

## **COMPARISON OF SATURATION EXPONENT DATA BY THE 'POROUS PLATE' AND BY THE 'CONTINUOUS INJECTION' TECHNIQUE WITH IN-SITU SATURATION MONITORING**

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### **ABSTRACT**

Saturation exponents ( $n$ ) of reservoir rocks, determined from electrical measurements on core samples enable the evaluation of the water saturation of hydrocarbon reservoirs. Errors in this parameter, as derived from the traditional 'porous plate' method have given rise to serious errors in the estimation of hydrocarbon saturation. The major sources of uncertainty have been measurement procedures, core handling and pore geometry.

These data have traditionally been obtained by using gas (non-wetting phase) to displace brine (wetting phase) from a 100 % water saturated core sample. This laboratory procedure mimics the drainage process by which the hydrocarbons entered the reservoir and displaced water. Using gas as a desaturation medium precludes the possibility of the displacing phase wetting the rock surface, thus maintaining a continuous water wetting film during desaturation. Oil displacing brine has not been used frequently because oil wetting may occur during brine displacement. A new approach of continuous oil injection is compared here with the industry standard 'porous plate' technique. During oil injection, X-Ray in-situ saturation monitoring has been used to define the saturation profile along the sample length as the test progresses.

## INTRODUCTION

The concept of a saturation exponent was developed by Archie (1942) on the basis of earlier work by, *inter alios*, Jakosky and Hopper (1937) and Leverett (1939). The saturation exponent ( $n$ ) forms part of an empirical equation used to relate water saturation ( $S_w$ ) to resistivity index (RI). RI is defined as the ratio of the resistivity of a partially electrolyte-saturated rock ( $R_t$ ) to the resistivity of the same rock when fully saturated with identical electrolyte ( $R_o$ ). This relationship took the form:

$$RI = S_w^{-n}$$

It was postulated to be valid for clean sands partially saturated with high-salinity brine where  $S_w > 0.15$ . Under these conditions it appeared that  $n$  approximated to a value of 2, which has been widely adopted as the accepted norm within the industry.

The laboratory evaluation of saturation exponent can result in large errors in hydrocarbon evaluation as described by de Waal *et al* (1989). These errors are largely caused by incorrect experimental procedures and core handling. Also, uncertainty has arisen because the saturation exponent has been assumed constant for a given (clean) water-wet sample of reservoir rock, Archie (1942). However, an increasing number of cases are being encountered where the saturation exponent has been observed to change with variations in fluid saturation within a given rock sample; Swanson (1985), Givens (1986), Rasmus (1986), Argaud (1989), Worthington (1989) and Longeron (1989). This means that in some cases, the simple Archie model is inadequate to describe the rock electrical behaviour. The cores should also be desaturated to the  $S_w$  values encountered within the reservoir. Incomplete desaturation may result in large errors in the 'n' value used to calculate water saturation from the logs as shown by Swanson (1985) and Worthington (1985).

The purpose of this paper is to compare the saturation exponent derived using the traditional 'porous plate' technique and that using the 'continuous injection' method as described by de Waal *et al* (1989). The shape of the desaturation profile and its influence on resistivity index was also investigated for both water and oil wet samples. The saturation distribution during the 'continuous injection' experiments was monitored using X-Ray attenuation. This provided  $S_w$  profiles along the sample length at selected times during the desaturation process.

Various workers have used in-situ saturation monitoring to study the phenomenon of uneven saturation distribution in reservoir rock samples. Lyle and Mills (1989) stated that valid saturation exponents were only obtained when the fluid saturations along cores were uniform. They

observed that saturation heterogeneity caused an increase in the calculated saturation exponent. The 'porous plate' method has also been used to obtain uniform desaturation, as described by Maerefat et al (1990). They discovered that homogeneous saturations will only occur if sufficient desaturation time is allowed for equilibrium. However, Sprunt et al (1991) found that if oil rather than gas is used to displace brine in high Sw carbonate rocks, non-uniform desaturation can occur.

The key element in this evaluation process is the quantification of saturation heterogeneity caused either by sample end effects, preferential oil wetting or rock heterogeneity. Should any of these factors occur then there would be deviation from the pre-condition that a uniform water saturation distribution must prevail for determination of valid saturation exponents.

## EXPERIMENTAL TECHNIQUES

### Samples Studied

The samples used (referred to in the text as 1 through 5) were obtained from three UK Continental Shelf reservoirs. These samples were all 1.5" diameter. They were chosen to possess certain key elements, namely oil wetness, micro-porosity and sharply uni-modal pore size distribution, to observe comparability of the two techniques for samples with these extreme characteristics. Sample petrophysical parameters are summarised in Table 1.

Sample	Permeability (mD)	Porosity (Fractional)	Formation Factor
1	7410	0.240	12.75
2	320	0.254	12.00
3	1400	0.258	11.20
4	1.6	0.263	12.50
5	5.3	0.290	10.21

Table 1, sample petrophysical parameters.

## Experimental Procedure

### i) 'Porous Plate' Samples (primary drainage cycle)

The capillary pressure characteristics of four samples (2, 3, 4 & 5) were previously determined at the BP Research Centre, Sunbury-on-Thames.

The samples were miscibly flush cleaned and saturated with simulated formation water. Removal of any residual air in the samples was verified by monitoring sample resistivity at two separate pore pressures whilst maintaining the same net confining stress.

The samples were loaded into a capillary pressure cell without confining stress. Free water was removed from the samples' surface by applying an air/brine capillary pressure just below the sample entry pressure as predetermined by mercury injection on an offset.

Once equilibrium was established, the samples were removed and allowed to come to temperature equilibrium in an incubator. Each sample in turn was then placed between two electrodes mounted with platinum blacked gauzes and a filter paper moistened with simulated formation water. The samples were held firmly in place between the electrodes by a hydraulic ram powered by 40 psig air pressure. A frequency sweep was used to determine the frequency which minimised non-resistive behaviour and  $R_0$  was determined. This optimal frequency for each sample was used for the resistance measurements at subsequent stages of desaturation.

The samples were replaced in the cell and desaturated at a series of increasing capillary pressures. Equilibrium was determined by the cessation of brine production at each pressure rather than selection of any arbitrary desaturation time interval. Sample weights were measured after each desaturation period and the sample impedance was measured as before. The use of a rapid computer logging system enabled sample resistance to be measured as soon as a good contact was achieved and before significant brine imbibition could occur. Departure from such rigorous procedures may result in significantly erroneous RI.

At the final stage of desaturation, the samples were placed in an oven and dried. This was to establish by weight loss, the volume of water still remaining in the sample at the highest capillary pressure. The volume of brine at this saturation was then calculated by subtracting any water imbibed during the final resistance measurement. All other saturations were then calculated relative to this base value. This procedure virtually eliminates any errors in the final water saturation which may be caused by error in pore volume or grain loss.

## ii) 'Continuous Injection' Samples

The initial preparation methods used here, except sample 1, were identical to those described above. After brine saturation, sample 1 was desaturated to an initial water saturation on a 'porous plate'. It was then saturated with oil and aged in dead crude for 40 days at reservoir temperature. Prior to loading into the 'continuous injection' system this sample was flooded with simulated formation brine to a residual oil saturation.

All samples were placed in horizontally mounted aluminium Hassler core holders within a linear track unit along which an X-Ray system travelled. Fully saturated membrane assemblies were placed at the base of each sample. The membranes used were molecular sieves which allowed the passage of water molecules but blocked the larger hydrocarbon molecules. The membrane was supported on a brine saturated high porosity glass sintered disc. An initial confining stress of 400 psig was applied. Brine was flowed through the system to ensure complete water saturation and the base resistance was recorded. The confining pressure was increased to 800 psig and the sample pore volume reduction was calculated based on the brine volume collected in pipettes attached to the outlet of each sample.

Each sample was then scanned using the X-Ray system travelling at 2mm/second. Contiguous 2mm slices were monitored along the length of each sample and the attenuation profile was logged as X-Ray counts/second. Mineral oil doped with iododecane was then injected at a low and constant flow rate into the samples. The X-Ray attenuation increased as the doped oil flowed into the sample, and thus showed the distribution of the oil along the length of the core.

Each core holder had a dedicated positive displacement pump. The piston of each pump was connected to a linear scale which accurately logged displacement. At the downstream end of the sample a graduated pipette was attached and the volume of brine displaced from the samples was recorded daily. An injection rate was selected such that an insignificant pressure drop existed across the sample throughout the desaturation process. Injection rates of approximately 0.02 cm<sup>3</sup>/hour were used, which desaturated the samples over a minimum of twenty one days. Corrections for the compressibility of the system with increasing oil injection pressure were made based on the oil injected versus brine out volumes. X-Ray scans were made at two-hourly intervals throughout the test period. Resistance, phase angle, temperature and oil pressure were logged hourly. The average saturation for each sample was calculated by deducting the volume of brine displaced from the pore volume. Resistivities were corrected for

slight temperature variations using the Arps equation (Arps 1953).

## RESULTS AND DISCUSSION

### 'Continuous Injection' - Basic Principles

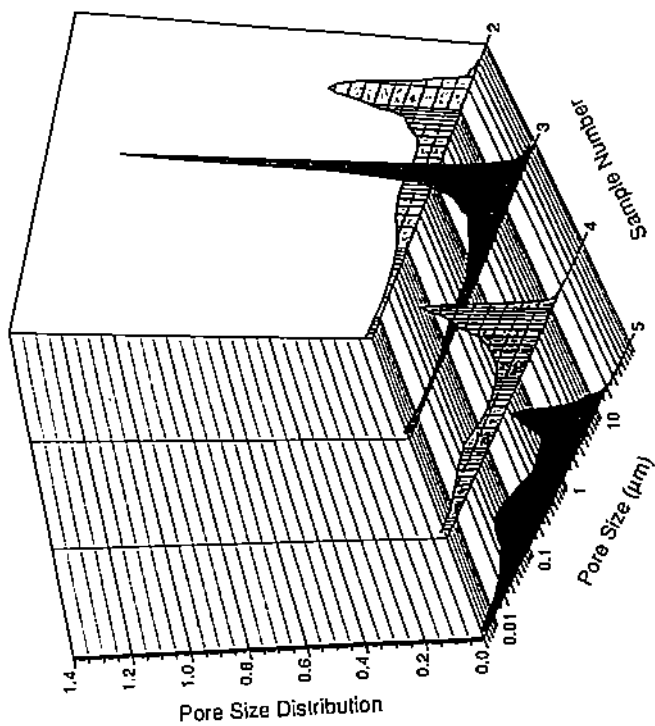
When oil is injected into a fully saturated water-wet sample, it will penetrate the largest diameter pore throats first since these represent the paths of least resistance. At this early stage of the procedure, oil moves through the sample as a flood front. Until this front progresses to the end of the core a saturation heterogeneity persists along the sample length which invalidates the  $Ri/S_w$  curve. It is argued that the largest pores (amounting to some 20 % of the pore volume in these samples) account for almost all of the sample permeability. Once continuity has been established through these pores, desaturation of the remaining bulk of the pore space will proceed uniformly down the length of the sample. It is also postulated that the non-equilibrium nature of the experiment is irrelevant since the pore throats still desaturate in monotonically decreasing order of size.

Certain scenarios are conceivable in which the above conditions may break down. For example, any oil wetting tendency will result in oil imbibition into smaller pores causing an uneven saturation profile. Maximum injection rate of oil is also an important sample specific parameter, which if too high, could result in a significant pressure drop across the sample. This would in turn lead to smaller pores being drained at the sample inlet relative to the sample outlet at any given time.

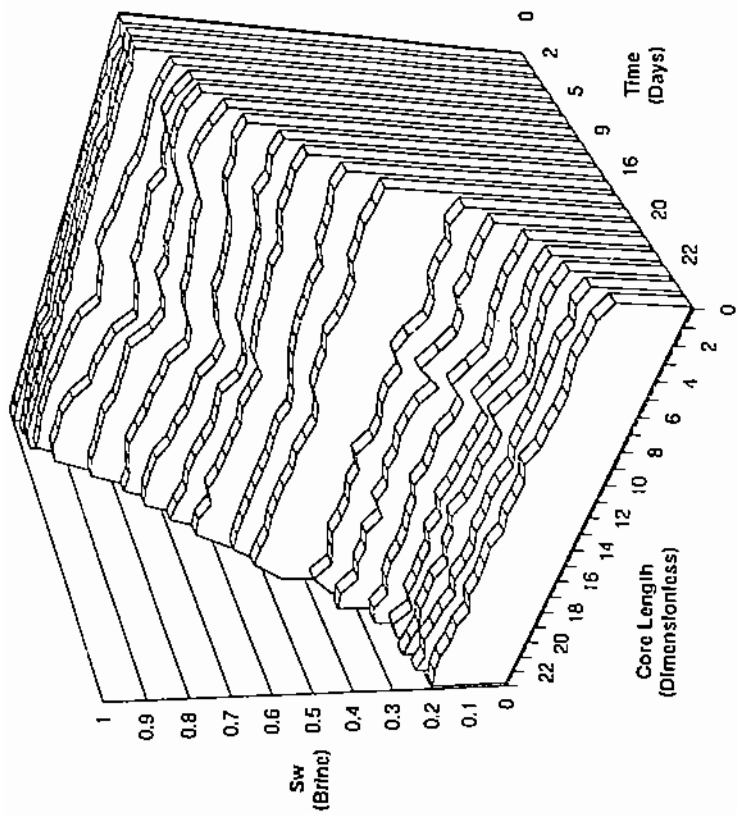
### Comparison Between 'Continuous Injection' and 'Porous Plate' Methods

Four water wet sandstone samples were chosen for comparison between 'porous plate' and 'continuous injection' techniques. Pore size distribution plots of these samples are presented in Figure 1. Samples 2 and 3 are high permeability, high porosity sandstones containing only a small amount of kaolinite clay. Samples 4 and 5 are also high in porosity, but large quantities of chlorite-induced microporosity have partially occluded the pore space thereby reducing mean pore size and inhibiting sample permeability.

The saturation profiles produced during 'continuous injection', as measured by X-Ray attenuation for samples 2 and 3, are presented as three dimensional plots in Figures 2 and 3. Uniform saturation

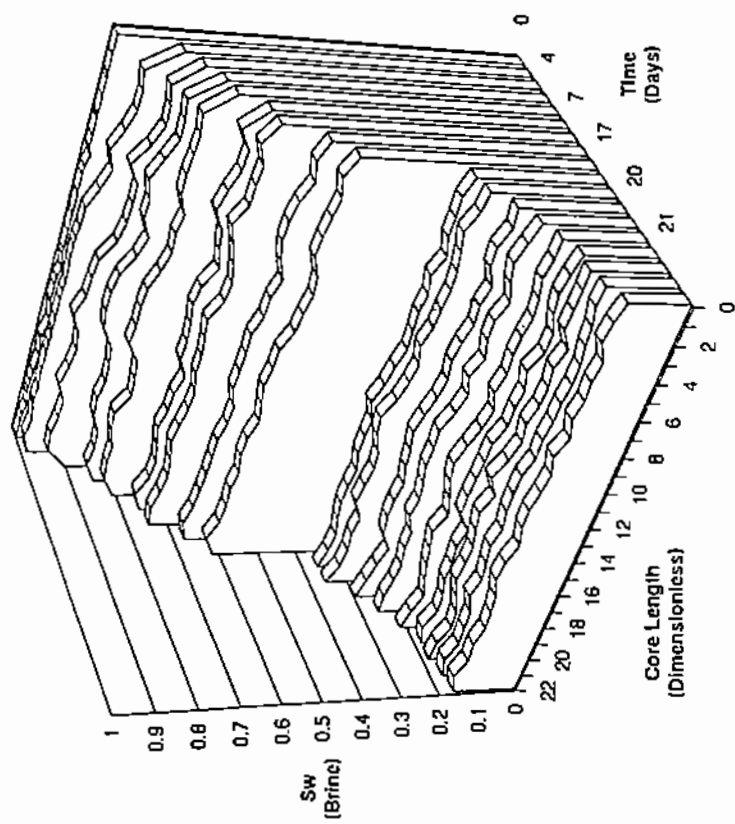


**Figure 1** Mercury injection derived pore throat size distribution multi-sample plot for the porous plate comparison samples.



**Figure 2** Three dimensional plot showing variation in saturation profile along sample with time (sample 2).





**Figure 3** Three dimensional plot showing variation in saturation profile along sample with time (sample 3).

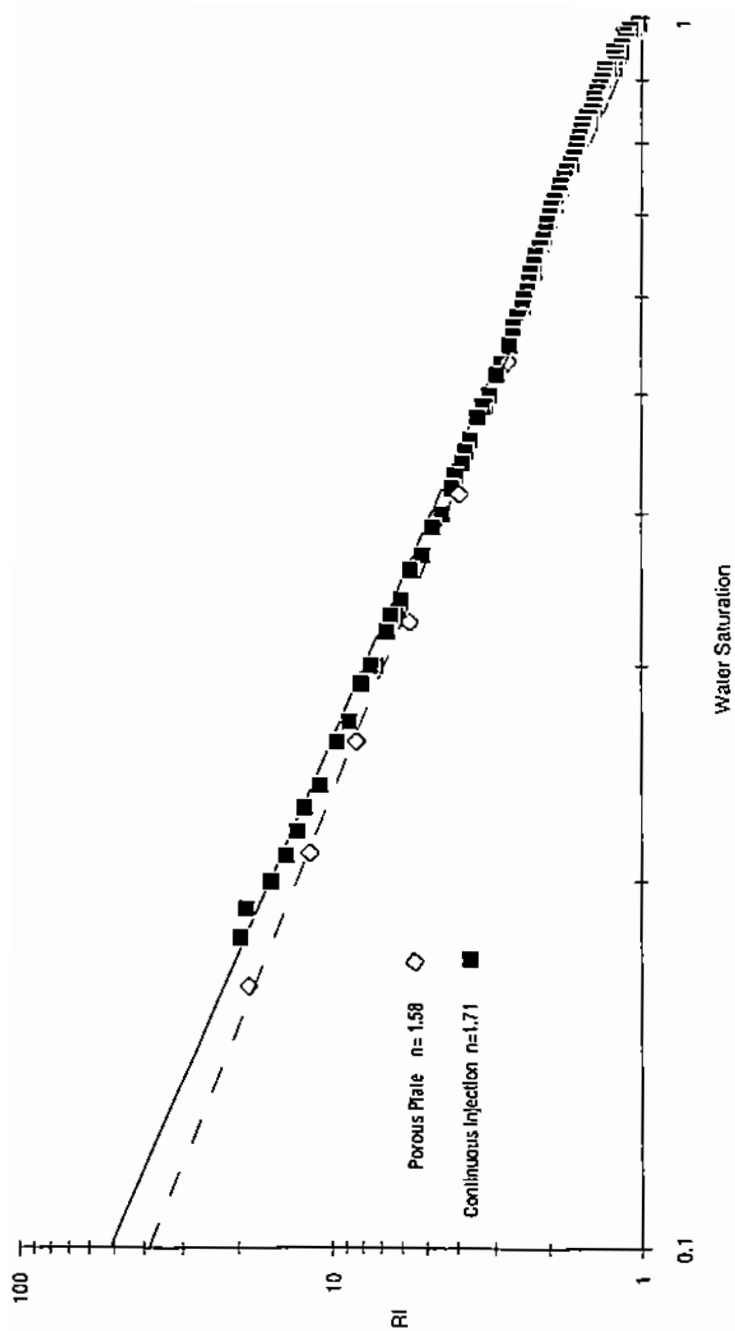
distributions developed quickly and were thereafter maintained in both cases. The corresponding  $R_i/S_w$  plots are given in Figures 4 and 5. After the attainment of uniform water saturation, the two methods appear to be comparable. For lower water saturations, however, a small systematic discrepancy appears to exist. In both cases the saturation exponent determined from 'continuous injection' is slightly higher. One possible explanation is that in the case of the 'continuous injection', some small drainage end effect may be present.

A one-dimensional 10 element model was developed to illustrate the effect of a small localised increase in  $S_w$  for a system where intrinsic  $n$  is equal to 2. Figure 6 illustrates that a small increment in  $S_w$ , such as that which would result from a sample end effect, could cause significant error in calculated saturation exponent. This is especially true where low water saturations are achieved, as in this case. The presence of a minor end effect, perhaps too close to the end platen to be observed by saturation monitoring with this configuration, could explain the small discrepancy between the two techniques for samples 2 and 3.

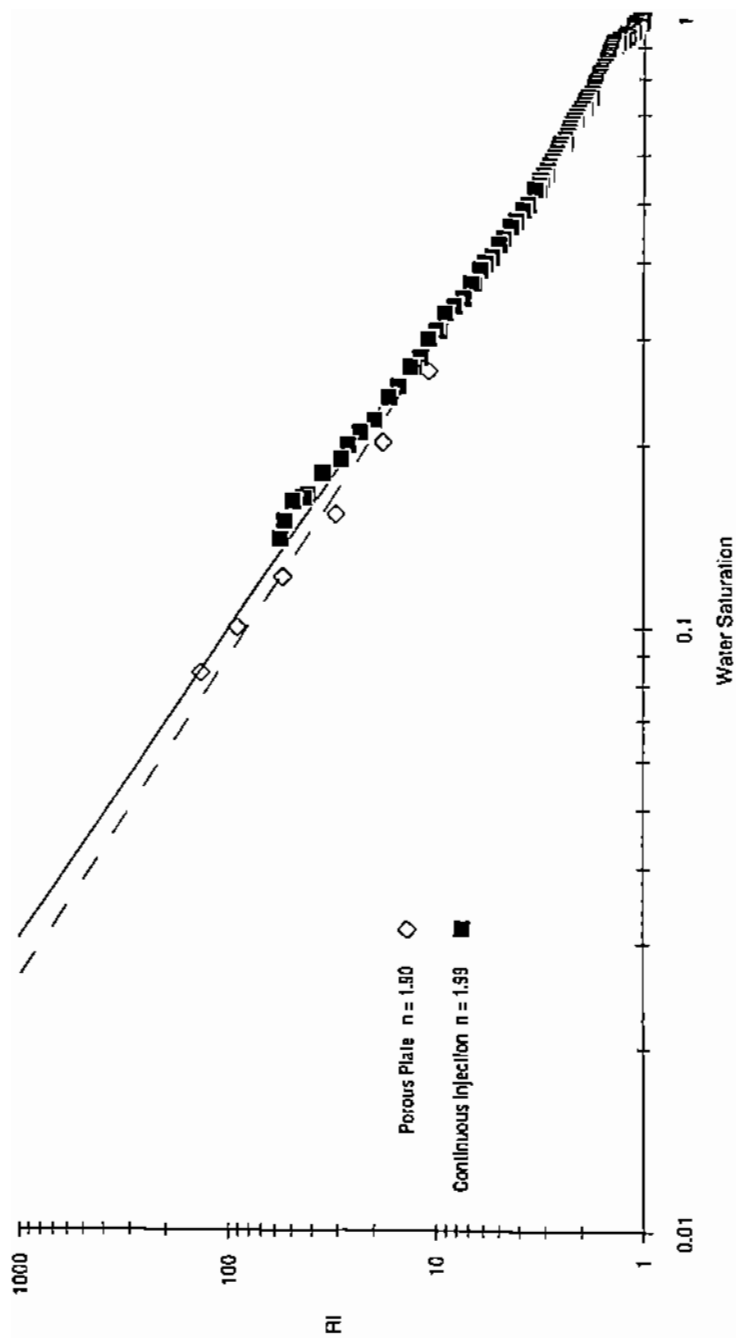
The saturation profile for sample 4 is presented in Figure 7. The saturation distribution is not as uniform as for samples 2 and 3 although this may be a consequence of bioturbation causing localised heterogeneity within this sample. The distribution does, however, improve greatly in terms of uniformity towards the end of the experiment. Saturation monitoring was not performed for sample 5. The resistivity index plots for samples 4 and 5 are displayed in Figures 8 and 9 respectively. The data points overplot closely when water saturation is less than 80 %.

### **Aged Sample**

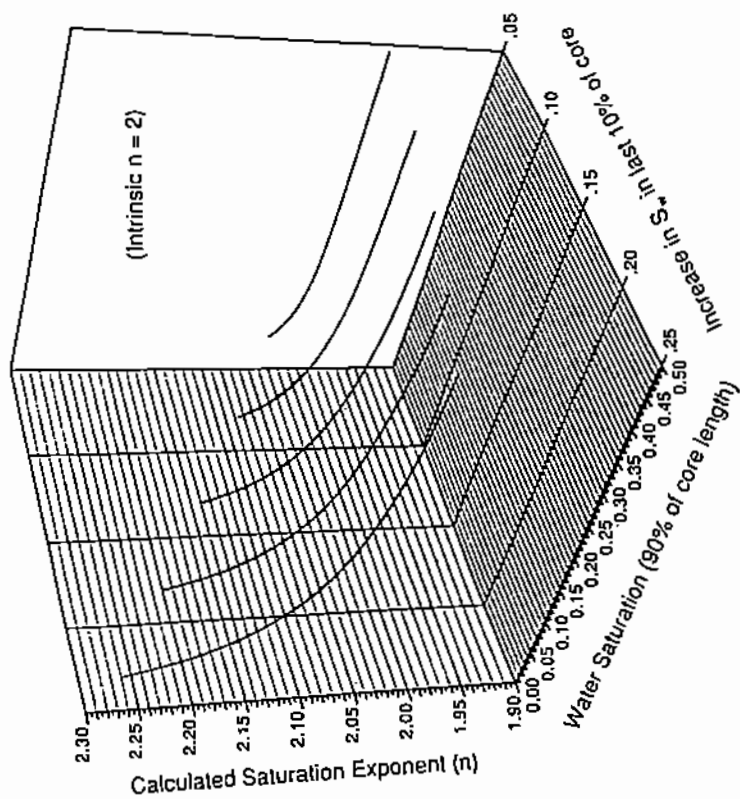
This sample was high permeability, high porosity clean and well sorted sandstone. The 'continuous injection' process here represents a secondary drainage cycle. A suite of saturation profiles for sample 1 are presented in the three dimensional plot, Figure 10. The saturation distribution remained uneven for most of the experiment with oil imbibition apparent at various stages. This resulted in an unrealistically high value of  $n$  until the saturation profile finally became uniform. The linear region of the plot is representative of the secondary drainage cycle but not the primary drainage cycle. This phenomenon is illustrated in the  $R_i/S_w$  plot, presented as Figure 11.



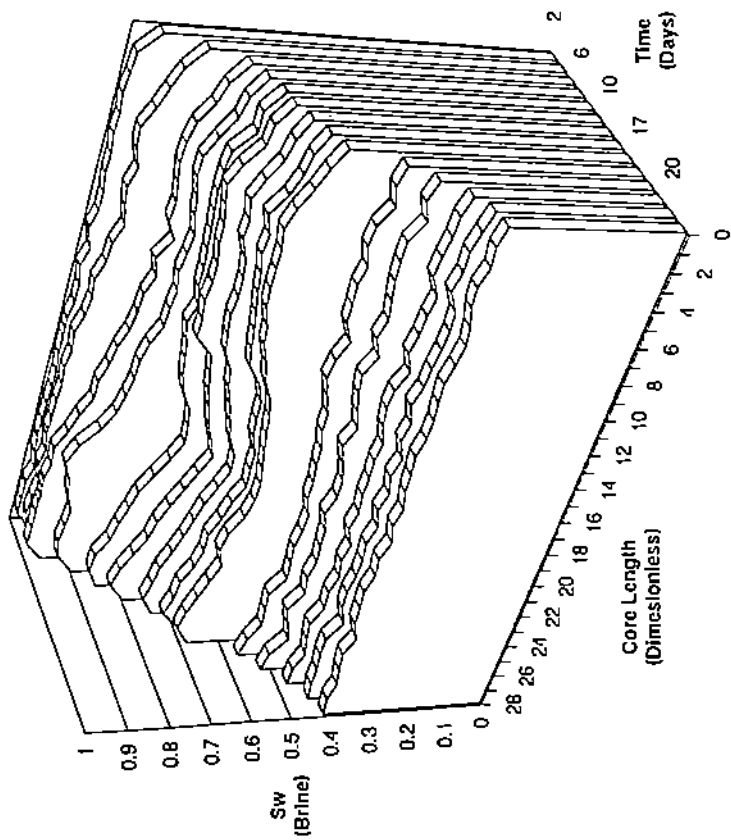
**Figure 4** Log/log plot of resistivity index versus fractional brine saturation comparing porous plate and continuous oil injection techniques (sample 2).



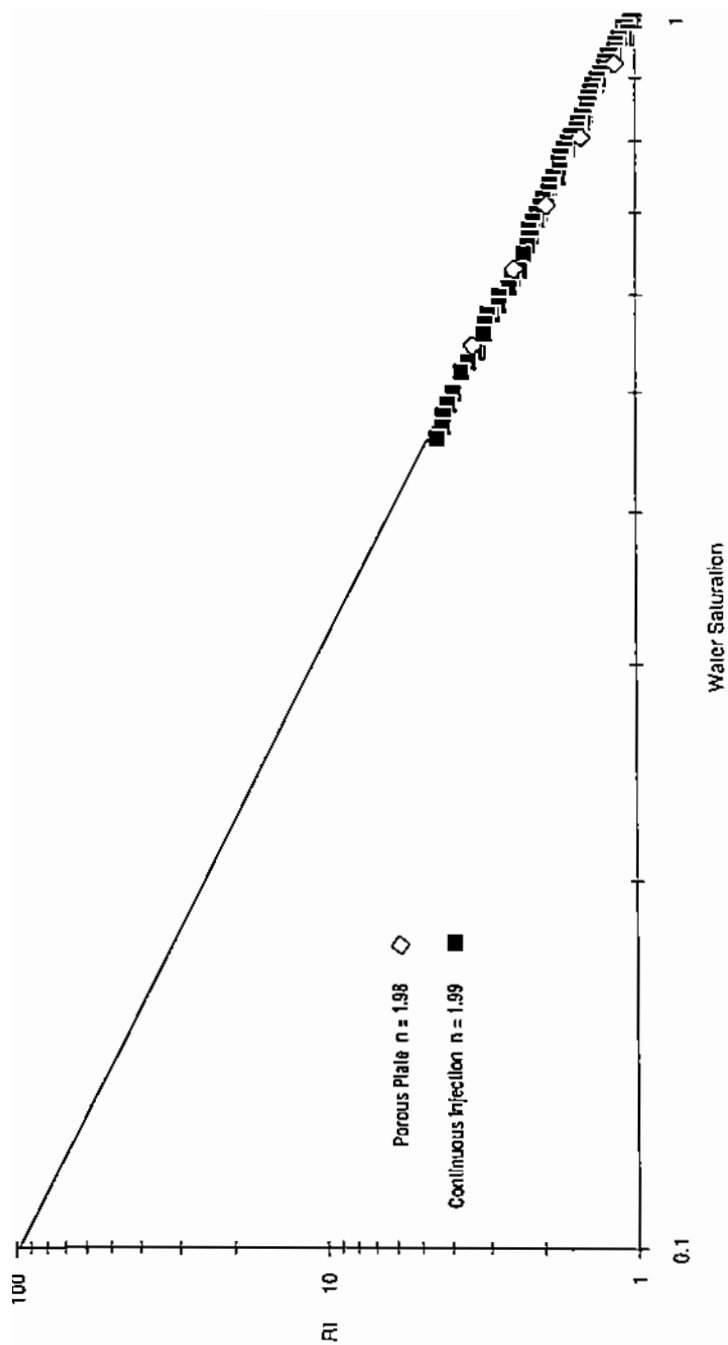
**Figure 5** Log/log plot of resistivity index versus fractional brine saturation comparing porous plate and continuous oil injection techniques (sample 3).



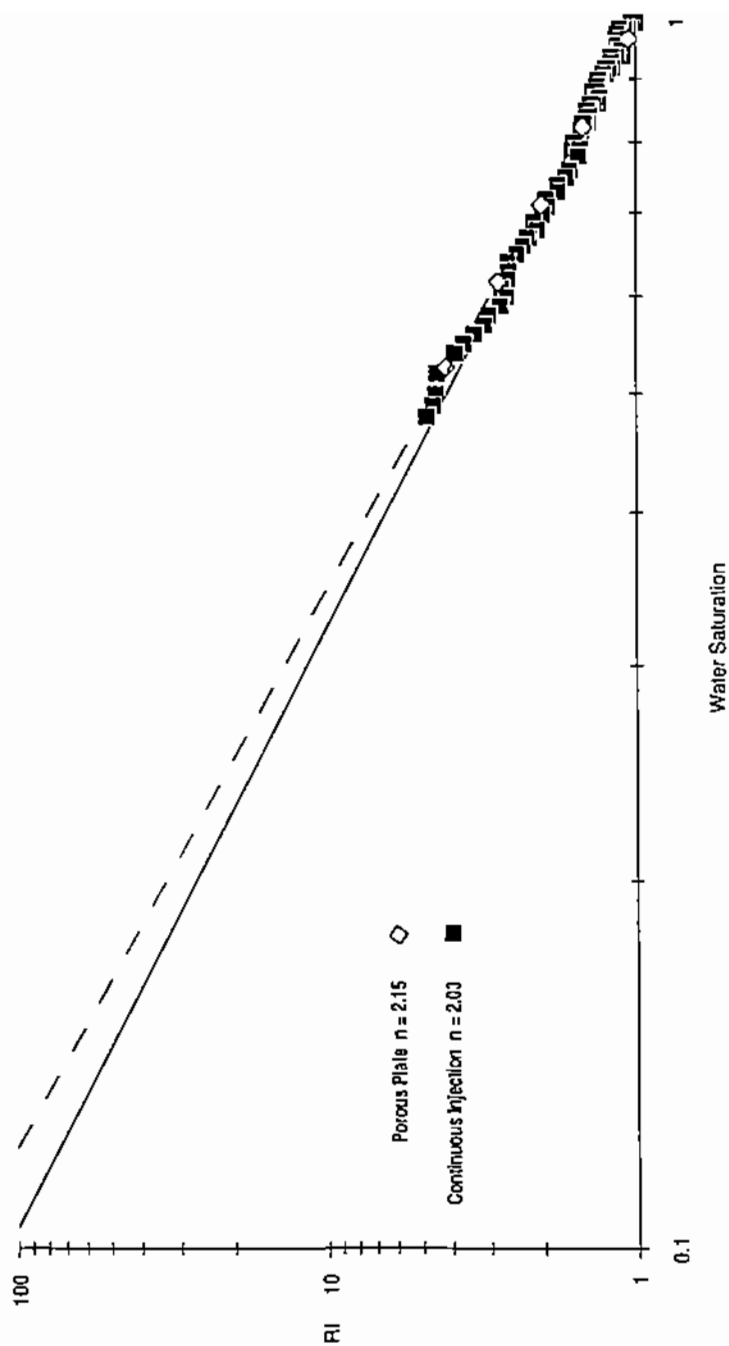
**Figure 6** 10 element model demonstrating the influence of saturation end effects in the last 10% of the core sample on the calculated saturation exponent.



**Figure 7** Three dimensional plot showing variation in saturation profile along sample with time (sample 4).

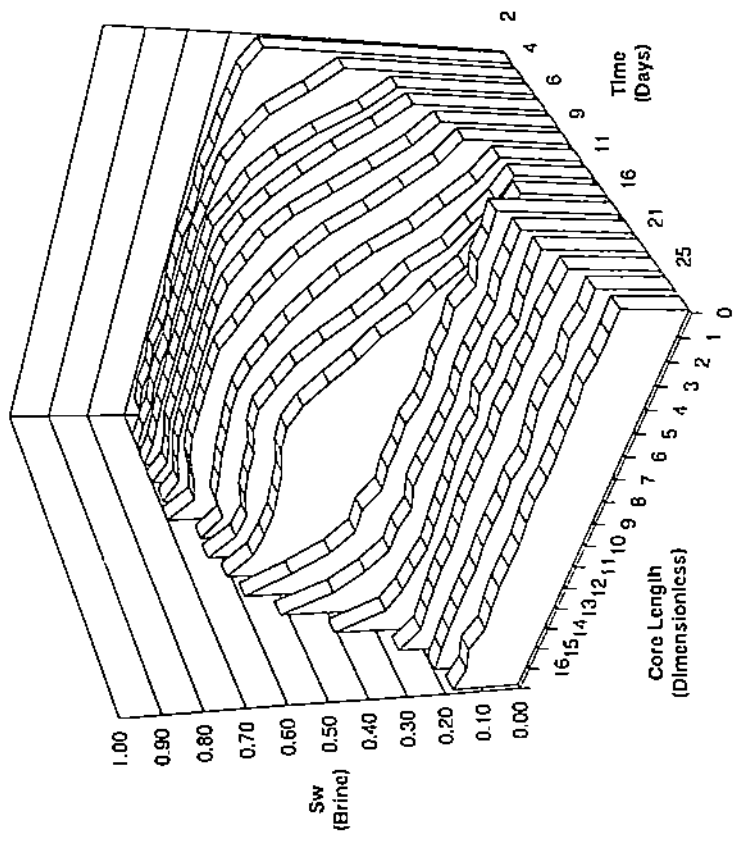


**Figure 8** Log/log plot of resistivity index versus fractional brine saturation comparing porous plate and continuous oil injection techniques (sample 4).

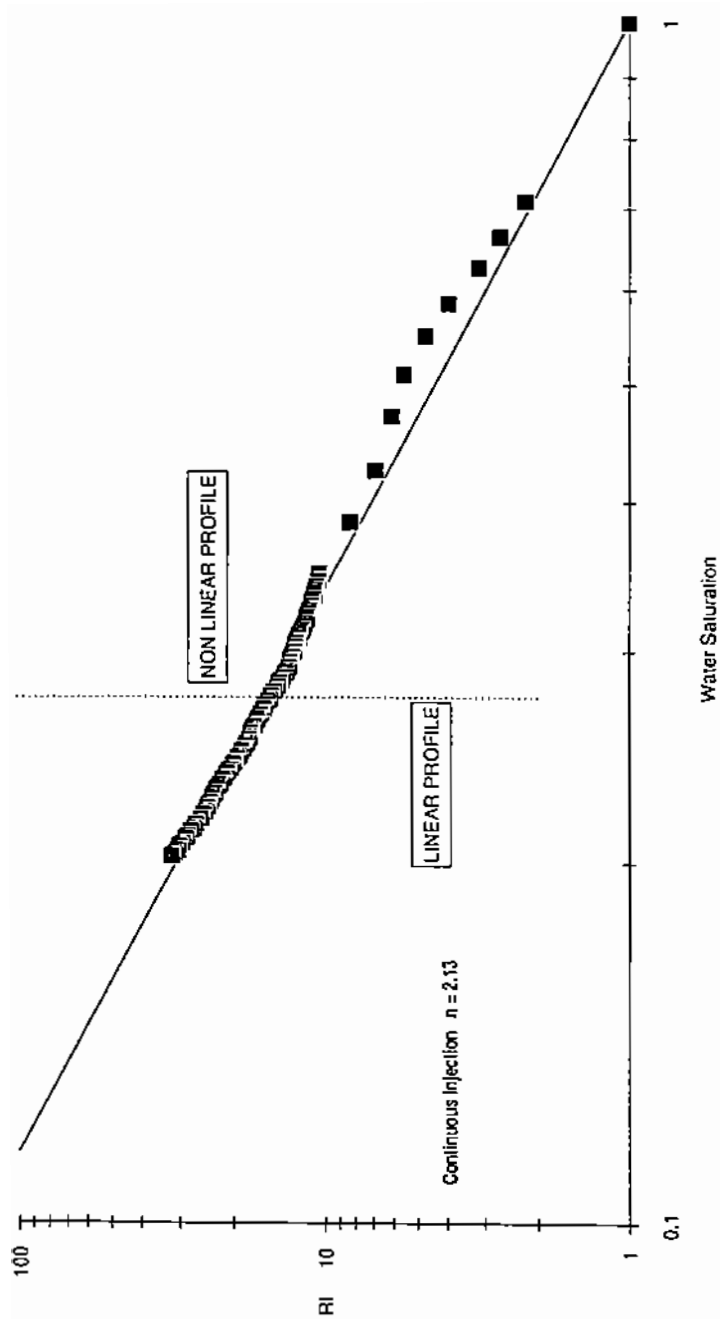


**Figure 9** Log/log plot of resistivity index versus fractional brine saturation comparing porous plate and continuous of injection techniques (sample 5).





**Figure 10** Three dimensional plot showing variation in saturation profile along sample with time (sample 1).



**Figure 11** Log/log plot of resistivity index versus fractional brine saturation using continuous oil injection technique (sample 1).

## CONCLUSIONS

1. Fair agreement was observed between 'porous plate' and 'continuous injection' techniques for the water wet samples.
2. The 'porous plate' method can provide good data if rigorous experimental procedures are followed.
3. The 'continuous injection' technique fails to achieve uniform saturation distribution in pores having oil wet tendency and in such cases will not produce valid RI data. If too high an oil injection rate is used then non uniform saturation and hence invalid RI data will also be produced.
4. The 'continuous injection' technique should offer a high degree of reproducibility and operator independence.
5. 'Continuous injection' gives the advantage of a continuous resistivity index/water saturation relationship in a greatly reduced timescale compared with 'porous plate', but does not provide an equilibrated capillary pressure curve.
6. Use of in-situ saturation monitoring has illustrated that for the water wet samples a uniform saturation distribution is established over much of the saturation range during the 'continuous injection' tests.

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## REFERENCES

1. Archie, G.E. "The Electrical Resistivity Log As An Aid In Determining Some reservoir Characteristics" *Trans., AIME* (1942) 146, 54-62.
2. Jakosky, J.J. and Hopper, R.H. "The Effect of Moisture on the Direct Current Resistivities of Oil Sands and Rocks", *Geophysics*, v.2, pp 33-55, 1937.
3. Leverett, M.C. "Flow of Oil-Water Mixtures Through Unconsolidated Sands", *Trans. Am. Inst. Min. Metall. Engrs.* V.132, pp.149-171, 1939.
4. De Waal J.A., Smits R.M.M., Graaf J.D., Schipper B.A., "Measurement and Evaluation of Resistivity Index Curves", SPWLA, 30th Symposium, June 1989.
5. Swanson, B.F., "Microporosity in Reservoir Rocks - Its Measurement and Influence on Electrical Resistivity", *The Log Analyst* (1985) 26(6), 42-52.
6. Givens, W.W., "Formation Factor, Resistivity Index and Related Equations based upon a Conductive Rock Matrix Model (CRMM)", *Trans. SPWLA 27th Annual Logging Symposium* (1986), Paper P.
7. Rasmus, J.C., "A Summary of the Effects of Various Pore Geometries and their Wettabilities on Measured and in-situ Values of Cementation and Saturation Exponents", *Trans. SPWLA 27th Annual Logging Symposium* (1986), Paper PP.
8. Argaud, M., Giouse, H., Straley, C., Tomanic, J. and Winkler, K., "Salinity and Saturation Effects on Shaly Sandstone Conductivity", *SPE Paper 19577* (1989).

9. Worthington, P.F. Pallatt, N. and Toussaint-Jackson, T.J. (1989), "Influence of Microporosity on the Evaluation of Hydrocarbon Saturation", SPE Formation Evaluation (1989), 4, 203-209.
10. Worthington, P.F. "The evolution of the shaly-sand concepts in reservoir evaluation" The Log Analyst (January-February 1985) 23-40.
11. Longeron, D.G., Argaud, M.J., and Feraud, J.P., "Effect of Overburden Pressure and the Nature and Microscopic Distribution of Fluids on Electrical Properties of Rock Samples", SPE Formation Evaluation (1989) 4, 194-202.
12. Lyle, W.D. and Mills, W.R. "Effect of Nonuniform Saturations on Laboratory Determination of the Archie saturation Exponent", SPE Formation Evaluation (1989) 49-52.
13. Maerefat, N.L. et al "Guidelines for Saturation and Desaturation Techniques of Core Plugs During Electrical Resistivity Measurements", The Log Analyst (1990) 31, No. 2, 68-75.
14. Sprunt, E.S. et al "CT-Scan Monitored Electrical-Resistivity Measurements Show Problems Achieving Homogeneous saturation", SPE Formation Evaluation (1991) 134-140.
15. Arps, J.J., "The Effect of Temperature on the Density and Resistivity of Sodium Chloride Solutions", Journal of Petroleum Technology (1952), Technical note 195, 17-20.



## **Rock-Fluid Interaction**

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