Advances in Nuclear Magnetic Resonance (NMR) Logging for Hydrogeologic Investigations via Direct Push Technology

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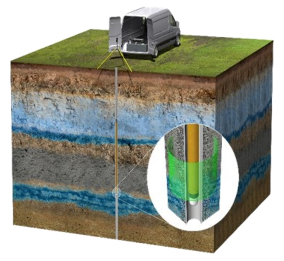
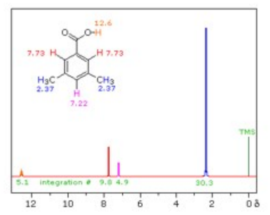
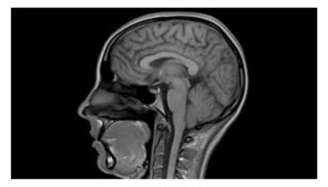
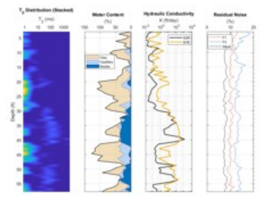
Nuclear Magnetic Resonance (NMR) is an extremely powerful and non-destructive technology for fluid characterization and quantification. The technology has a wide range of chemical (high-field NMR spectrometers), medical (MRI scanners), and geophysical applications (NMR borehole logging instruments).

Organic Chemistry | **Medical MRI** | **NMR Geophysics**

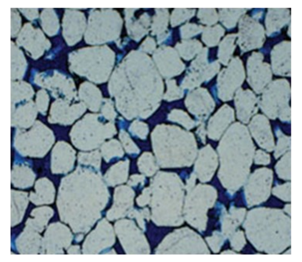


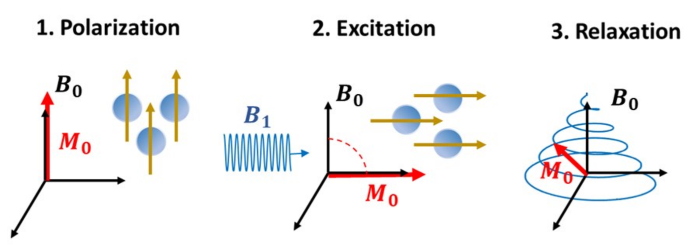
The first successful observations of NMR were seen in 1946. Shortly after this the petroleum industry recognized the potential of NMR measurements for determining: reservoir rocks, pore fluids, and fluid displacement. Multiple companies invested in research to develop a commercially reliable product. This was not achieved until 1984 with the Schlumberger NML tool. In 1978, the Los Alamos National Laboratory developed a logging tool that used permanent magnets and a pulsed radio frequency (RF) (pulse-echo) NMR method.

In general, NMR measurement is conducted in the presence of magnetic field and probes the response of hydrogen spins to magnetic field perturbation. In the presence of the magnetic field (B0), the hydrogen spins in the formation fluids get polarized and produce a net nuclear magnetization that aligns parallel to main B0 field. To detect this magnetization and its associated NMR signal, the spins must be excited into a higher energy state from their equilibrium parallel to the main magnetic field. This perturbation is achieved by application of a pulsed oscillating magnetic field B1 that is tuned to a Larmor frequency of the spins and excites spins. Immediately after excitation, the magnetization left in the perpendicular plane starts to precess about the B0 field at Larmor frequency relaxing back to its equilibrium. The coherent precession of magnetization generates a detectable magnetic field that oscillates at the Larmor frequency. 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.

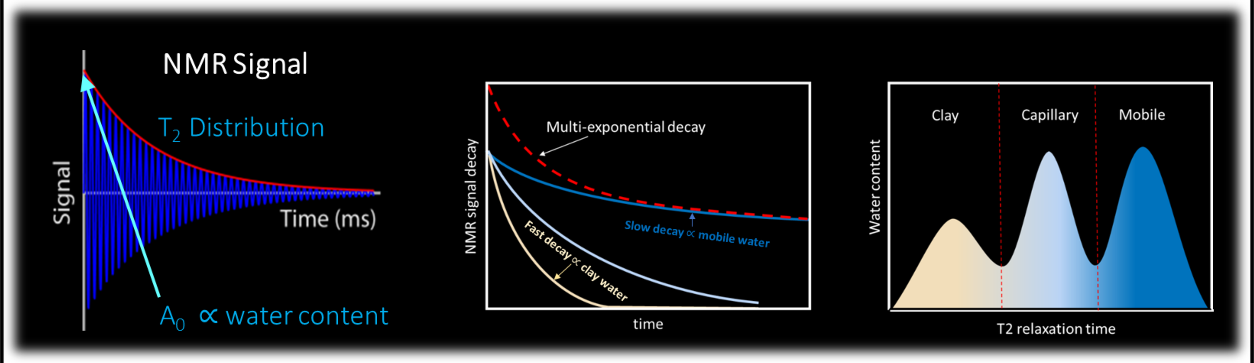
Formation with a water in the pore space



NMR principle



NMR Detection of Water



The initial amplitude of NMR signal represents the amount of detected hydrogens therefore it is directly related to the amount of water in the pore space, or porosity if the formation is fully saturated. The decay rates of NMR signal are used to estimate the relaxation times (T1 and T2) that reflect molecular interactions in pore fluids and between grain surfaces. These relaxation times are strongly correlated with the size of the pore space and so the observed relaxation time distribution is used to distinguish the quantity of water bound in small pores from more mobile water in large pores. The larger the pore size is the longer the relaxation times are. For example, T2 relaxation time of water in large pores such as gravel and coarse sand can be around 1 sec. On the other hand, silts-clays may have relaxation times of just a few msec while bulk water can see relaxation times up to 3 sec. The relaxation times allow for the estimation of pore size distribution and bound and mobile water fractions. Based on the estimates of porosity and T2 relaxation times, the hydraulic conductivity can be estimated using empirical formulas.

Geoprobe Systems® has been partnered with Vista Clara, Inc., Mukilteo, WA, to develop two different NMR tools which are applied with direct push technology. The Direct Push Dart 140N (DP140N) probe consists of a 1.4in diameter fiberglass tube containing the downhole electronics, magnet arrays, and transmit/receive coil. To deploy this tool, a 2.25in casing is driven to depth with an expendable point. Once at the bottom of the borehole, the DP140N probe with attached logging cable can be pushed to the bottom of the casing. The rods are retracted around the NMR probe exposing it out the end of the rods. The operator can then begin logging the formation from the bottom up as the rods are retracted.

The DP140J consists of steel rod upper and lower sections with a non-metallic fiberglass-ceramic composite “window” between them. The NMR sensing electronics are inserted into the steel section with the magnet arrays and coil being positioned directly within the non-metallic window section of the probe. This probe is built with a CPT sub at the bottom of the probe section where a CPT cone can be installed. The DP140J is a static push only tool and would typically be operated collecting CPT data during the advancement to depth while the NMR electronics are turned off. When the terminal depth is reached, the CPT electronics are turned off and the NMR is turned on and the NMR log data is collected during the rod retraction.

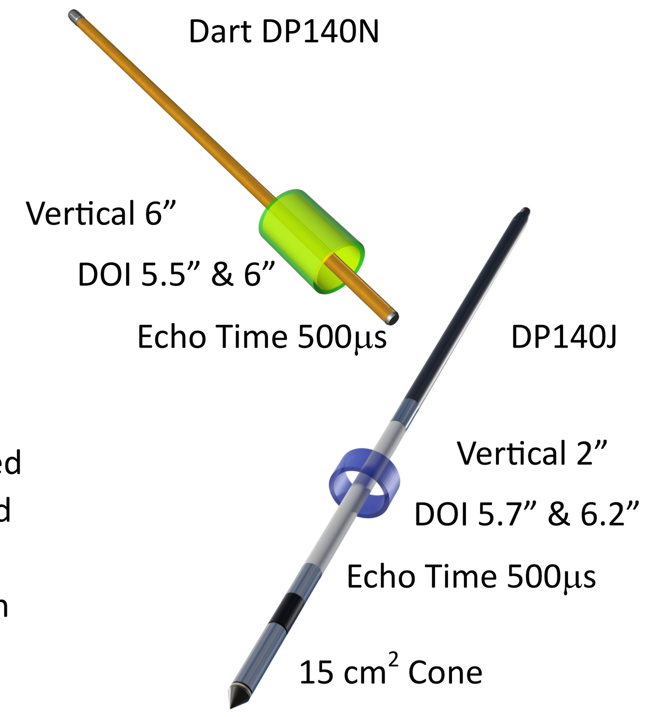
The DP NMR tools are operated by an NMR Surface station and logging cable which are connected to the NMR Tool. The control unit is powered by a 24VDCbattery pack.

NMR directly detects hydrogen nuclei in formation water. Therefore, measuring the NMR signal enables direct quantification of the volume and spatial distribution of groundwater. The behavior of the NMR signal also provides information about the pore scale hydrogeologic environment. It can be used to estimate critical properties governing the flow and storage of groundwater, such as aquifer porosity and permeability in fully saturated formation.

Geoprobe® VISTACLARA INC. NMR GEOPHYSICS

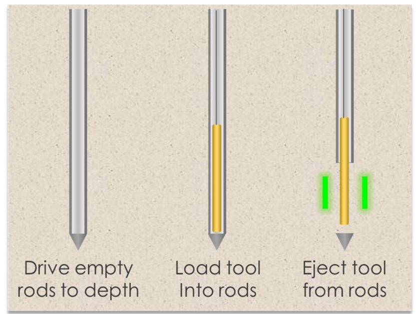
Technology Examples and Direct Push Operation

In geophysical applications, the NMR measurement can be tuned several inches away from the actual logging sensor to focus the measurement into a cylindrical shell within the undisturbed earth formation. The measurement zones of the DP140N probe used with Direct Push is 6in vertically and 5.5in and 6in diameter shells around the probe. The DP140J probe can be led with a 15cm^2 CPT cone on the front end of the tool and has NMR measurement zones of 2in vertical and 5.7in and 6.2in diameter shells around the probe.






Deployment of the DP140N starts with percussion driving 2.25in empty casing to depth with an expendable point on the tip. Once at depth the DP140N probe is inserted into the 2.25in casing along with the attached logging cable and pushed to depth using extension rods. When the probe is at the bottom of the rods, water is added to the rods to prevent soil heave. Then the probe is held at depth with the extension rods while the outer casing is retracted—dropping the expendable point and exposing the dart probe to the formation. Collection of the NMR log can now begin from the bottom of the borehole to the top as the rods are retracted from the ground. As rods are removed from the rod string they will be laid out on the ground until all rods are out and the cable can be pulled through.

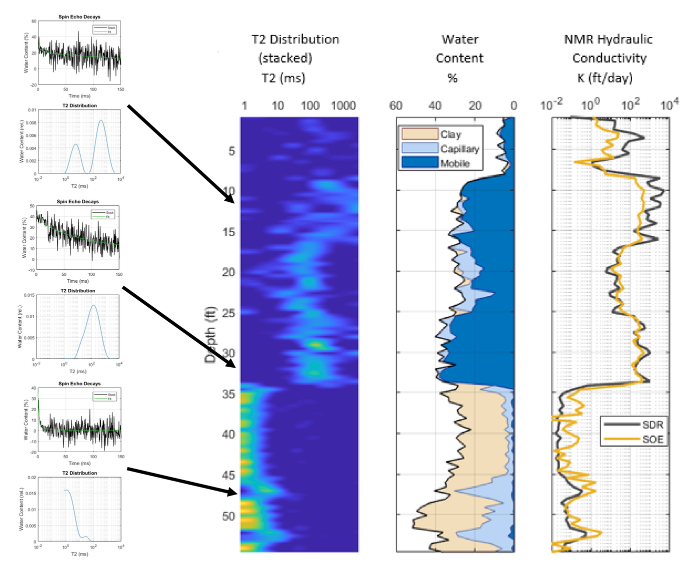






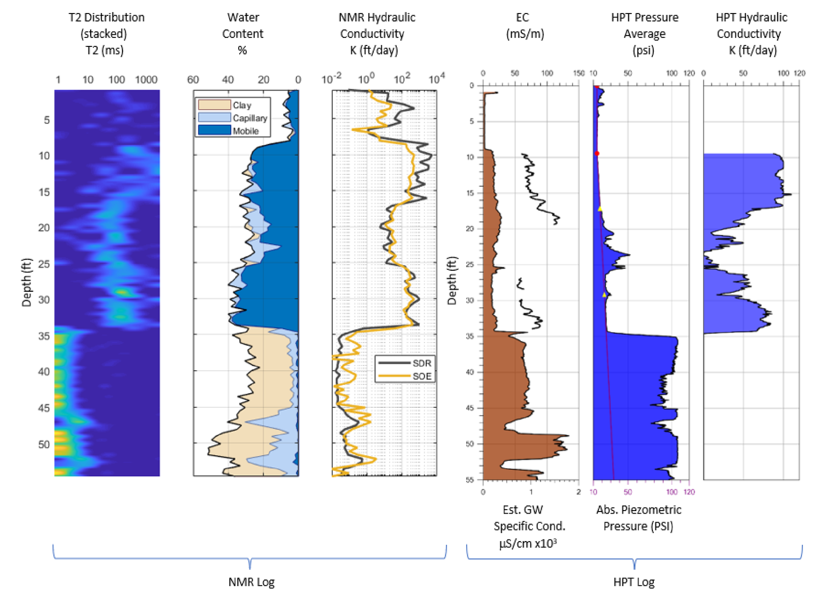
Deployment of the DP140J requires utilization of an anchored direct push rig or 20T CPT truck or cabin crawler. Here we have a 7822DT direct push machine with a single anchor in place to provide 15 tons of push force. As the probe is pushed into the ground a CPT log is collected. Once the log terminal depth is reached the CPT acquisition is turned off and the NMR is turned on. As the rods are retracted the NMR log is collected. The NMR logging cable is strung up through all of the 1.5 or 1.75in rods which is common amongst most Direct Image tools.

NMR Log Examples

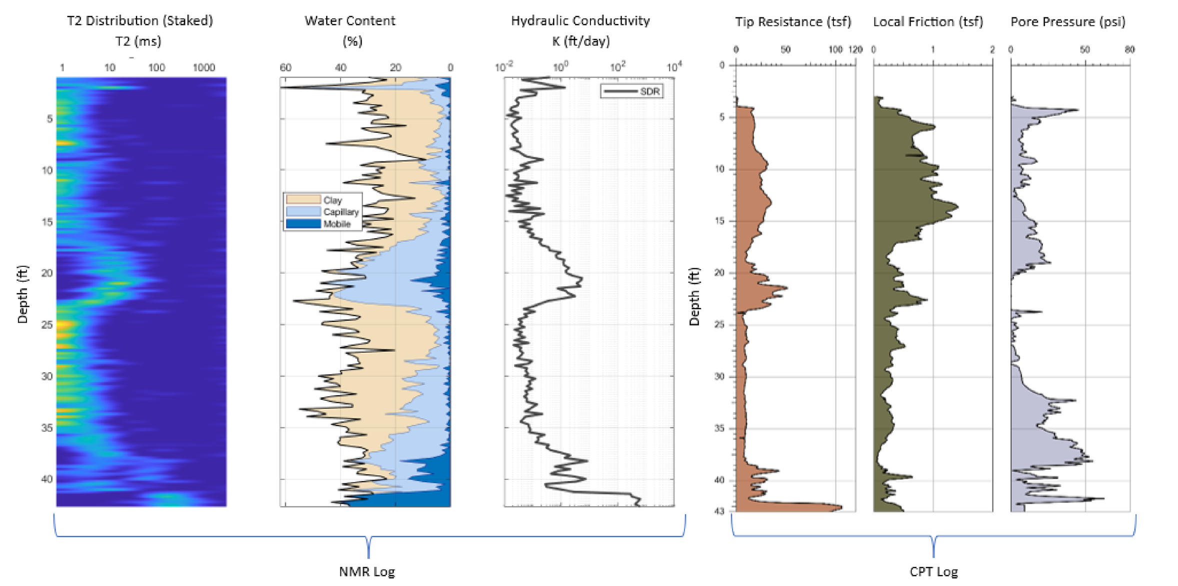


The T2 distribution is associated the varying pore size throughout the log from highly permeable, longer relaxation times of sands and gravels in the top 34ft of the log to much quicker relaxation times of silts ands clays below 34ft. The varying formation structure can be seen within the spin-echo decay times and T2 distribution call outs.

The T2 distribution can then be interpreted into the water content graph. The initial response on the spin echo decay graph is equal to the formation water content and the rate of the decay is used to differentiate between “mobile” water in high permeable formations and “bound” water in silts and clays. The processing software also generates two models of hydraulic conductivity (k) including Schlumberger-Doll research and the sum-of-echoes equations.



This NMR log was collocated with an HPT log which confirm the static water level at approximately 9ft, a highly permeable aquifer between 8-34ft as well as some silty material between 20-25ft and a couple slightly more permeable zones between 45-55ft. The HPT hydraulic conductivity (K) estimation reaches its model limits of ~75ft/day in the top 7ft of the aquifer and between 30-35ft. The NMR models can effectively estimate K an order of magnitude above and below the HPT estimations.



The NMR Log above was performed with the JP140J probe along with CPT. The formation at this location is predominately silts-clays from the surface to around 38ft before it transitions into a sandy aquifer at the base of the log. There is also a silty sand layer from 17-22ft. The clays can be observed within the NMR log with faster T2 distributions and lower K values while on the CPT log they are displayed by higher local friction caused by sticky clays above 20ft, higher pore pressure values and lower tip resistance noticed especially from 19-38ft. The silty sand zone from 17-22ft shows slightly longer T2 relaxation times, higher K values on the NMR and increased tip resistance and lower pore pressure on CPT. These same relationships are also seen below 38ft as the formation transitions into an increasingly sandy formation.