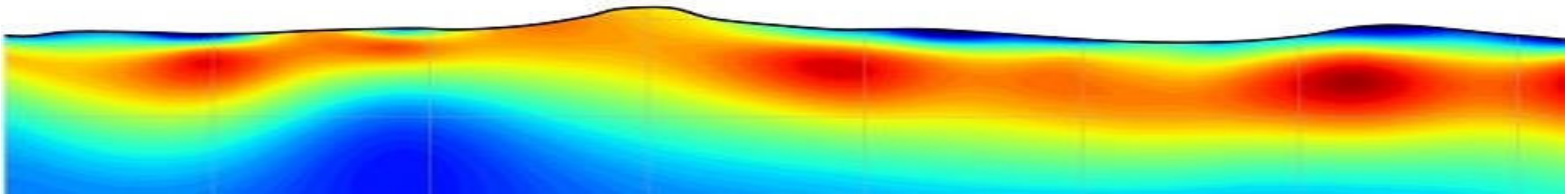
ESS302 Applied Geophysics II

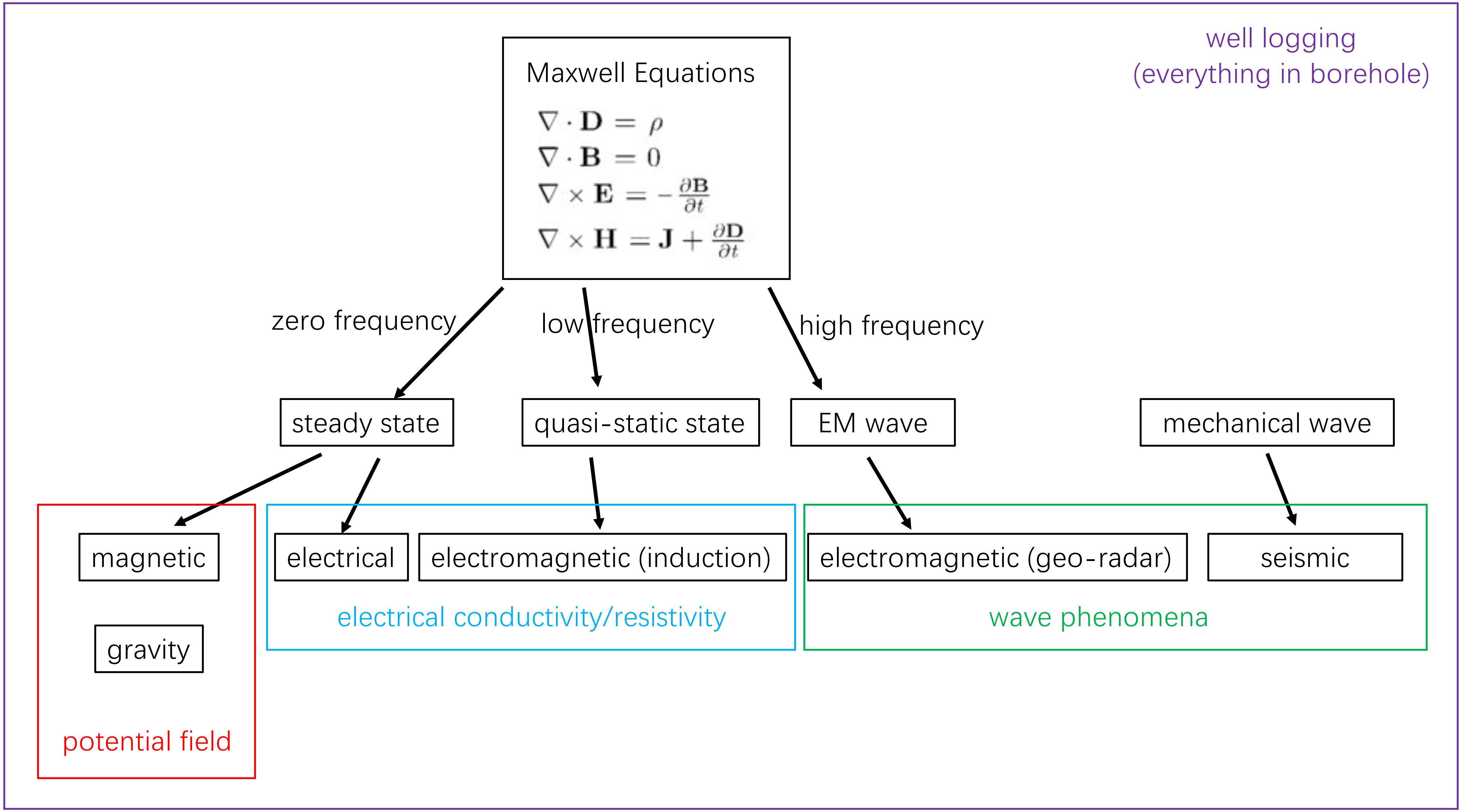
Gravity, Magnetic, Electrical, Electromagnetic and Well Logging

Electrical Extra

Instructor: Dikun Yang

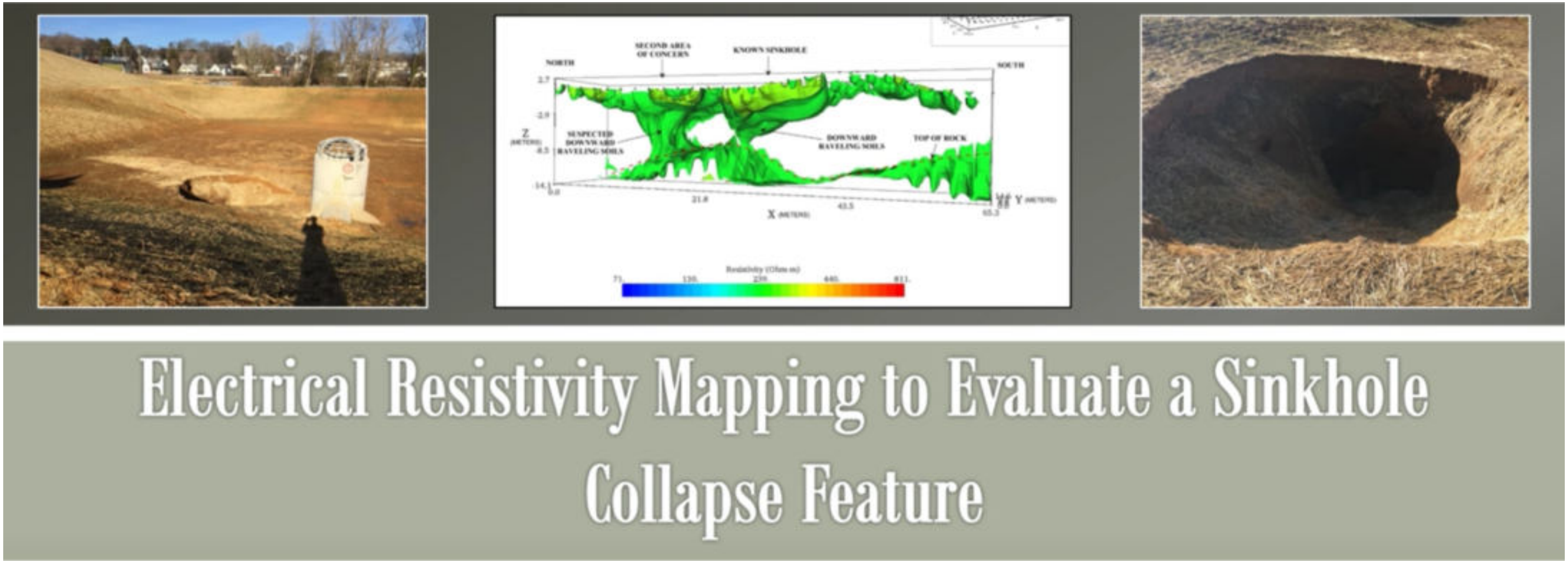
Feb – May, 2020





well logging
(everything in borehole)
Maxwell Equations
$\nabla \cdot \mathbf{D} = \rho$
$\nabla \cdot \mathbf{B} = 0$
$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$
zero frequency
low frequency
high frequency
steady state
quasi-static state
EM wave
mechanical wave
magnetic
gravity
potential field
electrical
electromagnetic (induction)
electrical conductivity/resistivity
electromagnetic (geo-radar)
seismic
wave phenomena

Learn From YouTube



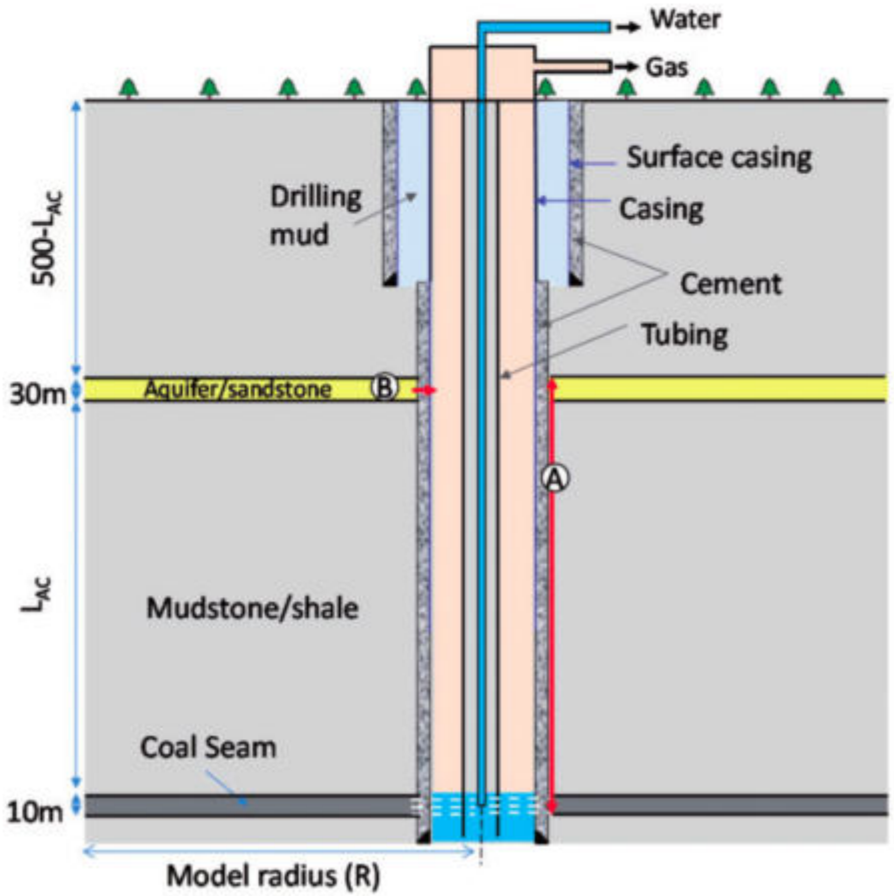
https://youtu.be/T9_EVjijNhE

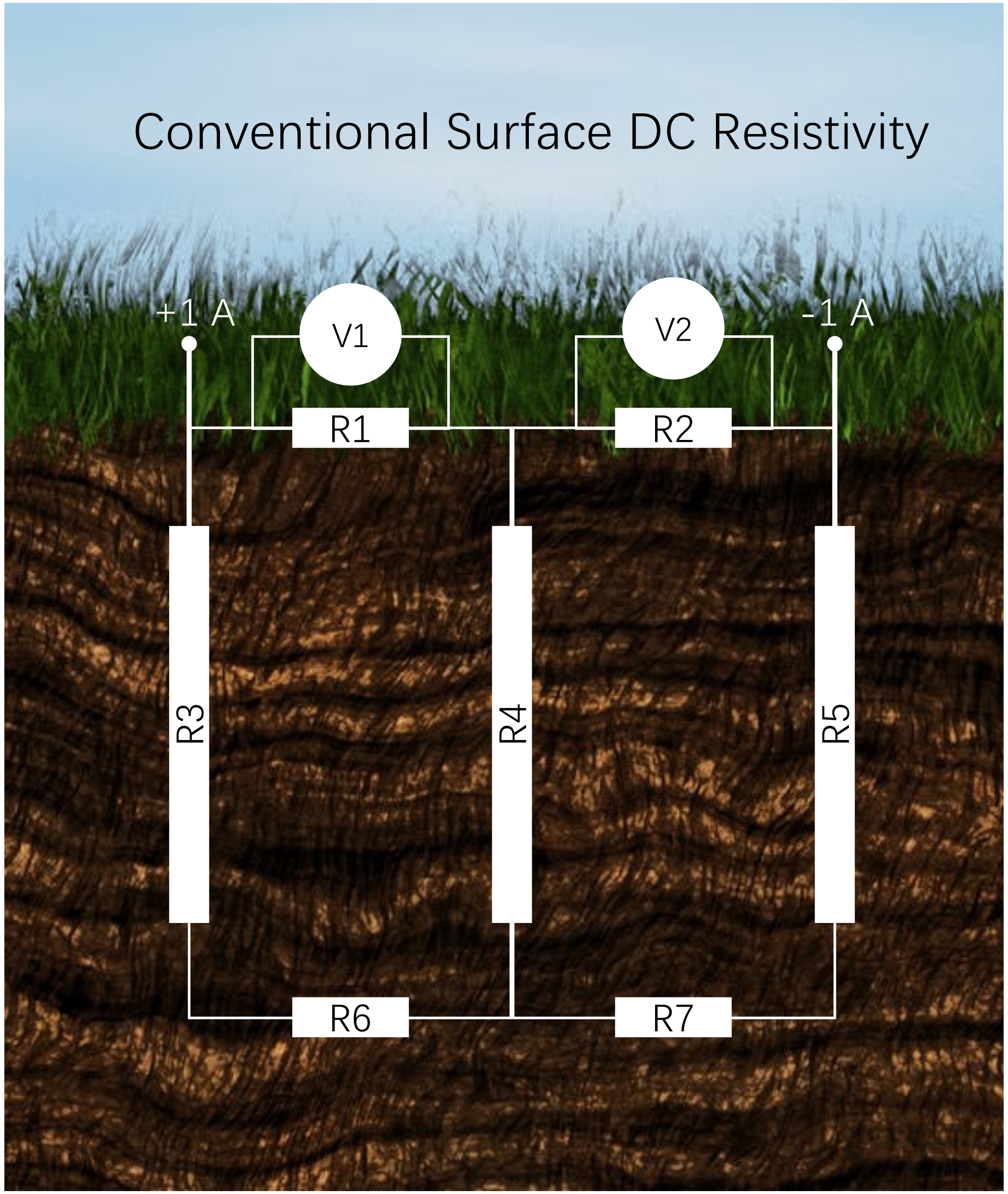
Questions

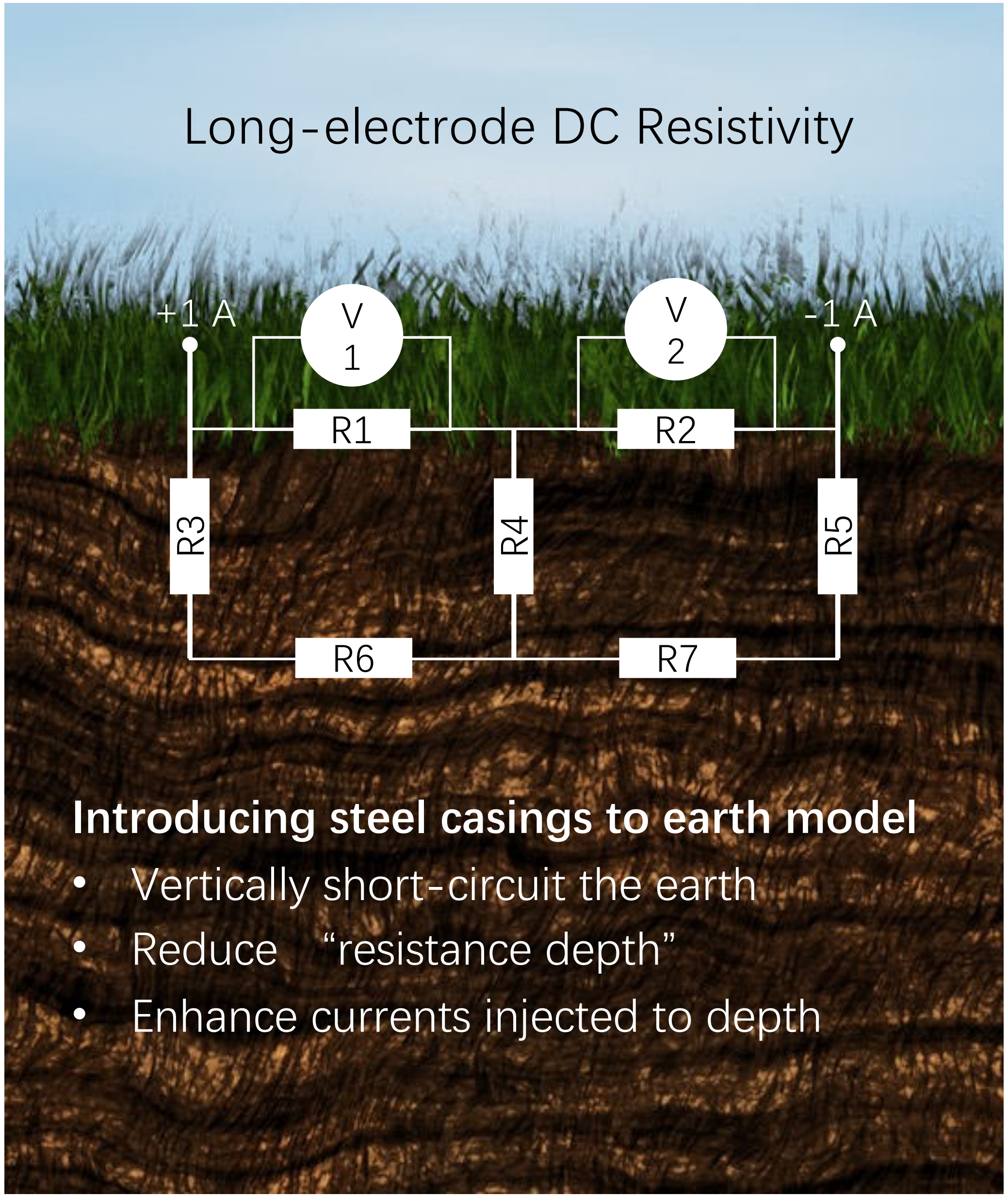
- What are the geological problems at this site in Tennessee?
- What was the electrical survey layout? What is the line and electrode spacings?
- What are the three major geological units imaged by the survey? And what are their resistivity ranges?
- What is the approximate depth of investigation of this survey?
- How did the interpreter find the disappeared in-filled sands?
- How were the 3D resistivity models created?
- In addition to confirming the known sinkhole, what else did the interpreter find in the 3D models?

Long Electrode (Casing) Electrical Method

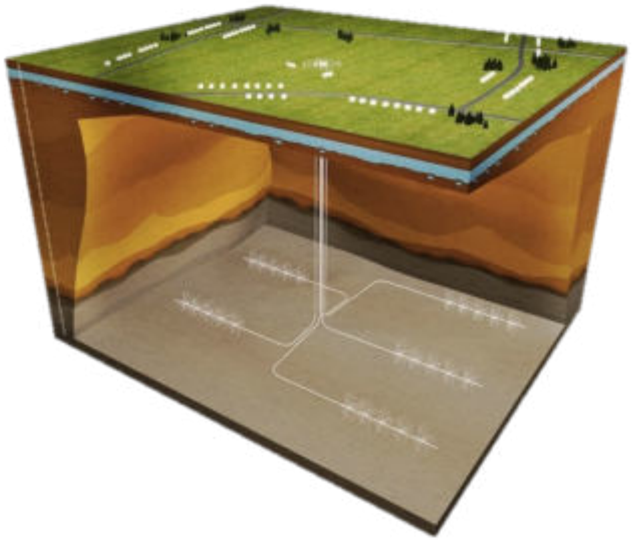
Use steel well casings as the electrodes: **electrical probes at depth**



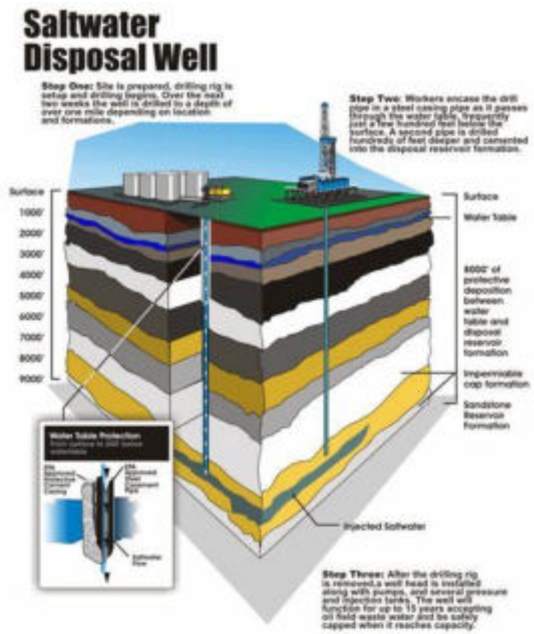

Conventional Surface DC Resistivity
+1 A
V1
V2
-1 A
R1
R2
R3
R4
R5
R6
R7


Long-electrode DC Resistivity
+1 A
V
1
V
2
-1 A
R1
R2
R3
R4
R5
R6
R7
Introducing steel casings to earth model
• Vertically short-circuit the earth
• Reduce “resistance depth”
• Enhance currents injected to depth

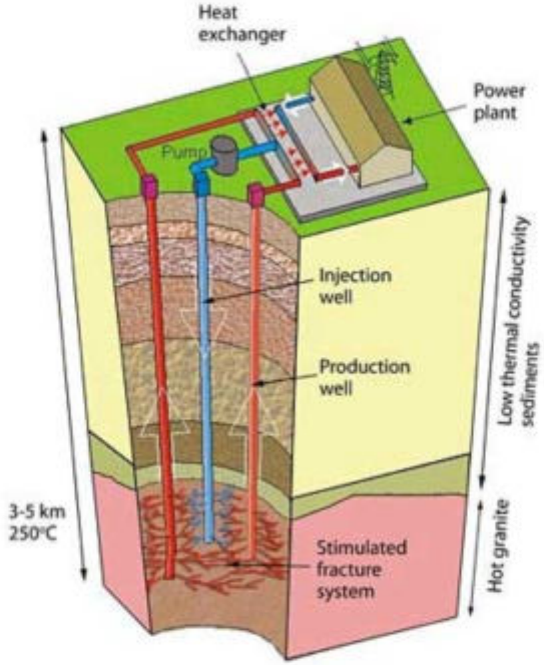
Monitoring of Injected Fluid



Shale gas hydraulic fracturing

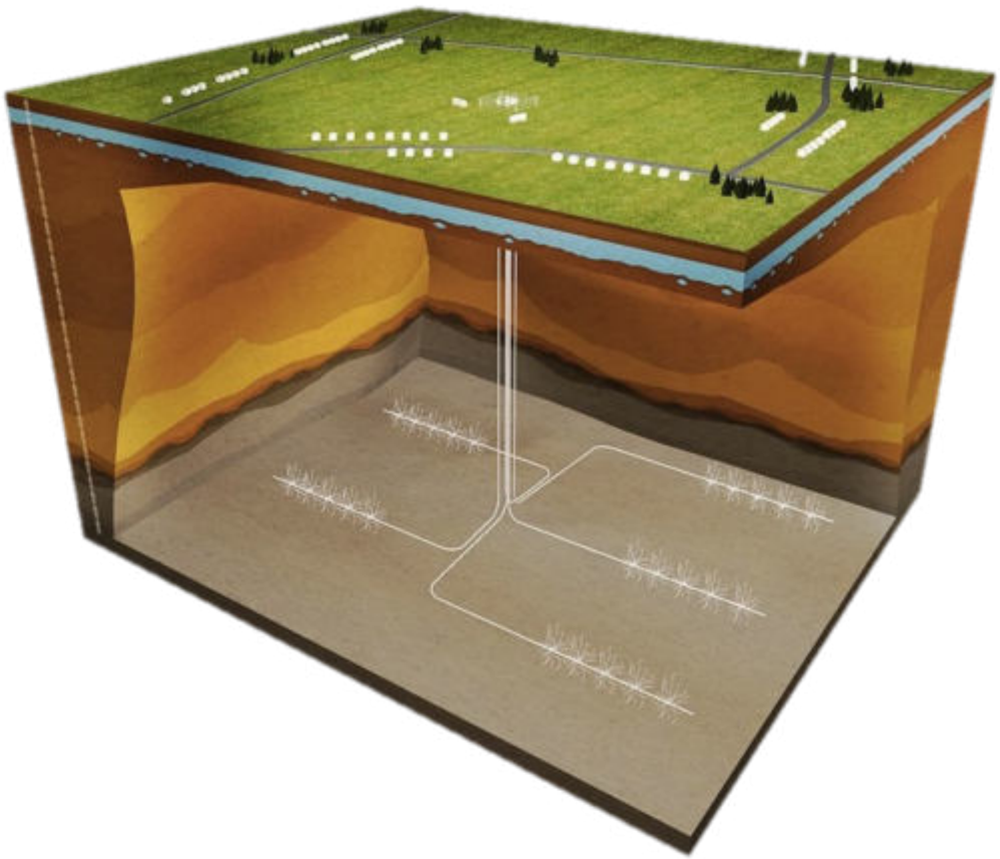


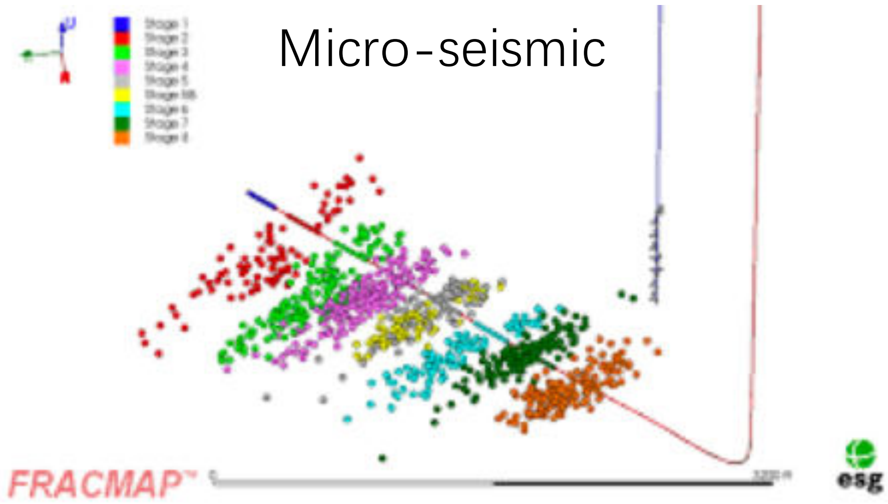
Waste water disposal



Enhanced Geothermal System

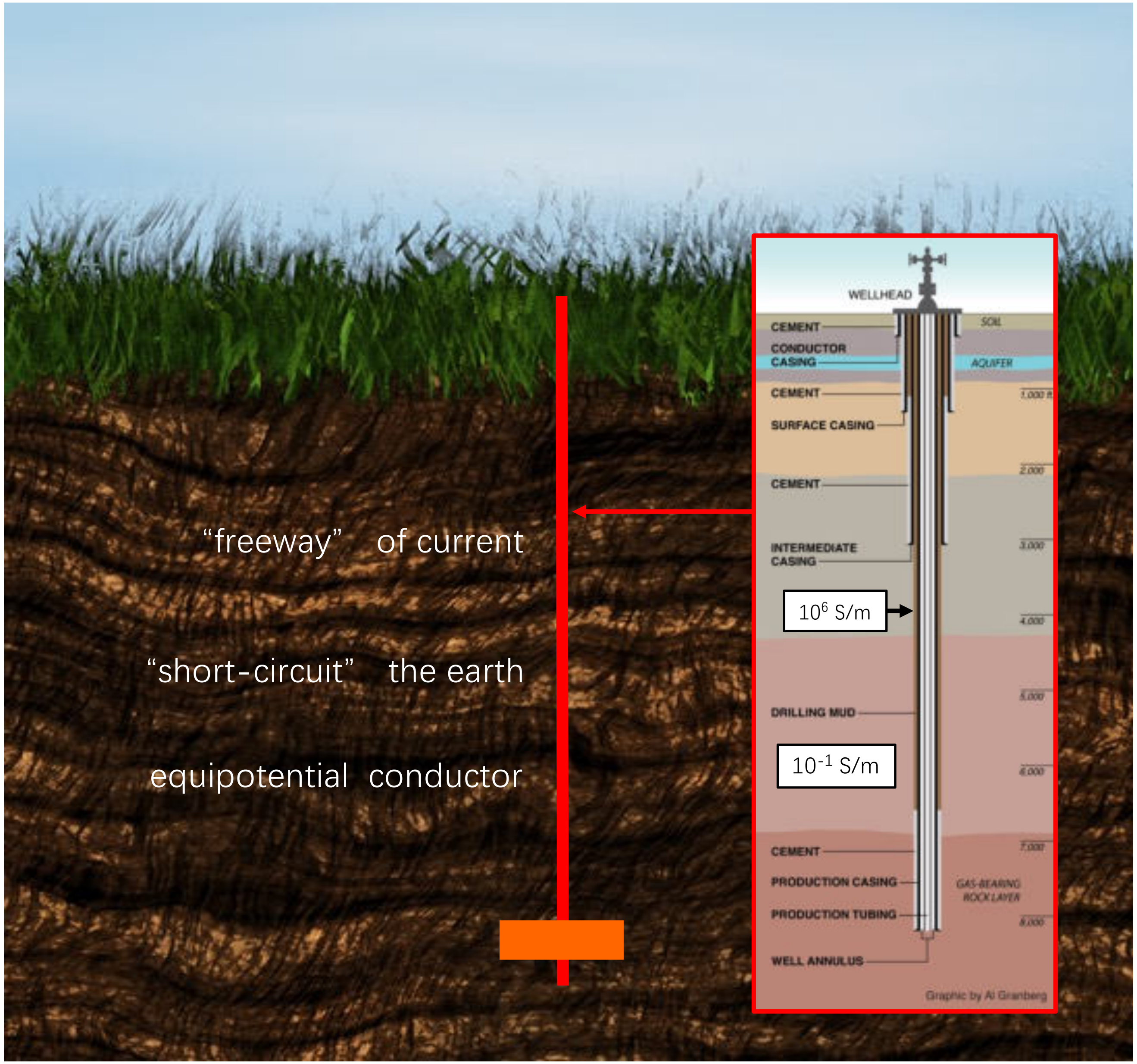
Shale Gas Hydraulic Fracturing





But where is **fluid**?

- Pumping schedule
- Groundwater contamination
- Induced seismicity



Alternatively Electrical?

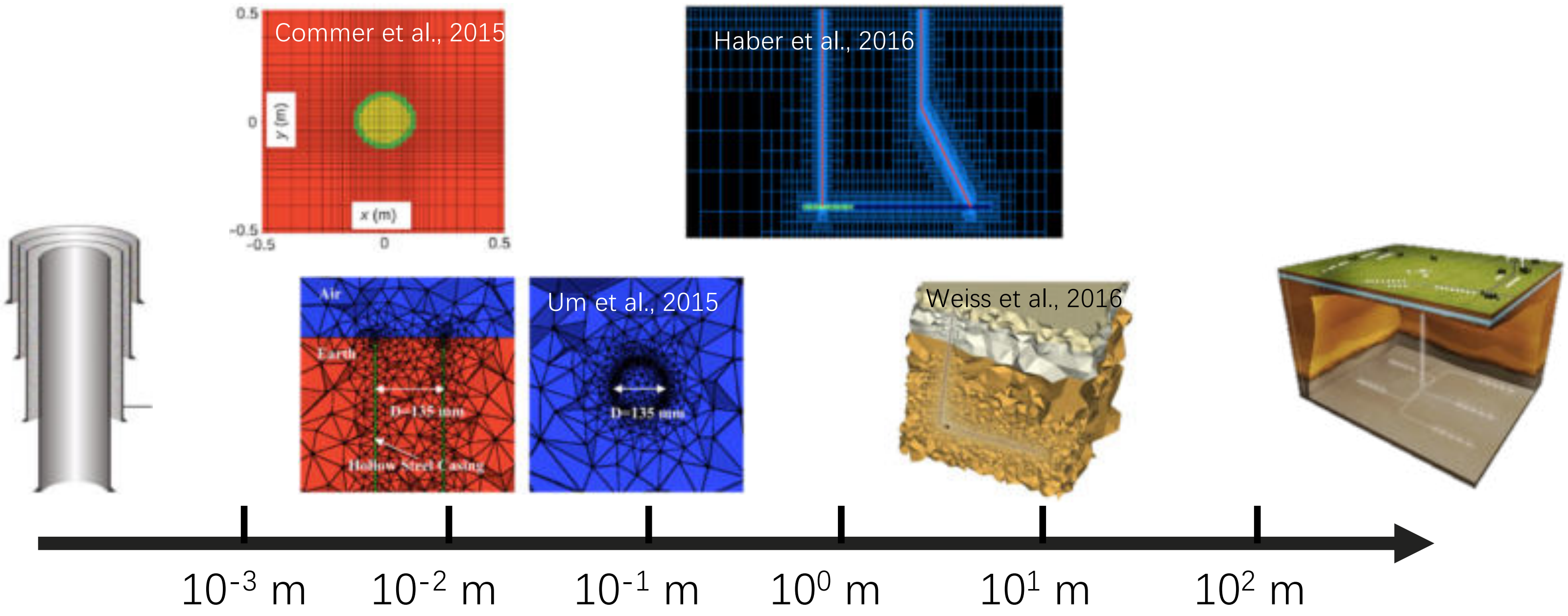
Conductivity contrast

- Hydro-frac: brine, additives, treated proppant, etc.
- Wastewater: used frac fluid

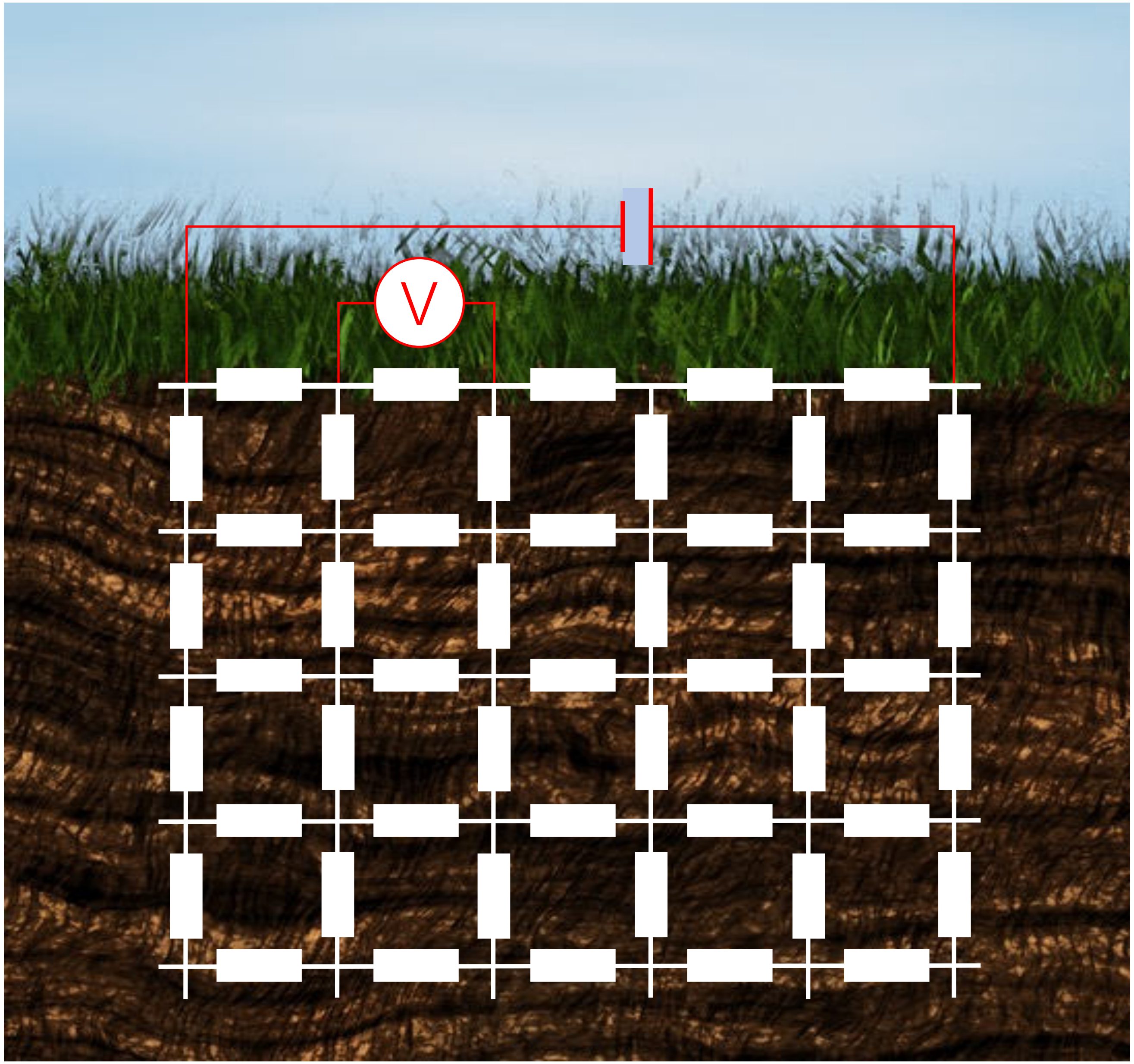
Detectable signals

- Small perturbation (10^1 m) at a great depth (10^3 m)
- Interference from metallic infrastructure
- Possible with **steel casings**

Difficulty: Simulation of Steel Casings



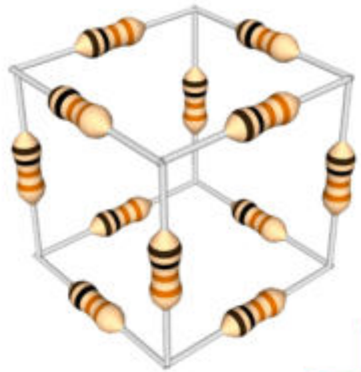
- Require 3D mesh generation and refinement
- Difficulty in modeling multiple wells and and pipelines
- Computing time not matching the temporal scales of injection (minutes)
- Not fast enough for real-time analysis



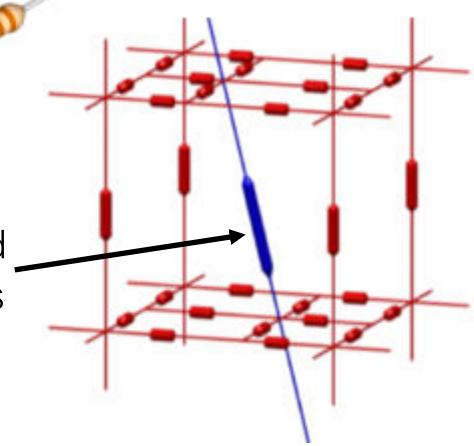
RESnet:

A circuit perspective

3D earth model

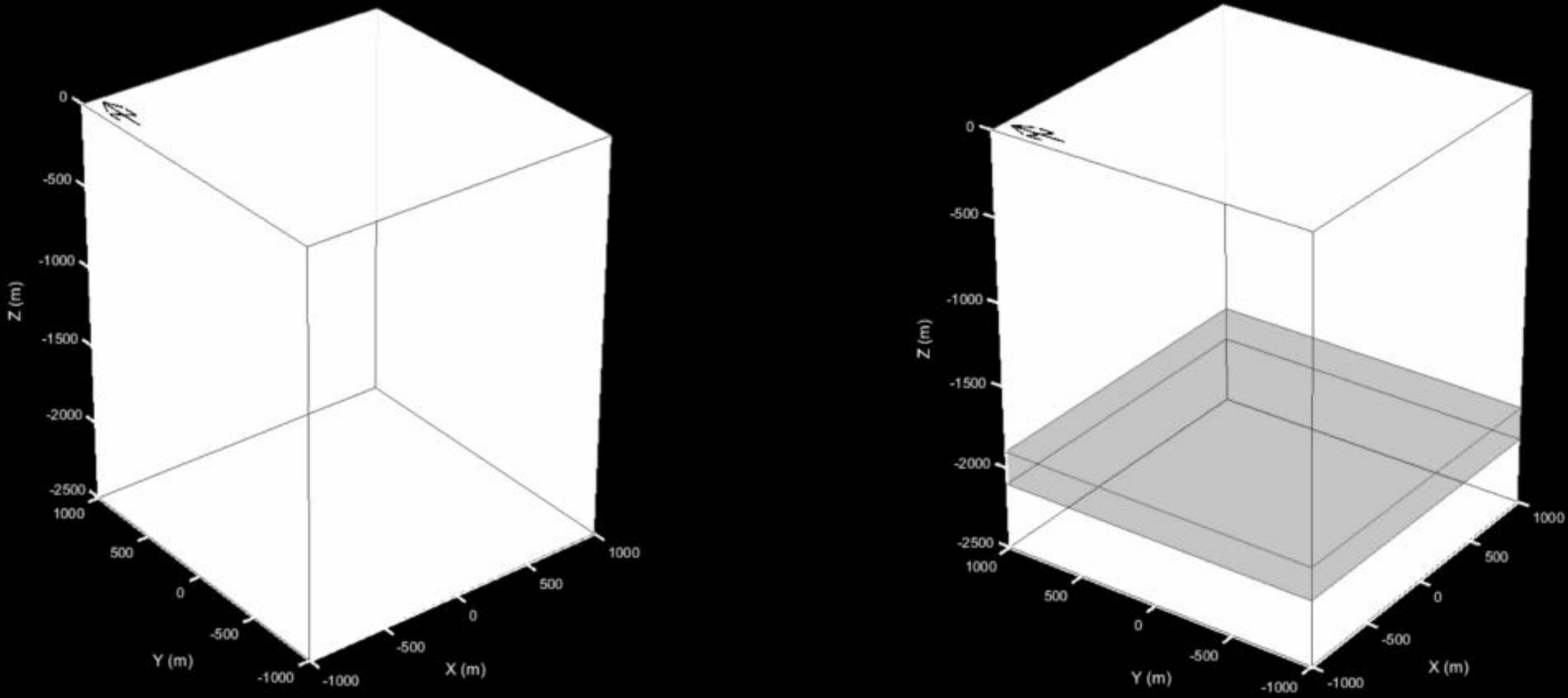


Casing modelled as new branches

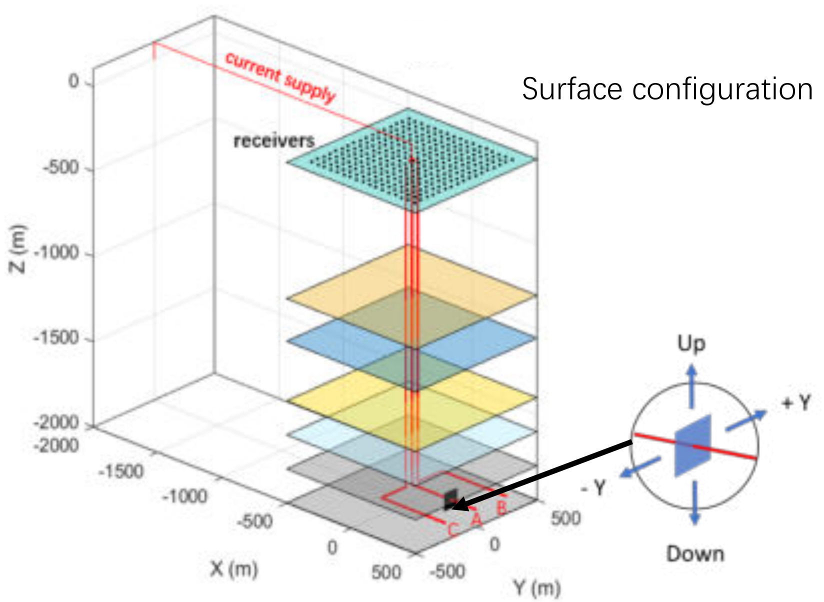


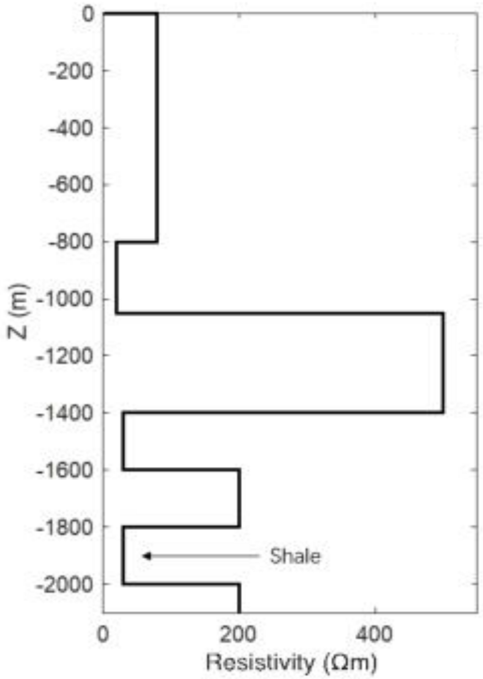
3D resistor network

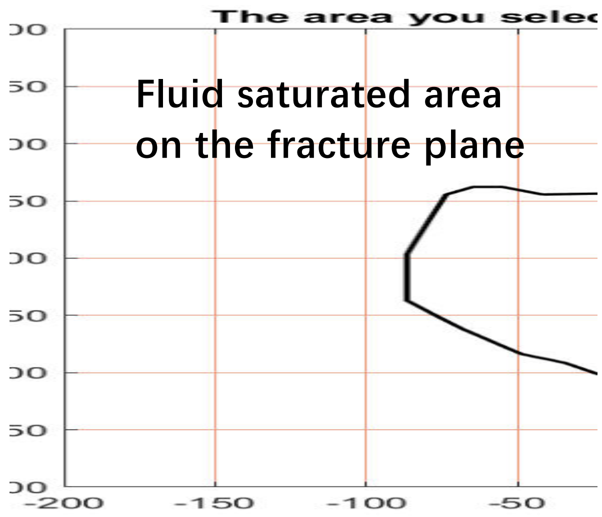
Monitoring Injected Fracturing Fluid with Casings

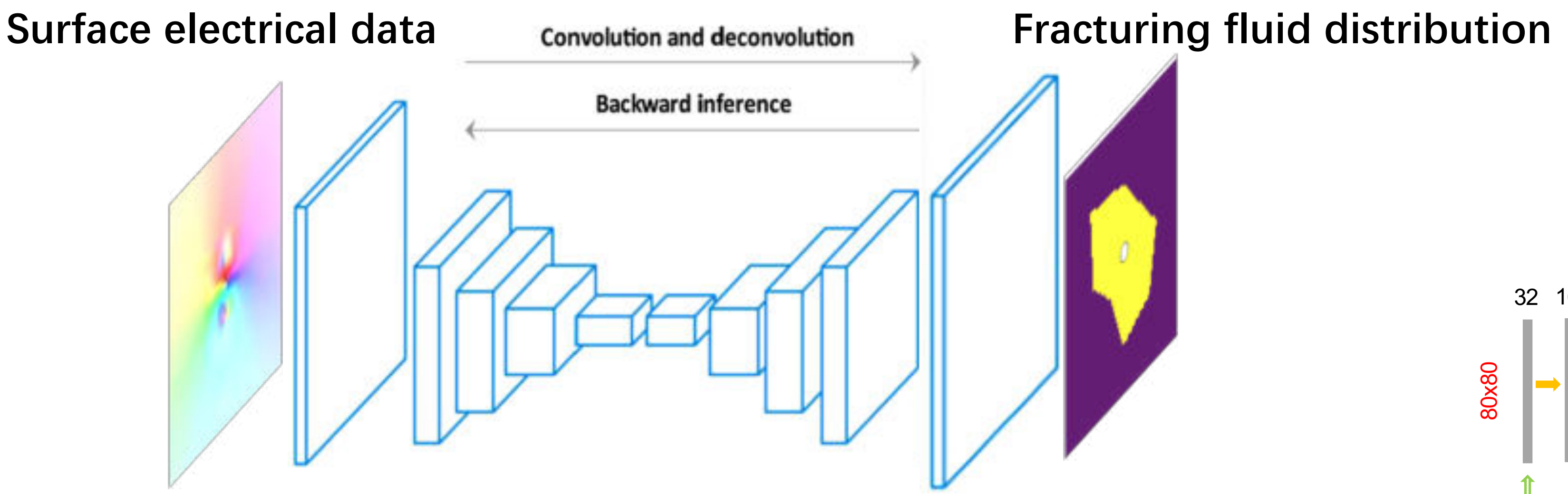


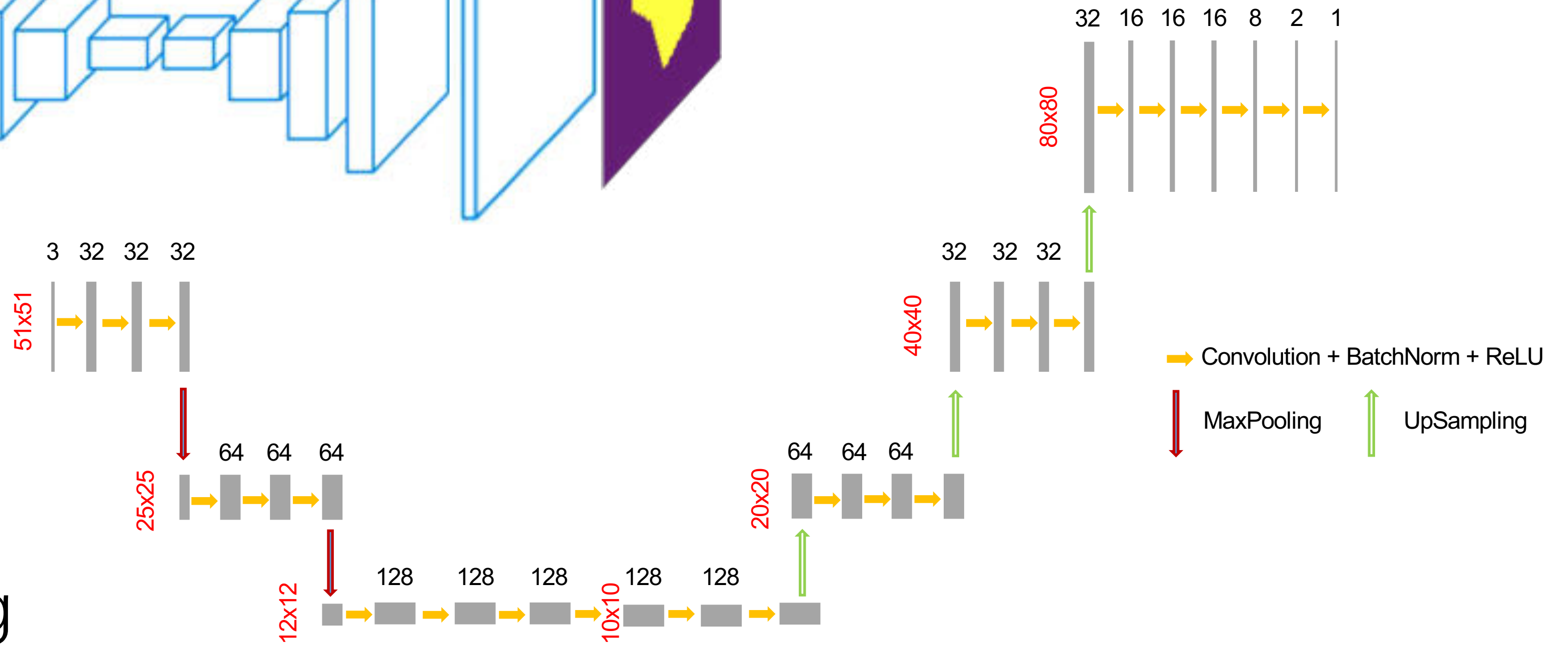
High Resolution Imaging of Fracturing Fluid







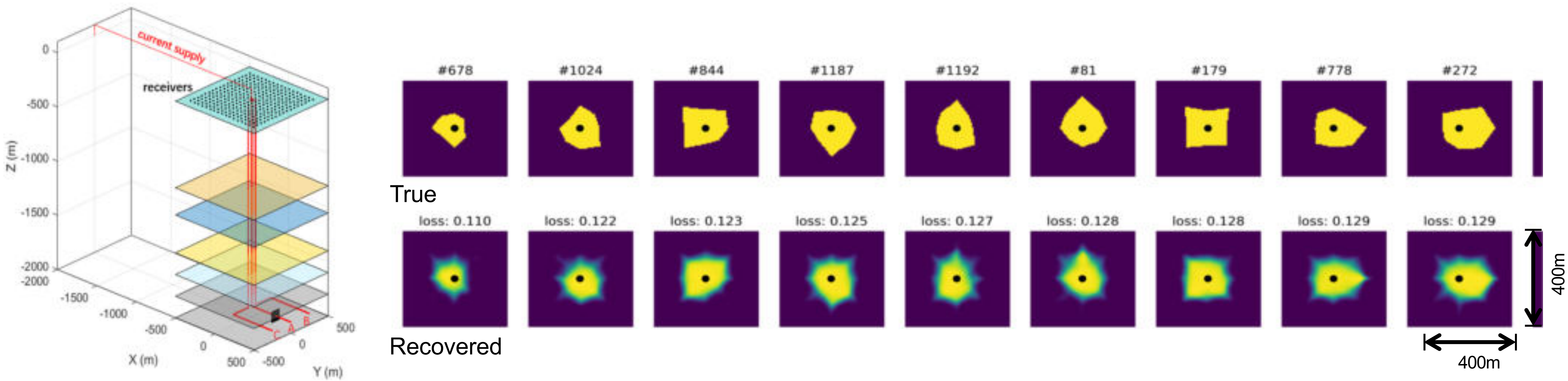




A deep learning imaging method

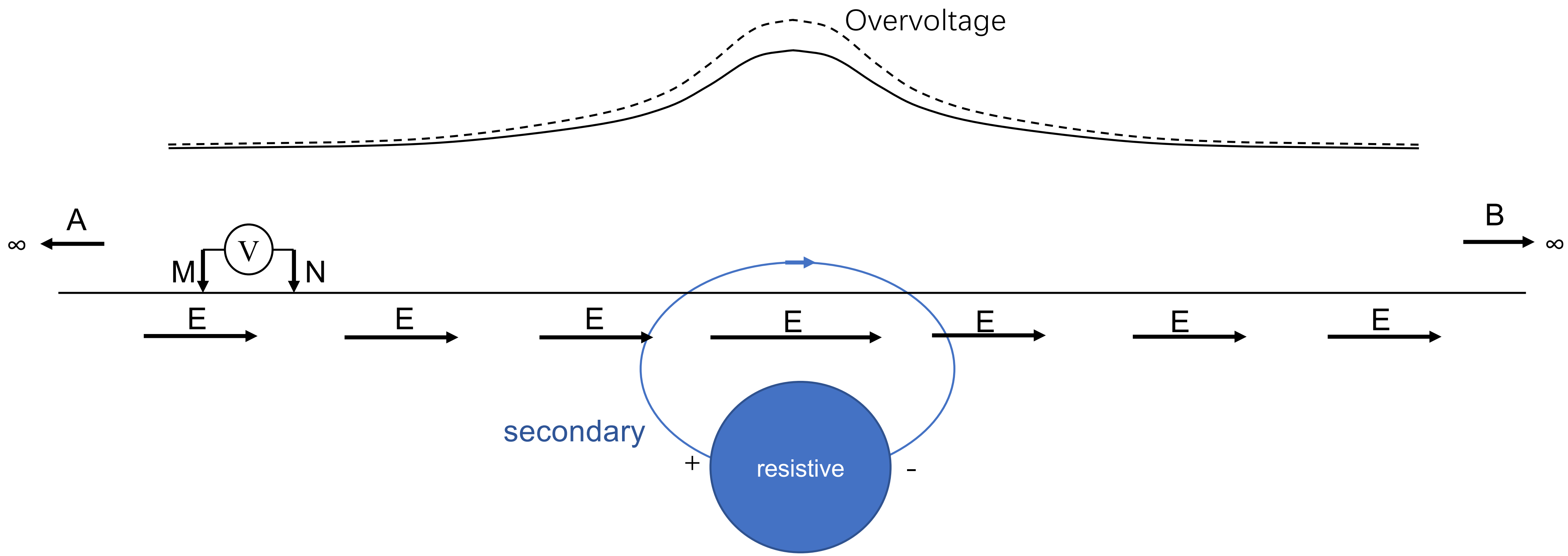
- Simulate a number of examples for training

Electrical and Deep Learning Imaging Results

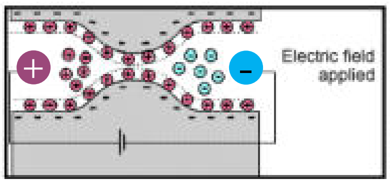


A resolution that regular surface methods can never achieve

Induced Polarization (IP)



- If narrow pore throats exist
- Ions accumulate at narrows in response to external field
- Additional electrical dipole moment
- Cause overvoltage in measured potentials



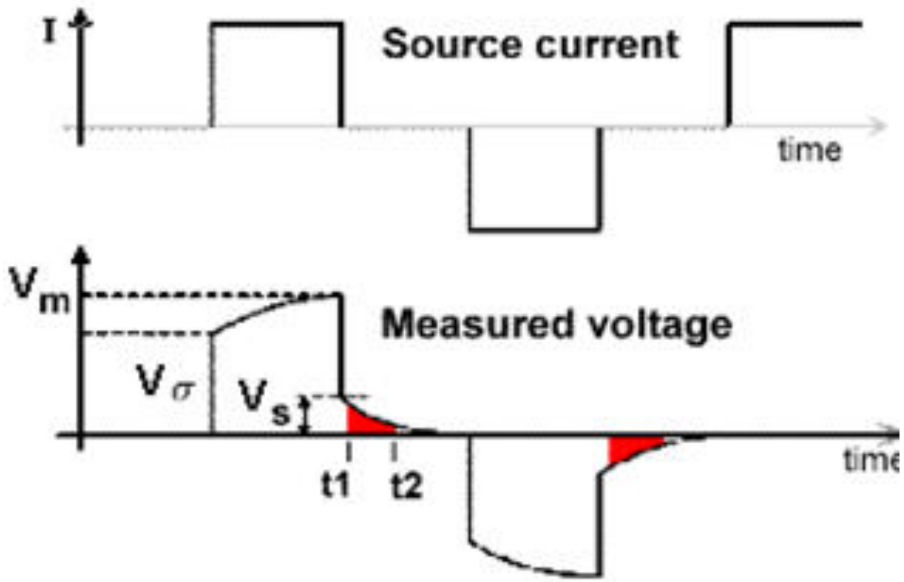
IP Effect in DC Data

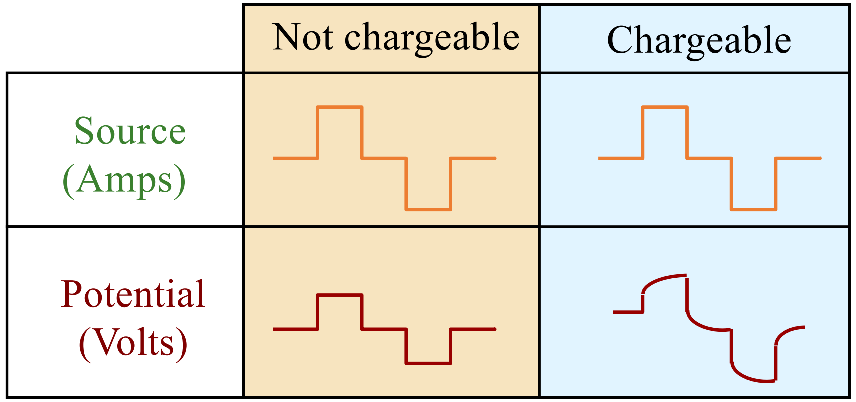
1) Voltage applied by transmitter
   → instantaneous (V_σ) increase due to ρ
2) Voltage increases as ions accumulate:

$$V_{off}(t) = V_s\, e^{-t/\tau}$$

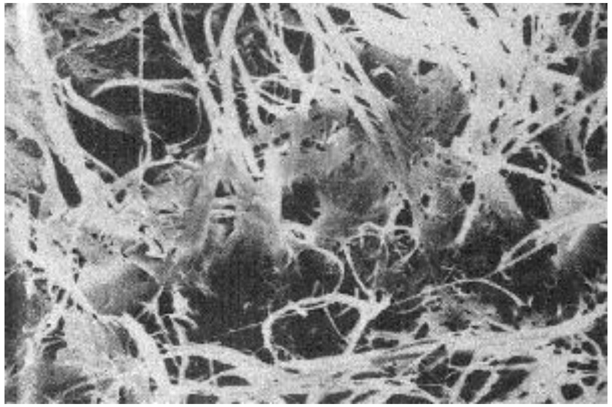
3) Saturation of ionic charges
   → DC voltage ($V_m = V_\sigma + V_s$)
4) Voltage from transmitter removed
   → instantaneous loss in secondary potential (equal to V_σ)
5) IP voltage discharges during off-time

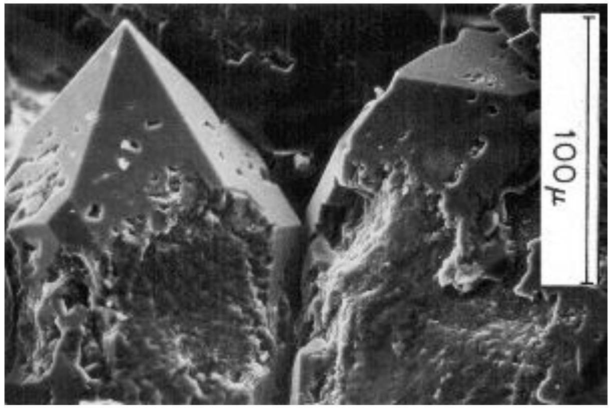
$$V_{on}(t) = V_\sigma + V_s\left[1 - e^{-t/\tau}\right]$$



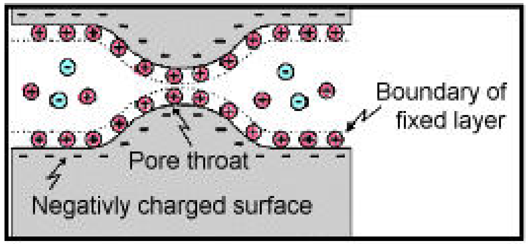


Chargeability – Capability of Holding Charges

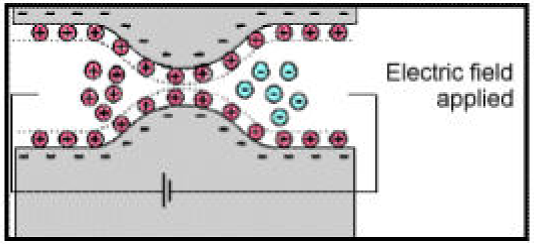




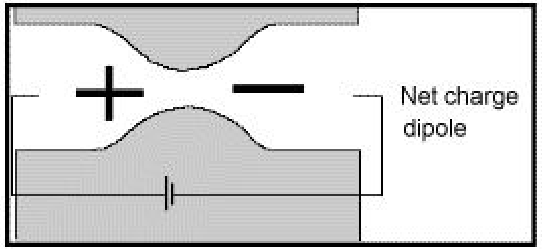
Type 1: Membrane polarization - ions accumulate at pore throat



Equilibrium State

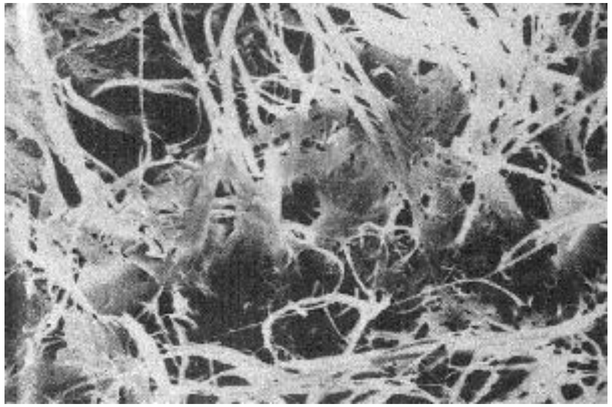


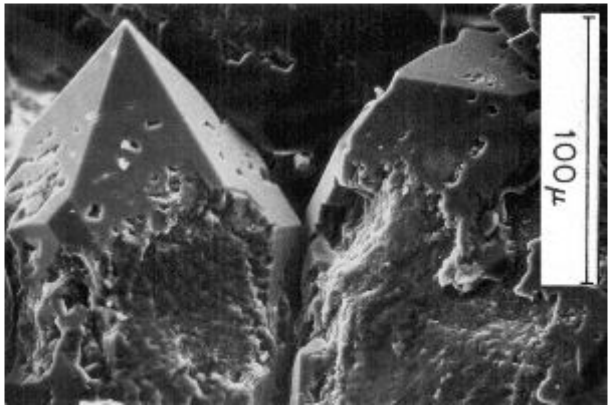
Voltage Applied



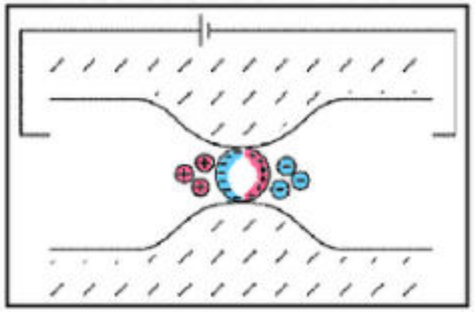
Separation of +ve and –ve ions

Chargeability – Capability of Holding Charges



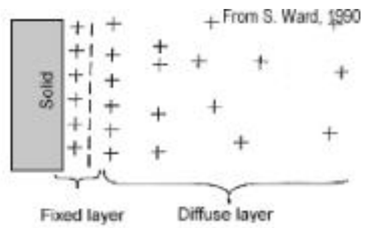


Type 2: Electrode polarization: Ions accumulate at metals



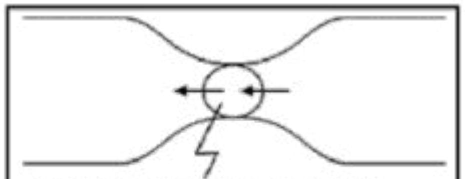
- Pore space is blocked by metallic particles
- Metallic particles become electrically charged and attract nearby ions
- This is why the waveform of dc survey switches polarity

Electric double layer



Hypothetical anomalous ion distribution near a solid-liquid interface.

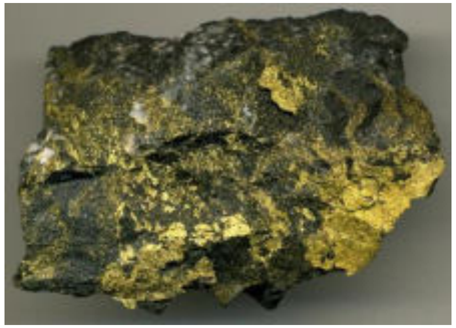
Net electric dipole moment



Two electrical double layers.

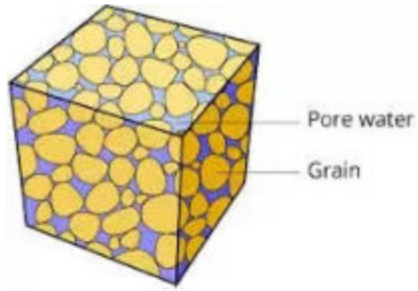
Chargeability – A Diagnostic Physical Property

Chargeability is not thoroughly understood in theory but it is often related to:

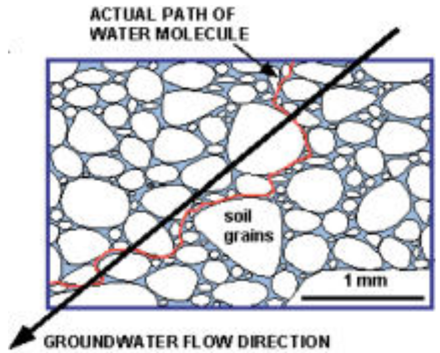


Sulphide Mineralization

Clays



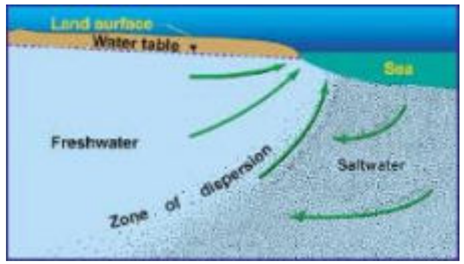
Pore-Water Salinity



Tortuosity

Use chargeability to characterize the earth:

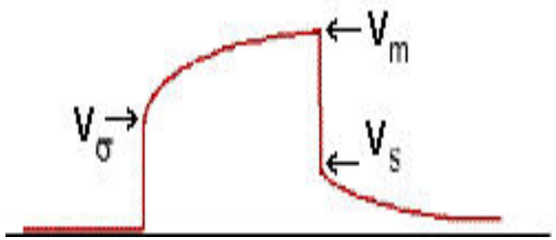
- Environmental: Contamination, groundwater…
- Mining: Disseminated sulphides (porphyry)
- Oil/gas:



Time-domain IP Data

Intrinsic chargeability (dimensionless)

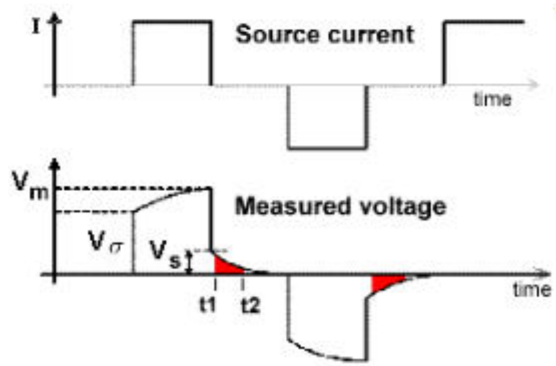
$$\eta = \frac{V_s}{V_m}$$



$$d_{IP} = \frac{V_s(t)}{V_m} \quad \text{mV/V}$$

Integrate over the decay (discharge period)

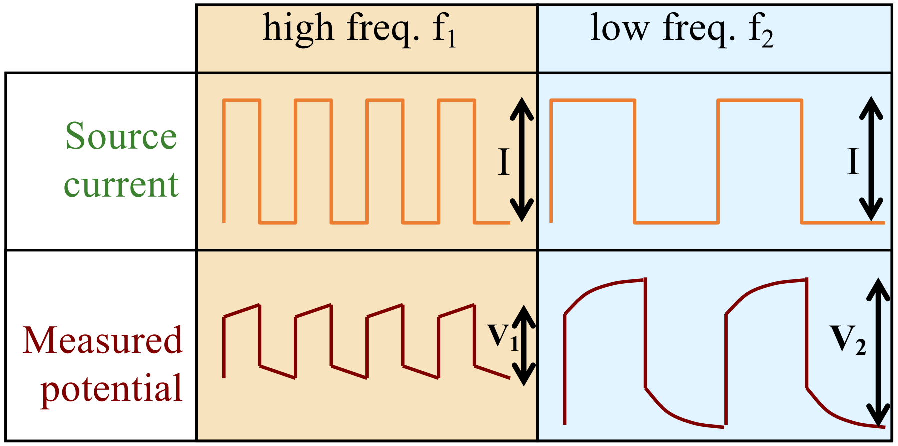
$$d_{IP} = \frac{1}{V_m}\int_{t_1}^{t_2} V_s(t)dt \quad \text{(msec)}$$



Frequency-domain IP Data

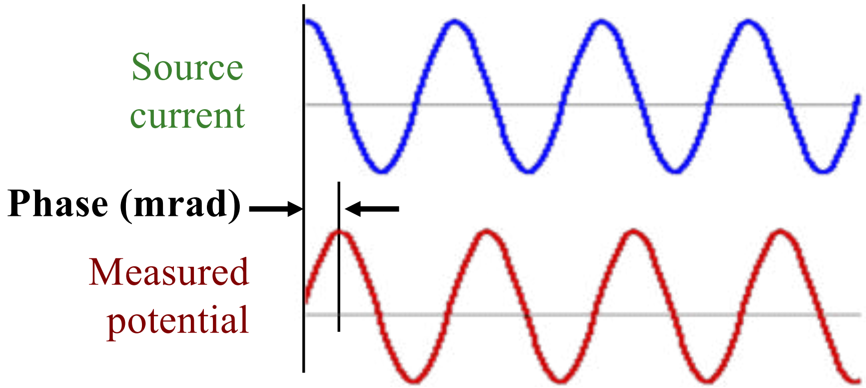
Percent frequency effect:

$$d_{IP} = \quad PFE = 100\left(\frac{\rho_{a2} - \rho_{a1}}{\rho_{a1}}\right)$$



Phase:

$$d_{IP} = \textbf{phase (mrad)}$$

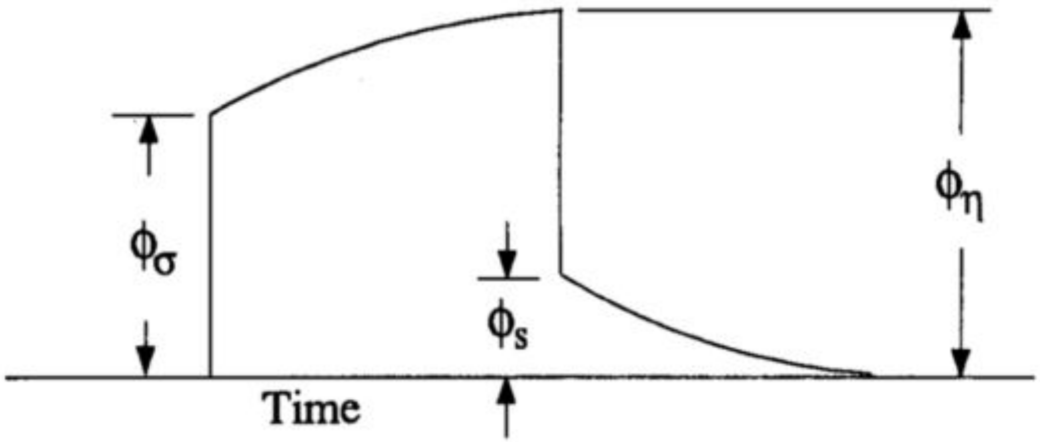


IP Modeling

Chargeability: alter conductivity

$$\sigma = \sigma(1 - \eta)$$

$$\phi_\eta = \mathcal{F}_{dc}[\sigma(1 - \eta)]$$



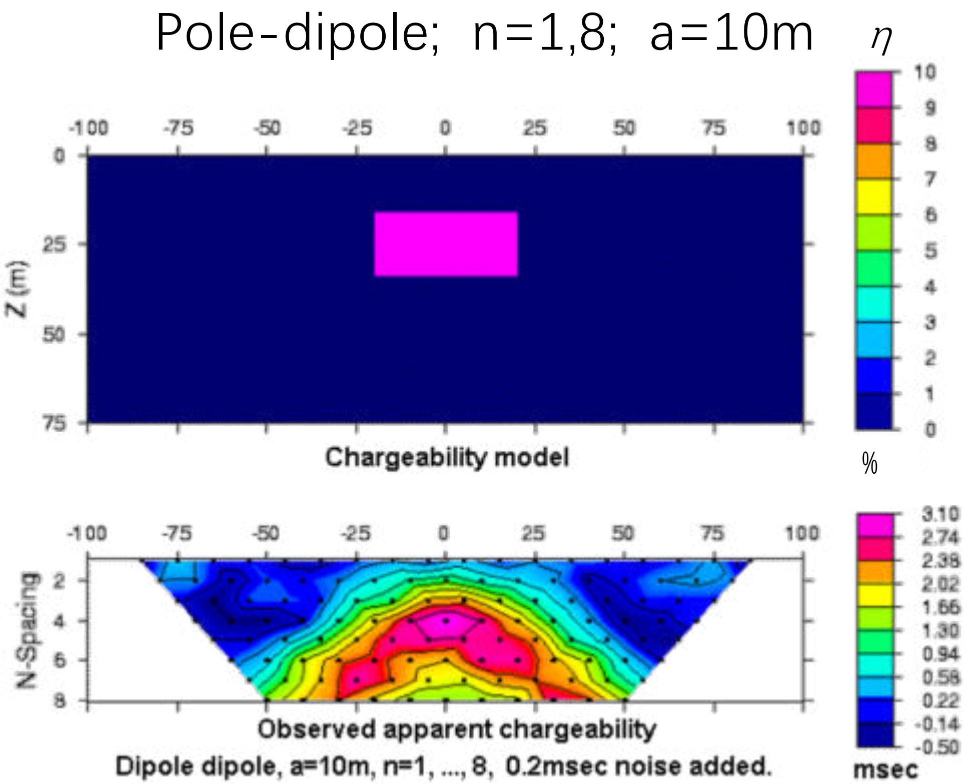
Apparent chargeability

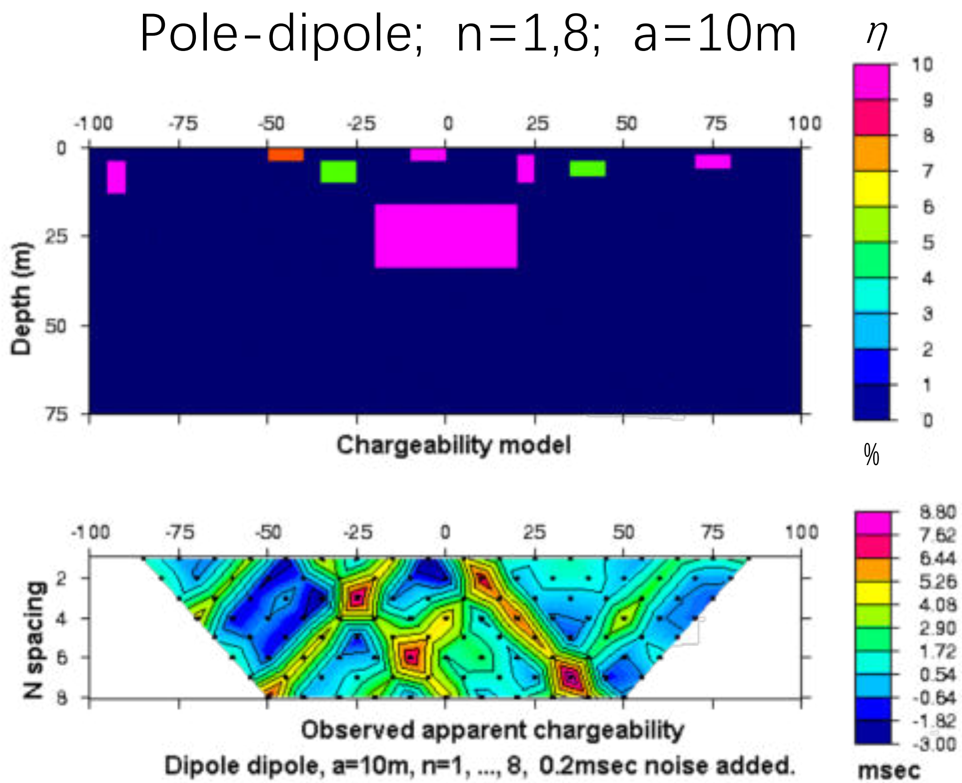
$$\eta_a = \frac{\phi_s}{\phi_\eta} = \frac{\phi_\eta - \phi_\sigma}{\phi_\eta}$$

$$\eta_a = \frac{\mathcal{F}_{dc}[\sigma(1 - \eta)] - \mathcal{F}_{dc}[\sigma]}{\mathcal{F}_{dc}[\sigma(1 - \eta)]}$$

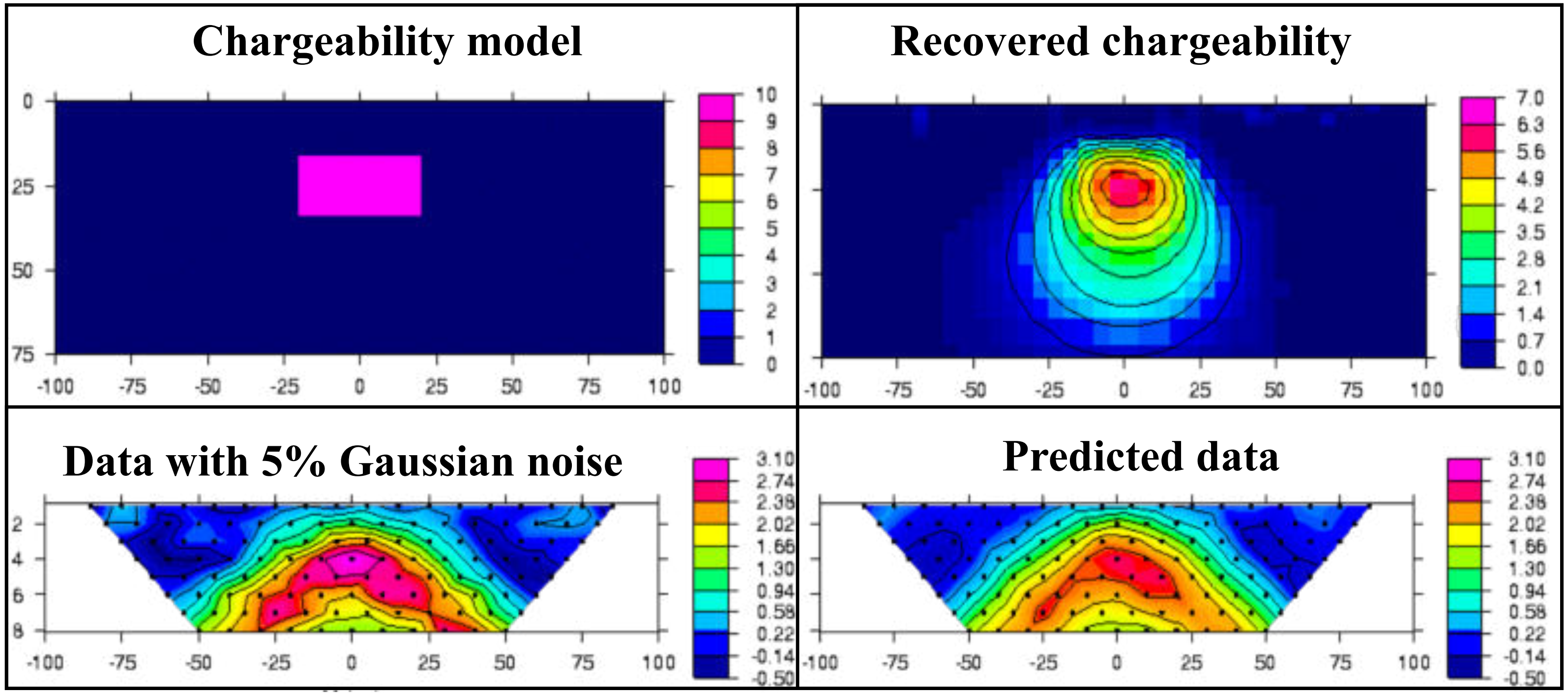
Oldenburg, D. W., and Y. Li, 1994, Inversion of induced polarization data: Geophysics, **59**, 1327-1341.

IP Data of Chargeable Blocks

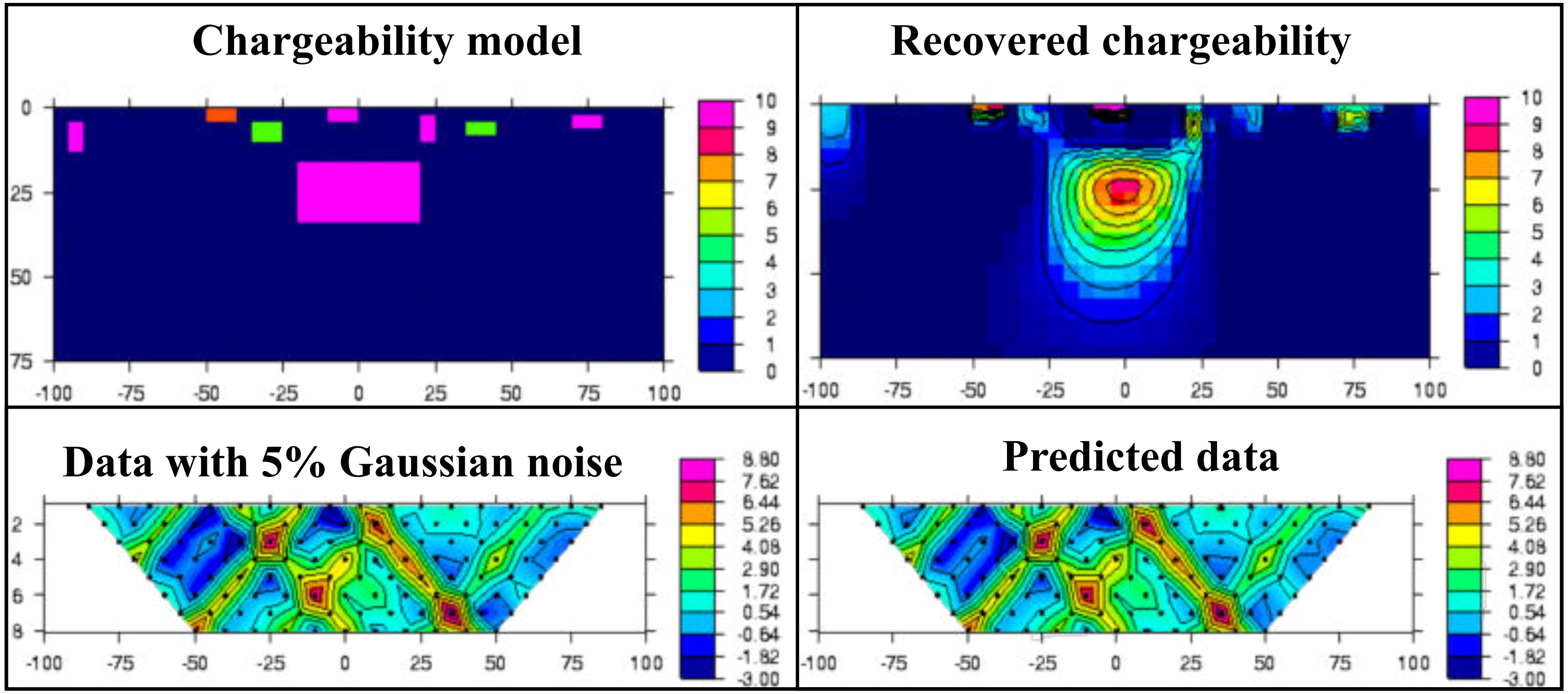




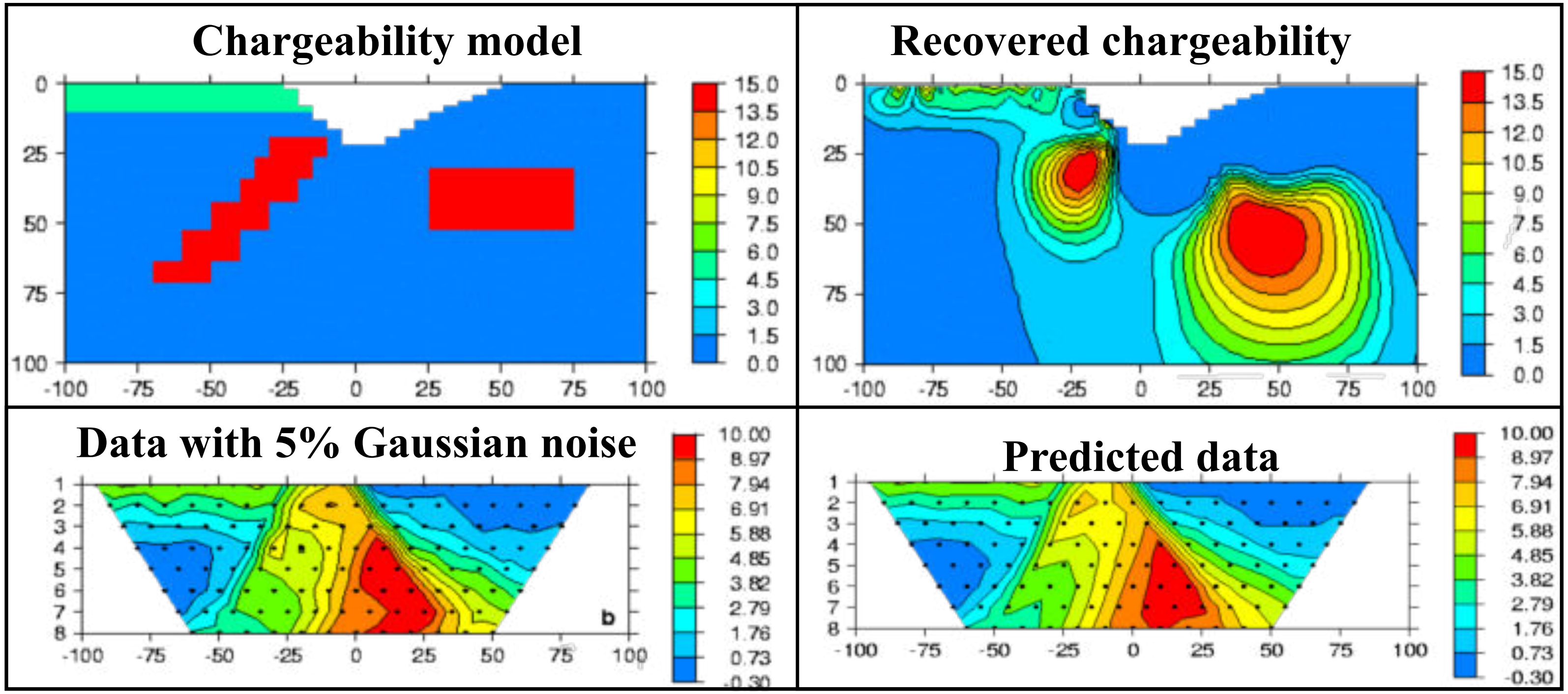
IP Inversion for Chargeability



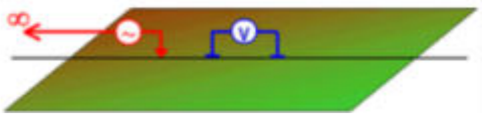
IP Inversion for Chargeability

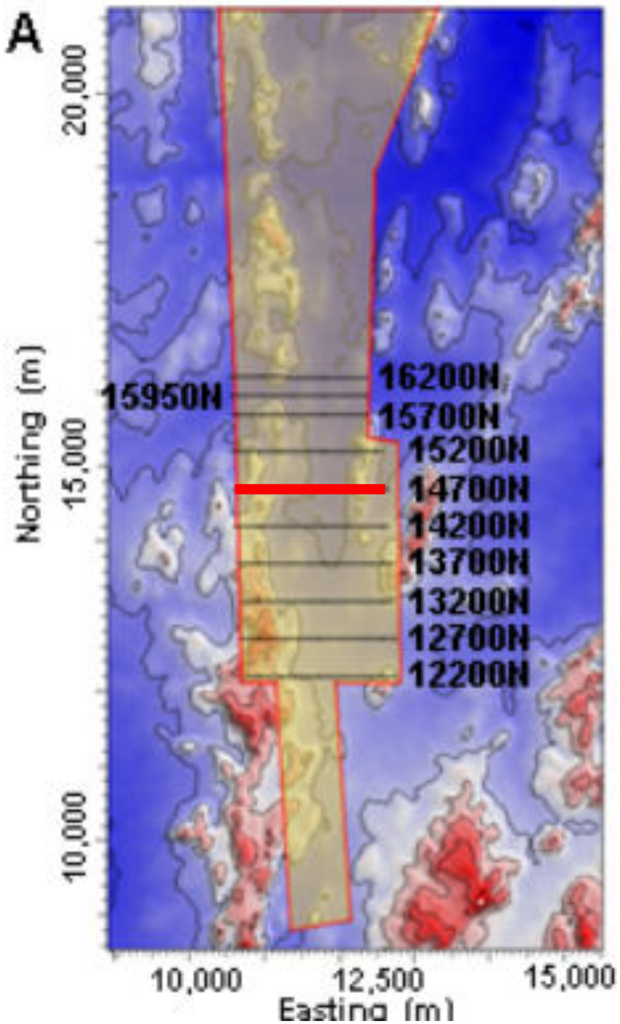


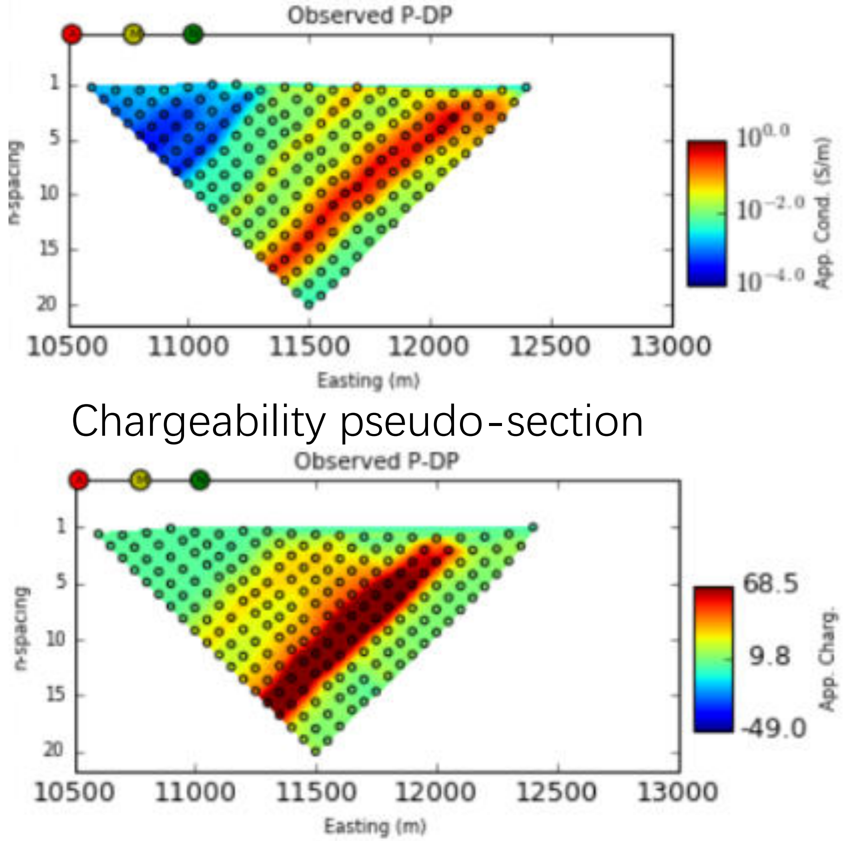
IP Inversion for Chargeability



Mt. Isa Mineral Exploration



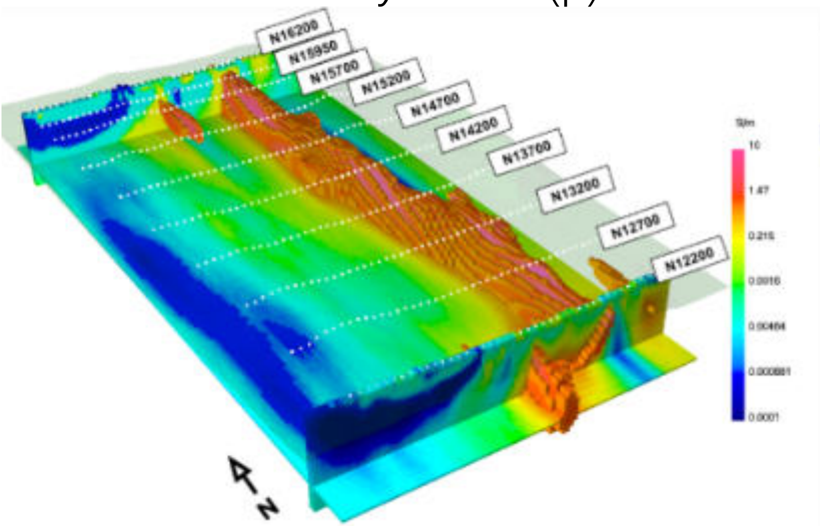




3D DC/IP Inversion

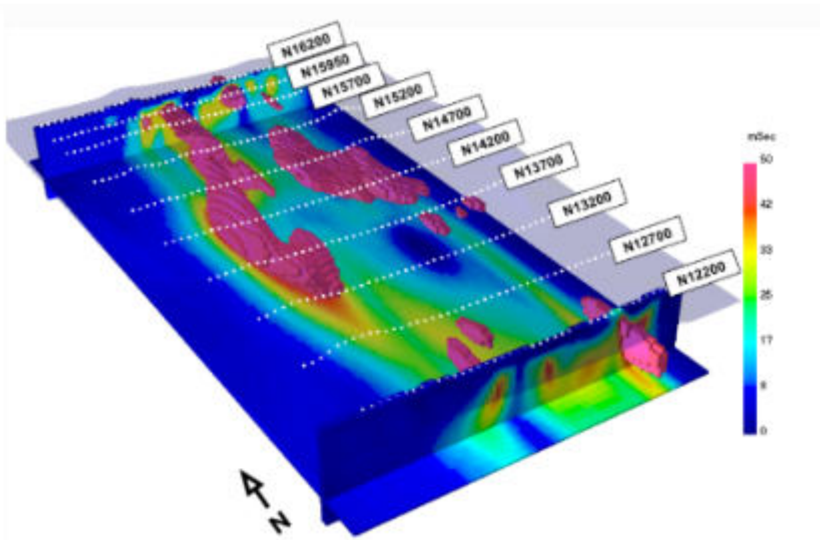
Apparent resistivity data ($\boldsymbol{\rho_a}$)

Resistivity model (ρ)



Integrated chargeability data ($\boldsymbol{d_{IP}}$)

Chargeability model (η)



Summary

- Long-electrode with steel casings
  - Novel application of old electrical methods
  - Novel simulation method – equivalent resistor network
  - AI-based imaging (deep learning)
  - Applications: shale gas fracturing, wastewater disposal, etc.
- Induced polarization (IP) method
  - Data collected with DC resistivity
  - Another physical property: chargeability
  - IP data in time-domain and frequency-domain
  - IP data inversion
  - Applications: minerals, fluid (water, oil, gas), environmental