ESTIMATION OF CAPILLARY BOUND WATER IN CARBONATE RESERVOIR SAMPLES BY NMR IMAGING AND RELAXATION MEASUREMENTS

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Abstract

In recent years, Nuclear Magnetic Resonance (NMR) logging technologies have been successfully deployed in a number of sandstone reservoirs. In contrast, comparatively little information concerning the potential performance and the interpretation methodologies exist for carbonate reservoirs. To evaluate the potential application of NMR wireline logging technologies for improving the formation evaluation of a dolostone reservoir, laboratory NMR relaxation measurements were carried out using a low field NMR instrument (2 MHz). Saturation variations and the spatial variability of the pore space in the samples was investigated using high field NMR imaging techniques.

This paper highlights the need for caution in the determination of irreducible water saturations by both centrifuge and porous plate desaturation techniques. Sample desaturation by the centrifuge technique was not a viable method for this NMR study because saturation gradients were observed by NMR imaging in some of the samples. These saturation gradients did not dissipate even after two weeks in some of the samples. Desaturation of the samples by porous plate at 100 psi required sixty days to complete, much longer than is normally recognised by conventional core analysis. This gave rise to capillary bound water values much lower than expected from the sample's permeability and porosity. The low residual water saturations were confirmed for a number of samples by mercury injection data.

The prediction of the gravimetric porosity by the NMR measurements was excellent and well within experimental error. The prediction of vug porosity from the low field NMR data using a 750 ms T_2 cut-off value compared reasonably with that obtained from the high field NMR imaging and relaxation experiments. Due to the low capillary bound water saturations determined using the porous plate, the T_2 cut-off values obtained for the capillary bound water fraction were much lower than the values obtained by previous carbonate researchers using a similar desaturation pressure. Although considerable variability exists, the majority of the capillary bound fluid cut-off values are less than 30 ms. The prediction of permeability using the Schlumberger equation ($k \sim \varphi^4 T_{2g}^2$) or the Coates equation [$k \sim \varphi^4 (FFI/BVI)^2$] did not improve predictions made by simple porosity vs permeability estimates. Permeability estimation from the porosity with T_2 less than 750 ms using the relationship $k \sim (\theta_{<750})^4 [T_{2(<750)}]^2$ did not improve the fit. Clearly, further laboratory work on vuggy dolostone samples is required before the full benefits of the NMR logging technology can be realised.

Introduction

Nuclear Magnetic Resonance (NMR) logging has revolutionised formation evaluation, offering the potential to reliably estimate total and effective porosities, capillary bound water saturations and permeabilities. In favourable circumstances, NMR can be employed to obtain information concerning residual oil saturations and gas volumes.

Nuclear Magnetic Resonance data interpretation is more challenging in carbonate reservoirs due to the broad range of pore sizes, complex pore structures and low surface relaxivity values found. The successful implementation of the logging technology requires a detailed understanding of the physical properties that directly affect the NMR measurements. An evaluation of the suitability of the NMR logging technology can be made through the use of low field laboratory investigations.

To evaluate the potential application of NMR wireline logging technologies for improving the formation evaluation of a dolostone reservoir, laboratory NMR relaxation measurements were carried out using a low field NMR instrument (2 MHz). Saturation variations and the spatial variability of the pore structure in the samples was investigated using high field NMR imaging techniques.

Experimental Details

After cleaning and conventional petrophysical core analysis (helium porosity and air permeability), a total of 35 core plugs were saturated *in vacuo* with a synthetic formation brine. The sample dimensions are approximately 78 mm by 38 mm. Samples subjected to desaturation by the centrifuge had to be trimmed to a length of 50 mm.

The samples are typical of vuggy sucrosic dolomite reservoirs in which the vug porosity pores are less than 2 mm in size and appear disconnected. Although the entire reservoir sequence has been dolomitised, the primary sedimentary fabrics have been preserved. The fabrics suggest that the depositional environment was typical of a low energy restricted marine. The reservoir sequence exhibits features such as cryptalgal and stromatilitic algal lamination that are characteristic of subtidal to intertidal platform / lagoon carbonates. Sedimentary breccias occur in some sections and indicate a periodic re-working of the lithified sea floor and/or solution brecciation in a supertidal environment. Dolomitisation of the limestones has led to intercrystalline pore networks. Secondary mouldic and vuggy porosity has developed as a result of selective leaching of grains prior to dolomitisation. Pyrobitumen is present in some of the samples.

The Carr-Purcell-Meiboom-Gill (CPMG) pulse sequence was employed to evaluate the relaxation characteristics of the sample at both high and low magnetic fields. Low field NMR Relaxation measurements were performed on the Resonance Instruments, Maran 2 operating at a frequency of 2 MHz, while high field measurements were performed on the Bruker Biospec instrument. The relaxation measurements were made using the CPMG pulse sequence, using a repetition delay of 20 s and an inter-echo time on the order of 1 ms. Sufficient transients were acquired to ensure a signal-to-noise ratio of 100:1. The relaxation behaviour of the samples was obtained under the following conditions: (1) saturated with a 2% KCl brine and (ii) desaturated by either porous plate or capillary pressure methods. The data from both instruments was processed using the DXP inversion algorithm (licensed from Resonance Instruments) to obtain the relaxation time distributions.

In situ spatial visualisation of the fluid distribution was obtained using a Bruker Biospec 24 / 30 (2.35 Tesla) magnetic resonance imaging system. The hydrogen detection mode was used which operates at an excitation frequency of 100 MHz. Spatial localisation (volume selection) within the sample was obtained by applying secondary x, y and z magnetic field gradients. The imaging methods used in this study are as follows: (i) Saturation profiles were obtained in which the fluid distribution is spatially resolved in the axial (lengthwise) direction of the sample. This method provides a means of investigating the *in situ* saturation profile of the sample. The signal observed along the x-axis represents the total fluid volume at each point in the core. (ii) Full volume images were acquired in which the fluid distribution is resolved in two directions (lengthwise and vertically) and appears as a 2 dimensional image. These images provide a means of investigating the overall spatial variations of the fluid distribution. The thickness of the image is equal to the entire diameter of the sample (single slice). (iii) Volume selective (multiple thin slice) images were acquired in which the fluid distribution is spatially encoded in three directions and a slice volume (thickness) is specified. The slice volume depends on the number of slices, the imaging method and the size of the sample. Volume selective images can be performed in a lengthwise or radial fashion in which the “slice thickness” of each slice is 1 cm or less. The slice thickness for the lengthwise volume selective images is 1.5 mm and for the transverse (radial) images is on the order of 5 mm.

Three samples were centrifuged at a speed of 4000 rpm for a period of not less than 12 hours using the Beckman Ultra-centrifuge (air / brine displacement). The samples were spun in only one direction. The imaging and relaxation characteristics of the samples were measured immediately after

desaturation and were re-measured regularly over a period of two weeks. Two out of the three samples had saturation gradients present. After two weeks, the saturation gradient in one of the samples had dissipated, while the saturation gradient in the other sample had not changed significantly. It was decided that the remaining samples would be desaturated using a porous plate with a capillary pressure of 100 psi. The drainage process was slow, requiring 60 days for completion. Efforts were made to make sure the samples did not dry out during the porous plate de-saturation measurement. For comparison purposes, a number of the samples were desaturated by porous plate for 18 days.

Results and Discussion

Conventionally, in sandstone reservoirs, NMR data is interpreted by describing the decay of the NMR signal in terms of a statistical distribution of T_2 relaxation times, which in turn is considered to be representative of a pseudo pore size distribution. Discrimination techniques (e.g. T_2 cut-off or Spectral BVI) are applied to determine the fraction of the pore structure occupied by non-producible fluids. In the case of the T_2 cut-off method it is generally assumed that a T_2 time of the order of 33 ms discriminates between these two fluid times (Figure 1). Averaged relaxation times (geometric mean) are determined from the relaxation distributions and from these data, permeabilities are subsequently estimated using a variety of permeability algorithms (ie: Schlumberger-Doll Research and Coates Equations).

Previous workers who have investigated the NMR relaxation properties of carbonates and dolomites have drawn attention to fundamental differences in carbonate NMR relaxation properties. (Ref. 2 - 7) In particular, the surface relaxivity of carbonates is significantly lower than sandstones, and as a result, to discriminate between non-producible and producible fluids T_2 cut-off times of the order of 98 ms or higher are more applicable. Furthermore, the presence of dissolution pores or vugs within carbonate rocks is known to complicate the interpretation of NMR data because of the insensitivity of the relationship between pore size and NMR relaxation times at large pore sizes. It is suggested, however, that in favourable circumstances the volume of the pore structure attributable to the presence of these dissolution pores or vugs can be quantified by determining the fraction of the NMR signal which is characterised by T_2 relaxation times greater than 750 ms, (Figure 1) and in cases where the vug porosity is poorly interconnected (e.g. where the inter-granular pore system dominates permeability), examination of the NMR signal below a cut-off of 750 ms can provide a better means of predicting permeability.

In an effort to determine optimal T_2 cut-off times necessary for the quantification of capillary bound fluid volumes (ie: irreducible water saturations), three core samples were de-saturated using the Beckmann centrifuge. Saturation gradients were observed in two out of the three samples. The saturation gradient in one sample had dissipated after two weeks, while the saturation gradient had not changed significantly for the other sample. (Figure 2) Saturation gradients in centrifuge desaturation experiments have been observed for Berea sandstone and Bedford limestone core plugs by previous workers (Ref. 1). Saturation gradients are troubling because they suggest that a broad distribution of pores will remain saturated at the end of the measurement. Although the samples in this study were spun in only one direction, there is no evidence in the literature to our knowledge, that reversing the sample around and spinning it in the opposite orientation will mitigate the saturation gradient. For these reasons, it was decided to desaturate the remaining samples using a porous plate device.

Porous plate desaturation yielded what appeared to be more reasonable results, with no measurement induced saturation gradients observed. However, the complete de-saturation of the samples required a number of weeks (60 days !!) before brine production ceased. This length of time is considerably longer than expected and is much longer than the industry standard of approximately two weeks. The capillary bound water saturation values appear to be abnormally low when compared to their porosity and permeability values (Figure 4, 5). Because of these low values, efforts were made to ensure that the samples were not simply drying out during the desaturation process. The measurements were repeated (by another in-house laboratory) to verify that the results were correct, and mercury injection data were acquired on several samples to further establish the sample's drainage behaviour. Because of the low bound fluid values, the optimal T_2 cut-off times are substantially lower than previously published

carbonate results, indeed, the values are more indicative of what one might anticipate for sandstones than carbonates. Although considerable variability exists (Figure 5), the majority of the capillary bound fluid cut-off values are less than 30 ms, and a number of samples have T_2 cut-off times of less than 10 ms. We are currently unable to explain the low bound fluid volumes for these samples.

The prediction of the gravimetric porosity by the NMR measurements went much smoother and was well within experimental error (Figure 6). The vug porosity estimates made from the low field NMR data using a 750 ms T_2 cut-off value compares reasonably with that obtained from the high field NMR imaging and relaxation experiments. (Figure 7).

A crossplot between the measured permeability values and the gravimetric porosity values is shown in Figure 8. The relationship is better than expected considering a number of samples have dissolution (vug) porosity present.

Predictions of core permeability using the Schlumberger-Doll Research (SDR) permeability algorithm ($k = 4\ \varphi^4\ T_{2g}^2$) gave rise to poor results (Figure 9). When the log normal T_2 and the porosity values are modified by removing the signal from the vugs, { ie: $k = 4\ (\theta_{<750})^4\ [T_{2g(<750)}]^2$ } the permeability prediction is inferior (Figure 10). This suggests that although the vugs appear to be isolated, they contribute to the flow properties of the samples. Permeability predictions made using the Coates equation [$k \sim \varphi^4\ (FFI/BVI)^2$] are particularly poor, (Figure 11) due largely to the abnormally low bound fluid values and their effect on the FFI / BVI ratio (the bound fluid values used are those determined from the porous plate desaturations). The low irreducible water saturations (BVI) observed in these samples are typically seen in samples with much higher permeabilities.

Conclusions

The prediction of petrophysical parameters other than porosity using NMR data is important in order to maximise the benefits of the NMR technology. Clearly the current data interpretation strategies are insufficient to realise those benefits in the vuggy dolomite reservoir investigated in this study and further development work is required.

References

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Figures

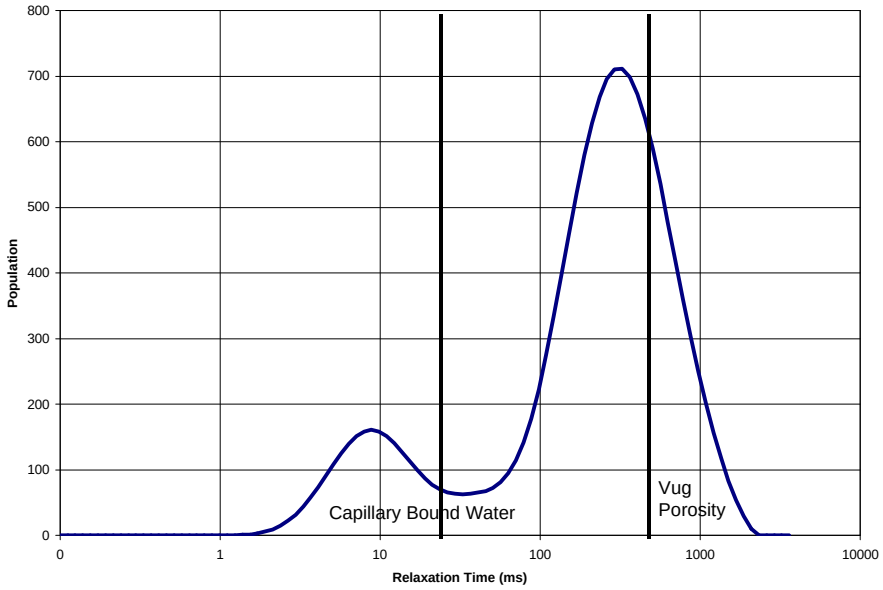

Figure 1: Fixed T_2 cut-off technique applied to a multi-exponential T_2 distribution for determination of vug porosity and capillary bound water

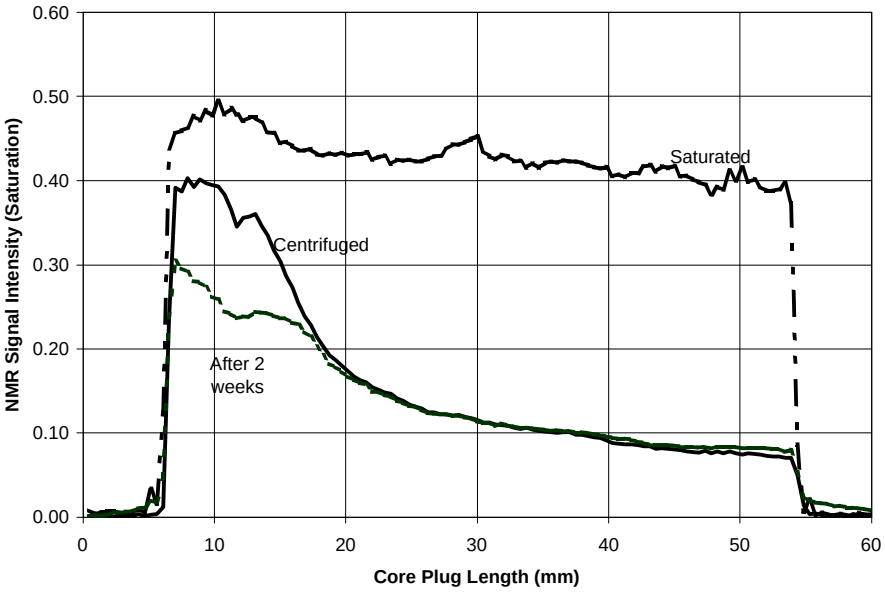

Figure 2: NMR *In Situ* saturation profiles obtained from a sample desaturated in the centrifuge (Sample dimensions are 50 mm by 38 mm)

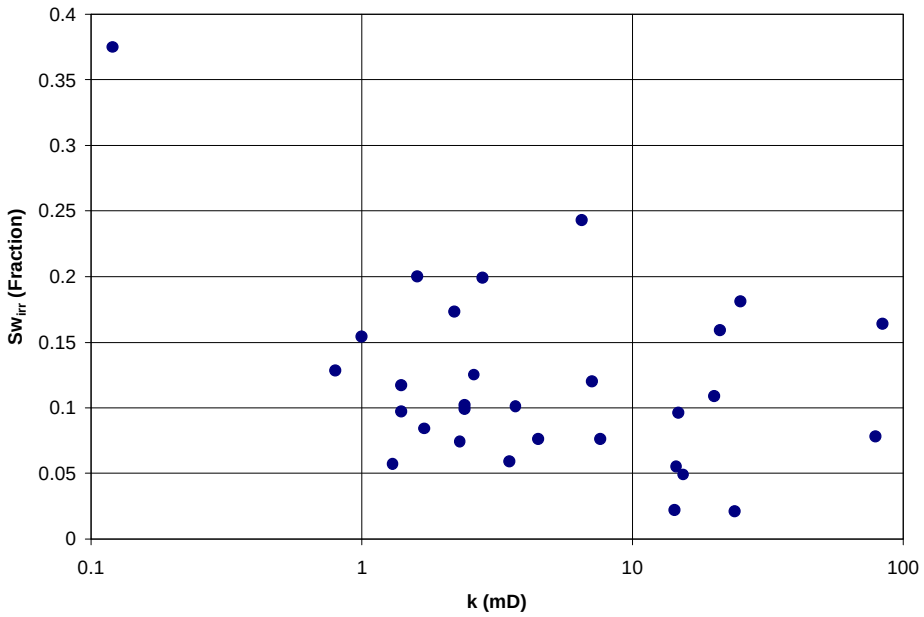

Figure 3: Crossplot of capillary bound water (Sw_{irr}) determined by porous plate and air permeability values.

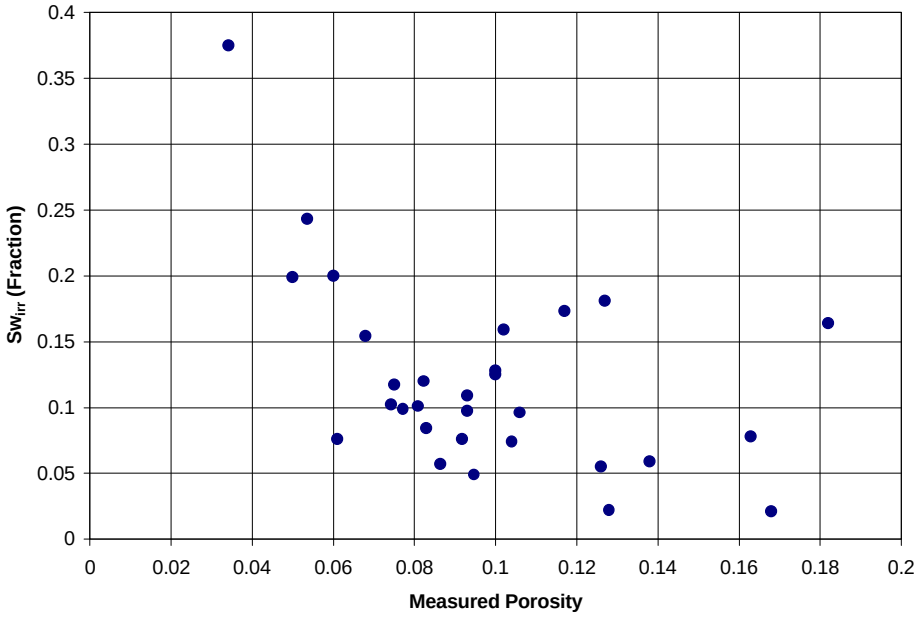

Figure 4: Crossplot of capillary bound water (Sw_{irr}) determined by porous plate and gravimetric porosity values.

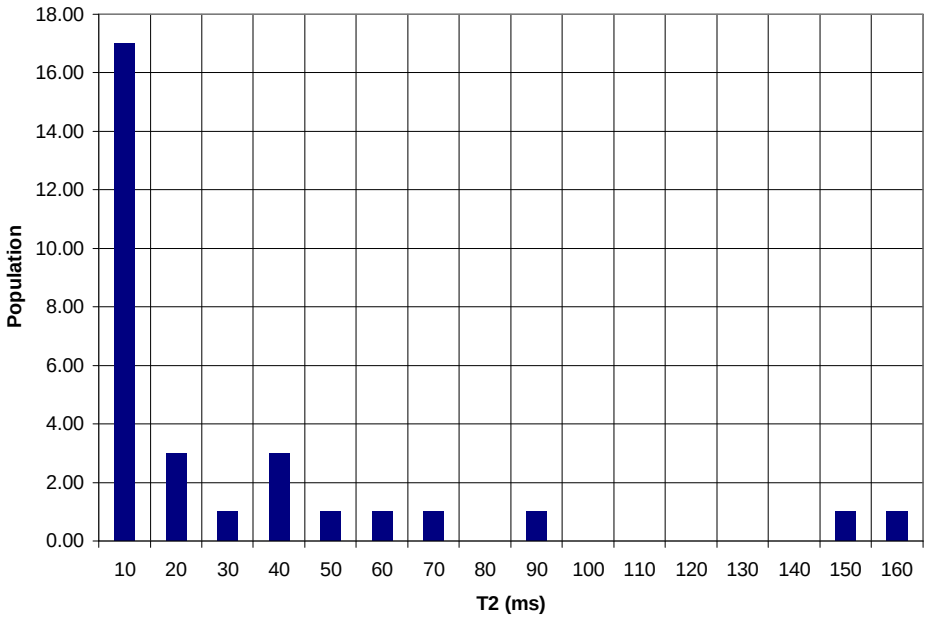

Figure 5: T_2 cut-off values obtained from the low field relaxation distributions after comparison with the porous plate desaturation experiments

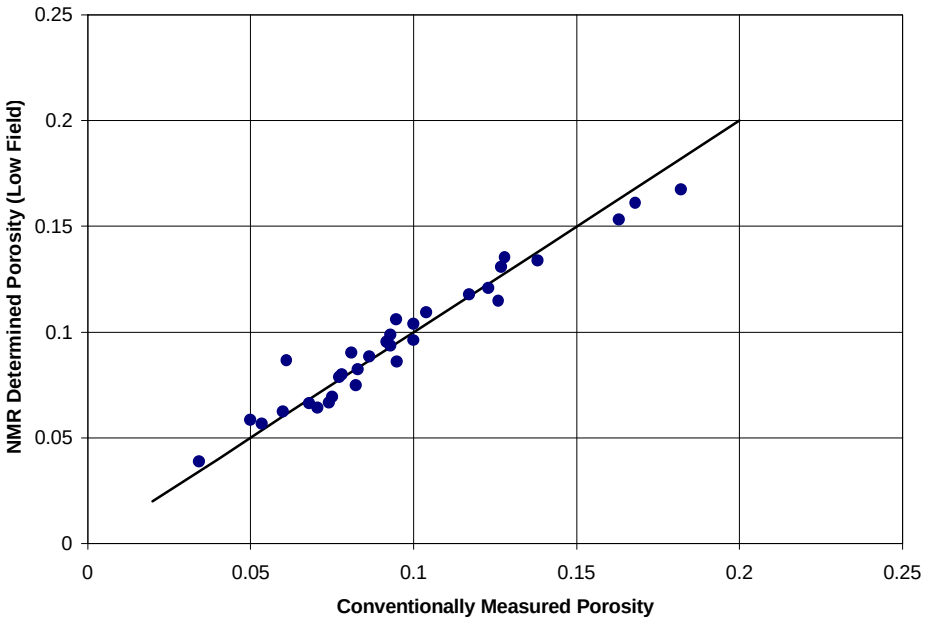

Figure 6: Comparison of Low Field NMR determined porosity with conventionally measured porosity (gravimetric) (r = 0.9687)

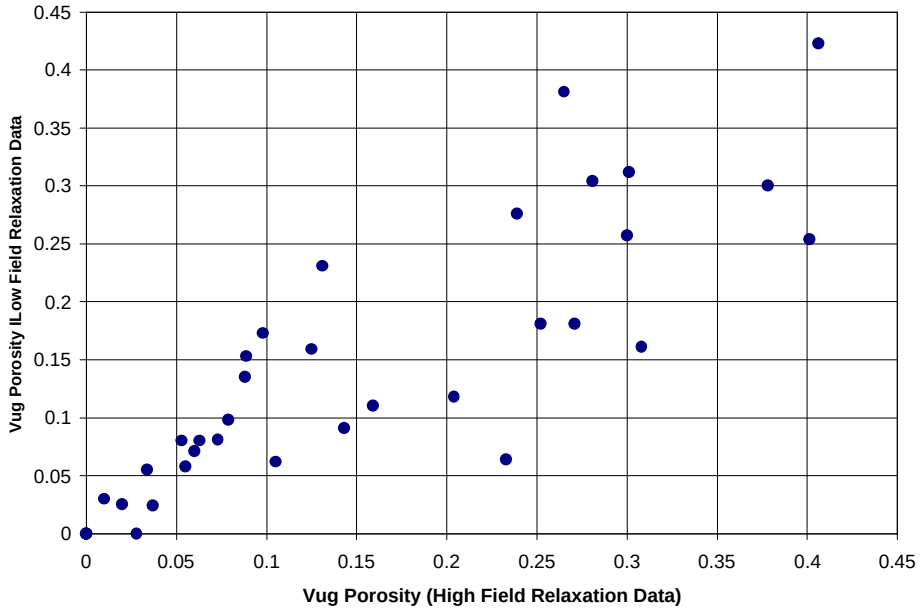

Figure 7: Comparison between Vug Porosity Determined from the Low Field NMR Relaxation Data and the Vug Porosity Determined from High Field Relaxation Data

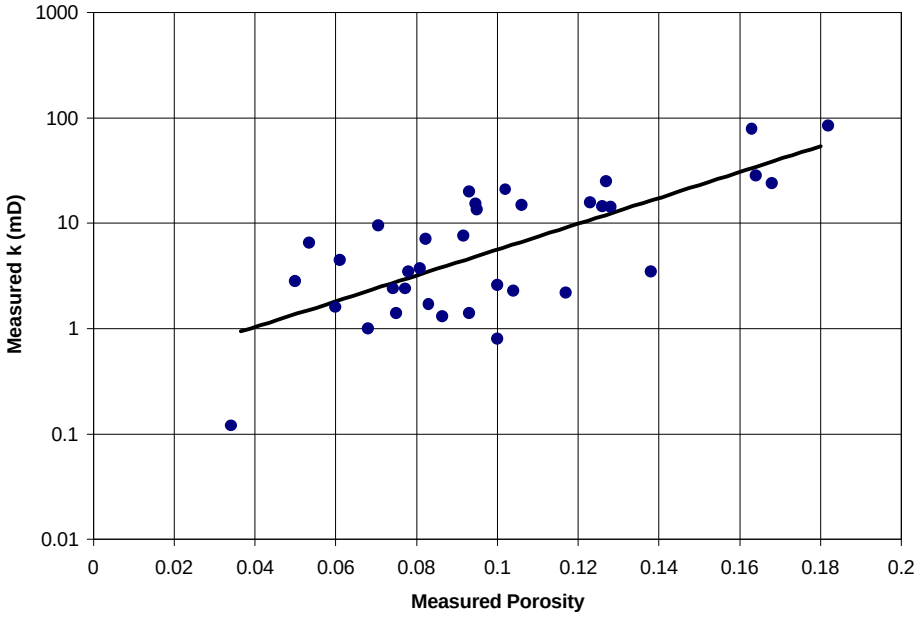

Figure 8: Crossplot of Measured Permeability and the Gravimetric Porosity (r = 0.7085)

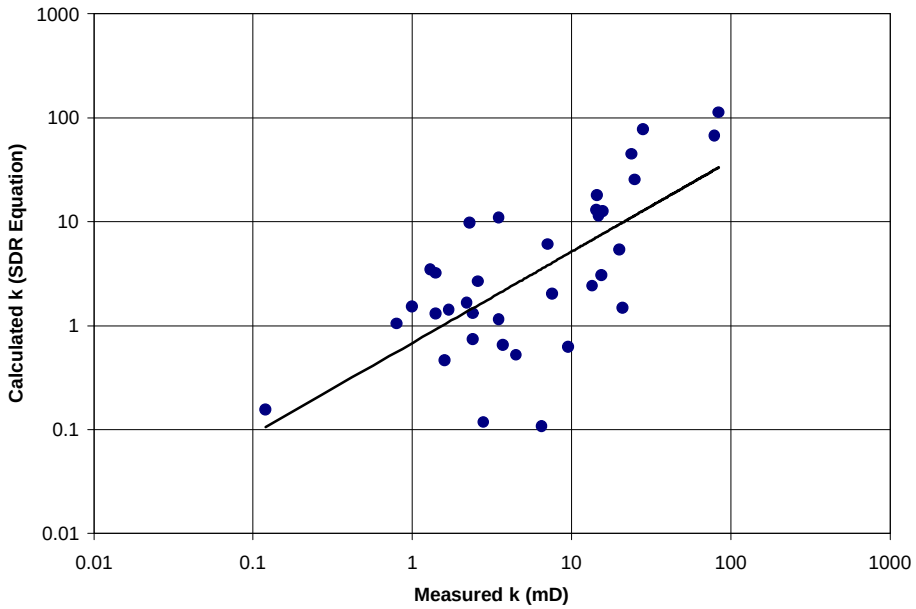

Figure 9: Comparison between permeability calculated using the Schlumberger Doll Research Algorithm and the Conventionally Measured Air Permeability (r = 0.6878)

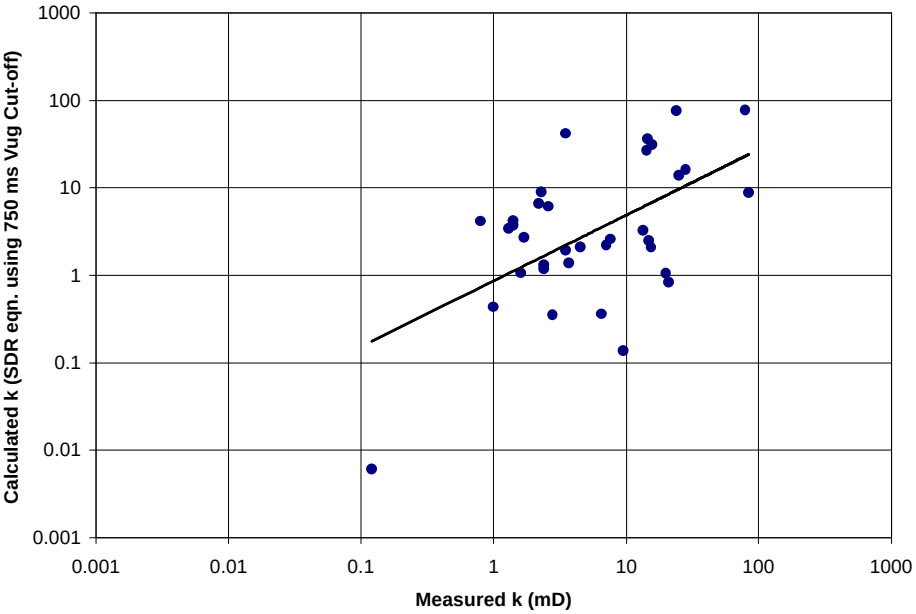

Figure 10: Comparison between permeability calculated using the Schlumberger Doll Research Algorithm; $k = 4 (\theta_{<750})^4 [T_{2g(<750)}]^2$ and the Conventionally Measured Air Permeability (r = 0.5557)

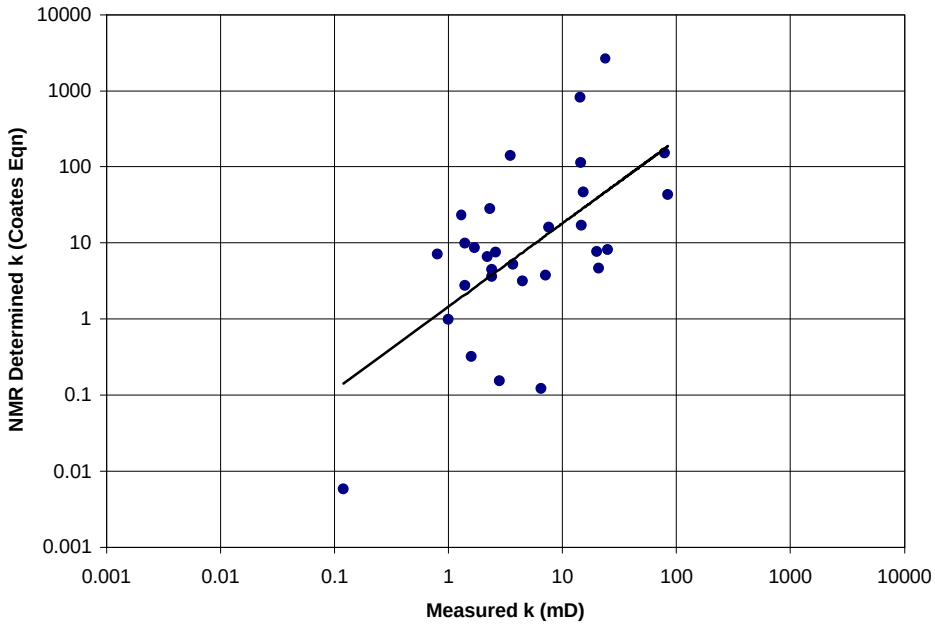

Figure 11: Comparison between permeability calculated using the Coates Algorithm; MPERM = $(\theta /16)^4$ $(FFI/BVI)^2$ and the Conventionally Measured Air Permeability (r = 0.6126)