ASEG-PESA 2015
Geophysics and Geology together for Discovery
24th International Geophysical Conference and Exhibition
15–18 February 2015 Perth, Western Australia

Surface NMR to Image Aquifer Properties in a Magnetic Subsurface

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SUMMARY

Surface Nuclear Magnetic Resonance (NMR) is a non-invasive geophysical technique providing the ability to image and investigate aquifer properties. In order to produce reliable images and interpretations of subsurface properties accurate modelling of the underlying physics is required. In magnetic environments, where the background magnetic field varies spatially, challenges can arise that lead to difficulty accurately modelling the excitation process and interpreting the signal's time dependence. We demonstrate using field data collected in the Anangu Pitjantjatjara Yankunytjatjara (APY) Lands of South Australia that neglecting the influence of the magnetic environment can significantly alter the final images and interpretation of the subsurface structure and properties.

Key words: NMR, hydrogeophysics, groundwater

INTRODUCTION

Surface Nuclear Magnetic Resonance (NMR) is a non-invasive geophysical technique providing the ability to investigate aquifer properties. The NMR experiment involves measuring a subsurface magnetization, which originates from the immersion of hydrogen nuclei in a background magnetic field ($\mathbf{B_0}$). As this magnetization is generally too small to measure directly a secondary magnetic field ($\mathbf{B_1}$) is used to perturb the magnetization, and its subsequent return to equilibrium (decay) is monitored. The signal's amplitude and time-dependence provide insight into the subsurface water content, pore-sizes, and permeability (Kenyon et al., 1988; Coates et al., 1991). In addition to characterizing the pore-scale environment surface NMR provides the ability to image subsurface water content allowing aquifer thickness and extent to be investigated.

The ability to produce representative images, and build reliable models of the subsurface requires accurate modelling of the physics governing both the perturbation and decay processes. One situation where this becomes challenging is when the subsurface geology contains magnetic components. Magnetic susceptibility contrasts lead to a background magnetic field that varies spatially (Hurlimann, 1998), from the pore-scale to field scale (~100 m). As a result, magnetizations at different spatial locations precess at different rates, impacting the perturbation and the signal's time dependence due to processes known as off-resonance excitation and dephasing, respectively.

We present an analysis of data collected in the Anangu Pitjantjatjara Yankunytjatjara (APY) Lands of South Australia, demonstrating the impact that neglecting $\mathbf{B_0}$ inhomogeneity may have on the resulting aquifer model. We highlight the difficulty in selecting the correct transmit frequency in magnetic environments, illustrating how to determine the correct frequency from field data and the consequences of choosing an incorrect frequency. Additionally, we demonstrate that in magnetic environments the role of dephasing on the signal's time-dependence can significantly impact the interpretation of the pore-scale environment.

IMPACT OF $\mathbf{B_0}$ INHOMOGENEITY IN SURFACE NMR

In order to measure the subsurface magnetization, oscillatory currents are pulsed in a surface coil to generate the perturbing $\mathbf{B_1}$ field at depth. The frequency of oscillation is called the transmit frequency, ω, and is ideally set equal to the precession frequency of the magnetization, called the Larmor frequency, ω_0. This satisfies a condition called on-resonance excitation, which maximizes the efficiency of the excitation process. In this case the signal phase is controlled by the conductivity structure of the subsurface (Trushkin et al., 1995).

Generally the Larmor frequency is determined using a magnetometer to measure $\mathbf{B_0}$ and the relation: $|\omega_0|=|\gamma\mathbf{B_0}|$, where γ is the gyromagnetic ratio of the hydrogen nuclei. The transmit frequency is set equal to this frequency, and the experiment conducted. However, several situations exist where the magnetometer determined ω_0 might not be accurate. The magnetometer reading is conducted at the surface, a different spatial location than the origin of the signal at depth. Therefore, a gradient in $\mathbf{B_0}$ may lead to the selection of a transmit

frequency that is distinct from ω_0. This leads to a condition referred to as off-resonance excitation. In this case, the perturbation process is different than that caused by on-resonance excitation, resulting in a variation of the signal's amplitude and phase (Walbrecker et al., 2011). Additionally, the spatial distribution of excited signal in the subsurface will be different following off-resonance excitation than that following on-resonance excitation.

To generate water content images using surface NMR, the sensitive volume in the subsurface is controlled using a parameter called the pulse moment, q; where q is equal to the product of the pulse duration and the current amplitude in the surface coil. Small q sample shallow depths while larger q sample the greatest depths (typically to a depth roughly equivalent to the coil dimension). An inversion is employed to determine the spatial distribution of water content in the subsurface. In order to correctly determine the spatial origin of the measured signal, the physics of the excitation process must be accurately modelled. Traditionally, the excitation is treated as on-resonance and the kernels used in the inversion contain this as an implicit assumption. As such, off-resonance excitation that is incorrectly inverted using on-resonance kernels may lead to inaccurate water content images (Grombacher and Knight, 2014).

Another impact of magnetic sediments is that the time-dependence of the measured signal may be significantly altered. A magnetic susceptibility contrast between grains and the pore fluid leads to $\mathbf{B_0}$ variation across the pore space that causes an accelerated decay. Magnetizations at different spatial locations within the pore precess at different rates (dephase), leading to destructive interference and subsequent signal loss. This dephasing can obscure the relationship between the time-dependence of the signal and the geometry of the pore space; *i.e.* the connection to pore-size and permeability. If the contribution of dephasing to the measured decay is ignored, a biased interpretation of pore-size and permeability will be formed; pore-sizes and permeability will be underestimated. The free-induction decay (FID) measurement, a standard measurement in surface NMR, is very sensitive to dephasing (Muller et al., 2005; Grunewald and Knight, 2011). In order to better inform pore-sizes and permeability estimates, an alternative measurement called a CPMG is employed to reduce the sensitivity of the signal's time dependence to $\mathbf{B_0}$ inhomogeneity (Grunewald and Walsh, 2013).

FIELD STUDY

To demonstrate the importance of identifying and considering the influence of $\mathbf{B_0}$ inhomogeneity on surface NMR studies we present results collected during a field campaign in May 2014, in the APY Lands of South Australia. The site is located approximately 1200 km northwest of Adelaide, near the township of Fregon. The site was chosen as part of a larger study to verify the presence of a potential fresh-water aquifer identified during an airborne magnetics survey.

Little hydrogeological information is available in the area; wells are typically drilled to depths of 50 m in alluvial, calcrete, Aeolian, and fractured rock environments. The remote location of the sites made for ideal surface NMR conditions where low noise was recorded at nearly all sites, requiring little stacking (typically 2 stacks) for high quality data (SNR ~ 50). The sites of the surface NMR measurements conducted in this study were observed to have strong magnetic effects. Figure 1 displays an image of a magnet after lightly dragging it ~10 cm through the surface sediments at one of the sites, where a significant portion of the soil was observed to be magnetic. Magnetometer readings taken at the south edge, center, and north edge of the surface coil were often observed to vary by ~100 nT (equivalent to a change in the transmit frequency of ~4 Hz), making the selection of the correct transmit frequency challenging.

Figure 1. Magnetic particles attached to a magnet that was dragged through the surface sediments at one of the surface NMR sites.

To illustrate the impact of off-resonance excitation on the measured signals Figure 2 illustrates the sounding curves for data collected using on-resonance and off-resonance excitations at two sites. At each site off-resonance data were collected (accidentally) because of challenges selecting the correct transmit frequency. The off-resonance data were used to better inform the true ω_0 allowing an on-resonance survey to take place afterwards. The results shown below in the left column were collected with an offset of 7 Hz between ω and ω_0, while the data shown in the right column were collected with an offset of 4 Hz.

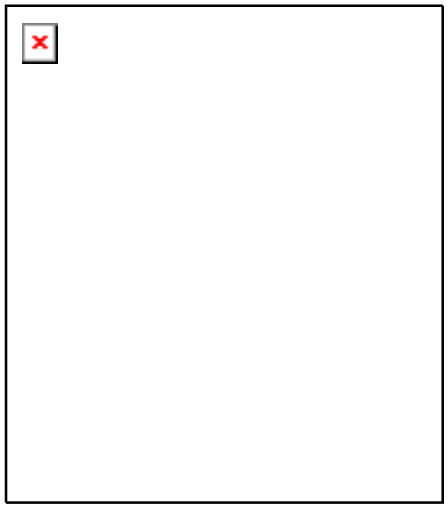

Figure 2. Sounding curves at two sites in the APY lands for surveys conducted with on-resonance excitation (solid) and off-resonance excitation (dashed). The real, quadrature, and absolute sounding curves are shown are blue, red, and black lines, respectively.

Off-resonance excitation is observed to result in significant variation in the signal's real and quadrature components, as well as the signal's dependence on *q*. In each case, the real and quadrature sounding curve following off-resonance excitation is observed to be smaller and larger, respectively, than that following on-resonance excitation. The absolute magnitude of the signal is also observed to be larger following off-resonance excitation at large *q*.

Figure 3 illustrates the water content profiles predicted using the on-resonance and off-resonance data at each site, where inversions were performed using the standard surface NMR kernels that assume on-resonance excitation. Inversions were performed using the Vista-Clara inversion package. The left and right columns of Figure 3 correspond to the left and right columns, respectively, of Figure 2.

Figure 3. The estimated water content profiles using on-resonance (blue) and off-resonance (red) data sets where the inversions utilized the standard surface NMR kernels that assume on-resonance excitation. Off-resonance effects are observed to lead to different estimates of the water content profiles.

The water content profiles estimated using on-resonance excitation generally predict a single water-bearing unit that ends at a depth consistent with the depth to bedrock estimated using TEM measurements. The off-resonance water content profiles tend to differ from the on-resonance profiles predominantly at depth, where the aquifer is predicted to both extend to a greater depth and have increased water content at depth. As discussed by Grombacher and Knight (2014), this is likely an inversion artifact based on inaccurate modelling of the physics of the excitation process. The only mechanism for an inversion that uses on-resonance kernels to generate a quadrature component is to place additional water at depth. Only at the greatest depths does water contribute significantly to the signal's quadrature component during on-resonance excitation. Therefore, to explain the increased variation in the quadrature sounding curve the inversion places additional water at depth. Furthermore, off-resonance excitation produces signals of larger absolute magnitude for the largest *q*; the *q* that sample the greatest depths. Thus, the inversion requires more water at depth in order to explain the larger signal amplitude using the incorrect kernels. All water content profiles fit the data equally well.

Figure 3 demonstrates that off-resonance data inverted with incorrect on-resonance kernels may produce different images of the aquifer leading to biased interpretations, where the aquifer tends to be thicker, and have higher water content than would be predicted using an on-resonance excitation paired with the correct kernel.

In addition to imaging water in the subsurface, surface NMR also produces depth profiles of relaxation times, which control the time-dependence of the measured signal. Traditionally, these relaxation times are interpreted as representative of the pore-size. However, in magnetic environments the relaxation times controlling the decay during a FID, called T_2*, are very sensitive to dephasing. As such, T_2* profiles are often not reflective of the pore-size or permeability. Figure 4 illustrates the T_2* and T_2 (estimated using a CPMG) profiles predicted at two sites in the APY lands; the sites correspond to the water content profiles shown in Figure 3.

Figure 4. The estimated T_2* (red) and T_2 (blue) profiles using FID and CPMG measurements.

Figure 4 illustrates that in this magnetic environment $T_2^* << T_2$, demonstrating that dephasing is the dominant mechanism controlling the decay following the FID. As such, any interpretation of the T_2* profile as representing the pore-size profile, would lead to significantly underestimated pore-sizes and permeability. Without the complementary CPMG measurement that allow T_2, which is more closely linked to pore-size, to be measured these aquifers could potentially be interpreted as having low permeability whereas T_2 suggests otherwise. Note that the large spike in the T_2* profile in the right column at ~37m depth corresponds to a water content of ~1% (see 37 m depth in the right column of Figure 3) meaning that this value is not a reliable estimate.

IDENTIFYING MAGNETIC INFLUENCES IN SURFACE NMR FIELD DATA

We have demonstrated that the influence of magnetic sediments, which manifest as off-resonance excitation and dephasing, must be considered when working in a magnetic environment. As such, we must always look for markers in the data that indicate these processes are present.

To identify conditions leading to off-resonance excitation, specifically when the selected transmit frequency is distinct from the Larmor frequency we can look at the signal's spectrum and the time dependence of the signal phase (of the

demodulated signal). To identify the optimal transmit frequency (equal to ω_0) we look at the spectrum of the signal, and identify the center frequency. If this frequency is distinct from the transmit frequency used, a second survey should be performed using the correct frequency. This method is more robust than purely estimated the transmit frequency based on magnetometer measurements given that the NMR signal itself informs the spectrum; therefore we recommend that it should be trusted more than the frequency determined using a magnetometer. An alternative method to identify the optimal transmit frequency is to examine the time-dependence of the signal phase. Typically when viewing the signal in the time-domain, we view the signal after demodulation by the transmit frequency. We assume that this demodulates the signal to baseband. However, if the transmit frequency and Larmor frequency are distinct the demodulated signal will not be at baseband and phase wraps will be observed, as illustrated in Figure 5.

Figure 5. The signal demodulated by the correct (top) and incorrect (bottom) frequency. The signal phase is observed to wrap when the demodulation is performed at the wrong frequency.

The top image illustrates a clean NMR signal, identified by the coherent phase persisting along both the time and pulse moment axes. Alternatively, the banded phase structure observed in the bottom plot of Figure 5 reveals that the demodulation was not performed at the correct frequency. It represents the time-domain equivalent of the demodulated spectrum not being centered at 0 Hz. The frequency of the phase bands reveals the magnitude of the offset between transmit and Larmor frequencies.

To identify if dephasing has impacted the measured T_2*, FIDs should be complemented with CPMG experiments. If a significant difference is observed between T_2* and T_2, T_2* should not be considered a reliable representation of pore sizes as it is likely being strongly influenced by dephasing.

CONCLUSIONS

To produce accurate images of the subsurface water content and gain insight into the pore-scale environment using surface NMR we must understand the physics controlling the excitation and decay processes. This is particularly challenging in magnetic environments where $\mathbf{B_0}$ gradients make it difficult to identify the optimal transmit frequency and can obscure the relationship between the signal's time-dependence and the pore geometry. As such, it is imperative that we identify and consider the influences of $\mathbf{B_0}$ inhomogeneity on the measured signal.

We demonstrate at two sites in the APY lands of South Australia, that neglecting these effects may lead to a different hydrologic interpretation. Off-resonance excitation is observed to lead to overestimated water contents and increased estimates of aquifer thicknesses when inverted using the standard on-resonance kernels. Additionally, the relaxation times in these conditions do not accurately reflect the pore-size and provide biased estimates.

ACKNOWLEDGMENTS

This work was supported by funding from the Geoscientists *Without* Borders project entitled "Near Surface Geophysics for Informed Water Management Decisions in the Anangu Pitjantjatjara Yankunytjatjara (APY) Lands of South Australia". We would also like to acknowledge the contributions of CSRIO in supporting the field work.

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