

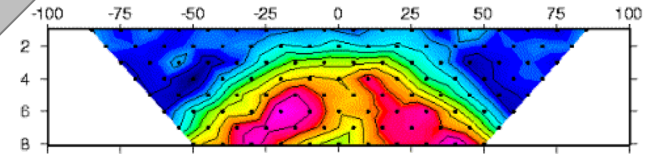
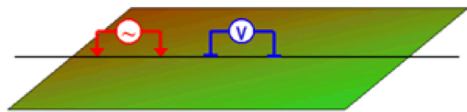
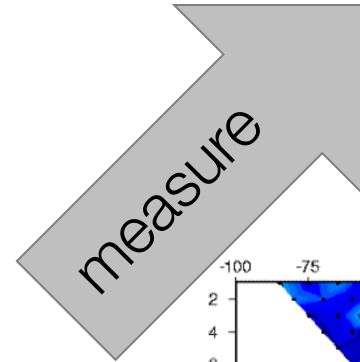
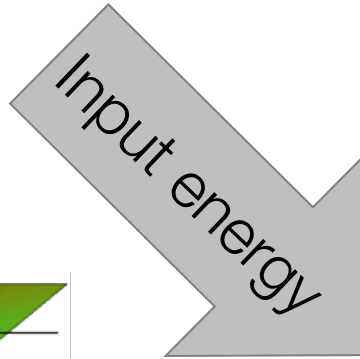
# DC Resistivity



# DC Resistivity Survey

Source

Data



$\rho$

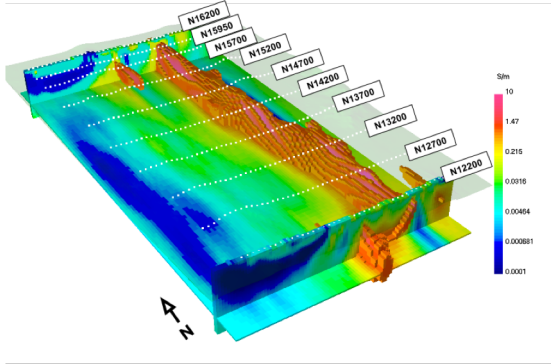
$$\rho = 1/\sigma$$

$\rho$  : resistivity

$\sigma$  : electrical conductivity

# Motivation

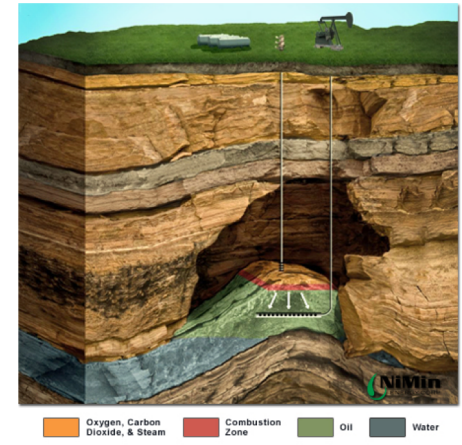
## Minerals



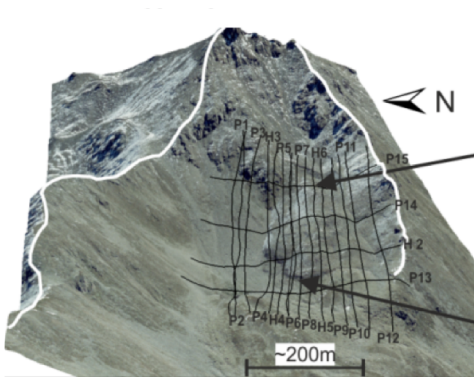
## Water inflow in mine



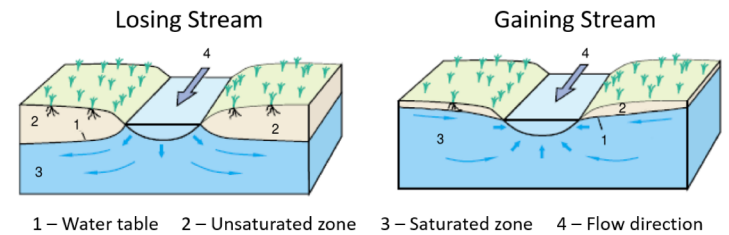
## Oil and Gas



## Geotechnical

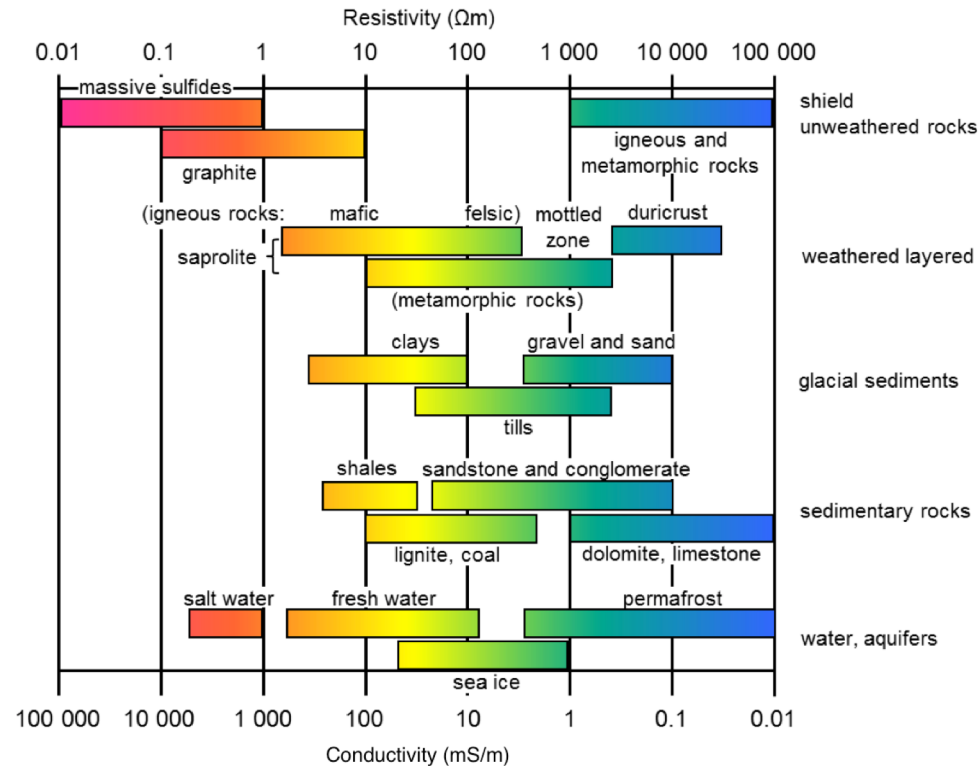


## Groundwater



# Electrical conductivity

- DC resistivity is sensitive to:
  - $\sigma$ : Conductivity [S/m]
  - $\rho$ : Resistivity [ $\Omega\text{m}$ ]
  - $\sigma = 1/\rho$
- 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

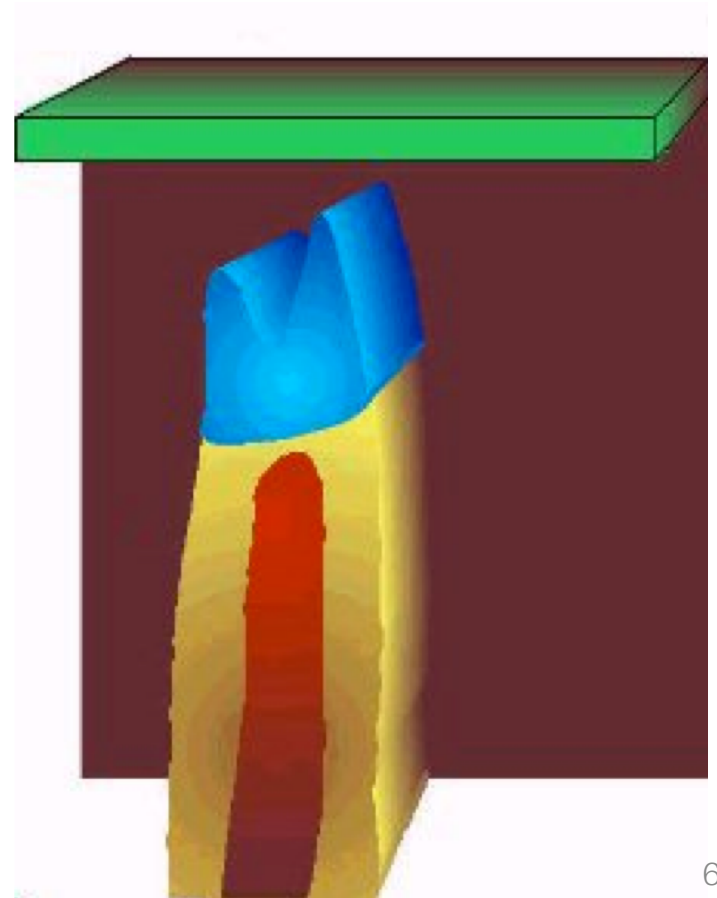
- Basic experiment
- Currents, charges, potentials and apparent resistivities
- Soundings, profiles and arrays
- Data, pseudosections and inversion
- Sensitivity
- Survey Design
- Case History – Mt Isa
- Case History – Reservoir monitoring for oil sands
- Steel casing + DC
- Working with the apps
- Effects of background resistivity

# Basic Experiment

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

Elura Orebody Electrical resistivities

<i>Rock Type</i>	<i>Ohm-m</i>
Overburden	12
Host rocks	200
Gossan	420
Mineralization (pyritic)	0.6
Mineralization (pyrrhotite)	0.6

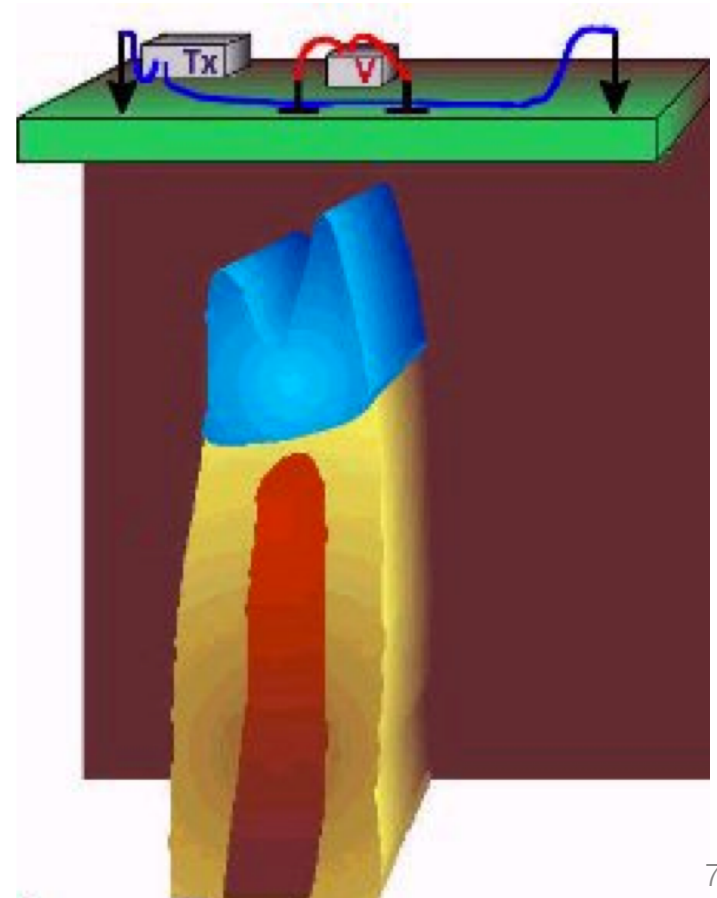


# Basic Experiment

- **Target:**
  - Ore body. Mineralized regions less resistive than host
- **Setup:**
  - Tx: Current electrodes
  - Rx: Potential electrodes

Elura Orebody Electrical resistivities

Rock Type	Ohm-m
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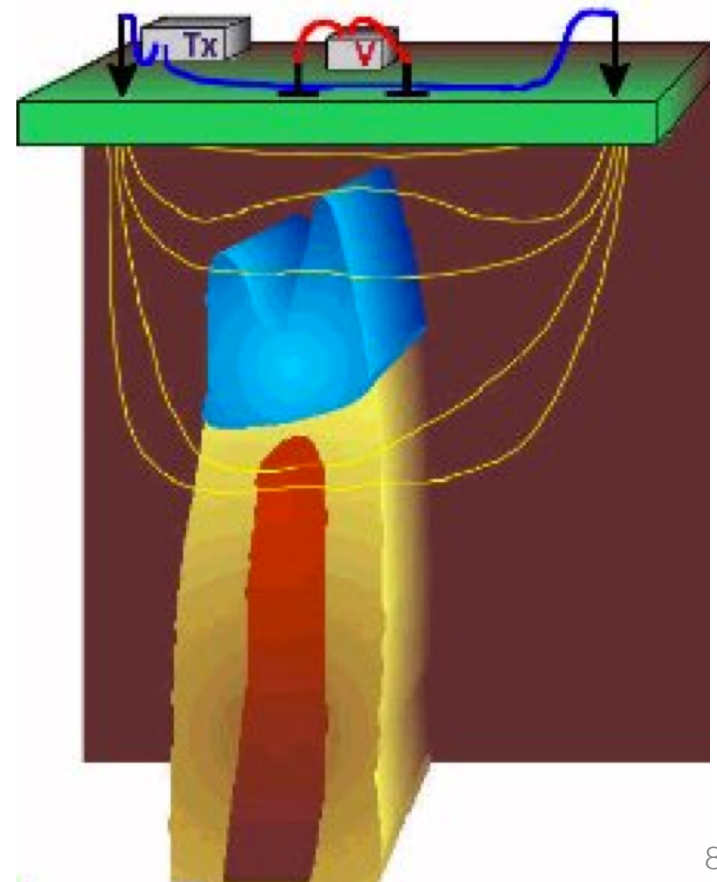


# Basic Experiment

- **Target:**
  - Ore body. Mineralized regions less resistive than host
- **Setup:**
  - Tx: Current electrodes
  - Rx: Potential electrodes
- **Currents:**
  - Preferentially flow through conductors

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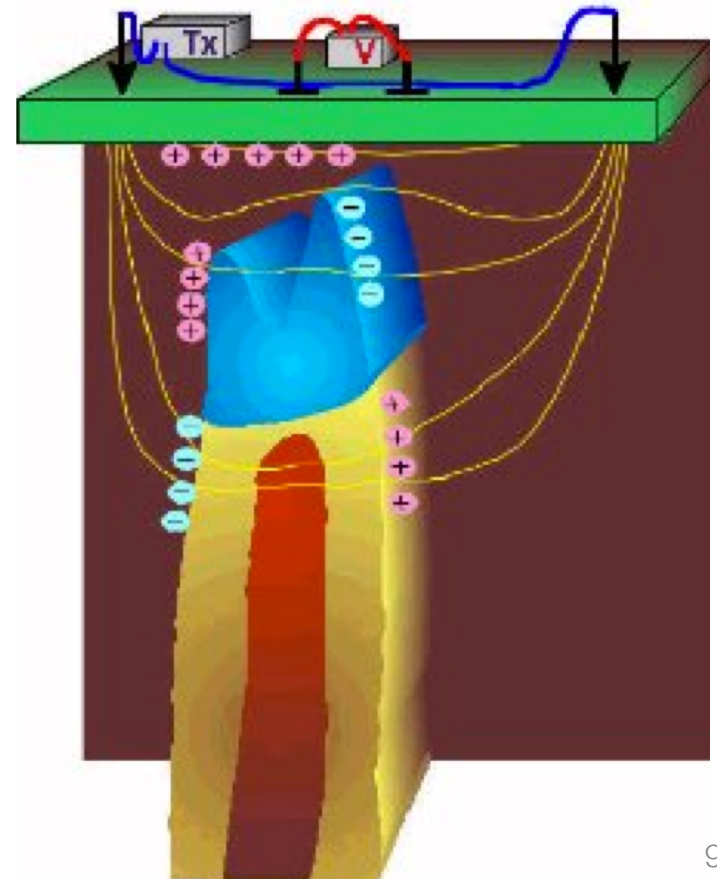


# Basic Experiment

- **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

Elura Orebody Electrical resistivities

Rock Type	Ohm-m
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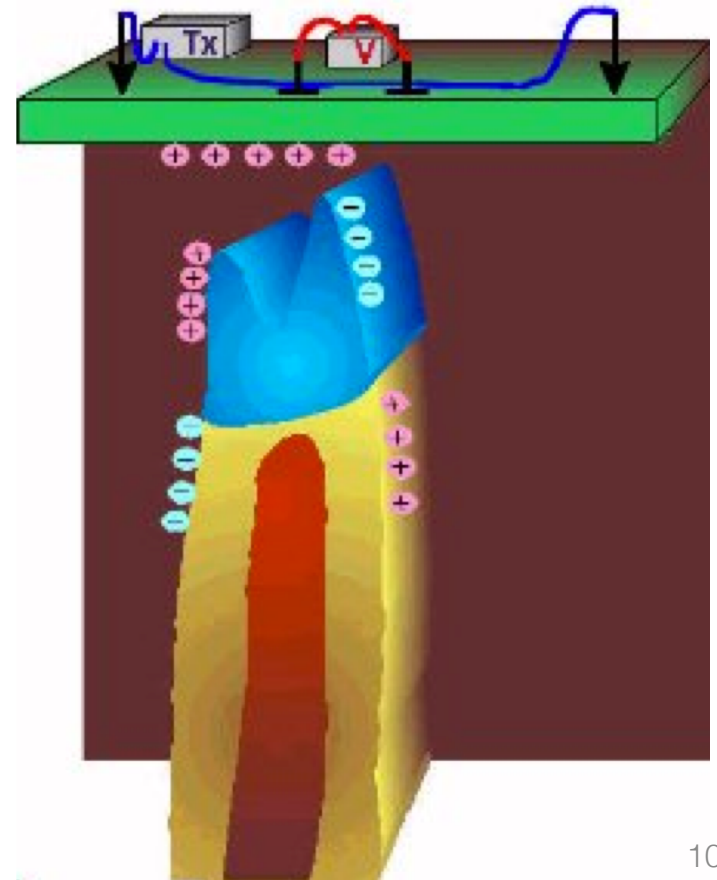


# Basic Experiment

- **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

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



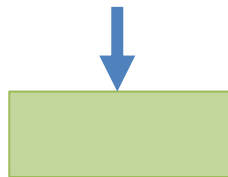
How do we obtain resistivity?

# Steady State Maxwell equations

	Full	Steady State
Faraday	$\nabla \times \vec{e} = -\frac{\partial \vec{b}}{\partial t}$	$\nabla \times \vec{e} = 0 \quad \vec{e} = -\nabla V$
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

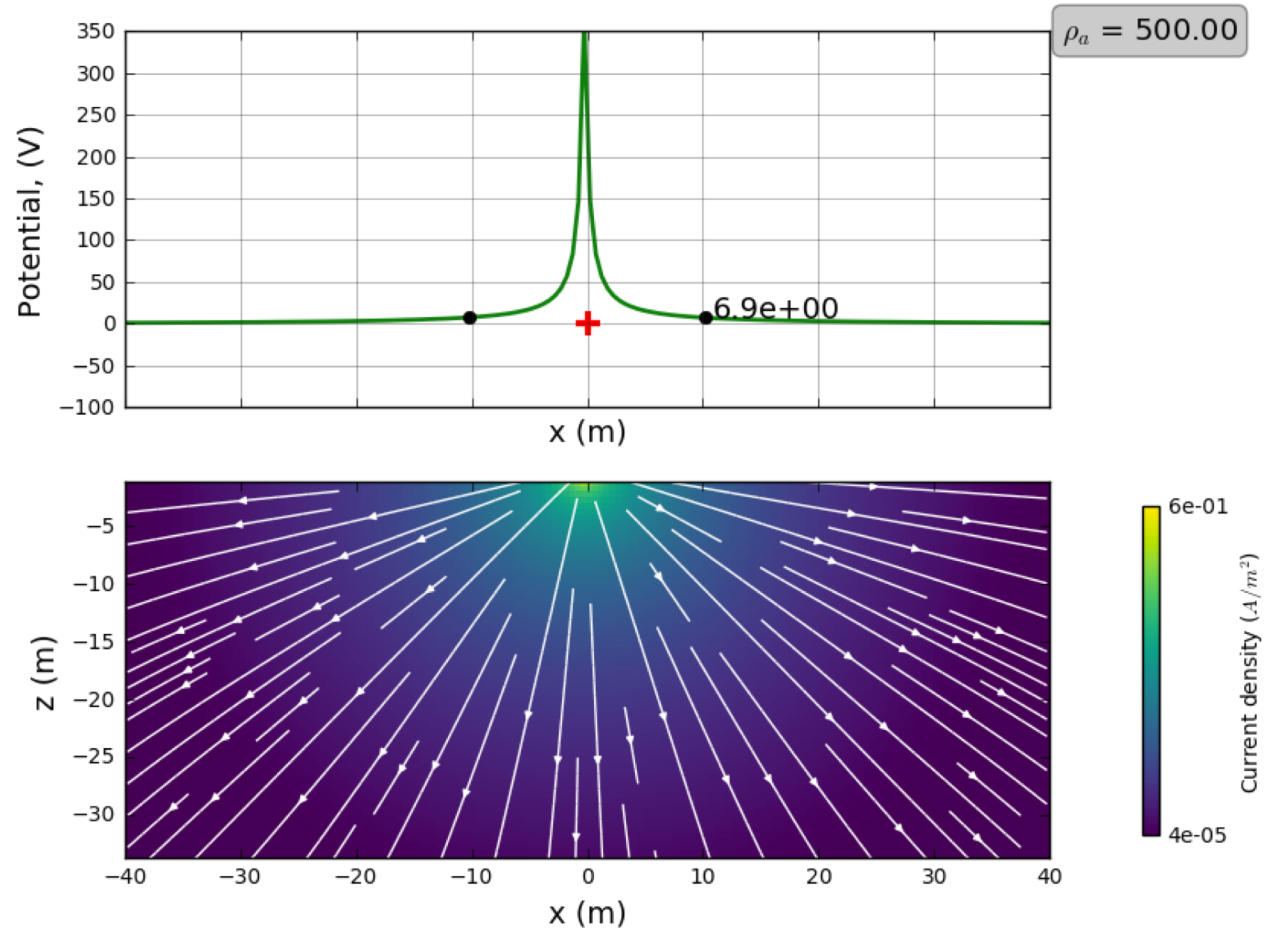


$$V = \frac{I}{2\pi\sigma} \frac{1}{r}$$

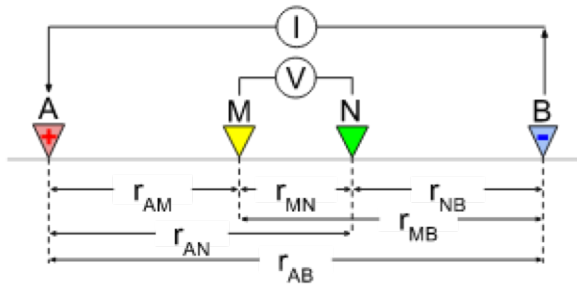
$$V = \frac{\rho I}{2\pi r}$$

# Currents and potentials: halfspace

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



# Currents and potentials: 4-electrode array

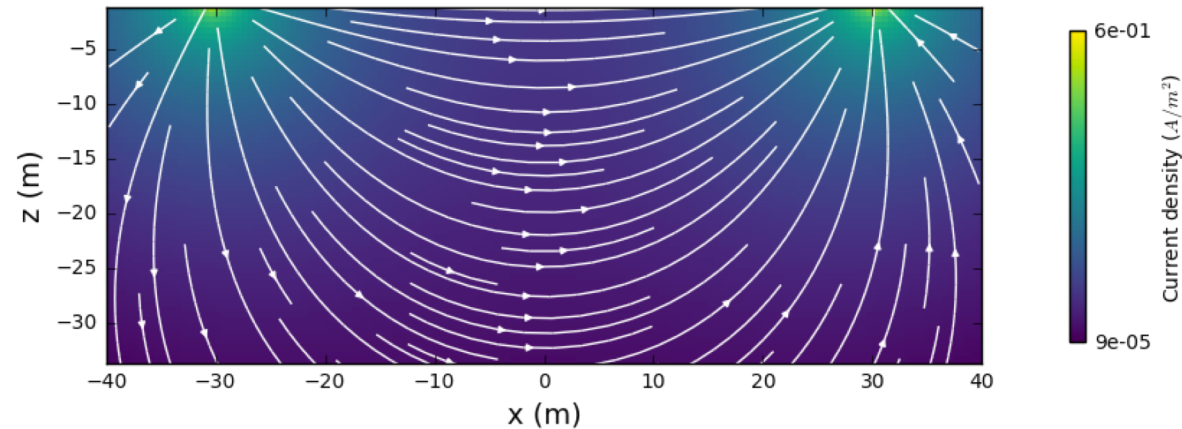
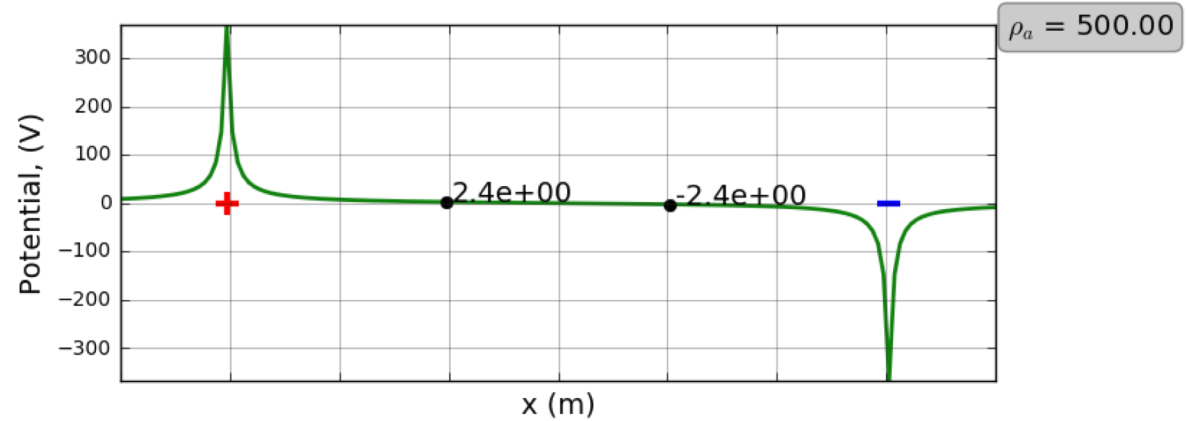


$$\Delta V_{MN} = \rho I \underbrace{\left[ \frac{1}{AM} - \frac{1}{MB} - \frac{1}{AN} + \frac{1}{NB} \right]}_G$$

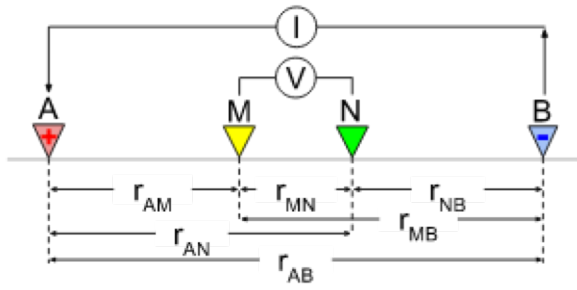
Resistivity

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

Halfspace ( $500 \Omega m$ )



# Currents and Apparent Resistivity

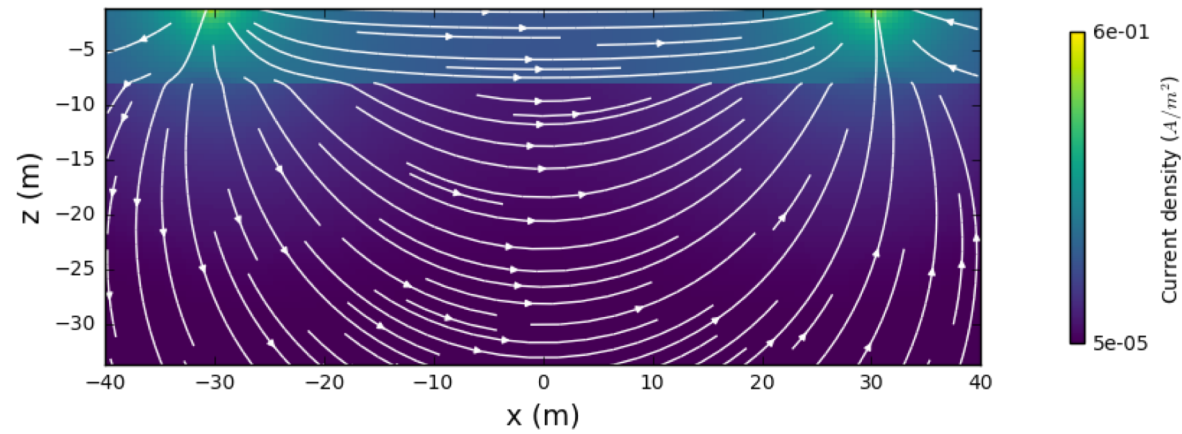
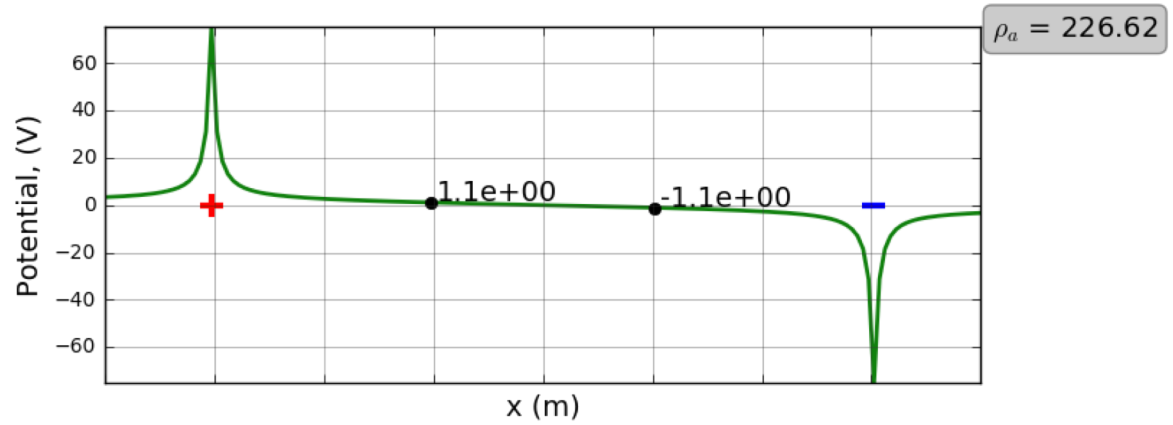


$$\Delta V_{MN} = \rho I \underbrace{\frac{1}{2\pi} \left[ \frac{1}{AM} - \frac{1}{MB} - \frac{1}{AN} + \frac{1}{NB} \right]}_G$$

Apparent resistivity

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

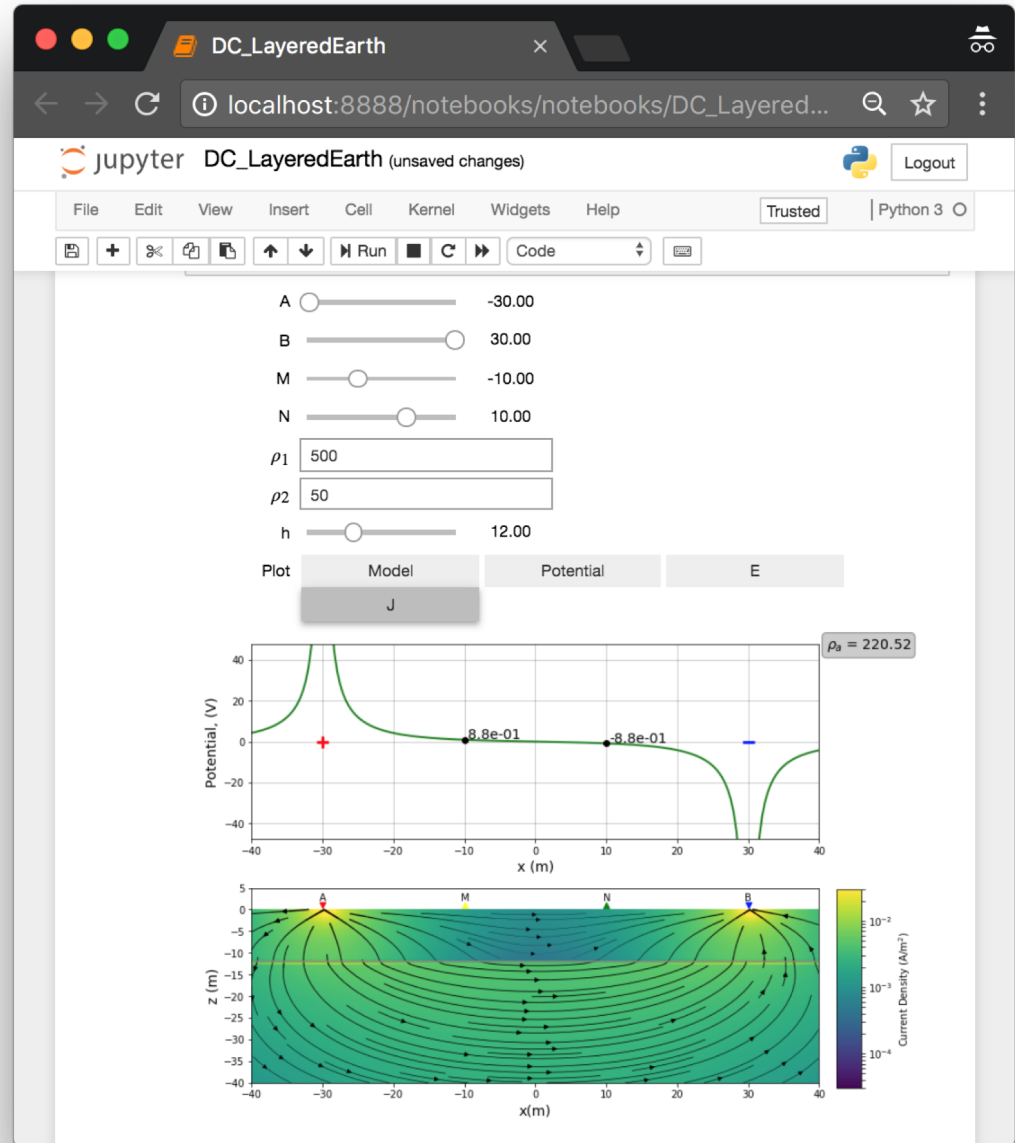
Conductive overburden ( $100 \Omega m$ )



# DC Layer App

Why interactive apps?

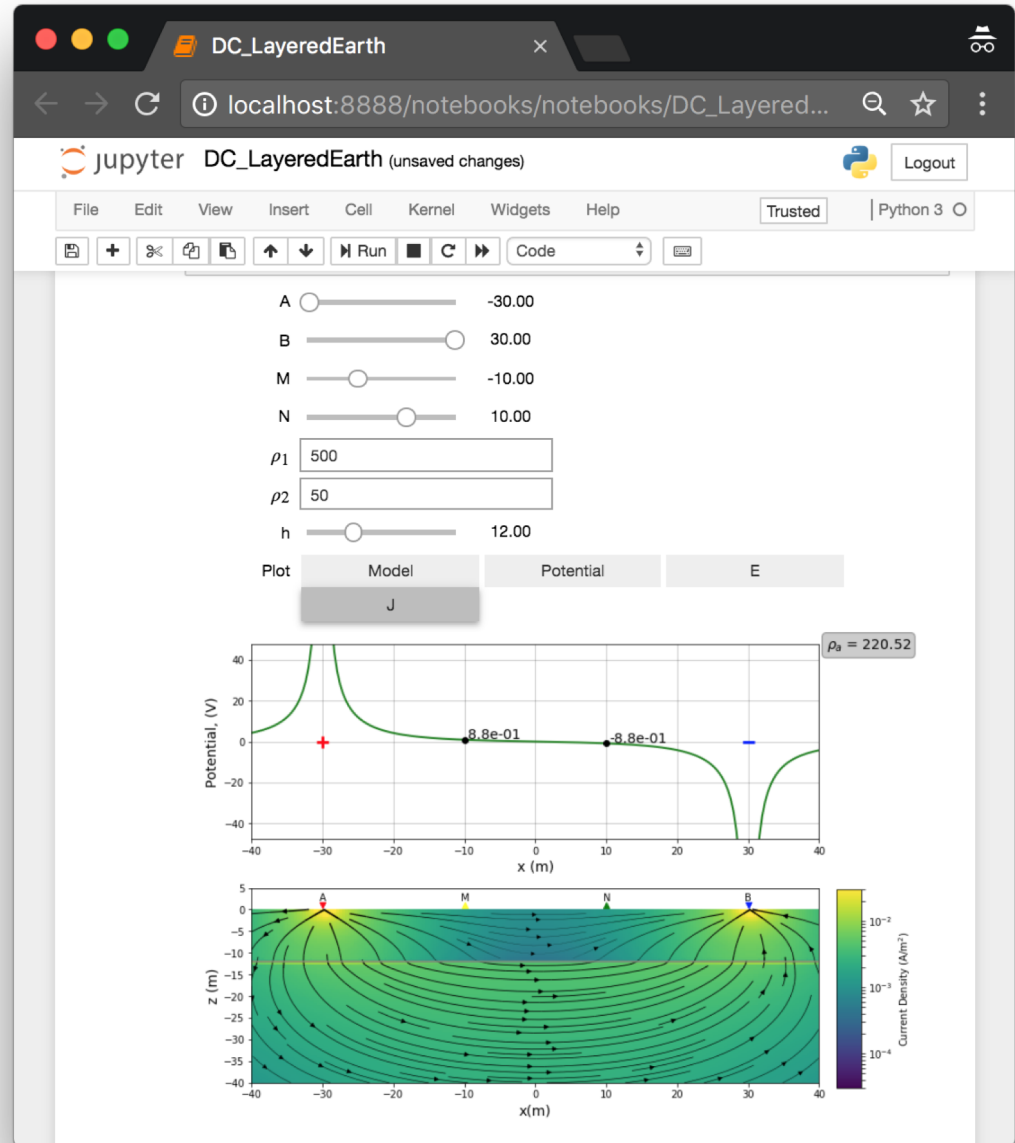
- Visualization aids understanding
- Learn through interaction
  - ask questions and investigate
- Open source:
  - Free to use
  - Welcome contributions!





# DC Layered earth (Demo)

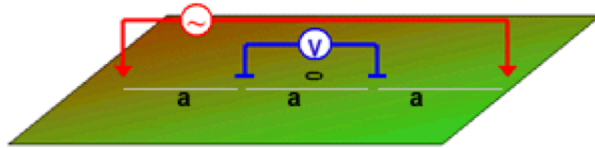
- DC\_LayeredEarth.ipynb
- Parameters:
  - Layer resistivities
  - Layer thickness
  - Electrode locations
- View:
  - Model
  - Electric potential
  - Electric field
  - Current density



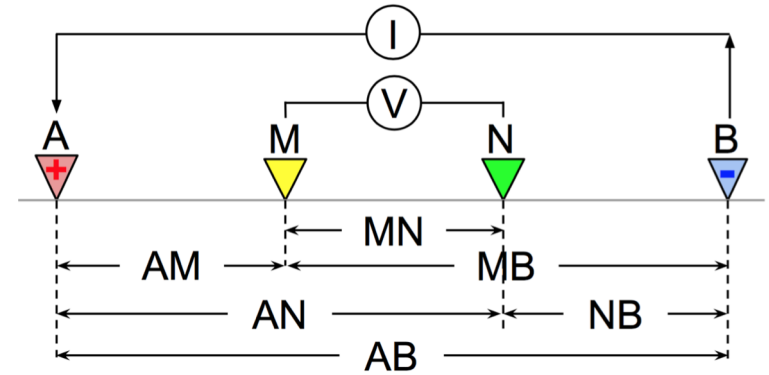
# Soundings and Arrays

## Geometry

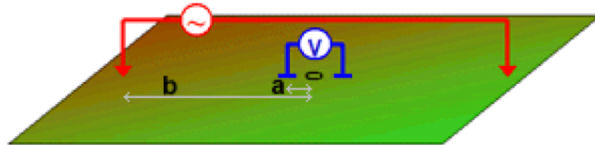
### Wenner



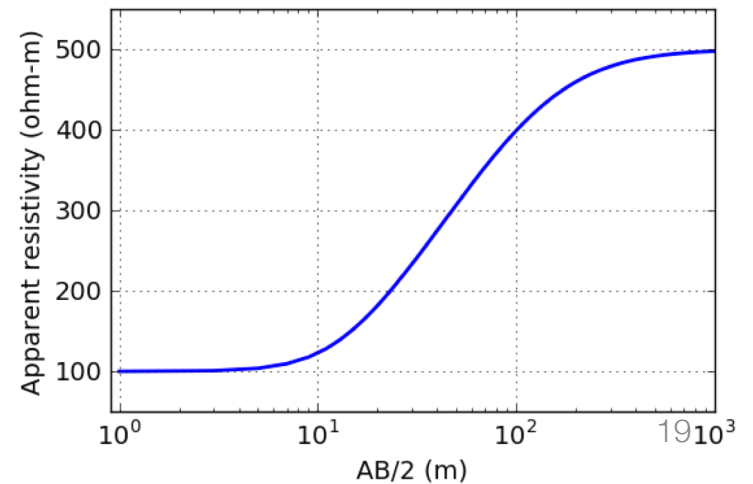
### 4 electrode Array



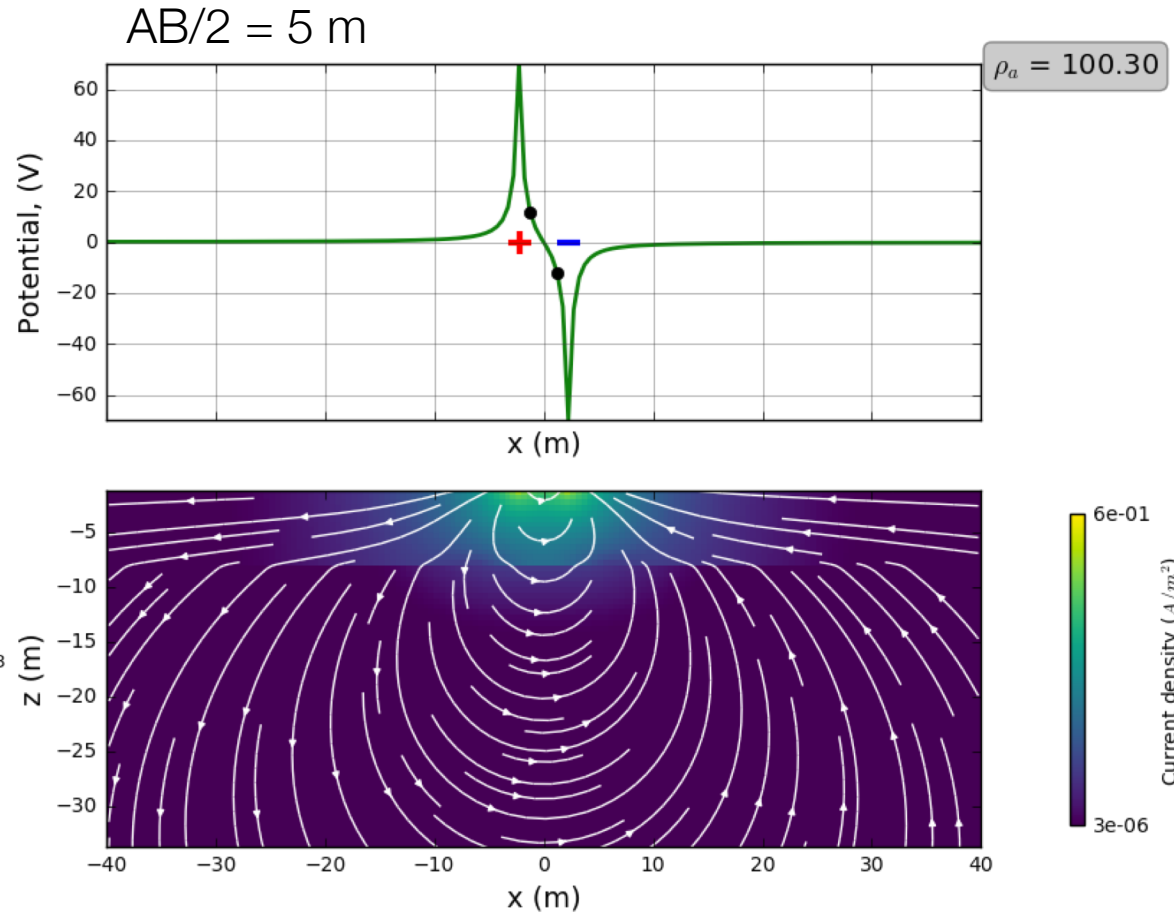
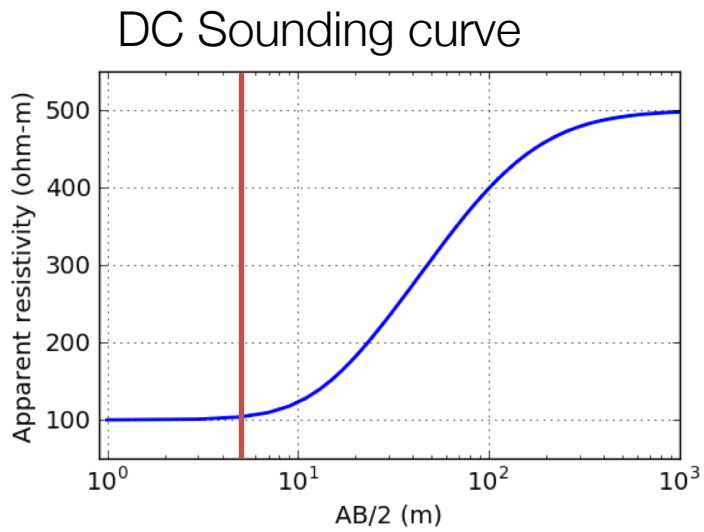
### Schlumberger



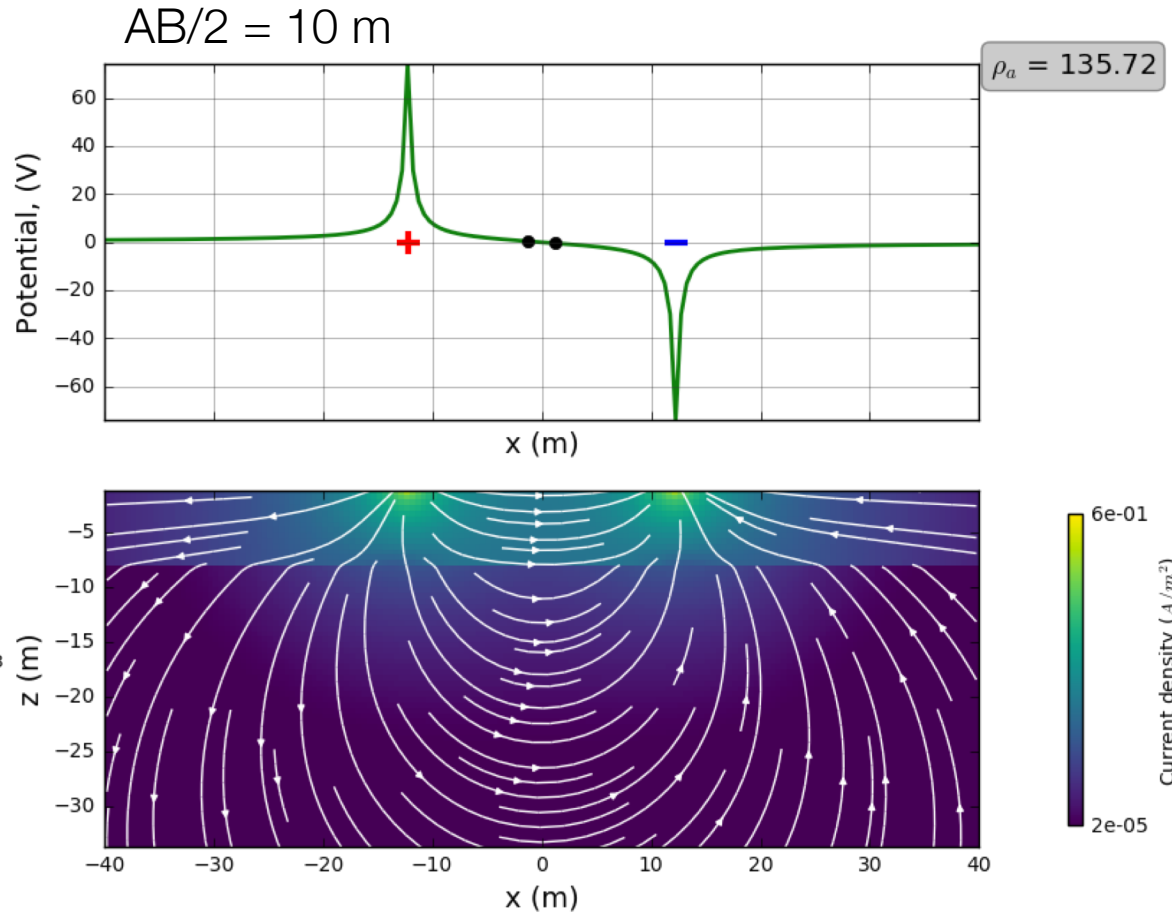
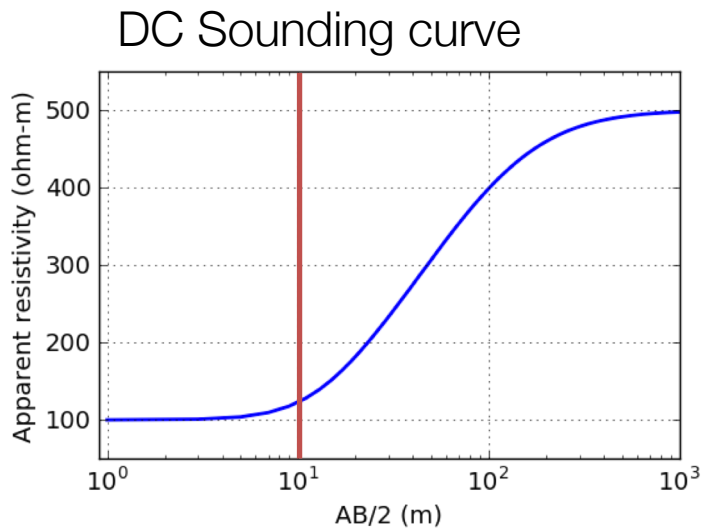
## Sounding



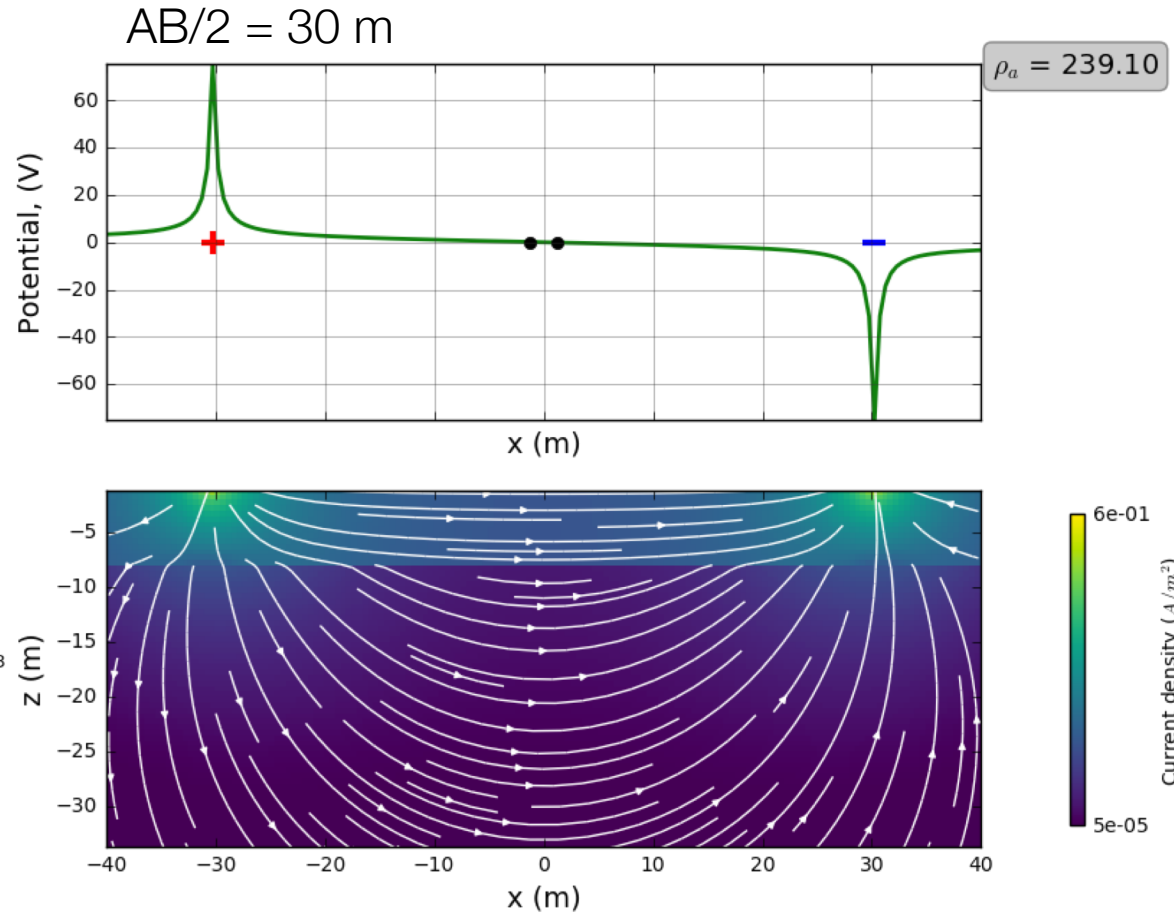
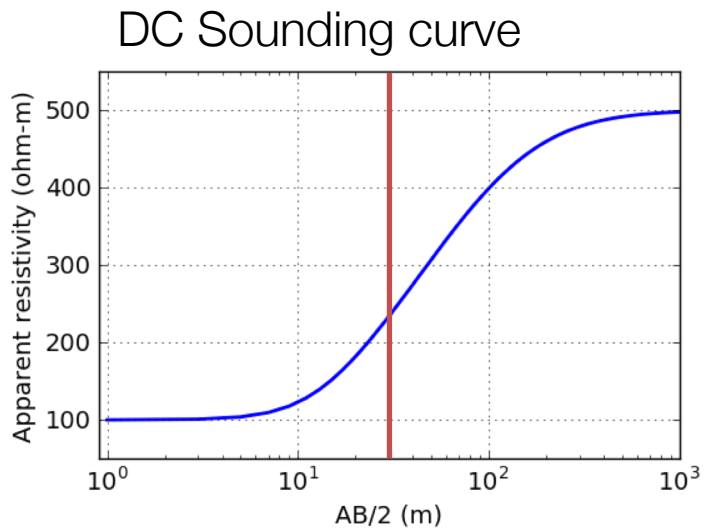
# Soundings



# Soundings

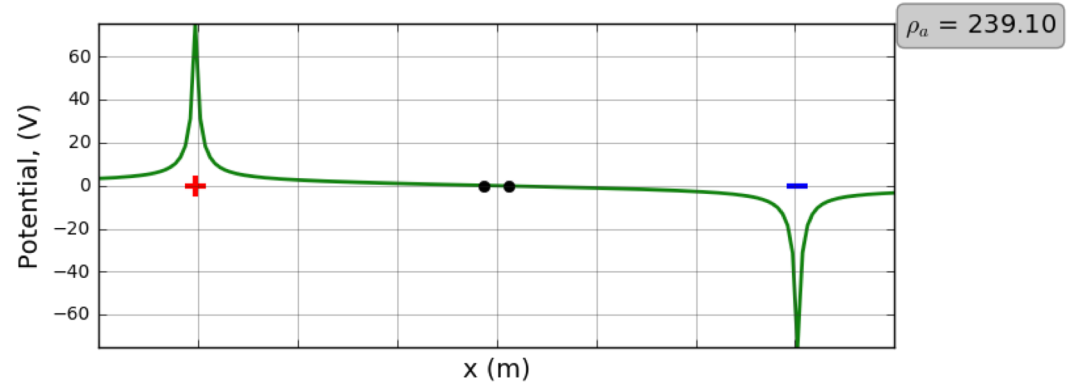
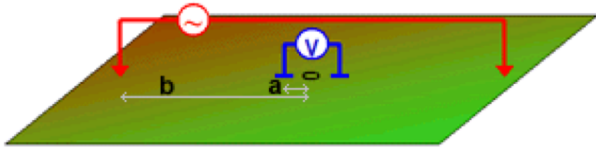


# Soundings

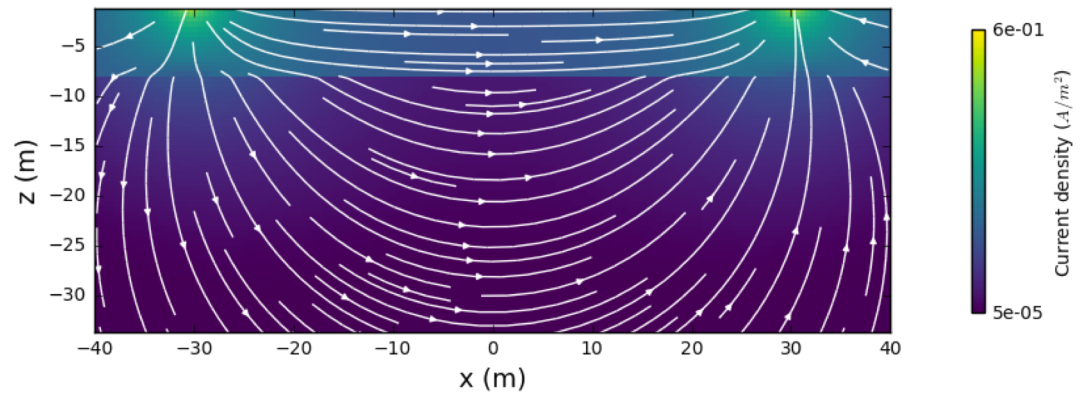
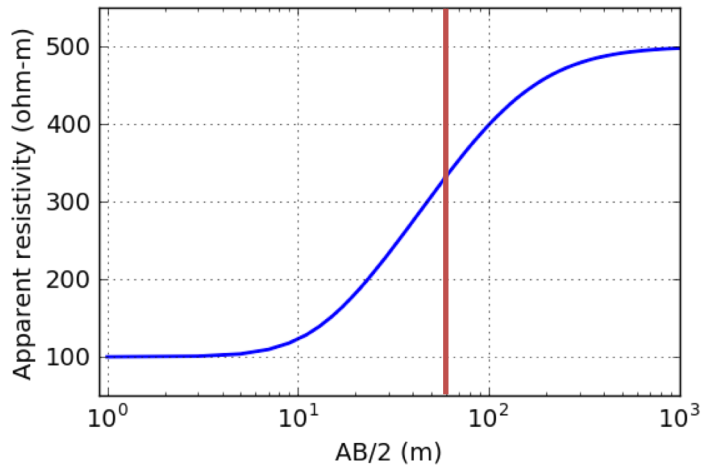


# Summary: soundings

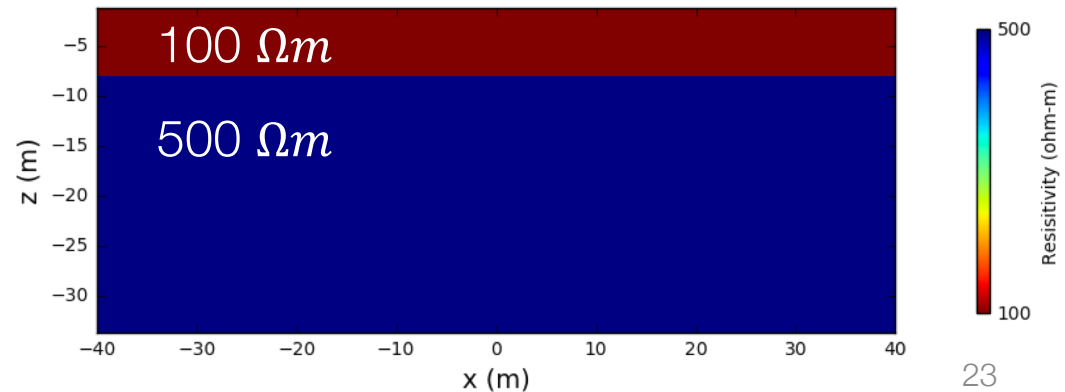
Schlumberger array



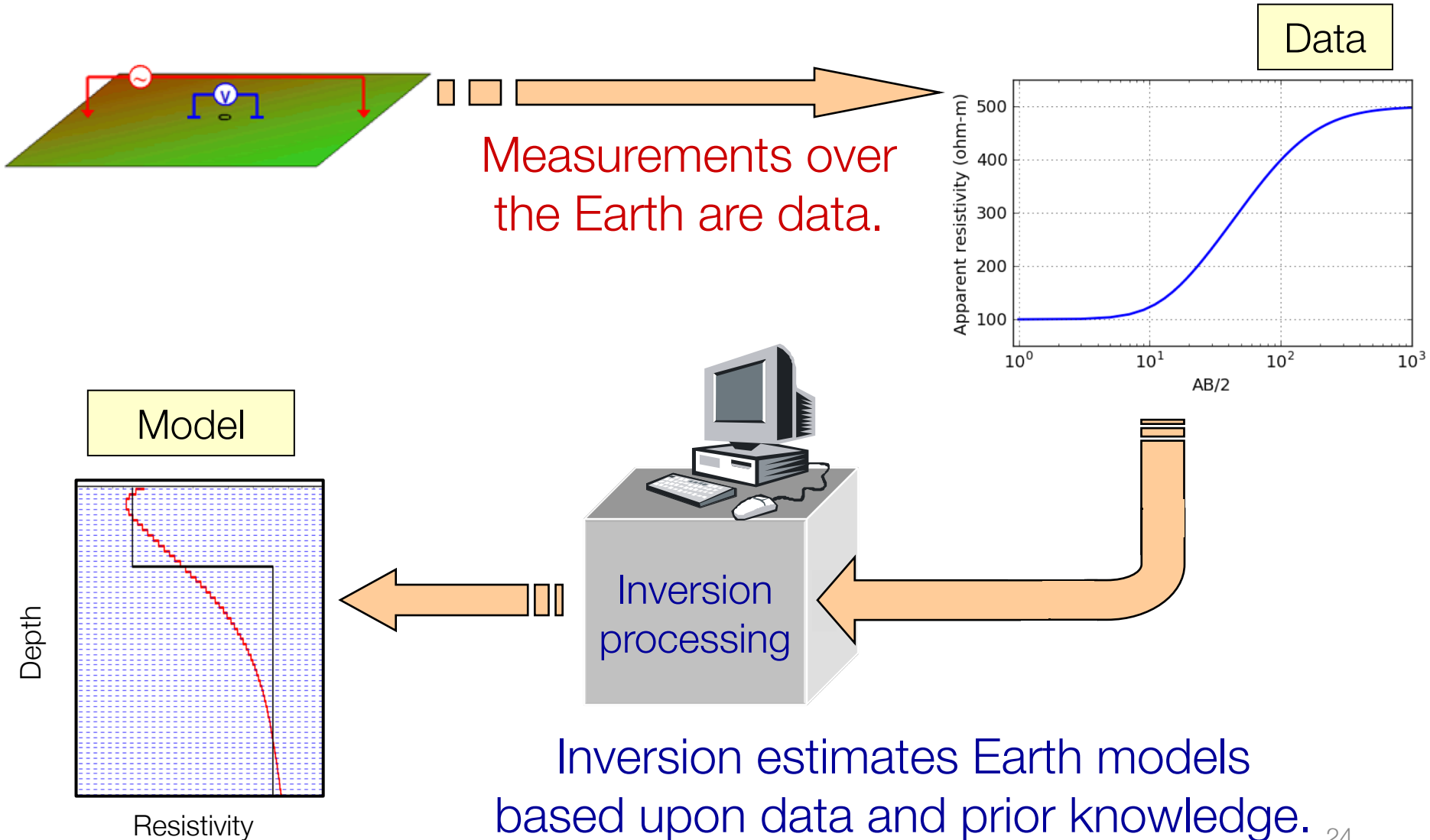
DC Sounding curve



Scale length of array must be large to see deep



# Inversion



# DCR for a confined body

- Useful to formally bring in the concept of charges

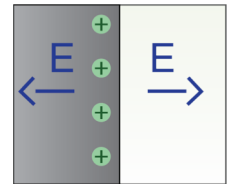
Normal component of current density is continuous

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

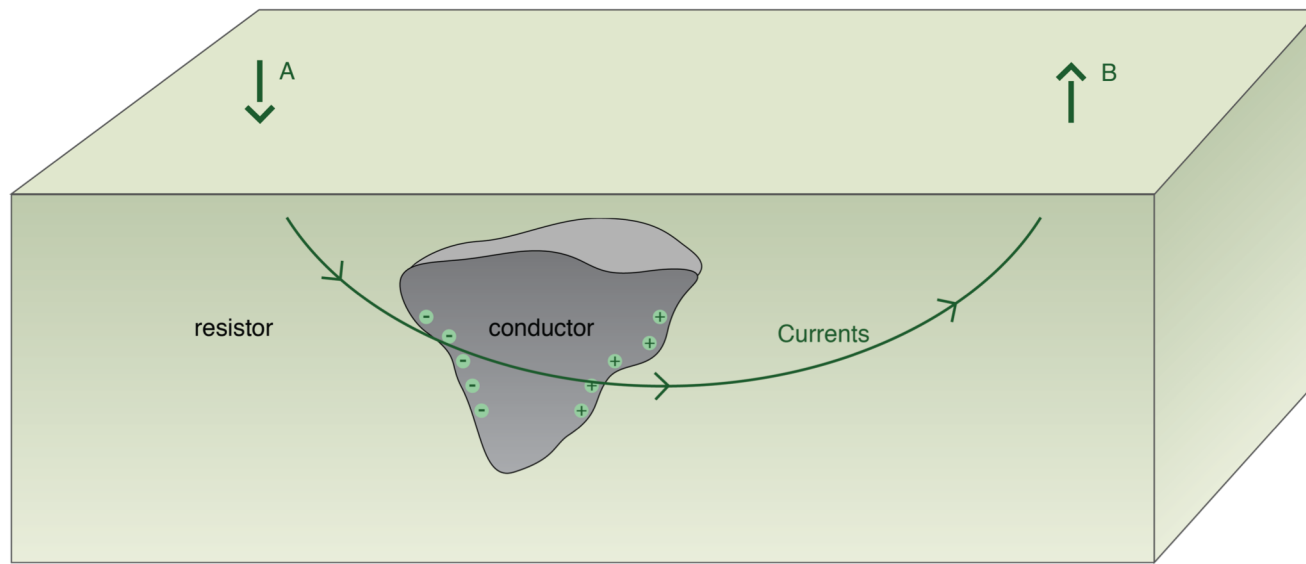
Conductivity contrast

$$\sigma_1 \neq \sigma_2$$

- Electric field discontinuous
- Charge build-up



$$\mathbf{E} = \frac{Q}{4\pi\epsilon_0|\mathbf{r} - \mathbf{r}'|^2}\hat{\mathbf{r}}$$





# Charges at conductivity contrasts

- Useful to formally bring in the concept of charges

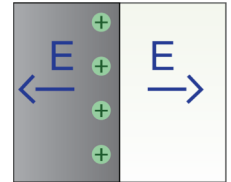
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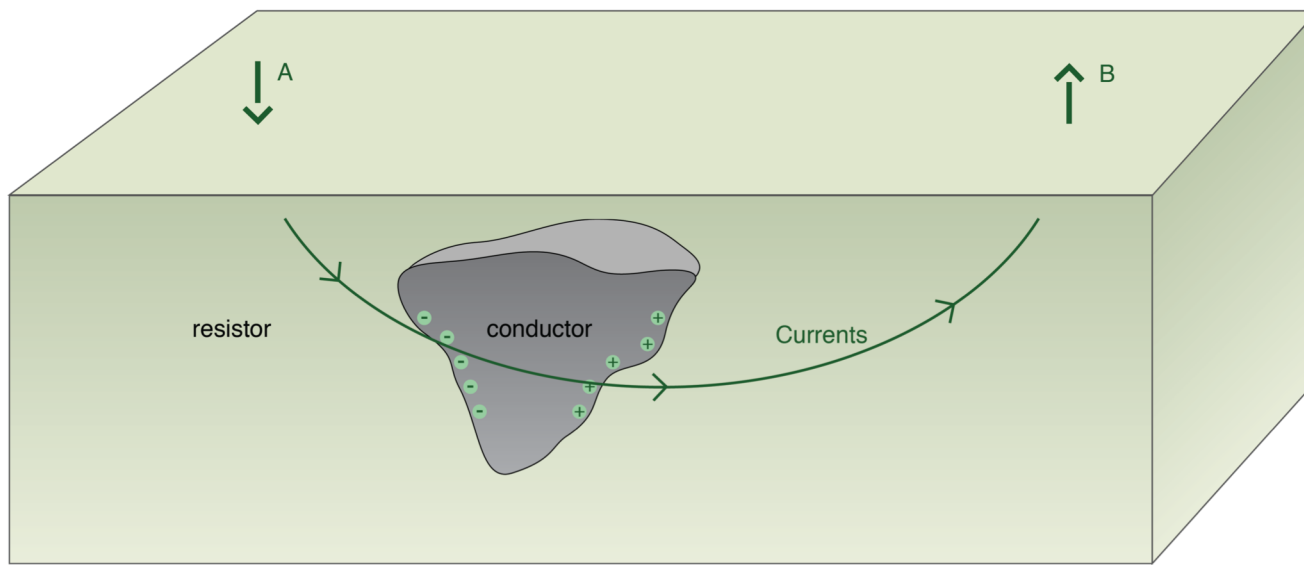
Conductivity contrast

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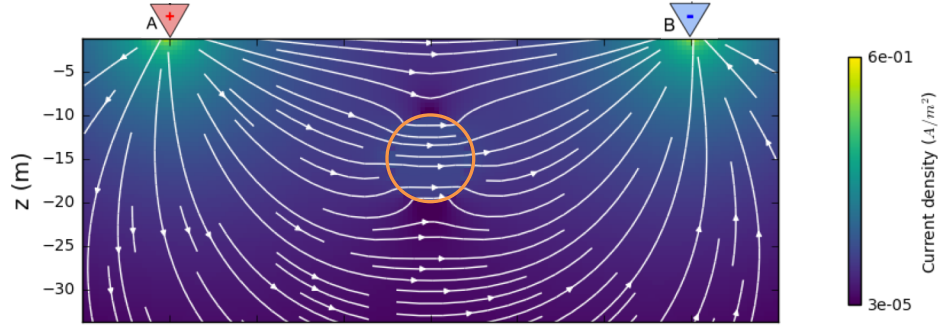


$$\tau_f = \varepsilon_0 \left( \frac{\sigma_1}{\sigma_2} - 1 \right)$$

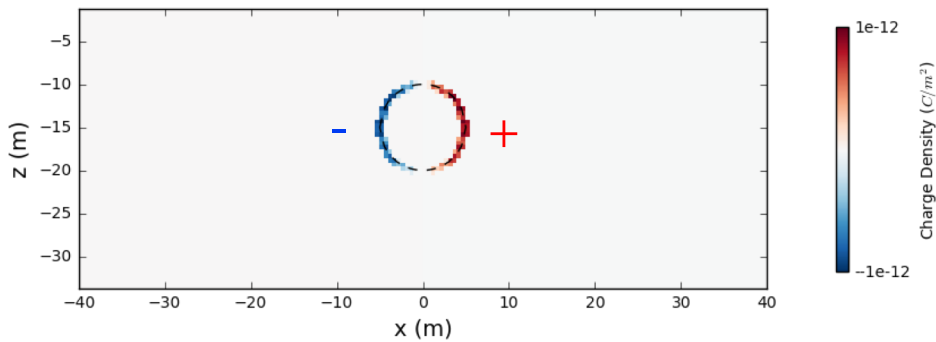
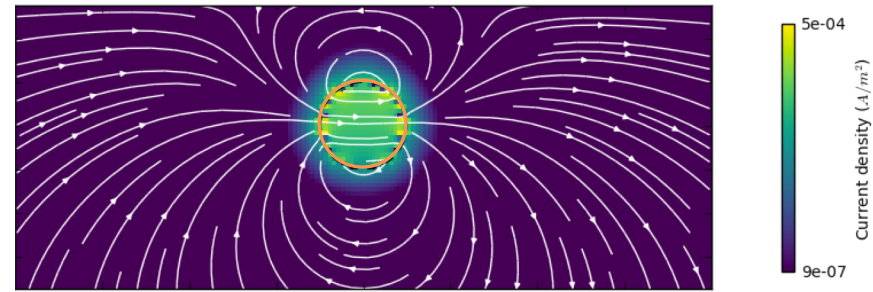


# Currents, charges, and potentials

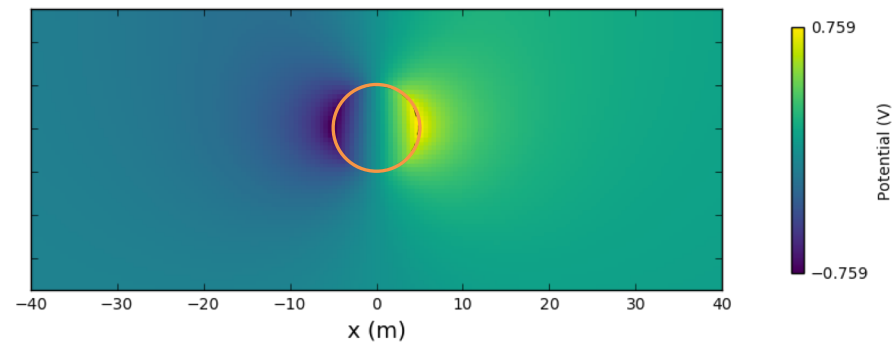
Total currents:  $J$



Secondary currents:  $J_s$



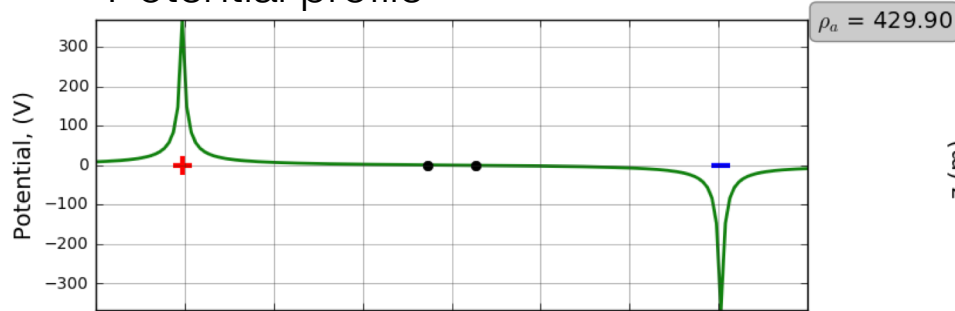
Secondary charges:  $Q_s$



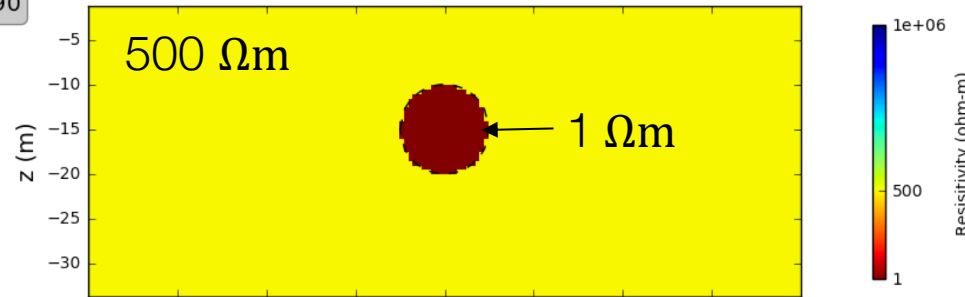
Secondary potential:  $\phi_s$

# Measurements of DC data: gradient array

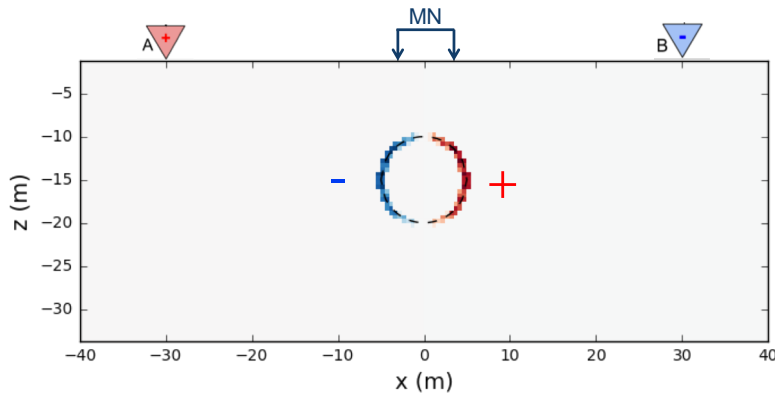
Potential profile



Resistivity model

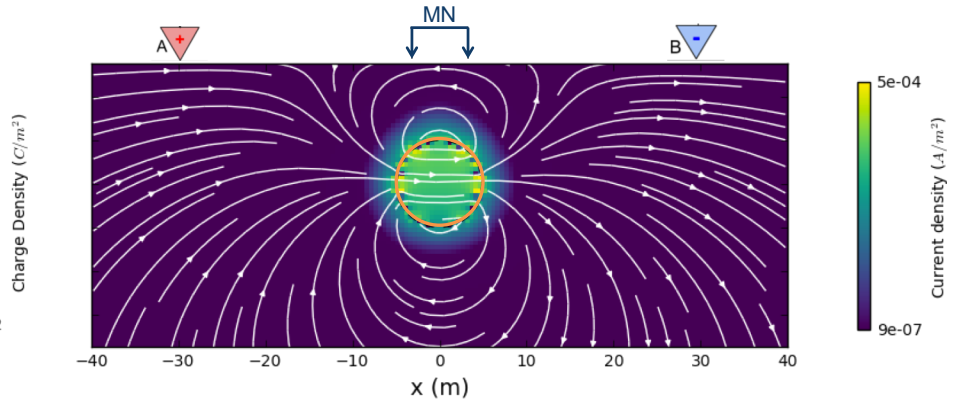


$\rho_a = 430$



Secondary charges:  $Q_s$

$\rho_a = 430$



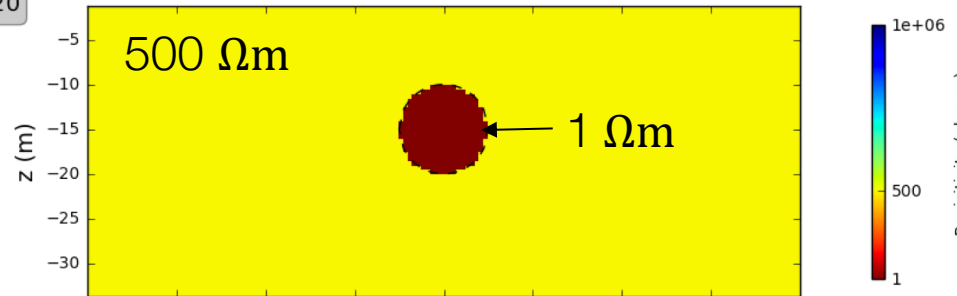
Secondary currents:  $J_s$

# Measurements of DC data: gradient array

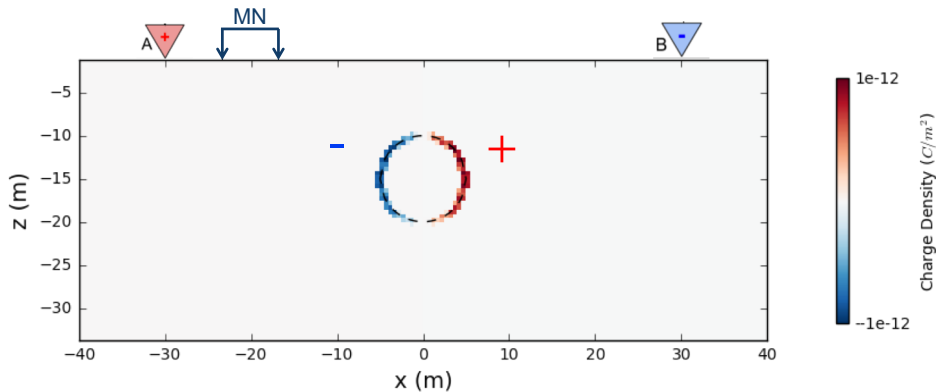
Potential profile



Resistivity model

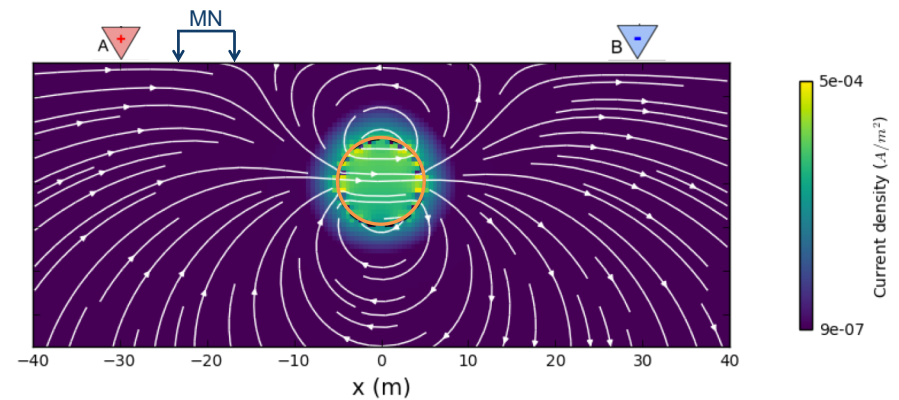


$\rho_a = 502$



Secondary charges:  $Q_s$

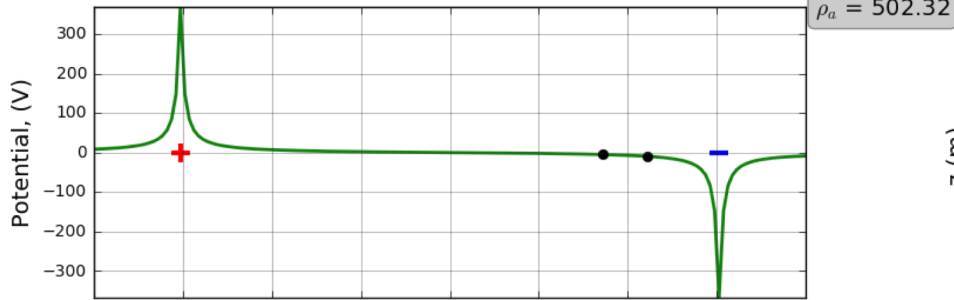
$\rho_a = 502$



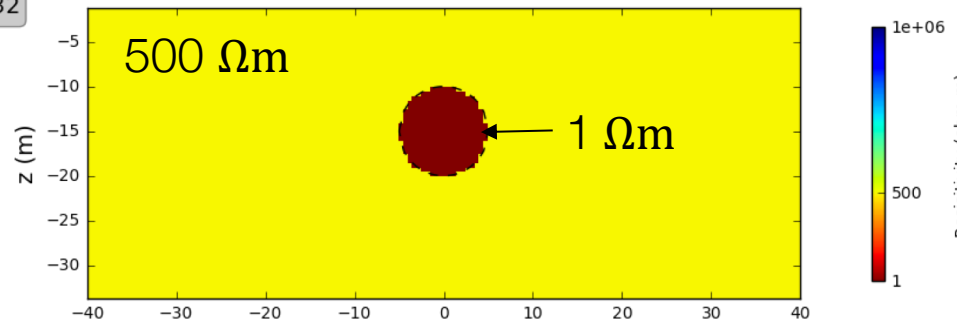
Secondary currents:  $J_s$

# Measurements of DC data: gradient array

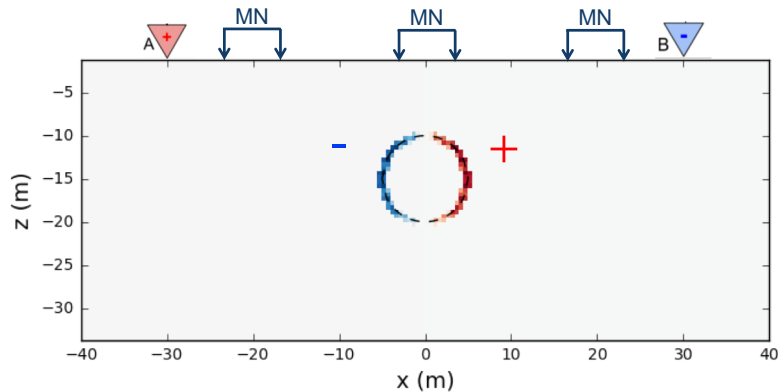
Potential profile



Resistivity model

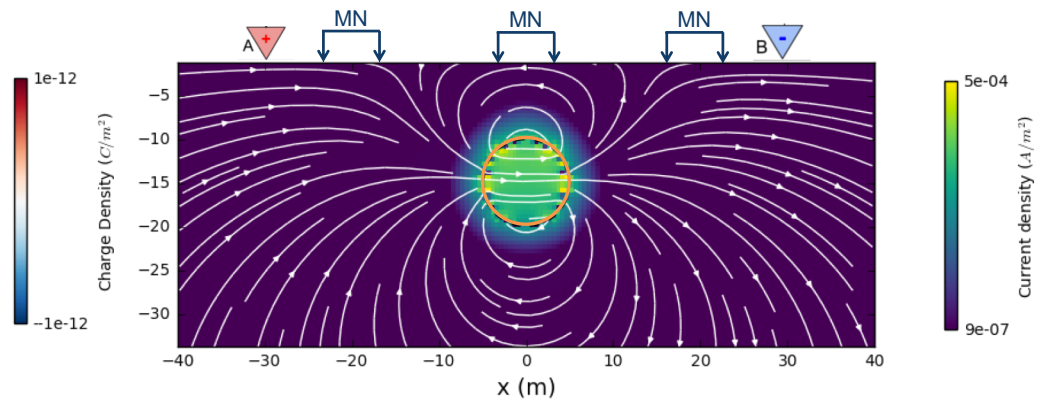


$\rho_a = 502$   $\rho_a = 430$   $\rho_a = 502$



Secondary charges:  $Q_s$

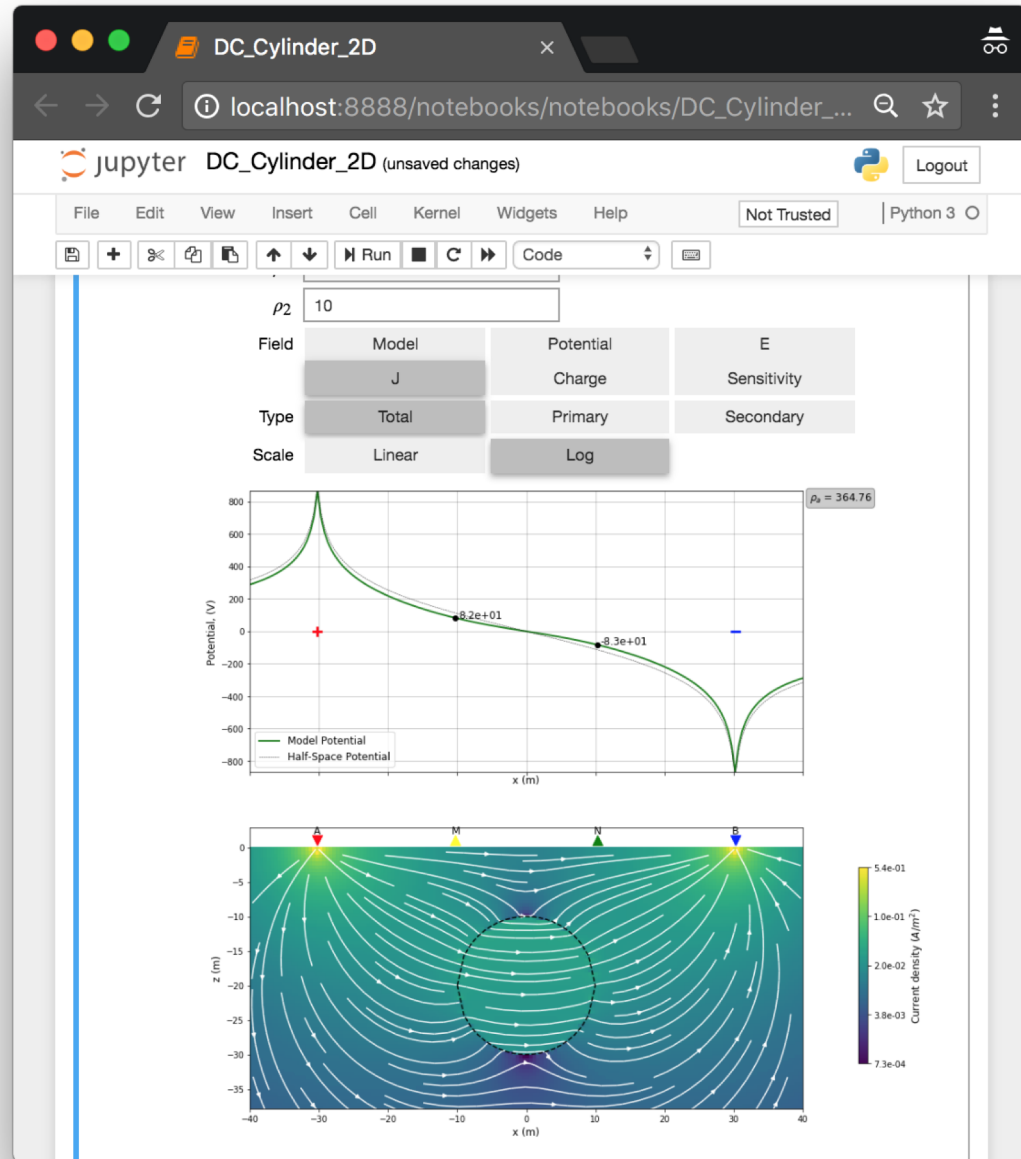
$\rho_a = 502$   $\rho_a = 430$   $\rho_a = 502$



Secondary currents:  $J_s$

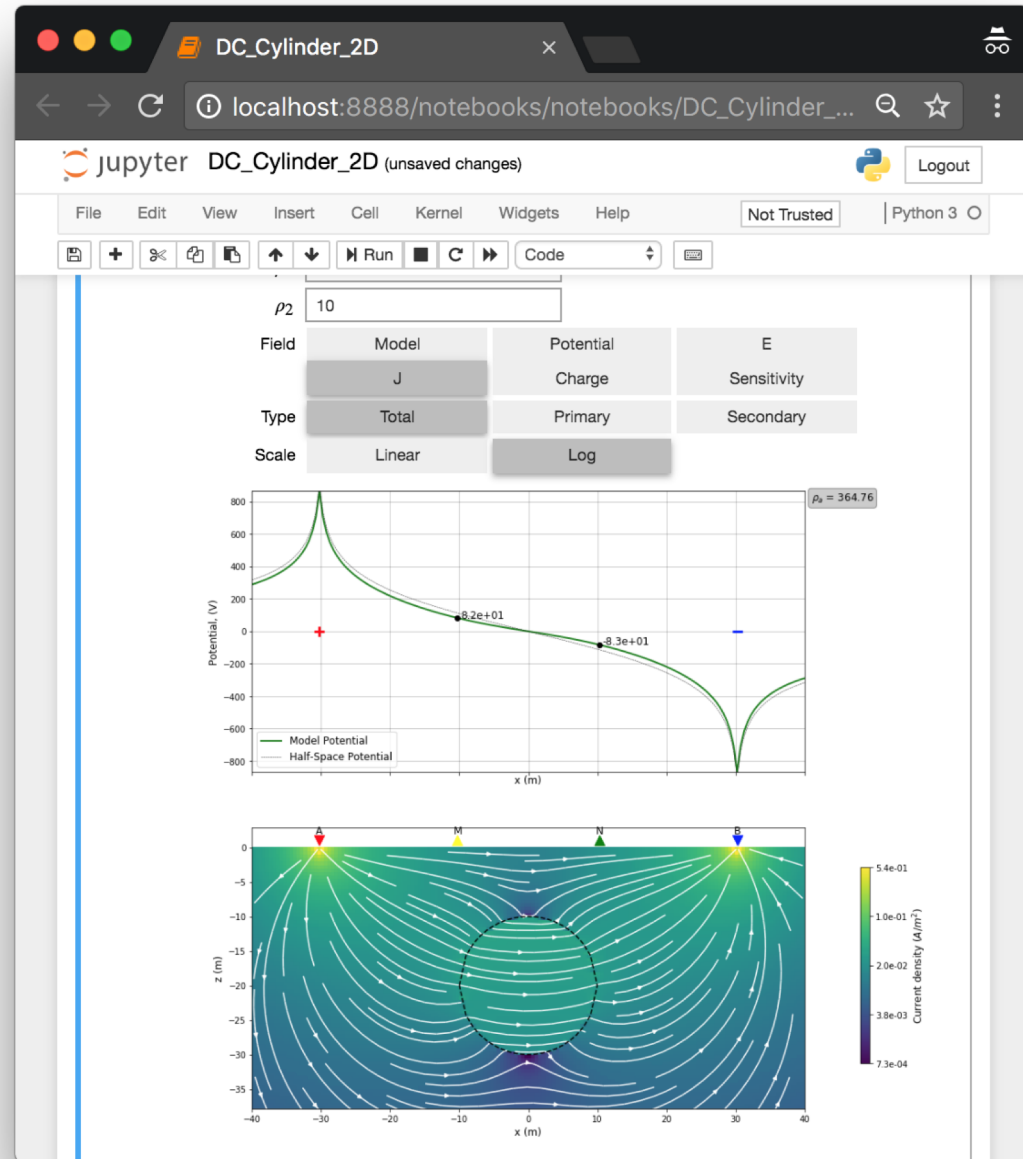
# DC cylinder

- DC\_Cylinder\_2D
- Parameters:
  - Resistivity of background cylinder
  - Geometry of cylinder
  - Location of electrodes
- View:
  - Model
  - Electric potential
  - Electric field
  - Charges
  - Current density



# DCR: cylinder (Demo)

- How does the charge vary with location of the current electrode?
- How does the apparent resistivity vary with source electrode location?
- Up next...
  - Profiling, sounding, and ability to see the cylinder at various depths.



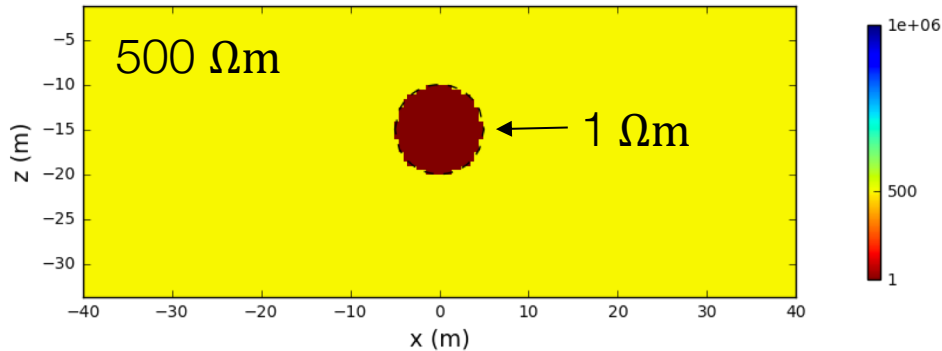
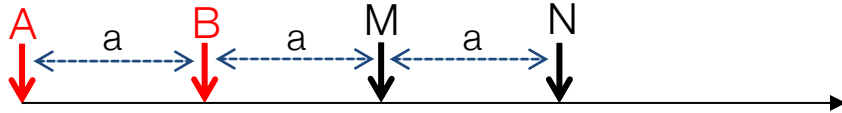
# Profiling

Fixed geometry: Move laterally

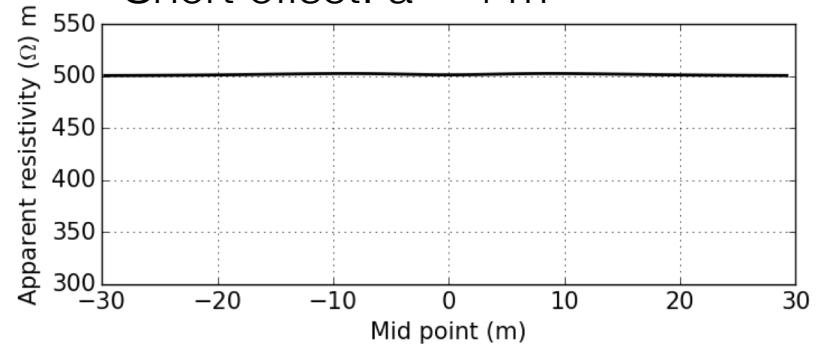
Short offset,  $a=4\text{m}$



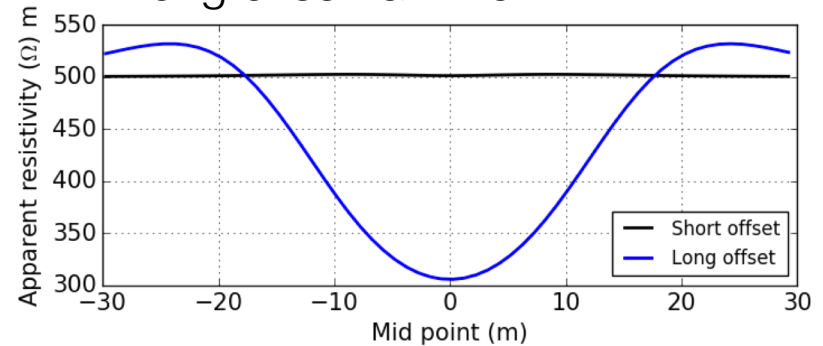
Long offset,  $a=20\text{m}$



Short offset:  $a = 4\text{ m}$



Long offset:  $a = 20\text{ m}$



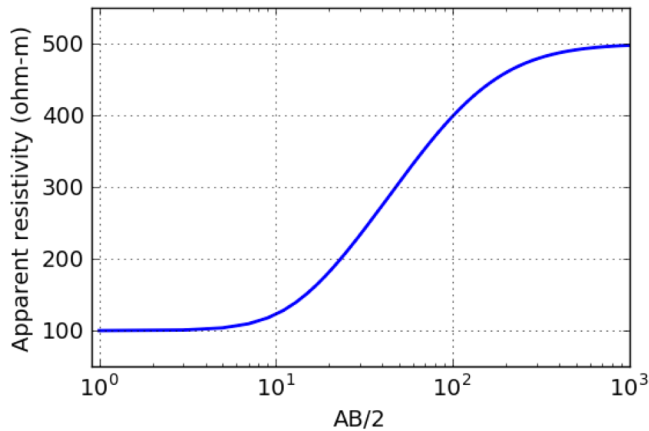
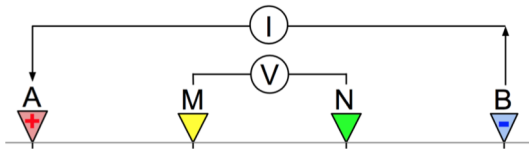
Depth of investigation depends upon offset or array length



# Summary: Soundings and Profiles

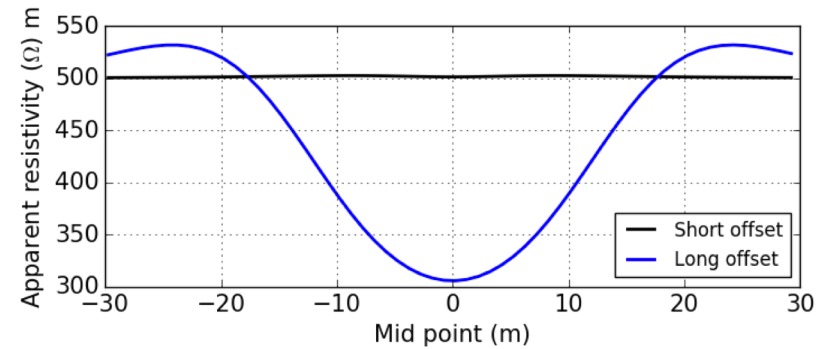
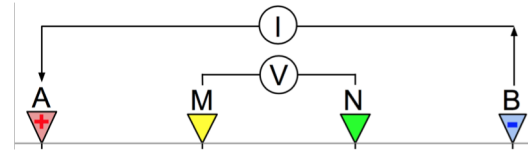
## Sounding

Expand



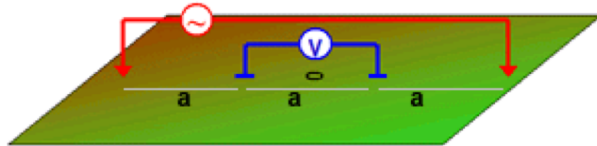
## Profiling

Translate

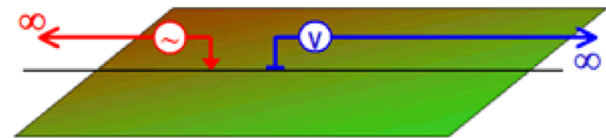


# Basic Survey Setups

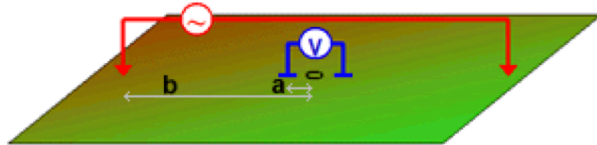
Wenner



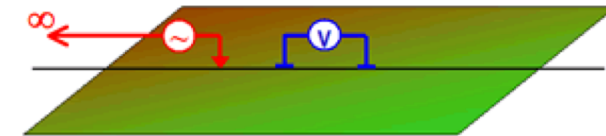
Pole-Pole



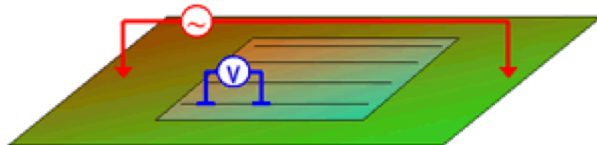
Schulmberger



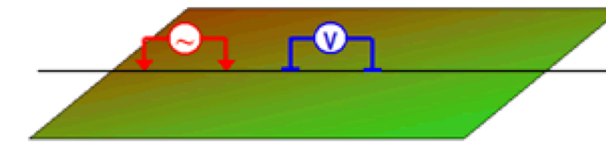
Pole-Dipole



Gradient



Dipole-Dipole



# Well-logging

- Same physical principles, different geometry

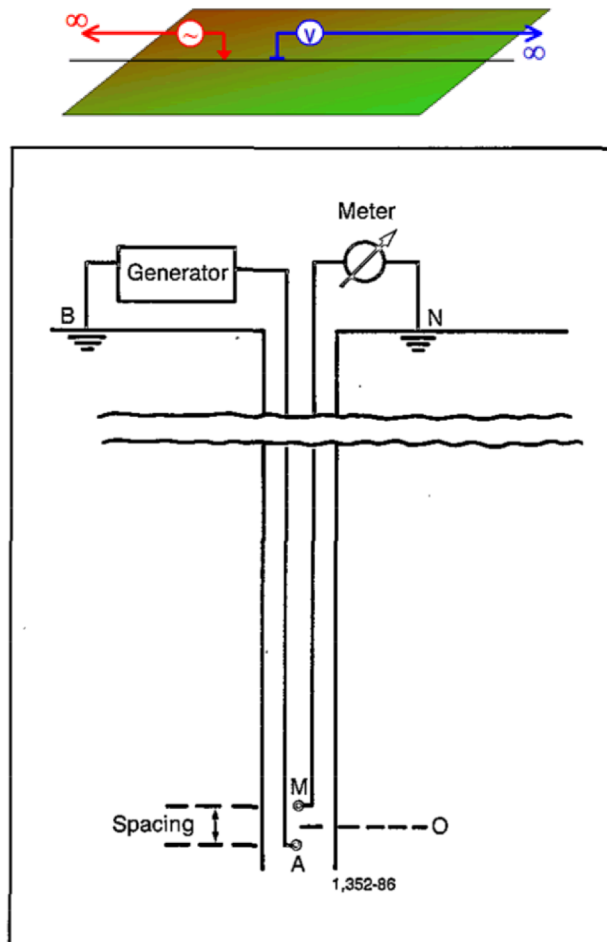


Fig. 7-1—Normal device—basic arrangement.

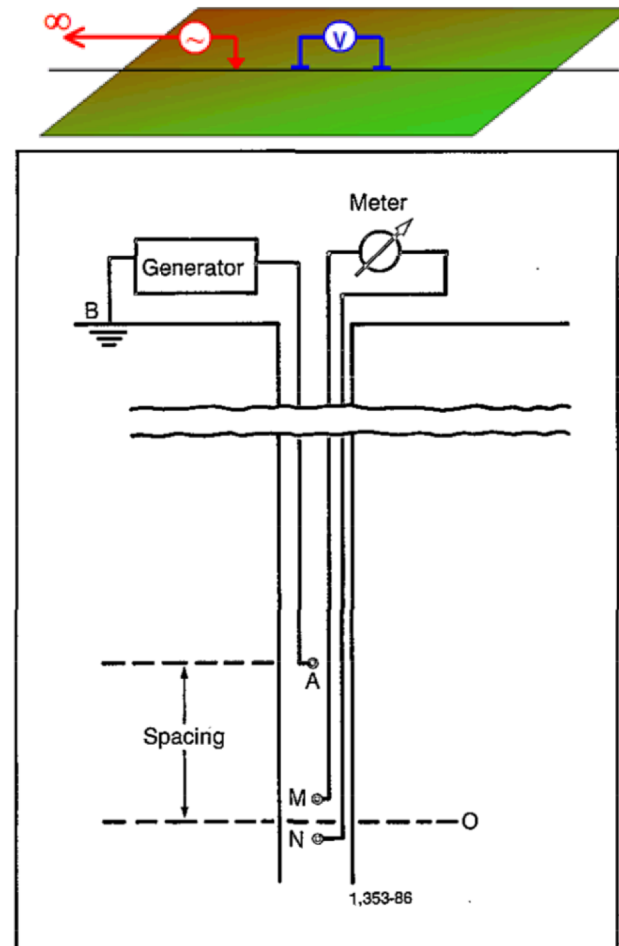
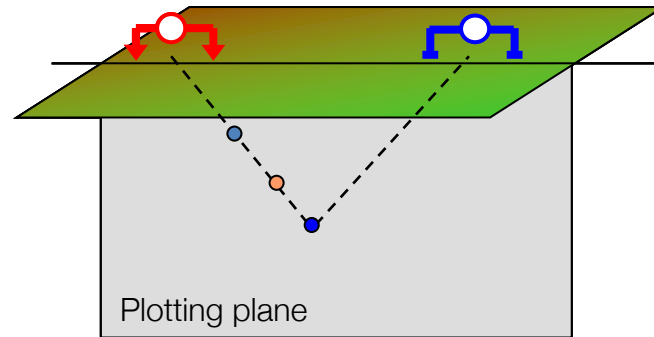
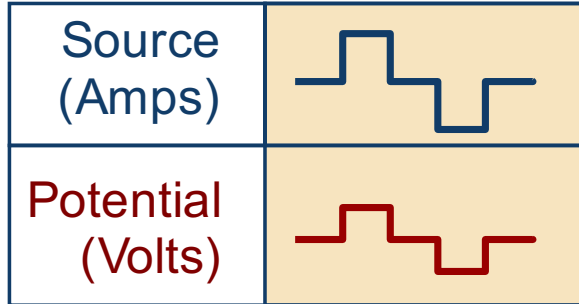


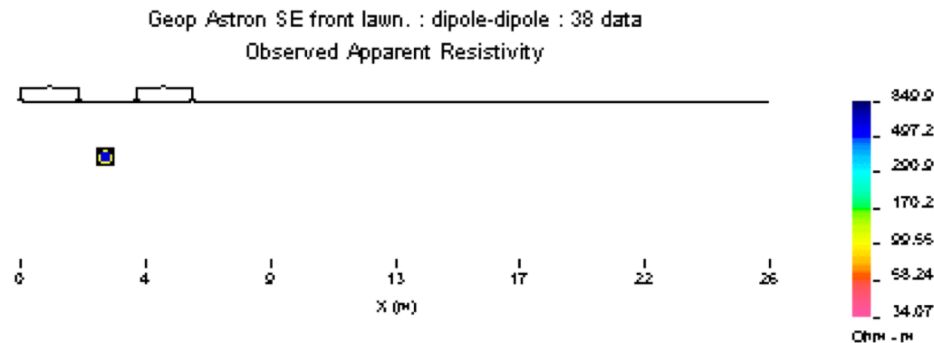
Fig. 7-2—Lateral device—basic arrangement.

# DC resistivity data



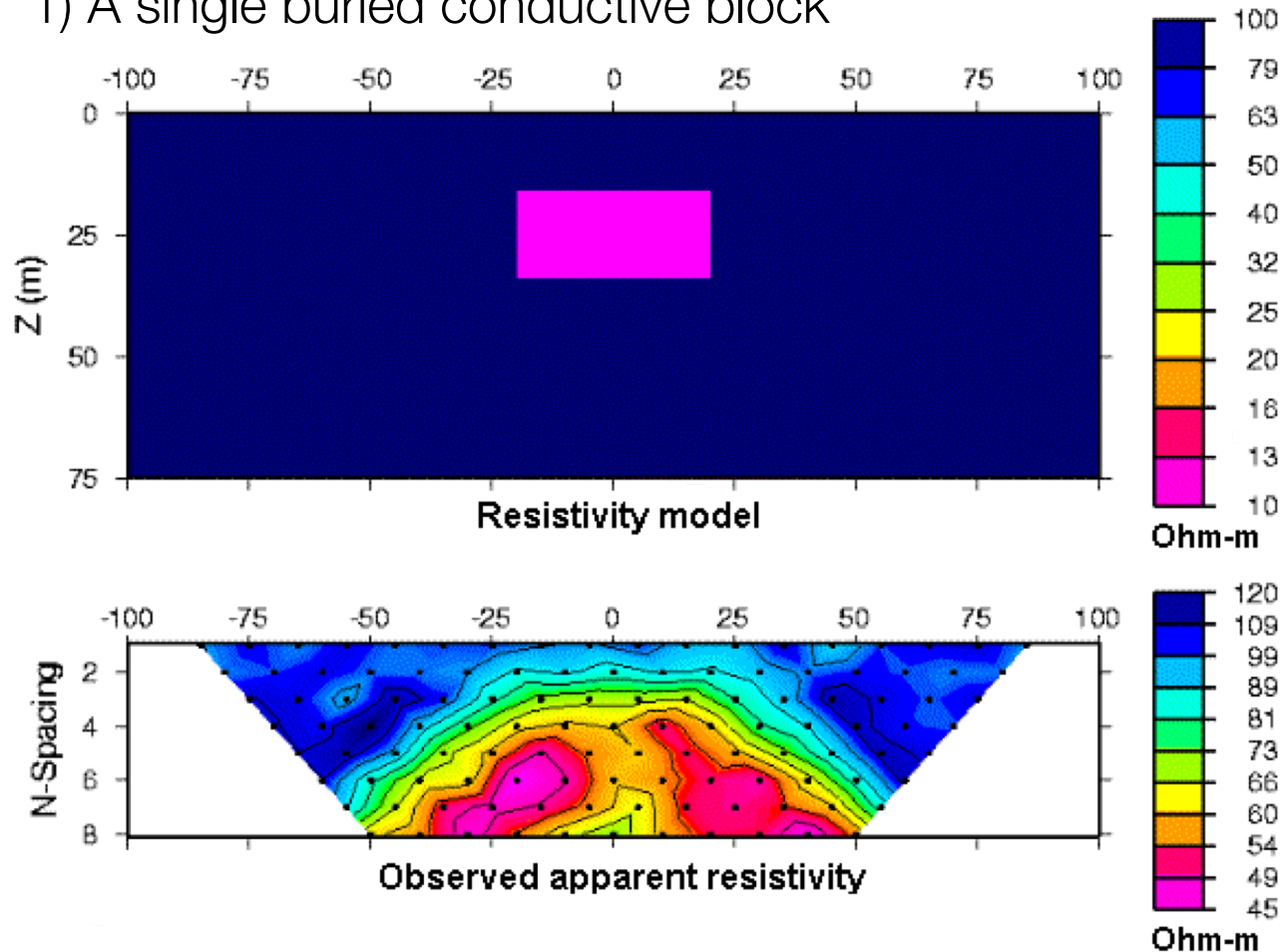
Each data point is an apparent resistivity:

$$\rho_a = \frac{2\pi\Delta V}{IG}$$

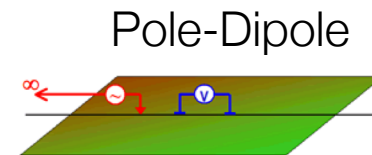


# Example pseudosections

1) A single buried conductive block

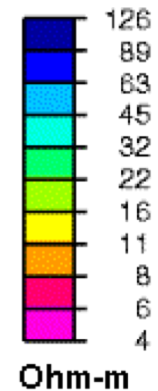
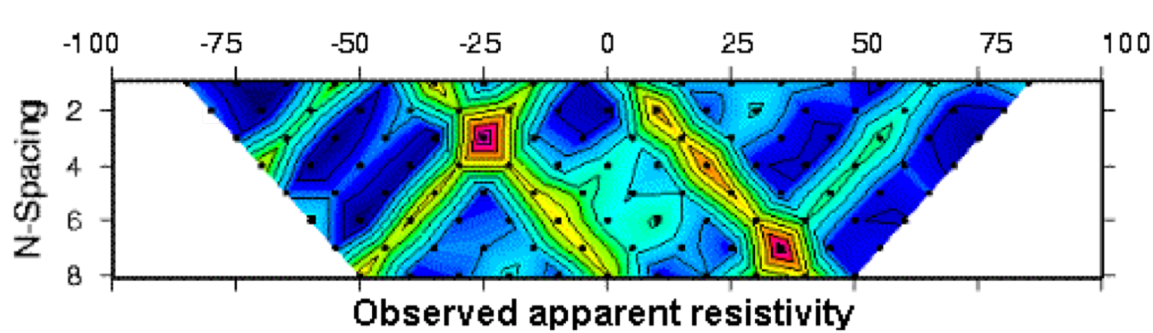
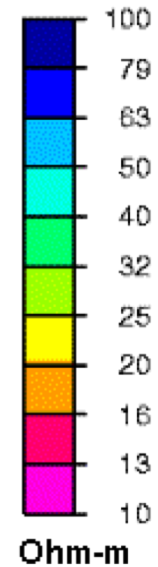
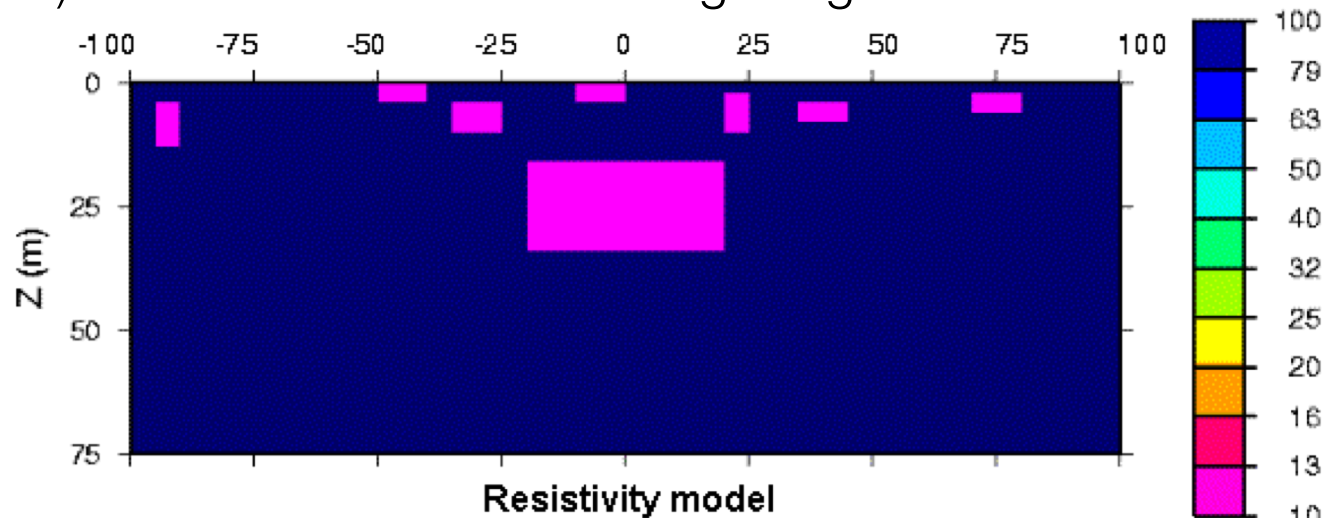


- Pole-dipole;  $n=1,8$ ;  $a=10\text{m}$ ;  $N=316$

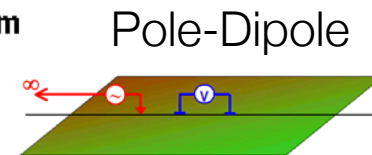


# Example pseudosections

2) The conductive block with geologic noise.

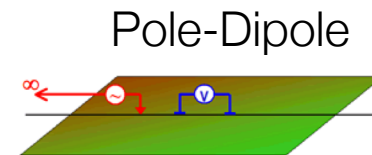
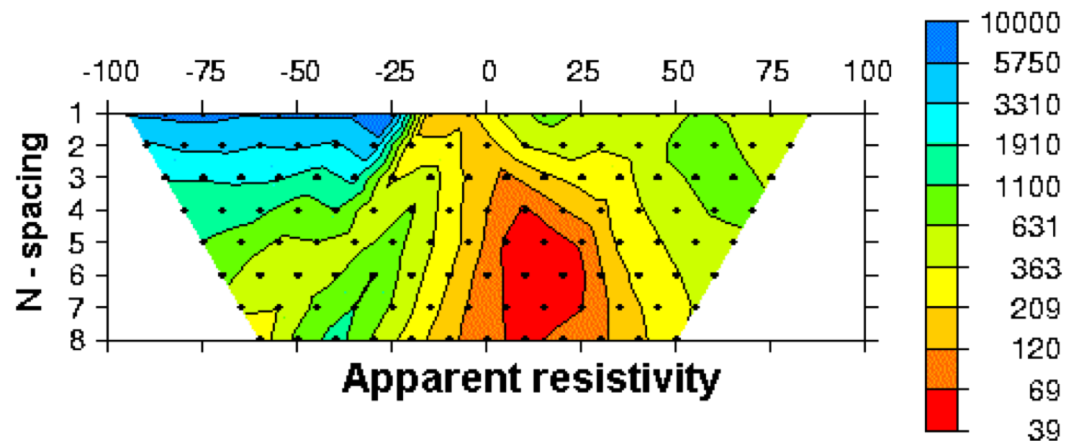
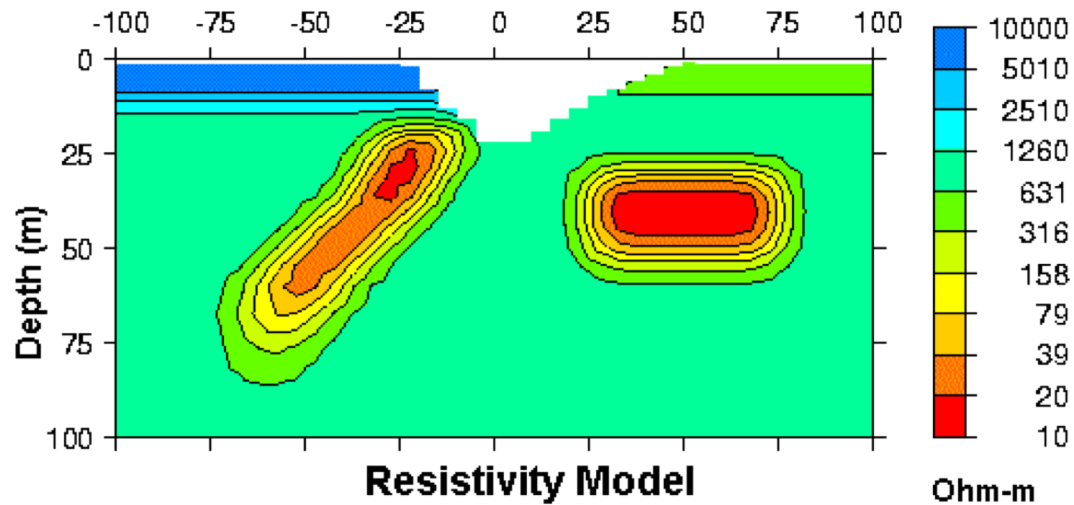


- Pole-dipole;  $n=1,8$ ;  $a=10\text{m}$ ;  $N=316$



# Example pseudosections

## 3) The “UBC-GIF model”



# Pseudo-section app

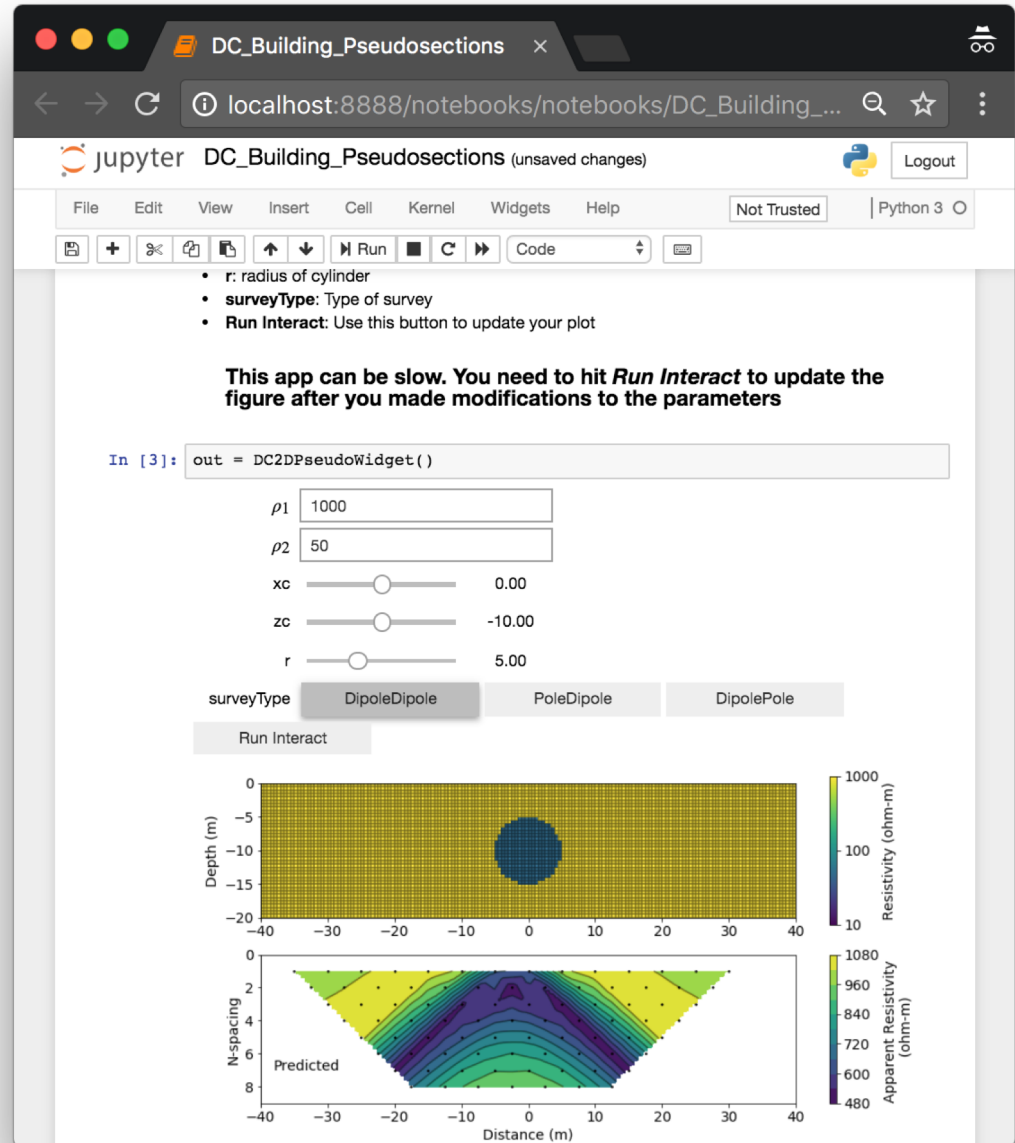
- DC\_Building\_Pseudosections

- Parameters:

- Resistivity of background, layer, sphere
- Geometry of sphere, layer
- Location of electrodes

- View:

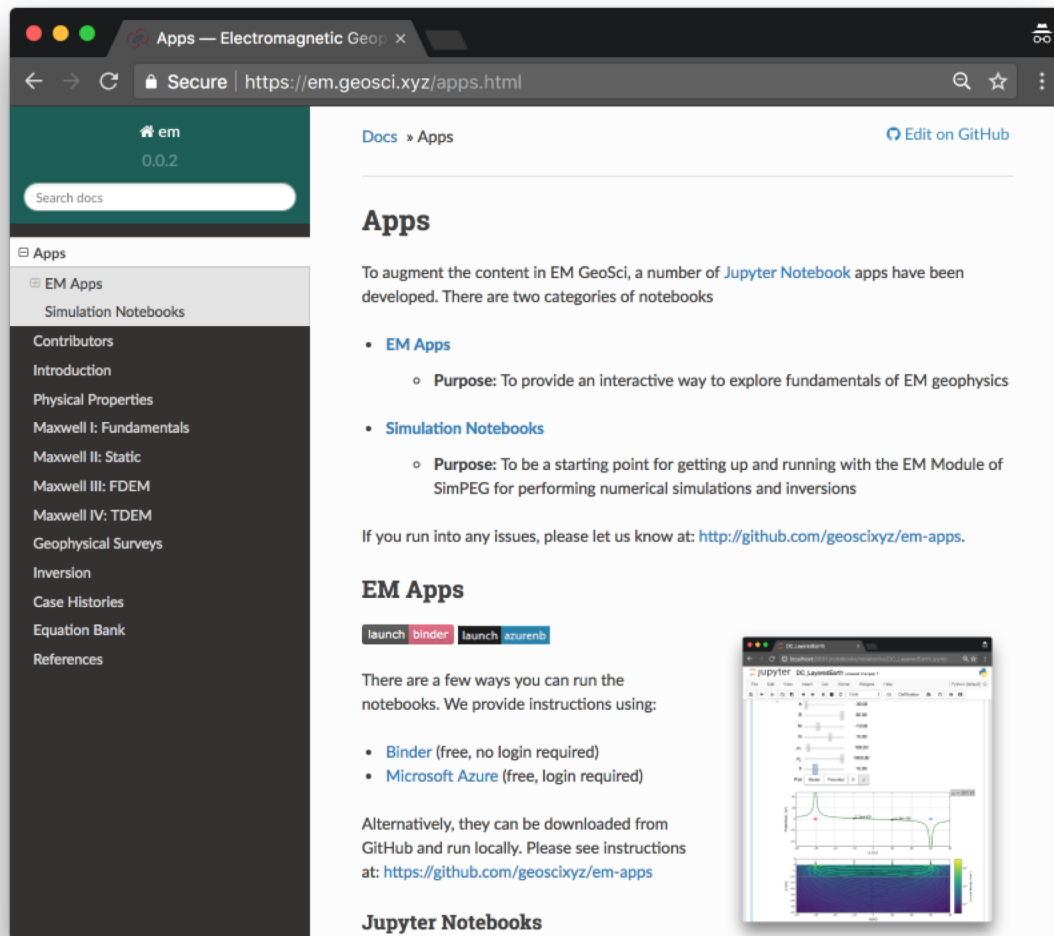
- Model
- Pseudosection





# Using the apps

<https://em.geosci.xyz/apps.html>



The screenshot shows a web browser window with the URL <https://em.geosci.xyz/apps.html>. The page has a dark green sidebar on the left with a search bar and a navigation menu. The main content area is white and contains the following text:

Docs > Apps [Edit on GitHub](#)

## Apps

To augment the content in EM GeoSci, a number of [Jupyter Notebook](#) apps have been developed. There are two categories of notebooks

- **EM Apps**
  - **Purpose:** To provide an interactive way to explore fundamentals of EM geophysics
- **Simulation Notebooks**
  - **Purpose:** To be a starting point for getting up and running with the EM Module of SimPEG for performing numerical simulations and inversions

If you run into any issues, please let us know at: <http://github.com/geoscixyz/em-apps>.

## EM Apps

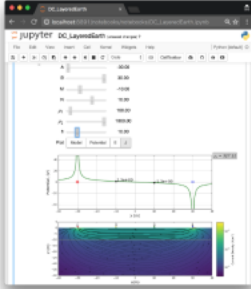
[launch binder](#) [launch azurenb](#)

There are a few ways you can run the notebooks. We provide instructions using:

- [Binder](#) (free, no login required)
- [Microsoft Azure](#) (free, login required)

Alternatively, they can be downloaded from GitHub and run locally. Please see instructions at: <https://github.com/geoscixyz/em-apps>

## Jupyter Notebooks



# Jupyter Notebooks



The screenshot shows a Jupyter Notebook interface in a browser window. The browser address bar shows the URL `localhost:8892/notebooks/notebooks/DC_LayeredEarth.ipynb`. The notebook title is `DC_LayeredEarth (autosaved)`. The menu bar includes `File`, `Edit`, `View`, `Insert`, `Cell`, `Kernel`, `Widgets`, and `Help`. The `Cell` menu is open, showing options: `Run Cells`, `Run Cells and Select Below`, `Run Cells and Insert Below`, `Run All`, `Run All Above`, and `Run All Below`. A red arrow points to the `Run All` option. The text `run all` is written in red next to the arrow. Below the menu, the notebook content is visible, including a code cell with `from em_examp` and `import matplotlib`, and text sections: **Purpose**, **Investigati**, **Background: Computing Apparent Resistivity**, and mathematical equations for  $V_M$  and  $V_N$ .

```
In [1]: from em_examp
import matplotlib
```

**Purpose**

**Investigati**

Using the widgets available in this notebook, we will explore the physical principals governing DC resistivity including the behavior of currents, electric field, electric potentials in a two layer earth.

The measured data in a DC experiment are potential differences, we will demonstrate how these provide information about subsurface physical properties.

**Background: Computing Apparent Resistivity**

In practice we cannot measure the potentials everywhere, we are limited to those locations where we place electrodes. For each source (current electrode pair) many potential differences are measured between M and N electrode pairs to characterize the overall distribution of potentials. The widget below allows you to visualize the potentials, electric fields, and current densities from a dipole source in a simple model with 2 layers. For different electrode configurations you can measure the potential differences and see the calculated apparent resistivities.

In a uniform halfspace the potential differences can be computed by summing up the potentials at each measurement point from the different current sources based on the following equations:

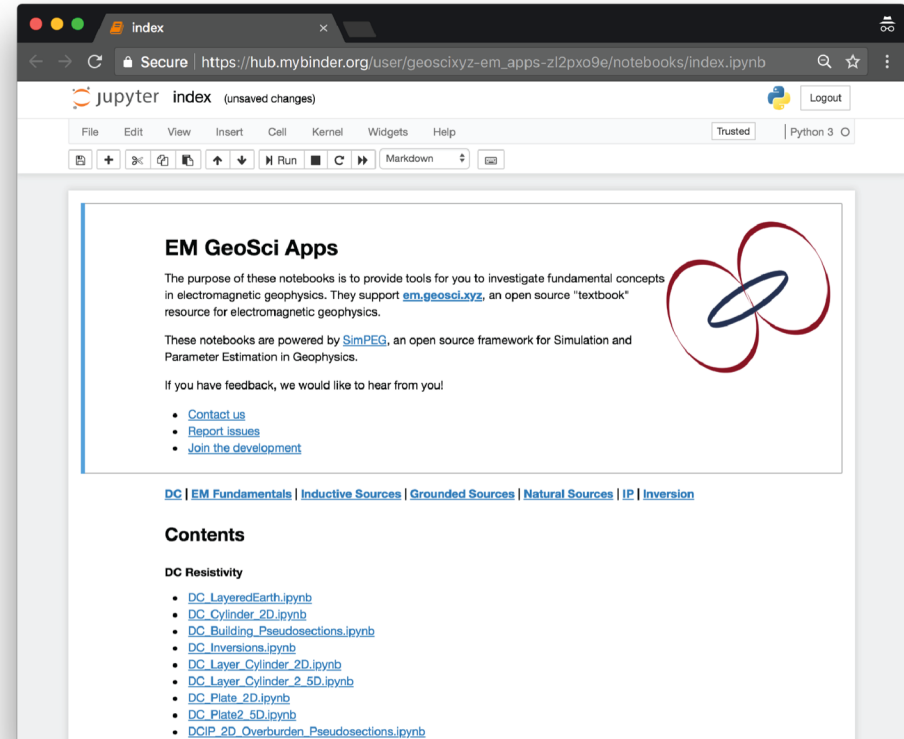
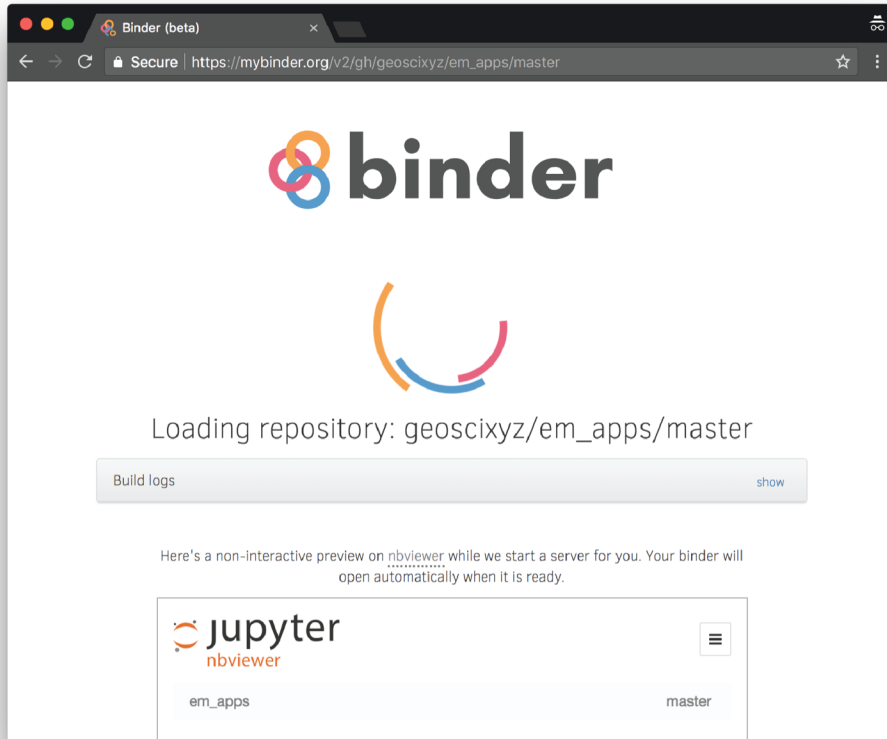
$$V_M = \frac{\rho I}{2\pi} \left[ \frac{1}{AM} - \frac{1}{MB} \right]$$
$$V_N = \frac{\rho I}{2\pi} \left[ \frac{1}{AN} - \frac{1}{NB} \right]$$

# Running the Apps

launch binder

1. Load the repository  
(be patient...)

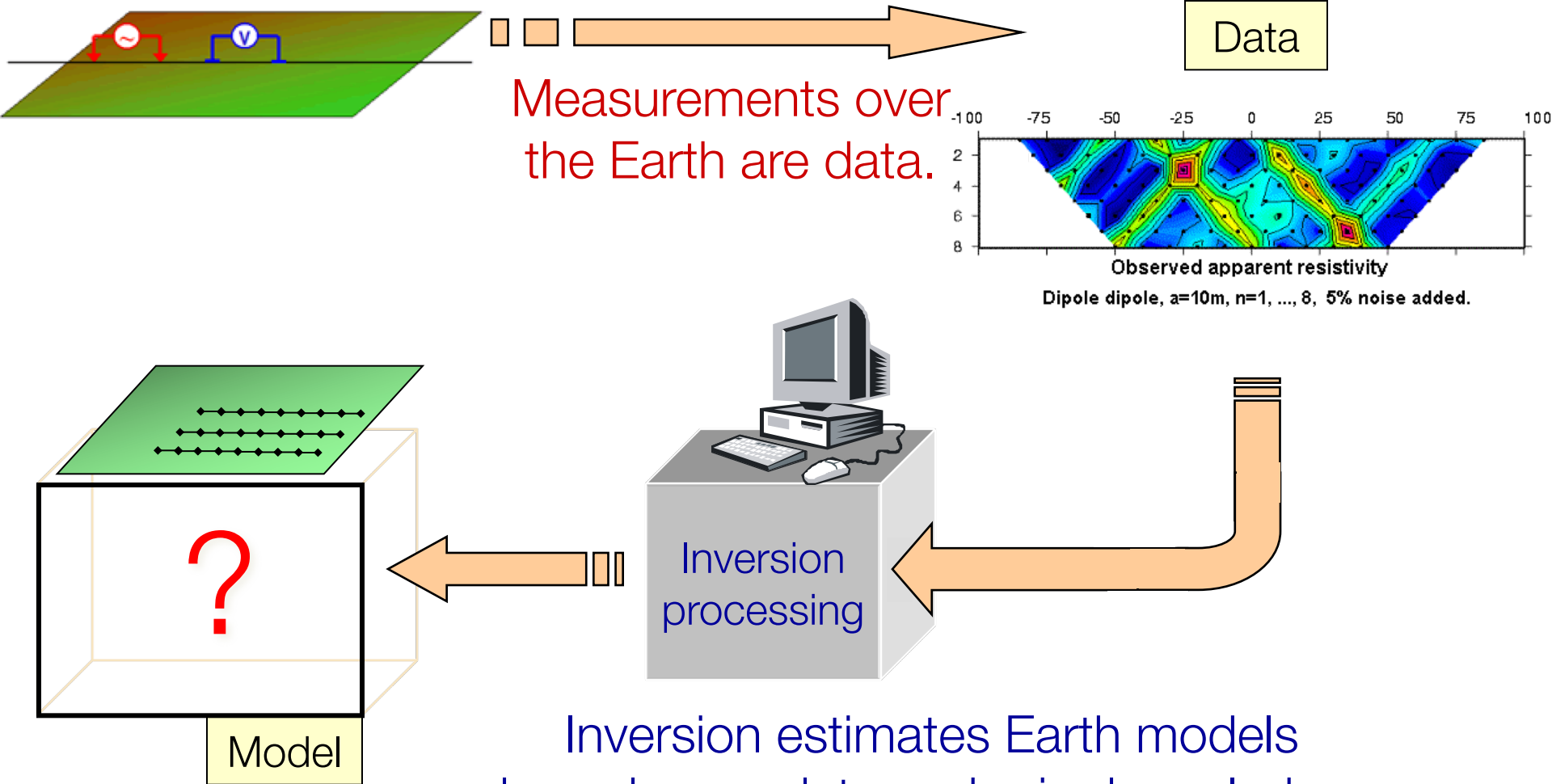
2. Select notebook from  
contents



# Questions

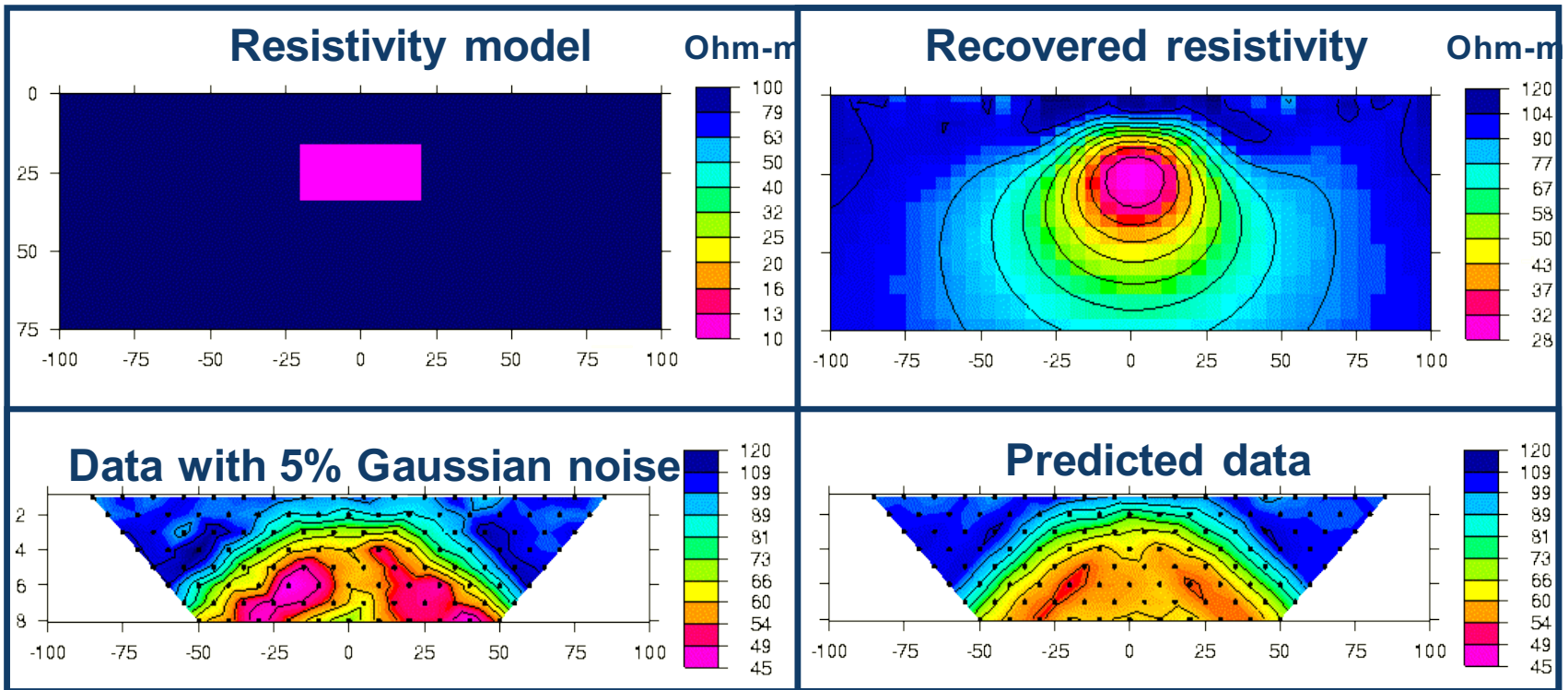
- **DC\_LayeredEarth**
  - Start with a top layer that is conductive ( $50 \Omega\text{m}$ ).
    - What is the minimum A-B separation we need to see the second layer in our data?
    - What happens if the layer is more conductive / resistive?
    - What happens if the layer is thicker?
- **DC\_Cylinder\_2D**
  - You have been charged with finding 2 tunnels: (1) Filled with salty water, (2) filled with air
    - How are the charges distributed for both tunnels if you use a pole source?
    - How does the apparent resistivity vary with changing the parameters of the tunnel (resistivity, radius, depth)?
- **DC\_Cylinder\_2D cont...**
  - For a conductive cylinder ( $10 \Omega\text{m}$ ) in a resistive background ( $500 \Omega\text{m}$ ), can you generate a pole-pole example where the apparent resistivity is  $> 500 \Omega\text{m}$ ? How do you explain this (hint: look at the charges)
- **DC\_Building\_Pseudosections**
  - For which survey setup's are the “pant-legs” symmetric over the target? Which aren't?
  - Can you demonstrate an example of non-uniqueness? E.g. If the sphere has a radius of 2m and a resistivity of  $50 \Omega\text{m}$ , is there a model that produces similar data?

# Inversion



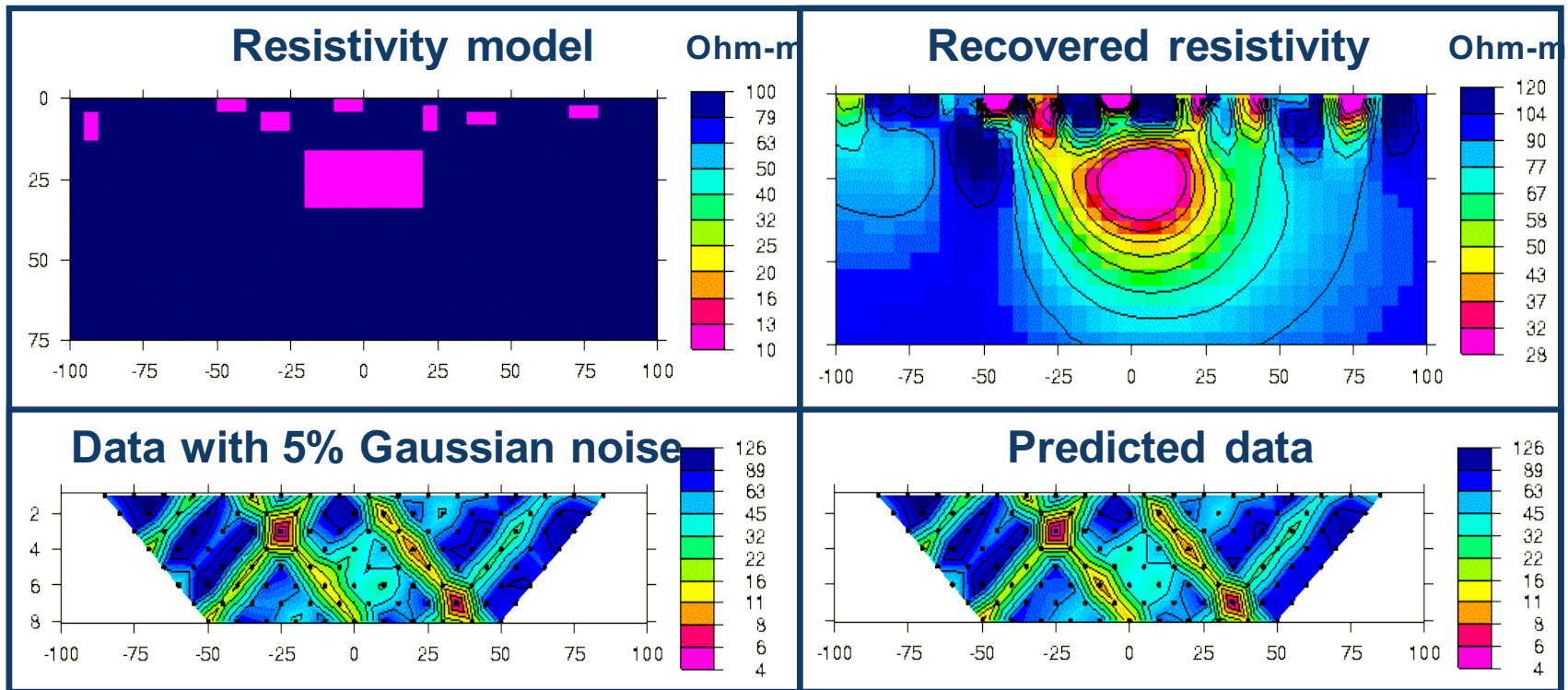
Inversion estimates Earth models based upon data and prior knowledge.

# Example 1: buried prism



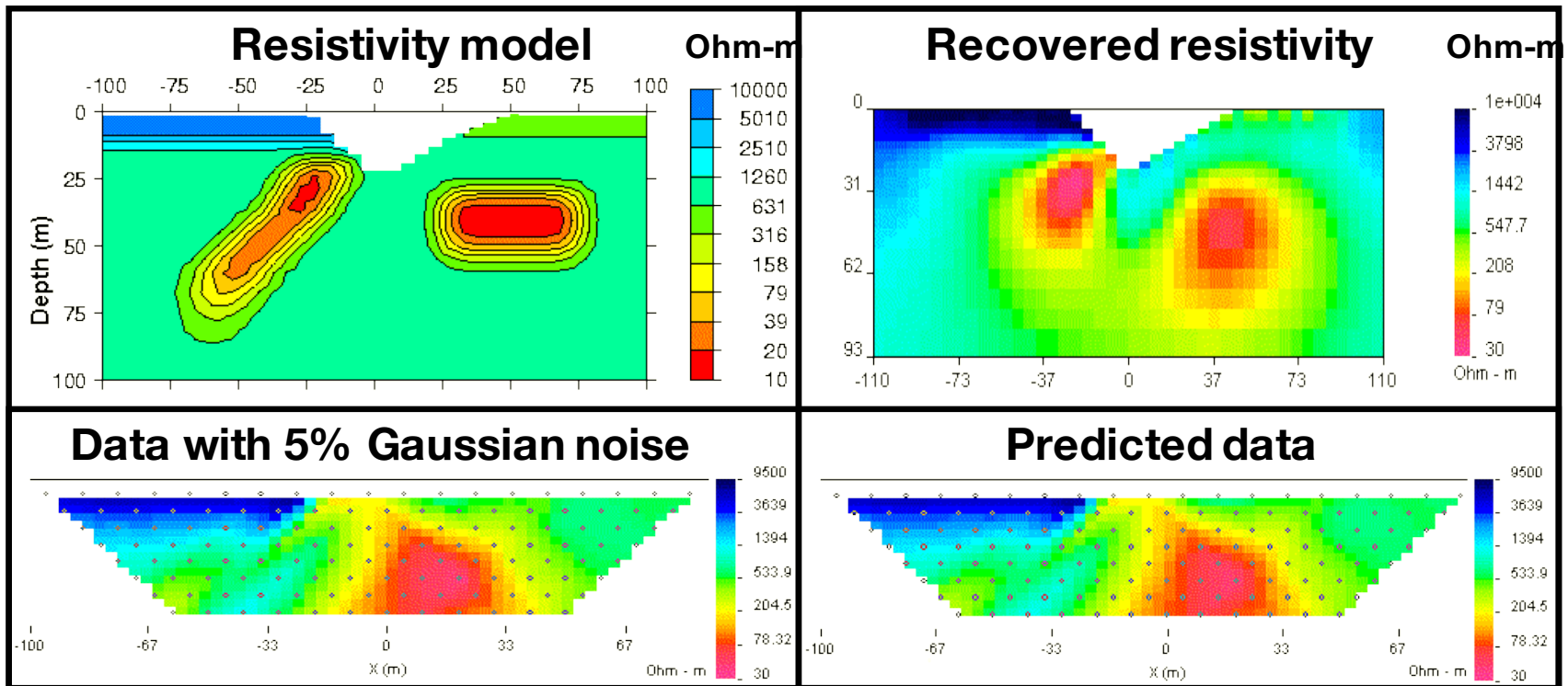
- Pole-dipole;  $n=1,8$ ;  $a=10\text{m}$ ;  $N=316$ ;  $(\alpha_s, \alpha_x, \alpha_z)=(.001, 1.0, 1.0)$

# Example 2: prism with geologic noise



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

# Example 3: UBC-GIF model



- Pole-dipole;  $n=1,8$ ;  $a=10\text{m}$



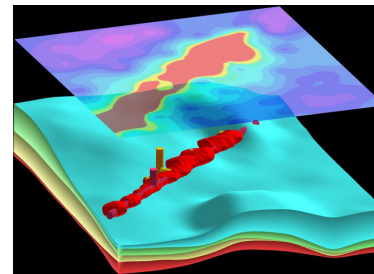
# The world is 3D

- 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**

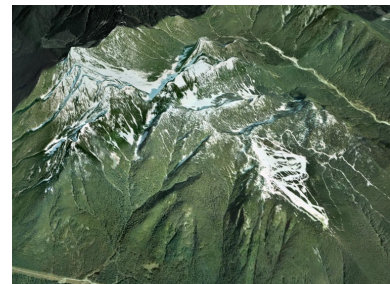
Host



Ore body



Topography

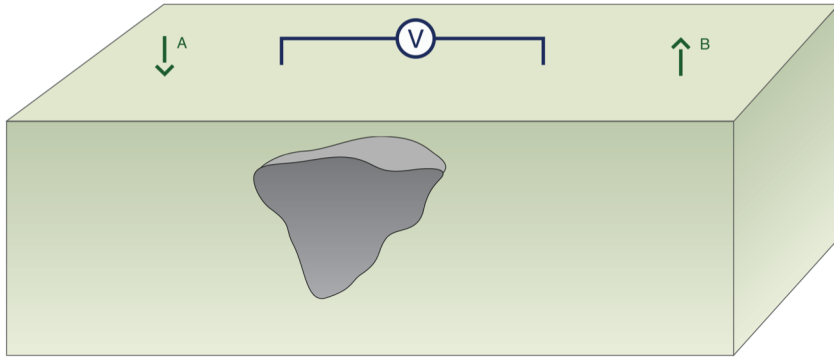


Water underground



# Sensitivity

# Sensitivity Function



Is the measured potential *sensitive* to the target?

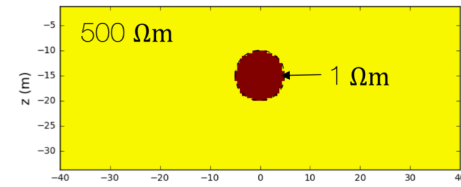
Quantified by the sensitivity

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

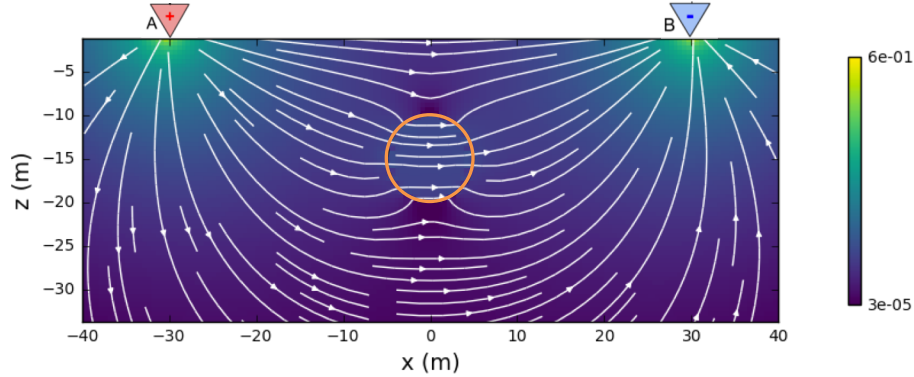
- Collect the data that are sensitive to the target
  - Need to **excite** the target
  - Need to have sensor **close** to the target

# Exciting the target

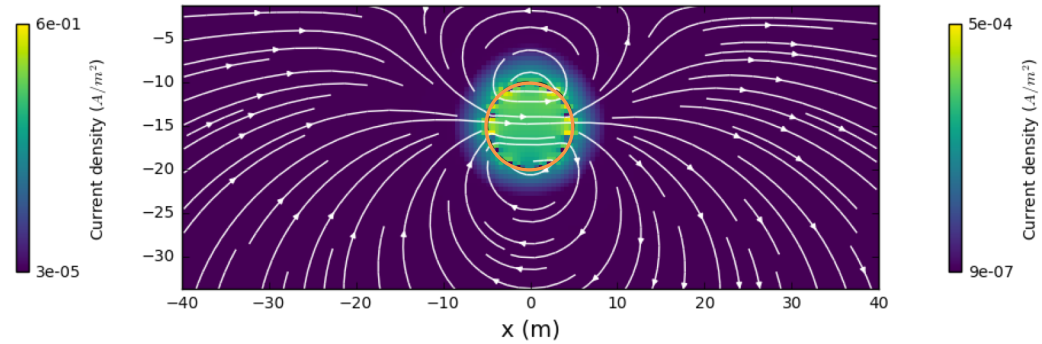
Resistivity model



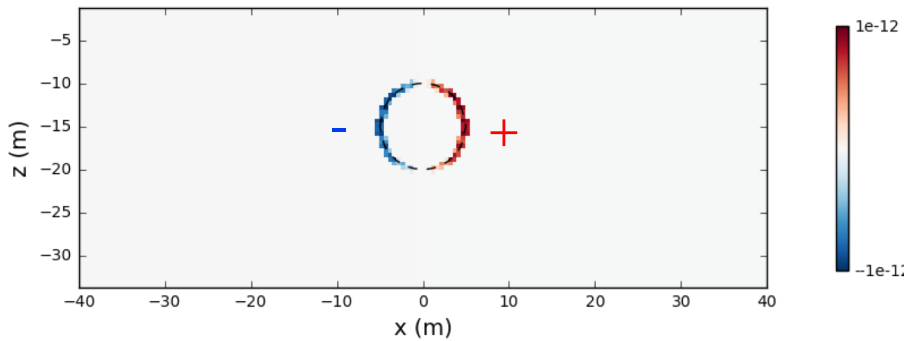
Total currents:  $\mathbf{J}$



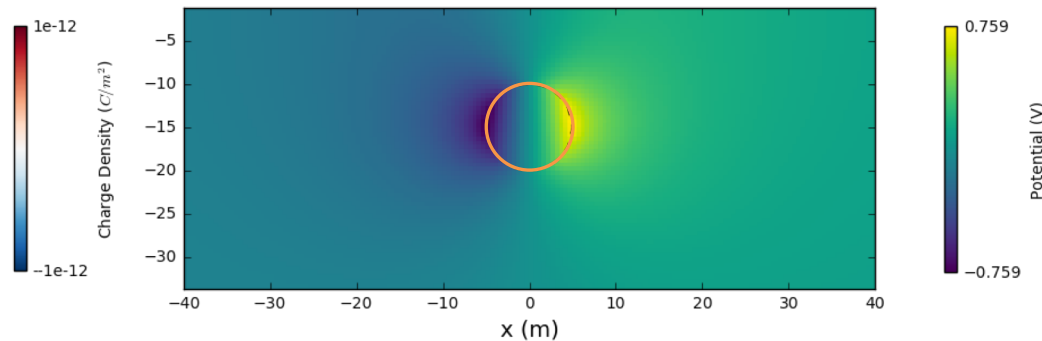
Secondary currents:  $\mathbf{J}_s$



Secondary charges:  $Q_s$

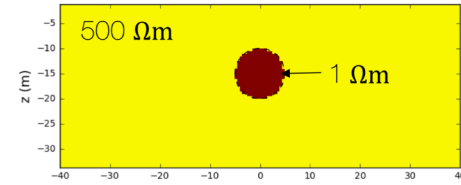


Secondary potential:  $\phi_s$

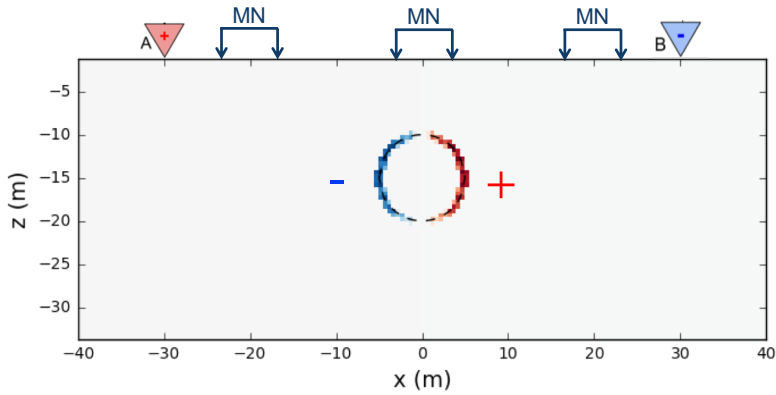


# Measurements

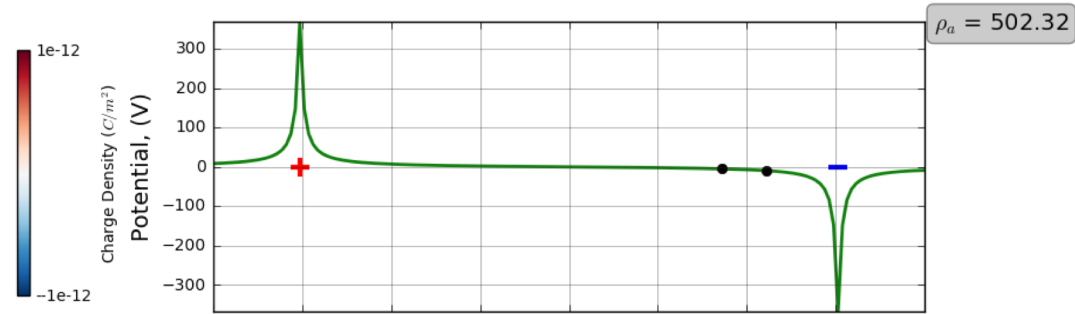
Resistivity model



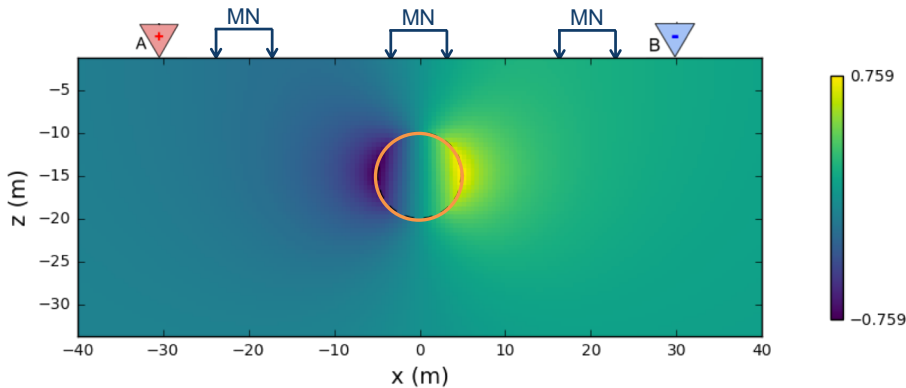
Secondary charges:  $Q_s$



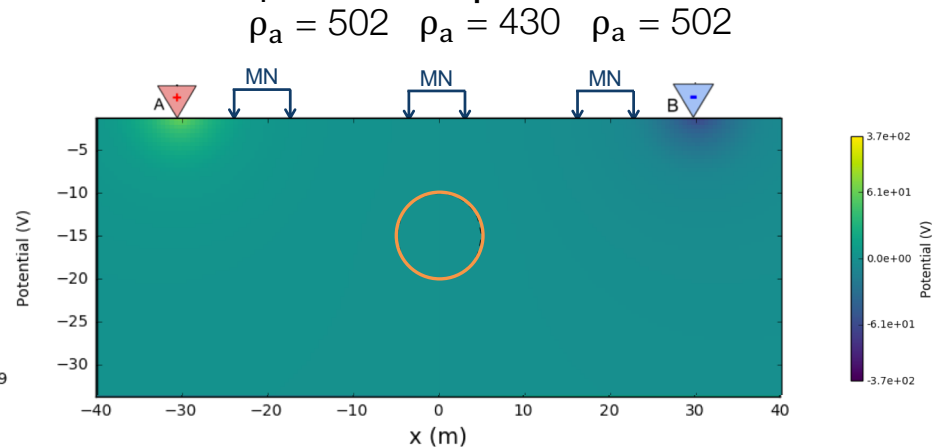
Potential profile



Secondary potential:  $\phi_s$

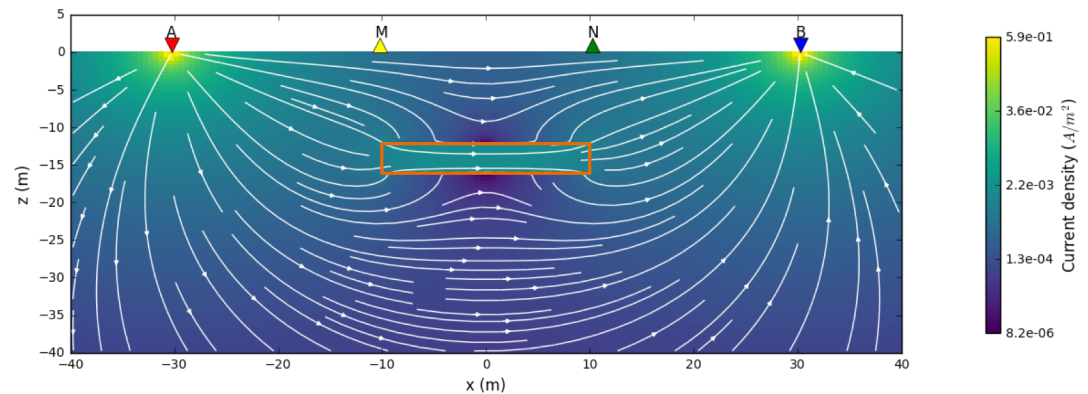
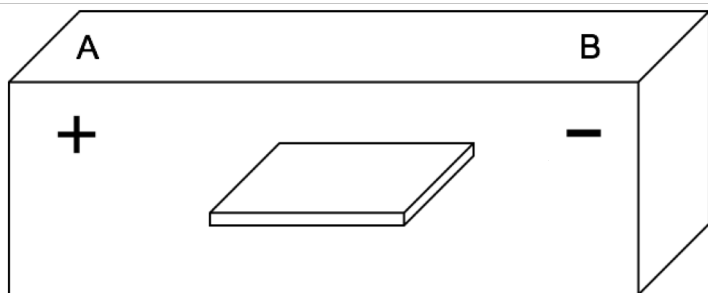
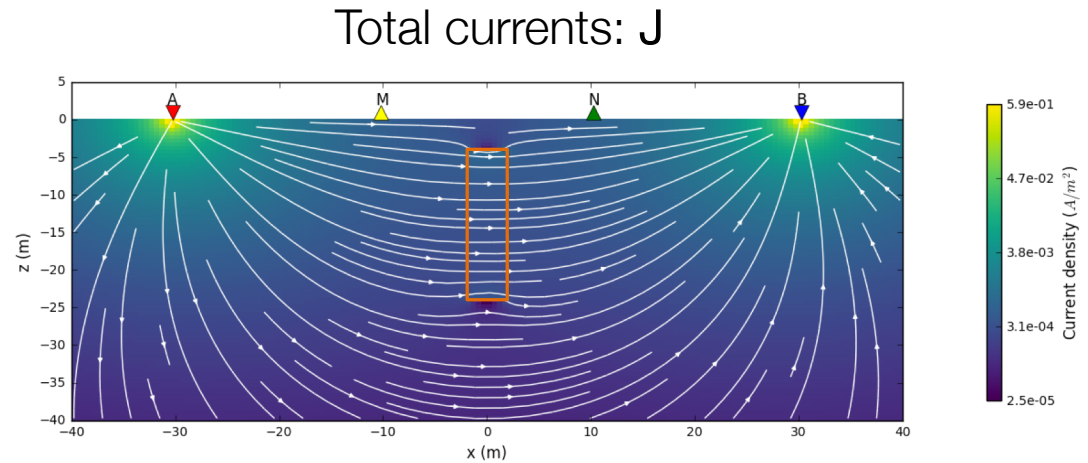
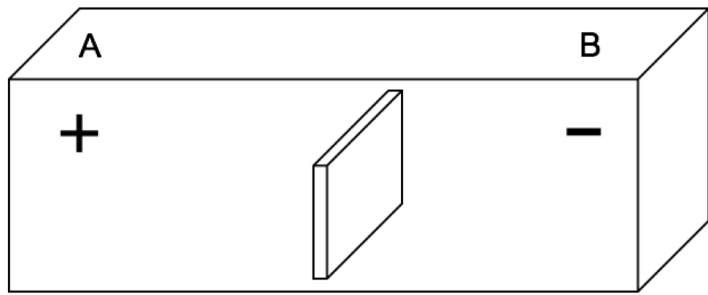


Total potential:  $\phi$



# Coupling

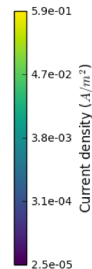
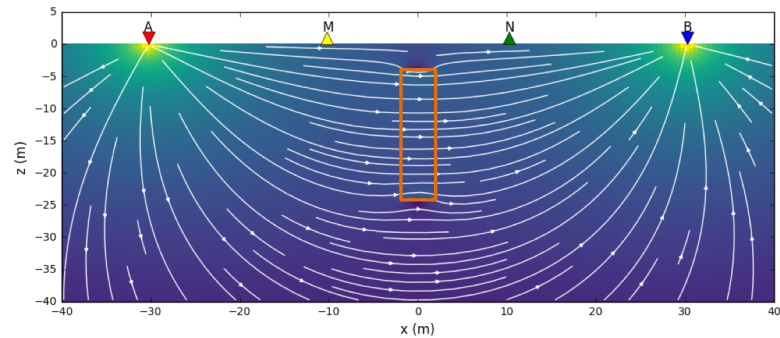
- Thin plate – different orientations  
→ different data



# Conductive vs. Resistive Target

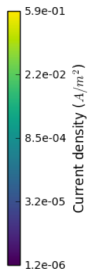
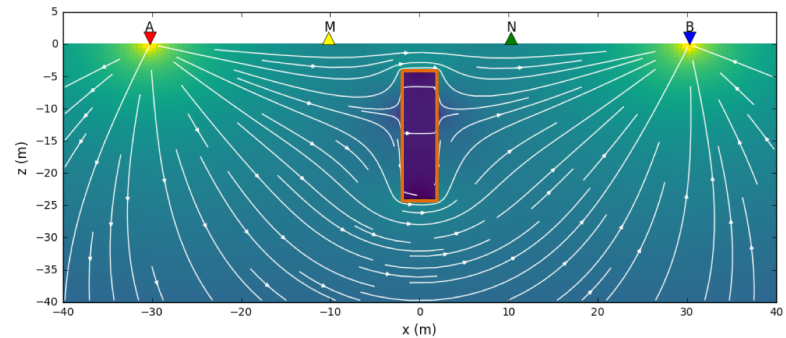
## Conductive Target

Total currents:  $J$

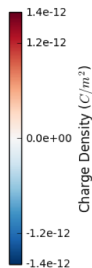
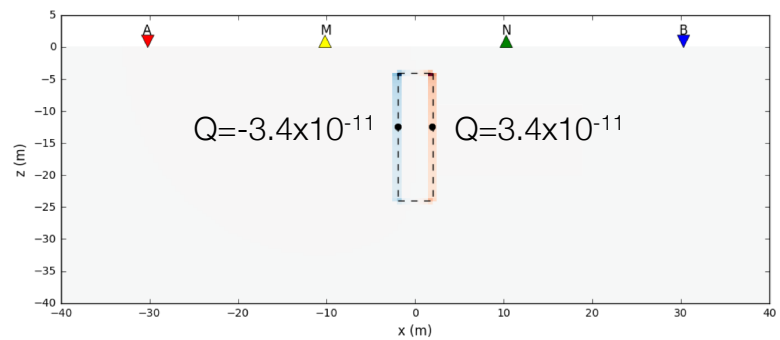


## Resistive Target

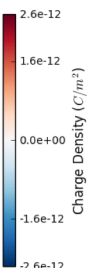
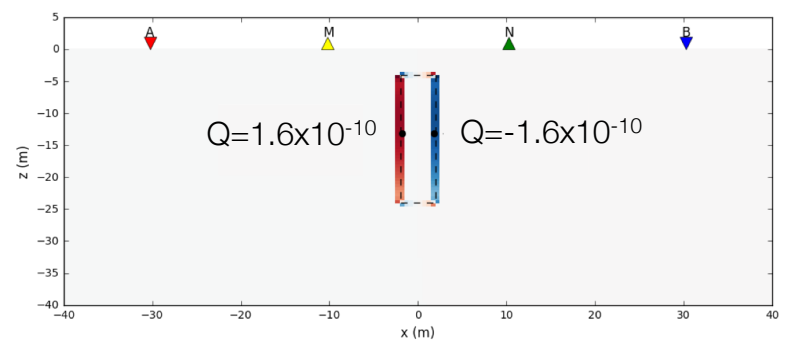
Total currents:  $J$



Secondary charges:  $Q_s$

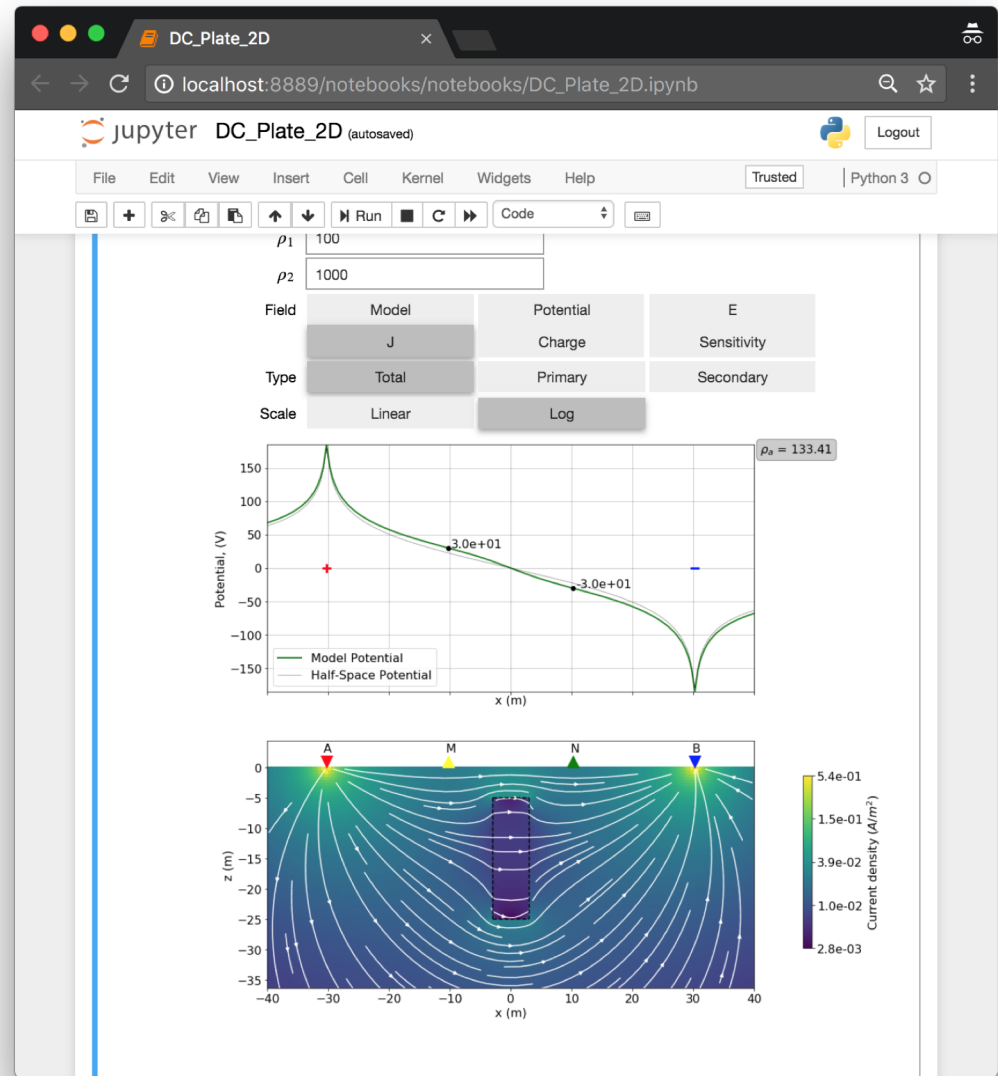


Secondary charges:  $Q_s$



# DC 2D Plate app

- DC\_Plate\_2D
- Parameters:
  - Resistivity of background, plate
  - Geometry and location of plate
  - Location of electrodes
- View:
  - Model
  - Electric potential
  - Electric field
  - Charges
  - Current density

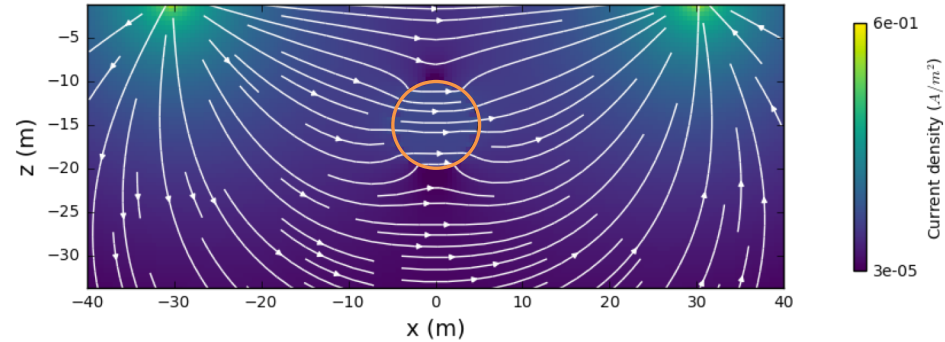




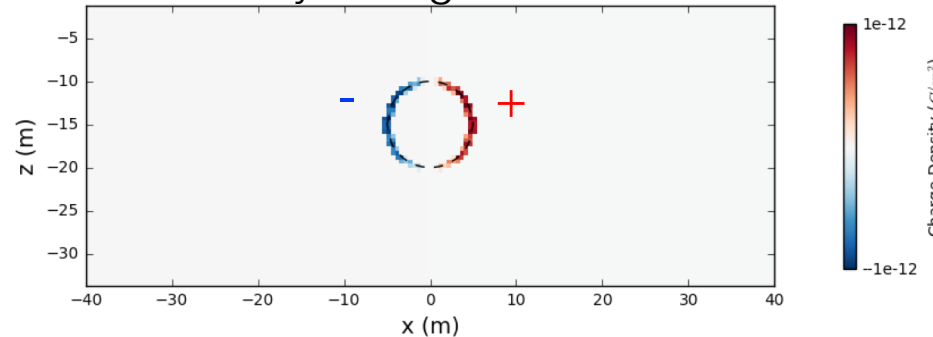
# Summary: Sensitivity

- “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

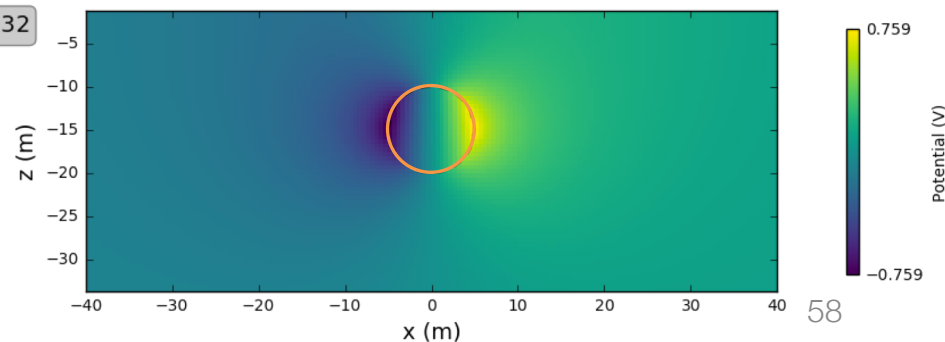
Total currents:  $J$



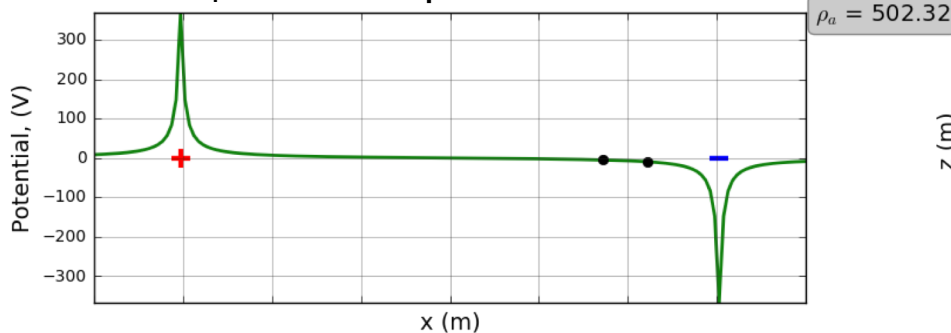
Secondary Charges:  $Q$



Secondary potential:  $\phi_s$

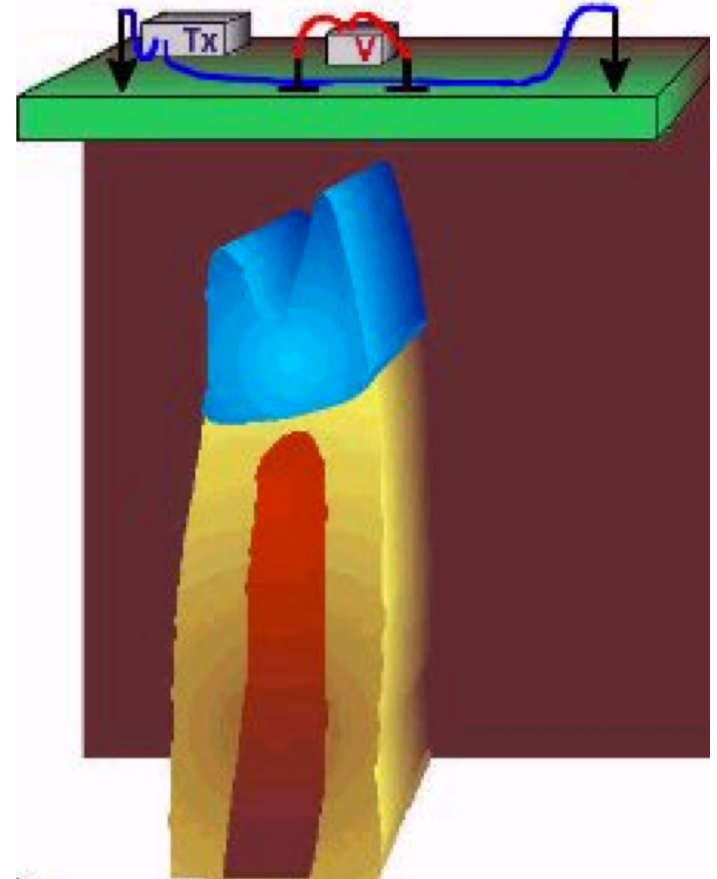


Total potential:  $\phi$

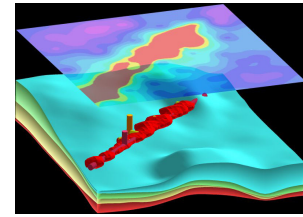


# Survey Design: Questions

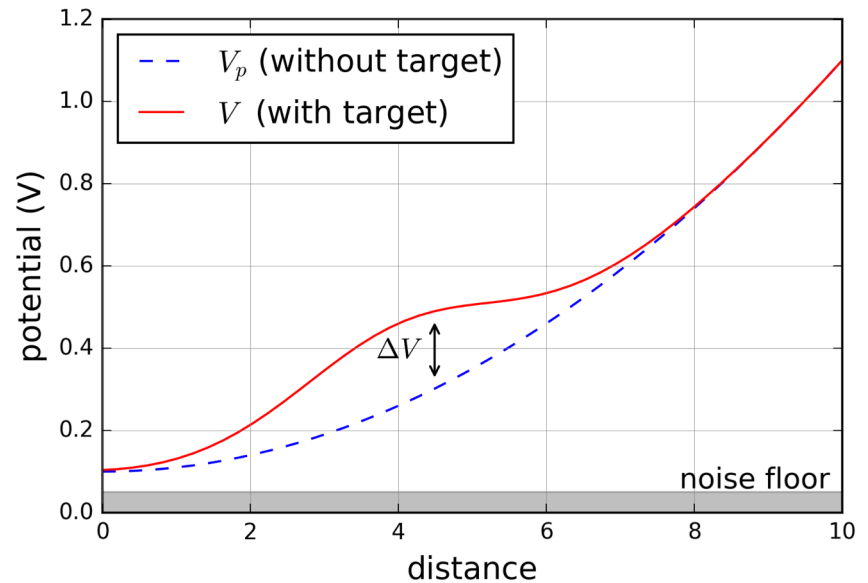
- What is objective?
  - Layered earth (1D)
    - do a sounding
  - Target body (2D)
    - profile, sounding perpendicular to geology
  - Target body (3D)
    - need 3D coverage
- What is the background resistivity?
- What are the noise sources?  
fences, power lines, ...



# 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

$$\Delta V > \textit{floor}$$

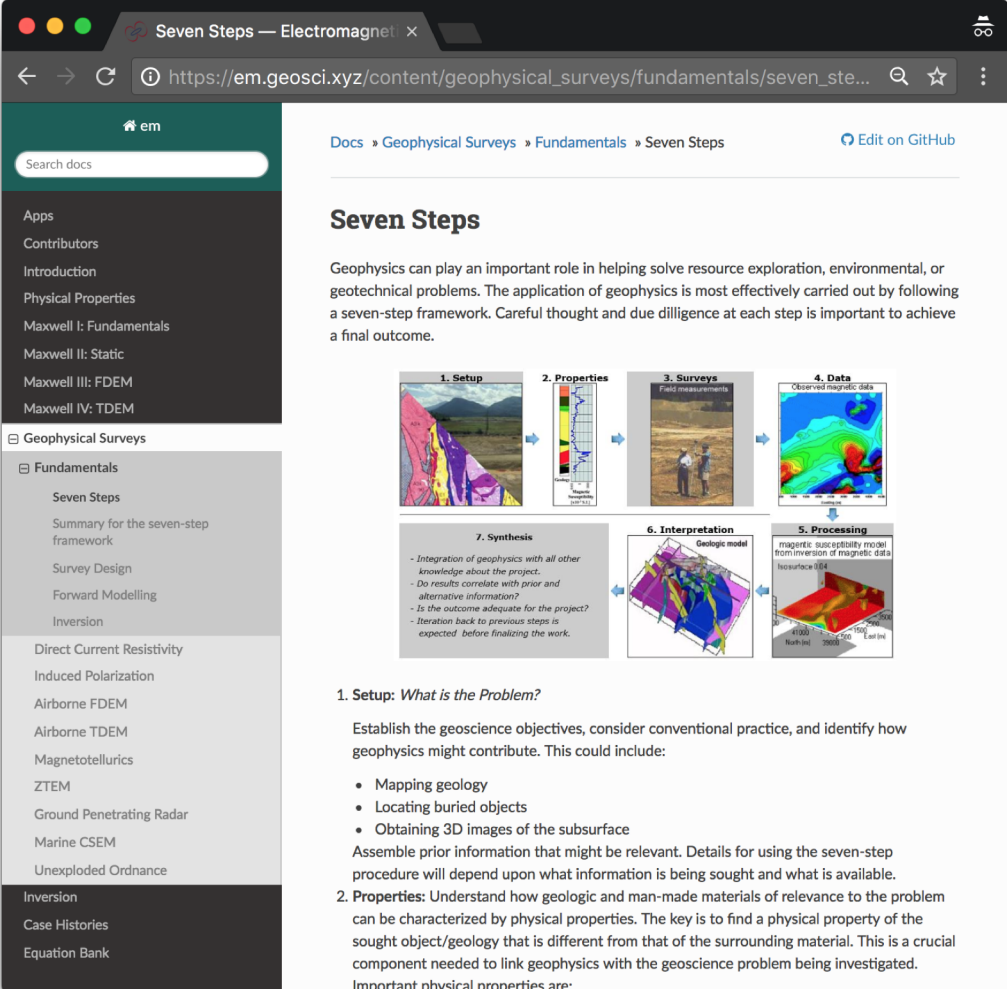
$$\frac{\Delta V}{V_p} > \%|V|$$

# 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 – Reservoir monitoring for oil sands
  
- Steel casing + DC
- Working with the apps
- Effects of background resistivity

# Geophysical Surveys using EM.GeoSci

- Geophysical Surveys
  - Fundamentals
  - Seven Step Framework for case histories
  - Survey Design Considerations
  - Forward Modelling

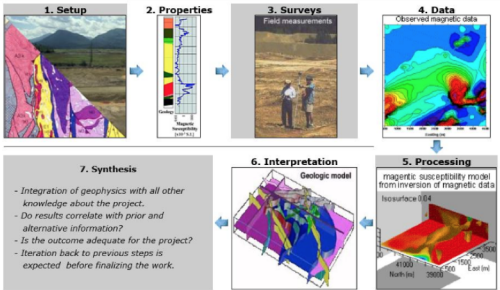


The screenshot shows a web browser displaying the 'Seven Steps' page on the EM.GeoSci website. The page title is 'Seven Steps — Electromagnet...' and the URL is 'https://em.geosci.xyz/content/geophysical\_surveys/fundamentals/seven\_ste...'. The page content includes a navigation menu on the left, a search bar, and a main section titled 'Seven Steps'. The 'Seven Steps' section is divided into seven numbered steps, each with a corresponding image and description. The steps are: 1. Setup (What is the Problem?), 2. Properties (Understand how geologic and man-made materials of relevance to the problem can be characterized by physical properties), 3. Surveys (Field measurements), 4. Data (Observed magnetic data), 5. Processing (magnetic susceptibility model from inversion of magnetic data), 6. Interpretation (Geologic model), and 7. Synthesis (Integration of geophysics with all other knowledge about the project). The page also includes a 'Docs' navigation menu and an 'Edit on GitHub' link.

Docs » Geophysical Surveys » Fundamentals » Seven Steps [Edit on GitHub](#)

## Seven Steps

Geophysics can play an important role in helping solve resource exploration, environmental, or geotechnical problems. The application of geophysics is most effectively carried out by following a seven-step framework. Careful thought and due diligence at each step is important to achieve a final outcome.



**1. Setup** **2. Properties** **3. Surveys** **4. Data**  
**5. Processing** **6. Interpretation** **7. Synthesis**

**1. Setup: What is the Problem?**  
Establish the geoscience objectives, consider conventional practice, and identify how geophysics might contribute. This could include:

- Mapping geology
- Locating buried objects
- Obtaining 3D images of the subsurface

Assemble prior information that might be relevant. Details for using the seven-step procedure will depend upon what information is being sought and what is available.

**2. Properties:** Understand how geologic and man-made materials of relevance to the problem can be characterized by physical properties. The key is to find a physical property of the sought object/geology that is different from that of the surrounding material. This is a crucial component needed to link geophysics with the geoscience problem being investigated. Important physical properties are:

# DC Surveys using EM.GeoSci

- Geophysical Surveys:  
Direct Current Resistivity
- Contents:
  - Physics
  - Survey
  - Data
  - Interpretation
  - Practical Considerations

**Direct Current Resistivity**

**Purpose**

To illustrate the fundamentals of a DC resistivity survey, provide a vision for how it is applied in the field, and demonstrate potential uses.

Variations in **conductivity** can be diagnostic, for example, when aiming to characterize a mineral deposit (e.g. *Mt. Isa*), where the conductivity of the mineralized zone is often higher than the host rock.

In a Direct Current Resistivity (DCR) experiment, a generator is used to inject current into the earth. The current path depends upon the variation of **conductivity** or equivalently, its reciprocal, the electrical resistivity. **Currents** are channeled into good conductors and flow around resistors. Electrical charges are **built up** on interfaces that separate units of different conductivity and these charges generate an electric potential.

**Data** are acquired at the surface or in boreholes by measuring the potential difference between two electrodes. The measured voltage depends upon the positions of the current and potential electrodes with respect to the target as well as the earth's conductivity. Obtaining information about the spatial distribution of conductivity requires many measurements at different locations and electrode configurations. A **Schlumberger** survey involving two current and two potential electrodes is shown in **Fig. 149**. Artistic representation of the current density and charge build-ups are illustrated for (a) conductive and (b) resistive spheres in a uniform half-space.

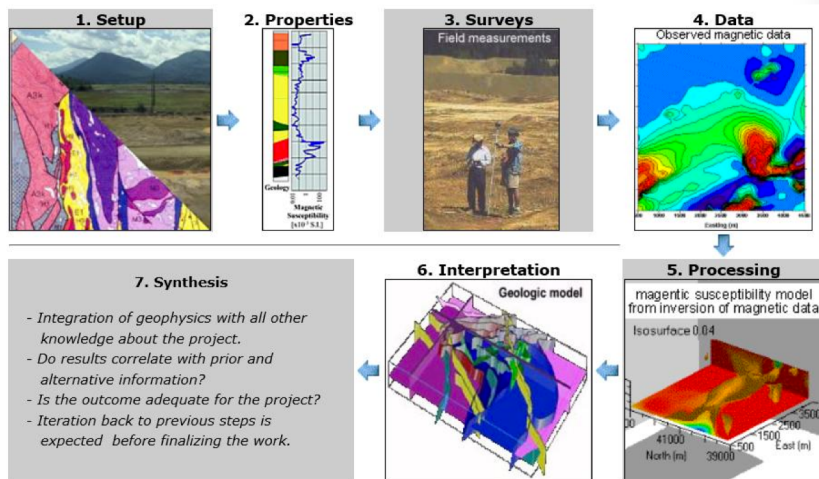
**Contents**

- [Physics](#)
- [Survey](#)
- [Data](#)
- [Interpretation](#)
- [Practical Considerations](#)

**Fig. 149 Direct Current Resistivity (DCR) experiment showing current path and charge built up near a (a) conductive and (b) resistive anomaly.**

# Case History using EM.GeoSci

- All case histories follow 7-step framework



Mt. Isa — Electromagnetic Geophysics

Secure [https://em.geosci.xyz/content/case\\_histories/mt\\_isa/index.html](https://em.geosci.xyz/content/case_histories/mt_isa/index.html)

**Mt. Isa**

- Authors: Dom Fournier, Dr. Kris Davis
- Editor: Douglas Oldenburg

**Prelude**

This case history follows the inversion of DC/IP data to delineate ore-bearing rock units at Mt. Isa, Queensland, Australia.

**Special Thanks**

Thanks to CSIRO publishing for permission to reproduce figures and adapt text from the source material. This Case History is based upon the paper: [2-D and 3-D IP/resistivity for the interpretation of Isa-style targets](#) by Rutley, Oldenburg and Shekhtman [ROS01].

**Abstract**

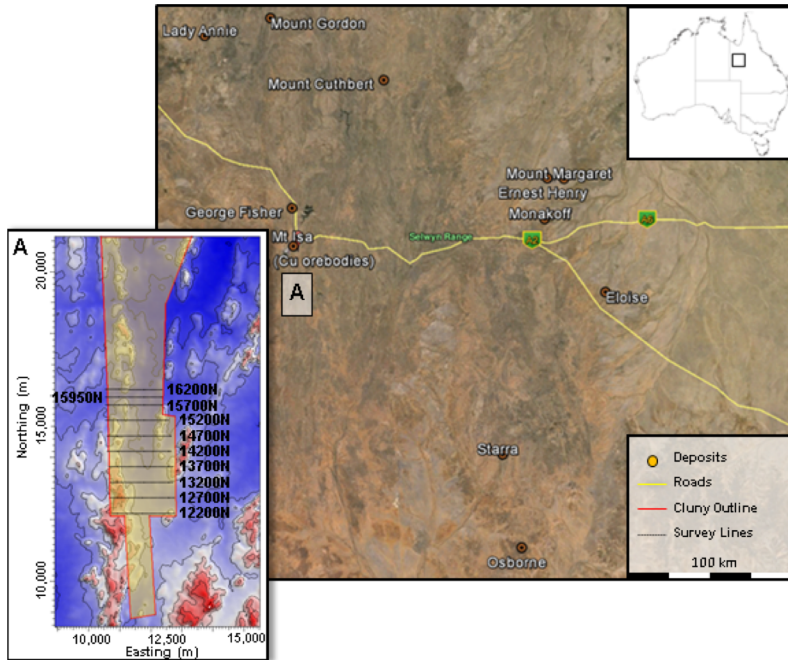
Here, we show one of the first examples of inverting DC/IP field data to recover 3D distributions of resistivity and chargeability. Prior to this, the inversion of field data was primarily carried out in 2D. We use this case history to provide an example for inverting DCR and IP data and to link different parts of the survey and processing to the fundamentals of EM as presented in EM.GeoSci. We have re-inverted the data but have kept as many details as possible to be the same as in the original paper. This enables us to show how current technology has increased the ability to recover details about the subsurface.

**Navigation Menu:**

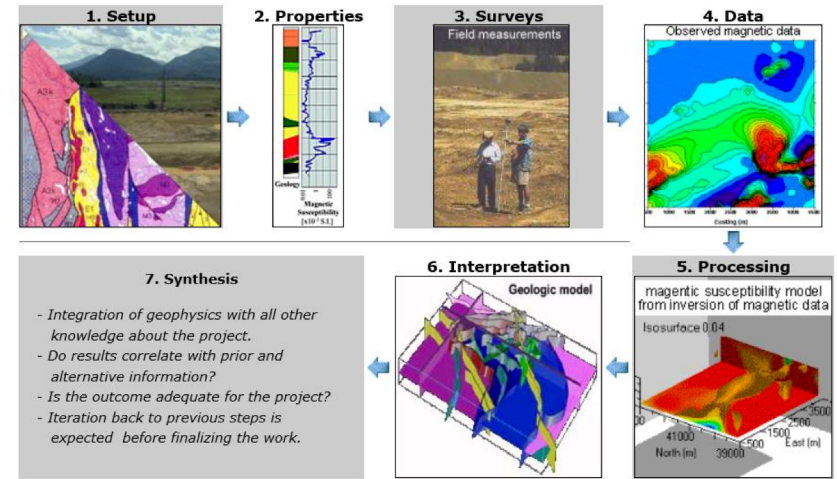
- Physical Properties
  - Maxwell I: Fundamentals
  - Maxwell II: Static
  - Maxwell III: FDEM
  - Maxwell IV: TDEM
  - Geophysical Surveys
  - Inversion
- Case Histories
  - Albany
  - Wadi Sabha
  - Bookpurnong
  - Aspen
  - Lalor
  - Elevenmile Canyon
  - DO-27/DO-18 (TKC)
  - West Plains
  - Furggwanghorn
  - SAGD
  - Mt. Isa
    - Setup
    - Properties
    - Survey
    - Data
    - Processing
    - Interpretation
    - Synthesis
    - Lessons worth highlighting
  - Norsminde
  - Red Sea
  - Barents Sea
  - Saurashtra

# Mt. Isa

## Mt. Isa (Cluny prospect)



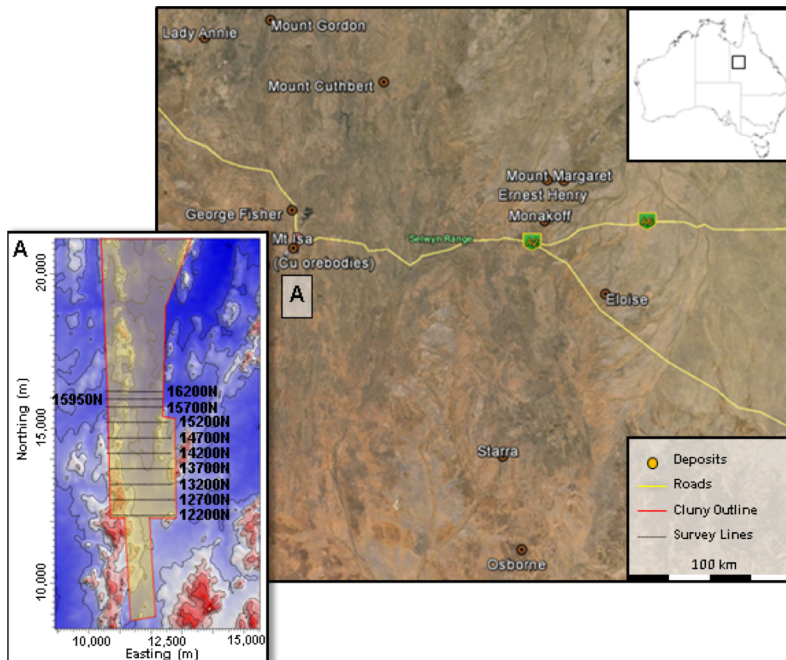
## Seven Steps



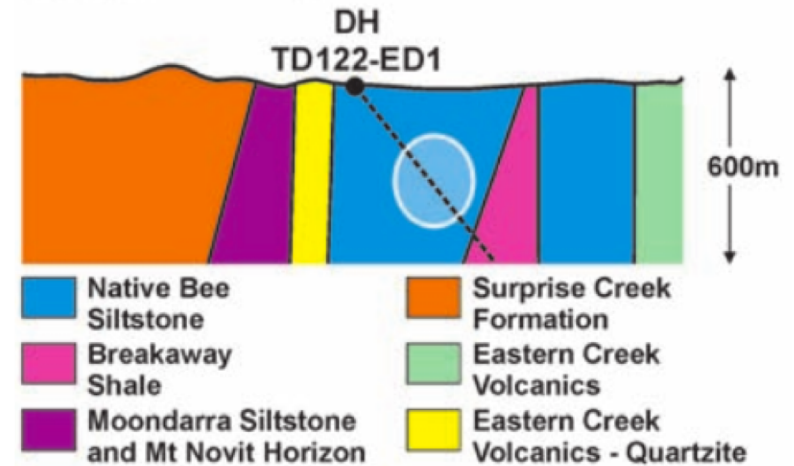


# Setup

## Mt. Isa (Cluny prospect)



## Geologic model

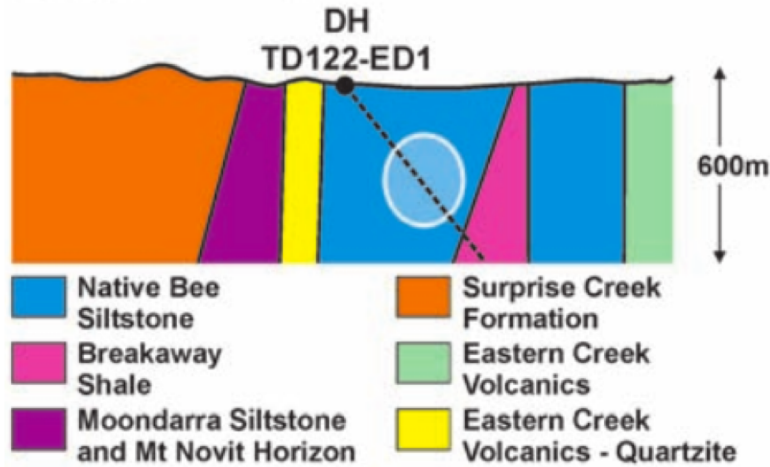


## Question

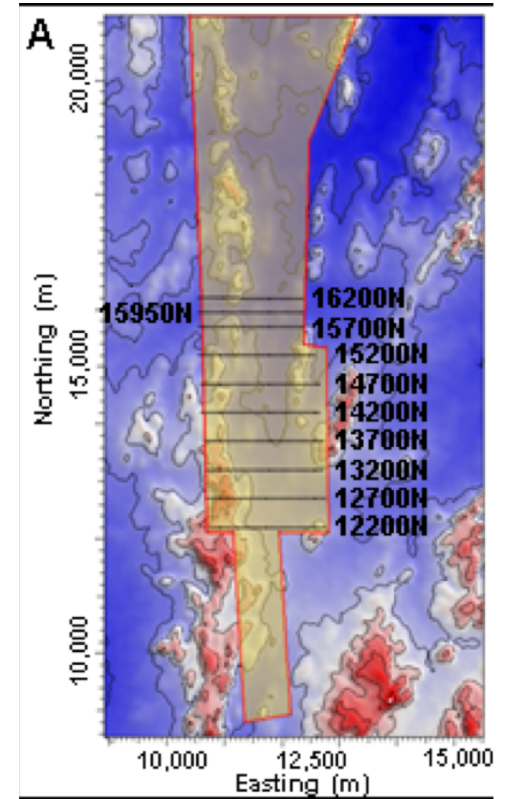
- Can conductive units, which would be potential targets within the siltstones, be identified with DC data?

# Properties

Geologic model



Surface topography

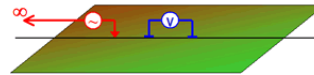
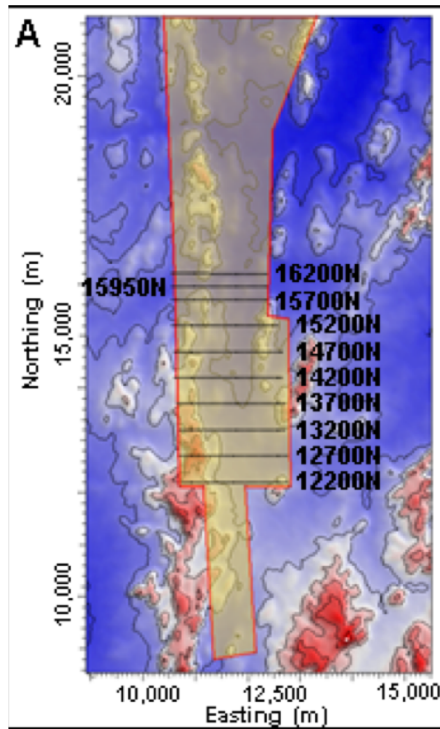


Rock Unit	Conductivity
Native Bee Siltstone	Moderate
Moondarra Siltstone	Moderate
Breakaway Shale	Very High
Mt Novit Horizon	High
Surprise Creek Formation	Low
Eastern Creek Volcanics	Low

# Survey and Data

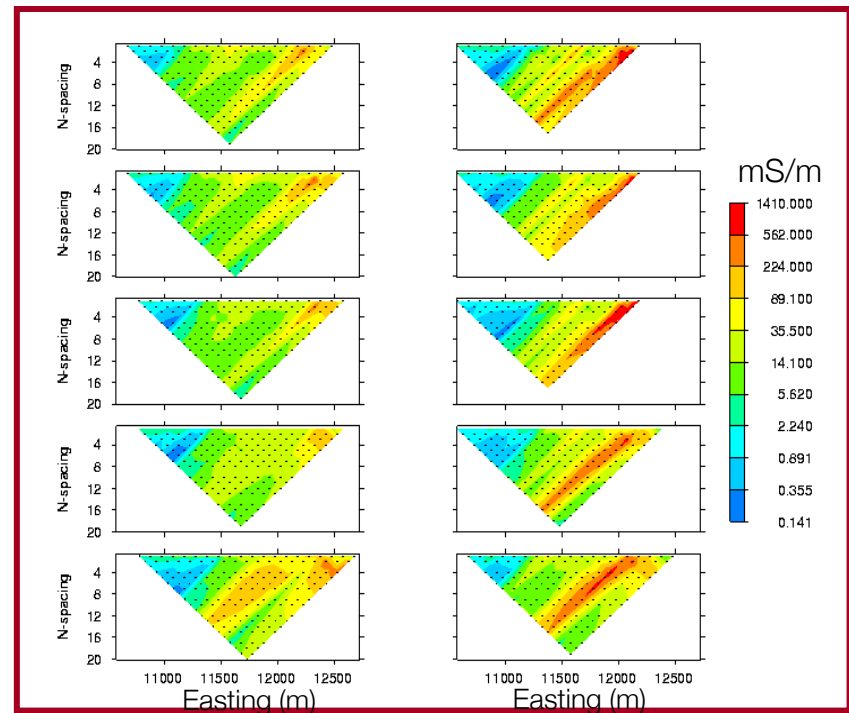
- Eight survey lines
- Two survey configurations.

Surface topography



Data set #1:

Apparent resistivity,  
pole - dipole.

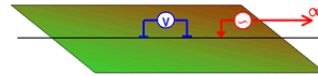


# Survey and Data

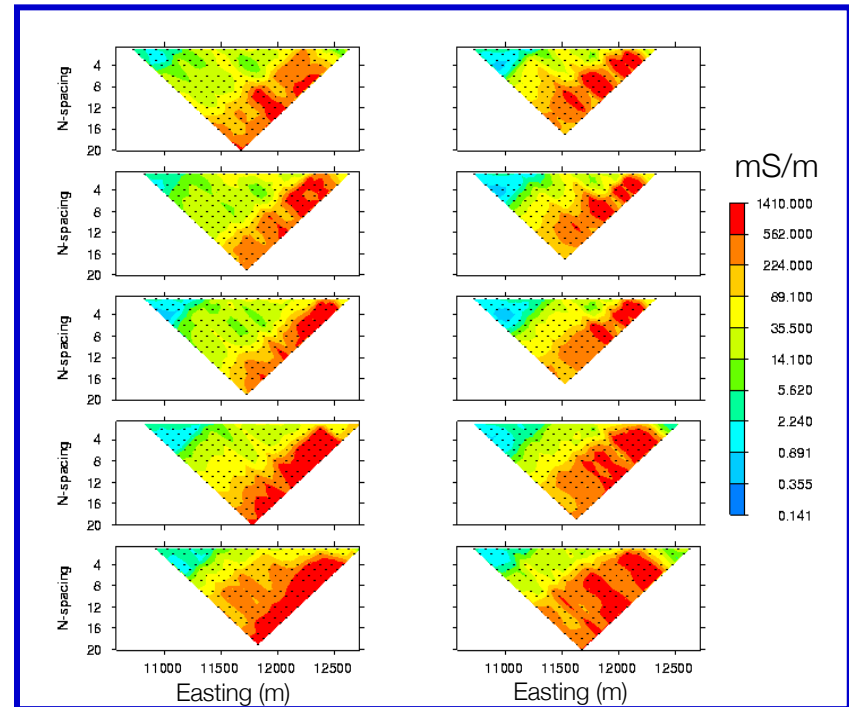
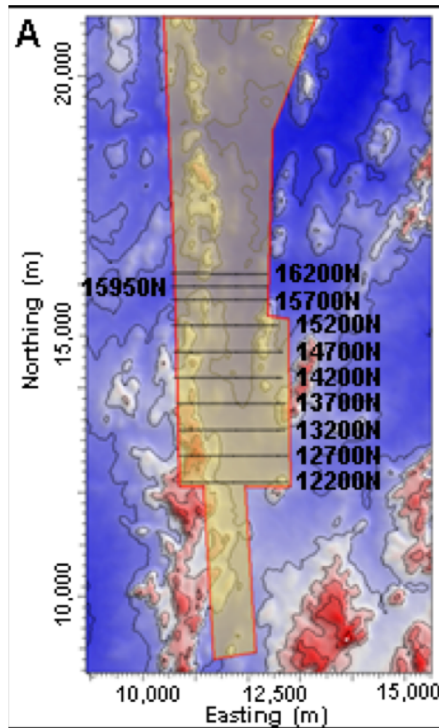
- Eight survey lines
- Two survey configurations.

Data set #2:

Apparent resistivity,  
dipole - pole

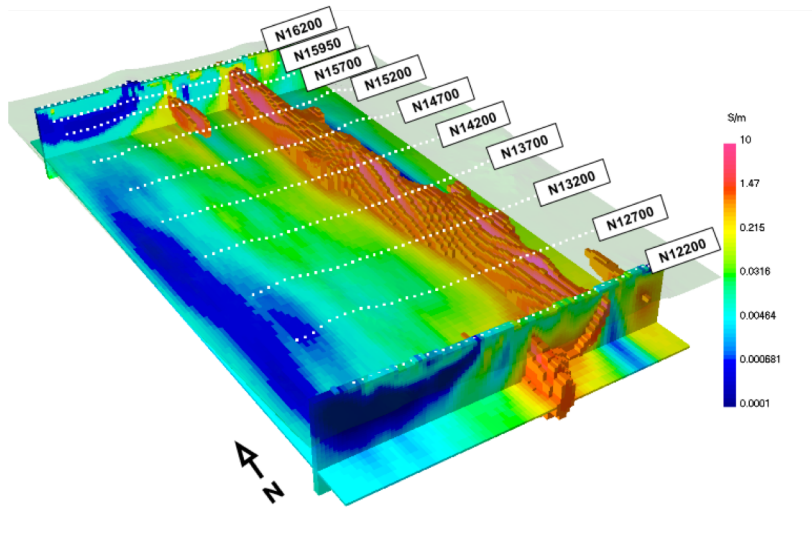


Surface topography

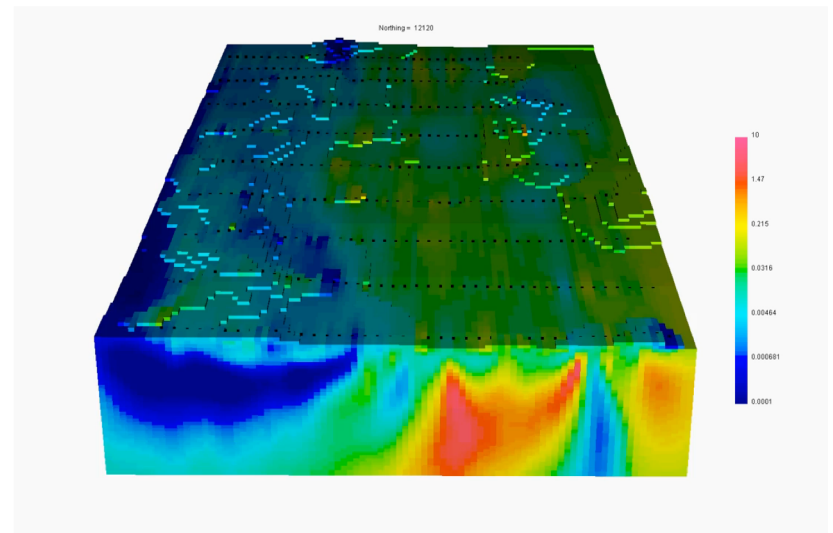


# Processing and interpretation

3D resistivity model



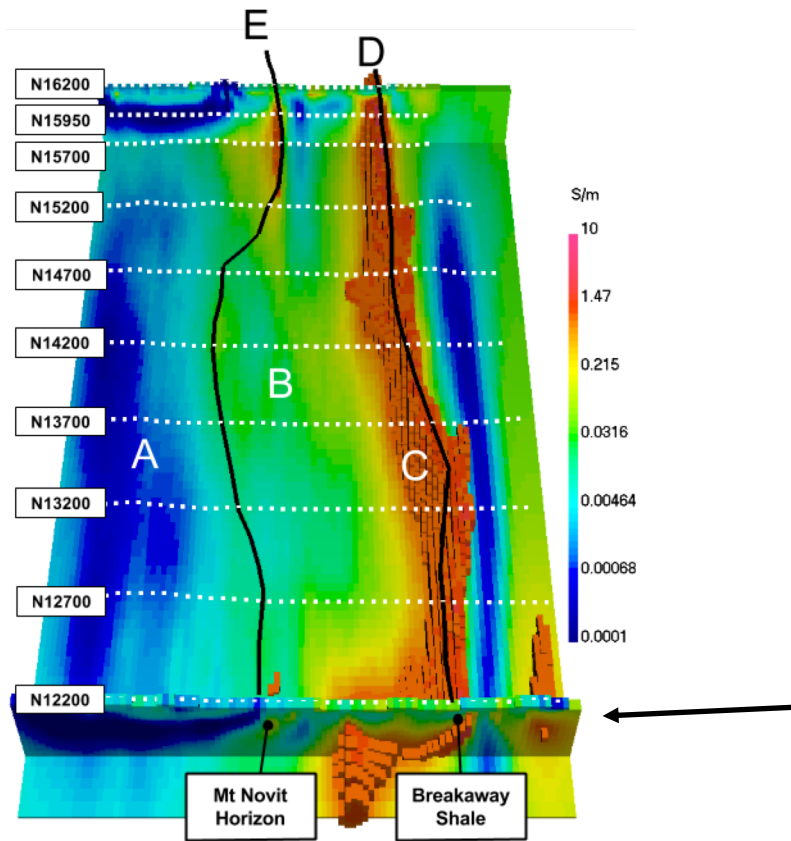
Animation



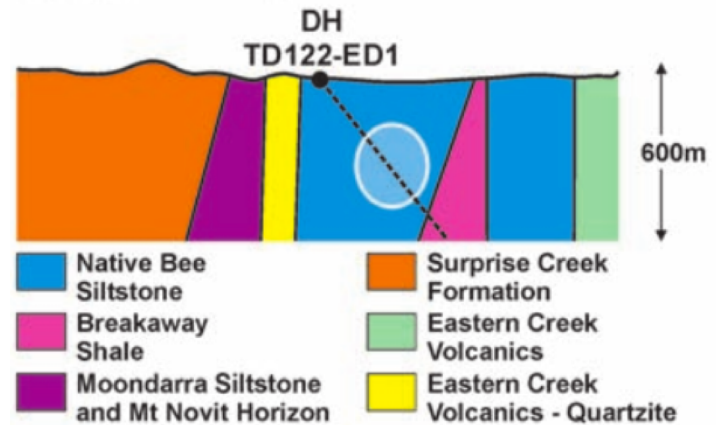
# Synthesis

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

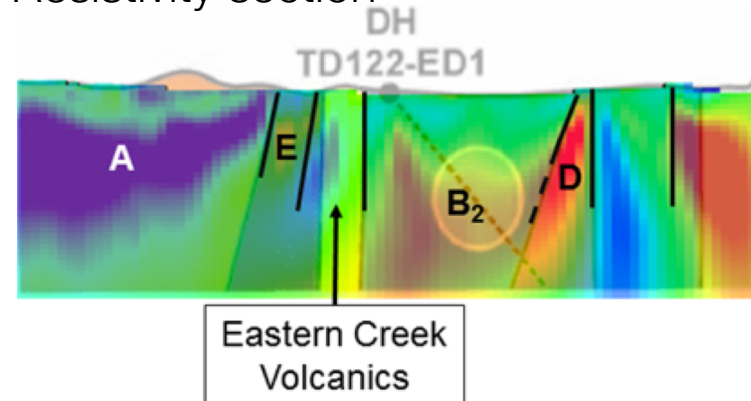
3D resistivity model



Geologic section



Resistivity section



# Mt. Isa in em.geosci.xyz

The screenshot shows a web browser window with the URL `https://em.geosci.xyz/content/case_histories/mt_isa/index.html`. The page title is "Mt. Isa — Electromagnetic Geosci". The left sidebar contains a navigation menu with categories: Physical Properties (Maxwell I: Fundamentals, Maxwell II: Static, Maxwell III: FDEM, Maxwell IV: TDEM, Geophysical Surveys, Inversion), Case Histories (Albany, Wadi Sabha, Bookpurnong, Aspen, Lalor, Elevenmile Canyon, DO-27/DO-18 (TKC), West Plains, Furggwanghorn, SAGD), Mt. Isa (Setup, Properties, Survey, Data, Processing, Interpretation, Synthesis, Lessons worth highlighting), Norsminde, Red Sea, Barents Sea, and Saurashtra.

## Mt. Isa

- **Authors:** [Dom Fournier](#), Dr. Kris Davis
- **Editor:** [Douglas Oldenburg](#)

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- [Setup](#)
- [Properties](#)
- [Survey](#)
- [Data](#)
- [Processing](#)
- [Interpretation](#)
- [Synthesis](#)
- [Lessons worth highlighting](#)

The figure consists of three panels illustrating the inversion process. The left panel shows a 2D resistivity cross-section with depth markers on the y-axis ranging from 0 to 16000. The middle panel shows a 2D resistivity map with a color scale from blue (low resistivity) to red (high resistivity). The right panel shows a 3D resistivity model with a color scale from blue to red, representing the subsurface structure.

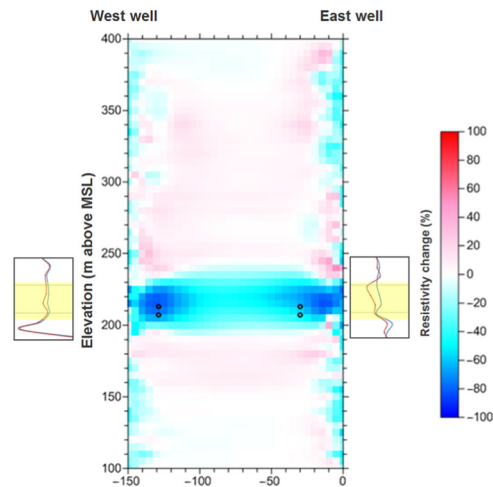
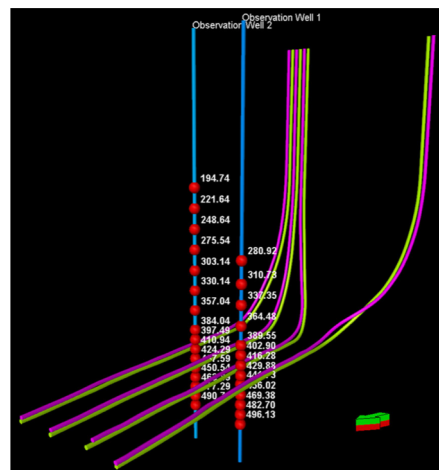
# Outline

- 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 – Reservoir monitoring for oil sands
- Steel casing + DC
- Working with the apps
- Effects of background resistivity



# Case History: Crosswell ERT monitoring

Tondel et al. 2014

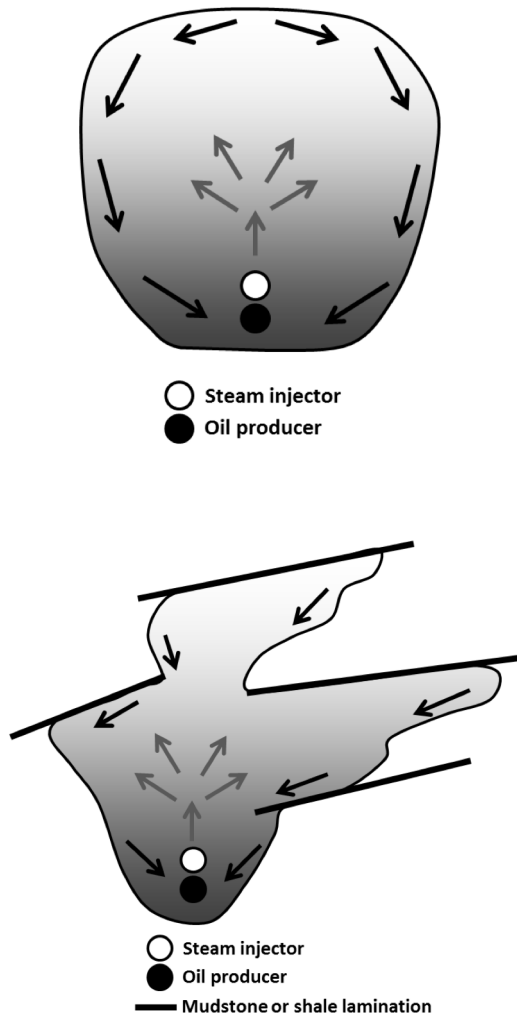


# Setup



- Athabasca Oil Sands
  - The largest oil sand region in North America
- Facility for steam-assisted gravity drainage (SAGD)
- Statoil purchased North American Oil sand Corporation (2007)
- Developing Leismer Demonstration Area
  - Research initiatives
  - E.g. “Which crosswell surveys should be used to map SAGD?”

# Steam assisted gravity accelerated drainage (SAGD)

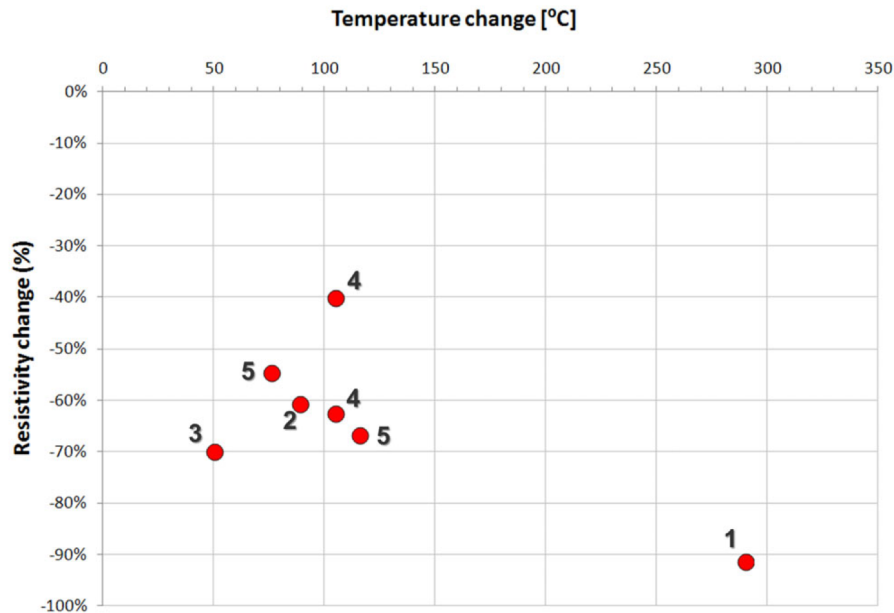


- In-situ recovery process used to extract bitumen from the Athabasca oil sands
- Uses two horizontal wells drilled at the bottom of the reservoir
- Top well (injection): produces a steam chamber
- Bottom well (production)
- Bottleneck: inhomogeneity in the reservoir

Want to know extent of the steam

# Properties

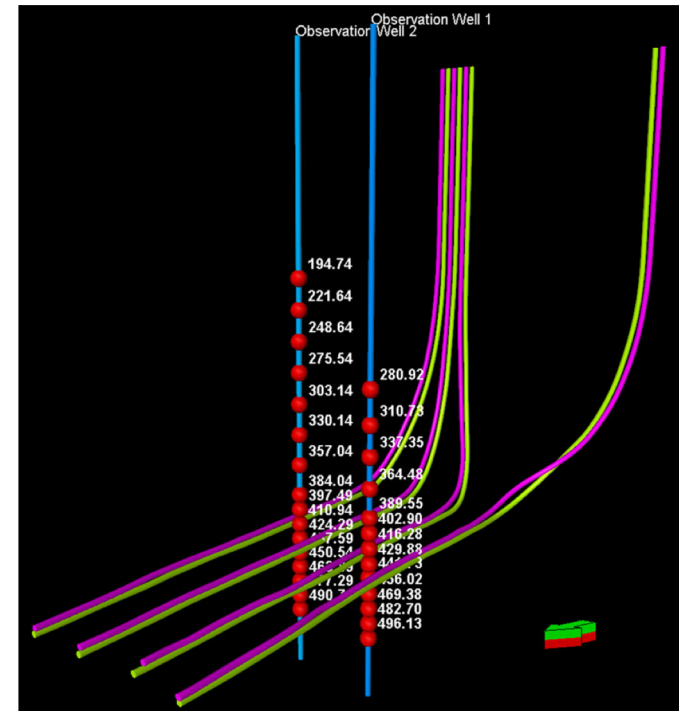
- Temperature can exceed 250°C
- Resistivity decrease indicates
  - Temperature increase
  - Replacement of produced oil by brine
- Resistivity increase indicates
  - Condensed steam → dilutes brine



- 1: Englemark (2007)
- 2: Mansure (2003)
- 3: Martinez (2012)
- 4: Ramirez (1993)
- 5: Ranganyaki (1992)

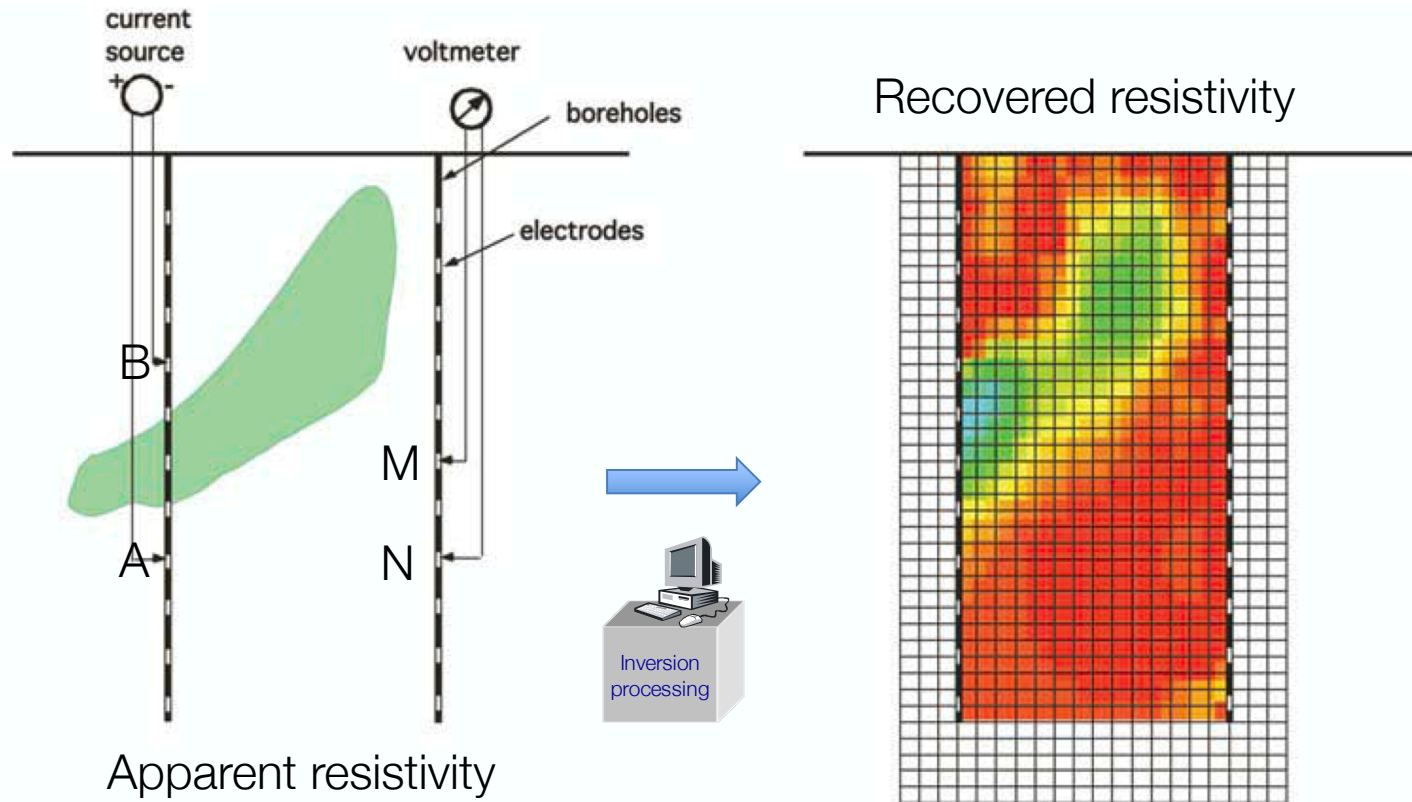
# Which crosswell surveys to monitor steam?

- Options to consider:
  - – 3D vertical seismic profile (VSP)
  - – Crosswell seismic tomography
  - Crosswell EM
  - – Crosswell DC (or ERT)
- Challenges:
  - High temperature (up to 250°C)
  - Steel casing (often imperfectly insulated)
  - Repeatability

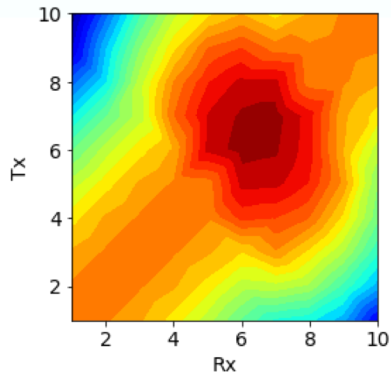


Our focus is crosswell DC

# Crosswell DC survey

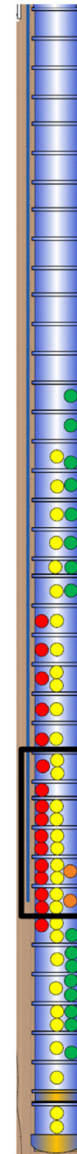
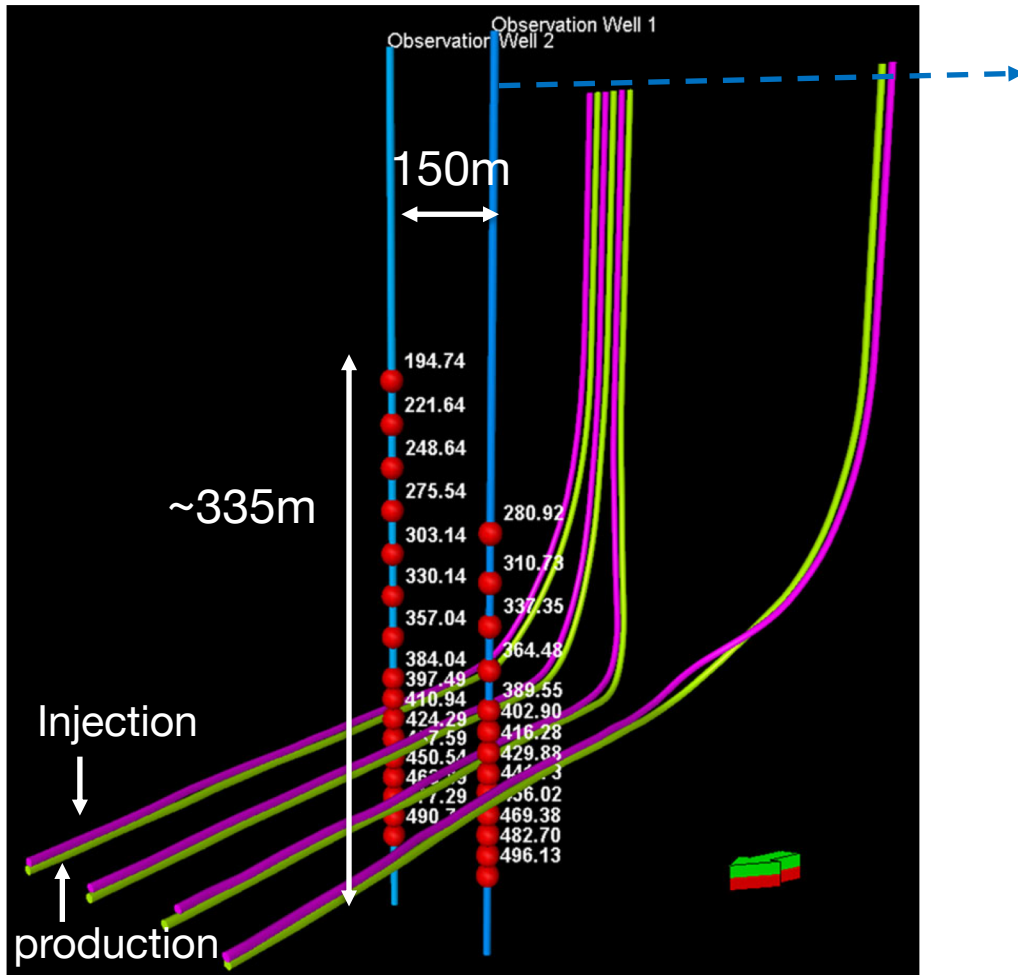


Apparent resistivity



# Crosswell DC survey for SAGD

Observation, injection, and production wells

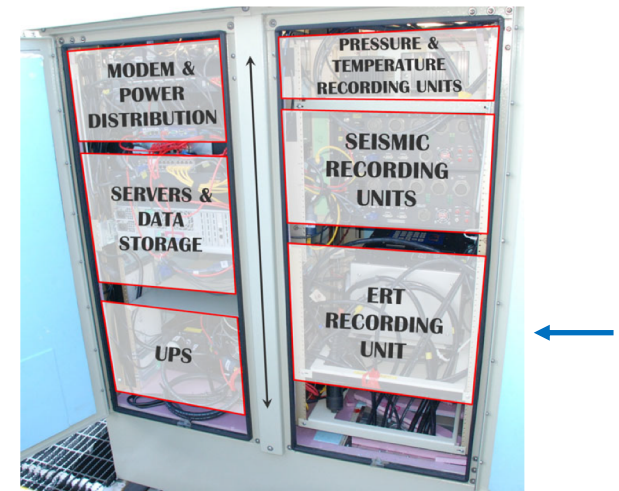
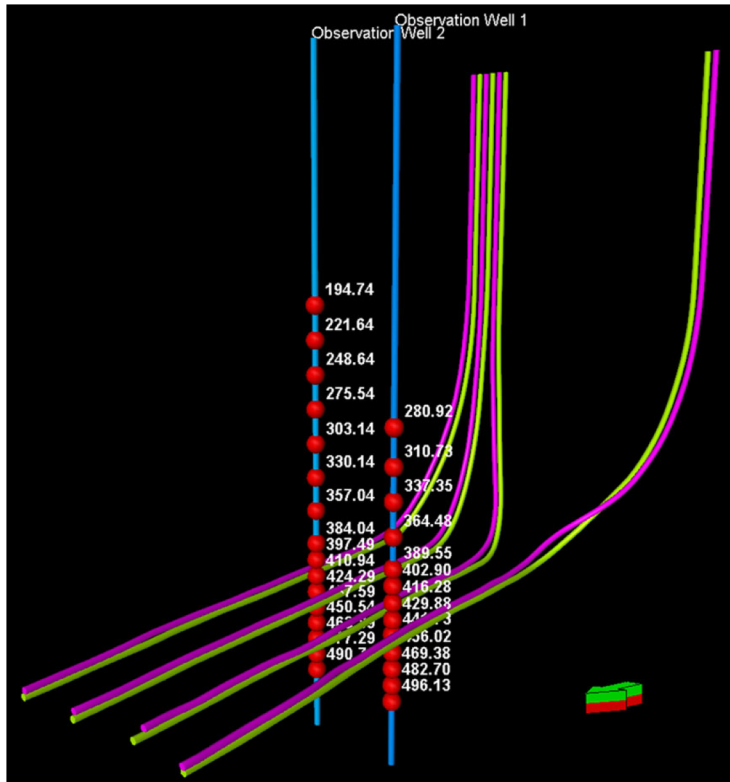


- For each observation well
- 32 electrodes  
- denser at reservoir
- Distributed temperature sensing (DTS) system
- Need to endure high temperature

→ Reservoir

- ERT ●
- Geophones ● ●
- Pressure ●
- DTS |

# Autonomous setup for monitoring

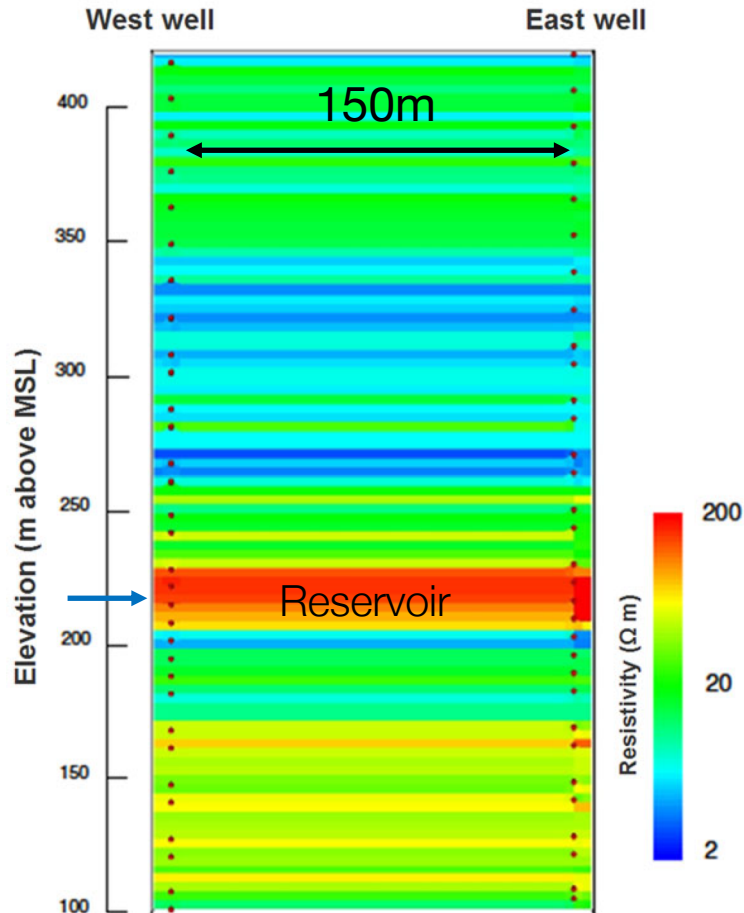


- Fully autonomous system
  - Nobody in the field
- Measure 2 full DC data per day
- High quality data
  - ~2% error

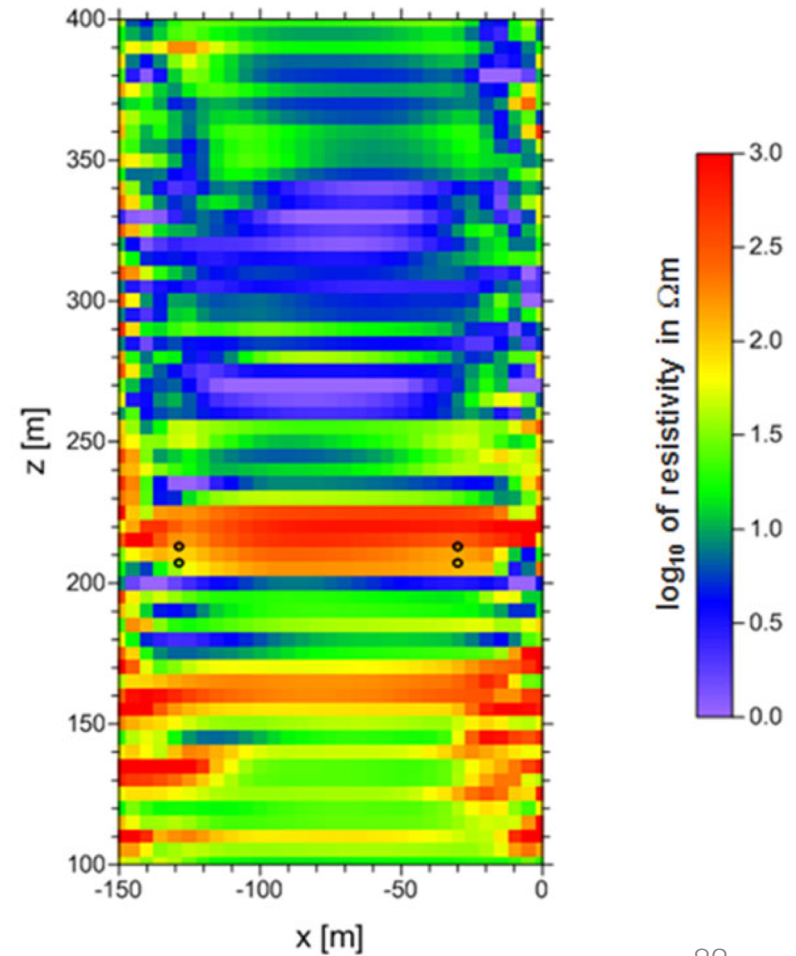


# Inversion: baseline (March 2011)

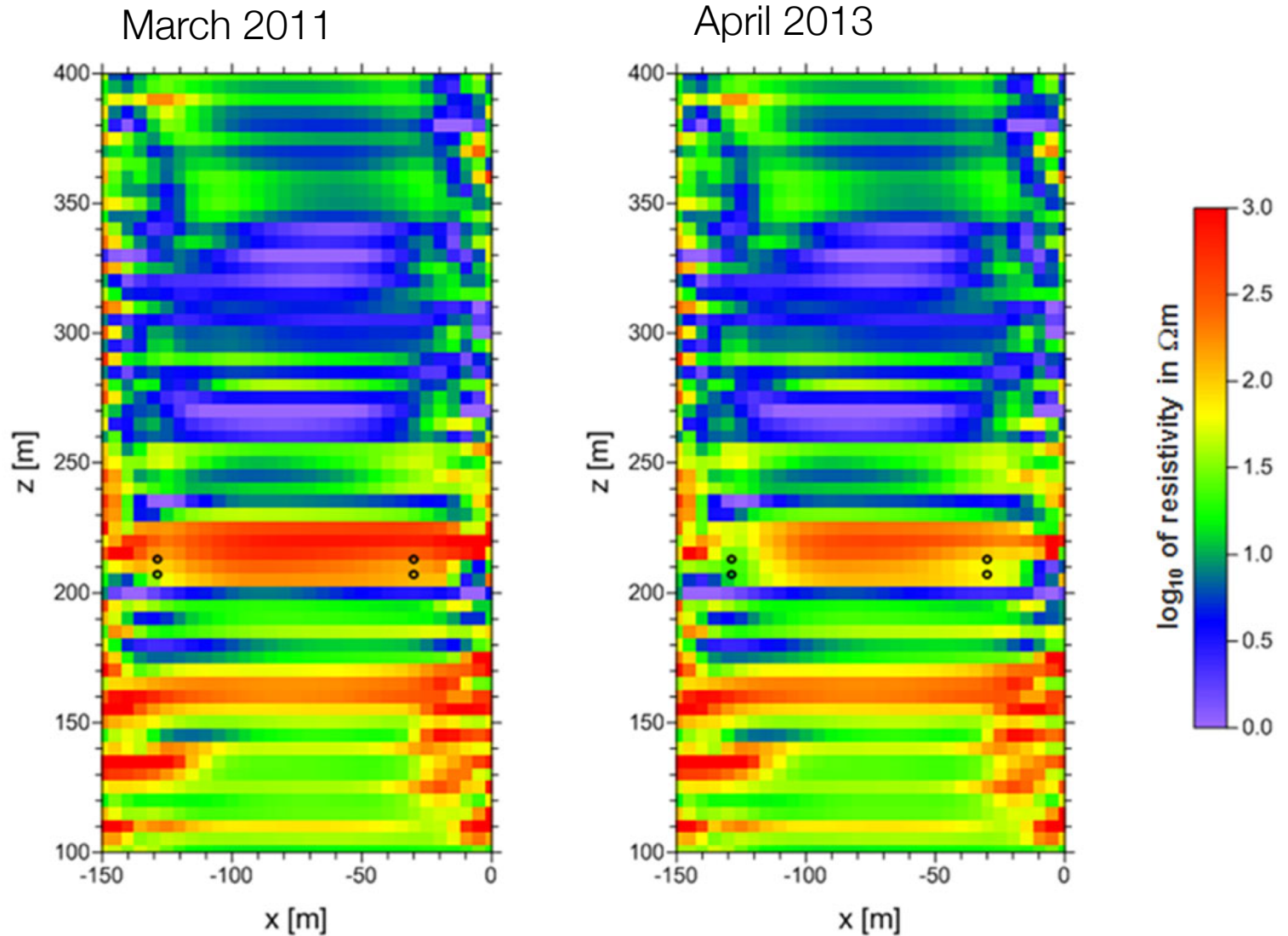
Initial model from well logs + geology



Recovered resistivity (March 2011)

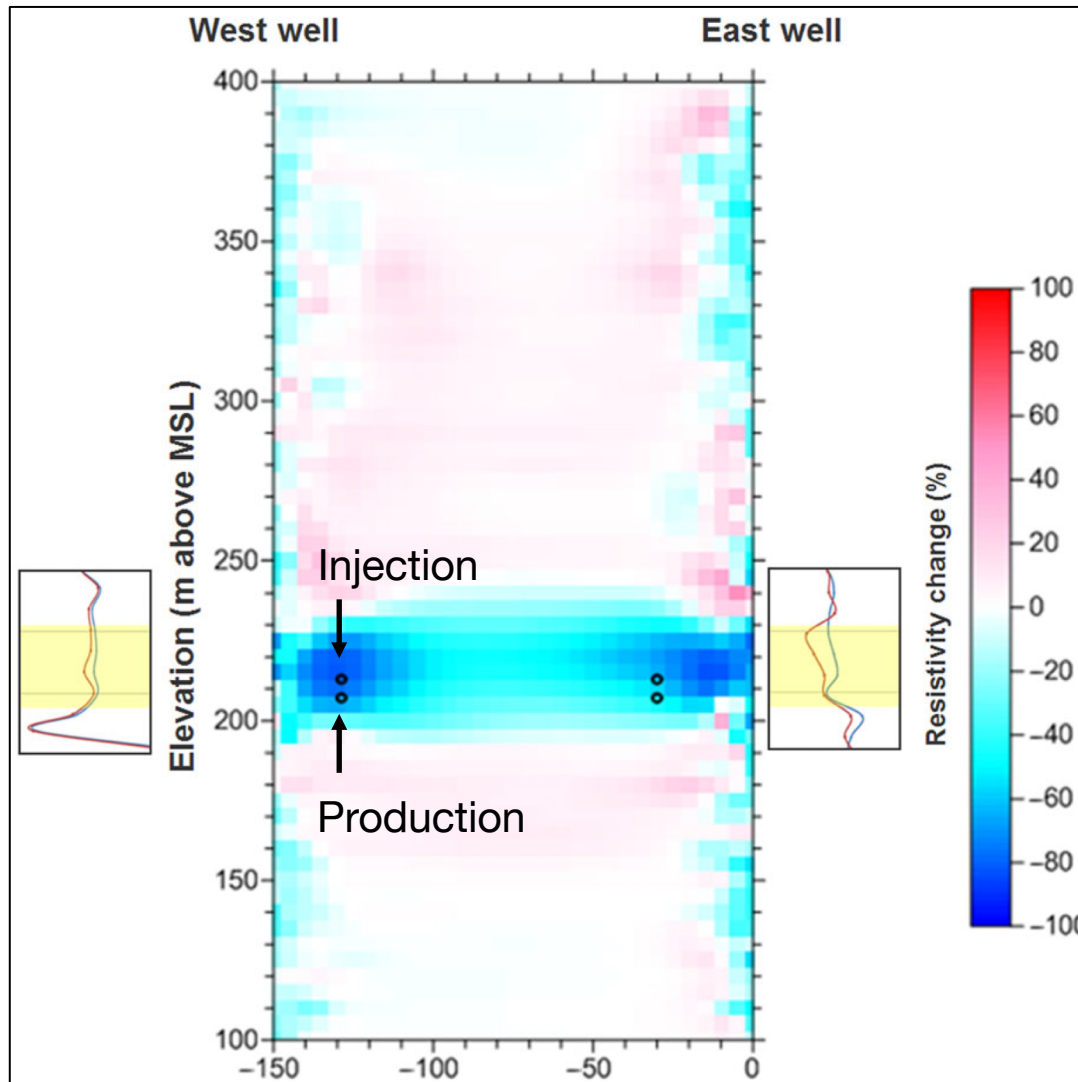


# Inversion: time-lapse

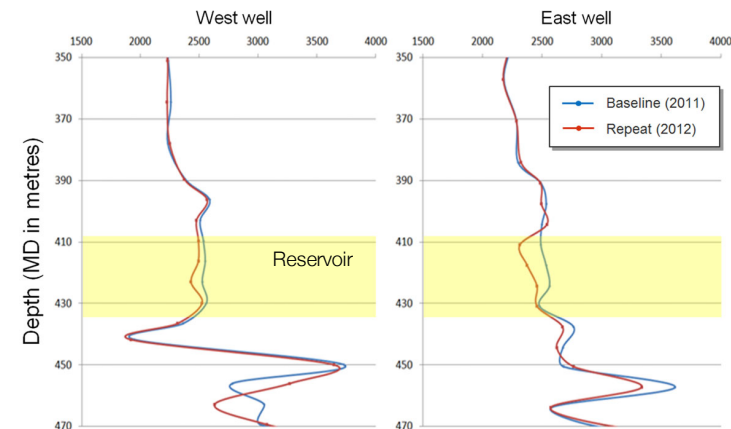


Around electrodes: artefacts due to current leakages to steel casing(?)

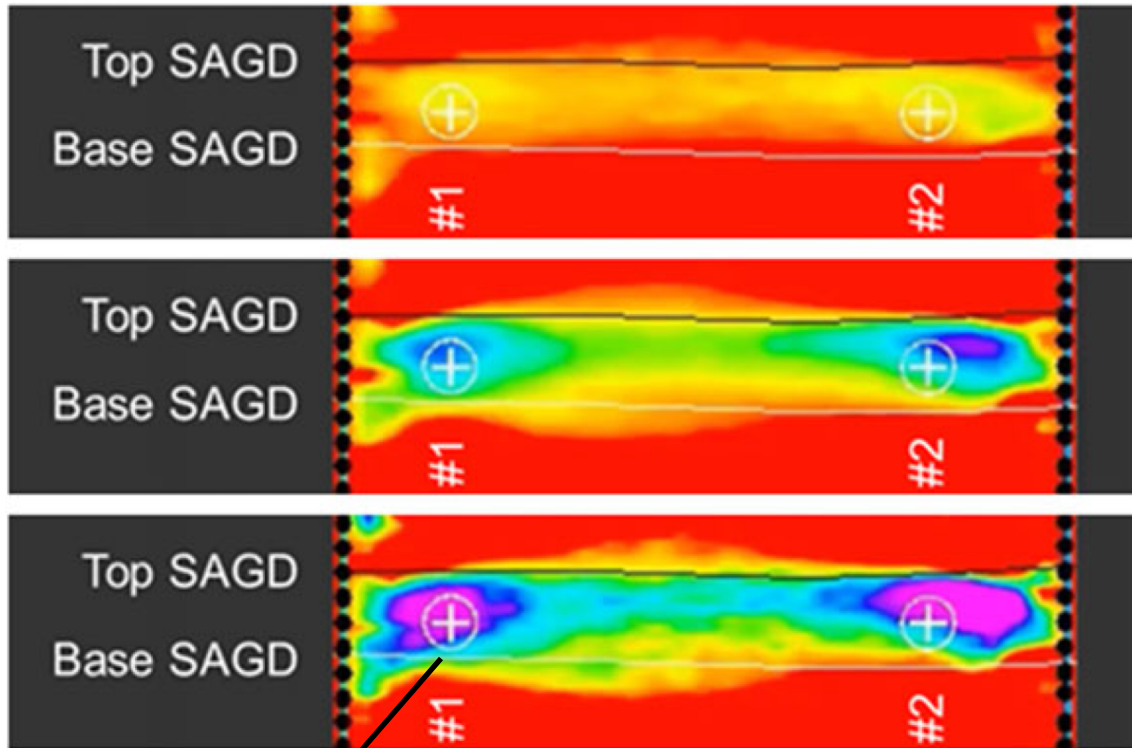
# Interpretation: resistivity difference



- Significant changes at the reservoir
- Maximum resistivity change: -85%
- Match with VSP



# Interpretation: resistivity difference

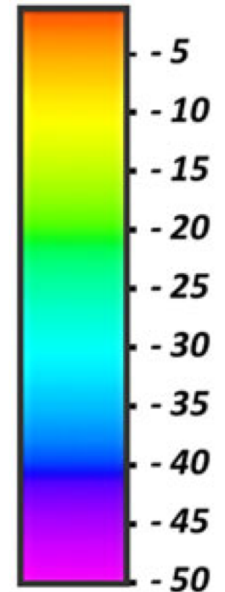


month 6  
Nov 2011

month 12  
May 2012

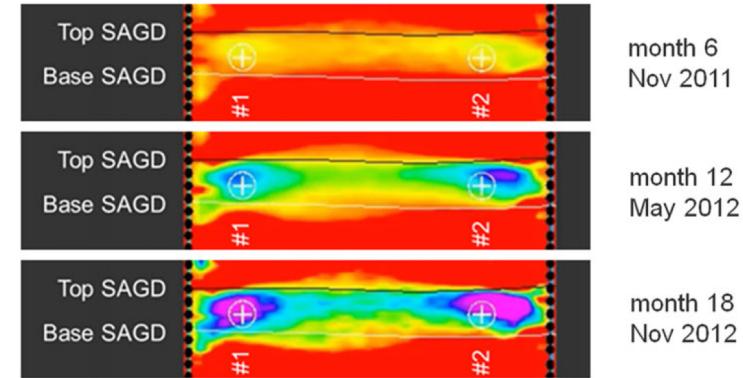
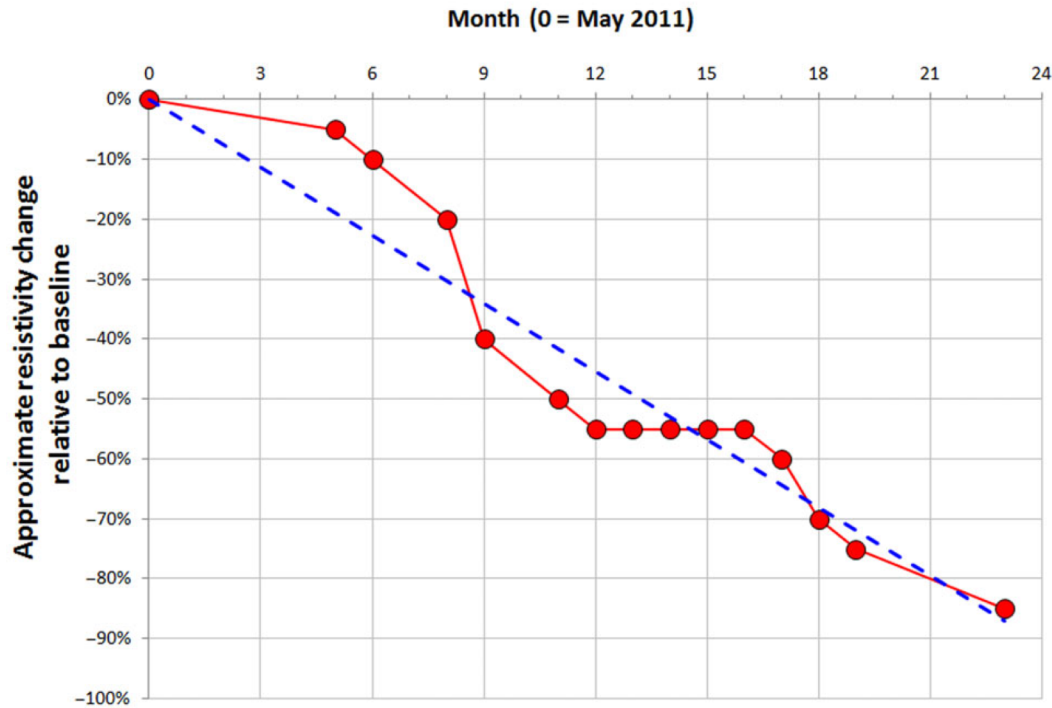
month 18  
Nov 2012

*Difference (%)*



Steam  
injector

# Synthesis

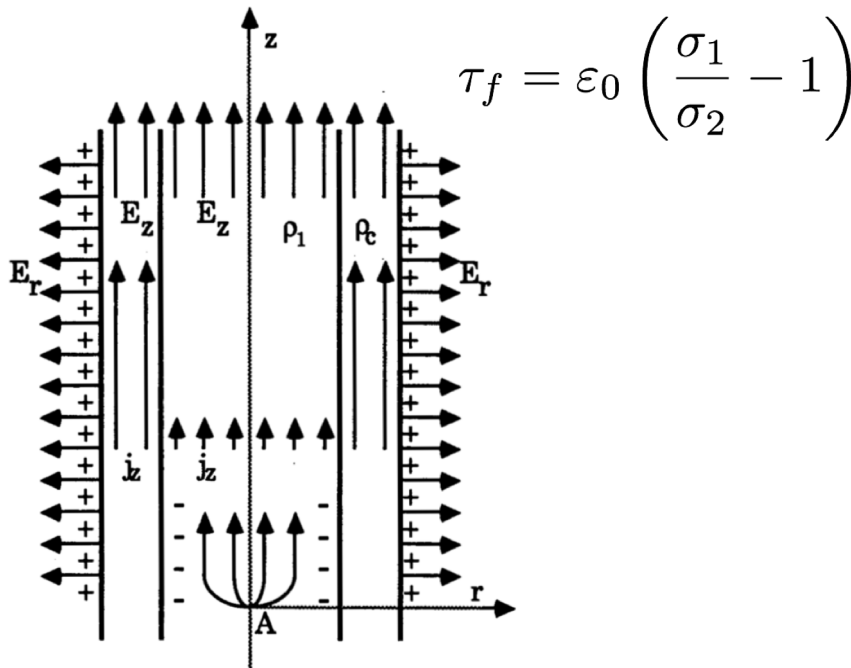


- Can see changes in the reservoir
  - Nearly linear changes (-4% per month)
  - Maximum resistivity difference is -85%
- Crosswell DC can be an effective option for monitoring SAGD
  - Great repeatability + endurance for temperature + low cost

# DC Resistivity with steel cased wells

# Initial work: Logging through steel-cased wells

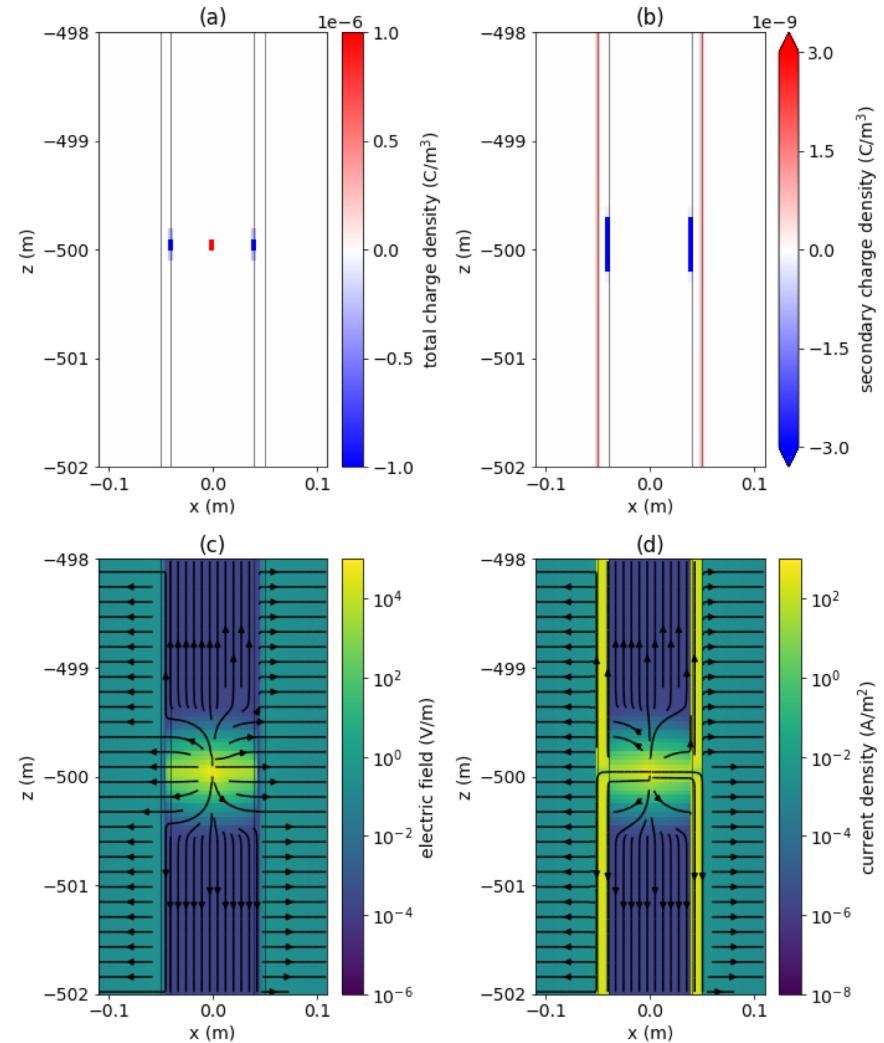
- Kaufman, 1990
  - Currents vertical within casing
  - Positive charges on outside surface of casing
  - Electric field radial outside casing



(Kaufman, 1990)

$$\tau_f = \varepsilon_0 \left( \frac{\sigma_1}{\sigma_2} - 1 \right)$$

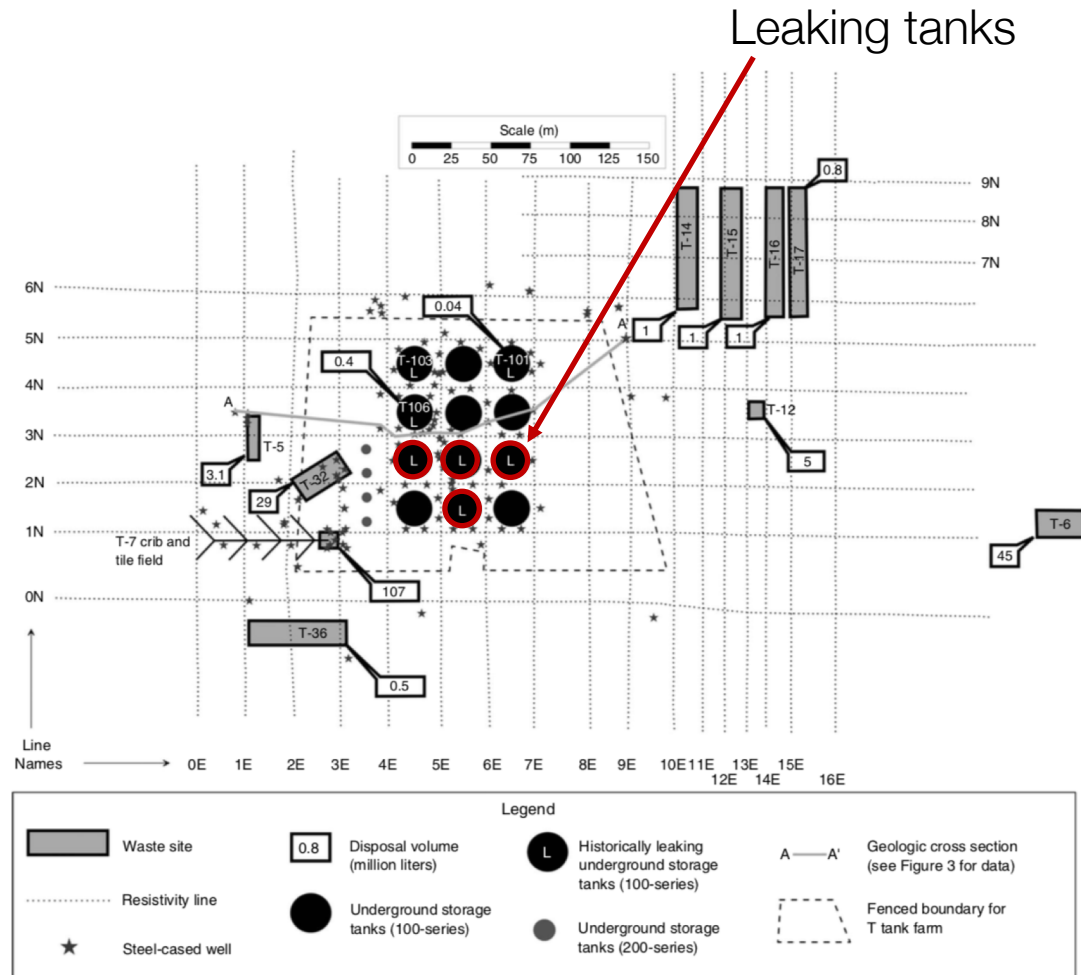
- Now we can solve numerically



(Heagy & Oldenburg, 2018)

# Using steel casing as an “Extended Electrode”

- Fracturing, enhanced oil recovery, carbon capture and storage, Small targets, etc.
  - Deep
  - Steel cased wells
- Previous studies:
  - E.g. (Rucker, 2010): Detecting leaks from underground storage tanks
  - Use wells to get beneath conductive near surface & surface infrastructure

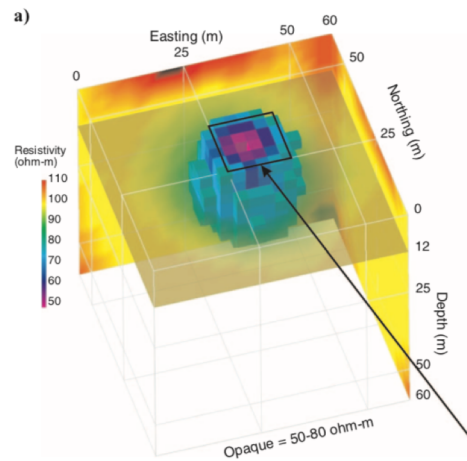




# Using steel casing as an “Extended Electrode”

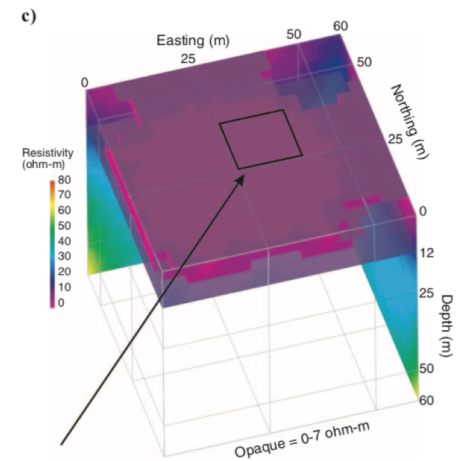
- Synthetic inversion example:  
conductive block

Conductive block in halfspace

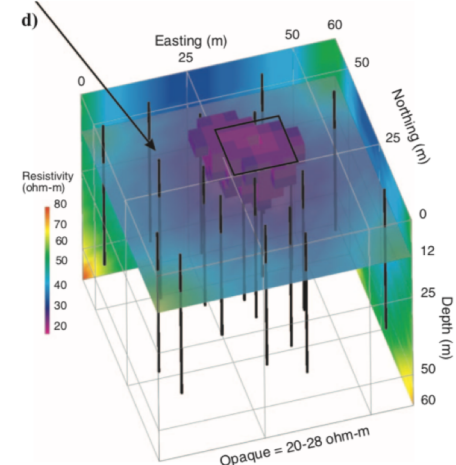
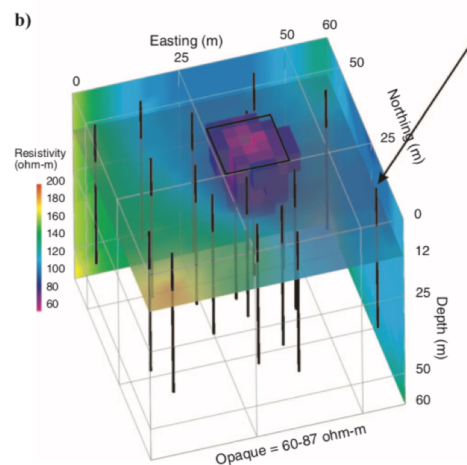


Surface electrodes

Conductive block +  
conductive overburden

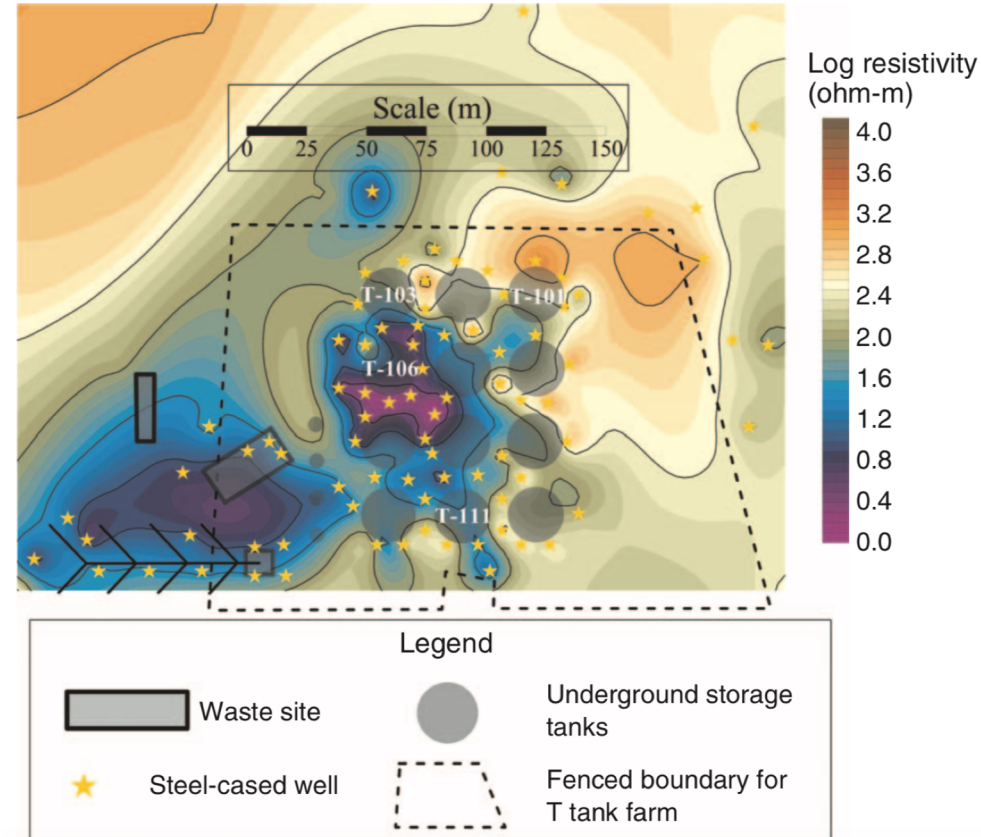
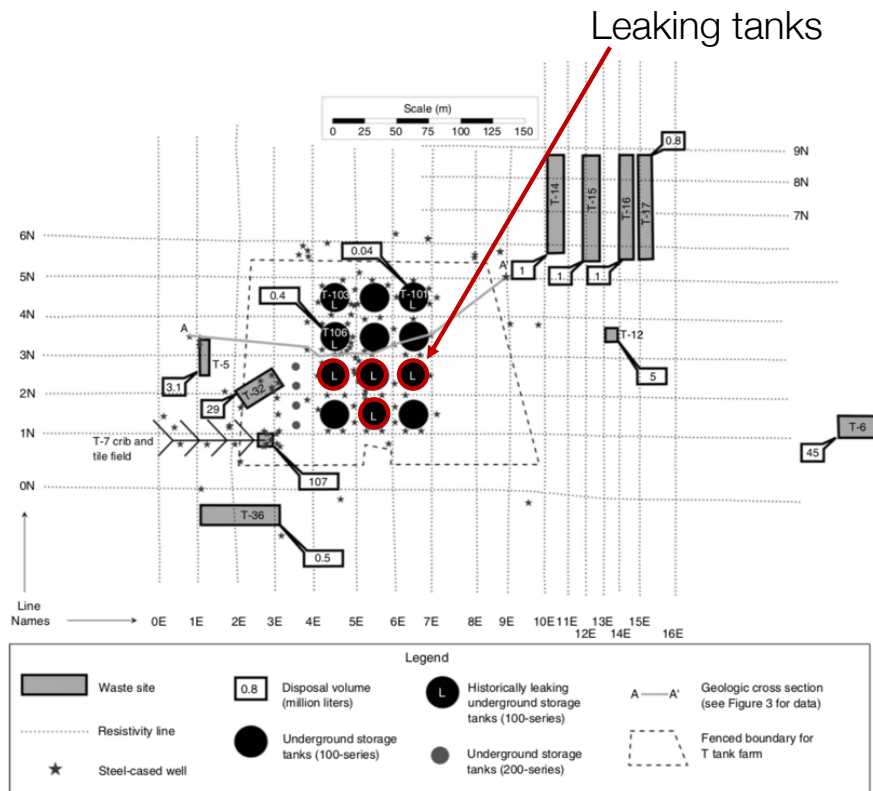


Steel-casing electrodes



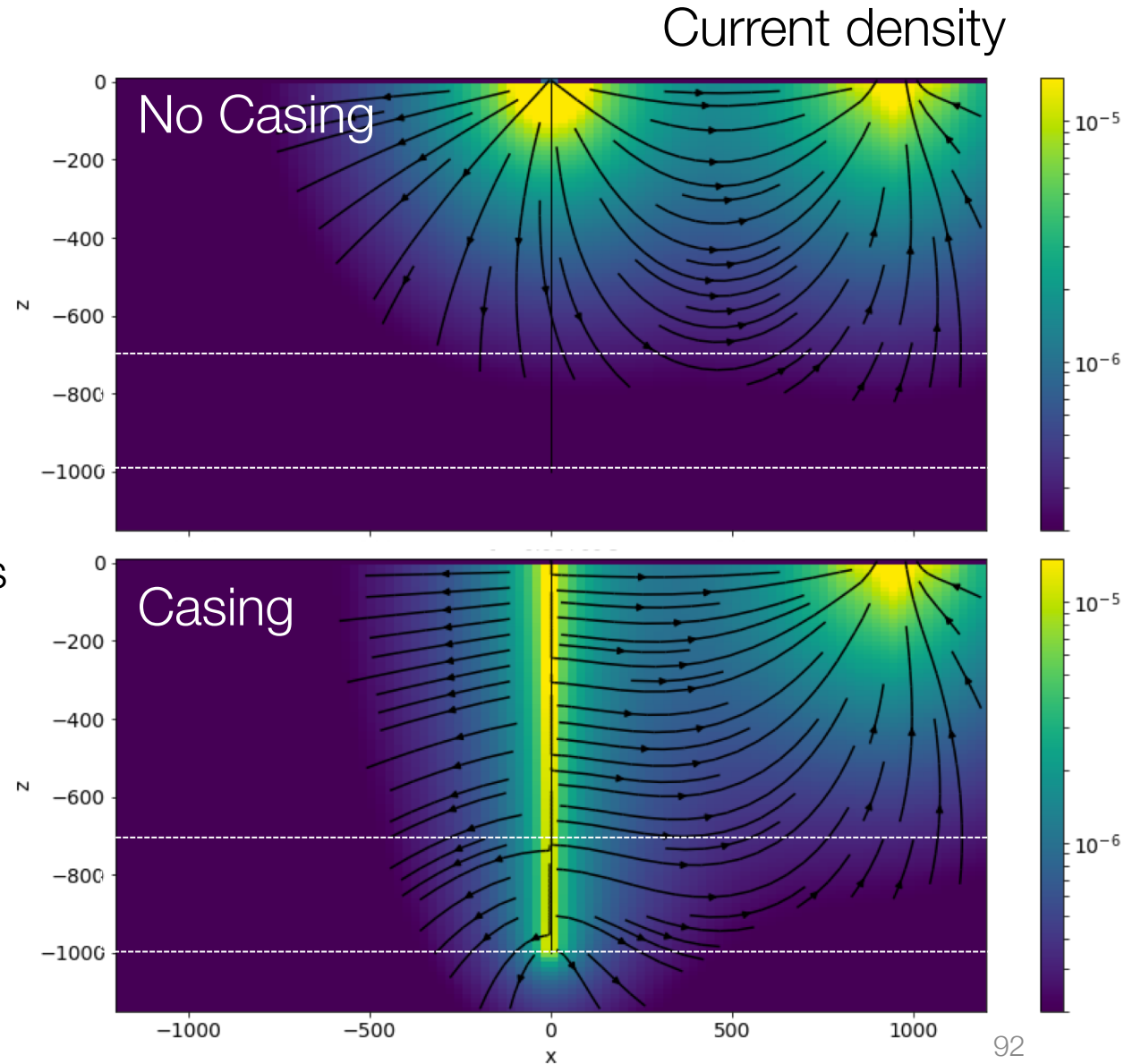
# Using steel casing as an “Extended Electrode”

- Field study: imaged conductive waste beneath leaking tanks



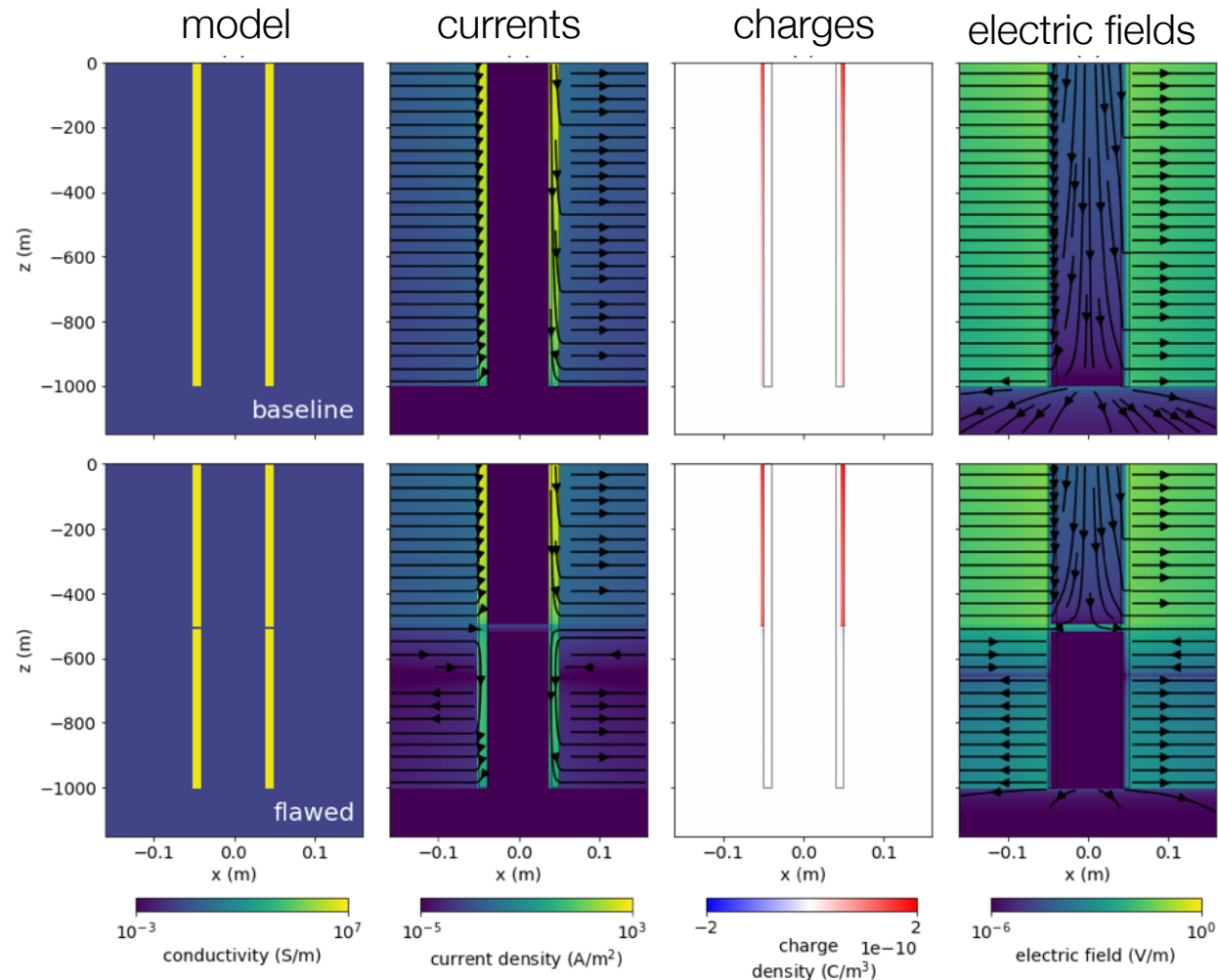
# Using steel casing as an “Extended Electrode”

- Fracturing, enhanced oil recovery, carbon capture and storage, ...
  - Small targets
  - Deep
  - Steel cased wells
- Use casing to deliver current to depth



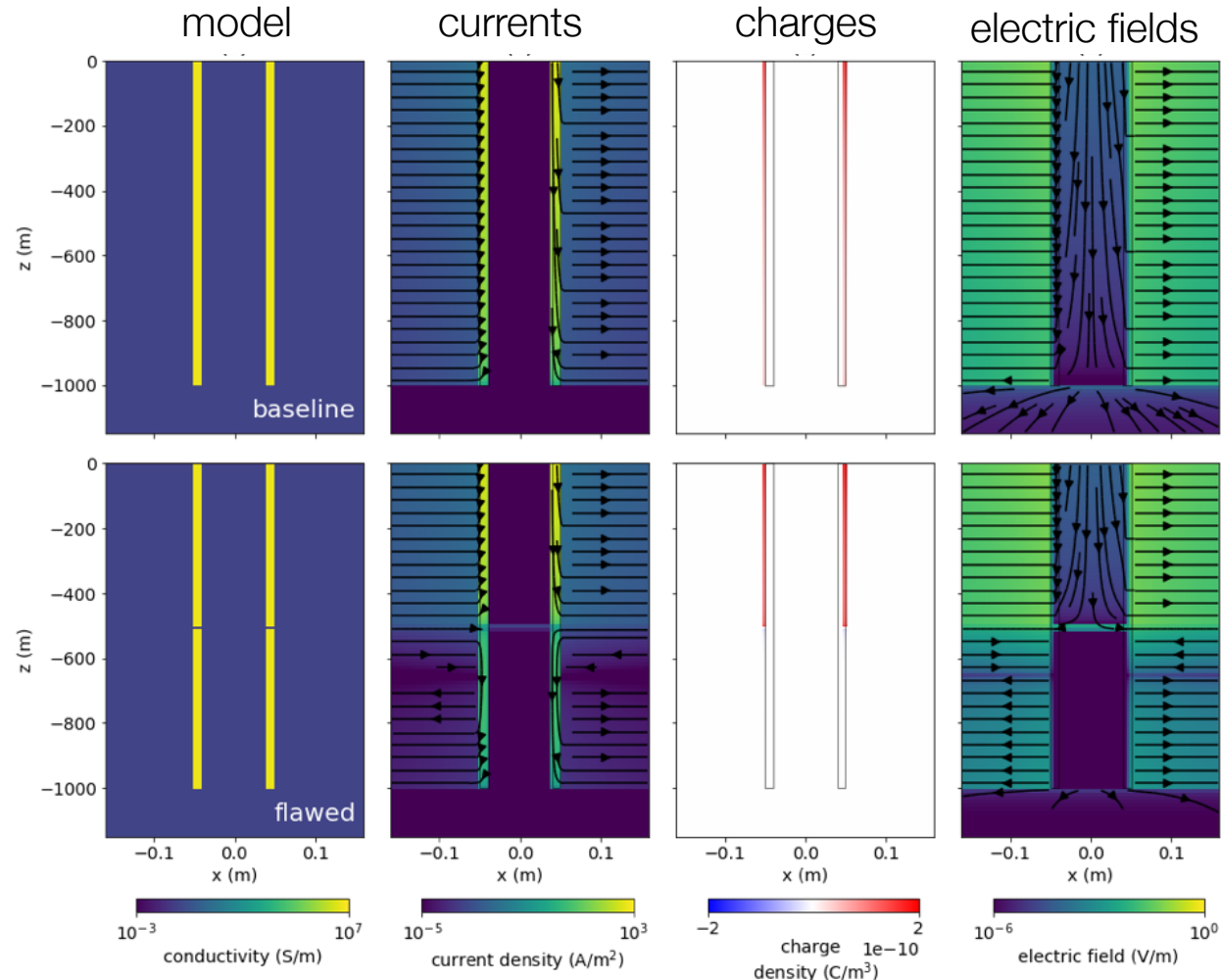
# Casing integrity

- Can we detect flaws in the casing from the surface?
  - e.g. corrosion

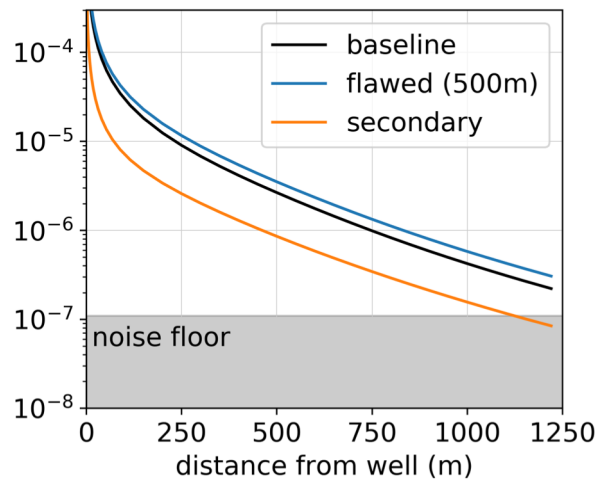


# Casing integrity

- Can we detect flaws in the casing from the surface?
  - e.g. corrosion



## Electric field at surface



# Jupyter Notebooks



The screenshot shows a Jupyter Notebook interface in a browser window. The browser address bar shows the URL `localhost:8892/notebooks/notebooks/DC_LayeredEarth.ipynb`. The notebook title is `DC_LayeredEarth (autosaved)`. The 'Cell' menu is open, and the 'Run All' option is highlighted with a red arrow. The notebook content includes a code cell with the following code:

```
In [1]: from em_examp
import matplotlib.pyplot as plt
```

The notebook content also includes the following text:

**Purpose**

**Investigati**

Using the widgets contained in this notebook, we will explore the physical principals governing DC resistivity including the behavior of currents, electric field, electric potentials in a two layer earth.

The measured data in a DC experiment are potential differences, we will demonstrate how these provide information about subsurface physical properties.

**Background: Computing Apparent Resistivity**

In practice we cannot measure the potentials everywhere, we are limited to those locations where we place electrodes. For each source (current electrode pair) many potential differences are measured between M and N electrode pairs to characterize the overall distribution of potentials. The widget below allows you to visualize the potentials, electric fields, and current densities from a dipole source in a simple model with 2 layers. For different electrode configurations you can measure the potential differences and see the calculated apparent resistivities.

In a uniform halfspace the potential differences can be computed by summing up the potentials at each measurement point from the different current sources based on the following equations:

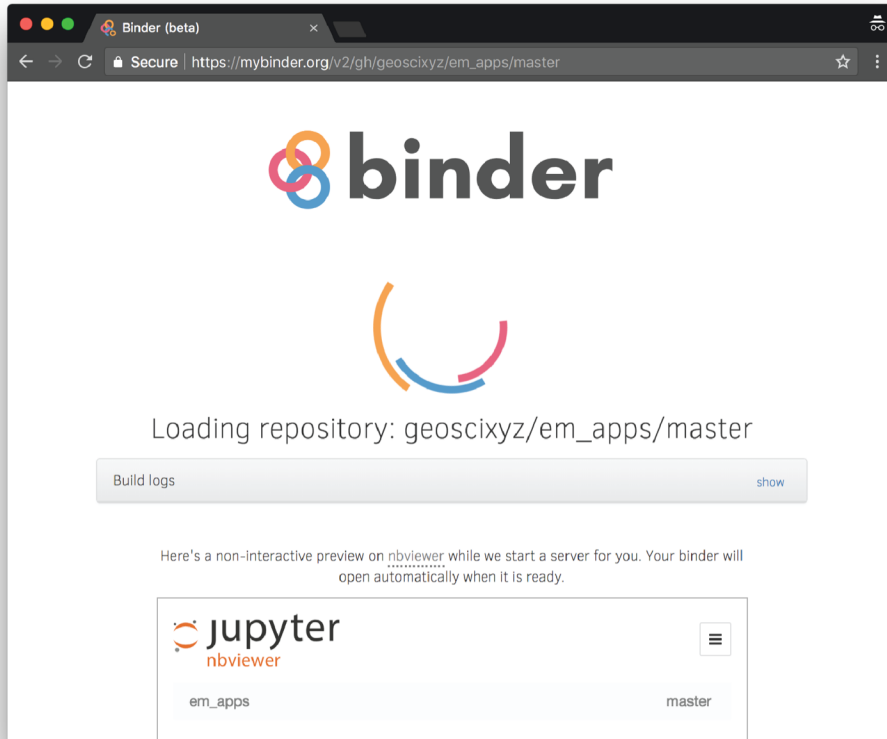
$$V_M = \frac{\rho I}{2\pi} \left[ \frac{1}{AM} - \frac{1}{MB} \right]$$
$$V_N = \frac{\rho I}{2\pi} \left[ \frac{1}{AN} - \frac{1}{NB} \right]$$

# Running the Apps

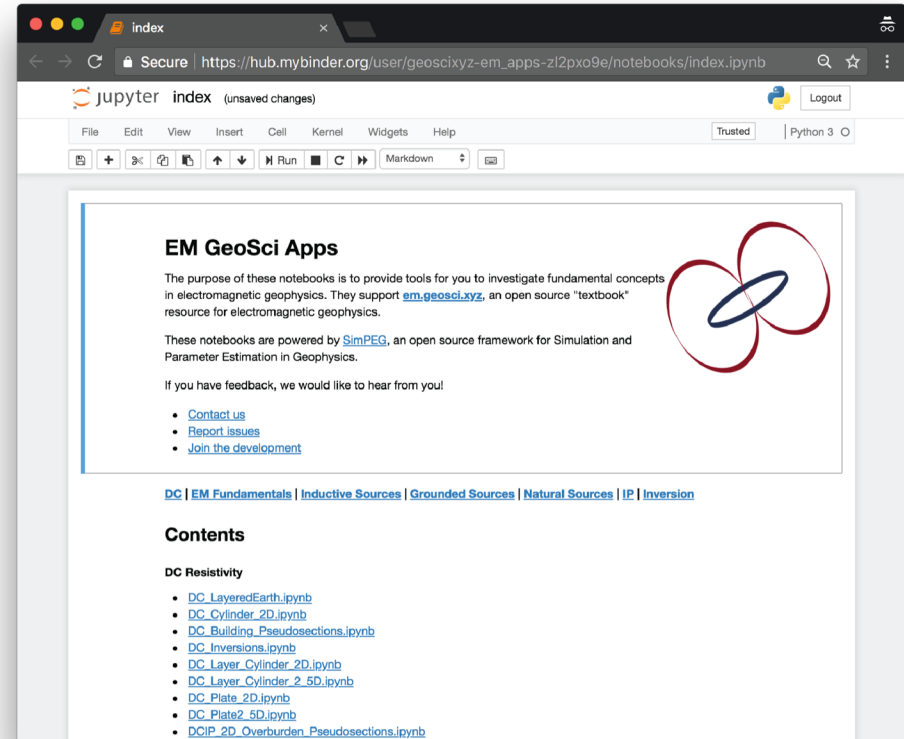
launch binder

1. Load the repository  
(be patient...)

2. Select notebook from  
contents



The screenshot shows the Binder (beta) website. The browser address bar displays `https://mybinder.org/v2/gh/geoscixyz/em_apps/master`. The main content area features the Binder logo and the text "Loading repository: geoscixyz/em\_apps/master". Below this, there is a "Build logs" button with a "show" link. At the bottom, a preview of the Jupyter nbviewer interface is shown, displaying the repository name "em\_apps" and the version "master".



The screenshot shows the Jupyter index page for the EM GeoSci Apps repository. The browser address bar displays `https://hub.mybinder.org/user/geoscixyz-em_apps-zl2pxo9e/notebooks/index.ipynb`. The page title is "index" and it shows "unsaved changes". The main content area includes the "EM GeoSci Apps" title, a description of the notebooks, and a list of links for feedback. Below this, there is a "Contents" section with a list of notebook titles, including "DC LayeredEarth.ipynb", "DC Cylinder\_2D.ipynb", "DC Building\_Pseudosections.ipynb", "DC Inversions.ipynb", "DC Layer\_Cylinder\_2D.ipynb", "DC Layer\_Cylinder\_2\_5D.ipynb", "DC Plate\_2D.ipynb", "DC Plate2\_5D.ipynb", and "DCIP\_2D\_Overburden\_Pseudosections.ipynb".

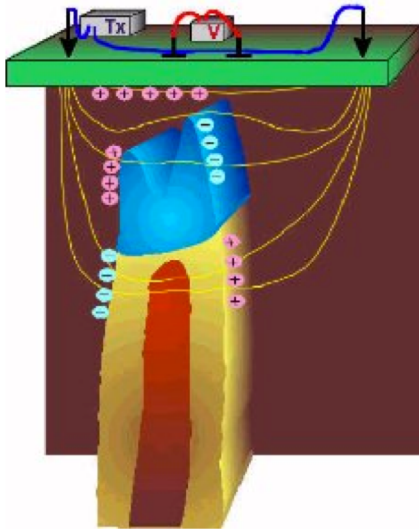
# Questions

- **DC\_LayeredEarth**
  - Start with a top layer that is conductive ( $50 \Omega\text{m}$ ).
    - What is the minimum A-B separation we need to see the second layer in our data?
    - What happens if it is more conductive / resistive?
    - What happens if the layer is thicker?
- **DC\_Cylinder\_2D**
  - You have been charged with finding 2 tunnels: (1) Filled with salty water, (2) filled with air
    - How are the charges distributed in each of these cases?
    - How are the charges distributed if you use a pole source?
- **DC\_Cylinder\_2D cont...**
  - For a conductive cylinder ( $10 \Omega\text{m}$ ) in a resistive background ( $500 \Omega\text{m}$ ), can you generate a pole-pole example where the apparent resistivity is  $> 500 \Omega\text{m}$ ? How do you explain this (hint: look at the charges)
- **DC\_Building\_Pseudosections**
  - For which survey setup's are the “pant-legs” symmetric over the target? Which aren't?
  - Can you demonstrate an example of non-uniqueness? E.g. If the sphere has a radius of 2m and a resistivity of  $50 \Omega\text{m}$ , is there a model that produces similar data?

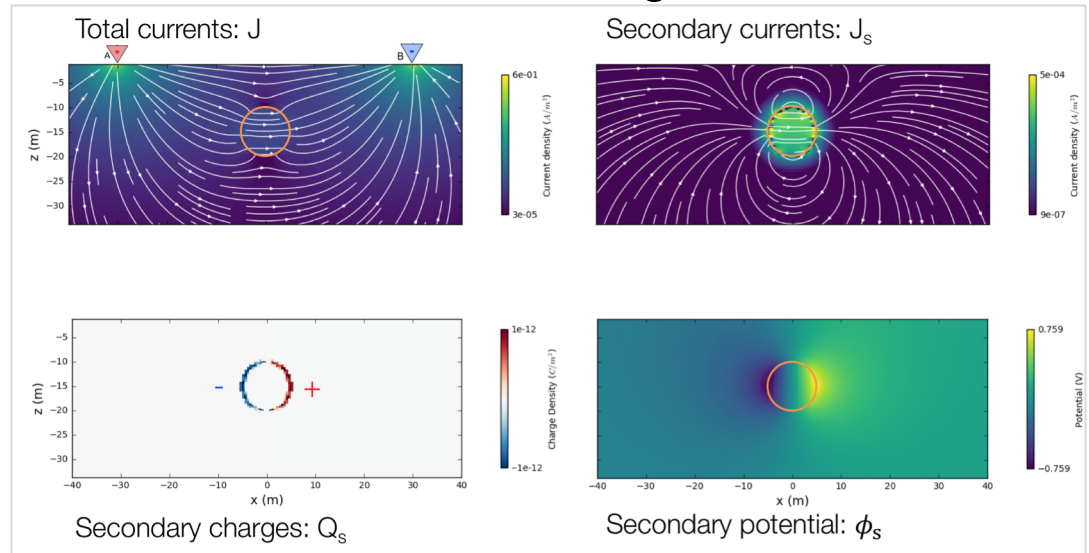


# Summary

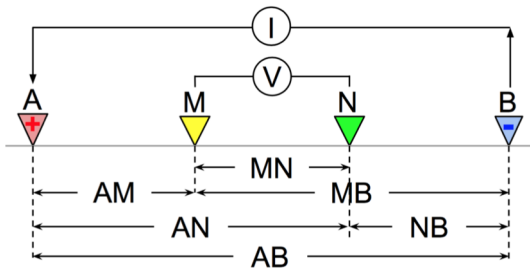
## Basic experiment and physics



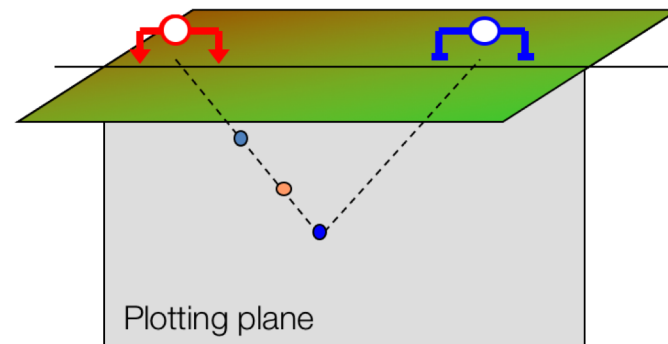
## Confined targets



## Soundings and arrays

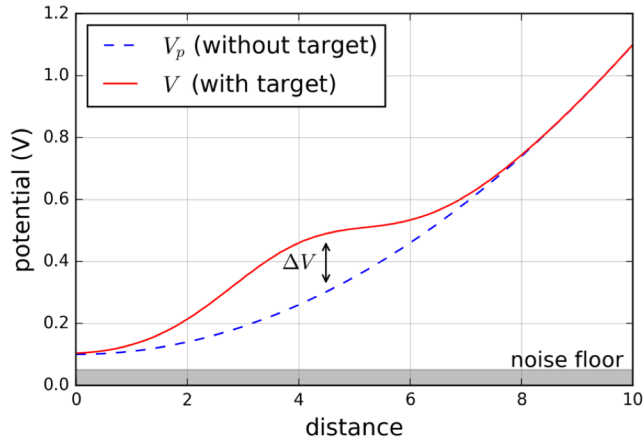


## Pseudosections

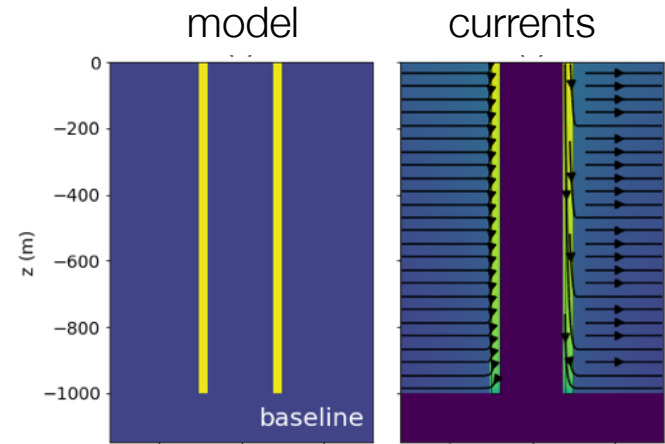


# Summary

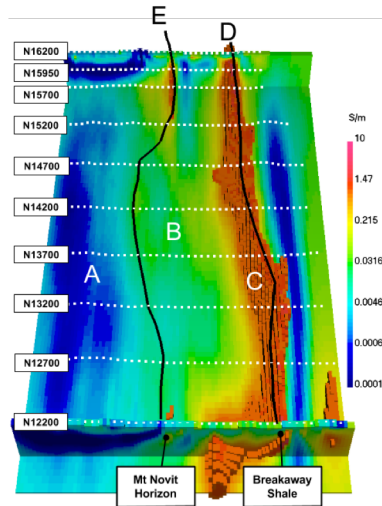
## Sensitivity + survey design



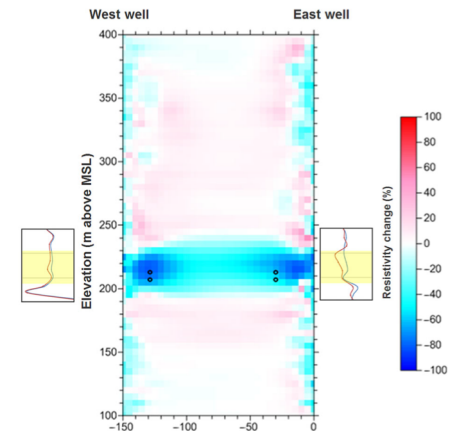
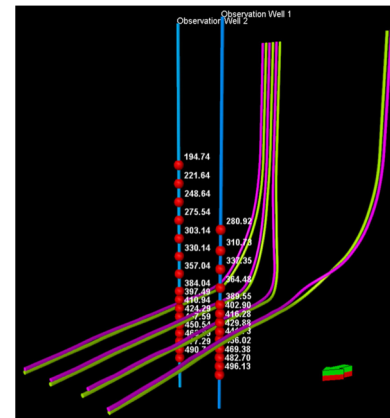
## DC with steel cased wells



## Case History: Mt. Isa

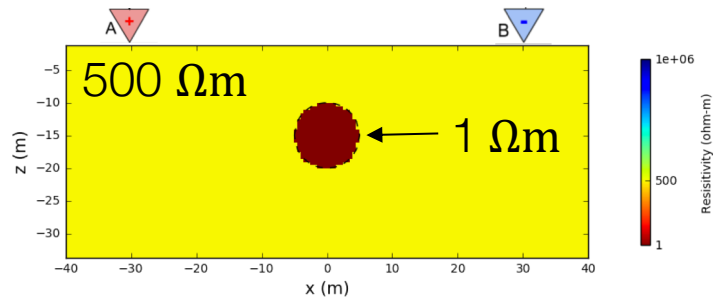


## Case History: Reservoir Monitoring



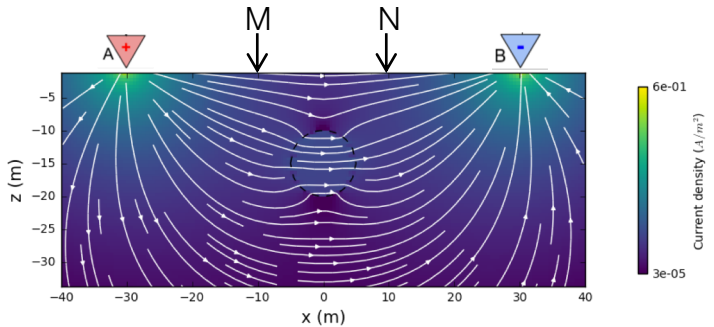
# Effects of background resistivity

Resistivity models (thin resistive layer)



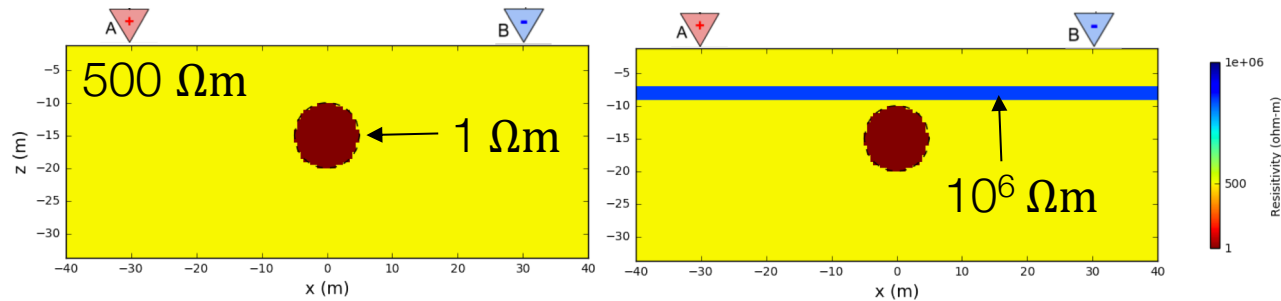
Currents and measured data at MN

$\rho_a = 430 \Omega\text{m}$

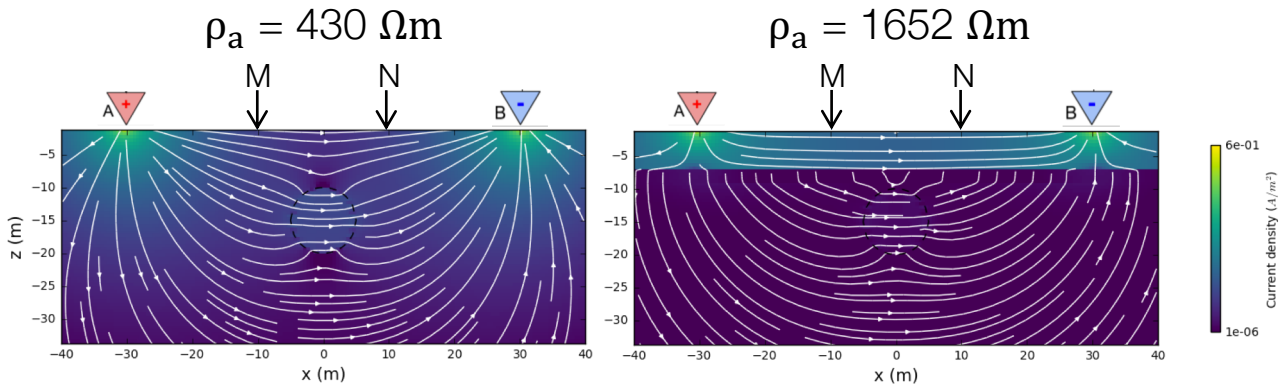


# Effects of background resistivity

## Resistivity models (thin resistive layer)

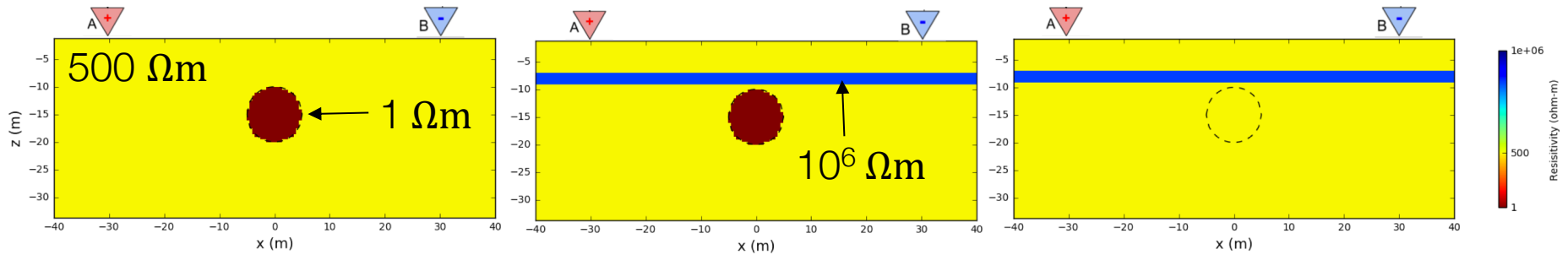


## Currents and measured data at MN

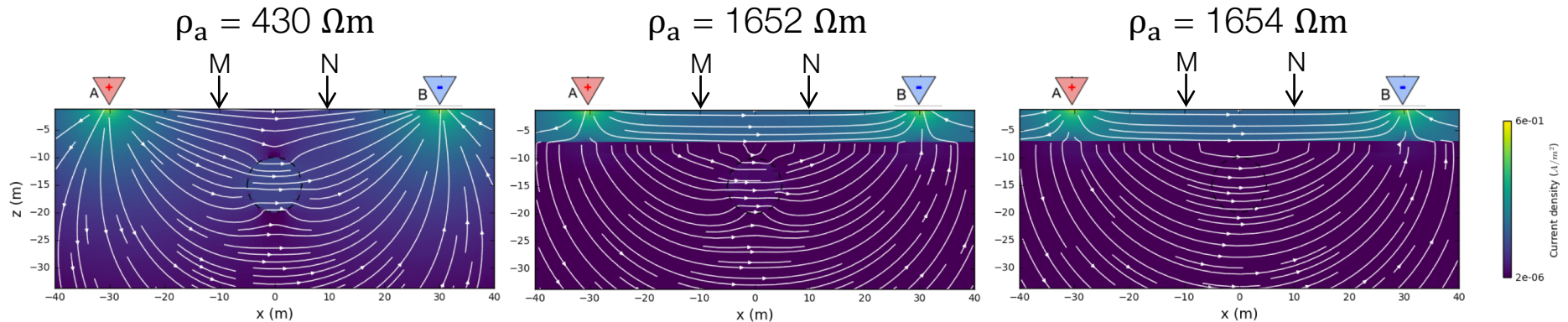


# Effects of background resistivity

## Resistivity models (thin resistive layer)

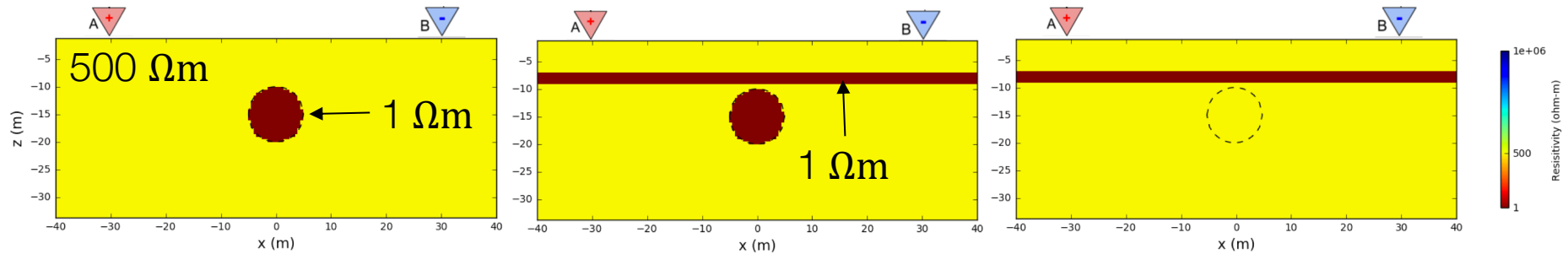


## Currents and measured data at MN

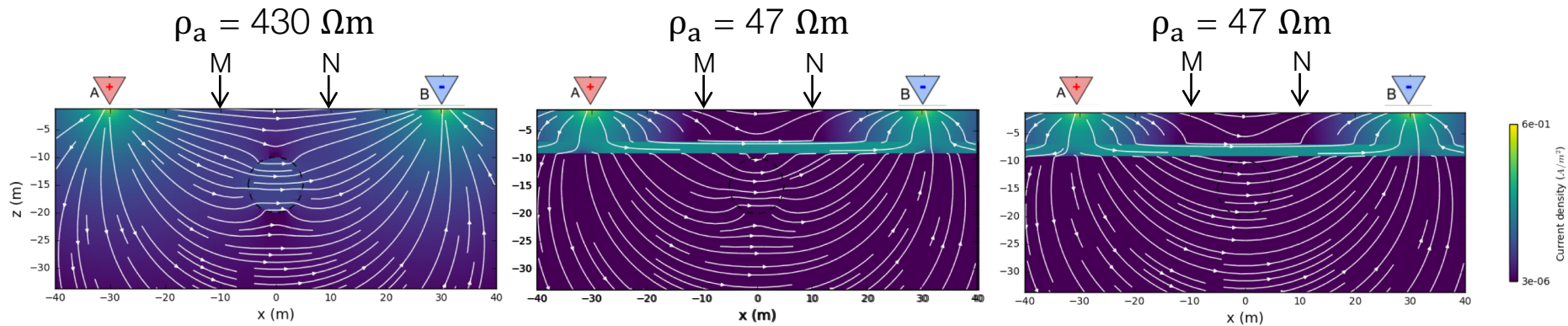


# Effects of background resistivity

Resistivity models (thin conductive layer)



Currents and measured data at MN



# DC Layered earth + cylinder

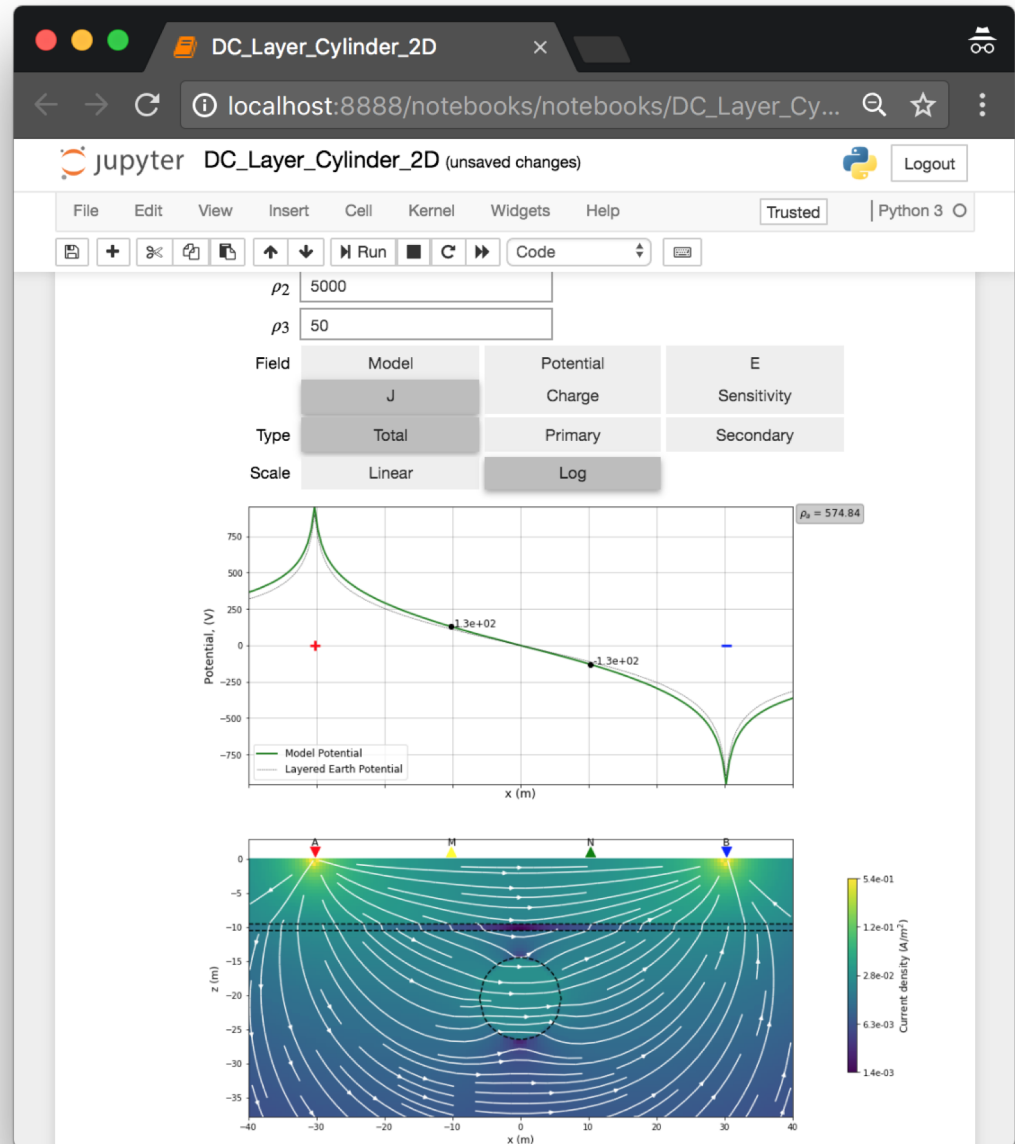
- DC\_Layer\_Cylinder.ipynb

- Parameters:

- Resistivity of background, layer, sphere
- Geometry of cylinder, layer
- Location of electrodes

- View:

- Model
- Electric potential
- Electric field
- Charges
- Current density



# End of DCR

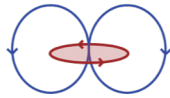
Next up



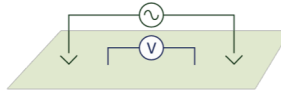
DC Resistivity



EM Fundamentals



Inductive Sources



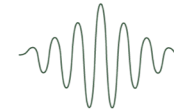
Grounded Sources



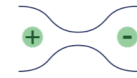
Natural Sources



Inverse Theory



GPR



Induced Polarization



The Future