Groundwater Assessment in a Coal Measures Sequence Using Borehole Magnetic Resonance

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SUMMARY

Hydraulic behaviour of an aquifer is defined in terms of the volumes of water present, both producible and not (specific yield and specific retention), and the productivity of the water (hydraulic conductivity). These parameters are typically evaluated using pumping tests, which provide zonal average properties, or more rarely on core samples, which provide discrete point measurements. Both methods can be costly and time-consuming, potentially limiting the amount of characterisation that can be conducted on a given project, and a significant measurement scale difference exists between the two.

Borehole magnetic resonance has been applied in the oil and gas industry for the evaluation of bound and free fluid volumes, analogous to specific retention and specific yield, and permeability, analogous to hydraulic conductivity, for over twenty years. These quantities are evaluated continuously, allowing for cost-effective characterisation, and at a measurement scale that is intermediate between that of core and pumping tests, providing a convenient framework for the integration of all measurements.

The role of borehole magnetic resonance measurements in hydrogeological characterisation is illustrated as part of a larger hydrogeological study of a coal measures unit and associated overburden. Borehole magnetic resonance has been used for aquifer and aquitard identification, and to provide continuous estimates of hydraulic properties. These results have been compared and reconciled with pumping test and core data, considering the scale differences between measurements. Finally, an integrated hydrogeological description of the target rock units has been developed.

Key words: coal measures, hydrogeology, magnetic resonance, well logging.

INTRODUCTION

Hydrogeological characterisation of aquifer rocks requires several parameters describing both the storage and flow capacity of the aquifer. Storage parameters include the total volume of water present—the porosity or, in the vadose zone, moisture content—as well as the volumes of water that can and cannot be produced—the specific yield and specific retention. Other storage parameters include the rock and water compressibilities, which together define specific storage. Specific storage and specific yield together define storativity. Flow parameters include the hydraulic conductivity and transmissivity. Storativity and transmissivity are fundamental descriptors of aquifer behaviour.

Hydrogeological parameters are typically determined using a variety of well testing methods, which generally have greatest sensitivity to flow properties such as hydraulic conductivity. Measurements on core samples can also be used to characterise many hydrogeological parameters, although core data is not acquired as commonly as well test data. Core analysis provides characterisation of small, discrete samples of an aquifer. While well tests sample a larger aquifer volume, they also provide only discrete measurements of aquifer properties. A significant scale difference in the range of ten orders of magnitude also exists between the two types of measurement so reconciling both sources of data, when available, can be extremely challenging. Acquiring core data and test data can both be time consuming and costly exercises, which may limit the amount of characterisation that can be conducted on a given project.

Quantitative use of borehole geophysical measurements, which provide continuous data over an entire aquifer interval, is usually limited to evaluating porosity or water content. Geophysical measurements may also be used qualitatively for applications such as lithology identification, stratigraphic correlation, or fracture description. This is due to the lack of sensitivity of most borehole geophysics methods to pore geometry, which controls properties such as specific retention, specific yield, and hydraulic conductivity. Borehole magnetic resonance, which is a measurement sensitive to both pore volume and pore geometry, has been used in the oil and gas industry for over twenty years to evaluate storage and flow properties of hydrocarbon reservoirs. The use of borehole magnetic resonance in hydrogeological characterisation is increasing as the technology becomes more readily available. Borehole magnetic resonance provides continuous measurements of hydrogeological properties at a scale intermediate between core and well test data, providing a convenient framework for integration of all data.

BOREHOLE MAGNETIC RESONANCE

Borehole magnetic resonance (BMR) takes advantage of interactions between hydrogen nuclei and applied (electro)magnetic fields. Hydrogen nuclei possess both angular momentum and a magnetic moment; simplistically they behave like magnets spinning around their magnetic axes. The rate at which the nuclei spin is a function of the magnetic field strength they are exposed to. In a volume of water, or other hydrogen-containing fluids, the magnetic fields of the various hydrogen nuclei in the different fluid molecules will be randomly oriented. If an external magnetic field is introduced, these nuclei will align themselves with the external magnetic field, or polarise. If the effect of this external magnetic field is then removed, the nuclei will over time dephase, until they are again randomly oriented.

A magnetic resonance measurement consists of two steps (**Error! Reference source not found.**). In the first step, an external magnetic field B0 is introduced for a certain period, the wait time or polarisation time. During this period, the hydrogen nuclei align with the B0 field. In the second step, the effect of the external magnetic field is removed. In practice, this is done by applying an electromagnetic pulse at a frequency in resonance with the spin rate of the hydrogen nuclei, tipping the nuclei through 90° into the secondary B1 field plane. As well as effectively removing the influence of the B0 field, this also results in the tipped hydrogen nuclei rotating around the B0 direction and perpendicular to their magnetic axes, or precessing. The precessing hydrogen nuclei generate an oscillating electromagnetic field that can be detected. This rotation rate is governed by the initial spin rate of the nuclei, which is governed in turn by the B0 field strength.

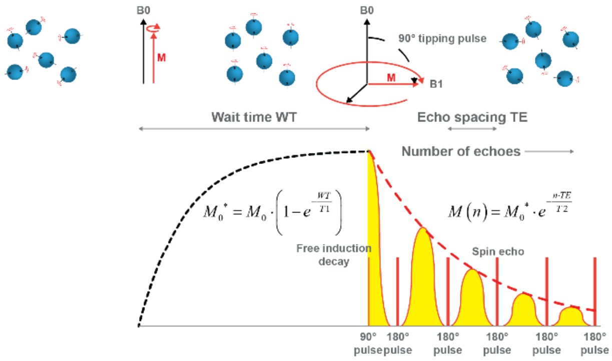

Figure 1: Making a magnetic resonance measurement. Spinning hydrogen nuclei polarise under the influence of an external magnetic field B0, and dephase when the influence of this magnetic field is removed; this is achieved by tipping the nuclei through 90° into the B1 plane using a resonant frequency electromagnetic pulse. While rotating in the B1 plane, the hydrogen nuclei in turn generate an oscillating electromagnetic signal that is measured. Polarisation and dephasing are quasi-exponential processes characterised by time constants T1 and T2.

When all the hydrogen nuclei are precessing in alignment, a peak electromagnetic signal is generated. However, due to local heterogeneities in the B0 field, nuclei will precess at different rates and hence quickly dephase, causing a reduction in the net electromagnetic signal. This process, known as free induction decay, is an experimental artefact and is reversible. Applying an appropriate electromagnetic pulse will tip the nuclei by 180°, effectively reversing the direction of rotation. This will bring the faster and slower precessing nuclei back into alignment, causing a new peak signal, or spin echo, to be generated. By applying a series of 180° pulses at a regular interval, or echo spacing, the precessing nuclei can be continually refocussed.

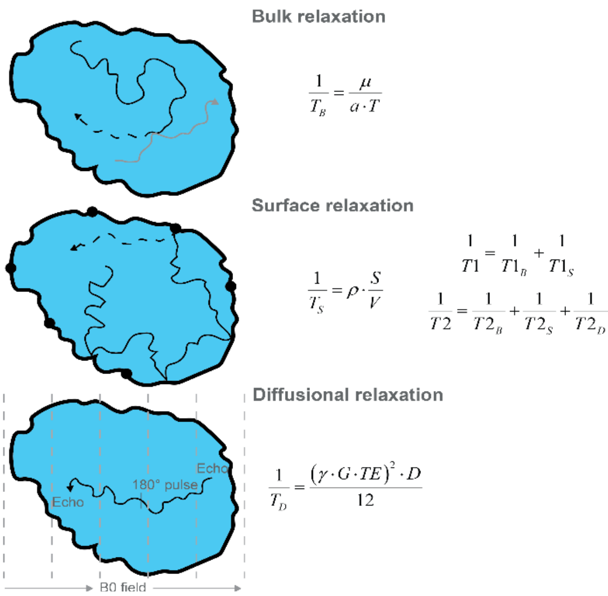

Figure 2: Polarisation (longitudinal relaxation) and dephasing (transverse relaxation) involve two processes, bulk and surface relaxation, occurring in parallel. Dephasing is additionally influenced by diffusional relaxation.

While this is taking place, the hydrogen nuclei are also undergoing irreversible dephasing; this has the effect of moving the axis of rotation of the nuclei out of the B0 direction so that they no longer contribute to the measured signal. Therefore, over time the amplitude of the spin echoes reduces as nuclei undergo irreversible dephasing. Both polarisation and dephasing of the hydrogen nuclei are quasi-exponential processes, with the rate of polarisation described by the longitudinal relaxation time T1 and the rate of dephasing described by the transverse relaxation time T2. The rates at which polarisation and dephasing take place are controlled by interactions between the magnetic fields of the hydrogen nuclei and other local magnetic fields (Figure 2); this includes interactions with the magnetic fields of other hydrogen nuclei in the fluids, known as bulk relaxation, and interactions with magnetic fields generated by paramagnetic atoms such as iron and manganese that may occur in the minerals bounding fluid-containing pores in a rock, known as surface relaxation. Another contributor to dephasing is diffusional relaxation, which takes place when fluid molecules move to areas of differing magnetic field strength during a magnetic resonance measurement, and are therefore not refocussed successfully by applied 180° pulses. Each of these relaxation mechanisms operates in parallel, and so the overall relaxation rate is dominated by the fastest mechanism.

HYDROGEOLOGICAL APPLICATIONS OF BOREHOLE MAGNETIC RESONANCE

For the case of water in a porous medium such as a rock, surface relaxation is the primary mechanism driving polarisation and dephasing of hydrogen nuclei. Surface relaxation involves interactions between the magnetic fields of individual hydrogen nuclei and the magnetic fields generated by paramagnetic atoms such as iron and manganese. Such atoms occur as part of the chemical structure of the rock matrix, and so as fluid molecules move around within pores in a rock, the hydrogen atoms in these molecules may interact with such atoms occurring close to the surfaces of the pores. For a pore of a given volume, the higher its surface area the more likely it is that molecules will approach the pore walls and interact, so the surface-to-volume ratio of a pore is a major control on the rate of surface relaxation. There is also a direct correlation between surface-to-volume ratio and pore size, so the rate of surface relaxation reflects pore size in a rock. For a rock with a range of different pore sizes, a range of relaxation rates will be observed. The signal amplitude related to each relaxation rate indicates the pore volume of the associated pores.

The T2 distribution, or distribution of signal amplitudes related with different transverse relaxation rates, is the fundamental output of a borehole magnetic resonance measurement, concisely summarising the results of the measurement (Figure 3). Signal amplitudes are calibrated to a water reference, so the amplitude related with each relaxation rate is a direct measure of the amount of water, or pore volume, associated with that relaxation rate (pore size). The first hydrogeological property that can be determined from the T2 distribution is the total water content or total porosity, this is simply the sum of amplitudes of each element in the distribution. This porosity is derived directly from the magnetic resonance measurement itself and is independent of any lithology effects.

As well as looking at the sum of amplitudes of all the elements in the T2 distribution, it is useful to look at the sum of amplitudes of the elements within a range of T2 values, corresponding to a range of pore sizes. This can be used to determine the water volume that is free to move, the specific yield, and the water volume held in place in the rock by capillary forces, the specific retention. The T2 values used to separate bound and free fluid are well defined for typical lithologies, or can be determined from core measurements.

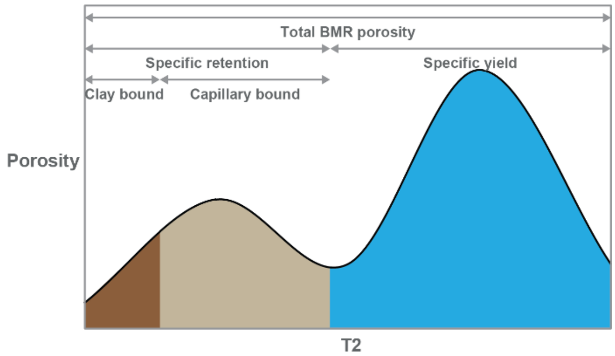

Figure 3: The T2 distribution reflects the volumes of fluid occupying different pore sizes. Integrating amplitudes over the full T2 distribution gives the total porosity, while integrating amplitudes over a range of T2 values allows subdivision into different fluid types based on pore size, such as specific yield and specific retention.

The pore size information summarised in the T2 distribution can also be used to estimate permeability. Two main approaches have been employed for permeability estimation from magnetic resonance data. The first approach builds on a range of empirical relationships between porosity, permeability, and irreducible water saturation that have developed over the years; the most common equation of this form is the Timur-Coates permeability equation $k_{Timur-Coates} = 10000 \cdot a \cdot n^b \cdot \left(\frac{S_y}{S_r}\right)^c$, where $k_{Timur-Coates}$ is the permeability estimated from the Timur-Coates equation (mD), n is the porosity (1), S_y is the specific yield (1), S_r is the specific retention (1), and a, b, and c are constants with typical values of 1 (mD), 4 (1), and 2 (1). The second approach is based on Kozeny-Carmen-type models, with average pore size information coming from the logarithmic or geometric average of the T2 distribution; the most common equation of this form is the SDR permeability equation $k_{SDR} = a \cdot n^b \cdot T2_{LM}{}^c$, where k_{SDR} is the permeability estimated from the SDR equation (mD), $T2_{LM}$ is the logarithmic mean value of the T2 distribution (ms), and a, b, and c are constants with typical values of 4 (mD/ms^2), 4 (1), and 2 (1). Dlubac *et al*. (2013) reviews the origins of these equations, and discusses the application of borehole magnetic resonance-based permeability estimates in aquifer characterisation.

Hydraulic conductivity K (m/sec) can then be derived from permeability as $K = \frac{9.869233E-10 \cdot k \cdot \rho \cdot g}{\mu}$, where k is the permeability (mD), ρ is water density (g/cm^3), g is the acceleration due to gravity (9.80665 m/s^2), and μ is the dynamic viscosity (cP). Transmissivity T (m^2/s) can further be derived from hydraulic conductivity as $T = K \cdot b$ where b is thickness (m).

Therefore, due to the sensitivity of magnetic resonance measurements to both pore volume and pore size, a range of storage and flow properties characterising hydrogeological behaviour can be estimated from such data.

APPLICATION OF BOREHOLE MAGNETIC RESONANCE DATA IN GROUNDWATER ASSESSMENT

In the southern Sydney Basin, underground coal mining operations take place near aquifers that are in contact with water supply catchments. Therefore, accurately characterising hydrogeological properties is essential to identify, understand, and mitigate potential interactions between the coal mining operations and groundwater supplies. Two main groundwater systems exist in the area, a shallow system and a deep system separated by a major regional aquiclude. The deep groundwater system includes the coal measures sequence targeted by mining operations.

A series of boreholes have been drilled in the study area to allow hydrogeological characterisation. The boreholes have been fully cored, and core analysis has been conducted for hydrogeological properties. A suite of borehole geophysics measurements has been acquired in each hole, including borehole magnetic resonance. Finally, an extensive program of packer tests has been conducted in each borehole, providing contiguous coverage over the full well intervals.

Figure 4 displays the characterisation measurements for one of the boreholes in the study area. Track 1 displays the natural gamma ray, while Track 2 displays density and neutron porosity measurements. These measurements provide important information about lithological variations in the section encountered in this borehole. For example, the major regional aquiclude mentioned above can be identified by the large separation between density and neutron porosity measurements between 155 and 175 m, while thinner shaly intervals can be identified by smaller separations between the density and neutron porosity measurements, and elevated natural gamma ray values. Also noteworthy is the suppression of neutron porosity response above 97 m; this corresponds to the air-water interface in the borehole and negates the use of neutron porosity for water content evaluation above this depth. Track 3 displays the total porosity or water volume from borehole magnetic resonance, as well as the core porosity. As the borehole magnetic resonance measurement is not sensitive to borehole fluid type, equally valid measurements are obtained when the borehole is both water- and air-filled. Track 4 displays the partitioning of total water volume into the specific retention and specific yield fractions. The expected correspondence between lower specific retention in clean sand intervals and higher specific retention in shaly intervals can be observed. Track 5 displays hydraulic conductivity from core measurements, from borehole magnetic resonance using the Timur-Coates equation, and from packer tests. For ease of comparison, both the continuous hydraulic conductivity estimate from borehole magnetic resonance, and the borehole magnetic resonance estimate upscaled to the packer test intervals is displayed. This upscaling was performed by taking the arithmetic average of hydraulic conductivity values over the depth interval of each packer test; this is representative of the average horizontal hydraulic conductivity in each packer test interval. The T2 distribution from borehole magnetic resonance is shown in Track 6.

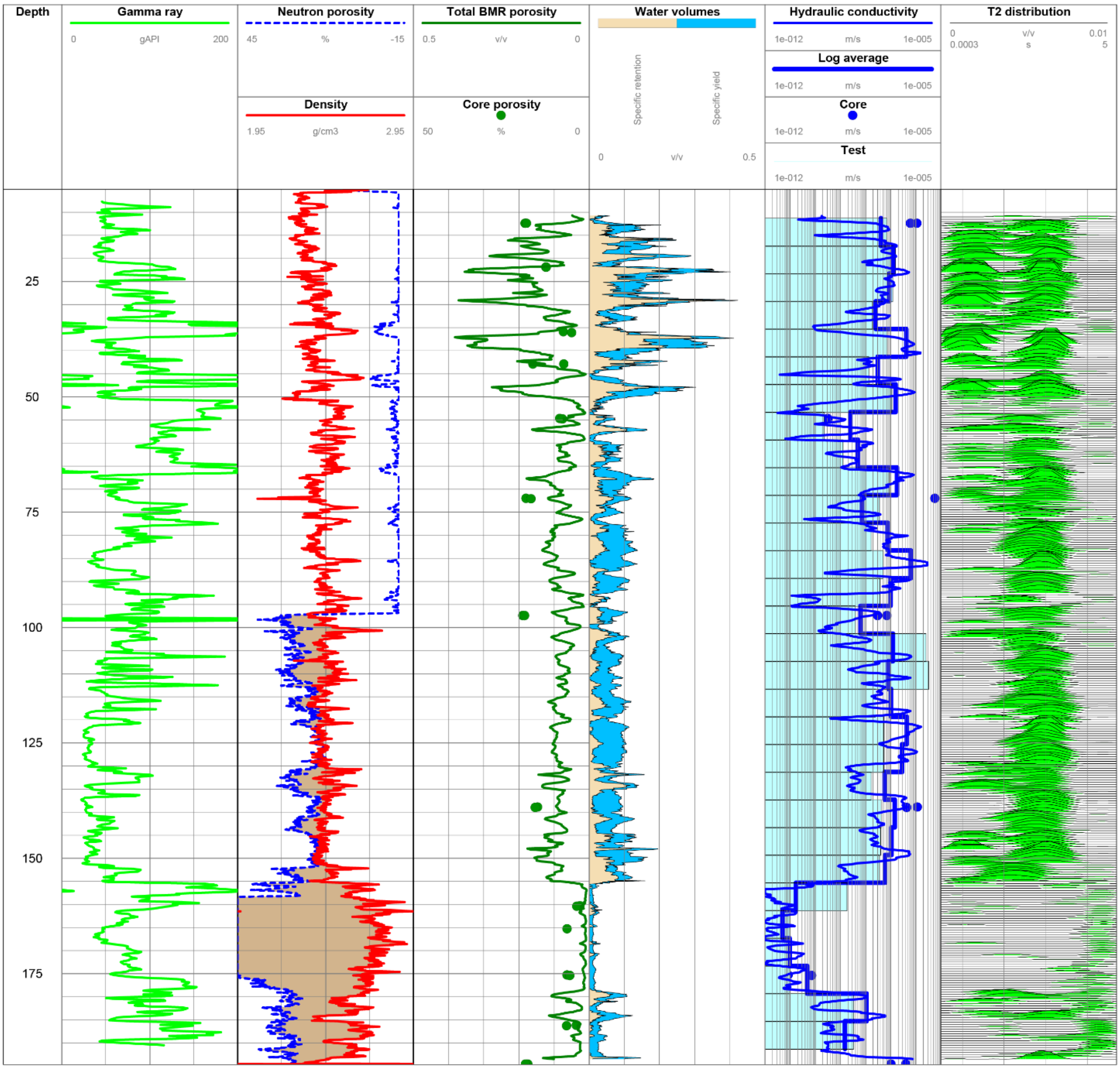

Figure 4: Comparison of hydrogeological parameters derived from core analysis, borehole magnetic resonance, and packer testing. Core and borehole magnetic resonance porosity are compared in Track 3, and hydraulic conductivity from core, borehole magnetic resonance, and packer testing are compared in Track 5.

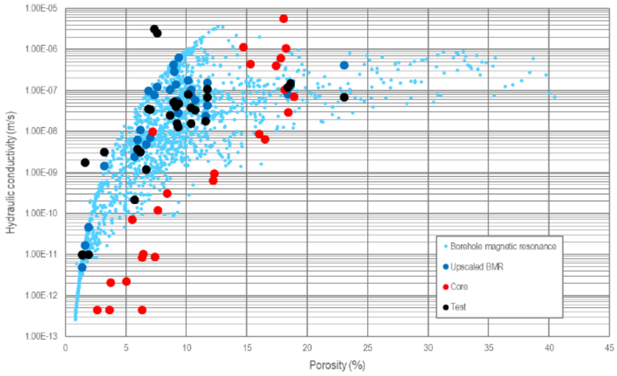

Figure 5: Hydraulic conductivity versus porosity cross-plot comparing data from core analysis, borehole magnetic resonance, upscaled borehole magnetic resonance, and packer testing. Average porosity from borehole magnetic resonance is used over packer test intervals.

Figure 5 illustrates the comparison between core analysis, borehole magnetic resonance, and packer test measurements of porosity and hydraulic conductivity. Overall, a very good correspondence is observed between the borehole magnetic resonance and packer test estimates of hydraulic conductivity, particularly when the upscaled borehole magnetic resonance results are considered. The most significant discrepancies are higher observed values for hydraulic conductivity in packer tests in the interval between 100 and 115 m and at the top of the regional aquiclude at 155 to 160 m. This may be attributed to difficulties in establishing good packer seals in these intervals, which are typically more shaly than other intervals tested.

Although a similar trend is observed between porosity and hydraulic conductivity in both the core and borehole magnetic resonance measurements, the observed porosity is generally higher in core measurements.

The continuous nature of borehole magnetic resonance measurements facilitates another interesting application, estimation of vertical hydraulic conductivity. For a layered system, the harmonic average of hydraulic conductivity values provides an estimate of vertical hydraulic conductivity over the averaging interval. This assumes that the hydraulic conductivity in each discrete measurement volume being averaged is isotropic, which in the case of the eight centimetre vertical resolution borehole magnetic resonance measurement is a reasonable assumption. As the packer test data acquired in this borehole is contiguous, a similar approach can be applied to this data. However, by comparing the borehole magnetic resonance and packer test estimates of hydraulic conductivity, it is evident that the zone covered by each packer test, which were conducted over a six metre interval, cannot be considered isotropic. Table 1 presents average horizontal and vertical hydraulic conductivity for the shallow groundwater system aquifer in this well, over the interval from 15 to 155 m.

Table 1: Comparison of borehole magnetic resonance and packer testing estimates of horizontal and vertical hydraulic conductivity.

	Horizontal hydraulic conductivity (m/s)	Vertical hydraulic conductivity (m/s)
Borehole magnetic resonance	1.38E-07	1.43E-10
Packer testing	2.81E-07	3.87E-09

Although the overall horizontal hydraulic conductivity of this interval estimated by the two methods is in close agreement, borehole magnetic resonance estimates a vertical hydraulic conductivity over an order of magnitude lower than that coming from packer testing. This has significant implications in terms of vertical flow of water within this groundwater system.

CONCLUSIONS

Borehole magnetic resonance has proven to be a useful addition to data acquisition programs for hydrogeological applications. As it is sensitivity to both pore volume and pore geometry, it can be used to characterise both storage properties such as total porosity or water content, specific retention, and specific yield, and flow properties such as hydraulic conductivity and transmissivity. The continuous nature of the measurement allows these properties can be upscaled to any required resolution, and the data can be used to estimate both horizontal and vertical hydraulic conductivity over intervals of interest. These capabilities have made borehole magnetic resonance a time- and cost-effective replacement for packer testing, and ongoing studies in this area are using borehole magnetic resonance as the primary source for hydrogeological characterisation data.

REFERENCES

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