ENERGY GeO Hackathon

Society of Petroleum Engineers

#DatafyingEnergy

From October 21, 2024

2024 SPE Europe Energy GeoHackathon

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Geothermal Petrophysics

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What is Geothermal Energy?

Geothermal energy is heat within the earth. The word geothermal comes from the Greek words geo (earth) and therme (heat). Geothermal energy is a renewable energy source because heat is continuously produced inside the earth. People use geothermal heat for bathing, to heat buildings, and to generate electricity

(from https://www.eia.gov/energyexplained/geothermal/)

What Are Petrophysics and Formation Evaluation?

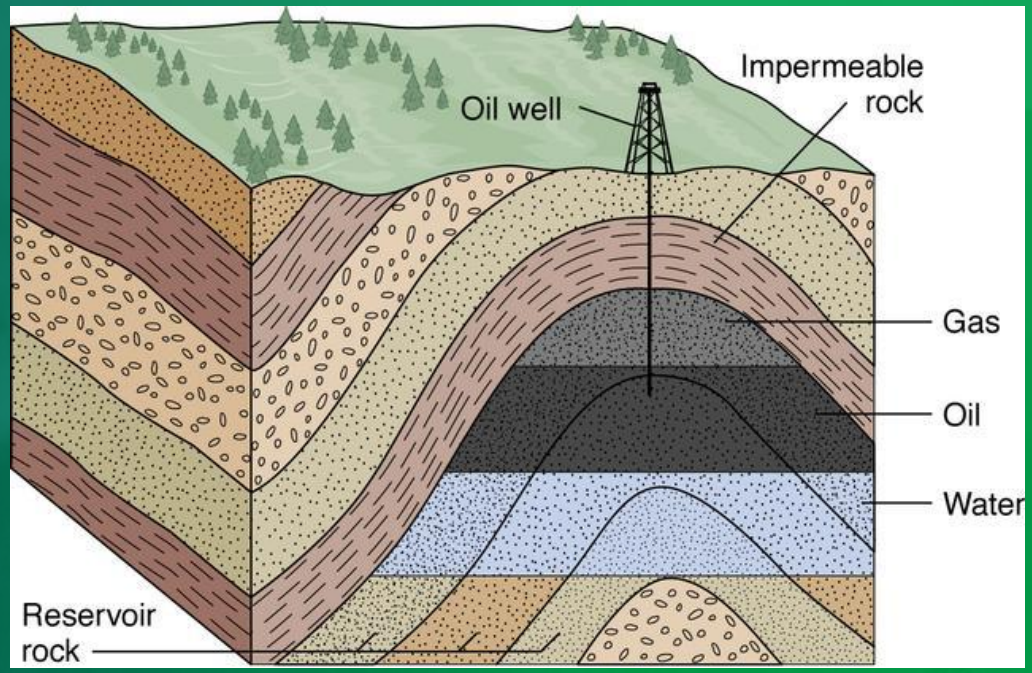
- **Petrophysics** (from the Greek πέτρα, *petra*, "rock" and φύσις, physis "nature") is the study of physical and chemical rock properties and their interactions with fluids
- In oil and gas, its' value has been recognised for many years,
  - Detailed subsurface petrophysical knowledge is a key input into many other processes for decision making throughout a project's life
  - Oil and Gas companies typical perform extensive data acquisition (most commonly LWD and wireline) throughout the life of a project to acquire the data they need.
- Historically for geothermal, formation evaluation was limited.
  - Limited data acquisition – sometimes only as needed for formation identification
  - Often based on analysis of historical offset wells
- What does this mean for geothermal?
  - Limited subsurface knowledge
  - Lots of uncertainty
- Benefits of having detailed subsurface knowledge is beginning to be recognised
  - How can detailed subsurface knowledge benefit geothermal projects?

Which Formation Properties are Important?

What's Important for Oil and Gas?

What's Important?
Where are the hydrocarbons
How much is there
Are they producible
What will it cost

What Controls These?
Reservoir structure, thickness and aerial extent
Porosity
Hydrocarbon Saturation
Permeability
Recovery factor



What's Important for Geothermal?

Property
Temperature
Permeability
Effective porosity
Fractures

What's Important for Geothermal?

Property	What do we want?
Temperature	Higher is better
Permeability	Higher is better
Effective porosity	Higher is better
Fractures	More open fractures is better

What's Important for Geothermal?

Property	What do we want?	Why?
Temperature	Higher is better	More heat produced
Permeability	Higher is better	Greater flow, more heat production
Effective porosity	Higher is better	More surface area, more heat transfer
Fractures	More open fractures is better	More surface area, better permeability, greater flow, more heat

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Property
Lithology and geochemistry
Formation water
Formation and reservoir structure
Geomechanical properties

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Property	Why?
Lithology and geochemistry	Different lithologies behave differently with injection = scaling potential, pore plugging
Formation water	Dissolved solids, scale (radioactive?) and corrosion
Formation and reservoir structure	Is the well in the optimal position? Better location = better flow = more heat. Is the injected water going where you think it is?
Geomechanical properties	Rock strength, fracture strength. Subsidence and seismicity, wellbore stability

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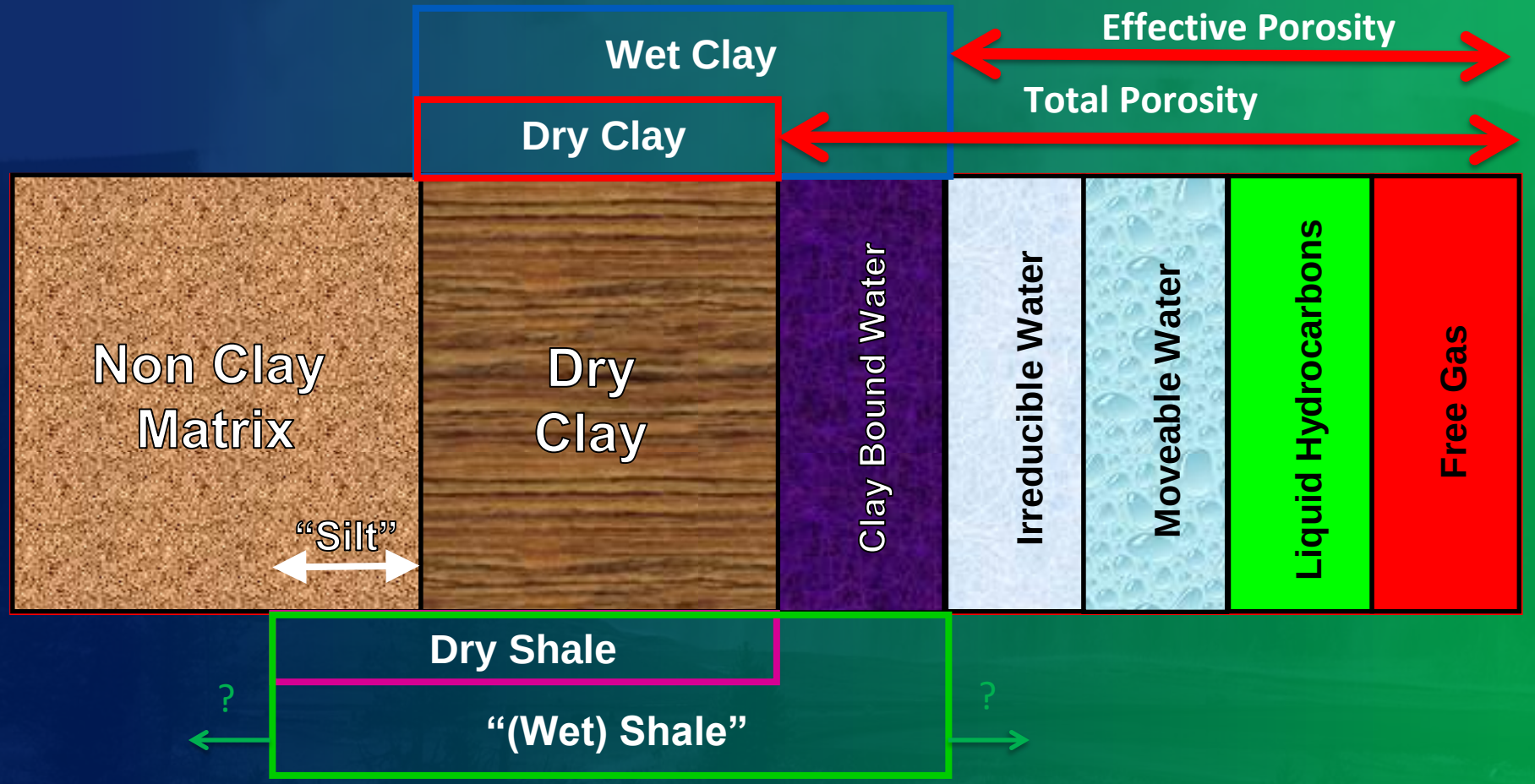
Is there more? What don't we know? What must we learn?

A Petrophysical Model

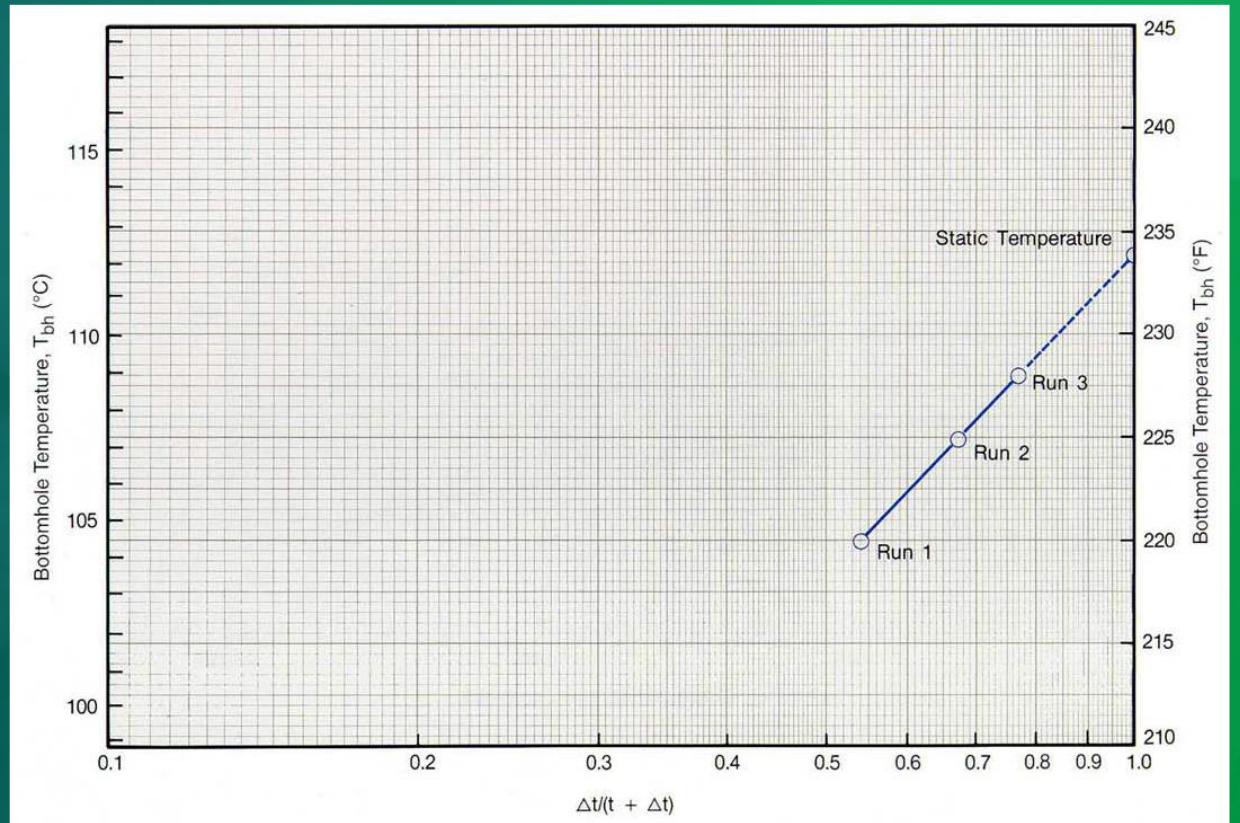
A Simple Rock Model



How can we determine reservoir properties?

Temperature

- Hotter is generally better – higher temperatures = more energy
- Most wireline and LWD logging strings include a temperature measurement
- However will this measure the true (static) formation temperature?
- No!
  - Logging Whilst Drilling
    - Circulation will cool borehole (often significantly)
    - Temperature can be significantly lower than true formation temperature
  - Open Hole Wireline
    - Often acquired soon after drilling
    - Formation temperature still recovering from cooling by drilling circulation
    - Methods are available to estimate true formation temperature by comparing temperature from multiple logging runs
- Temperature from production logs (recorded whilst well is on production) may be more representative of true formation temperature.
  - Formation temperature should have recovered from cooling during circulation



This chart is used to predict the static bottomhole formation temperature by recording the bottomhole temperature on each successive trip in the well. Each bottomhole temperature is plotted vs. the borehole fluid circulation time relationship on a semilog graph. Passing a straight line through the plotted points to the right ordinate will provide an estimation of the static bottomhole formation temperature.

Porosity

- Porosity is the ‘space’ in the rock
  - volume of fluid in formation (water, hydrocarbons, other gases)
- High effective porosity (porosity that can flow) means more fluid to produce = more energy
- High porosity often (BUT not always) related to high permeability
- How to measure porosity?
  - Conventional logs
    - Density, Neutron, Acoustic
    - Multiple log combinations - crossplots
  - Advanced Logs
    - Nuclear Magnetic Resonance
    - Dielectric

Sandstone, Rotliegend

Vuggy porosity and fracture in Silurian dolostone,Illinois

Density, Neutron, Acoustic Porosity

- Knowing matrix and fluid responses, porosity can be estimated from density and acoustic measurements

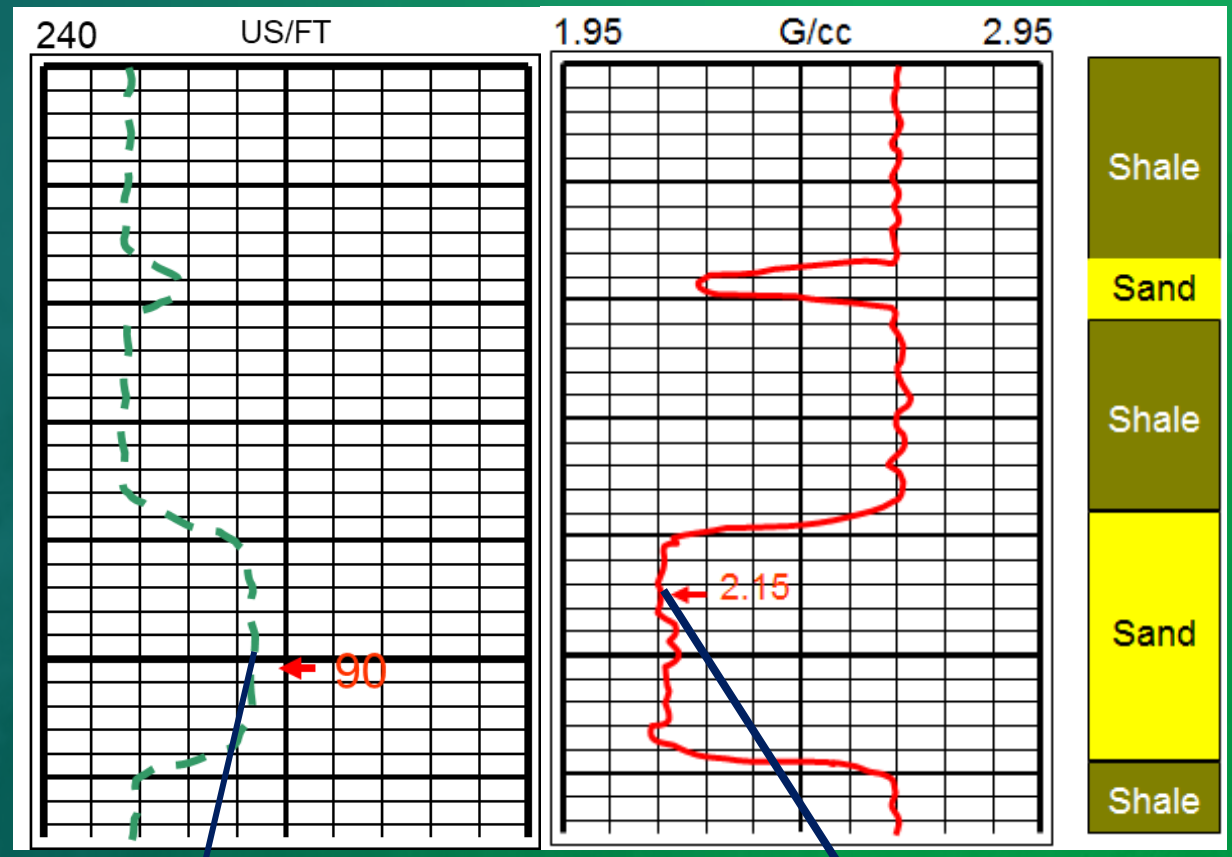
$$\emptyset = \frac{\rho_{matrix} - \rho_{bulk}}{\rho_{matrix} - \rho_{fluid}}$$

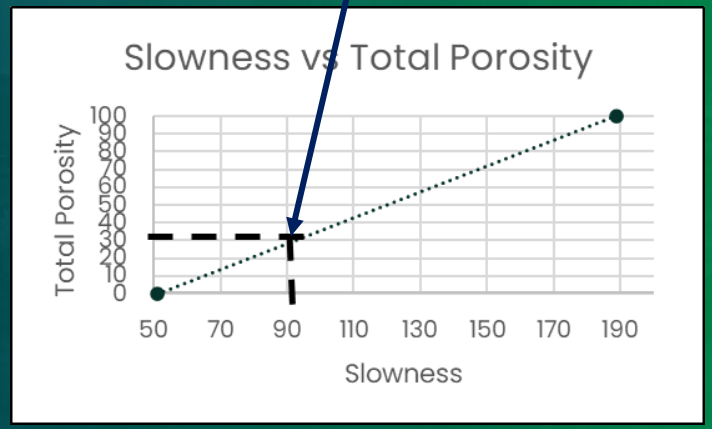
$$\emptyset = \frac{DT \quad - DT_{matrix}}{DT_{fluid} - DT_{matrix}}$$

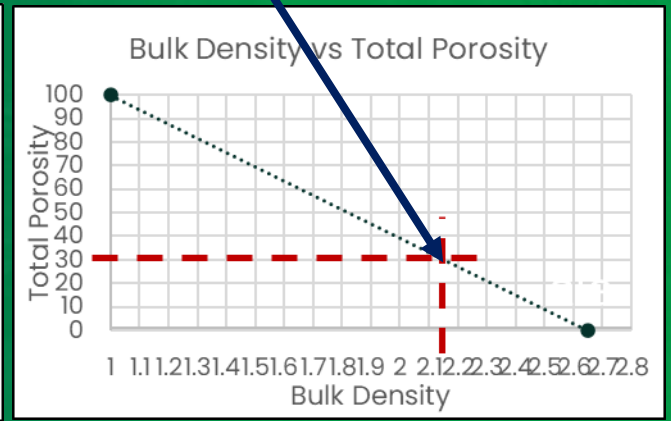
- Neutron porosity estimated by measuring the interactions of low energy neutrons with the formation.

However

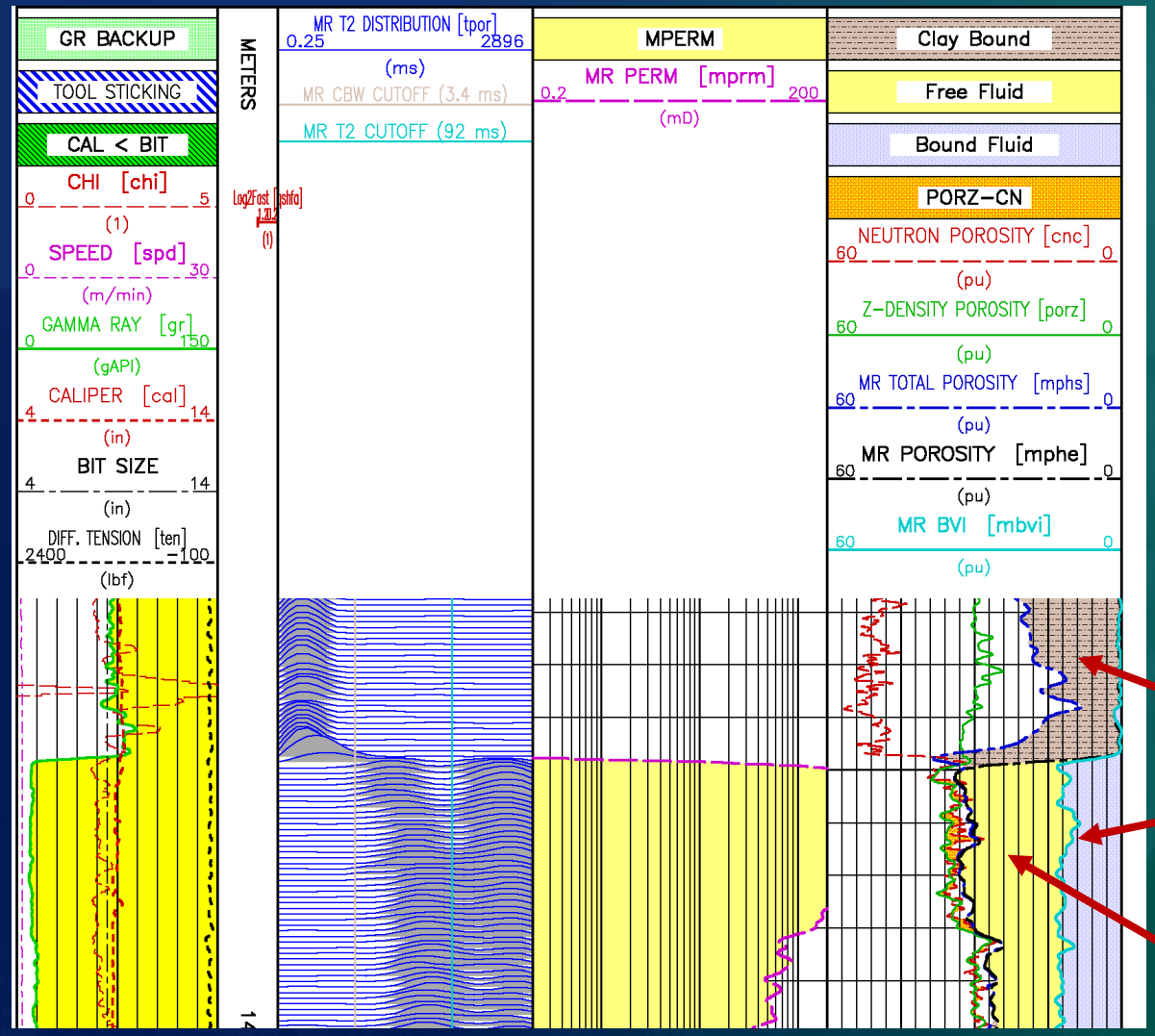
- Density and Neutron tools use strong radioactive sources – HSE concern
- Density measures 'Total Porosity' – not all necessarily connected and moveable
- Acoustic can be insensitive to secondary porosity – e.g. fractures and vugs
- Neutron reading also influenced by properties other than porosity
- Need to know matrix and fluid properties confidently to accurately estimate porosity
  - Increased uncertainty in complex formations e.g. mixed mineralogy







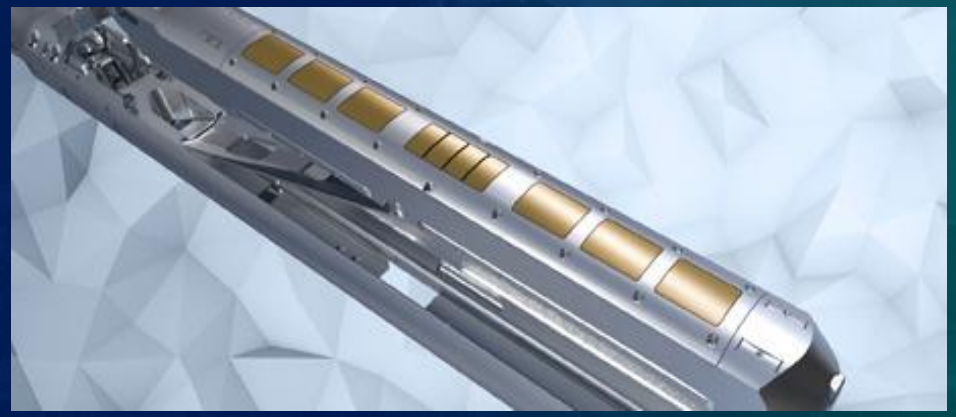
Nuclear Magnetic Resonance Porosity

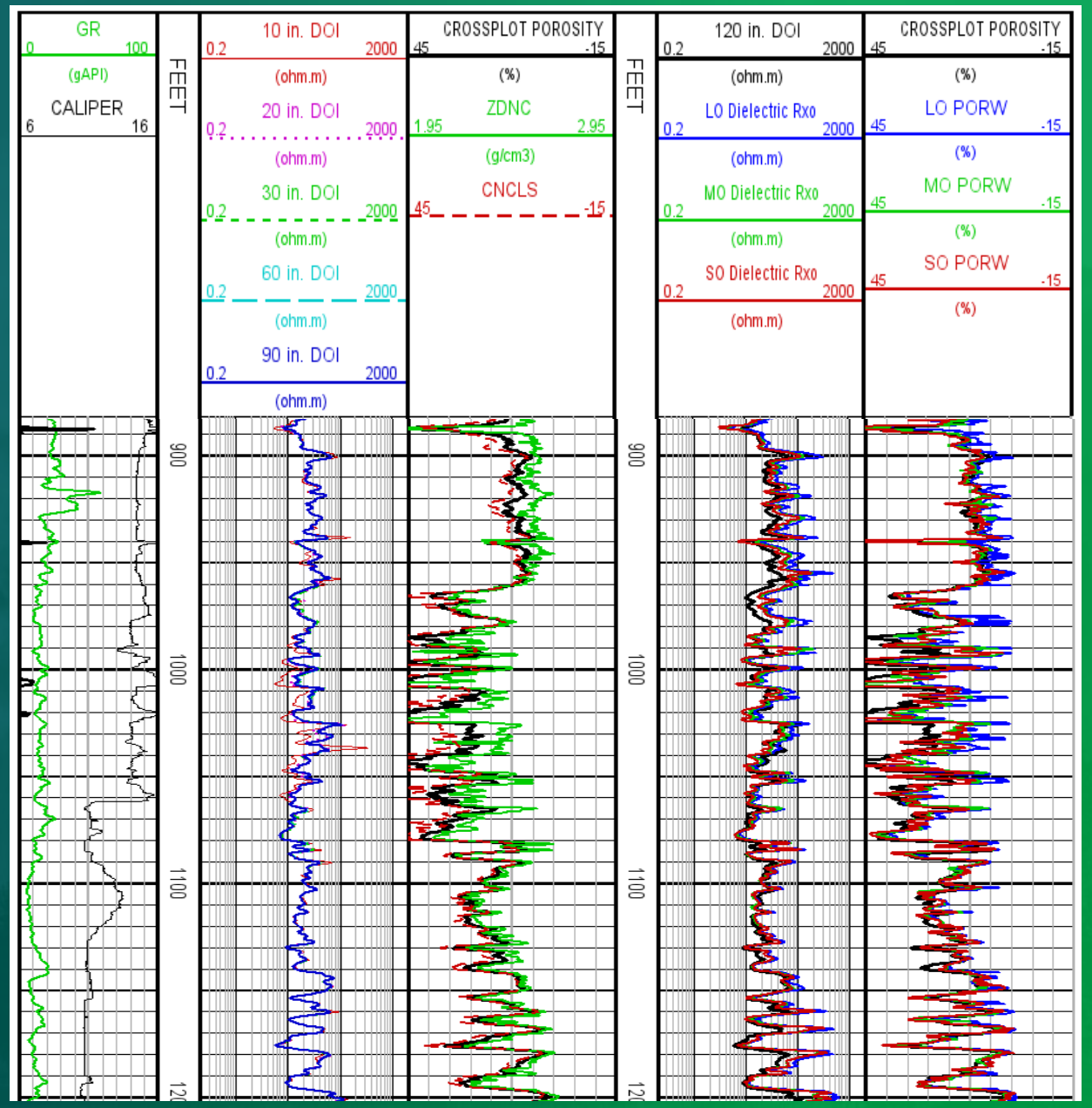


- Nuclear Magnetic Resonance logging tools
- Uses same physics as medical MRI scanners
- Responds to hydrogen in formation
  - Essentially fluid fraction only
  - Response influenced by fluid type and pore size distribution
- Allows us to determine moveable vs non-moveable porosity (unlike other porosity measurements)
- 'Sourceless' – No nuclear sources. safer than radioactive porosity measurements (density/neutron)

Dielectric Porosity

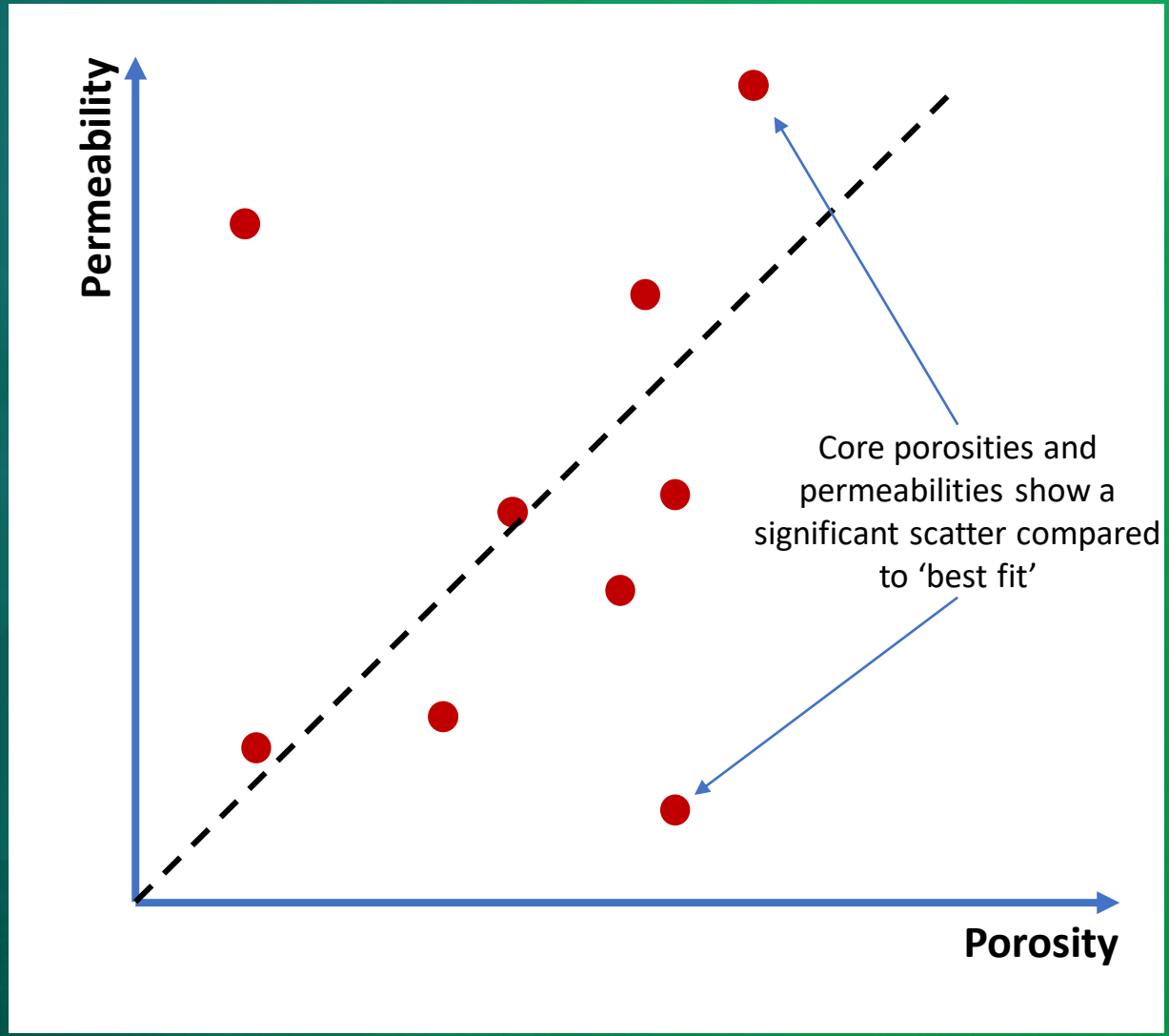
- Wireline dielectric tools
- Responds to water filled porosity in formation
- Can also derive textural properties that are important for some analysis methodologies
- Difference between water filled and total porosity from other measurements will give information if other fluids (e.g. hydrocarbons) are present





Permeability

- ‘Flow is everything’ is commonly heard in geothermal
  - Greater hot water production = more energy produced
- Flow is controlled by permeability
  - Ease of how different fluids flow through a formation, measured in Darcies (or more commonly Millidarcies)
- How can we measure it with logs?
  - Simple methods
    - Porosity/permeability relationships – e.g. Timur
    - Assumption that as porosity increases permeability also increases - greater flow
  - BUT not always the case
    - Fractured formations (e.g. igneous, carbonates) often have very low porosity but high permeability.
    - Vuggy carbonates and cemented clastics can have a very high porosity but low permeability

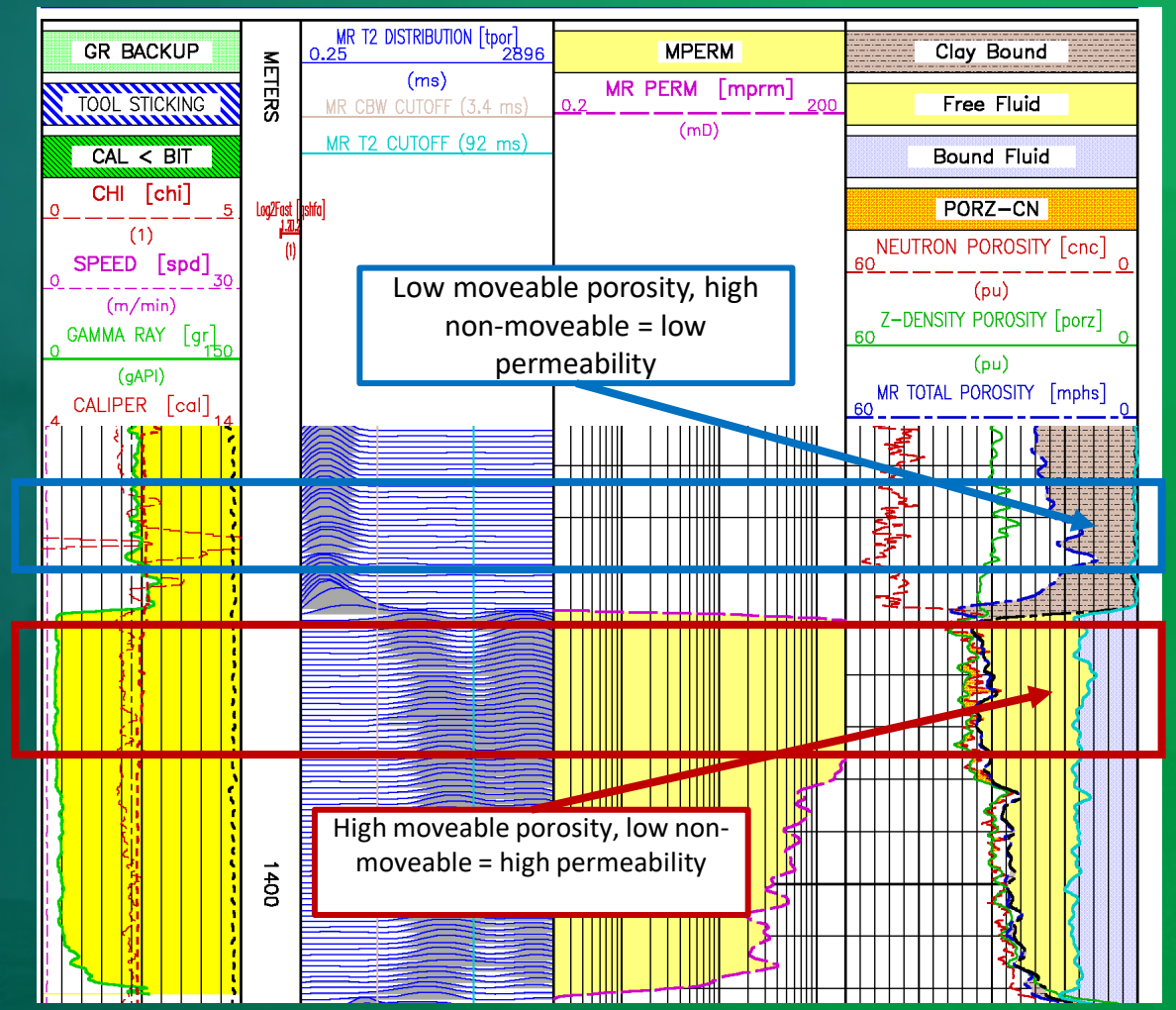


Nuclear Magnetic Resonance Permeability

- NMR logging responds to the relationship between moveable vs non-moveable porosity
  - E.g. Coates Equation - high moveable vs low non-moveable porosity = high permeability (and vice versa)
  - Often works well in clastic formations
  - less suited for fractured formations

$$k = \left(\frac{MPHE}{C}\right)^{m} \times \left(\frac{MBVM}{MBVI}\right)^{n}$$

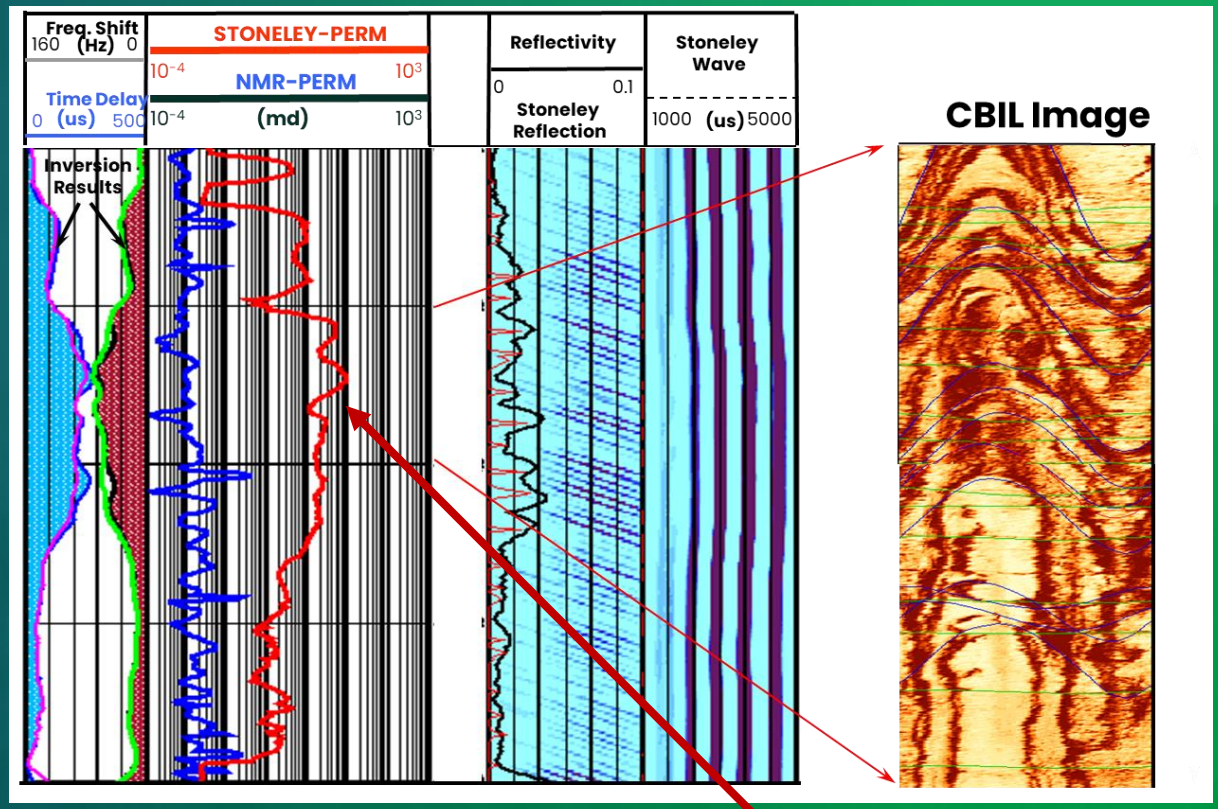
- Important to remember that unless m, n and C coefficients are calibrated to reference permeabilities, this gives a relative permeability index



Acoustic Stoneley Permeability

Stoneley waves can be measured by acoustic logging tools

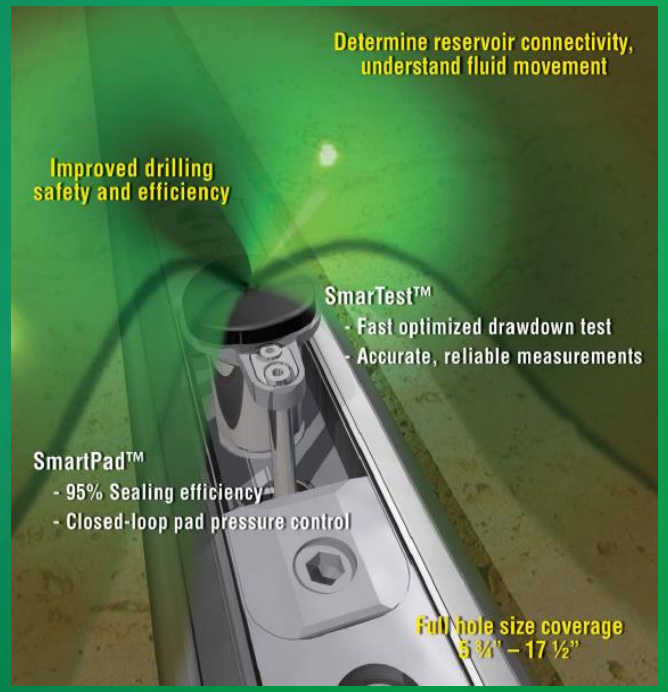
- Velocity of Stoneley waves in a borehole is influenced by movement of the pressure pulse across the borehole wall
- Related to the permeability of the formation
  - Measured Stoneley velocity < Theoretical Stoneley velocity indicates permeability
  - Velocity difference is proportional to permeability magnitude
- Stoneley permeability often much more representative in fractured formations than NMR derived permeability
- Important to remember that unless calibrated to reference permeabilities, this gives a relative permeability index

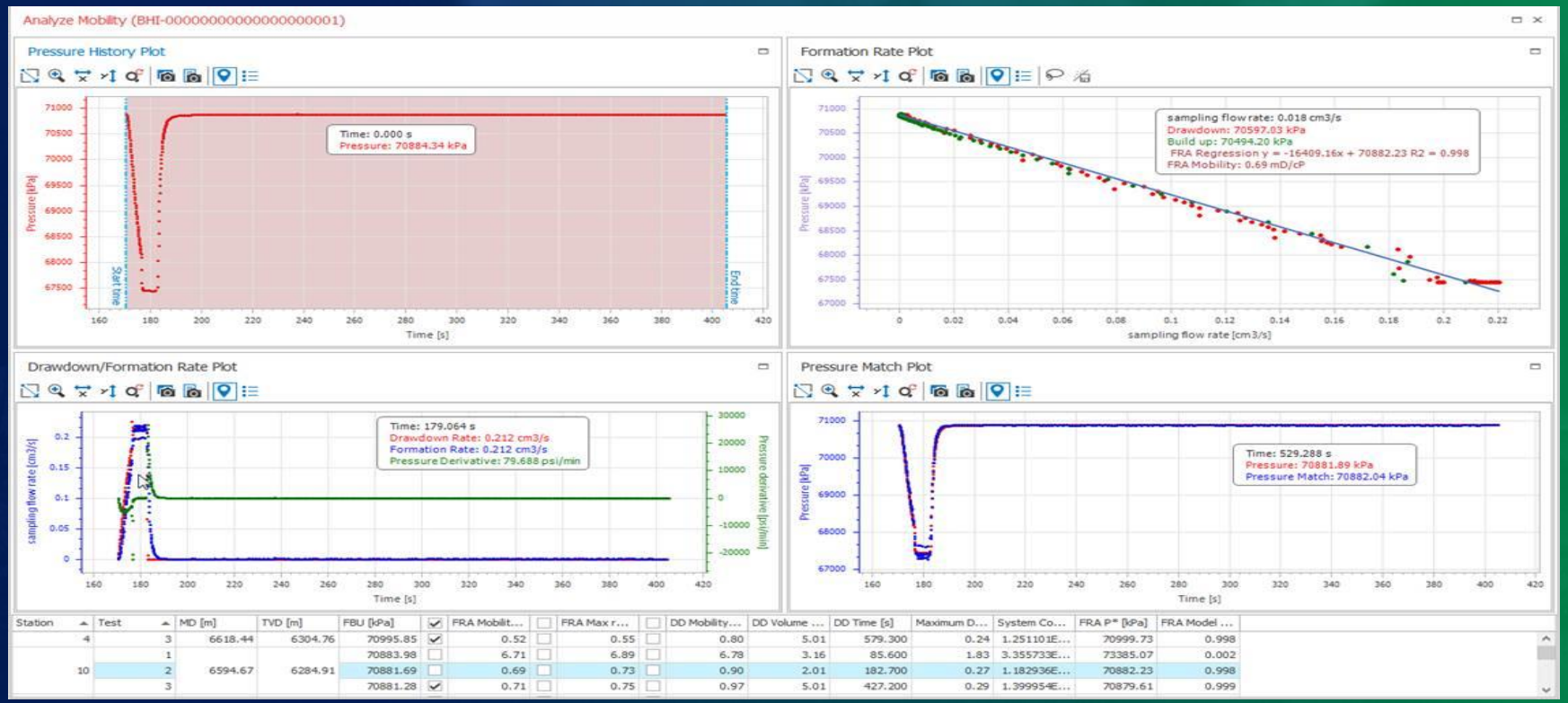


- High Stoneley permeability across low porosity fractured interval is more representative
- NMR estimated permeability is unrealistically low

Formation Tester Permeability

- Formation tester tools – LWD and Wireline
- Point measurement
- By monitoring pressure change in formation vs time whilst a pressure test is being conducted, formation mobility can be directly estimated by formation testers
- Multiplying this by fluid viscosity will give permeability
- This can then be used to calibrate NMR and Stoneley derived permeabilities



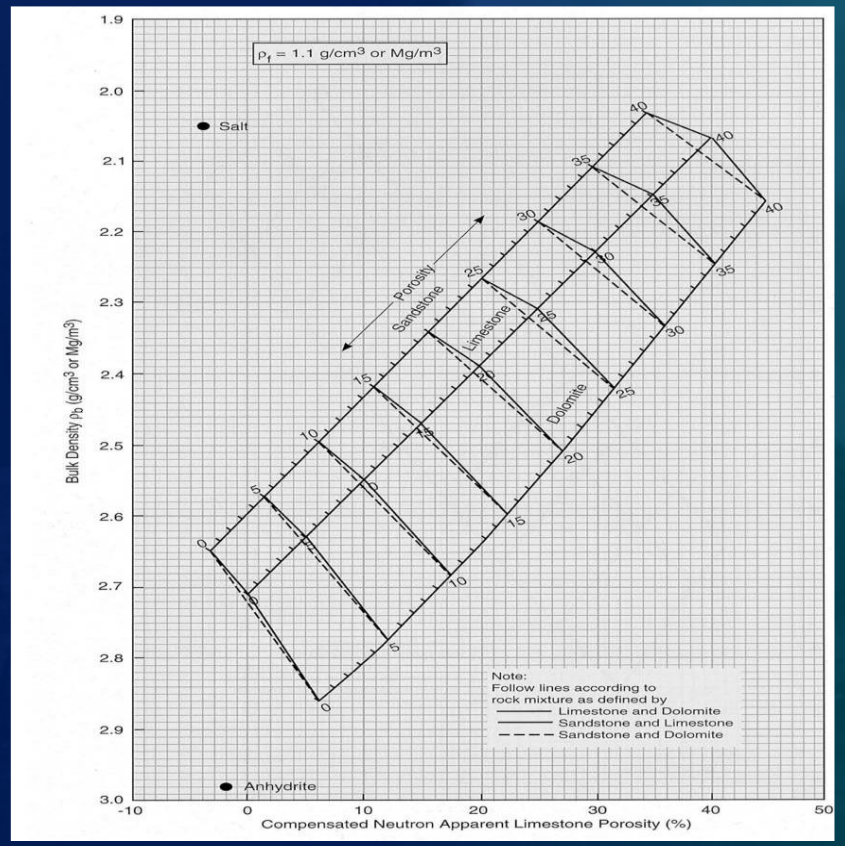


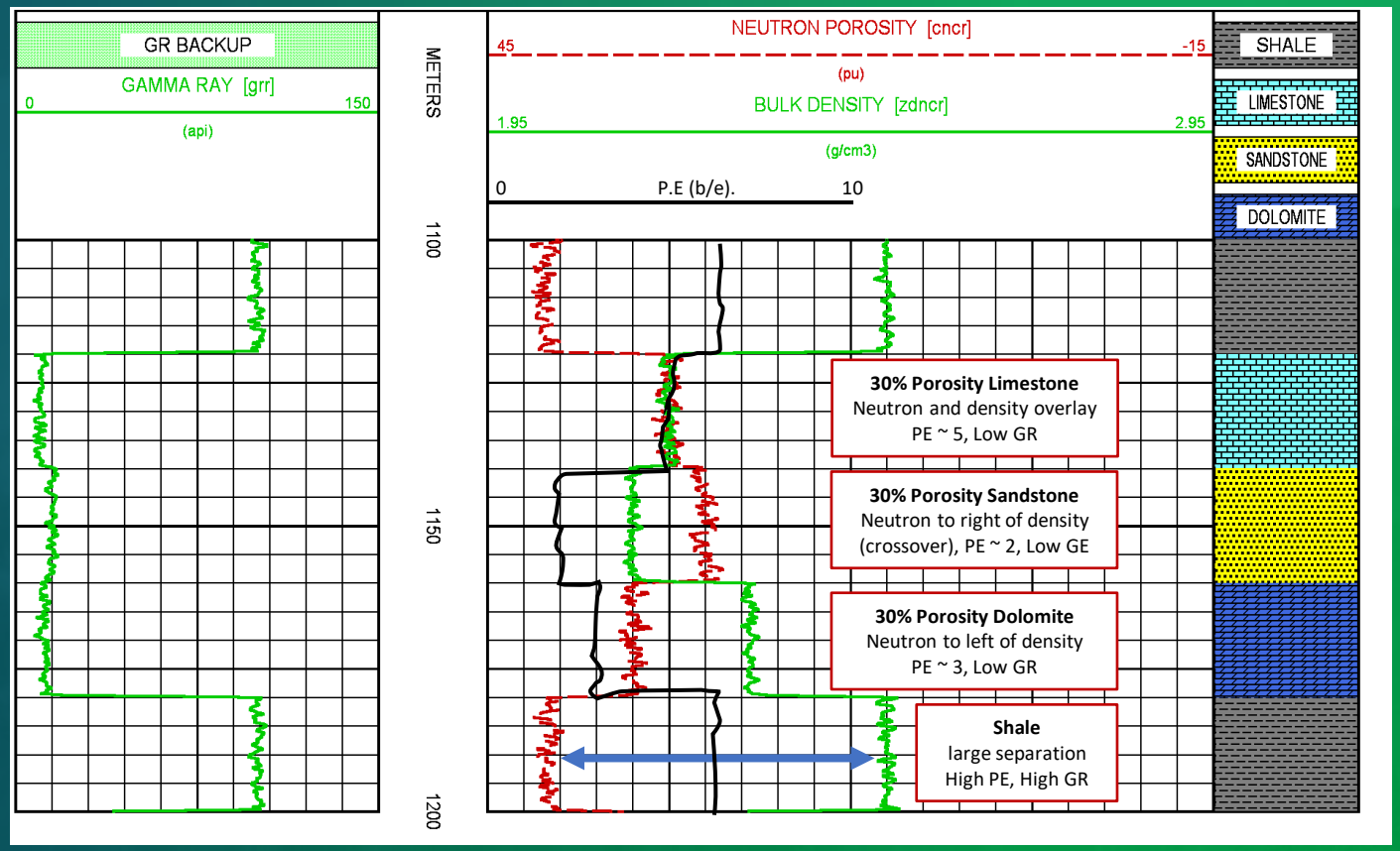
Lithology and Geochemistry

- Lithology can be related to total heat storage capacity of the formation
- Lithology can be directly related to geomechanical properties
- Formation fluids can interact with formation mineralogy
  - Pore plugging – reduces flow
  - Dissolution/breakdown of matrix
    - Sand production etc
- How to determine lithology and mineralogy?
  - Conventional logs (gamma ray/density/photoelectric/neutron/acoustic) – basic mineralogy (shale/sand/limestone/dolomite/igneous)
  - Spectral gamma ray (potassium/thorium/uranium concentration) – basic elemental composition
  - Elemental spectroscopy – detailed mineralogy
  - Rotary (and less commonly percussion) sidewall coring – point core samples
  - Pulsed Neutron logs through casing for porosity, lithology and saturation

Lithology estimation from conventional logs

- Lithology can be estimated from relationships between gamma ray, density, photoelectric, neutron and acoustic (and other) curves
- Effective porosity can also be estimated
  - ‘Average’ of porosity measurements
- Basis of crossplotting technique

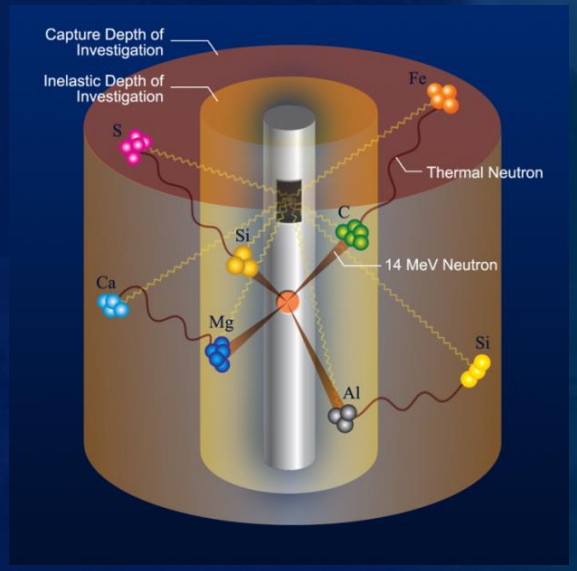


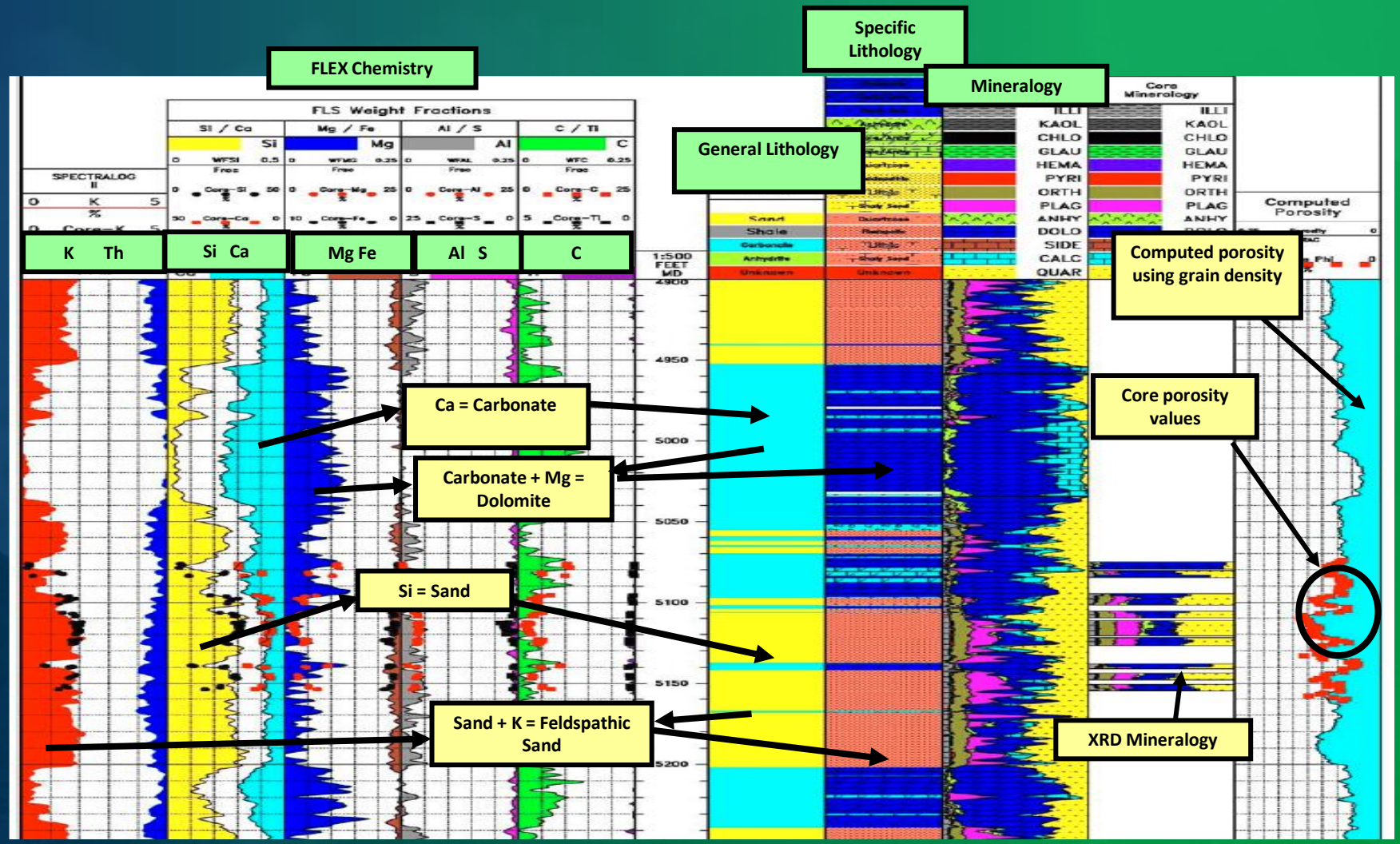


Density and Neutron logs plotted on limestone scales and matrix

Advanced Mineralogy – Elemental Spectroscopy

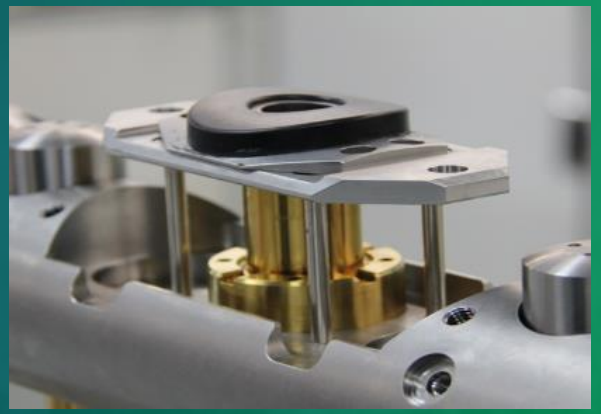
- Chemical and pulsed neutron source elemental spectroscopy tools
- Derives elemental composition from response of formation to neutron bombardment.
- Gives detailed elemental composition from which mineralogy can be derived

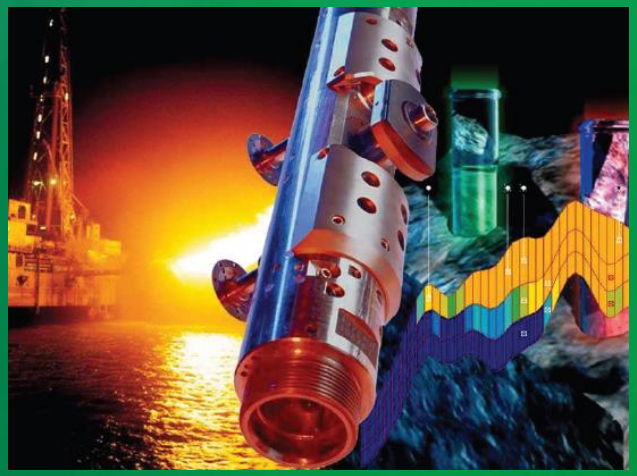




Formation Fluid Composition and Properties

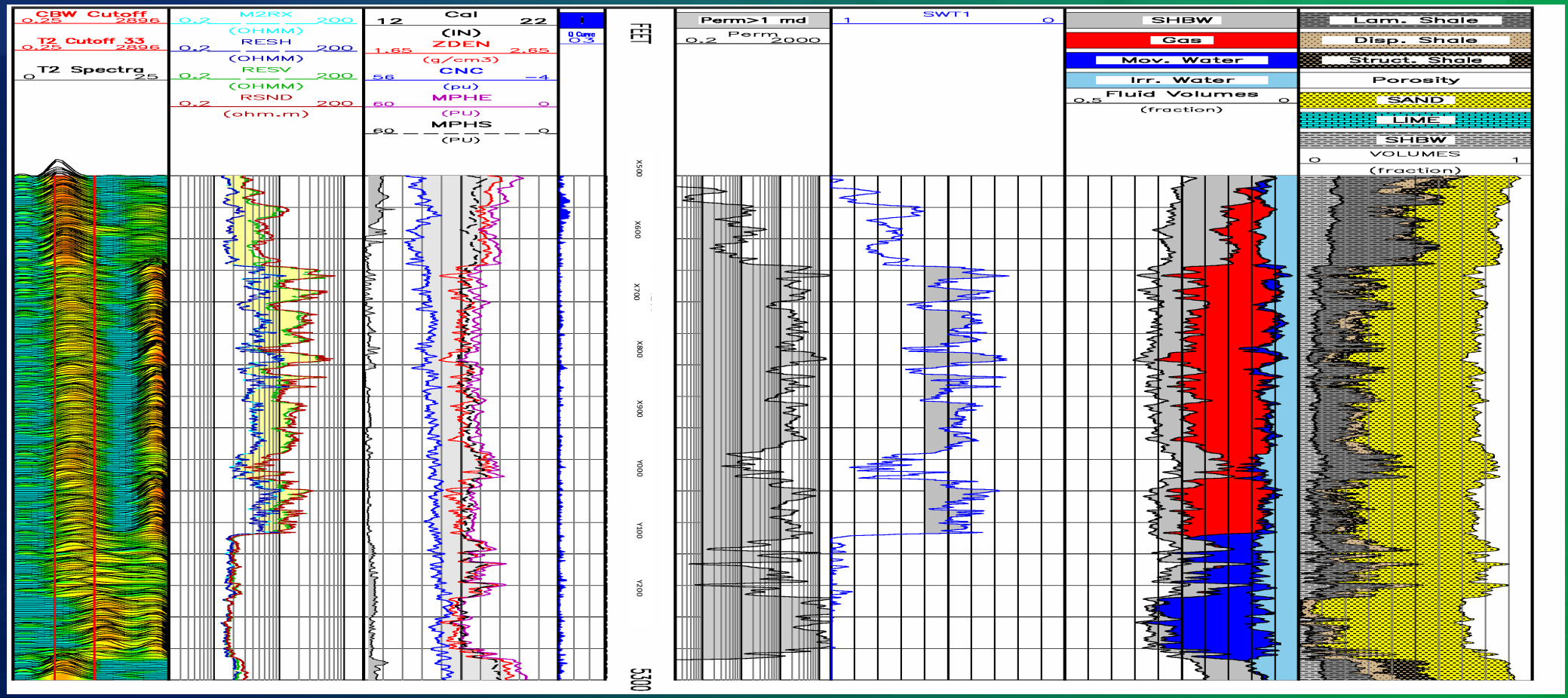
- Formation fluids can influence the geothermal system
  - Formation water can interact with the formation – plugging
  - Dissolved salts interact with downhole hardware and surface facilities
    - Scaling and corrosion
  - If hydrocarbons and other gases (CO_2, H_2S etc) are present they have to be dealt with
- How to determine fluid properties?
  - Hydrocarbon saturation and gas identification:
    - Resistivity, Nuclear Magnetic Resonance, Dielectric, formation pressure gradients, pulsed neutron (through casing)
  - Water properties
    - Pressure gradients, dielectric measurements, formation fluid samples





Integration – the big picture

- No single measurement will give all the answers
- Integrating multiple answers gives the most comprehensive interpretation

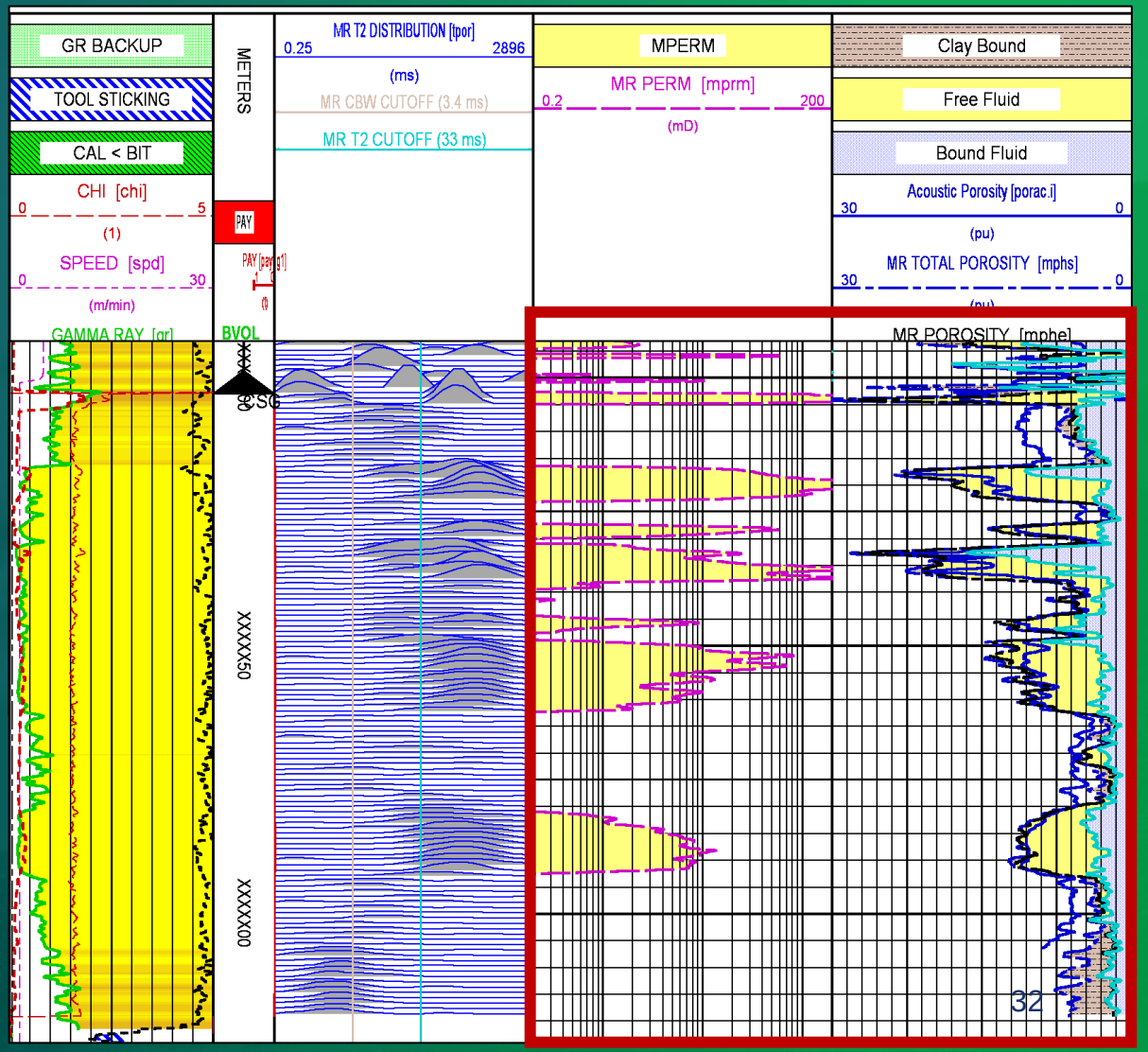


How Can Subsurface Knowledge Benefit A Geothermal Project?

A Case Study

The Implications Of Limited Subsurface Knowledge

- Fractured carbonate geothermal well – 113m open hole completed interval
- Assumed majority of interval will flow
- Nuclear Magnetic Resonance (NMR) and acoustic logs run for porosity determination
- Porosities up to 15%, NMR derived Coates permeability up to 200mD



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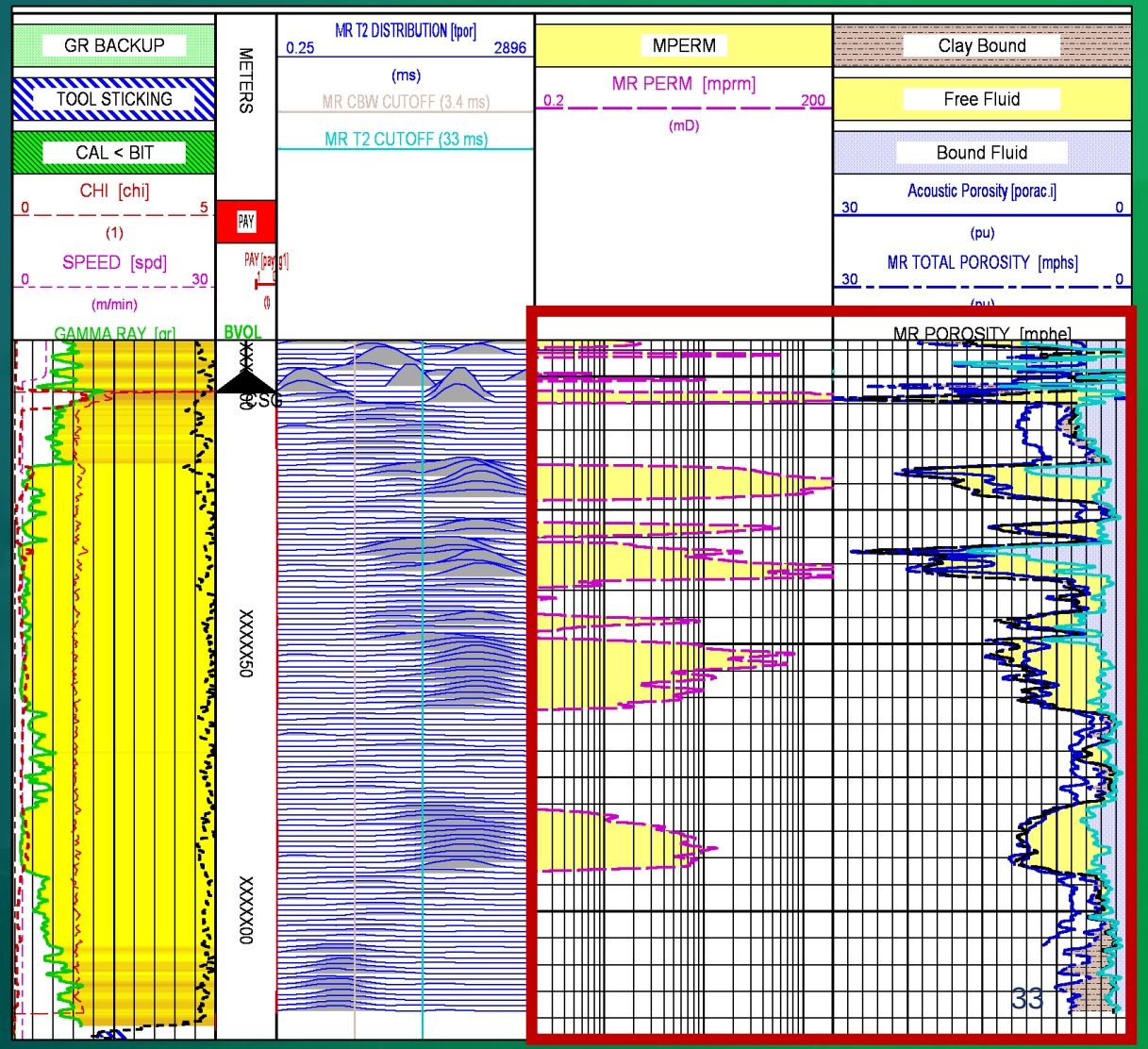
Net-to-gross estimation

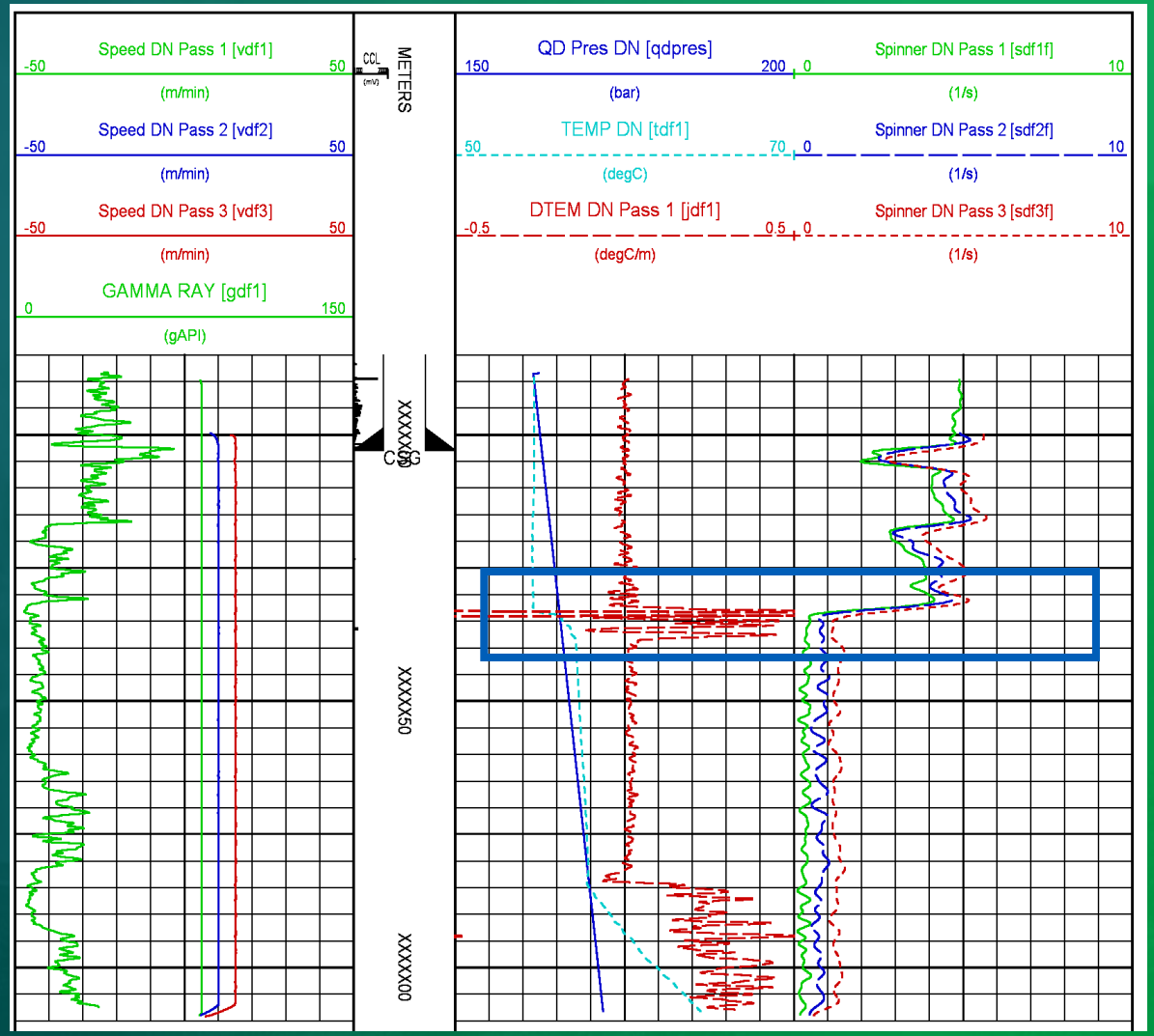
Min Moveable Porosity (%)	Min Permeability (mD)	Productive Interval (m)	Net/Gross
5	2	36.5	0.323



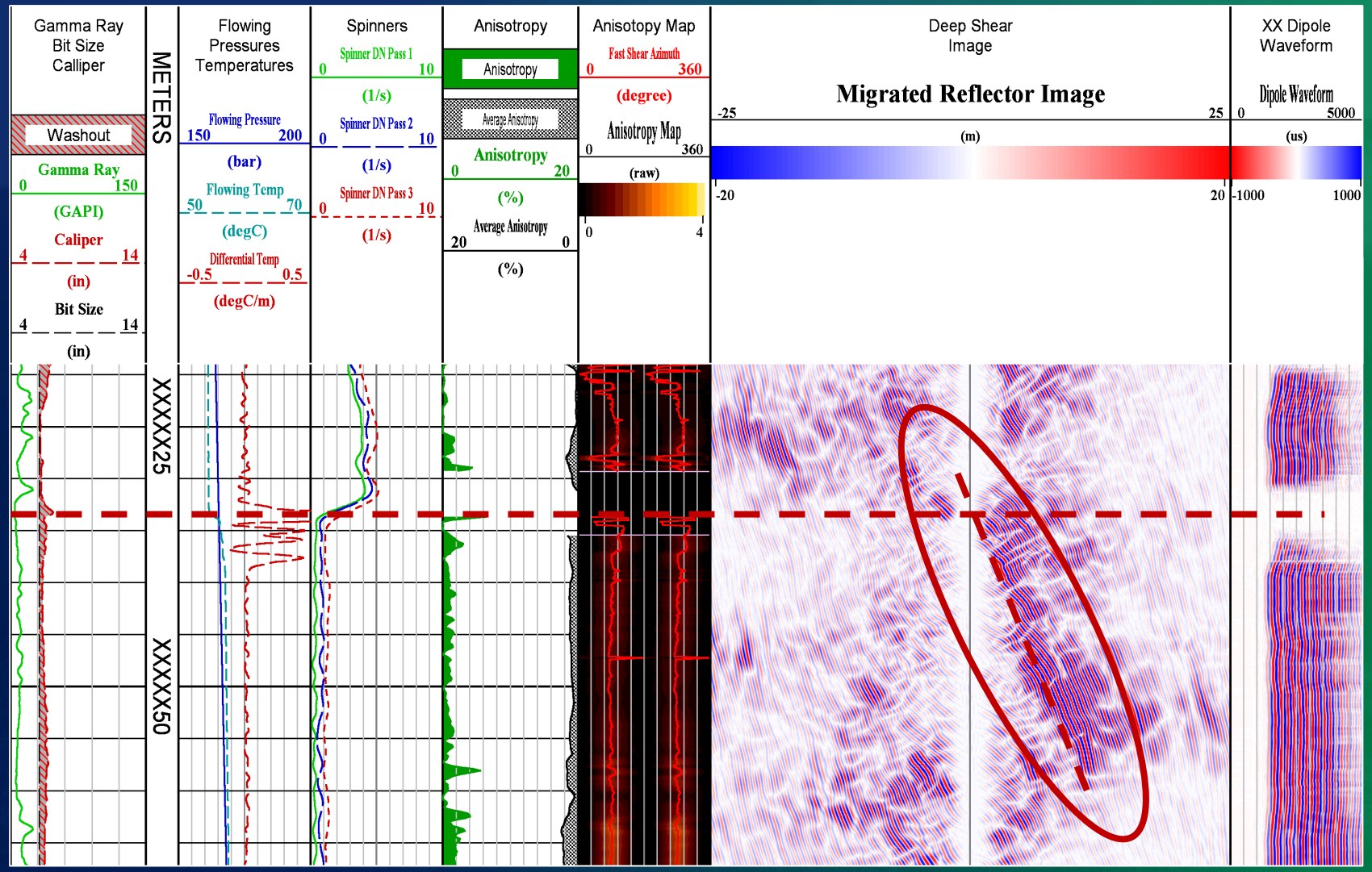
Where's The Flow Coming From?

But does it all flow?

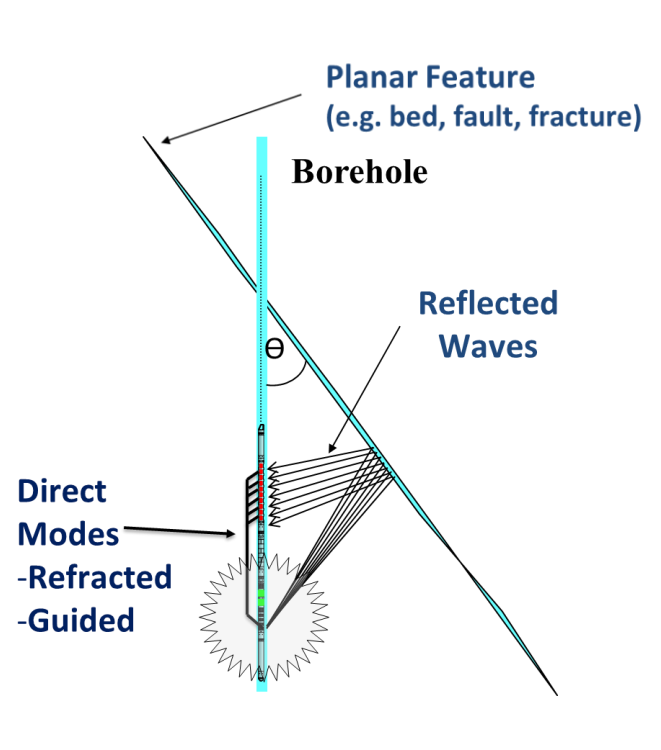
- Production logs (spinners, pressure, temperature) run for flow identification
- Significant flow over only one interval
- Why?



Why Is Only This Interval Flowing?



Acoustic Wellbore Reflection Imaging Theory



What Are The Implications?

How can lack of subsurface knowledge affect a project?

- Poorer performance than expected
- Lower economic return - Less attractive to investors
- Lack of geochemical knowledge? – Corrosion, Scaling?
- Unexpected solids production? Pump Wear?
- Reactivation of faults? – Seismicity?
- What else?

Conclusions

Current application of subsurface evaluation to geothermal is often limited, but the value is gives is becoming recognised

- Subsurface data acquisition often seen as unnecessary expense that should be minimised
- Well established oil and gas evaluation principles equally applicable to geothermal
- Significant opportunities for us to apply our knowledge
- Additional direct measurement of certain key properties would be very beneficial
  - May only become apparent many years in the future
  - Acquisition later in life of well may be impractical or impossible, and expensive
- Potential to increase heat production and cost savings through efficiency and optimisation of prospects

Any Questions, Thoughts, Ideas, Comments?

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