ESTIMATING RESOURCE AND OPTIMISING PRODUCTION IN ISR AND BRINE MINING USING NUCLEAR MAGNETIC RESONANCE

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Hydrogeology in ISR and Brine Mining

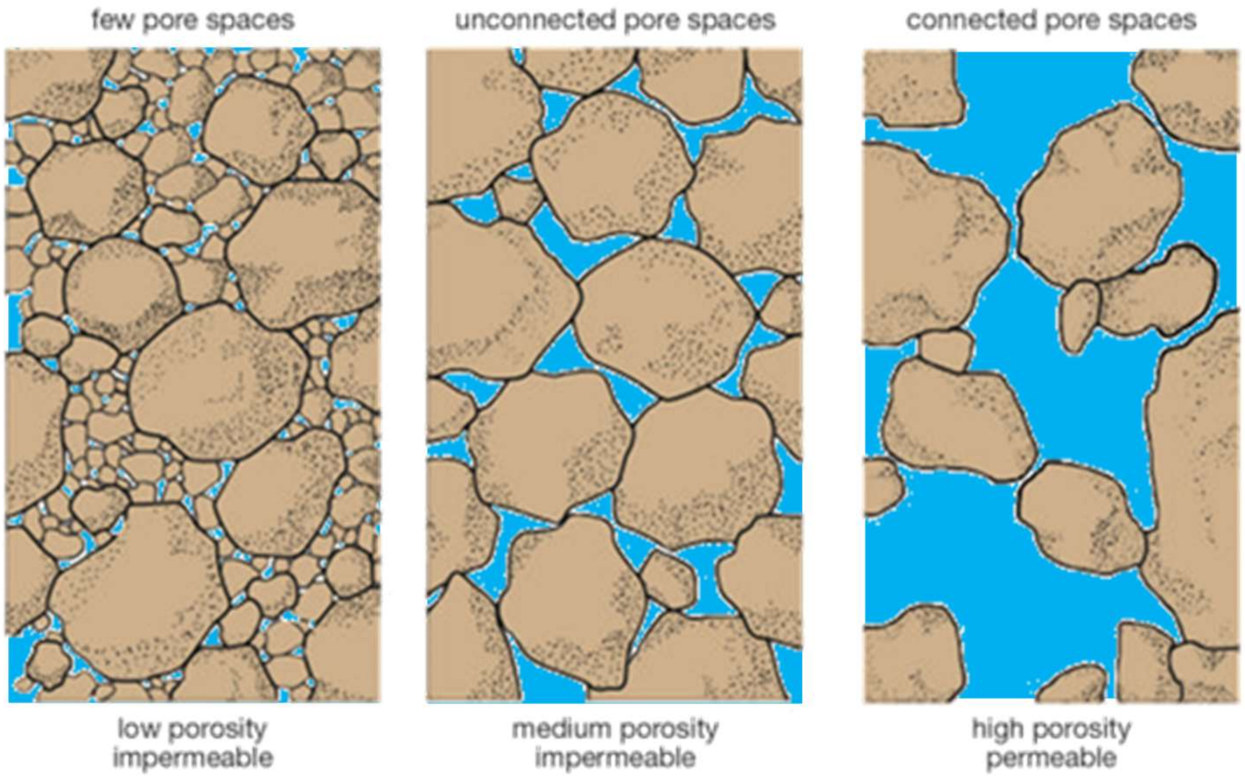
Porosity and Permeability From Wireline Data

Porosity and Permeability

Porosity: Percentage of void space in a rock. It is defined as the ratio of the volume of the voids or pore space divided by the total volume.

Permeability: measure of the ease of passage of liquids or gases or specific chemicals through the material.

Hydraulic Conductivity / Transmissivity: aquifer properties calculated from permeability, aquifer extent and fluid properties.



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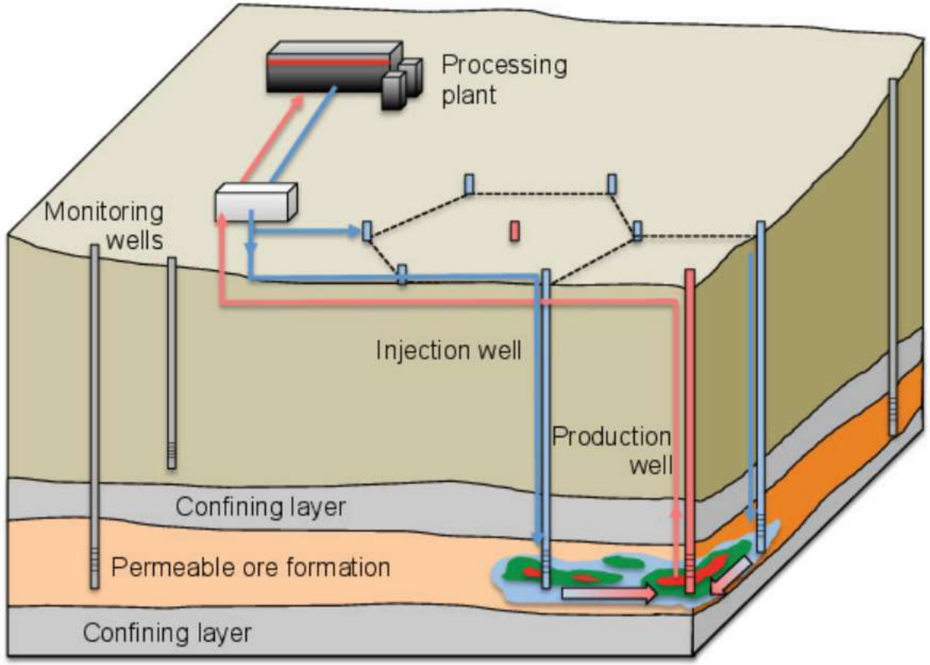
Importance in ISR and Brine Mining

- **Porosity**
  - Define resource explicitly (Brine Mining)
  - Inform the volume and chemistry required to effectively mine (ISR)
  - Calculate dry bulk density for resource calculations (ISR)
- **Permeability**
  - Quantify Production rates
  - Inform Infrastructure decisions: well spacing, pump sizing, pipe sizing …



(Lagneau et al, 2019)

Traditional Techniques

- **Core Analysis**
  - Physical lab tests can be performed to measure core scale porosity and permeability
- **Packer (Drill Stem) Testing**
  - Isolate Specific well sections using inflatable packers.
  - applying a constant hydrostatic pressure measured at the ground surface, and monitoring the water flow into the formation over time
- **Pump Testing**
  - Similar to packer testing.
  - Extract/inject water from/into a completed well and measure its effect on nearby wells

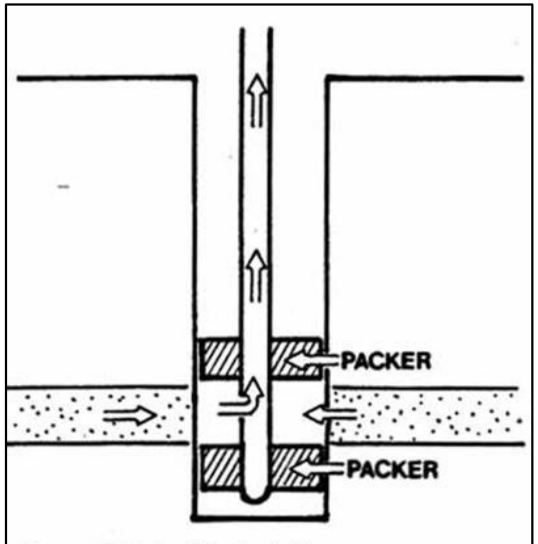


Figure 18-2 A drill stem test.

Packer Test Example (Left). Grain volume apparatus (Bottom Left), pore volume apparatus (Bottom Right)

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How to Estimate Porosity Downhole

Tool	Porosity Relationship	Additional Information	Drawbacks
Gamma-Gamma Density	$\boldsymbol{\rho_{bulk}} = \emptyset\rho_{fluid} + (1-\emptyset)\rho_{matrix}$	Fluid, matrix density	Requires active radiation source Spurious results in gamma producing zones
Resistivity	$\frac{\boldsymbol{R_t}}{R_w} = a\emptyset^{-m}$	a, m, fluid resistivity	Constants formation specific
Sonic	$\frac{1}{\boldsymbol{v}} = \frac{\emptyset}{v_{fluid}} + \frac{(1-\emptyset)}{v_{matrix}}$	Velocity of fluid and matrix	Matrix velocity often formation specific
Neutron	$\log\emptyset \propto \boldsymbol{Neutron\ Count\ Rate}$	Salinity Formation chemistry	Requires active radiation source Complex tool dependent relationship, clay effect
Borehole Magnetic Resonance (BMR)	$\emptyset = \sum T2$	Salinity if very high	Sensitive to magnetic / conductive / chargeable material

How to Estimate Porosity Downhole

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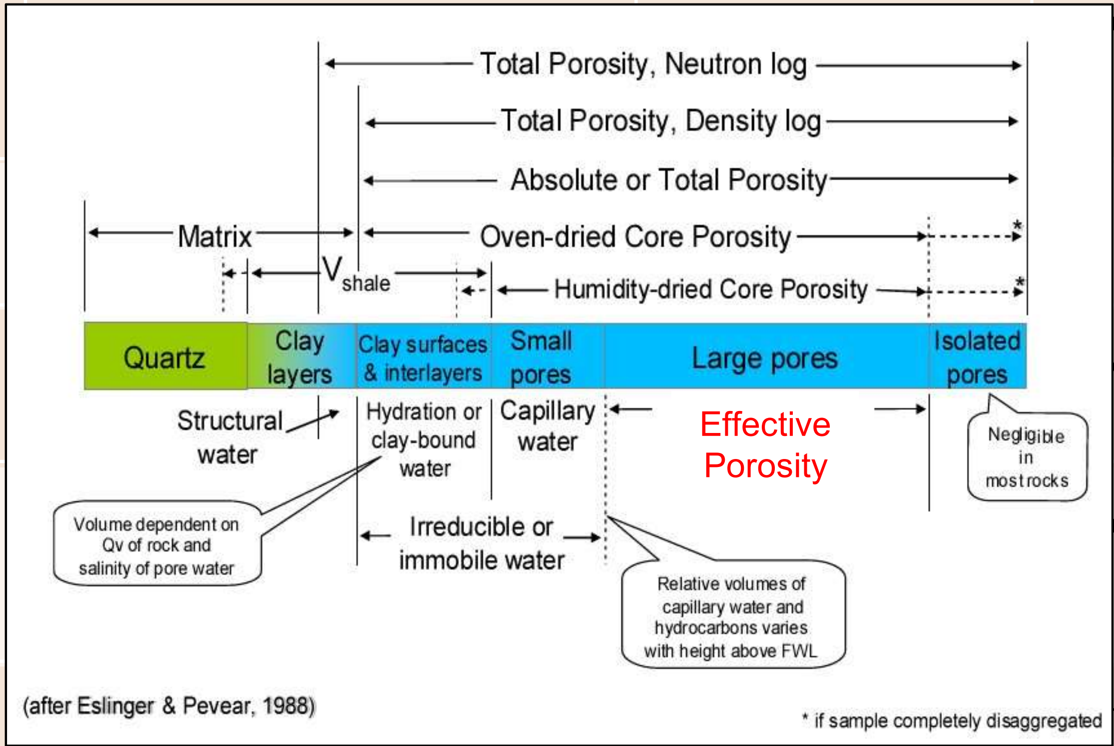
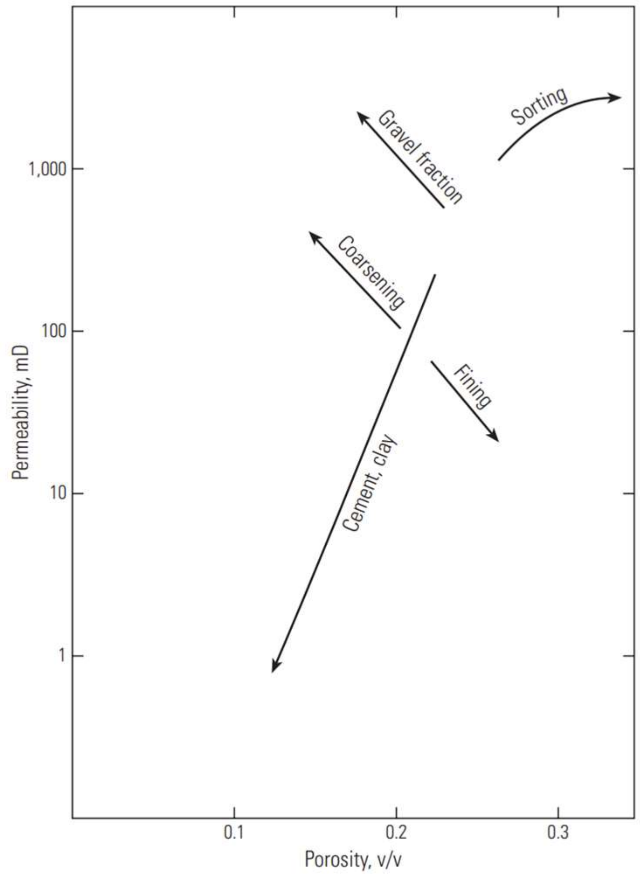


How to Estimate Permeability Downhole

- Any measure of porosity can be used to estimate permeability empirically.
  - Generally: $\log k \propto \emptyset^b$
  - Limited by understanding of local lithology, chemistry and geometry
- Petrophysical Approach using the **Kozeny-Carman Relationship** that describes pore space as a bundle of independent, tortuous tubes of different radii.
  - Can be leveraged to estimate permeability using results from BMR.



Generalised Poro-Perm relationships
Nelson PH (1994) Permeability-porosity relationships in sedimentary rocks.

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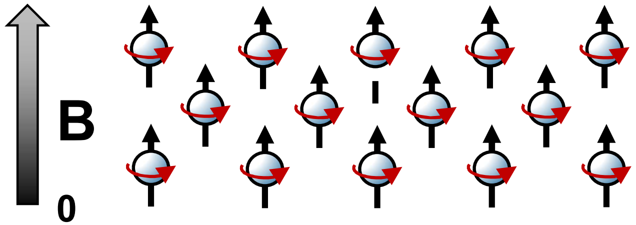
Nuclear Magnetic Resonance

Science and Application

NMR BASICS

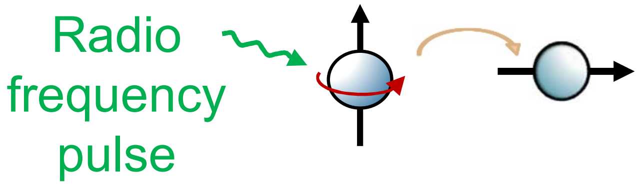
Nuclear magnetic resonance (NMR) is a physical phenomenon in which nuclei in a **strong static magnetic field** are **perturbed by a weak oscillating magnetic field** and respond by **producing an electromagnetic signal** with a frequency characteristic of the magnetic field at the nucleus.

1. Polarisation



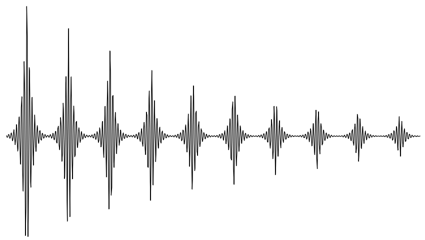
Atoms interact with a magnetic field

2. Excitation



Magnetised atoms are excited using electromagnetic radiation

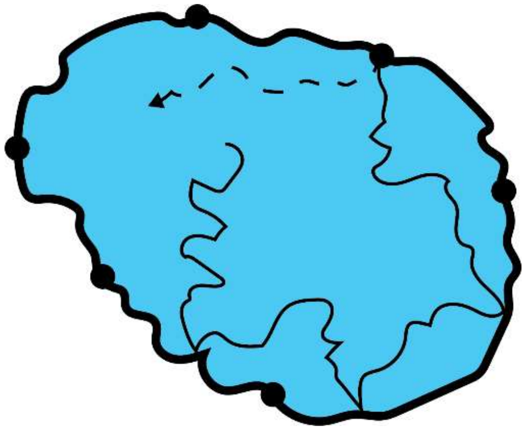
3. Detection

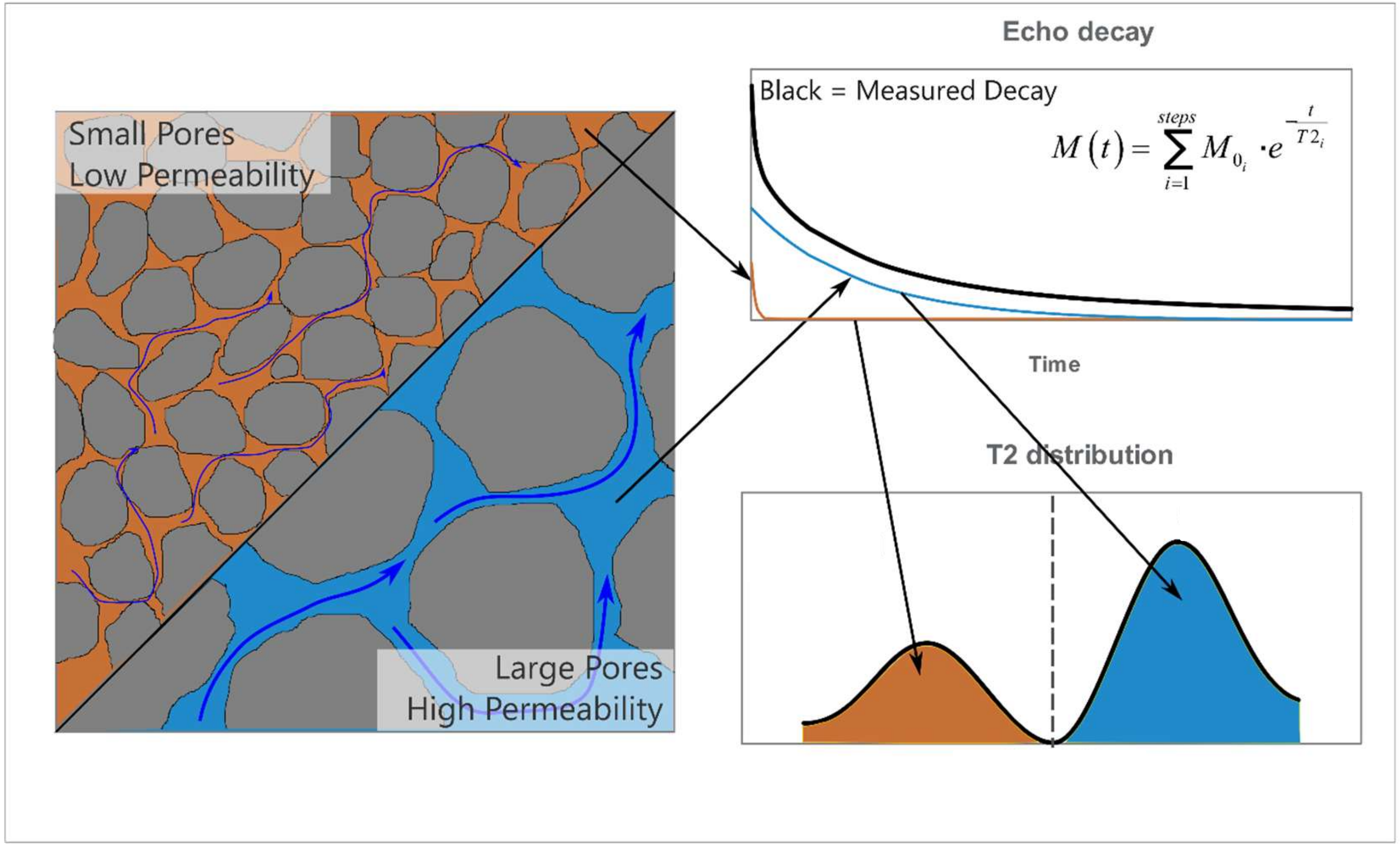


Excited atoms resonate and emit a detectable signal

NMR and Pore Interactions

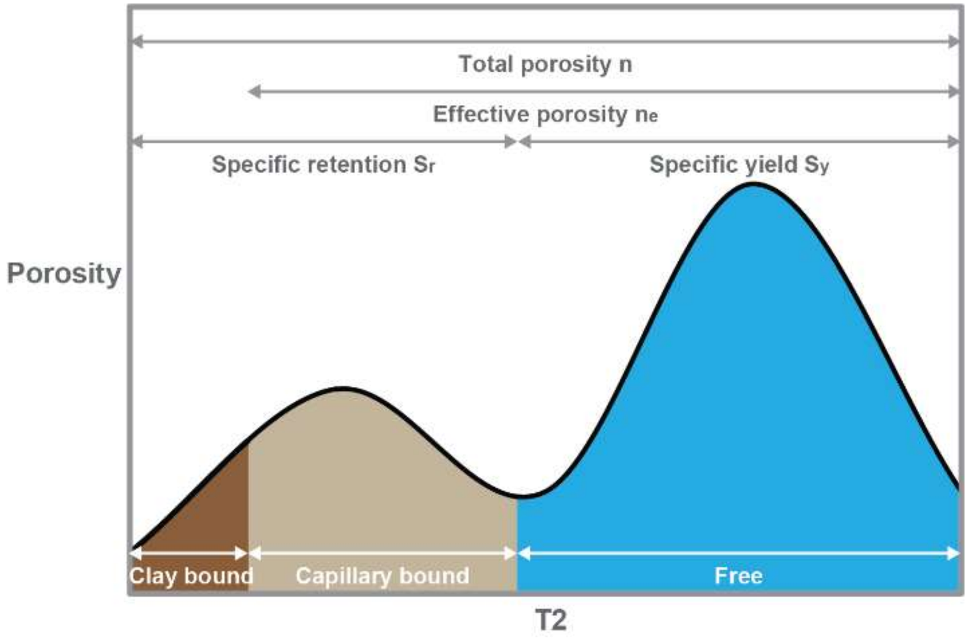
Primary control on energy loss is interaction with pore boundaries (surface relaxation)





Porosity, Cutoffs, and Fluid Volumes

- Total area under T2 represents the total porosity.
- Pore geometry information in magnetic resonance comes from surface relaxation effects.
- Driven by two properties
  - Pore geometry
  - Surface relaxivity
    - Variations in surface relaxivity related to concentration of paramagnetics (iron, manganese, …)

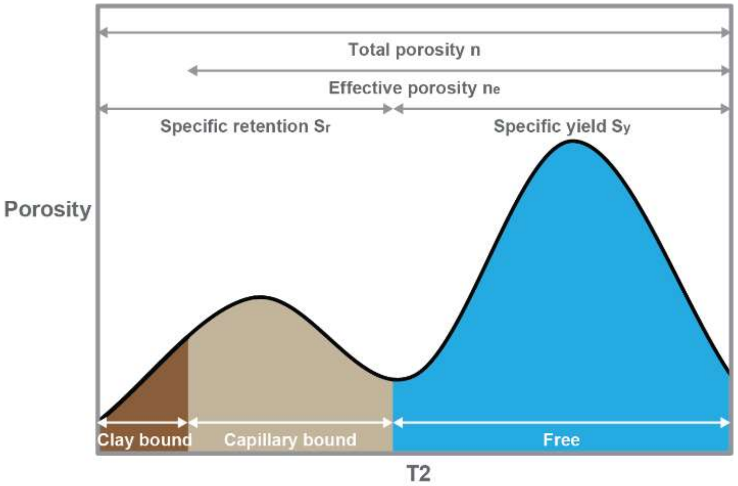


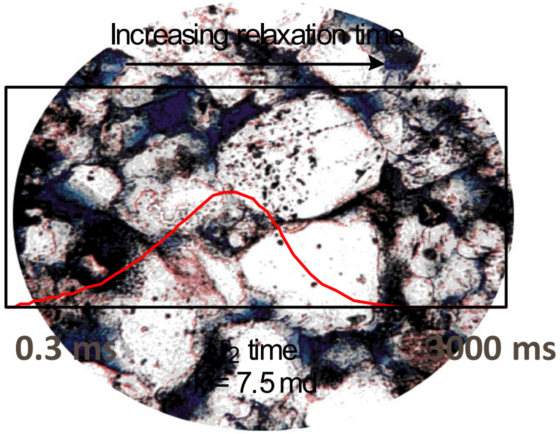
Permeability Estimation

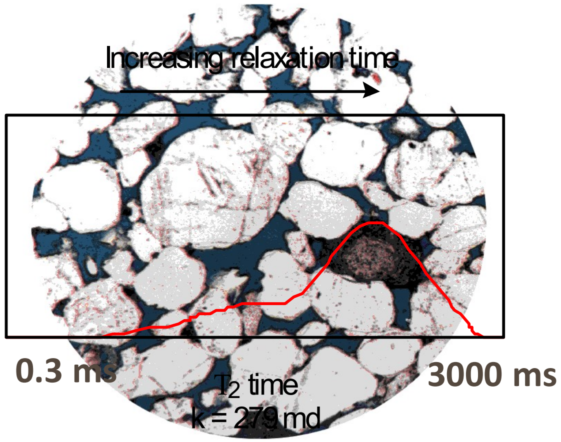
Permeability relates to porosity, surface to volume ratio, and a lithology geometry factor.

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

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



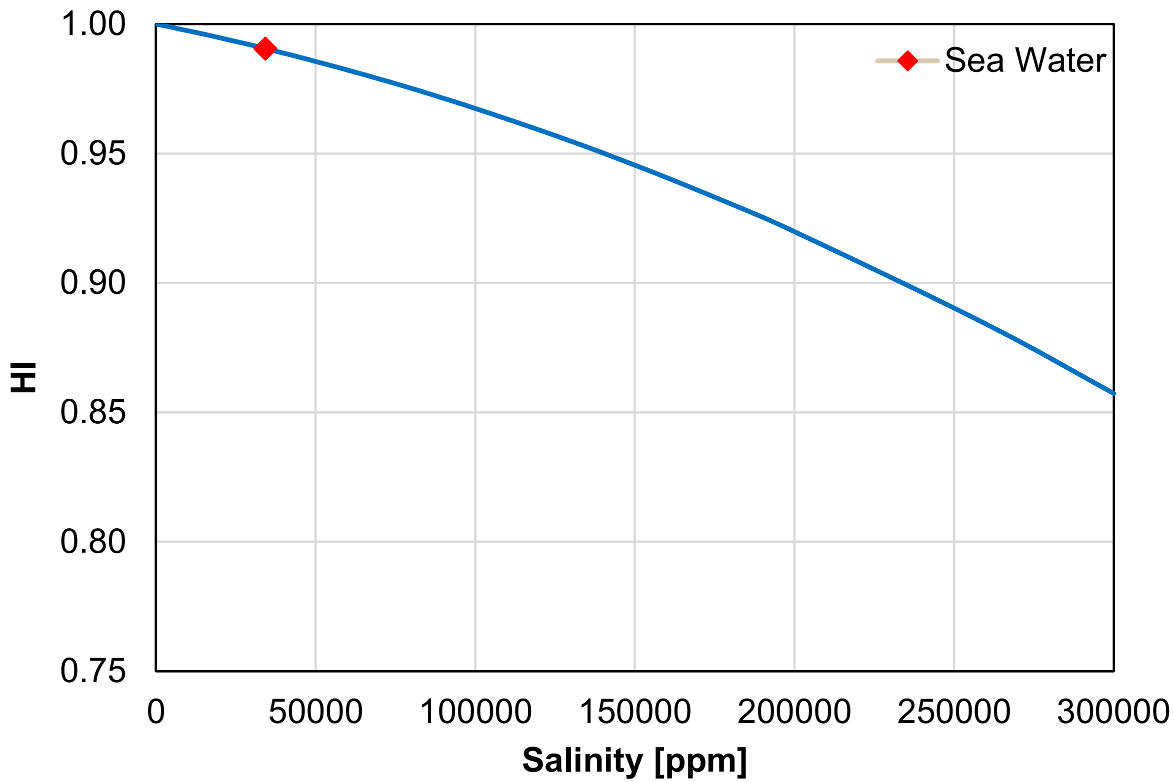




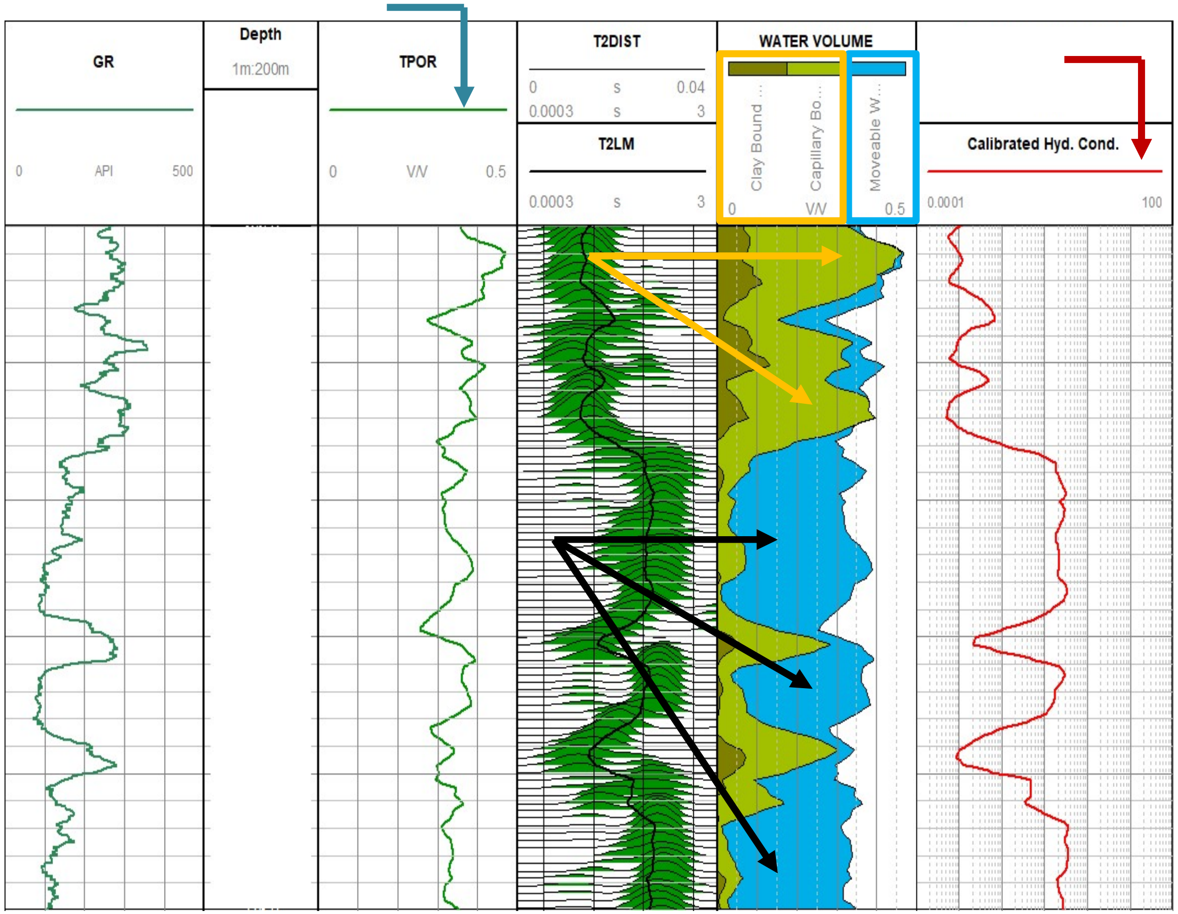
Correcting For Salinity

$$Apparent\ (Measured)\ Water\ Volume = HI\ \times True\ Water\ Volume$$

- Tool response lower than true water volume.
- Relevant in Brine Mining. Regularly see 250,000 ppm
- Calculate Hydrogen Index (HI) by calculating an effective sodium solution density.
- Definition: *The number of hydrogen atoms per unit volume divided by the number of hydrogen atoms per unit volume of pure water at surface conditions.*
- HI of pure water is 1.



Downhole BMR Data



- Aquifer / Reservoir
- Aquitard / Aquiclude
- Permeability / Hydraulic Conductivity
- Total Porosity
- Moveable Fluids (Specific Yield)
- Irreducible Fluids (Specific Retention)

Potash Brine Mining

Lake Throssell

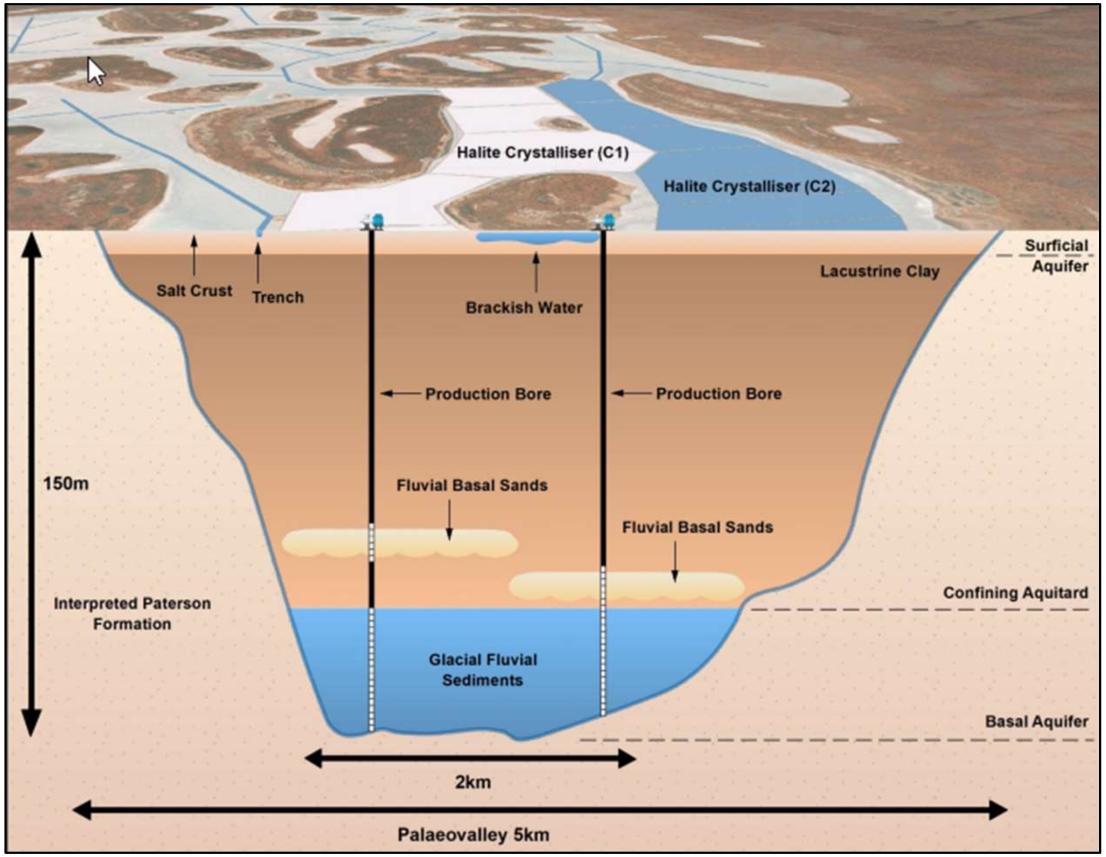
Potash Brine Mining

- Potassium sulphate, or sulphate of potash (SOP), is mainly used in fertilisers and contains important nutrients for plant growth. It does not contain chloride which can be a detriment to plants that are chloride-sensitive such as avocados and coffee beans.
- Only 35% of SOP comes from natural resources and is considered a rarity.
- SOP is water soluble and can form mineable deposits below the subsurface hosted within hypersaline groundwater.
- SOP can be mined by extracting hypersaline groundwater via trenching or through boreholes and processing via evaporation ponds and a purification plant.

(Images courtesy Trigg Minerals)

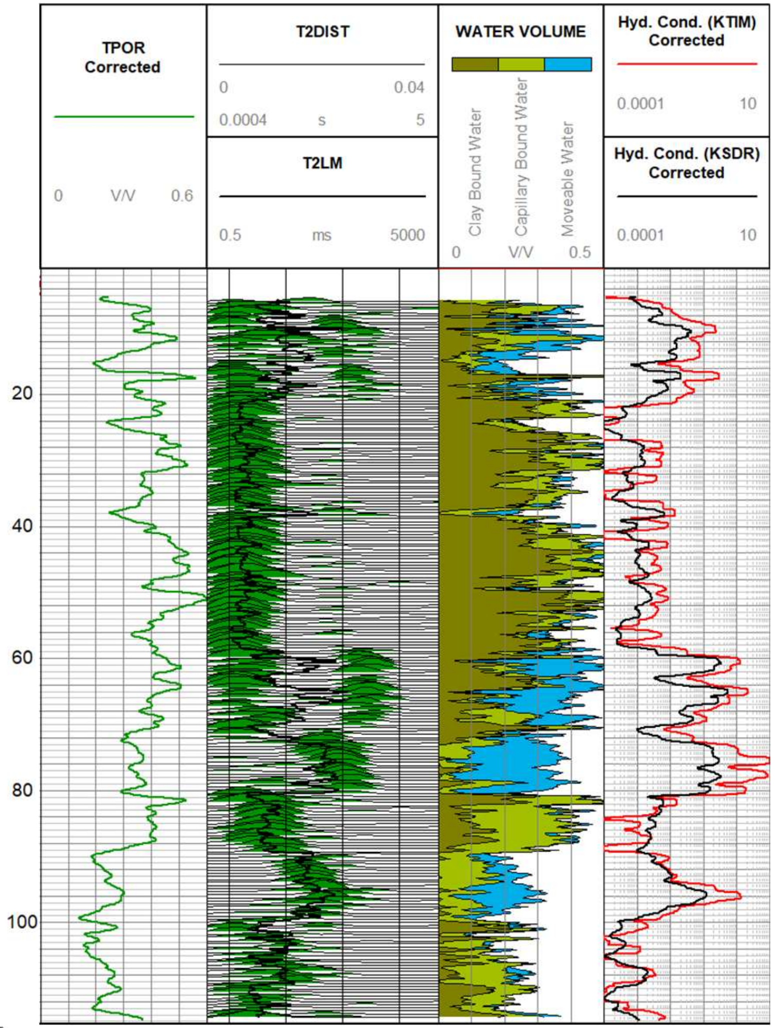
Lake Throssell

- The Lake Throssell Project covers an area of 1,085km² approximately 180km east of Laverton, Western Australia.
- The Project contains a total drainable Mineral Resource Estimate of 13.3Mt of SOP with an initial 21-year mine life.
- The salt lake acts as a point of discharge for the regional groundwater system. Groundwater flow in the shallow sediments within the lake's catchment flows towards the lake surface where evaporation is dominant and there is a net loss to the system making the groundwater hypersaline in nature.
- Average grade of 4,760 mg/L potassium.



ASX Announcement 1/02/2023: Positive Brine Assay and Borehole Magnetic Resonance Results from Lake Throssell
ASX Announcement 5/10/2021: Scoping Study Results Presentation

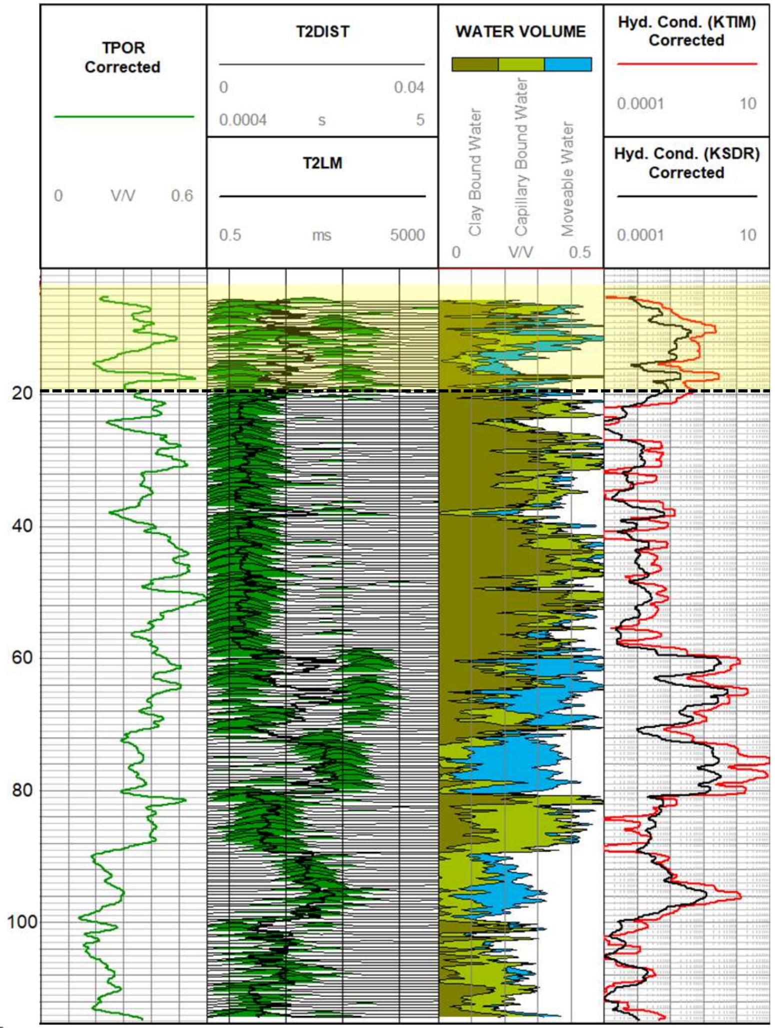
BMR Results



- Clear delineation of sand / clay and bound / free fluid intervals
- Allow calculation of specific yield (defined as movable water)
- Estimate hydraulic conductivity to inform aquifer performance.
- Salinity Correction on HI=0.908, i.e increase of fluid volumes of 10%.

ASX Announcement 5/10/2021: Scoping Study Results Presentation

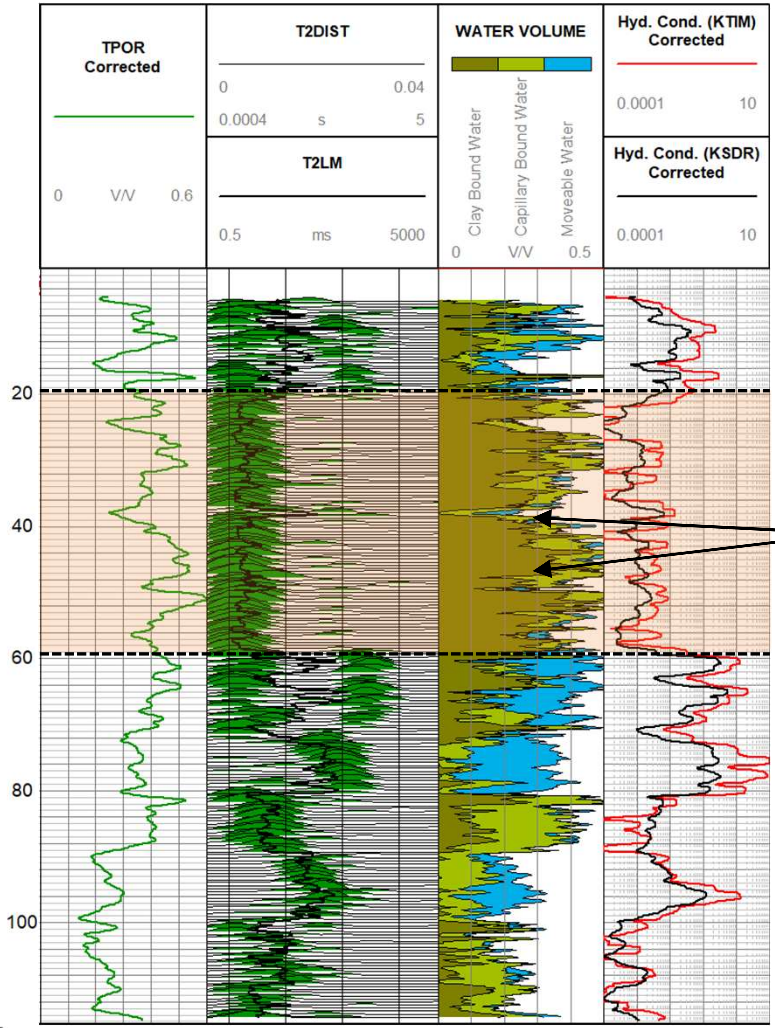
Alluvium



- Upper clay dominated aquifer
- Dual T2 peaks indicate presence of small and large pores. Dominated by small pores.
- Sy=0.11

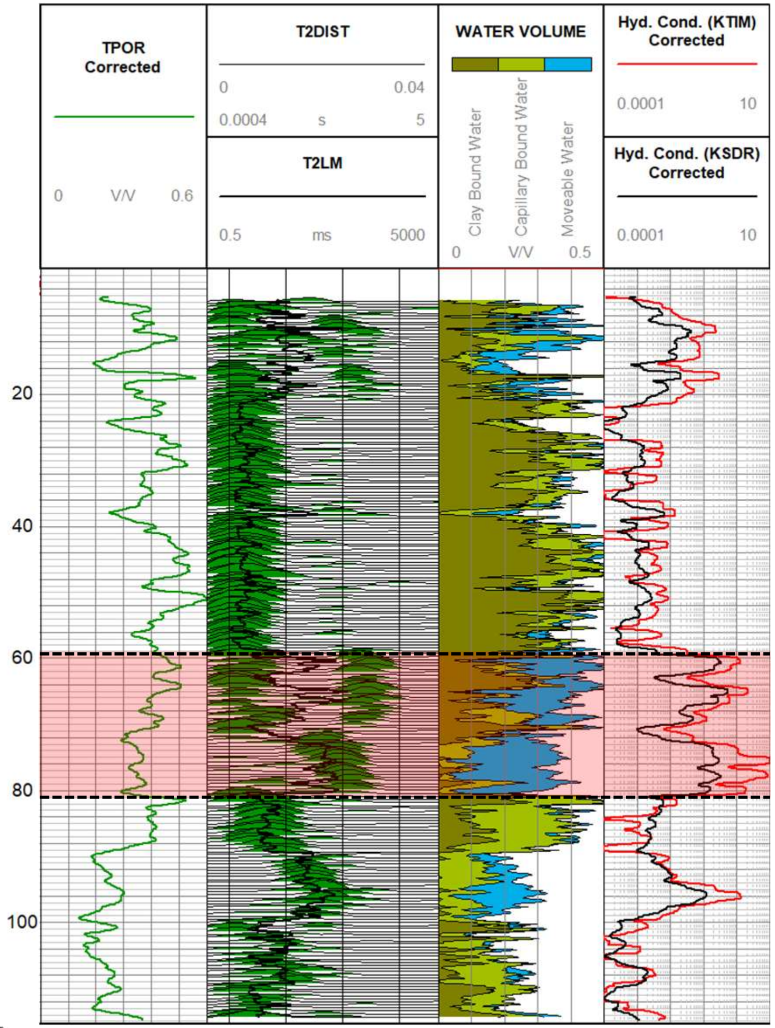
ASX Announcement 5/10/2021: Scoping Study Results Presentation

Lacustrine Clay



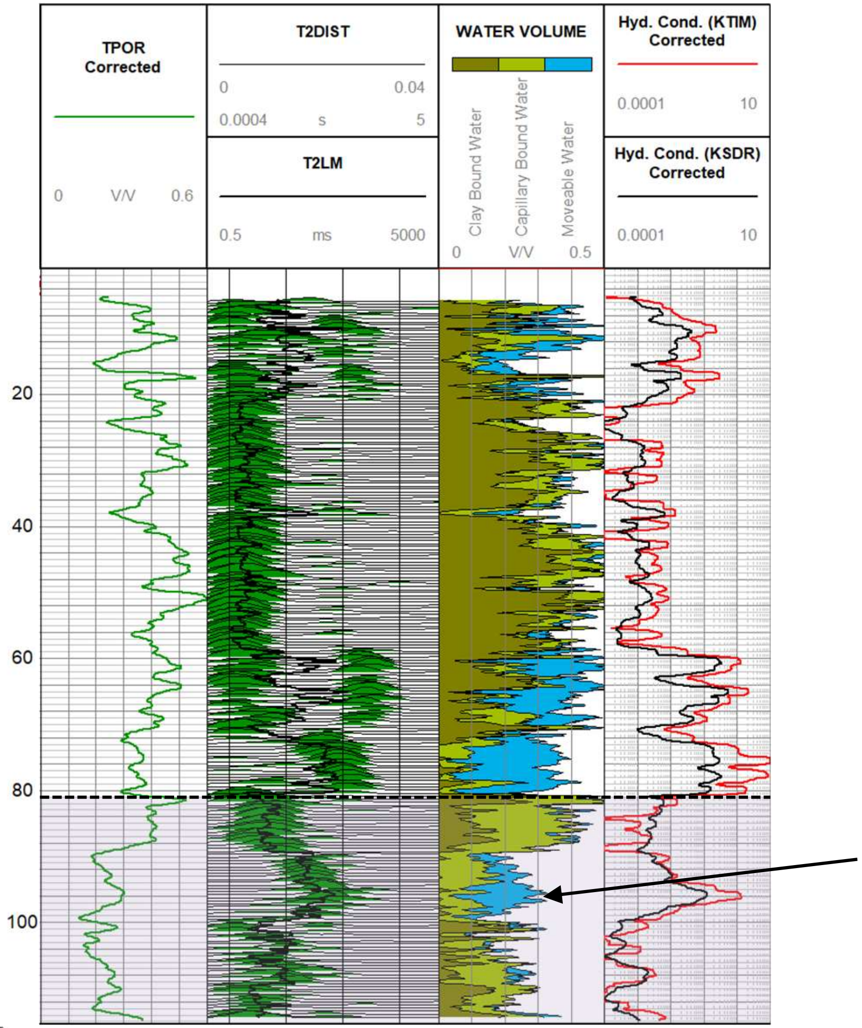
- Short single peak T2 indicated clay lithology
- Clay Dominated
- Notable Calcrete bands with which will yield brine
- Sy=0.03

Fluvial Sand



- Primary production aquifer
- Dual peak at top of unit with clay peak not present further down. Indicates clay/sand transition into sand dominated unit.
- Fluvial / Clayey sands
- Sy=0.20

Saprolite



- Intermediate T2 peaks indicate capillary bound water / silt dominated lithology.
- Basal Aquifer
- Minor gravelly sand zone
- Sy=0.05

Conclusions

Conclusions and Outcomes

- Poro-perm measurements are critical in knowing whether an ISR project is feasible.
- Traditional Hydrogeological data acquisition is time consuming, requires specialized expertise and can be expensive.
- BMR using NMR principles can give:
    - Differentiate bound and free fluid
    - Can provide lithological characterisation.
    - Logged without use of radioactive sources.

- Case study outcomes:
    - The BMR measurements confirm the presence of high free fluid aquifer units.
    - Enable Estimation of Specific Yield on an aquifer-by-aquifer basis.
    - Directly inform resource estimate.
    - Account for BMR logging in flowing sands during planning (case in PVC)

(Images courtesy Trigg Minerals)

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Acknowledgements

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