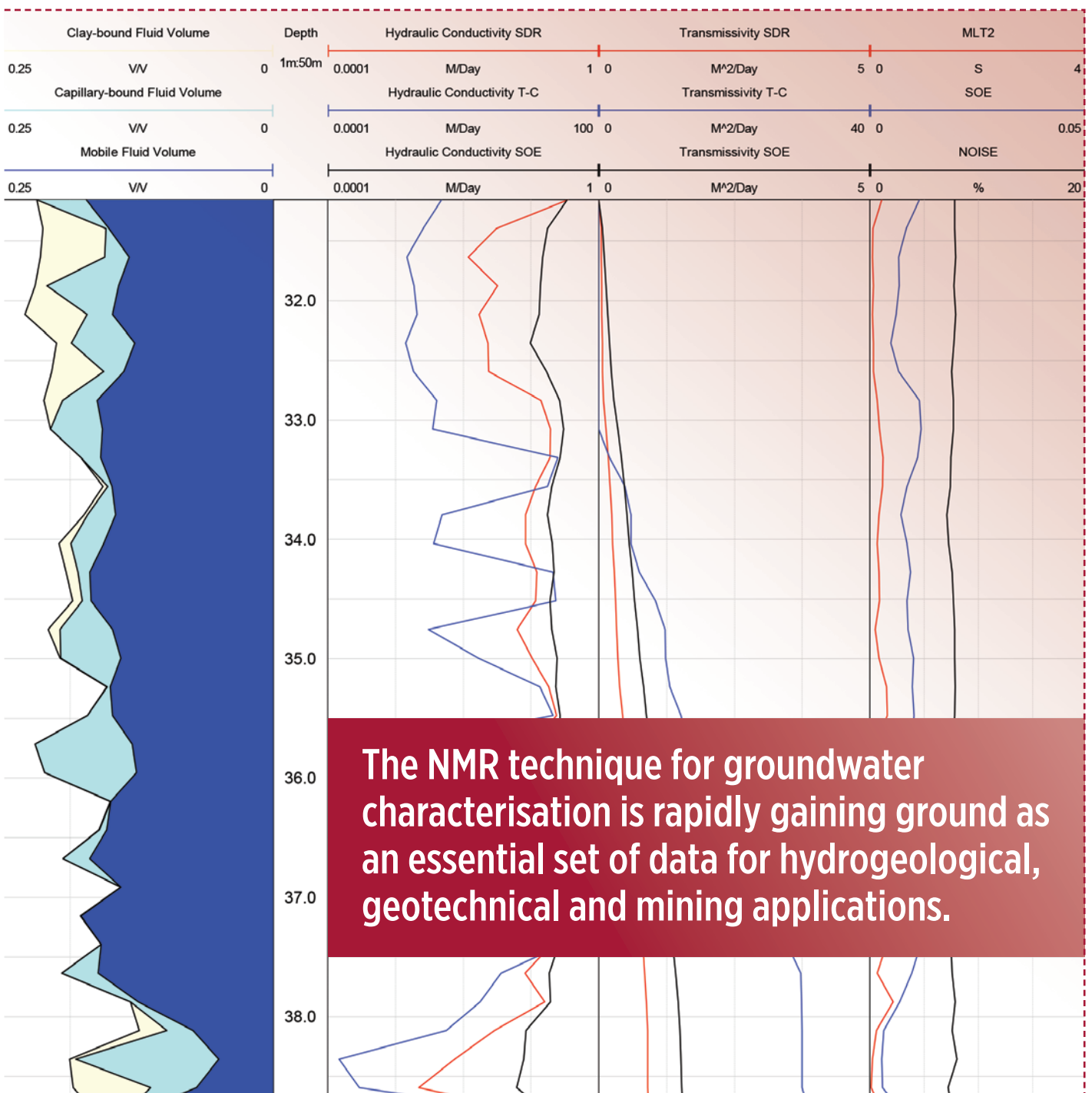
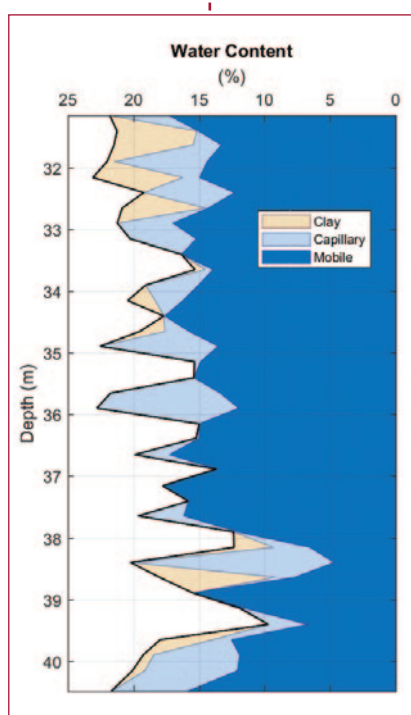
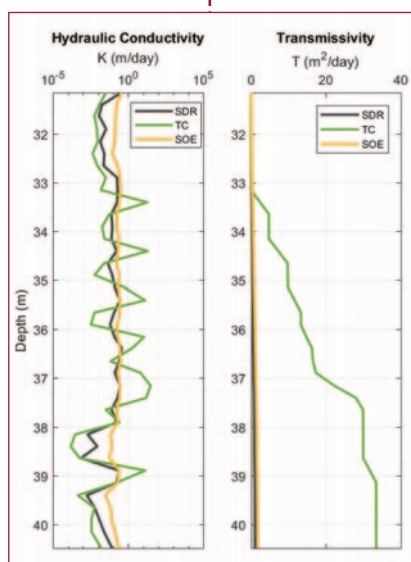


# NMR for Geotechnical, Hydrogeological and Mining Applications





Above: Examples of NMR borehole data.

## NMR versus Neutron Porosity Logging and Hydraulic Testing Techniques

Before the introduction of borehole NMR technology for measuring ground water pore size characteristics, estimates of hydraulic conductivity have traditionally been obtained by hydraulic testing techniques. There are a variety of established tests including slug tests, airlift tests, packer tests and pumping tests, with packer tests being popular for geotechnical boreholes. Packer tests involve isolating sections of the borehole with inflatable packers and then pumping water under pressure to enable measurement of the resulting fluid flow. The data resulting from the tests and the interpretation of it is well documented and understood.

Neutron porosity logs have enjoyed a lot of success measuring the water content in formations i.e. the total porosity. However, it is not possible with this method to identify how the fluid is held within the formation, whether it is mobile, capillary or clay bound.

In addition to the above, standard wireline probes are often run to provide further information about the groundwater conditions. Caliper and Televier data can indicate suitable sections of borehole over which the hydraulic tests can be run with Televiers also providing information on fractures and bedding. Resistivity logs, long established as a standard for water logging, provide information on bedding layers and fluid distribution. Temperature Conductivity logs and flow meter logs also provide information relating to ingress and egress of borehole fluid from aquifers.

Packer tests can be time consuming and may not be suitable for very high or very low permeability formations. In addition, a clean rotary drilled borehole is required to prevent leakage around the packer which can cause false interpretation of the test results.

The disadvantages of neutron porosity logging are the limited data provided and the complex regulatory and safety overhead of systems using strong AmBe nuclear sources.

*The advantage of the NMR technique is that it quickly provides detailed repeatable results characterising the groundwater profile from a single borehole including, most significantly, details of how the fluid is held within the formation.*

## Hydrogeology

Characterising and understanding groundwater conditions is vital for hydrogeologists involved with water production including public water supply, flood and drought management, water quality and contamination issues including wastewater and impacts on protected habitats.

Where NMR logging is conducted in the unsaturated zone above the water table good data is achievable from the reduced level NMR signal. However, only the water content of the formation will be measured yielding a volumetric water content as some of the pore space will not be water filled. Also, estimates of hydraulic conductivity using the standard formulas are not meaningful in the unsaturated zone.

Below the water table the NMR produces profiles with depth of water content distribution by pore size and values for hydraulic conductivity and transmissivity using three estimation techniques: Sum of Echoes, Schlumberger-Doll Research and Timor-Coates.

## Geotechnical

For major civil engineering projects, designers will also need the expertise from hydrogeologists to understand how groundwater considerations may affect their designs. The information provided by NMR logging would be relevant for sub-surface structures, pile design and projects involving tunnels, therefore most major civil engineering projects.

## Mining and Minerals

In the mining and minerals industry there are many hydrogeological factors that impact on the development and working of mines. To understand the hydrogeological conditions data may be collected from existing exploration boreholes initially, but as the project advances it may be necessary to drill additional boreholes purely for hydrogeological testing purposes. Apart from surface and groundwater considerations it is vital that geotechnical and hydraulic parameters of formations around the mine are understood as they may have implications on mine stability and depressurization. NMR logging, as with most geophysical probes can augment data from other investigation techniques providing valuable information on the undisturbed or ground state of the formation.

**Robertson Geo Operational Services teams have been using NMR technologies at several locations and applications.**

### Lower Thames Crossing

In 2019, as part of a full suite of geophysical logging probes, Robertson Geo was asked to provide NMR logging. In partnership with Vista Clara Inc it supplied an NMR system using the Javelin JP238 probe with four depths of investigation or frequencies. Data quality was very good but deploying this tool through 100mm steel drill casing was problematic due to the strength of the magnets and relatively low weight of the tool (35 lbs). Consideration was then given to deploying the wireline Javelin probe which is heavier and contains fewer permanent magnets. Vista Clara also developed a new non-conductive standoff and centralizer specifically for deploying through these 100mm drill pipes.

### HS2

HS2 is the largest infrastructure project in Europe and involves the construction of more than 300 bridges and 70 viaducts for the first phase alone. Robertson Geo has been working on the project since 2015 and site investigation work is continuing as new phases are undertaken. In the early days of HS2 site investigation NMR logging was not available but has now been included for work in the northern section between Birmingham and

Manchester in 2021. The Javelin JPY238 probe with two depths of investigation continues to be used on this project.

## Kendal

Robertson Geo secured a contract to conduct a comprehensive geophysical survey for a major flood management scheme in Kendal. Part of the remit was to conduct NMR logging which was performed using a Vista Clara Javelin 238 probe with two depths of investigation. This operates in a standard wireline configuration which meant that the same winch could be used for NMR as for the rest of the geophysical probes, simplifying operations and reducing client costs. This project is still ongoing with NMR data being collected on all boreholes to date.



**Robertson Geo engineers on-site at the flood management project site Kendal UK.**  
(GeoUnlocked issue 11, page 7)

## BGS

At Sutton Bonington, in collaboration with BGS and Nottingham University, Robertson Geo is involved in pioneering research for carbon sequestration. Several deep boreholes have been constructed to provide a field site for the testing of carbon dioxide injection and monitoring its dispersal in a target formation. As part of the logging suite, NMR has been included to help understand the groundwater conditions across the test location. The boreholes being logged are cased with PVC which presents no problems when acquiring NMR data.

## NMR Field Practice

The Javelin 238 probe deployed in its wireline configuration can, in many aspects be managed like any other probe, albeit quite long (3.6m) and heavy (30kg) with a 60mm diameter. It runs on 300V DC internally, and additional safety protocols have been put in place for its operation.

The CE certified Javelin Wireline system comprises a probe and a surface unit, from Vista Clara, and a custom-made patch box was designed by Robertson Geo development to connect with a standard four core winch. Due partly to Covid restrictions initial training was provided by video link from USA. Once staff were all trained, consideration was given to additional controls for working in the field environment. This covered the voltage, steelwork precautions, permanent magnets, power on/off sequencing, connectivity and manual handling of the probe.

In most cases the probe would be raised by use of a sheave wheel on the drill rig with centralisers/offsets affixed which reduced the potential adhesion of the magnets to the casing; this meant that entry to and exit from the borehole was easily achieved.

The probe is run from the bottom up to achieve smoothness and cannot be switched on near to metal casing. Log speed is typically less than 1 metre/minute and there is an option to run statically at discreet intervals.

As the majority of geotechnical boreholes are now drilled to 146mm "Geobor S" and are logged in sections it was vital that the probe could readily pass through the "Geobor S" drill bit without the magnets adhering. For the two depths of investigation system this worked perfectly.

## NMR System Calibration

All geophysical logs conducted by Robertson Geo Operational Services are backed by a valid conformance certificate. As designers and manufacturers of practically all its own equipment the calibration and conformance requirements are similarly designed as an integral part of the development process.

*The NMR, manufactured by Vista Clara, has its own calibration regime as below:*

Pulse sequence parameters including pulse length and echo time shift are determined by testing in 100% water using repeated long repetition times until a maximum amplitude on the echo signals is achieved.

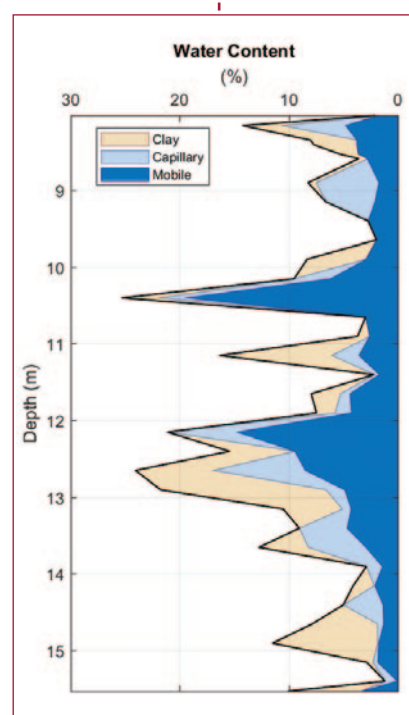
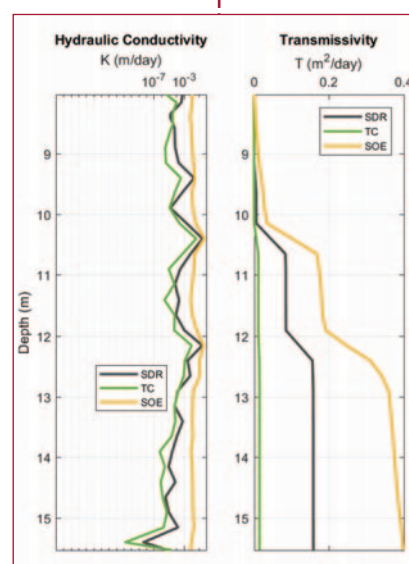
A second calibration is then run, in a similar manner in the same tank, to determine the conversion factor from NMR spin echo amplitude (in volts) to water content as a percentage of volume, as well as calibrating the phase of the signal.

Once the above calibrations have been conducted there is unlikely to be significant change in the calibration unless some components are changed. As the requirements for the calibration are strict, (i.e. sufficient water tank size, no metal or steel in proximity and no external RF interference) this calibration is probably best left to the manufacturers. However, there is a facility in the Javelin Pro Processor software to enable this to be conducted anywhere where there is an acceptable test unit.

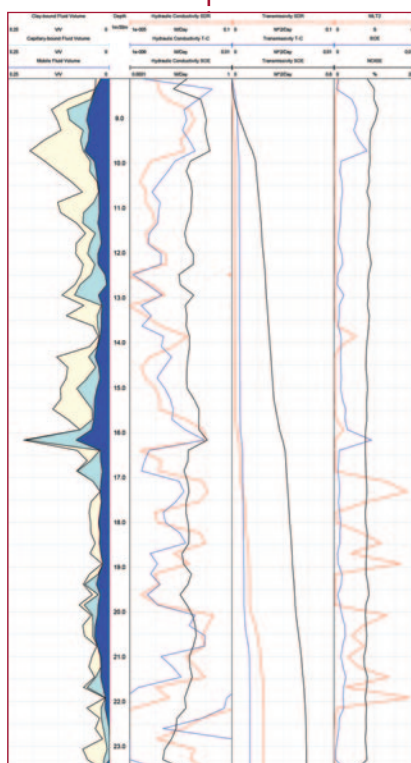
Vista Clara routinely re-calibrates all rental probes that pass through their manufacturing facility and for all probes the software can export a calibration report which will indicate if noise levels remain acceptable or if any calibration parameters have changed significantly.

## Multiple Investigation Depths (or frequencies)

To ensure that the resulting data from NMR relates to an undisturbed part of the formation it is vital that there is sufficient depth of investigation. Oil well boreholes with their relatively large diameters and invasive mudcake adhering to the walls require a deep radius of investigation, usually with four discreet radii (or frequencies). For geotechnical and mineral exploration boreholes



*Above: Examples of NMR borehole data.*



Above: Example of NMR borehole data.

## The NMR probe produces the following outputs versus depth:

OUTPUT	UNIT	DESCRIPTION
Total Porosity $\phi$	V/V	A unit equal to the percentage of pore space in a unit volume of rock, measured from the longitudinal relaxation rate
Clay Bound Fluid Volume	V/V	Percentage of pore space attributable to clay bound fluid, measured from a cut-off on the transverse relaxation rate T2
Capillary-bound Fluid Volume	V/V	Percentage of pore space attributable to capillary bound fluid, measured from cut-offs on the transverse relaxation rate T2
Mobile Fluid Volume	V/V	Percentage of pore space attributable to mobile fluid, measured from a cut-off on the transverse relaxation rate T2
Hydraulic Conductivity SDR	M/Day	Measure of how easily water can pass through soil or rock using Schlumberger Doll Research equation
Hydraulic Conductivity T-C	M/Day	Measure of how easily water can pass through soil or rock, estimated using Timur-Coates equation
Hydraulic Conductivity SOE	M/Day	Measure of how easily water can pass through soil or rock, estimated using Sum of Echoes
Transmissivity SDR	M <sup>2</sup> /Day	Measure of how much water can be transmitted horizontally using Schlumberger Doll Research equation
Transmissivity T-C	M <sup>2</sup> /Day	Measure of how much water can be transmitted horizontally using Timur-Coates equation
Transmissivity SOE	M <sup>2</sup> /Day	Measure of how much water can be transmitted horizontally using Sum of Echoes
MLT2	log base 10 (sec)	Mean Log transverse relaxation rate (of T2)
SOE	$\mu$ V	Sum of echoes
Noise	%	Percentage of signal attributed to noise

the diameter is generally less than 150mm and two depths of investigation gives sufficient radius to measure the undisturbed zone.

routine as it provides a cost-effective means of augmenting or confirming data from other methods.

## NMR Glossary of Data Outputs

The outputs from NMR logging show a variety of information, most of which will be familiar to hydrogeologists including hydraulic conductivity and transmissivity estimates. The detailed porosity data it provides however, being directly linked to pore size is difficult to obtain by other means.

As more data becomes available and comparative studies between NMR and existing techniques take place acceptance of NMR is expected to become

## The Future of NMR

With a wealth of invaluable information and relatively straightforward deployment the NMR technique for groundwater characterisation is likely only to gain in popularity over time. Currently the price point for NMR logs remains significantly higher than other logs due to the cost and complexity of the systems, but Robertson Geo has committed to it as the way forward for groundwater investigation. If the point is reached when NMR can be accepted as a replacement for the established practice of packer testing then the price can quickly look extremely cost effective.

 **MORE: Javelin JPY238 NMR Probe** (GeoUnlocked issue 9, page 6)

# Javelin Wireline Slim

## Small-Diameter Magnetic Resonance Wireline Logging Tool

### For professional geophysical logging operators

The new Javelin® Wireline Slim provides high-resolution, continuous measurements of principal aquifer properties for groundwater and environmental investigations:

- Porosity
- Bound and mobile water content
- Pore size distribution
- Hydraulic conductivity
- Natural gamma

### Applications

- Geotechnical site investigations
- Groundwater resource management
- Aquifer storage and recovery
- Environmental site characterization
- Mine water engineering
- Brine and leach mining

Two independent measurement shells (shown to scale)

