Subsurface Characterization Enabled by Geophysical Logging

Applications for Mining

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Enabling Technologies for Hard-Rock Mining Applications
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Outline

- Overview of characterization needs & current practices
  - Our understanding of mining
  - Comparison to oil & gas
- Advanced geophysical logging
  - Specific applications in mining (by mine characterization domain)
  - Examples
- Data integration and spatial upscaling
- Final thoughts
- Questions and discussion
Mining Needs for Subsurface Characterization

Ore characterization
- Ore Delineation
- Complex Geology
- Ore Grade/Type
- Condemnation

Ore Extract/Proc.
- Ore Grade Control
- Blast Optimization
- Heap Leaching

Water Management
- Dewatering Optimization (incl. Directional Drill)
- Water Supply
- Pore Pressure Control

Geotechnical Optmz
- Pit Slope Stability
- Block Caving
- Underground Working Stability

Waste Management
- Strip Ratio Optimization
- Acid Mine Drainage

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Key subsurface parameters/conditions that impact mining engineering and operations

<table>
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<tr>
<th>Hydrogeology</th>
<th>Rock Mass</th>
<th>Geology</th>
<th>Structure</th>
<th>Stress/Strain</th>
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<tbody>
<tr>
<td>• Mine water management (dewatering and supply), pore pressure control</td>
<td>• Pit slope stability, block caving, underground working stability, blasting opt.</td>
<td>• Ore delineation, mine design, ore grade, waste rock management, leaching, blasting opt., geotechnical stability</td>
<td>• Mine design and geotechnical stability</td>
<td>• Mine design and geotechnical stability/risk</td>
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<td>• Flow, storage, pressure</td>
<td>• Elastic and rock strength properties</td>
<td>• Lithology</td>
<td>• Delineation and orientation of faulting and other major structures</td>
<td>• In-situ state of stress around pit wall and underground workings</td>
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<td>• Fracture evaluation</td>
<td>• Bulk density</td>
<td>• Mineralogy</td>
<td>• Fracture/joint evaluation (orientation, spacing, width, length)</td>
<td>• In-situ state of strain</td>
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<tr>
<td>• Secondary porosity evaluation</td>
<td>• Porosity</td>
<td>• Ore assay and density</td>
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<td>• Monitor changes</td>
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<td>• Matrix hydrogeologic properties</td>
<td>• Water content</td>
<td>• Alteration and fracture fill material</td>
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Ultimately the goal is to reduce overall uncertainty, as efficiently as possible, about parameters/conditions that significantly impact the engineering problem – enabling improved and more timely decision making.
Subsurface Characterization – Methods Practiced in Mining

- Airborne geophysics, surface geophysics (early exploration)
- LOTS of drilling and coring, visual logging, selective sampling and lab analysis
- Some borehole geophysics (mostly rudimentary) – gamma, SP, resistivity, caliper, gyro (sometimes density, ATV/OTV borehole imaging, sonic)
- Some well testing (slug, packer, pumping)
- Monitoring – pore pressure monitoring (VWP), geotech stability monitoring (slope stability radar, micro-seismic)
- The majority of existing mine assessment is performed by physical sampling (core drilling, cuttings from RC drilling)
- Borehole geophysical logging is mostly low tier/low tech and qualitative
- Geophysical log data processing is very limited and results marginally used
Limitations of Current Wireline Practice in Mining

- Don’t measure “true” formation (unfocused, no corrections for drilling effects)

- Non-quantifiable measurement uncertainty (limited/no log quality control, even for depth control)

- Difficult/impossible to relate measured parameter to property of interest (e.g., porosity, permeability)

- Rarely incorporated in workflow of site characterization
Oil & Gas Reservoir Characterization is focused on integration of high quality borehole and surface geophysics, as well as wireline-conveyed discrete depth packer testing and downhole sampling.

- Compared to physical sampling, the advantage of in-situ, non-invasive measurements:
  - more representative of actual subsurface conditions
  - measure a much larger volume and have higher spatial sampling
  - much more efficient to acquire and fully analyze (faster and requiring fewer personnel)
  - much more objective
- Field analytical mud logging
Conventional core/cuttings – negligible DOI and VOI, resol. dependent on sample freq./prep.

Geophysical logs – mm to meter DOI and resol., but continuous in depth

Surface geophysics – 100m to 10s of km DOI, 10 to 100s m resol., very large VOI

Cross-hole methods to image the inter-well space

Measurement integration to fill the gaps
Schlumberger wireline technology can measure all the following subsurface parameters of interest to mining (assuming large enough hole, fluid-filled)

**Key Properties for Mining – Measured with Advanced Geophysical Logs**

**Hydrogeology**
- Mine water management (dewatering and supply), pore pressure control
  - Flow, storage, pressure
  - Fracture evaluation
  - Secondary porosity evaluation
  - Matrix hydrogeologic properties

**Rock Mass**
- Pit slope stability, block caving, underground working stability, blasting opt.
  - Elastic and rock strength properties
  - Bulk density
  - Porosity
  - Water content
  - Lithology

**Geology**
- Ore delineation, mine design, ore grade, waste rock management, leaching, blasting opt., geotechnical stability
  - Lithology
  - Mineralogy
  - Ore assay and density
  - Alteration and fracture fill material

**Structure**
- Mine design and geotechnical stability
  - Delineation and orientation of faulting and other major structures
  - Fracture/joint evaluation (orientation, spacing, width, length)

**Stress/Strain**
- Mine design and geotechnical stability/risk
  - In-situ state of stress around pit wall and underground workings
  - In-situ state of strain
  - Monitor changes

The value that Schlumberger brings is proven workflows to integrate the individual measurements into an accurate and cohesive model of the subsurface from which to make more accurate and timely mine development decisions.
Advanced In-Situ Ore Deposit Characterization Workflow

(1) Job Planning - Technology Selection

(2) Field Log Acquisition

(3) Real-Time Field Log Processing/Solutions

(4) Real-Time Data Transmission to Processing Center

(5) Preliminary Analysis for Well Completion & Rapid Decisions (e.g., future well placement, blast design)

(6) Full Analysis & Integrated Data Model
## Schlumberger Wireline Technologies to Address Mining Needs

<table>
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<th>Mining Application</th>
<th>SLB Wireline Services</th>
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<tr>
<td>Fracture Evaluation</td>
<td>Electrical imaging, ultrasonic imaging, azimuthal sonic, wireline packer testing</td>
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<tr>
<td>Rock Elastic Mechanical Properties</td>
<td>Bulk density, dipole sonic</td>
</tr>
<tr>
<td>Rock Strength Properties</td>
<td>Bulk density, dipole sonic, geochemical spectroscopy, neutron porosity, wireline packer</td>
</tr>
<tr>
<td>In-Situ State of Stress</td>
<td>Borehole imaging, azimuthal sonic, wireline packer</td>
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<tr>
<td>Hydrogeology Characterization</td>
<td>Magnetic resonance, electrical imaging, acoustic imaging, bulk density, neutron porosity, dipole sonic, wireline packer testing/sampling</td>
</tr>
<tr>
<td>Geochemical, Ore Grade</td>
<td>Geochemical spectroscopy, dielectric scanner, litho-density</td>
</tr>
<tr>
<td>Rock Matrix, Bulk Properties</td>
<td>Bulk density, neutron porosity, magnetic resonance, dipole sonic</td>
</tr>
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</table>
Overall Schlumberger Geophysical Logging Capabilities – by hole size

- **Standard RC/Blast Hole**
  All tools, including litho-density, porosity/water content, resistivity, gamma ray, SP, electrical and acoustic imaging, dipole array sonic, wireline packer testing and sidewall coring, elemental spectroscopy, borehole geometry (oriented 3D profile)
  - Minimum 6.25” hole size

- **Slim Hole**
  Litho-density, array sonic, porosity/water content, resistivity, elemental spectroscopy, borehole fluid temperature, gamma ray, SP, caliper, acoustic imaging
  - Minimum 3” hole size

- **Within drill pipe / casing**
  Litho-density, porosity/moisture, elemental spectroscopy, possible sonic
  - Minimum 2.75” ID
  - Requires casing/pipe to be close to borehole wall (<1 in.); good coupling to rock for sonic
Currently Available Schlumberger Logging Capabilities in Slim Holes

- **Multi-Express Quad Combo (3” min hole/casing)**
  - Bulk Focused Resistivity (shallow, deep, high res.)
  - Neutron Porosity (air or fluid-filled hole)
  - Bulk Density / Photoelectric Factor
  - Full Waveform Array Sonic (compressional and shear wave)
  - 2.25" OD, < 16 ft individual tool length
  - Hole size 3.0” – 12.75” (min drift ID of 2.75” for through drill pipe operation)

- **RST Slimhole Elemental Spectroscopy (2.25” min hole/casing)**
  - Rock elemental concentrations (Si, Fe, Ca, S, Ti, Gd, H)
  - Neutron Capture Cross Section (sensitive to lithology and water, used to derive volumetric water content)
  - Borehole Fluid Temperature
Geology & Ore Characterization

- **Lithology** using triple-combo (Platform Express, Multi-Express) or quad-combo (add sonic) [<3 in. hole]
  - Focused bulk resistivity (stratigraphy, thin beds)
  - Neutron porosity, gamma ray (water content)
  - Litho-density [rad. source], micro-resistivity, and caliper (density, photoelectric factor, thin beds)
  - Array sonic (porosity, hardness)

- **In-situ mineralogy** using neutron-gamma ray spectroscopy and litho-density [<2.25 in. hole, best measurement > 5.5 in. hole]
  - Large suite of rock-forming elements – silicon, iron, calcium, sulfur, titanium, gadolinium, (Na, Al, Mg, K w/ ECS; Mn, C, TOC w/ Litho-Scanner)
  - Bulk density & photo-electric factor [rad. source]
  - In-situ Acid-Base Accounting from sulfide and carbonate mineralogy evaluation

- **In-situ assay of ore** using neutron-gamma ray spectroscopy [<5.5 in. hole]
  - NOW – copper, iron, aluminum, potassium, titanium
  - Future – nickel, moly, cobalt, chromium, others
Ore Grade Evaluation Example: In-Situ Nickel (Sudbury, Ontario)

- 20 x 50 ft. blast holes logged w/ RST (8 co-located w/ core)
- 1 x 250 ft. core hole logged – full logging suite (co-located w/ core)
Continuous quantitative measurements along entire drill hole of key geologic and geomechanical properties

- Metal ore assay, elemental geochemistry, mineralogy, fracturing and structure, rock mechanics
Comprehensive In-Situ Ore Body Analysis

Much greater volume measured than core samples

No sample handling & lab work
Geostatistics from wireline in-situ assay Ni in 20 x blast holes

Ordinary Kriging
Nickel Ore Grade Control Via Wireline

**Current Practice**

Cutting Sampling/Assay
(Slow, significant uncertainty)

**Proposed Alternative**

In-Situ Assaying with Elemental Spectroscopy
(Near real-time, low uncertainty)
- Heap leach geochemical monitoring
- In-situ measurement of bulk elemental concentrations
- Rock-forming elements: Si, Fe, Al, K, Ca, S, Na
- Ore elements: Cu
- Other: Ti, Gd
Wireline Monitoring of Copper Through Time

The graph illustrates the Cu % Recovery over time for different leach systems and comparison to baseline data. The x-axis represents Days under leach while the y-axis shows Cu % Recovery. The graph includes multiple lines representing different leach systems such as Column - Leach Pad (revised), Column - Belt (revised), Drill WL123, Stingray (WL123), 0' to 19' (WL123), and Fitted (WL123).
- Integrated log analysis of elemental concentrations along with other wireline log measurements (density, neutron porosity, magnetic resonance)
- Dry mineral concentrations
- Water & air-filled porosity, saturation
- Fluid conductivity/resistivity
- Permeability (liquid & air)
Structural Characterization

- **Delineation of faulting, folding, and other major structures** using cross-hole seismic/EM [>4.5 in. hole]
  - High resolution seismic velocity and reflection imaging between drill holes
  - Electrical conductivity imaging between drill holes

- **Bedding/foliation orientation** using borehole imaging and azimuthal resistivity [>6.25 in. hole]
  - Automated bed picking for strike and dip

- **Discrete fracture/joint evaluation** using borehole imaging [>6.25 in. hole]
  - Automated fracture trace picking, orientation, aperture, fill, intensity
Traced fracture segments (discontinuous)

Classified fracture traces – low and high angle (continuous)

Dip azimuth and angle of fracture segments & dips

Fracture density, trace length, and porosity

Fracture segment aperture

3-d "iCore" Image

Dip Angle Rosette
(shows two sets of fractures – low and high angle)
Highly fractured Diabase – automated trace picking

**FMI Image – static normalization**
**# frac. segments /m depth (red)**
**Fracture segment aperture**
**Fracture trace length / unit borehole surface area (green)**
**Sonic Porosity**

**Fracture Porosity**

**Aperture along fracture trace**

**FMI Image – dynamic normalization**
Borehole Electrical Imaging – Comprehensive Fracture Evaluation

Highly fractured Diabase – zoomed out to show variability
Comprehensive Fracture and Structure Analysis

**Event Classification**

**Spatial Analysis**

**Fracture Density**

**Regional Dip**

**Feature Analysis**

**3D Integration & Visualization**
Example Fracture Log Analysis for In-situ Block Size

**Observed Data**

- FMI Image Fracture Analysis
- Stereonet Analysis of Fracture Sets

**Discrete Fracture Modeling Based on Data Analysis**

- Modeled vs. Observed Fracture Sets
- Discrete Fracture Network Model

- Block/Fragment Size From Modeled Fracture Geometry


- Evaluates vertical and spatial geologic structure and stratigraphy, potentially physical and chemical parameters with calibration

- Electromagnetic (EM) tomography (measures electrical conductivity, high vs. low electrically conductive zones, often associated with ore mineralization)

- Seismic tomography / reflection (measures acoustic properties)

- Can be acquired in cased wells (well separation <= well depth)

- Nearly complete spatial coverage between wells

- Relatively high spatial resolution (seismic 3m or less. EM ~5% of well spacing)
Geomechanics Characterization for open pit slope stability and blasting impacts, underground workings, and block caving progression and impacts

Key Technologies:
- Elastic and rock strength properties from dipole array sonic and bulk density
- Fracture Network Characterization from borehole imaging
- State of stress/strain from dipole array sonic, borehole imaging, wireline-conveyed packer hydraulic fracturing, fiber optic strain
- Mechanical Side-Wall Coring for full lab geomechanical analysis
Rock Mass Characterization

- **Elastic and rock strength properties** using dipole array sonic and bulk density (>5.5 in. hole)
  - Poisson’s ratio, Young’s modulus, bulk compressibility, UCS

- **State of stress/strain** using dipole array sonic, borehole imaging, wireline-conveyed packer hydraulic fracturing (> 6.25 in. hole)
  - Overburden (vertical) stress magnitude versus depth
  - Min./max. horizontal stress orientation and anisotropy
  - Minimum horizontal stress magnitude

- **State of strain** using fiber optic strain monitoring (any hole size in which fiber can be emplaced)
  - Strain magnitude [and direction with multiple oriented installations]

- **Sidewall core sampling** using wireline-conveyed large volume rotary coring tool (>6.25 in. hole)
  - 1.5-in-OD by 2.5-in-long sidewall core samples suitable for geomechanics and petrophysics lab analysis
Schlumberger Key Logging Technologies – Geomechanics

**Electrical Imaging/ Ultrasonic Imaging**
*FMI (Fullbore Formation MicroImager), UBI (Ultrasonic Borehole Imager)*
- Rock structures, fracture aperture, texture, heterogeneity and facies analysis, secondary porosity analysis, borehole geometry

**Array Sonic**
*DSI (Dipole Shear Sonic Imager), Sonic Scanner, slimhole array sonic*
- Elastic properties, rock strength, stress orientation & anisotropy

**Litho-Density**
*TLD (Triple Detector Litho-Density), slimhole litho-density*
- Bulk density, total porosity, lithology, thin bed delineation

**Modular Dynamics Testing**
*MDT (Modular Dynamics Tester)*
- Mini-hydraulic fracturing for minimum stress, rock strength
- Pore pressure profile

**Sidewall Core Sampling**
*XL-Rock (Large-Volume Rotary Sidewall Coring Service)*
- 1.5-in-OD by 2.5-in-long sidewall core samples equivalent to conventional core plugs
- Core for full lab geomechanical analysis
- Petrophysical analysis

**Core Scratch Testing**
*TerraTek Mechanical Properties Profile Service*
- Continuous, high-resolution UCS over entire core interval
Example In-Situ Geotechnical Characterization Using Advanced Wireline Logging and Analysis

- Dynamic Young's Modulus
- Dynamic Shear Modulus
- Unconfined Compressive Strength
- Electrical Image Fracture Analysis
- Hydrogeology (porosity, estimated permeability)
- Quantitative Lithology (mineral/dry wts)
- Static Young's Modulus
- Poisson's Ratio
- Vertical Stress
- Fast Shear Azimuth (max. horizontal stress orientation)
- Horizontal Stress
- Pore Pressure
- Water Services
The Mechanical Earth Model (MEM) Workflow

- QC/validate existing data
- Rock Strength & Property Logs + Calibration to Select Core
- Fracture Image QC, picking, and interpretation
- Import Structure + Property Logs + Fractures Into Integrated Model
- Build DFN from fracture sets
- Upscale property logs to 3D grid
Example in-situ geotechnical and hydrogeology characterization program

Exploration drill holes for slim wireline tools (20-30 x HQ or small diameter RC)

- Bulk density
- Lithology
- Bulk porosity, water content, estimated perm.
- Discrete fracture evaluation (orientation, intensity)
- Elastic properties (calibrated to some core analyses)
- Estimated strength (UCS, tensile – calibrated to some core)
- Overburden stress
- Indicator of horizontal stress orientation

Larger diameter drill holes to run additional wireline tools (6-8 x 6½ inch or larger RC)

- Additional benefits:
  - Improved lithology/mineralogy
  - Cu ore grade (+ other elements of interest)
  - Matrix water storage (bound and moveable water), permeability
  - Improved fracture evaluation (including fracture aperture/estimated transmissivity)

- Improved strength estimates (including 3d anisotropy)
- Principal horizontal stress orientations and magnitude
- Discrete depth pore pressure, permeability, and groundwater samples
- Wireline sidewall core for lab geomechanics testing
- Geologic structure from crosshole geophysics

3D integrated high resolution and block model produced from data

- Geologic structure, rock mass and lithologic properties, Cu ore grade distribution, fracture distribution (bulk properties) and discrete fracture network model
- Dynamic model (near real time updating), versatile outputs for mine models/workflows
FMI (formation micro-imager) electrical imaging

- mines only using acoustic/optical televiever
  - limited ability to ascertain quality images across wide variety of borehole and geologic conditions
  - limited analysis performed
- FMI works in any fluid-filled hole (even large washed-out holes filled with mud)

Auto-trace fracture image analysis (FMI image)

- huge efficiency gain in highly fractured rock typical in mining, reduces subjectivity

Robust sonic measurement and analysis for rock mechanical properties

- mines only using basic sonic tools and have limited ability to ascertain quality compressional, shear and Stoneley across wide variety of borehole and geologic conditions

Advanced log processing and integrated data analysis

- log data highly underutilized in mining since no capability or expertise for proper analysis
Wireline Hydrogeology Technologies

- **Hydrogeology Characterization** for mine water management (dewatering, depressurization, water supply) and in-situ mining

- **Key Technologies:**
  - **Fracture, secondary porosity and structure evaluation** from borehole imaging and advanced sonic
  - **Rock mass hydrogeologic properties** from magnetic resonance, neutron, density, advanced sonic
  - **Packer testing** for discrete depth pore pressure, permeability, and groundwater samples
Hydrogeology Characterization

- **Fracture and secondary porosity evaluation** using borehole imaging and array sonic [>6.25 in. hole]
  - Automated fracture trace picking, orientation, aperture, fill, intensity
- **Matrix hydrogeologic properties** using magnetic resonance and/or neutron, density, sonic [>3 in. hole, best measurement > 6.25 in. hole]
  - Total and effective porosity, specific yield/capacity, saturation
  - Pore-size distribution, hydraulic conductivity
- **Pore pressure profile, packer testing and groundwater sampling** using wireline-conveyed single/dual packer [> 6.25 in. hole]
  - Discrete depth pore pressure, pore pressure profile
  - Discrete depth pressure transient testing for hydraulic conductivity
  - Discrete depth groundwater sampling
In-Situ Evaluation of Matrix + Fracture Hydrogeology

Unsaturated Fanglomerate

Highly Fractured and Permeable Zones Within Basalt
- High iron, titanium, aluminum, & calcium
- Basalt lava flow with permeable fractured/breccia interbeds

- Thin basalt lava flow

- High iron, alum., pota. & water
- Thick, very high clay content bed

- High silicon & potassium, predominantly low iron & aluminum
- Quartz and feldspar-rich alluvial deposits (fanglomerates)
Two uncased holes logged with advanced logs, one spinner flow log after completion in one of the wells

One well

- High resolution borehole electrical image, dipole array sonic, induction resistivity, gamma ray

Results

- Fracture and structure evaluation
- Discrete fracture aperture and estimated transmissivity
- Estimated well flow profile from fracture evaluation
- Estimated matrix porosity
Second well:

- **Prior to completion (uncased)** – high resolution borehole electrical image, induction resistivity, gamma ray
- **After completion (cased)** – Continuous flow profile at different pumping rates; wellbore water temperature and temp. gradient

Results

- Fracture and structure evaluation
- Discrete fracture aperture and estimated transmissivity
- Estimated matrix porosity
- Well flow profile
Advanced geophysical logs run when pump was being repaired

- Matrix + Gravel Pack Porosity
- Bulk Permeability, Transmissivity
- Elemental Concentrations
- Quantitative Matrix+Fluid Volumes
- Borehole Fluid Properties
- Est. Specific Storage

Evaluation of Geology and Hydrogeology in Deep Cased Dewatering Well – Nevada
Mine Deep Dewatering Well Flow Profiling – Nevada

- Two 3,500 ft. deep existing dewatering wells
- Static (unpumped) and dynamic (pumping) conditions
- Quantitative flow characterization
  - Continuous profile flow velocity and rates
  - Continuous log of fluid properties
    - Temperature and temp. gradient
    - Pressure
    - Density
Wireline Logging Solutions for Mines

Multi-purpose characterization in single drill hole

Hydrogeology/Geology
- Porosity, Specific Storage, Fracture Aperture
- Matrix & Fracture Permeability
- Quantitative Lithology, Formation Picks
- Well Design

Geomechanics
- Poisson's Ratio
- Elastic Moduli
- Rock Strength

Fracture Auto-trace Analysis
- Electrical Image w/ Auto-traced Fractures
- Fracture Orientation
- 3D "iCore" Image
- Fracture Aperture
- Fracture Density, Trace Length, & Porosity

Schlumberger
Water Services
Some Key Benefits of Advanced Geophysical Logging for Mining

- Evaluation of **multiple properties/parameters of interest in single borehole** (geochemistry, lithology/mineralogy, geologic structure, rock mass/geomechanics, fracturing, hydrogeology,)
- **Much greater volume of investigation** than core – logging tool depth of investigation is typically 6 to 12 in. beyond borehole wall and essentially a continuous-in-depth measurement
- More **objective** than core/cuttings geologic logs (automated processing; can easily retrieve actual geophysical logs/images to re-process and interpret if necessary)
- **In-situ measurement more representative** of fracture regime and geomechanical properties (as well as geochemistry)
- **Near real-time answers** for mining operations decision making
- Multi-well property and structural analysis facilitating **integrated high resolution multi-purpose 3d modeling** – based on combination of hydrogeologic, geologic, and geomechanical geophysical logs, cross-hole and surface/airborne geophysics, any other subsurface data (drill hole core/cuttings, surface/pit/tunnel data, etc.)
Unique Borehole Geophysics Capabilities for Mining - Summary

**Electrical micro-resistivity imaging** *(uncased only, fluid-filled, >5 7/8” hole)*
- mines currently using acoustic/optical televiewer with limited analysis
- high quality imaging even in RC or Blast Holes, insensitive to borehole fluid
- quantitative evaluation of Fracture Fill, Aperture, Density, and Distribution

**Auto-trace fracture image analysis** *(uncased only, fluid-filled, >5 7/8” hole)*
- huge efficiency gain in highly fractured rock typical in mining, reduces subjectivity

**Robust sonic measurement and analysis for rock mechanical and strength properties** *(uncased & cased, fluid-filled, >3” [open], >2.75” [cased])*  
- mines mostly using basic sonic tools and have limited ability to ascertain shear and Stoneley

**In-situ ore assay and mineralogy using neutron-gamma spectroscopy** *(uncased or cased; >2.25”, but >5.5” hole best)*  
- now validated for copper

**Advanced log processing and integrated data analysis**  
- log data highly underutilized in mining since no capability or expertise for proper analysis  
- derive continuous in-situ logs of hydrogeologic, geologic, and geomechanical properties  
- multi-well 3d property and structural analysis and modeling
Example of Multiple Sources of Mine Data Integrated in Petrel
Hole types
- Diamond bit core holes (HQ, NQ) – limited to slim logging suite, partially air-filled (no sonic or acoustic imaging)
- RC holes – can only drill to certain depths in hard rock, partially air-filled (no sonic or electrical imaging)
- Direct rotary (mud) – can drill to any depth, no wireline tool limitations
- Blast holes (air percussion) – shallow, large diameter air-filled holes (require water for fracture and rock mass characterization)
- Slant – if over 30-degrees from vertical could require different tool conveyance (using drill rods, downhole tractor)

Fluid in hole
- Water, mud – no wireline tool limitations
- Air – no sonic, acoustic or electrical borehole imaging (requires optical imaging)

Logistics
- Early exploration – often very limited accessibility (e.g., small load helicopter only)
- Blast holes – very fast drilling (limited time for logging)
- Underground – little room to maneuver and set up
- Radioactive sources – risk of getting stuck in unstable holes (only tool that requires rad. Source is bulk density, but that is a very important rock property of interest
Questions and Discussion
## Typical mine cost problems where technology can provide potential solutions

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<th>Issue</th>
<th>Description</th>
<th>Potential Solutions</th>
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<td>Water</td>
<td>Multiple users competing for same water resource, Water increasing treatment and disposal costs, use of sea water for mine water needs.</td>
<td>Mine water balance optimization, increased mine dewatering management, alternate water source evaluation.</td>
</tr>
<tr>
<td>Energy</td>
<td>Mining in remote areas without access to low cost energy sources, higher use of concentrators for Cu sulfide ore.</td>
<td>Use of heap leach for sulfide ore extraction, ore control to reduce waste rock processing.</td>
</tr>
<tr>
<td>Labor</td>
<td>Increasing labor costs and desire to reduce onsite personnel to reduce safety risks.</td>
<td>Automated operations, remote evaluation of exploration data, less in-pit dewatering</td>
</tr>
<tr>
<td>Grade</td>
<td>Reduced number of high grade deposits, new finds are typically lower ore grade that increases processing costs.</td>
<td>Higher resolution exploration, advanced wireline logging of exploration holes. Real time characterization to improve material handling.</td>
</tr>
<tr>
<td>Geology</td>
<td>New ore discoveries are being found in increasingly complex geologies that are requiring new technologies to economically produce.</td>
<td>In-situ geotechnical evaluation for block cave operations, use of directional drilling during exploration.</td>
</tr>
<tr>
<td>Forecasting</td>
<td>Accurately predict and quantify ore production</td>
<td>Heap leach monitoring, advance resource estimation models</td>
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Comparison – Typical Exploration and Development Mine Project

Current Practice

- 104,726m total drilling (55,750m core; 48,976m RC)
- Core/sample assay – very small sample volume, ex-situ (may not be representative, uncertain depth)
- Visual logging – highly subjective (geologist dependent), requires expensive technical personnel
- Basic wireline logs (typically gyro + some qualitative logs, sometimes borehole imaging)
- Wireline logs rarely analyzed quantitatively and directly incorporated in mine models
- Separate drilling campaigns for assay/geotech/hydro

SLB Replacement (Wireline)

- 91,000m total drilling (23,350m core; 67,650m RC) → $6.2M cost savings just in drilling
- Quantitative wireline geochem, geo/fracture, hydrogeo, geomech logs in all RC holes (subset in HQ/NQ holes)
- In-situ measurement → 2 x orders greater volume measured than sampling
- Multi-purpose, fast turn-around, objective borehole measurements in exploration holes
- Replace diamond core drilling and sample assaying with less expensive RC drilling and advanced wireline logs (assume 50%)
- Optimize placement of drill holes to maximize footage through economic ore (assume 10% less)
- Optimize drill footage by combining geotech/dewater/assaying drill campaigns
- Reduce drilling by maximizing hole utilization for multi-purpose (assume 50% reduction in dedicated geotech/hydro)
Data Acquisition – An Innovative Approach

**Current Practice**

| Regional Reconnaissance | Airborne Geophysics  
|                        | Regional Geology Mapping  
|                        | Soil and Sediment Sampling |
| Phase I Drilling       | 20 cores or RC holes  
|                        | Assay/Visual Logs/Gyro  
|                        | Local Geology Mapping |
| Phase II Drilling      | 20 cores  
|                        | Assay/Visual Logs/Gyro  
|                        | More geology mapping |
|                        | First hydro holes (4) |
| PFS                    | 60 mineral holes (60% core, 40% RC, 300m ctr)  
|                        | Assay/Visual Logs  
|                        | 5 to 10 Hydro Holes  
|                        | 5 to 10 Geotech Holes  
|                        | Borehole Geophysics (ATV, Hydro, Gyro)  
|                        | Process tests (Columns) |
| FS                     | Infill drill mineral holes to ~100m center  
|                        | (50 to 100 holes, Cores and RC (30/70%))  
|                        | Assay/Visual Logs  
|                        | 10 dedicated hydro holes  
|                        | 20 dedicated geotech holes  
|                        | Borehole geophysics (ATV, Hydro, Gyro)  
|                        | Pilot processing tech (Pilot mill, leach, column) |

**Enhanced In-Situ Characterization**

| Regional Reconnaissance | Airborne Geophysics  
|                        | (Simultaneous Joint Inversion)  
|                        | Regional Geology Mapping  
|                        | Soil and Sediment Sampling |
| Phase I Drilling       | 20 cores or RC holes (50% core replaced by RC)  
|                        | Assay/Visual Logs/Gyro (50% lab assay replaced by in-situ assay)  
|                        | Targeted Surface Geophysics & Joint Inversion  
|                        | Crosswell Geophysics for enhanced imaging of geology & ore body  
|                        | Local Geology Mapping |
| Phase II Drilling      | 10 cores and 10 RC holes (optimized placement)  
|                        | Assay/Visual Logs/Gyro (50% lab assay replaced by in-situ assay)  
|                        | Crosswell Geophysics for enhanced imaging of geology & ore body  
|                        | More geology mapping  
|                        | Dedicated hydro holes needed reduced by 50% (log Wireline in RC holes) |
| PFS                    | 50-60 mineral holes (30% core, 70% RC, 300m ctr, optimized placement)  
|                        | Assay/Visual Logs (50% lab assay replaced by in-situ assay)  
|                        | Crosswell Geophysics for enhanced ore & geology volumetrics  
|                        | Dedicated hydro holes reduced by 50% (log Wireline in RC holes)  
|                        | 5 Geotech Holes (fewer dedicated geotech holes needed)  
|                        | Borehole Geophysics (geochem, hydro, geomech) in all RC holes  
|                        | Process tests (Columns - fewer required) |
| FS                     | Infill drill mineral holes to ~100m center (optimized placement)  
|                        | (50 to 100 holes, Cores and RC (15/85%))  
|                        | Assay/Visual Logs (50% lab assay replaced by in-situ assay)  
|                        | Dedicated hydro holes reduced by 50% (log Wireline in RC holes)  
|                        | 10 Geotech Holes (fewer needed, run Wireline geomech in RC)  
|                        | Borehole Geophysics (geochem, hydro, geomech) in all RC holes  
|                        | Pilot processing tech (Pilot mill, leach, column - fewer required) |

**Final Design and Mine Construction**

- Ore Control Drilling
- (50% replaced by RC & in-situ assay)
- Use large scale surface geophysics to define the extent of the mineralized ore zone and surrounding geology
- Refine using strategically designed cross-well surveys
- Rock properties and composition measured with high resolution geophysical logs in optimally placed multi-purpose characterization boreholes
- A significant percentage of core holes could be replaced with standard rotary drilled holes – reducing drilling, lab, and personnel costs
- More significantly, the much more extensive and representative geophysics data could be integrated with other physical sample data to develop much more accurate mine site subsurface geology, structure and property models using Schlumberger’s 3-D spatial data analysis and modeling workflow tools, in turn used for optimal mine design.
- This is where the real high value of advanced in-situ subsurface characterization is derived – improving operational efficiency/productivity and reducing risk.
Improved subsurface ore and mine site characterization throughout the mining process

Higher quality/accuracy of data, e.g. higher resolution than is currently possible in ore body characterization, continuous in-situ geomechanical properties along boreholes.

Much greater volume characterized, e.g. larger areas of ore body evaluated through targeted geophysics.

Real time data availability for more timely decision making, e.g. real-time in-situ copper grade measurement.

Previously unavailable valuable measurements, e.g. in-situ ore grade, in-situ strain and stress, cross-hole imaging.

Maximum usage and integration of all data, e.g. allowing for multiple aspects of mine planning such as geo-mechanics, geochemistry, hydrogeology etc. to be integrated into exploration, mine development and operational plans.
Schlumberger In-Situ Subsurface Evaluation Workflow

- Advanced technology solutions to provide **significantly improved** subsurface mineral deposit and host rock characterization and optimization throughout the mining process.

- Advanced characterization to improve:
  - exploration accuracy and efficiency
  - certainty in resource delineation and estimation
  - waste rock characterization and planning
  - geotechnical and hydrogeologic characterization
  - Integrated assessment of mine feasibility & mine design

- *with* impacts on NPV, ore deposit understanding, asset management, risk management.