diffusion-fundamentals.org

The Open-Access Journal for the Basic Principles of Diffusion Theory, Experiment and Application

Dynamic correlations between susceptibility gradients and T_2-relaxation as a probe for wettability properties of liquid saturated rock cores

Tina Pavlin,[1] *John Georg Seland,*[2]

[1] Centre for Integrated Petroleum Research, University of Bergen, Norway
[2] Department of Chemistry, University of Bergen, Norway

Corresponding author: John Georg Seland, Dept. of Chemistry, University of Bergen, NO-5007, Bergen, Norway, E-Mail: John.Seland@kj.uib.no

(received 13 September 2010, accepted 11 January 2011)

Abstract

We explore the use of correlations between susceptibility gradients, G_0, and T_2-relaxation (G_0-T_2), and show how the difference in response for oil and water with respect to G_0 can be used for improved characterization of wettability of the internal surface in porous rock cores.

Keywords

NMR, diffusion, susceptibility gradients, relaxation, wettability.

1. Introduction

The oil/water wettability is an important property of rock core samples from oil reservoirs. The dynamic behavior (relaxation and diffusion) of the NMR signals from liquids confined in such rock core samples is sensitive to surface interactions and can potentially be used for characterization of wettability properties [1]. The T_2-distributions of water and oil do however often overlap. The use of diffusion-T_2 (D-T_2) correlation measurements can be used for a separation of the oil and water signals, increasing the resolution of the measurement [2]. We however explore the use of correlations between susceptibility gradients and T_2-relaxation (G_0-T_2) [3], and show how the difference in response for oil and water with respect to G_0 can be used for improved characterization of wettability [4]. We compare the use of G_0-T_2 correlations to regular T_2 measurements, and to measurements of D-T_2 correlations.

2. Materials and Methods

All measurements were performed at 35°C on a Maran DRX 12 MHz spectrometer (Resonance Instruments), with a gradient probe providing a maximum gradient strength of 225 Gauss/cm. The sample studied was a water-wet sandstone Berea rock core (1.5''). T_2, G_0-T_2, and D-T_2 measurements were compared in water-saturated (S_w) and irreducible water saturated (S_{wi}) states. To reach the S_{wi} state synthetic oil (Marcol82, Exxon Mobile) was flooded through the rock core.

T_2 was measured using the regular Carr-Purcell-Meiboom-Gill (CPMG) pulse sequence. For measurement of G_0-T_2 and D-T_2 correlations the sequences given in Fig. 1 were used. Notice that G_0 is never measured directly, but through DG_0^2. The value of τ' was varied (25 steps), between 0.1 and 10 ms and the gradient strength, g, was varied (25 steps) between 0 and 200 Gauss/cm. The other parameter values were: $\tau = 0.1$ ms, $t1 = 20$ ms, $\delta = 3$ ms, $\tau'' = 3.9$ ms, $n = 12000$.

The CPMG data were analyzed using (1D) Inverse Laplace Transformations (ILT). The D-T_2 data were analyzed using 2D-ILT [2], while for the G_0-T_2 data we compared the use of 2D-ILT with a semi-discrete analysis [5] where the T_2-decays for oil and water were separated based on the difference in response to diffusion in susceptibility gradients. The outline of the semi-discrete analysis is as follows: At a certain τ'-value (τ'_c), the faster diffusing signal from water has dephased. For each echo in the T_2-decays at $\tau' > \tau'_c$ a linear fit with respect to varying τ' can be performed, and can then be extrapolated to find synthetic T_2-decays for oil at $\tau' < \tau'_c$. The synthetic T_2-decays can be subtracted from the original T_2-decays to obtain synthetic T_2-decays for water at varying τ'. 1D-ILT can be performed on the synthetic oil and water T_2-decays, and the obtained signal intensity for each T_2 component vs τ' can be used to determine DG_0^2. For more details we refer to the similar description given in ref. [5].

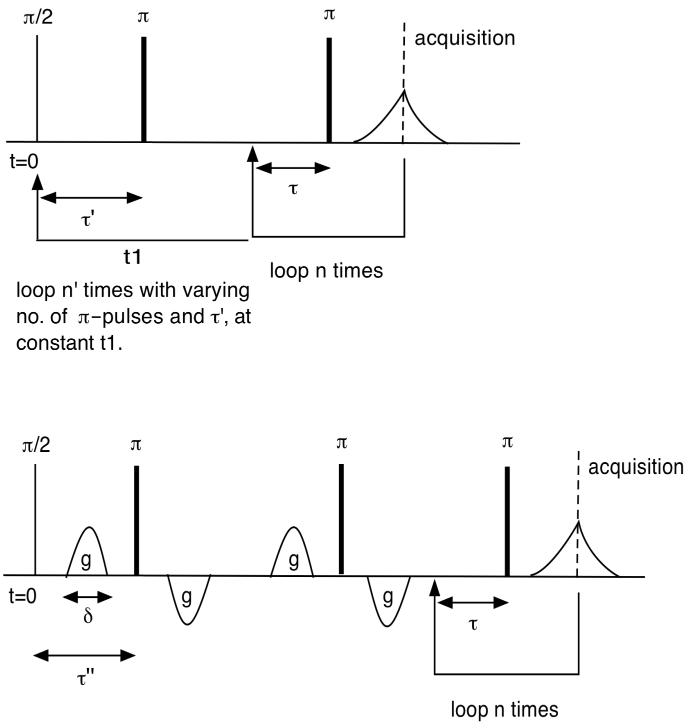

Fig. 1: Pulse sequences used to measure G_0-T_2 [3] (upper figure) and D-T_2 correlation [5] (lower figure).

The echo attenuation for the G_0-T_2 correlation can be expressed using a continuous function (for 2D-ILT analysis) or as discrete functions (for the semi-discrete analysis):

$$M(\tau',2n\tau) = \iint f(DG_0^2,T_2) e^{-\frac{t1+2n\tau}{T_2}} e^{-\frac{\gamma^2 DG_0^2 \tau'^2 2n'\tau'}{3}} dT_2 d(DG_0^2) \approx \sum_{i=1}^{n}\sum_{k} q_{ik} e^{-\frac{t1+2n\tau}{T_{2ik}}} e^{-\frac{\gamma^2 D_{ik} G_{0ik}^2 \tau'^2 2n'\tau'}{3}} \quad (1)$$

The index i indicate a sum over liquids with different dynamic behavior, while index k indicate a sum over all possible discrete values for D, G_0 and T_2.

Correspondingly, for the D-T_2 correlation we have:

$$M(g,2n\tau) = \iint f(D,T_2) e^{-\frac{4\tau''+2n\tau}{T_2}} e^{-(\frac{16}{\pi^2})\gamma^2 D g^2 \delta^2 (\frac{3\tau''}{2}-\frac{\delta}{8})} dT_2 dD \times \int e^{-\frac{\gamma^2 D G_0^2 \tau''^2 4\tau''}{3}} dV$$

$$\approx \sum_{i=1}^{n} \sum_{k} p_{ik} e^{-\frac{4\tau''+2n\tau}{T_{2ik}}} e^{-(\frac{16}{\pi^2})\gamma^2 D_{ik} g^2 \delta^2 (\frac{3\tau''}{2}-\frac{\delta}{8})} \times \int e^{-\frac{\gamma^2 D_{ik} G_{0ik}^2 \tau''^2 4\tau''}{3}} dV \qquad (2)$$

Notice the last attenuation term in Eq. (2) due to diffusion in susceptibility gradients during the measurement, which is integrated over the total volume of the sample.

3. Results and Discussions

The T_2-values for bulk water and oil were 3000 and 136 ms respectively, while the diffusion coefficient for water at 35°C was $2.9 \cdot 10^{-5}$ cm^2/s. The CPMG measurements (data not shown) resulted in a broad distribution of T_2-values in the S_w state. In the S_{wi} state T_2-signals from water and oil were strongly overlapping.

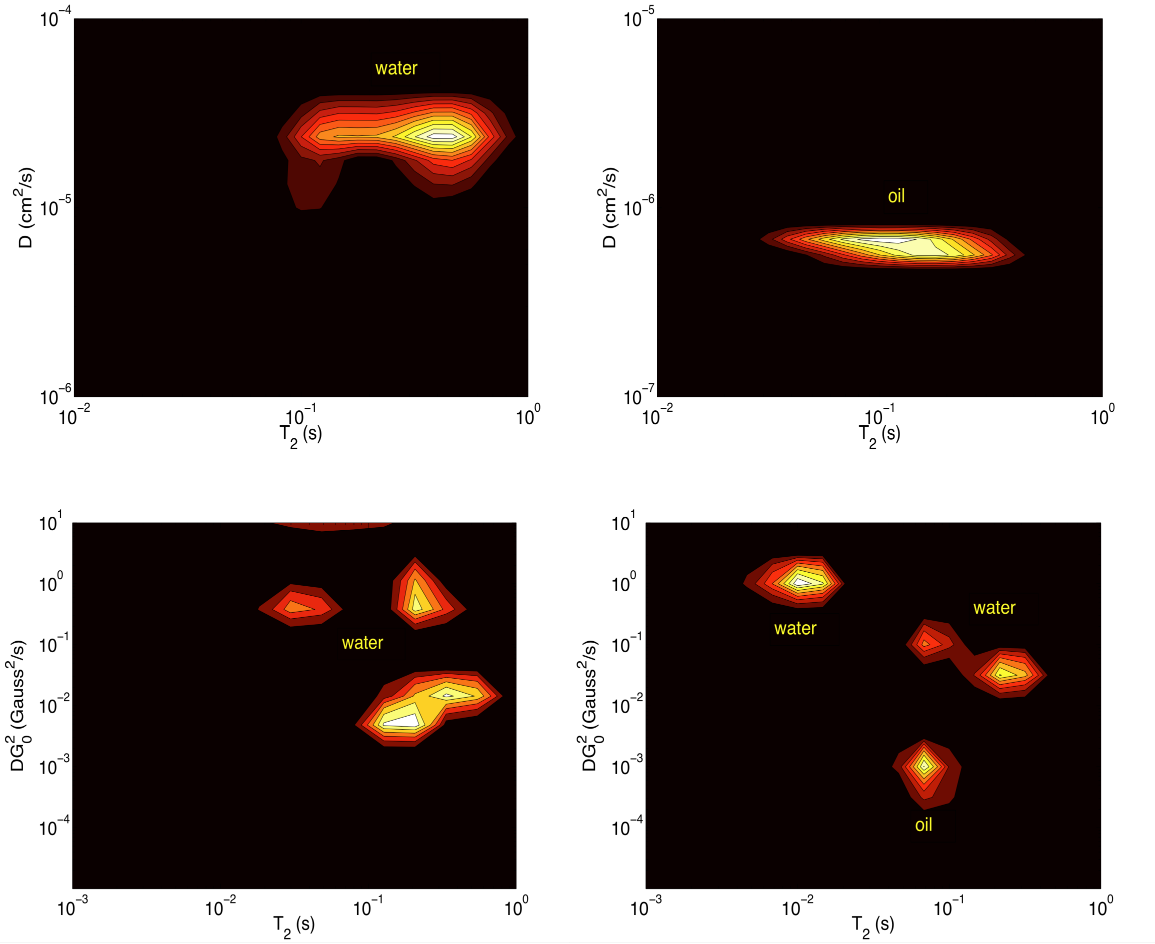

Fig. 2: D-T_2 correlation maps (top row), and DG_0^2-T_2 correlation maps (lower row) in S_w (left column) and S_{wi} (right column) states. Assignments of the signal originating from water and oil are given.

The D-T_2 maps (Fig. 2, top row) show a narrow distribution of diffusivities for water centered around $2.3 \cdot 10^{-5}$ cm^2/s in the S_w state. τ'' in the PGSE-part was 3.9 ms, resulting in a strong attenuation due to diffusion in susceptibility gradients, so signals with $T_2 < 100$ ms were therefore lost. Due to the same effect, and since oil displaces bulk water; all signals from water in the S_{wi} state were lost. The mean diffusivity for the remaining oil was $6 \cdot 10^{-7}$ cm^2/s. From the DG_0-T_2 maps (Fig. 2, lower row), and using the measured diffusion coefficient of water, the values for G_0 in the S_w state are in the range 10-200 Gauss/cm. In the S_{wi} state, the signals from oil and water are separated along the DG_0^2-dimension. Clearly, oil displaces the bulk water. When normalized with respect to the measured diffusion coefficients, G_0 for the water peaks are 50 and 200, and for the oil peak 30 Gauss/cm.

The dynamic range along the DG_0^2 dimension is larger than what is obtained along the corresponding D- or T_2-dimensions, making it more sensitive to surface effects and changes in wettability.

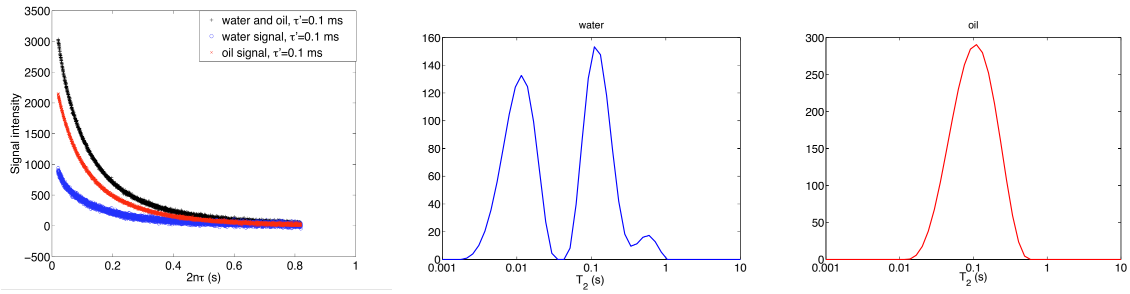

Fig. 3: Results obtained from the semi-discrete analysis of the G_0-T_2 data in the S_{wi} state. Synthetic T_2-decays for oil and water are plotted together with the T_2-decay for the total signal (left figure). The other two figures show the resulting T_2-distributions for water (middle figure) and oil (right figure) obtained using 1D-ILT. All plots were obtained at the minimum τ'-value (0.1 ms).

From the DG_0^2-T_2 correlation map the relative amount of water in S_{wi} state is 0.6, which is higher than expected. Using the semi-discrete analysis described above, the fraction of water was determined to be 0.29, which is more typical for the S_{wi} state. The positions of the T_2-peaks (Fig. 3, middle and right) correspond reasonably well with results obtained in the DG_0^2-T_2 correlation maps. Obtained results from the semi-discrete analysis are summarized in the table below. The values for G_0 of water signals are somehow higher than the values obtained using 2D-ILT, but the overall correspondence is good.

Table 1: Values for T_2 and G_0 obtained from the semi-discrete analysis of the G_0-T_2 data in the S_{wi} state.

	$T_2(1)$ (ms)	$T_2(2)$ (ms)	$G_0(1)$ (Gauss/cm)	$G_0(2)$ (Gauss/cm)
water	30	160	500	80
oil	110	------------	30	--------------------

4. Conclusions

We have shown that G_0-T_2 correlations are potentially a more sensitive wettabilty probe for liquid saturated rock cores compared to D-T_2 correlations. The separate responses of oil and water to diffusion decay in susceptibility gradients can be used for a separation of the T_2-decays when they are overlapping in the T_2-dimension. A semi-discrete analysis of the G_0-T_2 data gave quantitatively more reliable results compared to a 2D-ILT analysis.

References

[1] K.-J. Dunn, D.J. Bergman, G.A. Latorraca, *Nuclear Magnetic Resonance. Petrophysical and Logging Applications*, Pergamon, New York (2002).
[2] M. D. Hurlimann, L. Venkataramanan, *J. Magn. Reson.*, **157**, 31 (2002).
[3] B. Sun, K.-J., Dunn, *Phys. Rev. E.*, **65**, 051309 (2002).
[4] J.G. Seland, K.E. Washburn, H.W. Anthonsen, J. Krane, *Phys. Rev. E.,* **70**, 051305 (2004).
[5] J.G. Seland, G.H. Sørland, H.W. Anthonsen, J. Krane, *Applied Magn. Reson.,* **24**, 41 (2003).