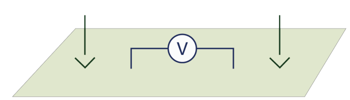
DC Resistivity

DISC 2017

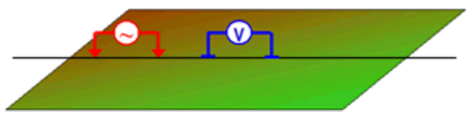
Electromagnetics Fundamentals and Applications



DC Resistivity Survey

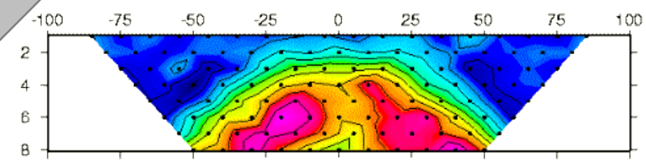
Source

Input energy



measure

Data



ρ

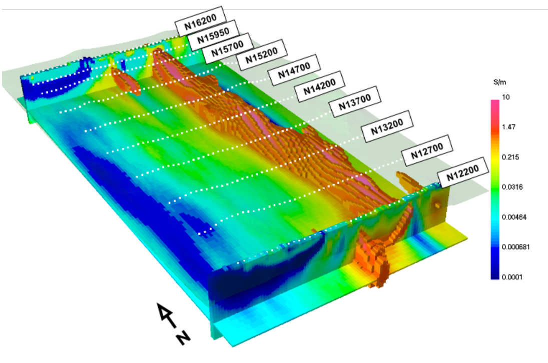
$\rho = 1/\sigma$

ρ : resistivity

σ : electrical conductivity

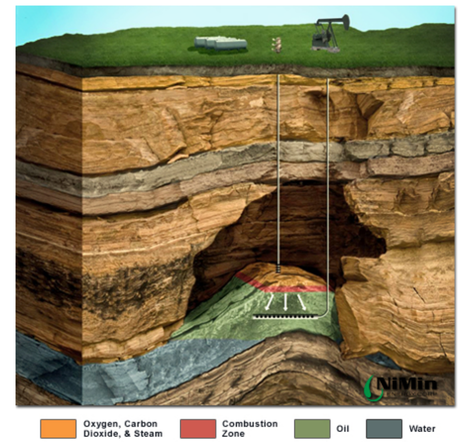
Motivation

Minerals

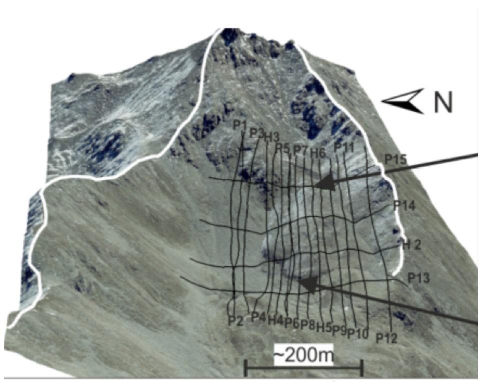


Water inflow in mine

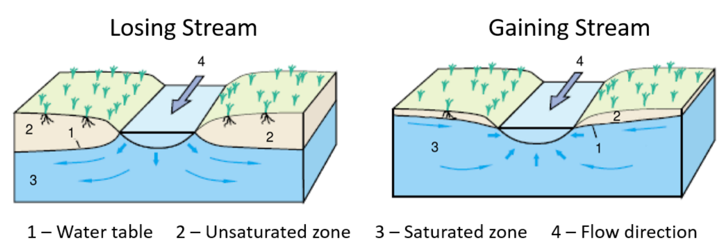
Oil and Gas



Geotechnical

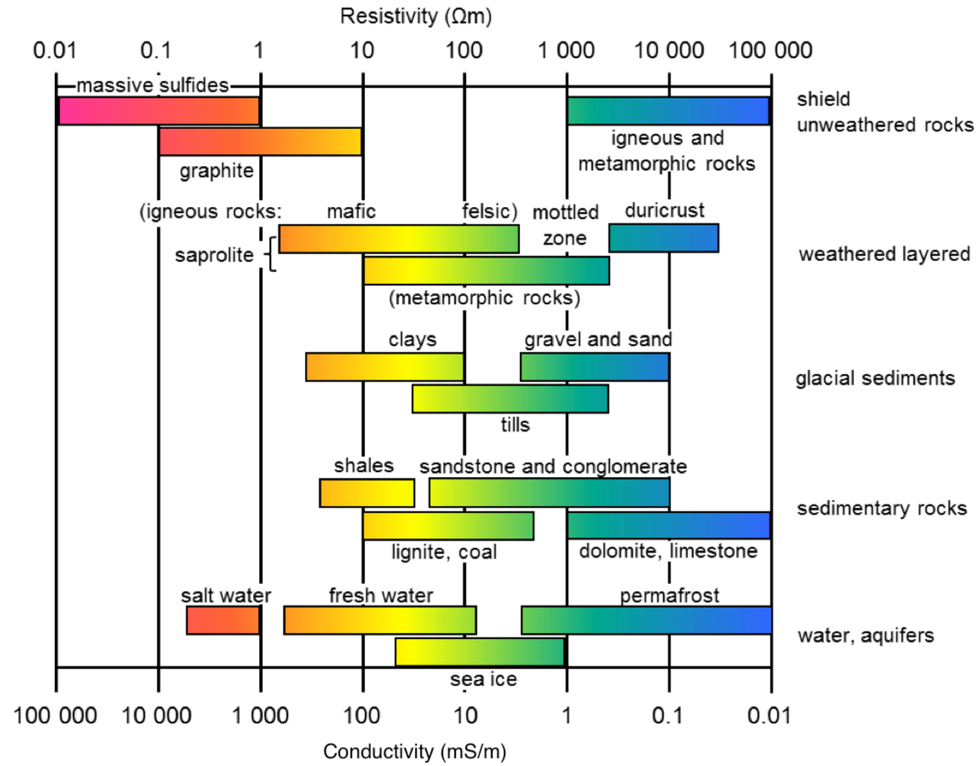


Groundwater



Electrical conductivity

- DC resistivity is sensitive to:
  - σ: Conductivity [S/m]
  - ρ: Resistivity [Ωm]
  - $\sigma = 1/\rho$
- Varies over many orders of magnitude
- Depends on many factors:
  - Rock type
  - Porosity
  - Connectivity of pores
  - Nature of the fluid
  - Metallic content of the solid matrix



Outline

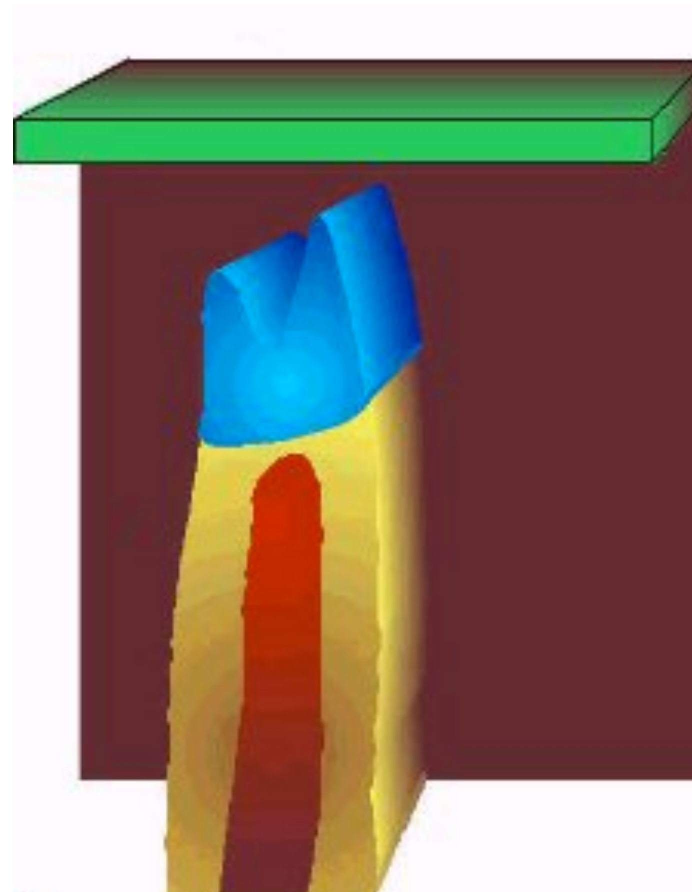
- Basic experiment
- Currents, charges, potentials and apparent resistivities
- Soundings, profiles and arrays
- Data, pseudosections and inversion
- Sensitivity
- Survey Design
- Case History – Mt Isa
- Case History – Dam Monitoring
- Effects of background resistivity

Basic Experiment

- **Target:**
  - Ore body. Mineralized regions less resistive than host

Elura Orebody Electrical resistivities

Rock Type	*Ohm-m*
Overburden	12
Host rocks	200
Gossan	420
Mineralization (pyritic)	0.6
Mineralization (pyrrhotite)	0.6



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- **Setup:**
  - Tx: Current electrodes
  - Rx: Potential electrodes

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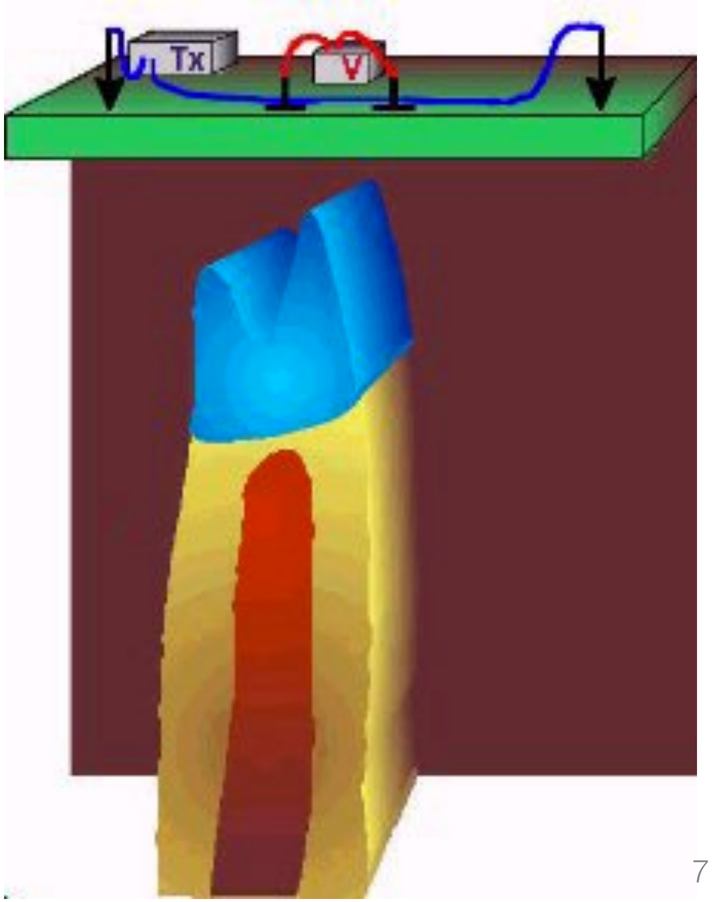

Basic Experiment

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- **Currents:**
  - Preferentially flow through conductors

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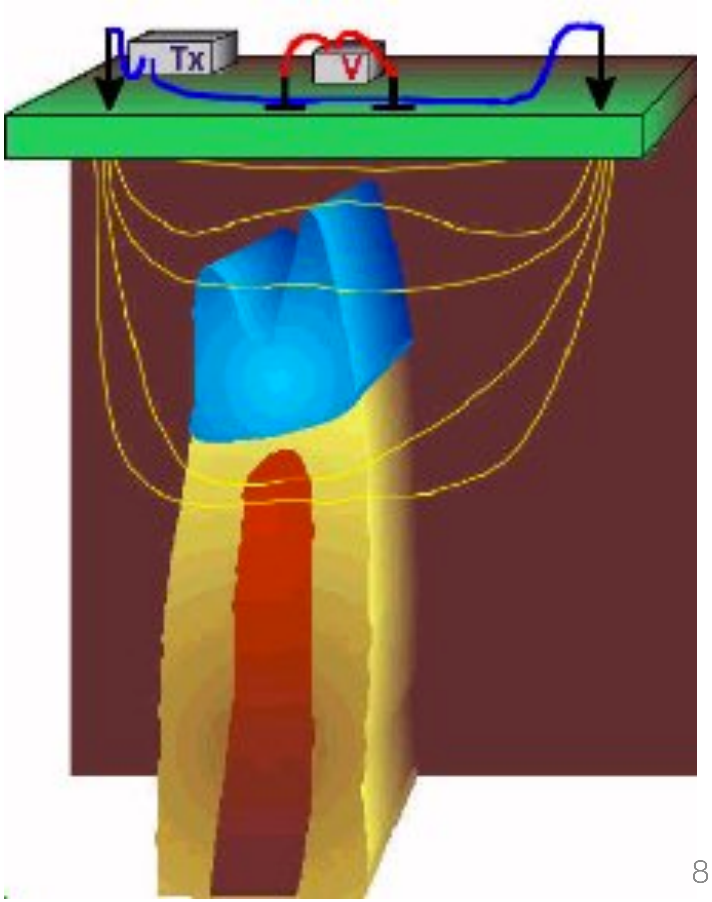

Basic Experiment

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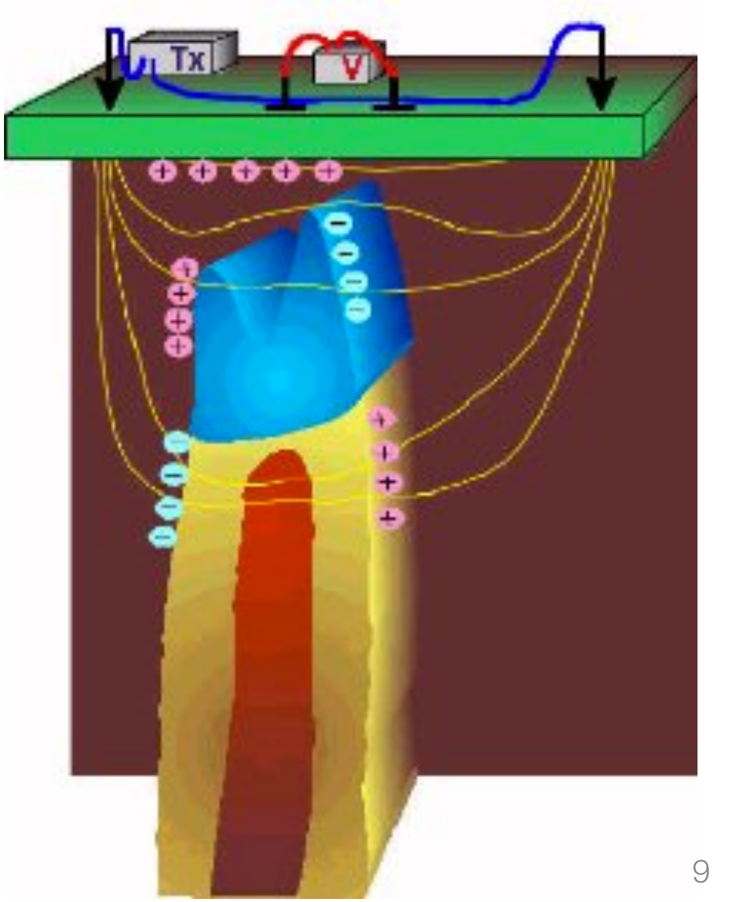
  - Tx: Current electrodes
  - Rx: Potential electrodes
- **Currents:**
  - Preferentially flow through conductors
- **Charges:**
  - Build up at interfaces



Basic Experiment

- **Target:**
  - Ore body. Mineralized regions less resistive than host
- **Setup:**
  - Tx: Current electrodes
  - Rx: Potential electrodes
- **Currents:**
  - Preferentially flow through conductors
- **Charges:**
  - Build up at interfaces
- **Potentials:**
  - Associated with the charges are measured at the surface

Elura Orebody Electrical resistivities

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Gossan	420
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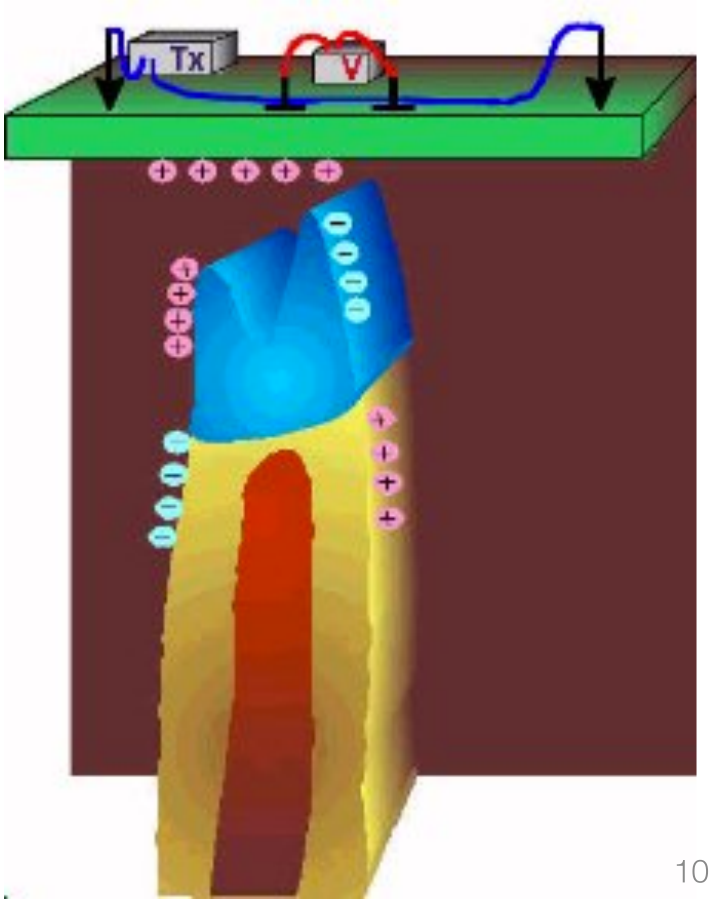
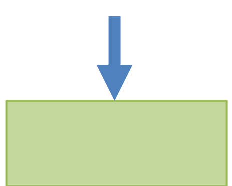


How do we obtain resistivity?

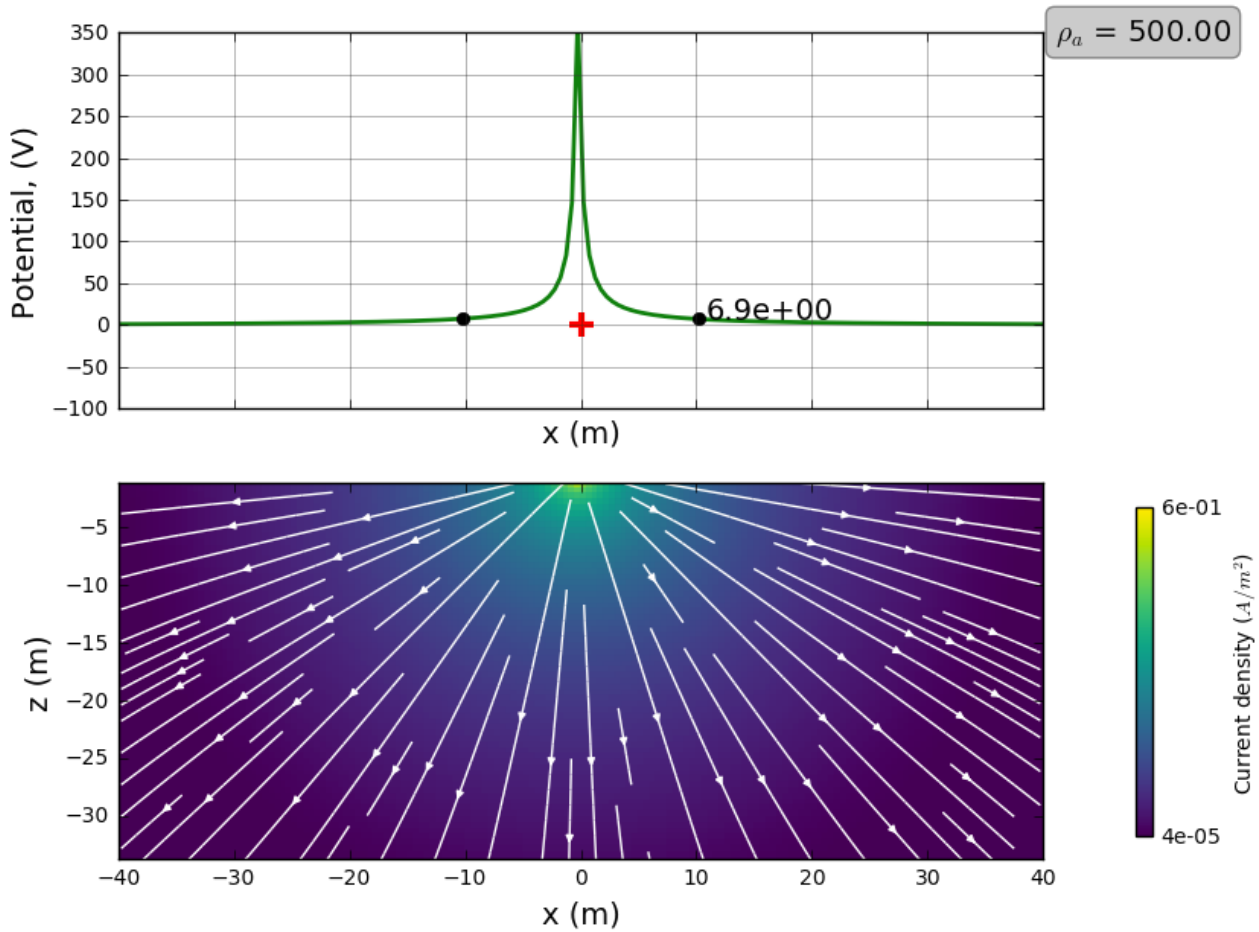
Steady State Maxwell equations

	Full	Steady State
Faraday	$\nabla \times \vec{e} = -\frac{\partial \vec{b}}{\partial t}$	$\nabla \times \vec{e} = 0 \qquad \vec{e} = -\nabla V$
Ampere	$\nabla \times \vec{h} = \vec{j} + \frac{\partial \vec{d}}{\partial t} + \vec{j}_s$	$\nabla \cdot \vec{j} = -\nabla \cdot \vec{j}_s$
Ohm's Law	$\vec{j} = \sigma \vec{e}$	
Put it together		$\nabla \cdot \sigma \nabla V = I\delta(r)$
Potential in a homogeneous halfspace		$V = \frac{I}{2\pi\sigma}\frac{1}{r} \qquad V = \frac{\rho I}{2\pi r}$

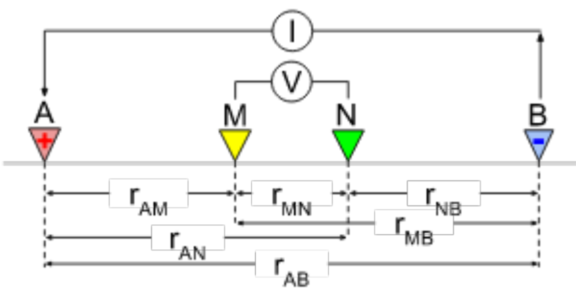
Currents and potentials: halfspace

$$V = \frac{\rho I}{2\pi r}$$

$$\rho = \frac{2\pi r V}{I}$$



Currents and potentials: 4-electrode array

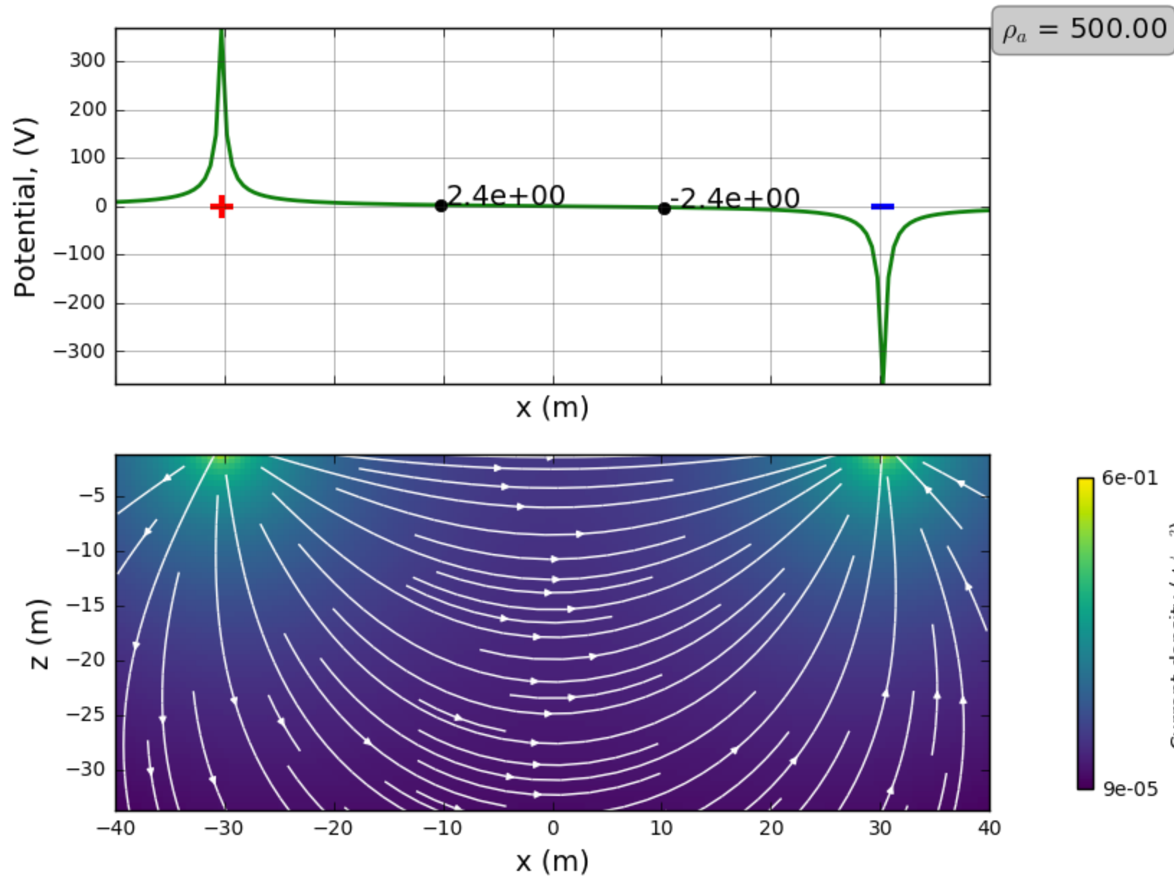


$$\Delta V_{MN} = \rho I \underbrace{\frac{1}{2\pi}\left[\frac{1}{AM} - \frac{1}{MB} - \frac{1}{AN} + \frac{1}{NB}\right]}_{G}$$

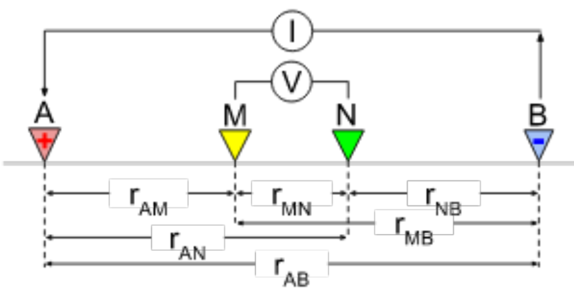
Resistivity

$$\rho = \frac{\Delta V_{MN}}{IG}$$

Halfspace (500 Ωm)



Currents and Apparent Resistivity

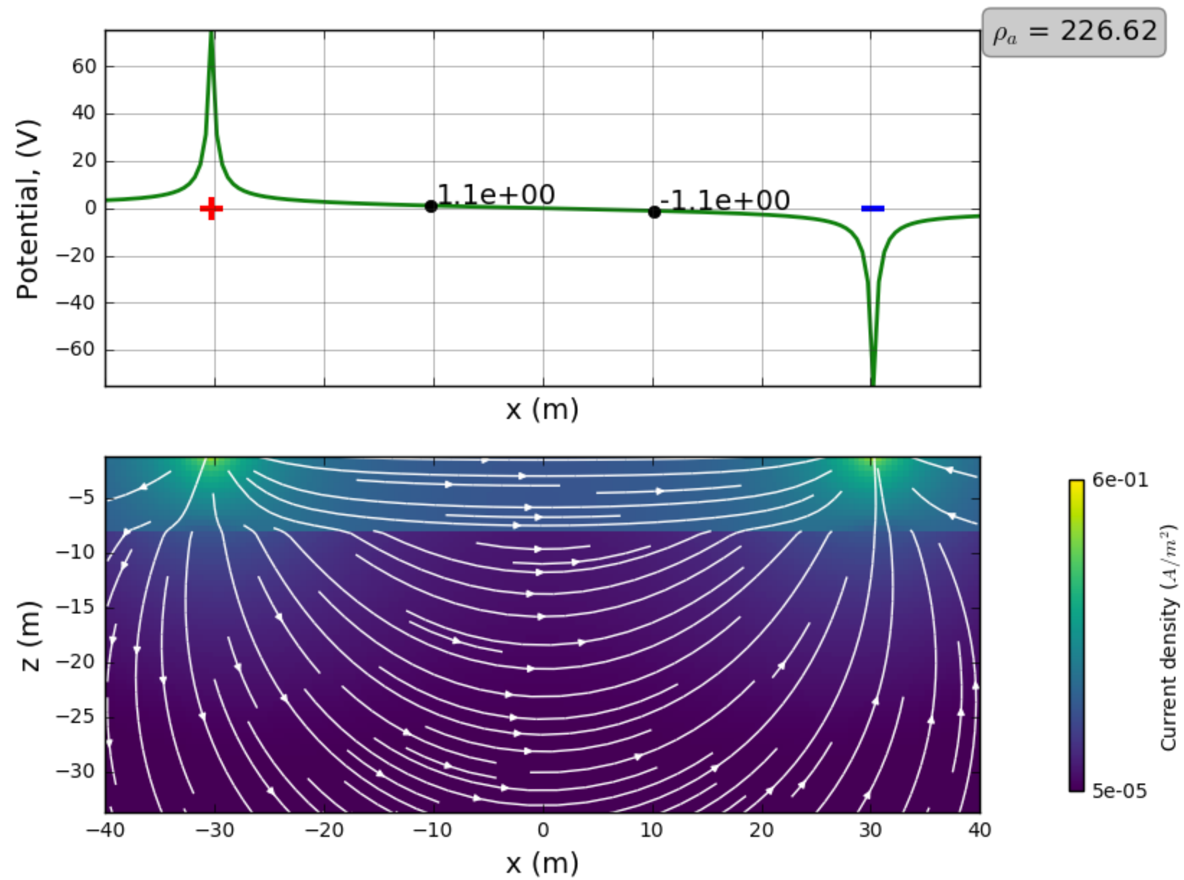


$$\Delta V_{MN} = \rho I \underbrace{\frac{1}{2\pi}\left[\frac{1}{AM} - \frac{1}{MB} - \frac{1}{AN} + \frac{1}{NB}\right]}_{G}$$

Apparent resistivity

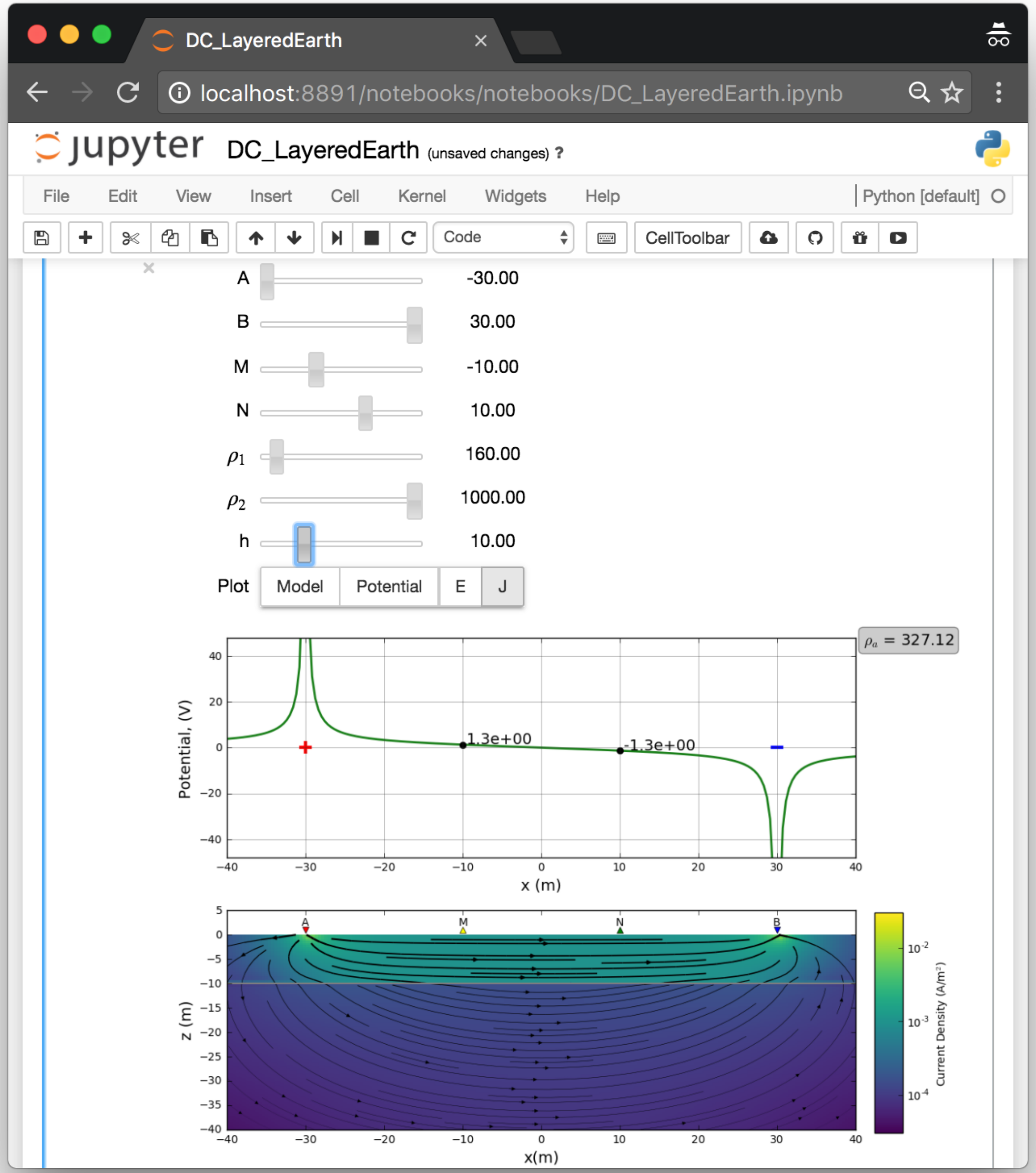
$$\rho_a = \frac{\Delta V_{MN}}{IG}$$

Conductive overburden (100 Ωm)



Why interactive apps?

- Visualization aids understanding
- Learn through interaction
  - ask questions and investigate
- Open source:
  - Free to use
  - Welcome contributions!

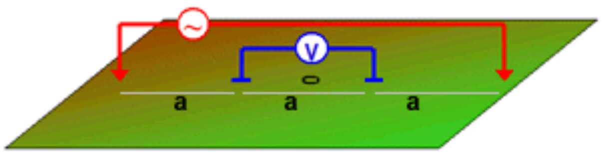


http://em.geosci.xyz/apps.html

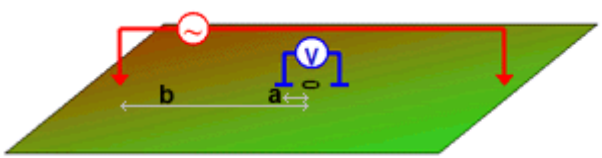
Soundings and Arrays

Geometry

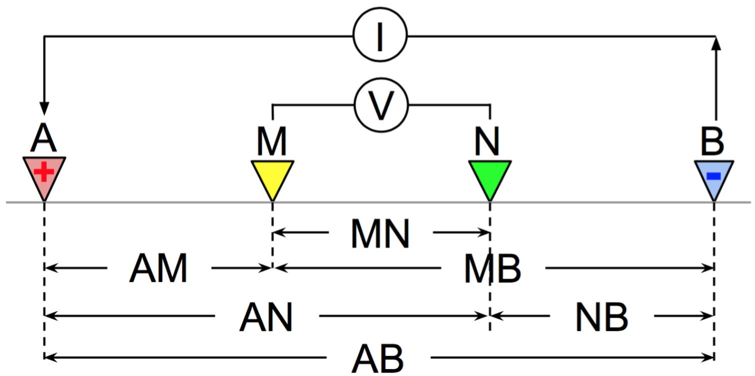
Wenner



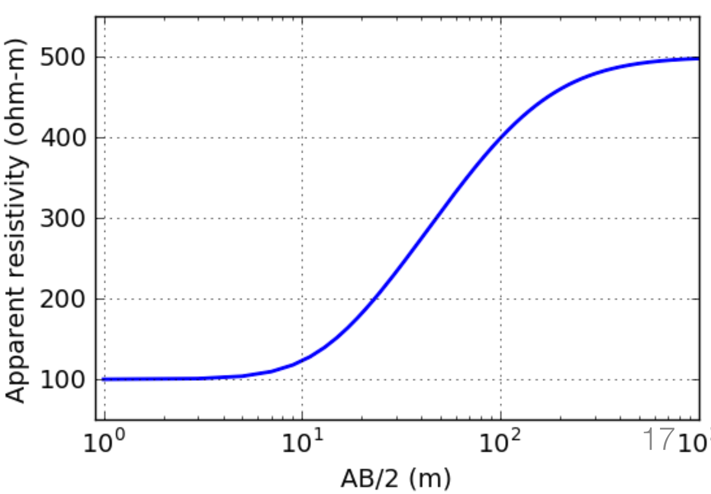
Schlumberger



4 electrode Array

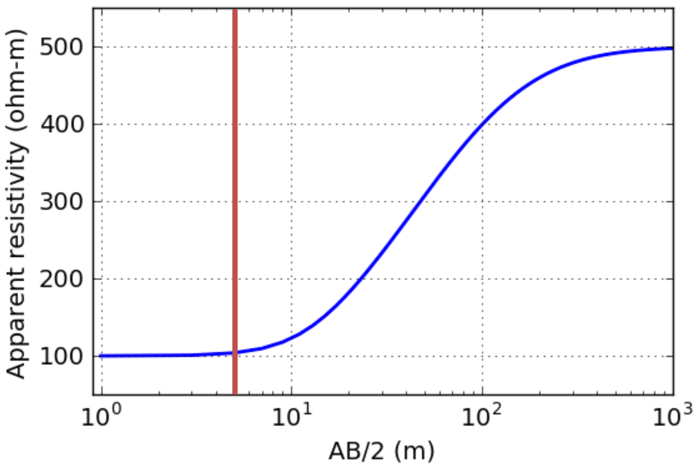


Sounding

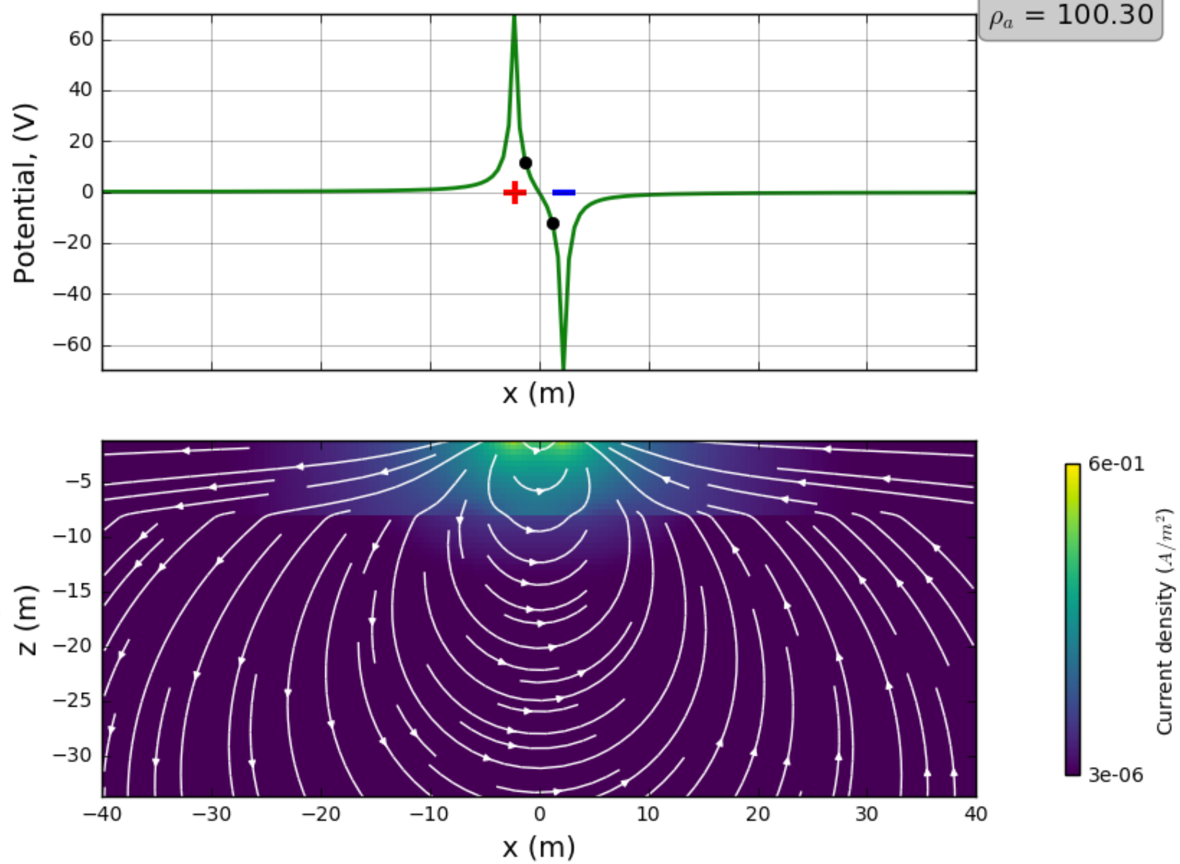


Soundings

DC Sounding curve



AB/2 = 5 m



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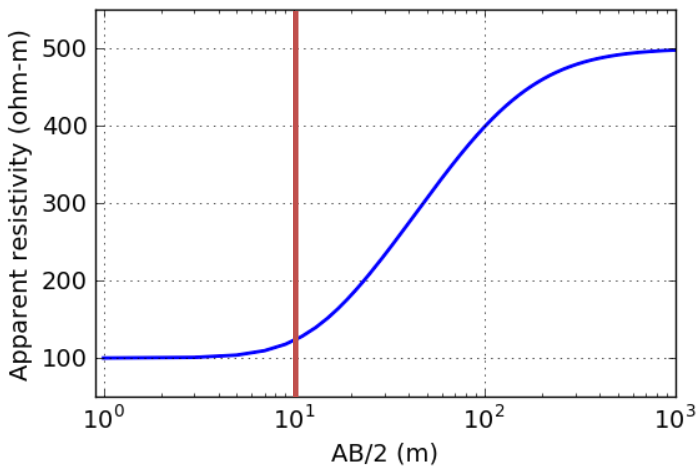
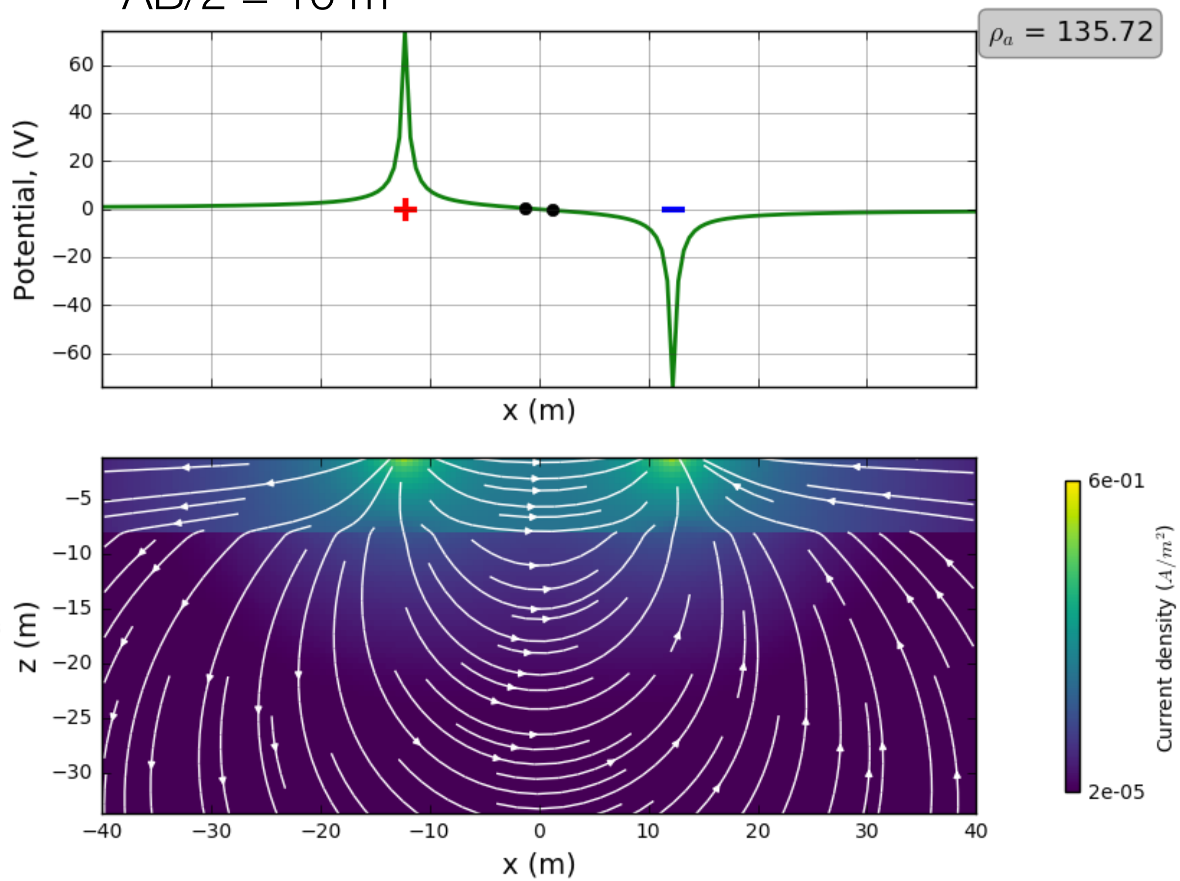


AB/2 = 10 m



Soundings

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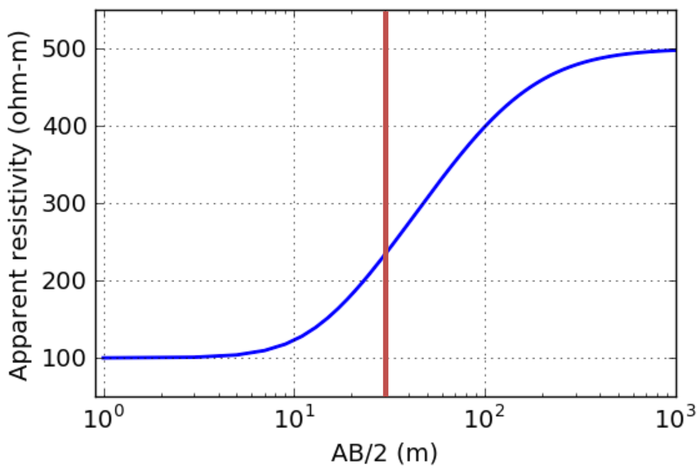
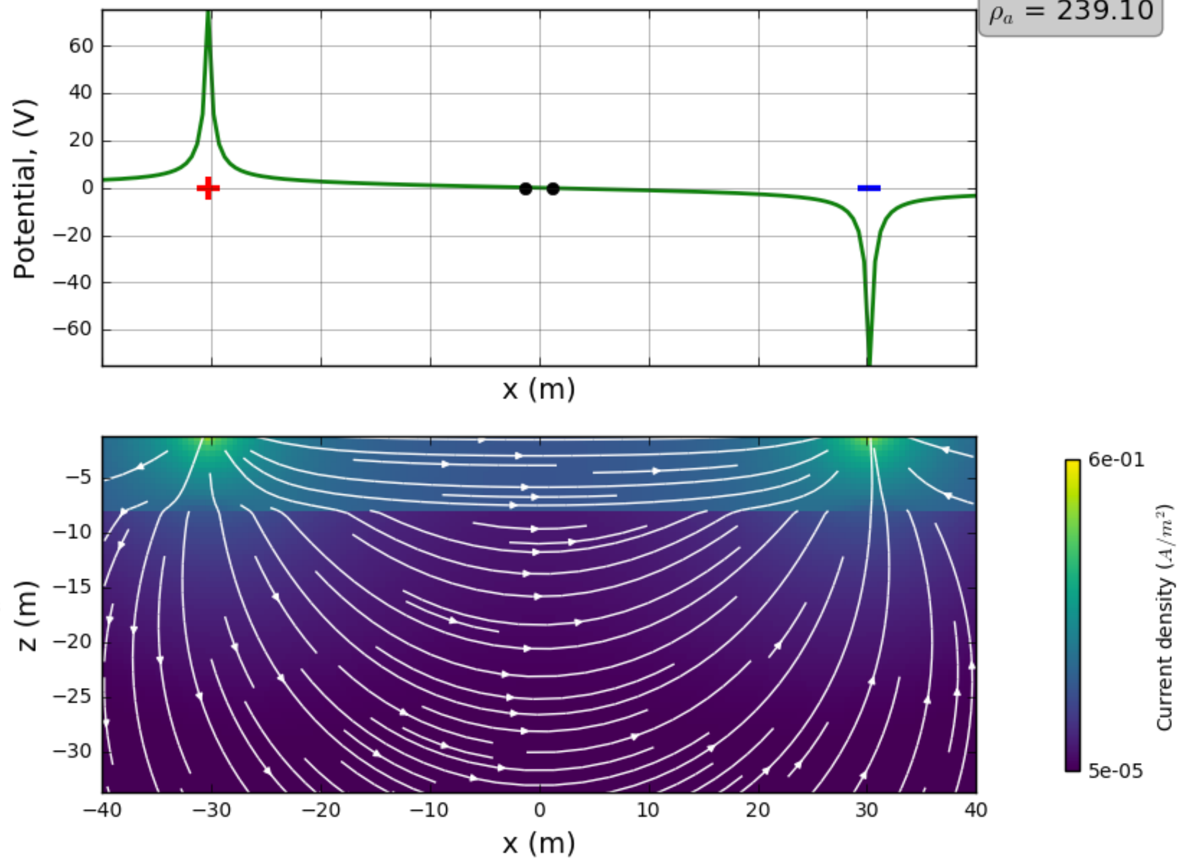
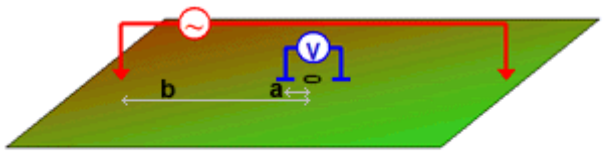


AB/2 = 30 m

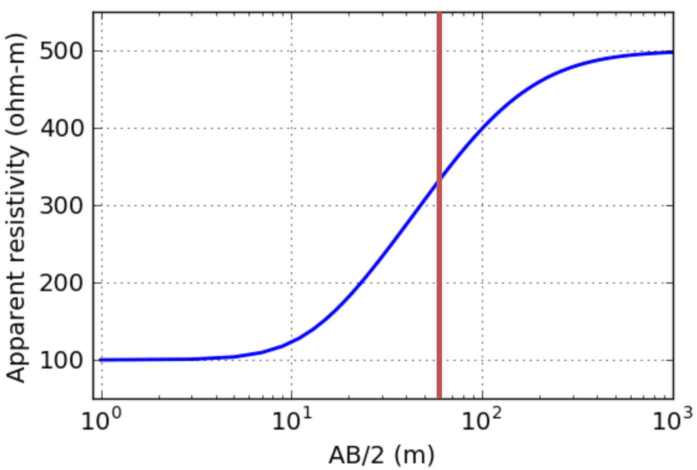


Summary: soundings

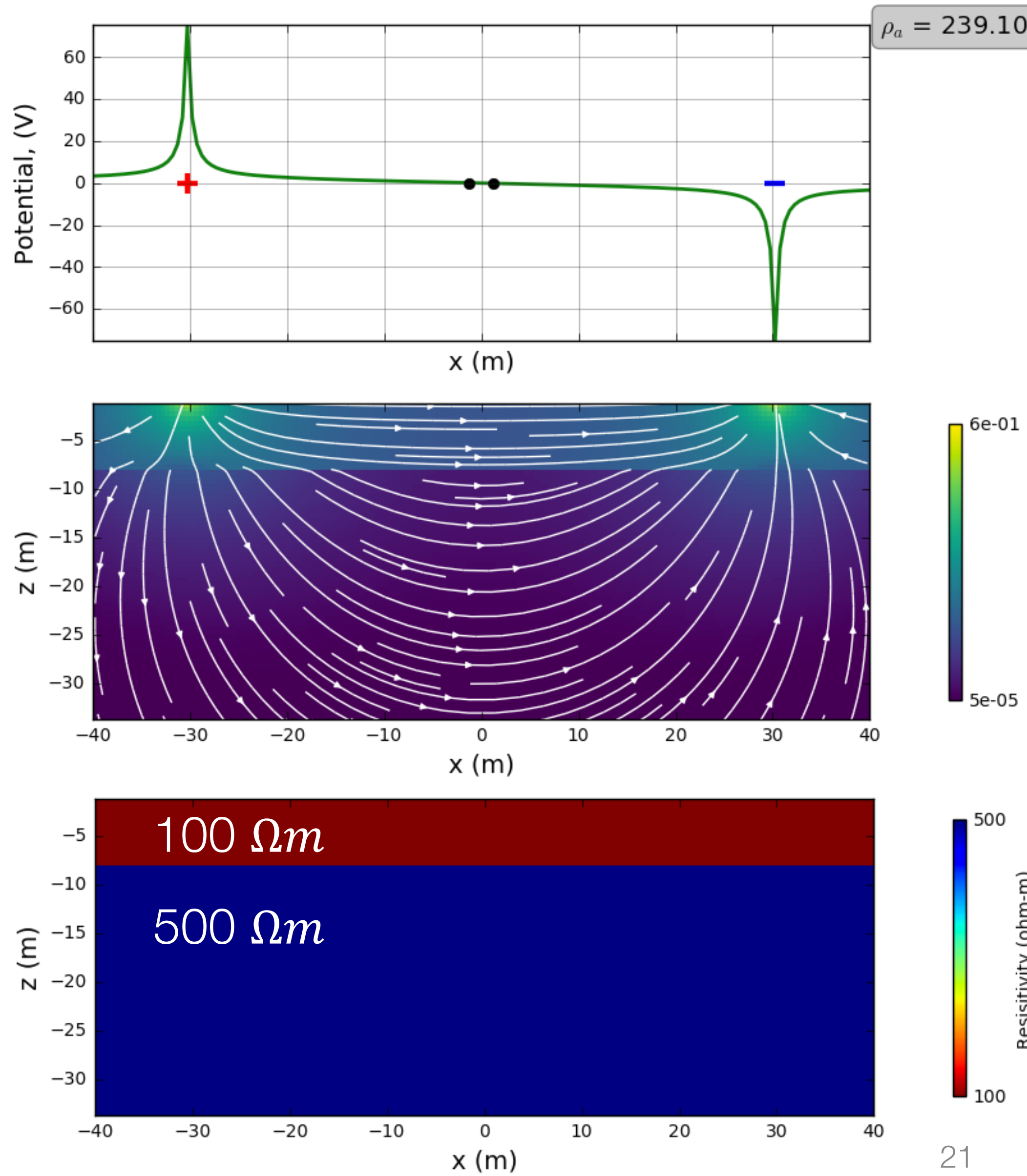
Schlumberger array



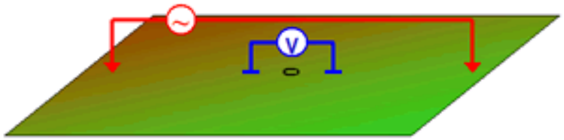
DC **Sounding** curve



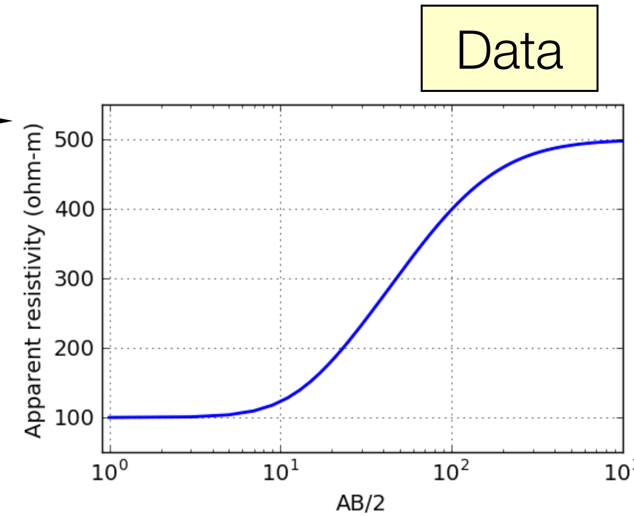
Scale length of array must be large to see deep

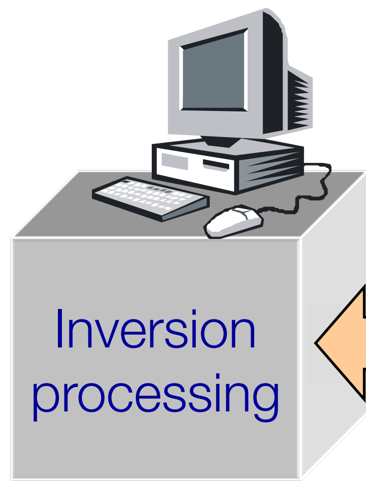


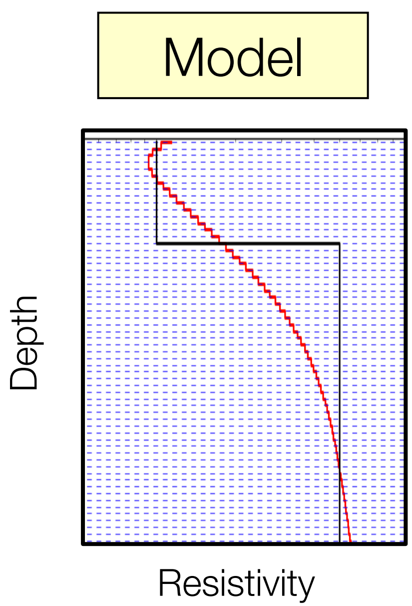
Inversion



Measurements over the Earth are data.







Inversion estimates Earth models based upon data and prior knowledge.

DCR for a confined body

- Useful to formally bring in the concept of charges

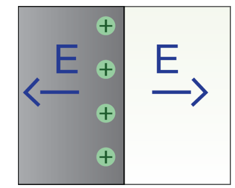
Normal component of current density is continuous

$$J_{1n} = J_{2n}$$
$$\sigma_1 E_{1n} = \sigma_2 E_{2n}$$

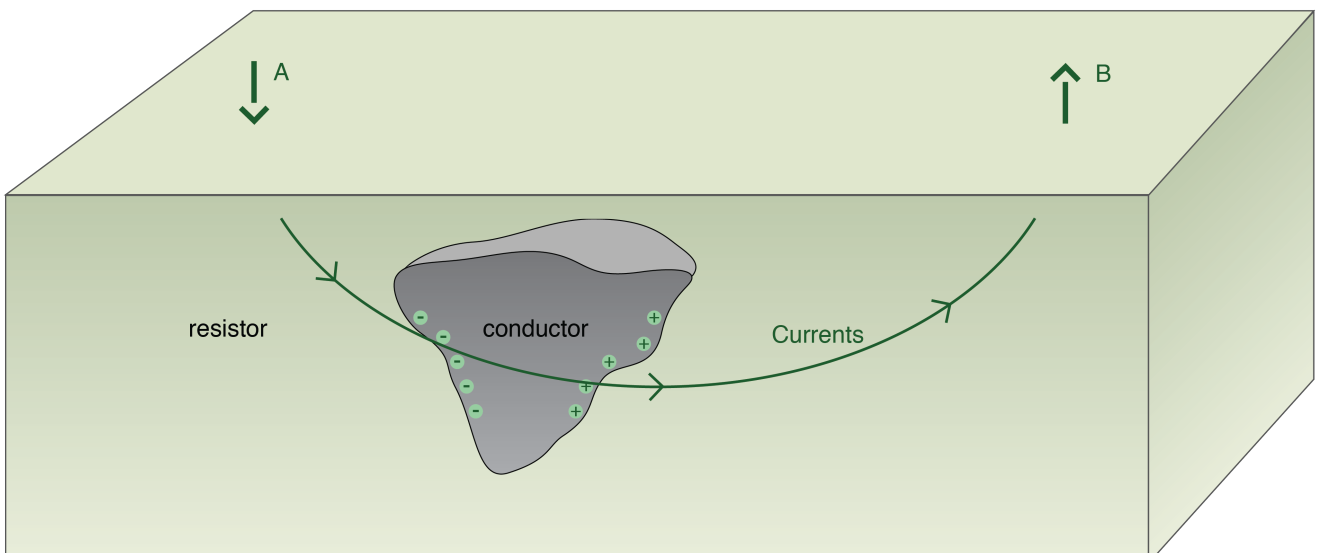
Conductivity contrast

$$\sigma_1 \neq \sigma_2$$

- Electric field discontinuous
- Charge build-up

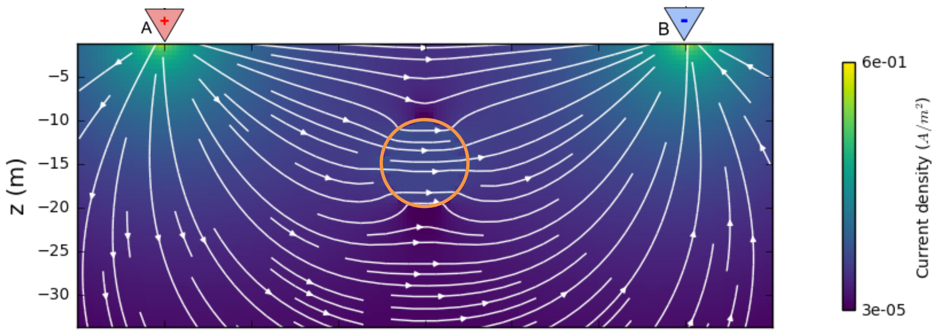


$$\mathbf{E} = \frac{Q}{4\pi\varepsilon_0 |\mathbf{r} - \mathbf{r}'|^2}\hat{\mathbf{r}}$$

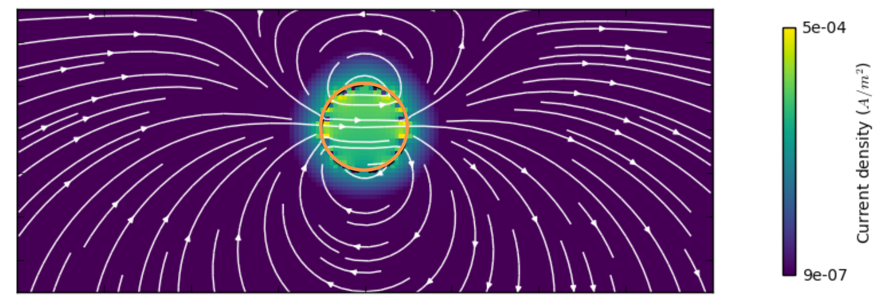


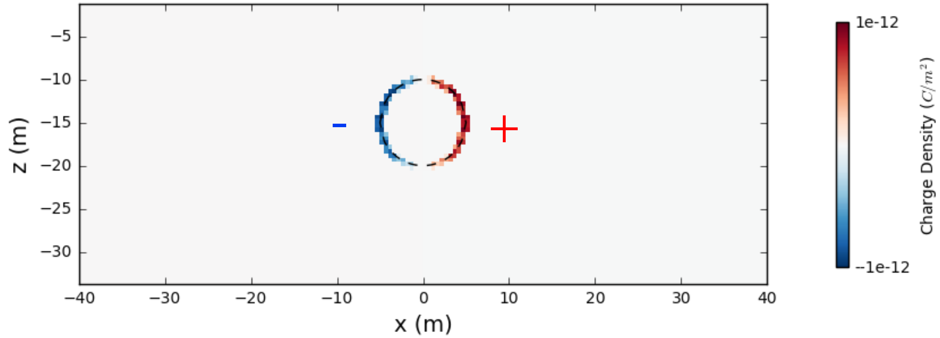
Currents, charges, and potentials

Total currents: J

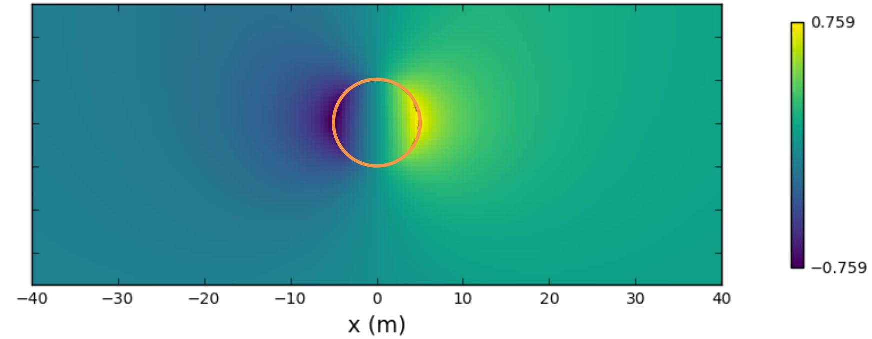


Secondary currents: J_s





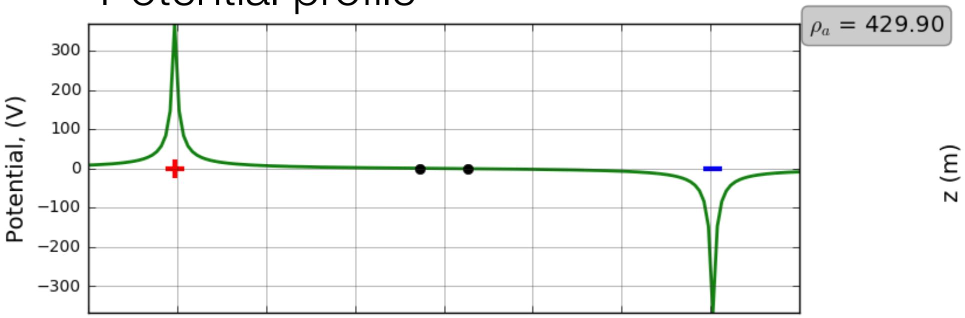
Secondary charges: Q_s



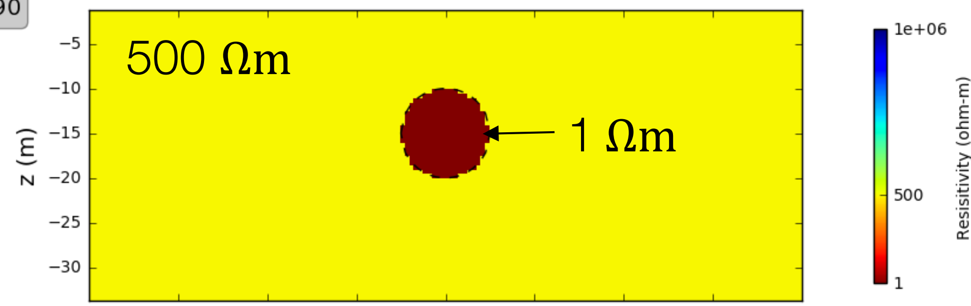
Secondary potential: ϕ_s

Measurements of DC data: gradient array

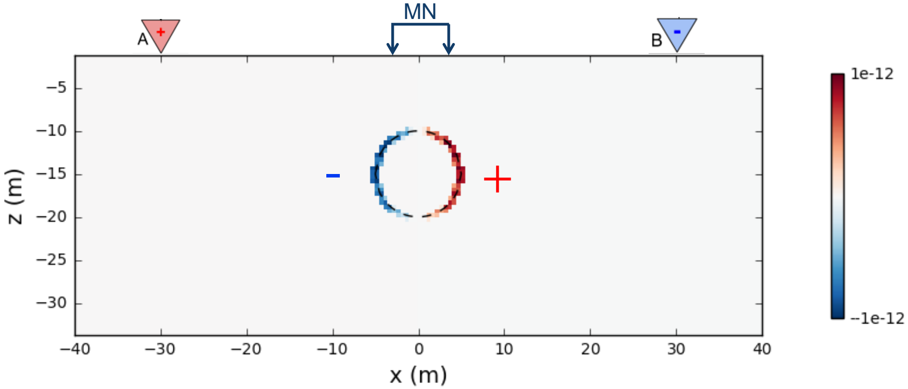
Potential profile



Resistivity model



$\rho_a = 430$



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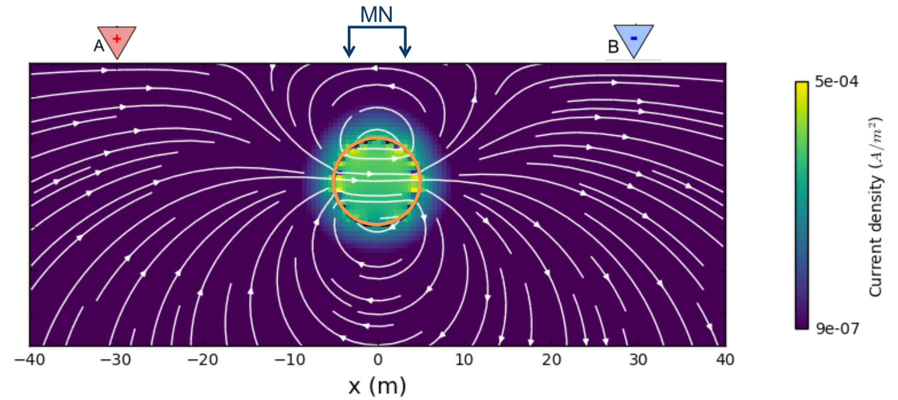
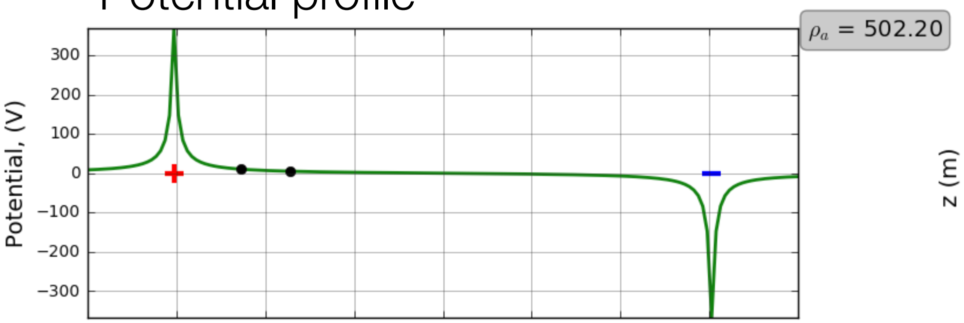


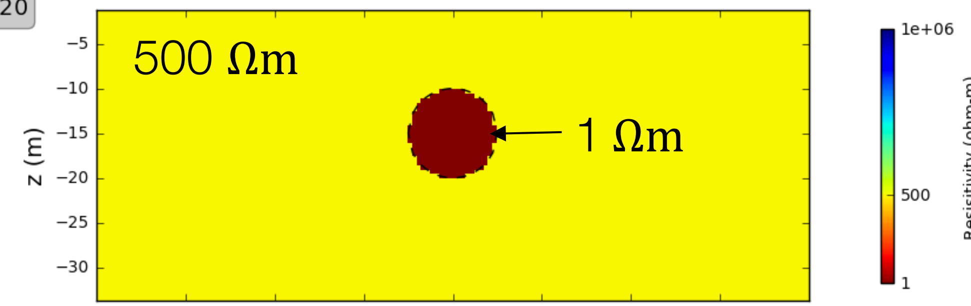
Secondary currents: J_s

Measurements of DC data: gradient array

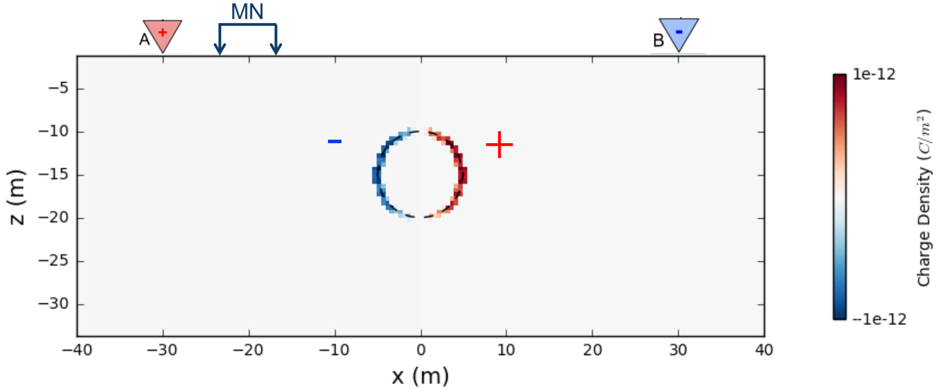
Potential profile



Resistivity model

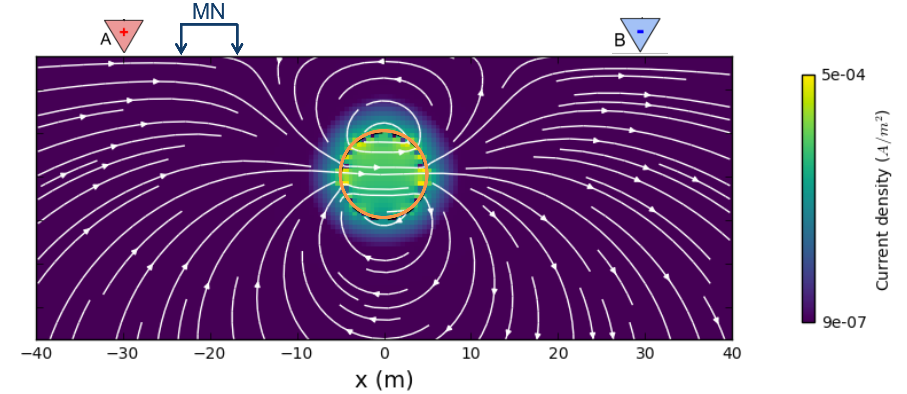


ρ_a = 502



Secondary charges: Q_s

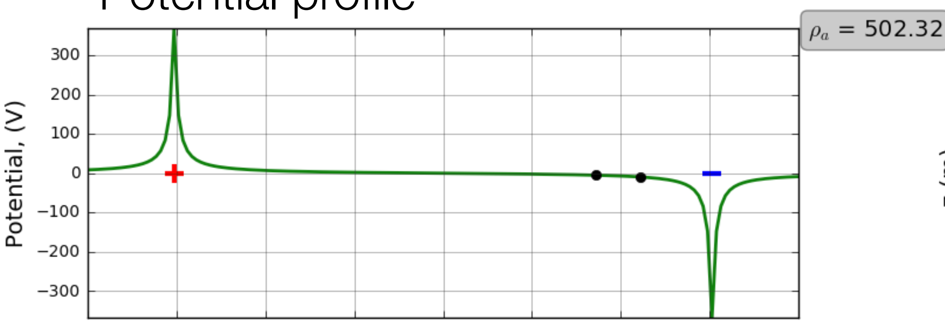
ρ_a = 502



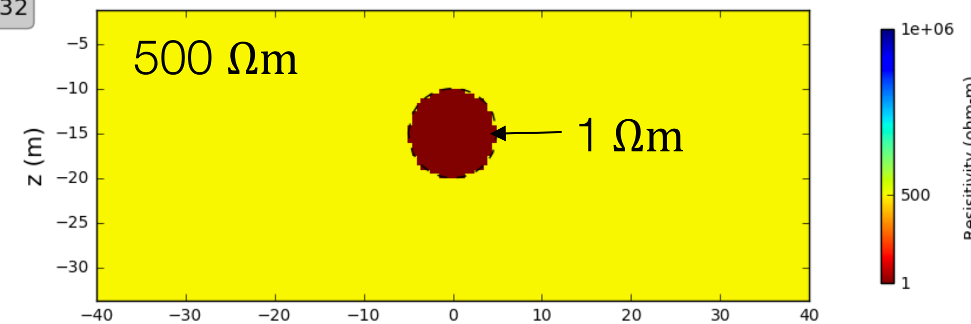
Secondary currents: J_s

Measurements of DC data: gradient array

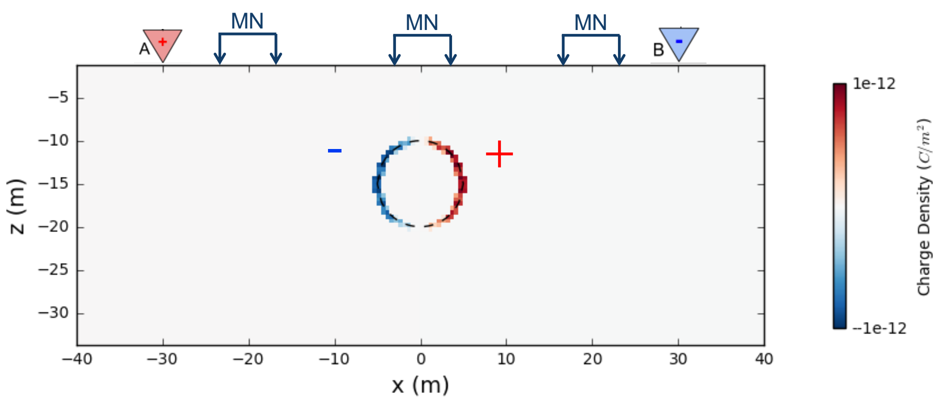
Potential profile



Resistivity model

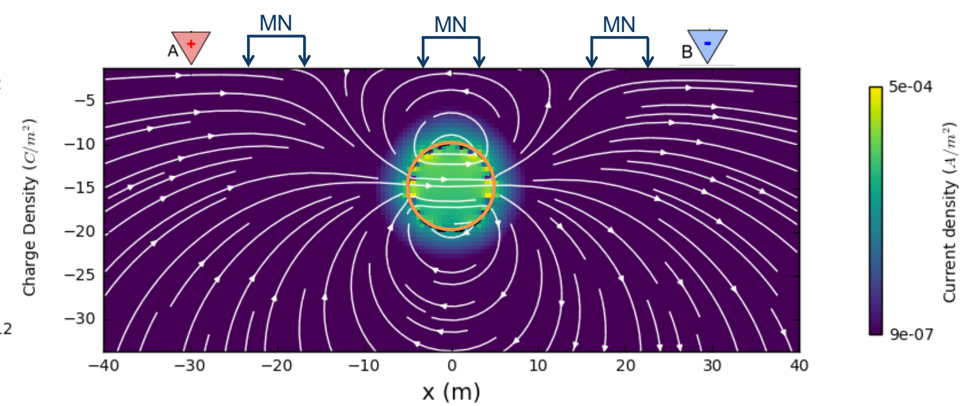


ρ_a = 502 ρ_a = 430 ρ_a = 502



Secondary charges: Q_s

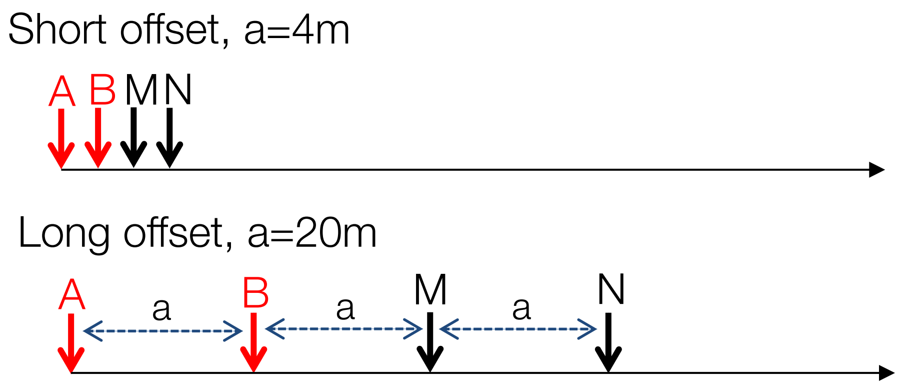
ρ_a = 502 ρ_a = 430 ρ_a = 502

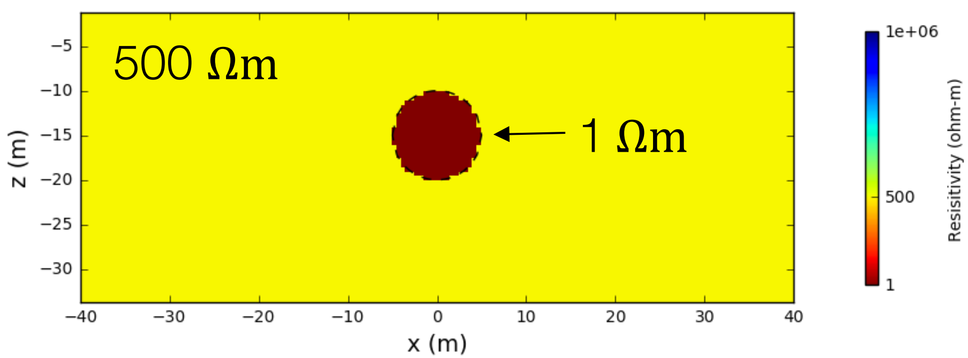


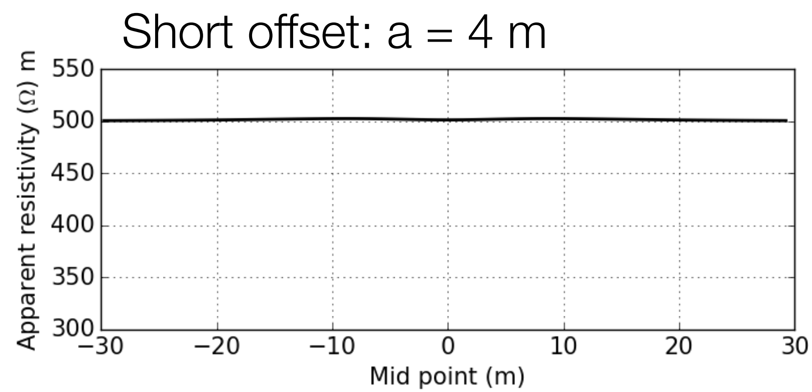
Secondary currents: J_s

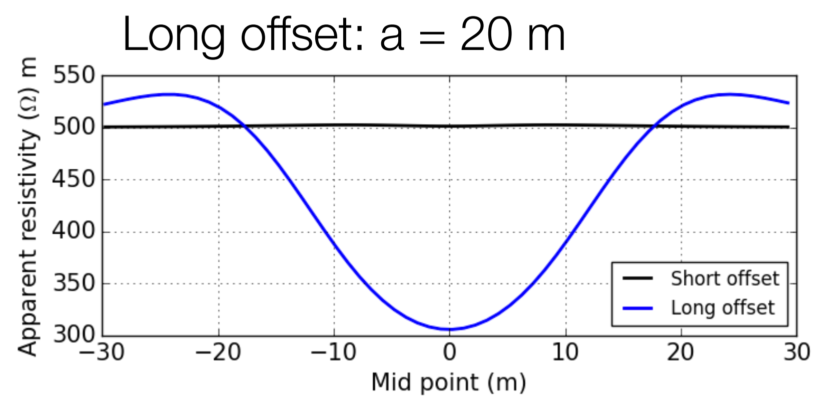
Profiling

Fixed geometry: Move laterally







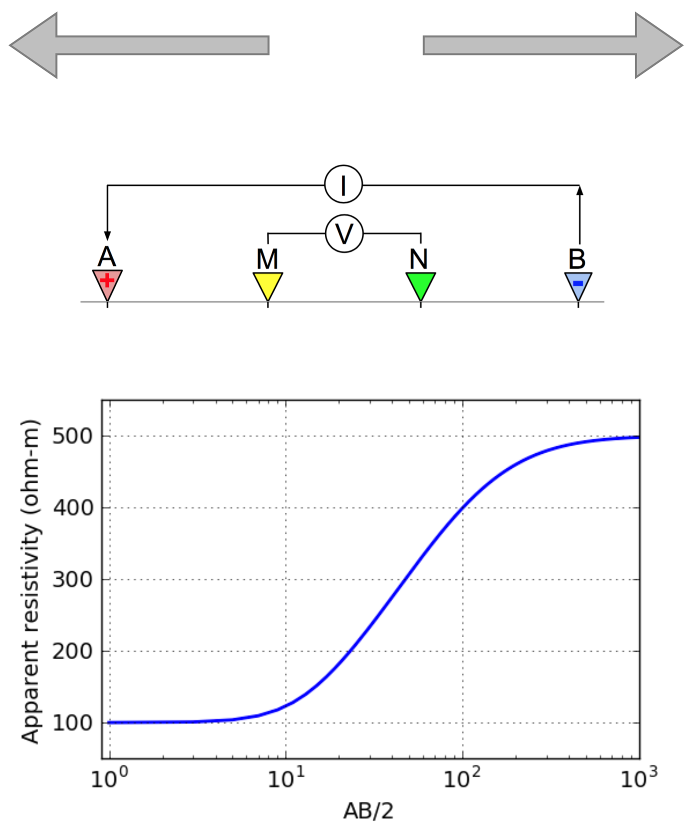


Depth of investigation depends upon offset or array length

Summary: Soundings and Profiles

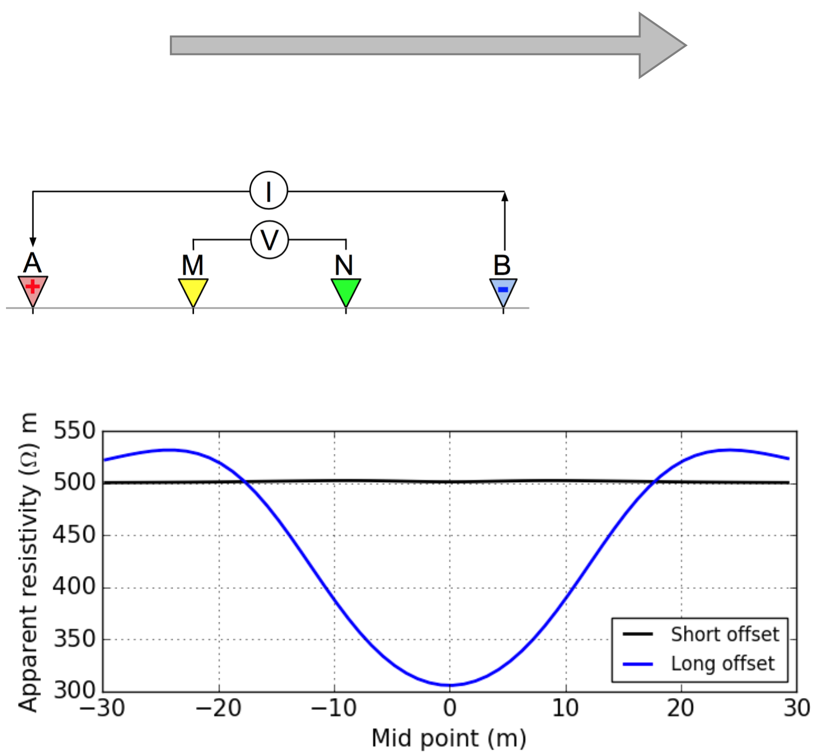
Sounding

Expand



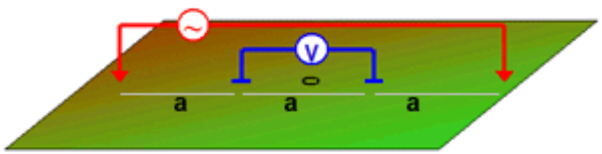
Profiling

Translate

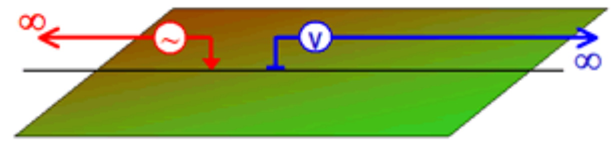


Basic Survey Setups

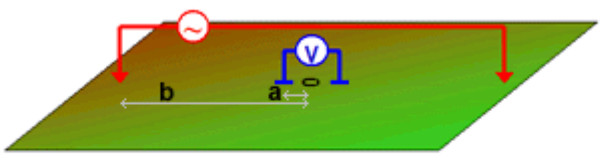
Wenner



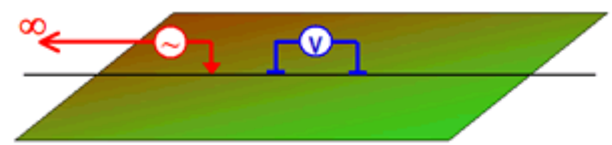
Pole-Pole



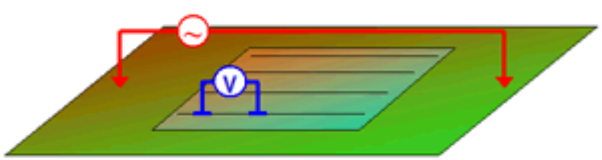
Schulmberger



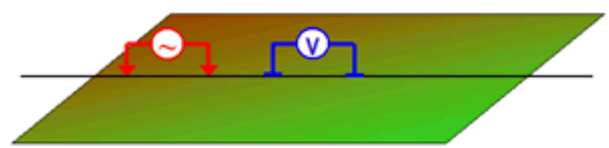
Pole-Dipole



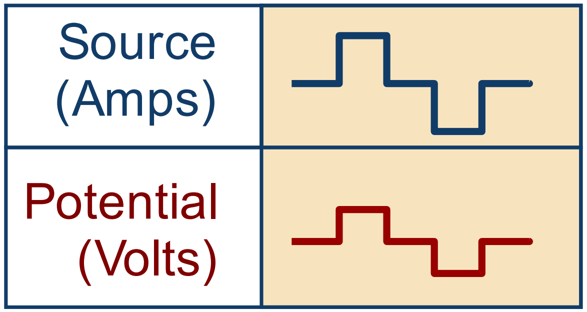
Gradient

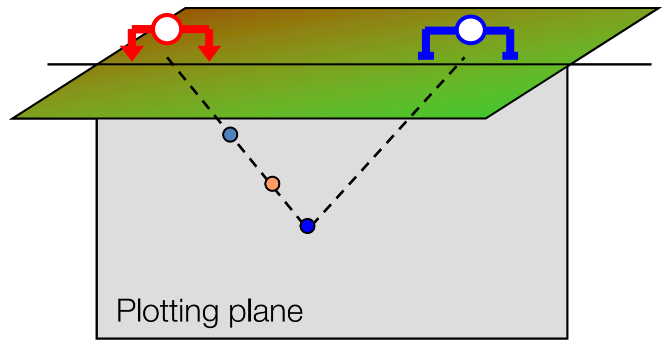


Dipole-Dipole

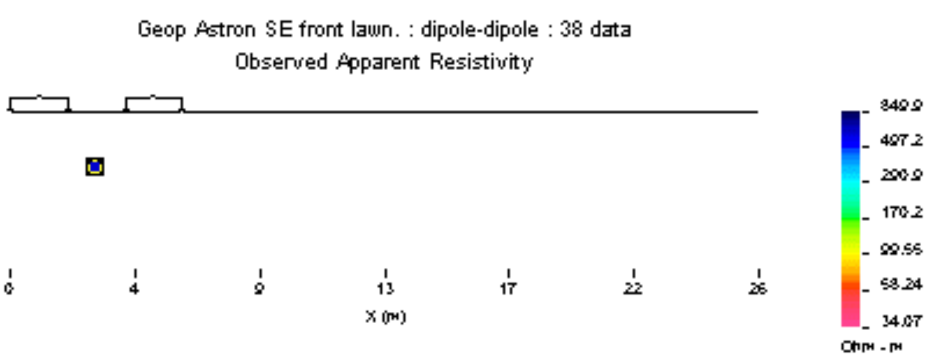


DC resistivity data



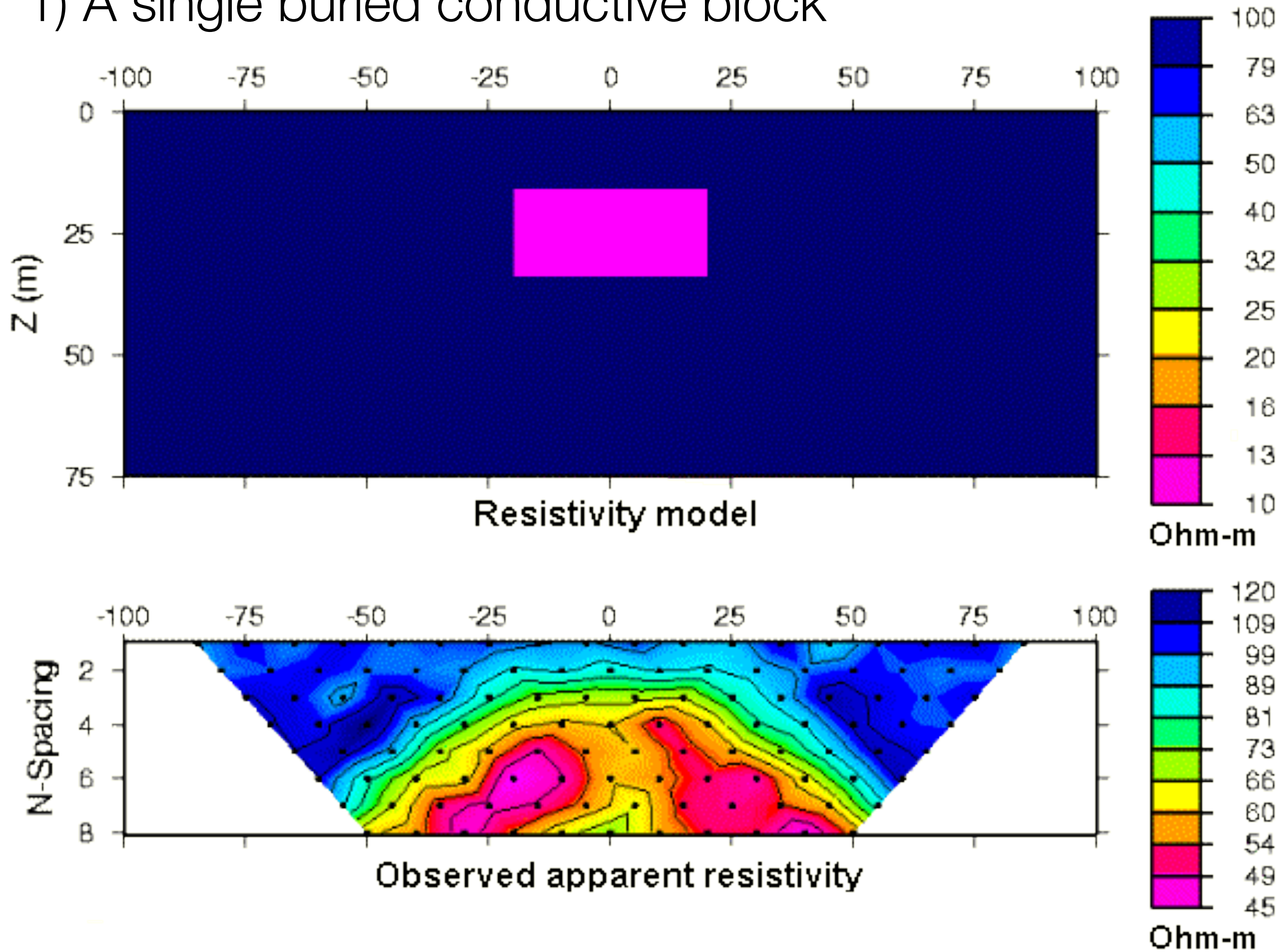


Each data point is an apparent resistivity: $$\rho_a = \frac{2\pi\Delta V}{IG}$$

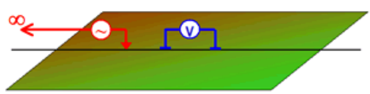


Example pseudosections

1) A single buried conductive block



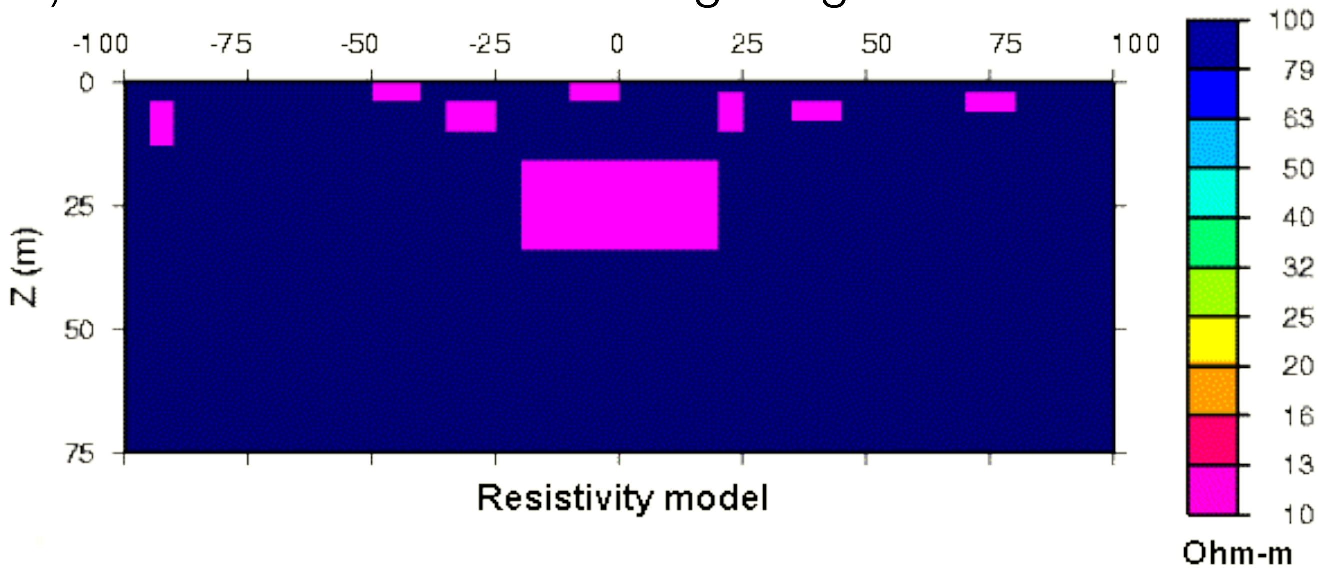
Pole-Dipole

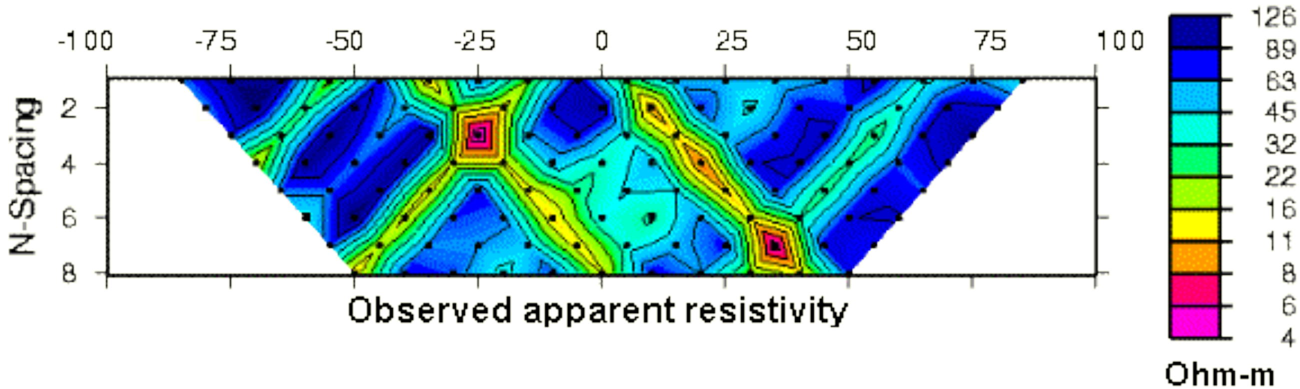


- Pole-dipole; n=1,8; a=10m; N=316

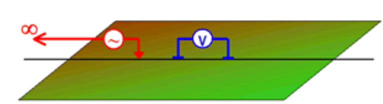
Example pseudosections

2) The conductive block with geologic noise.





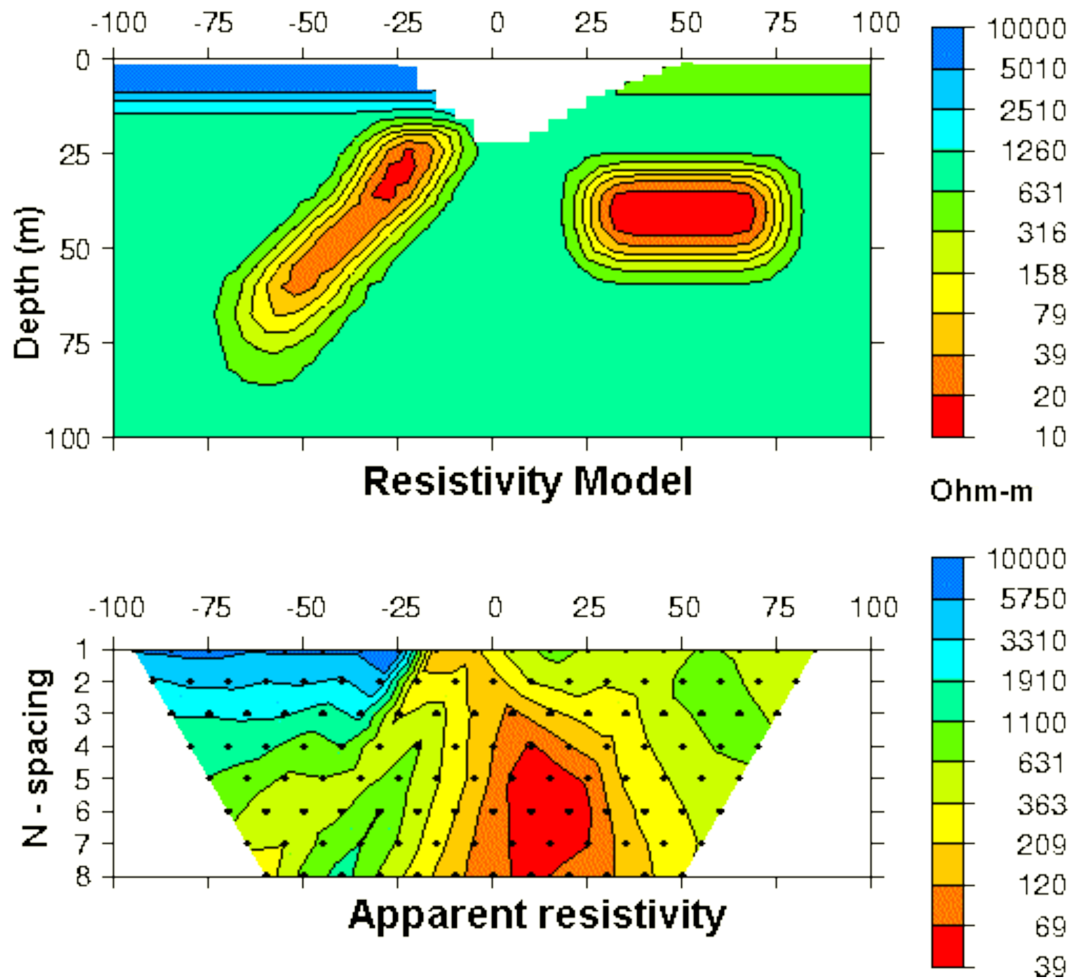
Pole-Dipole



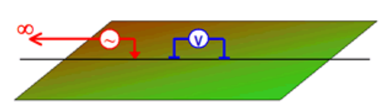
- Pole-dipole; n=1,8; a=10m; N=316

Example pseudosections

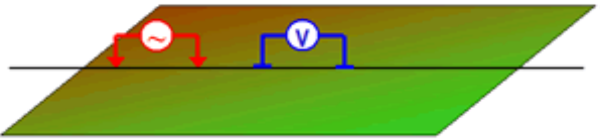
3) The “UBC-GIF model”



Pole-Dipole

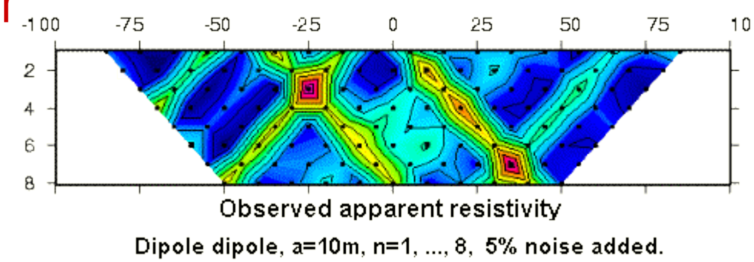


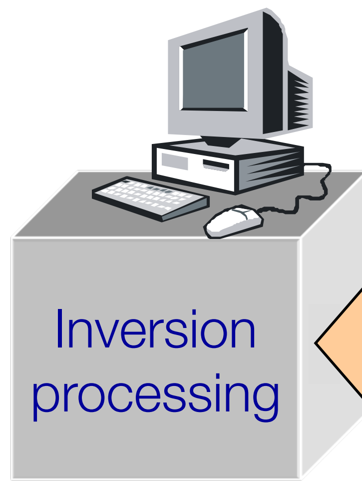
Inversion

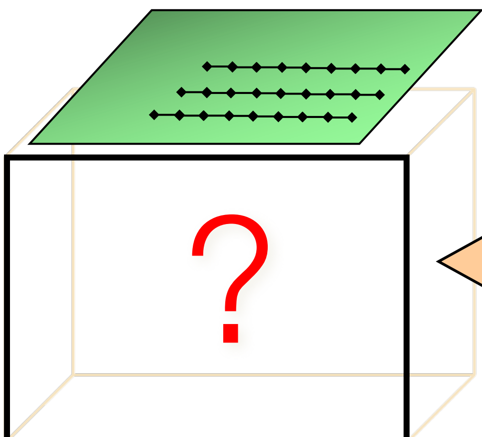


Measurements over the Earth are data.

Data



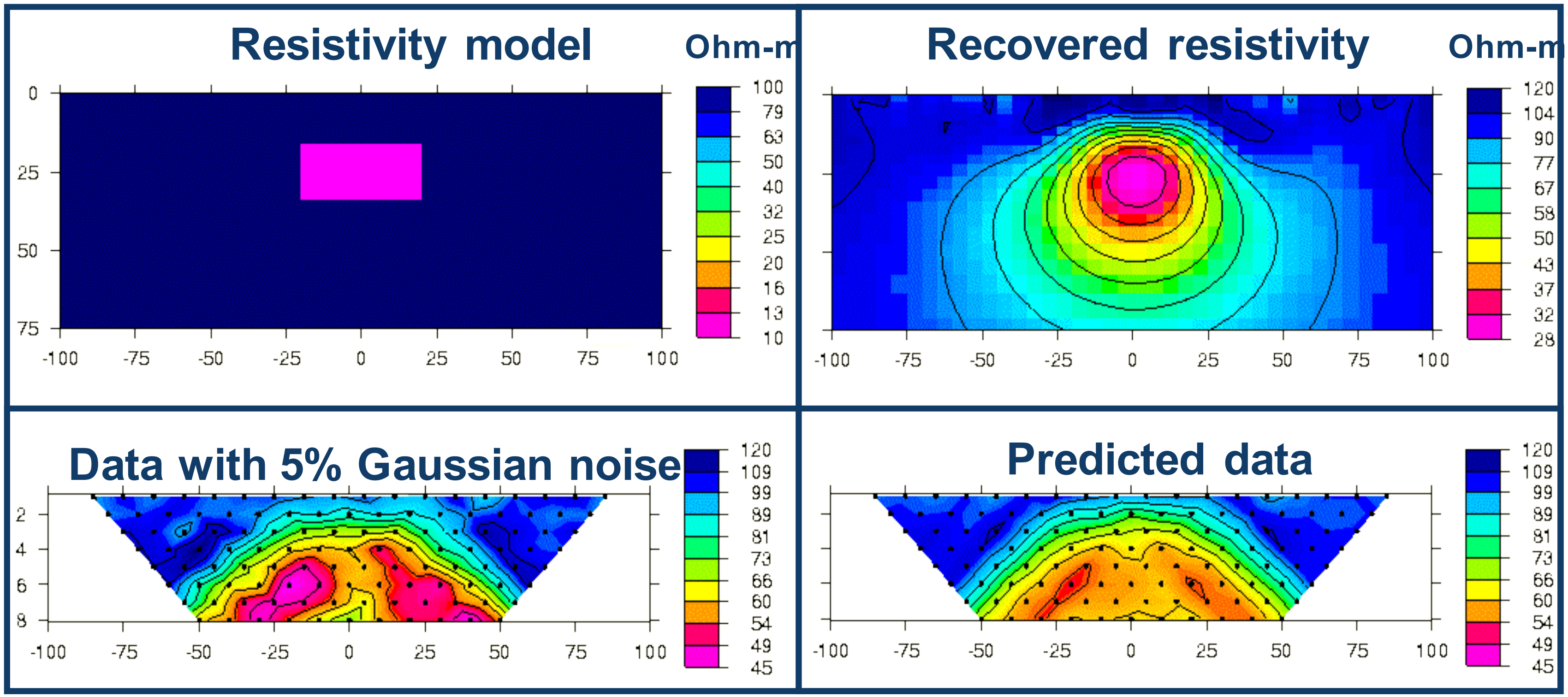




Model

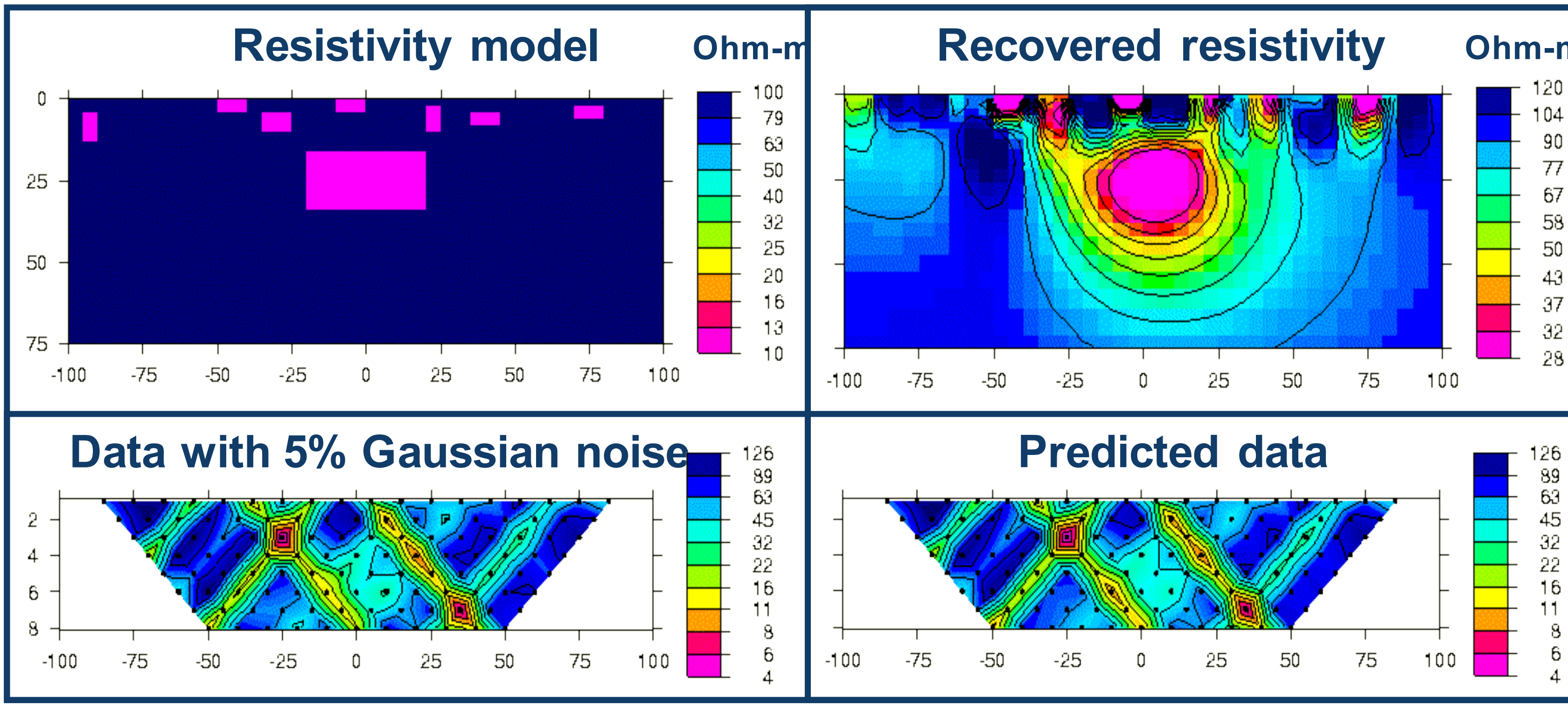
Inversion estimates Earth models based upon data and prior knowledge.

Example 1: buried prism



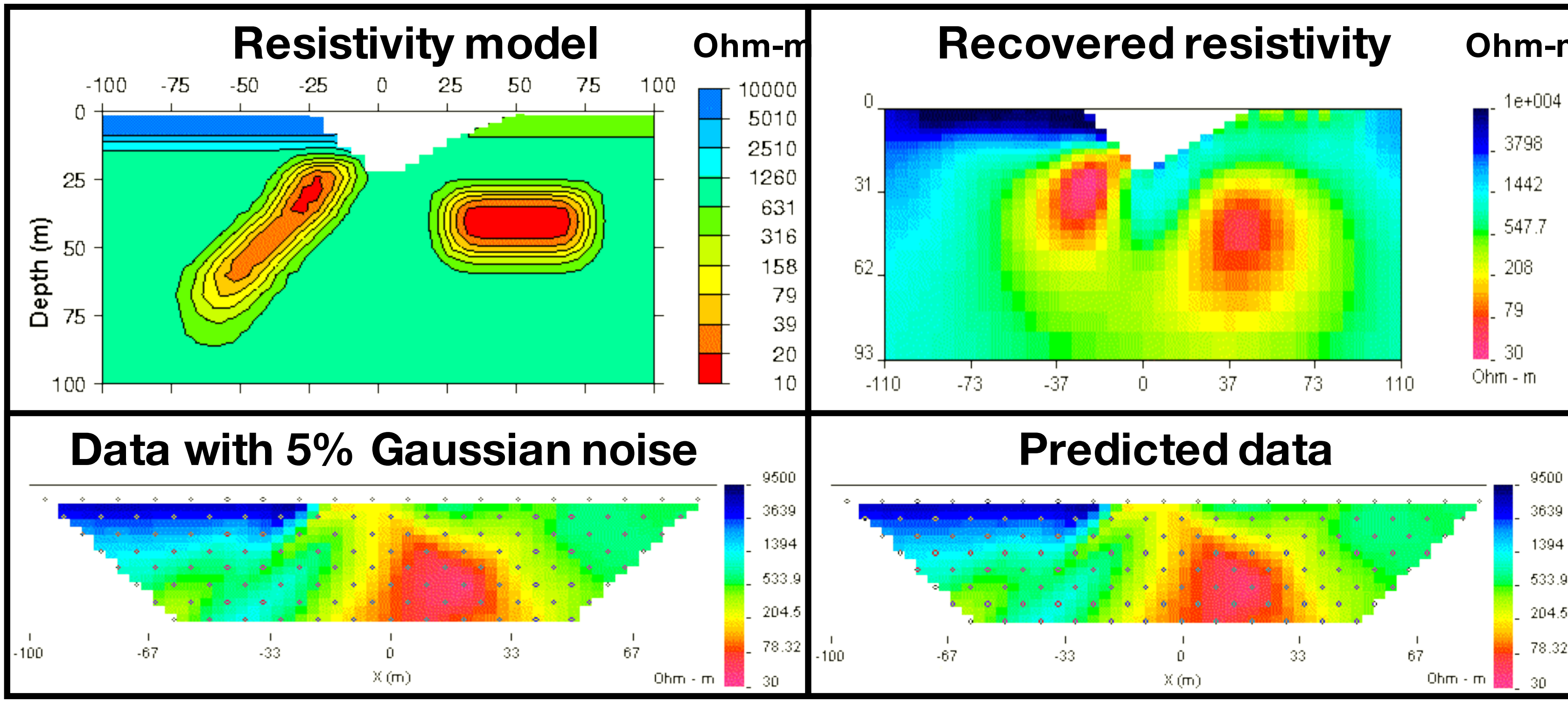
- Pole-dipole; n=1,8; a=10m; N=316; $(\alpha_s, \alpha_x, \alpha_z)$=(.001, 1.0, 1.0)

Example 2: prism with geologic noise



- Pole-dipole; n=1,8; a=10m; N=316; $(\alpha_s, \alpha_x, \alpha_z)$=(.001, 1.0, 1.0)

Example 3: UBC-GIF model



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

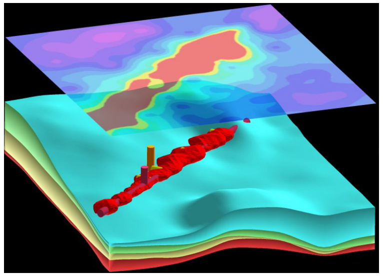
The world is 3D

- Target
  - Size, shape, depth
- Background
  - Variable resistivity
- Questions
  - Where to put currents? 2D acquisition? 3D?
  - Where to make measurements?
  - Which measurements?
  - Effects of topography?
- These are survey design questions
- Crucial element is the **sensitivity**

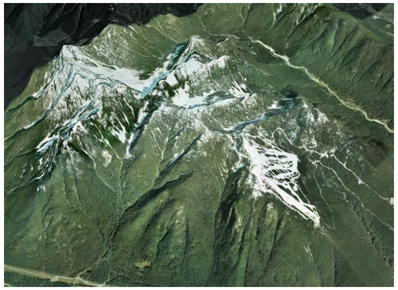
Host

Water underground

Ore body

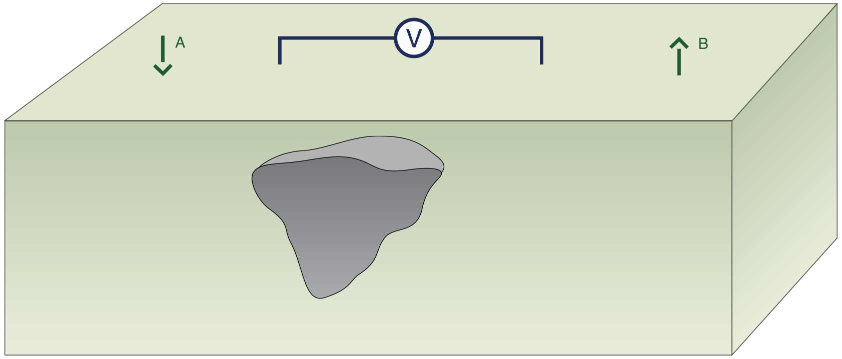


Topography



Sensitivity

Sensitivity Function



Is the measured potential *sensitive* to the target?

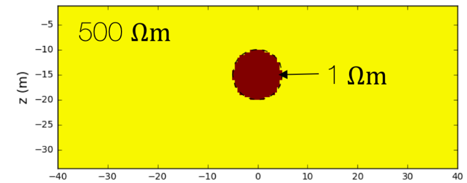
Quantified by the sensitivity

$$G = \frac{\Delta d}{\Delta p} = \frac{\text{change in data}}{\text{change in model}}$$

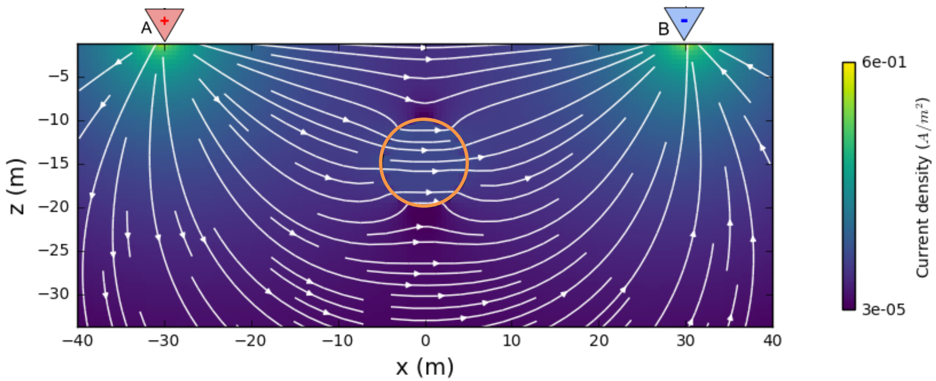
- Collect the data that are sensitive to the target
  - Need to **excite** the target
  - Need to have sensor **close** to the target

Exciting the target

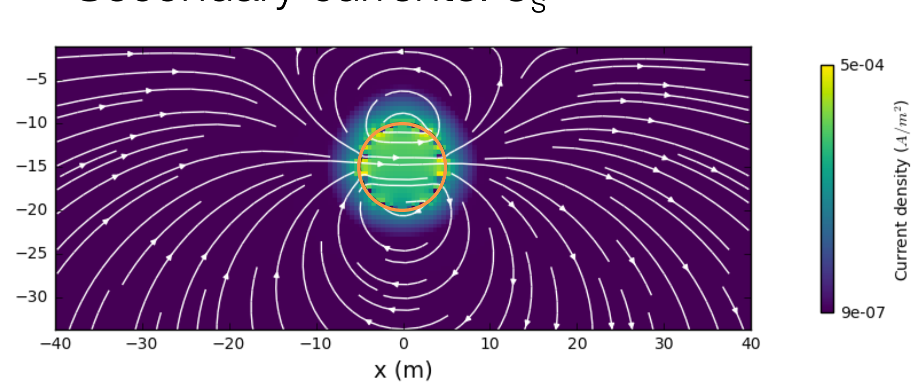
Resistivity model



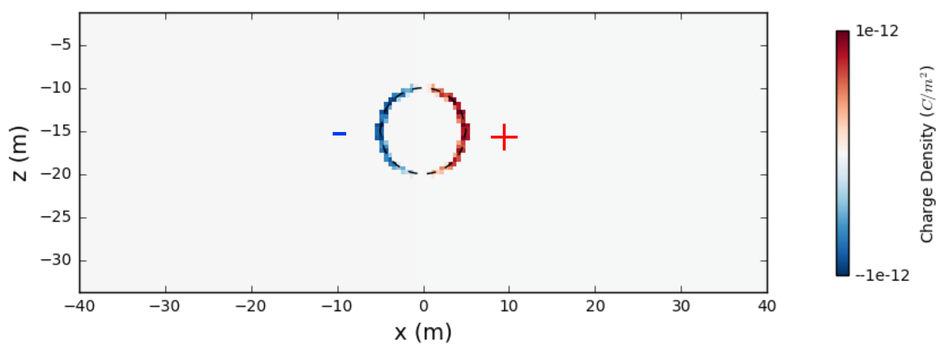
Total currents: **J**



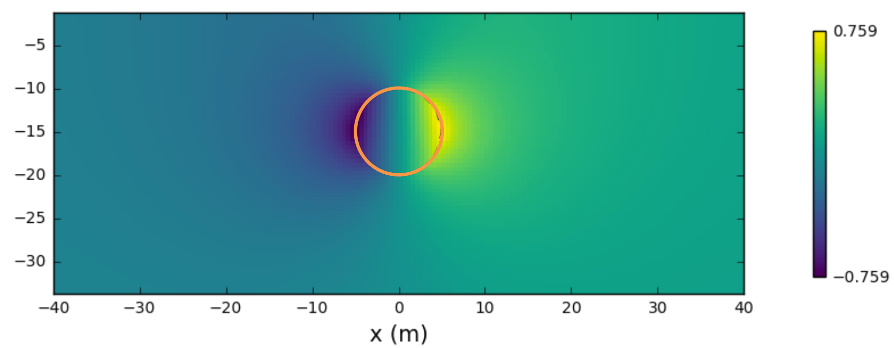
Secondary currents: $\mathbf{J}_s$



Secondary charges: Q_s

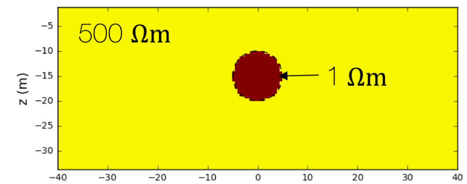


Secondary potential: ϕ_s

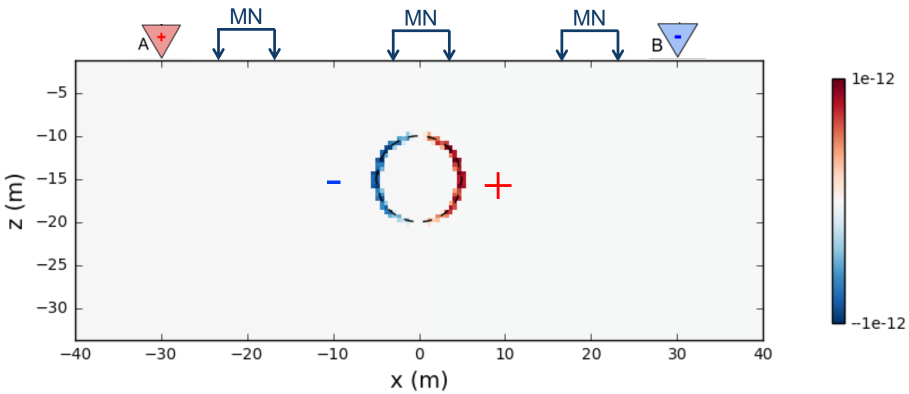


Measurements

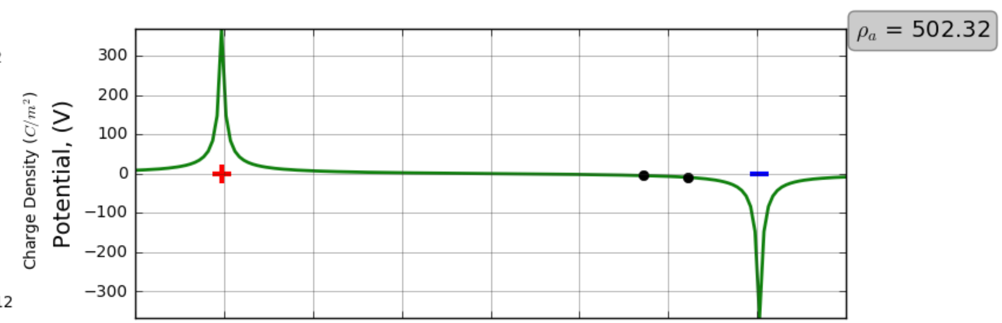
Resistivity model



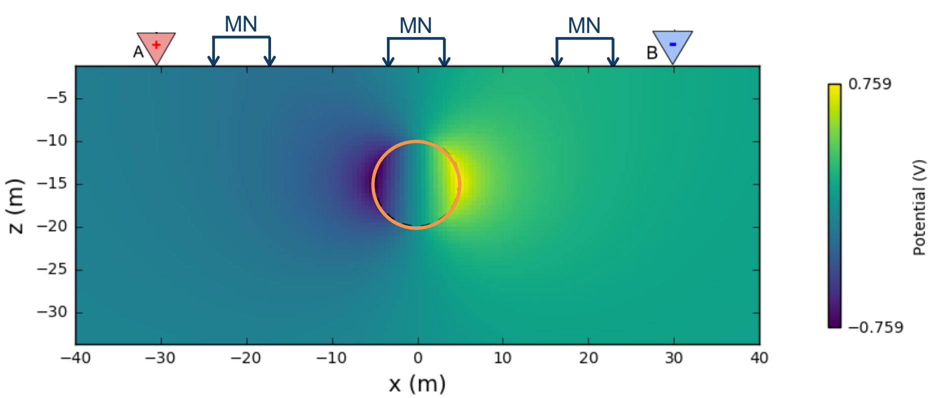
Secondary charges: Q_s



Potential profile

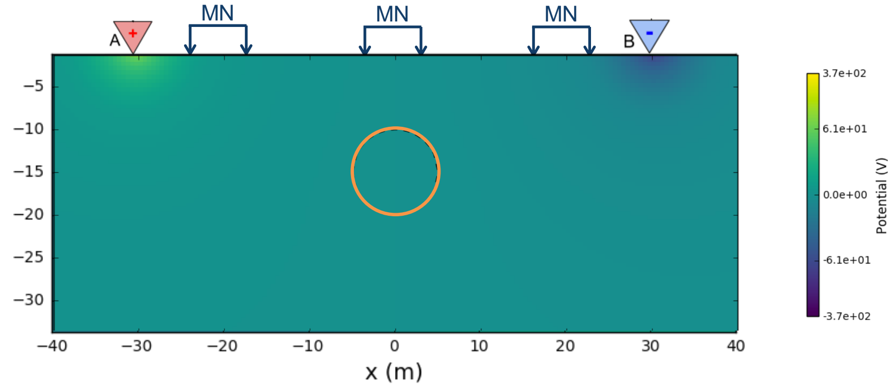


Secondary potential: ϕ_s



Total potential: ϕ

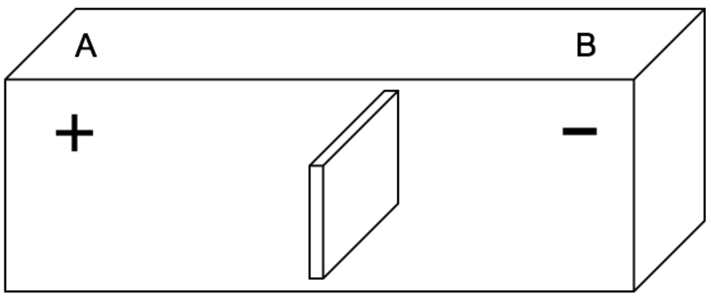
$\rho_a = 502$ $\rho_a = 430$ $\rho_a = 502$

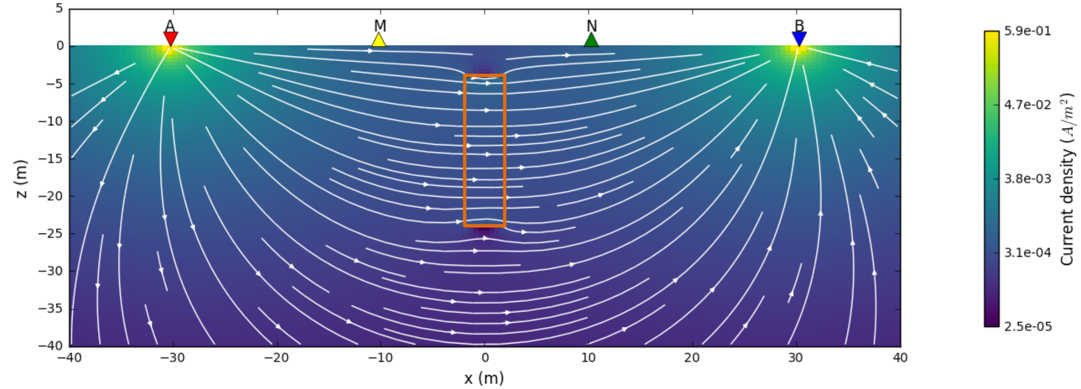


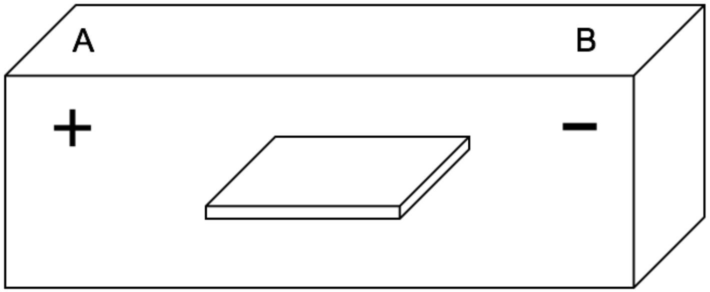
Coupling

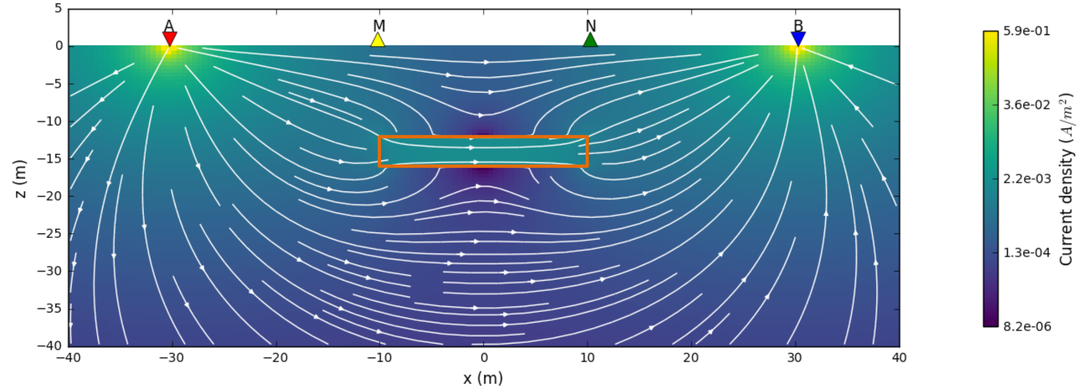
- Thin plate – different orientations
  → different data

Total currents: **J**





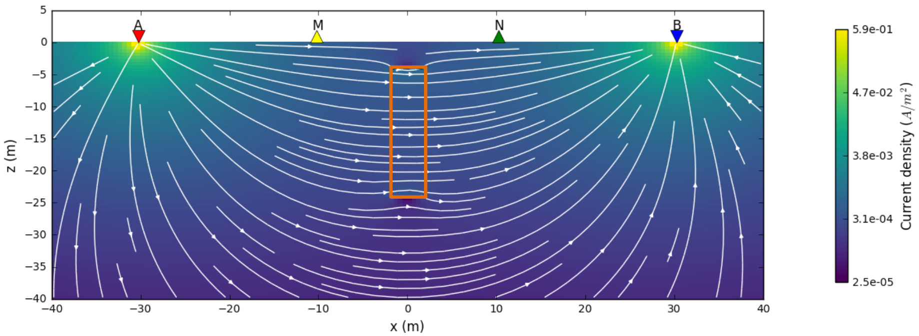




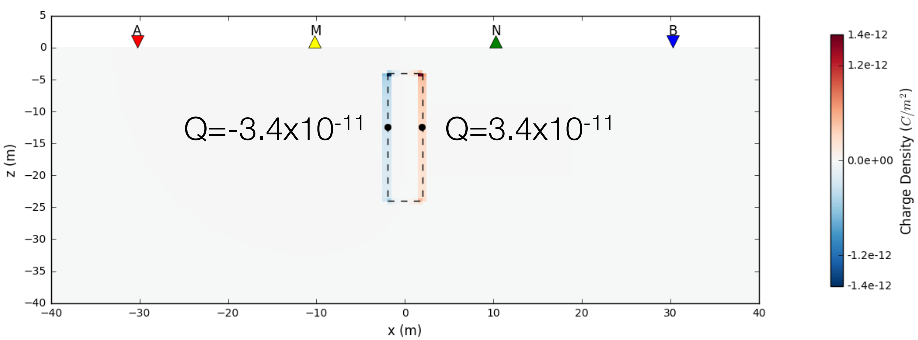
Conductive vs. Resistive Target

Conductive Target

Total currents: **J**

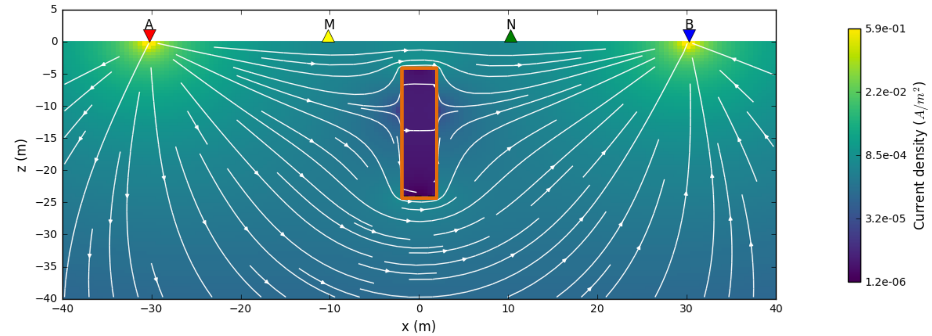


Secondary charges: Q_s

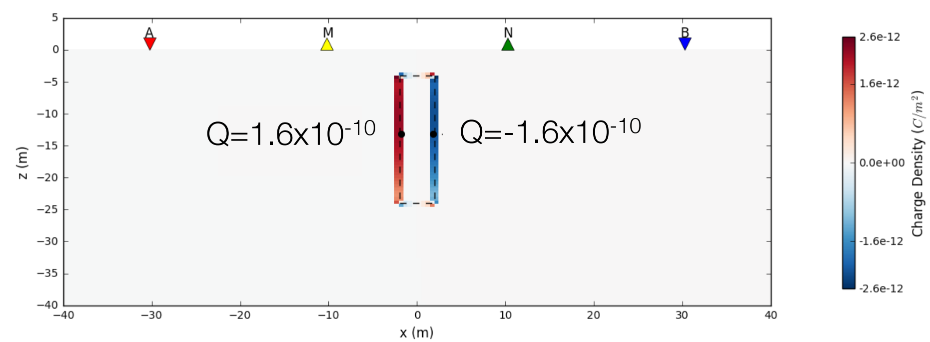


Resistive Target

Total currents: **J**



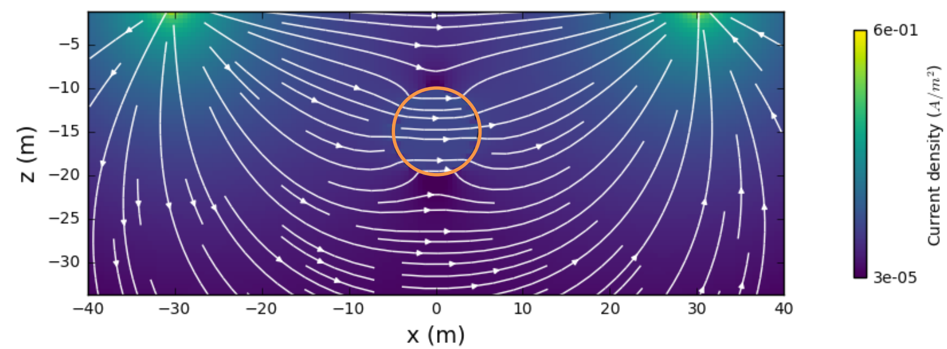
Secondary charges: Q_s



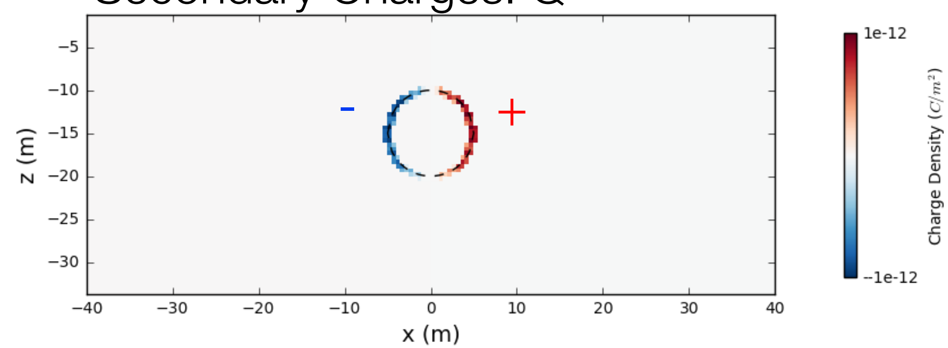
Summary: Sensitivity

- "Excite" the target
  - Drive currents to target
  - Need good coupling with target
- Measuring a datum
  - Proximity to target
  - Electrode orientation and separation
- Background resistivity is important

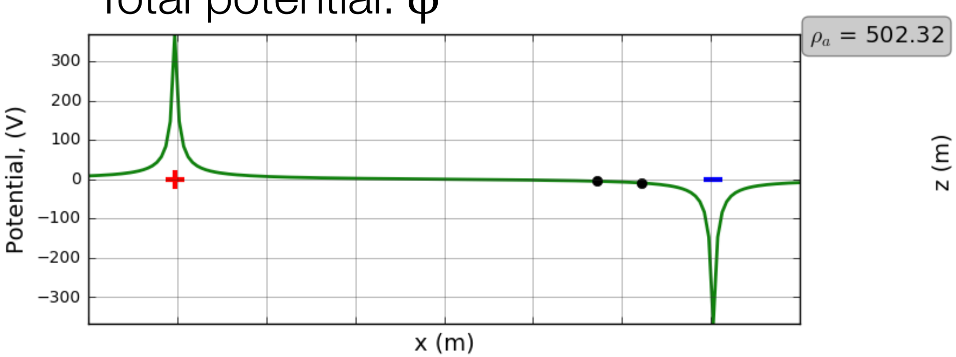
Total currents: **J**



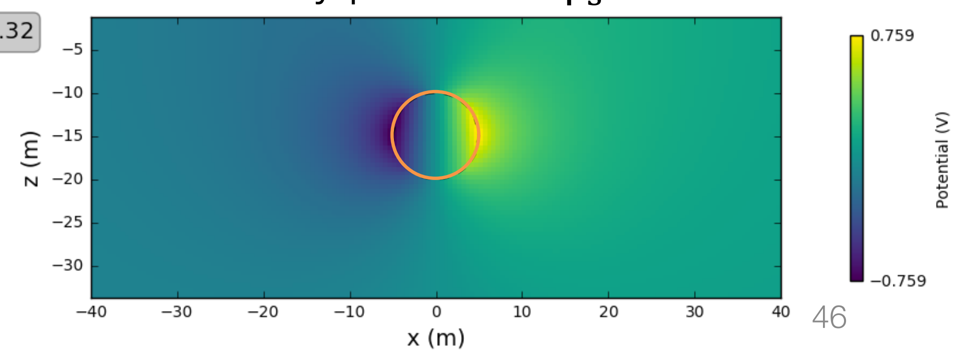
Secondary Charges: Q



Total potential: ϕ

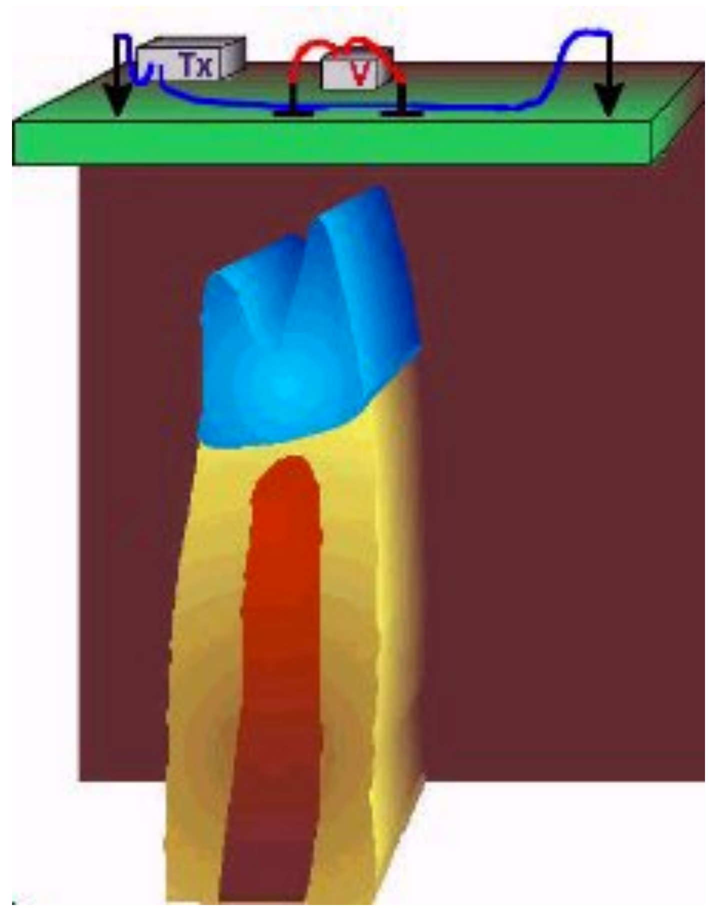


Secondary potential: ϕ_s

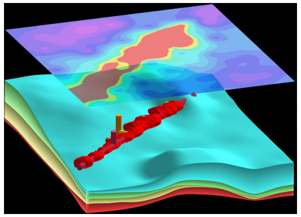


Survey Design: Questions

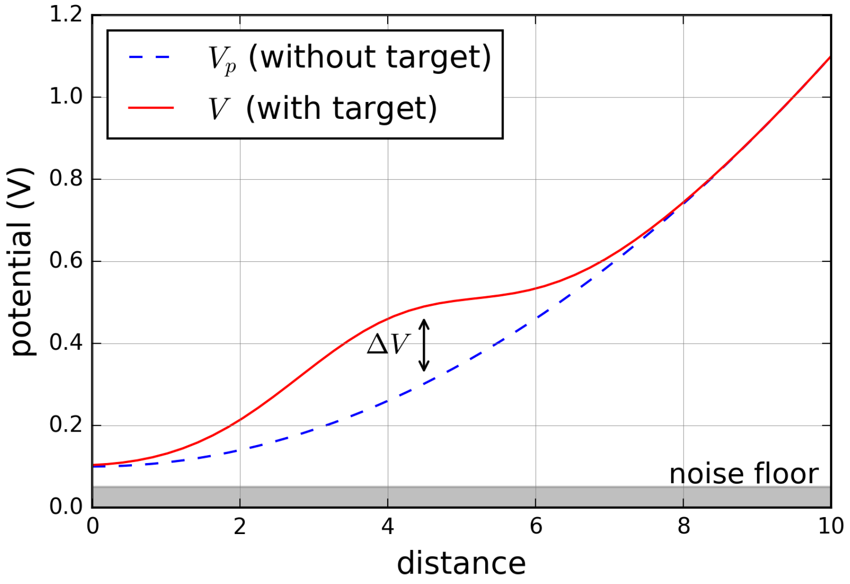
- What is objective?
  - Layered earth (1D)
    → do a sounding
  - Target body (2D)
    → profile, sounding perpendicular to geology
  - Target body (3D)
    → need 3D coverage
- What is the background resistivity?
- What are the noise sources? fences, power lines, …



Survey Design: in general



- Numerical simulation – can we **see** the target?
- Steps:
  - Define a geologic model
  - Assign physical properties
  - Select a survey
  - Simulate with (V) and without (V_p) target



- Best practice
  - Assign uncertainties to simulated data
  - Invert with code you will use for the field data

Signal from target

$$\Delta V = V - V_p$$

Need

$$\Delta V > floor$$

$$\frac{\Delta V}{V_p} > \%|V|$$

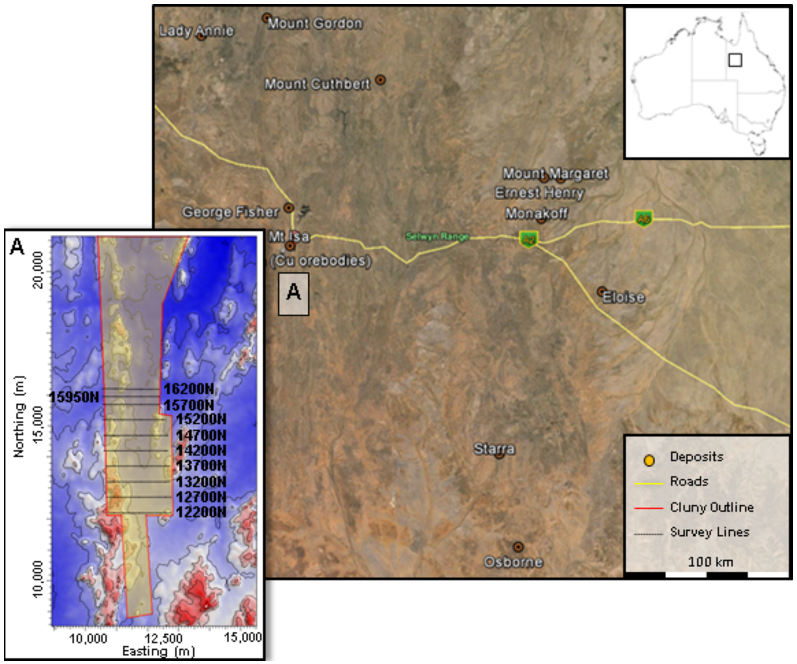
Outline

- Basic experiment
- Currents, charges, potentials and apparent resistivities
- Soundings, profiles and arrays
- Data, pseudosections and inversion
- Sensitivity
- Survey Design

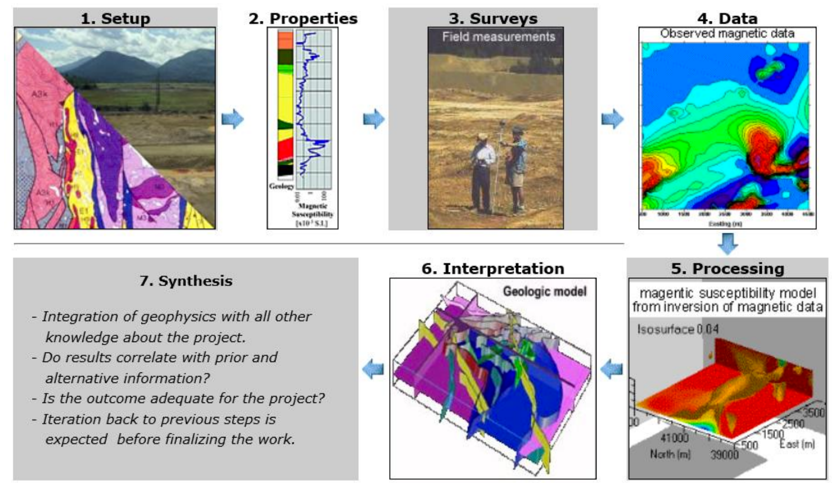
- Case History – Mt Isa
- Case History – Dam Monitoring
- Effects of background resistivity

Mt. Isa

Mt. Isa (Cluny prospect)

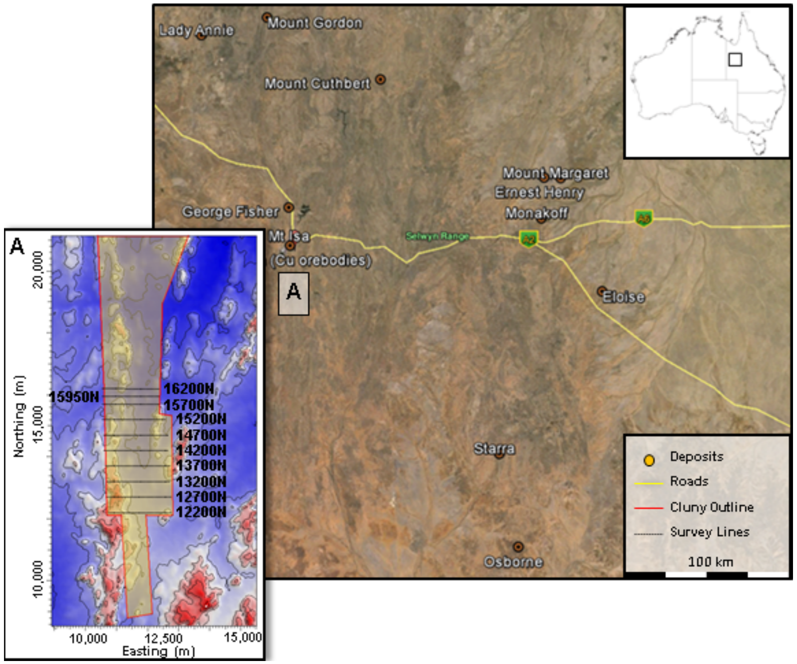


Seven Steps

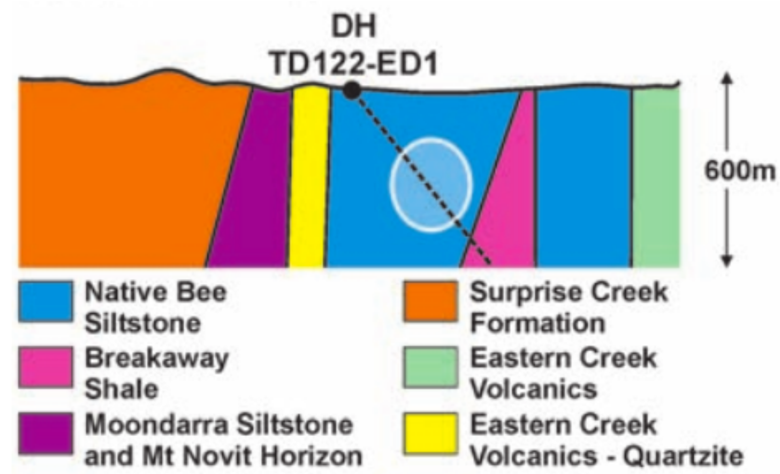


Setup

Mt. Isa (Cluny prospect)



Geologic model

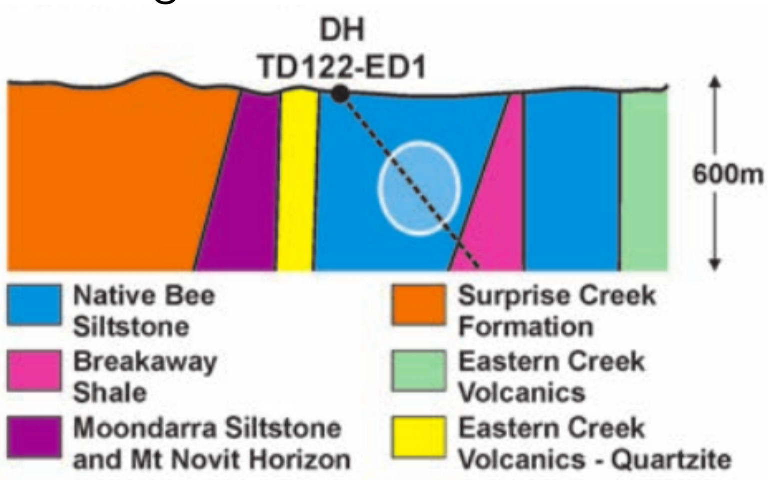


Question

- Can conductive units, which would be potential targets within the siltstones, be identified with DC data?

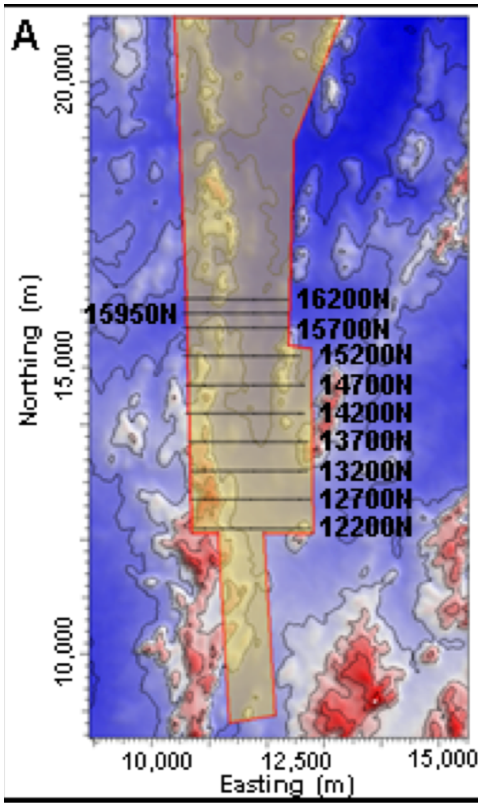
Properties

Geologic model



Rock Unit	Conductivity
Native Bee Siltstone	Moderate
Moondarra Siltstone	Moderate
Breakaway Shale	Very High
Mt Novit Horizon	High
Surprise Creek Formation	Low
Eastern Creek Volcanics	Low

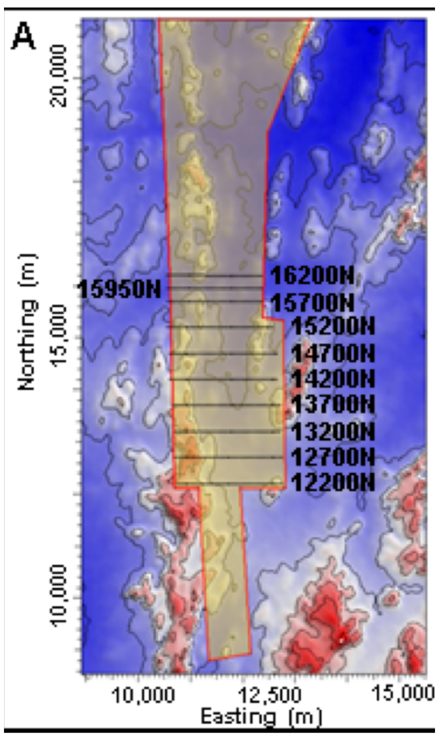
Surface topography



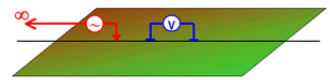
Survey and Data

- Eight survey lines
- Two survey configurations.

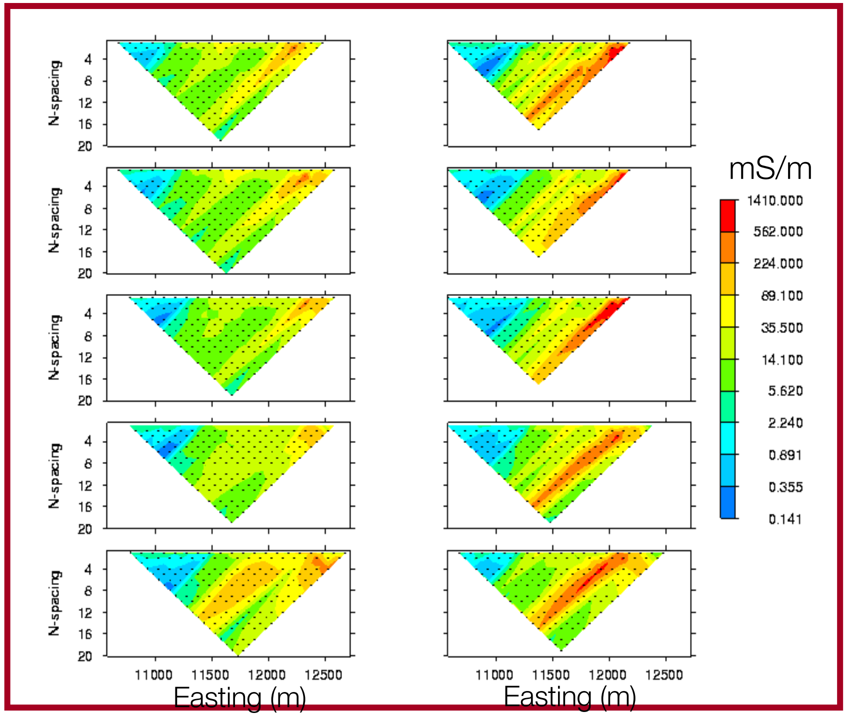
Surface topography



Data set #1:



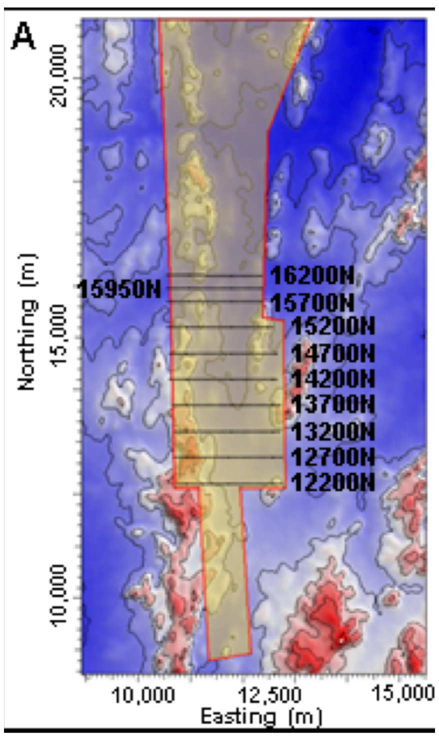
Apparent resistivity, pole - dipole.

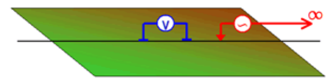


Survey and Data

- Eight survey lines
- Two survey configurations.

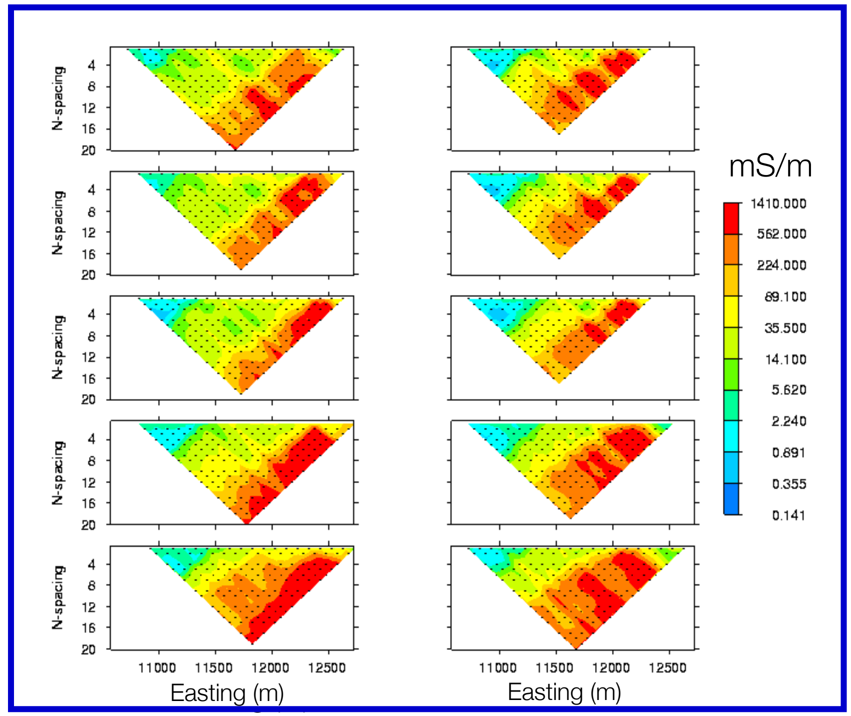
Surface topography





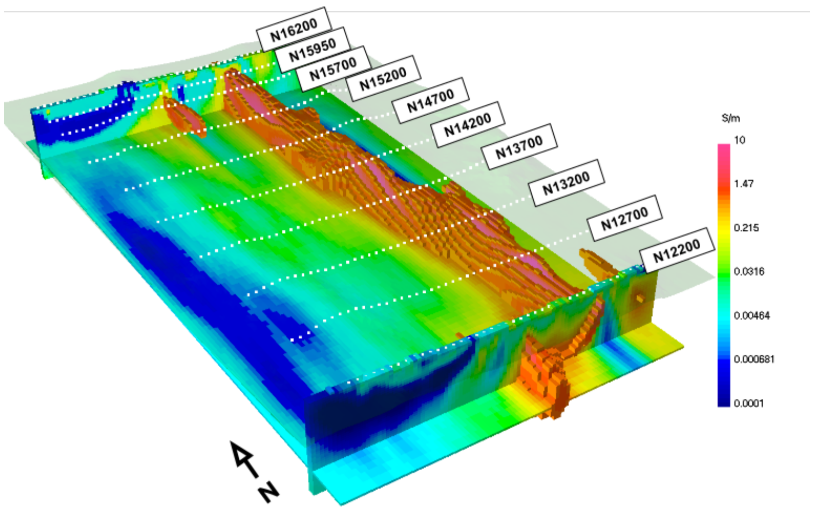
Data set #2:

Apparent resistivity, dipole - pole

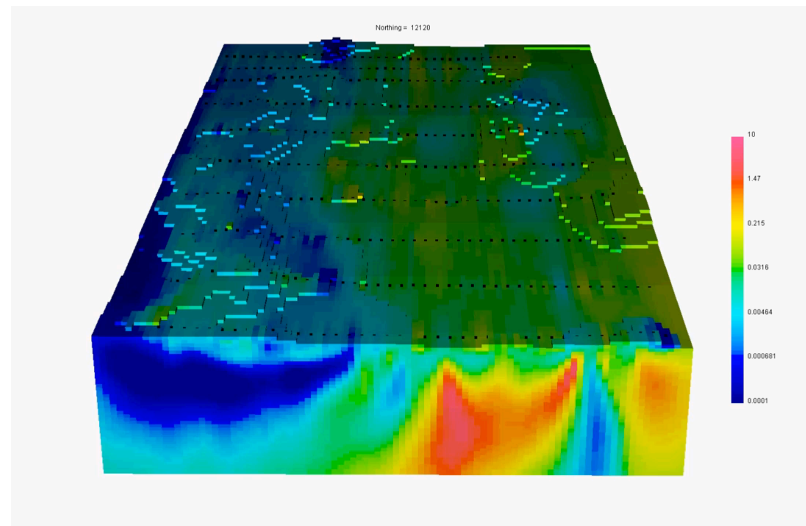


Processing and interpretation

3D resistivity model



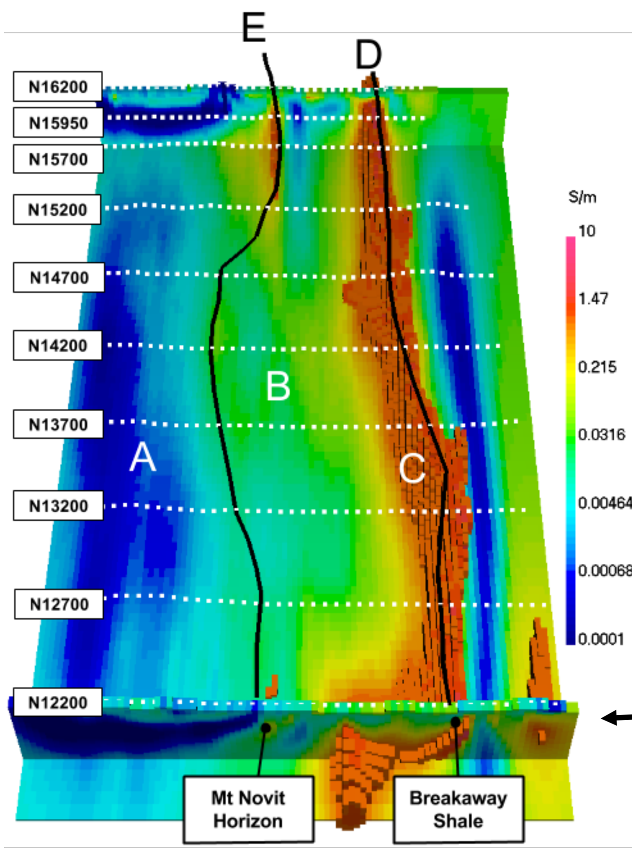
Animation



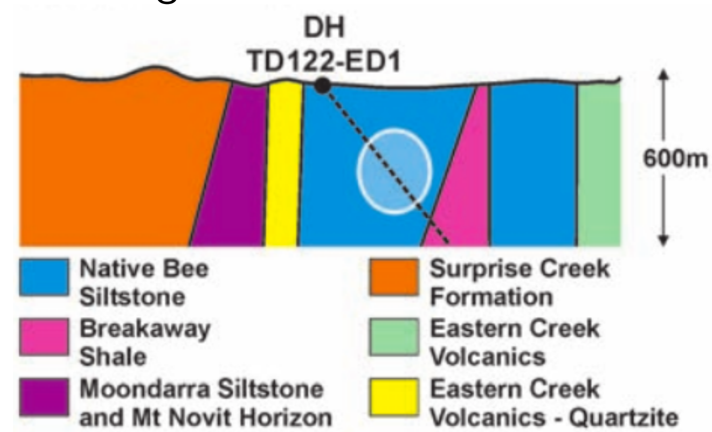
Synthesis

- Identified a major conductor → black shale unit
- Some indication of a moderate conductor

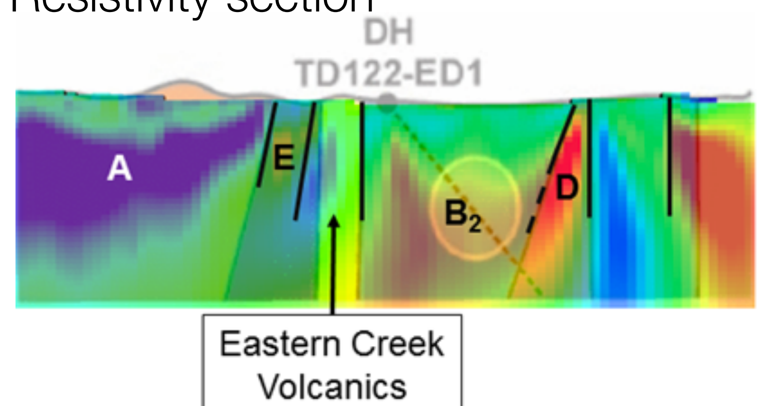
3D resistivity model



Geologic section

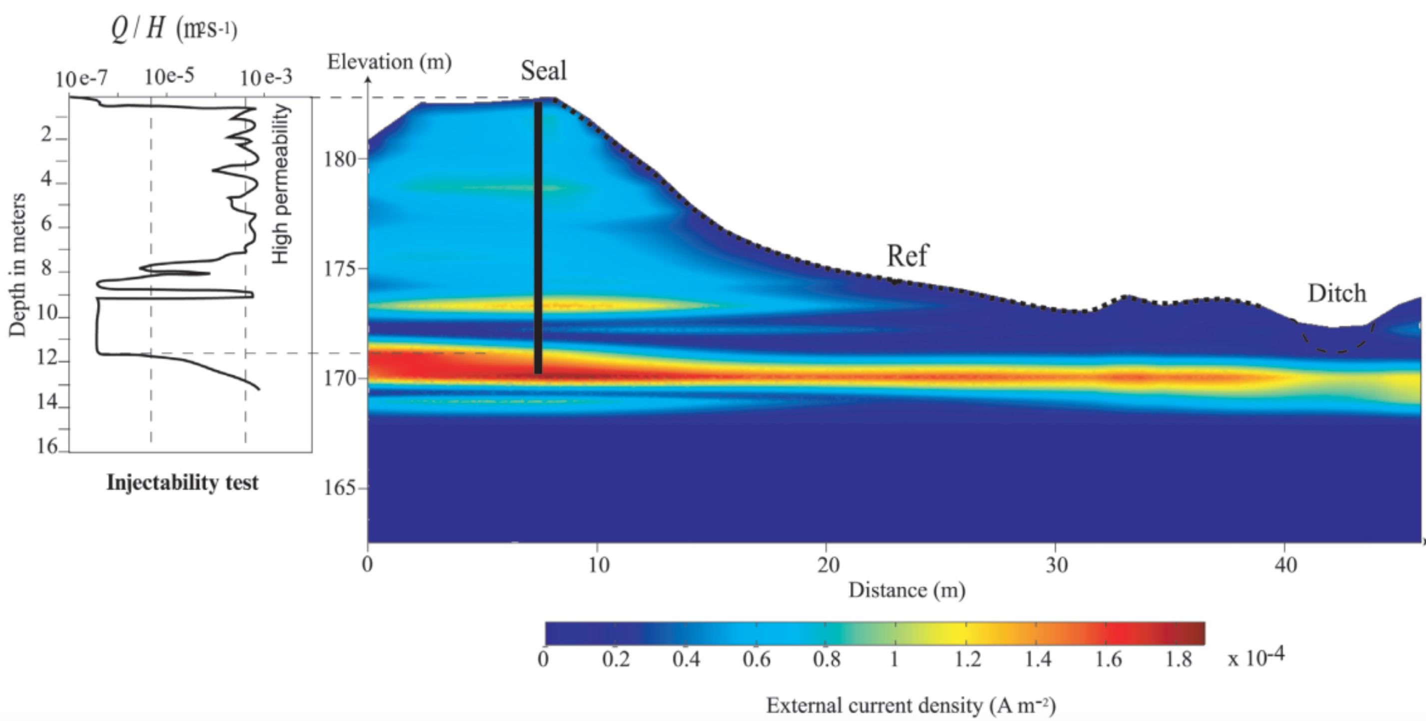


Resistivity section



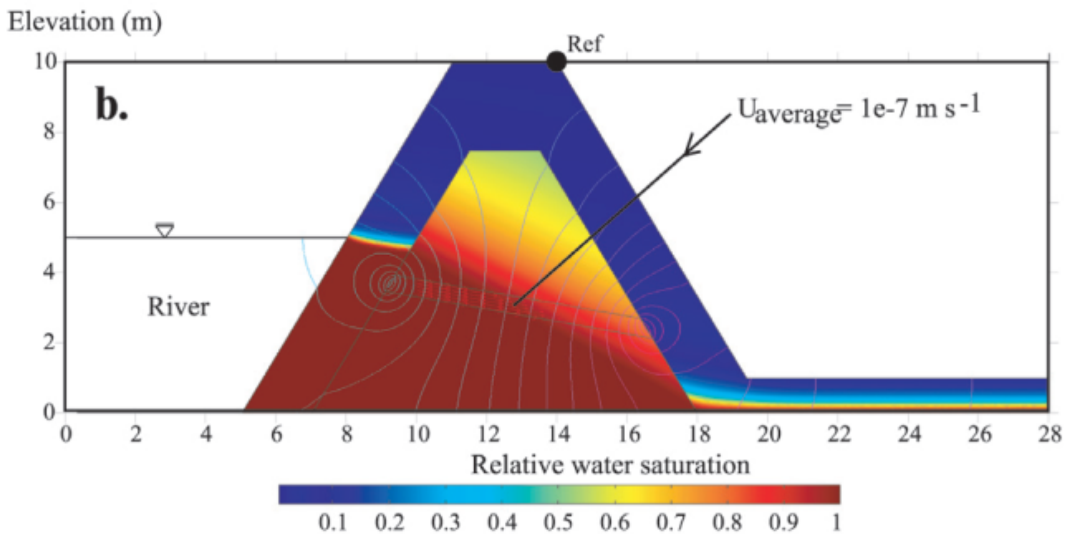
Case History:
Monitoring an embankment dam
Rhone river, France

Boleve and Revil., 2009



Physics of streaming potential

Fluid flow



Steady-state, unsaturated flow

$$\vec{u} = K \nabla h$$

$$\nabla \cdot \vec{u} = 0 \qquad \text{With B.C.}$$

$$K = k_r(S_w, ...)K_s$$

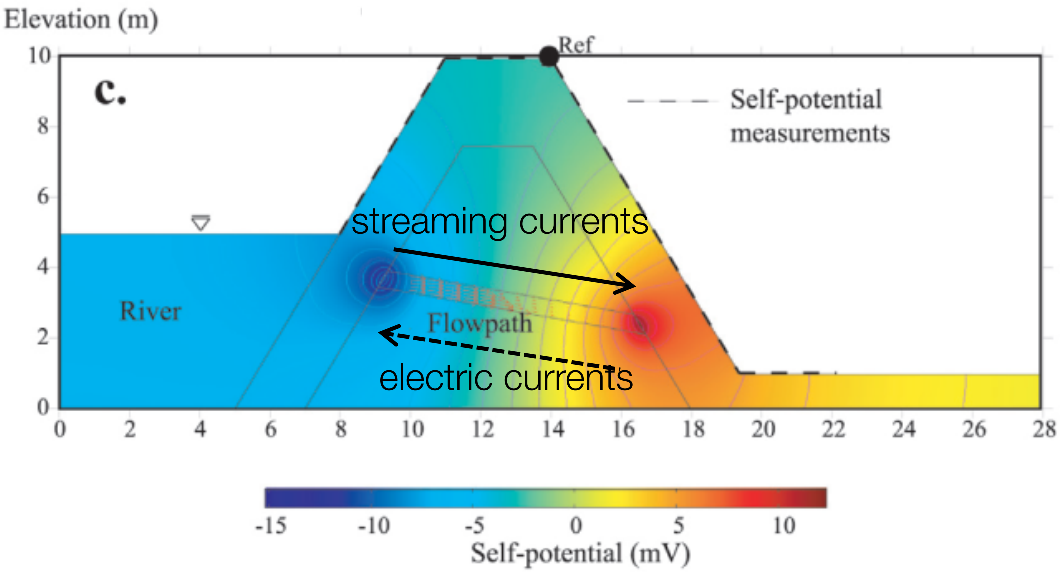
$\vec{u}$: fluid velocity [m/s]
h: hydraulic head [m]
K: hydraulic conductivity [m/s]

S_w: saturation
K_s: hydraulic conductivity at S_w=1
k_r: relative permeability

Materials	K_S (m s^{-1})
Sand	1.10^{-5}
Clay	1.10^{-9}
Leaking area	1.10^{-6}

Physics of streaming potential

Streaming potential



Streaming currents

$$\nabla \cdot \vec{j} = 0$$

$$\vec{j} = \vec{j}_e + \vec{j}_s$$

$$\vec{j}_e = -\sigma \nabla \phi \qquad \vec{j}_s = \frac{Q_v}{S_w} \vec{u}$$

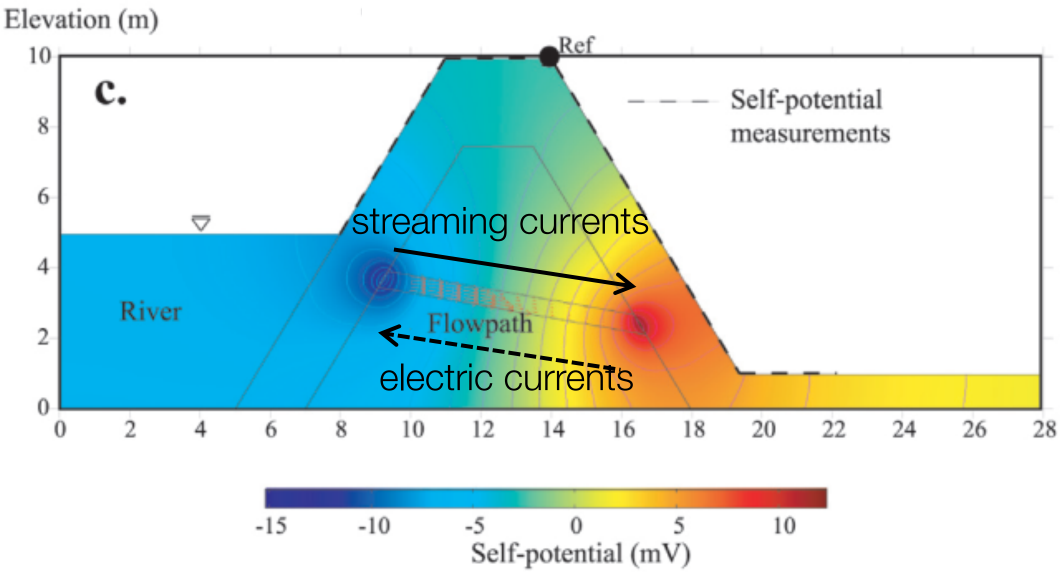
$$\nabla \cdot \sigma \nabla \phi = \nabla \cdot \vec{j}_s$$

Materials	σ(S m^{-1})	$\overline{Q}_V$(C m^{-3})	K_S (m s^{-1})
Sand	$3.3.10^{-3}$	0.5	1.10^{-5}
Clay	1.10^{-2}	500	1.10^{-9}
Leaking area	1.10^{-2}	500	1.10^{-6}

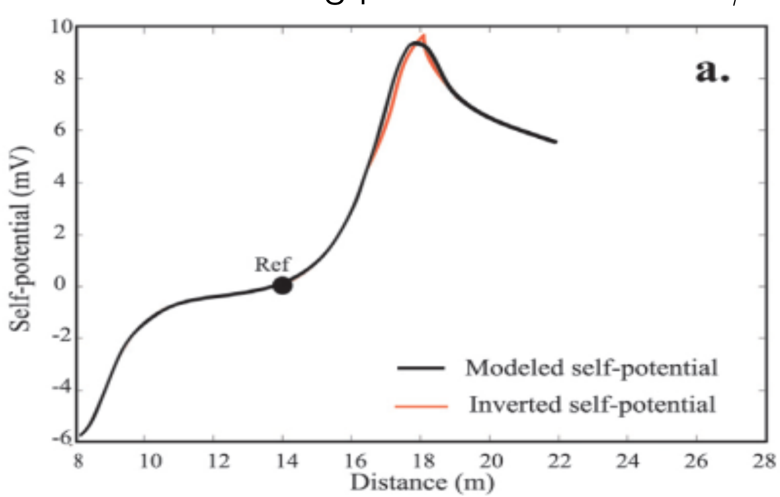
Q_v: excess electrical charge per unit pore volume [C/m^3]

Physics of streaming potential

Streaming potential



Measured streaming potential difference: $\phi - \phi_{ref}$



Streaming currents

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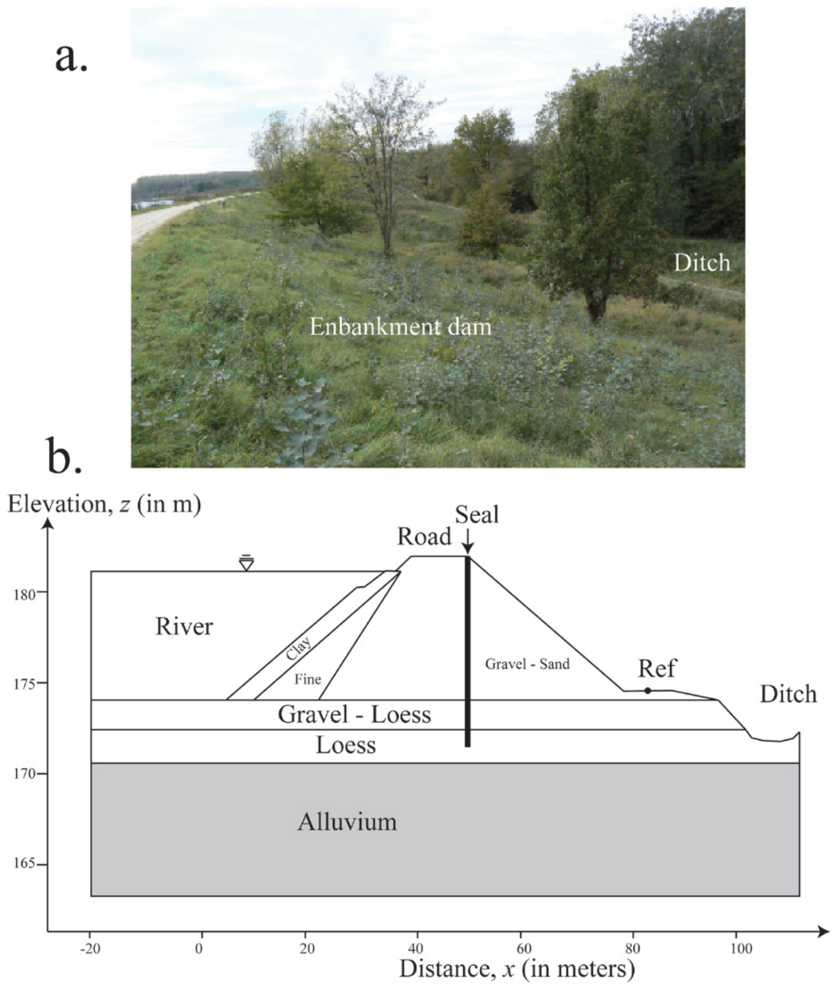
$$\vec{j}_e = -\sigma \nabla \phi \qquad \vec{j}_s = \frac{Q_v}{S_w} \vec{u}$$

$$\nabla \cdot \sigma \nabla \phi = \nabla \cdot \vec{j}_s$$

Setup

Embankment dam in southeast France along the Rhone River

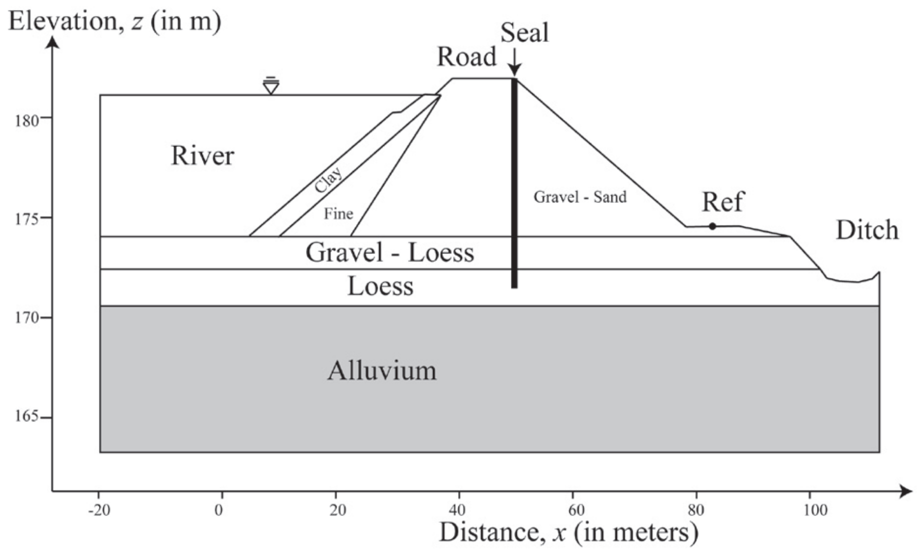


- Unconsolidated materials:
  - sand + gravels
- Riverside impermeable layer
  - cemented clay and silt
- Expected water seepage
  - leakage water collected in a ditch
- Piezometers
  - measure water level
  - every ~150m
- Vertical sealing
  - cement + bentonite
  - 12 m height and 12cm width

Can we image the preferential seepage zone, and determine velocity?

Properties

Geologic section

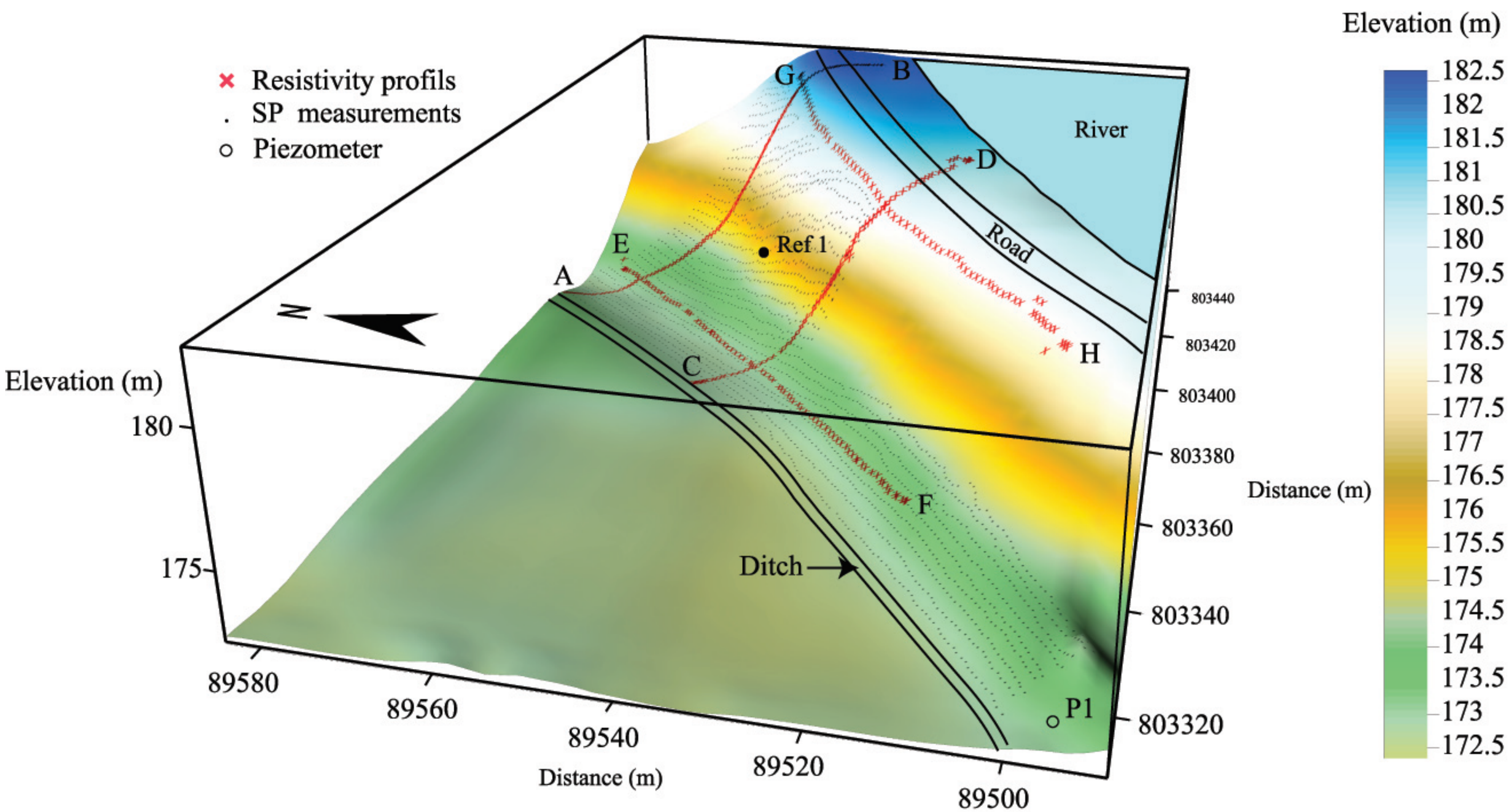


Physical property table

Materials	K_s (m s^{-1})	σ(S m^{-1})	$\overline{Q}_V$(C m^{-3})
Loess	1.10^{-5}	3.10^{-3}	10
Gravel and loess	1.10^{-4}	$1.25.10^{-3}$	0.1
Gravel and sand	1.10^{-4}	$3.3.10^{-3}$	10
Silt	1.10^{-13}	$2.5.10^{-2}$	100
Cemented clay	1.10^{-18}	5.10^{-2}	1.10^{6}

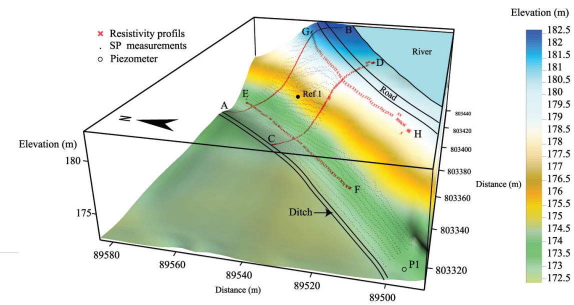
- Low permeability zone
  - Cemented clay & silt
  - Seal
- High permeability zone
  - Gravels
- High electrical conductivity
  - Silt and clays
- High Q_V
  - Cemented clay

Survey

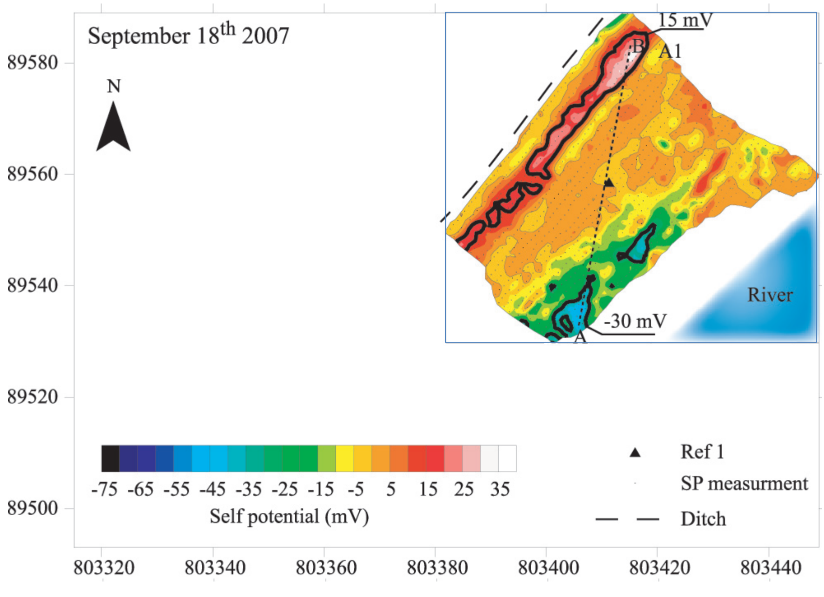


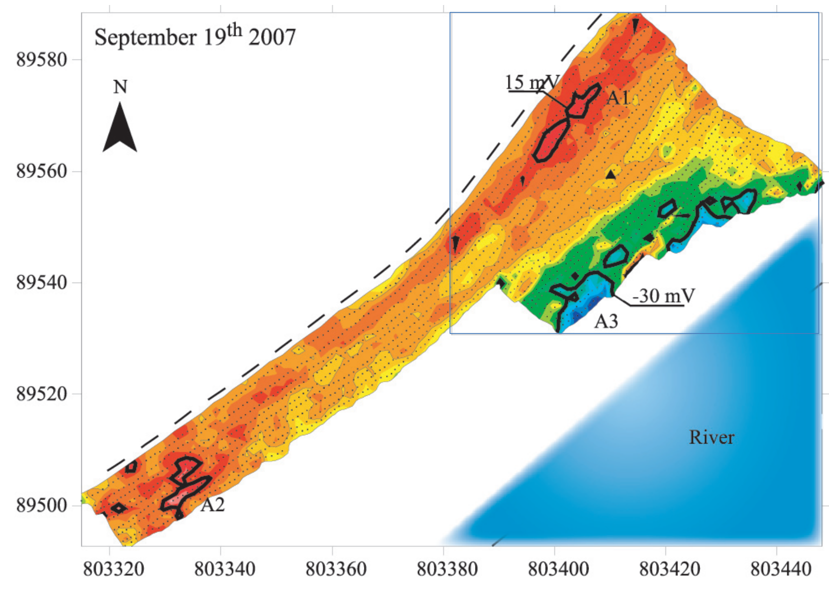
- DC survey
  - 4 profile lines
  - Wenner array
- SP survey (2 days)
  - 2007/09/18: 1169 data
  - 2007/09/19: 2076 data

Data

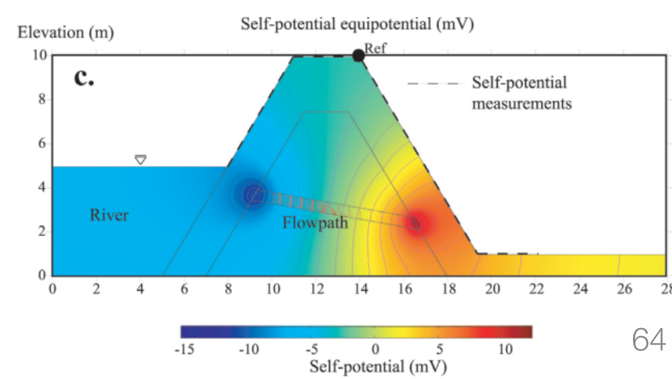


- SP maps on two different days

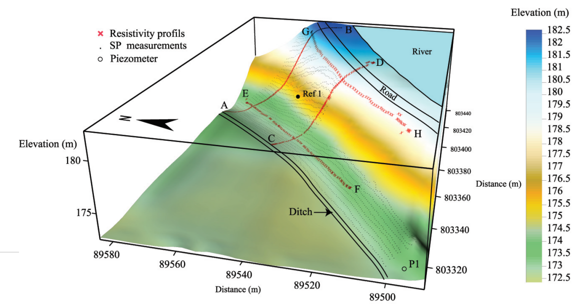




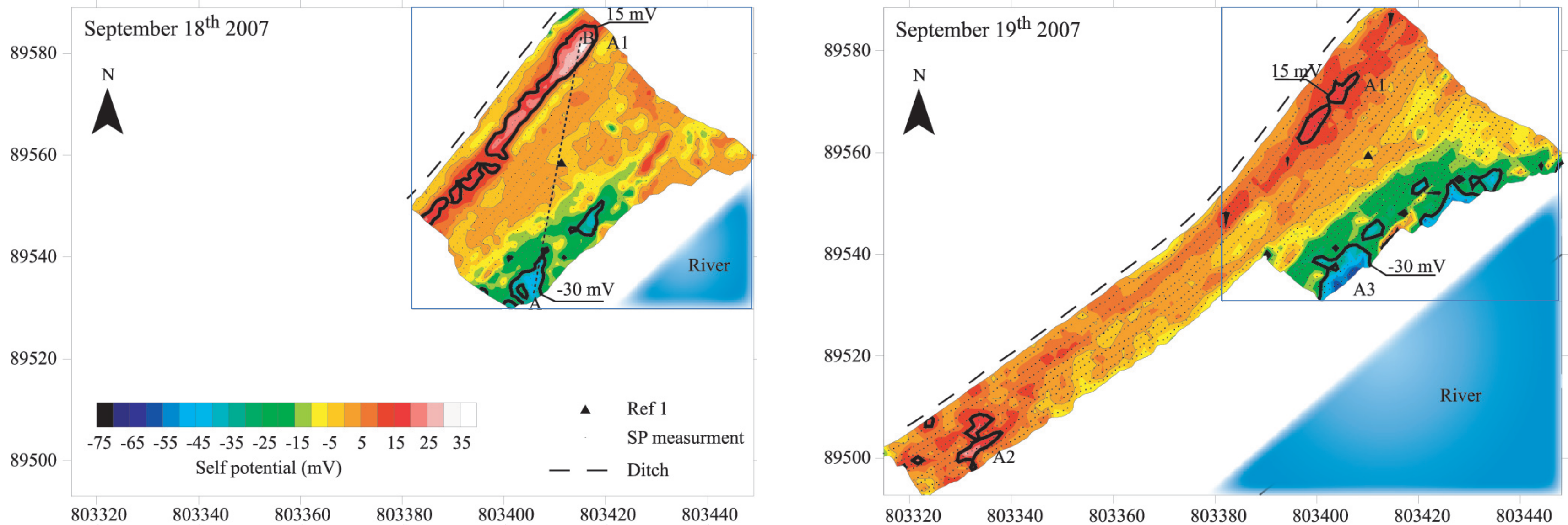
- A3 (riverside): negative SP anomalies
- A1 and A2 (near ditch): positive SP anomalies



Processing



- SP maps on two different days



- Goal: recover streaming currents

data

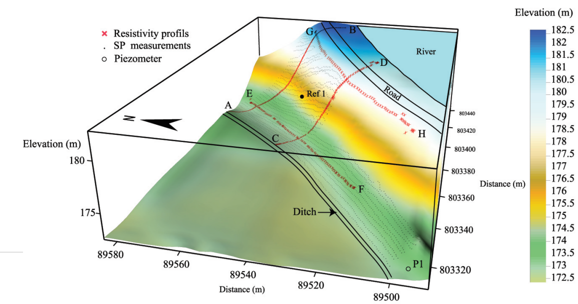
streaming currents

$$\nabla \cdot \sigma \nabla \phi = \nabla \cdot \vec{j}_s$$

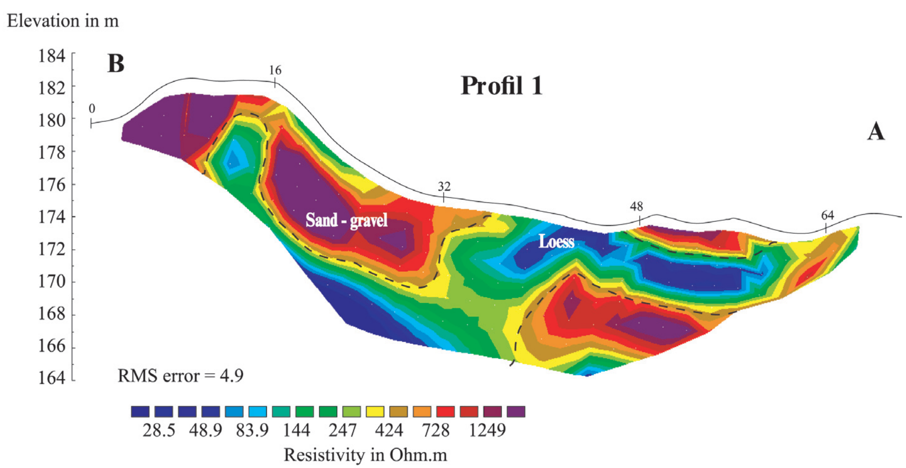
conductivity

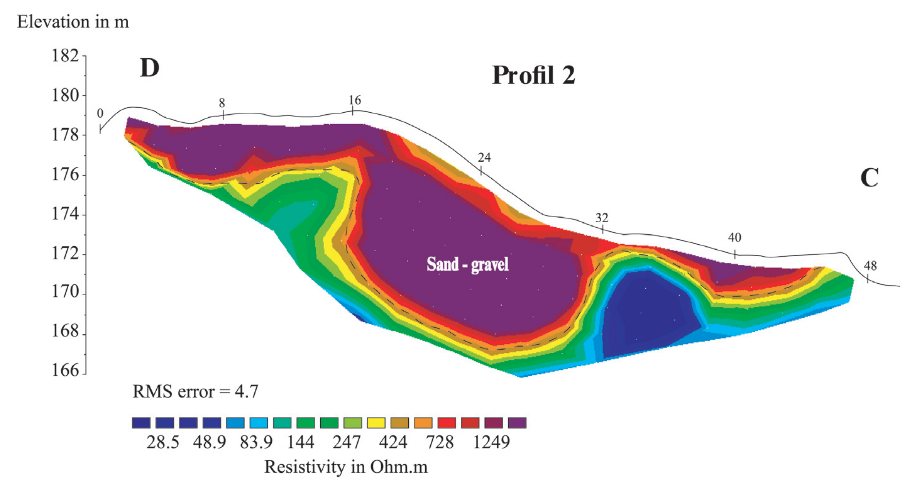
Obtain conductivity from DC

Processing



- Resistivity from DC Inversions





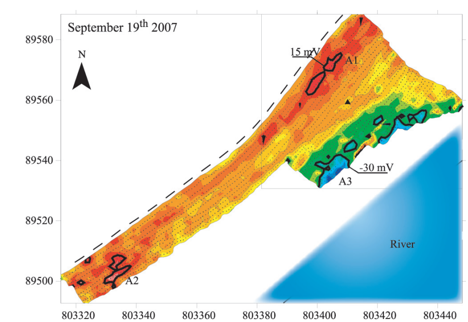
- Goal: recover streaming currents

data

streaming currents

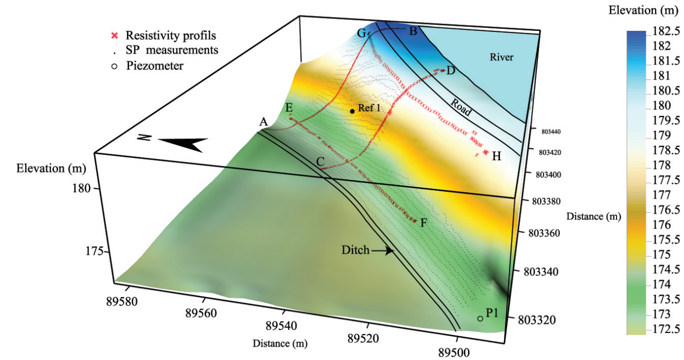
$$\nabla \cdot \sigma \nabla \phi = \nabla \cdot \vec{j}_s$$

conductivity



Invert SP data to recover $\vec{j}_s$

Processing and inversion

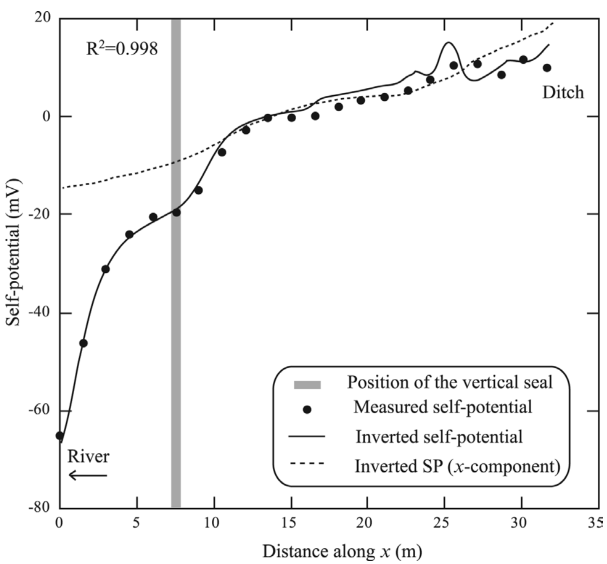


- Invert SP data to recover $\vec{j}_s$

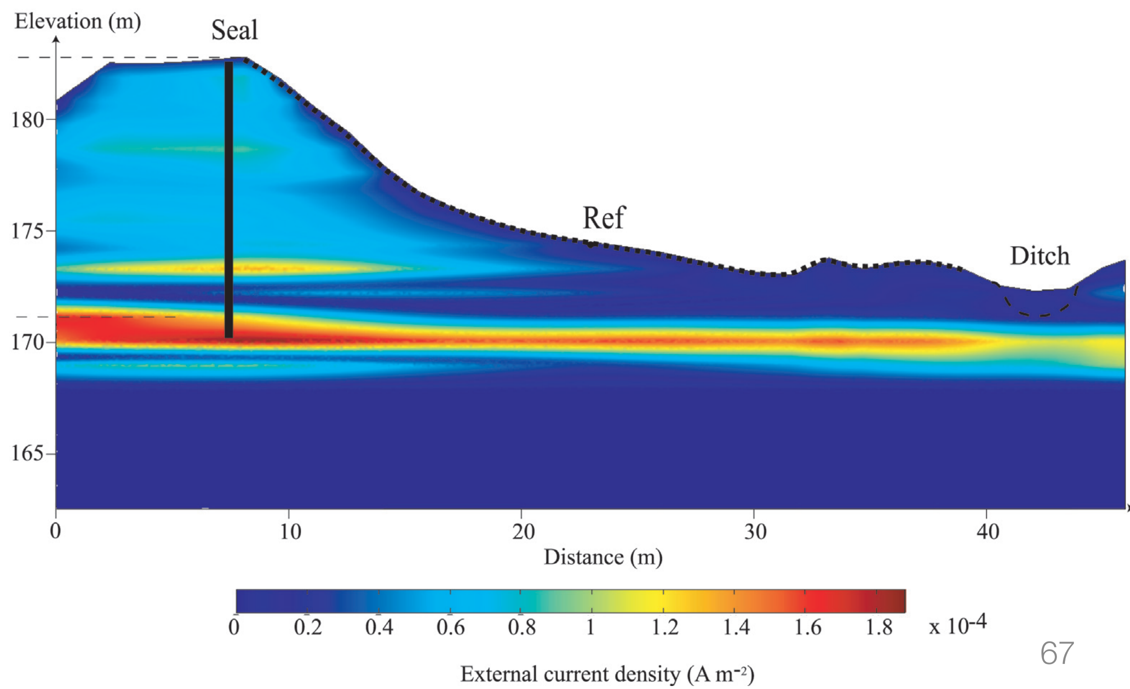
$$\nabla \cdot \sigma \nabla \phi = \nabla \cdot \vec{j}_s$$

- $\vec{j}_s$ is a vector
- Depth weighting (~1/z^3) is used (similar to magnetic inversion)

SP data



Recovered streaming current (magnitude) $|\vec{j}_s|$

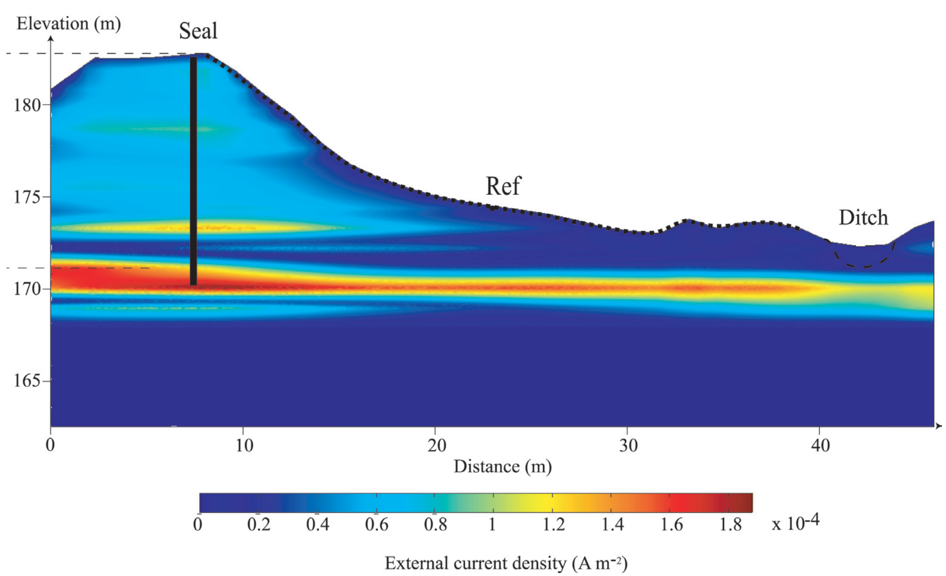


Processing and interpretation

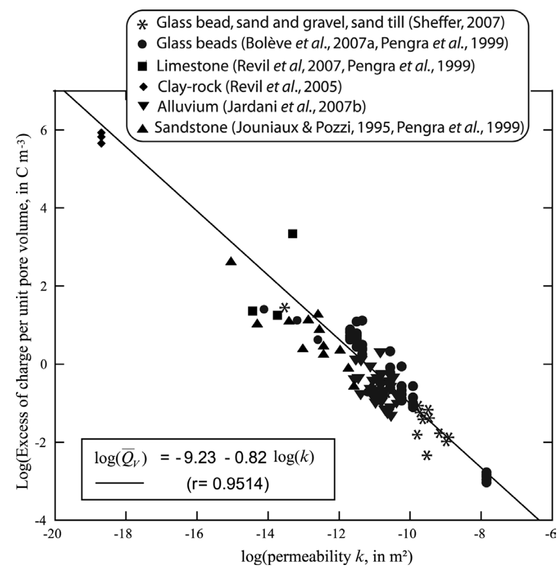
How do we obtain seepage velocity, $\vec{u}$?

$$\vec{u} = \frac{\vec{j}_s}{Q_v}$$

Recovered streaming current (magnitude) $|\vec{j}_s|$



Q_v vs. k



How do we get hydraulic permeability, k?

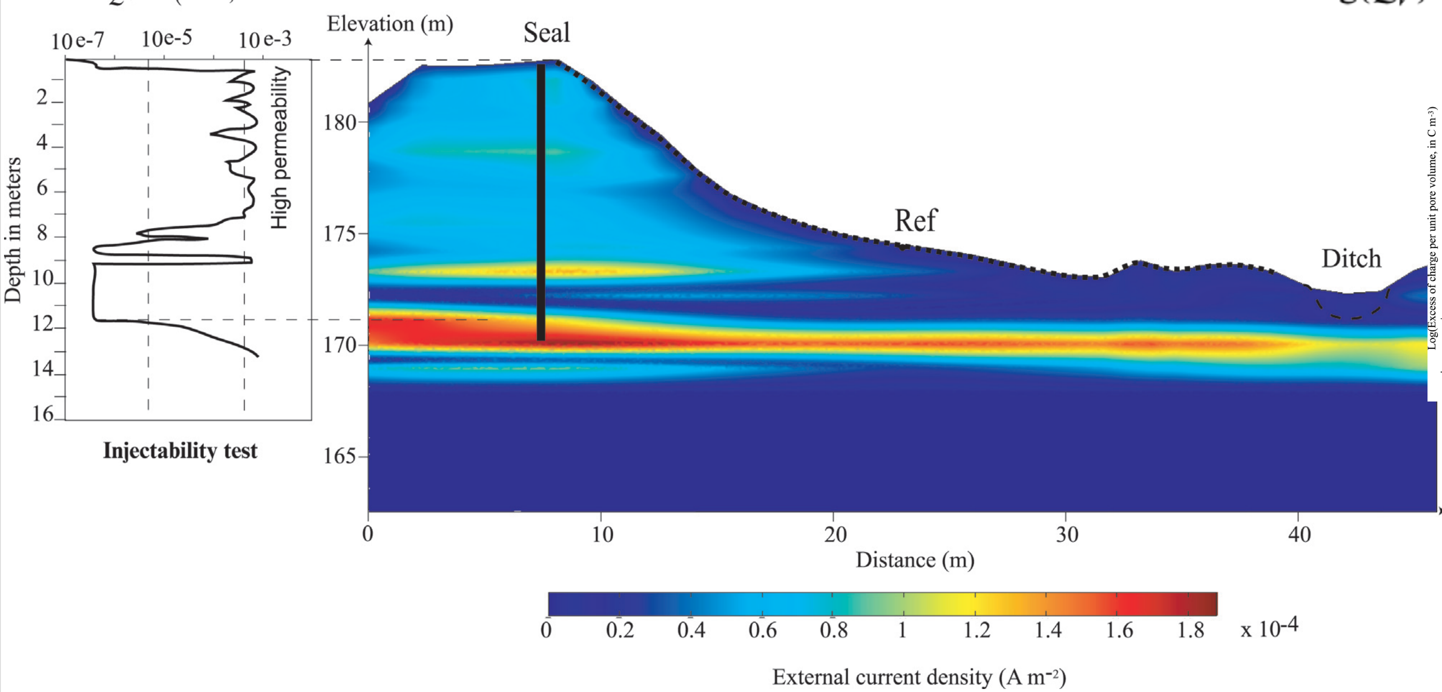
Interpretation and Synthesis

How do we obtain seepage velocity, $\vec{u}$?

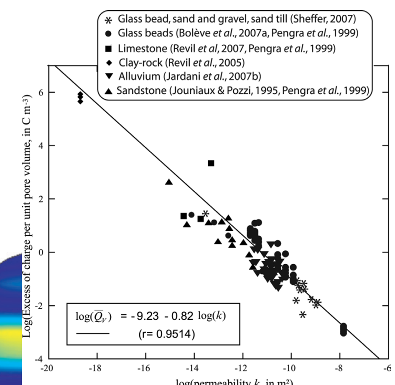
$$\vec{u} = \frac{\vec{j}_s}{Q_v}$$

Perm. test

Recovered streaming current (magnitude) $|\vec{j}_s|$



$$\log(\overline{Q}_V) = -9.23 - 0.82 \log(k)$$



Fluid velocity: 3×10^{-3} m/s

Flow rate: 3 litres /s

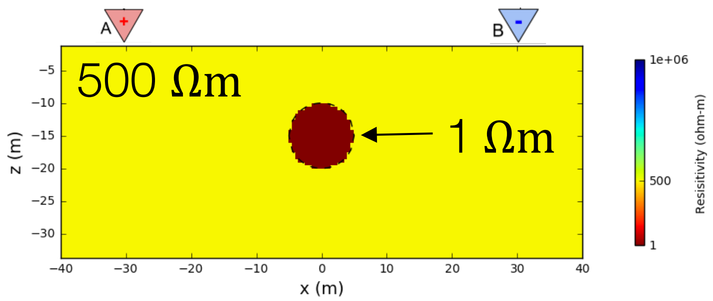
Outline

- Basic experiment
- Currents, charges, potentials and apparent resistivities
- Soundings, profiles and arrays
- Data, pseudosections and inversion
- Sensitivity
- Survey Design
- DC app
- Case History – Mt Isa

- Effects of background resistivity

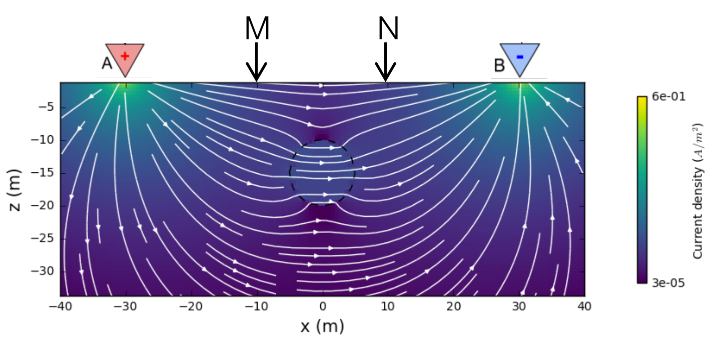
Effects of background resistivity

Resistivity models (thin resistive layer)



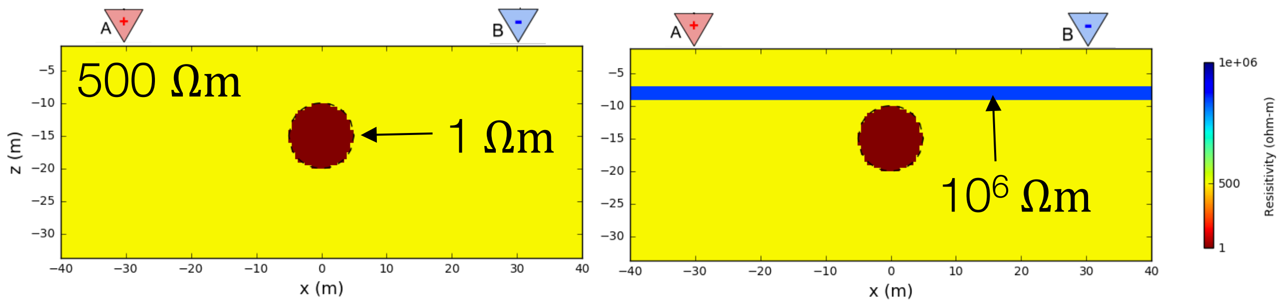
Currents and measured data at MN

$\rho_a = 430\ \Omega m$



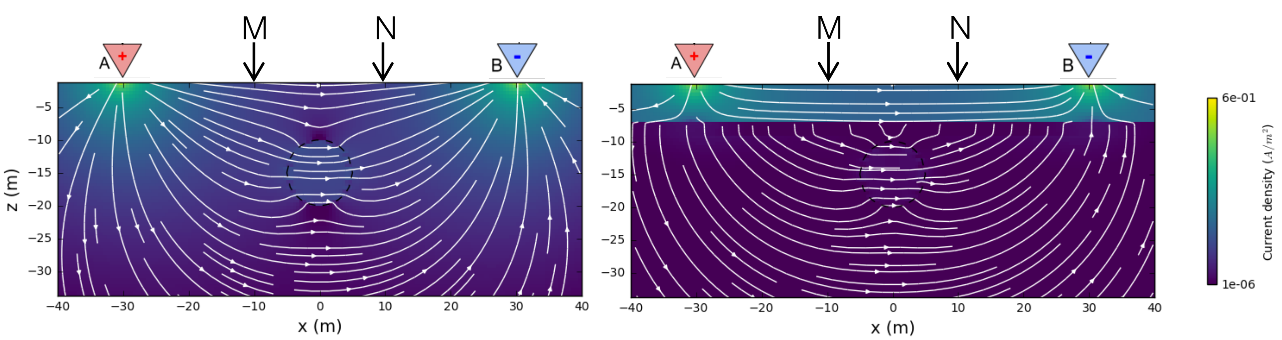
Effects of background resistivity

Resistivity models (thin resistive layer)



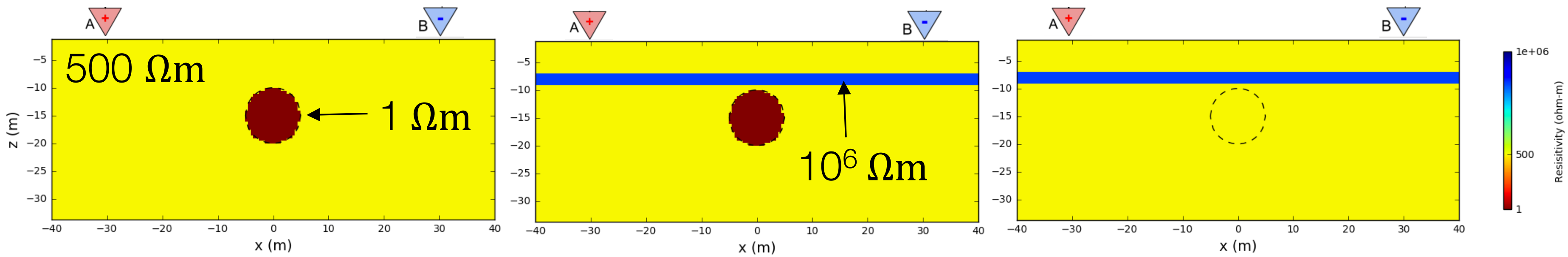
Currents and measured data at MN

$\rho_a = 430\ \Omega m$ $\rho_a = 1652\ \Omega m$

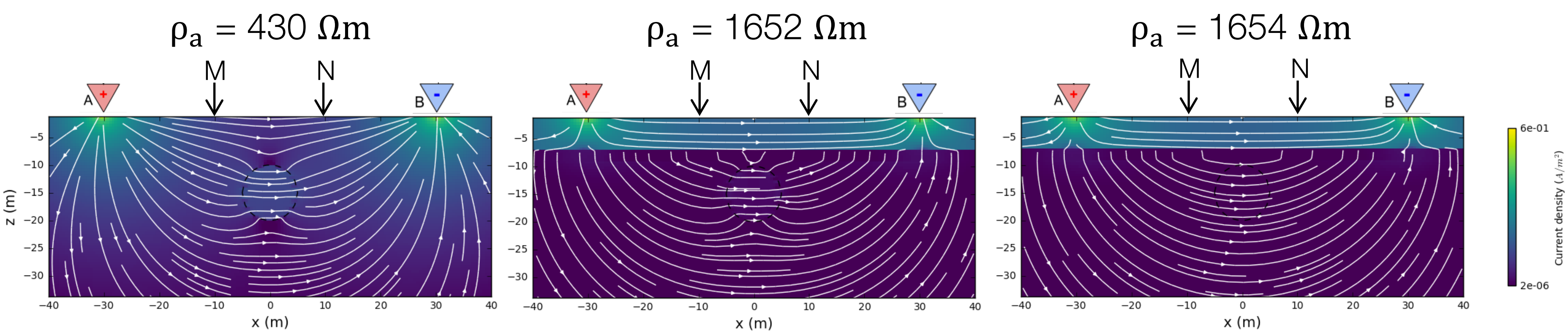


Effects of background resistivity

Resistivity models (thin resistive layer)

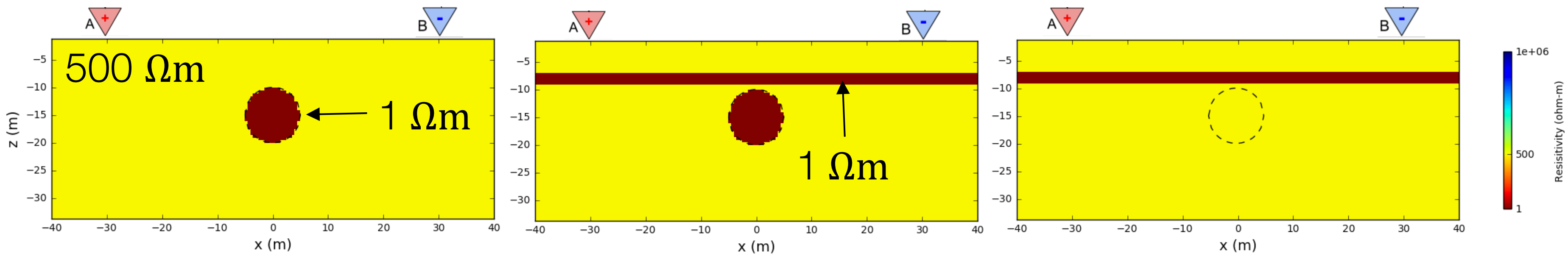


Currents and measured data at MN

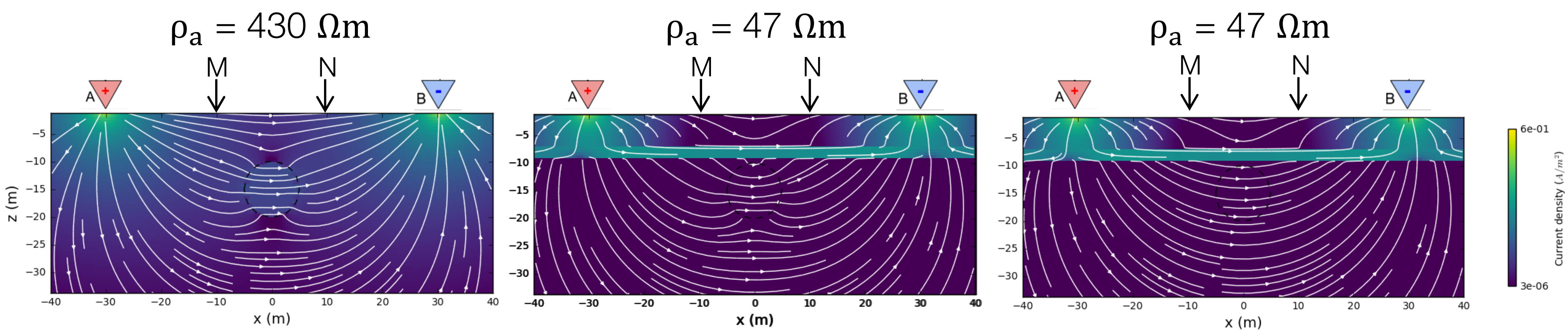


Effects of background resistivity

Resistivity models (thin conductive layer)

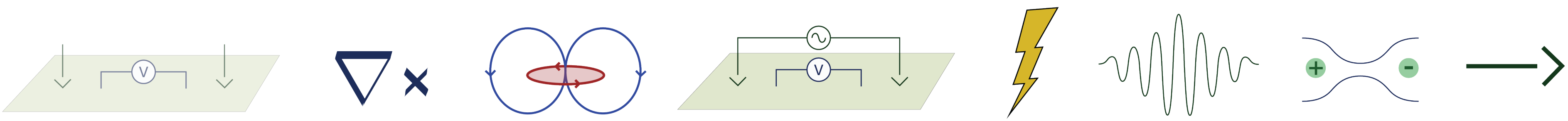


Currents and measured data at MN



End of DCR

Next up



DC Resistivity

EM Fundamentals

Inductive Sources

Grounded Sources

Natural Sources

GPR

Induced Polarization

The Future

Lunch: Play with apps