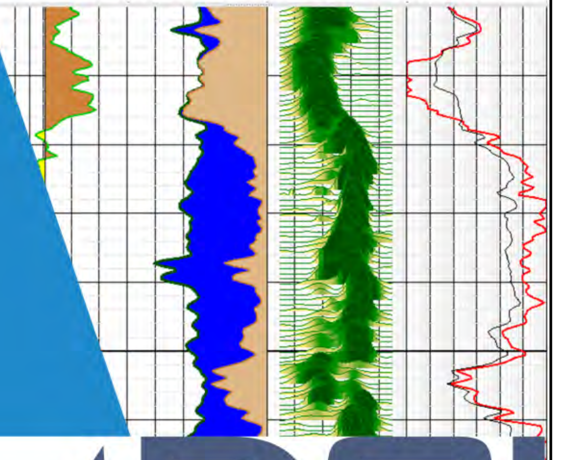
Using borehole magnetic resonance to detect free and bound water in tailings and estimate hydraulic conductivity to predict resistance to static liquefaction failure in upstream tailings dams

Marcus Donaldson, Qteq
Riaz Tejani, DGI Geoscience

Qteq
Economic Innovations



DGI
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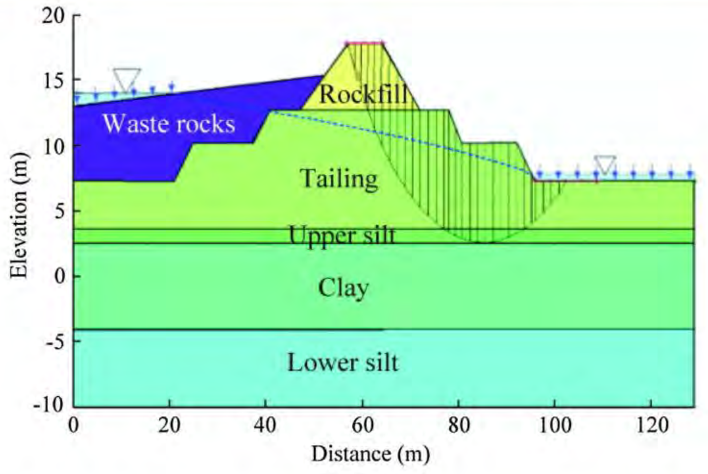
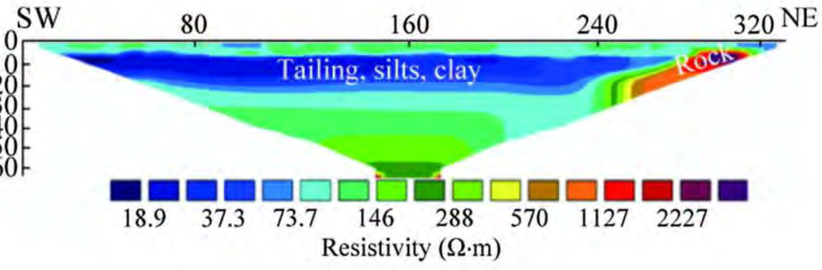
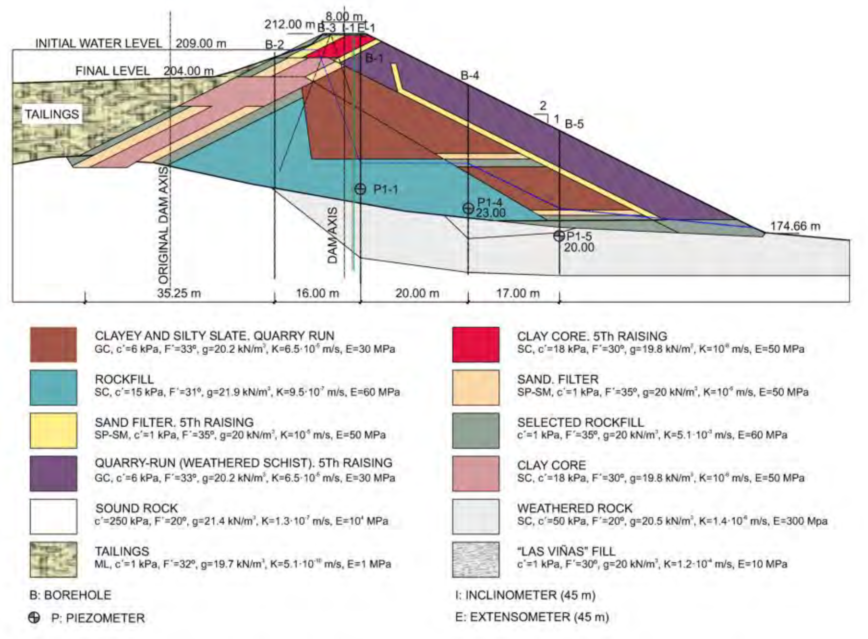
Tailings dams are not homogenous







Coulibaly, et al. International Journal of Mining Science and Technology, 27,4 (2017)
Justo, et al. Bulletin of Engineering Geology and the Environment, 78, 5, (2019)

Understanding the heterogeneity of tailings is crucial for predicting and preventing dam failure

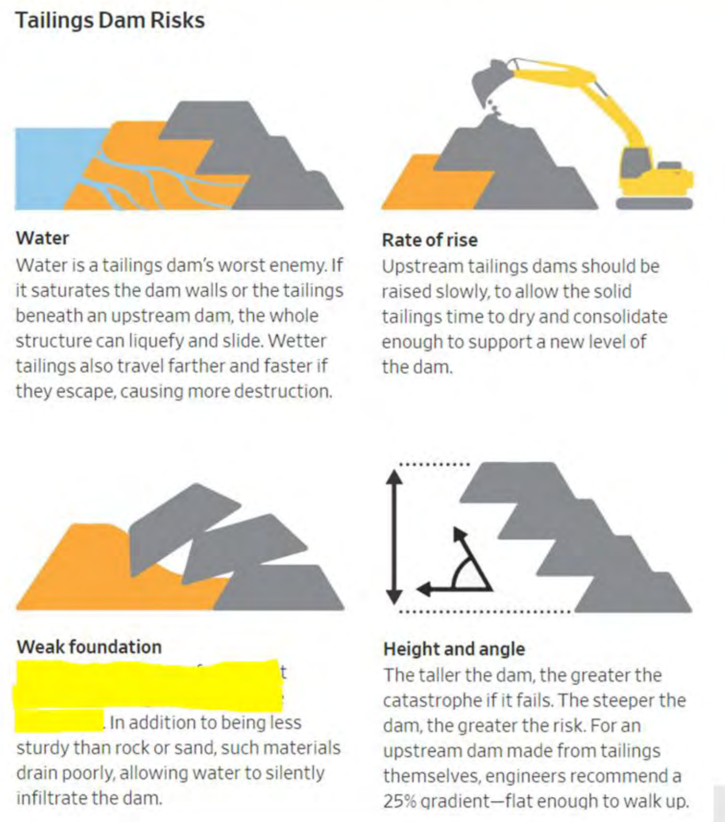
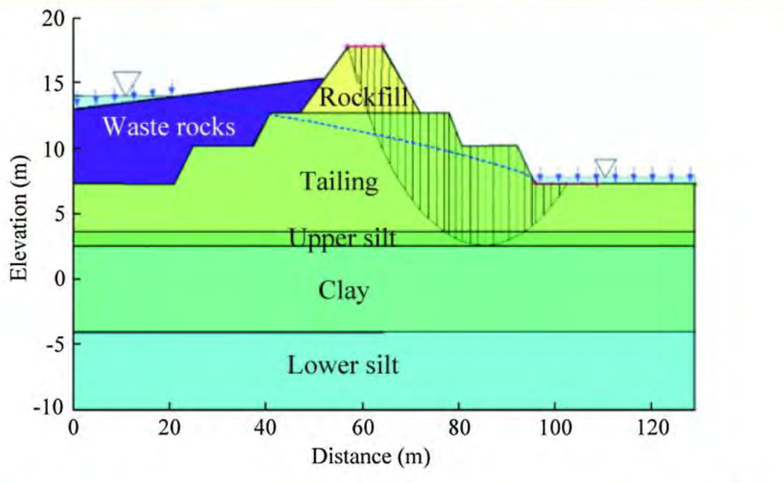
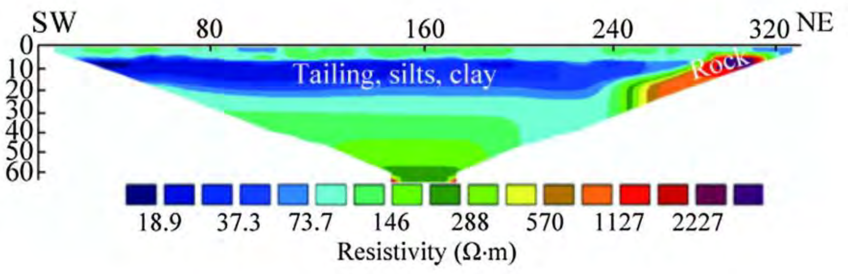
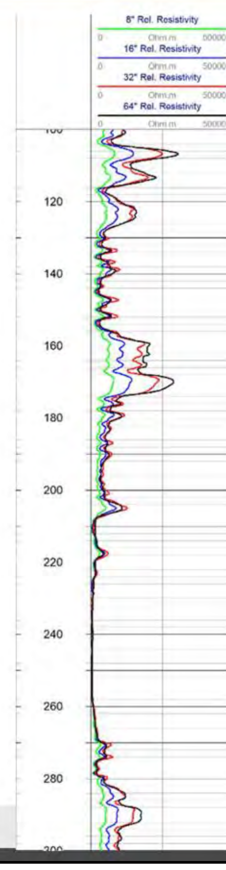


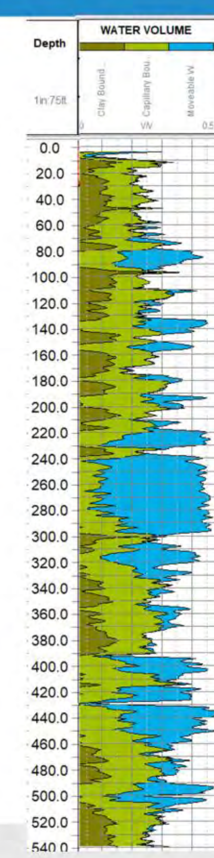
Photo: Magno; Graphic: MacDonald and Hoyle, WSJ, 26 Feb 2019

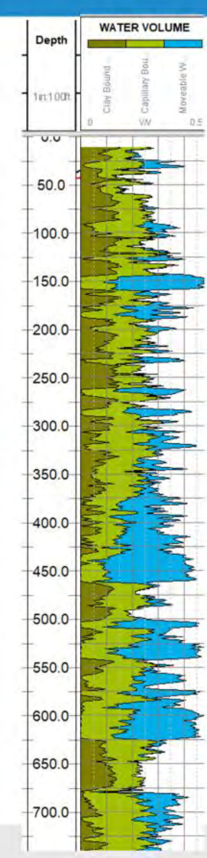
Borehole geophysics can capture the heterogeneity within tailings dams and deliver highly resolved and accurate data







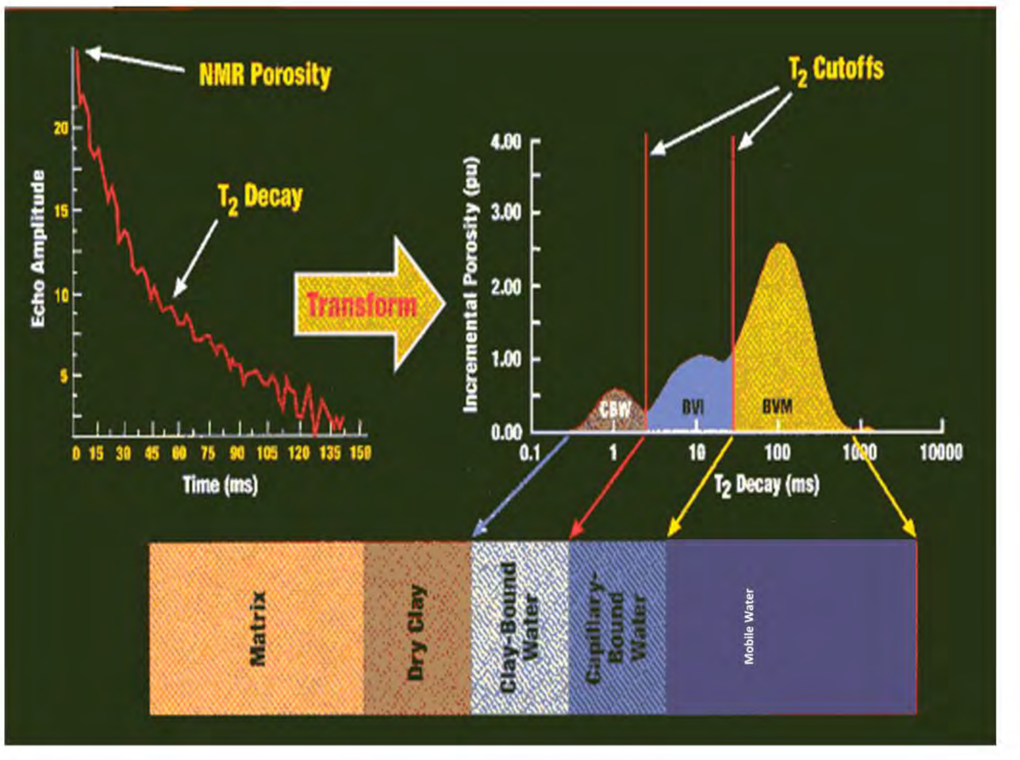




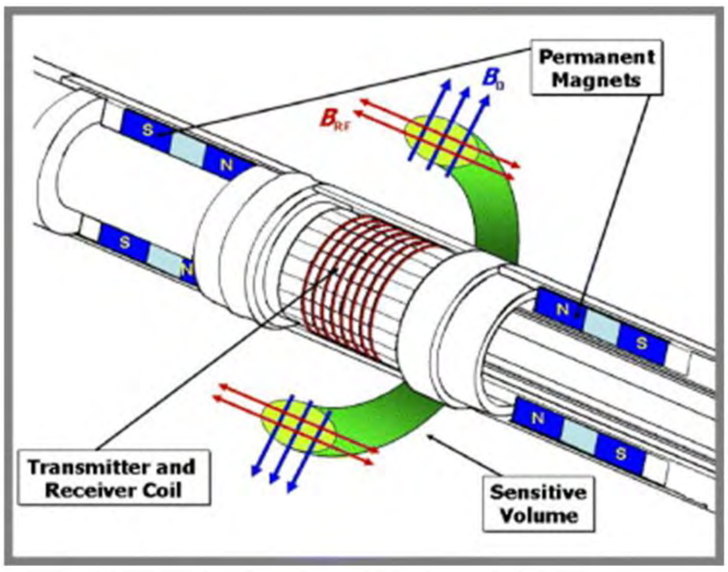
Borehole Magnetic Resonance provides multiple answers with a single measurement without the use of nuclear sources

Measured Parameters
Total porosity
Pore size distribution (PSD)
Free water porosity (specific yield)
Capillary-bound porosity
Clay-bound porosity

Computed Parameters
Permeability
Dry weight density (need bulk density)
Adsorbed and free gas content of coals
Multi-mineral modelling (with other log suites)



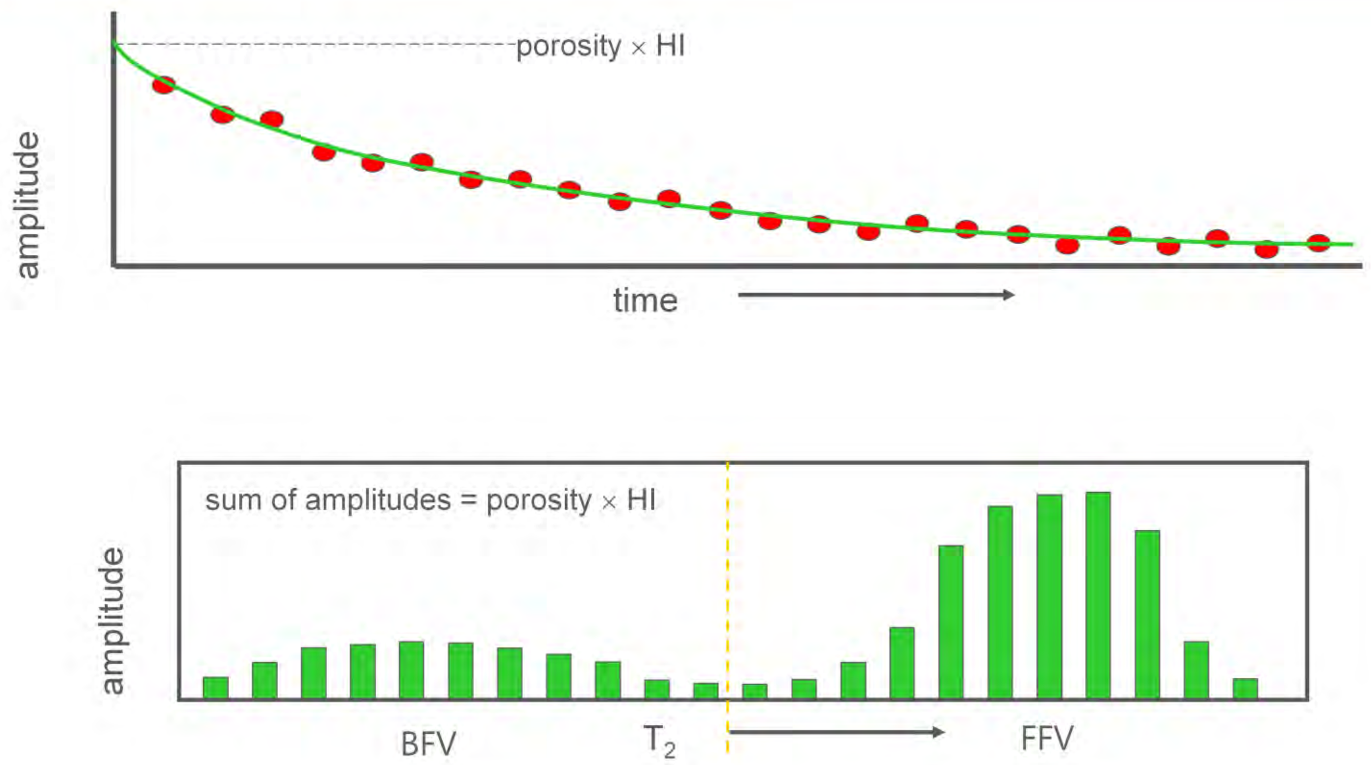
Borehole Magnetic Resonance (BMR) uses the same technology as hospital MRI



Borehole Magnetic Resonance (BMR)
Same technology used in MRI in hospital; MRI looks internally, BMR looks externally
Run on standard wireline like any other tool
Completely safe – no chemical sources, no radiation, magnetic material only

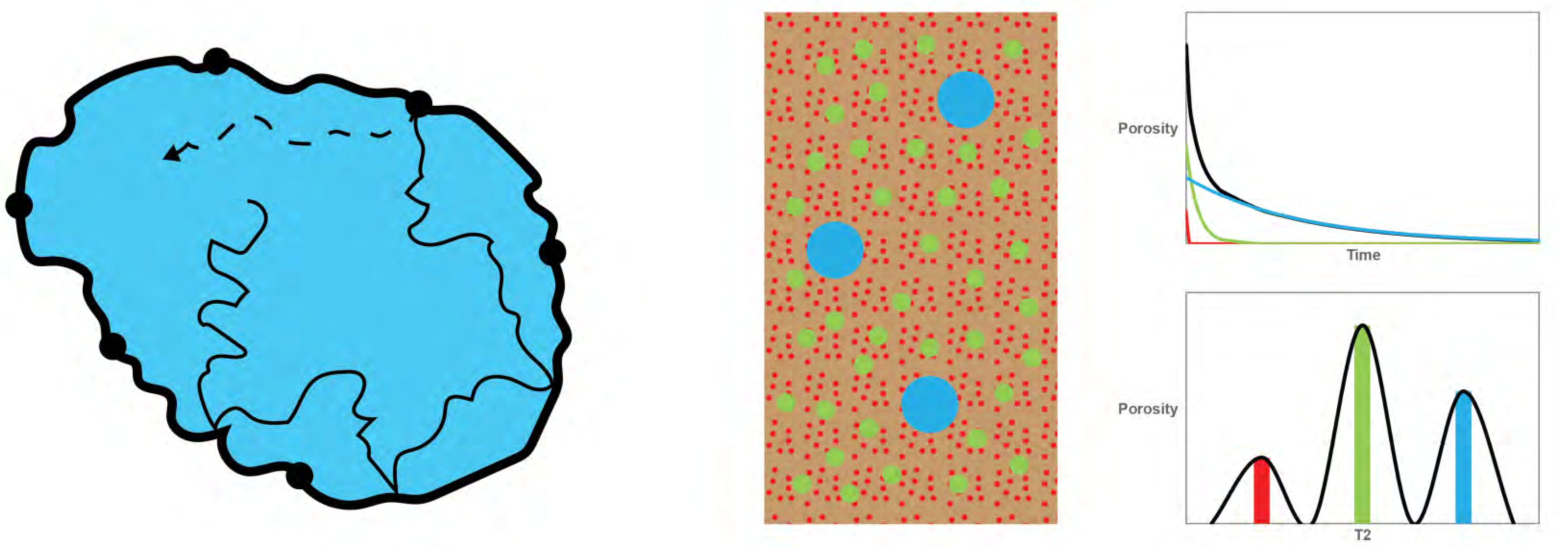
- Used in oil and gas for over 20 years to evaluate storage and flow properties
- continuous measurements at a scale intermediate between core and well test data, providing a convenient framework for integration of all data
- Ability to resolve specific yield and specific retention
- Lithology independent measurement without the use of nuclear sources.

BMR signal is interpreted after the measured decay is inverted to a T_2 distribution.



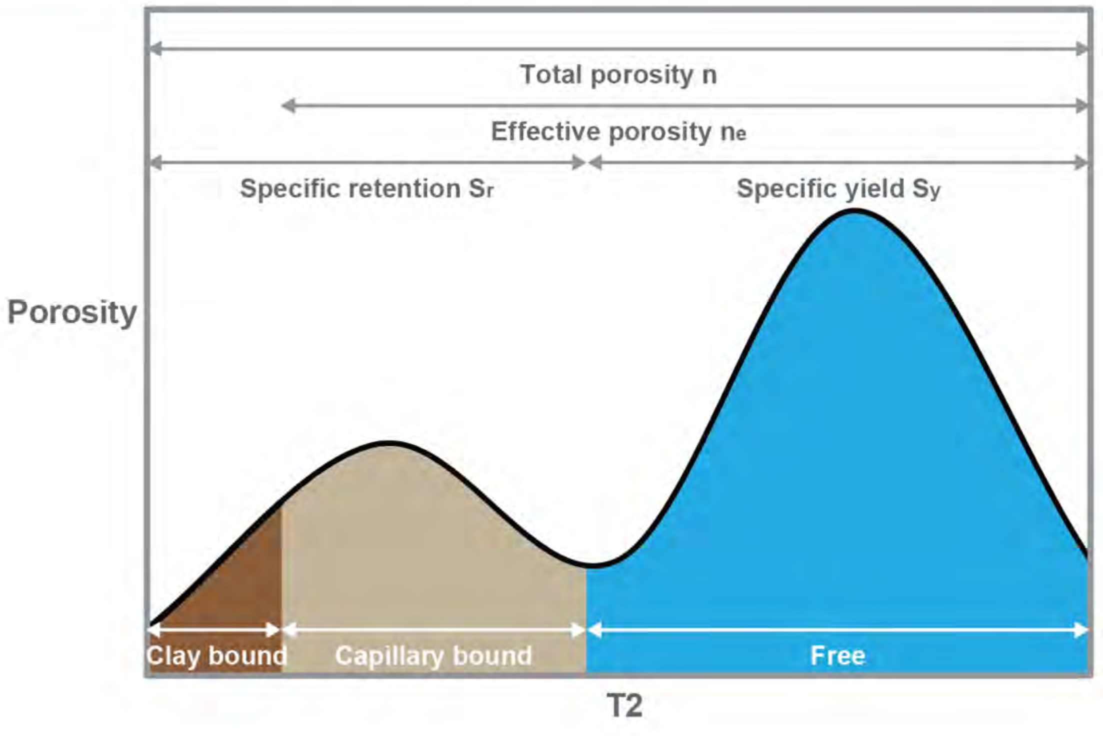
The typical BMR experiment involves a series of RF pulses to continually tip the spins and record an NMR echo between each set of pulses. Over time there is some irreversible loss of energy that causes a decay in the signal. This decay is made up of a series of exponentials that when inverted to a time spectrum, gives a distribution of relaxation rates called a T2 distribution. In the simplest case the distribution is directly related to the pore size distribution, small pores have low T_2s and large pores have long T_2s. The integrated area under the distribution is equal to the total porosity in the rock and this is lithology independent.
From this then, a knowledge of mineralogy can be used to determine cutoffs in the distribution to separate out the bound and free water components, i.e. the component of moisture likely to remain in the formation even after dewatering.
And it is also possible from this to estimate a permeability or hydraulic conductivity.
There are 2 critical parameters to consider:
Firstly the echo spacing or time between successive NMR echos. If the decay is rapid, the tool must be able to measure the very short TEs in order to fully characterize the decay signal.
Secondly, the inversion is very susceptible to noise in the early part of the decay.
These factors in particular place a premium on successful design of a tool in iron ore.

All pore spaces are measured simultaneously and the porosity of each is easily determined



A major cause of dephasing is interaction between hydrogen nuclei and paramagnetic atoms such as iron occurring in mineral grains making up the walls of a pore in a rock; this is known as surface relaxation. Now the smaller the pore, the more time each hydrogen nucleus will spend close to the pore walls, and therefore the more chance they will interact with these paramagnetic atoms, which results in a faster decay.
[CLICK]
In a rock with, for example, three different sizes of pores, the hydrogen in the water in each of these pores will decay with a relaxation rate governed by the pore size. What we measure with a magnetic resonance measurement is the total decay, the sum of these individual decays. In processing of the magnetic resonance data, we take this total decay and from that recover the T2 distribution, the distribution of different relaxation rates and how much pore volume is associated with each.

T_2 distributions are interpreted for hydrogeological terms such as specific yield and hydraulic conductivity



Permeability

$$k_{Timur-Coates} = a \cdot n^b \cdot \left(\frac{S_y}{S_r}\right)^c$$

$$k_{SDR} = a \cdot n^b \cdot T2_{LM}{}^c$$

Hydraulic Conductivity

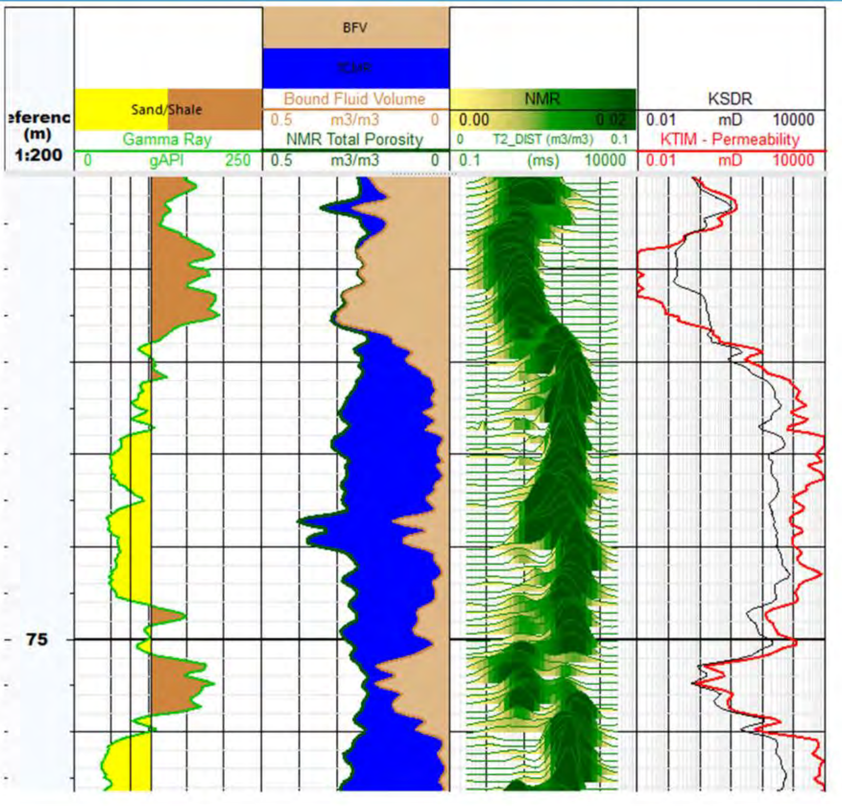
$$K = \frac{k \cdot \rho \cdot g}{\mu}$$

Transmissivity

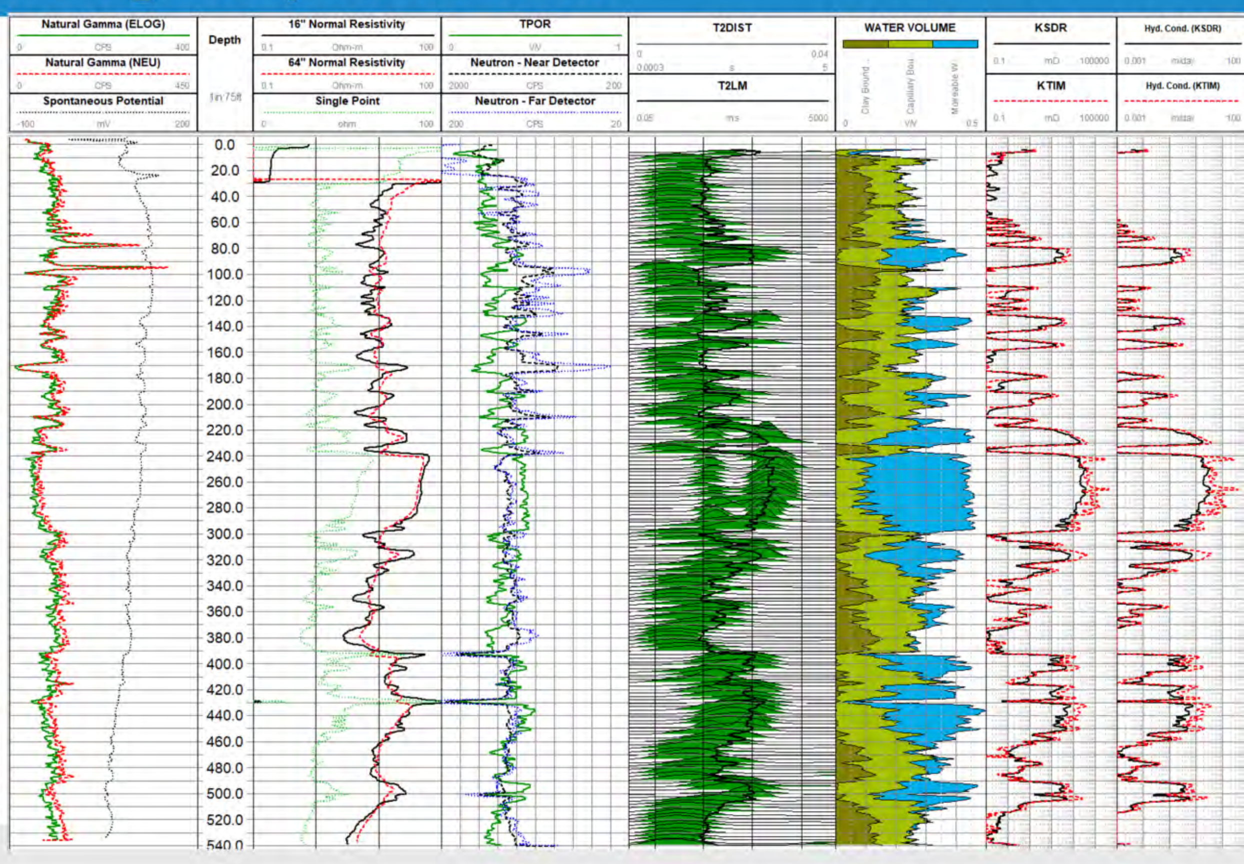
$$T = K \cdot b$$

So the basic output of a borehole magnetic resonance measurement is the T2 distribution. The total amplitude of the distribution is equal to the total porosity, while the variation as a function of T2 reflects the pore size distribution of the rock being sampled. Based on this link to pore geometry, the total pore volume can be subdivided into the specific yield and specific retention.
[CLICK]
Attributes of the T2 distribution can also be used to estimate permeability using empirical models analogous to those used to estimate permeability from grain size distributions, and once permeability is available then quantities such as
[CLICK]
hydraulic conductivity and
[[CLICK]
transmissivity can be determined.

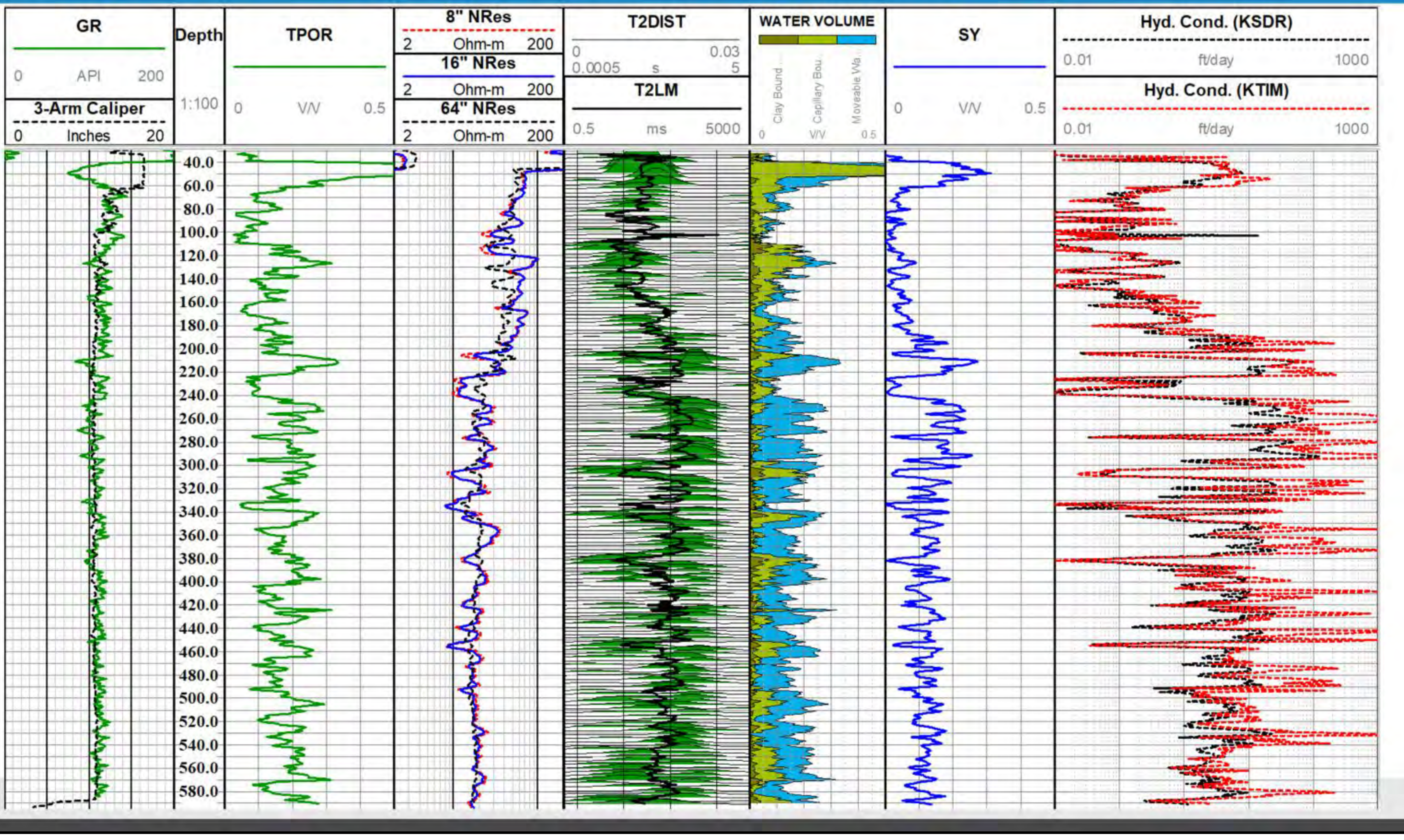
A basic BMR log shows depth correlated measurements the length of the well



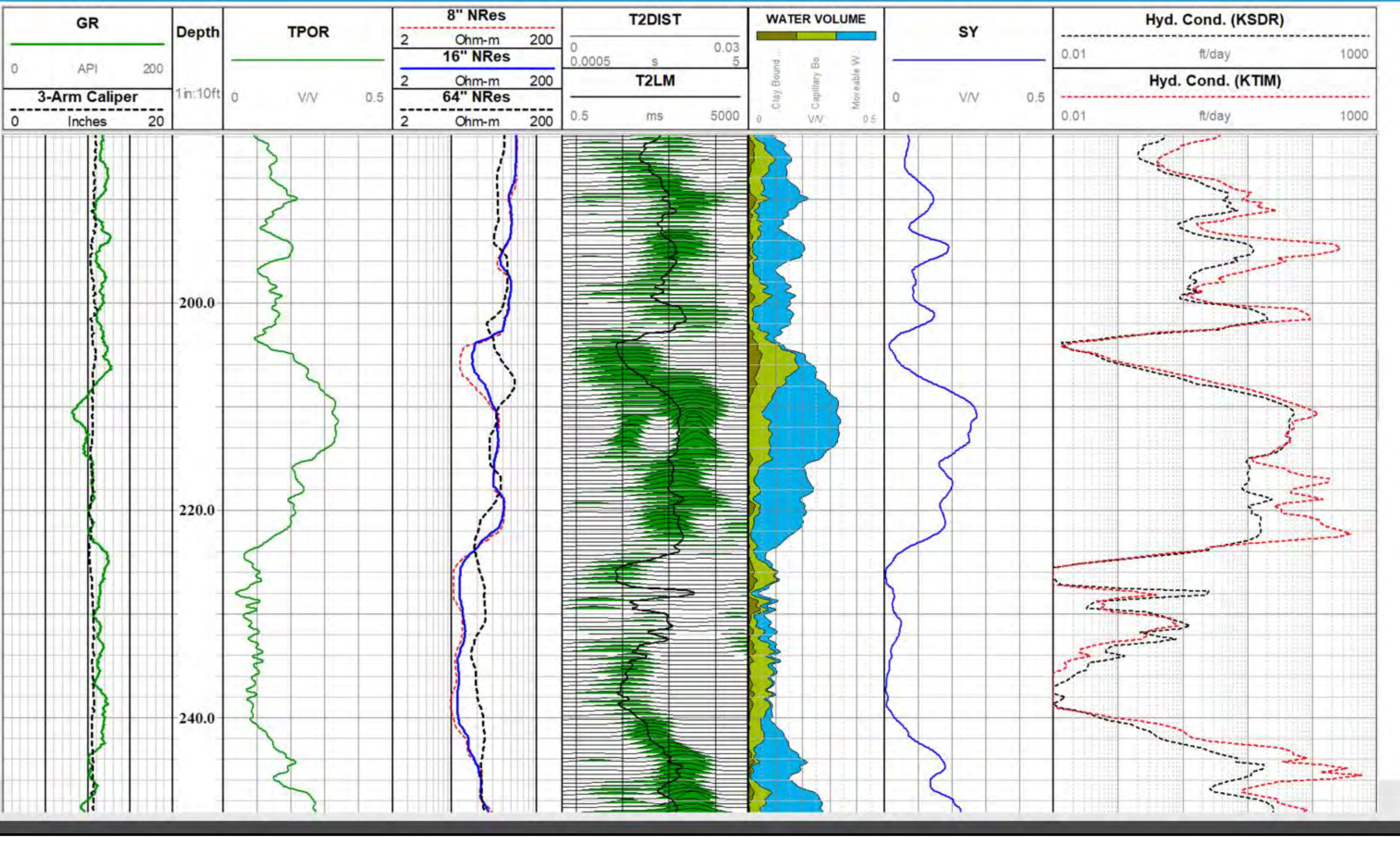
BMR has been used in unconsolidated aquifers to give hydrological parameters



BMR gave good quantification of total porosity and specific yield; significant heterogeneity was noted



High resolution allows for identification of thin zones



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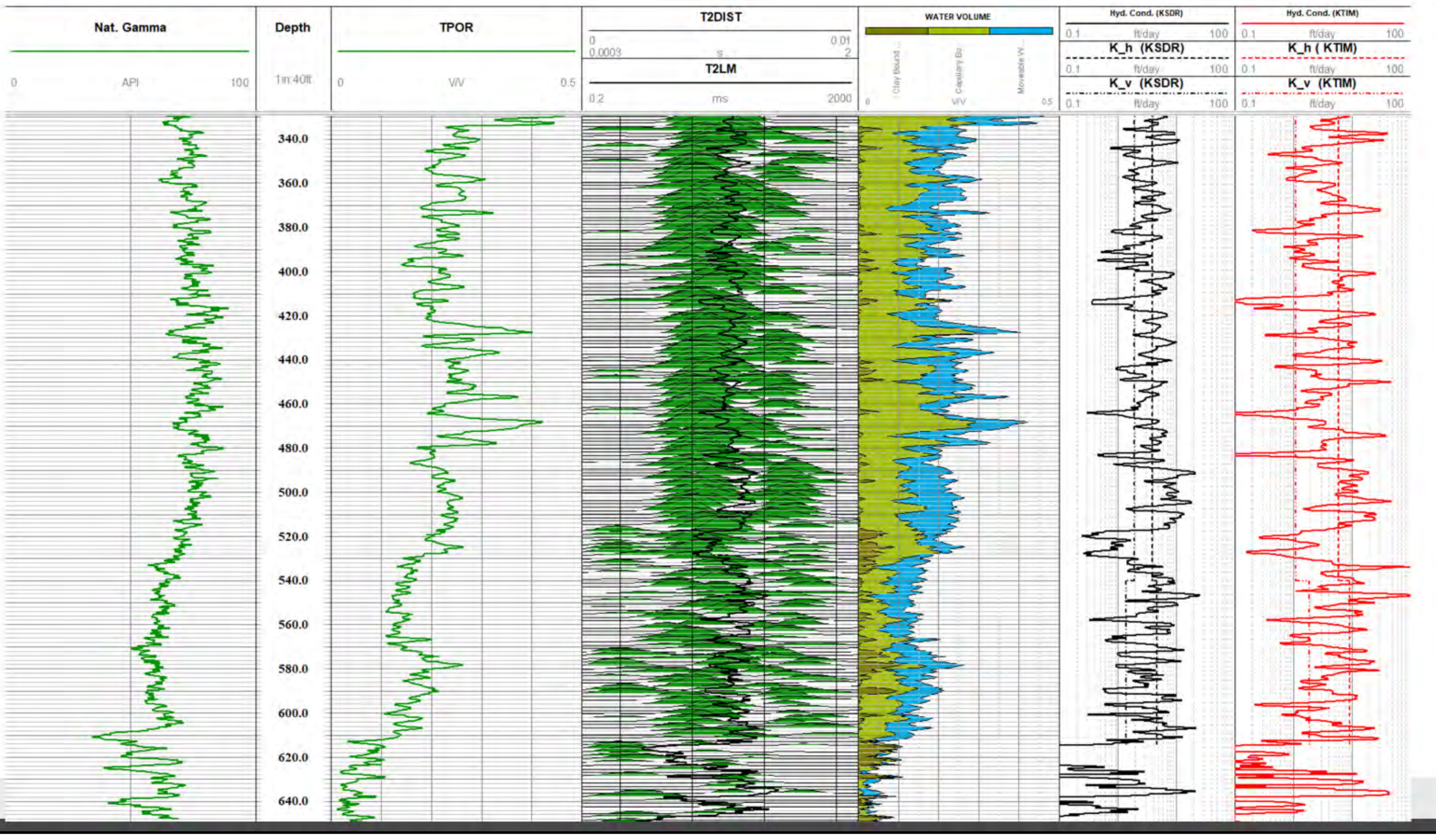
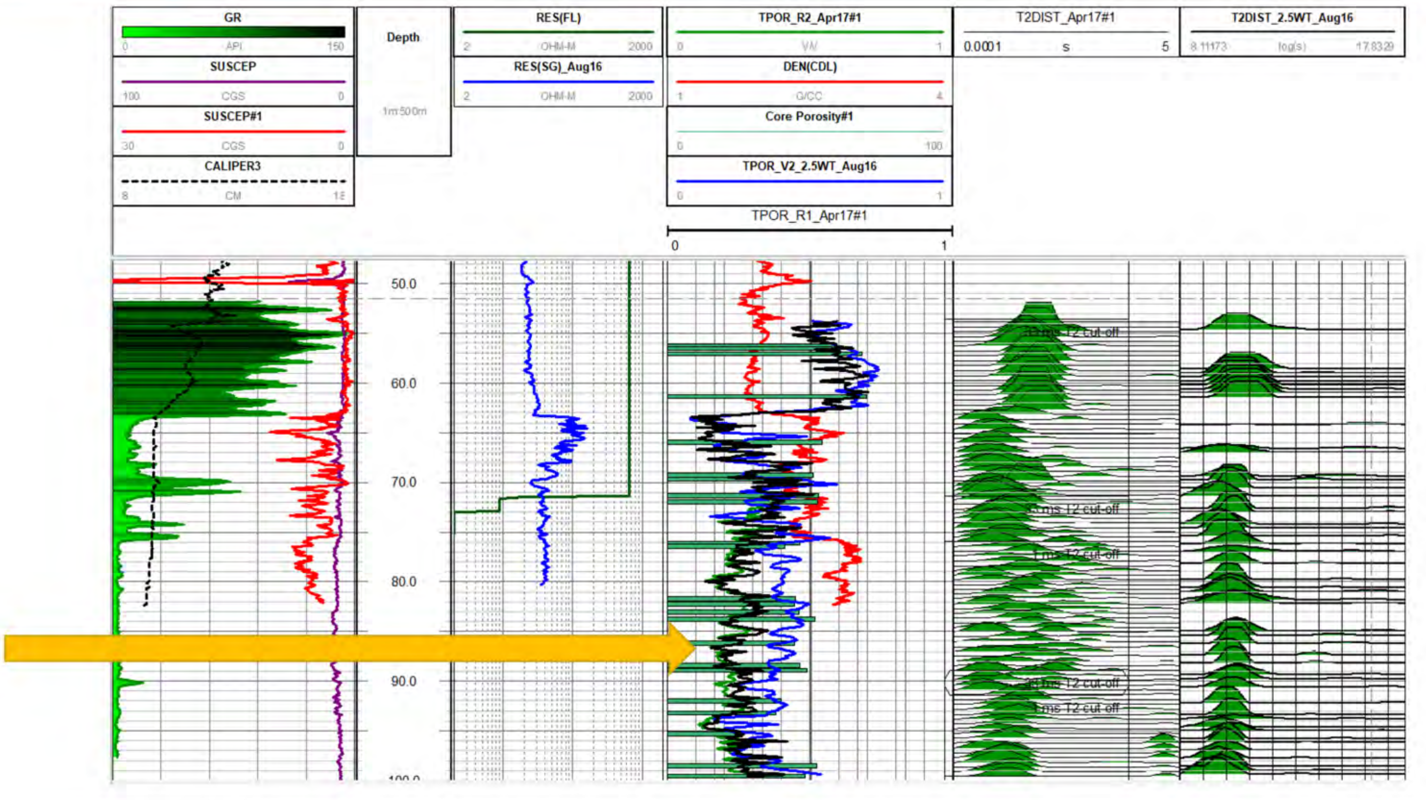
Empirical formulae can be developed to model hydraulic conductivity



Measurements over time allow for quantification of changes



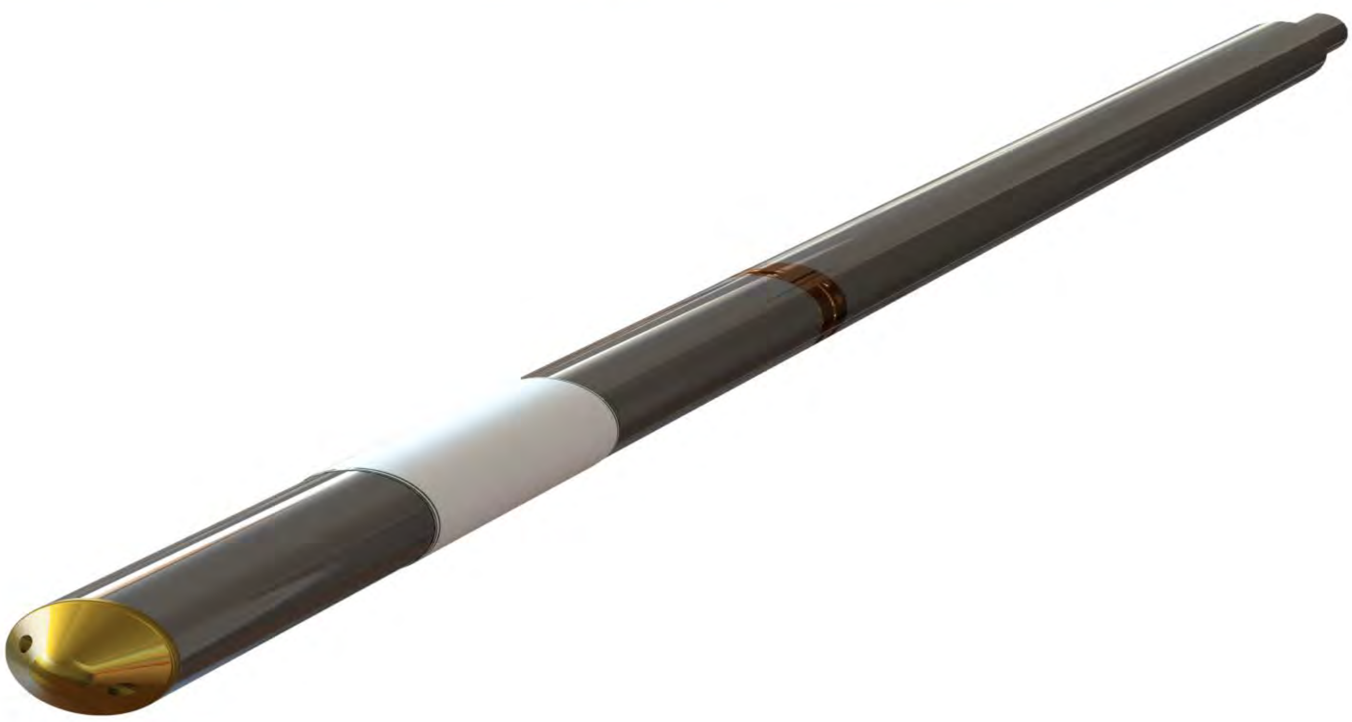
There are many commercially available MR tools; most are big and expensive.

	QTEQ QL40 BMR-60 QL40 BMR-90	SLB MR Scanner	SLB CMR Plus	BHI MREX	HAL MRIL	HAL XMR	WFT NMRT	Vista Clara (40-133 mm OD)
Hole Size	3 – 12.25 in	5.8 – 14 in	6.5 – 14 in	5.8 – 14 in	5.8 – 12 in	5.8 – 17.5 in	7 - ? in	2 – 12.25 in
Temp & Press	100 C, 3 Kpsi	150 C, 20 Kpsi	175 C, 25 Kpsi	160 C, 20 Kpsi	175 C, 25 Kpsi	175 C, 35 Kpsi	125 C, 11.6 Kpsi	60 C, 1.5 Kpsi
Salinity (Rm)	< 0.01 Ohmm	0.02 Ohmm	< 0.01 Ohmm	0.015 Ohmm	0.02 Ohmm	0.04 Ohmm	0.04 Ohmm	unknown
Size & Weight	2.01 m, 19 kg 2.15 m, 25 kg	9.8 m, 544 kg	4.3 m, 136 kg	7.3 m, 282 kg	15.8 m, 670 kg	8.2 m, 385 kg	6.7 m, 265 kg	1.5-4.2 m 10-73 kg
Echo spacing	320 us 600 us	350-600 us	200 us	400 us	600 us	300 us	800 us	700-2000 us
Logging Speed	60-180 m/hr	70 m/hr	168 m/hr	274 m/hr	183 m/hr	180 m/hr	~180 m/hr	5-40 m/hr
Cable Type	Standard 4 core or Standard 7 core	Standard 7 core	Standard 7 core	Standard 7 core	Standard 7 core	Standard 7 core	Standard 7 core	Standard 4 core to 1000m
Crew Size	1 person	2-3 ppl	2-3 ppl	2-3 ppl	2-3 ppl	2-3 ppl	2-3 ppl	1-2 ppl

So what other tools are available to the industry? This table is a sample of information that can be gleaned from company websites and in the published literature.
Typically these tools are designed to withstand the temperature and pressures encountered in deep oil wells of several kilometers are big and heavy requiring large logging trucks and a logging crew to operate, with attendant higher cost to deploy.
This is of low importance for the mining industry where economic depths generally don't exceed 1000m, and in bulk, near surface commodities like iron ore, even 200m is a deep borehole!
A 6 inch diameter tool is already too big to fit into 145mm RC percussion drill holes that are the general standard for drilling in the Pilbara.
Notable, just one tool has a echo spacing that we now consider short enough for iron ore.

- Hole size
  - Larger holes require sidewall tools.
  - Larger diameter of investigation means decrease in signal to noise
- Formation
  - Does not work in Magnetite/Mahgemite
  - Does work in Hematite
  - May miss some data due to local remnant magnetization
- Completion type (if any)
  - PVC or Fiberglass
  - Non-metal centralizers
- Cost
  - Less expensive services at moderate depths and environmental conditions
- Time
  - Physics prohibit quick logging (max 60m/hr with good resolution)

Borehole Magnetic Resonance can be used to identify clays and impermeable layers in tailings dams



Nuclear magnetic resonance gives direct and interpreted hydraulic parameters
- Total porosity (lithology independent)
- Grain size distribution
- Specific yield and specific retention
- Permeability
- Hydraulic conductivity
- Transmissivity
- Salinity (with other logs)

Close to real time answers
Continuous log data – allows for zoning of data

Magnetic Resonance provides lithology-independent porosity/permeability information
- Nuclear logs affected by lithology and borehole conditions

No radioactive sources.

Important for all georesources industries
- Groundwater
- Mining
- Oil and Gas
- Geotechnical