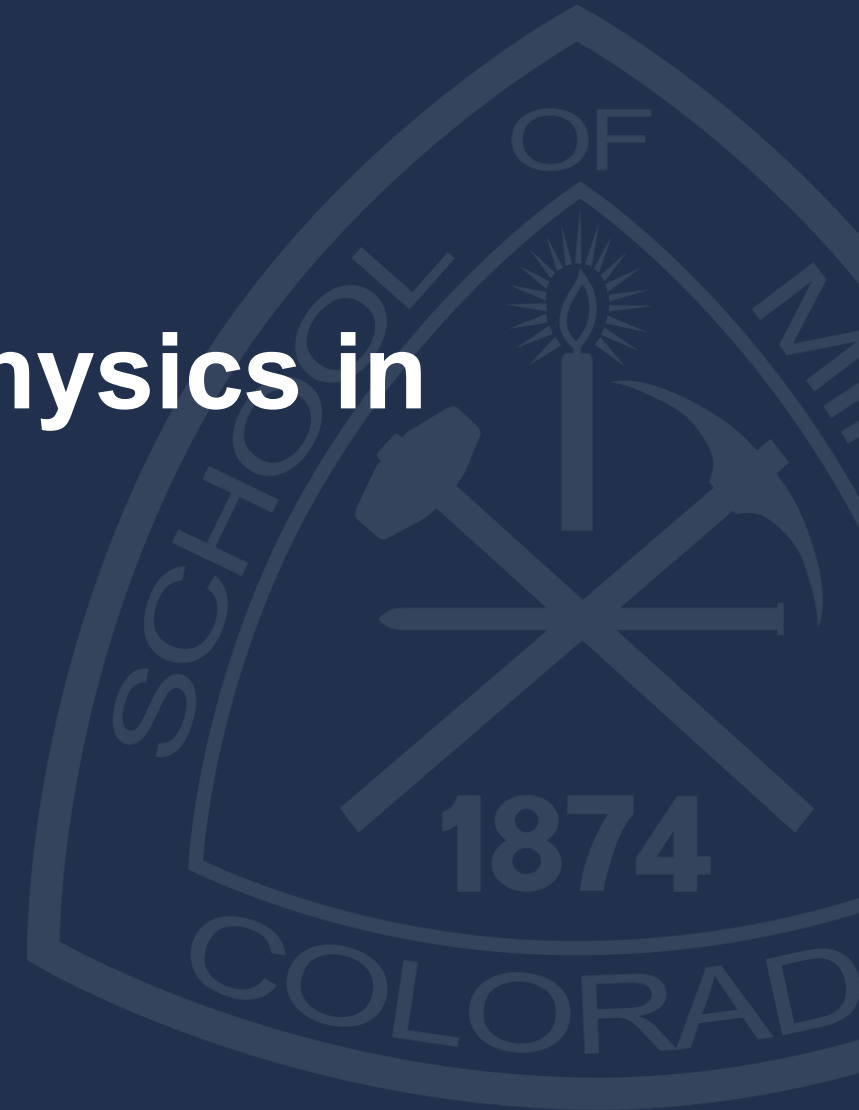


Introduction to the use of geophysics in Minerals Exploration

John Bradford

Vice President for Global Initiatives

Colorado School of Mines



What is geophysics?



Geophysics in Subsurface Science

- What is Geophysics?
- What is the connection of Geophysics to the subsurface?
- What questions about the subsurface are we trying to answer?



What is Geophysics?

- Geophysics involves the application of physical theories and measurements to discover the properties and processes of the earth.
- The study of the earth by quantitative physical methods :
 - seismic reflection and refraction
 - gravity, magnetic
 - electrical, electromagnetic
 - radioactivity methods.

From Robert E. Sheriff's
*Encyclopedic Dictionary of Applied
Geophysics*



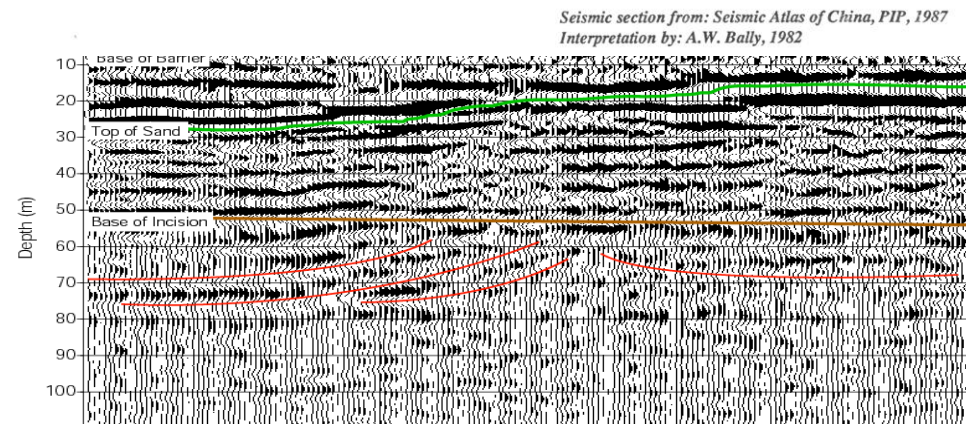
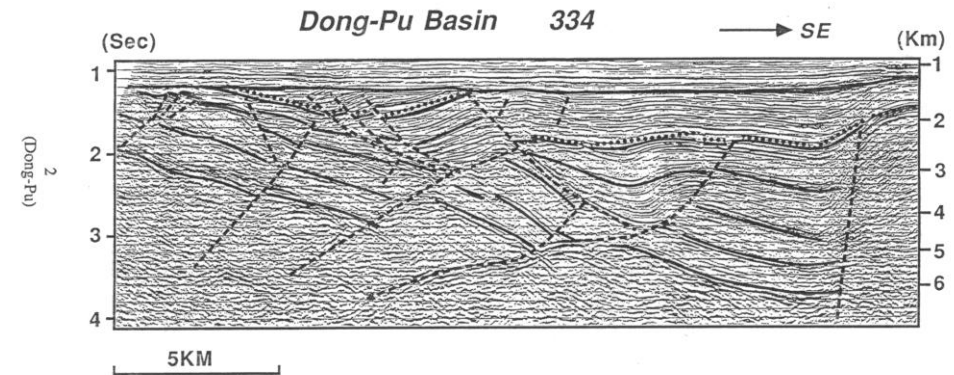
Brief History of Geophysics

- Began with prediction of Earthquakes (still an unsolved problem)
- Major development in 1500 A.D. (Gravity & Magnetism)
- Rapid development in 20th Century (Seismic, Electrical, Electromagnetics, NMR, Radioactivity)
- Geophysics has contributed significantly in the understanding of many physical processes that lead to scientific and economic contribution to our society.



Branches of Geophysics

- Solid Earth Geophysics
 - Plate Tectonics
 - Geodynamics
- Exploration Geophysics
 - Oil and Gas exploration
 - Minerals exploration
- Environmental & Engineering Geophysics
 - Groundwater exploration
 - Contaminant delineation
 - Utility or object detection



Geophysics in Mineral Exploration

Methods, Workflows, and Modern Technological Trends



Primary Methods & Physical Properties

- Magnetics: Measures magnetic susceptibility (detects iron, magnetite).
- Gravity: Measures density variations (detects massive sulfides).
- Electrical/EM: Measures conductivity and chargeability (detects sulfides, graphite).
- Seismic: Measures acoustic impedance (maps deep structural layers).
- Radiometrics: Measures gamma-ray emissions (K, U, Th) for mapping alteration zones.



From Regional Surveys to Drill Targets

- **Step 1: Regional Airborne:** Covering thousands of km² via helicopter/plane to find anomalies.
- **Step 2: Ground Follow-up:** High-resolution surveys (IP, EM, Seismic) to refine target geometry.
- **Step 3: Borehole Geophysics:** Probing "off-hole" anomalies



Summary Table: Method vs. Property

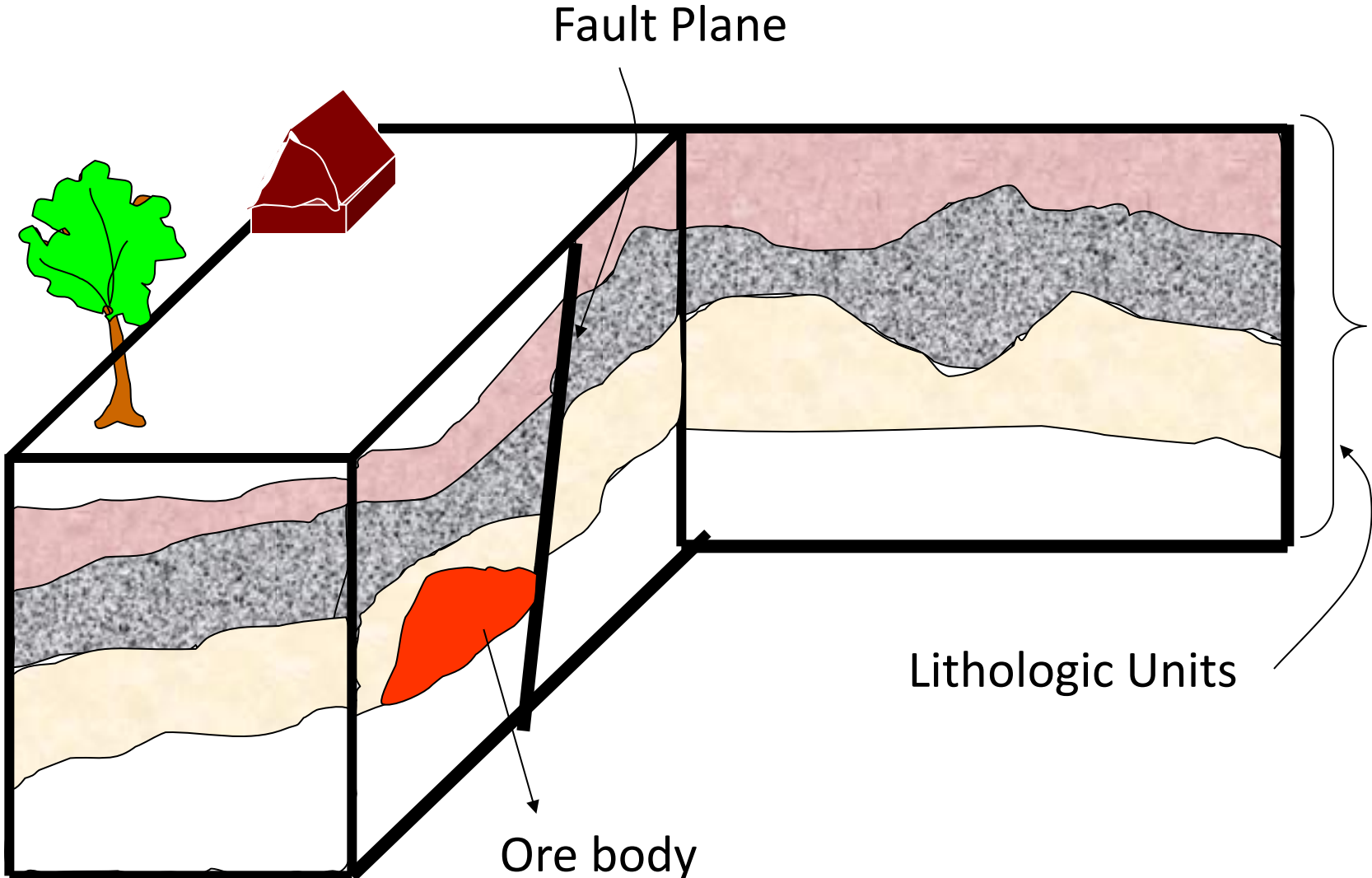
<u>Method</u>	<u>Physical Property Measured</u>	<u>Typical Mineral Target</u>
Magnetics	Magnetic Susceptibility	Iron ore, Gold, Diamonds (Kimberlites)
Gravity	Density	Massive Sulfides, Iron, Coal, Salt Domes
IP / Resistivity	Chargeability / Resistance	Copper Porphyry, Disseminated Gold
Electromagnetics	Electrical Conductivity	Nickel, Lead-Zinc-Copper (VMS), Graphite
Radiometrics	Gamma-ray Emissions (K, U, Th)	Uranium, Rare Earth Elements (REE)
Seismic	Acoustic Impedance (Velocity x Density)	Deep Structural Mapping, Reef- type Gold, Potash



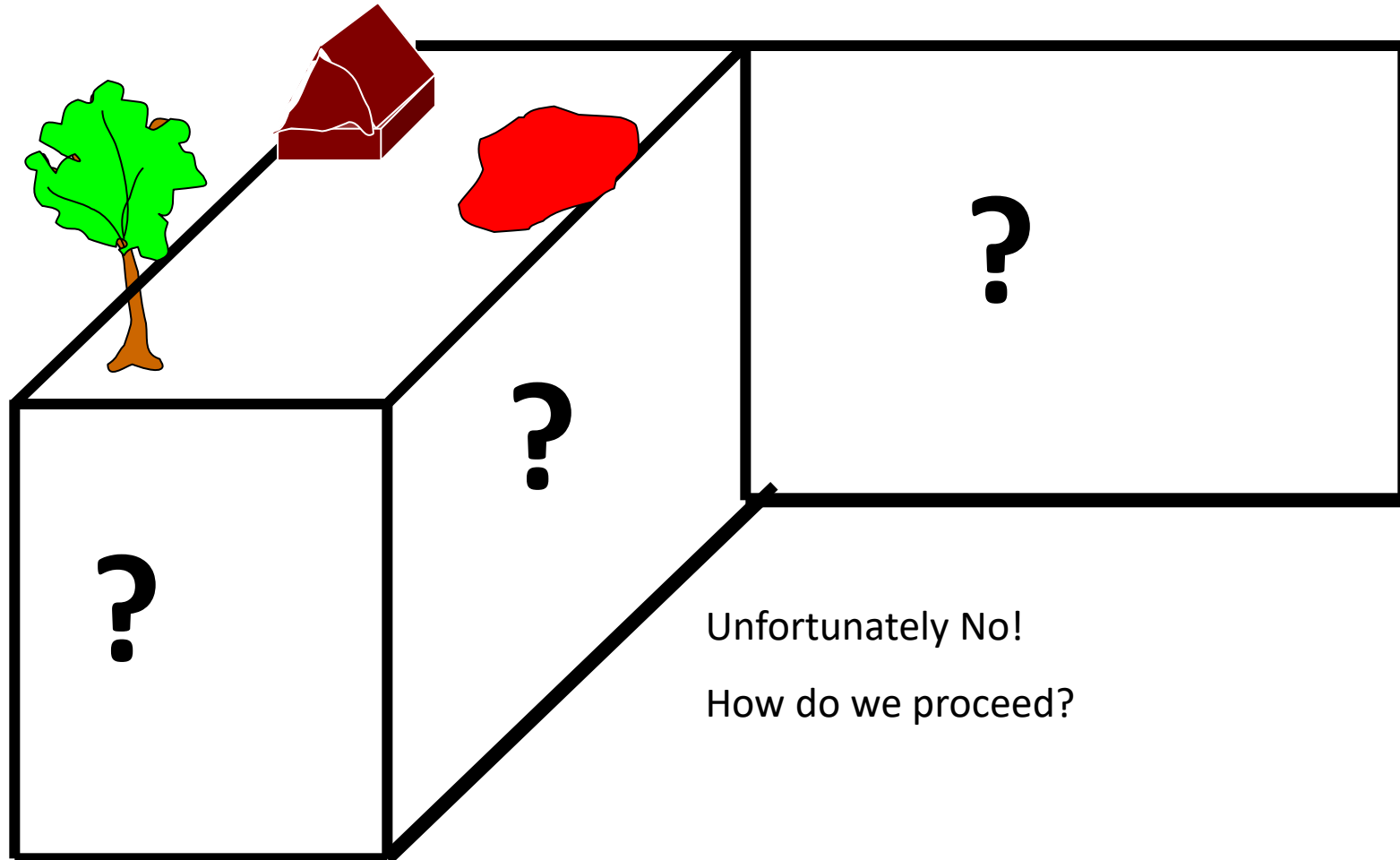
How do geophysical methods work?



Subsurface Model



Do we know what's inside?



Need to look inside the subsurface

- First we ask what is the problem we are trying to solve?
- Decide the “appropriate” physics and “appropriate” scale that will allow us to probe the Earth.

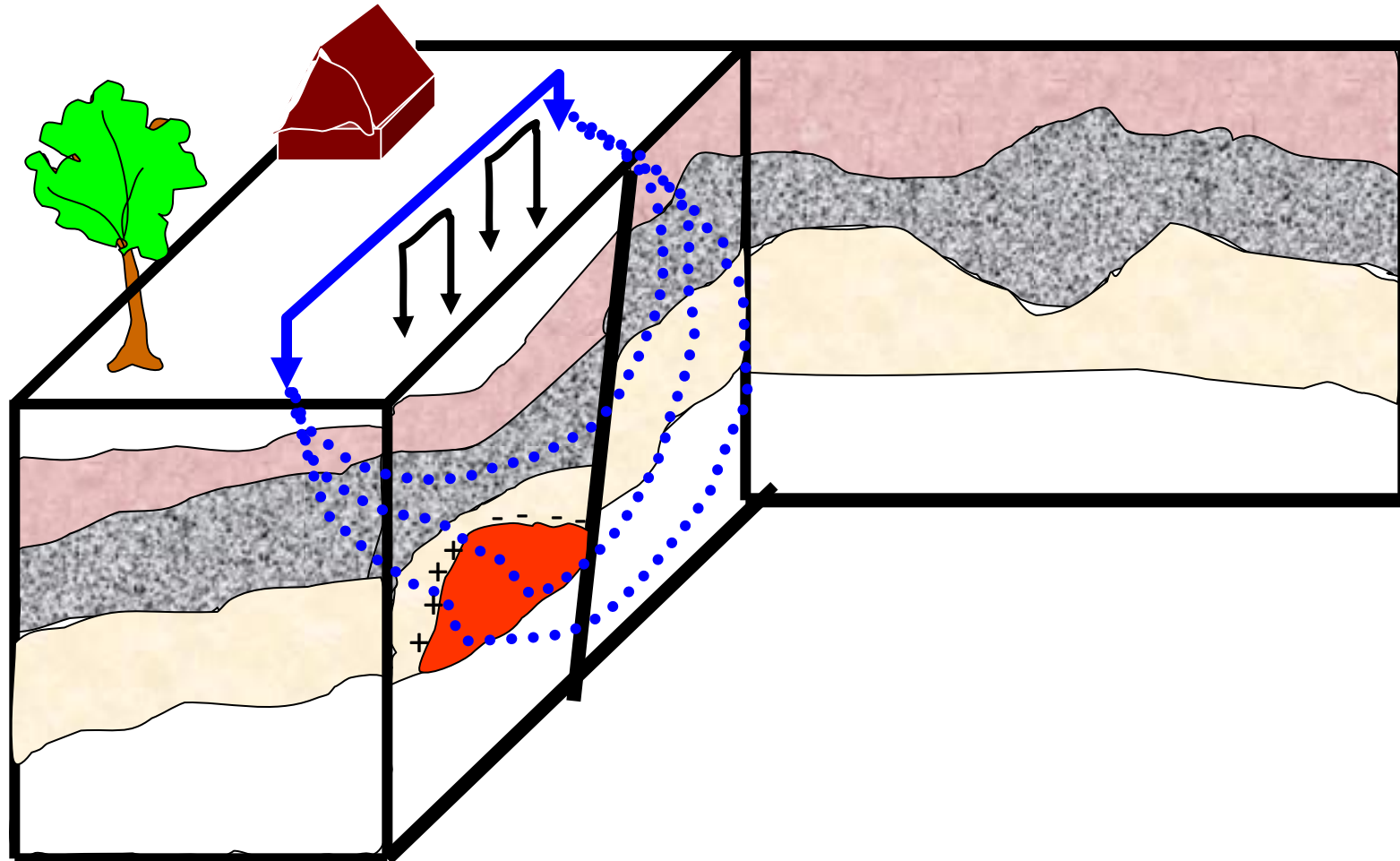


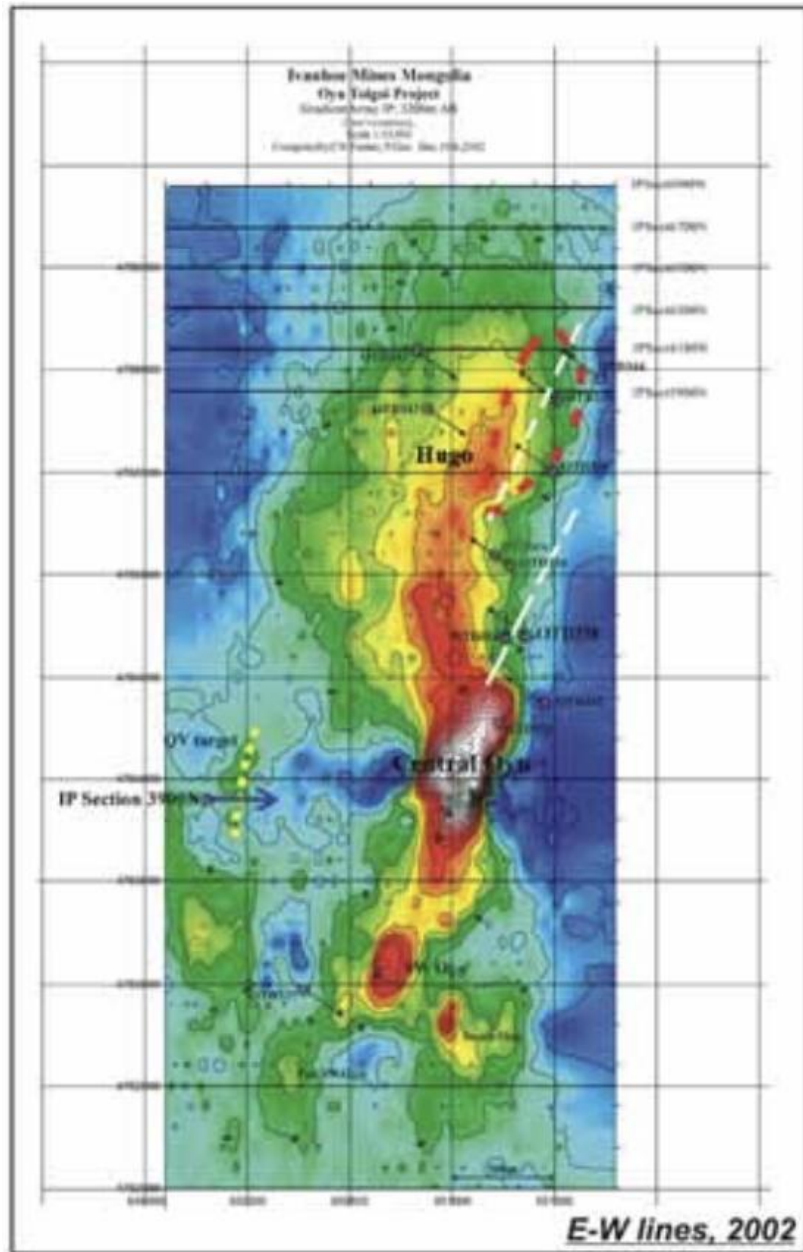
Why Physics?

- In most cases geophysics is an indirect way of obtaining information about subsurface.
- First associate what change in subsurface will give rise to the understanding of the problem.
- Changes or **Anomaly** are crucial and they are linked to physical properties changes in subsurface such as :
 - density of material, electrical conductivity, magnetic susceptibility, dielectric property, rigidity, bulk modulus
- Based on the property choose the governing physics.



Looking inside the Subsurface: IP and Resistivity (Electric)



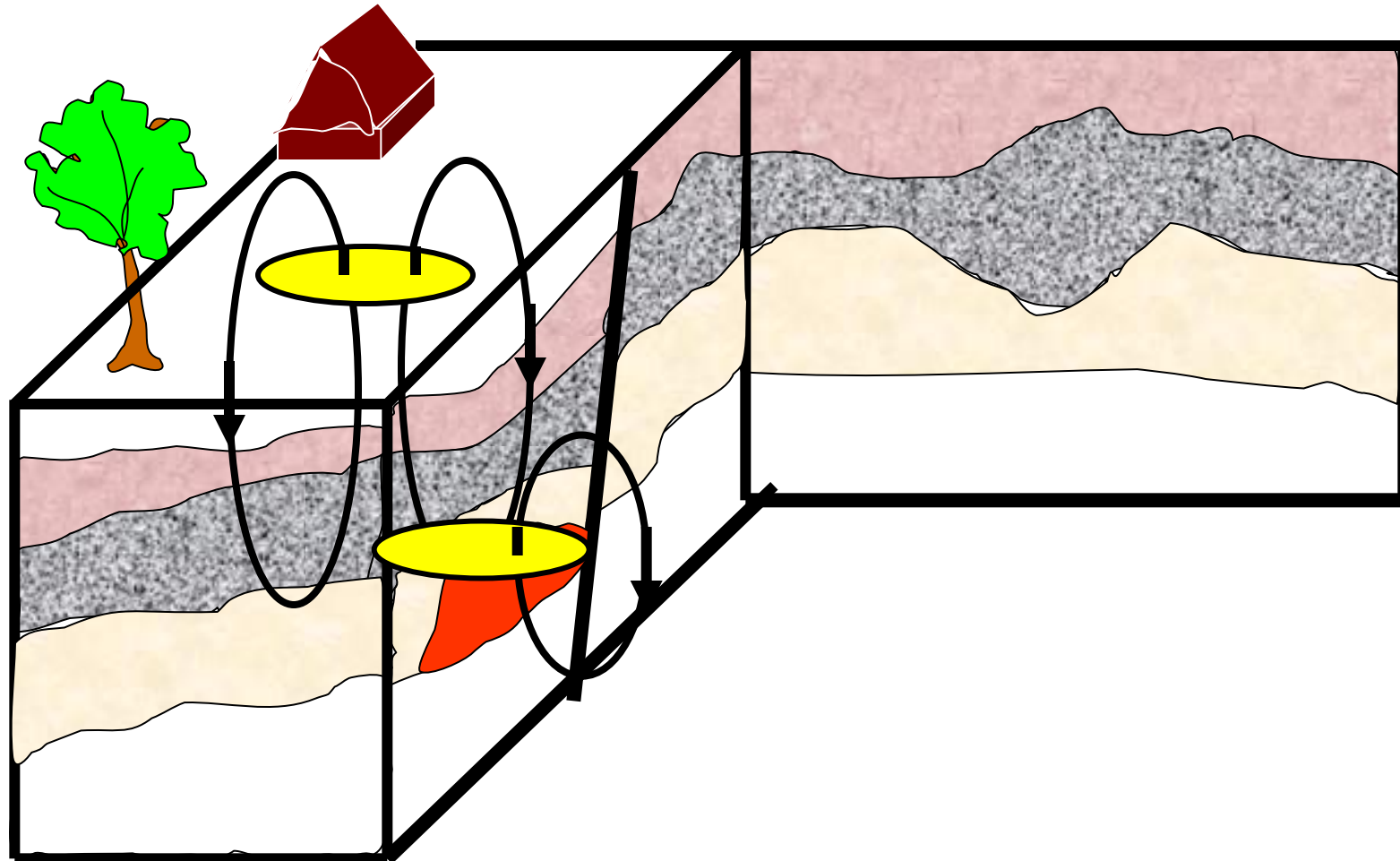


THE OYU TOLGOI COPPER-GOLD PORPHYRY DEPOSITS, SOUTH GOBI, MONGOLIA

D.J. Kirwin, C.N. Forster, I. Kavalieris, D. Crane, C. Orssich, C. Panther, D. Garamjav, T.O. Munkhbat, G. Niislelkhuu, 2005



Looking inside the Subsurface: Electromagnetics

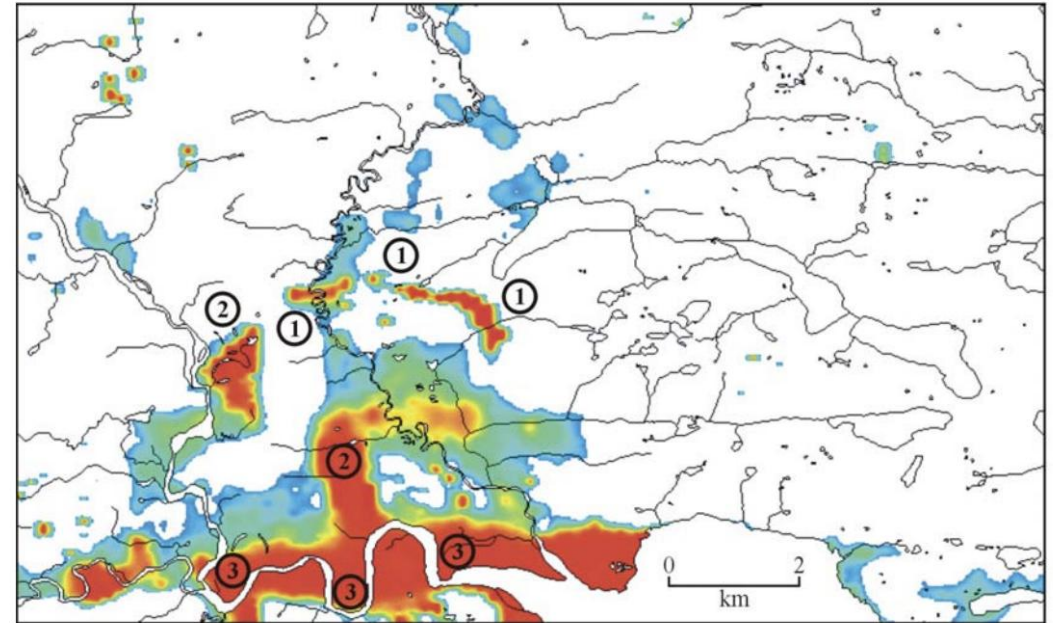


Ni-Cu Sulphide Deposits in Voisey's Bay, Newfoundland and Labrador, Canada

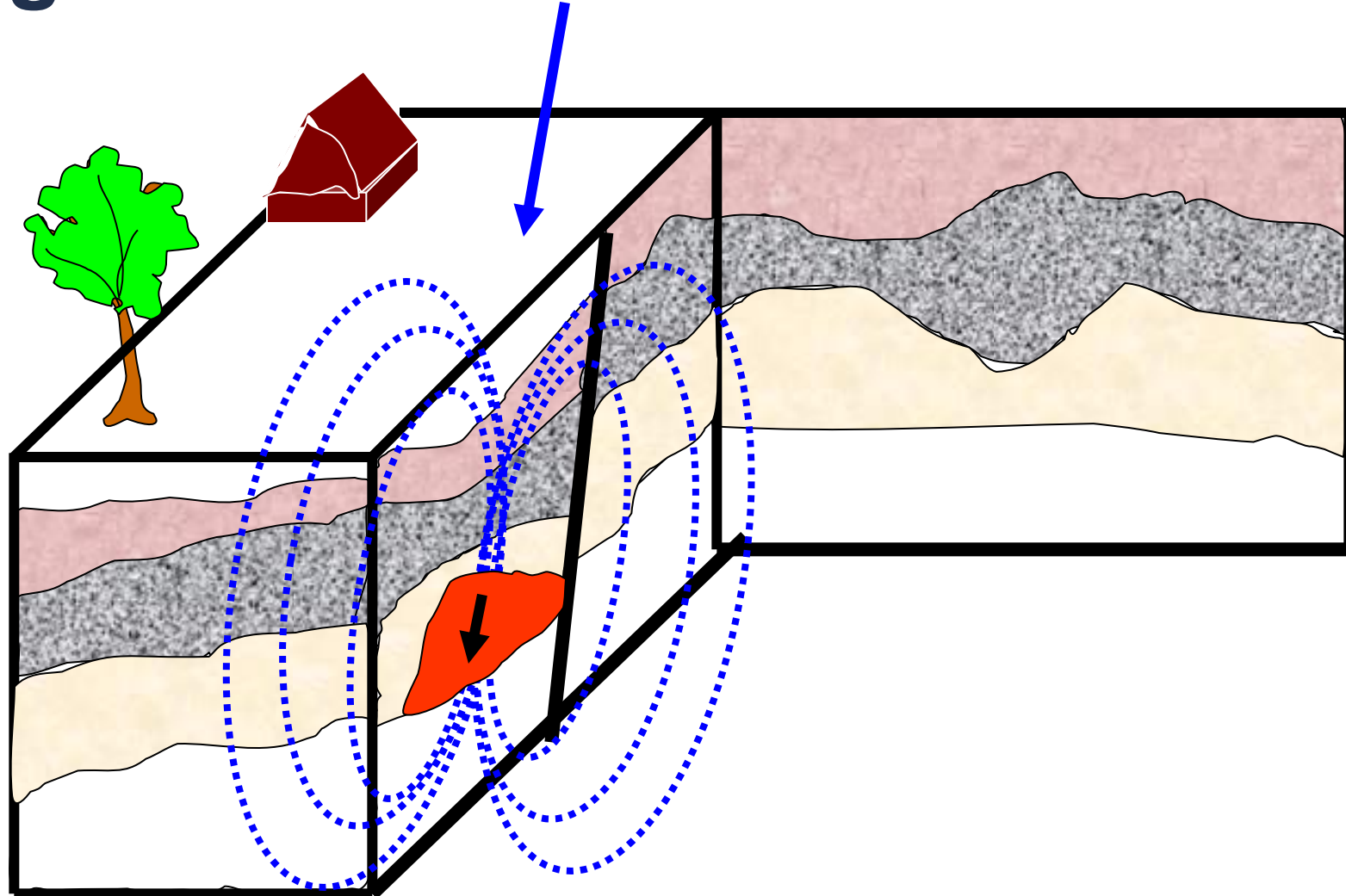
HEM identifies conductivity anomalies associated with known deposits (1), regional graphite conductors (2), and conductive sediments associated with sea water on the coast (3)

Stephen Balch, 2000

a) HEM apparent resistivity

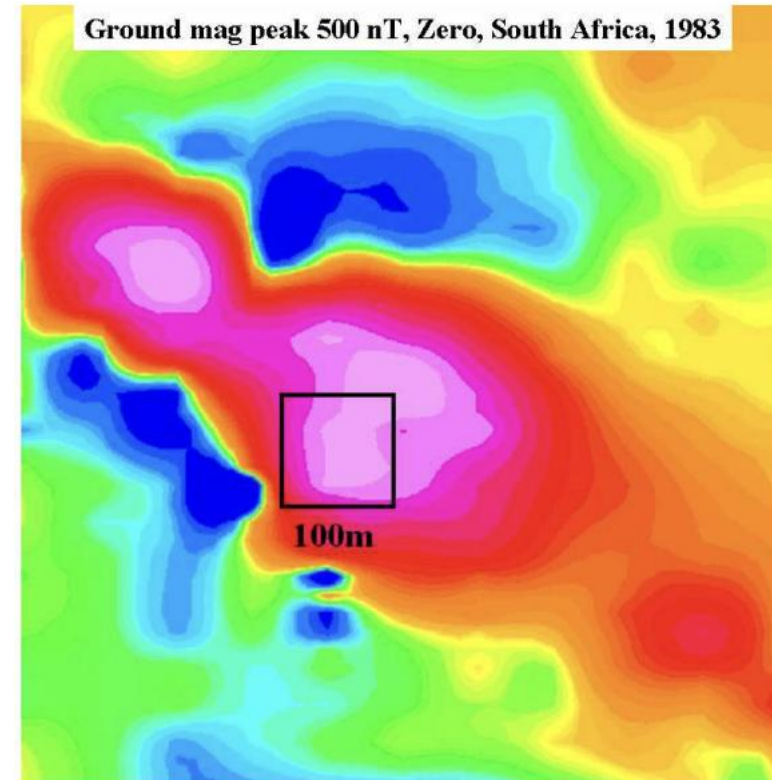


Looking inside the Subsurface: Magnetics

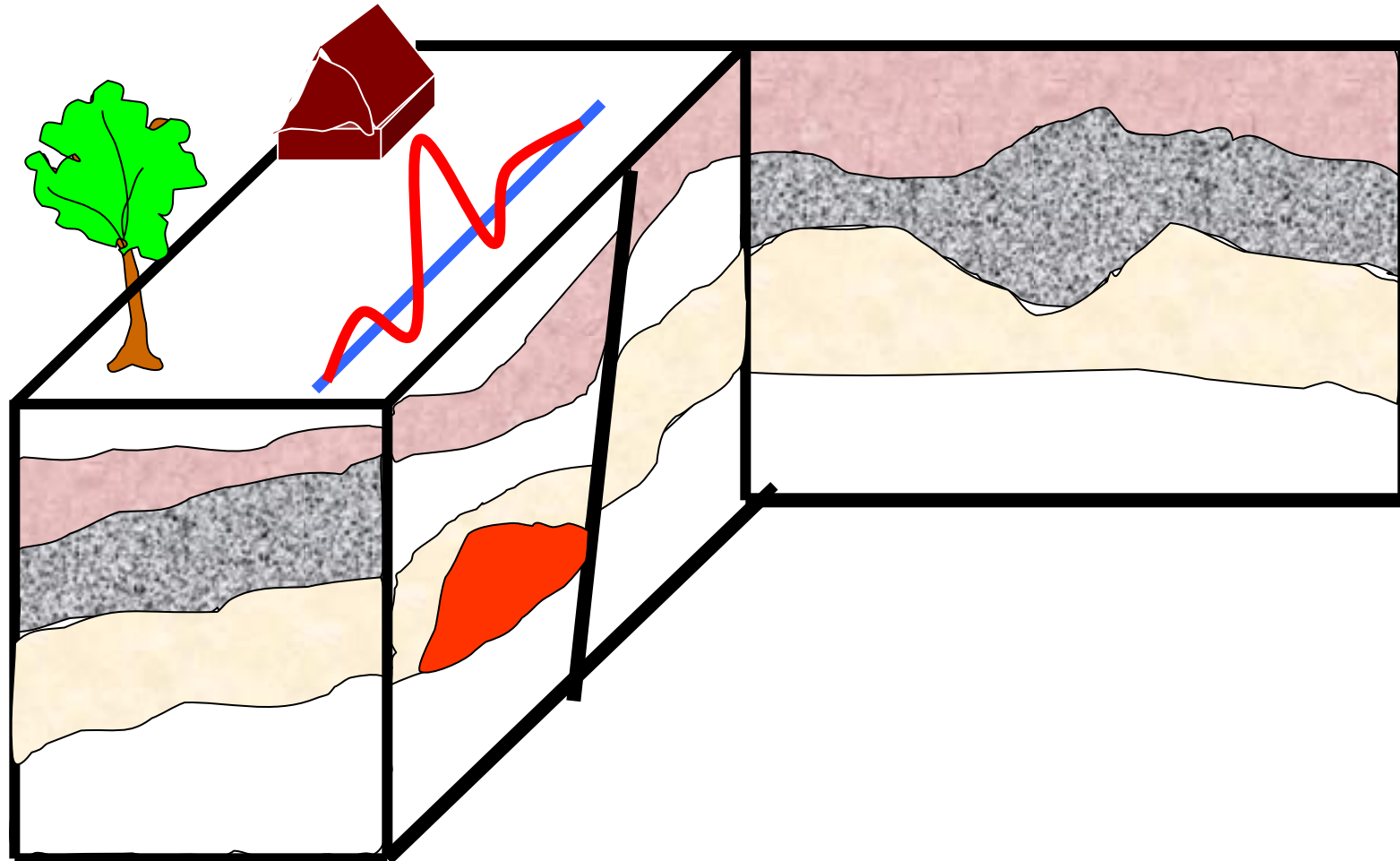


Ground magnetic survey over the Zero kimberlite pipe in South Africa

Reed, L. E. and Witherly, K. E., 2007

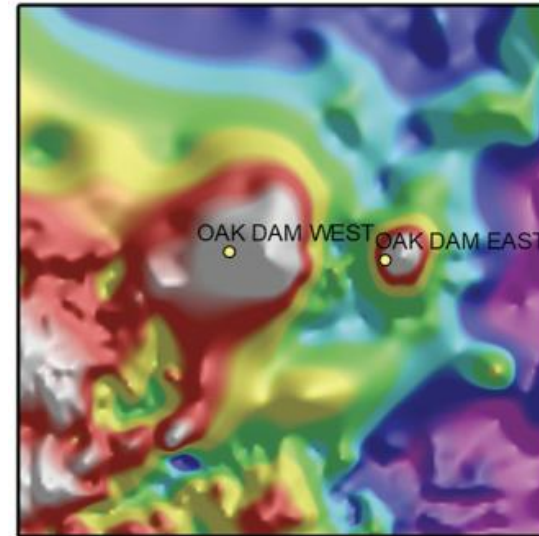


Looking inside the Subsurface: Gravity

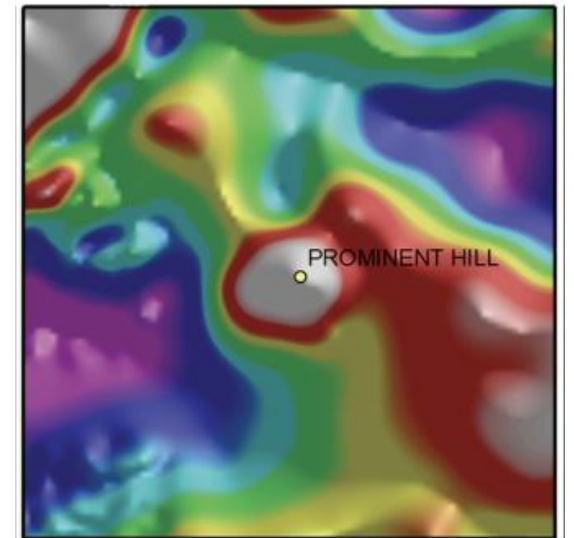


Gravity expression of iron oxide – copper–gold (IOCG) deposits at Olympic Dam, South Australia

Laszlo Katona, 2020

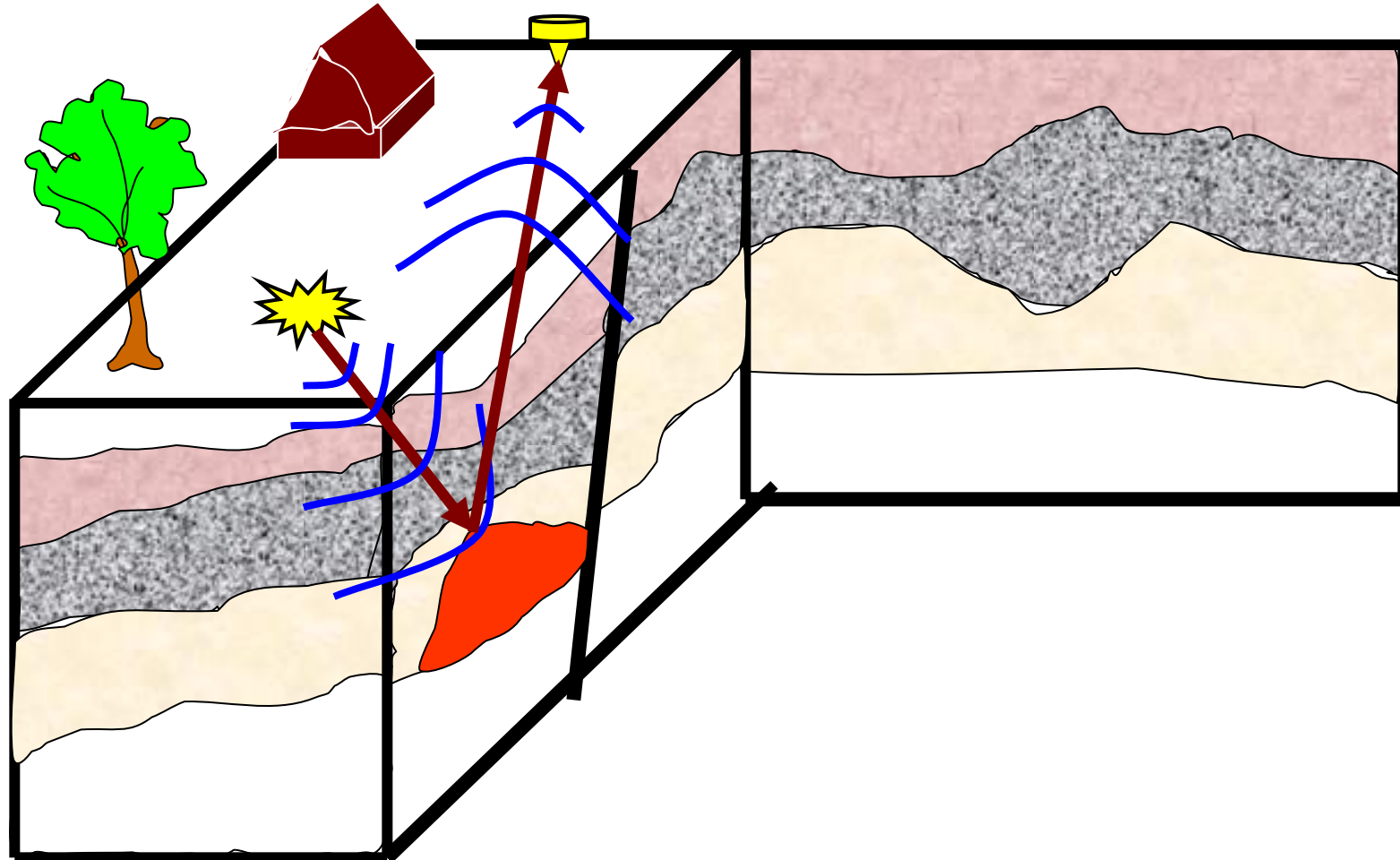


Bouguer gravity (mGal)
High: 2.2852 Low: -2.35114



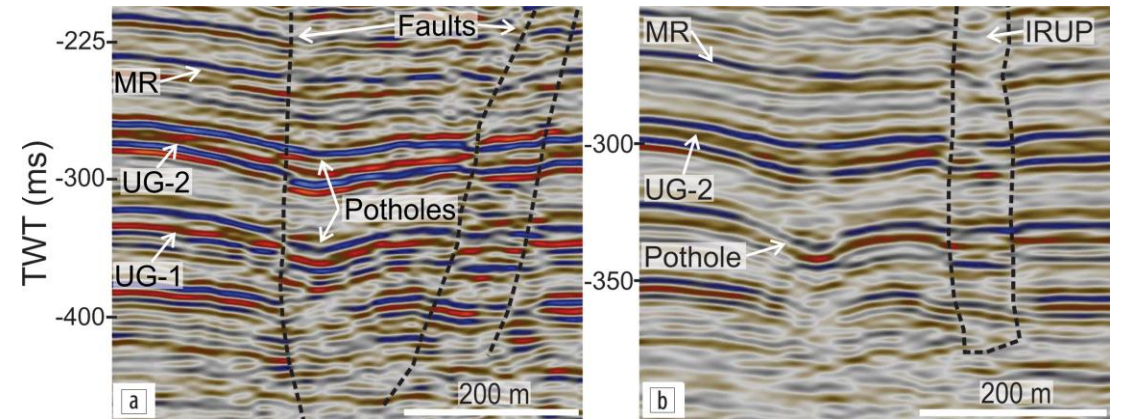
Bouguer gravity (mGal)
High: 8.42159 Low: -2.73677

Looking inside the Subsurface: Seismic

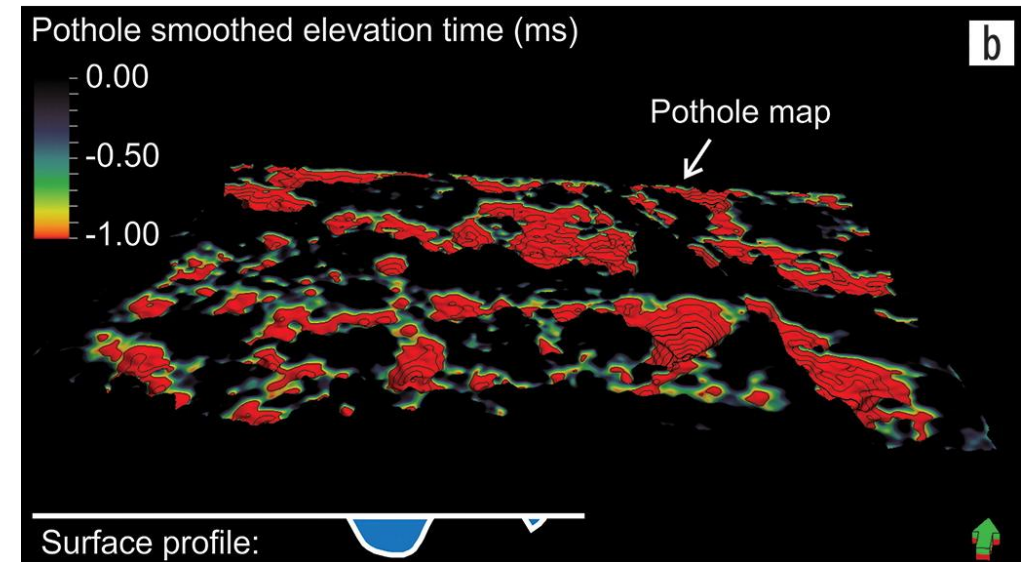


Use of novel 3D seismic technology and machine learning for pothole detection, characterization, and classification — Case study in the Bushveld Complex (South Africa)

Zhang et al., 2021, *The Leading Edge*



- World's largest platinum and chromium deposits
- Potholes have a significant impact on mine design and can impede economic production
- Integrating 3D seismic and ML holds significant promise for industry

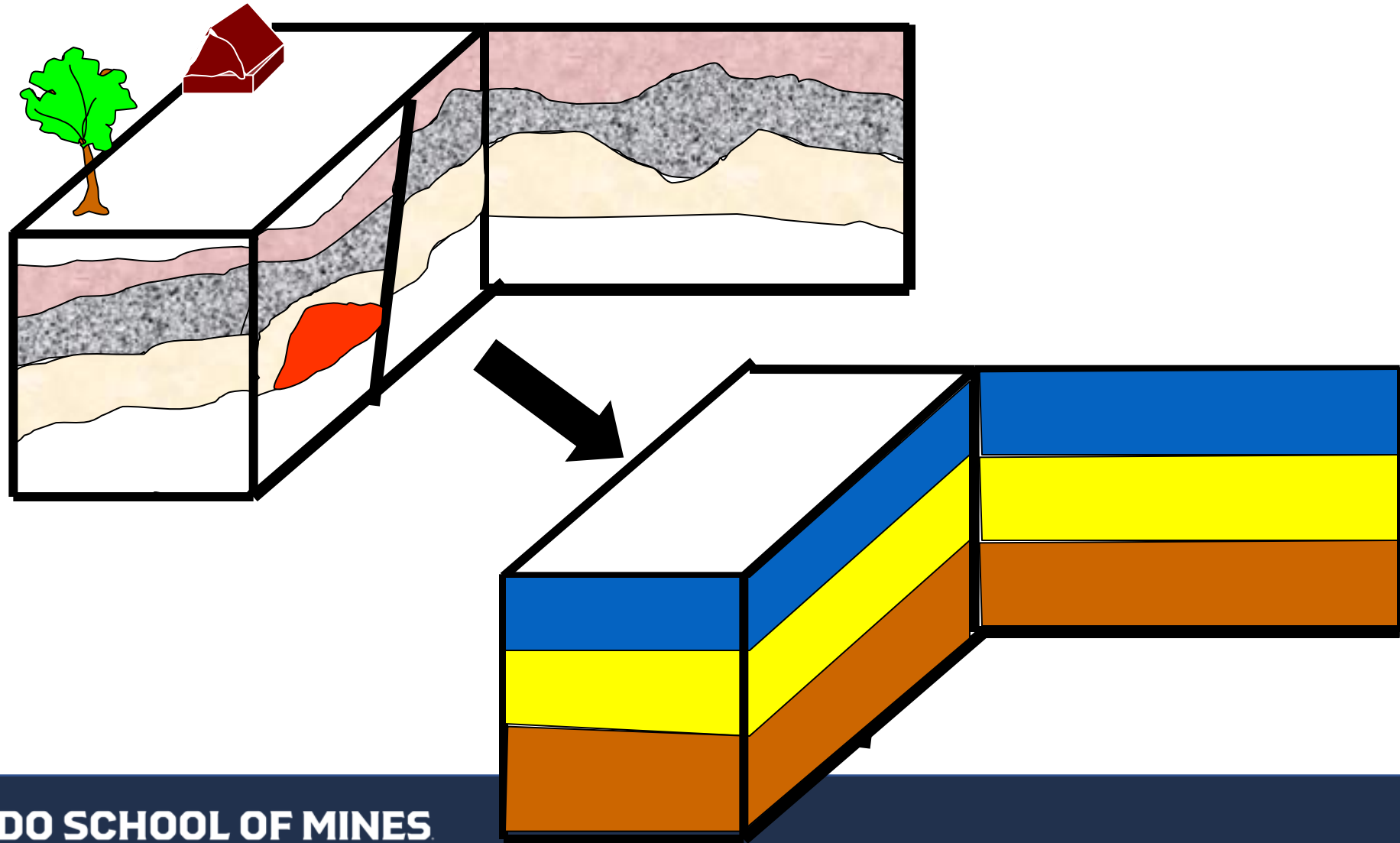


What do we do with the Data?

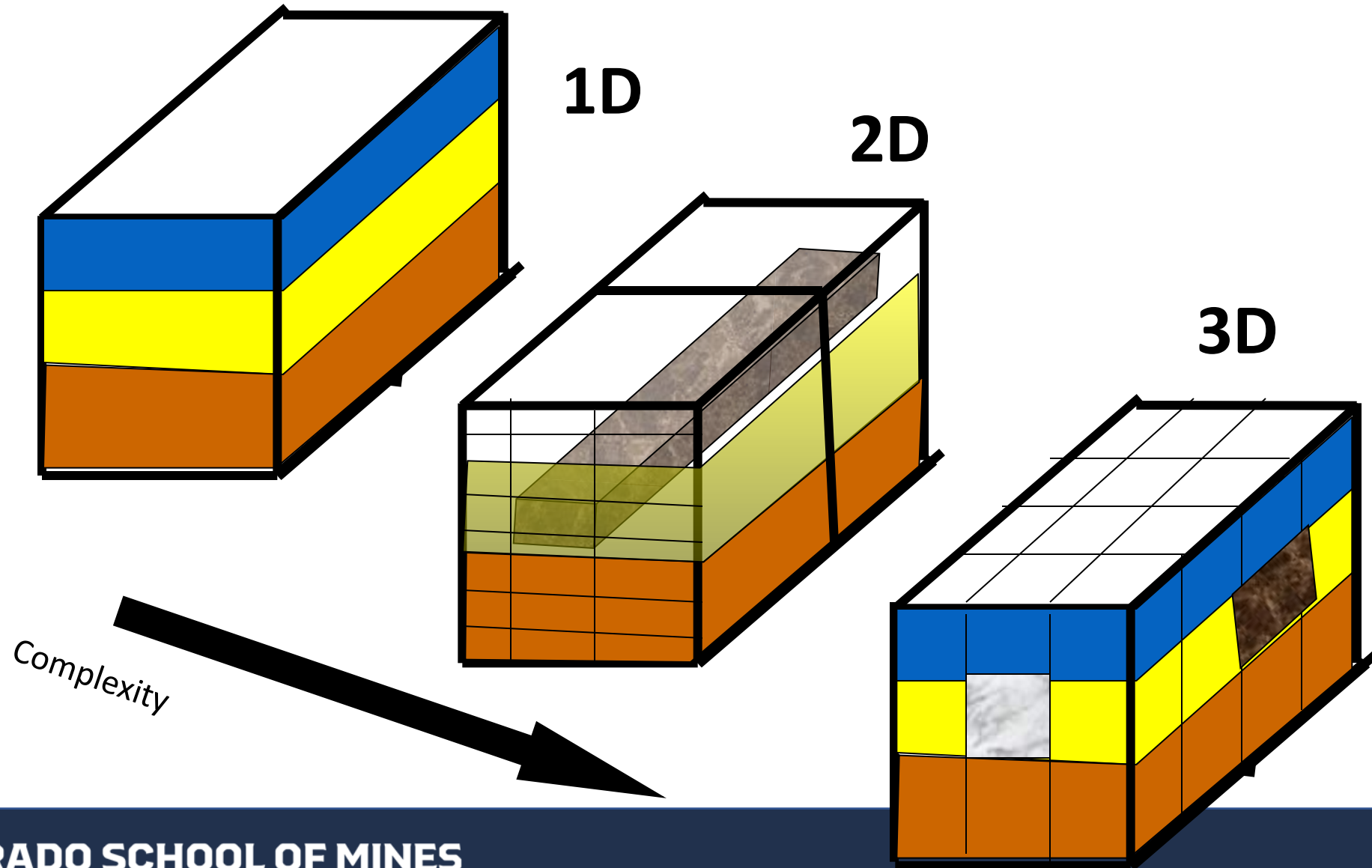
- Goal is to generate appropriate Earth model that would explain our data.
- This introduces us to generating Geophysical Model that are simplification of real Earth models.



Subsurface Model → Geophysical Model



Different Types of Geophysical Models

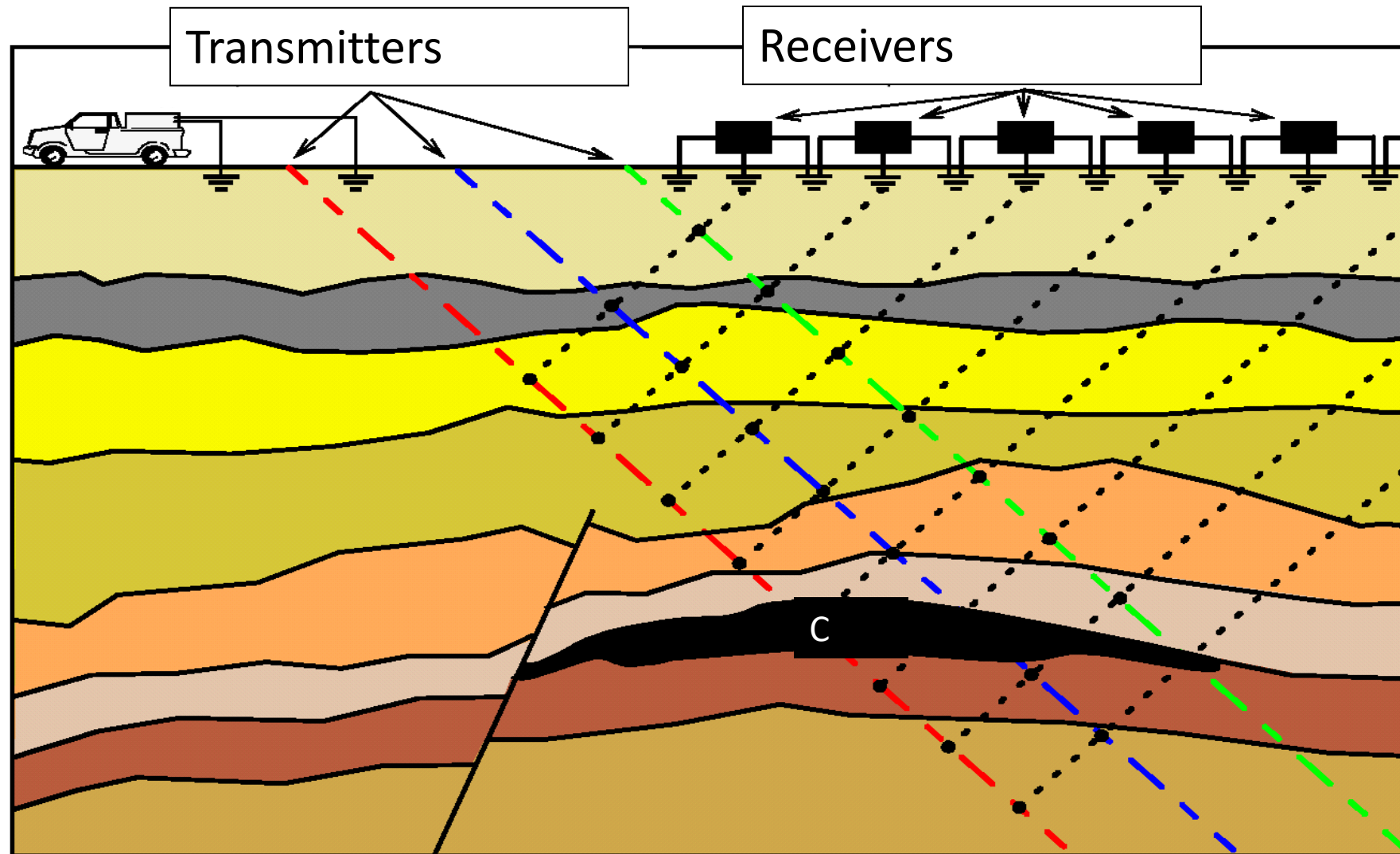


Use the Geophysical Model to explain our data

- Basic step is to come up with a geophysical model that explains the data that provides information about the subsurface.
- So we need to solve the Physics that generated our data. This is called the FORWARD PROBLEM.
- The science of unraveling the physics from the data to get a picture of the subsurface is called IMAGING, similar to medical imaging like X-Rays and MRI. The mathematical foundation of this science is called INVERSE PROBLEM.



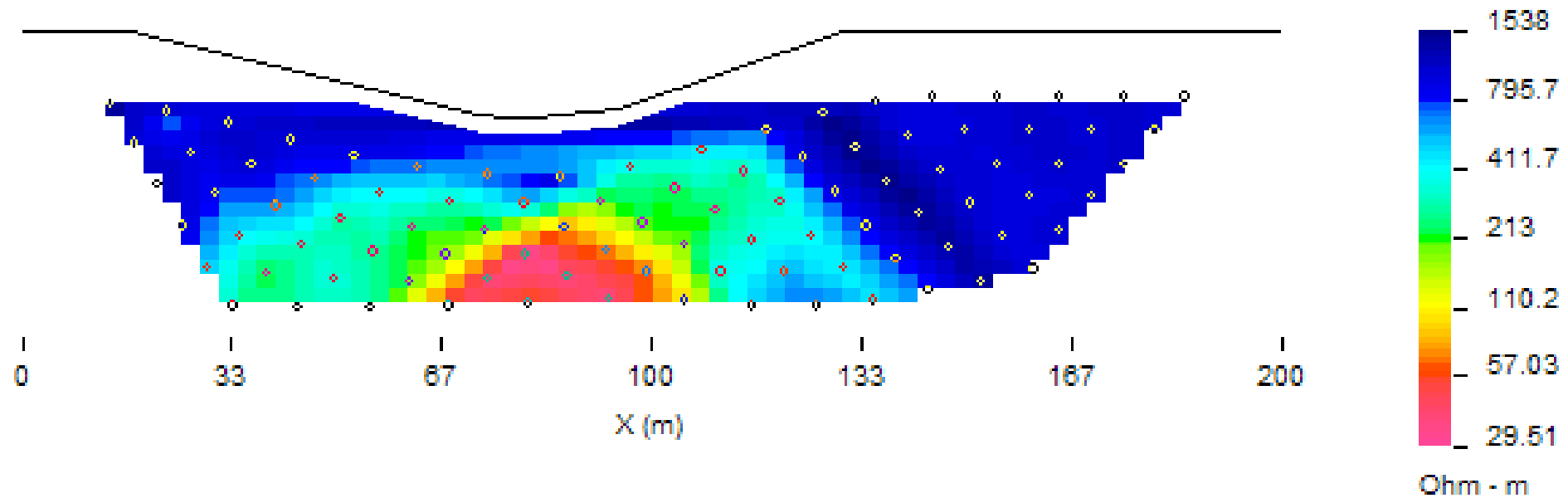
Direct Current Resistivity Survey



Example: Direct Current Resistivity

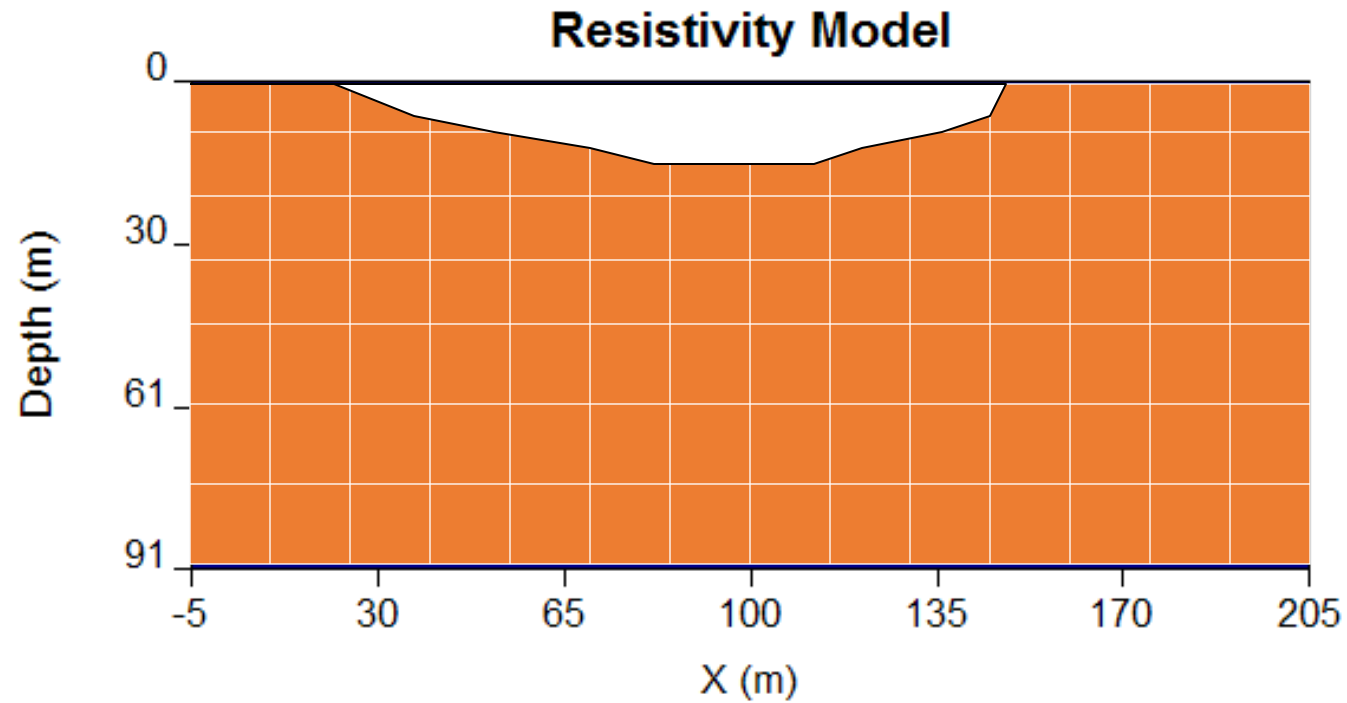
Data From DC Survey

TOTAL POTENTIALS : dipole-dipole : 93 data
Observed Apparent Resistivity



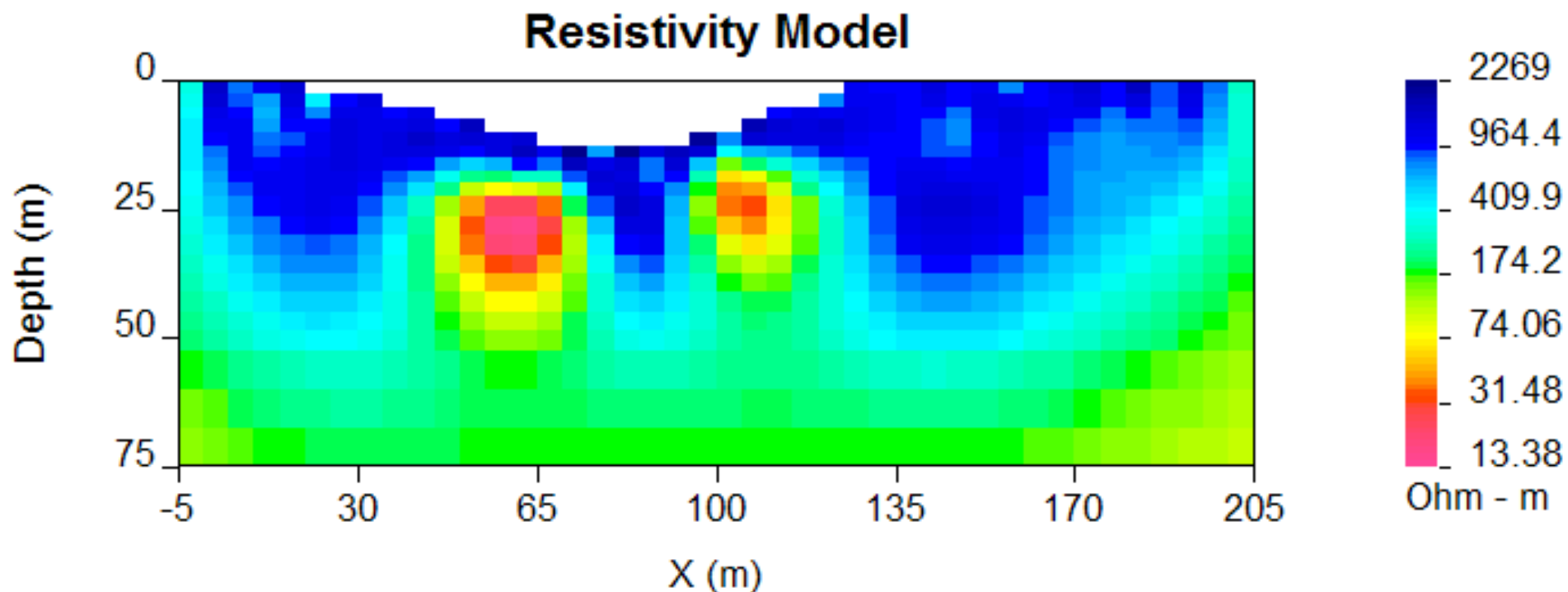
Example: Direct Current Resistivity

Subsurface Model → Geophysical Model



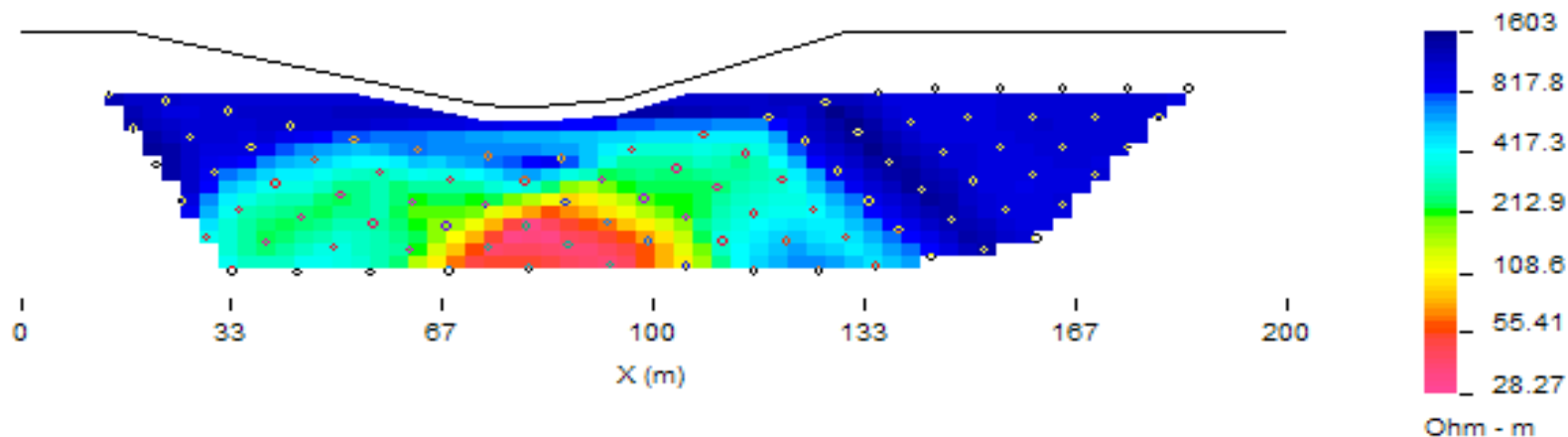
Example: Direct Current Resistivity

Geophysical Model from Analysis of Data

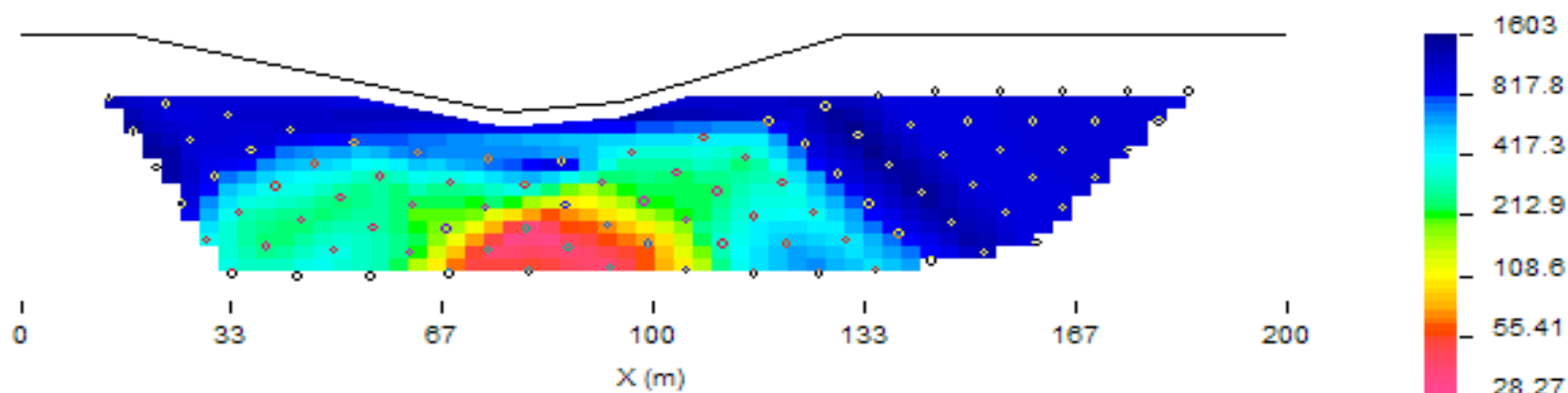


Example: Direct Current Resistivity

TOTAL POTENTIALS : dipole-dipole : 93 data
Observed Apparent Resistivity



Predicted Data



Summary of the Process:

- Formulate the problem.
- Use “right” Physics and acquire data.
- Process / Analyze the data: Data → Geophysical model.
- Interpret the information: Geophysical Model → Subsurface Model

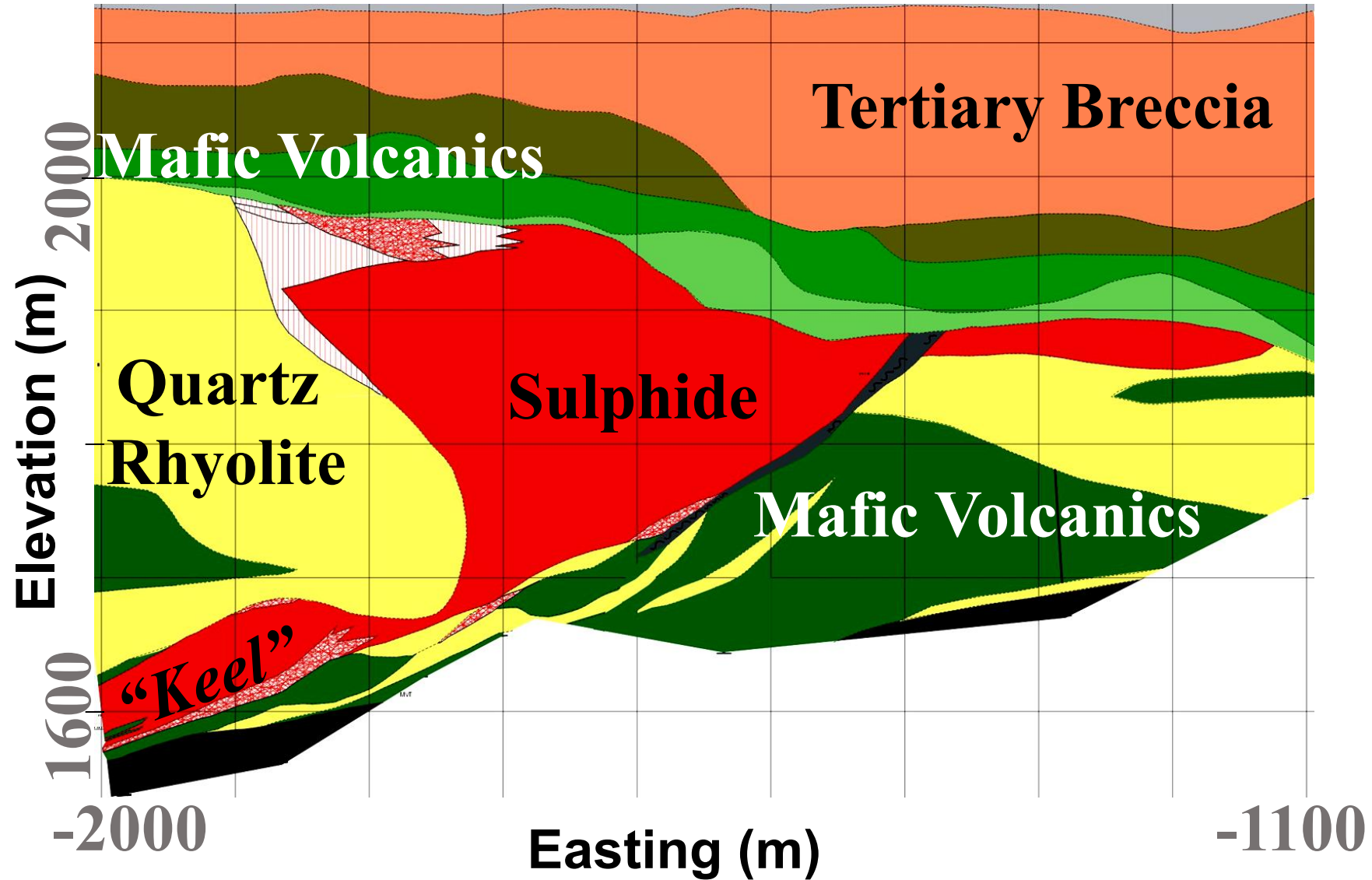


Example: Comparison of Several Methods

Courtesy of Partha Routh

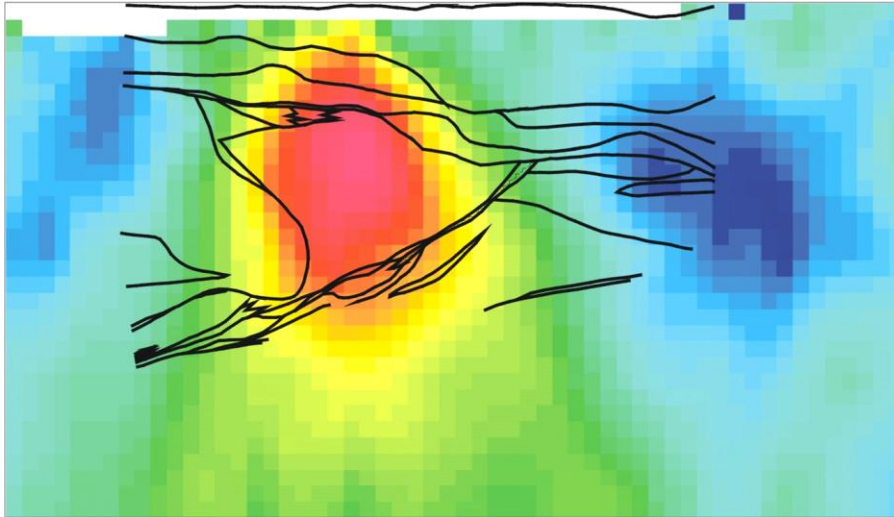


Geologic cross-section: line 400S

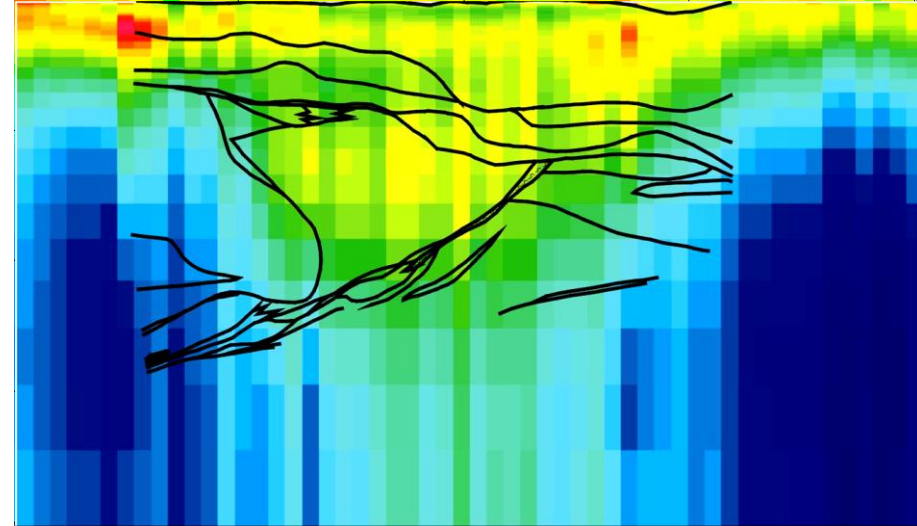


Cross-section of model with Geological boundaries

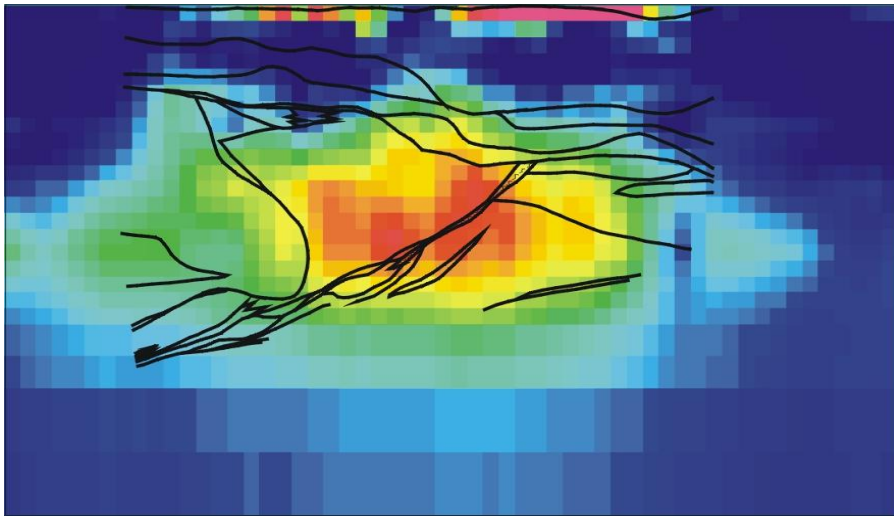
density-contrast



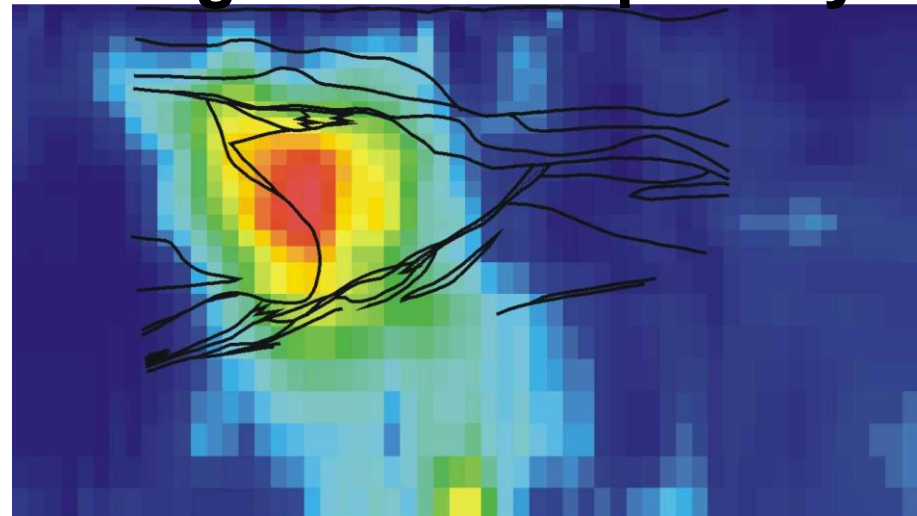
conductivity



chargeability



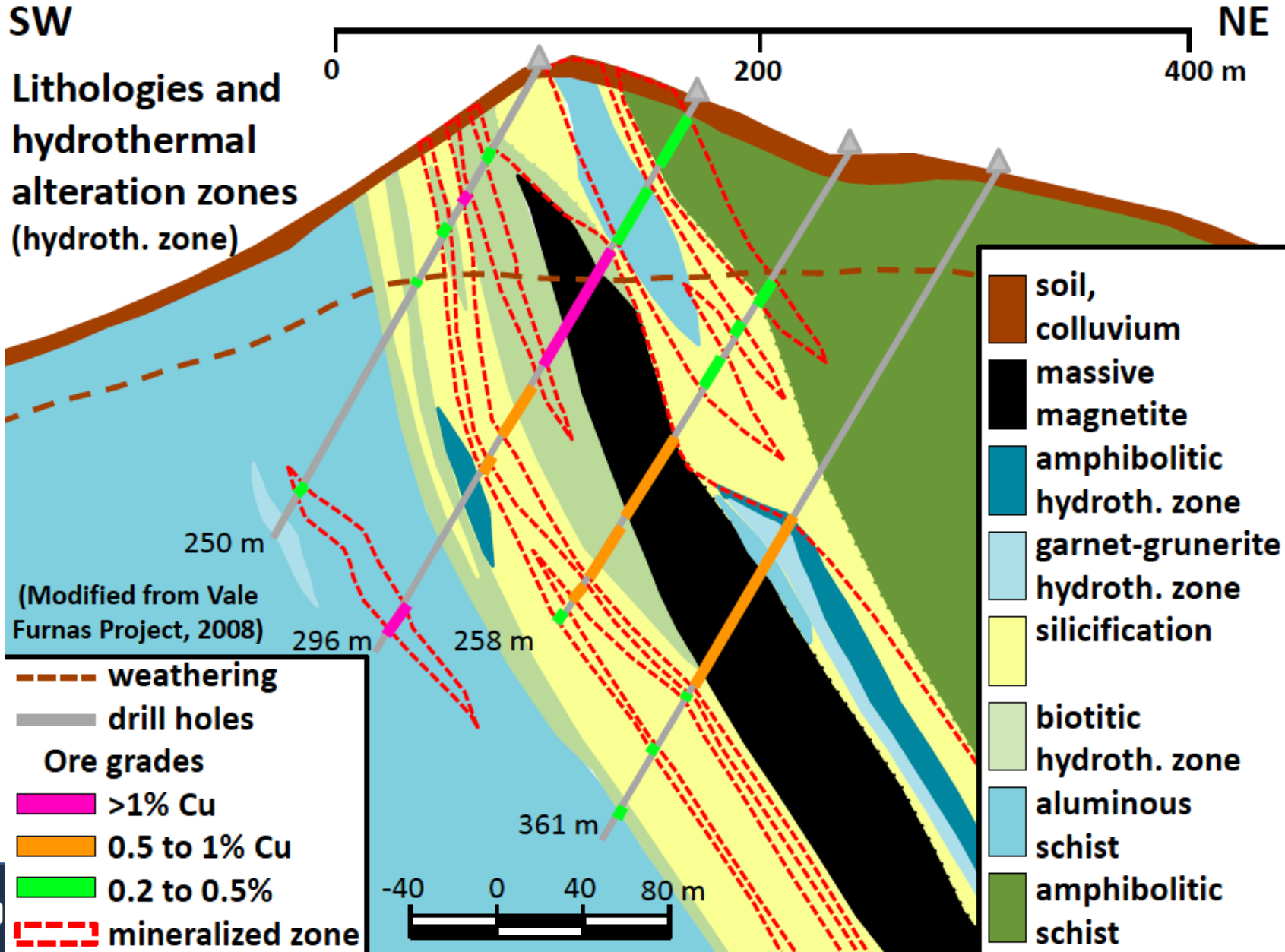
magnetic susceptibility



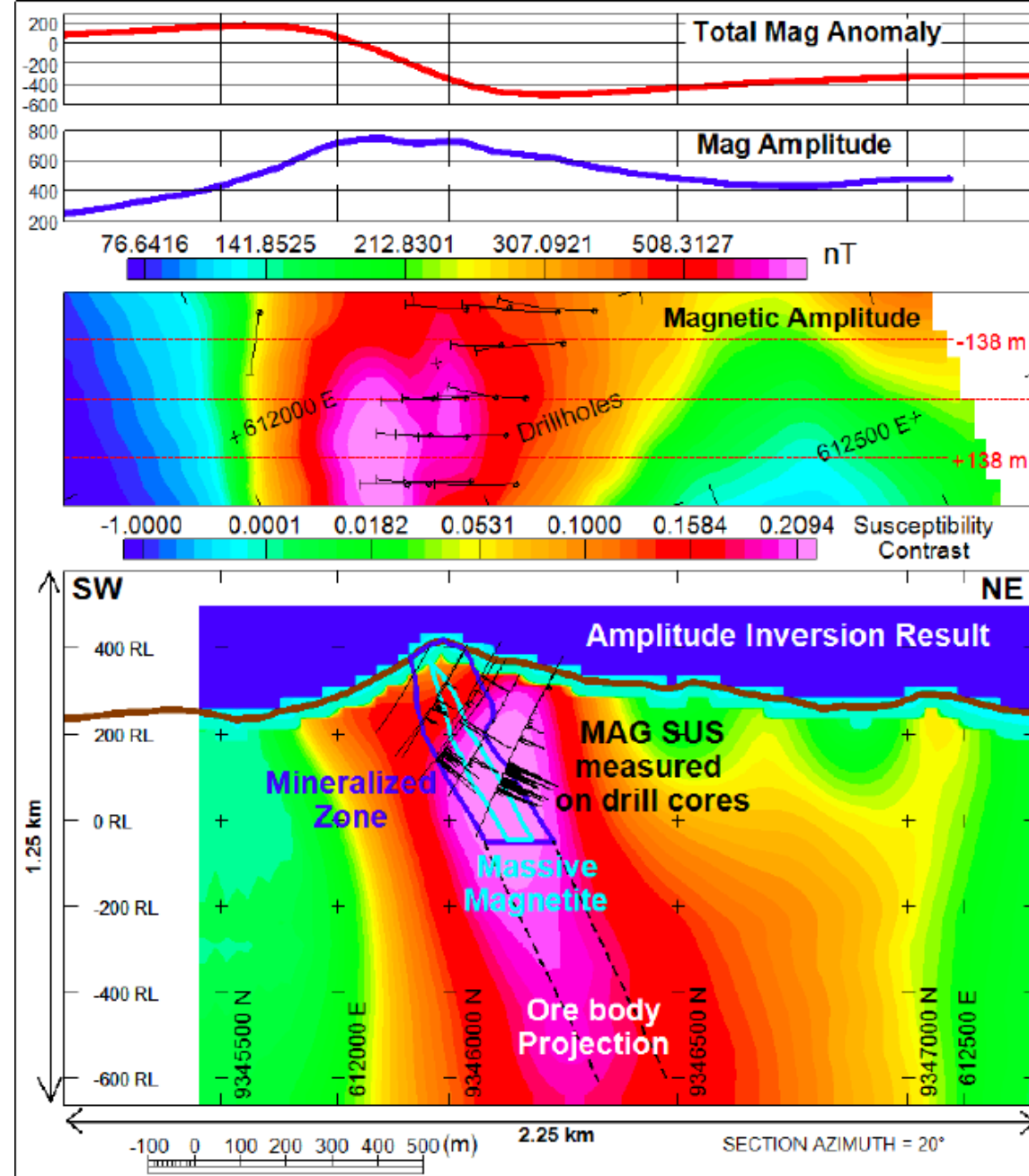
Example: Magnetic Susceptibility

Courtesy of Yaoguo Li





Comparison with known geological section



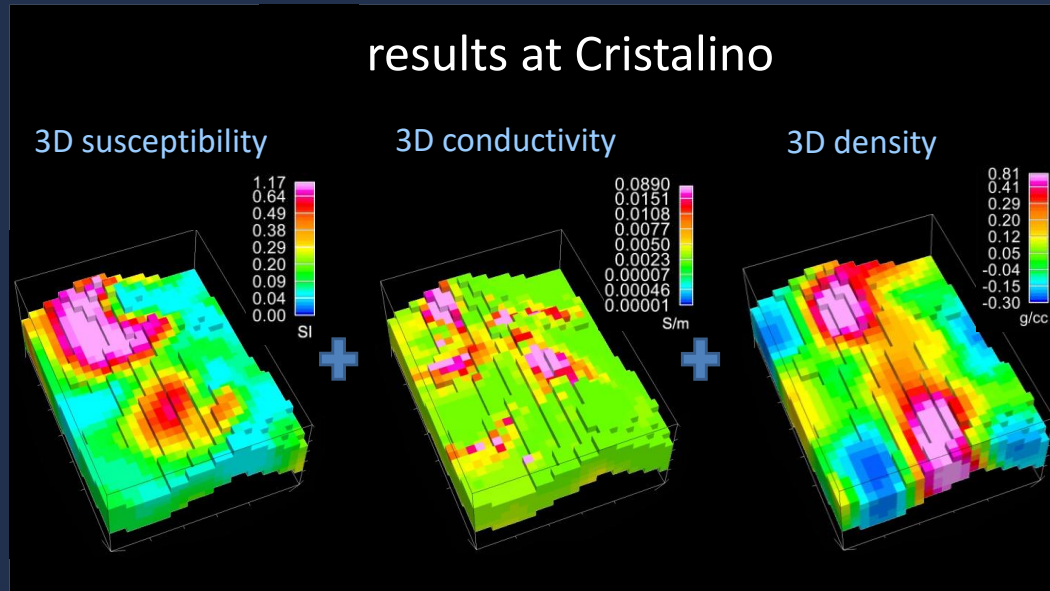
Innovation in Deep & Efficient Exploration

- **Drone-borne Surveys (UAVs):** Low-altitude, high-resolution magnetics at reduced costs.
- **Multi-Physics Inversion:** Integrating multiple methods into single subsurface property model
- **Machine Learning (ML):** Integrating geophysical, geological, and geochemical data for predictive "favorability mapping."
- **Deep Exploration:** Identifying "blind" deposits buried 1km+ underground.

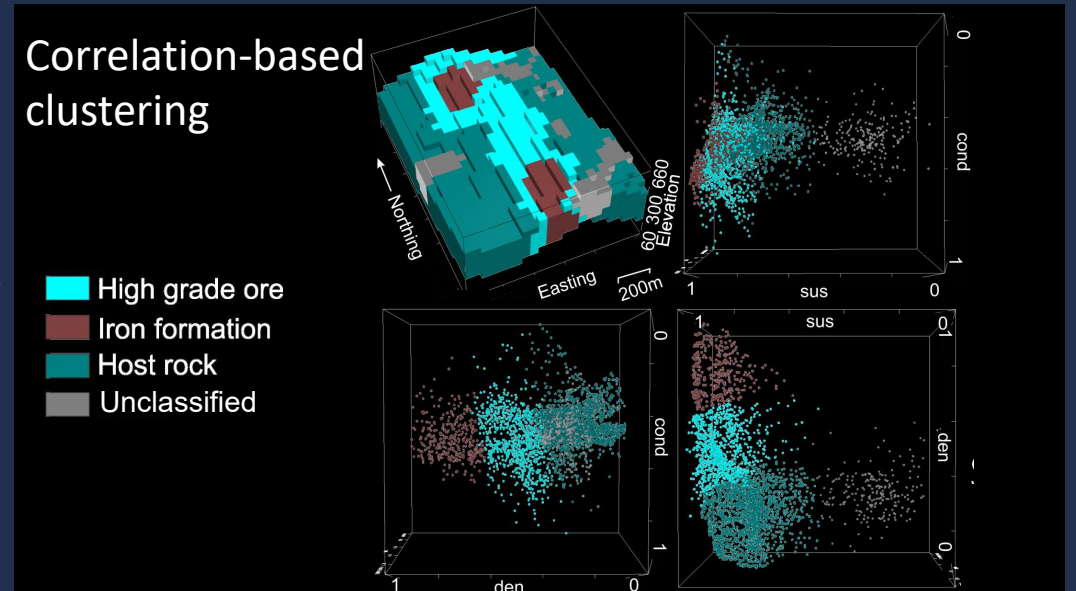


3D Geology Differentiation

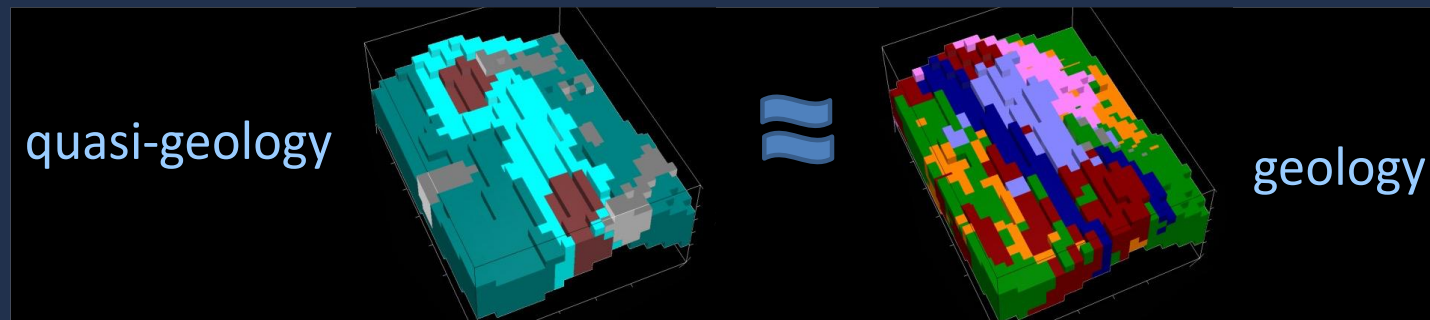
3D Geophysical Inversions



Unsupervised Machine Learning



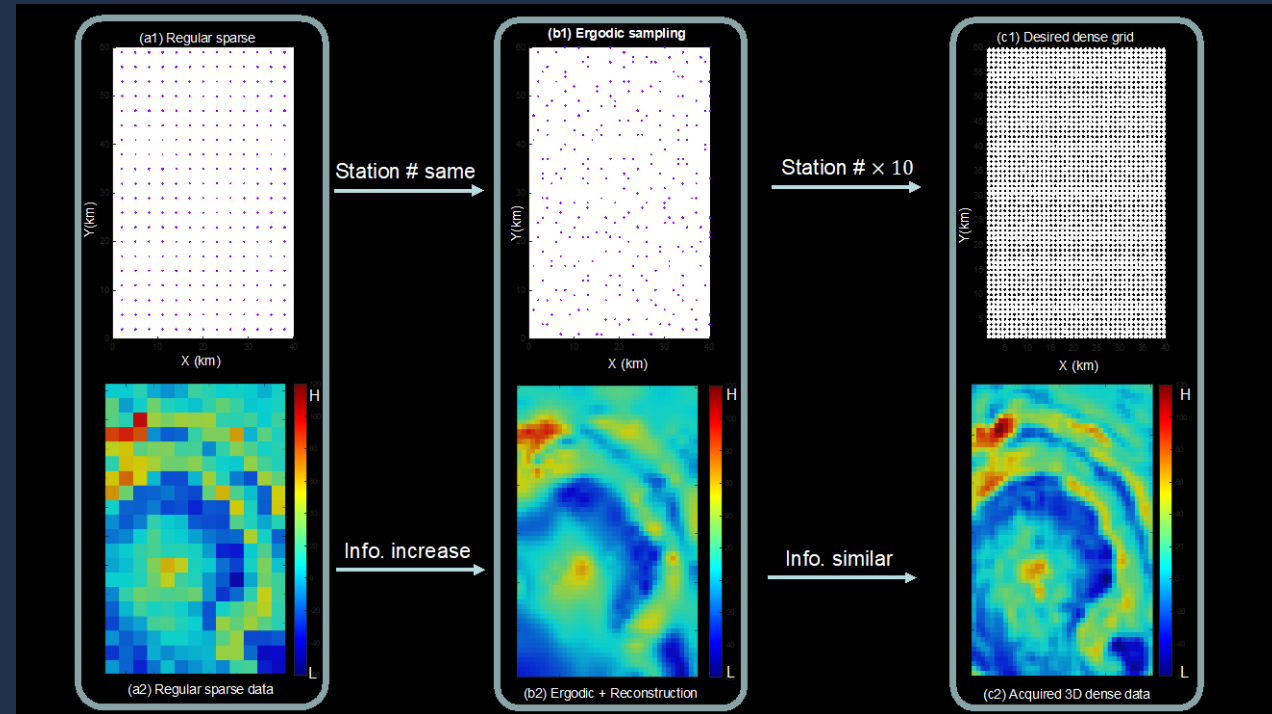
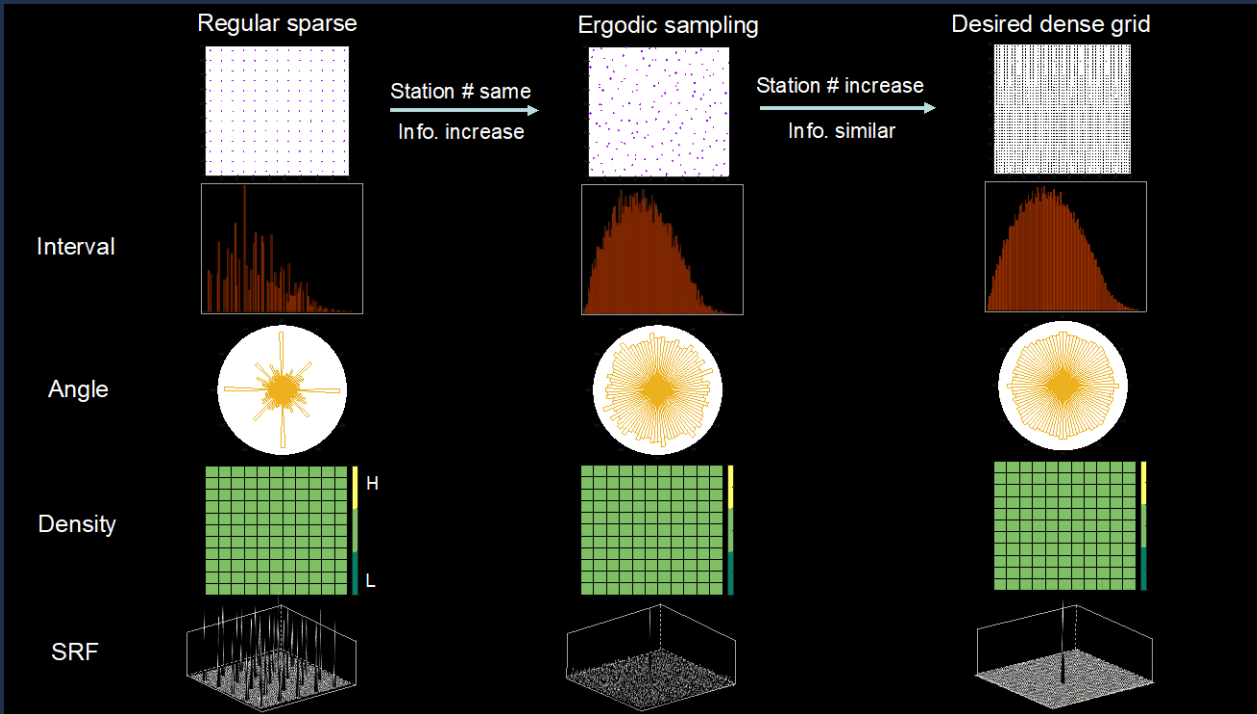
Geologic Image



A new enabler: Ergodic data acquisition

Ergodic acquisition design

Cost-reduction up to 10 times



- Cost reduction for same data (10x)
- Information increase for same budget
- Rapid reconnaissance exploration
- Rapid reduction of search space



Efficient geophysical data acquisition (low footprint)

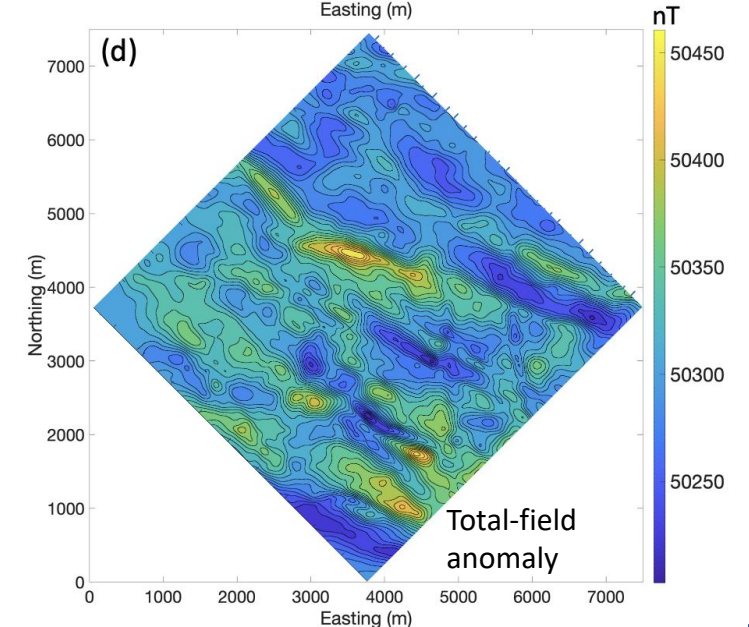
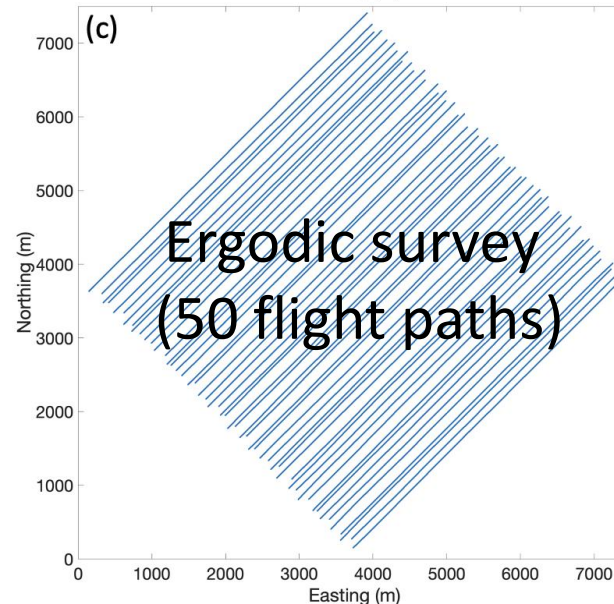
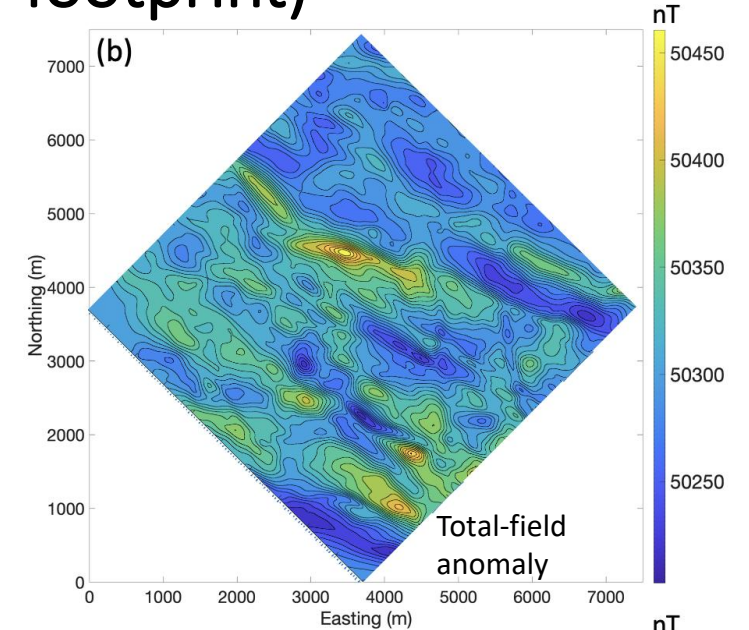
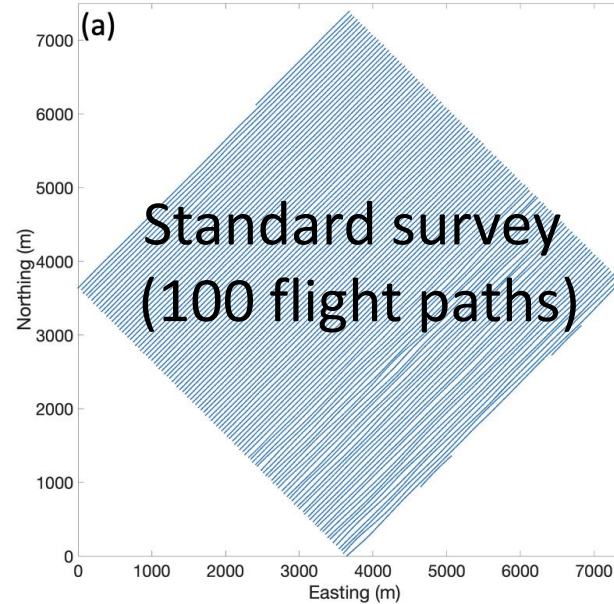
Two different survey designs but equivalent magnetic data quality

Ergodic survey :

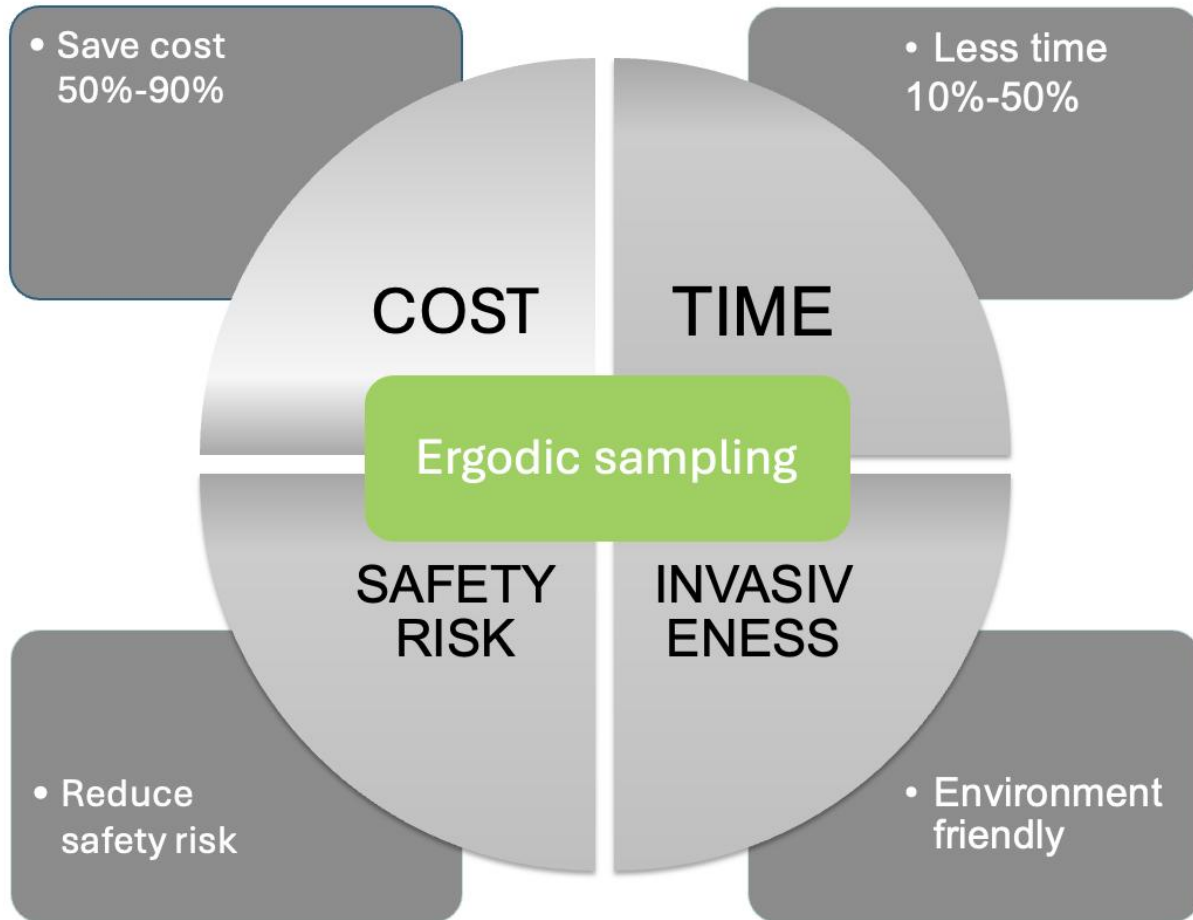
Half the cost

Half the time

Low footprint



Advantages of ergodic survey



United States Patent **Zhang et al.**

(10) **Patent No.:** **US 12,189,073 B2**
(45) **Date of Patent:** **Jan. 7, 2025**

Increase economic efficiency

Reduce environmental impact

Increase data collection & AI usage