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Field experiment provides ground truth for surface nuclear magnetic resonance measurement

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Field experiment provides ground truth for surface nuclear magnetic resonance measurement

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[1] The need for sustainable management of fresh water resources is one of the great challenges of the 21st century. Since most of the planet's liquid fresh water exists as groundwater, it is essential to develop non-invasive geophysical techniques to characterize groundwater aquifers. A field experiment was conducted in the High Plains Aquifer, central United States, to explore the mechanisms governing the non-invasive Surface NMR (SNMR) technology. We acquired both SNMR data and logging NMR data at a field site, along with lithology information from drill cuttings. This allowed us to directly compare the NMR relaxation parameter measured during logging, T_2, to the relaxation parameter T_2^* measured using the SNMR method. The latter can be affected by inhomogeneity in the magnetic field, thus obscuring the link between the NMR relaxation parameter and the hydraulic conductivity of the geologic material. When the logging T_2 data were transformed to pseudo- T_2^* data, by accounting for inhomogeneity in the magnetic field and instrument dead time, we found good agreement with T_2^* obtained from the SNMR measurement. These results, combined with the additional information about lithology at the site, allowed us to delineate the physical mechanisms governing the SNMR measurement. Such understanding is a critical step in developing SNMR as a reliable geophysical method for the assessment of groundwater resources. **Citation:** Knight, R., E. Grunewald, T. Irons, K. Dlubac, Y. Song, H. N. Bachman, B. Grau, D. Walsh, J. D. Abraham, and J. Cannia (2012), Field experiment provides ground truth for surface nuclear magnetic resonance measurement, *Geophys. Res. Lett.*, *39*, L03304, doi:10.1029/2011GL050167.

1. Introduction

[2] One of the great challenges of the 21st century is providing fresh water for human consumption, agricultural and industrial use, while balancing the needs of natural ecosystems. Effective and sustainable long-term management of fresh water resources requires accurate information about the quantity of water that can be extracted for use. While it is relatively straightforward to determine the quantity of available water in lakes, rivers, and surface reservoirs, it is very difficult to obtain information about the quantity of producible water in groundwater aquifers, which can extend from the surface to depths of hundreds of meters, and laterally over thousands of square kilometers. With 98.9% of the planet's liquid fresh water held in groundwater aquifers [*Shiklomanov*, 1993], and with groundwater estimated to provide 43% of the water used for irrigation [*Siebert et al.*, 2010], there is a need for improved methods of characterizing groundwater aquifers. Conventional methods typically involve the drilling and pumping of wells, an approach that is expensive and time-consuming, and rarely provides the spatial density of sampling needed for effective management of the resource.

[3] Geophysical methods provide a means of remotely sampling, or imaging, groundwater aquifers. This approach utilizes the link between what can be measured with geophysical instruments placed on Earth's surface or in boreholes, and the subsurface properties of interest. The problem, to date, with using geophysical methods for evaluating groundwater aquifers is the complexity of the link between the measured geophysical response and the properties of the aquifer. For example, electrical methods cannot discriminate between the presence of conductive groundwater and the presence of conductive minerals. There is one form of measurement, however, that can provide a more direct link to the presence of water in the pore space of geological materials – proton Nuclear Magnetic Resonance (NMR). The link is through the detection of the nuclear magnetization of the hydrogen nuclei (protons) in the water. The NMR measurement is the basis of MRI (magnetic resonance imaging), used in medical applications to characterize biological tissue. Of specific interest for groundwater applications is the measurement of the NMR relaxation time constant, referred to as T_2, which represents the time it takes for the nuclear spins associated with the hydrogen nuclei to return to equilibrium after perturbation by an electromagnetic pulse. The parameter T_2 is well-known to be sensitive to the geometry of the water-filled pore space [*Cohen and Mendelson*, 1982] so can be related to the hydraulic conductivity, which controls the rate at which water will flow within, or can be pumped from, an aquifer. NMR measurements can thus provide information about a groundwater aquifer essential for water-resource evaluation and management.

[4] Geophysical instruments that can be lowered in boreholes or wells to measure the NMR response of the surrounding geological material were first developed in the 1960's [*Brown and Gamson*, 1960]. With advancements of

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these instruments in the last two decades, borehole NMR is now considered a proven technology for acquiring high quality T_2 measurements. Borehole NMR, however, has the same fundamental limitation common to any borehole-based measurement: drilling is expensive, and measurements in boreholes have limited spatial coverage, providing only a depth profile at a single location.

[5] In recent years, the geophysical community has seen the development of a new surface-based form of proton NMR measurement. Surface NMR (SNMR) is a non-invasive geophysical method that uses a loop of wire (up to ~150 m diameter) on the surface to probe the underlying material to a depth of ~100 m, without the need to drill boreholes [*Shushakov*, 1996; *Legchenko and Shushakov*, 1998; *Legchenko and Valla*, 2002; *Walsh*, 2008]. In the same way that the development of MRI revolutionized non-invasive medical imaging, the ability to obtain NMR measurements from Earth's surface could revolutionize the way we approach the non-invasive evaluation and management of groundwater aquifers. An important question exists, however, about what is actually measured with SNMR. The NMR relaxation time constant T_2 has a well-established link to hydraulic conductivity. SNMR measures a different NMR relaxation time constant, referred to as T_2^*. While there have been field studies designed to assess the link between T_2^* and hydraulic conductivity [*Legchenko et al.*, 2002], it is not straight-forward. The description of the physics of the SNMR measurement clearly shows that T_2^* is related to, but not necessarily equivalent to, T_2 [*Müller et al.*, 2005; *Grunewald and Knight*, 2012]. Furthermore, recent numerical and laboratory studies have shown that the relationship between T_2^* and T_2 is likely to depend upon the composition of the sampled material [*Grunewald and Knight*, 2012].

[6] The direct comparison of borehole and surface NMR measurements made over the same region of the subsurface can provide tremendous insights into the data acquired with the SNMR method. A previous field experiment used this approach to compare the amount of water detected by the two methods [*Müller-Petke et al.*, 2011]. In this study we acquired SNMR T_2^* data and borehole NMR T_2 measurements, at the same field site, in order to understand the relationship between T_2^* measured with SNMR and the desired NMR parameter of interest T_2.

2. Borehole and Surface NMR Measurements

[7] Both borehole and surface measurements of the NMR response of water in a porous geological material are described by the same fundamental physics [*Dunn et al.*, 2002]. In the presence of a static magnetic field (B_0), the nuclear spins associated with the hydrogen nuclei of the water molecules align, producing a net magnetic moment in the direction of B_0. This results in a macroscopic magnetization, defined as the net magnetic moment per unit volume. The spins precess about the background field at the Larmor frequency *f*, related to B_0 as follows:

$$f = \frac{\gamma}{2\pi}|B_0| \tag{1}$$

where γ is the gyromagnetic ratio of hydrogen, equal to 0.2675 rad/(nT s). The NMR experiment involves applying an electromagnetic pulse, oscillating at the Larmor frequency and perpendicular to B_0, that tips the spins into a plane transverse to B_0. Precession of the spins in the transverse plane generates a detectable signal that decays over time as the spins relax to their equilibrium position. The initial signal amplitude, just after the applied pulse, is directly proportional to the total amount of water sampled by the NMR measurement. The measured change in signal amplitude over time, referred to as the NMR decay-curve, contains information about the porous material saturated with water. The important differences between the borehole and surface NMR measurements, of relevance to this study, are the factors controlling the observed NMR decay-curve.

[8] The acquisition of borehole NMR measurements involves lowering an instrument into a borehole to obtain the NMR decay-curve at sub-meter intervals over the entire sampled depth (typically hundreds of meters). In this study we used both the Magnetic Resonance Scanner (MR Scanner, Schlumberger) and the Javelin tool (Vista Clara). One or more permanent magnets, mounted in the instruments, provide the static magnetic field with field strength on the order of ~0.005 T to 0.02 T, and a corresponding Larmor frequency of ~250 kHz to 1 MHz. Antennae in the tools generate a radio-frequency magnetic field to excite the spins and detect the NMR signal. During data acquisition, the MR Scanner is pushed up against the borehole wall to sample thin cylindrical shells with angular coverage of approximately 100 degrees in the horizontal plane. The sampled regions are ~1–2 mm thick and 46 cm long. Data are acquired at 4 cm, 7 cm, and 10 cm from the borehole wall; the data used in this study were acquired at 10 cm. The Javelin tool is centralized in the borehole and samples a thin cylindrical shell with a thickness of ~2 mm and a length of 46 cm, located a radial distance of 19 cm from the center of the tool.

[9] In an SNMR measurement, the static field is Earth's magnetic field with $B_0 \approx 30$–$60\ \mu$T resulting in Larmor frequencies between 1.3 and 2.6 kHz; at our field site the Larmor frequency was 2.2 kHz. Because the magnitude of Earth's field is much smaller than the field produced by a borehole instrument, a much larger volume of material (typically on the order of tens or hundreds of cubic meters) is sampled with SNMR in order to achieve an acceptable signal to noise ratio. Earth's static field is uniform over large distances, so this can be accomplished using wire loops at the surface, typically 50 m to 150 m in diameter, to transmit the oscillating magnetic field and to detect the NMR signal. The maximum depth of the sampled region is on the order of the diameter of the loop and also depends on the amplitude of the transmitted pulse and the electrical properties of the sampled materials. In this study we used the surface NMR instrument GMR, built by Vista Clara, Inc.

[10] The aspect of the NMR measurement that is of interest in our study is the character of the NMR decay-curve. The standard borehole NMR T_2 measurement uses a so-called Carr-Purcell-Meiboom-Gill (CPMG) pulse sequence [*Carr and Purcell*, 1954; *Meiboom and Gill*, 1958], designed to eliminate the influence of static inhomogeneous magnetic fields. The fundamental building block of the CPMG is the NMR echo, which is formed by successive additional RF pulses that have a specified echo spacing after the initial tipping pulse. Under the condition of fast diffusion, where

the diffusion of the hydrogen nuclei within the pore space is not the rate-controlling step in the relaxation process, the borehole NMR response of water in a single pore can be described as single exponential decay of the measured transverse magnetization signal A as a function of time t:

$$A(t) = A_o e^{-t/T_2} \quad (2)$$

where A_0 is the initial magnetization signal at t = 0, and T_2 is the transverse relaxation time. The corresponding relaxation rate T_2^{-1} is given by the following expression [*Brownstein and Tarr*, 1979; *Cohen and Mendelson*, 1982]:

$$T_2^{-1} = T_{2B}^{-1} + \rho_2 S/V \quad (3)$$

where T_{2B} is the relaxation time of the bulk fluid, S/V is the surface-area-to-volume ratio of the pore, and ρ_2 is the surface relaxivity, a property describing the capacity of the surface of the pore space to enhance relaxation. The term $\rho_2 S/V$, called the surface relaxation rate, typically dominates the measured T_2 relaxation time. Equation (3) assumes that the use of the CPMG pulse sequence effectively eliminates a third possible form of relaxation, referred to as diffusion relaxation, which occurs when the hydrogen nuclei diffuse in the presence of an inhomogeneous magnetic field. Given the short echo spacings used in the CPMG sequences, the field gradients inherent in the NMR tools did not produce significant relaxation due to diffusion in this study. In the case of the MR Scanner data shown in this paper, a diffusion- T_2 mode was used to measure and remove diffusion effects from the T_2 data [*Freedman and Heaton*, 2004].

[11] In a porous medium such as a groundwater aquifer, water is held in many pores with different pore sizes; thus the decay curve can be multi-exponential in form, resulting in a distribution of relaxation times. This distribution is commonly represented by the mean log T_2 value, T_{2ML}, which is considered representative of the mean pore size [*Kenyon et al.*, 1988]. The link between T_2 and the geometry of the pore space has led to the use of borehole NMR T_2 measurements for estimating the properties of petroleum reservoirs such as pore-size distribution, irreducible saturation, and permeability [*Seevers*, 1966; *Kenyon et al.*, 1988; *Straley et al.*, 1995]. In order to obtain estimates of permeability, measured NMR relaxation times have been used in the Kozeny-Carman expression [*Carman*, 1956] along with empirically determined constants [*Seevers*, 1966; *Kenyon et al.*, 1988]. Of great interest now is using a similar approach with the SNMR measurement to obtain estimates of hydraulic conductivity for groundwater aquifers.

[12] The standard SNMR method does not use a CPMG pulse sequence but instead uses a single pulse to measure a decay-curve. This measured SNMR decay-curve can be strongly influenced by the presence of an inhomogeneous magnetic field. Field inhomogeneity can arise from contrasts in the magnetic susceptibility of the components that make up the porous material, and/or larger (e.g., regional) scale magnetic field gradients. An inhomogeneous field causes nuclear spins at different positions in the pore space to precess at slightly different Larmor frequencies, such that the spins dephase over time and the measured signal undergoes a more rapid decay. For an SNMR measurement of water in a pore, the relaxation time T_2^* characterizes the decay-curve, with the corresponding relaxation rate T_2^{*-1} related to T_2 as follows:

$$T_2^{*-1} = T_2^{-1} + T_{2IH}^{-1} = T_{2B}^{-1} + \rho_2 S/V + T_{2IH}^{-1} \quad (4)$$

where T_{2IH}^{-1} represents the inhomogeneous-field dephasing rate. As with borehole systems, the data are inverted to obtain a distribution of relaxation times and represented by an averaged value, in this case referred to as $T_{2}^{*}{}_{ML}$. The variation in T_2^* with depth is obtained by using the dependence of the measurement sensitivity on the amplitude of the transmitted pulse.

[13] A critical issue in using SNMR data to estimate hydraulic conductivity is the magnitude of T_{2IH}, which if significant relative to $\rho_2 S/V$, would obscure the link to the geometry of the pore space provided by the parameter T_2. The magnitude of T_{2IH} can be approximated as $\gamma \Delta B_0/2$, where ΔB_0 is the variation in the background magnetic field. [*Grunewald and Knight*, 2012]; as the variation in the background magnetic field increases, T_{2IH} decreases. The coupled effect of T_{2IH} and $\rho_2 S/V$ on the relationship between T_2^* and T_2 has been shown in recent numerical experiments [*Grunewald and Knight*, 2012]. Another important consideration in comparing the NMR decay-curves measured with the borehole and surface systems is the time delay between the transmitted pulse and the first recording of the NMR signal. This limits the shortest decay time that can be captured in the T_2 or T_2^* relaxation time distribution, thus impacting the calculated T_{2ML} or $T_{2}^{*}{}_{ML}$ and thus the derived information about aquifer properties. For the processed GMR data, the shortest recorded time was 10 ms. In the case of the borehole measurements the earliest recorded time, also called the "echo-time", was 1.0 ms for the MR Scanner data and 2.5 ms for the Javelin data.

3. Description of Field Experiment

[14] Our field site near Lexington, Nebraska in the central United States, overlies one of the largest and most important aquifers in the world, the High Plains Aquifer. This aquifer stretches through parts of eight states in the central United States over an area of approximately 450,000 square kilometers [*McGuire*, 2009], and provides roughly 30 percent of the nation's groundwater used for irrigation [*Maupin and Barber*, 2005]. Over the past 8 years, there have been ongoing efforts by the Nebraska Cooperative Hydrology Study and Central Platte Natural Resources District to develop an improved groundwater flow model of the High Plains aquifer as it relates to the Platte River system. One component of this work has been an interest, on the part of the United States Geological Survey (USGS), in developing SNMR as a reliable means of determining the hydraulic conductivity of the two principle aquifer units comprising the High Plains Aquifer: the Quaternary Alluvial Aquifer, and the Tertiary Ogallala Aquifer.

[15] In April 2009, SNMR data were acquired with the GMR system using a square loop with sides 91 m in length. In November 2009, a 150 m-deep borehole was drilled inside the area enclosed by the GMR loop using a direct mud rotary drill rig with a mix of bentonite and water used as the drilling fluid. The drilling was paused every 1.5 m to allow the circulation of the drilling fluid to carry to the surface the "drill cuttings", the ground-up samples of the geologic

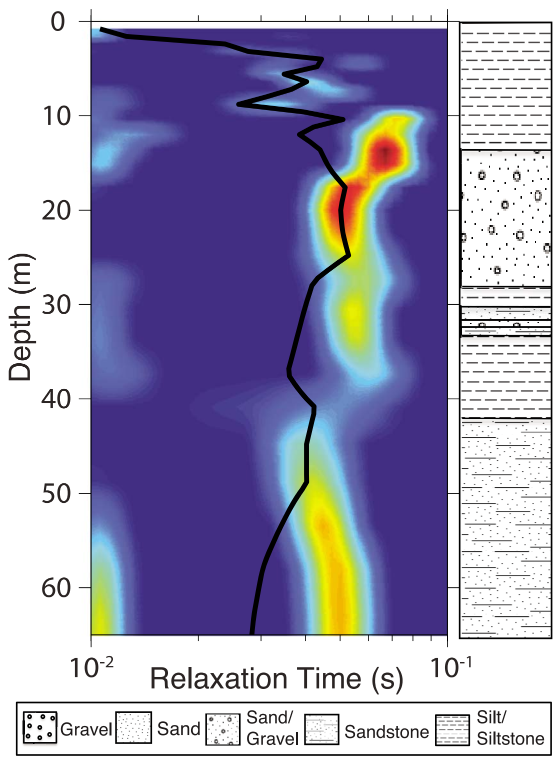

Figure 1. (left) Surface NMR relaxation time measurements. The horizontal distribution of colors at each depth interval represents the distribution of T_2^* values, with warm colors corresponding to high amplitudes. The line represents T_{2ML}^*. (right) The log gives the lithologic units described using the drill cuttings.

materials. Descriptions of the drill cuttings were used to compile a lithologic log, which provides information about the types of material probed by the NMR measurements. The description of the materials included sand, gravel, sandstone, silt, and siltstone. The drilling was completed in ~8 hours. The borehole was kept open for 2 days to acquire borehole geophysical measurements with a suite of well-logging instruments. Of interest here are the borehole NMR T_2 measurements made with the MR Scanner. After the initial logging, the borehole was cased with a PVC pipe. Three months later, borehole NMR T_2 measurements were repeated using the Javelin instrument over the depth range of 0 to 128 m. At the time of these measurements, the water table was at a depth of ~4 m below the ground surface.

4. Results

[16] Figure 1 shows the results of the SNMR measurement, along with the lithologic log. At each depth interval, the distribution of T_2^* values are displayed with warm colors corresponding to high amplitudes. The solid line represents T_{2ML}^*. These results were obtained through the processing and inversion of the acquired SNMR data using the methodology described by *Walsh* [2008]. Given the signal-to-noise ratio, we were able to acquire reliable data to a depth of 65 m. The vertical resolution, which is a function of the loop size and range in amplitude of the transmitted pulses, was on the order of ~1 meter at shallower depths, increasing to ~10 m at the maximum depth. The lateral dimension of the volume contributing to the measurement is approximately the size of the loop. It is important to note that the time of the first measurement with the SNMR system is 10 ms; this places a lower limit on the observed T_2^* distribution. The parameter $T_2^*{}_{ML}$ reaches its maximum values in the sand and gravel unit above 30 m, which corresponds to the Alluvial Aquifer.

[17] In Figure 2 we present the borehole NMR data obtained with the Javelin and MR Scanner, along with the lithologic log. Because of the size of the MR Scanner and geometric restrictions of the specific drilling rig configuration it was not possible to obtain data in the upper 12 m. For each set of borehole data we display the full T_2 distribution using a color bar, with a solid line to show the value of T_{2ML}. Included for comparison on each plot is a second solid line corresponding to $T_2^*{}_{ML}$.

[18] Let us first compare the two NMR data sets obtained with the borehole instruments. The general form of the data from both borehole NMR tools is similar, showing a level of variability in T_2 with depth that would be expected in this type of geologic material. Both data sets show the highest T_2 values in the units described as sands and gravels. As noted above, the MR Scanner collects a first measurement at 1.0 ms so is better able to capture shorter decay times. A clear example of this is seen in the silt unit between approximately 35 m and 40 m. The hatched region in the depth interval from 15 m to 18 m corresponds to a zone of extreme washout in the well. The long T_{2ML} values in the MR Scanner log (approaching 1 second) indicate fresh water, which is confirmed by the caliper logs and a separate shallow-reading MR Scanner log (not shown).

[19] Let us now address the question that motivated this study: What is the relationship between T_2^* measured with SNMR and the desired NMR parameter of interest T_2? Beginning at the top of the section, we see that in the uppermost silt unit $T_2^*{}_{ML} \sim T_{2ML}$. Within this unit, in places where T_{2ML} becomes very short (at a depth close to 8 m), we see more of a difference between $T_2^*{}_{ML}$ and T_{2ML} with $T_2^*{}_{ML} > T_{2ML}$; this can be attributed to the fact that the first SNMR measurement occurs at 10 ms, so the short decay times are not captured. In the underlying sand/gravel section, the difference between $T_2^*{}_{ML}$ and the Javelin T_2 is pronounced, with $T_2^*{}_{ML}$ now less than T_{2ML} throughout the section. The same is true in comparing $T_2^*{}_{ML}$ to the MR Scanner T_{2ML} in most of this sand/gravel section. One exception is for a thin fast-relaxing unit at ~25 m, captured only in the MR Scanner data that causes T_{2ML} to dip below $T_2^*{}_{ML}$. We see the same behavior, $T_2^*{}_{ML} < T_{2ML}$, in both data sets in the thin sand/sandstone/gravel section at ~30 m. In the remainder of the section, in both borehole data sets the relationship between $T_2^*{}_{ML}$ and T_{2ML} varies, presumably influenced by lithologic variation below the scale recorded in the lithologic log. Clearly seen in this comparison are the differences in the vertical resolution of the borehole and SNMR data, with much of the variability seen in the borehole data averaged out in the SNMR measurement.

5. Assessing the Relationship Between T_2^* and T_2

[20] We see in Figures 1 and 2 differences between the SNMR-measured T_2^* and the NMR parameter of interest T_2,

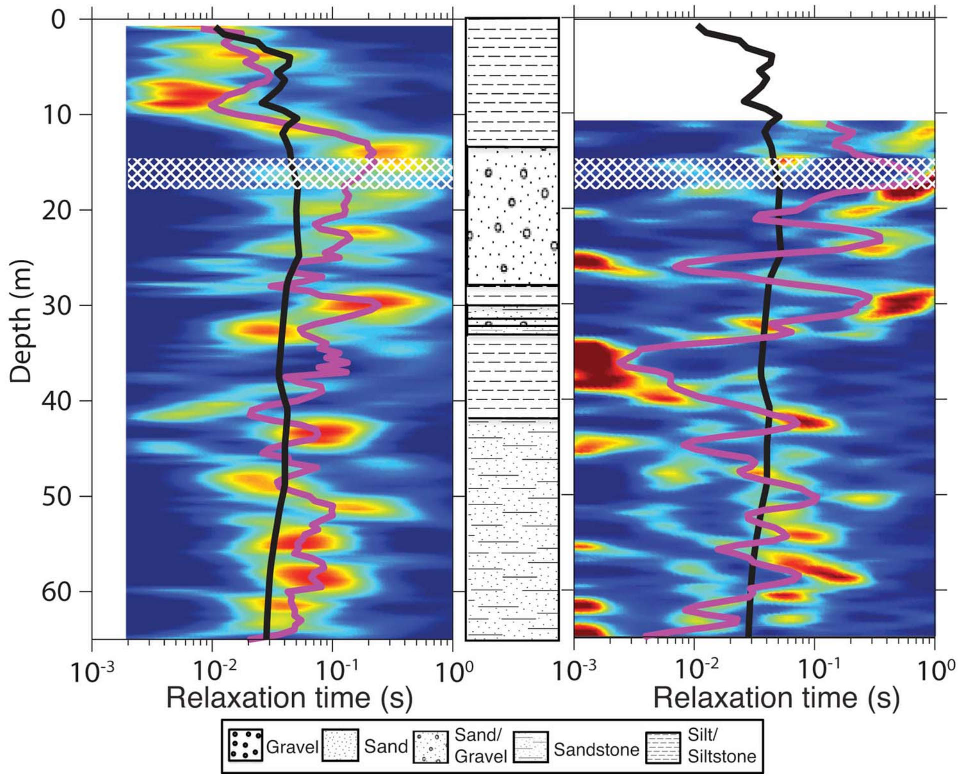

Figure 2. (left) Javelin NMR relaxation time measurements, (middle) the lithologic log, and (right) MR-Scanner relaxation time measurements. In the displays of the NMR data, the horizontal distribution of colors at each depth interval represents the distribution of T_2 values, with warm colors corresponding to high amplitudes; the magenta line represents T_{2ML}; the black line represents T^*_{2ML} from the SNMR data. The white hatched area indicates the presence of a large washout.

which can be used to obtain information about aquifer properties. We hypothesize that there are two factors primarily responsible for the observed differences. One factor is the T_{2IH}^{-1} term, which represents the effect that inhomogeneity in the magnetic field has on the SNMR decay curve. In cases where this term is significant relative to the surface relaxation term (i.e., in lithologic units with relatively high T_2 values), there would be a corresponding decrease in T_2^* relative to T_2. The other factor is the time of the first measurement, which is around 10 ms later for the SNMR measurement. Given that we see many examples in the borehole data of T_2 values less than 10^{-2} s, the absence of the early times (<10 ms) in the SNMR T_2^* measurements would cause T_2^* to be greater than T_2 measured on the same material. We thus hypothesize that we have two factors, one of which works to decrease T_2^* relative to T_2 and one which works to increase T_2^* relative to T_2.

[21] As a means of testing this hypothesis, we transformed the borehole data to account for these factors, and in doing so created "pseudo-T_2^*" data. By comparing our pseudo-T_2^* data to the SNMR-acquired T_2^* data we can assess the extent to which we can explain the relationship between T_2^* and T_2 by accounting for 1) the T_{2IH} term and 2) the time of first measurement. We first accounted for the influence of the T_{2IH} term, which is inversely proportional to the total variation in the background magnetic field. To estimate this term, we measured the magnetic field variation as a function of depth in the borehole using a fluxgate magnetometer. We found that the standard deviation of the magnetic field, when averaged over intervals on the order of meters, was approximately 35 nT corresponding to a 3 Hz spread in the Larmor frequency and a dephasing time of $T_{2IH} \sim 1/3\pi$ Hz = 100 ms. This estimated value of T_{2IH} was used to incorporate the influence of dephasing into the pseudo-T_2^* according to equation (4). Next, to account for the fact that times shorter than 10 ms are not recorded in the SNMR data, we clipped the modified pseudo-T_2^* distributions at early times, removing data for all T_2 values less than 10 ms. Shown in Figure 3 are the resulting pseudo-T_2^* data from the two borehole data sets. We show the pseudo-T_2^* distribution in color, with pseudo-T^*_{2ML} presented as the solid red line. The SNMR T^*_{2ML} is shown as the solid black line. Note, in comparing Figures 2 and 3, that the time axis in Figure 3 starts at 10 ms, the time of first measurement in the SNMR data.

[22] The comparison of the pseudo- and "true" T_2^* data lead us to conclude that the two identified factors – the time of the first measurement and the T_{2IH} term - are primarily responsible for determining the relationship between T_2^* and T_2. When we account for these factors, we significantly reduce the difference between these two NMR relaxation time constants. In the upper 30 m, we see close agreement in Figure 3 between the SNMR T^*_{2ML} and the Javelin pseudo-T^*_{2ML} leading us to conclude that the T_{2IH} term was responsible for the large observed differences between T_2^* and T_2. This is most evident in the sand and gravel unit where, as seen in Figure 2, T^*_{2ML} is significantly less than T_{2ML}; incorporating T_{2IH} had the effect of decreasing T_2 to become the pseudo T_2^*. We note that the agreement between

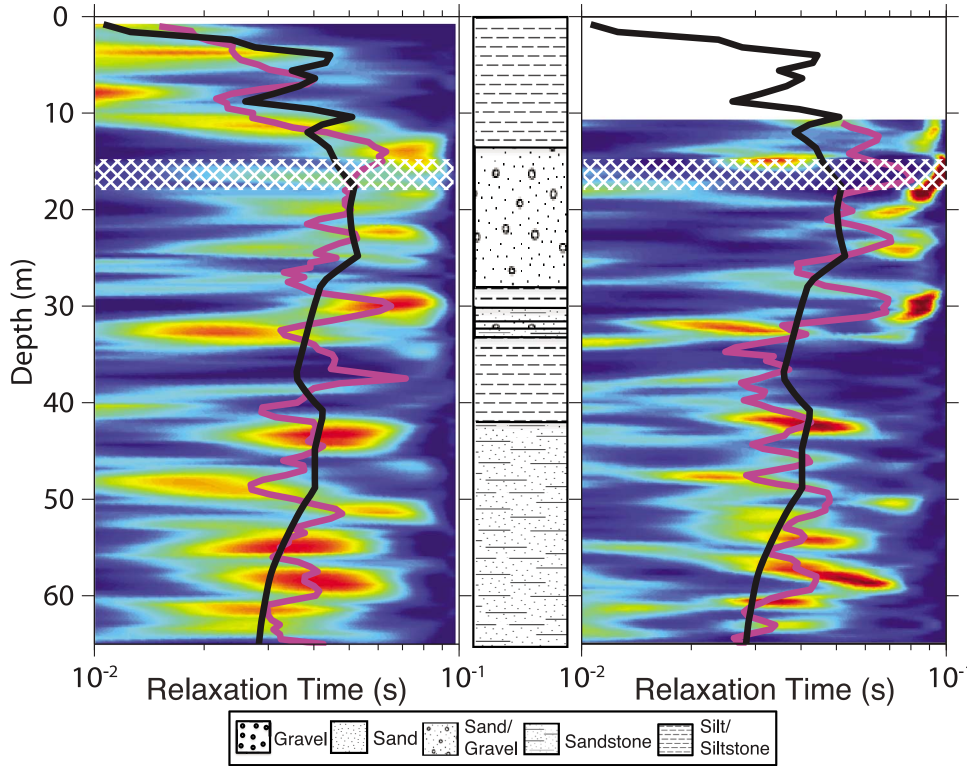

Figure 3. (left) Javelin pseudo-T_2^* values are shown, (middle) the lithologic log, and (right) MR-Scanner pseudo-T_2^* values. In the displays of the NMR data, the horizontal distribution of colors at each depth interval represents the distribution of pseudo-T_2^* values, with warm colors corresponding to high amplitudes; the magenta line represents pseudo-T_{2ML}^*; the black line represents T_{2ML}^* from the SNMR data. The white hatched area indicates the presence of a large washout.

the pseudo- and "true" T_2^* data is not as good in the sand/sandstone/gravel unit at ~30 m; it is possible that the SNMR measurement cannot resolve the response of this relatively thin unit. A comparison of Figure 3 to Figure 2 highlights the impact of the differences in the time of the first measurement in the borehole and surface NMR measurements. When the data are clipped at 10 ms, we no longer see the fast-relaxing unit at ~40 m.

6. Conclusions

[23] There is considerable interest in the use of SNMR as a means of obtaining information about the properties of groundwater aquifers; with specific interest in obtaining estimate of hydraulic conductivity by utilizing the link between NMR relaxation data and the geometry of the pore space. The challenge we face in advancing the broad application of the SNMR technique for aquifer characterization is the need to develop a full understanding of the physics underlying the relaxation mechanism specific to this technique. This field experiment provides ground truth for the SNMR relaxation time measurement by uniquely combining surface NMR and borehole NMR measurements so as to directly and quantitatively compare T_2^* and T_2.

[24] Our analysis of the data reveals factors directly affecting the relationship between T_2^* and T_2, along with the role of lithology and the specific characteristics of the measurement technology. After correcting for the time of first measurement of the borehole and surface NMR methods, we find that the difference between T_2^* and T_2 is greater in coarser-grained materials than in finer-grained materials and attribute this to the magnitude of T_{2IH}; in agreement with the numerical modeling results shown by *Grunewald and Knight* [2012]. This suggests that in finer-grained materials, where T_2^* can be approximately equal to T_2, reliable relationships could be found between T_2^* and hydraulic conductivity. For coarser-grained materials however, there is no theoretical basis to justify predicting hydraulic conductivity from measurements of T_2^* without first correcting for T_{2IH}. One approach to using SNMR T_2^* measurements for aquifer characterization might be to use hydrologic data, acquired in a borehole, to establish an empirical relationship between T_2^* and hydraulic conductivity that could then be applied throughout an area of interest. But this would require the assumption that any variation in the magnetic field be statistically similar over the region of interest; an assumption that is not easy to validate. An alternate and favored approach is to continue to explore the fundamental controls on the SNMR measurement, with the goal of devising new ways to directly measure the magnitude of the T_{2IH} term *in-situ*.

[25] The identified limitations of the SNMR measurement technique, such as the sensitivity to magnetic field heterogeneity and inability to record the fastest decay signals, suggest directions for future technical development. For example, multiple pulse techniques (such as spin echoes [*Hahn*, 1950]) commonly used in laboratory NMR/MRI could be applied to SNMR to reduce the sensitivity to field inhomogeneity. Given the current interest in this geophysical method, and the associated high level of research activity

in government, academic, and private sectors, the SNMR method has tremendous potential to significantly advance the way we evaluate and manage groundwater aquifers.

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