Internal gradients in sediments and their impact on NMR measurements

Emily Fay
Geophysics Department
Stanford University
emilyfay@stanford.edu

Denys Grombacher
Geophysics Department
Stanford University
denysg@stanford.edu

Rosemary Knight
Geophysics Department
Stanford University
rknight@stanford.edu

SUMMARY

Internal magnetic field gradients in porous materials can impact NMR measurements of the transverse relaxation time (T_2) and the diffusion coefficient (D), leading to possible interpretation errors. Internal gradients can shift signal to faster relaxation times and alter the shape of the T_2 distribution, complicating the link between pore size and measured T_2. Internal gradients can also cause errors in the calculation of D from NMR data, which will cause problems if we are interested in using D to separate signal from multiple fluid phases or to investigate pore geometry.

The aim of this work is to increase our understanding of when and how internal gradients impact NMR data, and how the magnitude of observed internal gradients are related to sediment properties. We use modelling and laboratory measurements of T_2 and D-T_2 to investigate the impact of internal gradients on NMR measurements in sediments. We assess the correlation between the internal gradients that we observe and measured sediment properties.

The results of this study indicate that internal gradients could have a significant impact on borehole measurements of D-T_2 and of T_2 in sediments with moderate to high magnetic susceptibility. In contrast, due to the scaling of internal gradients with the background magnetic field, we expect the effect of internal gradients on surface NMR data to be negligible due to the lower field.

Key words: NMR, T_2, D-T_2, magnetic susceptibility, borehole logging

INTRODUCTION

When a magnetic field is applied to a porous material, differences in magnetic susceptibility between the matrix and the pore fluid generate pore-scale inhomogeneities in the magnetic field (Brown, 1961; Song et al., 2000). These inhomogeneities are called internal gradients. Fluid molecules diffuse in the presence of these gradients, such that the magnetic field that they experience will change over the course of an NMR experiment, resulting in non-recoverable dephasing and signal attenuation. We call this phenomenon decay due to diffusion (DDIF), and its contribution to T_2 decay is utilized to measure the apparent diffusion coefficient of fluids (Hahn, 1950; Carr and Purcell, 1954).

The diffusion measurement is made using an externally applied magnetic field gradient; the calculation of the diffusion coefficient assumes that internal gradients are negligible compared to the applied gradient. When this is not the case due to large internal gradients, the diffusion coefficient will be over-estimated, causing problems for interpretation (Hürlimann et al., 2004; Leu et al., 2005).

Decay due to diffusion also contributes to the measured T_2 decay, although its impact can be minimized by using short echo spacings, which control the distance that spins can travel between refocusing pulses, and thus how much dephasing will occur. As the echo spacing is increased, the effect of internal gradients will increase, and the T_2 distribution may no longer be a good representation of the pore size distribution (Grombacher et al., 2014).

Measurements of T_2 and D-T_2 have many potential applications to groundwater problems; understanding how internal gradients will impact the data we collect is critical to moving forward with near-surface applications of NMR. Our approach to this problem combines computer modeling and laboratory experiments. The modeling allows us to calculate the magnetic field within a user-defined pore, and generate simulated NMR data for the model pore given its internal gradients. In the lab, we collect T_2 and D-T_2 data for a range of aquifer sediments and control samples, and compare the observed internal gradients to the properties of the sediments.

METHOD AND RESULTS

Modelling Study

Using COMSOL Multiphysics, the distribution of internal gradients was calculated for model pores with varying geometry, size, surface relaxivity, and matrix susceptibility. Figure 1 shows the calculated gradient field in a model pore and a histogram showing the distribution of gradient magnitudes for the same pore with four different matrix susceptibilities assigned. In every pore that we modelled, internal gradients spanned approximately three orders of magnitude, with gradient magnitudes controlled by susceptibility contrast.

Following the calculation of the gradient distribution within a pore, the magnetization decay was simulated using an eigenvalue solver. The output of this simulation is a series of eigenvalues and associated intensities representing the relaxation rates that contribute to the decay. These eigenvalues were then used to generate synthetic data from T_2 and D-T_2 experiments, with parameters selected to match the sequences run in the lab experiments. This allowed us to assess how the internal gradients observed in the two NMR experiments are related to the actual distribution of gradients in the pore, to the pore geometry, to the matrix susceptibility, and to the surface relaxivity. Figure 2 shows the calculated T_2 distributions for a pore as matrix susceptibility is increased, using two different echo spacings. The pore geometry is identical for all of these calculations, so we can clearly see the impact of increasing magnetic susceptibility and t_E on the T_2 distribution.

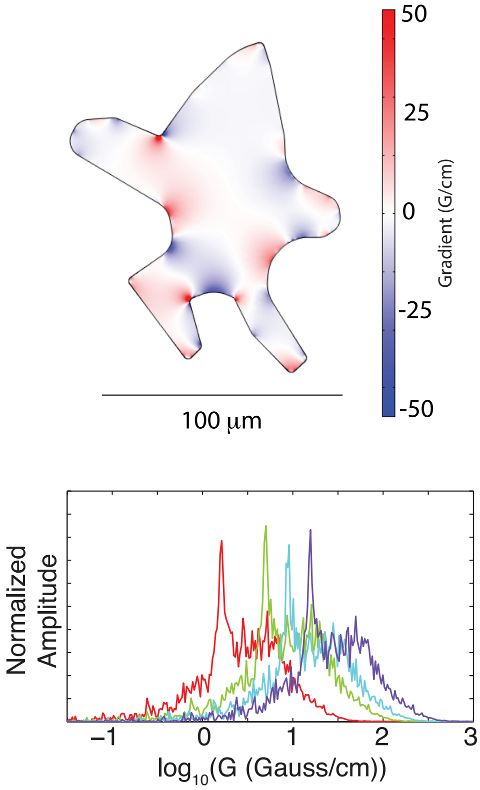

Figure 1. Above: The internal gradient distribution within a model pore due to a magnetic susceptibility contrast of 1e-4 (SI units) between the pore fluid and the matrix, in a background field of 50 mT. Below: Histogram of internal gradients for the pore shown above, with susceptibility contrasts ranging from 1e-4 (red) to 1e-3 (purple). Modified from Grombacher et al. 2014.

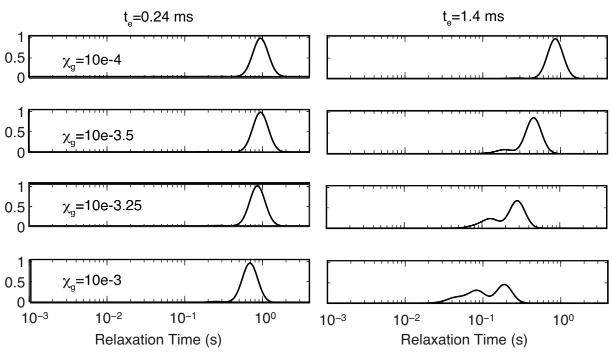

Figure 2. The T_2 distributions calculated in COMSOL for the model pore shown in Figure 1. Each row shows the distributions for a different susceptibility contrast; the column on the left shows the distributions calculated using t_E = 0.24 ms, and the column on the right shows the distributions calculated using t_E = 1.4 ms. Modified from Grombacher et al. 2014.

Laboratory Study

NMR data were collected for 47 sediment samples, including aquifer sediments and control samples made with clean quartz sand and magnetic minerals. Data were collected using a 2.2 MHz Maran Ultra NMR Core Analyzer (Resonance Instruments) with no applied gradients.

To measure the impact of internal gradients on T_2 measurements, CPMG data were collected with echo spacings ranging from 0.24 ms to 1.4 ms. Figure 3 shows the change in the T_2 distribution of a magnetic beach sand as t_E is increased. As predicted by our modelling results, the presence of internal gradients changes the shape of the distribution and shifts T_{2ML}, the mean log gradient, to faster times.

The observed gradients were calculated from the slope of T_{2ML}^{-1} vs. t_E^2, as described in Fay et al. (2015). The gradients observed from the T_2 measurements ranged from too small to detect to ~400 G/cm.

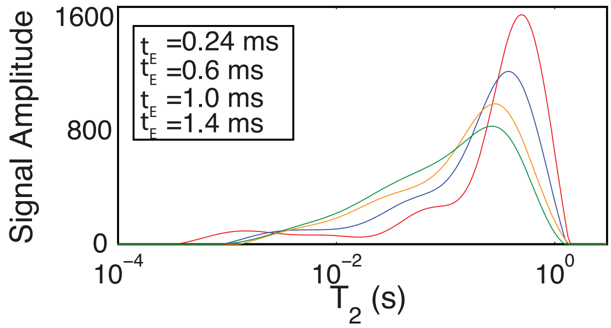

Figure 3. The measured T_2 distribution for a magnetic beach sand, measured using four different echo spacings. The shortest echo time is associated with the highest peak and longest relaxation times, the distribution spreads to shorter times as the echo spacing increases.

The impact of internal gradients on D-T_2 measurements was estimated using a two-part pulse sequence designed to encode decay due to diffusion in the first part, then measure the T_2 decay (Sun and Dunn, 2003). Figure 4 shows an example of the distribution of observed gradients (G_{obs}) vs. T_2.

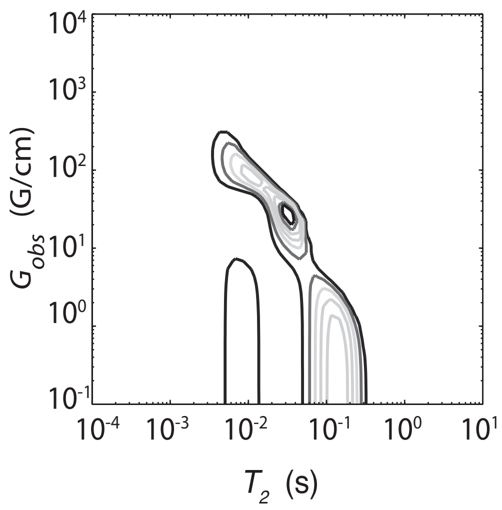

Figure 4. A distribution of observed gradients vs. T_2 for an aquifer sediment sample. Note the higher gradients observed in the smaller pores.

For the D-T_2 measurements, we were able to measure a distribution of gradients. For the more magnetic samples, gradients up to 1000 G/cm were observed. The mean gradients observed for the D-T_2 data ranged from 1 to 800 G/cm.

Comparing the gradients observed in the T_2 data to the mean of the gradient distributions observed in the D-T_2 data, we see not only that these two numbers are quite different, but that the relationship between them is impacted by pore size. The observed gradients show an increasing trend with magnetic susceptibility, but pore size also contributes to the observed gradients, such that they cannot be predicted with magnetic susceptibility alone.

CONCLUSIONS

Internal gradients in sediments are controlled by pore geometry and grain susceptibility. We calculated broad distributions of gradients in the pores we modelled; broad distributions were also observed in laboratory data.

Both the modelling and laboratory work found that internal gradient magnitudes in sediments can often be sufficiently large so as to impact T_2 and D-T_2 data collected with NMR logging tools, where applied gradients are typically 2-40 G/cm. The impact of the internal gradients on the T_2 distribution depends on the echo spacing, and can be reduced by employing short t_E values. If internal gradients do indeed scale with the background field as predicted by theory for paramagnetic grains, the impact on data collected at Earth's field will be negligible. The presence of ferromagnetic minerals could impact the scaling of internal gradients with the background field; more work is needed to address this question.

The mean internal gradient magnitudes observed in the laboratory samples depend on both the magnetic susceptibility of the sample and its pore size distribution, as seen in the modelling results and as predicted by theory.

The observed gradients were different for T_2 and D-T_2, implying that the error from internal gradients is not an inherent property of a sediment but is dependent on the measurement sequence. This means that if we want to correct for the effect of internal gradients, a different correction will need to be applied for T_2 data and D-T_2 data. Synthetic data calculated from our pore models support this conclusion; we found that the pore size, matrix susceptibility, and surface relaxivity of the model pores all contribute to the differences in the gradients observed with the two measurements.

ACKNOWLEDGMENTS

We would like to thank Yi-Qiao Song at Schlumberger for his help and for providing the 2D inversion codes. This research was supported by funding from the Hydrology Program and the GOALI (Grant Opportunities for Academic Liaison with Industry) Program of the U.S. National Science Foundation (Award no. 0911234), by the Natural Sciences and Engineering Research Council of Canada, and by the AAPG (American Association of Petroleum Geologists) Foundation.

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