Groundwater Monitoring&Remediation

Research Article

High-Resolution Direct Push NMR Tools for Groundwater Investigations

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Abstract

A small-diameter nuclear magnetic resonance (NMR) technology optimized for use with direct push (DP) and cone penetrometer test (CPT) drilling has been developed. The DP NMR tool can be deployed through 2.25-in. diameter DP and CPT drilling rods allowing high-resolution NMR logging measurements to be acquired during retraction of drill rods. DP NMR technology runs from a person-portable battery-powered control unit and provides significantly higher resolution in both the spatial (vertical) dimension and in the time domain of the NMR measurement than previously available NMR technology. In this study, we summarize the development of two different DP NMR tools and demonstrate their application at different sites within the United States. We believe that this technology can provide a leap forward in adoption of NMR technology for high-resolution hydrological and geophysical investigations in groundwater resources and environmental remediation applications.

Introduction

Nuclear magnetic resonance (NMR) is a unique and powerful technology that directly measures nuclei with non-zero spin number (e.g., ^{1}H, ^{13}C, ^{15}N, ^{31}P, and many others) (Claridge 2016). The NMR method is widely used in a variety of disciplines. For example, in chemistry, high-field NMR spectrometers are used to identify molecules and characterize their structure (Claridge 2016). In medicine, a multidimensional NMR imaging technique called magnetic resonance imaging (MRI) is used to provide images of the organs and structures inside the human body assisting in patient diagnostics (Brown et al. 2014; Atlas 2016). In geophysics, NMR logging technology has been widely used for several decades for petroleum exploration in the oil and gas industry (Coates et al. 1999; Freedman and Heaton 2004). More recently, smaller diameter, lower cost NMR logging systems were adopted for groundwater investigations where they directly measure water content in the native formation (Walsh et al. 2013), and are now widely used to characterize both groundwater and aquifer properties in environmental remediation (Keating et al. 2008; Kirkland and Codd 2018; Spurlin et al. 2019), groundwater resources (Ren et al. 2019; Flinchum et al. 2020; Kendrick et al. 2021; Pehme et al. 2022), and geotechnical applications (Kennedy 2018).

To date, the widespread adoption of NMR logging technology in groundwater, environmental, and geotechnical applications has been limited to logging of open boreholes and plastic-cased boreholes. In this embodiment, the NMR logging tool is connected to a multiconductor cable (typically 4-conductor wireline) and a motorized winch, and the NMR logging measurement is performed by running the tool up or down the borehole at a constant speed, while collecting NMR data in a continuous manner (Walsh et al. 2013). This type of measurement is particularly useful in three situations:

1. When an open, usually mud-filled borehole is available to log immediately following drilling of the borehole and before completion of the well. In this application, the NMR data are highly useful for locating optimal zone(s) for aquifer testing, and for positioning of well screens (i.e., optimizing the completion of groundwater production wells or environmental monitoring zones).
2. When an open borehole drilled in a competent consolidated rock formation, where the borehole is stable and can be left open for an indefinite period of time after drilling and cross-contamination between fracture zones is not a concern.
3. When the borehole has been drilled in unconsolidated sediments and then completed as a well with plastic casing. Such wells are very commonly installed for both groundwater production in resource applications, and groundwater monitoring in environmental remediation applications.

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While wireline geophysical NMR logging of open and plastic-cased boreholes serves a large segment of the need for high-resolution in-situ measurement of hydrogeological subsurface properties, wireline logging is not always feasible, economical, or appropriate for every hydrogeological characterization project. Plastic well casing is not universally utilized in the groundwater and environmental industry. Steel casing is common among older existing monitoring wells, but NMR logging tools will not work within a steel or other metal casing because the electrically conductive casing effectively shields the alternating magnetic field of the NMR tool from reaching the native undisturbed formation.

Direct push (DP) and cone penetrometer test (CPT) drilling methods provide an alternate approach to in-situ hydrological and geophysical measurements where conventional drilling is either prohibitively expensive, destructive, or both. DP drilling uses a relatively lightweight and mobile drilling rig to drive small diameter drilling rods and measurement tools into unconsolidated sediments, using a combination of static force and dynamic hammering (Maliva 2016; McCall et al. 2003, 2005). CPT drilling methods are similar to DP but rely exclusively on static pushing force and, therefore, tend to utilize larger and heavier drilling platforms (Schmertmann 1978; Perumpral 1987). DP drilling has been widely adopted in the environmental remediation industry, and CPT drilling has been widely adopted in the geotechnical industry.

DP and CPT drilling methods enable hydrological, geophysical, and geotechnical measurements to be performed in-situ, at high vertical resolution, without removing formation material, and without leaving a permanent borehole in the earth. The ability to perform in-situ measurements of sediment properties without producing drill cuttings is especially important in environmental remediation applications, where the expense of disposing of contaminated soil produced by conventional drilling can be significant. In addition, installation of permanent well casing is associated with added expense and potential liability, compared to DP or CPT measurements.

Geophysical and geochemical measurements that are commonly performed using DP instrumentation include electrical resistivity, hydraulic conductivity (K), optical imaging, and fluorescent and vapor-based detection of nonaqueous phase liquid (NAPL) contaminants (McCall et al. 2018, 2019). Taken together, the existing collection of DP in-situ measurement methods is often referred to as "high-resolution site characterization" (HRSC), though the term HRSC was traditionally broader and encompassed other methods than just DP, such as high-density core sampling. Geotechnical measurements that are commonly performed using CPT instrumentation include cone tip pressure, sleeve friction, pore pressure, and tilt angle. Additional sensors can be included into CPT instrumentation to measure shear wave velocity of soil in-situ, optical imaging profile of the soils, soil electric conductivity, and formation permeability (Kennedy 2022).

Considering the significant adoption of DP- and CPT-based measurement of hydrological and geophysical properties in groundwater resources and environmental remediation markets, the authors previously developed and commercialized a small diameter NMR logging tool that can be deployed via DP drilling with 3.25-in. diameter drill rods (Walsh et al. 2013). This tool was a simple variant of the original Javelin NMR logging tool (Walsh et al. 2013). The tool had a 2.38-in. outer diameter and thus was suitable for deployment using 3.25-in. drill rods. However, the commercial adoption of this 2.38-in. diameter logging tool was limited due to the need to use the relatively large 3.25-in. diameter drill rods, which are not commonly owned by DP drilling operators, and which have a decreased drilling depth compared to smaller diameter DP drill rods. Adoption of the originally available DP NMR tool was also limited by the relatively large and expensive Javelin surface station (Vista Clara, Inc.), which was the only commercially available NMR logging instrument at that time.

In this article, we introduce a newly developed 1.4-in. diameter NMR logging tool that is optimized for use with DP and CPT drilling. This tool is deployed by the more readily available 2.25-in. diameter DP and CPT drilling rods. It runs from a low-cost person-portable battery-powered control unit and provides significantly higher resolution in both the spatial (vertical) dimension and in the time domain of the NMR measurement. In this work, we summarize the development of this DP NMR technology and its demonstration in various applications and at different sites within the United States.

Physical Principles of NMR

The NMR measurement probes the response of hydrogen spins to a magnetic field perturbation. In the presence of a static magnetic field (B0), the hydrogen spins in the formation fluid (e.g., water) become polarized and produce a net nuclear magnetization that aligns parallel to the static magnetic field. To detect this magnetization and its associated NMR signal, the spins must be perturbed from their equilibrium state. This perturbation is achieved by the application of a pulsed oscillating magnetic field (B1) that is tuned to a Larmor frequency of the hydrogen spins and excites spins into a higher energy state. Immediately after excitation, the magnetization remaining in the perpendicular plane precesses about the B0 field at the Larmor frequency and begins to relax back to its equilibrium. 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 amount of excited hydrogen. Over a short period of time, the system relaxes back to equilibrium leading to a decay of the observed NMR signal due to a loss of spin coherence in the transverse plane. In the end of this process, the magnetization reestablishes parallel to main magnetic field, B0 (Haacke et al. 1999; Brown et al. 2014; Claridge 2016).

In geophysics, NMR directly detects hydrogens in pore fluids (Figure 1A).

The initial NMR signal amplitude is linearly proportional to the quantity of hydrogen in pore fluids and so directly reflects the total volumetric water content or saturated porosity (Figure 1B). The relaxation times of the NMR signal reflect molecular interactions in the pore fluid and between the fluid and the grain surfaces (Figure 1C). Equation 1 describes the multiexponential NMR signal equation used for NMR characterization of geological material.

$$S(t) = \sum_i A_{0i} e^{\frac{-t}{T_{2i}}} \quad (1)$$

Here the A_{0i} is the volume of fluid in the pore space associated with decay time of T_{2i}. In geological application, these relaxation times are strongly correlated with the size of the pore space. Based on the empirical T2 cutoffs, the observed relaxation time distribution is used to distinguish the quantity of water bound in small pores from more mobile water in large pores (Figure 1D). In this case, the T2 cut-off values of 33 and 3 ms are typically used to distinguish between "mobile" water, "capillary bound" water, and "clay bound" water.

NMR measurements are especially valuable in hydrogeological investigations because the NMR measurements provide direct, non-destructive, continuous, and quantitative measure of the most important hydrogeological properties of native formation including volumetric water content (equivalent to total porosity, if the formation is fully saturated), differentiation of bound and mobile porosity, and the relative pore size distribution. While volumetric fluid content and porosity are directly measured by NMR, K is indirectly estimated based on measured NMR signal properties. Specifically, when formation is fully saturated the NMR-estimated porosity and distribution of T2 relaxation times are used to estimate permeability or K of the formation (Parsekian et al. 2015; Knight et al. 2016; Ren et al. 2019).

More specifically, we are using two approaches to estimating K from NMR. The first approach is based on the Schlumberger-Doll Research Equation and uses an NMR estimated porosity (from the initial amplitude A_0) and the mean-log T2 decay time in the T2 distribution (Equation 2).

$$K(SDR) = C_{SDR} \varphi^M T_{2ML}^2 \quad (2)$$

where, C_{SDR} is an empirical factor that is adjusted for calibration to different lithologies (Knight et al. 2016), φ is porosity estimated directly from the NMR water content, T_{2ML}^2 is the mean-log of the T2 distribution that is used as a proxy for pore size. The exponent "M" on the porosity term is also adjusted depending on the lithology. Typically, and based upon prior research, we use $M=1$ for unconsolidated sediments, $M=2$ for semi-consolidated formations, and $M=4$ for consolidated rock such as sandstone or carbonates (Parsekian et al. 2015; Knight et al. 2016; Ren et al. 2019).

The second approach is based on the sum-of-echoes equation and estimates K directly from the NMR decay signal, rather than using fitted parameters of porosity and T2. The equation is based on the mean value of the spin echo decay curve, calculated for the first nE echoes.

$$K(SOE) = C_{SOE} \left(\sum_{i=1}^{nE} \frac{SE_i}{nE} \right)^2 \quad (3)$$

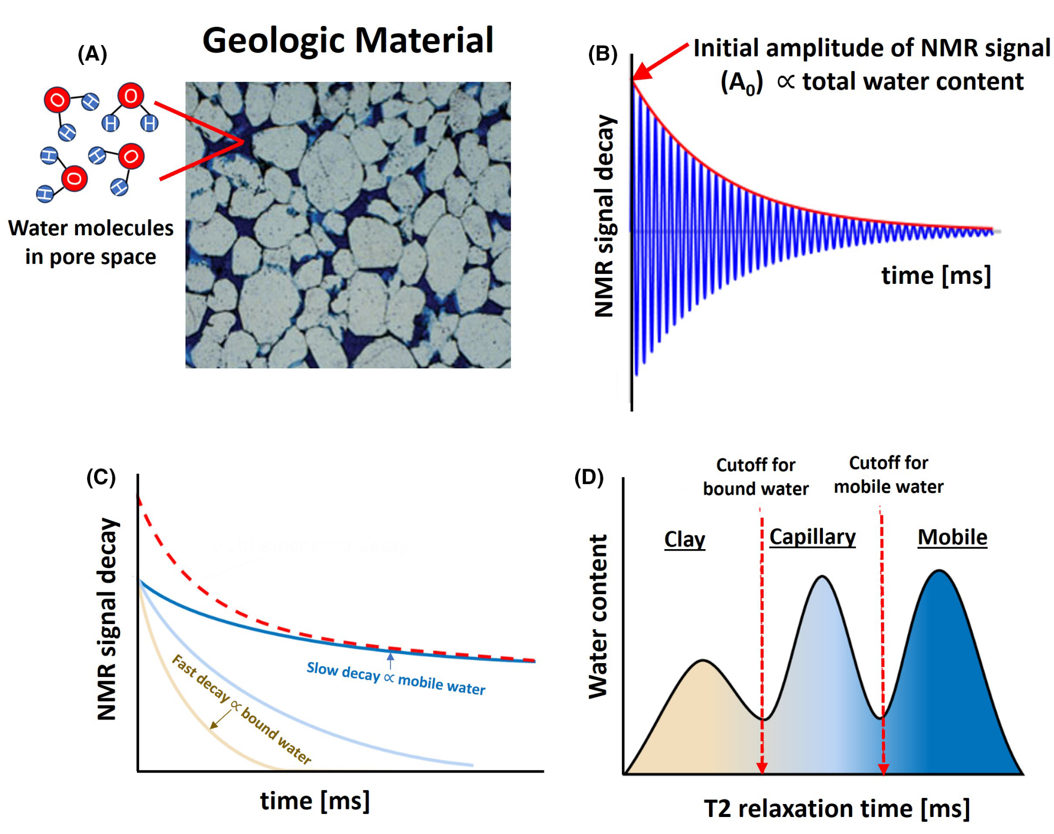

Figure 1. NMR in geophysics principle. (A) Image of sediments having pores filled with water. (B) NMR signal decay as a function of time. The initial amplitude of NMR signal is directly proportional to total water content. (C) Detected NMR signal has a multi-exponential signal decay corresponding to superposition of signal coming from water in variable pore sizes. (D) Distribution of T2 relaxation times obtained from multiexponential NMR signal decay shown in (C).

where, C_{SOE} is an empirical factor that is adjusted for calibration to different lithologies, *SE* is the spin echo decay curve.

The upper limit of NMR-measured hydraulic conductivity is defined by the ability of NMR to distinguish water in large pore spaces from bulk water. Thus, a practical numerical limit to distinguish very high values of hydraulic conductivity is set by the measured T2 relaxation time of bulk water. A second factor is the maximum total porosity that one would expect from a given type of formation. For example, for unconsolidated aquifers having well-sorted high-energy sand deposits, the upper limit of NMR-measured hydraulic conductivity estimated by Equation (2) using φ of 0.4, T_{2ML} of 0.9 s is about 9840 ft./day. On the other hand, the upper limit of HPT-estimated hydraulic conductivity is about 98 ft./day or less (McCall and Christy 2020).

NMR Logging in Geophysics

NMR logging tools were initially developed in the oil and gas industry to directly measure the NMR response of the formation fluids, and to estimate formation porosity and permeability (Coates et al. 1999; Olaide et al. 2020; Elsayed et al. 2022). However, due to tremendous size, weight, and cost of oilfield NMR instruments, adoption of NMR logging in the groundwater industry was avoided. The first NMR logging tool designed specifically for groundwater applications was introduced in 2010 by Vista Clara Inc. This tool incorporated optimized magnet and coil designs and re-engineered hardware to enable much smaller diameter probes to be manufactured, and at a much lower cost than oilfield NMR logging tools. The Vista Clara Javelin tools have evolved over the past 13 years to operate on 4-conductor wireline commonly employed for geophysical logging in groundwater boreholes, and the range of tools has expanded to enable NMR logging in a wide range of common groundwater wells from 2-in. polyvinyl chloride (PVC)-cased monitoring wells to 17-in. diameter open boreholes. At least one other manufacturer has joined the market offering NMR logging tools appropriately sized and priced for groundwater wells. To date, NMR borehole logging tools are used in variety of groundwater and earth science industries worldwide to estimate important hydrogeologic properties, such as bound and mobile water content, pore size distribution and porosity, and K.

Methods

DP NMR Tool Development

The main objective of this work was to develop a small size, cost-effective, and high-resolution NMR logging tool that can be deployed through drilling rods to conduct NMR measurements logged on the "way up." An illustration for how the DP NMR tool works is shown in Figure 2.

First, empty rods are advanced to the desired depth with an expendable point on the bottom of the rod string. Next, the small diameter NMR probe is deployed through the rods using extendable push rods. The push rods are necessary because the permanent magnets in the tool cause lateral force that tend to cause the tool to stick to the inside of the steel drill rods. Water can be added to the rod string prior to exposing the probe to the formation, which is often necessary to prevent sand influx if the drill string is in coarse sediments below the water table. Finally, the drill rods are retracted using the DP machine, while the extendable push rods are used to hold the probe in place. This causes the

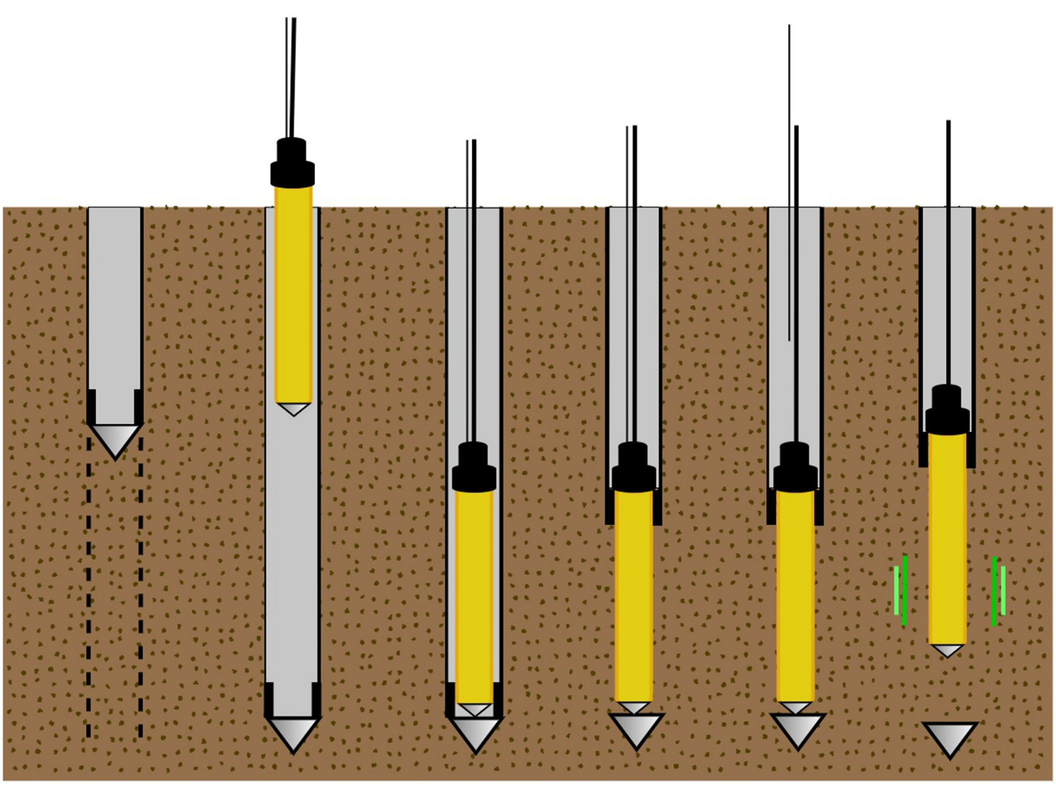

Figure 2. Illustration of the DP NMR tool deployment.

expendable drill point to be pushed out the bottom of the rods, exposing the NMR tool to the formation. The drill shoe at the bottom of the rods has a slightly smaller inner diameter than the toolhead on the probe. This prevents the toolhead from moving below the bottom of the drill string and provides a strong mechanical connection to enable the tool to be pulled up through the temporary borehole with the drill string. NMR measurements are performed in stepped mode, with the drill string raised at regular intervals and NMR measurements collected with the tool in static locations. The DP NMR tool has an outer dimeter of 1.4-in., making it feasible to be pushed through 2.25-in. drilling rods.

Two versions of DP NMR probes have been developed and deployed to date. The first version, DP140N, is a variation on the "Numar" magnet/coil geometry. In this embodiment, the tool has two independent sensitive zones, which are approximated as thin cylinders radially centered around the axis of the probe with vertical lengths of approximately 6 in. and diameters of approximately 5 and 6 in., respectively. A rendering of the sensitive zone geometries and vertical sensitivity of DP140N is shown in Figure 3A and 3B.

This tool operates at two frequencies of 475 and 425 kHz, corresponding to the sensitive shells of 5 and 6 in., respectively. The diameters of the sensitive zones can be adjusted, if desired, by simply retuning the coil and operating a different frequency. Retuning and operating the NMR tool at a lower frequency results in the sensitive zone diameter being larger and the signal to noise ratio (SNR) being lower. The DP140N tool has a high vertical resolution of 6 in., average noise levels of about 8% volumetric water content for individual echoes for 20 averages, and a minimum echo spacing of 0.4 ms, providing direct and accurate measure of the full spectrum of water content present in the saturated and unsaturated zones, including clay-bound, capillary-bound, and mobile pore water within the formation. The DP140N tool has a strong magnetic field gradient of about 30 G/cm, making it less susceptible to NMR signal loss due to the presence of magnetically susceptible materials in the formation. In addition, due to the presence of strong magnetic field gradient, the tool can be used to conduct advanced diffusion Carr-Purcell-Meiboom-Gill (CPMG) experiments to differentiate between the NMR signal of water and NAPL.

The second version of DP NMR tool is called DP140J and has a "Jackson" type magnetic/coil array. This tool has a more "donut" type sensitive zone centered around the axis of the probe. This probe has a slightly lower SNR as compared to DP140N and a much higher vertical resolution of approximately 2 in. A rendering of the sensitive zone geometries and vertical sensitivity of DP140J is shown in Figure 3C and 3D. The ability to conduct NMR investigations with such a fine resolution can be important for HRSC activities and monitoring of remediation processes in the very shallow subsurface. The DP140J tool operates at two frequencies of 460 and 360 kHz, corresponding to the sensitive shells of 5 and 5.5 in., respectively. These diameters of the sensitive zones can be adjusted somewhat by retuning the coil to different frequencies, but the magnet and coil geometry limits how much fine tuning of the sensitive zone geometries can be achieved through frequency selection alone.

DP NMR Tool Operation

The DP NMR tool is controlled using a Dart control unit (DCU) that is powered by a 24 V internal or external battery supply. The DCU provides high-voltage power to the DP NMR probe via the 8-conductor downhole cable and interfaces with the field computer through a USB data cable. The length of downhole cable varies between 66 and 394 ft. A length of 197 ft. provides adequate length and slack for use on most ground-based DP NMR investigations. All components of the DP NMR system are shown in Figure 4.

Data Acquisition and Analysis

Dart acquisition software is used to operate the DP NMR system. To estimate volumetric water content and distribution of T2 relaxation times, the DP NMR system is operated with dual wait time CPMG pulse sequence shown in Figure 5.

In this sequence, the data from two frequencies associated with different sensitivity shells are collected in a time-interleaved sequence. The sequence consists of CPMG trains collected with different recovery times (TR). TR long is associated with longer waiting times required for all water in the formation to be recovered between each measurement. TR short provides better measurement of fast relaxing compartments in the formation having short T2 values, such as water bound in small clay pores. Based on the site conditions, the experimental parameters of CPMG pulse sequence can be adjusted to estimate the most robust and accurate NMR results, and associated formation porosity and K measures. To obtain improved SNR, signal averaging of CPMG experiment can be done by increasing the number of averages (NA). The experimental parameters used to collect DP NMR data shown in this study are summarized in Table 1.

There are several important benefits to collecting multifrequency NMR data. First, a two-frequency measurement enables twice as much data to be collected at the same time as compared to a single-frequency measurement. This is because there is a required wait time of several seconds between two consecutive long wait time measurements on the same frequency, to allow the hydrogen magnetization in large pore water to fully relax back to its equilibrium state via T1 relaxation processes, before initiating another measurement at that frequency. By time-domain interleaving of measurements at different frequencies, we can take advantage of the required down time for T1 recovery on one frequency to collect NMR data at another frequency (and another physical volume) without any effect on the T1 relaxation for water in the first physical volume. These two data sets collected at different frequencies can be averaged together to yield lower overall noise compared to use of just one of the two data sets. Second, there are a multitude of potential radio-frequency noise processes that can add noise to the measurements and especially when the probe is located in the shallow subsurface above a water table. Having multiple data sets acquired at different frequencies provides added

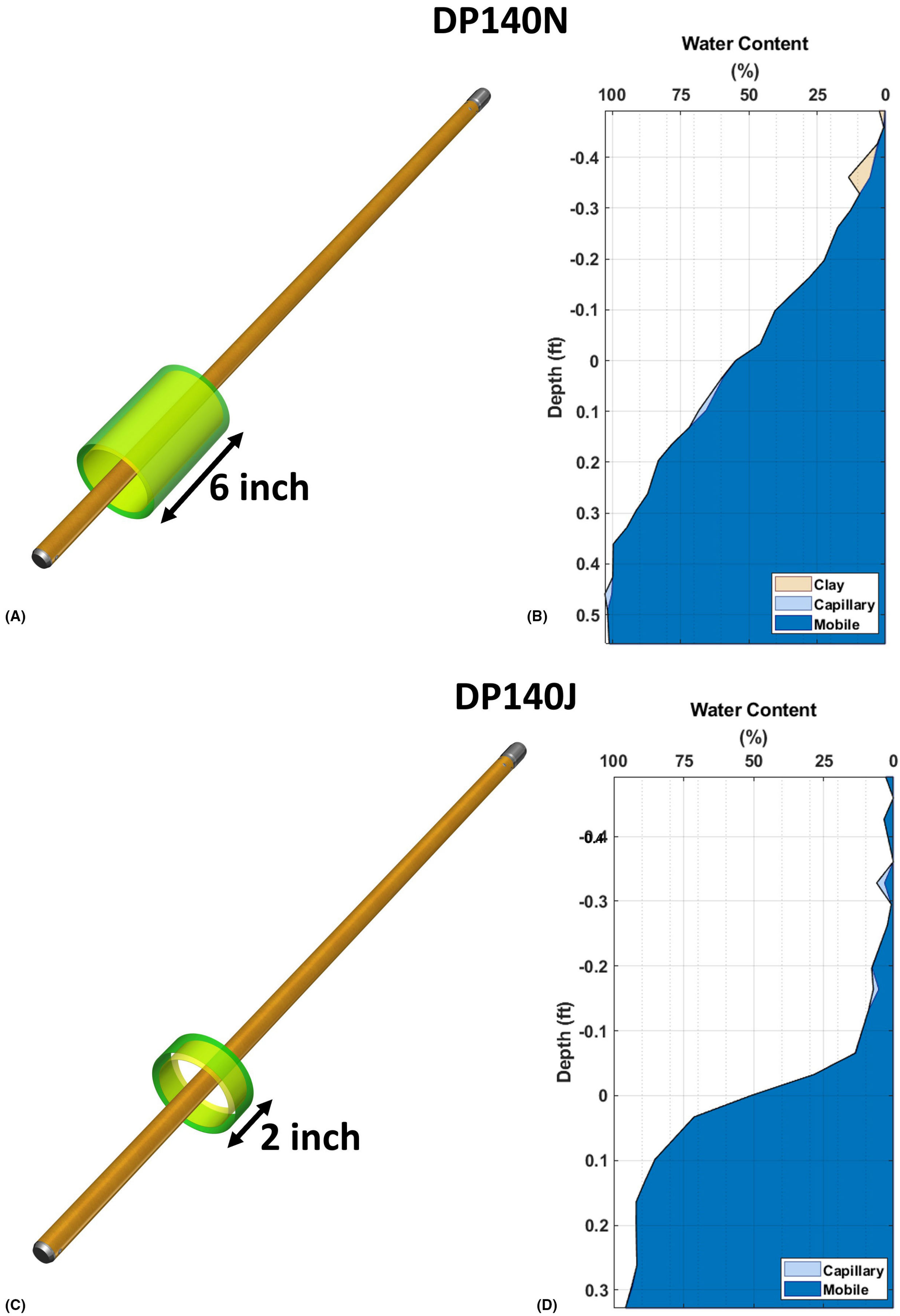

Figure 3. A 3D-rendering of DP140N (A) and DP140J (C) probes. Plots (B) and (D) show vertical sensitivity of DP140N and DP140J, respectively.

Figure 4. DP NMR system.

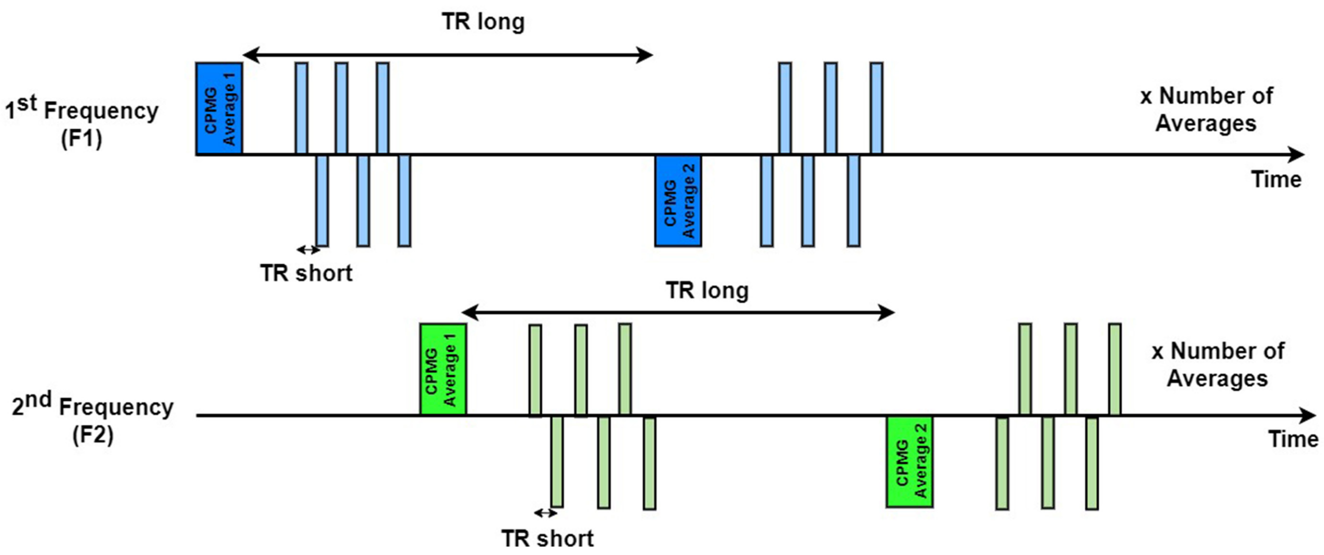

Figure 5. Dual wait time Carr-Purcell-Meiboom-Gill (CPMG) pulse sequence used in the current study.

Table 1
DP NMR Acquisition Parameters Used at Different Study Locations

	Probe	Echo time (Te) (sec)	Long TR (sec)	Long Scan length (sec)	Long NA	Short TR (sec)	Short Scan length (sec)	Short NA
Ebey Island, WA	DP140N	5×10^{-4}	3	150	8	0.1	20	48
Larned, KS	DP140N	5×10^{-4}	3	150	16	0.1	20	96
Mine Tailings site	DP140N	5×10^{-4}	4	400	10	0.2	40	40
Cosumnes River, CA	DP140N	5×10^{-4}	3	200	16	0.1	20	96
Salina, KS	DP140N	5×10^{-4}	3	300	18	0.15	30	72
	DP140J	0.5	3	150	8	0.1	20	48

statistical immunity to narrowband radiofrequency noise, which can often degrade data in one NMR frequency band while not affecting data in other NMR frequency bands.

In this study, the depths were logged manually using logging steps of 6 and 2 in. for DP 140N and DP 140J, respectively. The average logging time per single depth including transition to the next depth step was about 1.5 min. Depths can also be logged automatically using string pot- or quadrature-style depth encoders, which are commonly used with DP and CPT drill rigs.

The NMR data were analyzed using Javelin Pro Plus processing software. This software performs real-time NMR data processing, quality control, and interpretation of hydrogeological properties including the T2 relaxation time distribution, estimation of total water content, mobile, capillary-bound, and clay-bound water content, and K. The data can be processed using multilevel depth averaging to compensate for some temperature sensitivity in the electronics and obtain improved SNR. In this process, the raw NMR data of consecutive samples is averaged prior to actual T2 analysis. With two-level averaging, each depth point represents an average of data collected at two adjacent depth levels. So even though the number of samples remains the same, the "window" that each sample represents is larger. Therefore, the two-level depth averaging is associated with lower vertical resolution and higher SNR.

Results and Discussion

Ebey Island, WA

This site is located east of Everett, Washington, in the delta of the Snohomish River, and can be accessed year-round. We frequently use this site for tests and demonstrations of NMR technology. It is associated with a shallow water table and a network of actively retained dikes. For this study, we conducted a series of DP NMR (DP140N) investigations in September 2022 at three different locations at the site. The exact location of DP NMR tests and the experimental setup showing a DP rig with DP NMR probe are shown in Figure 6A. The DP NMR probe is depicted in Figure 6B.

High-resolution DP NMR logging results from this location are shown in Figures 7 through 9. In general, the

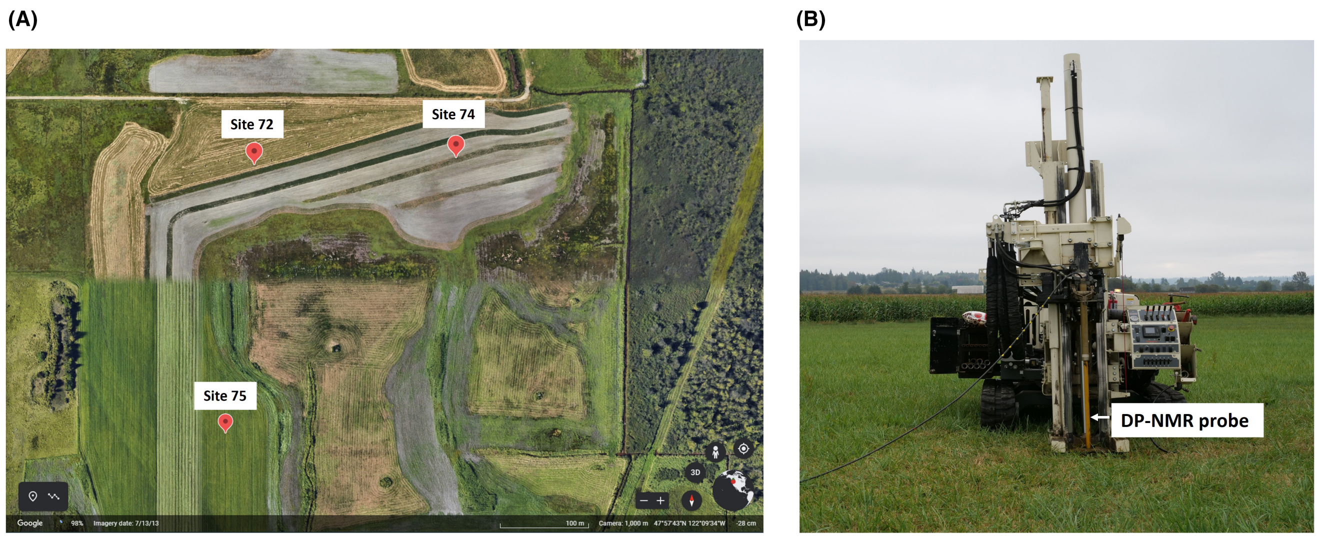

Figure 6. Location and experimental setup of DP NMR examinations at Ebey Island, WA. The DP NMR probe is depicted in (B).

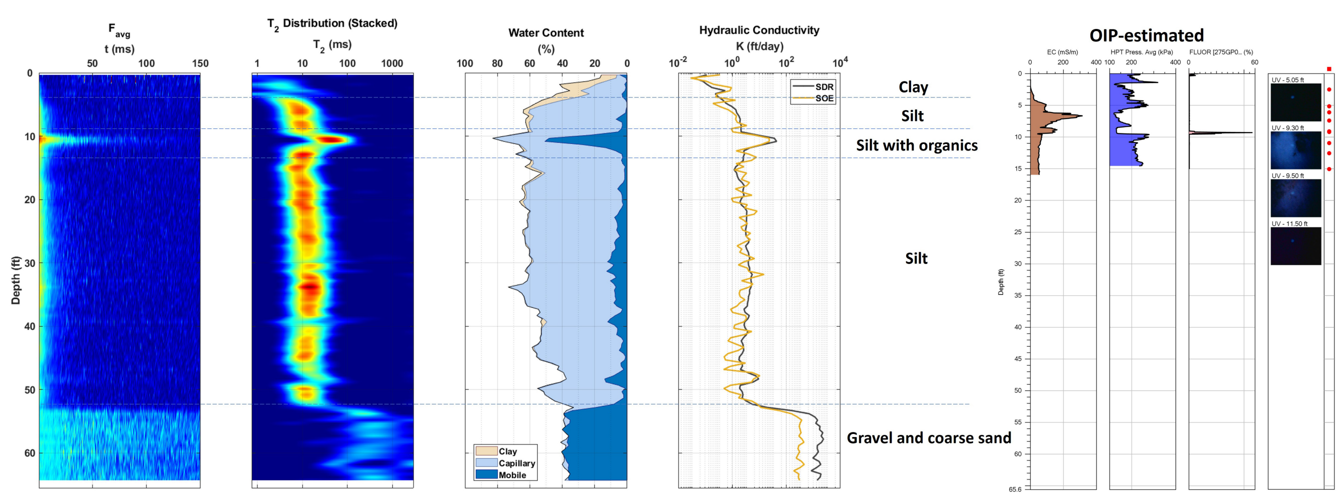

Figure 7. Experimental results obtained from DP NMR and OIP at site 74 in Ebey Island, WA.

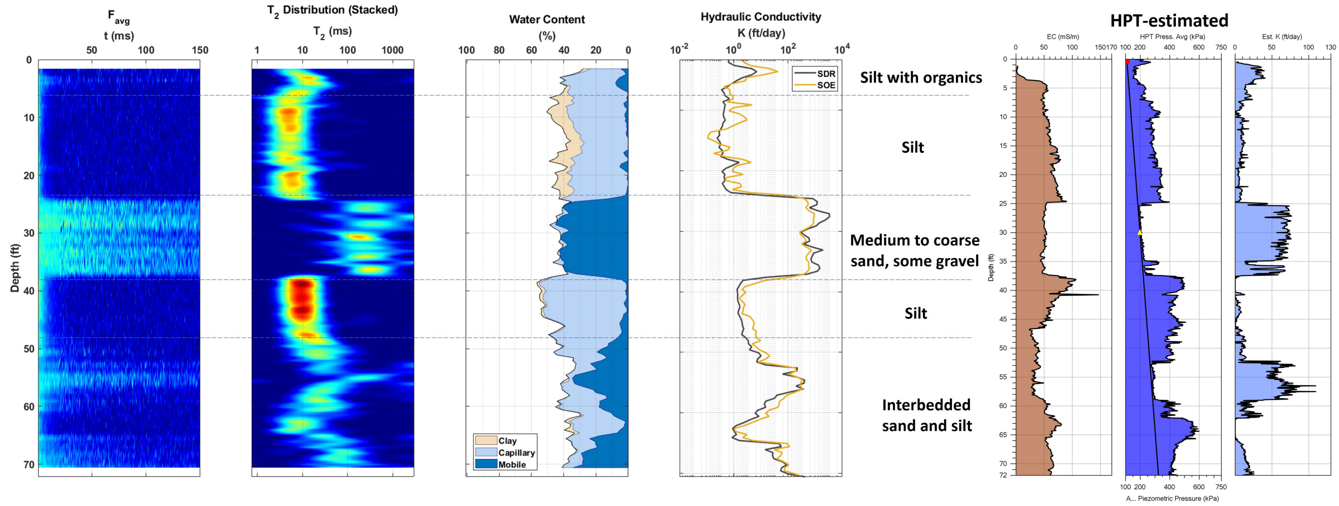

Figure 8. Experimental results obtained from DP NMR and HPT at site 72 in Ebey Island, WA.

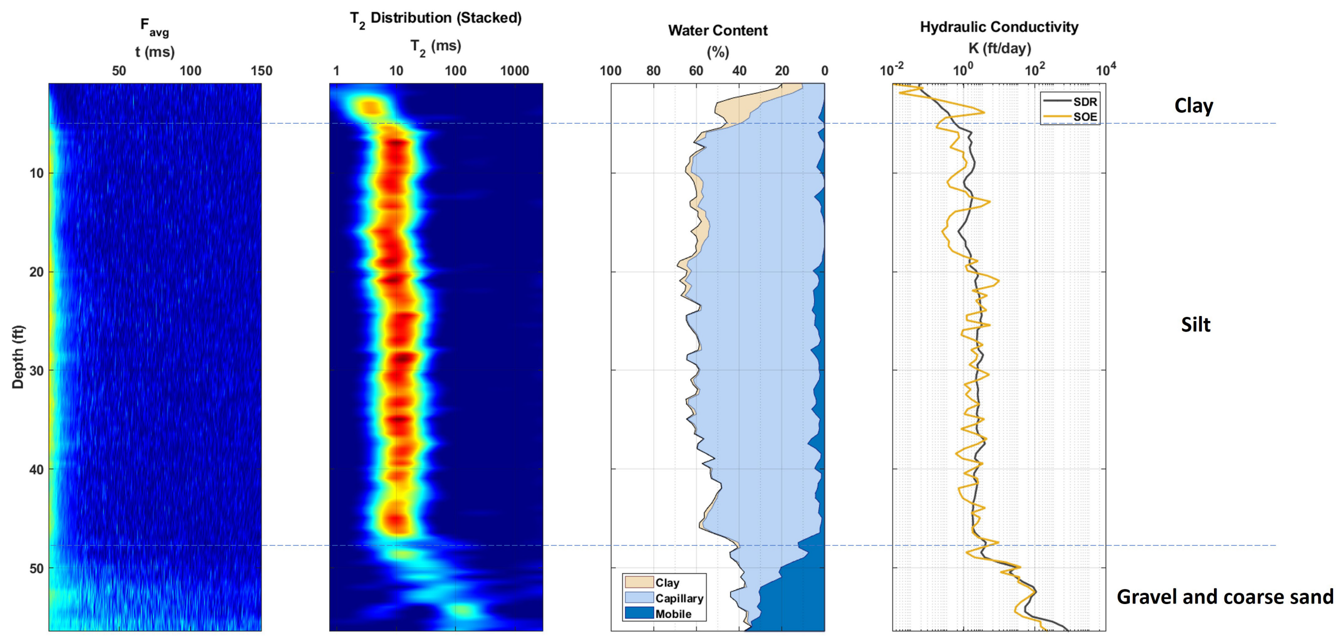

Figure 9. Experimental results obtained from DP NMR and HPT at site 75 in Ebey Island, WA.

sediments in these locations were mostly comprised of high-porosity silt and some sand. The DP NMR measurements accurately and precisely detected a thin layer (~1 ft) of organic matter in the shallow subsurface up to 12 ft. deep at sites 72 and 74 (Figures 7 and 8, respectively). The organic matter layer is characterized by intermediate T2 relaxation times between 10 and 100 ms, high porosity, and larger K as compared to that of the surrounding silt. The observation of organic matter was confirmed by investigating core samples collected from these two locations (Figure 10A) and by Optical Image Profiler (OIP) measurements that was conducted nearby the DP NMR measurement at site 74 (Figure 7). There, a high level of fluorescence indicated the presence of organic matter at the depth of 9.2 ft.

At site 72, the NMR tool detected a localized highly permeable medium to coarse sand layer between 24 and 37 ft., with an NMR-estimated K of about 984 ft./day. This result was confirmed by investigating core samples collected from this location (Figure 10B). An interbedded sand and silt layer between 49 and 72 ft. was found at this location (Figure 8). The NMR data were used to quantitatively estimate K to a much higher range than the HPT, whose upper sensitivity is limited to about 98 ft./day, as can be seen in right panel, Figure 8. In comparison, the upper sensitivity of NMR-derived K values is 9840 ft./day.

Larned, KS

We conducted additional DP NMR (DP140N) and HPT logs at Larned, KS, in February 2023. This site was chosen due to its well-known high-porosity Arkansas River alluvial aquifer between 8.8 and 34 ft., that is separated from the High Plains aquifer by a hard clay layer of about 16 ft. The 2.25-in. drive rods were unable to penetrate into the High Plain aquifer due to the hardness of the overriding clay.

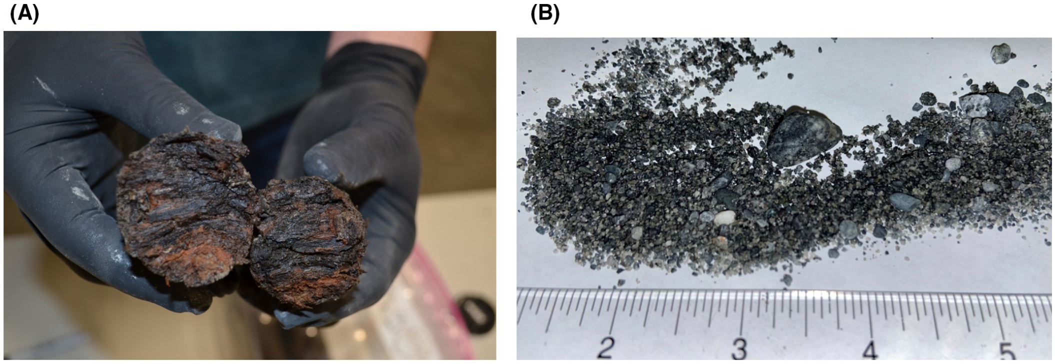

Figure 10. Core materials collected at Ebey Island, WA. (A) Core sample with organic matter from site 74. (B) Coarse sand and some gravel obtained between 24 to 37 ft at site 72.

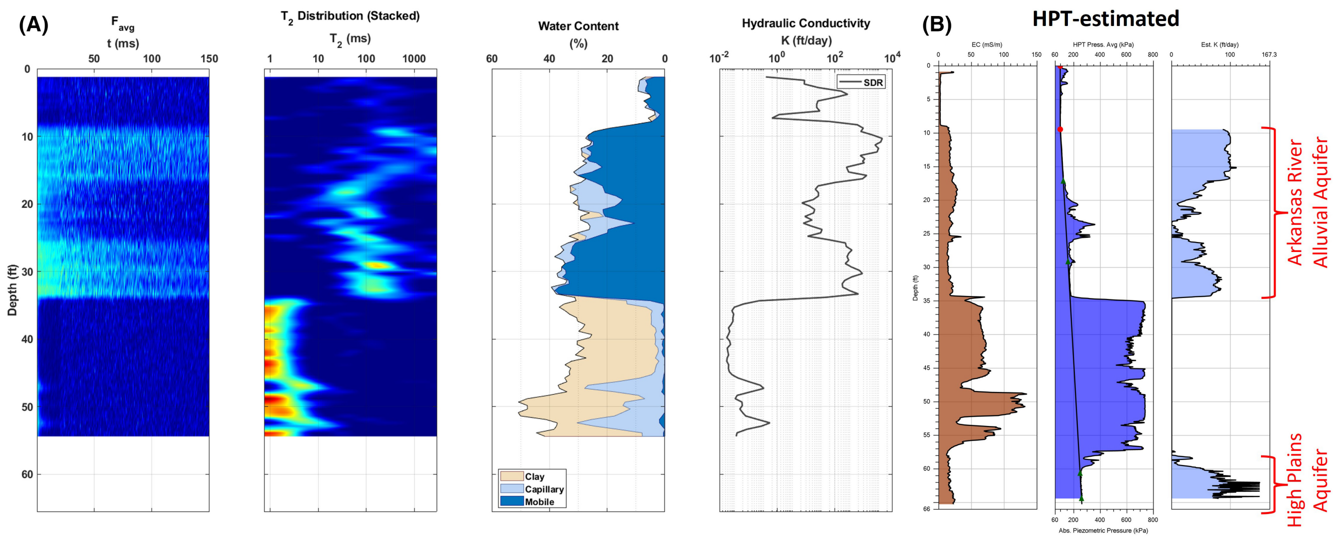

Figure 11. DP NMR (A) and HPT (B) results from Larned, KS.

Advancement of the drive rods ended just above where the DP NMR log began (Figure 11A). The top few meters of the High Plains aquifer were penetrated using an HPT tool and identified via the electrical conductivity and K logs from the HPT measurement (Figure 11B). The DP NMR tool resolves aquifer properties at high resolution, with direct measurements of porosity and relative pore-size distribution. Importantly, DP NMR was able to estimate much larger K values, as compared to HPT, and also differentiate between a very high K sand and gravel deposit (~3280 ft./day) zone at 8.8 to 16 ft., from moderate K sands (32.8 ft./day) between 16 and 25 ft. and high K sands (~328 ft./day) between 26 and 34 ft. The HPT measurement, in contrast, was limited to estimating a maximum K value of about 98 ft./day.

Mine Tailings Investigation

The DP NMR (DP140N) probe was deployed using the CPT machine at a mine tailings site in the United States in July 2022. The mine tailings site setup is shown in Figure 12. In this work, a 25-ton CPT machine was used to deploy the NMR tool though the 2.25-in. drilling rods into the tailings as shown in Figure 12A and 12B. We also collected borehole NMR data using a Javelin JPY238 NMR logging tool in a 3-in. PVC-cased monitoring well located 5 ft from the DP NMR location (Figure 12C). The results of borehole NMR logging were used for direct comparison the reproducibility of DP NMR results.

The results of high-resolution DP NMR are shown in Figure 13A. The NMR measurement includes a direct measurement of total water content in-situ and is equivalent to total porosity where the tailings are fully saturated. Total porosity is a critical parameter required for void ratio calculation. The NMR log also indicates relatively low mobile water content of less than 5% in the top 12 m. Both of these observations are important for the evaluation of mine tailings properties. The results of DP NMR correlated very with results of the borehole logging NMR collected within a nearby 3-in. PVC-cased monitoring well (Figure 13B).

Cosumnes River, CA

The Cosumnes River, in Central California, USA, is one of the last free-flowing rivers on the West side of the Sierra Nevada Range. As a result, the location of this site near Wilton California is prone to flooding during winter atmospheric river events. Moreover, diminishing groundwater levels cause parts of the river to run dry during the

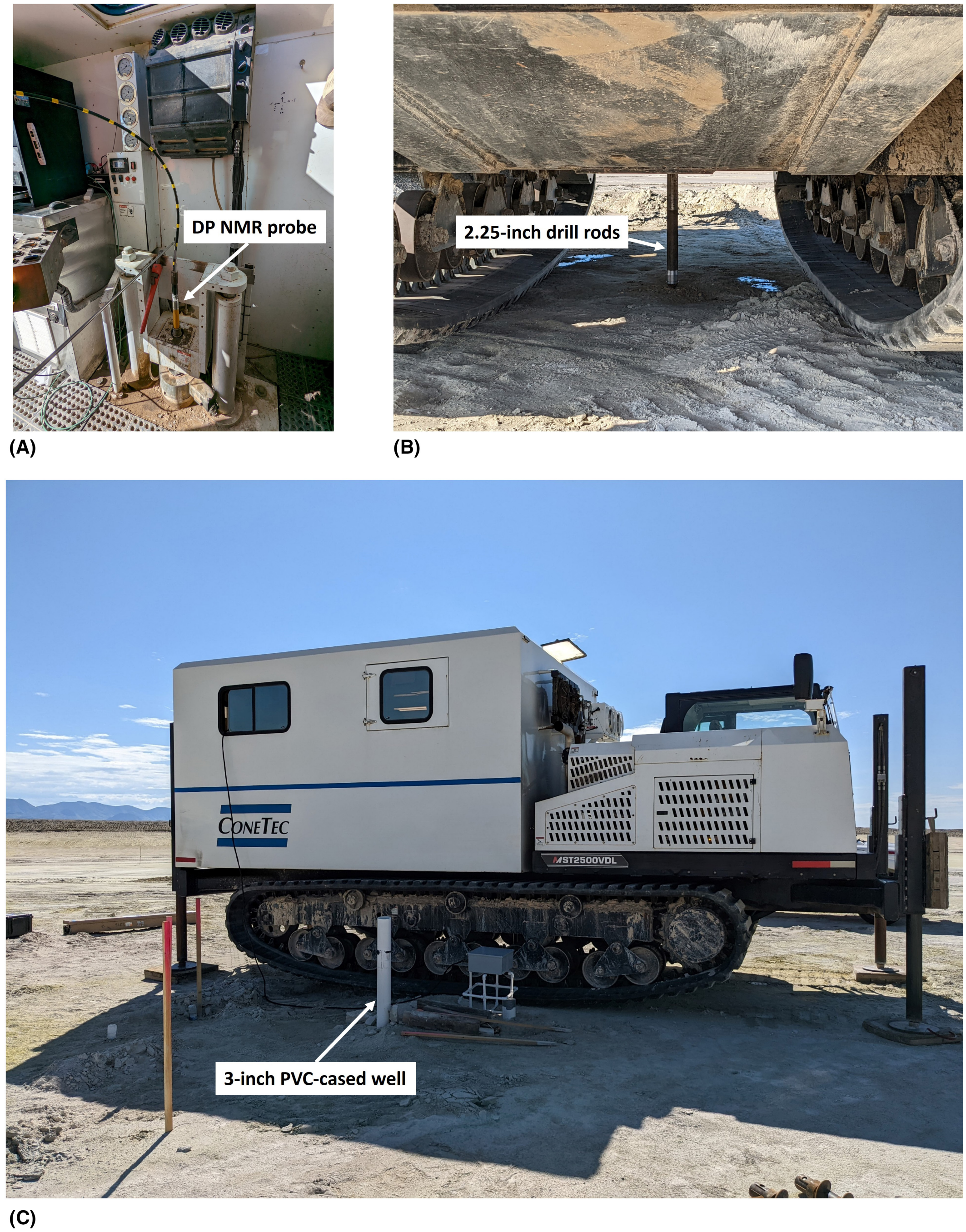

Figure 12. Mine tailings investigation setup. (A) Installation of DP NMR probe within CPT machine. (B) DP NMR probe is deployed through 2.25-in. drill rods into the formation. (C) 3-in. PVC-cased monitoring well located adjacent to DP NMR used to collect borehole NMR logging data for direct comparison with CPT NMR.

summer. We initially visited Consumnes River basin in March 2022 to characterize hydrogeology at candidate sites for managed aquifer recharge operations. In January 2023, a levee along the Cosumnes River collapsed, resulting in flooding of nearby land and major roads. The vineyards adjacent to Cosumnes River levee, where initial NMR work in 2022 was done, were also intentionally flooded as part of a managed aquifer recharge program. We re-visited the site in May 2023, after flooding had subsided, to identify the changes in subsurface water content due to the recent flooding.

Figure 14 compares the DP NMR logs measured at the same location in March 2022 and May 2023. The results in March 2022 indicate a zone of likely saturated aquifer materials between 39 and 62 ft., a clay layer below 62 ft., and an unsaturated zone above 39 ft. with increasing water content in fine sediments in the top 10 ft. probably associated with soil irrigation. The DP NMR log from May 2023 indicates similar water retention in the formation below 39 ft., but much higher water content in what appears to be fully saturated coarse-grained aquifer materials between 13 and 39 ft., with an apparent water table at 13 ft. (Figure 14A vs. 14B).

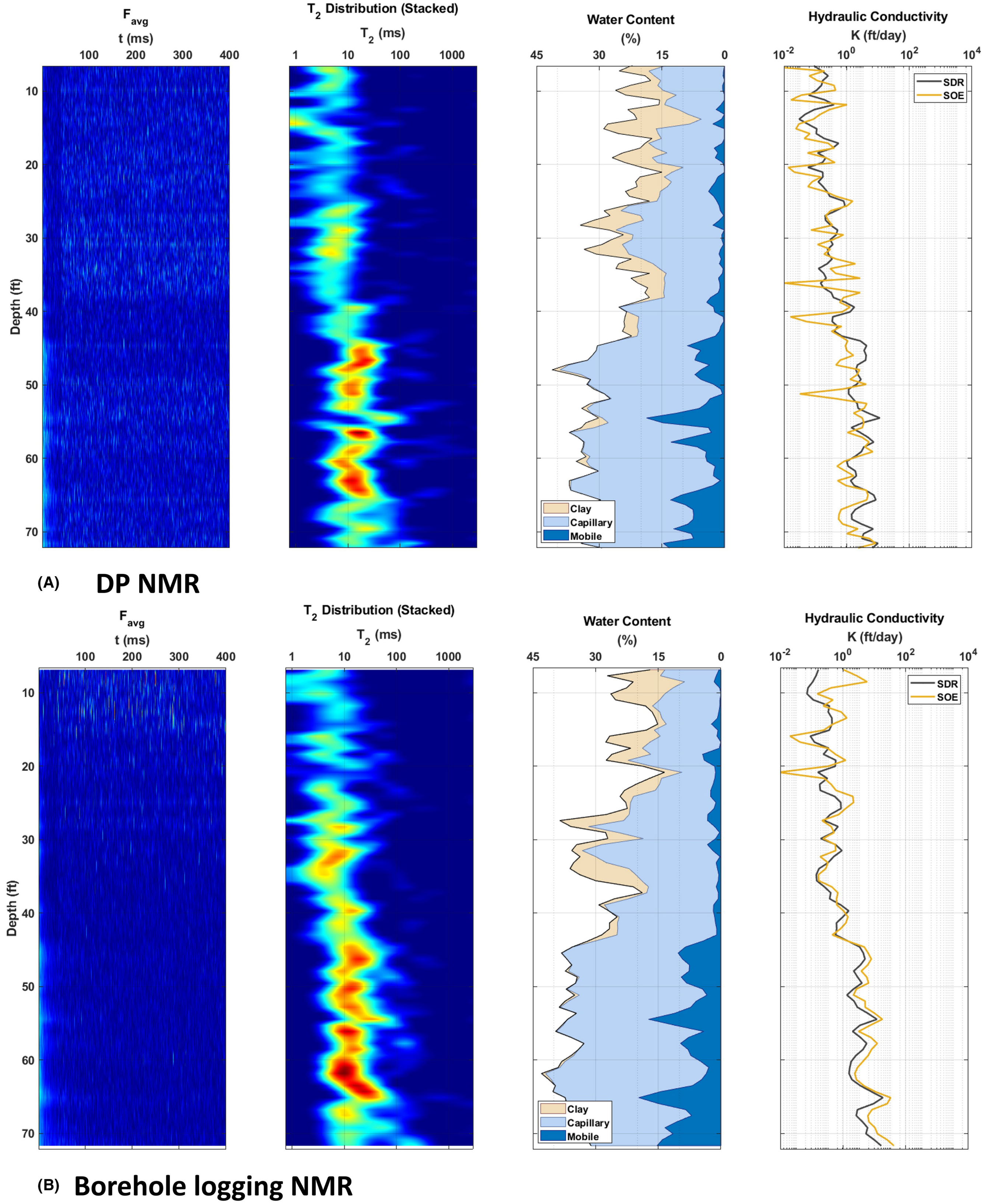

Figure 13. Comparison of NMR results obtained from DP NMR (A) and borehole NMR (B).

Salina, KS

Performance of the high-resolution DP140J probe was evaluated at Geoprobe test site at Salina, KS, in September 2023. DP NMR logging was conducted using a stepped log and the data were collected with high vertical resolution of 2 in. We compared the NMR data obtained from DP140J with results of DP140N probe collected a few meters away from this location in 2020 (Figure 15). Here, the DP140J and DP140N data were collected with vertical resolution of 2 and 6 in., respectively. We observed a good agreement

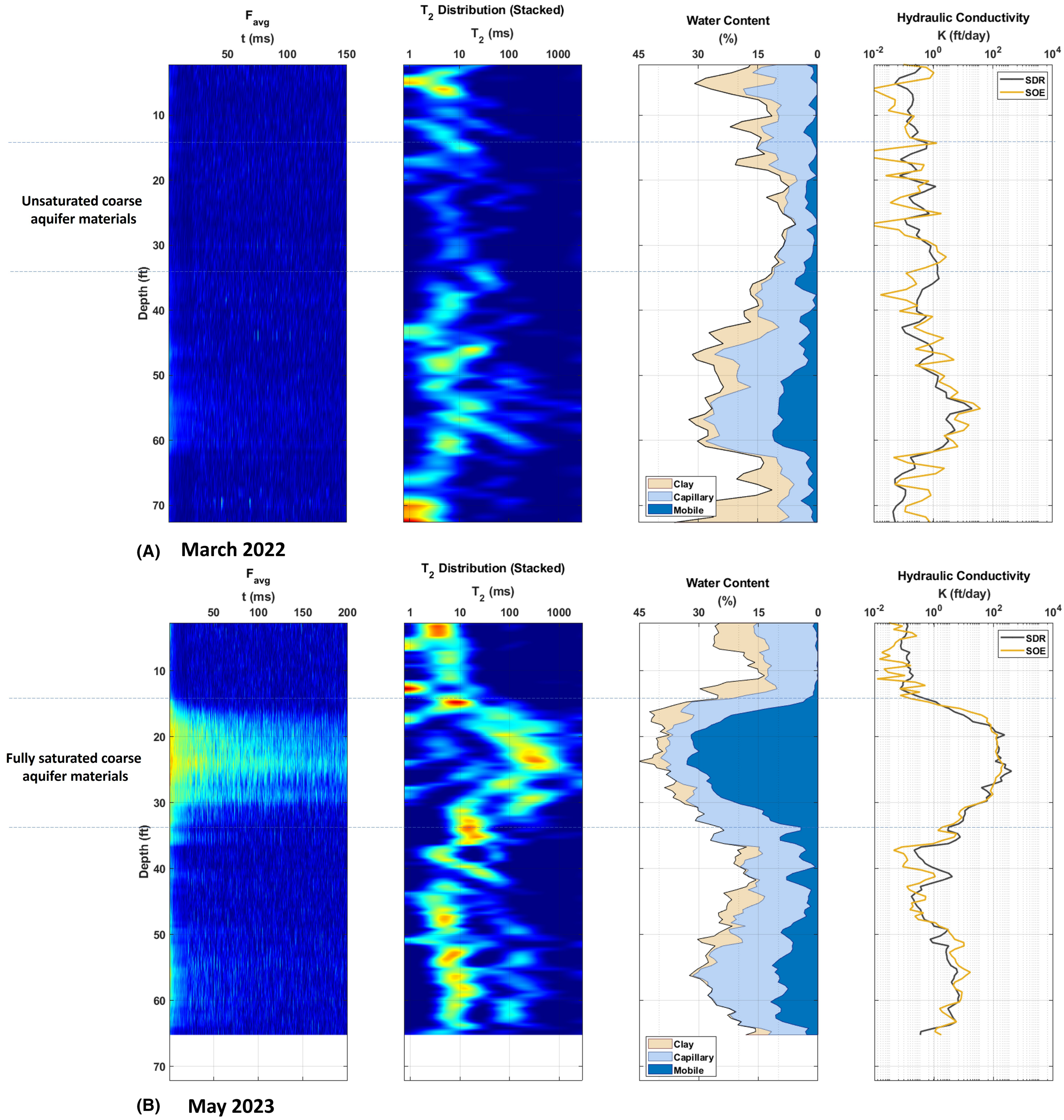

Figure 14. Cosumnes River results before (A) and after flooding (B).

between results collected with these two probes, though there are minor differences due to known lateral heterogeneity of the subsurface. Both probes were able to differentiate between different soil types and provide direct measurement of total porosity in-situ. The DP140J provided very high vertical resolution and was able to define small-scale subsurface characteristics that might be significant for geotechnical and environmental remediation investigations.

It is noted that the total measurement time for the high-resolution DP140J probe is expected to be three times as long as with a DP140N probe, simply due to the similar SNRs of the two tools, and the 2 in. vs. 6 in. native resolutions of the two tools. This would tend to favor the use of the DP140N probe where data collection speed is a priority and indicate the use of the DP140J probe where 2 in. vertical resolution is deemed critical and vertical/lateral coverage or total cost are of less importance.

Conclusions

In this study, we developed and evaluated the performance of novel NMR logging probes that can be deployed in the subsurface via DP methods. DP methods do not use drilling, instead the drilling rods are pushed into the ground

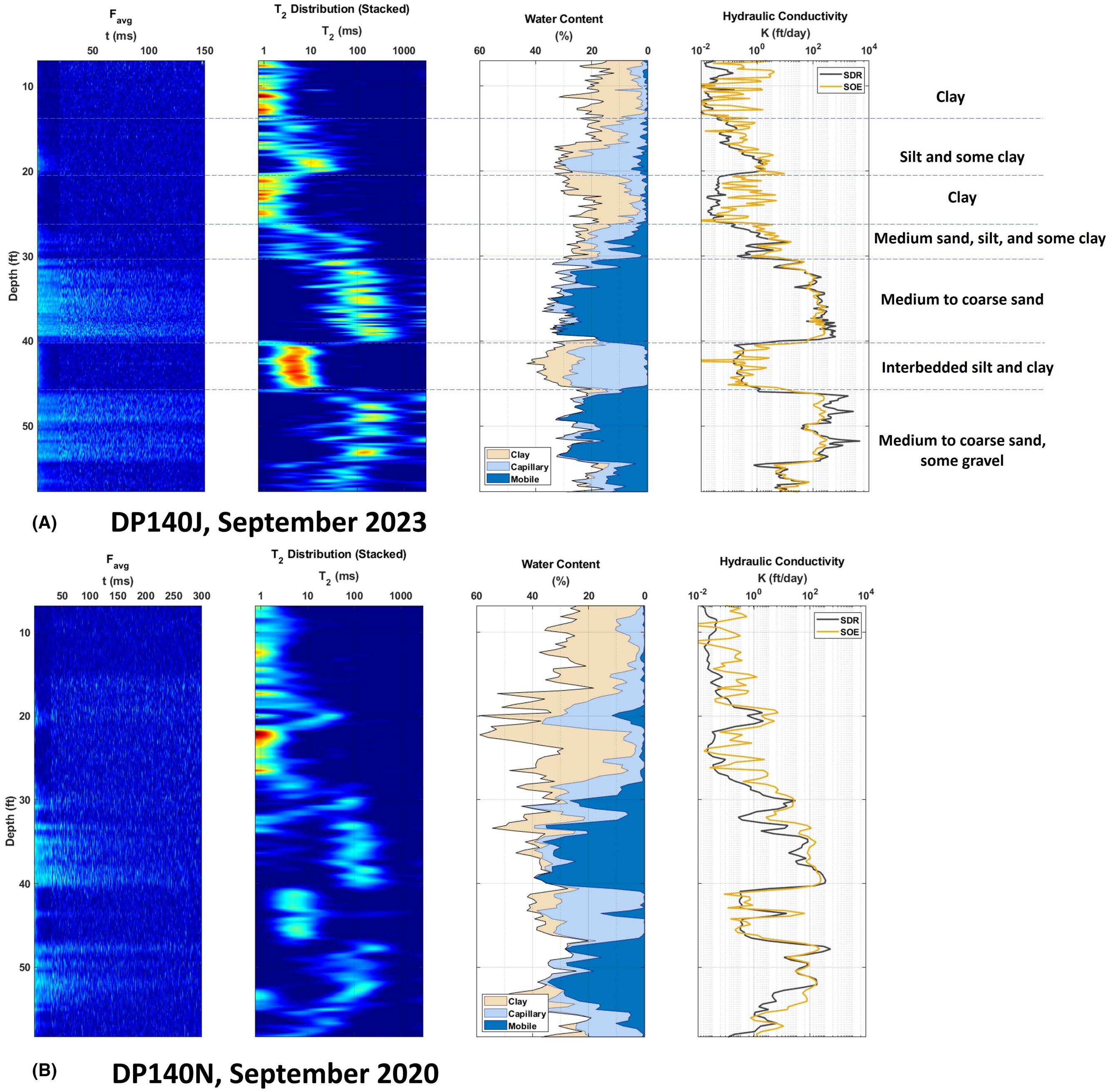

Figure 15. Comparison of DP NMR results obtained with DP140J probe (A, vertical resolution of 2 in.) and DP140N probe (B, vertical resolution of 6 in.).

displacing soil to create a vertical pathway for the geophysical tools, creating small disturbance to the native formation as compared to installation of wells. However, the greatest advantage of DP methods for groundwater examinations is that it is cost and time effective and does not raise issues regarding displacing materials after drilling.

The DP NMR probes introduced here were designed to have a small diameter to enable them to be pushed through widely available 2.25-in. diameter drilling rods. Both probes have a high vertical resolution and low measurement noise, enabling fast data acquisition and high SNR. In this study, DP NMR probes were designed to measure water signal in two cylindrical shells having diameters of approximately 5 and 6 in. that we believe are generally beyond the zone of compression from DP installation that depends on factors such as casing size, soil type etc. Additional studies need to be conducted to investigate the effect of soil compression due to driven casing on NMR measurement.

The DP NMR technology can be utilized with small, track-mounted DP and CPT drilling rigs and enables efficient data acquisition to be conducted in variety of field conditions. The DP NMR technology is applicable in many areas of earth sciences such as HRSC, environmental monitoring, mining, and groundwater resources.

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References

Atlas, S.W. 2016. *Magnetic Resonance Imaging of the Brain and Spine*. Lippincott Williams & Wilkins.

Brown, R.W., Y.C.N. Cheng, E.M. Haacke, M.R. Thompson, and R. Venkatesan. 2014. *Magnetic Resonance Imaging: Physical Principles and Sequence Design*. Hoboken, New Jersey: John Wiley & Sons, Inc.

Claridge, T.D.W. 2016. *High-Resolution NMR Techniques in Organic Chemistry*. Cambridge, MA: Elsevier.

Coates, G.R., L. Xiao, and M.G. Prammer. 1999. *NMR Logging Principles and Applications*. Halliburton Energy Services, Houston: Gulf Publishing Company.

Elsayed, M., A. Isah, M. Hiba, A. Hassan, K. Al-Garadi, M. Mahmoud, A. El-Husseiny, and A.E. Radwan. 2022. A review on the applications of nuclear magnetic resonance (NMR) in the oil and gas industry: Laboratory and field-scale measurements. *Journal of Petroleum Exploration and Production Technology* 12, no. 10: 2747–2784.

Flinchum, B.A., E. Banks, M. Hatch, O. Batelaan, L.J.M. Peeters, and S. Pasquet. 2020. Identifying recharge under subtle ephemeral features in a flat-lying semi-arid region using a combined geophysical approach. *Hydrology and Earth System Sciences* 24, no. 9: 4353–4368.

Freedman, R., and N.J. Heaton. 2004. Fluid characterization using nuclear magnetic resonance logging. *Petrophysics* 45: 241–250.

Haacke, E.M., R.W. Brown, M.R. Thompson, and R. Venkatesan. 1999. *Magnetic Resonance Imaging: Physical Principles and Sequence Design*. New York: John Wiley & Sons.

Keating, K., R. Knight, and K.J. Tufano. 2008. Nuclear magnetic resonance relaxation measurements as a means of monitoring iron mineralization processes. *Geophysical Research Letters* 35, no. 19: L19405, 1–5, https://doi.org/10.1029/2008GL035225

Kendrick, A.K., R. Knight, C.D. Johnson, G. Liu, S. Knobbe, R.J. Hunt, and J.J. Butler Jr. 2021. Assessment of NMR logging for estimating hydraulic conductivity in glacial aquifers. *Groundwater* 59, no. 1: 31–48.

Kennedy, K. 2022. *Introduction to Cone Penetration Testing*. AGS: Association of Geotechnical and Geoenviromental Specialists. https://www.ags.org.uk/2022/09/introduction-to-cone-penetration-testing/ (accessed September 20, 2022).

Kennedy, K. 2018. *Porosity and Permeability Values: Filling the Gaps with NMR (Nuclear Magnetic Resonance)*. AGS: Association of Geotechnical & Geoenviromental Specialists. https://www.ags.org.uk/2018/06/porosity-and-permeability-values-filling-the-gaps-with-nmr-nuclear-magnetic-resonance/ (accessed June 12, 2018).

Kirkland, C.M., and S.L. Codd. 2018. Low-field borehole NMR applications in the near-surface environment. *Vadose Zone Journal* 17, no. 1: 170007.

Knight, R., D.O. Walsh, J.J. Butler Jr., E. Grunewald, G. Liu, A.D. Parsekian, E.C. Reboulet, S. Knobbe, and M. Barrows. 2016. NMR logging to estimate hydraulic conductivity in unconsolidated aquifers. *Ground Water* 54, no. 1: 104–114.

Maliva, R.G. 2016. Direct-push technology. In *Aquifer Characterization Techniques: Schlumberger Methods in Water Resources Evaluation Series No. 4*, ed. R.G. Maliva, 383–402. Cham: Springer International Publishing.

McCall, W.D., and T.M. Christy. 2020. The hydraulic profiling tool for Hydrogeologic investigation of unconsolidated formations. *Groundwater Monitoring & Remediation* 40: 89–103.

McCall, W., T. Christy, D. Pipp, and B. Jaster. 2019. Optical Image Profiler (OIP) and Combined OIHPT Probe for Investigation of LNAPL Sites.

McCall, W., T.M. Christy, D.A. Pipp, B. Jaster, J. White, J. Goodrich, J. Fontana, and S. Doxtader. 2018. Evaluation and application of the optical image profiler (OIP) a direct push probe for photo-logging UV-induced fluorescence of petroleum hydrocarbons. *Environmental Earth Sciences* 77, no. 10: 374.

McCall, W., D.M. Nielsen, S.P. Farrington, and T.M. Christy. 2005. Use of direct-push technologies in environmental site characterization and ground-water monitoring. In *The Practical Handbook of Environmental Site Characterization and Ground-Water Monitoring*, Vol. 2, 345–472. Boca Raton: CRC.

McCall, W., T. M. Christy, and J. J. Butler Jr. 2003. Direct Push Technology and Application to Vertical Profiling of Hydraulic Conductivity in Unconsolidated Formations. International Conference on Radioactive Waste Management and Environmental Remediation.

Olaide, A.J., E. Olugbenga, and D. Abimbola. 2020. A review of the application of nuclear magnetic resonance in petroleum industry. *International Journal of Geosciences* 11, no. 4: 145–169.

Parsekian, A.D., K. Dlubac, E. Grunewald, J.J. Butler, R. Knight, and D.O. Walsh. 2015. Bootstrap calibration and uncertainty estimation of downhole NMR hydraulic conductivity estimates in an unconsolidated aquifer. *Groundwater* 53, no. 1: 111–121.

Pehme, P., H. Crow, B. Parker, and H. Russell. 2022. Evaluation of slim-hole NMR logging for hydrogeologic insights into dolostone and sandstone aquifers. *Journal of Hydrology* 610: 127809.

Perumpral, J.V. 1987. Cone penetrometer applications—A review. *Transactions of the ASAE* 30, no. 4: 939–944.

Ren, S., A.D. Parsekian, Y. Zhang, and B.J. Carr. 2019. Hydraulic conductivity calibration of logging NMR in a granite aquifer, Laramie range, Wyoming. *Ground Water* 57, no. 2: 303–319.

Schmertmann, J.H. 1978. Guidelines for Cone Penetration Test: Performance and Design.

Spurlin, M.S., B.W. Barker, B.D. Cross, and C.E. Divine. 2019. Nuclear magnetic resonance logging: Example applications of an emerging tool for environmental investigations. *Remediation Journal* 29, no. 2: 63–73.

Walsh, D., P. Turner, E. Grunewald, H. Zhang, J.J. Butler Jr., E. Reboulet, S. Knobbe, T. Christy, J.W. Lane Jr., C.D. Johnson, T. Munday, and A. Fitzpatrick. 2013. A small-diameter NMR logging tool for groundwater investigations. *Ground Water* 51, no. 6: 914–926.

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