SUSTech Southern University of Science and Technology

南方科技大学 SOUTHERN UNIVERSITY OF SCIENCE AND TECHNOLOGY

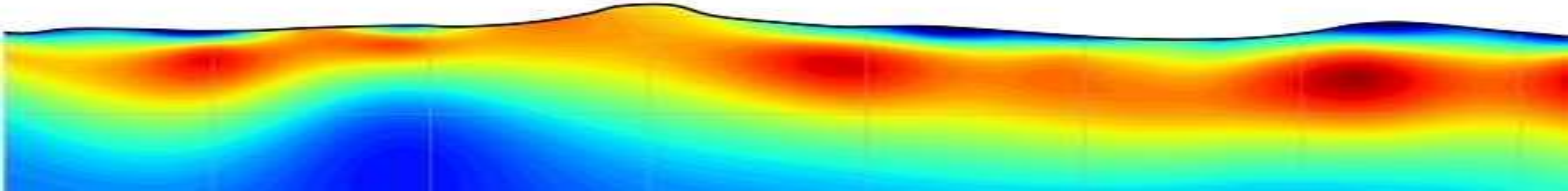
地球与空间科学系 DEPARTMENT OF EARTH AND SPACE SCIENCES

ESS302 Applied Geophysics II

Gravity, Magnetic, Electrical, Electromagnetic and Well Logging

Electrical 4: IP and More…

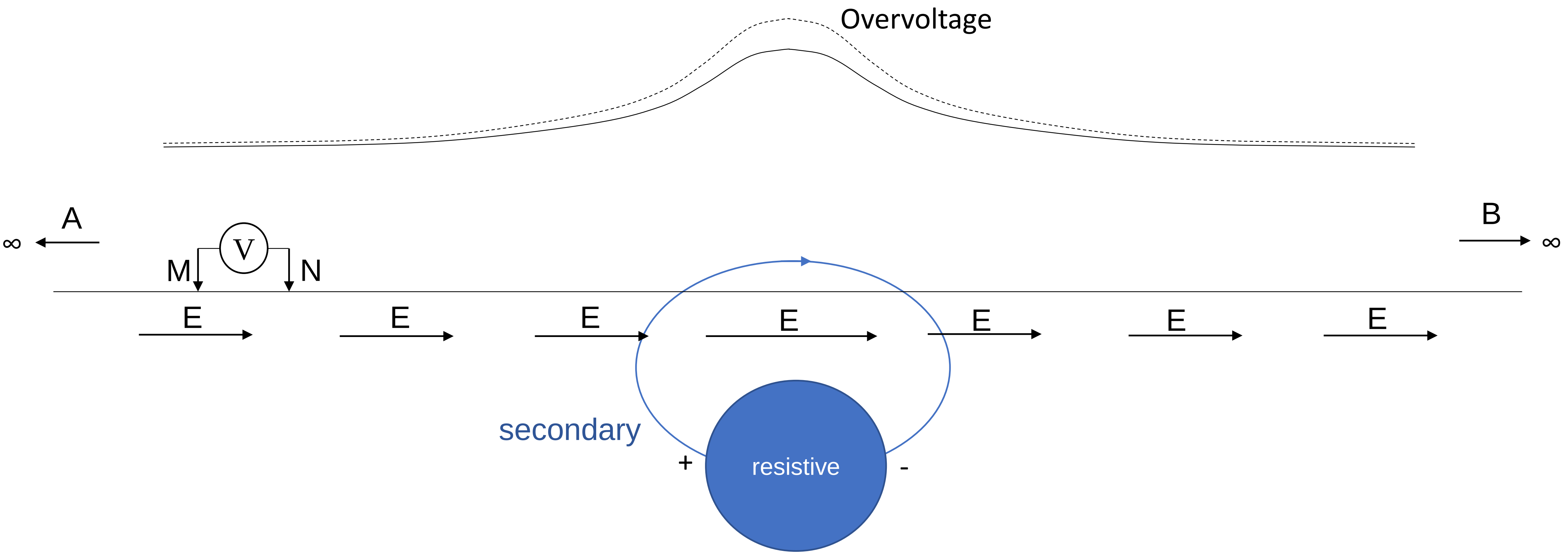
Instructor: Dikun Yang　　　Feb – May, 2019



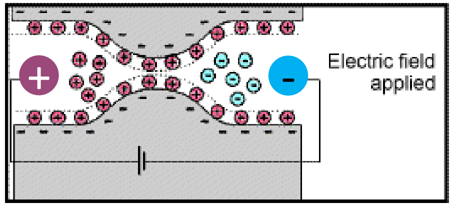
Contents

- Induced polarization (IP) effect
- Chargeability inversion
- Partial differential equation governing dc problem
- A circuit perspective
- Research frontier: steel cased wells in oilfield
- Electrical assignment

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



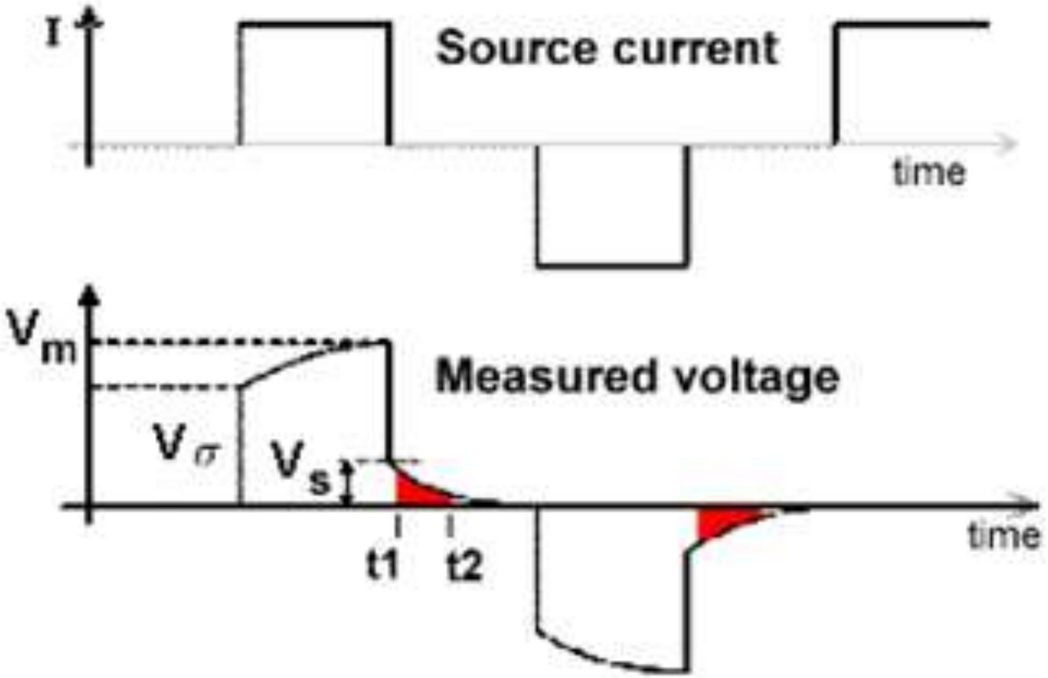
IP Effect in DC Data

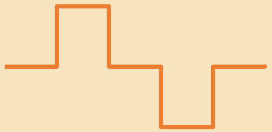
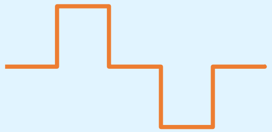
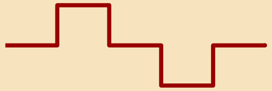
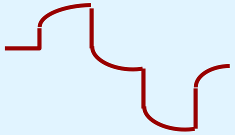
1) Voltage applied by transmitter
   → instantaneous (V_σ) increase due to ρ
2) Voltage increases as ions accumulate:

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

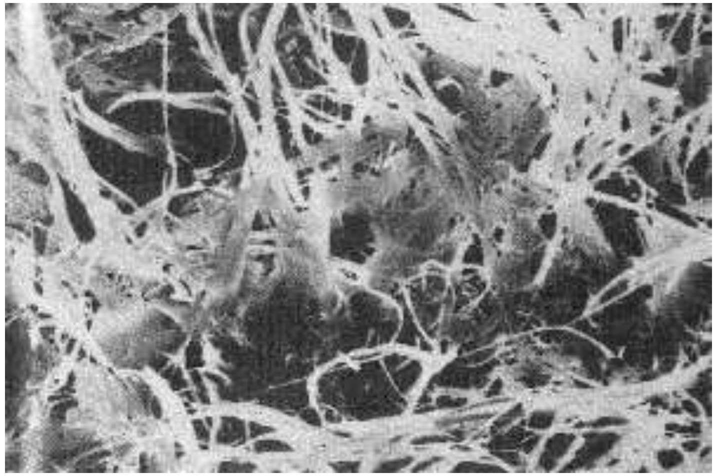
3) Saturation of ionic charges
   → DC voltage ($V_m = V_\sigma + V_s$)
4) Voltage from transmitter removed
   → instantaneous loss in secondary potential (equal to V_σ)
5) IP voltage discharges during off-time

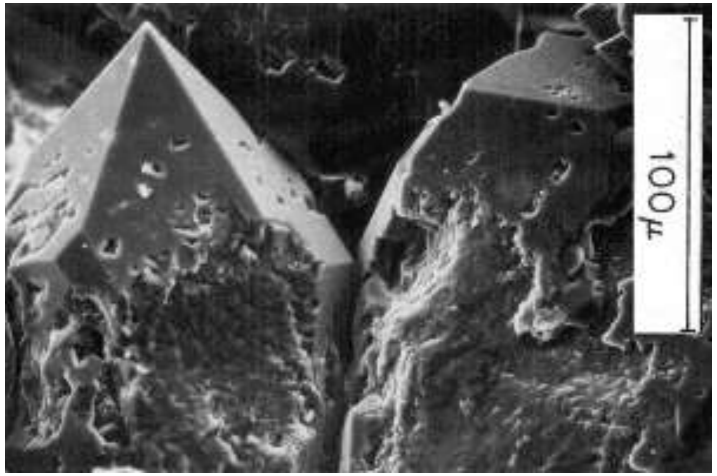
$$V_{off}(t) = V_s\, e^{-t/\tau}$$



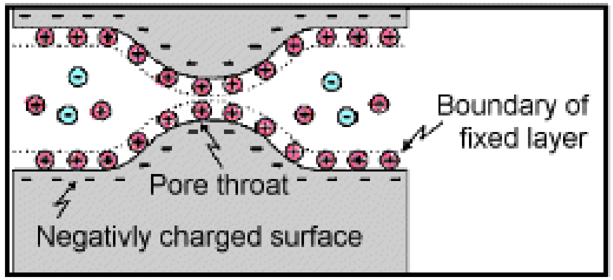
	Not chargeable	Chargeable
Source (Amps)		
Potential (Volts)		

Chargeability – Capability of Holding Charges

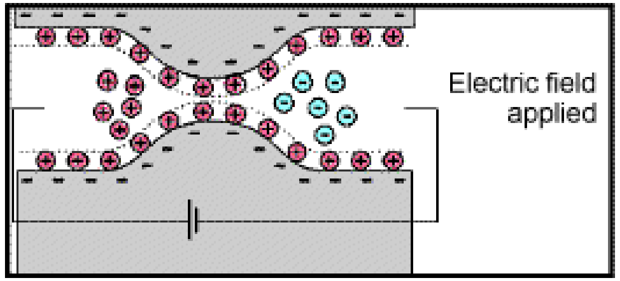




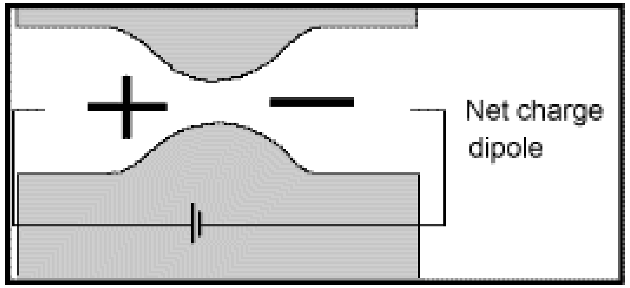
Type 1: Membrane polarization - ions accumulate at pore throat



Equilibrium State

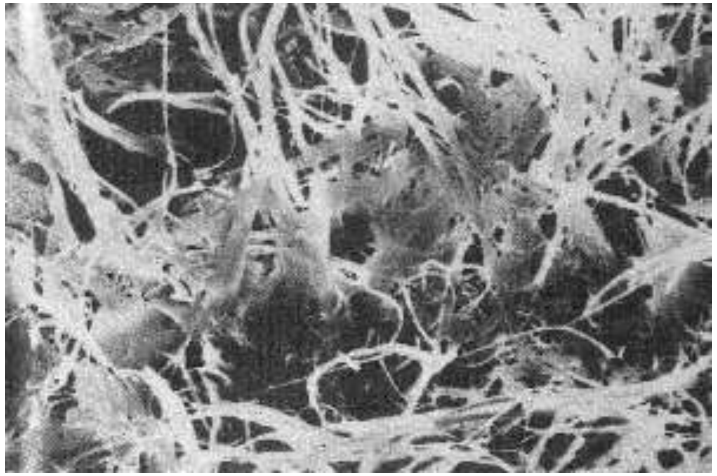


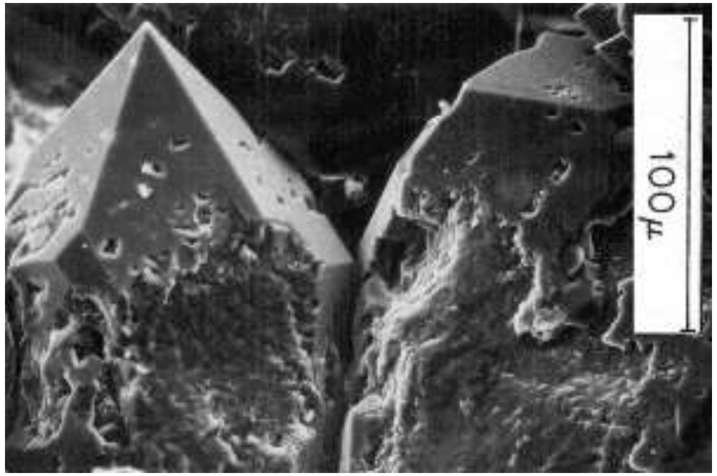
Voltage Applied



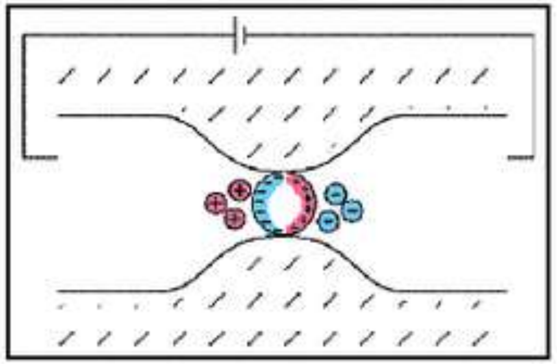
Separation of +ve and –ve ions

Chargeability – Capability of Holding Charges



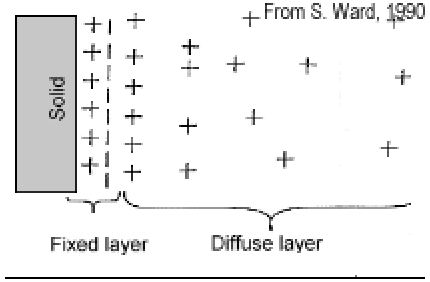


Type 2: Electrode polarization: Ions accumulate at metals



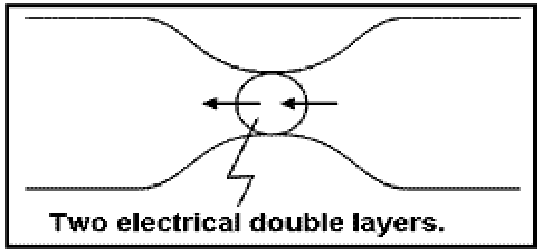
- Pore space is blocked by metallic particles
- Metallic particles become electrically charged and attract nearby ions
- This is why the waveform of dc survey switches polarity

Electric double layer



Hypothetical anomalous ion distribution near a solid-liquid interface.

Net electric dipole moment

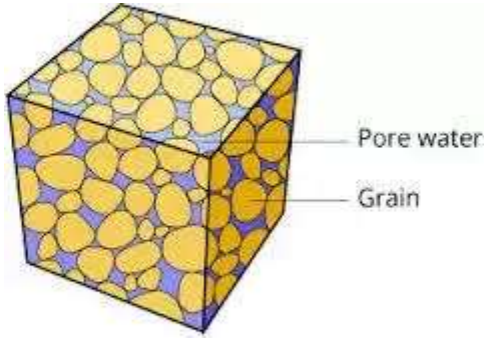


Chargeability – A Diagnostic Physical Property

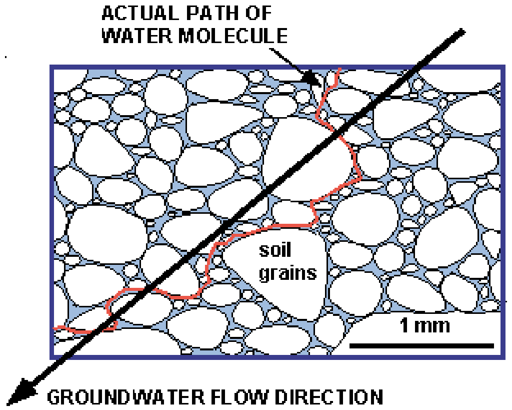
Chargeability is not thoroughly understood in theory but it is often related to:

Sulphide Mineralization

Clays



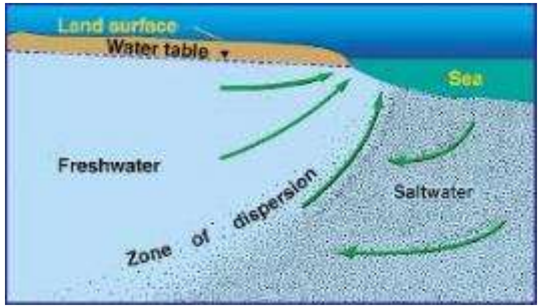
Pore-Water Salinity



Tortuosity

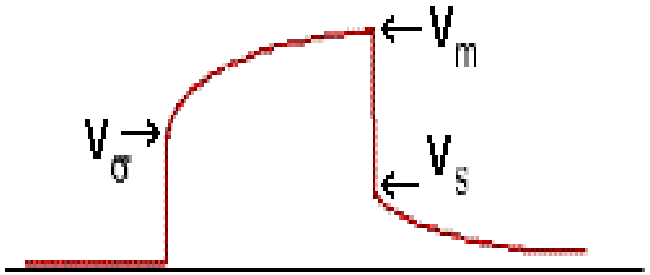
Use chargeability to characterize the earth:

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



Time-domain IP Data

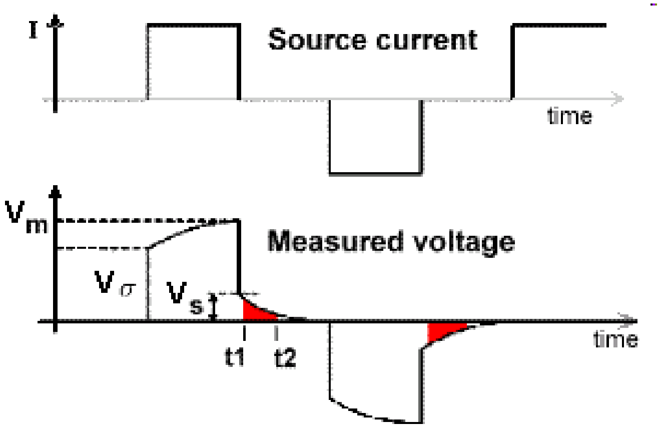
Intrinsic chargeability (dimensionless) $$\eta = \frac{V_s}{V_m}$$



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

Integrate over the decay (discharge period)

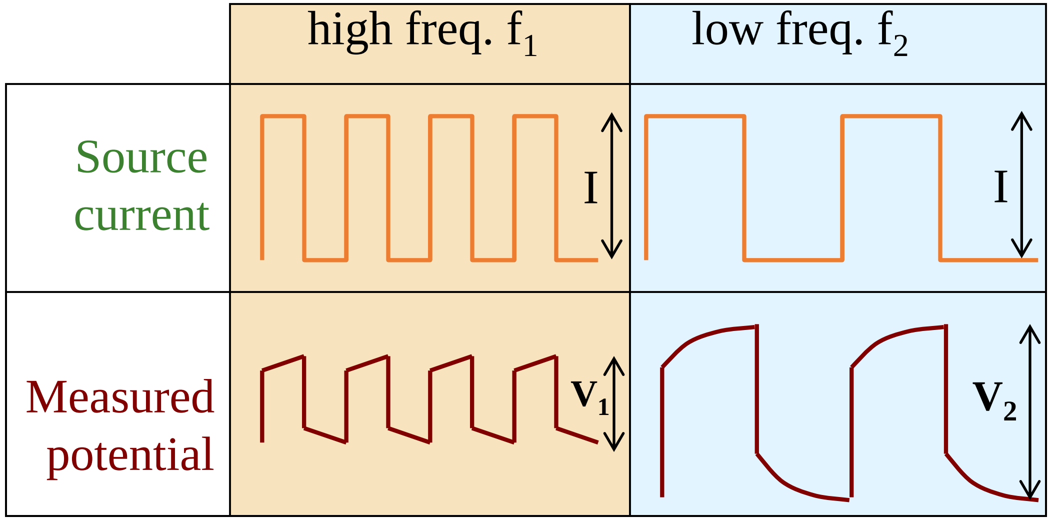
$$d_{IP} = \frac{1}{V_m}\int_{t_1}^{t_2} V_s(t)dt$$ (msec)



Frequency-domain IP Data

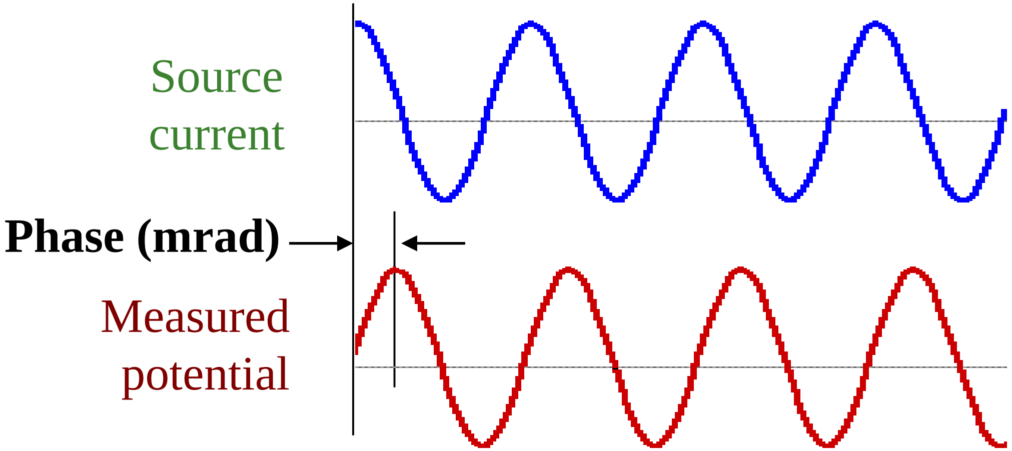
Percent frequency effect:

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

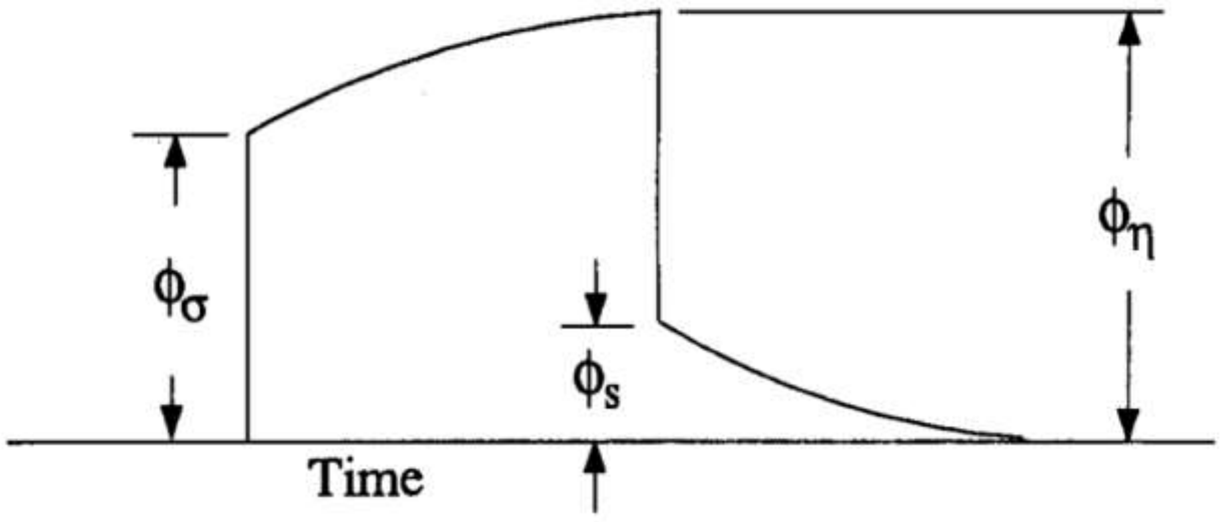


Phase:

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



IP Modeling



Chargeability: alter conductivity

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

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

Apparent chargeability

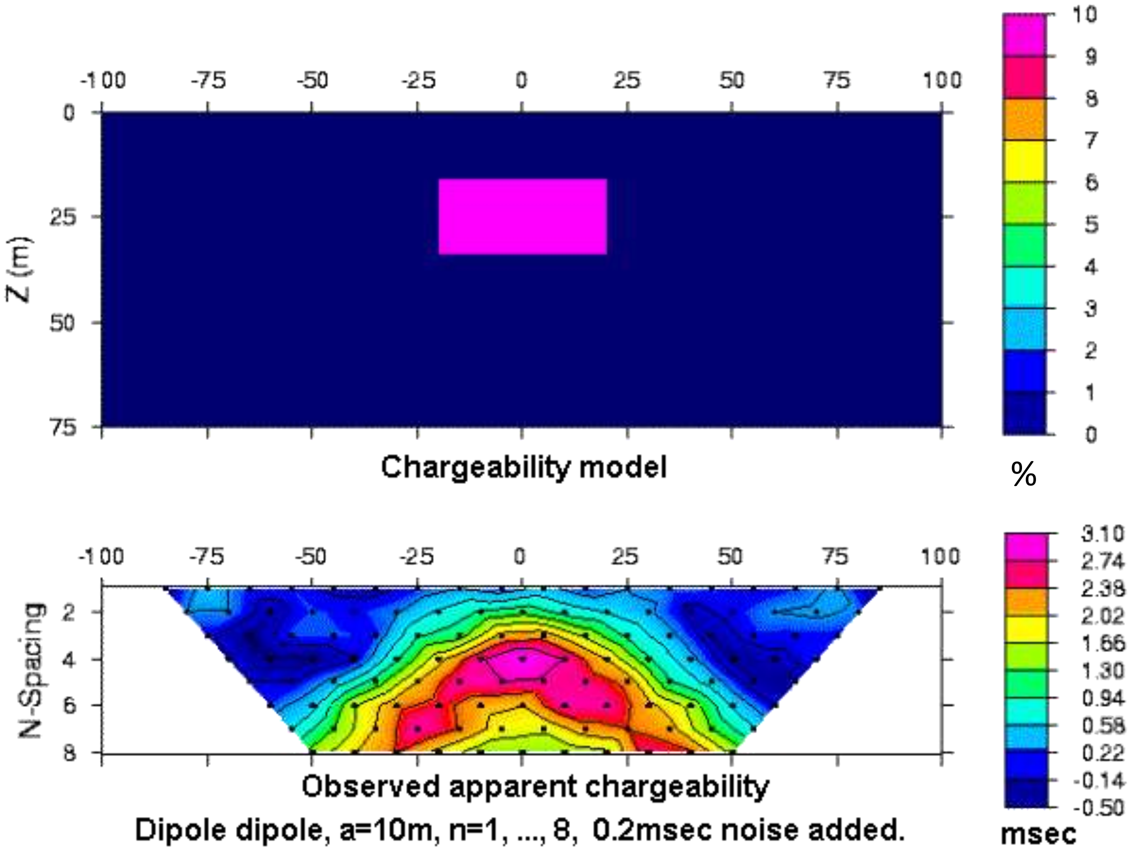
$$\eta_a = \frac{\phi_s}{\phi_\eta} = \frac{\phi_\eta - \phi_\sigma}{\phi_\eta}$$

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

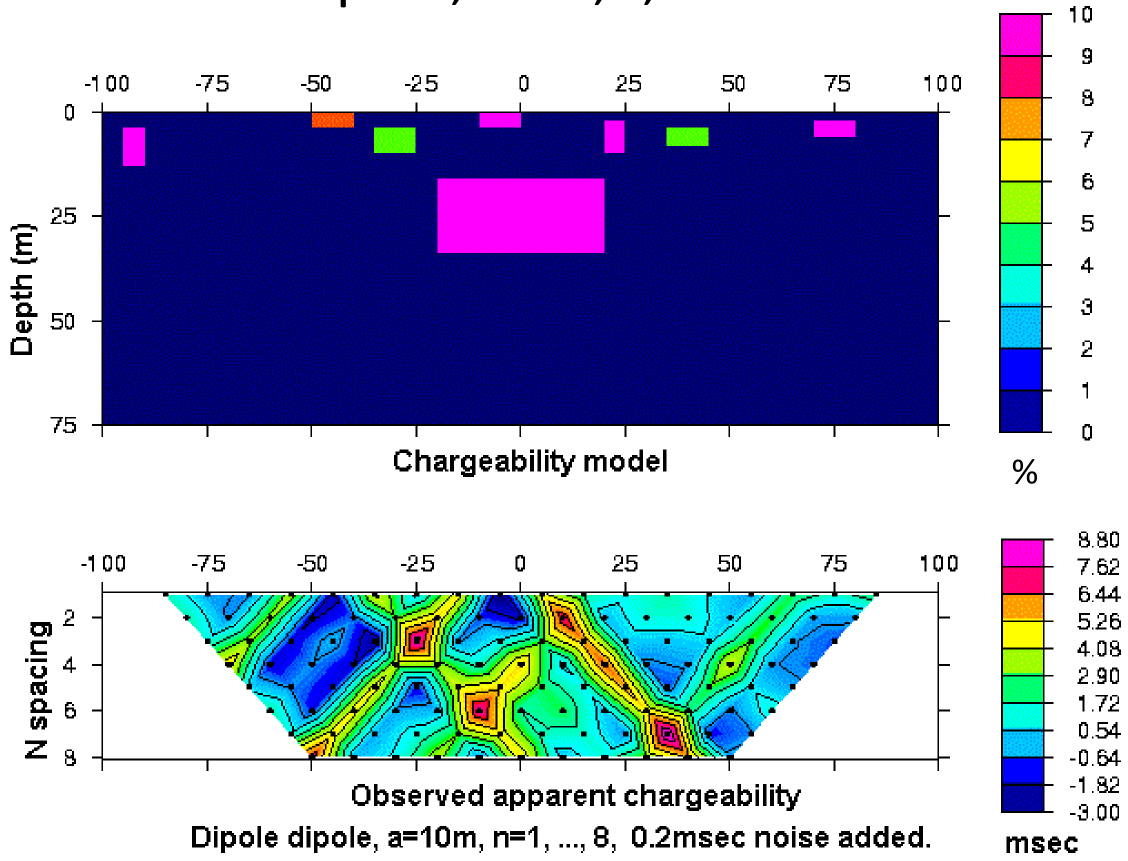
Oldenburg, D. W., and Y. Li, 1994, Inversion of induced polarization data: Geophysics, **59**, 1327-1341.

IP Data of Chargeable Blocks

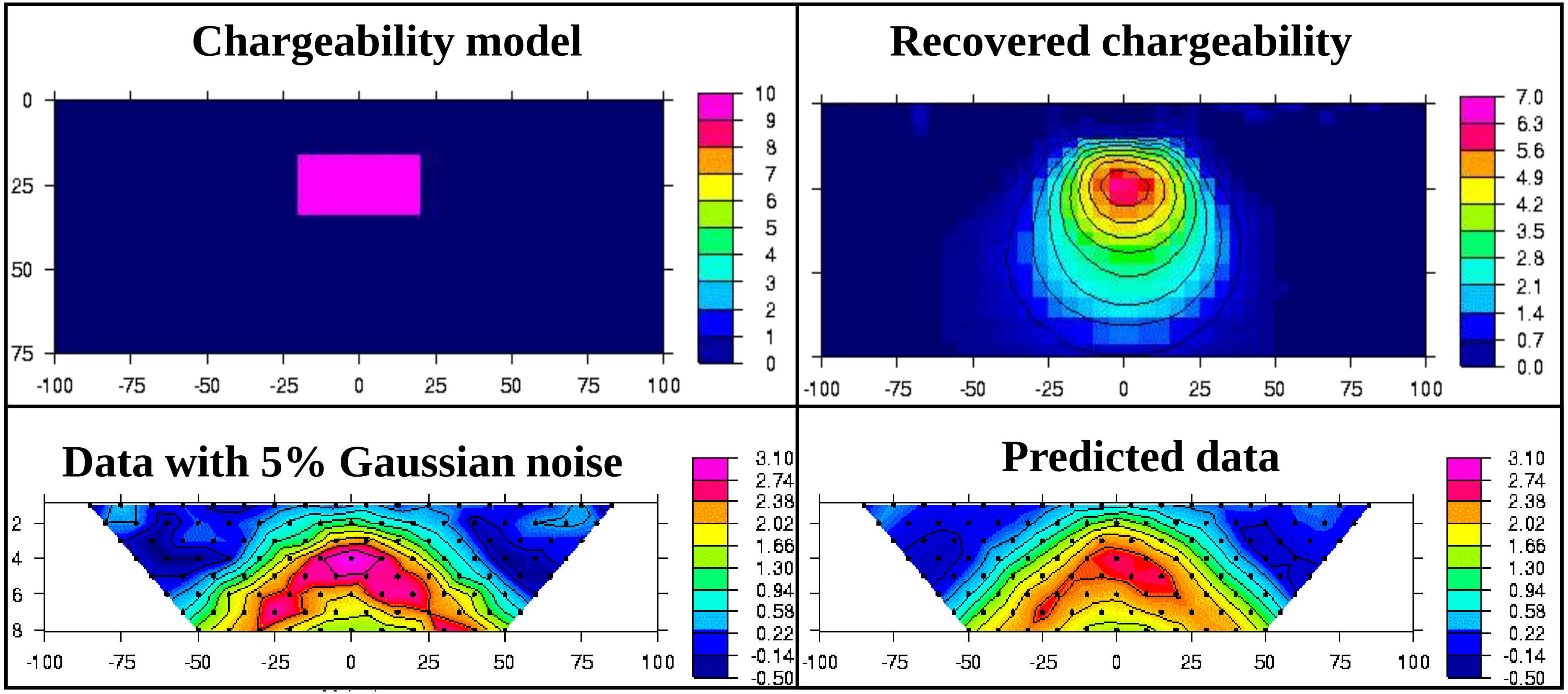
Pole-dipole; n=1,8; a=10m



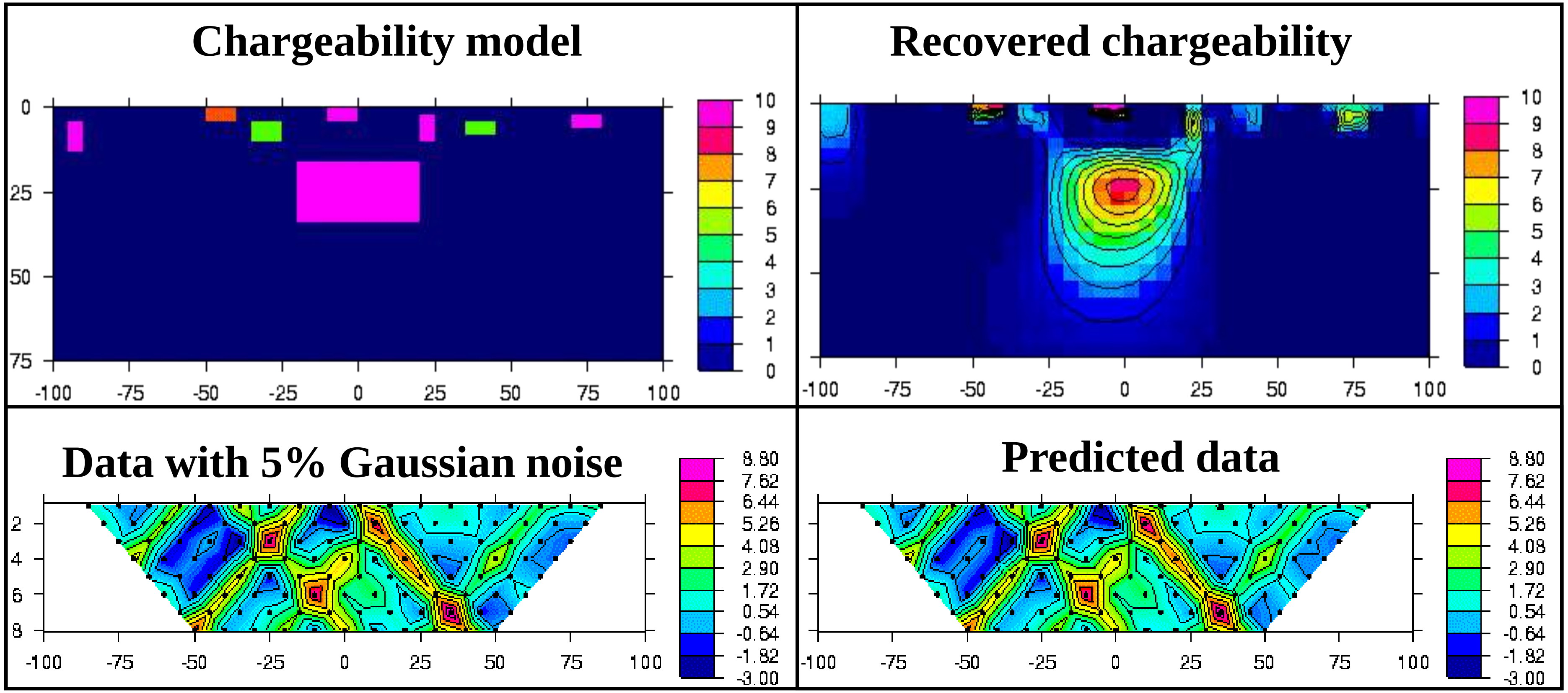
Pole-dipole; n=1,8; a=10m



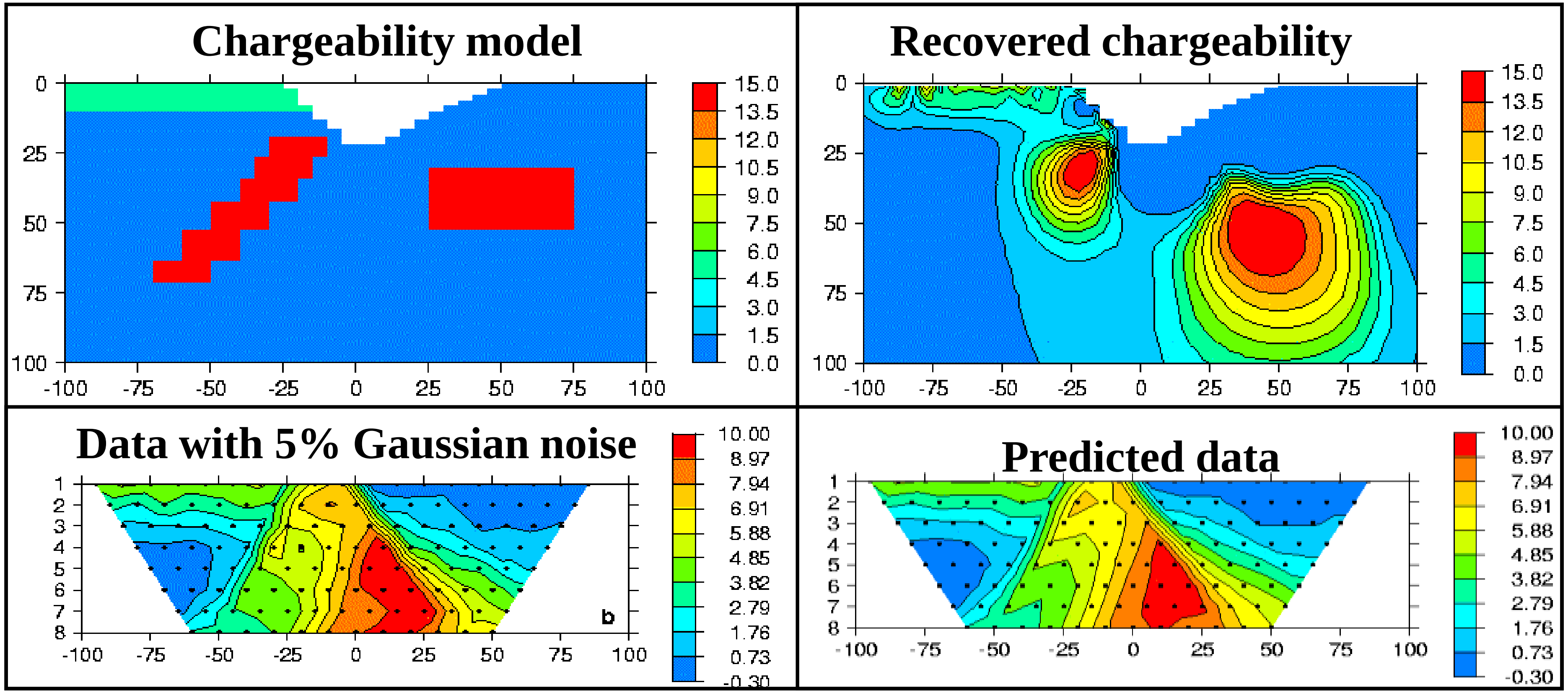
IP Inversion for Chargeability



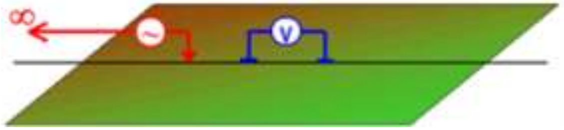
IP Inversion for Chargeability

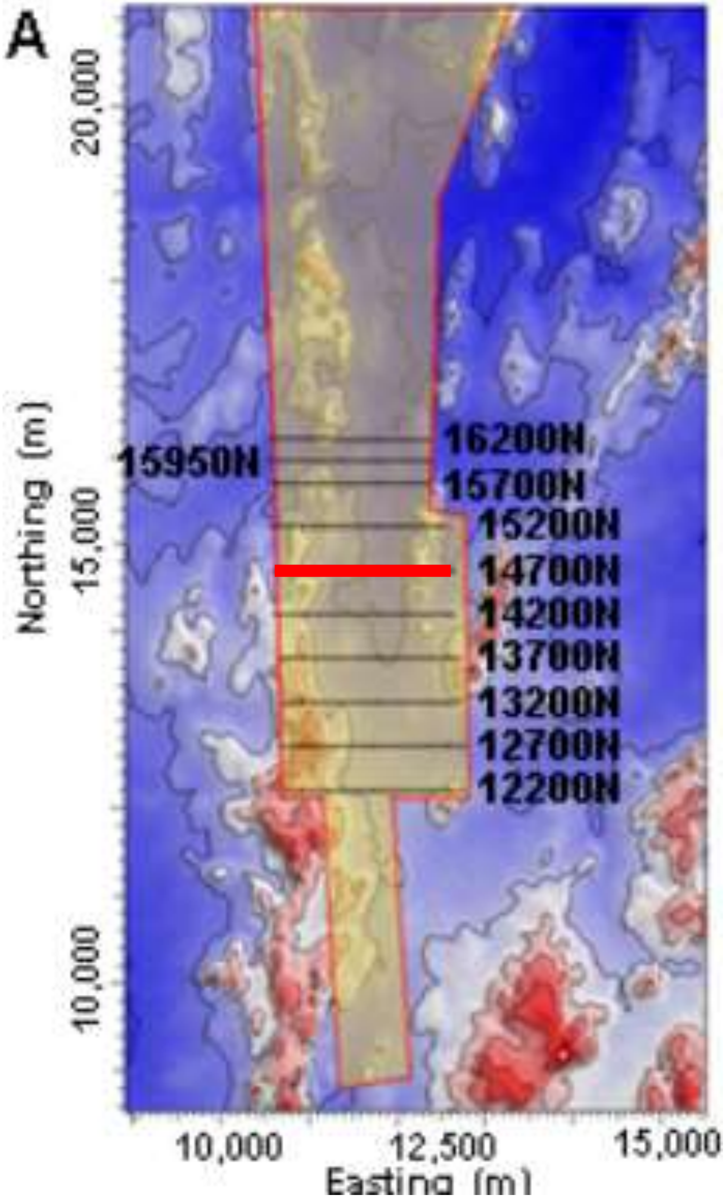


IP Inversion for Chargeability

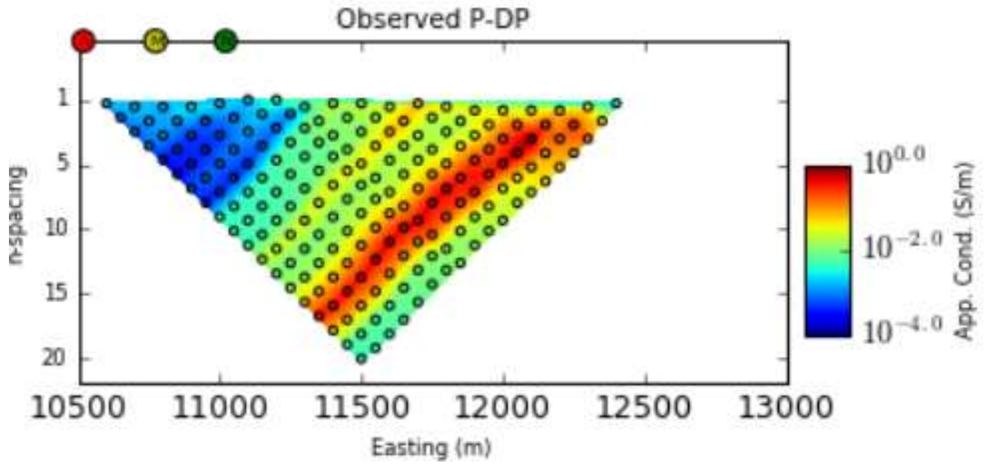


Mt. Isa Mineral Exploration

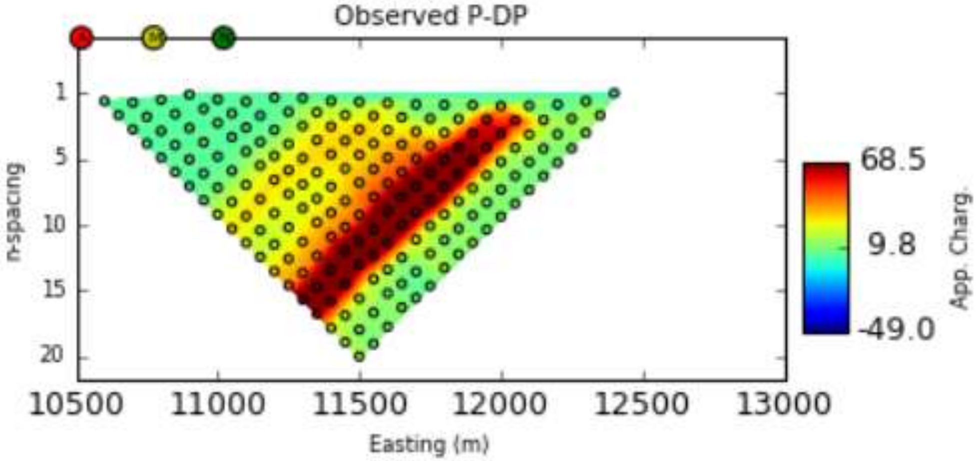




Conductivity pseudo-section



Chargeability pseudo-section



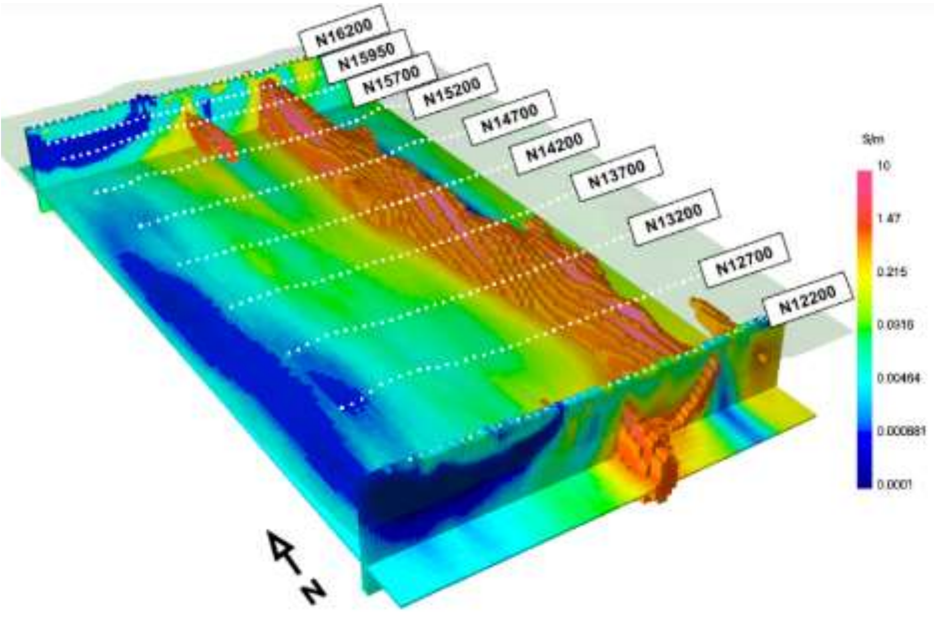
3D DC/IP Inversion

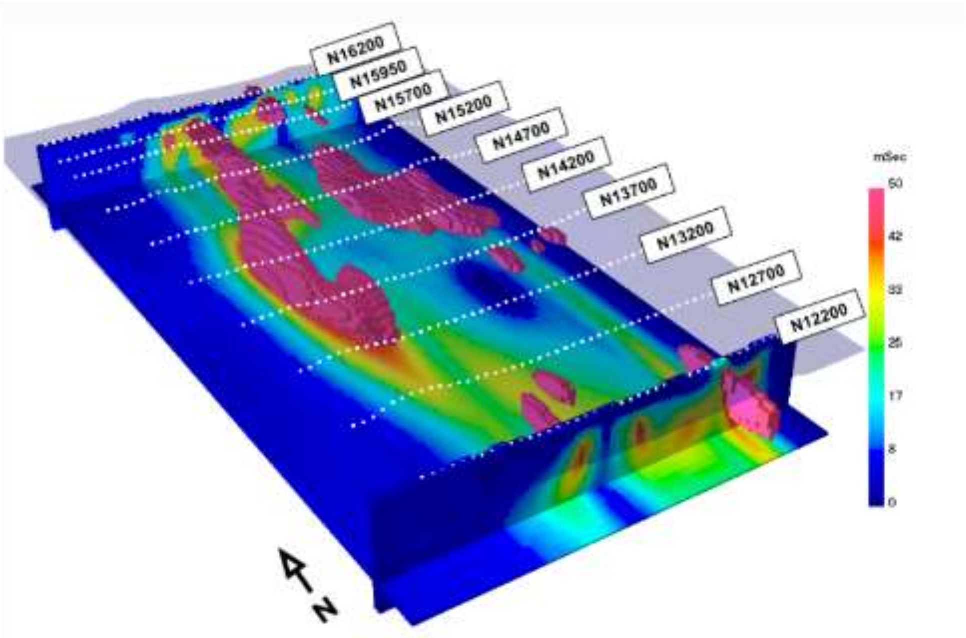
Apparent resistivity data ($\boldsymbol{\rho_a}$)

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

Resistivity model (ρ)

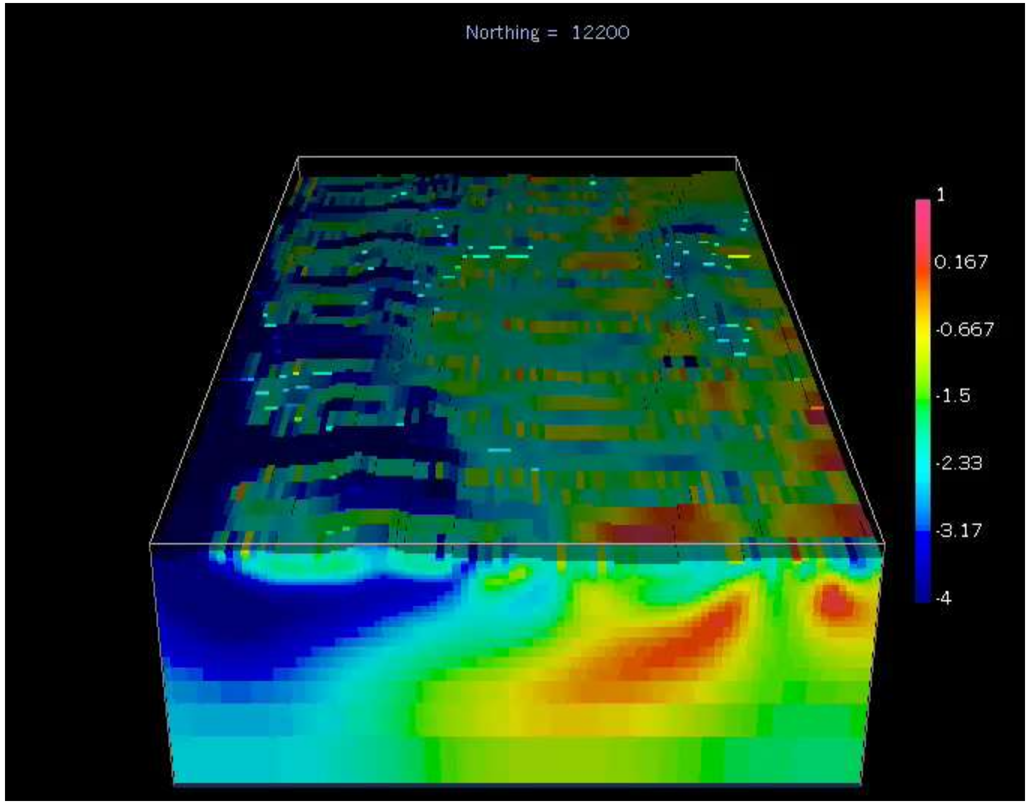
Chargeability model (η)



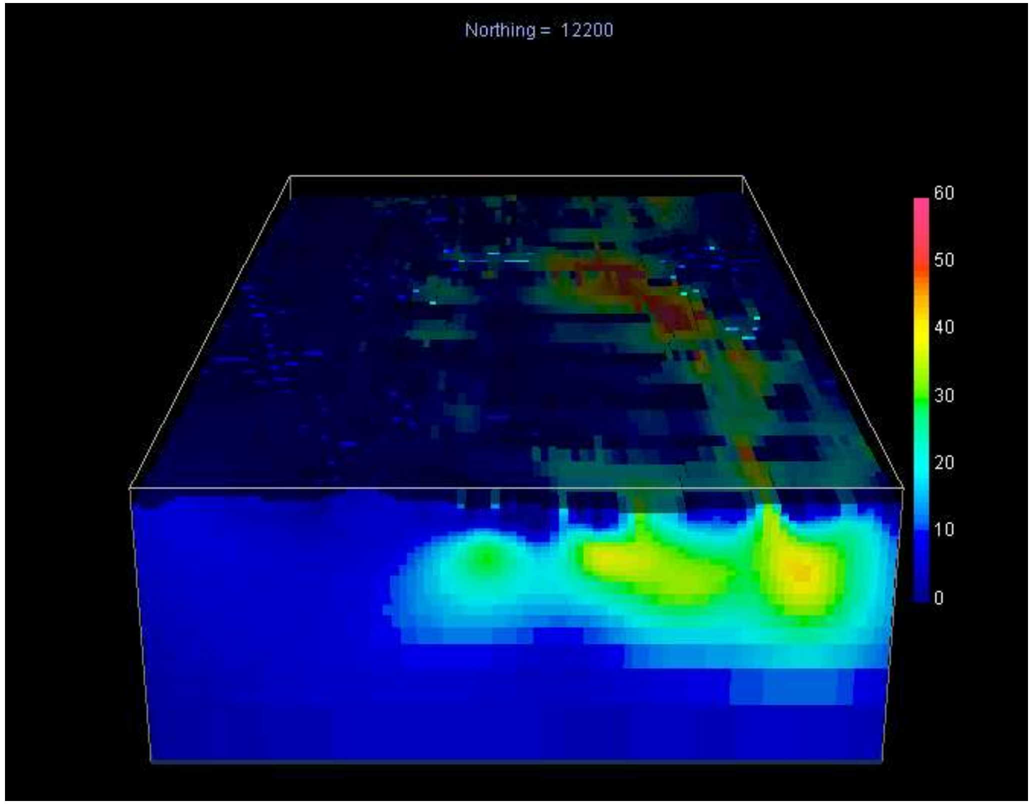


Consistent Models?

Volume rendered resistivity model



Volume rendered chargeability model



Governing Equation

$\mathbf{J} = \sigma \mathbf{E}$ Ohm's Law

$\mathbf{E} = \nabla V$ The electric field is the gradient of a scalar potential

$\nabla \cdot \mathbf{J} = -\partial Q / \partial t$ The divergence of current density equals the rate of change of free charge density

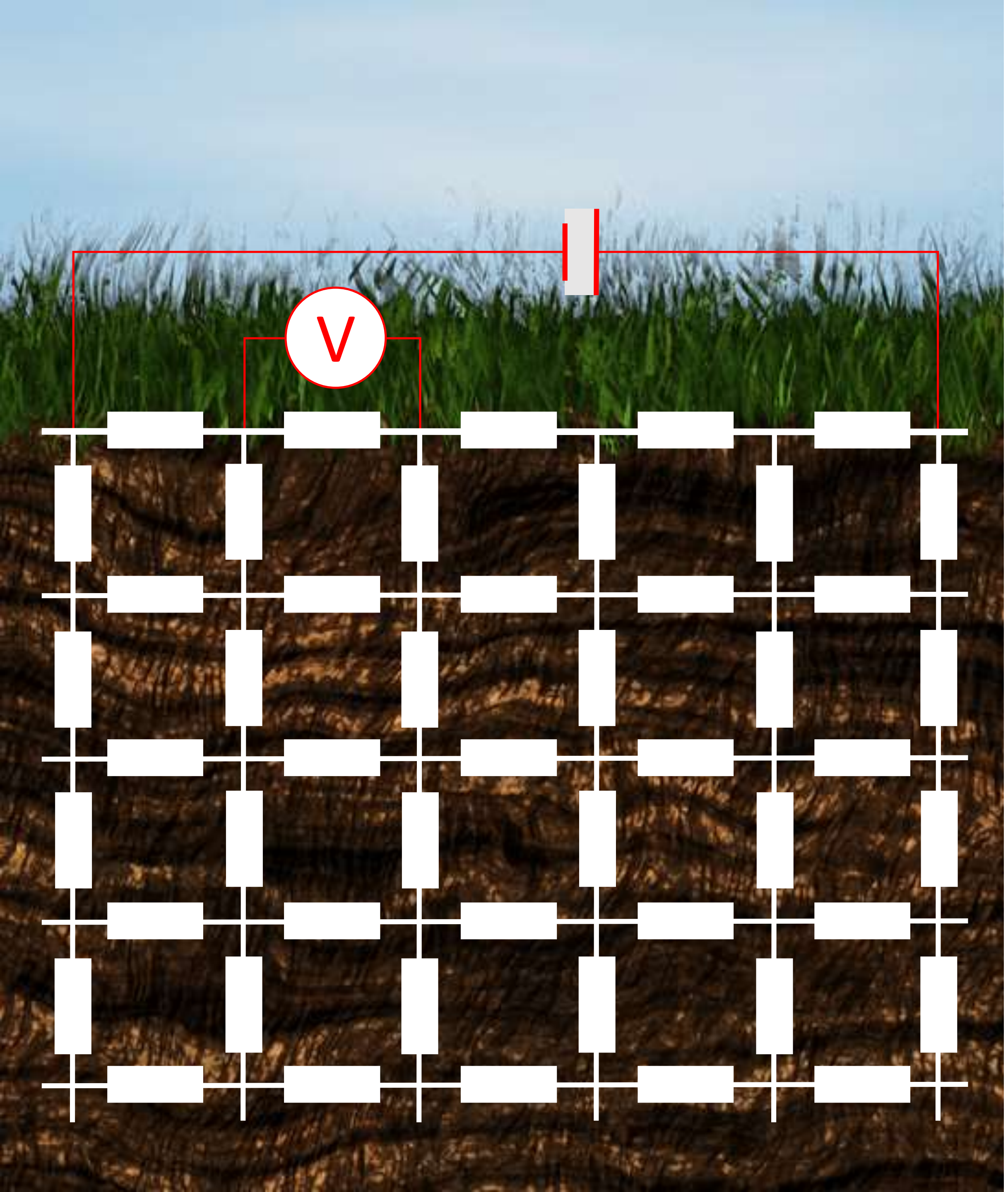
$$\nabla \cdot (\sigma \nabla V) = -\partial Q / \partial t$$

$$\boxed{\nabla \cdot (\sigma \nabla V) = -I\delta(\boldsymbol{r} - \boldsymbol{r}_s)}$$

With two boundary conditions:

(1) The change of potential across the free surface is zero ($\partial V/\partial n=0$ at $z=0$)

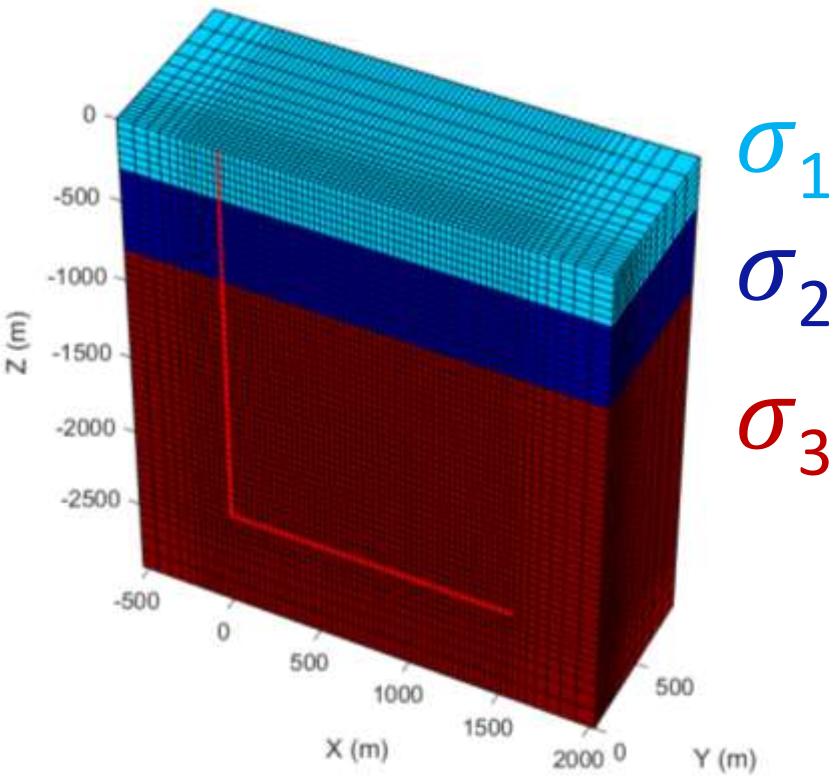
(2) V approaches 0 as $r-r_s$ approaches infinity

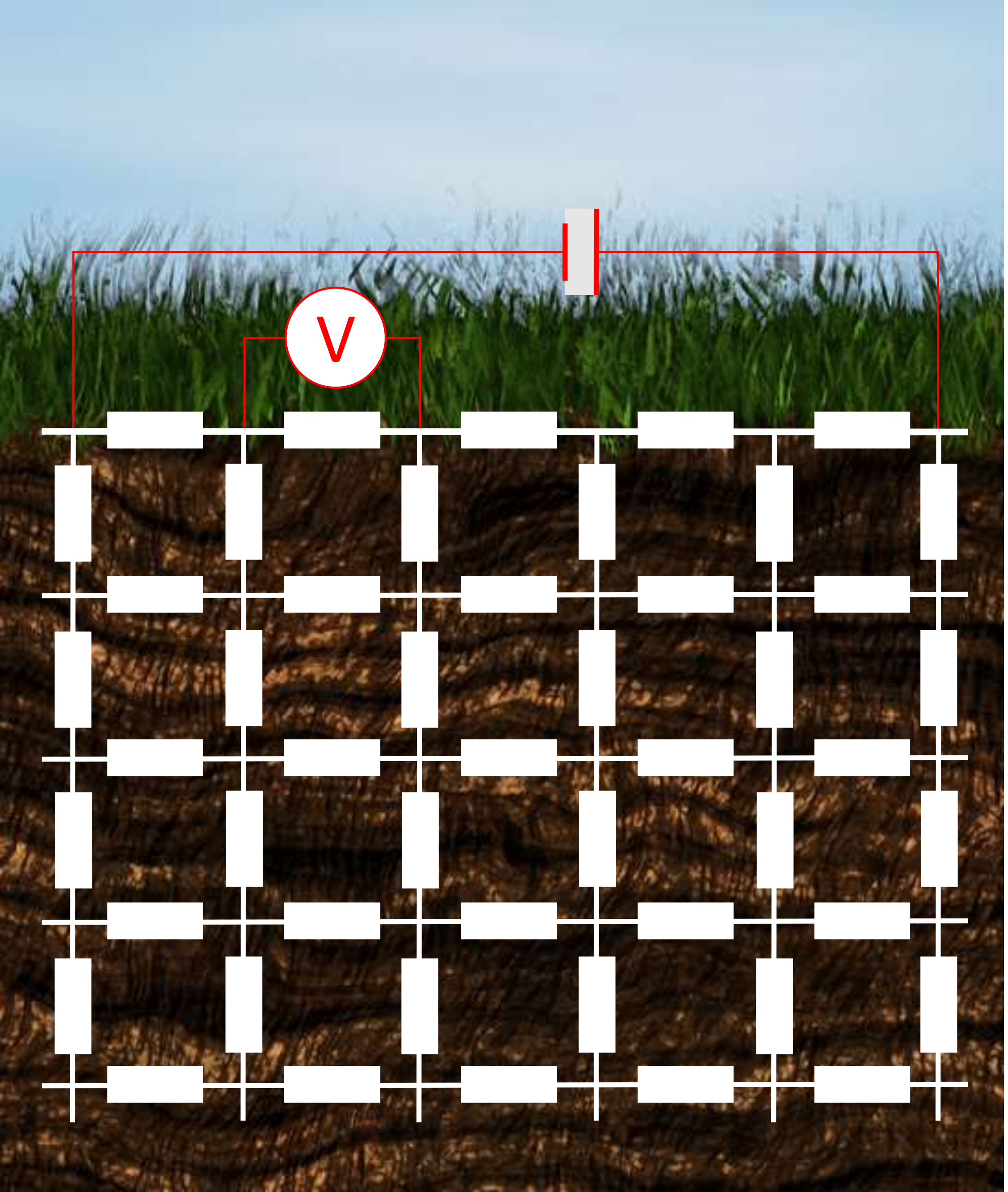


A circuit perspective

A 3D mesh:

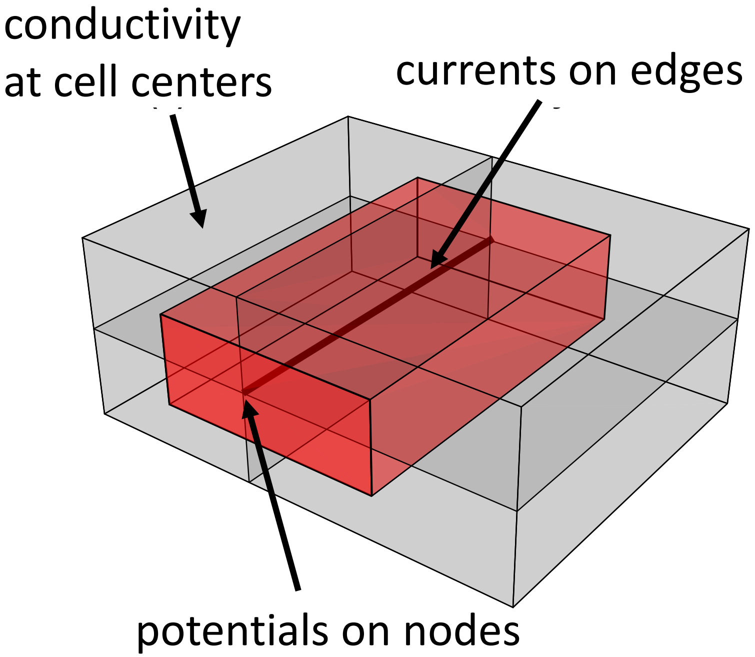
- Cell center: conductivity

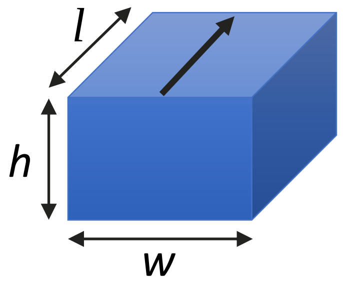




A circuit perspective

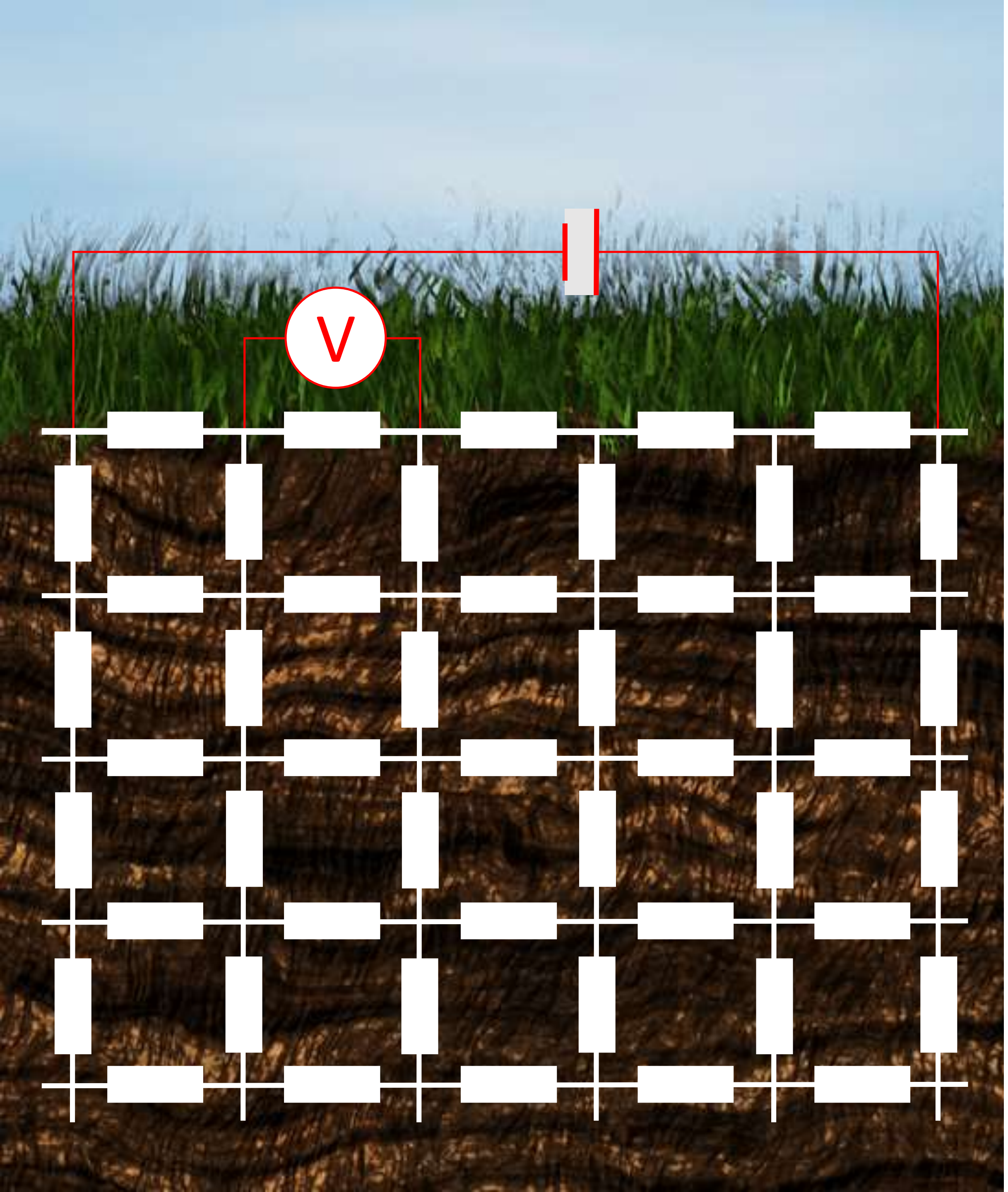
A 3D mesh:
- Cell center: conductivity
- Cell node: potential
- Cell edge: E-field, conductance and current





Conductivity to conductance

$$G = \frac{wh\sigma_c}{\ell}$$



A circuit perspective

Kirchhoff's current law

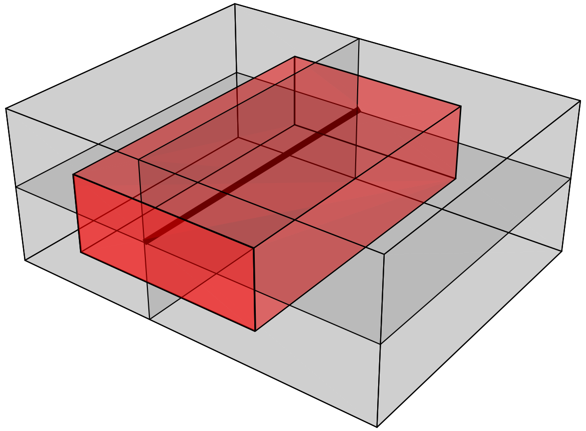
$$-\mathbf{G}^\top \mathbf{R}^{-1} \mathbf{G} \phi = \mathbf{I_s}$$

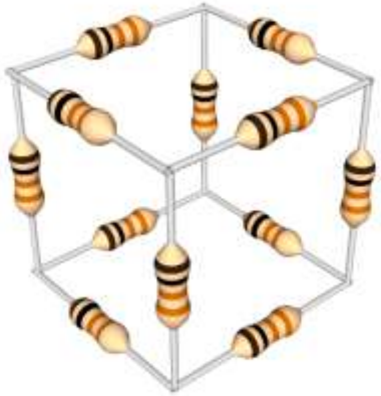
ϕ : electrical potential

$\mathbf{G}$: differential matrix of 1 and -1

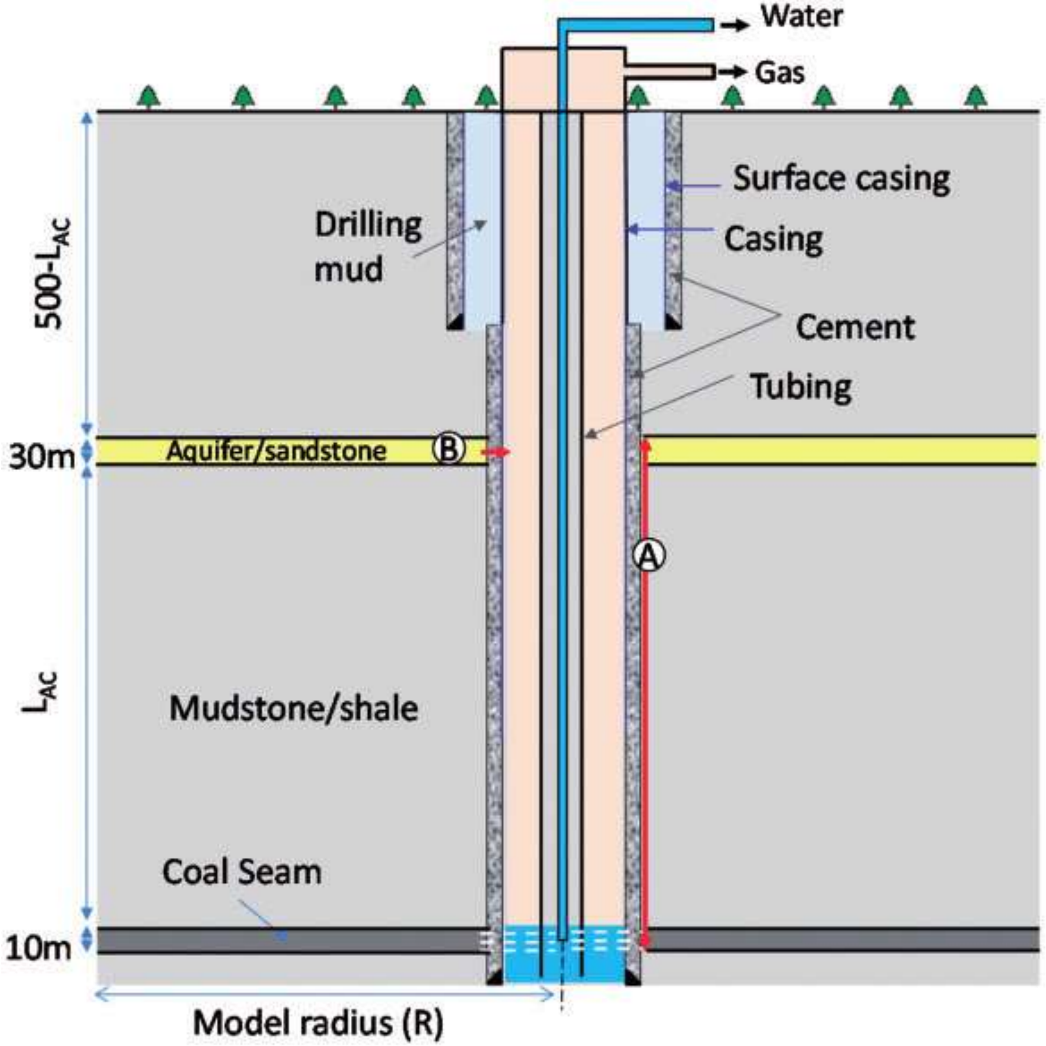
$\mathbf{R}$: resistance diagonal matrix

$\mathbf{I_s}$: current source intensity

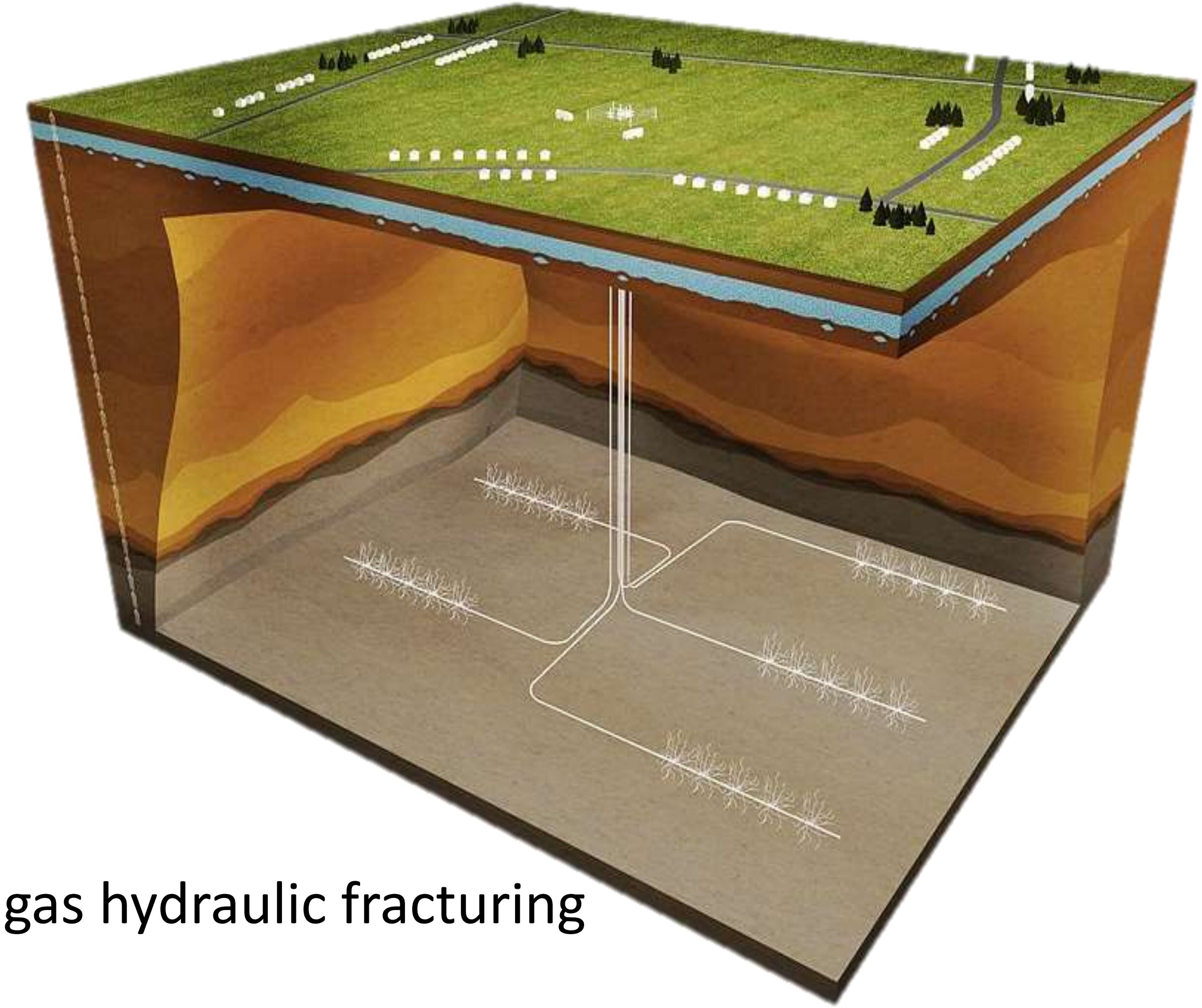




Electrical Modeling of Steel Casings

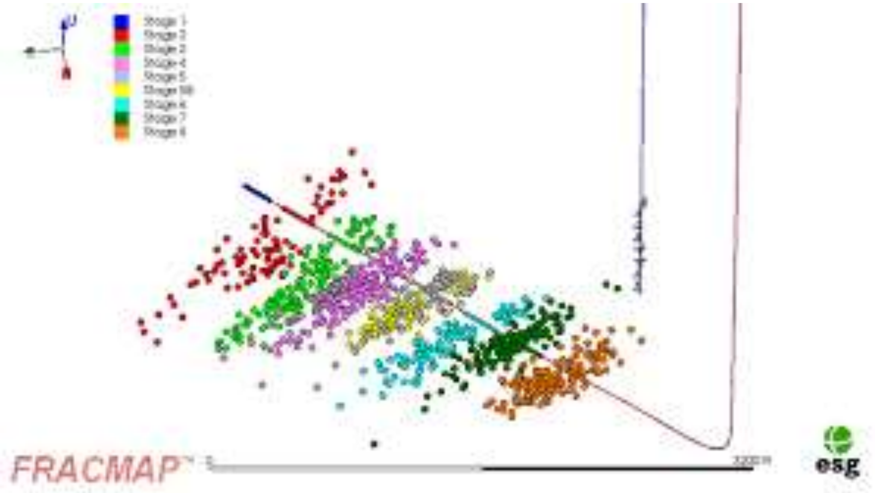


Monitoring of Injected Fluid



Shale gas hydraulic fracturing

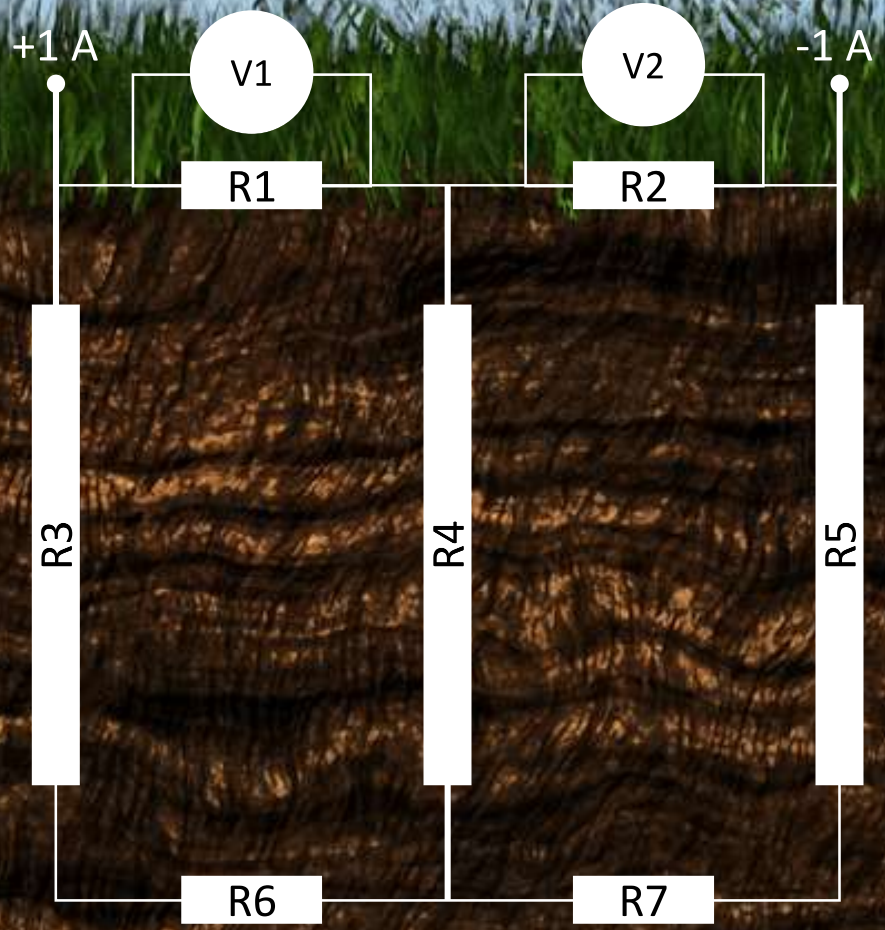
Micro-seismic



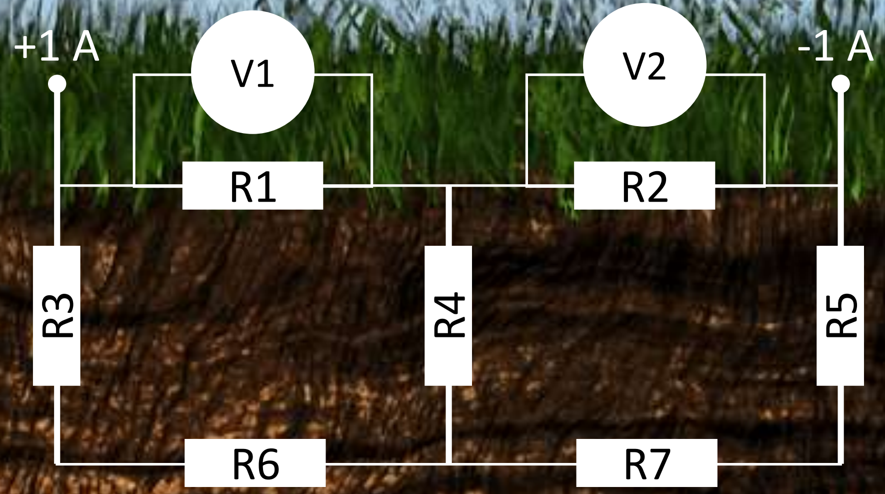
But where is fluid?

- Pumping schedule
- Groundwater contamination
- Induced seismicity

Conventional Surface DC Resistivity



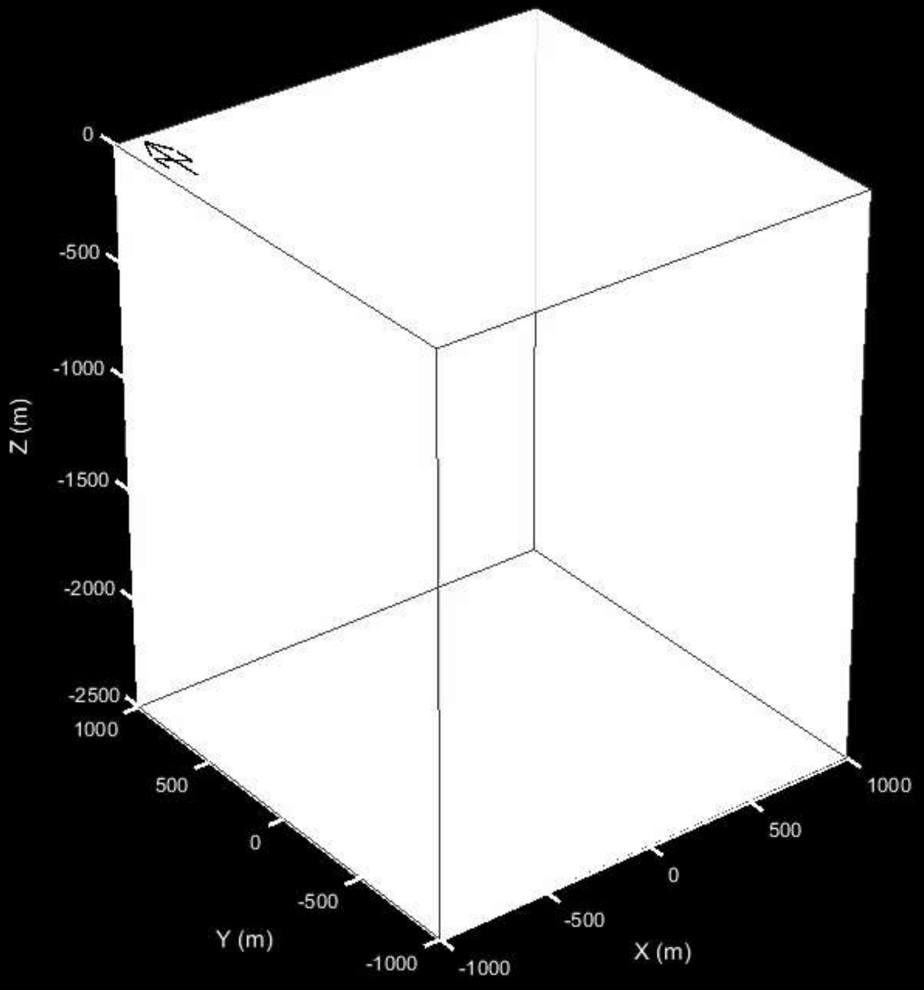
Long-electrode DC Resistivity

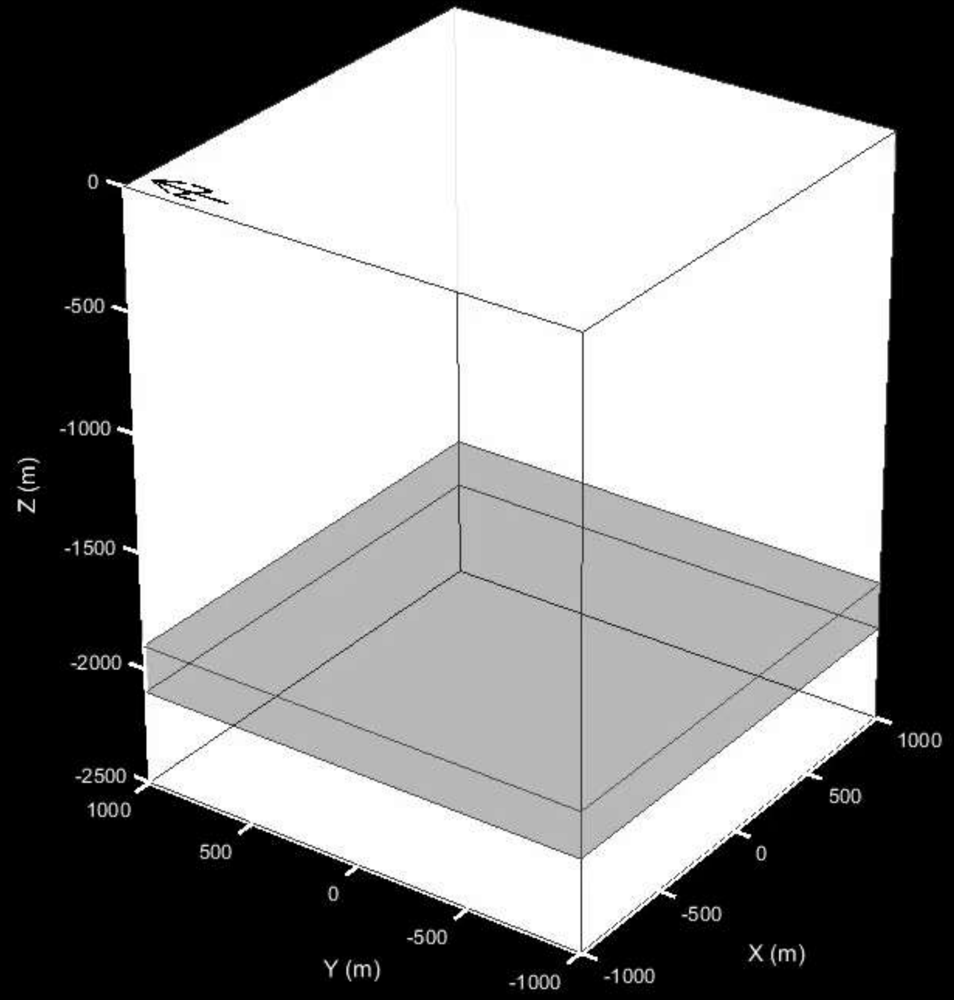


Introducing steel casings to earth model

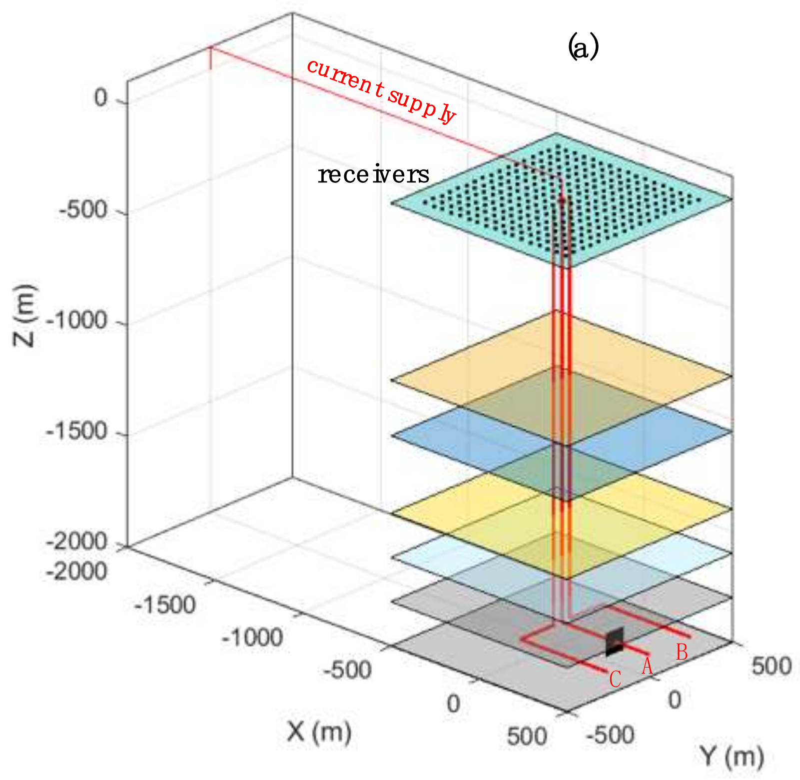
- Short-circuit the earth
- Reduce “resistance depth”
- Enhance sensitivity to injection

Monitoring Injected Fracturing Fluid with Casings

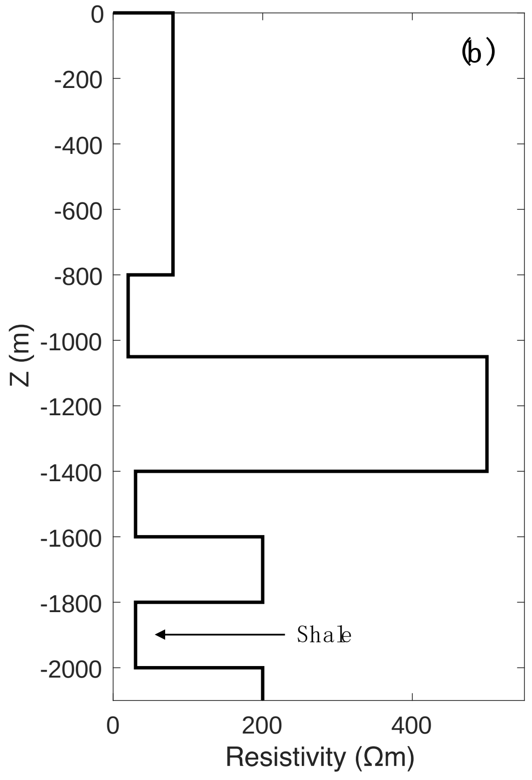




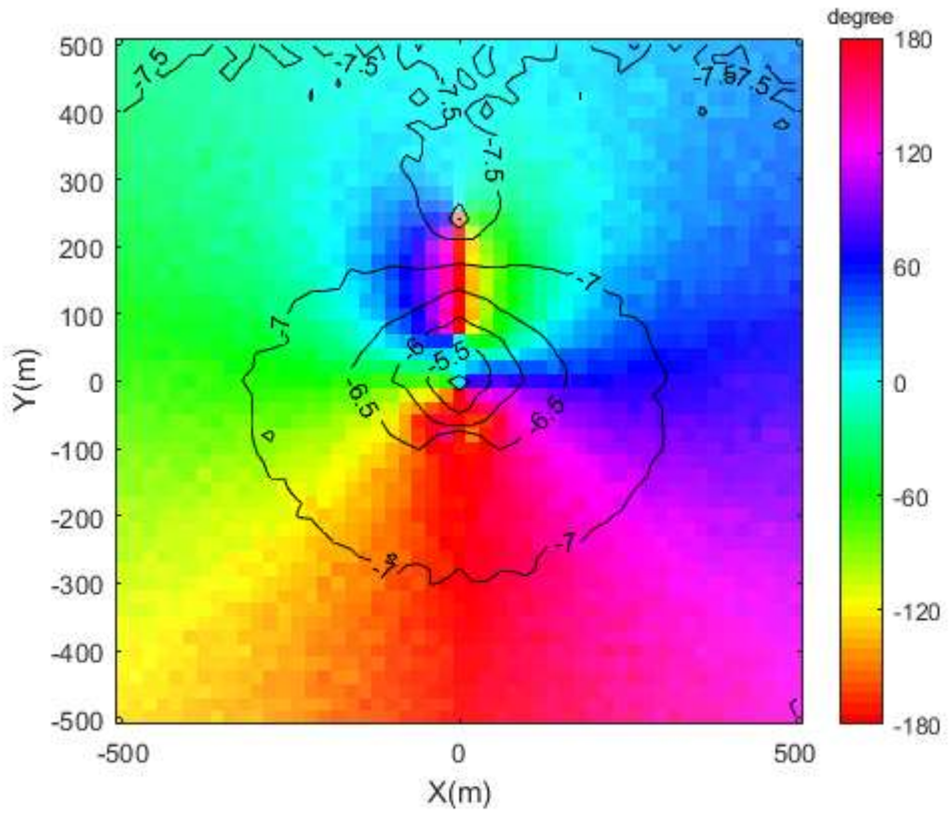
Interactive Inversion of Fluid-saturated Zones



Synthetic model



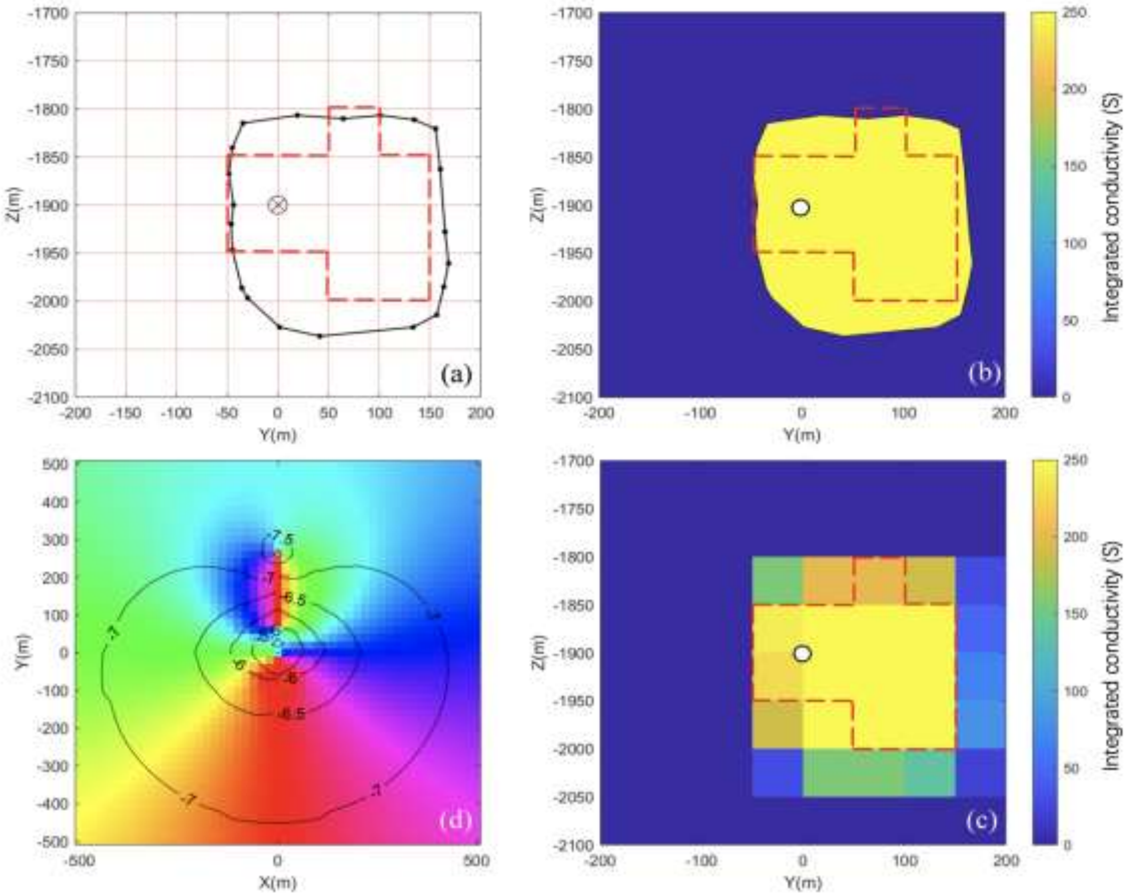
Resistivity log



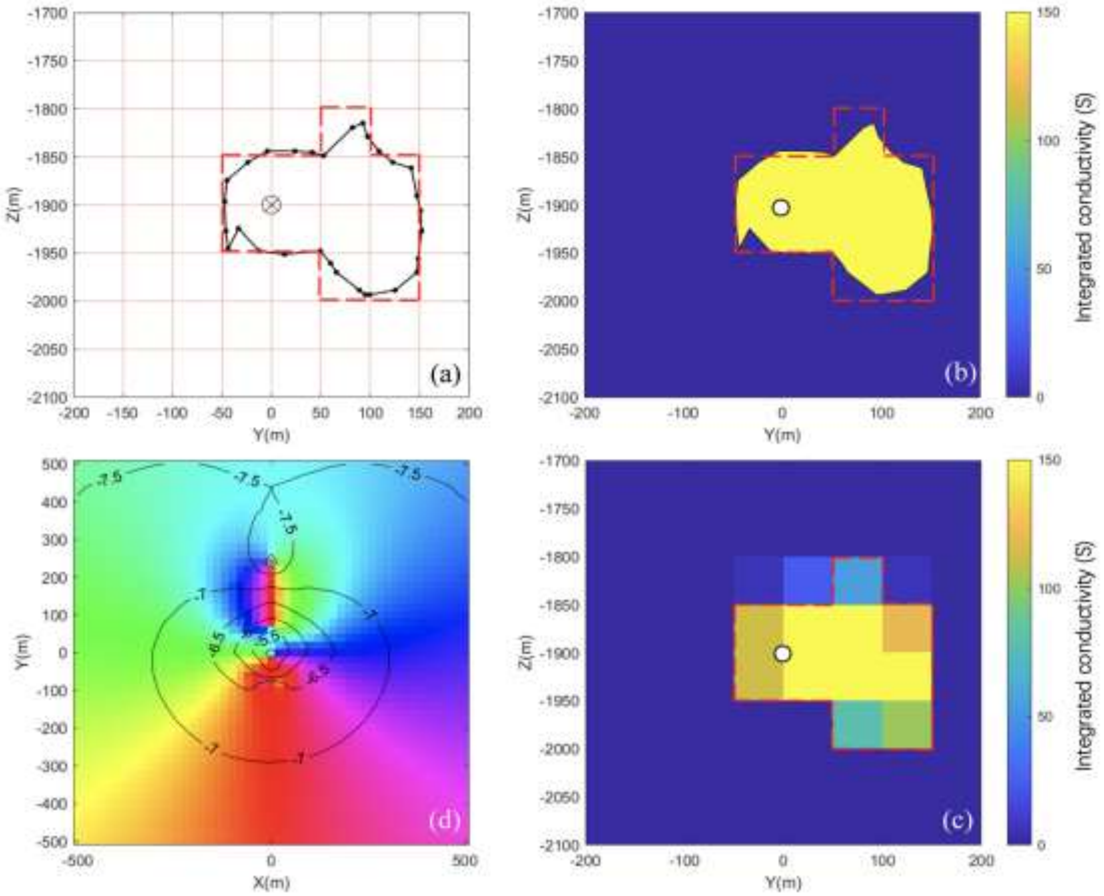
Differential electrical field data map

Interactive Inversion of Fluid-saturated Zones

First Trial



Last Trial



Summary

IP effect

- Physical intuition
- Mechanism of IP
- IP effect in data
- Chargeability inversion

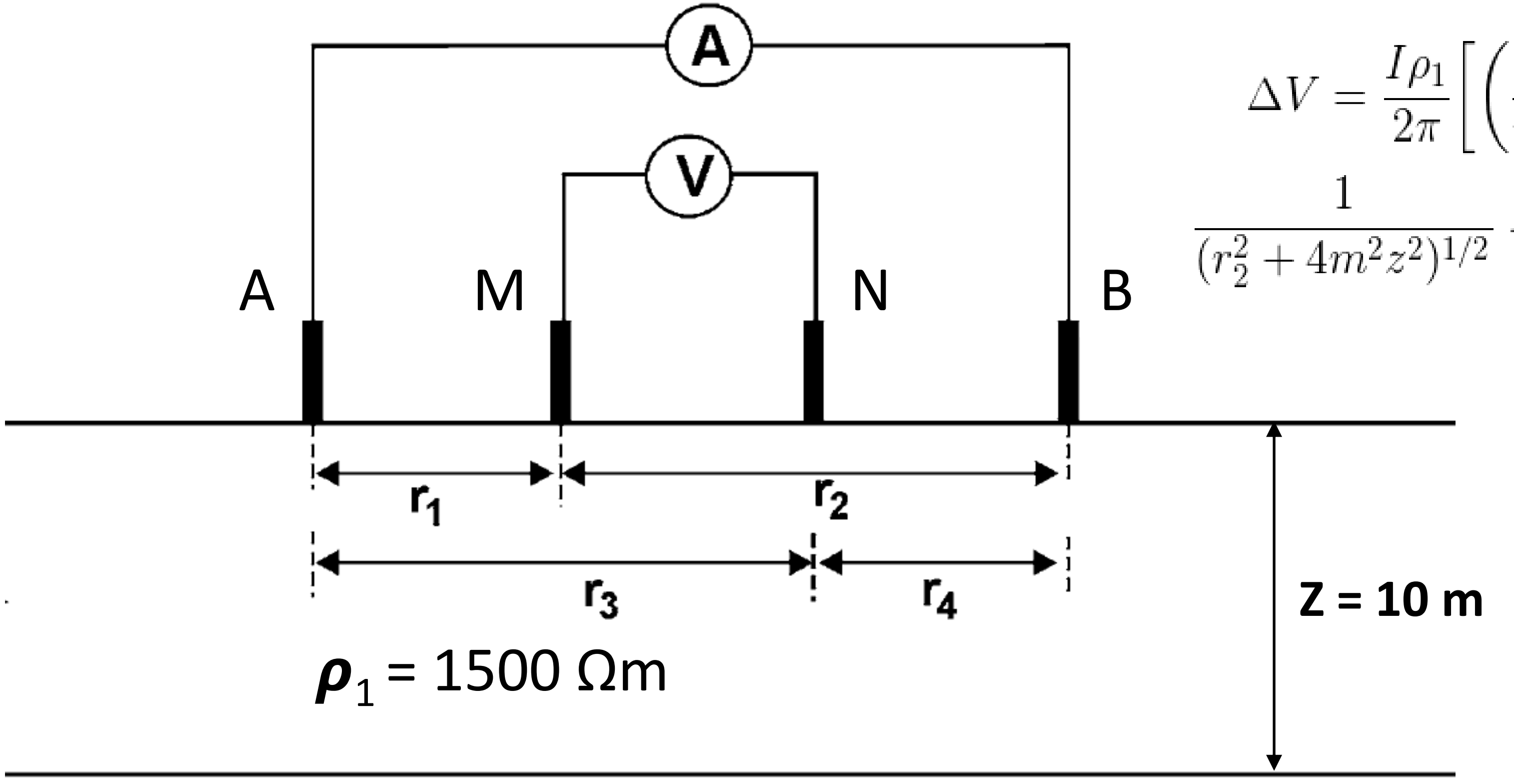
Governing equation

- Poisson equation (continuous medium)
- Equivalent circuit and KCL (lumped element approximation)

Research frontier

- Fracturing monitoring using electrical method

Electrical Assignment: Two-layer Model



$\boldsymbol{\rho}_1 = 1500\ \Omega\text{m}$

$\boldsymbol{\rho}_2 = 500\ \Omega\text{m}$

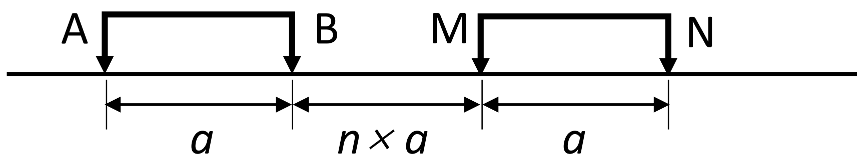
$$\Delta V = \frac{I\rho_1}{2\pi}\left[\left(\frac{1}{r_1}-\frac{1}{r_2}\right)-\left(\frac{1}{r_3}-\frac{1}{r_4}\right)+2\sum_{m=1}^{\infty}k^m\left\{\frac{1}{(r_1^2+4m^2z^2)^{1/2}}-\frac{1}{(r_2^2+4m^2z^2)^{1/2}}-\frac{1}{(r_3^2+4m^2z^2)^{1/2}}+\frac{1}{(r_4^2+4m^2z^2)^{1/2}}\right\}\right]$$

$$k = \frac{\rho_2-\rho_1}{\rho_2+\rho_1}$$

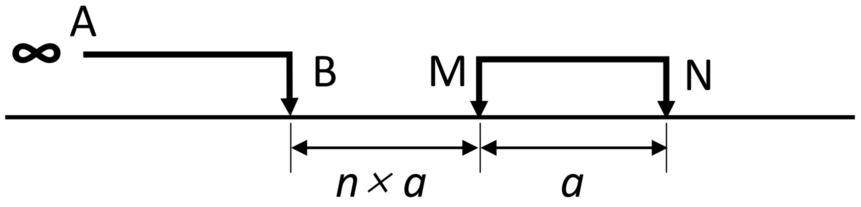
- Potential difference ***dV***
- Apparent resistivity $\boldsymbol{\rho}_a$

Four Types of Arrays

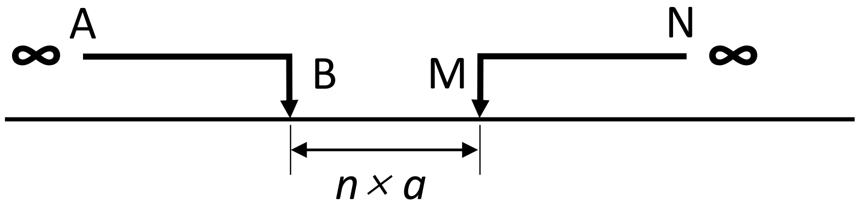
dipole-dipole



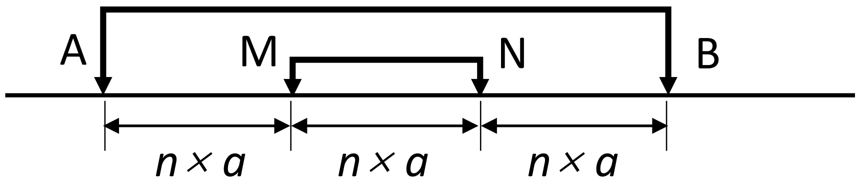
pole-dipole



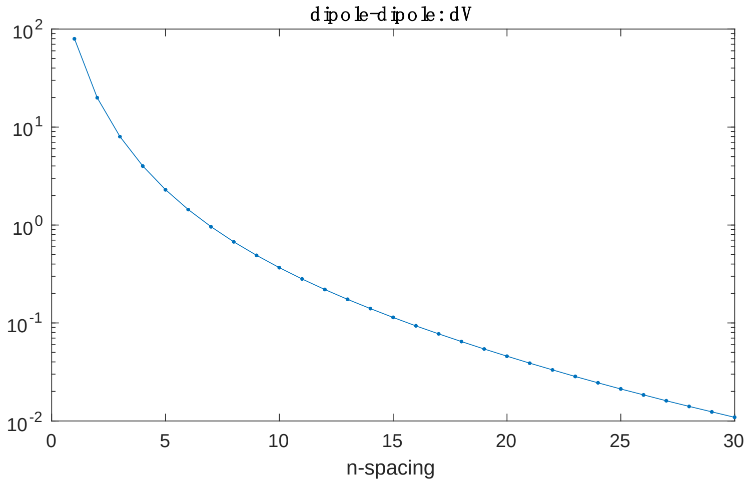
pole-pole

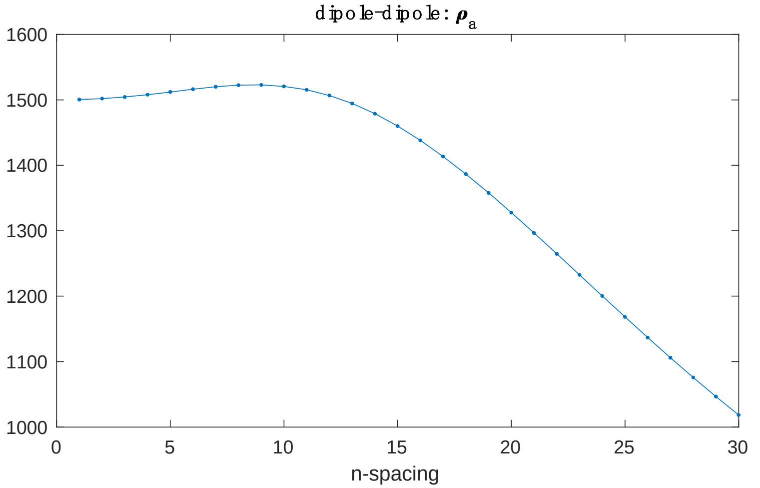


Wenner



dV vs. n-spacing & $\boldsymbol{\rho}_a$ vs. n-spacing





Make such plots for dipole-dipole, pole-dipole, pole-pole and Wenner arrays

(1) Which type of array has better resolution for the near-surface property? And how can you tell?

(2) Which type of array has better depth of penetration with the least n-spacing (less expensive field operation)? And how can you tell?

(3) Which type of array has the best balance between near-surface resolution and depth of penetration? And why?