HETEROGENEITY OF FRACTURED GRANITE: EFFECTS ON PETROPHYSICAL PROPERTIES AND WATER SATURATION OF PRESERVED CORES

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ABSTRACT

Heterogeneity of oil-bearing fractured granite of the Bach Ho oil field has been studied through petrophysical measurement. Full-size and plug core data of permeability and porosity were compared to show the scale of macroscopic heterogeneity of the rocks.

An attempt to evaluate the content of connate water was made on preserved cores (taken by using water-based mud). Excessive water (invaded into the macropores) was removed by capillary extraction using chalk powder. The regime of this process has been calibrated with porous plate technique. The percentage of invaded water was found close to the partition coefficient of macrofractures.

Electrical properties have been studied on preserved, "preserved after chalk" and cleaned cores. Scatter in resistivity index vs. water saturation cross-plots for these states was observed whereas a satisfactory relationship of formation factor vs. porosity was obtained. Rock matrix was found to obey Archie's law with certain cementation and saturation exponents. For samples with dual porosity (containing macrofractures) the slope "n" of RI-Sw curves changed from high a value of water saturation to low values. Electrical anisotropy was also investigated by measurements in perpendicular directions. The results show that electrical anisotropy exists due to the orientation of macrofractures while RI-Sw curves have the same characteristics.

Explanations of these irregularities of electrical properties can be found by reconstructing the theoretical model of fractured media with dual porosity. Fair agreement between the characteristics of electrical parameters of actual cores and reconstructed model shows the essential role of macrofractures in the behavior of fractured granite.

INTRODUCTION

The petrophysical properties of rock with intergranular porosity (sandstone, limestone) have been studied extensively over the last few years. Among the rock parameters, which are used in reservoir evaluation and prediction of its performance, perhaps permeability, porosity and oil-water saturation are the most important. Intergranular porous rocks of conventional reservoirs commonly are homogeneous on the micro and macro-scale in comparison with fractured rock. In the case of more homogeneous rock with intergranular porosity, standard approach in routine and special core analysis seem to be effective enough to provide representative core data. The oil-water saturation of these rocks has also been successfully determined from complex logs, based on the laboratory relationships between resistivity index and water saturation, formation factor and porosity established on the plug cores.

Good quality core data requires an understanding of specific characteristics of certain rock types we are dealing with. In the case of heterogeneous reservoir, core analysis program is also required to reflect true and as more as much the representative values of rock properties at reservoir conditions. Fractured oil-bearing granites are distinguished from the rocks of conventional reservoirs by the high heterogeneity of pore structure and by the distribution of macro, micro fractures. These specific characteristics of fractured rock create problem for core analysis in reflecting true nature of rock properties as mentioned above.

Understanding the influences of the rock heterogeneity on core properties is a key problem in core analysis. This paper addresses some problems in evaluation of the rock petrophysical properties and highlights some specific characteristics of fractured granite in the context with rock heterogeneity.

PERMEABILITY AT DIFFERENT CORE SIZES

Heterogeneity of fractured granite is expressed in terms of two main pore elements: macrofracture and matrix consisted of microfracture network. Permeability of this system depends on a number of factors, such as fracture distribution (fracture density), fracture aperture and orientation. The specific pore structure might have a great influence on the measurement of rock permeability on core sample. Routine measurement of gas permeability was performed in Hassler type coreholder, at a confining pressure of 15 bars on the core plugs of diameters 30 mm and 50 mm, maximum length to 7 cm. and on the full-size cores of diameter 70 mm (length > 10 cm.).

Figure 1 presents distribution of the values of permeability obtained on each core size. Comparison of the distribution characteristics on the histogram shows that the core samples of 30 mm diameter mainly represent low permeability range (<10 mD), while the ranges of "big plugs" of diameter 50 mm and full-size cores of diameter 70 mm is much wider, covering up to several Darcy. One reason for this is: due to the specific mechanical feature of rock, the small plug samples were mainly obtained from the tightest part of rock (matrix). On the strongly fractured core intervals any attempt to drill plugs of standard size failed and as a result small core plugs often get low value of permeability, appropriate to matrix block of microfractures network. If only matrix permeability was considered, we can see a similar situation as that conventional reservoir rock, since microfractures commonly are randomly oriented. Although macrofactures usually do not have a dominant contribution to rock porosity, but their distribution and orientation often control the rock permeability. That is why we did not find any correlation between K & $\varnothing$ as one usually exists for a certain type of intergranular or carbonate rocks.

One more important factor should be mentioned, is the influence of coring and core handling processes on rock permeability and porosity. During these processes a number of factors could lead to severe core damage, such as stress-release, temperature change etc. [1]. To evaluate an integral effect of these factors, we investigated the changes of permeability at reloading and unloading from ambient to reservoir effective stress conditions (400 bars). Results presented in Figure 2 show significant reduction of permeability (60 times) and a hysteresis during unloading, when permeability K_{stress} is only 10% of the initial value K_{atm} (ambient conditions).

The reason of significant permeability reduction, we supposed, is severe core damages. In the case of fractured granite, anisotropy of original rock, fractures and microcracks may support the formation of a large number of induced fractures. In addition to the changes of the true rock permeability, the changes of natural fracture (mainly in fracture width) also greatly contribute to increasing original rock permeability [2, 10]. The distinctive characteristics of induced fractures from natural fractures are the freshness of fracture surface and the absence of secondary minerals coating or growing on their surface. Another factor indicated induced fractures is absence of the sign for the dissolution process caused by circulated hydrothermal solution. Thus, induced fractures may easily be closed at low effective stress and also may not be significantly reopened during unloading. Therefore the hysteresis observed at full stress-release (return to initial P_{EFF}) can be partly or entirely attributed to the presence of induced fractures. From these results, a recommendation can be suggested that for heterogeneous fractured granite, the permeability measurement should be conducted at the conditions close to the reservoir ones, using full-size core.

WATER SATURATION OF PRESERVED CORE AND IRREDUCIBLE WATER SATURATION

Methods of evaluation and applicability

The most reliable core analysis method for determining the oil-water saturation is direct measurement (Dean-Stark) on the cores taken by using oil-based mud. But until now, on the field, due to several reasons (technological, environmental, economic etc.) no well using oil-based mud has been drilled. In this situation, an attempt was undertaken to use preserved cores drilled by water-based mud to extract the maximum of information concerning irreducible water saturation of the rock.

The results of experimental study modeling the process of coring (core drilling process and when core sample is taken from subsurface to surface conditions) [3] show that there are several factors which could affect the original water saturation such as mud filtrate invasion, expansion of dissolved (in oil) gas etc. In the case of water-based mud the average variation of water saturation ΔSw is +6.2% (compared with original Sw), and in the case of oil-based mud is -1.4 %. The variation of Sw could be much higher (to 20 %) when the original water saturation was low.

In order to eliminate the influence of invaded filtrate on Sw determination, and by taking their mobility in to consideration, the invaded filtrate can be displaced by injecting of high viscous oil at high ΔP or by centrifuge. This method has been successfully applied to intergranular porous rocks [4], but this is a time consuming method and it requires special equipment. For fractured granite, due to heterogeneity such as the orientation of fractures, the flow direction of displacing oil does not always coincide entirely with the orientation of macrofractures, and oil/gas injection may therefore have no influence on the invaded filtrate (see Figure 3). Obviously, macrofractures are more affected by filtrate invasion than adjacent low permeable matrix blocks. For this reason we applied the capillary extraction method using chalk powder which allowed us to extract the invaded filtrate from all directions, similar to those when invaded into the cores.

In the method of capillary extraction by chalk powder [5], core samples were first wrapped up by filter paper to prevent the pore space (macrofracture) from being filled with chalk powder. Core samples were then placed into chalk powder in the distance of 2 sample's diameter from each other. Preferentially, the chalk powder has been humidified by adding 30 ml of water to each one kilo of it. The required extraction time is 48 hours, which has been established on porous rock to get the value equivalent to irreducible water saturation obtained at 6 bars by porous plate technique. Then the chalk powder was well rammed to ensure good capillary contact with the core samples. After extraction, the cores were removed and water volume was determined by Dean-Stark. The advantage of this method is the simplicity and rapidity. The method does not require cores of exact size and in fact permits to use the cores of any form.

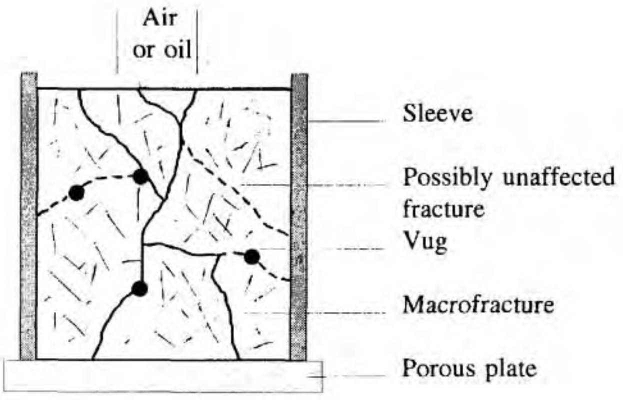

Figure 3. Scheme of fractured core in the porous plate method

Results and discussion

On the first set of 16 core samples we compared the water saturation at preserved state and irreducible water saturation of these cores after cleaning, obtained by semi-permeable porous plate at 6 bars.

As shown in Figure 4, the irreducible water saturation of cleaned cores by porous plate, in some cases is higher and in other cases lower than the value of Sw of preserved state, with average value $Swi2 = 34$ % against $Sw = 33.1$ % by direct measurements on preserved cores. But it is necessary to remember that the water saturation of preserved cores should always be more than the original one due to filtrate invasion. The question, why the values of Swi obtained by porous plate technique are almost the same as those of the preserved cores, while the last ones were strongly affected by mobile filtrate, can be explained as mentioned previously, by heterogeneity of rock which is expressed in different orientation of macrofracture and adjacent vugs so that they could not allow the mobile filtrate to be displaced from themselves. Therefore one conclusion can be made that the porous plate technique in some cases does not represent the true value of irreducible water saturation for fractured granite.

On the second set of samples, in Table 1, the values of water saturation of preserved cores (Sw) are compared with the values of water saturation of preserved core after capillary extraction by chalk powder (Swi1). From the data presented in the table it is clear that the values Swi1 are significantly lower than the value Sw of preserved cores, and that the average difference of water saturation is 16.2%, which was close to the value of partition coefficient of macrofracture of these cores ($C_F = 0.20$, determined from capillary pressure curves [6]). This difference means that the fraction of mobile water extracted from the pore space of rock and confirms that the capillary extraction could give the value of irreducible water saturation, which can be used in approximation to characterize the residual water saturation of heterogeneous fractured granite.

Table 1

Comparison of water saturation of preserved core before and after capillary extraction

Core intervals	Before			After		
	Sw, %	Mean porosity, %	Number of samples	Sw, %	Mean Porosity, %	Number of samples
A	31.5	7.1	6	21.1	6.3	6
B	22.1	6.9	4	12.3	7.7	8
C	32.3	6.3	12	13.5	7.9	9
D	38.1	4.1	10	23.0	3.1	4
E	34.9	6.0	8	19.3	5.8	6
Mean	33.1	5.9	-	16.8	6.6	-

EFFECTS ON ELECTRICAL PROPERTIES

Experimental procedures

Electrical properties of heterogeneous fractured granite have been studied on the full-size cores at the following saturation states:

- Preserved cores
- Preserved cores after capillary extraction.
- Fully saturated with water and partially saturated (after cleaning).

The selected cores can be divided into two groups: the first group consisted only of matrix with microfracture network, the second group is a set of cores containing both elements of rock, macrofractures and microfractures. This division was based on detail core description, capillary pressure characteristics and permeability data. Core resistivity was measured with a two-electrode system at high frequency (to 16 kHz).

Electrical measurements were first performed on preserved cores and on a part of these cores following capillary extraction by chalk powder. The water saturation of these cores was determined by Dean-Stark. Then the cores were cleaned in soxhlet, dried, and saturated with simulated formation brine. Total porosity and formation factors were determined. For cleaned cores, resistivity index was determined at partial water saturation in combination with the porous plate technique. All measurements were performed at room conditions. Resistivity was also measured on cubic samples of sizes 5×5×5 cm in different directions perpendicular to each other to investigate the effects of fracture orientation on electrical properties.

Results and discussion

A set of 36 preserved core samples with porosity 1.5-10.4 % were investigated. Resistivity of preserved cores varied from 35.8 to 6978 ohm.m, corresponding to the range of water saturation from 7.6 to 53%, resistivity of "after capillary extraction preserved cores" ranged from 209 to 22200 ohm.m, corresponding to Swi range from 8.6 to 53 %. Further these cores were recalled as fresh cores. For these cores resistivity index was calculated from Archie equation as follow:

$$RI = \frac{R \times \Phi^m}{Rw}$$

where resistivity of water was accepted in approximation equal to the resistivity of mud filtrate (Rm= 0.24 ohm.m @ T= 30°C). This approximation was based on the facts of filtrate invasion and that the resistivity of formation water was close to the resistivity of mud filtrate. Results presented in Figure 5 in the form of cross-plot of RI versus water saturation show a large discrepancy. For the given set of samples, the values of saturation exponent varied from 1.86 to 4.80.

Cross-plot of RI versus Sw "cleaned cores" is presented in Figure 6 with quite similar characteristic as in the case of fresh cores. The values of saturation exponent n of cleaned core varied in an almost similar range, from 1.68 to 3.80. Meanwhile, a satisfactory relationship between formation factor and total porosity was obtained (see Figure 7) on these cores, with the "cementation factor" m= 1.3-1.5 ($FF = 1.06/\varnothing^{1.43}$ correlation coefficient $R^2 = 0.9074$). These results show that electrical behaviour of fractured granite fully saturated with water was not significantly influenced by the rock heterogeneity, but that the rocks behaved quite heterogeneously in the case of partial saturation.

Typical RI - Sw curves of some of core samples are presented in Figure 8 and 9. Figure 8 is a set of RI-Sw curves obtained on low permeable matrix consisting of microfracture network. Figure 9 represents the curves for double porosity case (macrofractures + microfractures network). For matrix with microfractures (single porosity) we observe linear relationships between RI and Sw, but the values of saturation exponent n varied from sample to sample. This indicates that the electrical behaviour of microfractures network is not homogeneous. In the case of double porosity, non-linear characteristic of the relationship between RI and Sw was observed on a double logarithmic scale. Each RI - Sw curve can be divided into two linear segments with different slopes n. The first segment with higher slope n is always at high value of water saturation, and the second one with lower slope n - at low water saturation. If we take into consideration the capillary pressure curve obtained on each core sample, the first segment of RI - Sw curves with high value of slope n should correspond to macroporosity (i-e. macrofractures) and similarly, the low slope segment should correspond to the rock matrix of microfracture network.

Electrical anisotropy

Another aspect of rock heterogeneity is the orientation of macrofractures. Table 2 presents the values of resistivity measured in different directions on cubic samples. In the case of samples containing macrofacture, direction X denotes the direction of measurement that coincides with the orientation of macrofracture (parallel or subparallel to the fracture plane) and direction Z denotes the direction perpendicular to the fracture plane.

These results show that in the case of macrofractures there is significant difference in resistivity of fully saturated (with brine) sample measured in different directions. The lowest values obtained in the direction parallel to the macrofracture. The anisotropy coefficient $\lambda = \sqrt{Rz / Rx}$, is shown in the table varied from 1.24 - 1.35. The selected cubic samples contain only single macrofractures of aperture 80 - 150 microns (macrofracture porosity ≈ 0.5%). So far, the values of electrical anisotropy coefficient were not investigated in correlation with various values of macrofracture partition coefficient (proportion of macrofracture porosity) but from these results we can expect the higher values of λ for the case of higher macrofracture porosity.

For microfractured matrix, no significant difference of R at different direction was observed, the value of λ coefficient is 1.00 - 1.10. This confirms the influence of macrofractures on rock resistivity and also shows that the microfractures are randomly oriented.

Table 2

Electrical resistivity in different directions

Total porosity %	Resistivity, ohm.m		Anisotropy coefficient	Notes
	Direction X	Direction Z		
	Fully water saturated			
1.54	52.1	79.7	1.24	Double porosity
3.94	43.7	68.2	1.25	"
8.07	6.8	10.4	1.24	"
10.41	5.16	8.8	1.31	"
0.60	289.0	343.0	1.09	matrix
3.05	30.9	36.8	1.10	"
5.40	14.5	14.0	1.03	"
9.21	6.02	6.32	1.05	"
	Partially saturated (preserved cores)			
8.07	113.2	204.9	1.35	double porosity
2.54	912.0	1496.3	1.28	"
2.10	560.7	560.8	1.00	matrix
1.43	2557.3	2344.0	1.04	"

CONCLUSIONS

1. Heterogeneity of fractured granite led to the large difference of permeability obtained on plug and full-sizes core. Core plugs represent basically low permeable matrix consisting of microfractures network ($K < 10$ mD).

2. Rock permeability measured at room conditions is strongly influenced by stress- release and the presence of induced fractures. True rock permeability can only be obtained on full-size cores at simulated reservoir stress conditions.

3. For fractured granite, preserved cores taken by water-based drilling mud can be used to evaluate the value of irreducible water saturation in combination with capillary extraction by chalk powder.

4. Heterogeneity in pore structure has great influences on electrical properties of partial saturated rock. The saturation exponent of fractured granite varied greatly in a range from 1.68 to 4.80 and non-linear characteristic of RI-Sw relationship is caused by the presence of double porosities. Electrical behaviour of fully saturated granite and partially saturated microfractured matrix block is well described by traditional Archie equations: $FF=a/\varnothing^m$ and $RI = a/S_W^n$, but with varied value of saturation exponent n.

5. Rock electrical anisotropy related to orientation macrofractures and rock matrix is electrically isotropic.

NOMENCLATURE

Sw = water saturation of preserved core, % PV
Swi1 = Irreducible water saturation by capillary extraction, % PV
Swi2 = Irreducible water saturation by porous plate, % PV
K_{atm} = permeability at ambient conditions, mD
K_{stress} = permeability at simulated stress conditions, mD
$\varnothing$ = porosity, %
R = resistivity, ohm.m
RI = resistivity index
FF = formation factor
n = saturation exponent
m = cementation factor
C_F = partition coefficient of macrofracture porosity

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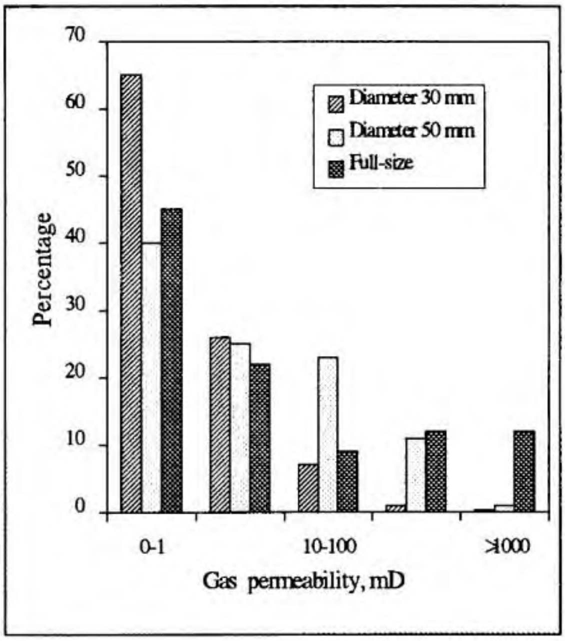

Figure 1. Distribution of rock permeability measured on the cores of different sizes.

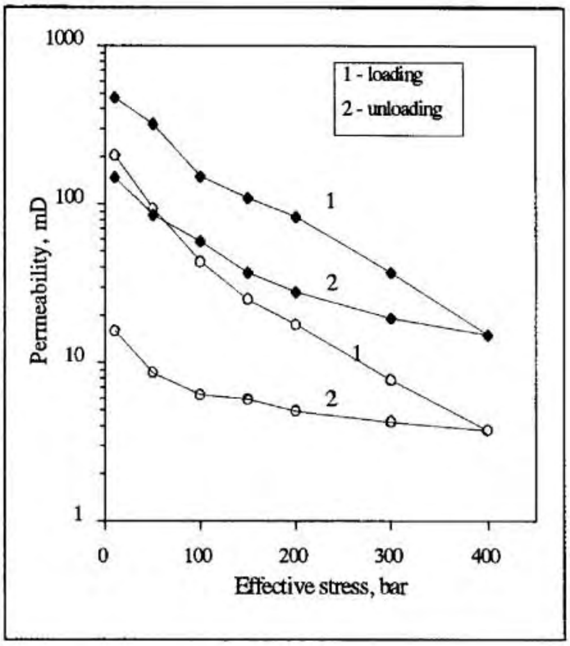

Figure 2. Permeability of fractured granite at various effective stress.

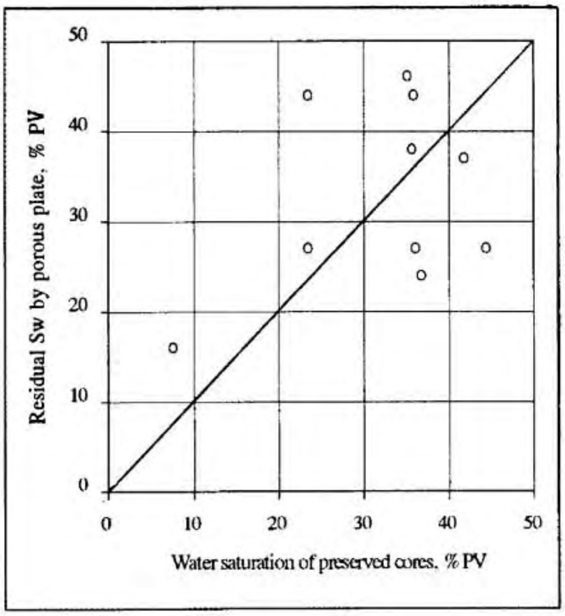

Figure 4. Comparison of water saturation obtained by different methods. Microfractured matrix.

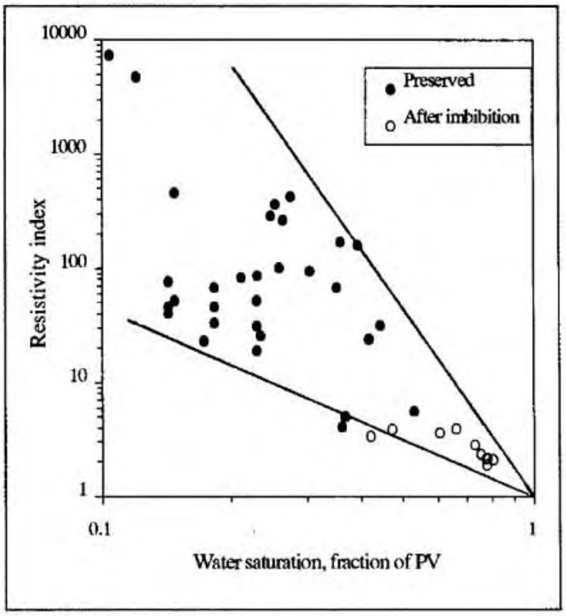

Figure 5. Resistivity indices vs. water saturation. Preserved cores.

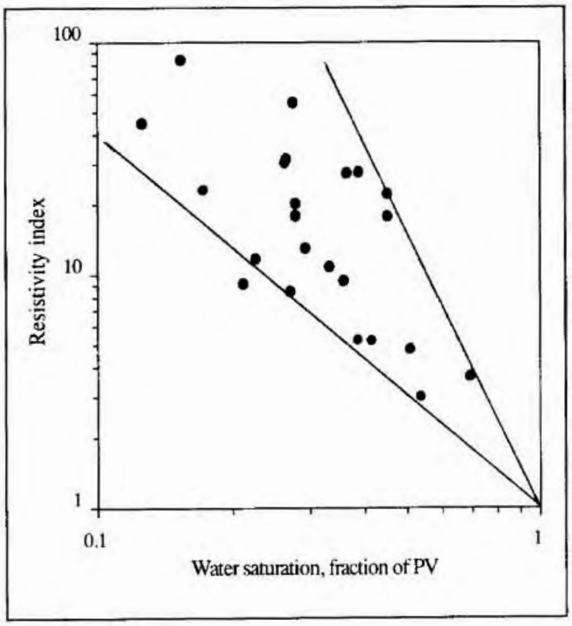

Figure 6. Resistivity indices vs. water saturation.
Cleaned cores.

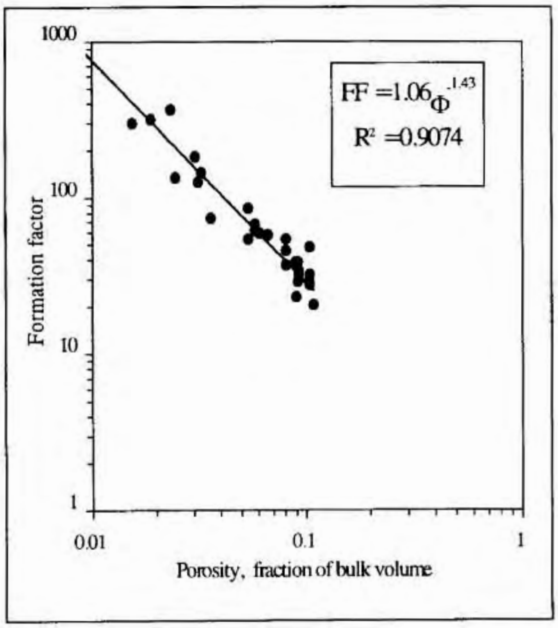

Figure 7. Formation resistivity factor vs. porosity.

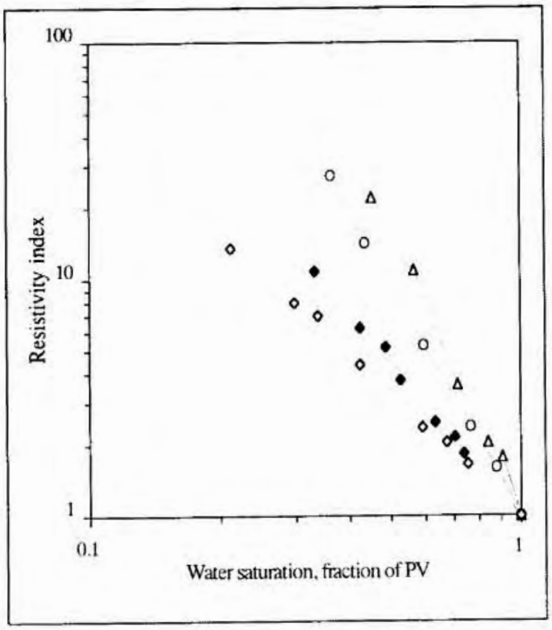

Figure 8. Resistivity index vs. water saturation.
Microfractured matrix.

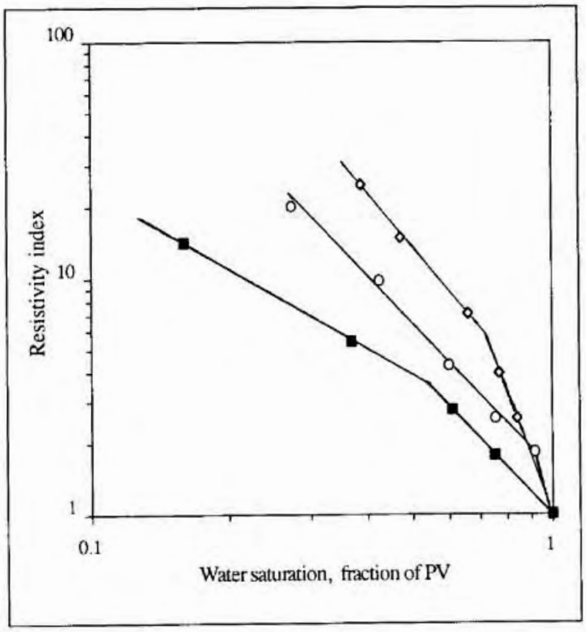

Figure 9. Resistivity index vs. water saturation.
Double porosity samples.