ID# 983
Integrated Logging Data Technique to Model Relative Permeability of Heterogeneous Reservoirs

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ABSTRACT

Relative permeability curves are commonly used for the dynamics and mobility of fluids in selected reservoir sections. This is a crucial information to assess reservoir performance and optimize its productivity. However, these curves are challenging to obtain without the aid of core data, especially for heterogeneous reservoirs. In this paper, we present an integrated workflow to predict relative permeability curves for oil-water system from in-situ downhole wireline logging data such as NMR, multi-frequency dielectric dispersion and fluid sampling.

Typical relative permeability curve follows the modified Brooks-Corey model which represents exponential functions with Corey's exponents. This model defines the curve end-points and curvature which maps fluids relative permeability with water saturation. Corey's exponents can be found by fitting laboratory data. We tried to match the laboratory from SCAL measurement with NMR and multi-frequency dielectric core data to build the relative permeability curve. The experiment is interrupted at two stages of saturation: irreducible water state, corresponding to reservoir section, residual oil state, corresponding to free water level section. At each state, we measure and interpret NMR and dielectric data and generate relative permeability curves based on pore size distribution index calculated from both measurements. The results are compared with typical Corey's exponents values for sandstone and limestone and relative permeability end-points measured from core data.

Based on relative permeability tests on two outcrops: one carbonate and one sandstone, geometrical parameters as interpreted from both NMR and multi-frequency data are shown to be sensitive to fluids mobility characteristics and tortuosity in a porous media. From Unsteady-state coreflooding, permeability end-points can be inferred from NMR, while saturation values can be easily calculated from dielectric data at 1GHz range. Textural exponents inverted from multi-frequency data, which is sensitive for rock fabric cementation and fluids geometrical distribution, is shown to be a good candidate to correlate with Corey's exponents. We observed good agreement between relative permeability curves estimated from downhole method and literature Corey's values for carbonate sample, which is better than sandstone sample that has non-cylindrical pore throats shape.

The method presented can potentially replace expensive and time-consuming laboratory testing to obtain dynamic properties of a reservoir per depth. Heterogeneous reservoirs with

unknown wetting fluids properties and complex pore structure can now be compensated for in relative permeability modeling by application of integrated advanced logging techniques such as NMR and dielectric data.

EXTENDED ABSTRACT

INTRODUCTION
Understanding fluids flow mechanism through porous media is crucial to design and predict hydrocarbon recovery and optimize production. Relative permeability is one of the important properties that governs the multi-phase flow and typically requires extensive and costly process to obtain from laboratories. Thus, many prior arts showed how relative permeability can be inferred from other rock's property such as capillary pressure (Purcell, 1949; Brooks and Corey, 1966) and resistivity data (Li, 2010). In the past two decades, a lot of efforts have been put to obtain relative permeability from in-situ conditions downhole data. Most of the efforts on relative permeability prediction were based on resistivity data and the assumption of the electrical and fluid connectivity are correlated (Toledo et al, 1994).

In a recent work, Al-Rushaid et al. (2017) demonstrated a method to obtain relative permeability using NMR and dielectric data at different reservoir sections for saturation determination. The data collected from bottom free water level, oil water contact, different points through transition zone up to oil zone. Altunbay et al. (2001) utilized a method using NMR T2 pore-body to pore-size distribution transformation to extract information about capillary pressure curve of a formation then estimate relative permeability curve using Purcell's permeability model. This method assumes spherical pore shape and cylindrical pore throats which are not always applicable especially in carbonate heterogenous formations. Also, the method requires some tuning parameters which has to be calibrated in laboratory for each formation.

In this study, we present a method that can be used at in-situ conditions without simplified assumptions of rock properties or need of laboratory calibration steps by integrating both NMR and multi-frequency data to estimate relative permeability and capillary pressure curves for reservoir intervals. The method can be potentially used for homogenous or heterogenous reservoirs with various wettability conditions.

THEORTICAL BACKGROUND
A. Relative Permeability and Capillary Pressure Modeling
Several models have been developed to describe the relative permeability and capillary pressure curves with respect to water saturation (S_w). The model pursued in this work is based on Brooks-Corey Model (Brooks and Corey, 1966), for relative permeability of water (wetting phase), k_{rw}; relative permeability of oil (non-wetting phase), k_{ro}; and capillary pressure p_c as follows:

$$k_{rw}(S_w) = (S_w^*)^{n_w} \qquad (1)$$

$$k_{ro}(S_w) = (1 - S_w^*)^2 \left[1 - (S_w^*)^{n_o}\right] \qquad (2)$$

$$p_c(S_w) = p_{ce} \times (S_w^*)^{-\frac{1}{\lambda}} \qquad (3)$$

where S_w^* is the normalized water saturation defined as: $S_w^* = (S_w - S_{wr})/(1 - S_{wr})$; S_{wr} is the residual water saturation; n_w and n_o are the Corey's exponents for the water and oil phases respectively; p_{ce} is the capillary entry pressure; and λ is the pore size distribution index (PSDI). In this study, the relative permeability is normalized by the absolute permeability of water at residual oil saturation S_{or}. Corey's exponents can be defined as function of PSDI as: $n_w = (2 + 3\lambda)/\lambda$ and $n_o = (2 + 3\lambda)/\lambda$.

B.   Relative Permeability from Advanced Measurement

The relative permeability of water can be computed from resistivity index (I) based on similarity theory between fluid flow and electrical current flow (Li 2005) as follows:

$$k_{rw}(S_w) = S_w^* \frac{1}{I} = S_w^* \frac{1}{(S_w)^{-n}} \qquad (4)$$

where n is the Archie's saturation exponent (Archie 1942) which can be estimated from core analysis of capillary pressure core flooding or approximated from dielectric constant (ε) measurement using effective medium theory as presented in (Al-Ofi et al. 2022). One can easily obtain λ by combining (Eqs. 1 and 4) and obtain k_{ro} and p_c.

NMR T_2 data can be utilized to estimate relative permeability based on PSDI or λ estimated using Fluid Substitution model (Li et al. 2021).

METHOD
A.   Unsteady-State Coreflooding

In this approach, we started with 100% core saturated with 50kppm NaCl brine. Two cycles were conducted; drainage then imbibition. Mineral oil (isopar 1000) was used to displace brine until Swi. Then, for imbibition, 50kppm NaCl brine was used to displace oil until Sor. The produced fluids volume were measured using a graduated cylinder and differential pressure is obtained across the sample for relative permeability calculations later, system schematic is shown in Figure 1.
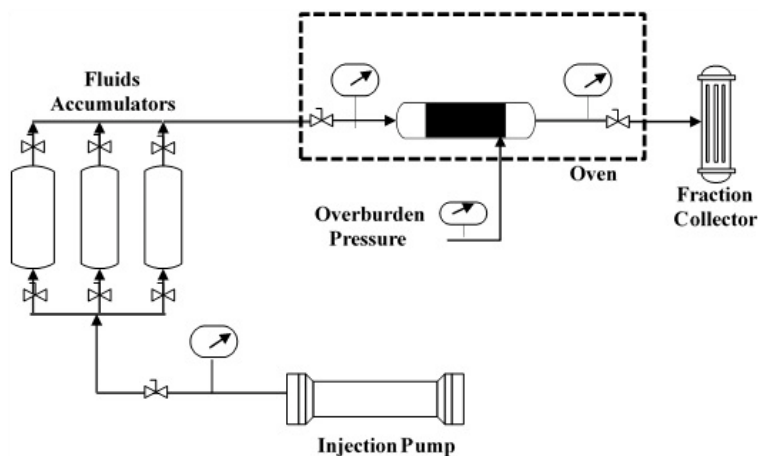
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Figure 1 A schematic diagram of the coreflood setup

B.   Saturated Plug Dielectric Measurement

Core Preparation and Routine Analysis

For core plugs measurements, different outcrop plugs were prepared. One sandstone sample labeled FB, and one limestone sample and labeled IL were also included. The core plug samples were trimmed to have a length of about 5 cm and diameter about 3.8 cm. We measured both helium porosity and N2 gas permeability for both dry core plugs.

Core Plug Dielectric Measurement

The dielectric setup comprises a Keysight Impedance analyzer (ENA series E4990A), which has an impeded Operating System (OS) for data acquisition. The samples are placed in a Teflon core holder and gently pressed to a coaxial probe to establish a good contact between the probe and the flat end of core plugs. The quality of contact between the sample and the co-axial probe is essential in reducing any measurement errors. The co-axial probe operates in reflection mode, shown in Figure 3. To perform a reflection measurement, only one port of the impedance analyzer is used. The S11 scattering parameter (S-parameter), also called reflection coefficient, is measured by the impedance analyzer on one flat end of the core plug and then the experiment is repeated on the second flat end. The method is described in detail in (Zhang et al. 2011).

Figure 2 Open-ended Coaxial Dielectric Probe

C. Saturated Plug NMR T2 Measurement

The NMR measurements were performed using a 2-MHz benchtop spectrometer at ambient conditions with the Carr-Purcell-Meiboom-Gill (CPGM) sequence with the following parameters: echo number 15,000, interecho time 100 μs, and a polarization time of 7 seconds. A CPMG sequence is conducted with a static magnetic field and two radiofrequency pulses. The static magnetic is used to polarize the protons in the fluids to a certain direction, e.g., z direction. The first radiofrequency pulse (90°) is used to tilt the magnetization into the transverse plane, then it is followed by a second radiofrequency pulse (180°), which flips the magnetization by 180° from its current position. The 180° pulse is repeated until there is no magnetization in the transverse plane, i.e., the magnetization has relaxed back to equilibrium. The measured T_2 echo trains were inverted to obtain the T_2 distributions.

RESULTS AND DISCUSSIONS

A. Routine Core Analysis

The petrophysical properties of both samples in this study are listed in Table 1. Both samples show distinct pore type behavior where porosity and permeability are not directly correlated.

Table *1* Dry Core Plugs Properties

Sample No	Lithology	Length (cm)	Diameter (cm)	Porosity (p.u.)	Permeability (mD)	Grain Density (g/cc)
IL	Sandstone	5.25	3.83	19.03	24.50	2.70
FB	Limestone	5.09	3.78	6.21	210.25	2.64

B. Advanced Core Measurement

Dielectric Measurement on Cores at Residual Water Saturation

After each cycle, drainage and imbibition, of core flooding, the samples have been measured by dielectric probe. Figure 3 shows the multi-frequency (dispersion) dielectric constant data for both samples. Our Bimodal inversion as presented in (Al-Ofi et al. 2022) shows distinct values for Archie's exponents. The cementation exponent m of sandstone sample FB and carbonate sample IL is 1.7 and 2.4 respectively, which agrees with typical values of such lithologies. The saturation exponent n is 2.1 for FB and 5.4 for IL. Variety of n values illustrate the wetting condition difference between the two lithologies, where sandstone sample tends to be strongly water wet and IL is mixed wet. From Eq. 1 and 4, we can estimate PSDI or λ for each sample as, 1.95 for IL and 3.15 for FB.
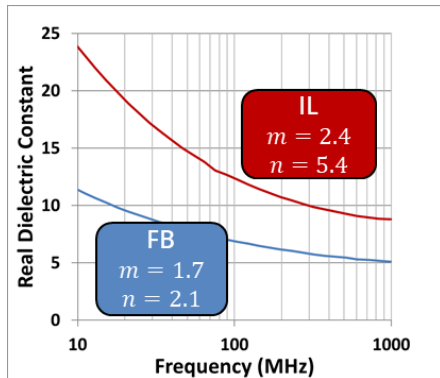
Figure 3 Real dielectric constant dispersion at residual saturation for IL and FB samples.

NMR Measurement on Cores at Residual Water Saturation

The measured NMR T_2 for both FB and IL samples are shown in Figure 4 for fully water 100% saturation, residual water saturation and the reconstructed 100% saturation T_2 from partially saturation condition using Fluid Substitution model (Li et al. 2021). We can observe a good reconstruction results with pore connection index for both samples, which can be used here as PSDI, of 2.28 for IL and 0.52 for FB.
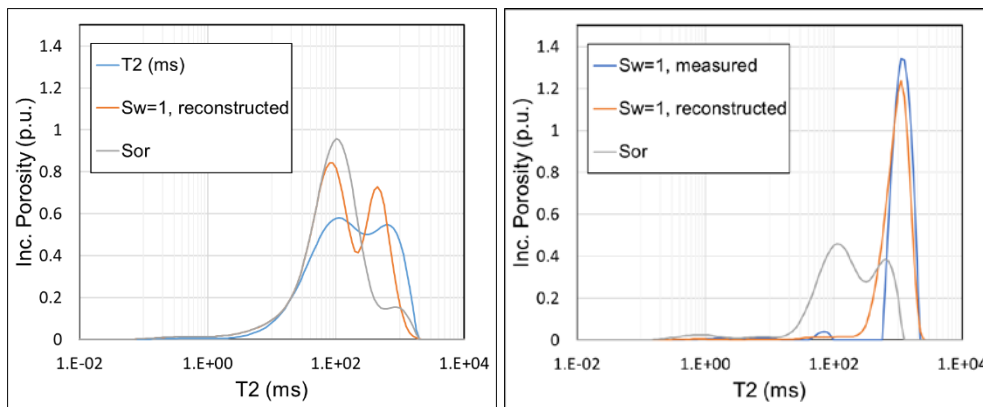

Figure 4 NMR T2 data for measured Sw1, partially saturated and modelled Sw1 for: IL (Left) and FB (Right).

C. Relative Permeability Curves

We integrated the modeled relative permeability curves using PSDI and Eg. 1 and 2 from dielectric and NMR T_2 data with literature values for consolidated well-cemented sands $\lambda = 2$ for IL and poorly cemented sand $\lambda = 3.5$ for FB. The reason for selecting higher PSDI for FB because this type of sand is originated from Fontainebleau that lacks cement and the grains are spherical leaving irregular pore throat shapes. The predicted curves match well with experimental effective pressure measured after drainage and imbibition unsteady-state core flooding, Figure 5. For carbonate limestone sample, IL, predicted relative permeability curves agree very well to each other indicating that dielectric and NMR derived PSDI values are sufficient enough. However for FB sample and due to non-cylindrical pore paths shape,

NMR derived PSDI from Fluid Substitution model needs to be improved to account for complex pore shapes.
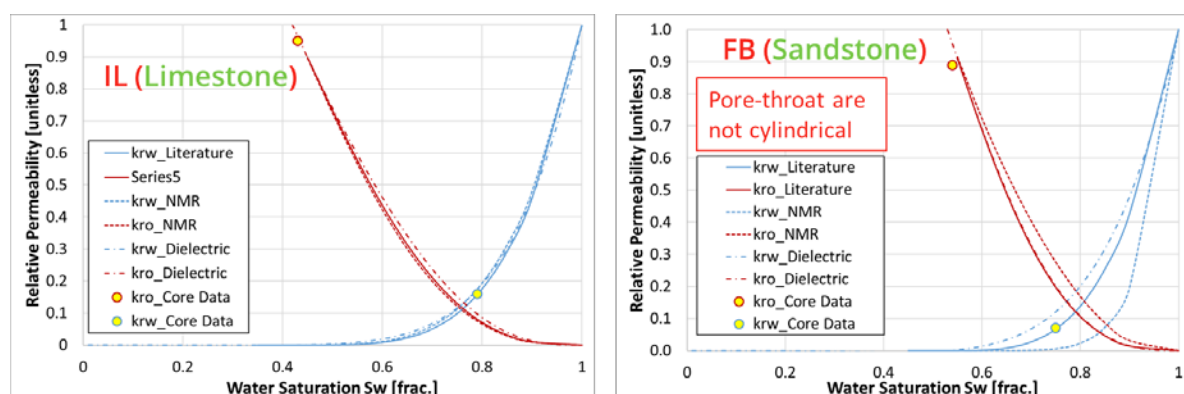

Figure 5 Comparison between predicted relative permeability curves from different type of measurements and lab end-points from unsteady-state flow experiment.

CONCLUSION

Advanced logging techniques such as dielectric dispersion and NMR are proven to be sensitive to pores geometry and fluids flow in them. This work showed how relative permeability models such as Brooks-Corey can be adapted from such measurements and achieve good results compared to literature values for different lithologies. Some pore structures are complex and typical geometrical models may impose discrepancies in applying the classical models of fluids flow. The current study focused more into the applications of such models from advanced techniques that can be applied downhole. However, more quantitative approach and uncertainty analysis are needed based on Steady-State core flooding data to associate the geometric parameters derived from advanced techniques to actual porous media flow behavior.

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