A STUDY OF THE CORRELATION BETWEEN RELATIVE PERMEABILITY, AIR PERMEABILITY AND DEPOSITIONAL ENVIRONMENT ON THE CORE-PLUG SCALE

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Abstract

The main objectives of this study have been to derive relationships between petrophysical properties, which are crucial for reservoir simulations. Furthermore, in order to get representative data, and thereby to conclude upon the range in the rock properties within each environment, it has been important to use a sufficient number of samples from different depositional environments.
Determination of relative permeability curves on 85 core plugs from one single well in a highly heterogeneous North Sea field have been carried out at ambient conditions.
The data have been analysed with respect to relationships between the variables. A number of significant correlations have been found. Linear regression on log-transformed air permeability within each depositional environment gives very good fit for the permeability related variables, as expected, and acceptable fit for the porosity and the irreducible water saturation. For the remaining variables the fit is satisfactory in some of the depositional environments and very bad in others, without any clear pattern.

INTRODUCTION

Over the last years there has been an increased interest in enhanced reservoir descriptions. It has become more and more common to apply stochastic techniques to describe heterogeneous reservoirs. The stochastic techniques are used to describe geological building blocks, faults and petrophysical properties. Lately a hybrid model, which initially generates the geological flowunits and then assigns petrophysical properties to each flow unit has been successfully used (Damsleth *et al.*, 1990).

So far, stochastic techniques have mostly been used to model air permeability and porosity. However, the endpoint relative permeabilities, together with the viscosities, determine the mobility, which in turn strongly affects the recovery. It is therefore important to take the relative permeabilities into account when generating a number of plausible reservoir realizations stochastically.

However, using stochastic techniques for generating a realistic spatial distribution of petrophysical properties throughout the reservoir requires even more knowledge about the variability in the parameters, compared to traditional reservoir simulator models. In addition to an expectation value and a variance for each flow unit, information about the spatial distribution of the properties is required.

The variation in permeability has the most significant influence on reservoir performance, since it affects the relationships between the viscous and gravitational and capillary forces. From these considerations, selection of the absolute permeability value as a possible correlating parameter can be inferred (Molina, 1980).

For this reason, the main objective of this study has been to derive relationships between air permeability and relative permeability. Furthermore, in order to get representative data, and thereby to conclude upon the range in the rock properties within each environment, it has been important to use a sufficient number of samples from different depositional environments. In the end we give recommendations for the number of samples needed to describe other reservoirs adequately.

The regressions found in this study, will be used in further studies involving stochastic modelling of both air permeability, porosity, and relative permeability.

SELECTION OF PLUGS, DEPOSITIONAL ENVIRONMENT

The very heterogeneous reservoir under study, is interpreted to be deposited in various sedimentary environments, including mouthbars, distributory channels and tidal bays. Deposits of the different environments alternate both vertically and laterally within the reservoir, and form a complex network of interfingering lithologies and facies.

The reservoir can be separated into several depositional environments, using the term 'building blocks' for these large scale bodies created by these different sedimentary environments:

M1Ad : distal mouthbar
M1Ap : proximal mouthbar
P1 : distributory channels
T : tidal bay

In this study strong effort has been made to collect a sufficient number of high quality relative permeabilities. Eighty-five plugs were selected from six intervals along the core from a single well in the reservoir. Within each interval the core plugs were drilled horizontally, with a vertical spacing of 20 cm.

In the laboratory the fresh core plugs were cleaned by flushing with synthetic formation water. Establishment of irreducible water saturation was done by the separate porous plate method. Then the relative permeabilities were measured at ambient conditions using an unsteady state technique. The injection rates were selected individually for each plug in order to avoid any end effects (Haugen, 1990). Finally, the core plugs were cleaned by Dean Stark extraction, and porosity and air permeability were measured. For describing the shapes of the relative permeability curves, the Corey exponents (Honarpour, 1982), n_o and n_w for oil and water respectively, have been calculated.

UNIVARIATE DESCRIPTION

The measured variables were analysed with respect to means, standard deviations and extreme values. Table 1 presents the univariate description for each depositional environment.

A common feature is that the tidal bay deposit always had a more narrow distribution than the other building blocks. The mean porosity is higher and the mean permeabilities lower than for the other building blocks. The proximal mouthbar deposit, M1Ap, had higher mean permeabilities than the distal mouthbar deposit, which is expected due the geological processes that have taken place. The coarse, less sorted material has been deposited close to shoreline, and the finer and better sorted sand has been carried away, and deposited more distant to the shoreline. Furthermore, the proximal mouthbar plugs showed low irreducible water saturations, and high endpoint permeabilities for water. The core plugs from the distributory channels are spread in range covered by the other plugs, with properties most similar to the distal mouthbar.

Tests for normal distributions of the data were also performed. If the probability of the null hypothesis (that the data is a random sample from a normal distribution) is less then 5 %, the null hypothesis is rejected and the data is said *not* to be normally distributed. Otherwise the assumption of a normal distribution is accepted. The results from these tests are also shown in Table 1. Table 1 indicates that a log-transformation of the permeabilities will led to improved normality in most cases.

To conclude, Table 1 shows that each depositional environment has quite distinct properties, and is significantly different from the other environments. Similar results have also been found when performing a cluster analysis. The cluster analysis is not shown in this paper. This shows that the depositional environments really represents different rock types.

TABLE 1 Univariate description for each depositional environment.

Variable	*Dep.env.*	*N*	*Mean*	*St. dev.*	*Min.*	*Max.*	*Norm.**
Φ [%]	M1Ad	41	21.4	2.2	15.1	24.8	no
	M1Ap	20	20.8	2.5	13.9	23.7	no
	P1	9	19.8	1.4	17.5	21.5	
	T	15	24.0	1.5	21.6	26.1	
$K_{air}[mD]$	M1Ad	40	319	458	12	2823	no
	M1Ap	20	2557	2521	9	8949	no
	P1	9	400	395	40	1197	
	T	14	134	56	62	279	
$\log_{10}(K_{air}[mD])$	M1Ad	40	2.28	0.43	1.09	3.45	
	M1Ap	20	3.04	0.79	0.96	3.95	no
	P1	9	2.36	0.52	1.61	3.08	
	T	14	2.09	0.17	1.79	2.45	
$K_w(S_{or})[mD]$	M1Ad	41	145	240	1	1417	no
	M1Ap	20	1526	1423	3	4093	no
	P1	9	174	200	11	626	no
	T	15	46	20	20	104	no
$\log_{10}(K_w(S_{or})[mD])$	M1Ad	41	1.78	0.62	-0.05	3.15	
	M1Ap	20	2.77	0.91	0.49	3.61	no
	P1	9	1.91	0.63	1.03	2.80	
	T	15	1.63	0.18	1.31	2.02	
$K_o(S_{wi})[mD]$	M1Ad	41	289	398	8	2455	no
	M1Ap	20	2537	2615	6	9385	no
	P1	9	337	343	30	1061	
	T	15	125	53	58	629	no
$\log_{10}(K_o(S_{wi})[mD])$	M1Ad	41	2.24	0.45	0.92	3.39	
	M1Ap	20	3.00	0.84	0.78	3.97	no
	P1	9	2.27	0.54	1.47	3.03	
	T	15	2.06	0.17	1.76	2.43	
$S_{wi}[frac.]$	M1Ad	41	0.221	0.074	0.070	0.488	
	M1Ap	20	0.144	0.098	0.026	0.375	no
	P1	9	0.230	0.101	0.075	0.363	
	T	15	0.180	0.040	0.129	0.271	
$S_{or}[frac.]$	M1Ad	41	0.266	0.049	0.200	0.392	no
	M1Ap	20	0.309	0.058	0.168	0.391	
	P1	9	0.284	0.048	0.205	0.351	
	T	15	0.311	0.029	0.257	0.359	
Corey exp. oil, n_o	M1Ad	40	3.14	0.63	2.24	5.33	no
	M1Ap	20	4.18	0.83	3.14	6.17	
	P1	9	3.69	0.60	2.92	4.66	no
	T	15	3.06	0.48	2.41	4.48	
Corey exp. water, n_w	M1Ad	40	2.61	1.05	0.69	6.78	no
	M1Ap	20	1.38	0.45	0.43	2.28	
	P1	9	1.71	0.56	1.14	2.82	
	T	15	2.20	0.43	1.20	2.76	
$k_{rw}(S_{or})$	M1Ad	41	0.39	0.15	0.06	0.69	
	M1Ap	20	0.60	0.13	0.28	0.77	no
	P1	9	0.44	0.10	0.31	0.59	
	T	15	0.37	0.06	0.28	0.49	

* "No" denotes significant deviation from the normal distribution at the 5 % level.

THE INTERACTION BETWEEN VARIABLES

With regard to the aim of this study: Using the results as input to a stochastic simulator, we need to predict the petrophysical properties for all the grid cells in the entire reservoir. The air permeability and porosity are the properties measured in routine core analyses, and the lateral permeability variations may be measured with a field minipermeameter on outcrops. It is therefore a goal to be able to use the air permeability alone or in combination with the porosity to predict the other rock properties required in a reservoir simulation study. For this reason some statistical techniques have been utilized in search for relationships between the variables.

Correlation matrices

For each depositional environment, the correlation matrix for the following variables were calculated: porosity, irreducible water saturation, residual oil saturation, the Corey exponents for oil and water, the endpoint relative permeability for water and the logarithms of air permeability, oil permeability at irreducible water saturation and water permeability at irreducible oil saturation. The upper triangle of the correlation matrices is shown in Table 2.

The correlation between two variables is considered strong when the correlation coefficient is greater than 0.7. According to this, the tables show strong correlations between $\log_{10} K_{air}$, $\log_{10} K_o(S_{wi})$ and $\log_{10} K_w(S_{or})$ for all the depositional environments (as expected). The permeabilities also are correlated with S_{wi}. For the distal mouthbar deposit there is a strong correlation between the permeabilities and endpoint relative permeability for water. There is also a strong correlation between the two Corey exponents. For this environment there are no significant correlations between the porosity and the other variables.

Furthermore, the proximal mouthbar deposit shows a strong correlation between the porosity and the permeabilities. Thus, the correlation between the endpoint relative permeability for water and the permeabilities are weaker for the proximal than for the distal mouthbar deposits.

The largest number of strong correlations is found for the distributory channels. In addition to the correlations discussed above, this is the only depositional environment where strong correlations are found between the permeabilities and residual oil saturation. There are also strong correlations between the porosity and the Corey exponents for water, and between the porosity and the endpoint relative permeability for water.

The tidal bay is similar to the distributory channels, the difference being that the tidal bay deposit lacks a correlation between the Corey exponents, and shows a strong correlation between the irreducible water saturation and the Corey exponent for oil.

The above analysis shows that the deposits differ with regard to the correlation between the measured variables. These differences show the importance of separating the core-plugs according to the depositional environments.

TABLE 2a Correlation coefficients for M1Ad.

	$\log_{10} K_{air}$	$\log_{10} K_o(S_{wi})$	$\log_{10} K_w(S_{or})$	S_{wi}	S_{or}	n_o	n_w	$k_{rw}(S_{or})$
Φ	0.44	0.43	0.38	-0.42	-0.02	-0.30	0.14	0.17
$\log_{10} K_{air}$		$\underline{0.98}$	$\underline{0.98}$	$\underline{-0.77}$	0.19	0.52	-0.59	$\underline{0.81}$
$\log_{10} K_o(S_{wi})$			$\underline{0.96}$	$\underline{-0.79}$	0.21	0.54	-0.60	$\underline{0.76}$
$\log_{10} K_w(S_{or})$				$\underline{-0.79}$	0.27	0.61	-0.63	$\underline{0.90}$
S_{wi}					-0.53	-0.37	0.58	-0.63
S_{or}						0.21	-0.35	0.32
n_o							$\underline{-0.73}$	0.67
n_w								-0.57

TABLE 2b Correlation coefficients for M1Ap.

	$\log_{10} K_{air}$	$\log_{10} K_o(S_{wi})$	$\log_{10} K_w(S_{or})$	S_{wi}	S_{or}	n_o	n_w	$k_{rw}(S_{or})$
Φ	$\underline{0.78}$	$\underline{0.78}$	$\underline{0.73}$	-0.64	-0.19	-0.58	0.39	0.06
$\log_{10} K_{air}$		$\underline{1.00}$	$\underline{0.99}$	$\underline{-0.89}$	0.01	-0.15	-0.09	0.50
$\log_{10} K_o(S_{wi})$			$\underline{0.99}$	$\underline{-0.89}$	0.02	-0.14	-0.09	0.51
$\log_{10} K_w(S_{or})$				$\underline{-0.89}$	0.03	-0.09	-0.14	0.59
S_{wi}					-0.28	0.19	0.00	-0.53
S_{or}						0.33	-0.26	0.12
n_o							$\underline{-0.82}$	0.32
n_w								-0.36

TABLE 2c Correlation coefficients for P1.

	$\log_{10} K_{air}$	$\log_{10} K_o(S_{wi})$	$\log_{10} K_w(S_{or})$	S_{wi}	S_{or}	n_o	n_w	$k_{rw}(S_{or})$
Φ	$\underline{0.87}$	$\underline{0.86}$	$\underline{0.87}$	-0.63	0.55	0.46	$\underline{-0.72}$	$\underline{0.79}$
$\log_{10} K_{air}$		$\underline{1.00}$	$\underline{1.00}$	$\underline{-0.90}$	$\underline{0.81}$	0.41	-0.62	$\underline{0.86}$
$\log_{10} K_o(S_{wi})$			$\underline{1.00}$	$\underline{-0.90}$	$\underline{0.80}$	0.40	-0.62	$\underline{0.86}$
$\log_{10} K_w(S_{or})$				$\underline{-0.89}$	$\underline{0.79}$	0.37	-0.61	$\underline{0.90}$
S_{wi}					$\underline{-0.92}$	-0.16	0.33	$\underline{-0.77}$
S_{or}						0.28	-0.37	0.63
n_o							$\underline{-0.91}$	0.16
n_w								-0.45

TABLE 2d Correlation coefficients for T1.

	$\log_{10} K_{air}$	$\log_{10} K_o(S_{wi})$	$\log_{10} K_w(S_{or})$	S_{wi}	S_{or}	n_o	n_w	$k_{rw}(S_{or})$
Φ	$\underline{0.74}$	$\underline{0.74}$	0.64	$\underline{-0.75}$	0.15	$\underline{-0.73}$	0.13	-0.16
$\log_{10} K_{air}$		$\underline{1.00}$	$\underline{0.93}$	$\underline{-0.75}$	0.44	-0.57	-0.16	-0.06
$\log_{10} K_o(S_{wi})$			$\underline{0.93}$	$\underline{-0.73}$	0.36	-0.56	-0.12	-0.03
$\log_{10} K_w(S_{or})$				-0.67	0.24	-0.45	0.08	0.34
S_{wi}					-0.43	$\underline{0.79}$	-0.30	0.05
S_{or}						-0.18	-0.39	-0.29
n_o							-0.37	0.20
n_w								0.49

Values above 0.7 are underlined, and indicate a strong correlation between the variables.

TABLE 3 Regression coefficients on log-permeability vs. different variables.

Variable	*Dep. env.*	*Intercept*	*Slope*	*Res. st. dev.*	R^2
Φ [%]	M1Ad	17.4*	1.77*	1.98	0.11
	M1Ap	13.5**	2.41**	1.59	0.60
	P1	14.4**	2.27**	0.71	0.76
	T	9.5*	6.95**	1.11	0.55
$\log_{10}(K_w(S_{or})[mD])$	M1Ad	-1.39**	1.38**	0.13	0.95
	M1Ap	-0.69**	1.14**	0.10	0.99
	P1	-0.92**	1.20**	0.06	0.99
	T	-0.43	0.99**	0.07	0.86
$\log_{10}(K_o(S_{wi})[mD])$	M1Ad	-0.05	1.00**	0.10	0.94
	M1Ap	-0.23*	1.06**	0.03	1.00
	P1	-0.17**	1.04**	0.03	1.00
	T	-0.05	1.01**	0.02	0.99
$S_{wi}[frac.]$	M1Ad	0.47**	-0.11**	0.044	0.48
	M1Ap	0.48**	-0.11**	0.046	0.79
	P1	0.64**	-0.17**	0.046	0.82
	T	0.55**	-0.18**	0.028	0.56
$S_{or}[frac.]$	M1Ad	0.24**	0.01	0.049	0.01
	M1Ap	0.31**	0.00	0.060	0.00
	P1	0.11	0.07**	0.030	0.65
	T	0.15	0.08	0.027	0.20
Corey exp. oil, n_o	M1Ad	1.21*	0.82**	0.54	0.27
	M1Ap	4.65**	-0.15	0.85	0.02
	P1	2.59*	0.46	0.58	0.17
	T	6.57**	-1.68*	0.42	0.33
Corey exp. water, n_w	M1Ad	6.26**	-1.56**	0.85	0.34
	M1Ap	1.53**	-0.05	0.46	0.01
	P1	3.29**	-0.67	0.47	0.39
	T	3.14	-0.43	0.44	0.03
$k_{rw}(S_{or})$	M1Ad	-0.31**	0.30**	0.09	0.63
	M1Ap	0.35**	0.08*	0.11	0.25
	P1	0.06	0.16**	0.06	0.73
	T	0.42	-0.02	0.06	0.00

** $p < 0.02$; * $p < 0.05$ when compared to zero.

Linear regression on log-permeability

As mentioned above, we intend to use some of the results from this study in a stochastic simulation of relative permeabilities. Hence, our objective is to predict the remaining variables as linear functions of log-transformed air permeability.

When performing a regression analysis one predicts the response variable from a linear function of the regressor variable, adjusting the intercept and slope parameters so that the sum of the squared deviations is minimized. The parameters are tabulated in Table 3, together with a value for the residual standard deviation, indicating the variability around the regression line, and R^2 indicating how much of the variance in the data which can be explained by the regression. Thus, if R^2 is equal to 0.5, half of the variance in the data can be explained.

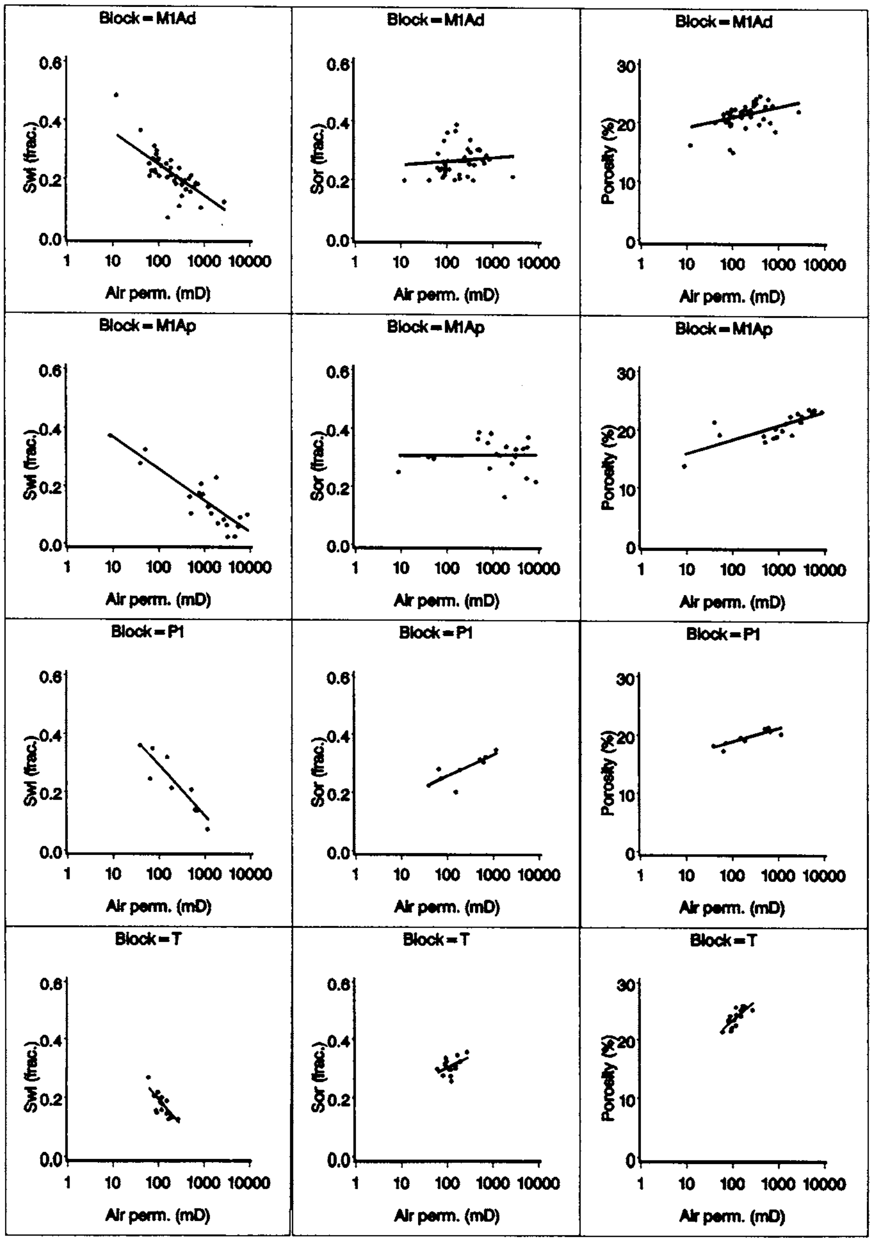

FIGURE 1a Regression plots of regression on log-transformed air permeability

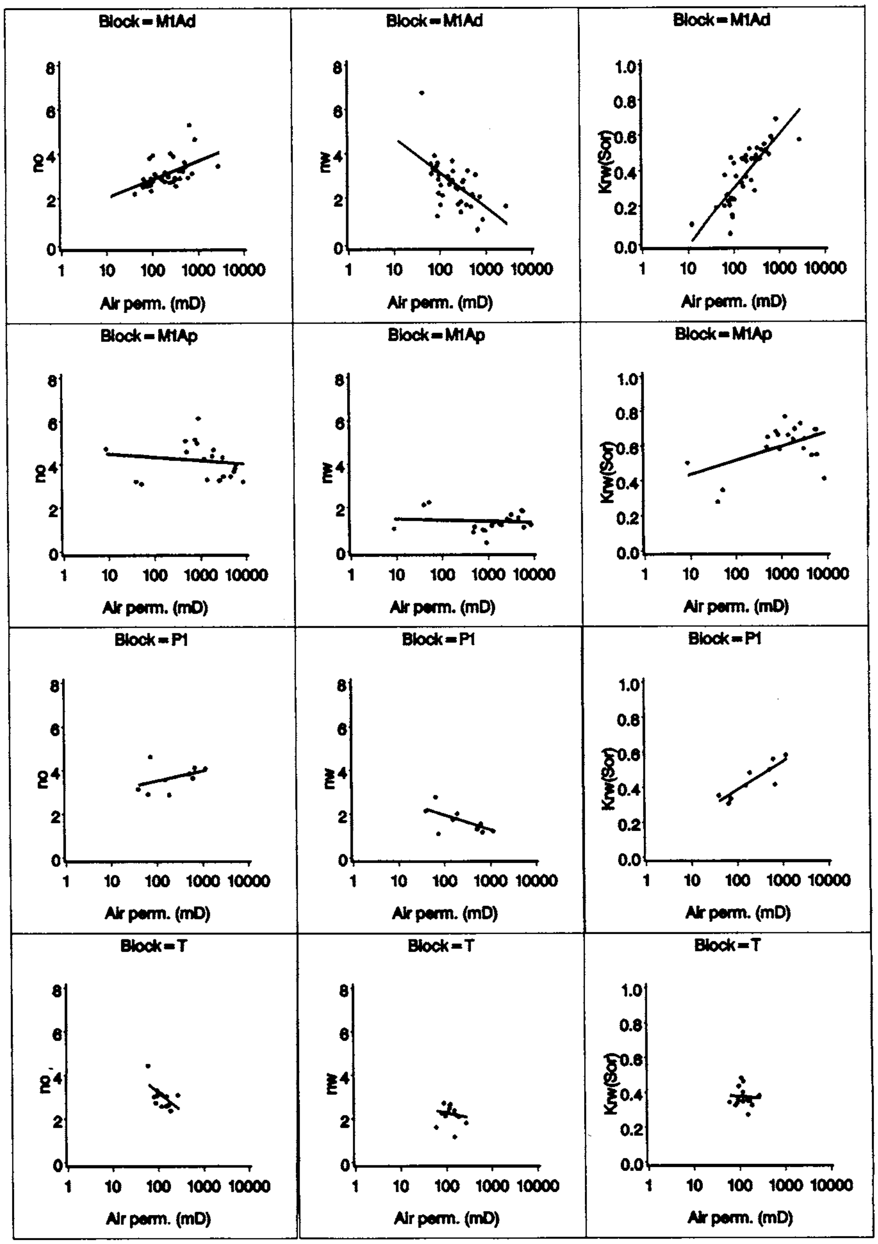

FIGURE 1b Regression plots of regression on log-transformed air permeability

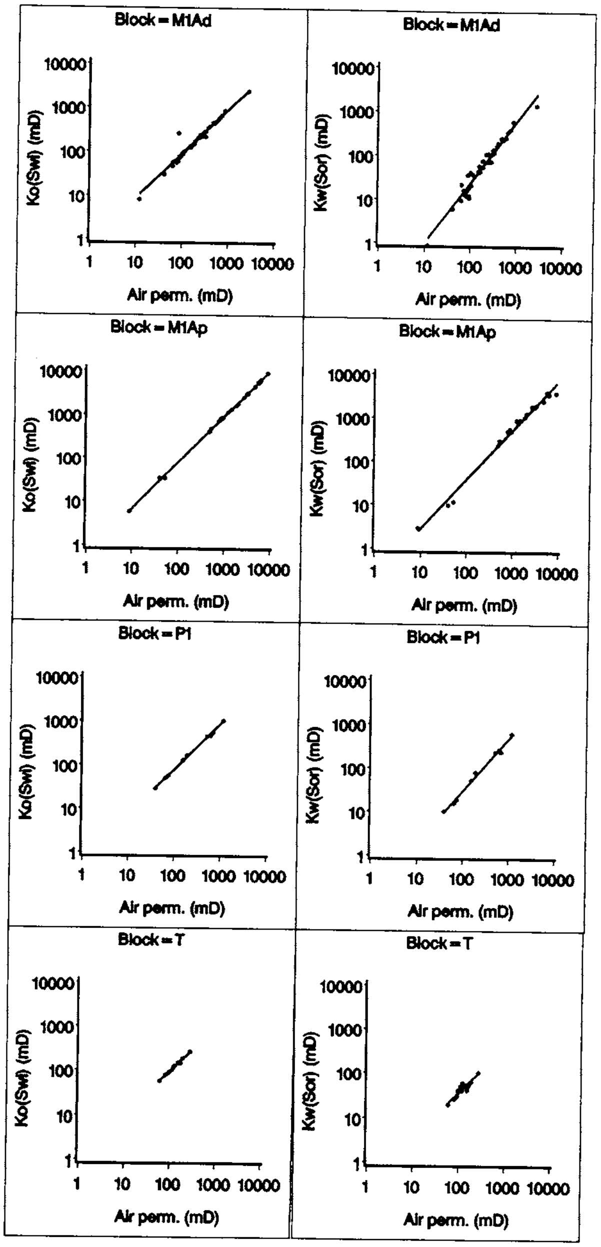

FIGURE 1c Regression plots of regression on log-transformed air permeability

For each variable and for each depositional environment, Figures 1a–c show the regression on the log-transformed air permeability. From Figures 1a–c and Table 2 strong correlation between $\log_{10} K_{air}$, $\log_{10} K_o(S_{wi})$ and $\log_{10} K_w(S_{or})$ is found for all the depositional environments (as expected). Furthermore, a strong correlation between $\log_{10} K_{air}$ and S_{wi} is found. For Φ and $k_{rw}(S_{or})$ there are a satisfactory fit in some of the environments. However, for the irreducible oil saturation there are no correlations, except for the P1 building block. The Corey exponents also show very weak correlation with the permeability. For the water exponent the slope factors are negative for all the depositional environments, but for the oil exponents the slopes are negative for the M1Ap and T blocks and positive for the two other blocks.

The regression lines for the distributory channels and from the tidal bays should be regarded as less significant than the regression lines for the mouthbars. They are based on limited numbers of observations, 9 and 15, respectively, and the samples from the tidal bays all have very similar permeabilities making the regressions very sensitive to small perturbations in the observations.

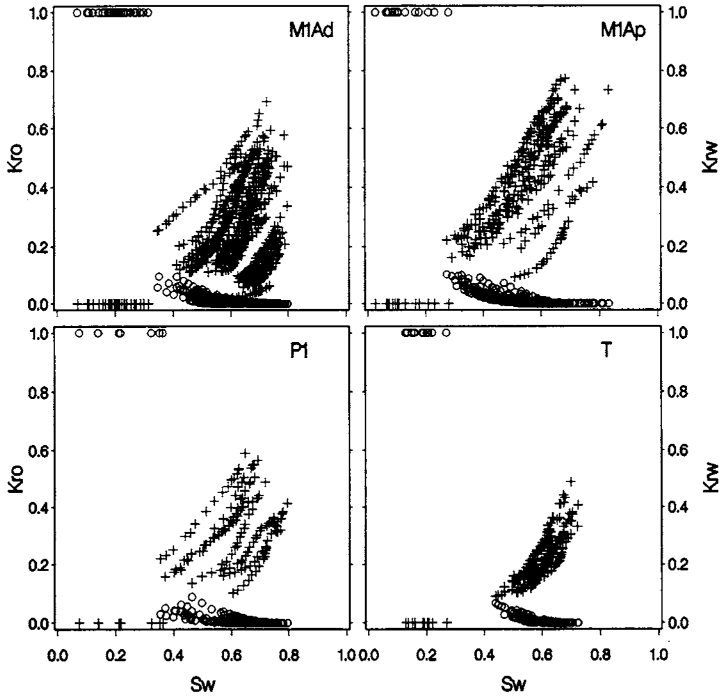

FIGURE 2 **Relative permeability curves.**

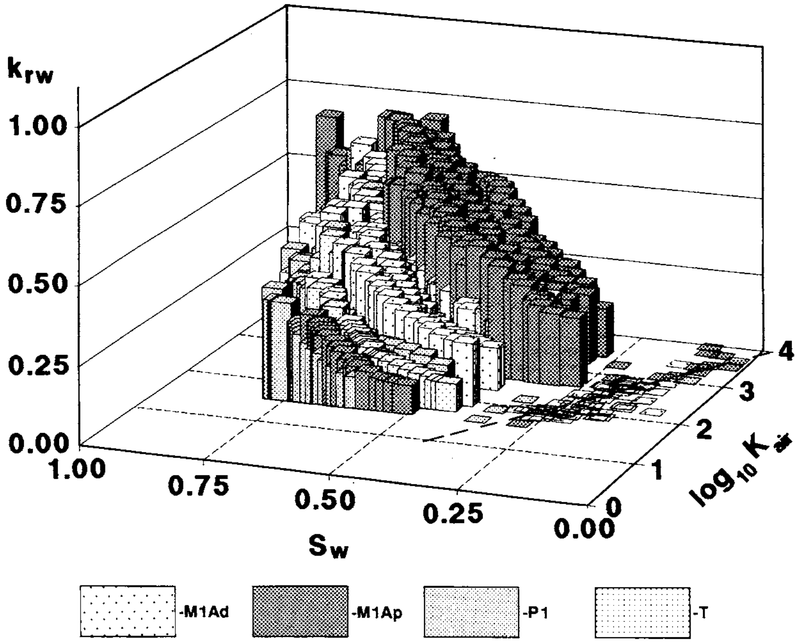

FIGURE 3 Relative permeability for water as a function of water saturation and log-transformed air permeability.

MEASUREMENT OF RELATIVE PERMEABILITY CURVES

The relative permeability curves for 83 core plugs (2 of the 85 plugs were damaged during the measurements) are shown in Figure 2.

These 2-dimensional plots indicate a trend towards higher endpoint relative permeability for water ($k_{rw}(S_{or})$) for the samples belonging to the proximal mouthbar than to the more distal mouthbar deposits and the distributory channels. Furthermore, from Figure 2d it can be seen that the tidal bay deposit is more homogeneous than the mouthbar, since the relative permeability curves are less spread. One should also notice that the oil relative permeability curves are less spread, and that no trends are notable.

Furthermore, the same data as in Figure 2 have been plotted in a 3-dimensional grid, Figure 3. The x-y plane is the plane for water saturation versus log air permeability, and the z-dimension express the relative permeability for water. The endpoints at irreducible water saturation form an oblique line, in the x-y plane, where the irreducible water saturation is reduced with increasing air permeability. Furthermore, a trend towards higher endpoint permeability for water with increasing air permeability is seen even more clearly in this 3-D plot.

Effects of the depositional environment

When separating the data into building blocks, the two mouthbar blocks (the distal and proximal) divides into two groups. The tidal bay deposits are in the same range as the mouthbar, but lie as a narrow band in the centre of the curves. The curves for the distributory channel cover more or less the whole range of data, and have less distinct properties than the other building blocks.

To conclude, a considerable part of the observed scattering of the data is variation due to the high degree of heterogeneity in the well. The variation is explained by the difference in the depositional environment and the variations in air permeability within and between the environments.

DISCUSSION

To what extent can our findings be generalized to other fields and depositional environments? The fact that the regression lines found in the section above varied significantly between the different building blocks makes the uncritical use of our results in a virgin field highly uncertain, unfortunately. The obvious question is then: How many cores are required from a new field to perform a study like this? The answer depends on the objective.

For example, when estimating correlation coefficients, the standard deviation of each correlation estimate is given approximately by

$$Std(R) \approx \frac{1-\rho^2}{\sqrt{n-1}}$$

where R is the estimate, ρ is the true value of the correlation, i.e. a parameter in the underlying probability distribution which generate our sample, and n is the number of observations used to calculate R. Thus, the larger the true correlation, the smaller the standard deviation. For example, if the true value is 0.7, the above formula gives the standard deviation of the estimate as 0.25 for n = 5, 0.2 for n = 8 and 0.1 for n = 27. Thus, a substantial number of observations are required to get precise correlation estimates, and estimates based on less than 8–10 observations are of limited value only, unless ρ is very close to ± 1.

When estimating the coefficients of a regression line, the cores should be chosen to obtain the maximum range for the permeability values. The larger this spread, the more precisely the coefficients can be estimated. If the spread is large enough, satisfactory results may be obtained with as few as five observations, but in general at least 10 data points should be used.

The statistical techniques utilized in this analysis are efficient tools to recover important features of the data. However, there are limitations to their applicability. We have only compared the various pairwise relationships between the parameters, not taking possible multivariate relations into account. Further, both correlation analysis and linear regression model the possible linear relationships between the parameters, and if there are strong non-linearities in the data, this may lead to erroneous conclusions. The various plots, however, do not indicate any such strong non-linear relationships.

CONCLUSION

The analyses above have shown that each depositional environment has its own distinct properties. There are differences in the average values and variances, as well as in the strength of the correlations between the variables. Hence it is necessary to sample core plugs from all the different depositional environments that are present in the reservoir under study.

In this study the following correlations have been found in most (three or four) of the depositional environments:

(i) a correlation between log-transformed air permeability and the end-point relative permeability for water
(ii) a correlation between log-transformed air permeability and irreducible water saturation
(iii) a correlation between log-transformed air permeability and porosity
(iv) a correlation between the oil and water Corey exponents.

Ordinary linear regression on $\log_{10} K_{air}$ naturally gives very good fit for the permeability related variables $\log_{10} K_w(S_{or})$ and $\log_{10} K_o(S_{wi})$, and acceptable fit for the porosity and for S_{wi}. For the remaining variables the fit is satisfactory in some of the building blocks and very bad in others, without any clear pattern.

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Elastic Properties