Groundwater

A Small–Diameter NMR Logging Tool for Groundwater Investigations

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Abstract

A small-diameter nuclear magnetic resonance (NMR) logging tool has been developed and field tested at various sites in the United States and Australia. A novel design approach has produced relatively inexpensive, small-diameter probes that can be run in open or PVC-cased boreholes as small as 2 inches in diameter. The complete system, including surface electronics and various downhole probes, has been successfully tested in small-diameter monitoring wells in a range of hydrogeological settings. A variant of the probe that can be deployed by a direct-push machine has also been developed and tested in the field. The new NMR logging tool provides reliable, direct, and high-resolution information that is of importance for groundwater studies. Specifically, the technology provides direct measurement of total water content (total porosity in the saturated zone or moisture content in the unsaturated zone), and estimates of relative pore-size distribution (bound vs. mobile water content) and hydraulic conductivity. The NMR measurements show good agreement with ancillary data from lithologic logs, geophysical logs, and hydrogeologic measurements, and provide valuable information for groundwater investigations.

Introduction

This work addresses the development and demonstration of nuclear magnetic resonance (NMR) logging technology for groundwater investigations. NMR provides direct measurement of hydrogen nuclei. NMR is exploited in medical MRI to image biological tissue containing hydrogen (Lauterbur 1973) and, in geophysics, can be used to characterize hydrogen-bearing fluids and their pore-scale environment. The unique sensitivity of NMR to the fluid-filled pore space has motivated extensive research into the NMR response of geologic materials, and has driven the development of specialized geophysical NMR instrumentation.

As a downhole logging technology, NMR has been widely used in the oil and gas industry. The first NMR logging tools were designed for petroleum exploration in the 1960s (Brown and Gamson 1960) and have been improved in the last two decades with modern pulsed NMR tools (Coates et al. 1991; Kleinberg 2001). Concurrent with instrument development, numerous theoretical, empirical, and field studies have demonstrated robust transforms between the measured NMR response and key hydraulic parameters including fluid-filled porosity (Timur 1969), pore-size distribution (Gallegos and Smith 1987), and permeability (Seevers 1966; Kenyon et al. 1988). In the oilfield, NMR is now widely regarded as a mature and indispensable technology, supporting improved resource identification, characterization, and production.

The capabilities of NMR already demonstrated in the oil industry are also of great value for hydrogeological and environmental investigations, where NMR-estimated hydraulic parameters govern groundwater availability, contaminant migration, and the response of hydrologic systems to changing climate. Despite the clear potential

for such applications, however, there have been few examples of NMR logging in groundwater studies (Knight et al. 2012; Maliva et al. 2009). Instead, environmental applications of NMR in groundwater have generally been constrained to surface-based measurements (Legchenko and Valla 2002; Walsh 2008; Walsh et al. 2011). While surface NMR measurements have the advantage of being noninvasive and economical, they provide a limited depth of investigation (Hertrich 2008) and less precise sensitivity to pore geometry (Grunewald and Knight 2011) as compared to NMR logging.

To date, the use of NMR logging for groundwater investigations has been hindered by two key barriers: the large size of existing oilfield instruments and the high cost of these tools and associated services. Oilfield instruments are engineered to operate under extreme conditions in deep boreholes, tolerating temperatures up to 150 °C and pressures up to 20,000 psi (138MPa). An example of one such instrument is the Schlumberger MRX Scanner ("MR Scanner," Schlumberger Marketing Communications, PDF brochure, December 12, 2012. http://www.slb.com/~/media/Files/evaluation/brochures/wireline_open_hole/petrophysics/nmr/mrscanner_br.ashx), which is 10 m long, weighs more than 540 kg, and operates in boreholes with a minimum diameter of 5.875 in (150 mm) (Freedman 2006). Given their size, these tools cannot be used in many groundwater applications where boreholes are commonly constructed with casing less than 12 cm (5 inches) in diameter, and where a large number of monitoring wells are use 50-mm (2-inch) casing. Although oilfield services companies offer state-of-the-art NMR measurements and interpretation, the cost of these services is prohibitively expensive for the majority of near-surface groundwater applications.

Groundwater and environmental research programs (e.g., Guillen and Hertzog 2004) have clearly expressed a need to develop NMR logging tools appropriate for groundwater studies. Recognizing the limitations of existing NMR logging tools and the outstanding potential of NMR logging for groundwater investigations, we have developed a novel NMR logging tool ideally suited to address near-surface characterization objectives. Our work has led to the successful deployment of a robust and economical NMR logging system with miniaturized downhole probes that can operate in open or PVC-cased boreholes as small as 50 mm (2 inches) in diameter. One version of the tool can be deployed using a direct-push machine.

In this paper, we describe the physics underlying the NMR measurement and the unique design considerations required for downhole probes that can operate in typical near-surface conditions. We then present selected case studies that demonstrate the functionality and capabilities of the downhole tools in environments previously inaccessible to NMR logging. The results illustrate the unique value and detail of information that can be obtained using NMR logging in near-surface studies and highlight the potential for new applications of the technology, made possible with these small-diameter tools.

Background and Motivation

NMR Physics

The physical principle of nuclear magnetic resonance underlying geophysical logging measurements is the same principle underlying MRI imaging in medicine and NMR spectroscopy in chemistry. NMR methods utilize a quantum physical property associated with hydrogen nuclei known as nuclear spin angular momentum. An NMR measurement investigates the response of these hydrogen spins to a magnetic field perturbation (Dunn et al. 2002).

When a fluid containing hydrogen is subjected to a static magnetic field $\mathbf{B}_0$, the spins associated with the hydrogen become polarized in an equilibrium state that produces a small net nuclear magnetization aligned parallel to $\mathbf{B}_0$ (defined as the "longitudinal" direction). In this equilibrium state, the nuclear magnetization is too small to be easily observed. The NMR measurement involves perturbing the spins from equilibrium to produce an observable signal.

In the background static $\mathbf{B}_0$ field, the spins are able to absorb and emit energy at a specific frequency known as the Larmor frequency ω_0, which is linearly related to the background magnetic field

$$\omega_0 = -\gamma |B_0| \qquad (1)$$

Here γ is the gyromagnetic ratio of the hydrogen nuclei (267.513×10^6 rad·s^{-1} T^{-1}). The application of a pulsed oscillating magnetic field $\mathbf{B}_1$ tuned to this Larmor frequency and applied in the plane perpendicular (or "transverse") to $\mathbf{B}_0$ acts as an effective torque that rotates the nuclear magnetization away from the longitudinal axis into a higher energy state in the transverse plane. Immediately after the $\mathbf{B}_1$ pulse is extinguished, the component of the nuclear magnetization left in the transverse plane will precess about the axis of the static field $\mathbf{B}_0$. The coherent precession of magnetization generates a detectable magnetic field that oscillates at the Larmor frequency, and has an initial amplitude directly proportional to the volume of excited hydrogen. Over a short period of time, the system returns (or "relaxes") back to its equilibrium state, leading to a decay of the observed NMR signal as the spins lose coherence in the transverse plane and reestablish longitudinal magnetization. The decay of magnetization in the transverse plane is described by the transverse relaxation time T_2.

A sequence of multiple $\mathbf{B}_1$ pulses is typically applied to provide improved sensitivity to the NMR relaxation dynamics. In the commonly used Carr-Purcell-Meiboom-Gill (CPMG) pulse sequence, shown in Figure 1, an initial excitation pulse provides a 90° rotation of the longitudinal magnetization into the transverse plane. The excitation pulse is followed by a sequence of 180° refocusing pulses repeated with a specified period denoted as the echo-time, t_E. Between each pair of refocusing pulses, a so-called "spin echo" NMR signal is observed; successive echoes in the CPMG train exhibit diminishing amplitude reflecting
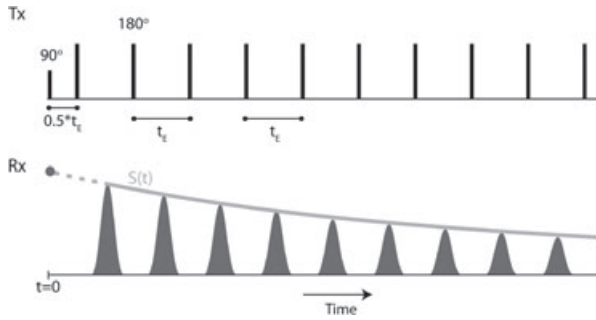
Figure 1. Schematic illustration of the CPMG pulse sequence showing timing of transmitted B_1 pulses in the top panel, and received NMR echo signals (dark gray) in the bottom panel. The lighter gray line represents the spin echo decay curve $S(t)$ with an initial amplitude proportional to water content and an exponential decay time T_2.

the transverse T_2 relaxation time. The resulting curve describing this the spin echo train decay $S(t)$ provides can be linked to key parameters of the physiochemical pore environment.

NMR Response of Geologic Materials

In a fluid-bearing geologic material, the initial $S(t)$ signal amplitude is directly proportional to the water content in the excited volume, while the T_2 decay time conveys information about the pore environment. The net observed T_2 relaxation time represents the contribution of three different relaxation mechanisms acting in parallel, each with a characteristic time (Kleinberg and Horsfield 1990):

$$\frac{1}{T_2} = \frac{1}{T_{2B}} + \frac{1}{T_{2S}} + \frac{1}{T_{2D}} \tag{2}$$

Here T_{2B} is the bulk-fluid relaxation time, T_{2S} is the surface relaxation time, and T_{2D} is the diffusion-gradient relaxation time. Bulk-fluid relaxation processes occur due to interactions between spins in the fluid and are independent of the pore space. For water, T_{2B} is typically $1-3$ s and is shorter in fluids with increased viscosity, with decreased temperature, or with an increased concentration of paramagnetic ions. Diffusion-gradient relaxation occurs because refocusing pulses in the CPMG sequence have a reduced efficiency when spins rapidly diffuse in the presence of a spatially variable background field. The magnitude of T_{2D} is proportional to the squared product of the magnetic gradient and the echo-time. In practice, the influence of diffusion relaxation can be mitigated by using a sufficiently short echo-time; however, if the magnetic gradient is very strong (i.e., very close to a strong magnet or in highly magnetic soils), diffusion relaxation may still shorten the observed decay time.

The second term, the surface relaxation time, typically dominates the relaxation response in geologic materials and provides critical information about the pore environment. Surface relaxation occurs as spins in the pore fluids diffuse to and interact with the grain surface; this relaxation proceeds more quickly in small pores

and more slowly in large pores. Considering a single fluid-filled pore in the condition of "fast-diffusion," which assumes diffusion to the grain surface is not the rate limiting process, $S(t)$ exhibits an exponential decay where the magnitude of T_{2S} is given by (Brownstein and Tarr 1979)

$$\frac{1}{T_{2S}} = \rho S/V \tag{3}$$

where ρ is the surface relaxivity and S/V is the surface area to volume ratio. The surface relaxivity describes the capacity of the surface to induce relaxation in the fluid and generally increases with the abundance of paramagnetic sites on the grain surface (Foley et al. 1996). In simple pore geometries, S/V is inversely proportional to the pore size (e.g., for a spherical pore of radius r, $S/V = 3/r$) and is strongly correlated with permeability.

In the simplest case of a single pore exhibiting a decay time of T_2, the spin echo decay curve can be described as a single exponential decay

$$S(t) = A_0 e^{-t/T_2} \tag{4}$$

where the initial amplitude A_0 is normalized by the initial amplitude for a sample of 100% water, and so reflects the fluid-filled volume. In geologic materials, which may contain a distribution of pores with different T_2, the signal is described more generally as a multiexponential decay

$$S(t) = \sum_i A_{0i} e^{-t/T_{2i}} \tag{5}$$

Here the A_{0i} reflects the volume of fluid associated with each decay time of T_{2i}. Conventionally, the measured $S(t)$ signal is processed using a Laplace inversion to obtain a fluid-volume weighted relaxation time distribution.

This multiexponential decay model is illustrated in Figure 2. In the left panel, a short decaying signal (magenta, corresponding to water bound in small pores) and a long decaying signal (blue, corresponding to mobile water in large pores) sum to produce the net observed multiexponential decay (black). The decay-time distribution following Laplace inversion exhibits a peak at short times and another peak at long times showing the volume fraction of water associated with each decay time; smoothing of the distribution may be associated with pore size gradation or regularization of the Laplace inversion. This distribution represents the water volume associated with each decay time and thus may be interpreted as a scaled pore-size distribution, assuming surface relaxation is the dominant decay mechanism (i.e., T_{2B} and T_{2D} are negligible), ρ is approximately constant, and pores are not strongly coupled by diffusion (Grunewald and Knight 2009). The total integrated amplitude of the T_2 distribution reflects the volume fraction of fluid (or porosity ϕ if the sample is saturated).

Permeability Estimation

One of the most valuable products available from an NMR measurement is an estimate of permeability k
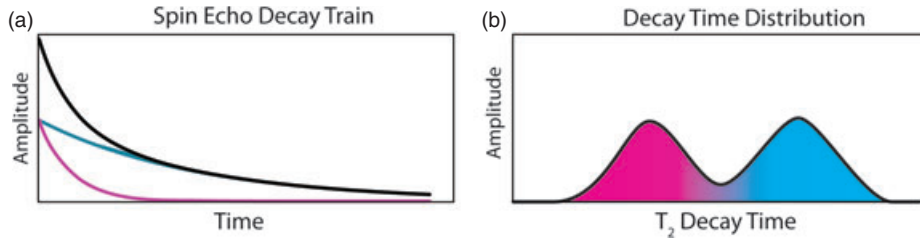
Figure 2. The multiexponential decay model. In (a) the net spin echo decay is the sum of a short decaying signal (magenta) and a long decaying signal (blue). In (b) the multiexponential decay time distribution shows the decay time and relative amplitudes of each component in the multiexponential decay.

or hydraulic conductivity K. The well-known Kozeny-Carman model of permeability can be written as

$$k = \frac{\phi}{\tau \left(\frac{S}{V}\right)^2} \tag{6}$$

where τ is tortuosity (Seevers 1966). This form of the equation highlights that the parameters derived from NMR are also the most critical variables controlling a material's permeability. Recognizing this correlation, NMR has been widely utilized in petrophysical models, such as the Schlumberger-Doll Research (SDR) equation (Kenyon et al. 1988) and the Timur-Coates equation (Timur 1969), to estimate permeability.

The generalized SDR equation can be derived by substituting variables from Equation 3 into the Kozeny-Carman model to yield:

$$k = C_{SDR}\phi_{NMR}^a T_{2ml}^b \tag{7}$$

Here ϕ_{NMR} is the NMR-derived porosity, T_{2ml} is the logarithmic mean of the T_2 distribution, and C_{SDR}, a, and b are empirically determined variables. For k in mD and T_{2ml} in ms, typical values of these variables for estimating permeability in oil-bearing formations are $a = 4$ and $b = 2$, and $C = 4$ or 0.1 for sandstones and carbonates, respectively (e.g., Chang et al. 1994; Kenyon 1997). A similar model, the "sum of squared echoes" (SOE) estimates permeability as a linear function of the squared echo decay curve

$$k = C_{SOE} \int S(t)^2 \, dt \tag{8}$$

The SOE model is approximately equivalent to Equation 6 (using a = 2 and b = 2), but is less susceptible to noise in the data (Walsh 2008). To improve the accuracy of permeability estimates, the value of a, b, and C are commonly refined on a site- or lithology-specific basis by calibration with direct flow measurements.

An empirical cut-off time $T_{2,cut}$ (typically 33 ms) is commonly used as the basis for distinguishing the bound fluid volume from mobile fluid volume (Timur 1969). The bound fluid volume (BFV) is defined as the integrated amplitude of the T_2 distribution for $T_2 < T_{2,cut}$; conversely, the amplitude of T_2 distribution integrated

for $T_2 > T_{2,cut}$ is associated with the mobile or free fluid volume (FFV).

Decades of application in oilfield logging and reservoir characterization have shown these NMR-based estimates to be robust for many applications. While it is likely necessary that these rock physics relationships require revision and calibration for new applications in near-surface lithologies, a more critical element in translating previous success of NMR logging to the near surface is the development of appropriate instrumentation to enable economical NMR measurements in small-diameter wells.

Design and Operation of Modern NMR Logging Tools

All modern pulsed NMR logging instruments share certain fundamental design aspects. In general, a down-hole NMR probe contains an array of permanent magnets, and one or more radio-frequency (RF) induction coils or antennae. The purpose of the permanent magnets is to project a strong static magnetic field $\mathbf{B_0}$ into the surrounding formation. Because the strength of the $\mathbf{B_0}$ field varies as a function of distance from the magnets, the Larmor frequency at which hydrogen nuclei will respond also varies as a function of distance from the tool.

The purpose of the RF coil is two-fold, serving to both excite and measure the NMR response. First, the RF coil provides the source of the $\mathbf{B_1}$ field. Transmitted RF pulses are tuned to a selected Larmor frequency corresponding to a specific distance from the probe; thus the pulses excite an NMR response from fluids only within a selective volume in the formation. The same coil (or another coil) is then used to detect the resulting CPMG NMR spin echo signals from fluids within this sensitive volume.

The geometry of the sensitive volume depends primarily on the magnet geometry and coil array. In some single-sided tools, such as the Schlumberger MRX (Kleinberg 2001), the sensitive zone forms a discrete saddle point on one side of the tool. In other tools, including the first pulsed logging tool designed by NUMAR (and subsequently adopted by Halliburton), the sensitive zone is a thin cylindrical shell with a discrete radial offset from the tool center (Coates et al. 1991). In this respect, NMR logging measurements are distinct from many other logging measurements, such as electrical induction, which provide diffuse sensitivity over an averaged volume surrounding the probe.

By varying the frequency and bandwidth of the B_1 pulse, the location of the sensitive zone can be adjusted to provide detection within different neighboring volume elements or "shells." Generally, higher frequencies provide sensitivity closer to the tool where the B_0 field is stronger and lower frequencies provide sensitivity deeper into the formation where the B_0 field is weaker. While higher frequency shells generally provide higher signal-to-noise ratios, lower frequency shells have the advantage of penetrating further into the formation, in a zone less likely to be perturbed by drilling; oilfield tools typically operate at 500 kHz to 2 MHz.

NMR logging tools designed for deep oil and gas exploration must meet a number of stringent technical requirements, including a high logging speed to minimize rig costs, and the ability to log in extreme environments up to 150 °C, 20,000 PSI and depths of up to 6 miles (10 km). Oilfield NMR logging tools are typically used in 6 inch (150 mm) diameter or larger boreholes. These requirements for oilfield logging have driven the designs of previous NMR logging tools, and these NMR logging tools excel in their intended applications. However, these same design constraints result in tools that are large, expensive, and generally not well suited for groundwater investigations in the top few hundred meters of the subsurface.

Some efforts have been made previously to develop smaller NMR tools for groundwater measurements. A prototype tool was developed under U.S. government funding (SERDP 1996) to be deployed in cased wells for detecting groundwater contamination, but was later cancelled. Sucre et al. (2011) presented a probe with a 48-mm outer diameter that was shown to provide reliable quantification of moisture content in model constructed soils. This tool, however, has a shallow depth of investigation (8 mm radial), limiting the practical ability to see beyond the zone of drilling disturbance; the tool also uses a high operating frequency of (9–12 MHz) resulting in strong magnetic gradients that dominate the measured decay times, due to diffusion relaxation, and thus limit sensitivity to permeability.

Methods

Design Requirements for a Small–Diameter NMR Logging Tool

The objective of this work was to develop small-diameter NMR logging tools with size, performance, and cost factors appropriate for groundwater investigations. A primary requirement was that a tool should be small enough to log 2-inch (50-mm) diameter PVC wells, which are common in the United States and many other countries. Another requirement was that the tool must be capable of accurately measuring the full spectrum of water content present in the saturated and unsaturated zones, including clay-bound, capillary, mobile pore water, and bulk water in fractures and voids, with reliable sensitivity to surface relaxation dynamics. Another requirement was that the sensitive region of each tool should be located

outside the drilling-disturbed zone, while simultaneously providing a high signal to noise ratio in a practically viable measurement time (i.e., logging speed).

It is normal practice to construct 2-inch diameter monitoring wells by using a 6- to 7-inch (150 to 180 mm) diameter auger or bit to drill a borehole, to position the PVC casing near the center of the borehole, and to complete the well by backfilling the annular space with filter pack and/or grout, or allow the formation to collapse against the casing. In such cases, the native formation is disturbed by the drilling and construction process, often a significant distance beyond the drilled diameter. For NMR logging measurements, it is thus desirable that the sensitive region lies outside the drilling-disturbed zone. For ideal logging of a 2-inch PVC well drilled with a 7-inch diameter auger, the tool itself must have a diameter less than 2 inches and its sensitive zone should be outside a 7-inch (180-mm) diameter region surrounding the center of the tool.

Design Approach and Initial Tool Development

The design philosophy for the tool was straightforward: locate the more expensive, complicated and bulky components, including the RF power amplifier, controller and various power supplies, at the surface. This approach reduced the downhole probe components to the essential elements required for effective NMR detection, principally the magnet array, RF coils and supporting electronics. This simple but significant departure from previous NMR logging tools enhanced the feasibility of producing small-diameter, relatively inexpensive downhole probes.

Evaluation and computer simulation of various existing tool designs led to selection of a magnet and coil design similar to the original "NUMAR" design (Strikman and Taicher 1987). This detection approach uses a centralized permanent magnet, with its dipole polarization oriented perpendicular to the tool axis; strong rare earth magnets are used to minimize the required magnet volume. The RF coil is wound around the outside of the magnet, longitudinally, such that the RF coil field is approximately perpendicular to the static magnetic field at most locations outside the probe. The NMR sensitive region is a very thin cylindrical shell of only a few millimeter thickness, centered about the tool as shown in Figure 3a. The length of the sensitive cylinder is approximately equivalent to the length of the RF coil (0.5 to 1 m) and defines the nominal vertical resolution of the probe.

Further studies of common well construction methods led us to tune and operate the tools in a lower frequency range (245 to 295 kHz) than is typically used for oil exploration. Operating at a lower frequency provides a critical measurement advantage: it increases the radius of the NMR sensitive region, selectively detecting fluids at a greater distance from the probe and thus further into the formation. A low operating frequency also limits the influence of diffusion-gradient relaxation on the measurement, particularly in moderately magnetic geologic settings. The choice of lower operating frequency and greater depth of investigation does however entail
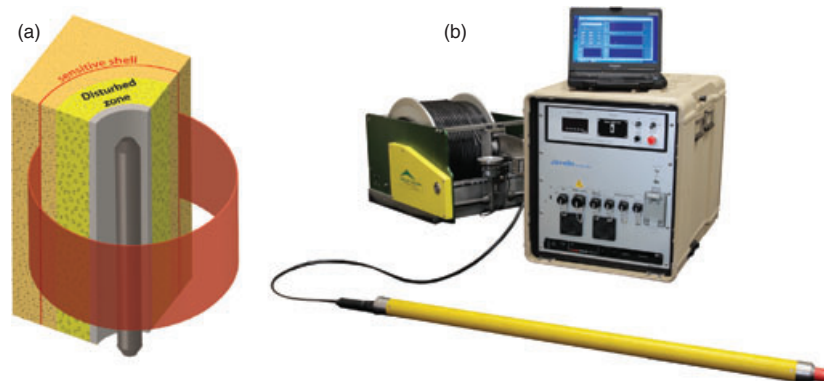
Figure 3. (a) Schematic illustration of the NMR logging probe. Ideally, the sensitive shell (red) is located beyond the zone disturbed by drilling (yellow). (b) Basic components of the NMR logging instrument, including notebook computer, surface electronics station, winch with downhole cable, and JP238 direct-push-compatible downhole probe shown here.

a significant reduction in NMR signal strength, because the source of the signal is farther from the detection coil and also because the NMR signal amplitude roughly scales as the square of the operating frequency. Hence, the selection of operating frequency involves a tradeoff between radial depth of investigation and logging speed. We have prioritized greater depth of investigation over logging speed, as reliability and usefulness of the acquired data are deemed of paramount importance.

To improve signal-to-noise ratio, the tool is operated in a stepped logging mode with stacking. The tool is held stationary at a single depth level, and repeated measurement stacks are acquired and averaged before the tool is raised or lowered to the next interval. Typically, the depth interval step is selected to be the same as the vertical resolution of the probe to perform non-overlapping measurements. Adaptive RF interference cancellation is applied using a reference coil to mitigate the influence of environmental noise, which can be significant at shallow depths.

Several interchangeable probes with different sizes and specifications (listed in Table 1) have been developed. First, a 3.5-inch (89 mm) diameter probe, named "JP350", was developed to operate at a single frequency, 250 kHz providing a radial depth of investigation of 7.5 inches (190 mm) from the tool center (i.e., the cylindrical sensitive region had a diameter of 15 inch) and with a vertical

resolution of 0.5 m. This 3.5-inch tool had a minimum echo spacing of 2.0 ms (a short echo spacing is required to detect short NMR signals, i.e., millisecond signals from water in clays and silts).

The 3.5-inch tool was extensively tested, in cooperation with researchers from the U.S. Geological Survey, the U.S. Department of Energy, the Kansas Geological Survey, Boise State University, and the Central Platte Natural Resources District. The tool was used to log PVC wells with inside diameters ranging from 4 to 8 inches (~100 to 200 mm), and was also used to log one uncased 6-inch well in a consolidated formation. The well depths ranged up to 460 feet (140 m).

Following successful testing of the 3.5-inch tool, a 1.67-inch diameter tool ("JP167") was designed, assembled and successfully tested in several 2-inch diameter PVC wells. This tool had a radial depth of investigation of approximately 3.5 inches, a minimum echo-spacing of 1.5 ms and was configured to operate at two frequencies, 250 and 295 kHz. In general, the signal-to-noise ratio scales approximately linearly with the diameter of the magnet and coil assembly. Hence, the JP167 probe has an inherently lower signal to noise ratio, and logging speed, than the larger JP350 probe.

Concurrently, we developed a version of the NMR logging tool to operate with a direct-push (DP) machine.

Table 1
Specifications of Interchangeable Downhole Probes

	Probe Name	Vertical Resolution	Diameter of Sensitive Shell	Probe Outer Diameter	Probe Length
Commercialized	JP350	0.5 m	7.5 inch/19 cm	3.5 inch/8.9 cm	4.5 feet/1.4 m
	JP238*	0.5 m	6 inch/15 cm	2.38 inch/6.1 cm	5 feet/1.5 m
	JP175B	1.0 m	4.0 inch/10 cm	1.75 inch/4.5 cm	7 feet/2.1 m
	JP175C	1.0 m	5.0 inch/12 cm	1.75 inch/4.5 cm	7 feet/2.1 m
Prototype only	JP167	1.0 m	4.0 inch/10 cm	1.67 inch/4.3 cm	7 feet/2.1 m
	JP255*	0.5 m	6 inch/15 cm	2.5 inch/6.4 cm	5 feet/1.5 m

*Can be deployed with a Geoprobe System (R)

A design and deployment scheme was conceived to avoid the feasibility challenges of embedding the NMR sensor in a load-bearing and conductive drill section. The DP machine is first used to drive hollow rods with a cone tip to the maximum depth. The NMR sensor is then pushed down the center of the rods to the bottom of the hole. The rods are filled with water to create a positive head. Then, while holding the probe in place, the rods are retratcted to eject the expendable point and expose the probe to the formation. The probe is held in place by a collar and NMR logging is performed from the bottom level upwards as the DP machine is used to raise both the drill rods and the probe. In 2010, the first DP-compatible version of the probe was developed and assembled. This probe (JP255), designed for use with 3.25-inch drill rods, had a diameter of 2.55 inches, a radial depth of investigation of 5.75 inches, a vertical resolution of 0.5 meter, and a minimum echo spacing of 1.75 ms, The probe was tested in cooperation with the Kansas Geological Survey and Geoprobe Systems.

Additional probes have since been added to the tool line (Table 1). The prototype NMR logging instrument described here was refined and commercialized in late 2010 under the tradename "Javelin." A photo of the commercial system is shown in Figure 3b. The system is operated from a laptop computer and can be powered by a portable 3kW generator or line power.

Results

Massachusetts Military Reservation, USA

Field tests of the NMR logging instrument were conducted in cooperation with the U.S. Geological Survey in May 2010 on the Massachusetts Military Reservation, near a site of known subsurface contamination from fuel spills and other activities. The Massachusetts Military Reservation is underlain by a glacial-drift aquifer that consists mainly of sand, with thin laterally discontinuous layers of silt that may be important in controlling the migration and fate of contaminants at the site (LeBlanc et al. 1991).

The NMR instrument with 3.5-inch diameter probe was used to log a 4-inch diameter, 99-m deep PVC-cased well (03GB1060) at a logging speed of 7 meters per hour and with a vertical resolution of 0.5 m. The resulting NMR log is shown in Figure 4a. The left panel shows the complete T_2 decay-time distributions with amplitude shown in warming colors; mean log value T_{2ml} is shown in black. The middle panel shows the total water content as well as estimates of bound water volume versus mobile water volume based on a standard cut-off time of 33 ms. The right plot shows estimated values of hydraulic conductivity based on a SDR model (black) and a more simple computation of the squared sum of spin echo amplitudes (red). For this example, site-specific calibrations were not developed for the SDR or SOE equations, so the values should be interpreted as "relative" hydraulic conductivity. The NMR log accurately indicates the water table located at 20 m, and shows a predominance of large pore, mobile water in the saturated aquifer below 20 m, with porosities primarily ranging from 20 to 35%, consistent with neutron log data from nearby well data. The T_2 distribution, estimates of bound and mobile water, and the estimated hydraulic conductivity all indicate low permeability silt at depths of 70 to 73 m, and 83 m. These NMR-identified silt zones, marked by an increase in short bound-water signals and a decrease
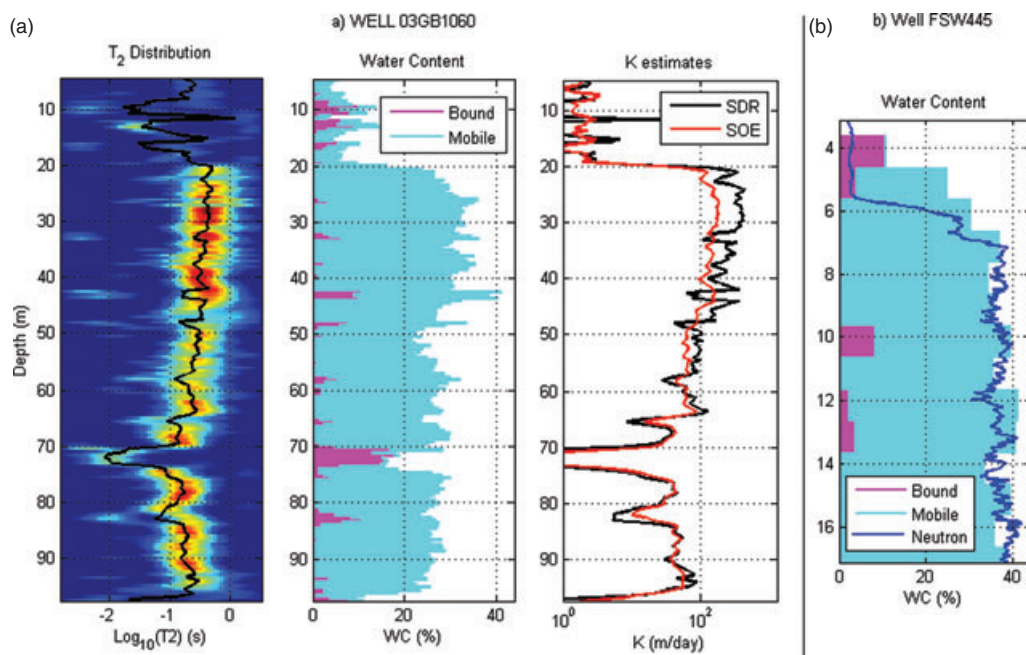

Figure 4. Logs from Massachussetts Military Reservation obtained May 2010 (a) NMR logs acquired in 4-inch well 03GB1060; (b) comparison of NMR log and neutron porosity log acquired in nearby 2-inch well FSW445.

in long mobile-water signals, are consistent with other logging measurements in this well. The NMR logging result also indicates a general reduction in pore size and hydraulic conductivity in the lower portion of the aquifer.

We note also the detection of water in the unsaturated zone includes both long and short signals. The elevated short T_2 water content at a depth of 13 m in the NMR log suggests a zone of increased silt, which may be responsible for retarding groundwater flow from overlying coarser materials, which exhibit longer decay times.

No neutron data was acquired in this well, however, a neutron log was acquired in nearby well (FSW445) with collocated NMR data, shown in Figure 4b. The elevation for this well is approximately 20 m lower than well 03GB1060, so the water table is encountered at a shallower depth of 5 m. The logged interval of FSW445 is dominated by sand and gravel with only small amounts of bond and mobile water detected. The NMR-derived water content estimates are in excellent agreement with the neutron logs, differing only in the top of the hole where the water table level had changed between the timing of the two measurements.

Geohydrologic Experimental and Monitoring Site, Lawrence, Kansas, USA

In 2010, extensive tests of the logging tools were conducted at the Geohydrologic Experimental and Monitoring Site (GEMS) of the Kansas Geological Survey (KGS). GEMS has been the site of extensive research on flow and transport in heterogeneous formations for more than two decades (Butler 2005). The near-surface stratigraphy at this site consists of three distinct zones: the uppermost zone from the surface to approximately 11 m consists of

silt and clay, with the water table typically at a depth of 4 to 5 m; a sand and gravel interval exists between depths of approximately 11 and 22 m, with thin interbedded and discontinuous clay layers; a the lower zone is bedrock.

Figure 5 shows an NMR log collected in well 4S in April 2010, using the 3.5-inch diameter logging tool. This 4-inch diameter PVC well was installed using an 11-inch diameter hollow stem auger, and the sand and gravel formation was allowed to collapse against the PVC casing. The fully screened interval in the sand and gravel was subjected to intensive development, including surging and pumping. The resulting NMR log in Figure 5 clearly shows the transition from silt and clay to sand and gravel, at approximately 11 m.

In the far right panel, calibrated NMR estimates of K show excellent agreement with results from multilevel slug tests (MLST) in this well (Butler 2005), following calibration. A site-specific calibration factor for SOE estimation equation ($C_{SOE} = 3000$ m/d) was determined by regression to the MLST data. We note that the calibration only adjusts the linear scaling of the estimated K curve. The trend of the SOE curve is not affected by the calibration, and closely tracks the MLST data, increasing in zones from 12 to 14 m and 16 to 18 m, and decreasing around 15 m.

An interesting finding was the detection of significant large-pore water content (~15%) in the unsaturated zone, between 2 and 5 m. The site had received heavy rains in the days and weeks prior to this logging measurement. A follow-up NMR log was conducted with the same tool, in the same well, during a drier period in October 2010, and at that time there was little mobile water detected in the unsaturated zone.
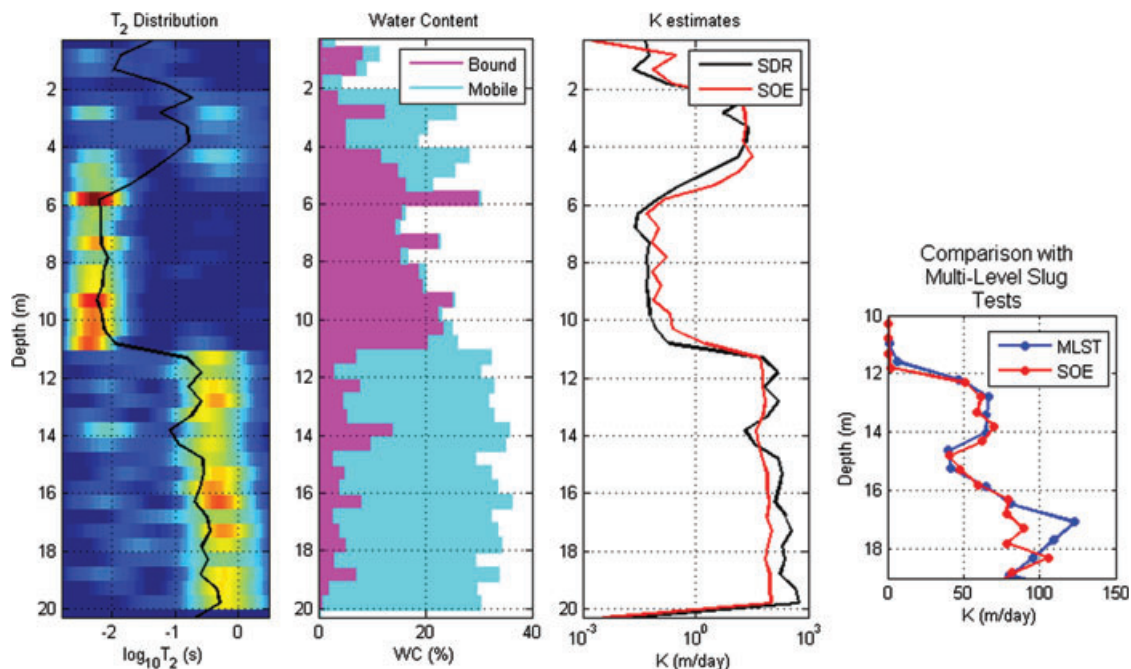

Figure 5. NMR log from GEMS well 4S, Lawrence Kansas, using the 3.5 inch diameter probe in a 4-inch diameter, PVC-cased well. At far right, NMR estimates of K (SOE) are compared to those from multilevel slug tests (MLST).
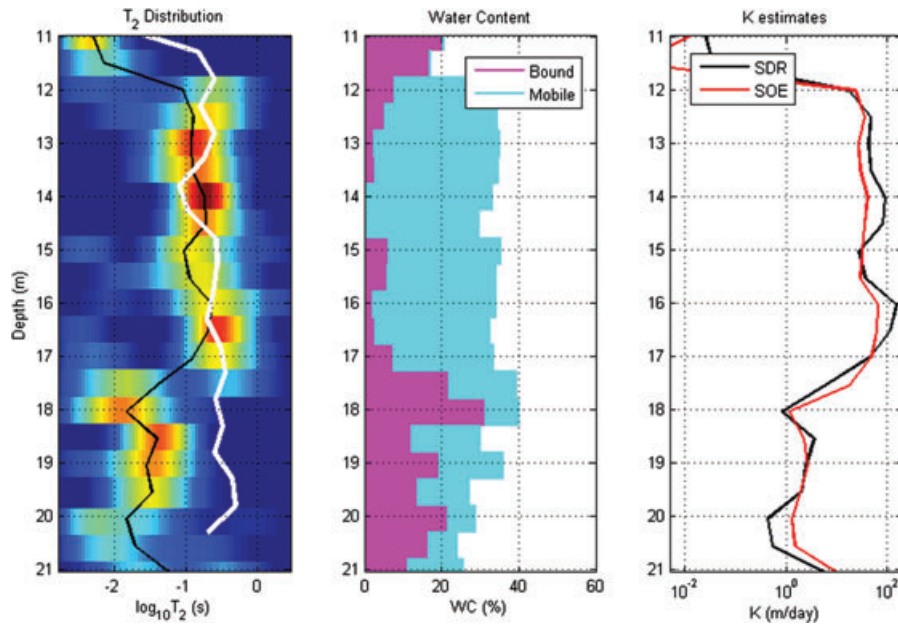
Figure 6. Direct-push NMR log of sand and gravel aquifer at GEMS acquired within 10 m of the 4-inch developed well in Figure 5. The T_{2ml} value for the 4-inch developed well is overlaid in white on the T_2-distribution log for comparison.

In October 2010, tests of the direct-push and 1.67-inch logging tools were conducted at GEMS. A direct-push NMR log obtained through the sand-and-gravel aquifer is shown in Figure 6. This direct push NMR measurement was located less than 10 m from the well shown in Figure 5.

Comparing the two NMR logs in Figures 5 and 6, the major differences are that the direct-push NMR logging unit detects water with shorter T_2 decays throughout the sand and gravel, and detects significantly shorter T_2 decays below 17 m. The shorter T_2 decays lead to smaller estimated K values that are not consistent with K estimates obtained using a wide variety of other techniques at the site (e.g., Butler 2005; Butler et al. 2007). The shorter T_2 values could be due to increased fines and paramagnetic surface relaxation sites; electrical conductivity data indicate thin, discontinuous clay lenses distributed within the sand-gravel interval and drillers logs report iron alteration in this zone. (Schulmeister et al. 2004a).

The difference between the NMR logs at the 4-inch diameter well and the direct-push profile could be due in part to the development activities that had been performed on the well. Development activities, by design, remove fine particles from the formation in the immediate vicinity of the well screen and thus could be removing fine materials at the radial depth of investigation.

Given the possible influence of well development, we expanded our tests at GEMS to directly investigate the use of NMR to sense pore-space changes associated with development. Two new 2-inch diameter PVC wells were installed using a direct-push machine with 3.25-inch diameter rods. The two new wells were screened over the sand-and-gravel interval, except for the lowest 1.5 m that consisted of a PVC-cased sump. Each well was logged using the 1.67-inch diameter NMR tool three times:

once before development and twice during and after development. The first stage of development consisted of packing off discrete zones and intensively pumping water for 15 to 20 min to remove fines. In a second stage of development, a surge block was used to repeatedly stress each discrete interval and then water was pumped until it ran clear. NMR logs were obtained after each stage of development to assess the sensitivity of the NMR logging measurement to the varying degrees of development.

The resulting data show that the NMR logging response is significantly altered by the development process. Figure 7 shows results from NMR measurements in well C1, before (red) and after the first (blue) and second (green) stages of development. In Figure 7a, we observe that the T_2 relaxation rate is made longer by development—indicating an increase in the mean pore size or pore volume to surface ratio. Similarly, the NMR-derived estimates of hydraulic conductivity from NMR measurements in well C1 (Figure 7b) also indicate uniformly higher hydraulic conductivity as a result of well development. The largest increase in NMR-estimated permeability is observed in the zone between 18 and 19 m. Thus, well-based NMR measurements do appear to be sensitive to well development. We note that these differences due to development are somewhat less than those observed between the NMR logs from the 4-inch diameter well and the direct-push unit below 17 m (Figures 5 and 6).

Tamala Limestone, Western Australia

The Tamala Limestone in Western Australia is the world's most extensive eolianite deposit and is an economically important source of groundwater (Brooke 2001). The formation underlies 40% of the Perth metropolitan area, and it is estimated that over A\$520
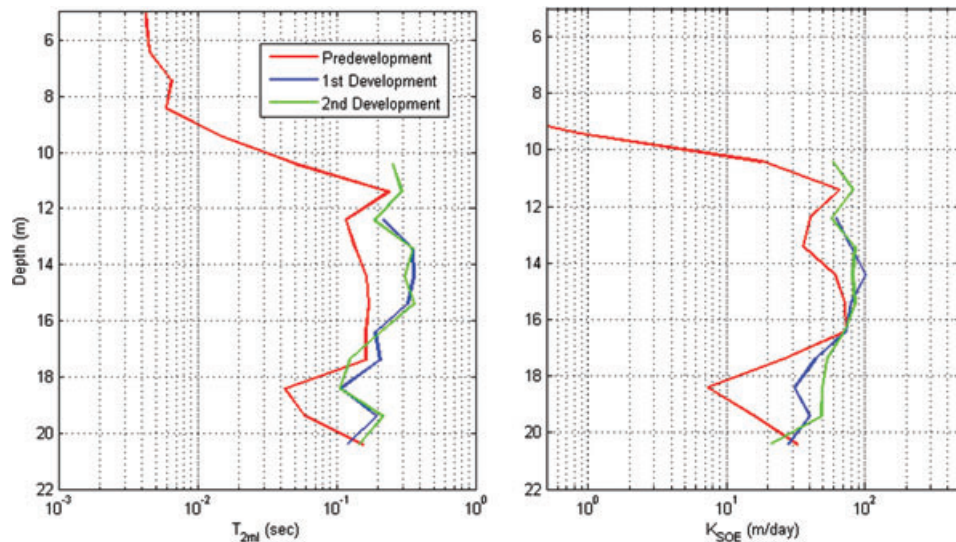
Figure 7. Repeated NMR logging data from GEMS well C1 before (red), and after the first (blue) and second (green) stage of development showing changes in the mean log T_2 value and the NMR-estimated hydraulic conductivity.

million of capital assets rely on this shallow aquifer. There has been recent concern over the potential for seawater intrusion, and as managed aquifer recharge schemes are considered, there is a need to develop a better hydrogeological model of the formation.

Cyclic inundation of the Tamala Limestone by the sea, coupled with a fluctuation of the aquifer watertable within the onshore extent of the formation is believed to have influenced diagenesis and the evolution of secondary porosity. The complex nature of the porosity and transmissivity has only recently been studied (Smith et al. 2011). In 2010, the Commonwealth Scientific and Industrial Research Organization (CSIRO) acquired NMR logs in several boreholes within and around Perth, to gain a better understanding the scale of variation associated with the hydraulic characteristics of the limestone aquifer. The boreholes were constructed using Mini-Sonic drilling, which allowed for some intact core recovery. Monitoring wells were installed using 80-mm (3.15 inch) diameter PVC casing. The NMR logging data were collected using the 2.5-inch diameter borehole NMR tool, with 0.5-m vertical resolution, echo spacing of 2.5 ms, and logging rates of 3 to 6 meters per hour.

Figure 8 depicts the NMR logging data and interpreted hydraulic properties from a well in East Rockingham (ER01); a lithologic log is also shown. The NMR-derived T_2 distribution, bound and mobile water content, and hydraulic conductivity estimates illustrate large differences in the hydraulic properties of the various lithologic units in the formation; K estimates are presented without calibration and so should be considered "relative" values of K. These results are consistent with an understanding that the Tamala Limestone has a high transmissivity owing to a well-developed dual pore system and that these variations in transmissivity occur over short distances both horizontally and vertically. In comparison to the lithologic log, the NMR log provides direct measurement

of the water content and estimates of hydraulic conductivity in each lithologic unit. The NMR log also identifies key hydrogeological layers, including apparent low permeability zone at depths of 7 to 8 m (described in the lithology log as weakly cemented calcarenite) and 16 m (not identified in the lithologic log); high porosity sand zones are well identified between 5 to 7 and 8 to 15 m.

Figure 9 depicts the NMR logging data from another well near Perry Lakes (PL01) and a lithologic log from the same well. The NMR-derived quantities reflect the less structured condition of the Tamala formation in this particular area, where finer textured sediments are present (clayey sands and sandy clays). As with the Rockingham log (Figure 9), the NMR data for the Perry Lakes area supports the observation that the hydrogeology of the Tamala Limestone exhibits high spatial variability, resolved at a 0.5 m scale in the NMR log.

Discussion

The new NMR logging tool design locates many of the bulky and expensive components on the surface as opposed to inside the downhole probe, in contrast to previous oilfield designs. This approach has several significant advantages for near-surface groundwater investigations. First, it enables the design and manufacture of small diameter NMR tools, with tool diameters ranging from 1.67 to 3.5 inches. It is possible that even smaller diameter tools could be constructed in the future using this approach. Second, the cost for manufacturing the system is greatly reduced by avoiding the need for custom-designed power supplies, power amplifiers, and data acquisition systems. Third, high RF transmitter power can be maintained and ultimately even increased compared to existing oilfield tools, because the RF power subsystems are not constrained to fit within a 5-inch diameter or smaller cylinder. High RF power is important, as it allows for
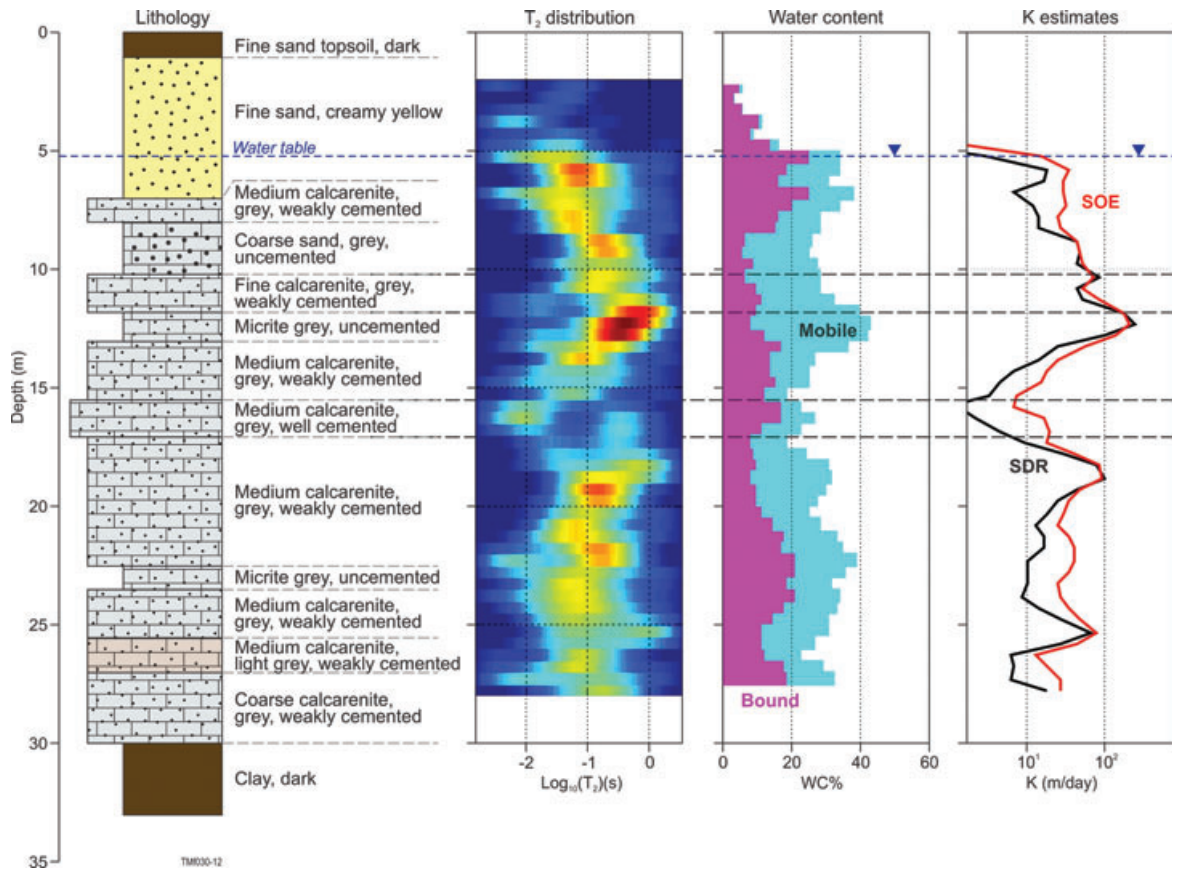
Figure 8. East Rockingham, Western Australia, NMR log (right three plots) compared to lithologic log (left).
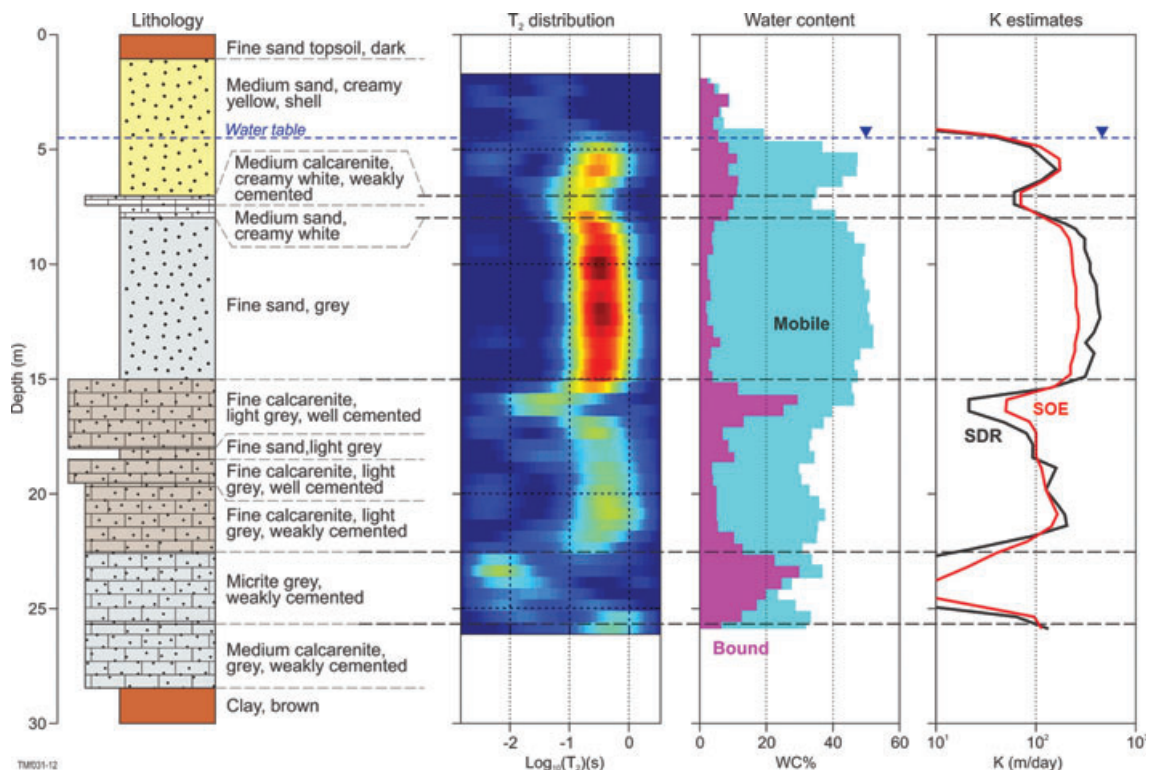

Figure 9. Perry Lakes, Western Australia, NMR log (right three plots) compared to lithologic log (left).

NMR sensing at a greater radius into the formation, as well as shorter pulses, and shorter echo spacing for detection of short NMR signals. All of these features are beneficial for NMR logging measurements.

The NMR logging tool provides important information about hydraulic properties including direct measurements of water content, estimation of relative pore-size distribution and hydraulic conductivity, notably without the use of a radioactive source that is required for neutron-based water content estimates. The tool provides high data quality, which a previous study has shown is comparable to that obtained with much larger and more expensive oilfield NMR logging tools (Knight et al. 2012; Dlubac et al. in press; Knight et al. in preparation).

The lower operating frequency of the small-diameter system relative to oil-field NMR logging tools does result in slower logging speeds on the order of 5 to 20 m/h. Another practical limitation of the tool design is that the downhole probe is presently configured to operate with an 8-conductor cable, with one line carrying significant RF power (up to 1 kV and tens of amps). Thus, the tool is currently not compatible with industry standard 4-core logging cable; however, other logging tools could be modified to operate on the custom 8-conductor cable. It is estimated that the current tool and its underlying design could be applied to depths up to 1600 m; the longest cable that has been tested to date is 400m. Increased logging depths would make the tool useful in shallow energy exploration markets including coal-bed methane, oil sands, and shallow oil exploration.

In addition to the examples provided in this paper, the tool has also been applied for managed aquifer storage and recovery, contamination remediation, and mining projects. More recent studies have demonstrated the value of NMR logging data for comparison or integration with surface NMR measurements (e.g., Knight et al. 2012; Walsh et al. 2011). Other potential applications include geotechnical investigations to assess soil stability and drainage, as well as cryosphere studies to characterize the state of frozen and unfrozen water in permafrost or ice (the NMR signal is eliminated for frozen water). Numerous laboratory studies have shown the potential of using NMR logging to directly detect organic contaminants (Bryar and Knight 2008) and to monitor changes in iron redox state associated with biological remediation of heavy metals (Keating et al. 2008). The tools may also be used to monitor the integrity of man-made structures such as dam and levees, or to investigate the effectiveness of well completions (e.g., grout or bentonite plugs that are intended as barriers to flow, or sand backfill intended to serve as permeable conduits). With reduced costs for downhole components, probes may even be permanently installed for long-term monitoring of engineered structures or natural formations.

Conclusions

Geophysical NMR logging measurements provide extremely valuable information, but in the past this technology has been largely restricted to use in the oil and gas industry due to the size and cost of available instrumentation. The successful development and demonstration of a small-diameter tool enables the widespread use of this powerful technology for critical near-surface groundwater applications. Measurements with the tool deliver direct and high-resolution information on formation properties that are of critical importance for groundwater investigations, including water-filled porosity, relative pore-size distribution, hydraulic conductivity, and moisture content distribution in the unsaturated zone. Following decades in which the application of NMR logging in near-surface applications was limited by the availability of appropriate instrumentation, the progress and utilization of NMR logging in the future should only be limited by the imagination of geoscientists and hydrologists familiar with this technology and its capabilities.

References

Brooke, B. 2001. The distribution of carbonate eolianite. *Earth-Science Reviews* 55, no. 1–2: 135–164.

Brown, R.J.S., and B.W. Gamson. 1960. Nuclear magnetism logging. *Transactions of the American Institute of Mining, Metallurgical and Petroleum Engineers* 219: 201–219.

Brownstein, K.R., and C.E. Tarr. 1979. Importance of classical diffusion in NMR studies of water in biological cells. *Physical Review A* 19: 2446–2453.

Bryar, T.R., and R.J. Knight. 2008. NMR relaxation measurements to quantify immiscible organic contaminants

in sediments. *Water Resources Research* 44: W02401. DOI:10.1029/2006WR005635

Butler, J.J. Jr. 2005. Hydrogeological methods for estimation of hydraulic conductivity. In *Hydrogeophysics*, ed. Y. Rubin and S. Hubbard, 23–58. The Netherlands: Springer.

Butler, J.J. Jr., P. Dietrich, V. Wittig, and T. Christy. 2007. Characterizing hydraulic conductivity with the direct-push permeameter. *Ground Water* 45, no. 4: 409–419.

Coates, G., M. Miller, M. Gillen, and G. Henderson. 1991. An investigation of a new magnetic resonance imaging log. Transactions on SPWLA Annual Logging Symposium, 32, paper DD.

Chang, D., H. Vinegar, C. Morriss, and C. Straley. 1994. Effective porosity, producible fluid and permeability in carbonates from NMR logging. SPWLA 35th Annual Logging Symposium.

Dunn, K.-J., D.J. Bergman, and G.A. Latorraca. 2002. *Nuclear Magnetic Resonance Petrophysical and Logging Applications*. Oxford, United Kingdom: Elsevier Science.

Dlubac, K., R. Knight, Y.-Q. Song, N. Bachman, B. Grau, J. Cannia, and J. Williams. The use of NMR logging to obtain estimates of hydraulic conductivity in the High Plains aquifer. *Water Resources Research*. In press.

Foley, I., S.A. Farooqui, and R.L. Kleinberg. 1996. Effect of paramagnetic ions on NMR relaxation of fluids at solid surfaces. *Journal of Magnetic Resonance A* 123: 95–104.

Freedman, R. 2006. Advances in NMR logging. *Journal of Petroleum Technology* 58, no. 1: 60–66.

Gallegos, D.P., and D.M. Smith. 1987. A NMR technique for the analysis of pore structure: Determination of continuous pore size distributions. *Journal of Colloid and Interface Science* 122: 143–153.

Grunewald, E., and R. Knight. 2011. The effect of pore size and magnetic susceptibility on the surface NMR relaxation parameter T_2^*. *Near Surface Geophysics* 9, no. 2: 169–178. DOI:10.1190/1.3581094

Grunewald, E., and R. Knight. 2009. A laboratory study of NMR relaxation times and pore coupling in heterogeneous porous media. *Geophysics* 74, no. 6: E215–E221.

Guillen, D.P., and R.C. Hertzog. 2004. A survey of Department of Energy-sponsored geophysical research for shallow waste site characterization. *Vadose Zone Journal* 3: 122–133.

Hertrich, M. 2008. Imaging of groundwater with nuclear magnetic resonance. *Progress in Nuclear Magnetic Resonance Spectroscopy* 53: 227–248.

Keating, K., K.J. Tufano, and R.J. Knight. 2008. Nuclear magnetic resonance relaxation measurements as a means of monitoring iron mineralization processes. *Geophysical Research Letters* 35: L19405. DOI:10.1029/2008 GL035225, 2008

Kenyon, W.E. 1997. Petrophysical principles of applications of NMR logging. *The Log Analyst*: 21–43.

Kenyon, W.E., P.I. Day, C. Straley, and J.F. Willemsen. 1988. A three-part study of NMR longitudinal relaxation properties of water-saturated sandstones. *SPE Formation Evaluation* 3, no. 3: 622–636.

Kleinberg, R.L. 2001. NMR well logging at Schlumberger. *Concepts in Magnetic Resonance* 13, no. 6: 396–403. DOI:10.1002/cmr.1026

Kleinberg, R.L., and M.A. Horsfield. 1990. Transverse relaxation processes in porous sedimentary rock. *Journal of Magnetic Resonance* 88: 9–19.

Knight, R., E. Grunewald, J. Butler, K. Dlubac, and D. Walsh. The integration of logging and surface NMR for mapping spatial variation in hydraulic conductivity. In preparation.

Knight, R., E. Grunewald, T. Irons, K. Dlubac, Y.-Q. Song, H. Bachman, B. Grau, D. Walsh, J. Abraham, and J. Cannia. 2012. Field experiment provides ground truth for surface NMR measurement. *Geophysical Research Letters* 39: L03304. DOI:10.1029/2011GL050167

Lauterbur, P.C. 1973. Image formation by induced local interactions – Examples employing nuclear magnetic resonance. *Nature* 242: 190–191.

LeBlanc, D.R., S.P. Garabedian, K.M. Hess, L.W. Gelhar, R.D. Quadri, K.G. Stollenwerk, and W.W. Wood. 1991. Large-scale natural gradient tracer test in sand and gravel, Cape Cod Massachusetts—1. Experimental design and observed tracer movement. *Water Resources Research* 27, no. 5: 895–910.

Legchenko, A., and P. Valla. 2002. A review of the basic principles for proton magnetic resonance sounding measurements. *Journal of Applied Geophysics* 50: 3–19.

Maliva, R., E. Clayton, and T. Missimer. 2009. Application of advanced borehole geophysical logging to managed aquifer recharge investigations. *Hydrogeology Journal* 6: 1547–1556.

Schulmeister, M.K., J.M. Healey, J.J. Butler Jr., and G.W. McCall. 2004a. Direct-push geochemical profiling for assessment of inorganic chemical heterogeneity in aquifers. *Journal of Contaminant Hydrology* 69, no. 3–4: 215–232.

Schulmeister, M.K., J.J. Butler Jr., E.K. Franseen, D.A. Wysocki, and J.A. Doolittle. 2004b. High-resolution stratigraphic characterization of unconsolidated deposits using direct-push electrical conductivity logging: A floodplain margin example. In *Aquifer Characterization, SEPM Concepts in Hydrogeology and Environmental Geology*, Vol. 2, ed. J.S. Bridge and D.W. Hyndman, 67–78. SEPM.

Seevers, D.O. 1966. A nuclear magnetic method for determining the permeability of sandstones. In 33rd Annual Logging Symposium, Society of Professional Well Log Analysts Transactions, Paper L.

Smith, A.J., S. Massuel, and D.W. Pollock. 2011. Geo-hydrology of the Tamala limestone formation in the Perth region: Origin and role of secondary porosity. CSIRO: Water for a Healthy Country National Research Flagship, 63. http://www.clw.csiro.au/publications/water forahealthycountry/2012/wfhc-tamala-geohydrology.pdf

Strikman, S., and Z. Taicher. 1987. Nuclear magnetic resonance sensing apparatus and techniques. U.S. Patent 4,710,713, filed March 11, 1986 and issued December 1, 1987.

Strategic Environmental Research and Development Program (SERDP). 1996. Fiscal Year 1996 Annual Report and Five-Year (1996–2000) Strategic Investment Plan, CU11-CU15.

Sucre, O., A. Pohlmeir, A. Miniere, and B. Blumich. 2011. Low-field NMR logging sensor for measuring hydraulic parameters of model soils. *Journal of Hydrology* 406, no. 1–2: 30–38.

Timur, A. 1969. Pulsed nuclear magnetic resonance studies of porosity, movable fluid, and permeability of sandstone. *Journal of Petroleum Technology* 21: 755–786.

Walsh, D.O. 2008. Multi-channel surface NMR instrumentation and software for 1D/2D groundwater investigations. *Journal of Applied Geophysics* 66: 140–150.

Walsh, D.O., E. Grunewald, P. Turner, A. Hinnell, and P. Ferre. 2011. Practical limitations and applications of short dead time surface NMR. *Near Surface Geophysics* 9: 103–111.