NMR CORE PLUG MEASUREMENTS TO COMPLIMENT SCAL STUDIES

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This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Abu Dhabi, UAE, 5-9 October, 2004

ABSTRACT

Nuclear magnetic resonance (NMR) measurements on reservoir core plug samples are often used to calibrate NMR logs. These core plug measurements supply valuable information about pore size variation throughout reservoir sections, free/bound fluid volumes and help to calibrate empirical permeability models. The NMR measurement provides information about the pore space which can not be obtained by any other non-destructive tests. NMR core plug studies are often commissioned purely for NMR log calibration, the data is rarely integrated into special core analysis (SCAL) studies. This paper describes how laboratory NMR core plug measurements can be used to compliment SCAL studies, providing valuable data early in a SCAL program, as well as aiding sample selection and quality control.

If the pore space of a core plug sample contains a single phase, NMR measurements can easily provide an accurate pore volume measure of the core plug. Samples with sensitivity to harsh cleaning strategies and oven drying often only have pore volume measurements performed at the end of a SCAL test program. Thus NMR can provide a pore volume measurement early in the test program. This is invaluable when calculating end point saturations and interpreting resistivity data for desaturated samples. NMR measurements can also be used to provide saturation information in core plugs containing two phases.

Within SCAL programs there is often a need to select duplicate samples, for mercury injection or wettability studies. There is always some uncertainty as to the similarity of two samples pore geometry. The T2 distributions measured by the NMR can be thought of as pseudo poresize distributions, thus if two core plugs have identical T2 distributions they can be considered as duplicate samples.

Other applications of NMR measurements within SCAL programs include: investigation of drilling mud filtrate particulate invasion investigation and detection of pore structure change.

We illustrate each SCAL application of NMR measurements with examples from a wide range of rock types and lithologies from ResLab ART's extensive database.

INTRODUCTION

Nuclear Magnetic Resonance (NMR) measurements have been used extensively to characterise reservoir rock pore geometry using logging and lab based NMR spectrometers [1]. NMR measurements on reservoir core samples are beneficial for improved interpretation of NMR log data. Estimates of permeability, pore size distributions, free fluid and bound volumes from NMR logs are significantly improved if the logs are calibrated with NMR measurements on representative and well characterised core samples [2], [3]. Previous studies by this author have described the qualitative effects of clay content and mineralogy on NMR data [4] and methodologies to formulate a model to estimate shale volumes from NMR core plug data [5]. This paper describes how laboratory NMR core plug measurements can be used to compliment SCAL studies, providing valuable data early in a SCAL program, as well as aiding sample selection and quality control.

NMR THEORY

Detailed descriptions of NMR theory and its application to porous rock systems can be found elsewhere [6]. For examples within this paper a CPMG sequence (Carr-Purcell-Meiboom-Gill) is used to measure NMR T_2 distributions of core plugs and trim samples in various saturation states.

In a porous rock system, there will be a continuous range of pore sizes, rather than several discrete sizes. This means that the CPMG echo-train comprises of a continuous range of relaxation times. Each pore-size has a distinctive T_2 value. The oscillating nuclei diffuse randomly in a fluid, and in a porous system some will come in contact with the pore surfaces, allowing them to relax (by energy transfer to the pore wall). In the fast diffusion limit, the relaxation time observed experimentally is an average relaxation time for all the nuclei in the pore. Therefore in either a small pore or wetting film, the nuclei are more likely to interact with the surface, and so the average relaxation will be faster and the time for relaxation shorter than in a large pore. The echo-train corresponding to one particular pore-size will have a characteristic T_2 value and signal amplitude proportional to the amount of fluid contained in pores of that size.

EXAMPLES OF NMR MEASUREMENTS ON SCAL CORE PLUGS

Porosity and Saturation Measurement using NMR

Samples with sensitivity to harsh cleaning strategies and oven drying may only have pore volume measurements performed at the end of a SCAL test program. Therefore porosity, saturation and electrical measurements are often only fully interpreted many months after the start of an analysis program. NMR measurements can easily provide an accurate pore volume measure of the core plug containing single or dual phases.

The signal amplitude of a NMR T_2 distribution is directly related to the volume of fluid within the pore space. The porosity of a sample fully saturated with a single fluid can be

calculated if hydrogen index of the fluid is known. The signal amplitude of the fully saturated sample is compared to that of a reference sample of known volume and hydrogen index. NMR porosity references are made up of mixtures of different concentration brines and D_2O. D_2O does not have a NMR signal. The ratio of brine to D_2O is adjusted to obtain fluid references with known porosity. The reference samples are sealed so that no evaporation can occur. NMR porosity is calculated using equation 1:

Equation 1

$$\phi_{plug} = \phi_{ref}\left[\frac{\left(V_{ref} \times S_{plug} \times HI_{ref}\right)}{\left(V_{plug} \times S_{ref} \times HI_{plug}\right)}\right]$$

ϕ_{plug} is the porosity of the plug (pore volume fraction)
ϕ_{ref} is the porosity of the reference sample (pore volume fraction)
V_{plug} is the volume of the plug sample (cc)
V_{ref} is the volume of the reference sample (cc)
S_{plug} is the NMR signal amplitude of the plug sample
S_{ref} is the NMR signal amplitude of the reference sample
HI_{plug} is the hydrogen index of the plug sample
HI_{ref} is the hydrogen index of the reference sample

Figure 1 shows a comparison of NMR porosity data with helium porosimeter measured porosities for a set of unconsolidated reservoir sandstone plugs. Permeability range was 682 mD to 7776mD. The average porosity difference between the two measurements is 0.41 porosity units. Due to the unconsolidated nature of these samples they were protected in heatshrink sleeves and PTFE end caps. For all plugs NMR porosity values are slightly larger than the helium porosity, this is caused by a small amount of bulk brine trapped between the sample and protective sleeve. Unconsolidated samples are also susceptible to deformation on application of confining stress. Although the helium porosity measurements are performed at a low confining pressure (400 psi) some pore space deformation will occur and this can lead to slightly lower porosity values compared to the NMR porosity measurements.

NMR measurements can provide an independent estimate of water saturation (Sw). The NMR porosity values can be used to calculate water saturation during air/brine desaturation. Figure 2 shows a plot of NMR measured saturation values against saturation measured using a combination of helium porosimetry derived pore volume and graviameteric analysis. The samples were sandstones with a permeability range of 0.78mD to 960mD. They were desaturated on a porous plate at a air/brine capillary pressure of 180 psi. The average saturation difference in Figure 2 is 0.23% pore volume. The NMR derived saturations allowed the evaluation of resistivity index data and the calculation of Archie saturation exponents, many months before the final helium porosimetry pore volume and saturation data was available. The Archie saturation exponents calculated using the two methods are compared in Figure 3. The average difference between the two Archie saturation exponent is 0.01.

Duplicate Sample Selection Using NMR

Within a SCAL program there is often a need to select duplicate/twin samples for parallel test strategies. Duplicate samples may be needed for wettability tests or for mercury injection analysis. The selection of such samples always leads to uncertainty about the pore structure of the duplicate samples being identical to the originals. Because the NMR T_2 distribution for a saturated sample can be thought of as a pseudo pore size distribution, a comparison of T_2 distributions for each sample provides a means of assessing if two samples have the same pore geometry. Figures 4a and 4b shows the NMR T_2 distributions for two pairs of samples. Sample 1 is a 0.03mD permeability sandstone plug sample, the NMR T_2 distribution for this plug and its trim are almost identical, Figure 4a. The trim could be used for mercury injection analysis and the results used with confidence when compared with sample 1. The NMR T_2 distributions for the sandstone plug sample 2 (1.46mD) and its trim show some differences, Figure 4b. This would indicate differences in the pore structure of plug and trim and thus the trim could not be used for mercury injection.

Drilling Mud Particulate Invasion Using NMR

Due to the sensitivity of NMR measurements to pore geometry variation it is an ideal technique for investigating drilling mud particulate invasion. Figure 5 shows the NMR T_2 distributions for native/preserved state sandstone plug and trim samples. The trim is close to the core edge and may have experienced some drilling mud particulate invasion. The plug is from deeper within the core and has a different shape distribution. It is assumed that the differences in NMR T_2 distributions are due to varying degrees of mud invasion. The drilling mud used in this well was tagged with deuterium, analysis of waters collected during Dean-Stark tests detected deuterium. This confirms that drilling mud filtrate has invaded the pore space. Whilst not confirming the occurrence of drilling mud particulate invasion, the presence of deuterium in the pore waters together with the results from the NMR analysis indicates it is highly probable.

Detection of Pore Structure Change Using NMR

SCAL plug samples often undergo test programs in which they are repeatedly cleaned, dried and saturated. This can cause damage to the sample and alteration of the pore geometry. Figure 6 shows the NMR T_2 distributions for a vuggy carbonate sample, which was cleaned in hot solvents, oven dried and saturated twice. After the second cycle of cleaning, drying and saturation an increase in NMR porosity from 14.95% to 15.35% was measured, pore space alteration was suspected. The pore space alteration is confirmed by the existence of long time T_2 relaxations, greater than 100 milliseconds, in the resaturated T_2 distribution. The large change in T_2 distribution could be caused by microfracture formation or changes in the surface texture of the pores reducing the occurrence of diffusion coupling.

CONCLUSIONS

Laboratory NMR core plug measurements can be used to compliment SCAL studies, providing valuable data early in a SCAL program, as well as aiding sample selection and quality control.

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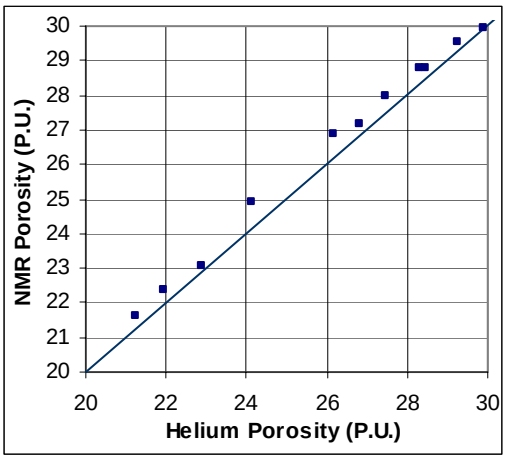

Figure 1: NMR Porosity Against Helium Porosity

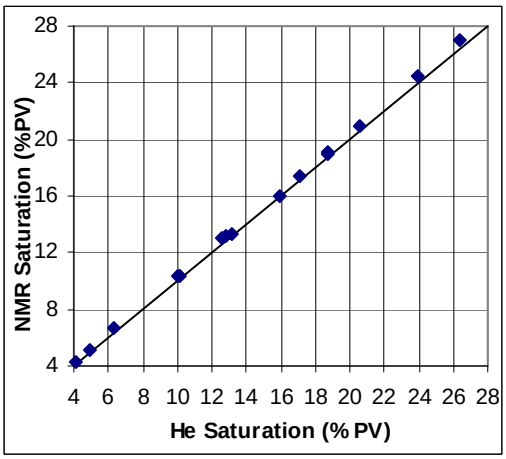

Figure 2: NMR Saturation Against Helium Derived Saturation

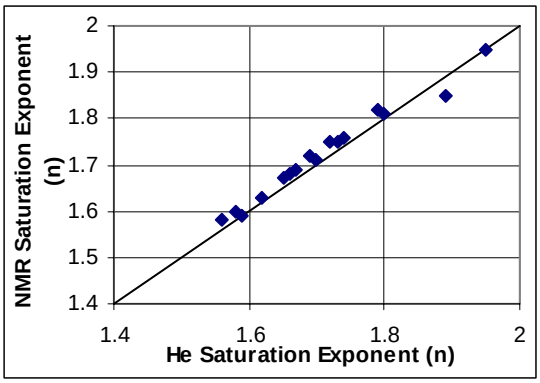

Figure 3: NMR Archie Saturation Exponent Against Helium Derived Archie Saturation Exponent

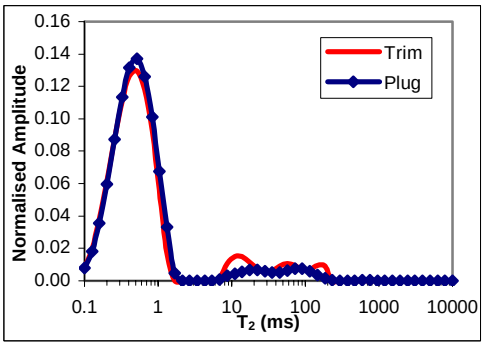

Figure 4a: NMR T_2 Distribution for Plug Sample 1 and Trim

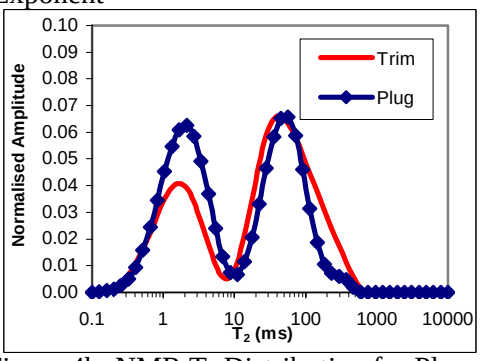

Figure 4b: NMR T_2 Distribution for Plug Sample 2 and Trim

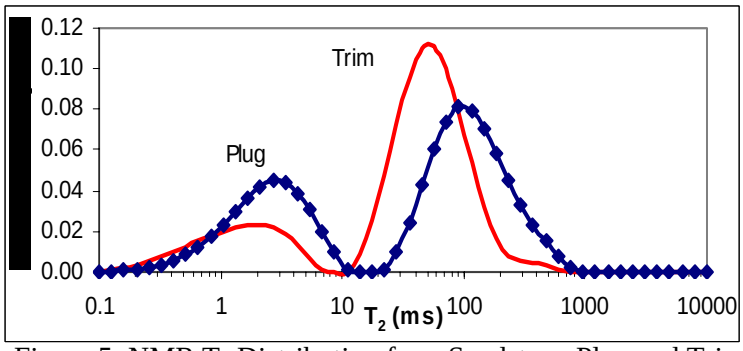

Figure 5: NMR T_2 Distribution for a Sandstone Plug and Trim, Indicating Possible Drilling Mud Particulate Invasion

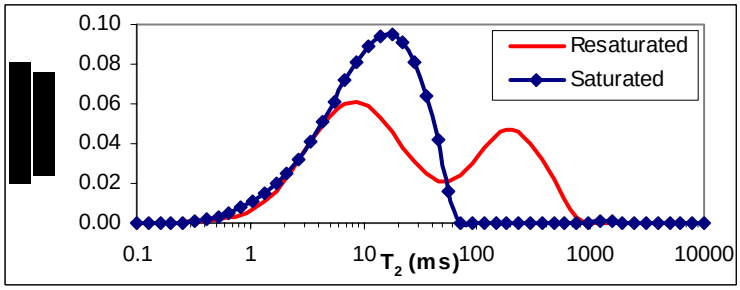

Figure 6: NMR T_2 Distribution for a Vuggy Carbonate Plug after First and Second Saturations.