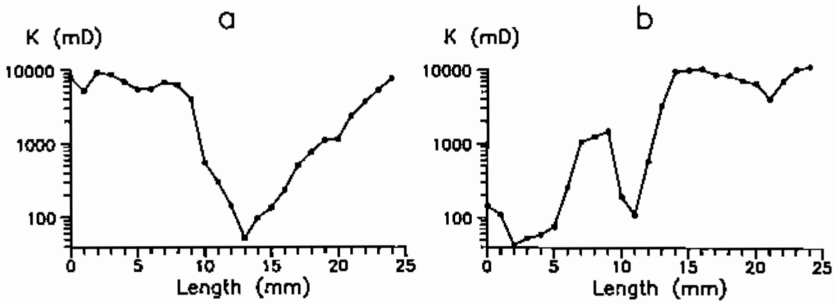

FIGURE 6 Probe permeameter response measuring at 1 mm intervals across thin low-permeable laminae in two plugs.

Assuming that both plugs (Figure 6) consist of *n* laminae in series, and applying Darcy's law, gives equation (1) to calculate the permeability of lamina *i*.

$$K_i = L_i/(L/K - L_1/K_1 - .... - L_n/K_n) \qquad (1)$$

L and K is length and permeability (Kh or Kv) of plug. L_i and K_i refer to the laminae. For flow parallel to laminae equation (2) is used.

$$K_i = (L \times K - L_1 \times K_1 - .... - L_n \times K_n)/L_i \qquad (2)$$

Equation (1) shows that Kv only is sensitive to the permeability and thickness of the low-permeable layer. For flow parallel to the laminae, equation (2) shows that Kh is sensitive to the permeability and thickness of the high-permeable laminae. Table 2 summarizes the data for the plugs shown i Figure 6.

TABLE 2 Calculated permeability of thin low-permeable laminae. KHAR is the harmonic average of the original probe measurements.

Plug	K	KHAR	L	L_1	L_2	K_2	K_1
a	35	581	33	3-4	29-30	> 1000	3-5
b	36	551	33	2-6	27-31	> 1000	2-7

Cube Measurements

For these measurements cubes with sides 23-24 mm were cut from core material. The permeability in the three orthogonal directions, Kx, Ky and Kz, was measured conventionally in a core holder with Kz in the vertical direction or normal to bedding, and Kx and Ky in the horizontal directions, or parallel to bedding. A rubber insert for the core holder with a square hole to fit the cube ensured confinement. In addition, probe permeameter measurements were made on the surfaces of each of the six cube sides in a 12x12 mm grid with gridpoint spacing 2mm.

Laminated material

For the first example, two cubes were cut from the laminated material shown in Figure 5. This was done firstly, to verify the results from the core plug measurements, and secondly, to investigate the probe permeameter response when measuring directly on the fine grained lamina material. The following confined permeability measurements were made:

Sample 1: Kx = 1682 mD; Ky = 1471 mD; Kz = 67 mD
Sample 2: Kx = 535 mD; Ky = 596 mD; Kz = 14 mD

Applying equation (1) to the cubes, the permeability of the laminae were estimated to be 1-5 mD. Subsequently, the cubes were cut at the boundary of the fine grained laminae so that the low-permeable material was exposed, and probe permeameter measurements made on the laminae surfaces (Figure 7 and 3b).

Mean permeability values for the laminae surfaces of 13 and 15 mD respectively, were measured. Two comments can be made about these measurements. Firstly, the laminae are not perfectly flat, so not all measurements are necessarily made on the lamina material (Figure 7c), and the thickness of the exposed lamina at the points of measurement will vary. Excluding values not believed to be representative from the datasets gave mean values of 5-6 mD.

Secondly, the lamina is thin enough for the high-permeable material below to substantially affect the probe response such that the apparent permeability will be higher than the real lamina permeability. These cube measurements show that the probe permeameter is sensitive to thin (less than 1 mm thick), low-permeable laminae directly below the probe as shown in Figure 3c. The measurements also confirm that it is the thin, fine grained laminae that cause the permeability anisotropy seen in this material.

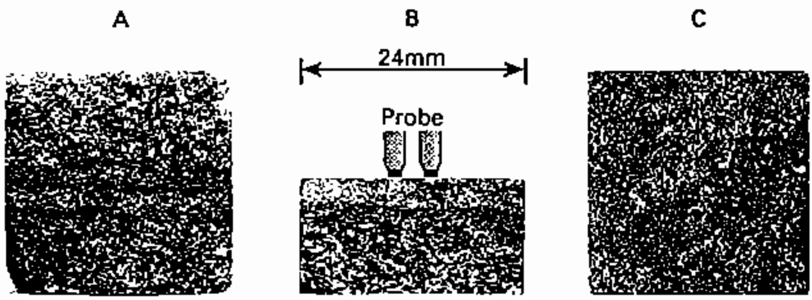

FIGURE 7 The figure shows how a cube (sample 2) with laminae (A) was cut (B) to measure with the probe permeameter on the laminae (C).

The second example concerns a cube taken from micaceous, fine grained, subtly laminated material. Figure 8a shows a contour plot of the probe measurements on the "top" of the cube, normal to the bedding (and the mica). As can be seen, there is little variation in permeability (97 ± 9 mD) with the "bottom" showing similar homogeneity (149 ± 19 mD). Measurements on the sides, i.e. parallel to bedding, show higher permeabilities and some lamination (Figure 9b), but the variation in permeability is still low (239 ± 24 mD) . In terms of permeability variation, this is very homogeneous material.

A layered model of the cube (top and bottom = 3mm, centre = 18 mm) was used to estimate the bulk permeabilities Kx, Ky and Kz from the probe measurements.

Probe (estimated):	Kx = Ky = 211 mD;	Kz = 190 mD
Confined (measured):	Kx = 215 mD; Ky = 216 mD;	Kz = 116 mD

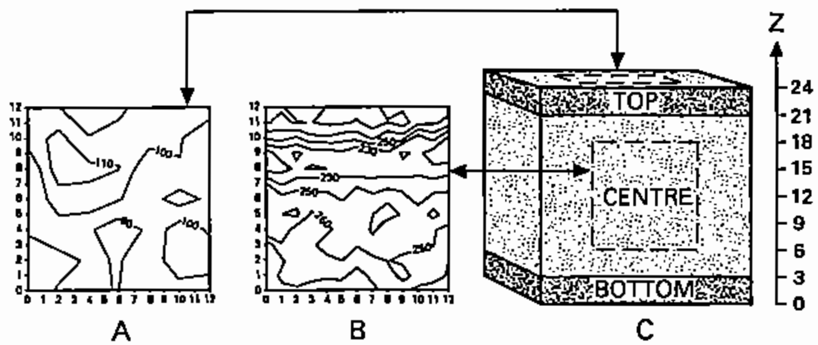

FIGURE 8 Contour plots of probe measurements on weakly laminated material with mica. A is normal to laminae, B is parallell. C shows layered model.

The cube was cut 6 times parallel to the X-Y plane at Z = 5, 6, 7, 10, 16 and 19, and probe measurements made on these surfaces. The calculated arithmetic averages were 160, 164, 197, 216, 170 and 220 mD respectively. Recalculating Kz using these values, gives Kz = 166 mD. The ratio of these values to the arithmetic averages of the horizontal probe measurements at the same values for Z came to 0.78 ± 0.07. If the "top" and "bottom" layer is corrected by 1/0.78, a value of 219 mD is calculated for Kx and Ky.

The probe measurements can predict Kx but not Kz. This indicates that the observed difference in permeability between Kx (or Ky) and Kz (Kx/Kz = 0.54) is not only due to heterogeneity or lamination at the mm-scale of the probe tip-seal, as neither the probe measurements nor visual inspection show the presence of any low-permeable laminae. Anisotropy at a smaller scale is suggested, perhaps the result of the orientation of the mica. The probe permeameter detects some of this anisotropy (the ratio 0.78), but is not as sensitive to it as confined measurements.

Homogeneous material

Two cubes were cut side by side from some visually homogeneous material, confirmed by fine grid measurements (Figure 9). The structure seen in the density plot running diagonally across the core from (depth = 100, y = 0) to (depth = 140, y = 50) was probably caused by a sawmark. The orientation of the cubes were along the axis of the well, so Kz would be approximately equal to the vertical permeability. Confined measurements gave the following results:

Sample 1: Kx=4408 mD; Ky=4450 mD; Kz=3332 mD
Sample 2: Kx=4220 mD; Ky=4146 mD; Kz=3254 mD

A Kz/Kx,y (Kv/Kh) ratio of 0.75 and 0.78 is calculated for sample 1 and 2 respectively. The arithmetic mean of the probe measurements on the surfaces of the cubes was calculated as 3597 mD and 3660 mD for sample 1 and 2 respectively, but the measurements did not show any lamination or anisotropy that would explain the observed Kv/Kh anisotropy. The measurements suggest that small-scale permeability anisotropy not detected by the probe permeameter is present in this material.

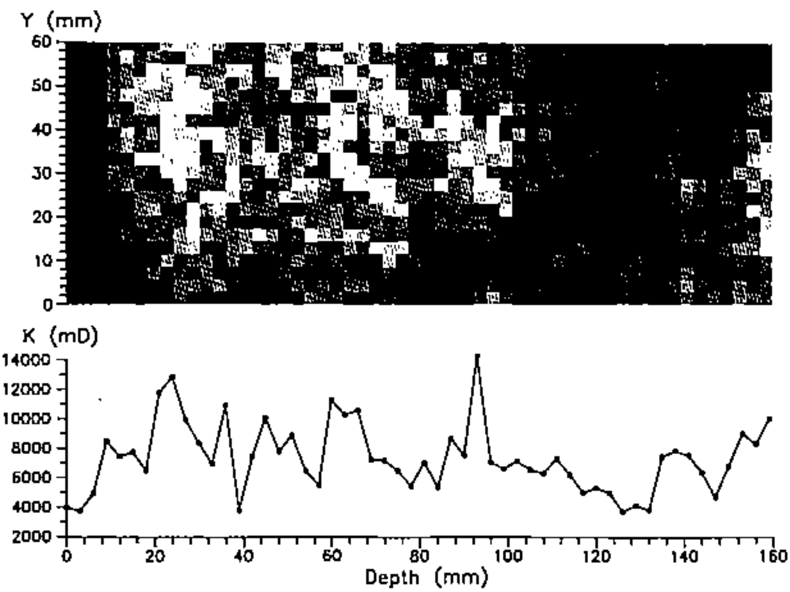

FIGURE 9 Density plot and cross section (y=30) of fine grid measured on homogeneous core. Gridpoint spacing is 3mm.

This conclusion could not as easily be drawn from conventional core plug measurements. In comparing Kx from sample 1 with Kz from sample 2 as would be the case for a horizontal and vertical plug, the argument could be made that the difference in permeability was due to the larger scale permeability variations shown in Figure 9.

Permeability Characterization at the Facies Level

Probe permeameter measurements were made every 4 mm on uncleaned, half-cut whole core down the length of a seven metres thick tabular crossbedded sandstone unit.

A smoothed (moving average, period = 50) graph of the probe permeameter measurements vs. depth is shown in Figure 10. A 50 cm example section of the raw data is shown in Figure 11.

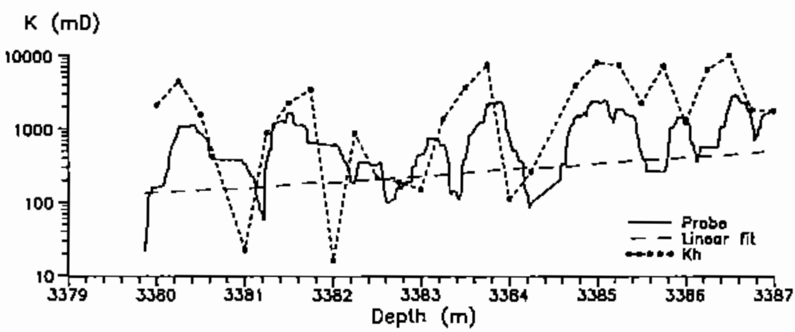

FIGURE 10 Smoothed graph of probe permeameter measurements with linear fit and Kh values from 7 m tabular crossbedded sandstone unit.

The arithmetic, geometric and harmonic means of the probe permeameter data and the horizontal and vertical routine plug data are summarized in Table 3. The test permeability evaluated from the kh product of the test data is given for comparison.

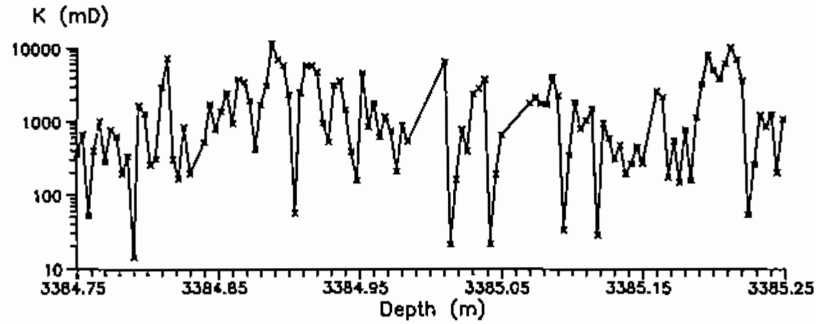

FIGURE 11 Section of the data shown in Figure 10 before smoothing.

TABLE 3 Averages of plug and probe data for tabular crossbedded sandstone unit with calculated test permeability.

Data set	Averaging method		
	ARIT	GEO	HAR
Kh	2819	1014	108
Kv	874	156	27
Kh&Kv	1847	397	43
Probe	960	253	44
	K(TEST) = 348 mD (h = 8 m)		

Effect of residual saturation

The half-cut core was clearly oil-stained, and it was suspected that this might produce artificially low probe permeabilities. The possible effect on the probe response was estimated by comparing probe measurements on plugs with probe measurements on the uncleaned core at the same depth. The horizontal plugs were used as the exact locations of the vertical plugs were difficult to ascertain. Due to the rapid variations in local permeability this is important for a valid comparison. A correction factor of 1.7 was obtained.

DISCUSSION

The plug and probe data summarized in Table 3, show that depending on averaging method and data set chosen, a wide range in the average permeabilty for the sandstone unit investigated is possible. Although a detailed investigation is beyond the scope of this paper, some of our views on what constitutes a probable range of permeability based on the experimental results and the geological interpretation is presented below.

Permeability Characterization of the Crossbeds.

The high frequency, high amplitude permeability variation caused by lamination in the measured section (Figure 11) tends to mask the more low frequent permeability character of individual crossbeds, and also a possible permeability trend within a series of crossbeds. The high frequency information was removed by a moving average method, allowing the lower frequency character of the crossbeds to become apparent (Figure 10). The crossbeds are separated by a low permeability zone denoting bottomset and finer grained sediments on top of crossbeds. There is a varying degree of upward decrease in permeability, a trend probably caused by a fining upward trend within bedforms. A thin interval with lower permeability occurs at the bottom of each crossbed, a feature which could be an effect of poorer sorting at the base of the bedform. This gives each crossbed the character of a sharp increase in permeability in the bottom part, a zone of maximum permeability in the lower half, or in the lower two thirds, of the crossbed, and then a marked decrease in permeability towards the top.

The two uppermost crossbeds are characterized by markedly lower permeabilities in the lower half compared to the upper half of the crossbed. The permeability decrease mentioned above in the uppermost part, and the sharp increase in the bottom part can also be distinguished in these crossbeds. These two uppermost crossbeds are thicker, and have a less pronounced lamination, as shown in the permeability characterization of lamina in Table 4. This may be indicative of the formation of the bedforms in a higher flow regime where sorting processes were less efficient.

Layering of Flow, Estimation of Permeability.

From the periodicity created by the maximum permeability interval of the crossbeds, alternating with zones of low permeability comprised by bottomsets and low permeability intervals at the bottom and top of the crossbeds, it follows that horizontal flow must be layered. This layering could in fact be an important characteristic for this type of architectural element, where individual crossbeds and crossbed-sets can extend up to 100 metres (Miall,1988). In this particular case, the layering also means that only about half the measured section will be important for flow.

The layering of flow also occurs at lamina level (macroscale) which is characterized by rapidly alternating low and high permeability intervals (Figure 11). Flow parallel to laminae within a crossbed will therefore be layered, and with the low-permeable laminae inactive during flow. Table 1 indicates that the arithmetic mean of the probe measurements best will predict the permeability parallel with the laminae, while the harmonic mean gives the best result for flow normal to laminae.

Accordingly, arithmetic and harmonic means of the probe data were calculated for the high permeable parts of each crossbed (Table 4). As the experimental results showed that the probe permeameter overestimates the permeability of the thinnest lamina, an attempt to correct for this was done for crossbed 5, 6 and 7 where these laminae primarily occur. This was done by substituting in lamina permeabilities obtained from the plug and cube measurements. Correction was also made for the effect of residual saturation.

TABLE 4 Average permeability (mD) of individual crossbeds. CB=crossbed, numbered from the top of the core. H = thickness of crossbed in meters.

CB	H	ARIT	HAR	HAR/ARIT
1	0.53	1328	559	0.42
2	0.78	1977	417	0.21
3	0.45	877	97	0.11
4	0.35	3182	568	0.18
5	0.66	3007	221	0.07
6	0.17	3232	145	0.04
7	0.47	4335	192	0.04

In calculating K(TEST) from the kh product, h has now been reduced to 3.41 m (the sum of H in Table 4), and correcting for this, gives a test permeability of 816 mD.

Using a layered model (arithmetic mean of individual crossbed permeabilities weighted by thickness) and the ARIT values gives a total permeability of 2441 mD. This is likely to be too high, both in view of the test permeability of 816 mD and from the observation that flow must at least in part go through low-permeable laminae. Using the same model with the HAR values gives a total permeability of 330 mD. This is closer to the test permeability, but is probably somewhat low.

Observing that CB1 and CB2 have less lamination than the others and thus might be closer to the ARIT values, using these plus HAR for the rest, gives a permeability of 806 mD.

CONCLUSIONS

We suggest that probe permeameter data have the potential of permeability characterization on several different scales. Going from the mm (probe) to the cm scale (plug), the probe measurements on plugs and cubes show that averaging the probe data arithmetically or harmonically according to the orientation of laminae with respect to the direction of flow, gives good agreement with conventional confined permeability measurements.

Due to the unconfined nature of the probe permeameter, permeability variation on lamina scale tends to be underestimated. By careful measurements with the probe permeameter on vertical core plugs, supported by conventional vertical permeability measurements, the permeability variation between adjacent laminae can be calculated. As shown in Figure 11, this variation can be quite considerable in distinctly laminated sandstones (2-3 orders of magnitude). By use of the above method, a representative permeability variation on lamina scale can be given.

On a larger scale, the closely spaced probe permeameter measurements ensure a much improved permeability characterization of crossbeds compared to routine plug measurements. An example of this is the detection of low permeable intervals between crossbeds in the tabular crossbedded sandstone unit, a heterogeneity which is in part missed by the routine plug data. By use of probe permeameter measurements, the permeability variation characterizing the heterogeneity level between crossbeds within a larger sandstone unit, can be found.

Probe permeameter data also give an improved basis for the determination of more low frequency information, such as permeability trends for series of crossbeds or for larger sandstone units.

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