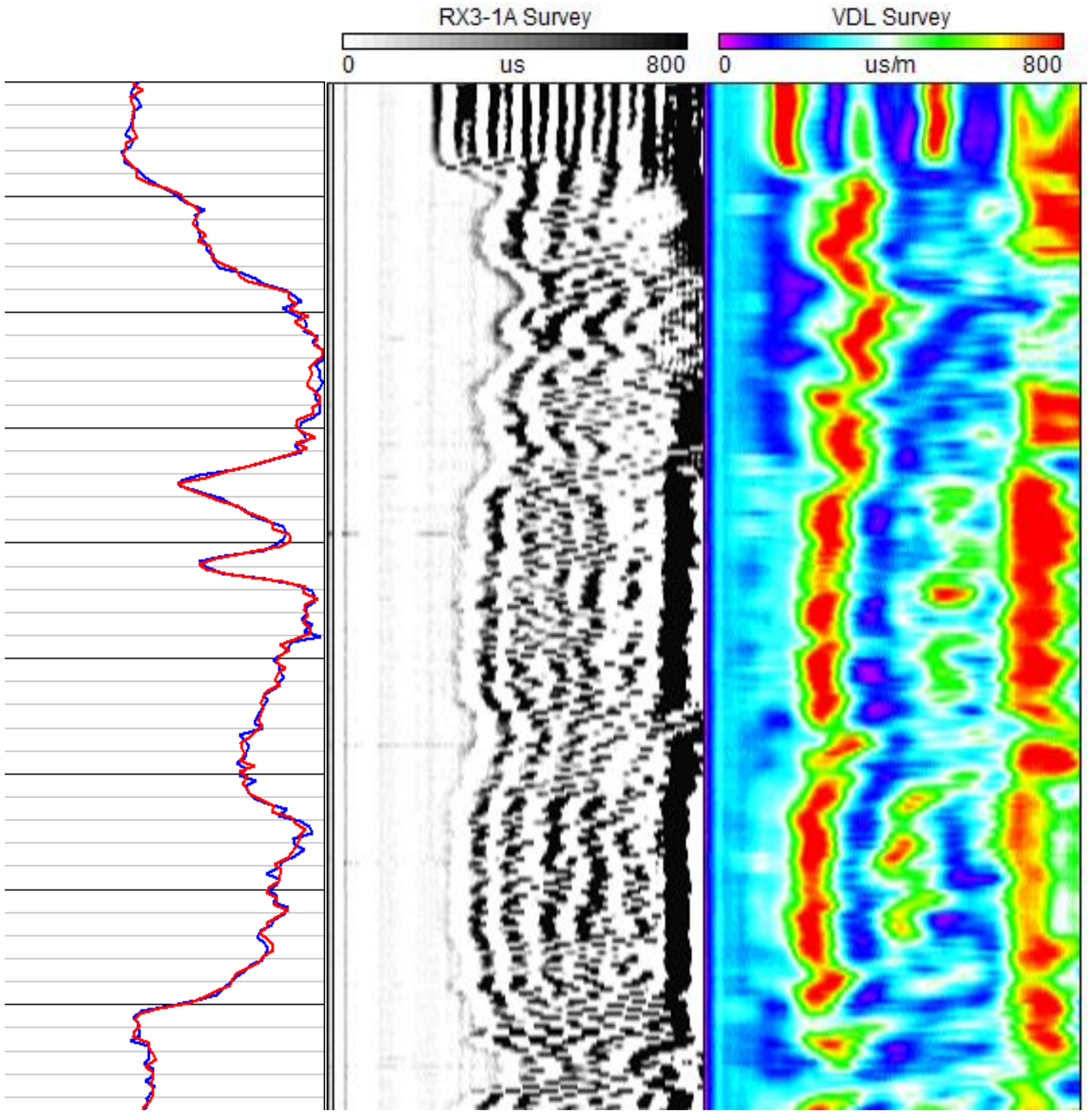
BOREHOLE DATA WITH A PURPOSE



MERC 2023 - Session 2

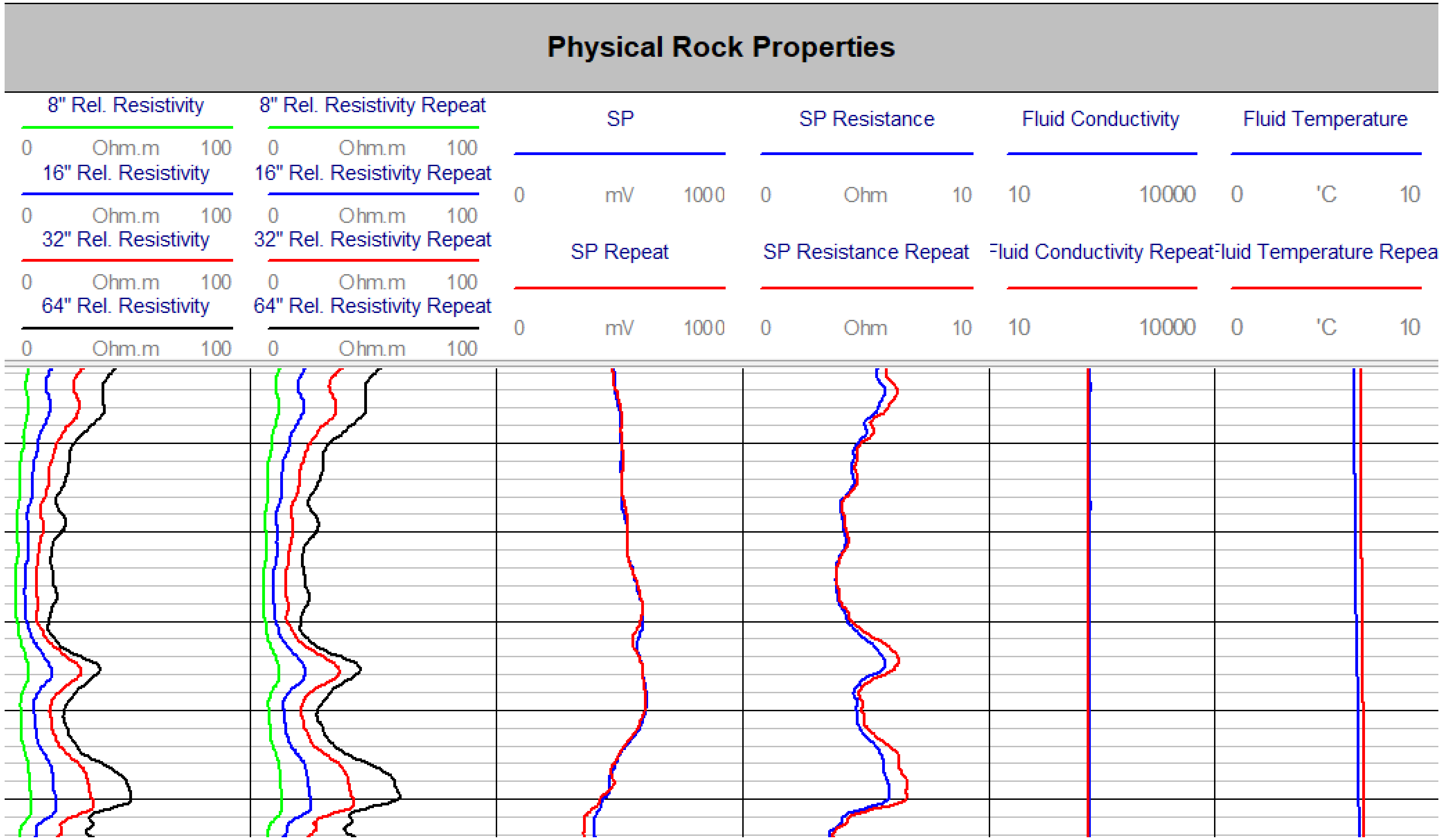
PHYSICAL PROPERTIES AND APPLICATION

Session 2 - Outline

- What are Physical Properties and their importance
- Methods to obtain them
- Types and Applications
- Borehole Survey Parameters
  - Density
  - Neutron
    - Coal Example Exercise
  - Gamma
  - Electrical and Magnetic parameters
  - Full Wave Sonic
  - Caliper and others
- Exercise

What Are Physical Properties

- A measurable property which describes a physical system's state/matter
- Independent of geological names
- Interdisciplinary – geology, geophysics, geochemistry, physics, engineering etc.



Importance of Physical Rock Properties

- Geophysics is the measurement of the physical properties of the earth
  - The science of exploiting physical rock property contrasts
- Physical rock properties are the quantitative link between geology and geophysics
- Respond to lithology, mineralization, alteration, porosity, and mechanical rock properties
- Quantitative physical rock properties are essential to map geology with geophysics
- Capable of providing key insights into ore grade, ore delineation, geometallurgy, geotechnical properties and hydrogeology

Methods to obtain Physical Properties

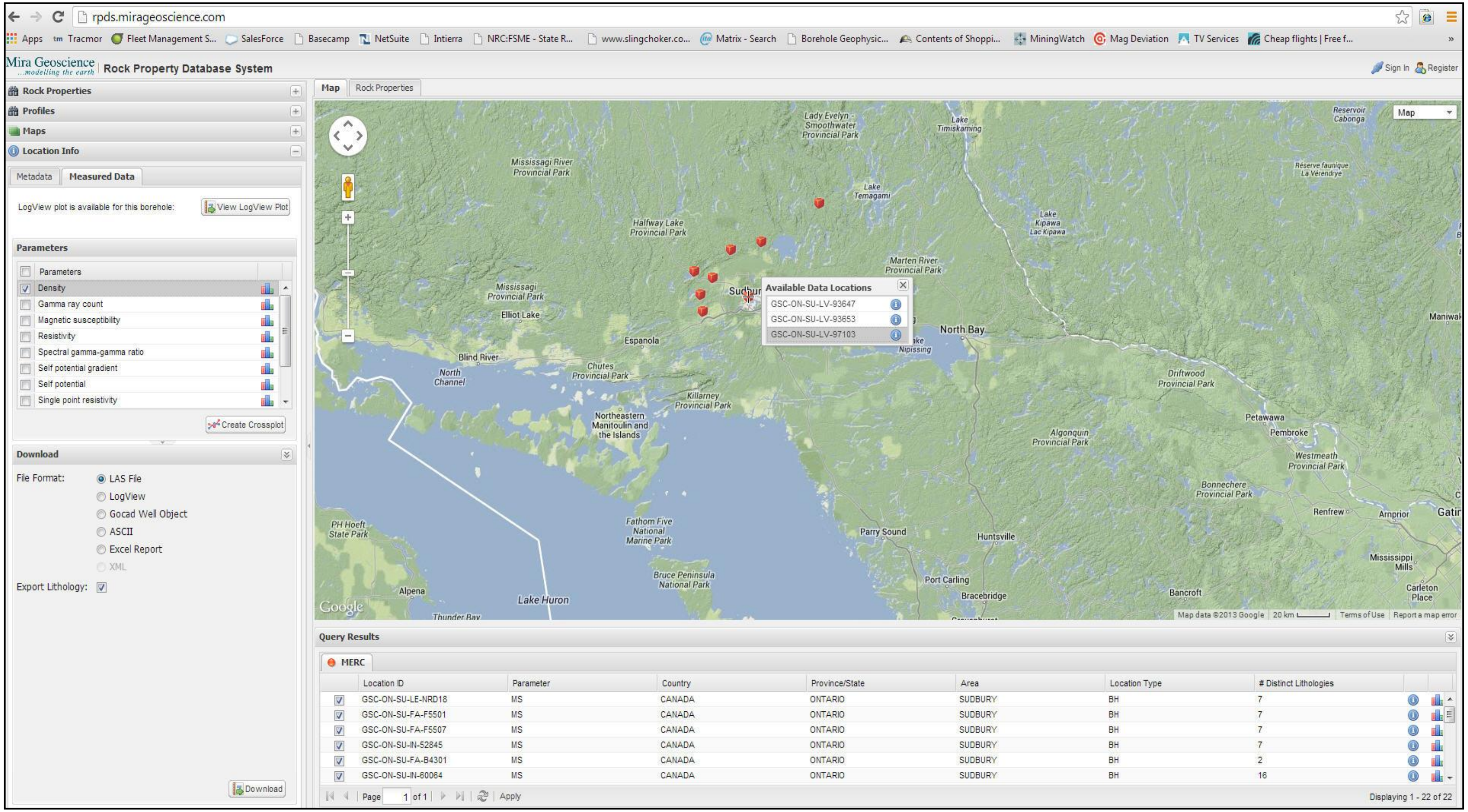
- Textbook/Google
- Rock Property Database System Led by Mira Geoscience
  rpds.mirageoscience.com
- Lab
- Core analysis
- Core scanner on site
- ***In-situ - Boreholes***

Methods to Obtain Physical Properties

Textbook/Literature

- Pros
  - Inexpensive
  - Fast
- Cons
  - Representative?
  - Data range
  - Out of date?

Methods to Obtain Physical Properties



Rock Property Database System Led by

Mira Geoscience

rpds.mirageoscience.com

Methods to Obtain Physical Properties

Lab

- **Pros**
  - Highly accurate
  - Rigorous controls
- **Cons**
  - Time & logistics
  - Sample Selection Bias
  - Sample Statistics
  - Sampling Procedure
  - Sample handling
  - Sample Scale

Powertech Labs, 2013

Methods to Obtain Physical Properties

Core Analysis

- Hand Held - Measure directly on core/outcrop
    - Magnetic Susceptibility e.g. KT –20
    - Gamma Ray Spectrometry
  - Pros
    - Fast
    - Accurate
  - Cons
    - Orientation/contact
    - Calibration
    - Location

Methods to Obtain Physical Properties

Core Scanner On Site

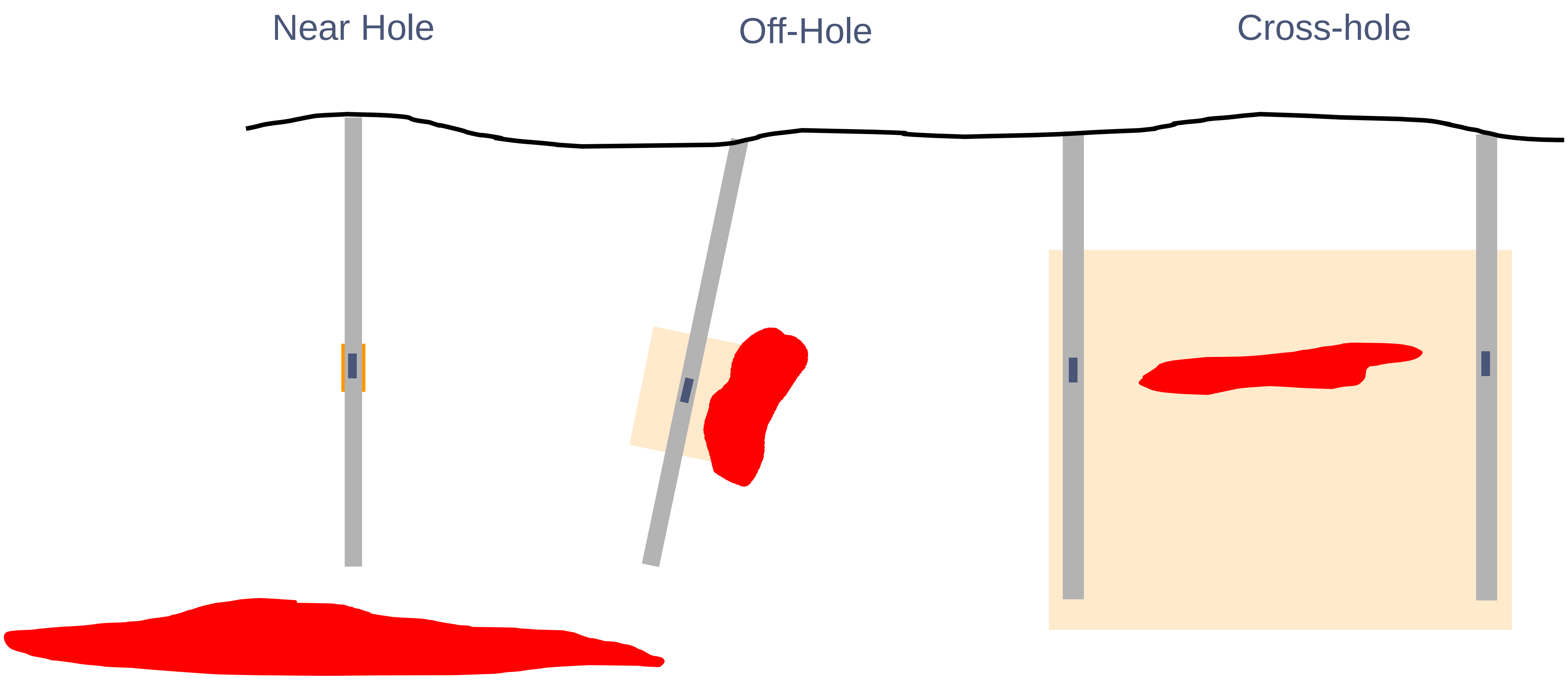
- E.g. Geotek can measure;
  - P wave
  - Density
  - Magnetic Susceptibility
  - Resistivity
  - Density
- **Pros**
  - On site
- **Cons**
  - Slow
  - Calibrations
  - Nuclear licence

Methods to Obtain Physical Properties

In Situ - Borehole

- Pros
  - Inexpensive
  - Fast
  - Continuous
  - Repeatable and Robust Measurements
  - Multi-parameter
  - Suited for statistical analysis
- Cons
  - Capital intensive to purchase equipment with long lead times and training
  - Rental
  - Hire contractor
  - Logistics – timing, camp costs, standby

Types of Borehole Geophysical Measurements



Physical Properties Constraining Geophysics to Geology

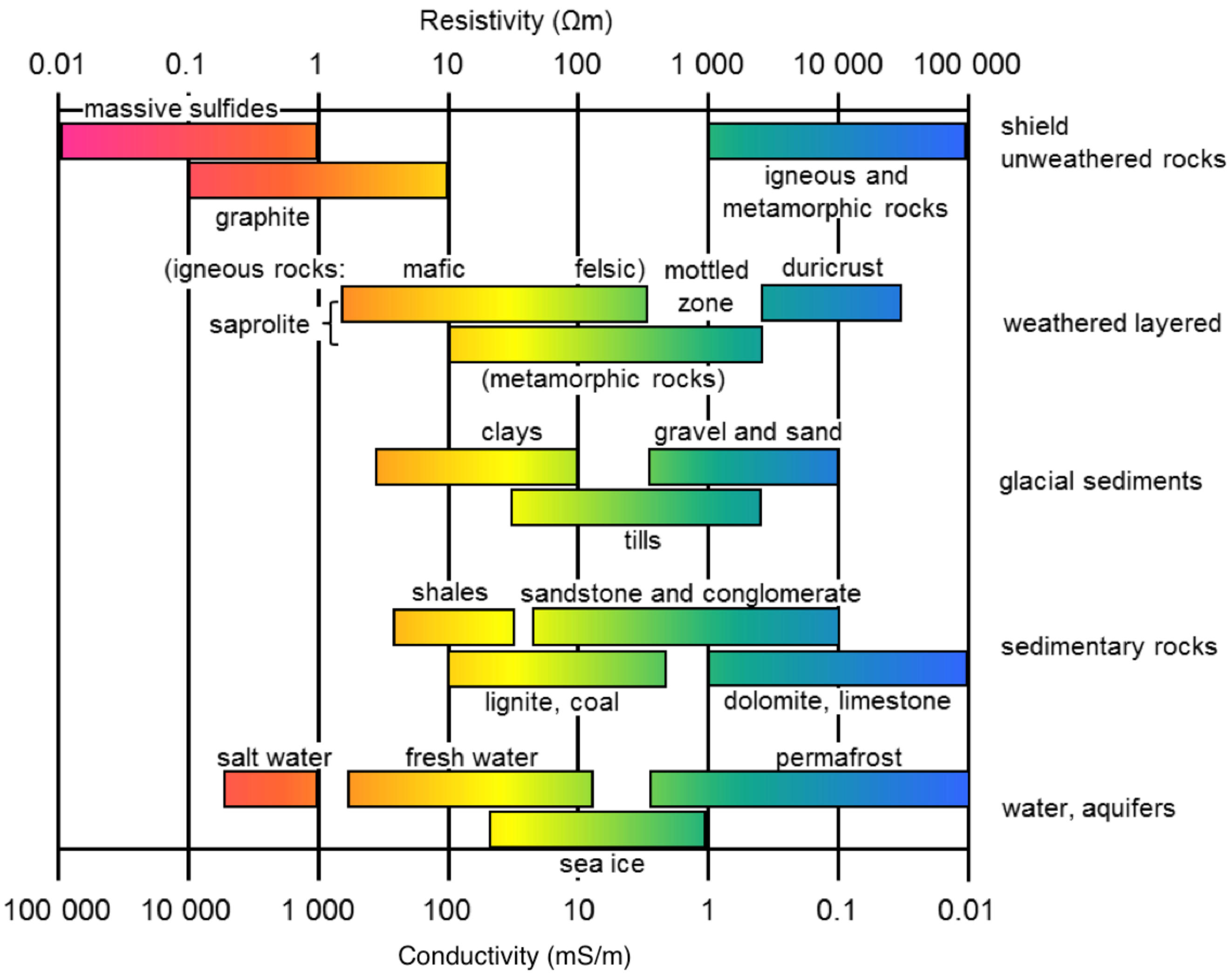
Geophysical Method	Parameter Measured	Physical Property
Gravity	Earth's Gravity Field	Density
Magnetic	Magnetic Field of Earth	Magnetic Susceptibility
Electromagnetic	Induced Electromagnetic Field	Conductivity
Radiometrics	Natural Gamma Radiation	Radioactivity
Seismic/Sonic	Velocity of Waves	Acoustic Impedance
Resistivity	Apparent Resistivity	Resistivity
Induced Polarization	Transient Voltage	Chargeability

Geological Survey of Canada, 2008

Lithology, Alteration and Mineralization Characterization

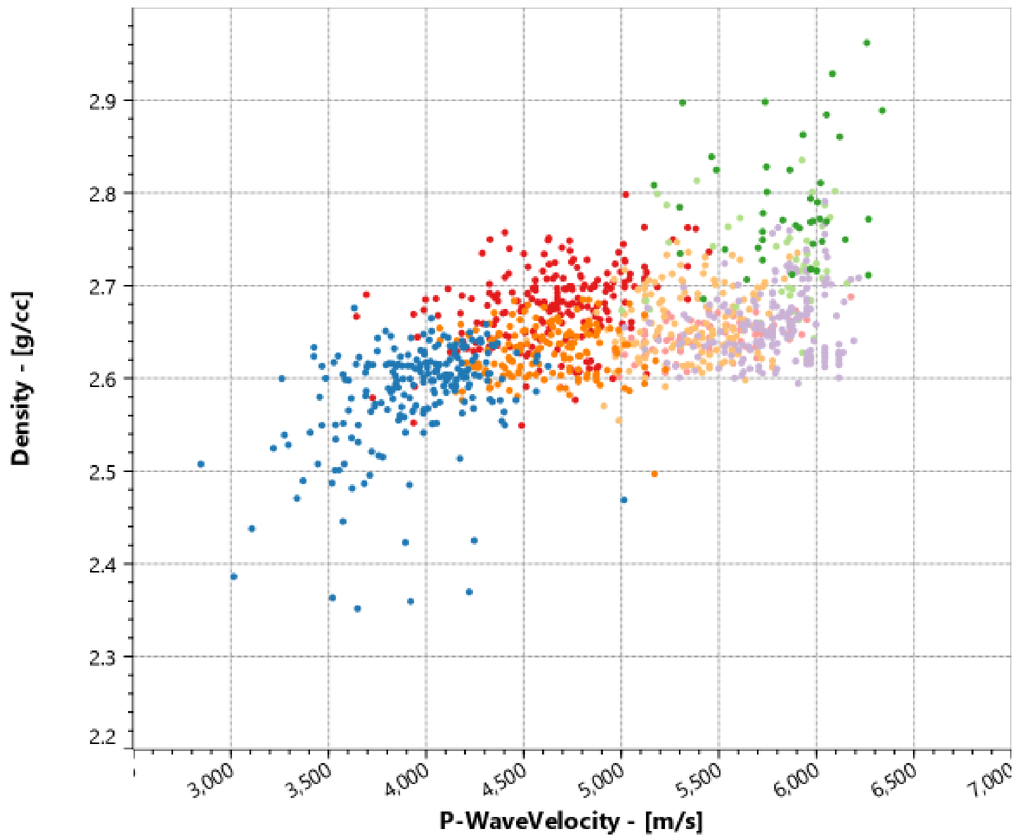
- As with other geophysical methods, you often want to run multiple types in the same area/borehole.
- A single lithology can have a wide geophysical response range – multiparameter approach

- Alteration changes the physical properties of a lithology. E.g.
  - Potassic alteration – natural gamma response
  - Argillic alteration – electrical response



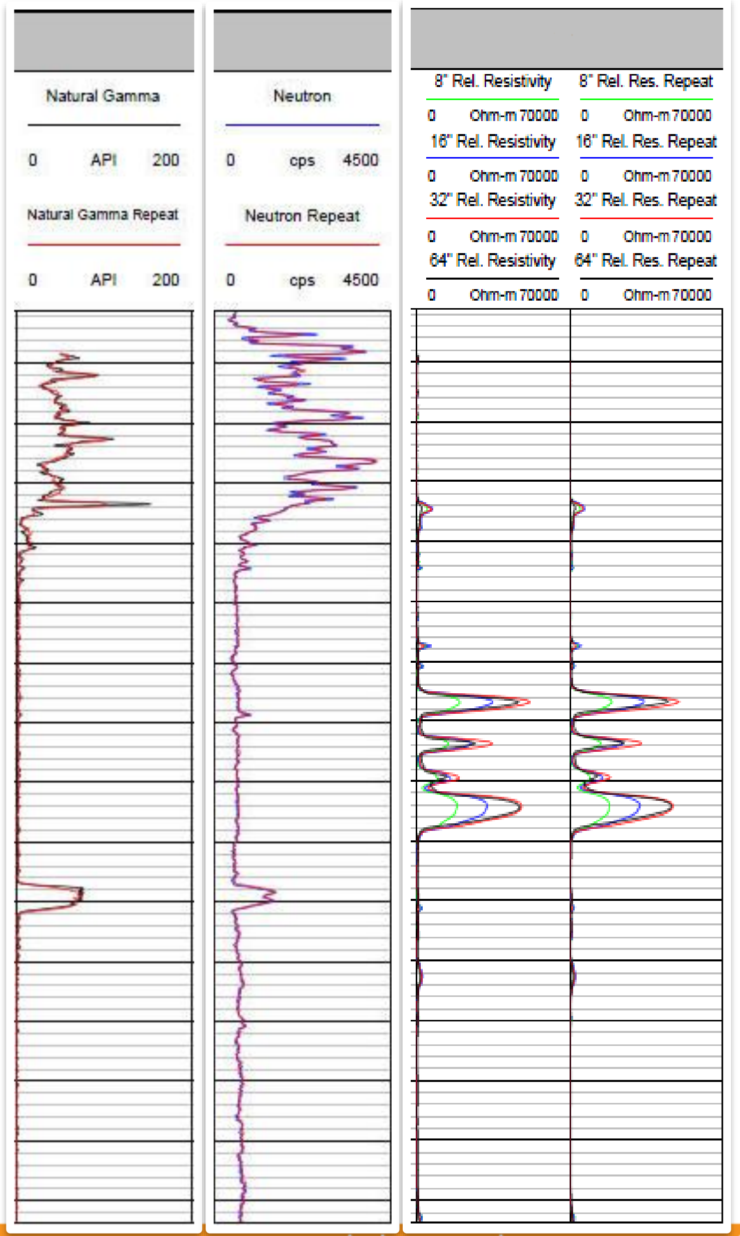
Applications of In-situ Data – What to do with it?

- Improve Geological Understanding
  - Rock properties to improve / assist / QA-QC core logging
  - Maximize information from non-cored drill holes
  - Lithology and alteration mapping
- Rock Property Characterizations of Lithology / Domains
  - Quantify and prioritize contrasts worth exploiting
  - Forward modeling with known (quantified) contrasts
  - Constrained Inversions - less assumptions = better results
- Data Integration and Cross Correlation
  - Establish relationships between disparate data set
  - Predict assay values from rock properties
  - Ore delineation



Borehole Physical Properties Surveys

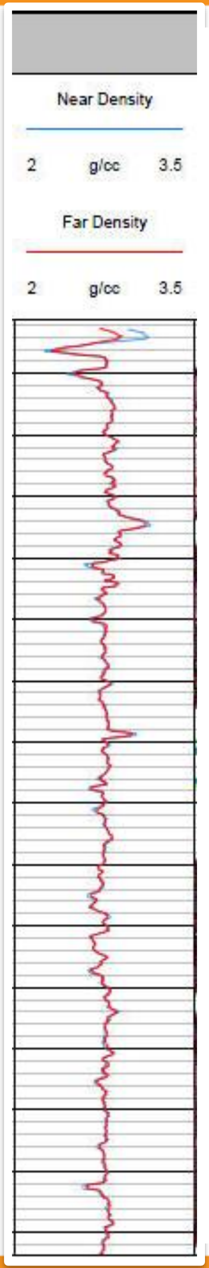
- Induction Logs
- Natural Radioactivity
- Electrical Logs
- Nuclear
- Mechanical Calipers
- Fluid Properties

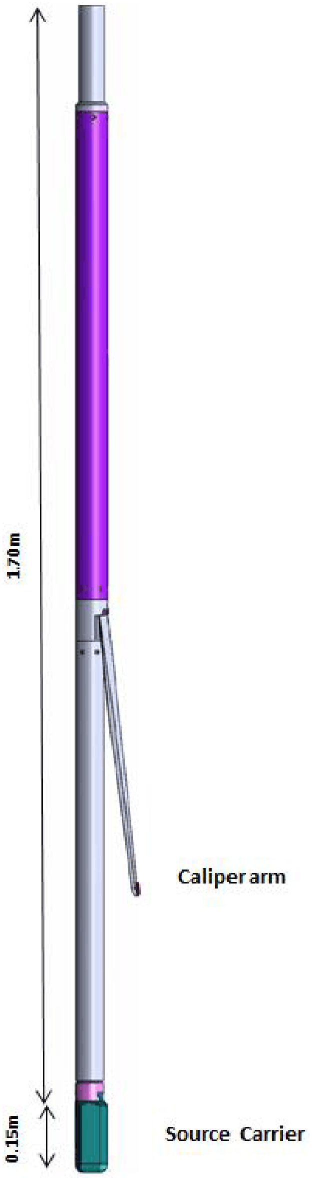


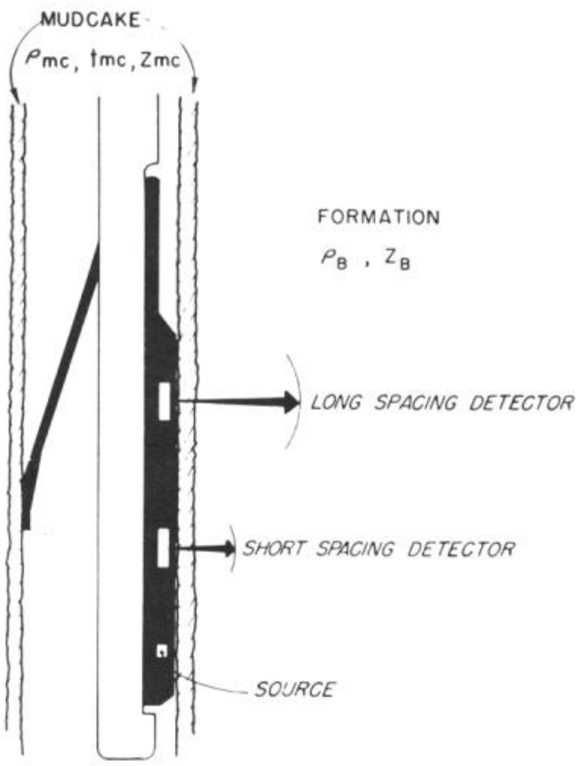
Density

- **Purpose**
  - Records variation in rock density.
- **Method**
  - Radioactive source emits gamma rays into formation.
  - Gamma rays interact with electrons in formation (Compton scattering).
  - Two detectors measure Compton scattering: near and far.
  - Proper calibration essential.
- **Applications**
  - Lithological characterization
  - Geotechnical calculations (when combined with full wave sonic data)

✗ **in casing** ✓ **above water**



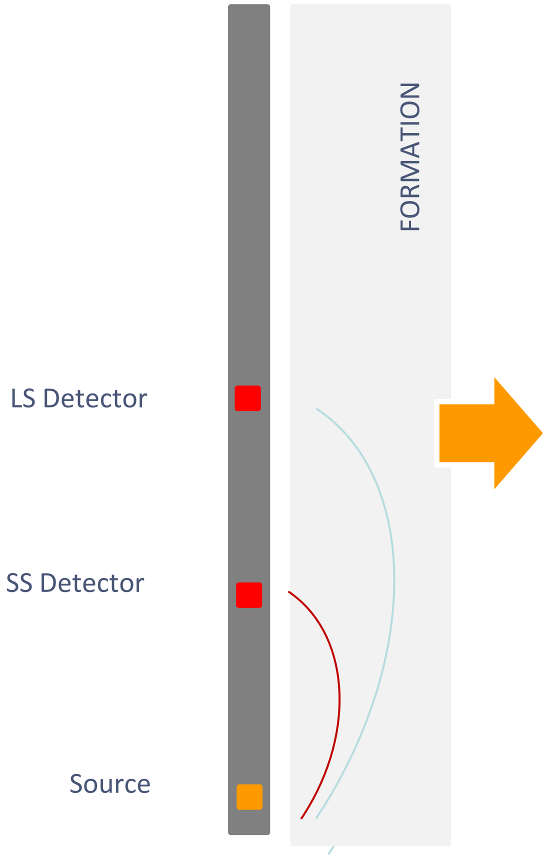


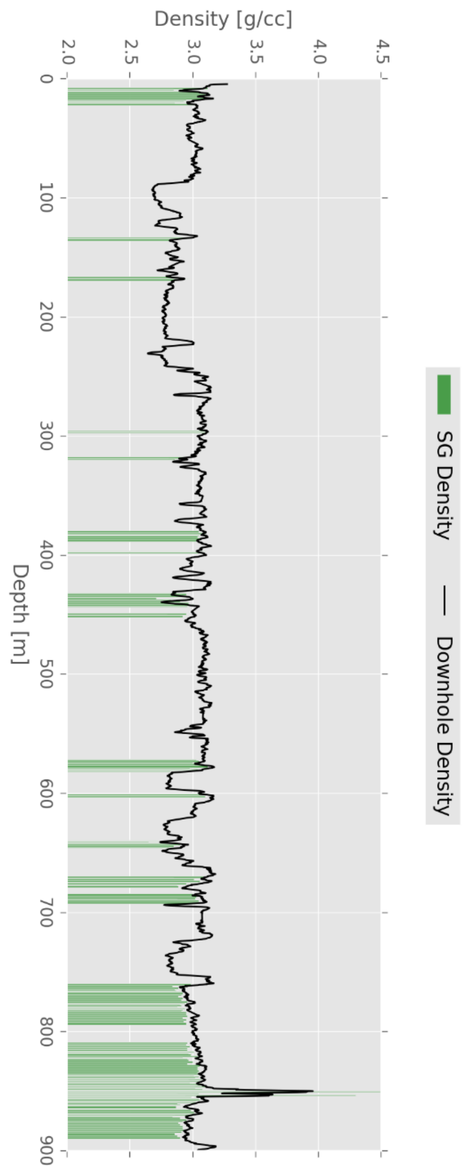


Compensated Density Sonde
(From Wahl et al, JPT, Dec. 1964)

Density for Resource Estimation

- Important for: ore tonnage calculations, geotechnical engineering and rock mechanics.
- Can affect the total resource and reserve estimate, mine design and planning.
- Downhole density:
  - Radioactive source emits gamma rays into formation; measure backscattering (returned radiation in CPS)
  - High density = lower backscattering/more absorption
  - CPS calibrated to known density
- Infill sparse core measurements. Quality Control. Continuous profile.





Density In Drill Rods

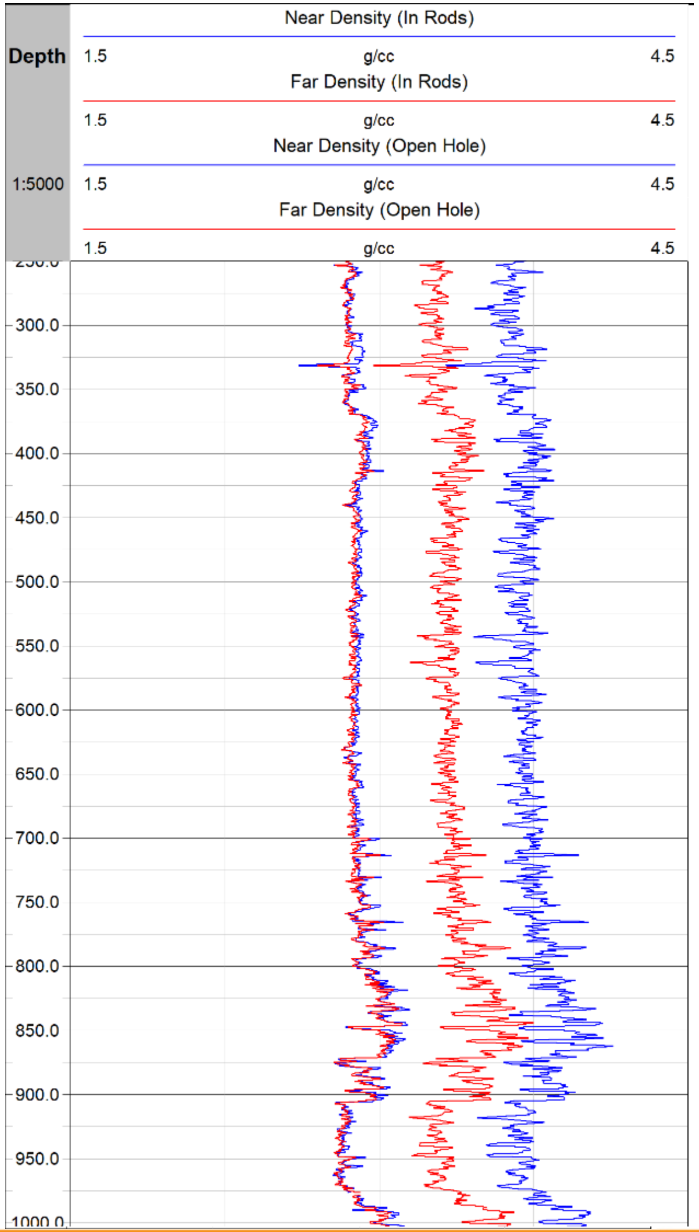
- Acquiring density data though drill rods:
  - Eliminates probe loss risk.
  - Allows for logging through regions of bad ground and highly weathered zones.

Challenge: Your volume of investigation now includes steel. How to compensate for the density of the drill rods?

Density In Drill Rods

Solution: Establish a calibration borehole.

1. Acquire density measurements through rods.
2. Acquire density measurements open hole on the same borehole.
3. Calculate a compensation for the steel that can be used on other boreholes.



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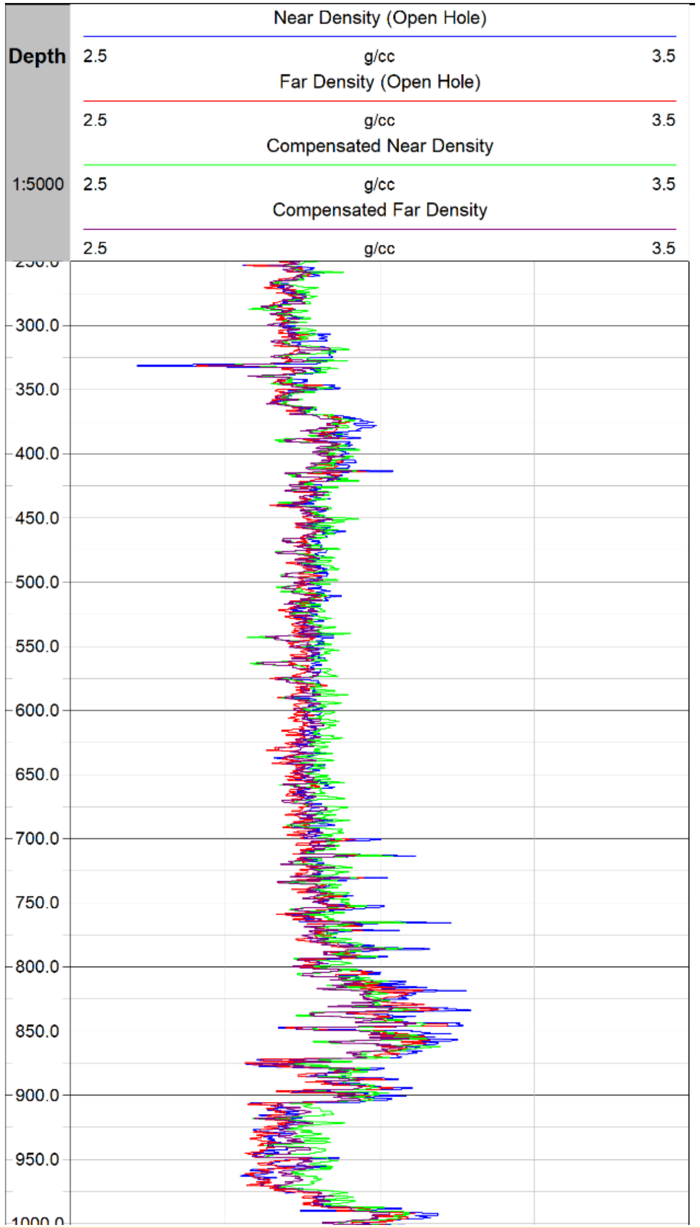
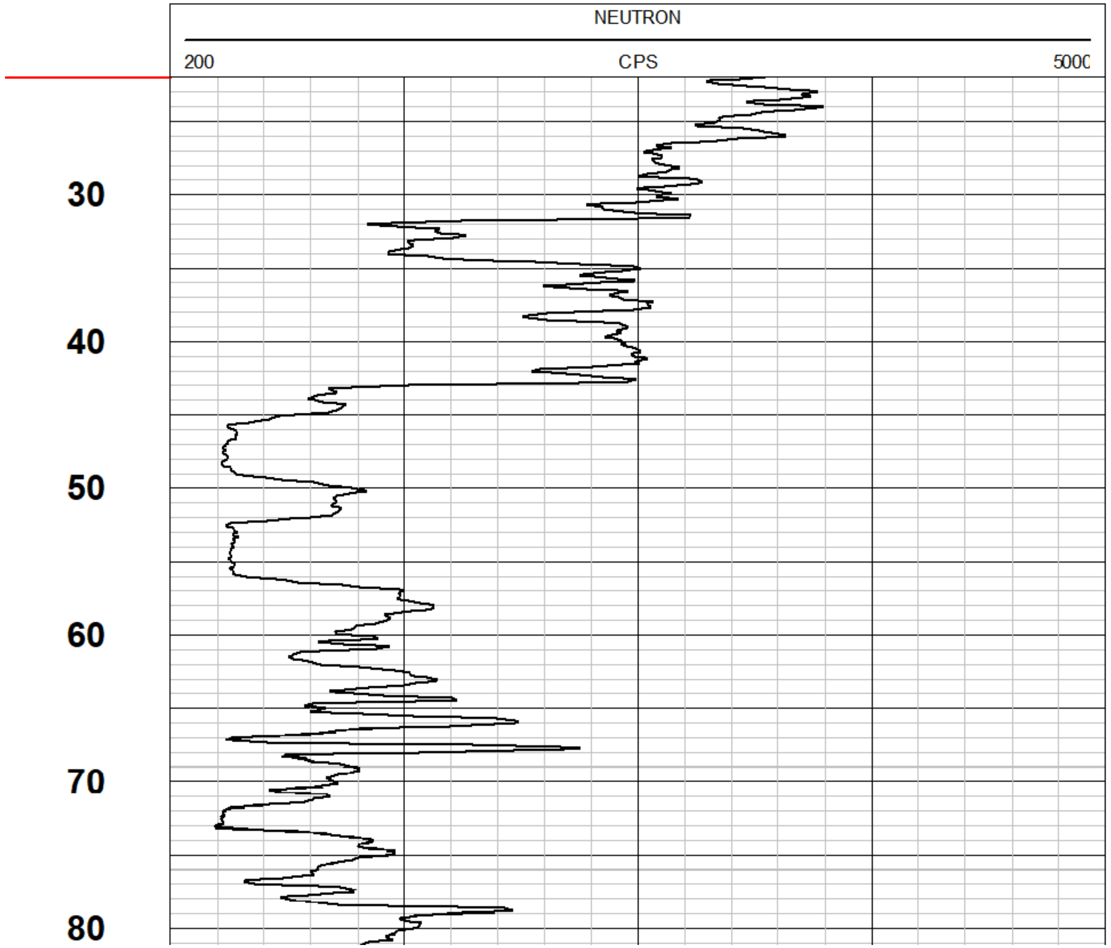


Min: 0 g/cc
Max: 0.25 g/cc
Avg: 0.037 g/cc

Neutron

- **Purpose**
  - Determine the porosity of the formation.
- **Method**
  - Radioactive source emits neutrons into the formation.
  - Neutrons collide with nuclei of atoms in formation, losing energy and creating gamma rays.
  - Returning radiation strikes neutron detector (Helium-3) in probe.
  - High neutron number: low porosity
  - Low neutron number: high porosity
  - Qualitative v. quantitative
- **Applications**
  - Porosity estimate
  - Can reflect changes in lithology

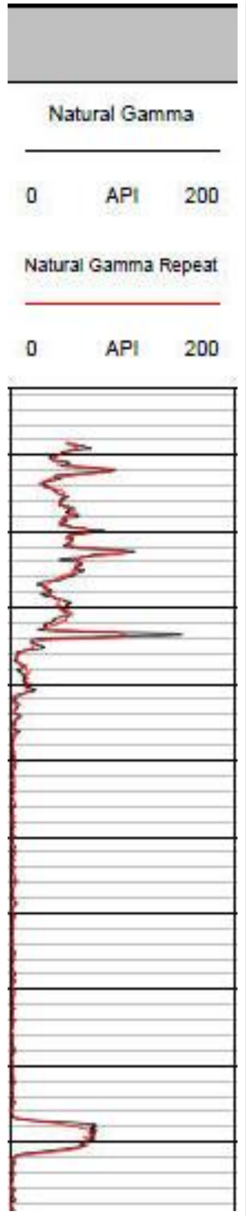


✓* in casing ✗ above water

* Casing must be below water level; some signal attenuation occurs.

Natural Gamma

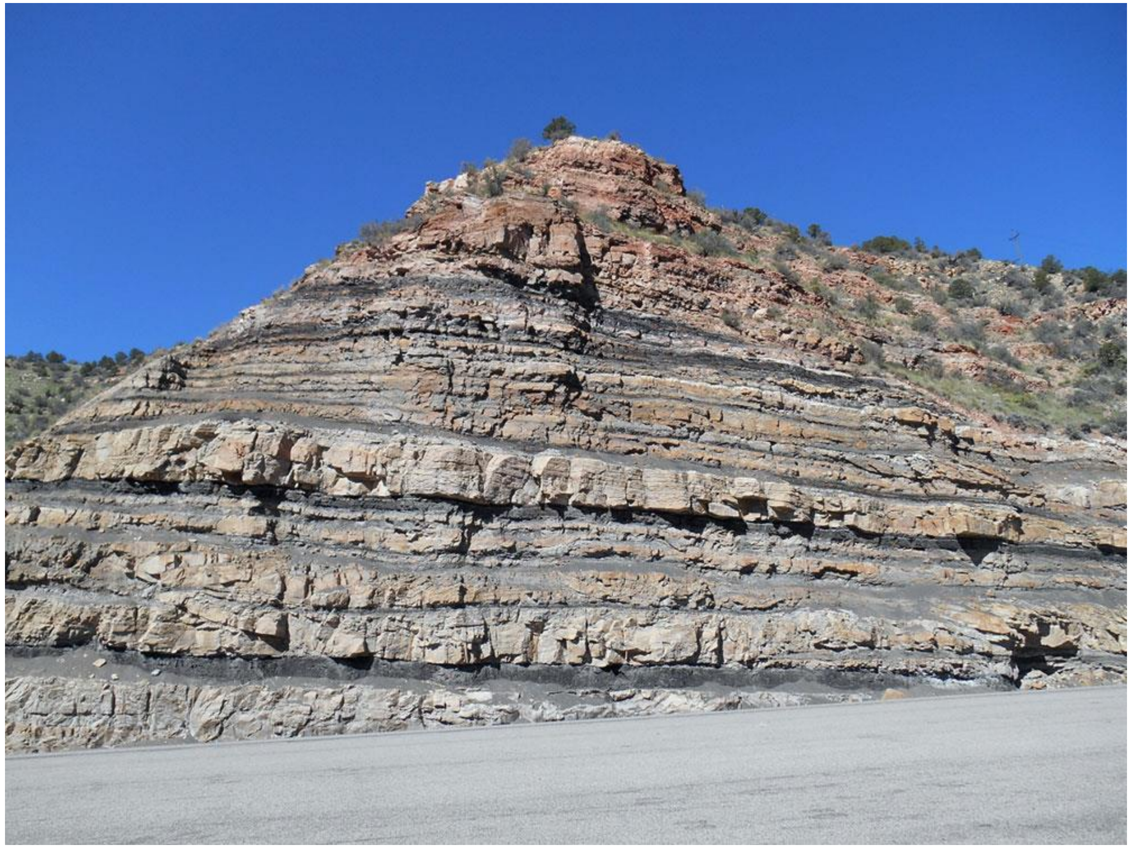
- **Purpose**
  - Measure variation in radioactivity of formation
- **Method**
  - Rocks emit gamma rays as a result of the decay of K, U & Th.
  - Gamma rays strike sodium iodide crystal in probe, creating a pulse of light.
  - Light is captured by a photo multiplier tube, which outputs a current that reflects the amount of radiation.
  - CPS converted to API measurement
- **Applications**
  - Lithological mapping
  - Detection of alteration zones
  - Grain size indicator



✓ in casing ✓ above water

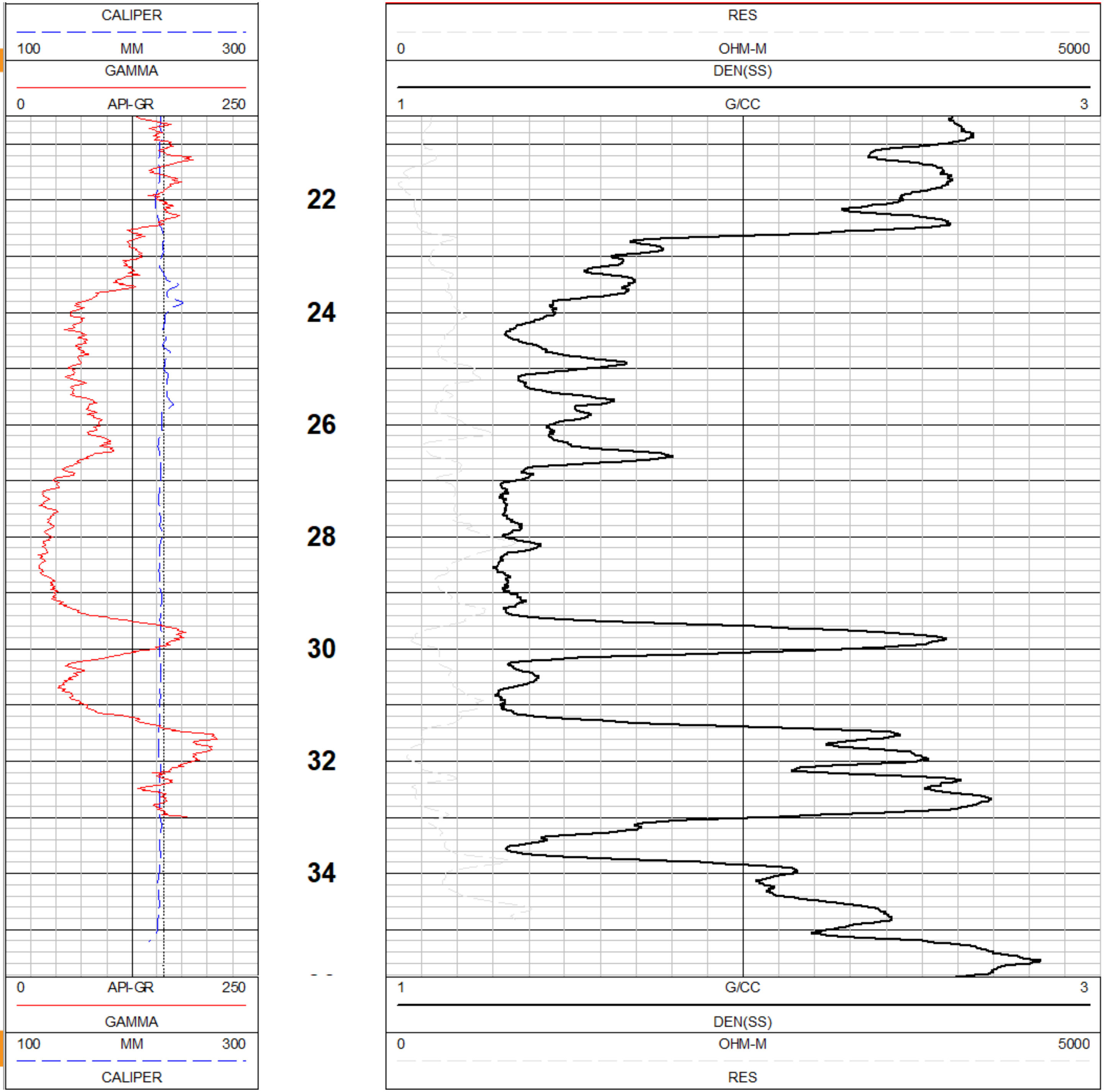
Neutron and Gamma – Working Example

- This example is from a coal exploration project
- AIM; identify coal seems
- Use several parameters in conjunction with one another



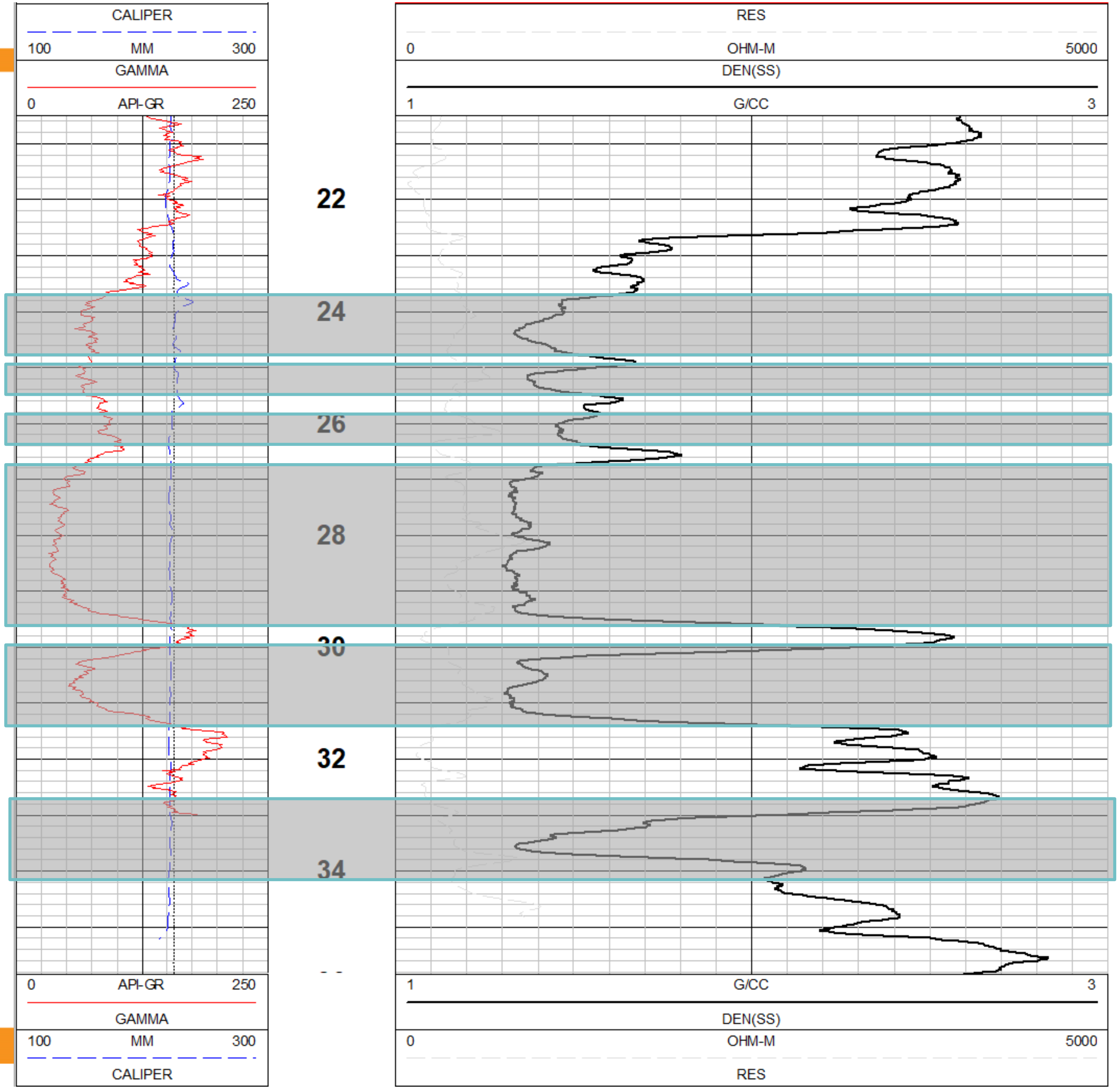
Find the Coal Seems

- HINT:
  - Coal is defined, in this example, as having LOW Density and LOW Gamma
  - Use all parameters to find them



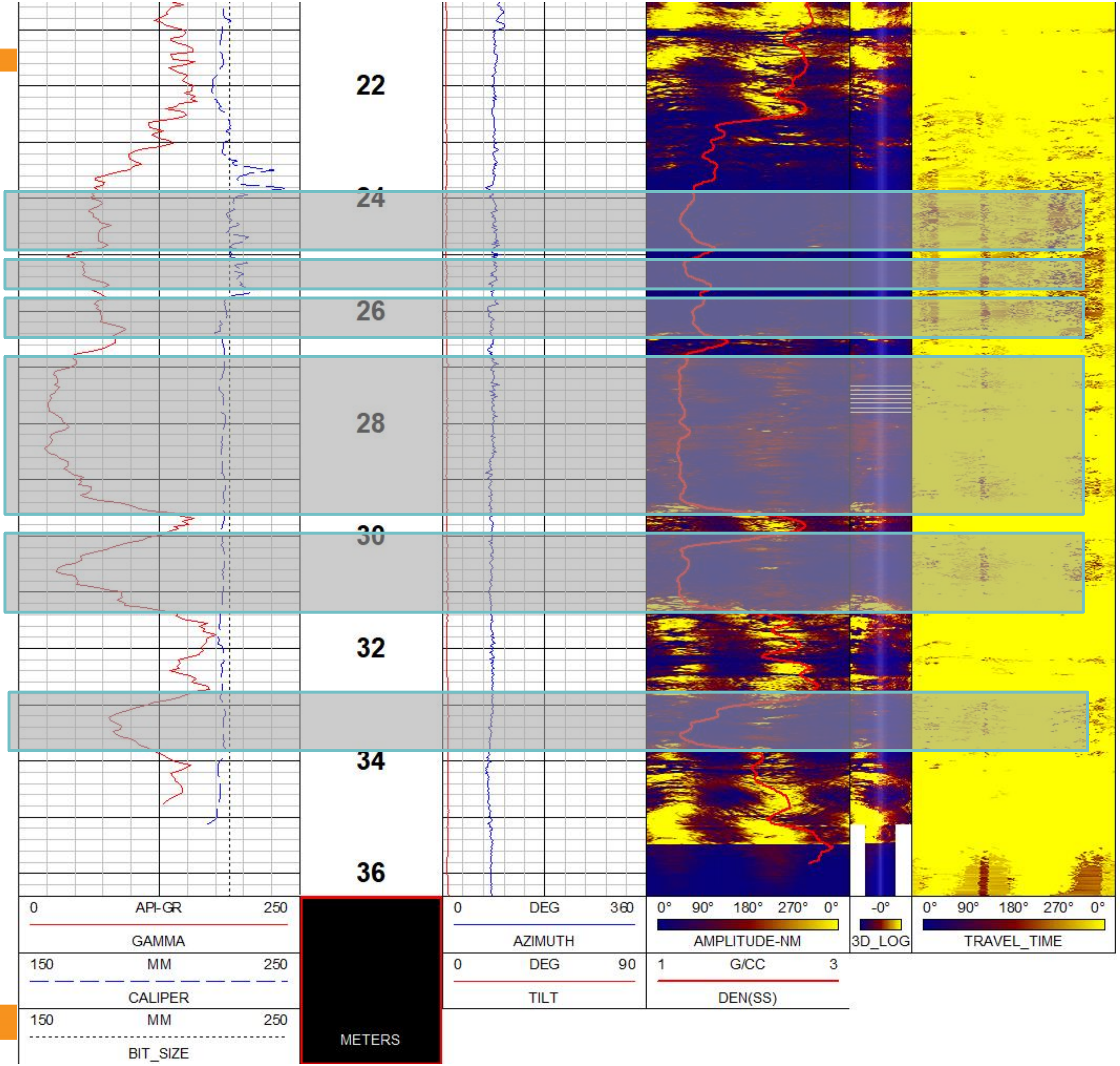
Find the Coal Seems

- Low Density, Low Gamma zones



Find the Coal Seems

- Potentially 5-6 seems
- Low Density, Low Gamma zones
- Check with Acoustic Televiewer

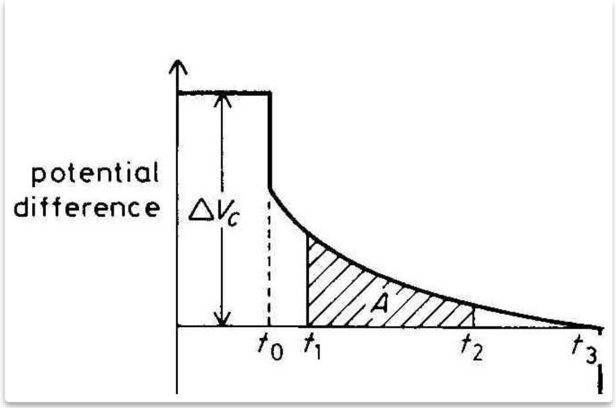


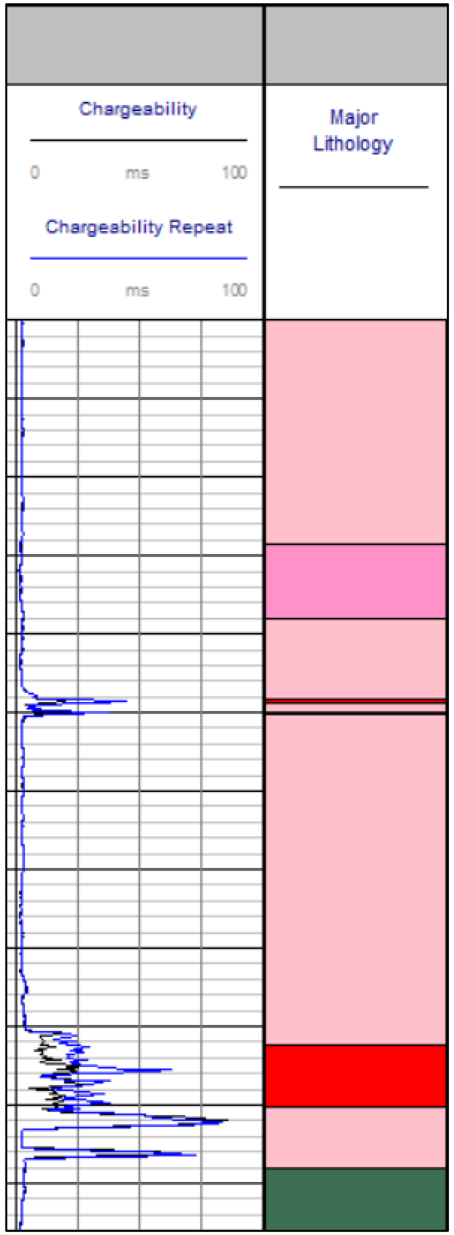
Spectral gamma

- Measures K, U, Th but able to distinguish energy windows
- Actually measuring daughter products, Potassium 40, Bismuth 214, Thallium 208
- Static Measurements
- Disequilibrium
- Temperature/Hole Size Considerations
- Calibration
- Used for mineral identification and clay typing (e.g., smectite)

Chargeability

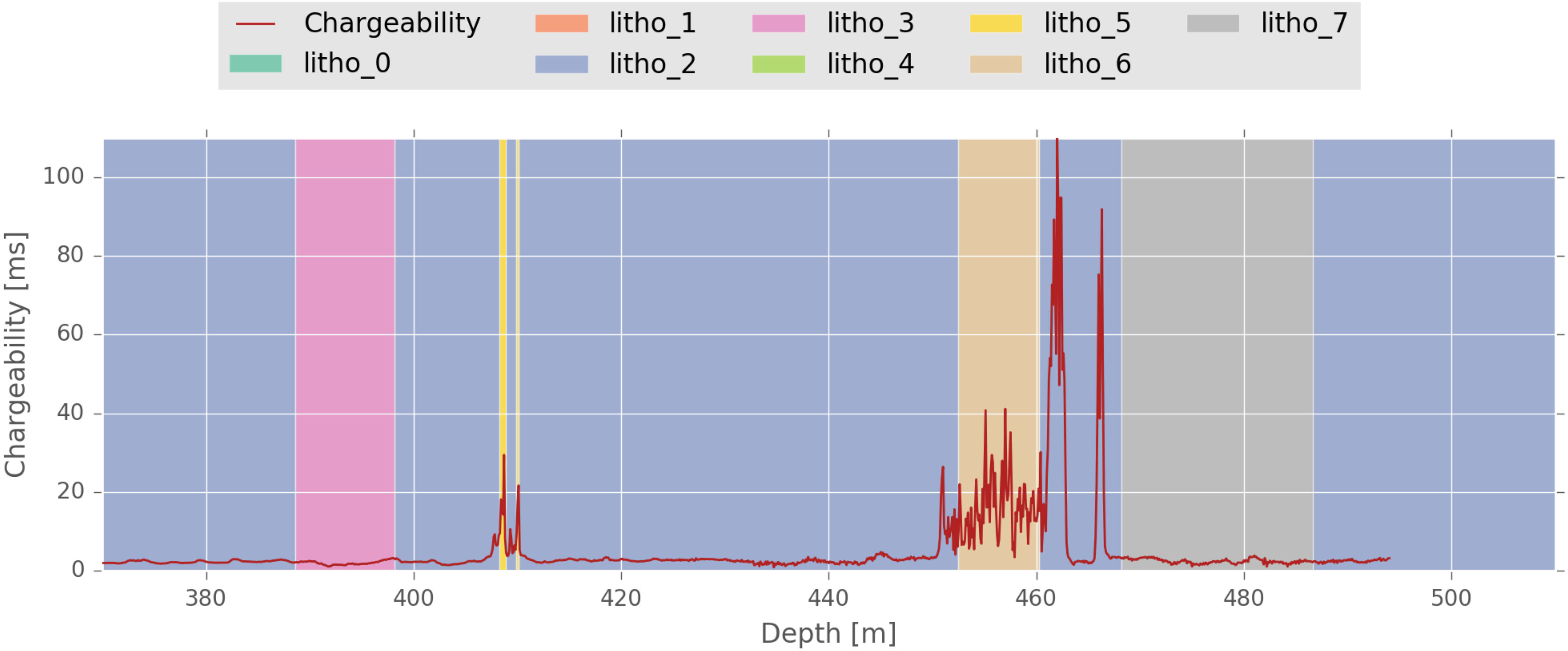
- **Purpose**
  - Calculate chargeability of formation.
- **Method**
  - Probe injects current into the formation.
  - Current is switched off.
  - Potential difference is measured over time.
  - Chargeability is equal to the integrated area under the decay waveform divided by the injection voltage.
- **Applications**
  - Lithological characterization
  - Certain minerals (eg. sulphides) have high chargeability





✗ in casing ✗ above water

In-situ Chargeability and Sulphide Zones

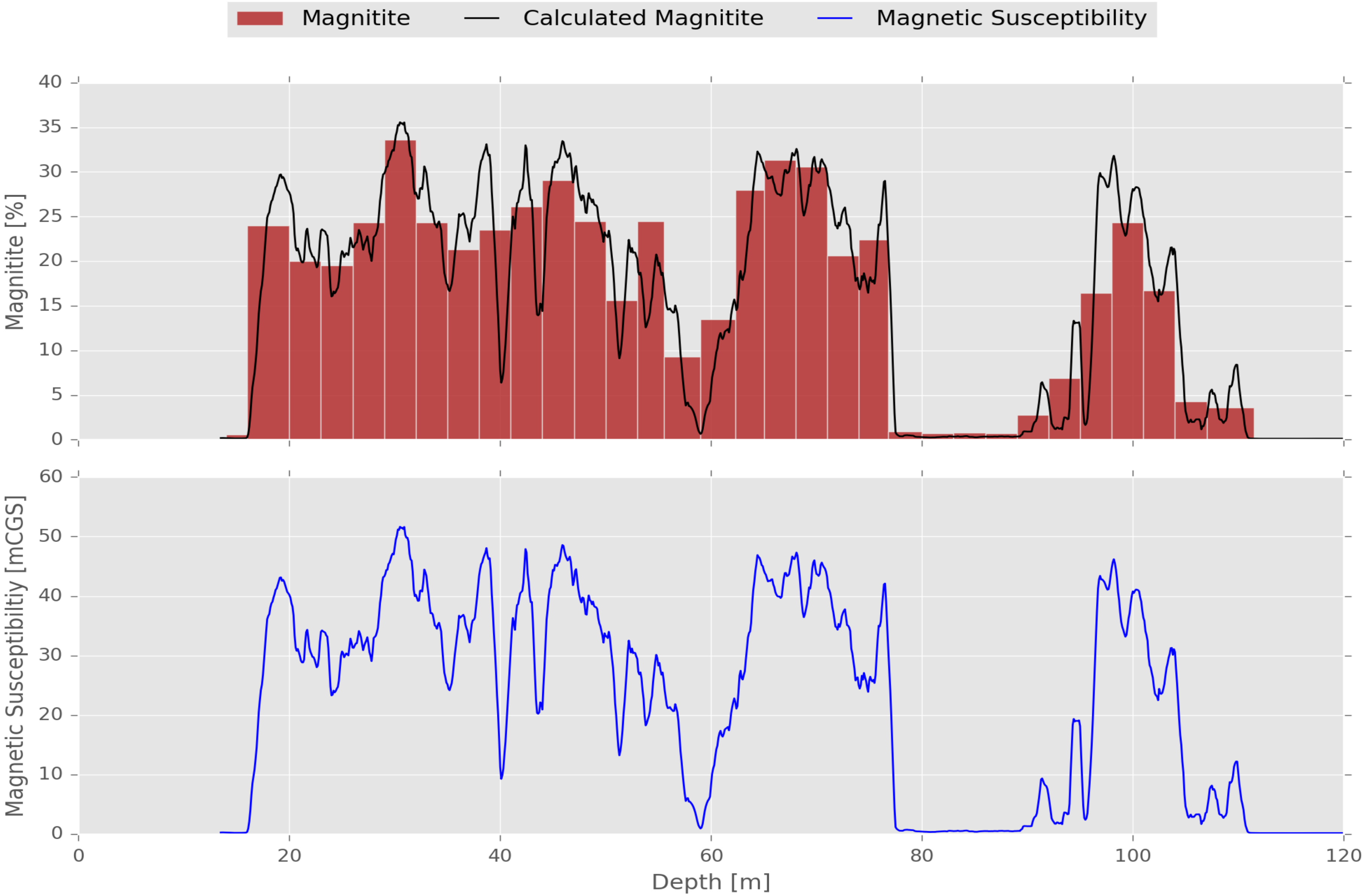


Magnetic Susceptibility

- **Purpose**
  - Measure magnetic susceptibility; reflection of the amount of magnetic materials in the formation.
- **Method**
  - Magnetic field varies in borehole due to amount of magnetic minerals in formation.
  - Varying magnetic field induces an electrical current in probe sensor (coil of wire).
  - Pre/Post Calibration checks important.
  - Corrections: Temperature, hole size and drift
- **Applications**
  - Magnetite assay estimates
  - Lithological characterization
  - Measure abundance of magnetic materials; location of magnetic ore body.

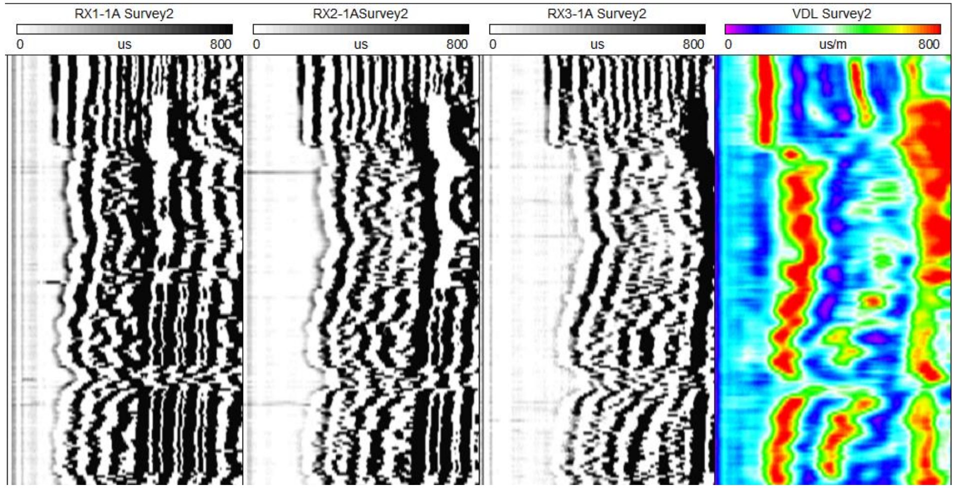
✗ **in casing** ✓ **above water**

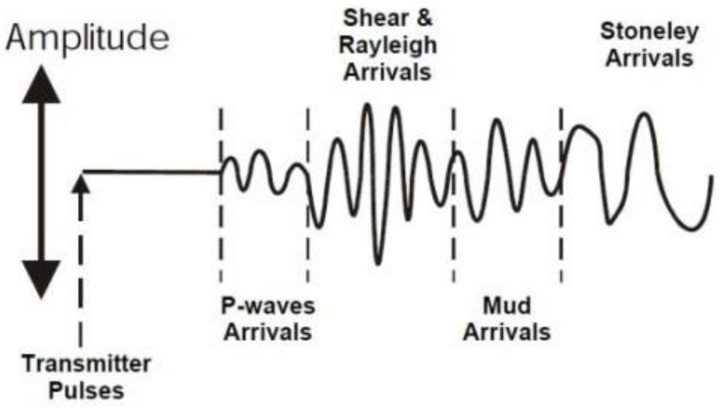
In-situ Assay for Magnetite

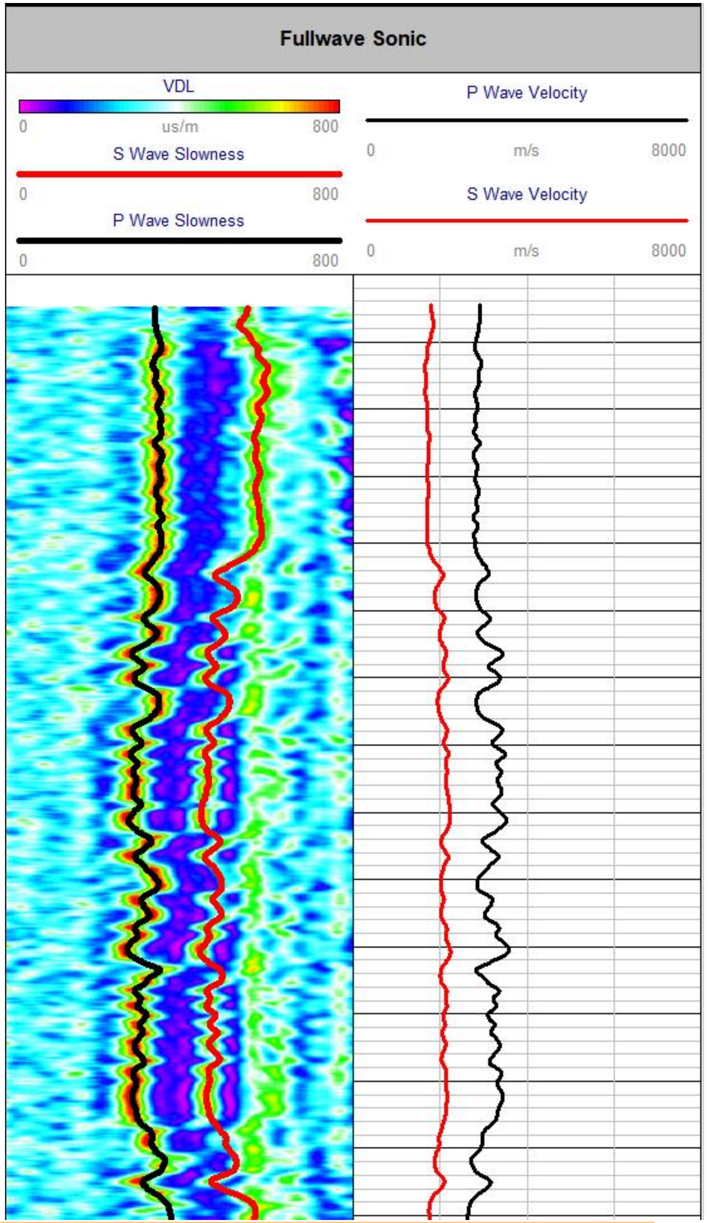


Full Wave Sonic (FWS)

- **Purpose**
  - Record acoustic waveform of the formation.
- **Method**
  - Waves are transmitted into the formation.
  - **Determine compressional (P) and shear (S) waves**
  - Allows for an estimate of the velocity of the formation (dependent on porosity and lithology type).



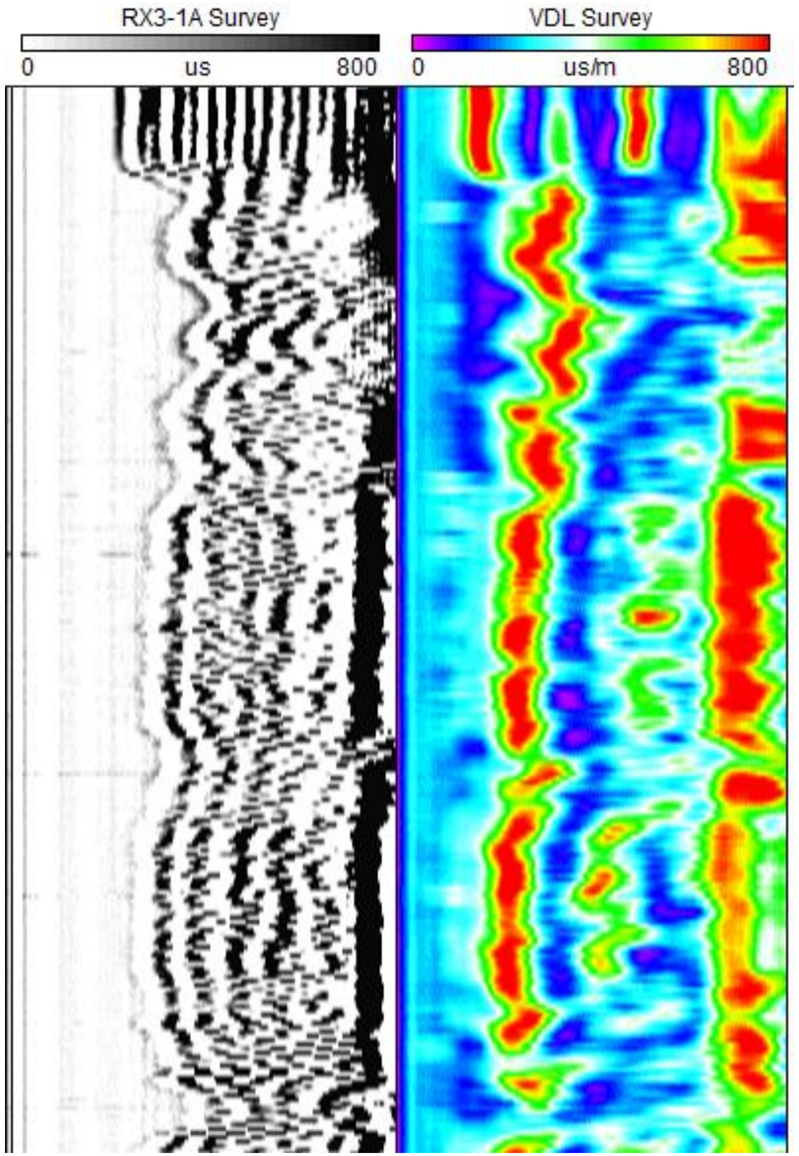




✓ **in pvc casing** ✗ **above water**

Full Wave Sonic (FWS)

- **Applications**
  - Rock strength and porosity
  - Locations of fractures
  - Geotechnical calculations (when combined with density information): Poisson’s Ration, Young’s modulus, bulk and shear modulus
  - Cement bond logs



Derived Rock Mechanics

Using full waveform sonic (P & S wave velocity) and focused density:

Poisson’s Ratio : $v = \dfrac{R^2 - 2}{2(R^2 - 1)}$ $where\ R = \dfrac{V_p}{V_s}$

Young’s Modulus : $E = vV_p^2\dfrac{(1 + v)(1 - 2)}{(1 - v)}$

Shear Modulus : $G = vV_s^2$

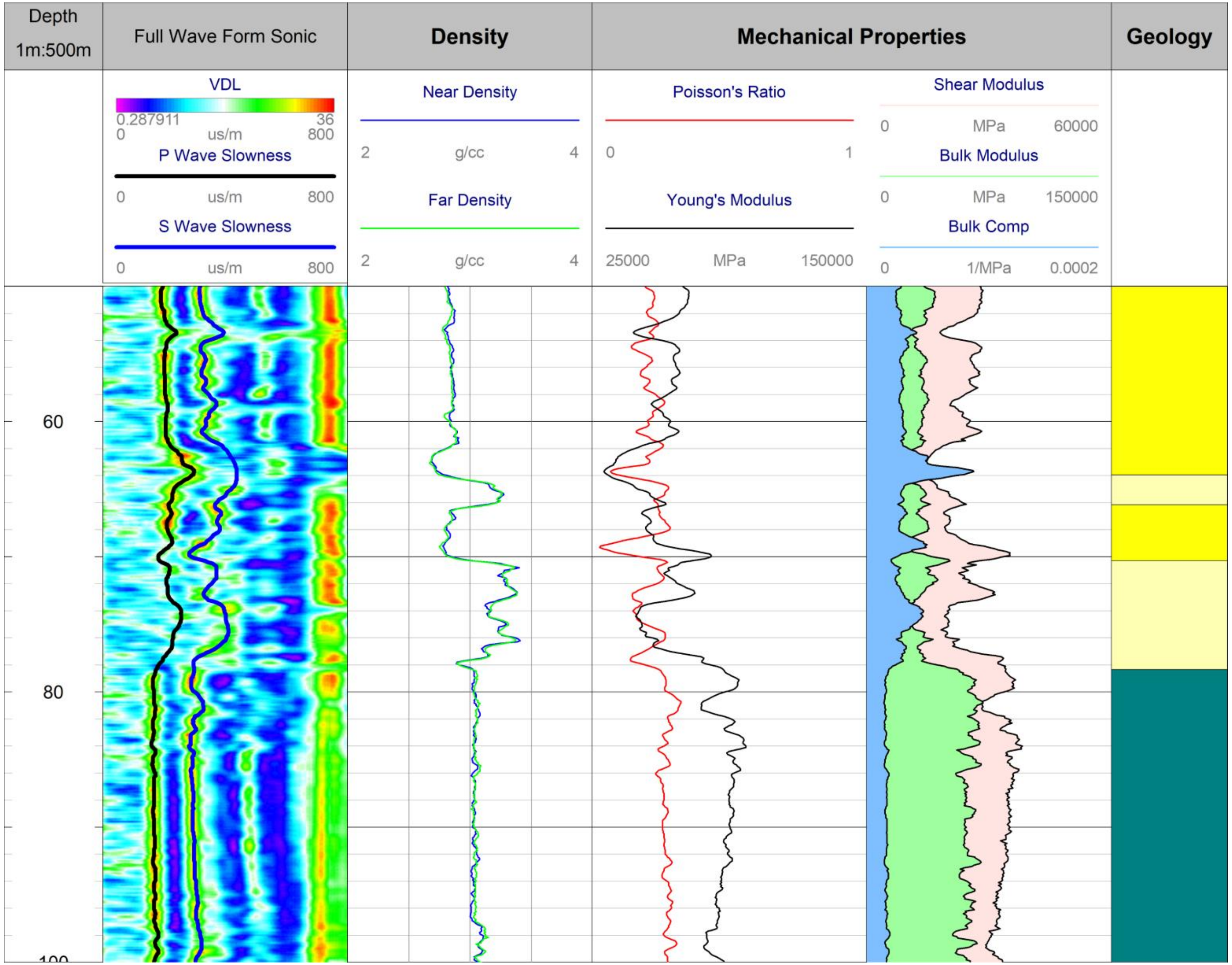
Bulk Modulus : $K = vV_p^2 - \dfrac{4}{3}G$

Where:

Compressional wave velocity V_p

Shear wave velocity V_s

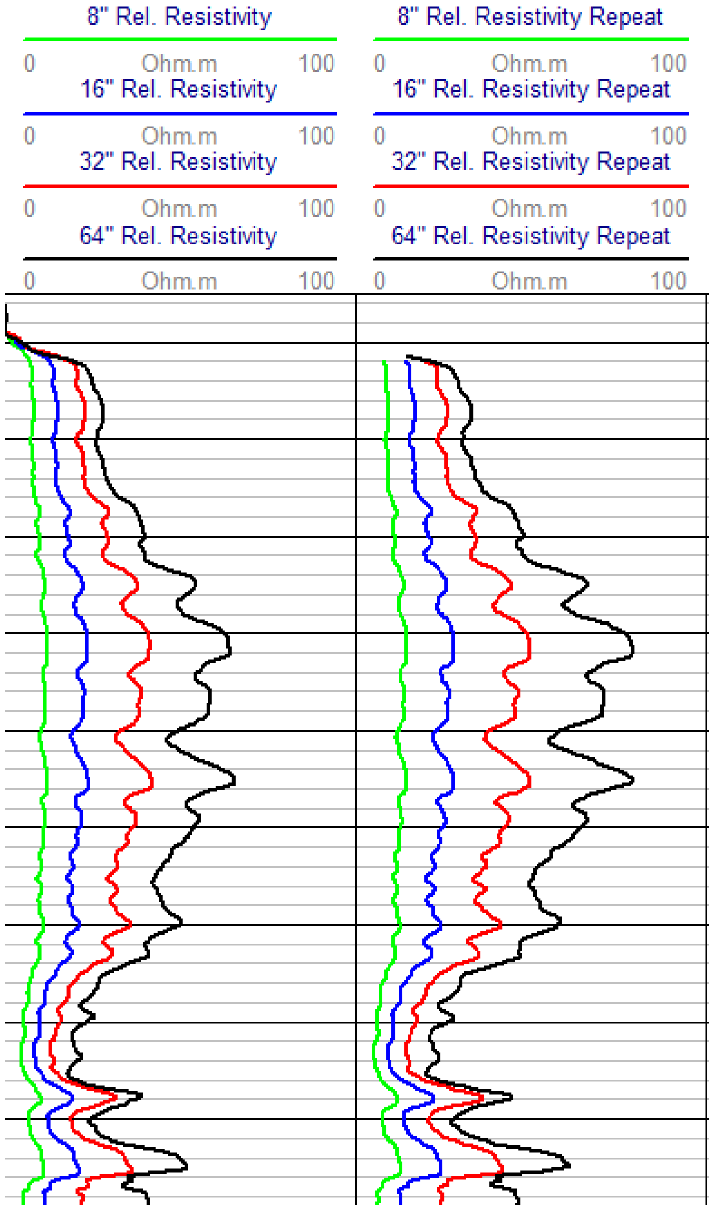
Density ρ



Electrical Resistivity

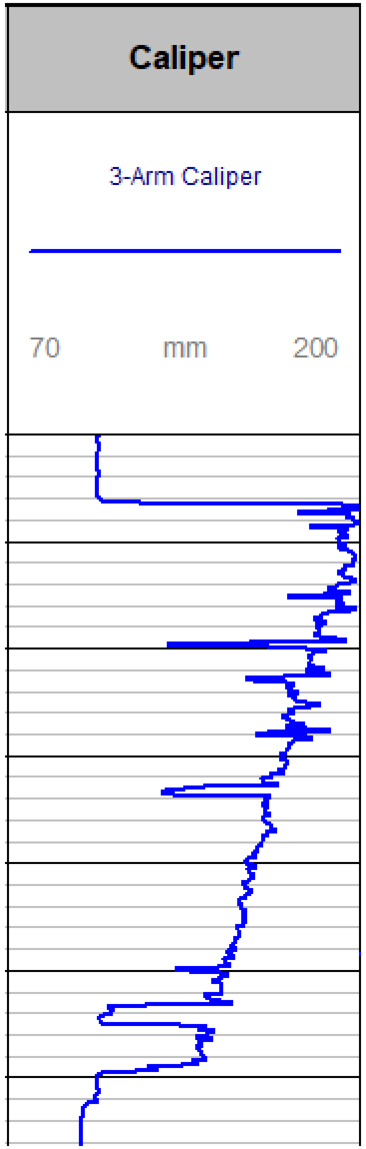
- **Purpose**
  - Measure the combined resistivity of rock and pore fluid
- **Method**
  - Transmit current into the formation
  - Measure voltage between transmitter and receiver
  - 4 different receiver distances measured; different volume of investigation
  - Calculate formation resistivity based on known current output and measured voltage
- **Applications**
  - Lithological characterization and identification
  - Fracture identification
  - Quantitative measurement

X **in casing** X **above water**



Mechanical Caliper

- **Purpose**
  - Record variation in the diameter of the borehole
- **Method**
  - Arm on probe opens and measures borehole size
  - More arms
  - Single arm caliper
    - Side walling device
  - 3-arm caliper
    - 3 arms linked together
    - Does not account for shape
  - 4-arm Caliper
    - X-Y measurement
- **Applications**
  - Detection of large open fractures
  - Changes in hole size

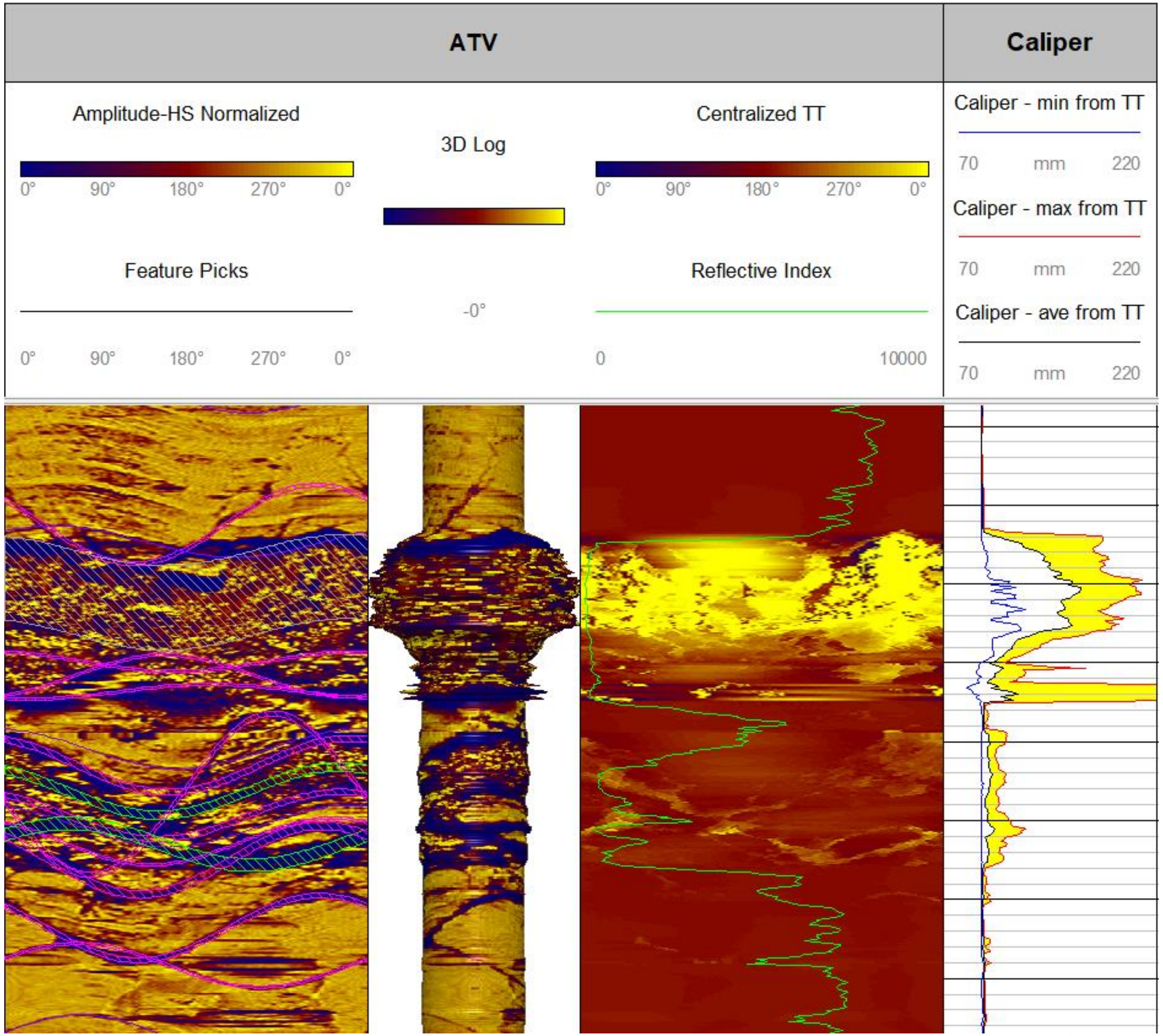


✓ in casing ✓ above water

3-Arm Caliper

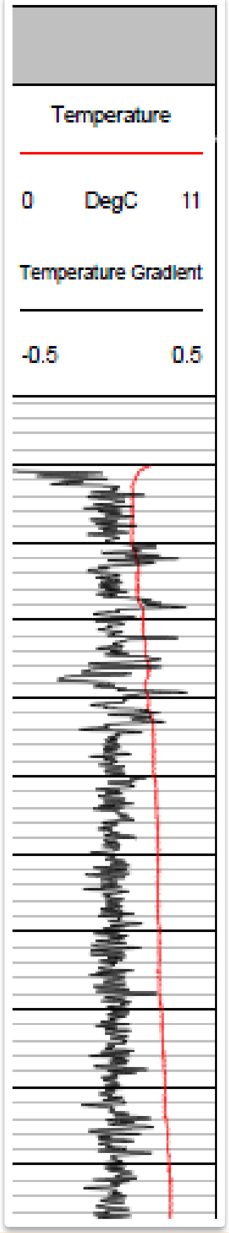
Synthetic Caliper

- Acoustic Televiewer can create an synthetic caliper
- Good QAQC of caliper or back up if caliper is broken
- Faster and therefore cheaper



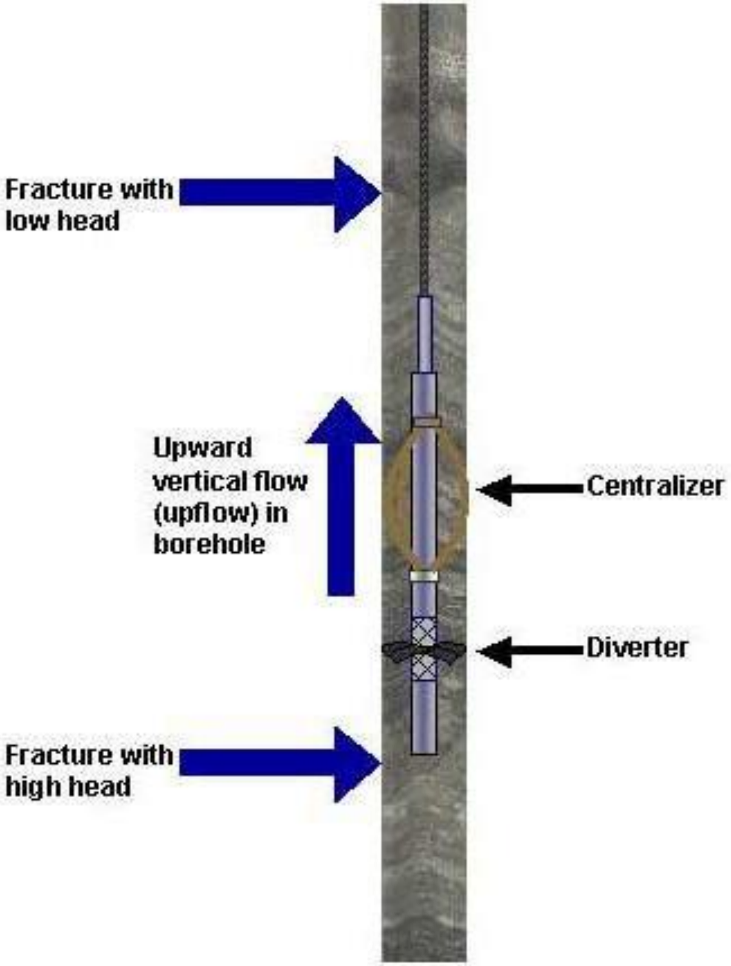
Temperature

- **Purpose**
  - Measure temperature of borehole fluid.
- **Method**
  - Thermal sensor on bottom of probe measures the temperature of the fluid.
  - Used in conjunction with other parameters; multi-parameter
- **Applications**
  - Indicative of fracturing and groundwater flow



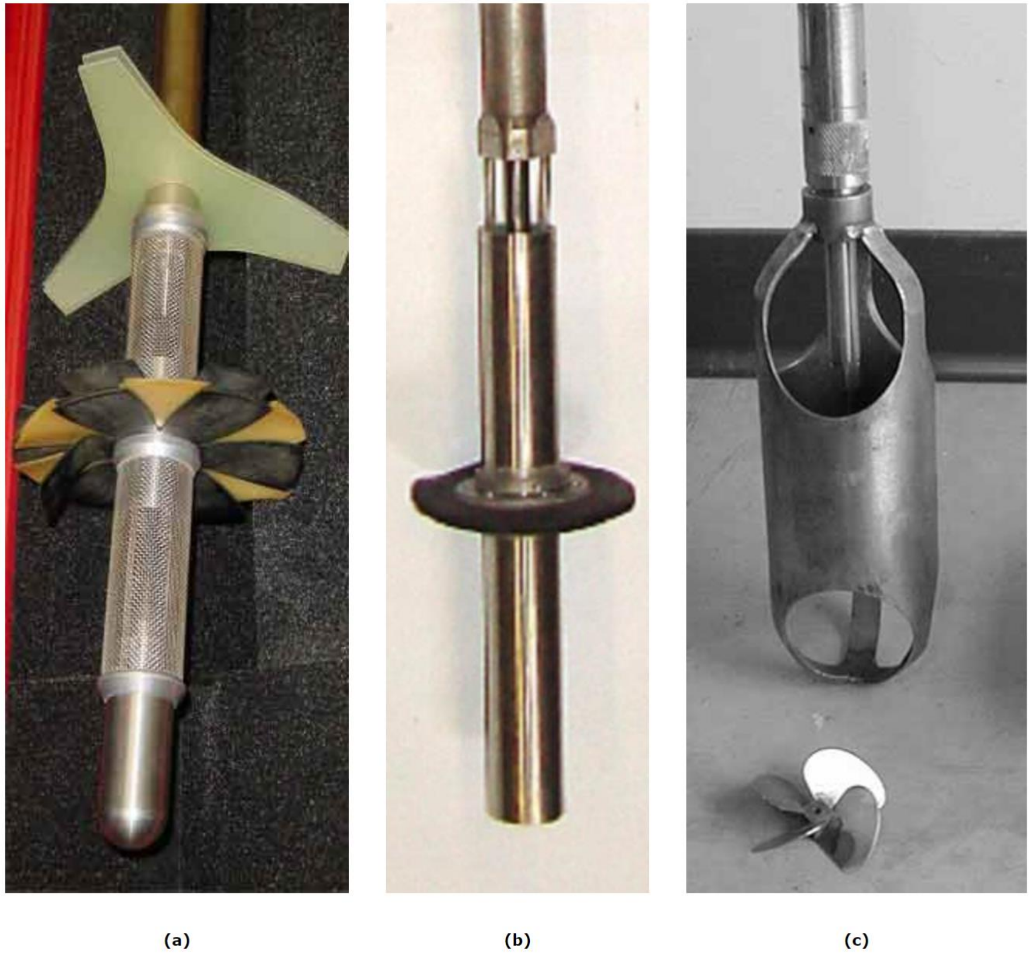
X in casing X above water

Hydrogeological - Flowmeters



USGS, 2013

- Measure L/min in-situ
- Dynamic or static measurements
  - A) Heatflow
  - B) Electromagnetic
  - C) Spinner



USGS, 2013

Borehole Magnetic Resonance

- Uses magnets to polarize the spins of hydrogen nuclei. Once the magnetic field is removed, measures the time it takes for the nuclei to return to their randomly oriented state.
- **Measure:** porosity.
- **Calculate:** permeability and hydraulic conductivity using KTIM and KSDR models.
- Formation porosity without radioactive source.
- Continuous vertical profiles of Permeability, Bound Fluid and Specific Yield.
- Packer test complement.

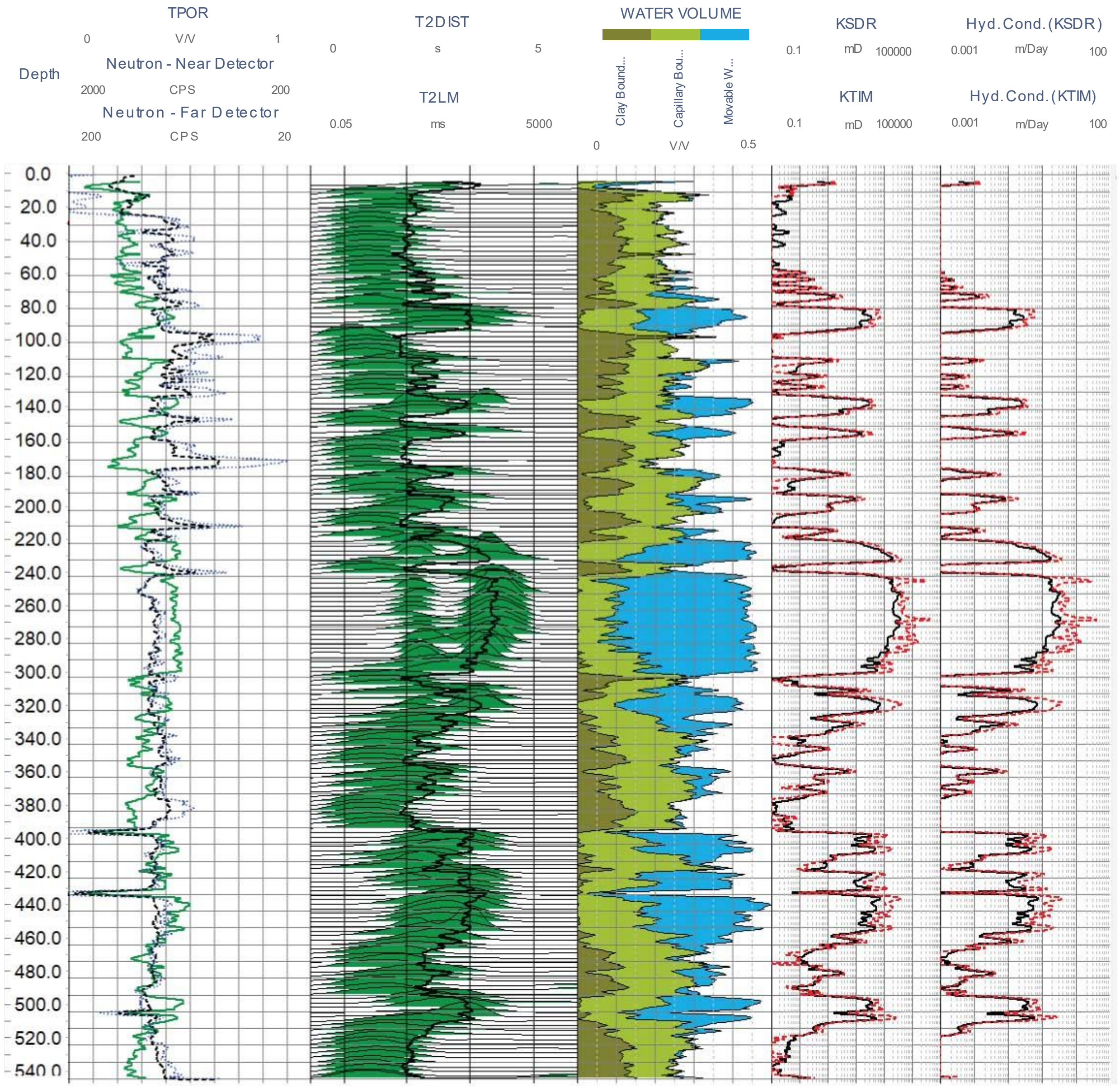
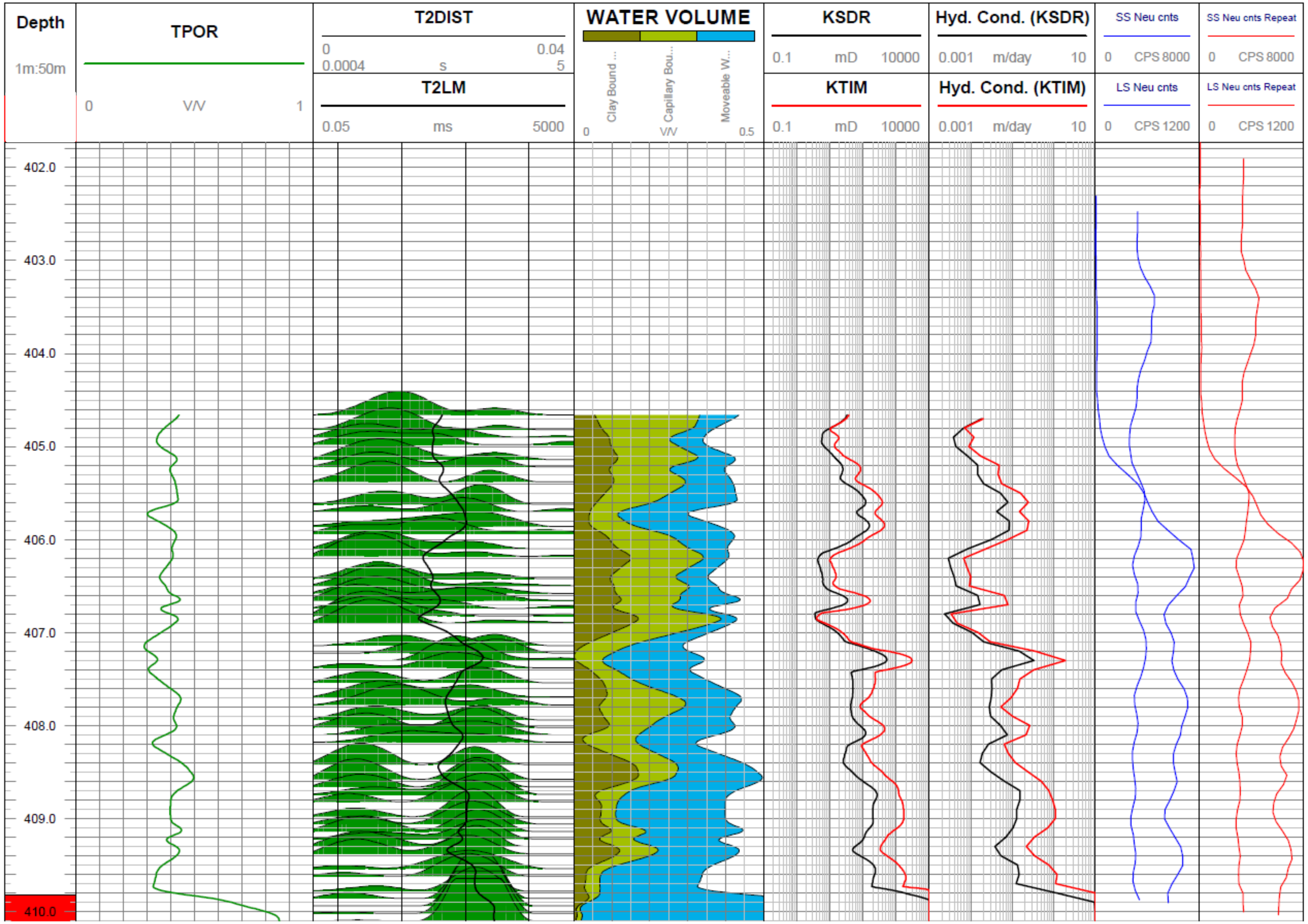
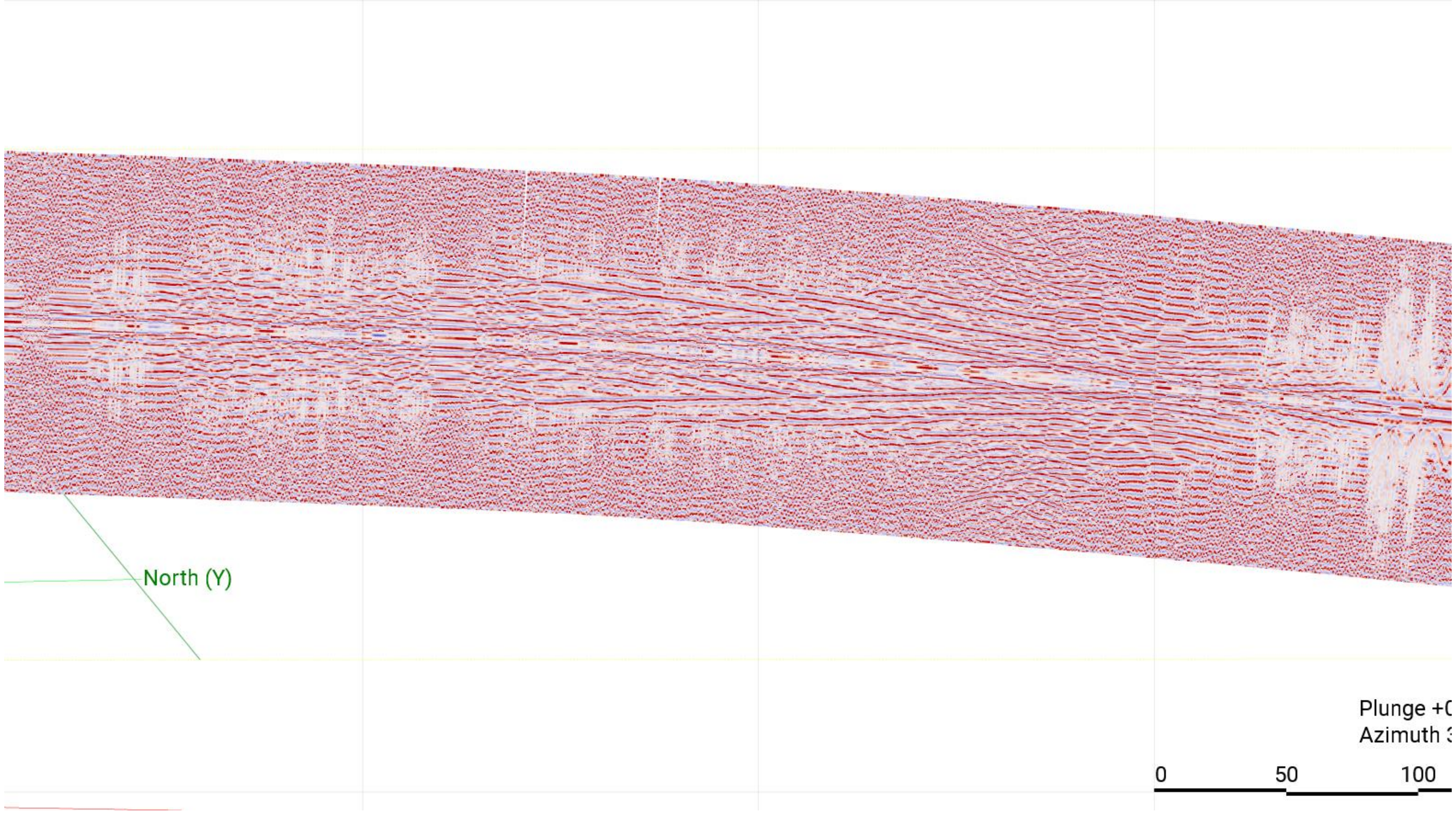


Image courtesy of QTEC

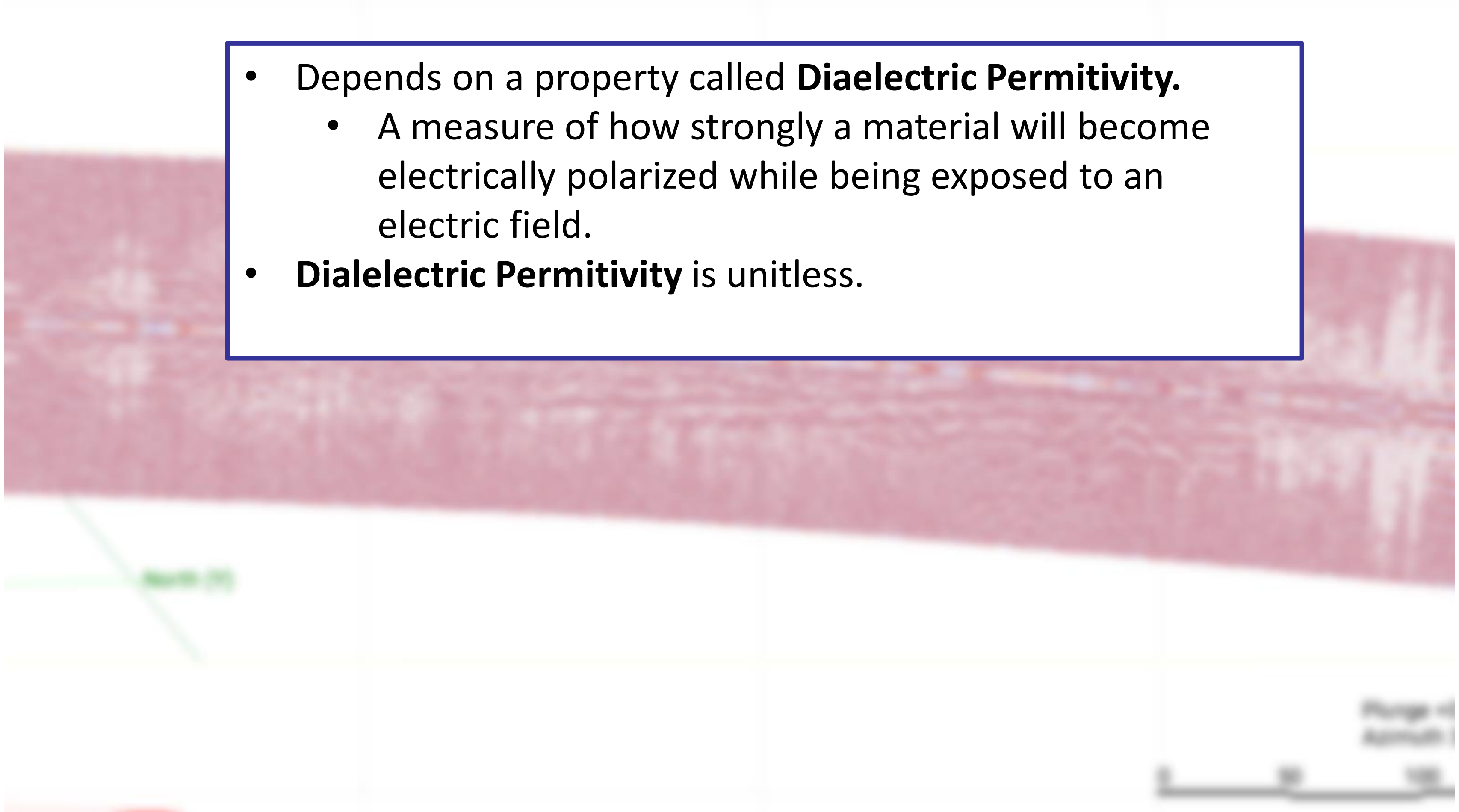
Borehole Magnetic Resonance



Borehole Radar

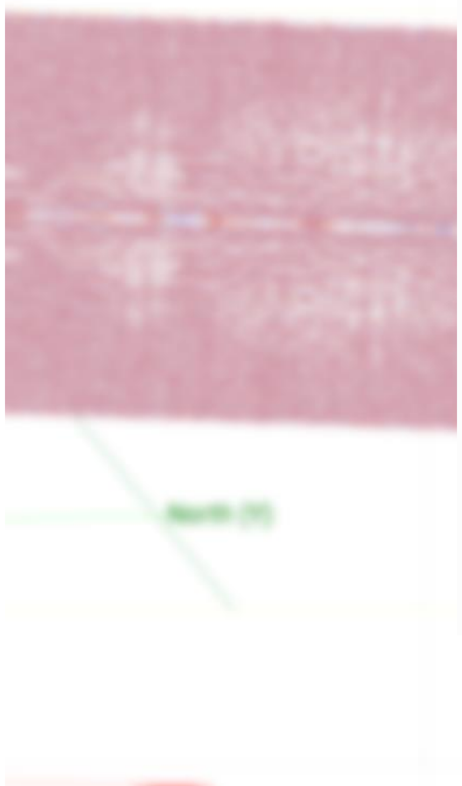


Borehole Radar

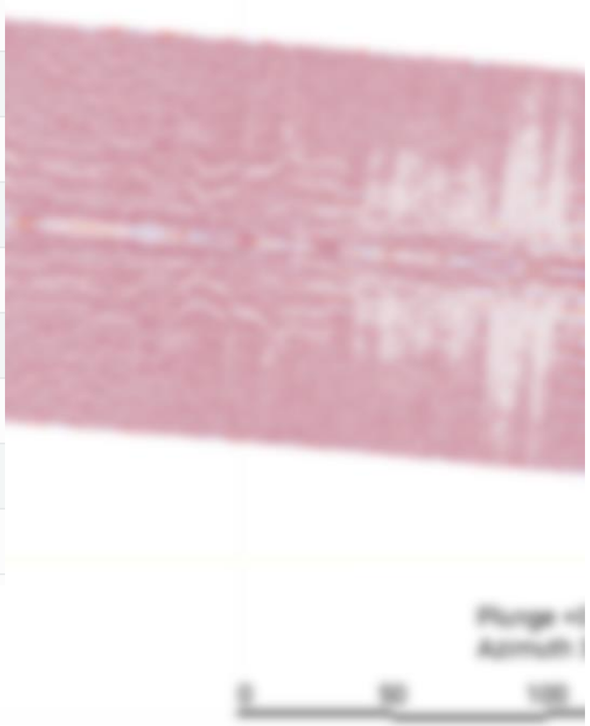


- Depends on a property called **Diaelectric Permitivity.**
  - A measure of how strongly a material will become electrically polarized while being exposed to an electric field.
- **Dialelectric Permitivity** is unitless.

Borehole Radar

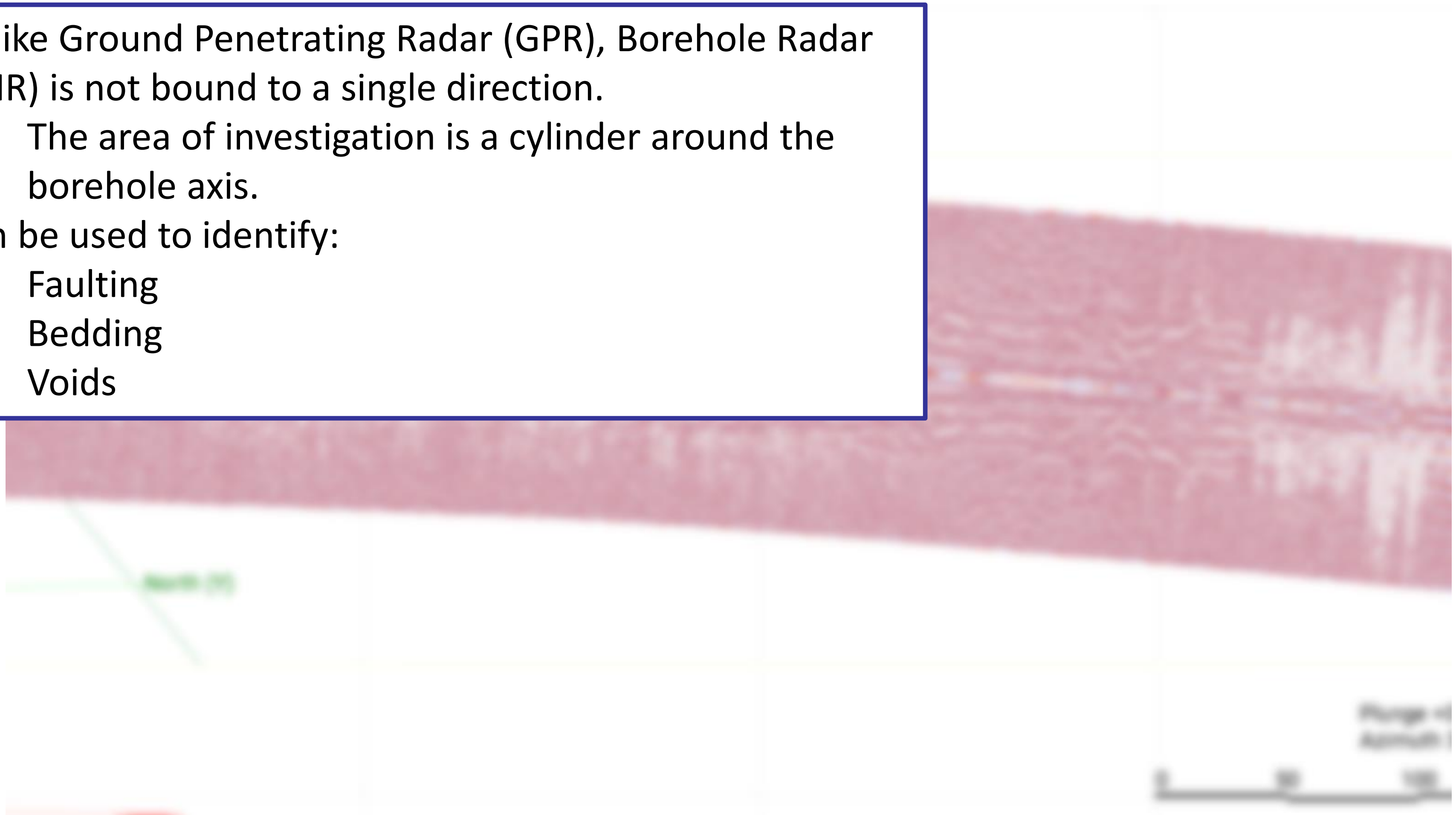


Material	Relative Permittivity
Air	1
Fresh Water	80
Sea Water	80
Ice	3-4
Dry Sand	3-5
Saturated Sand	20-30
Limestone	4-8
Shales	5-15
Silts	5-30
Clays	5-40
Granite	4-6
Anhydrites	3-4

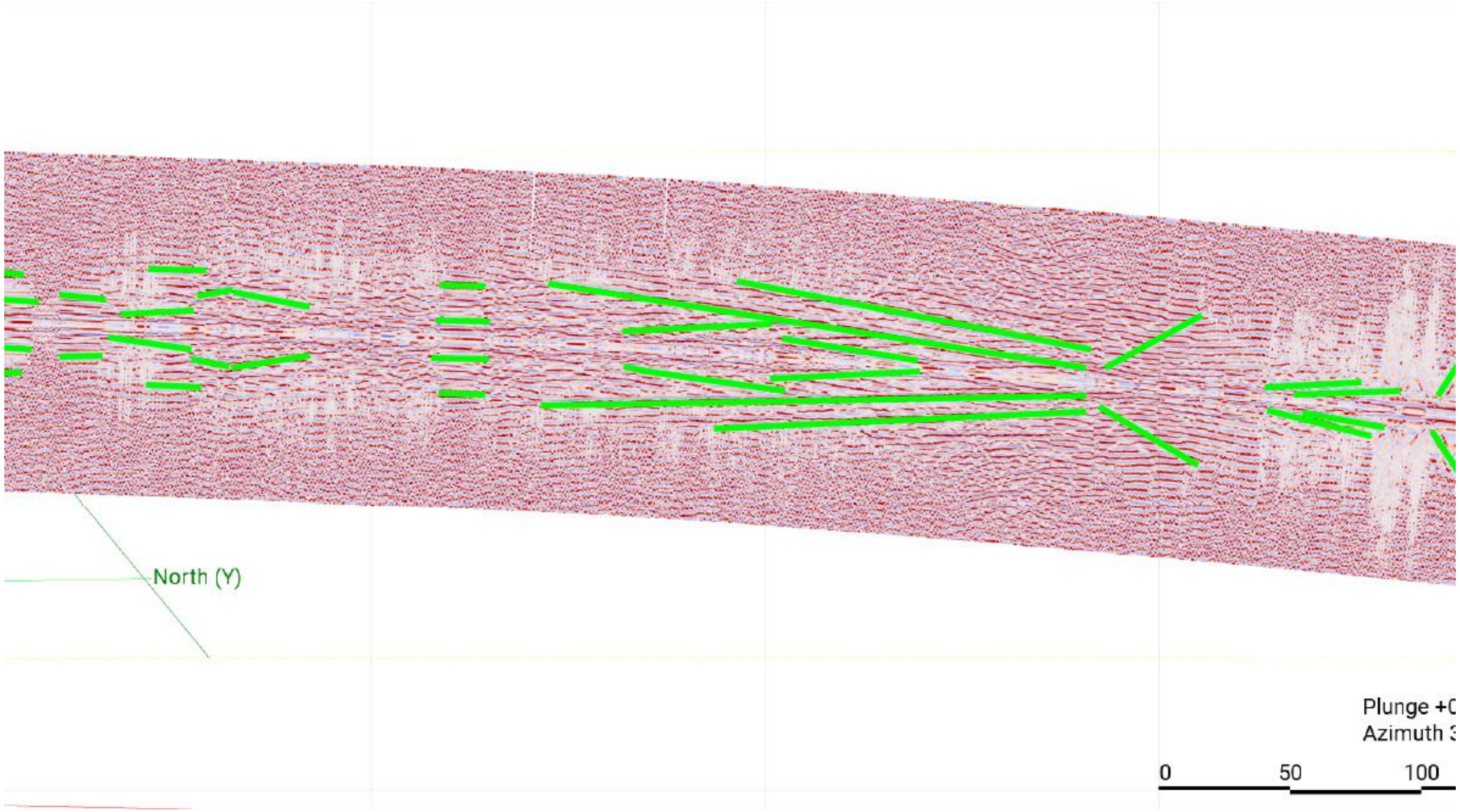


Borehole Radar

- Unlike Ground Penetrating Radar (GPR), Borehole Radar (BHR) is not bound to a single direction.
    - The area of investigation is a cylinder around the borehole axis.
- Can be used to identify:
    - Faulting
    - Bedding
    - Voids

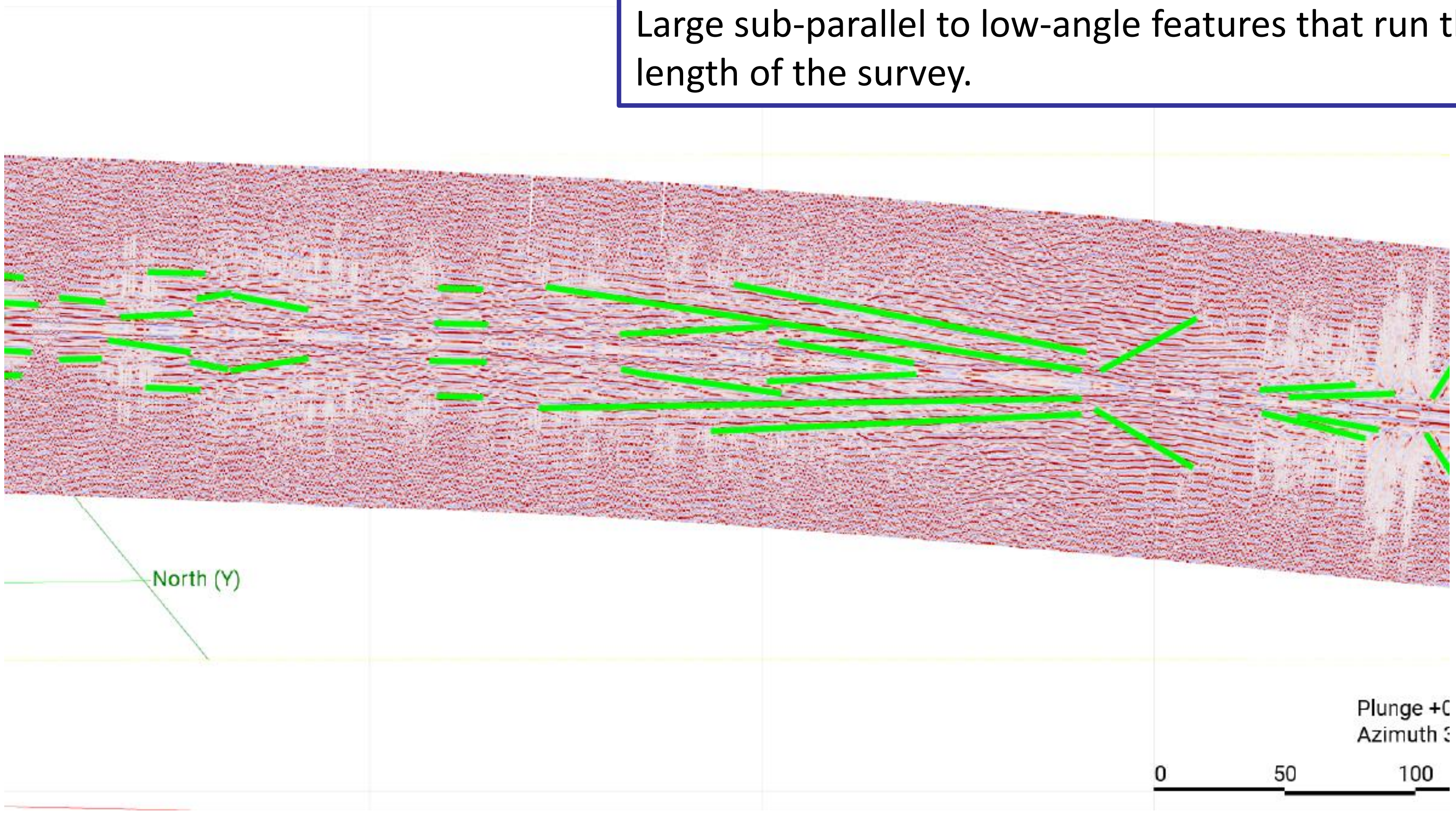


Borehole Radar



Borehole Radar

Large sub-parallel to low-angle features that run the length of the survey.



Borehole Physical Properties Surveys Cont'd

- Single Point Resistance
  - Measure resistance along the borehole to a surface point
- Laterolog
  - Focused resistivity with minimal fluid impact
- Down-hole Electromagnetics (DHEM)
  - Ideally suited for detecting conductive massive sulphide mineralization.
- MagnetoMetric Resistivity (DHMMR)
  - Ideally suited for detecting poorly conducting mineralization such as sphalerite (zinc sulphide) rich bodies.
- Vertical Seismic Profile (VSP)
  - Correlate with surface seismic data.
- Borehole Radar
  - Near off hole imaging
- Borehole Gravity
  - Detects mass excesses or mass deficits

Exercise
Physical Properties
Click Here to Open