Borehole logging

Borehole Logging Measurements and Applications

Outline

- What are physical properties
- Importance of physical properties
- Borehole physical properties
  - Survey design
  - New processes
  - Characteristics
  - Applications
  - Calibrations
  - Surveys
- Overview

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….

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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

Importance of Physical Rock Properties

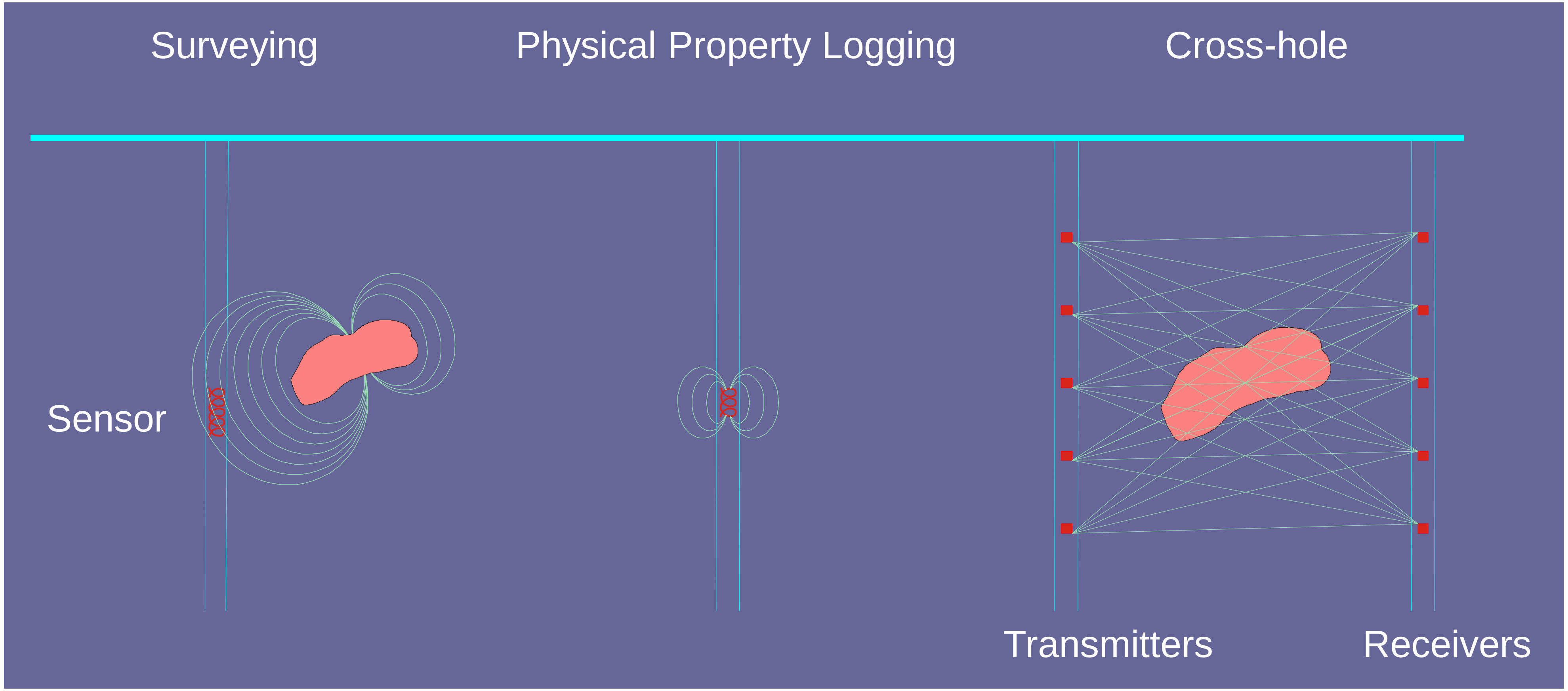
- Physical rock properties are the quantitative link between geology and geophysics
- Respond to lithology, mineralization, alteration, porosity, and mechanical rock properties
- Capable of providing key insights into ore grade, ore delineation, geometallurgy, geotechnical properties and hydrogeology.
- Can be used for unbiased classification into rock property domains and establish proxy relationships.

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

Types of Borehole Geophysical Measurements



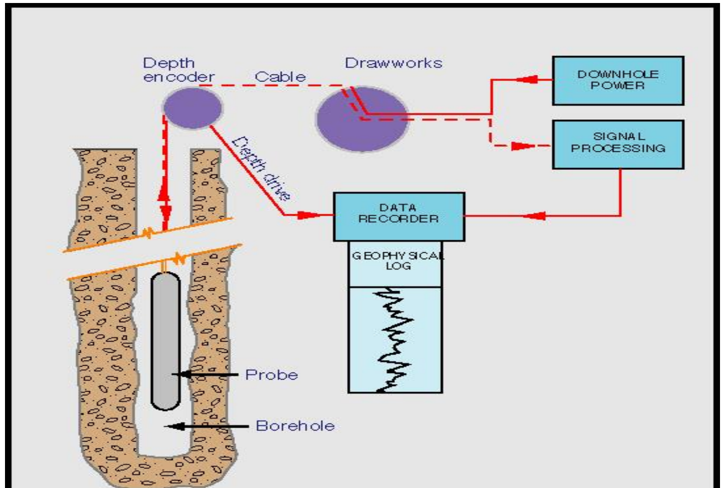
(Courtesy of Alan King)

Survey Design

- What is the goal?
  - Select the right technology
  - Resolution
  - Borehole conditions
  - Fluid conditions
  - Time available
  - Economics
- What are the QA/QC procedures?
  - Calibration
  - Documentation
  - Processing/Interpretation
- Data Management plan

Adapting to New Processes

- Challenging limitations on the directions the borehole probes can be logged in.
- New technologies/processes allow for probes to be run in:
  - Vertical boreholes
  - Horizontal boreholes
  - Incline or up-hole boreholes
- Logging in tough environments
  - Permafrost
  - Weathered rocks (Saprolite)
- Drilling
  - Core vs. non-core



Schematic drawing of a down-hole geophysical survey (Image: USGS)

Components of a Typical Downhole Survey System

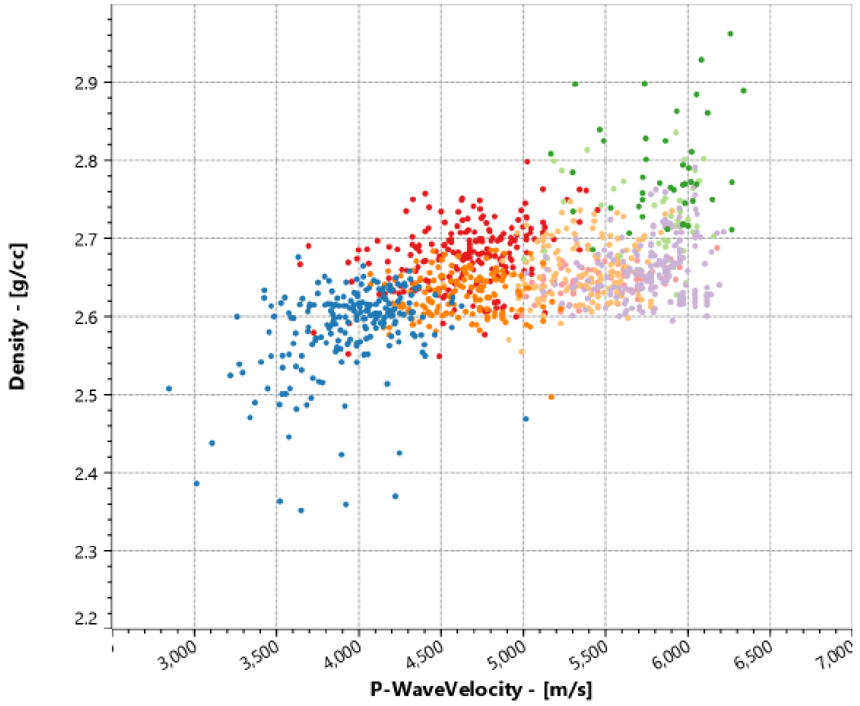
DGI Reformulating the Typical System at the Face

Characteristics of Borehole Physical Property Data

- Continuous in-situ data set – no data gaps
- Fast to acquire
- Repeatable measurements
- Quantitative and unbiased – with proper calibration and systematic, rigorous QA/QC protocols
- Multi-parameter – wealth of information
- High resolution data acquired efficiently
- Ideally suited for statistical analyses and machine learning.

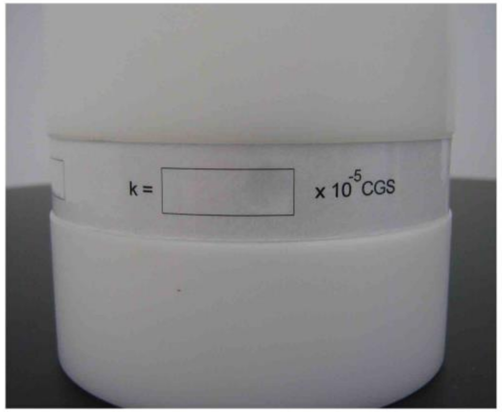
Applications of In - situ Data

- 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



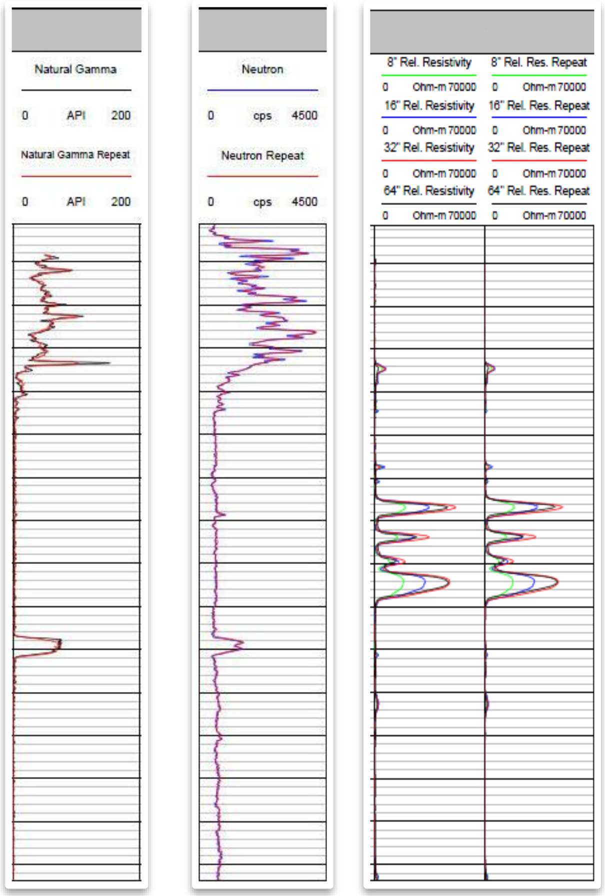
Calibrations

- Importance
- Standards
  - Auditable Trail
  - Process
- Types of Calibration
  - Factory Calibration
  - Field/jig calibration
  - Calibration holes
    - On site versus established
- Temperature drift
- Hole size
- Fluid conditions
- Measurement Range



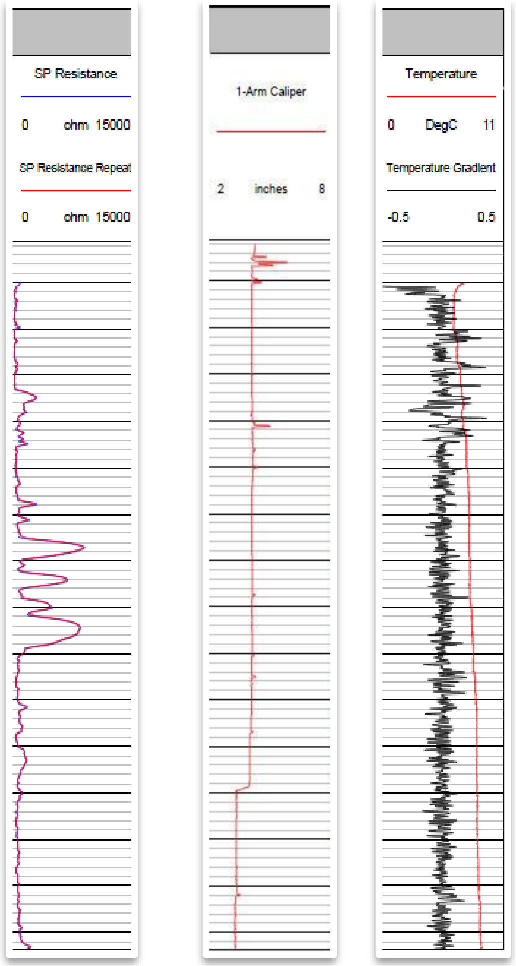
Borehole Physical Properties Surveys

- Natural Gamma
  - Ideal for lithological mapping
- Spectral Gamma
  - used for mineral identification and clay typing.
- Neutron
  - Qualitative measurement of porosity. New QL40-nGEN Neutron Generator by Mount Sopris Instrument Company set to be released in 2018.
- Induction Log
  - Inductive Conductivity can be used to map lithologies.



Borehole Physical Properties Surveys Cont'd

- Normal Resistivity
  - Measures apparent resistivity at different electrode spacing
- Single Point Resistance
  - Measure resistance along the borehole to a surface point
- Laterolog
  - Focused resistivity with minimal fluid impact
- Temperature
  - Indicative of fracturing and groundwater flow
- Mechanical Caliper
  - Records variations in the diameter of the borehole

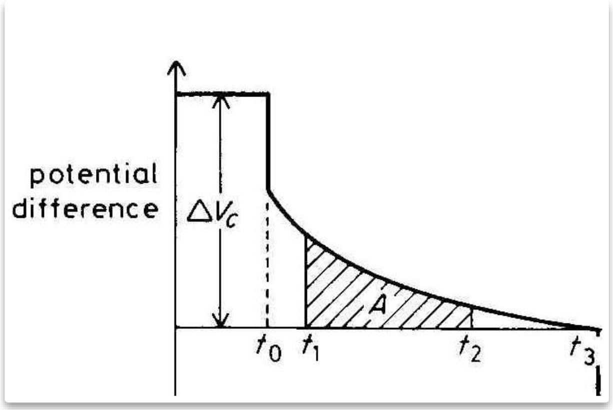


Borehole Physical Properties Surveys Cont'd

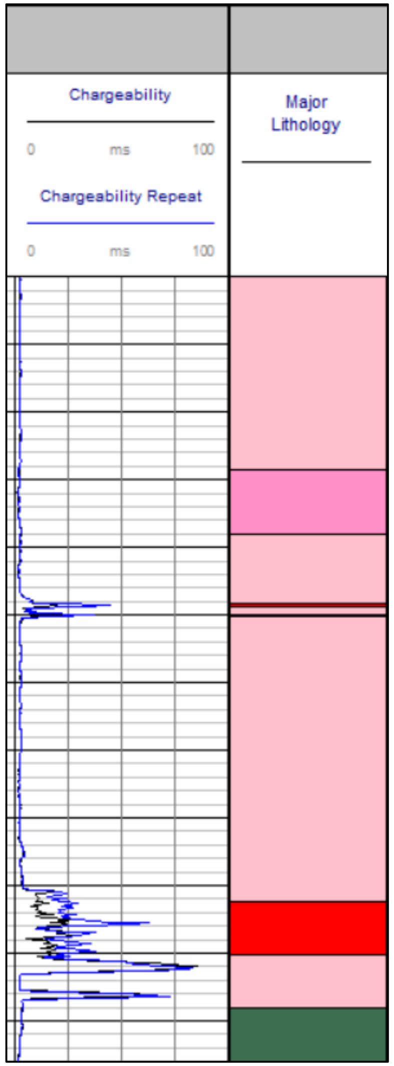
- Down-hole Electromagnetics (DHEM)
  - Ideally suited for detecting conductive massive sulphide mineralization.
- MagnetoMetric Resistivity (DHMMR)
  - Ideally suited for detecting poorly conducting mineralization such as sphalerite (zinc sulphide) rich bodies.
- Vertical Seismic Profile (VSP)
  - Correlate with surface seismic data.
- Borehole Radar
  - Near off hole imaging
- Borehole Gravity
  - Detects mass excesses or mass deficits

QL40-IP: 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.

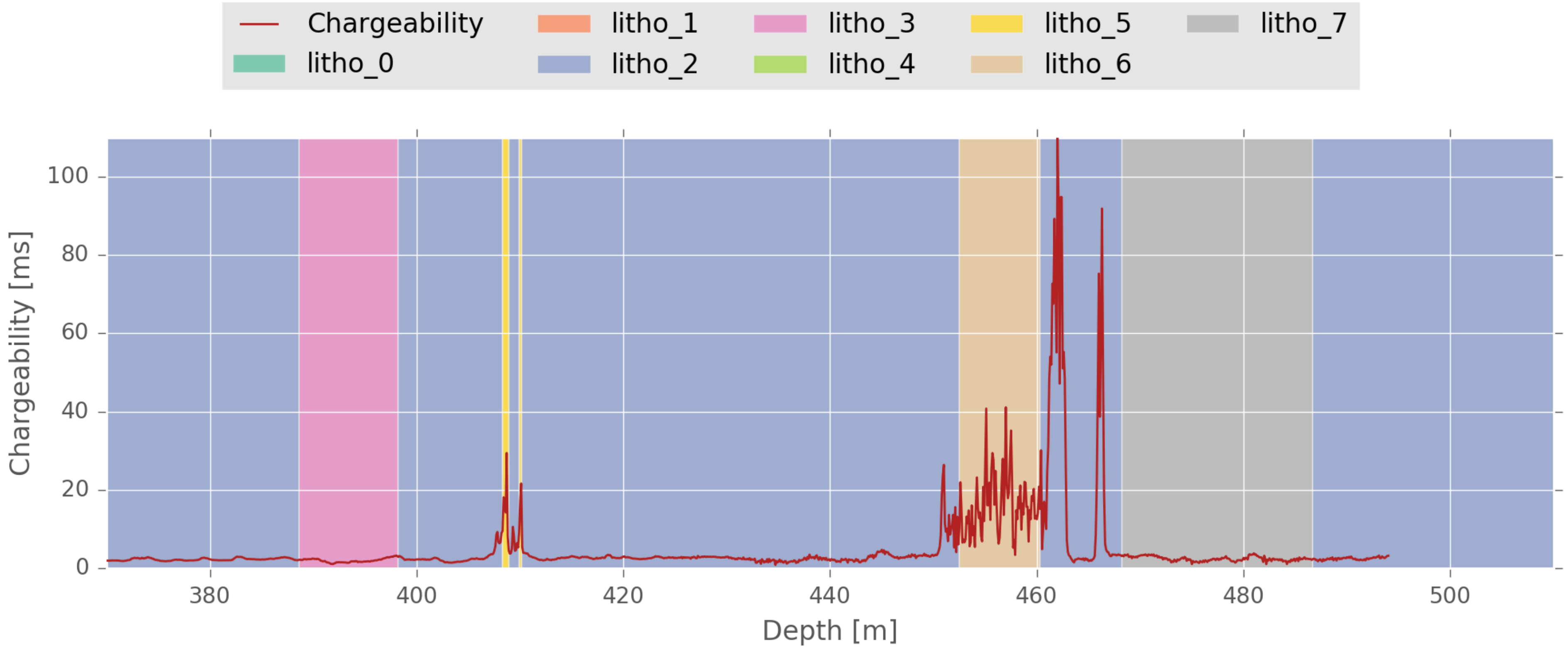


- **Applications**
  - Lithological characterization
  - Certain minerals (eg. sulphides) have high chargeability



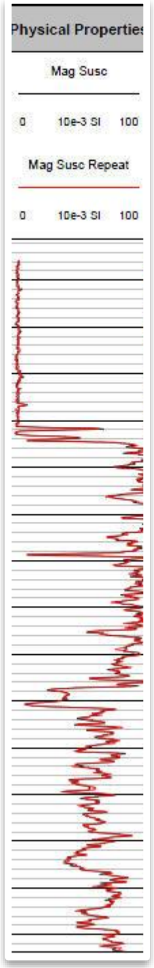
✗ in casing ✗ above water

In-situ Chargeability and Sulphide Zones



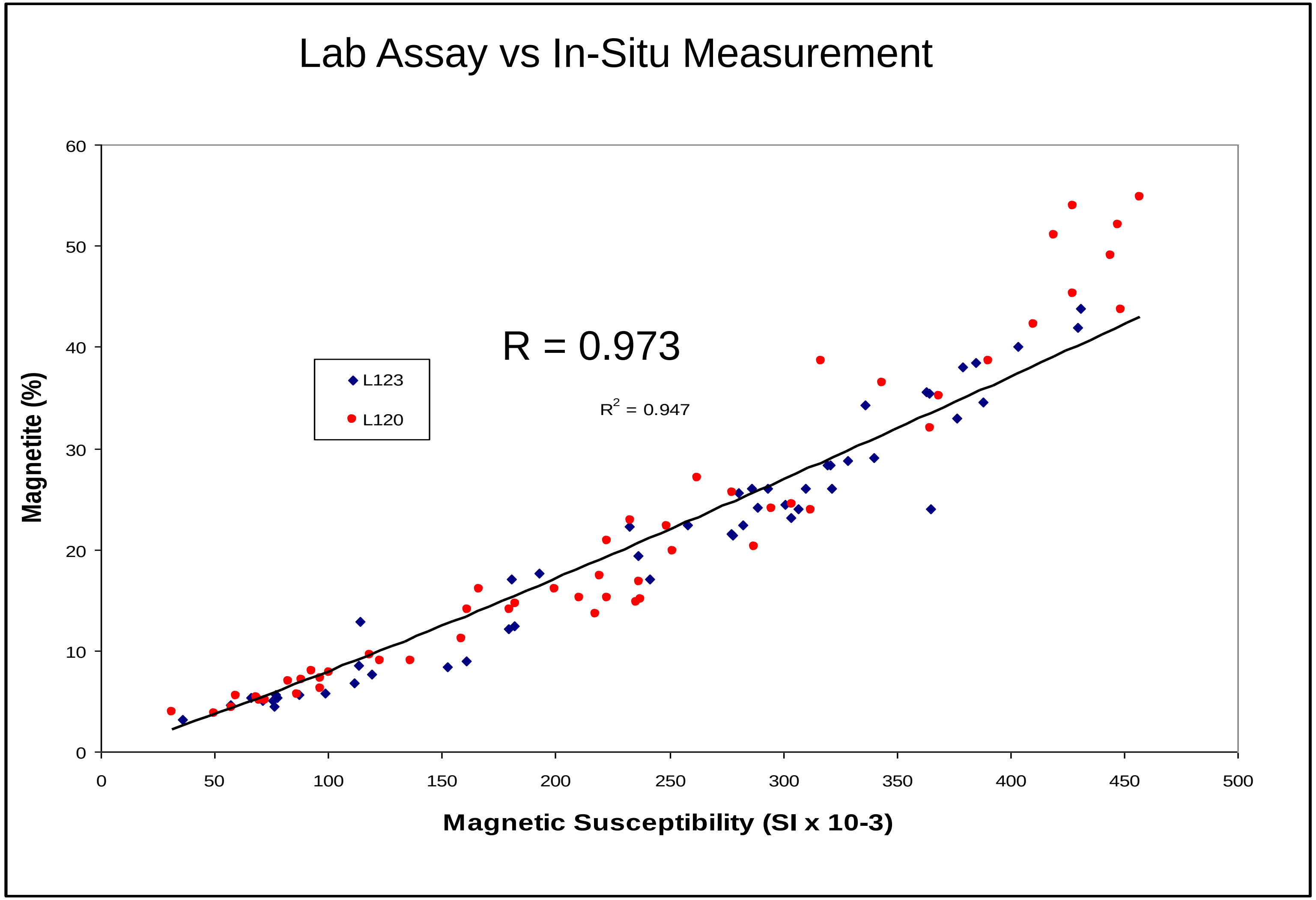
2BSA: Magnetic Susceptibility

- **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.

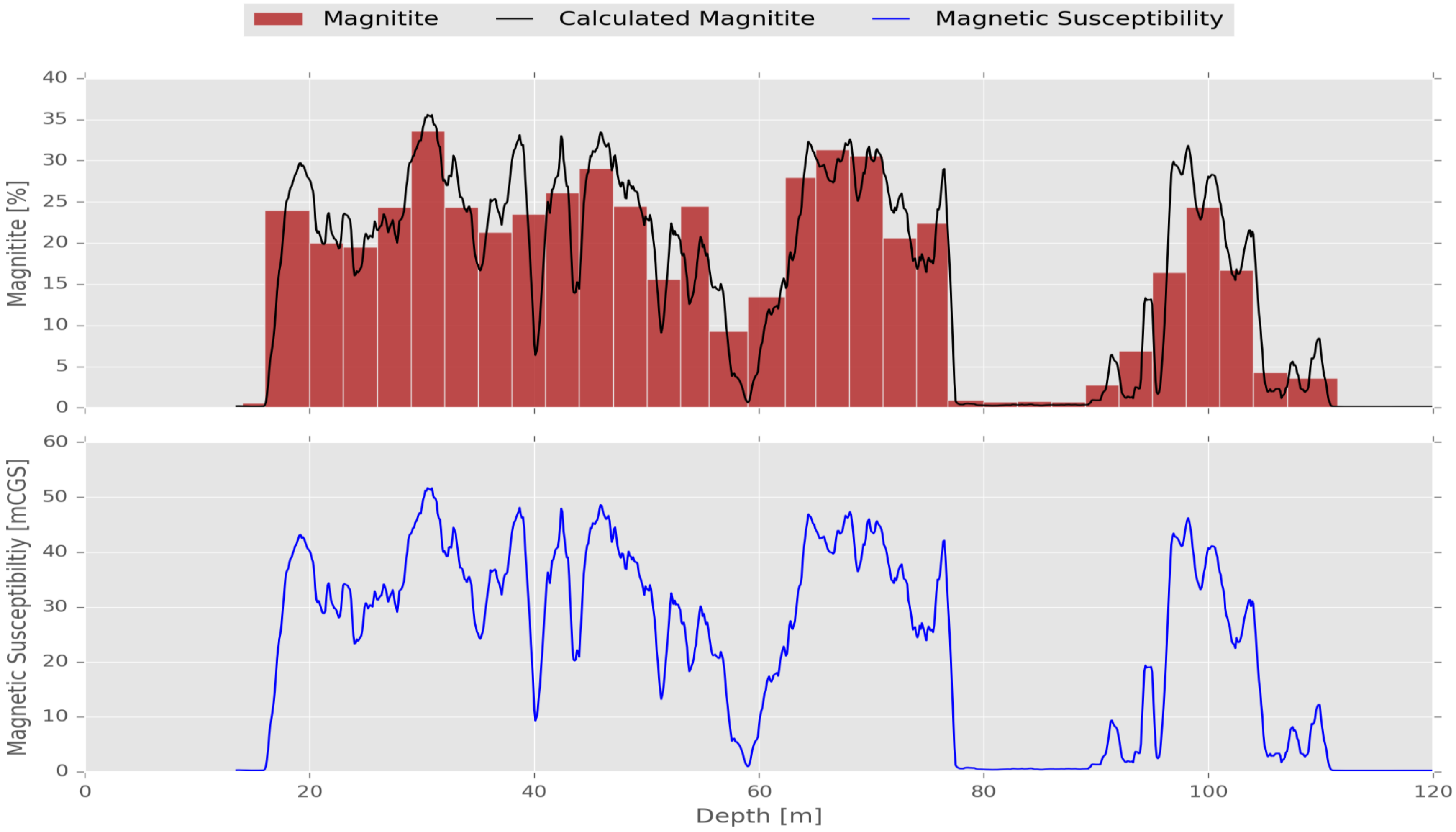


✗ in casing ✓ above water

In-Situ Magnetite Assay



In-situ Assay for Magnetite



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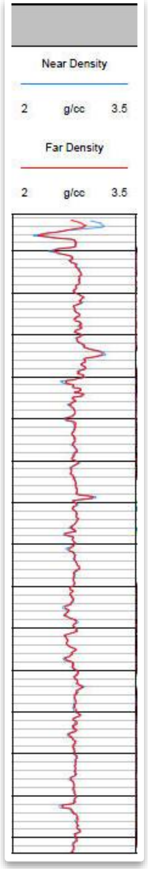
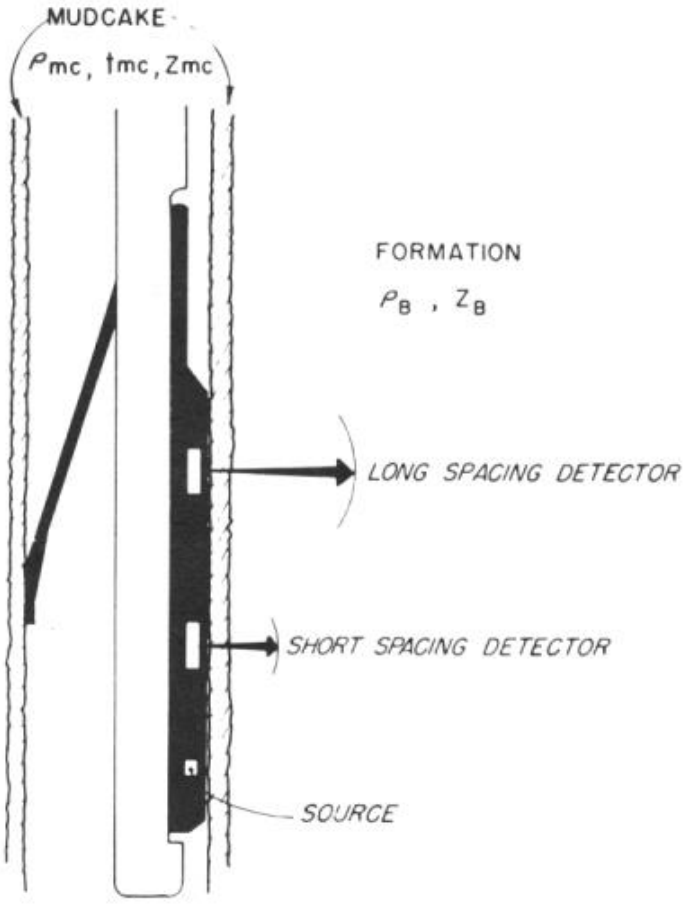
2GDA: Density

- **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)
    - **Omni directional (4π) (qualitative) probe**





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

✗ **in casing** ✓ **above water**

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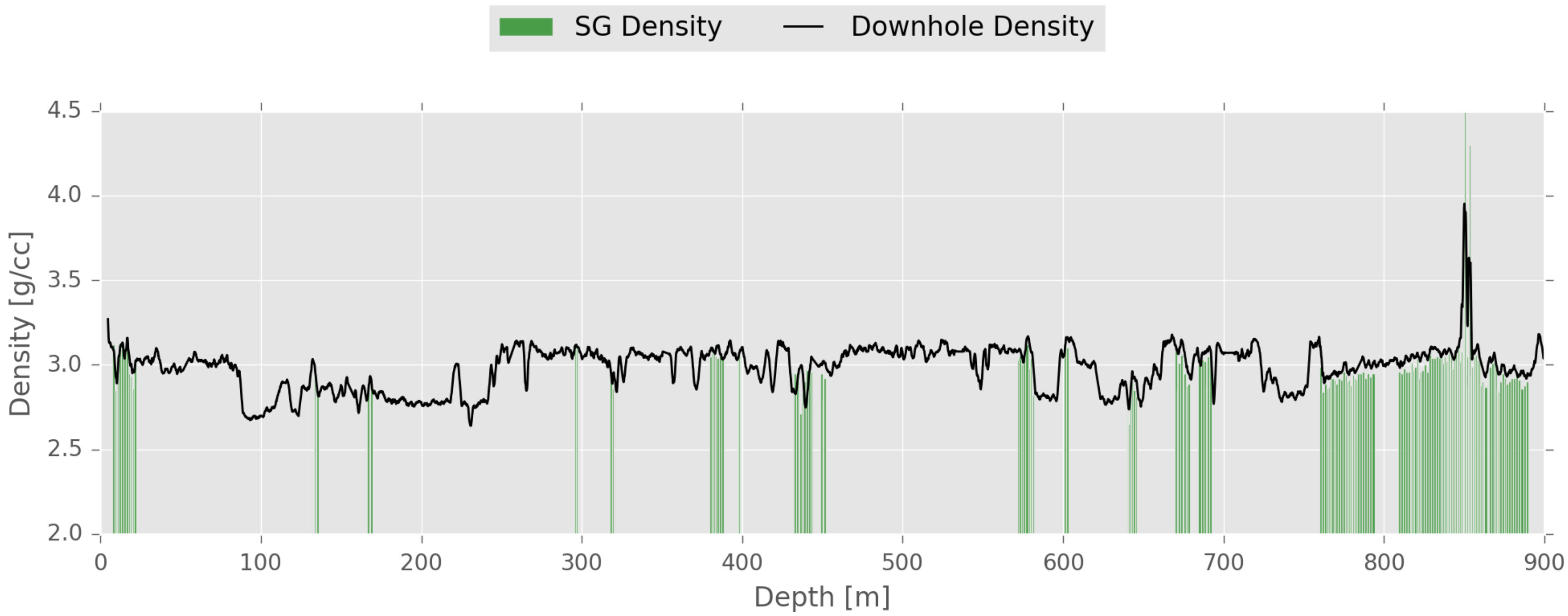
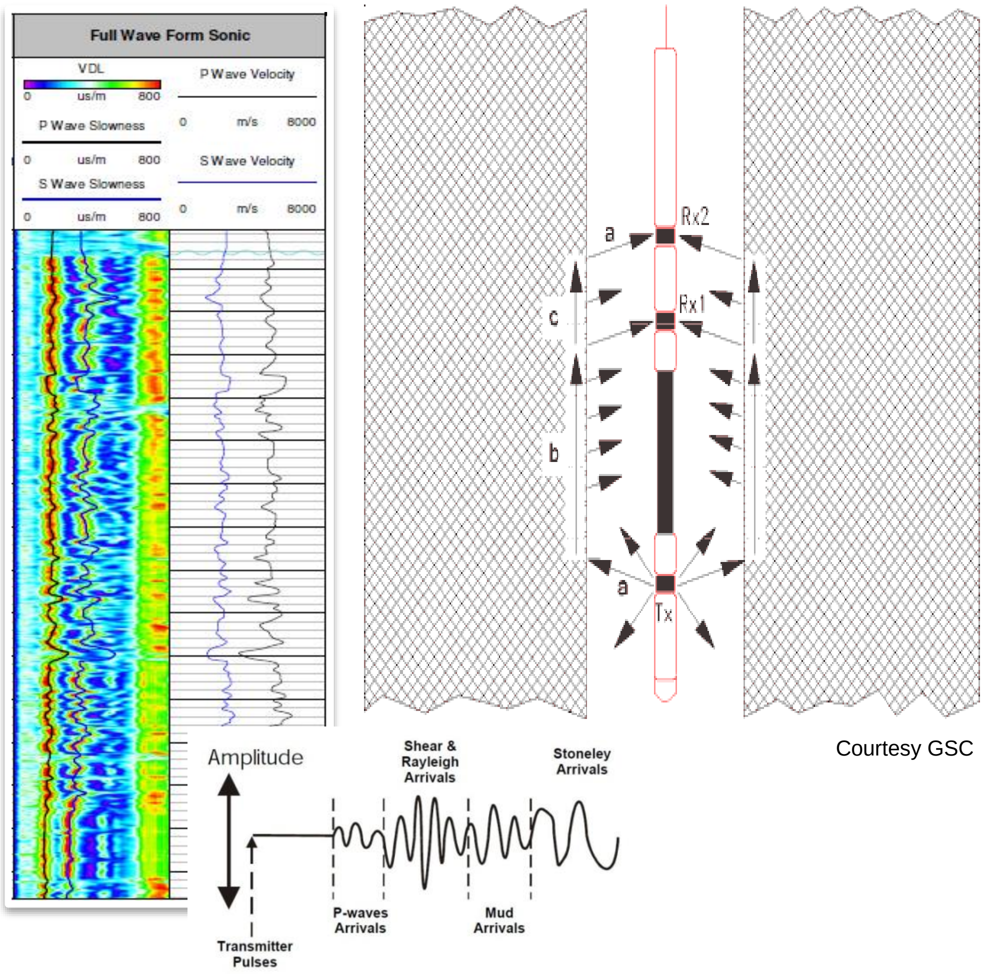
Density : In Situ vs. Lab Determined



FWS: Full Wave Sonic

- **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).
- **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



Courtesy GSC

✓ **in pvc casing** ✗ **above water**

Derived Rock Mechanics

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

Poisson's Ratio : $\upsilon = \frac{R^2 - 2}{2(R^2 - 1)}$ $where\ R = \frac{V_p}{V_s}$

Young's Modulus : $E = \upsilon V_p^2 \frac{(1+\upsilon)(1-2)}{(1-\upsilon)}$

Shear Modulus : $G = \upsilon V_s^2$

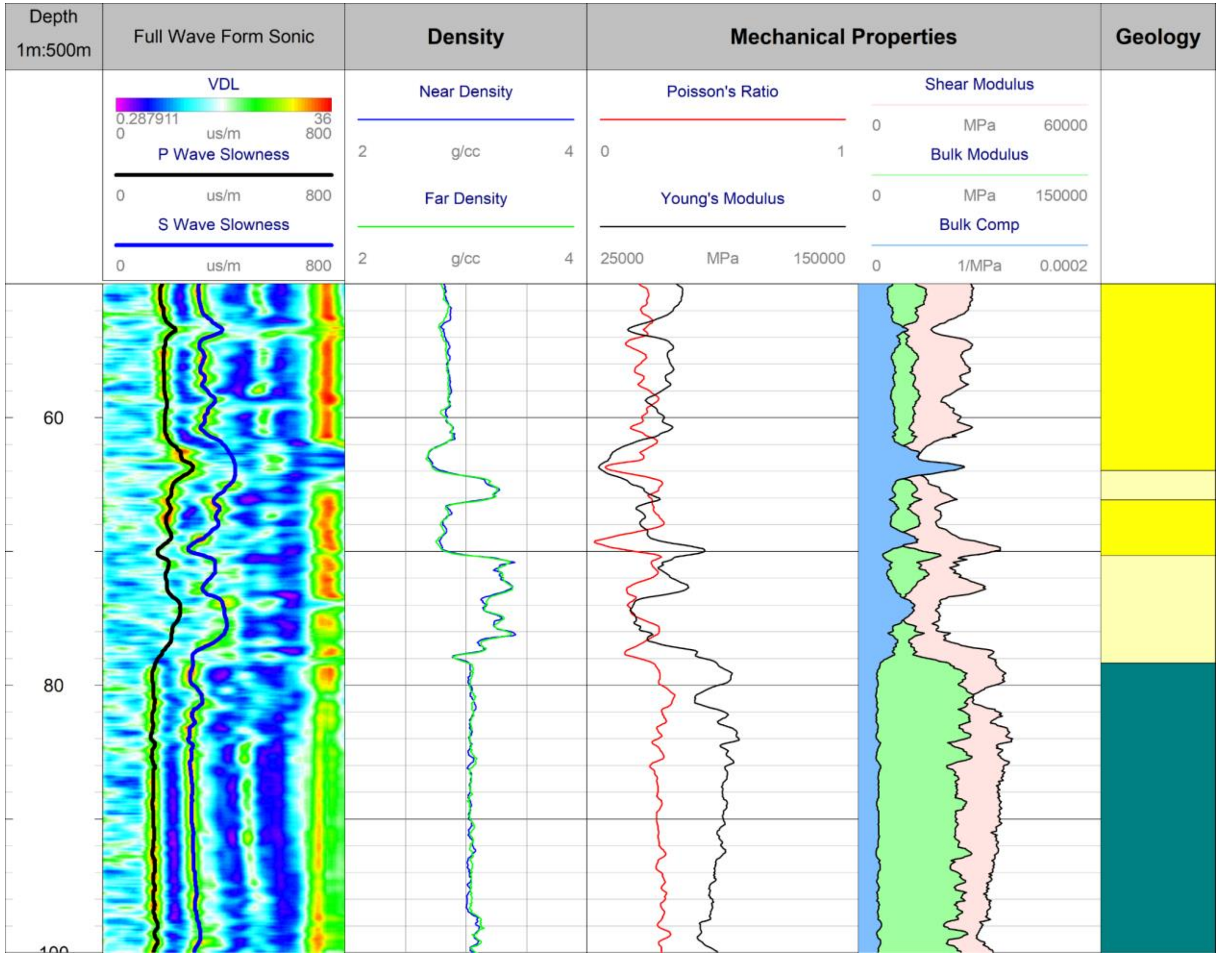
Bulk Modulus : $K = \upsilon V_p^2 - \frac{4}{3}G$

Where:

Compressional wave velocity V_p

Shear wave velocity V_s

Density ρ



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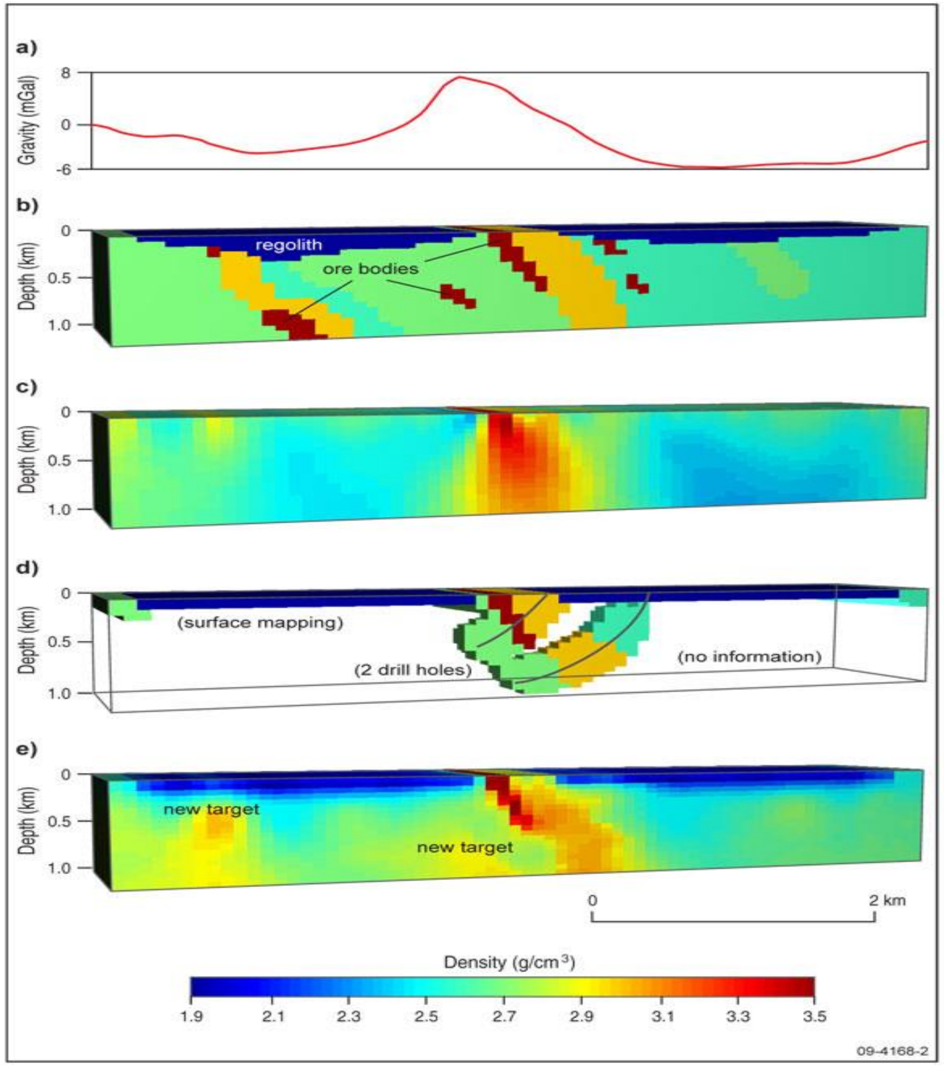
Inversion Constraints

- Figure a shows a profile through a measured gravity (from surface/airborne data).
- Figure b is a known block model to be tested against.
- The full gravity data set is inverted, a smooth 3D density model is recovered that explains the observed gravity data, as shown in Figure c.
- Figure d is new information (constraints) for the model, including basic surface mapping, two drill holes, and some density measurements.
- When this information is included in the gravity inversion, the predicted densities give a much more accurate depiction of the true subsurface (Figure e). This final inversion result can be more reliably used for further exploration or targeting.



Williams, Oldenburg, Lelievre, 2009

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Overview

- Comprehensive borehole geophysical rock property measurements can provide the critical quantitative link between all other forms of geophysics, geochemistry and geology.
- No longer limited to down hole measuring, competent borehole environments and long acquisition times by running multiple different probes.
- Acquiring quantitative, calibrated, repeatable data across multiple holes with multiple parameters , across multiple mobilizations with different instruments tied to a standard with an auditable trial.
- Improve inversion constraints and 3D modeling.
- Turning data into knowledge.

Thank You!