Electrical conductivity and its applications

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& the UBC-GIF team

https://courses.geosci.xyz/lapis2019

Outline

- Some problems of interest
- Electrical conductivity/resistivity (lab experiment)
- Governing equations:
- DC resistivity
- Case history: minerals exploration
- Inductive sources
- Case history: water resources
- Other applications
- Future

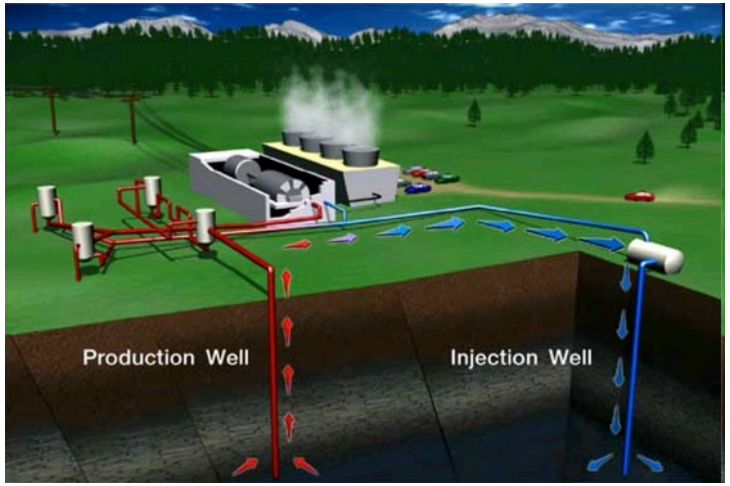
some problems of relevance …

Finding resources

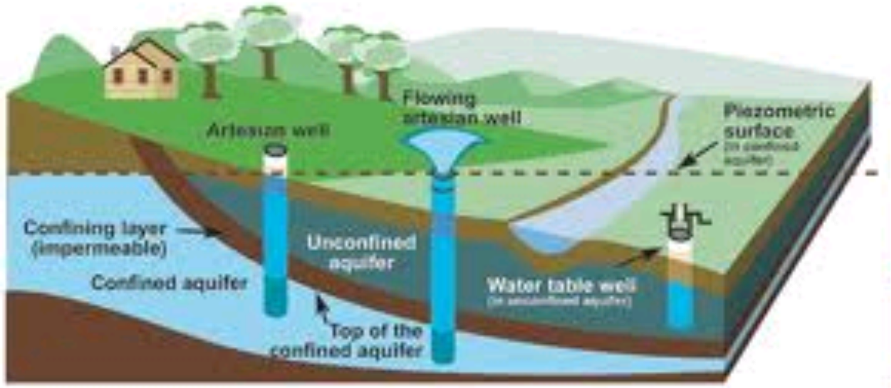
Hydrocarbons

Minerals

Geothermal Energy



Ground Water



Natural hazards

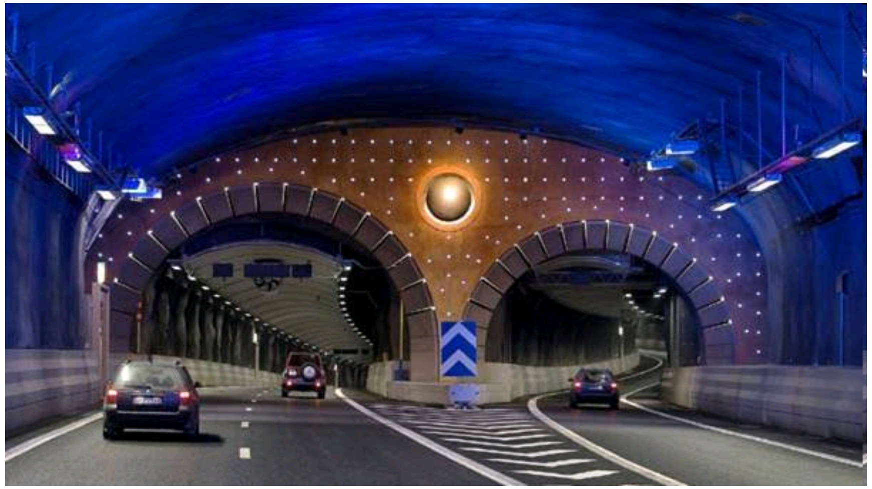
Volcanoes

Tsunami

Earthquakes

Geotechnical engineering

Tunnels

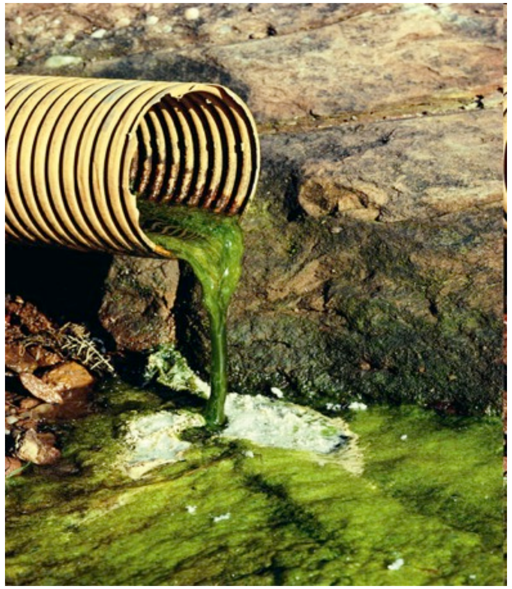


Slope stability

In-mine safety

Environmental

Water contamination



http://www.centennialofflight.gov

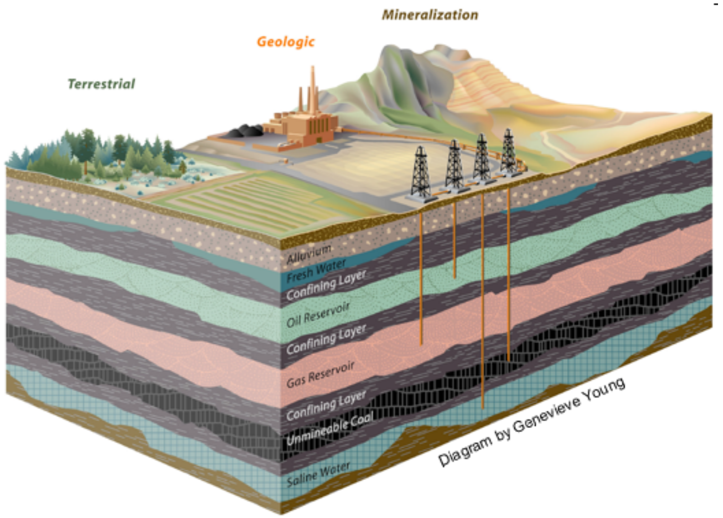
Salt water intrusion

Unexploded Ordnance (UXO)

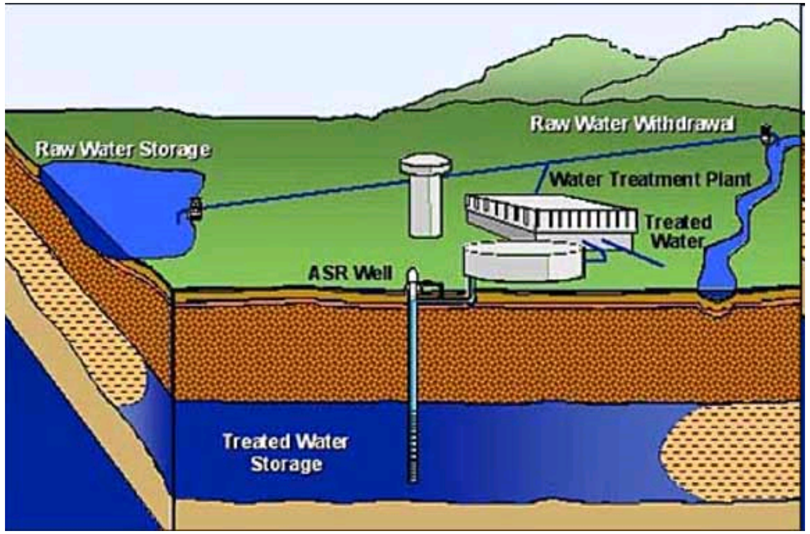
?

Surface or underground storage

CO2 sequestration



Aquifer Storage and Recover

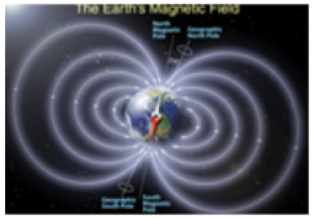


Industrial Waste Disposal

What do these problems have in common?

All require ways to see into the earth without direct sampling.

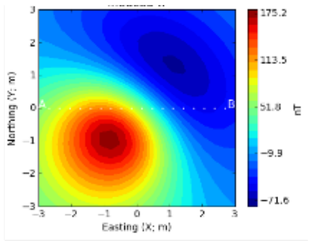
Source



Input energy

measure

Data

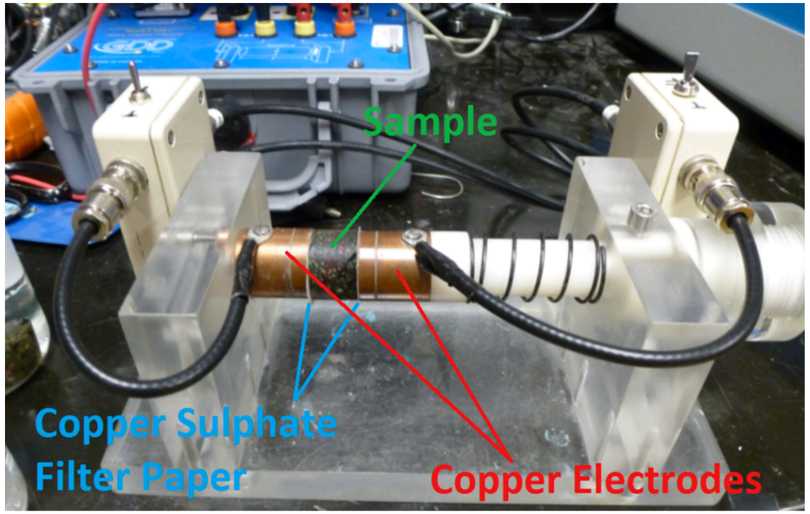


Physical Properties

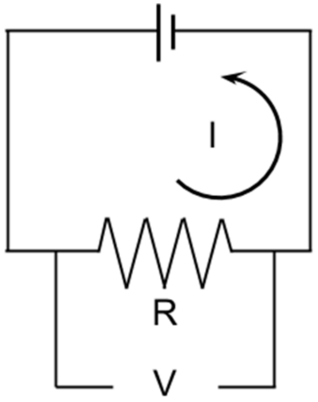
σ, μ, ε

Electrical resistivity and conductivity

DC resistivity and Ohm's Law



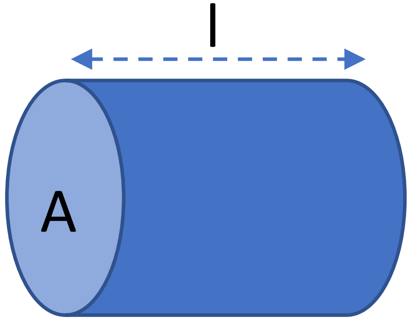
- Electric circuit:



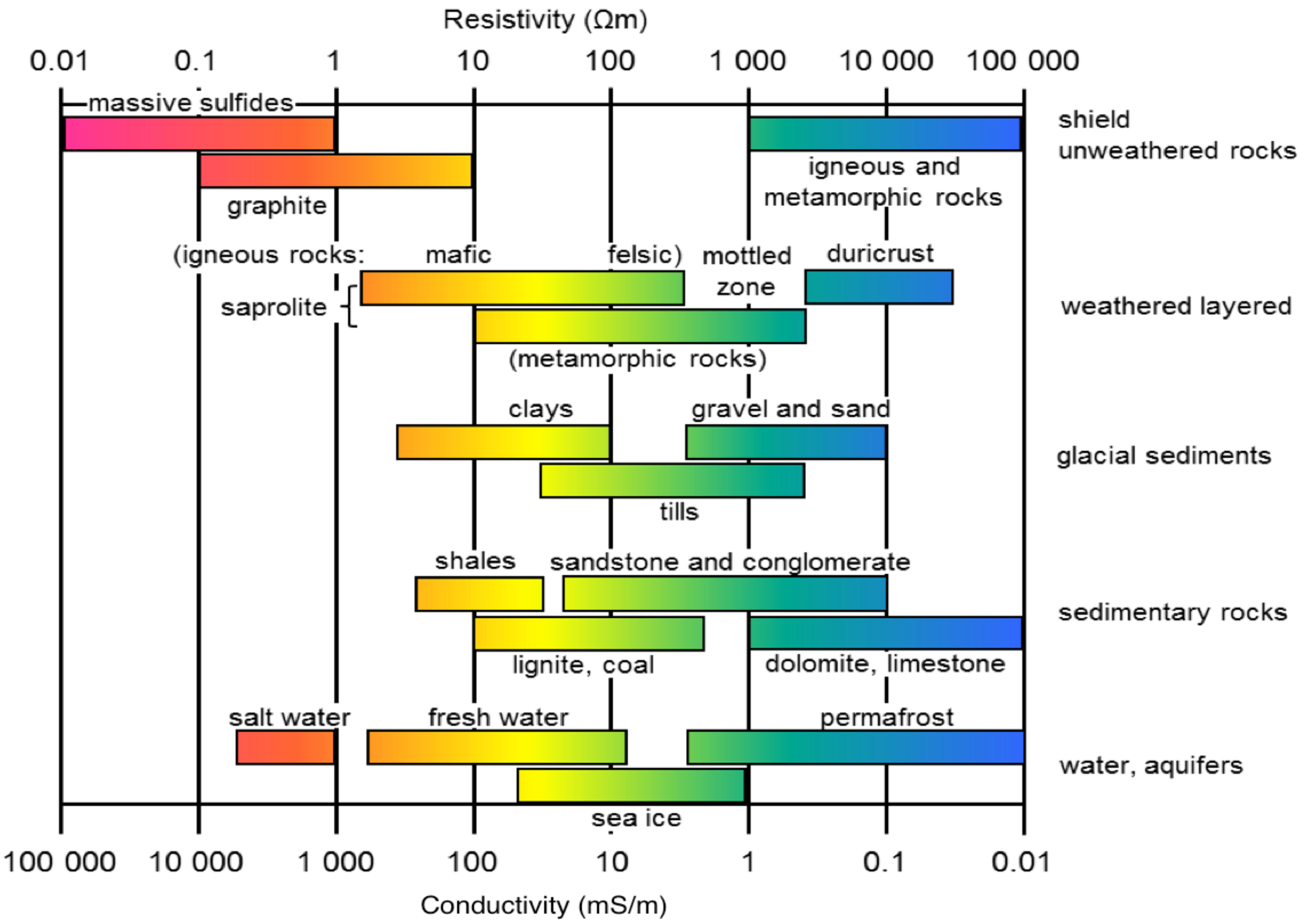
- Ohm's Law: $\Delta V = IR$

- Resistivity: $\rho = R\dfrac{A}{l}$

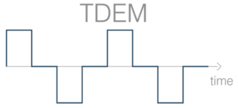
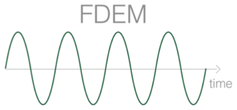
- Conductivity: $\sigma = \rho^{-1}$



Electrical Resistivity / Conductivity

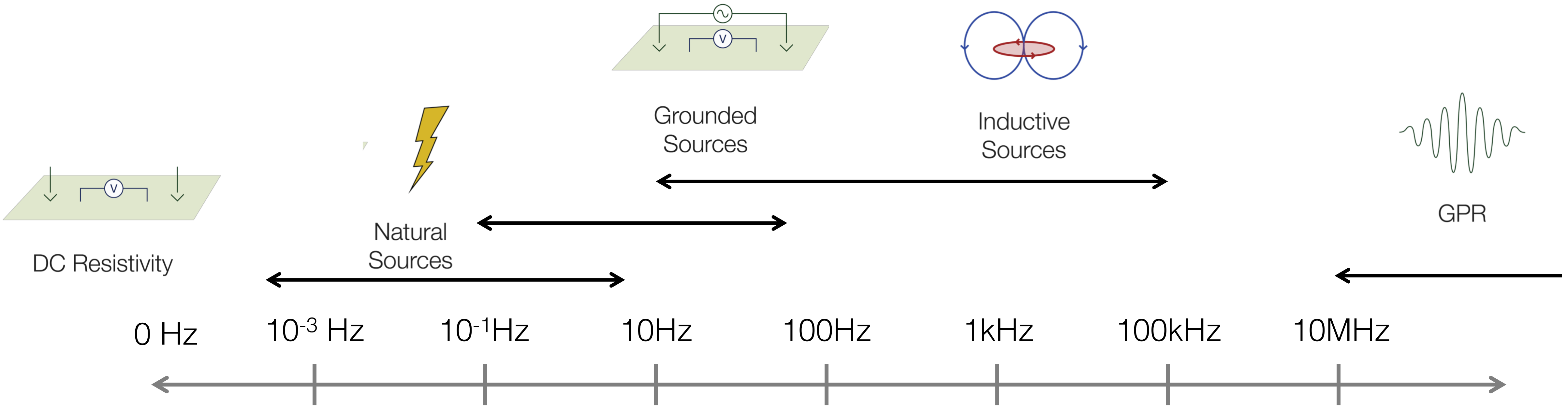


Basic Equations

	Time 	Frequency 
Faraday's Law	$\nabla \times \mathbf{e} = -\dfrac{\partial \mathbf{b}}{\partial t}$	$\nabla \times \mathbf{E} = -i\omega \mathbf{B}$
Ampere's Law	$\nabla \times \mathbf{h} = \mathbf{j} + \dfrac{\partial \mathbf{d}}{\partial t}$	$\nabla \times \mathbf{H} = \mathbf{J} + i\omega \mathbf{D}$
No Magnetic Monopoles	$\nabla \cdot \mathbf{b} = 0$	$\nabla \cdot \mathbf{B} = 0$
Constitutive Relationships (non-dispersive)	$\mathbf{j} = \sigma \mathbf{e}$ $\mathbf{b} = \mu \mathbf{h}$ $\mathbf{d} = \varepsilon \mathbf{e}$	$\mathbf{J} = \sigma \mathbf{E}$ $\mathbf{B} = \mu \mathbf{H}$ $\mathbf{D} = \varepsilon \mathbf{E}$

* Solve with sources and boundary conditions

EM Surveys and frequency

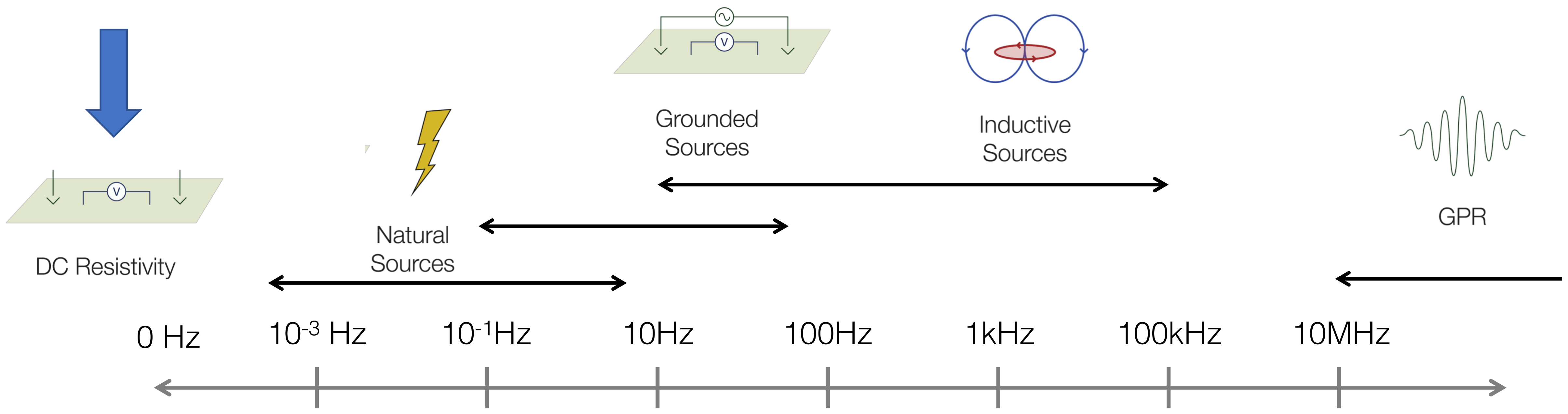


$$\nabla \cdot \sigma \nabla \phi = q$$

$$\nabla \times \nabla \times \vec{E} + \mu\sigma \frac{\partial \vec{E}}{\partial t} = 0$$

$$\nabla \times \nabla \times \vec{E} + \mu\sigma \frac{\partial \vec{E}}{\partial t} + \mu\epsilon \frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

EM Surveys and frequency



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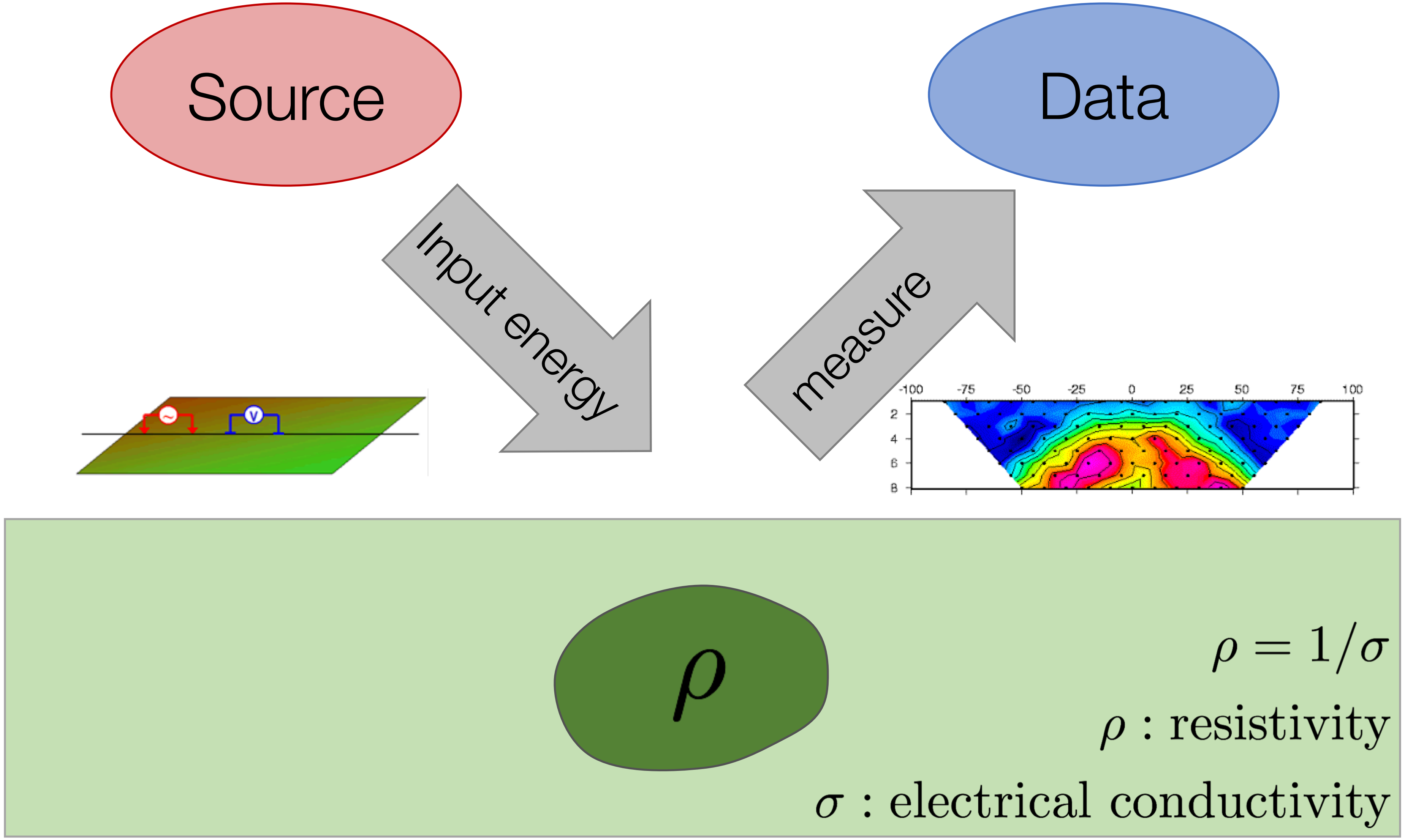
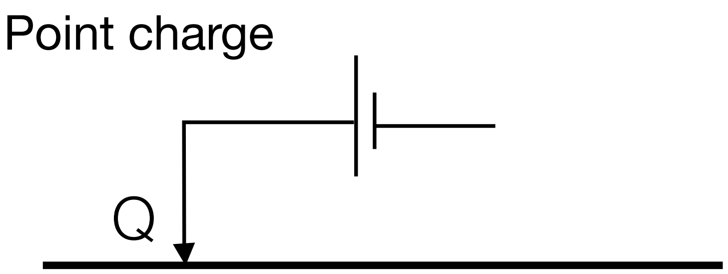
DC resistivity Survey

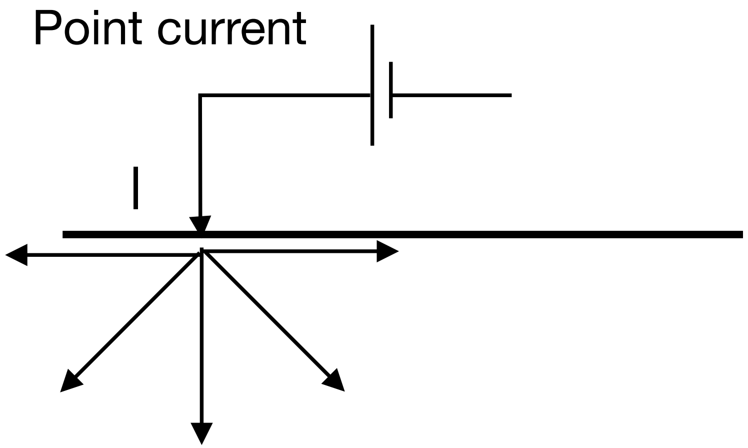
DC resistivity



Fundamental Physics



$$V = \frac{Q}{4\pi\epsilon_0 r}$$

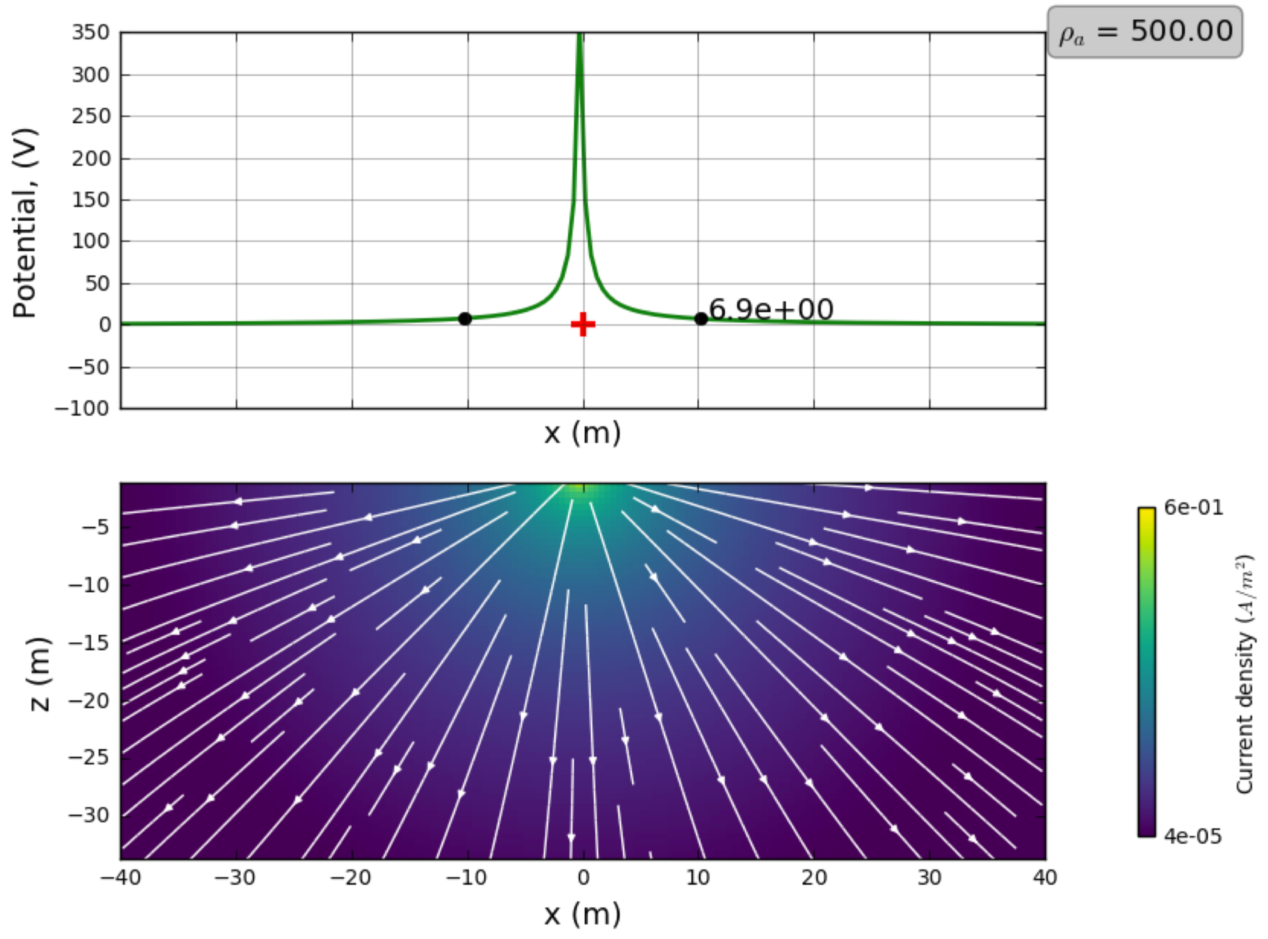


$$V = \frac{\rho I}{2\pi r}$$

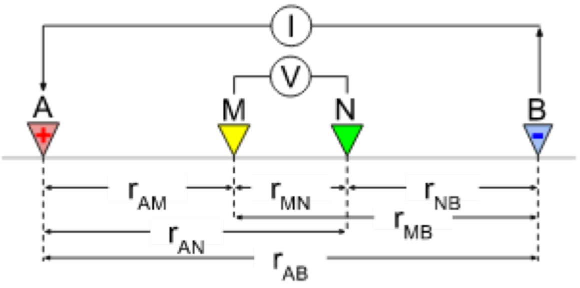
Currents and potentials: halfspace

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

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



Currents and potentials: 4-electrode array

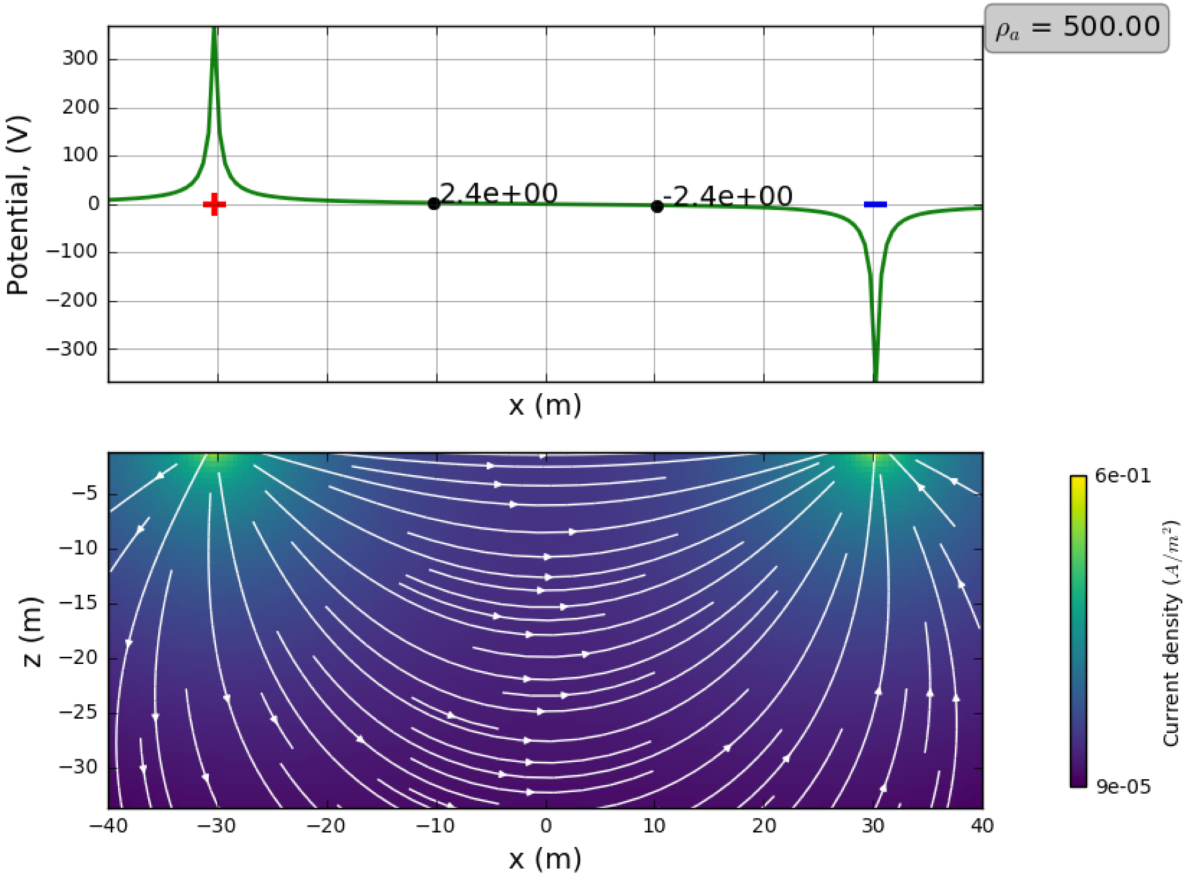


$$\Delta V_{MN} = \rho I \underbrace{\frac{1}{2\pi}\left[\frac{1}{AM} - \frac{1}{MB} - \frac{1}{AN} + \frac{1}{NB}\right]}_{G}$$

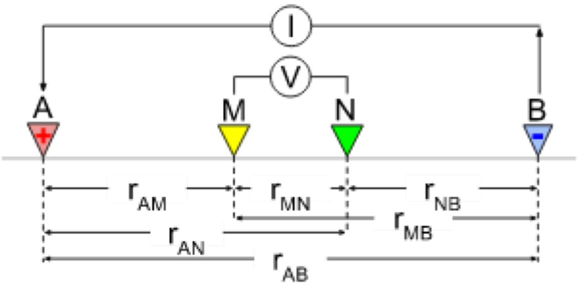
Resistivity

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

Halfspace (500 Ωm)



Currents and potentials: 4-electrode array

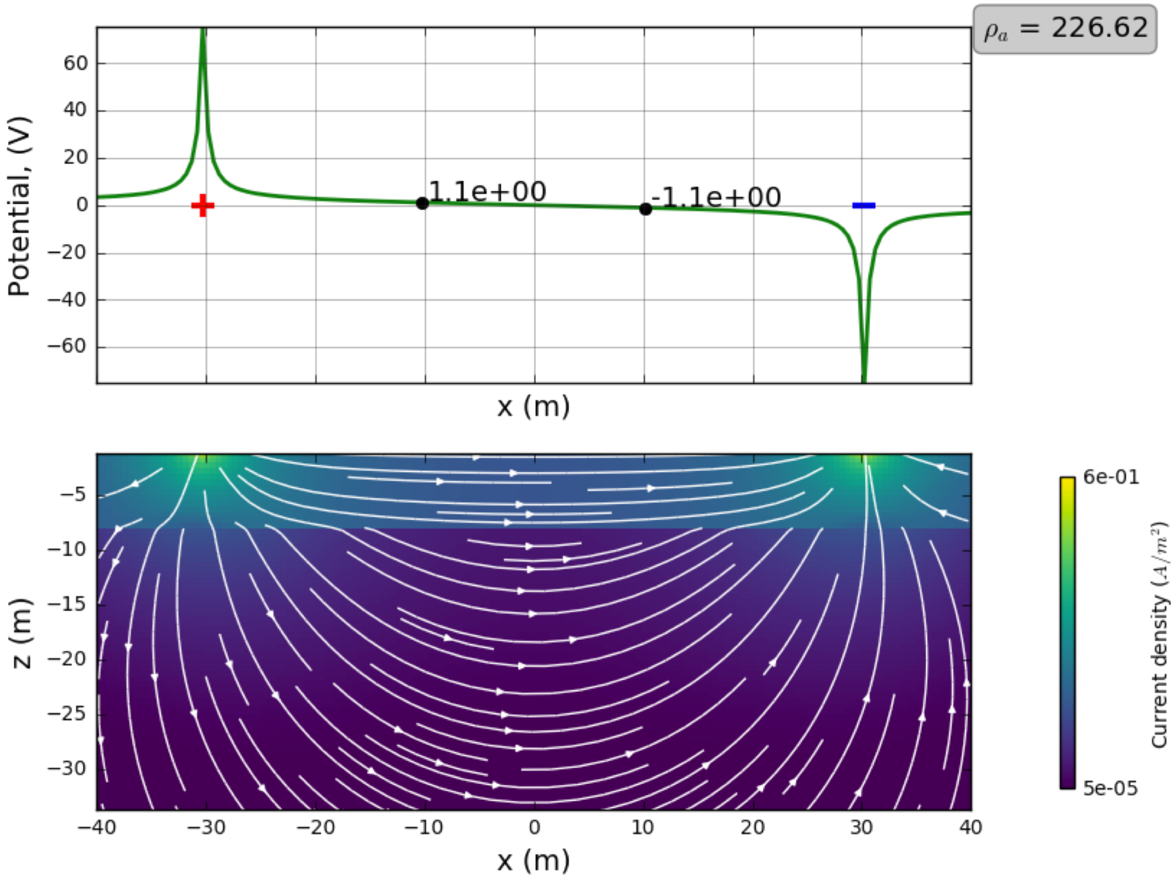


$$\Delta V_{MN} = \rho I \underbrace{\frac{1}{2\pi}\left[\frac{1}{AM} - \frac{1}{MB} - \frac{1}{AN} + \frac{1}{NB}\right]}_{G}$$

Apparent resistivity

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

Conductive overburden (100 Ωm)

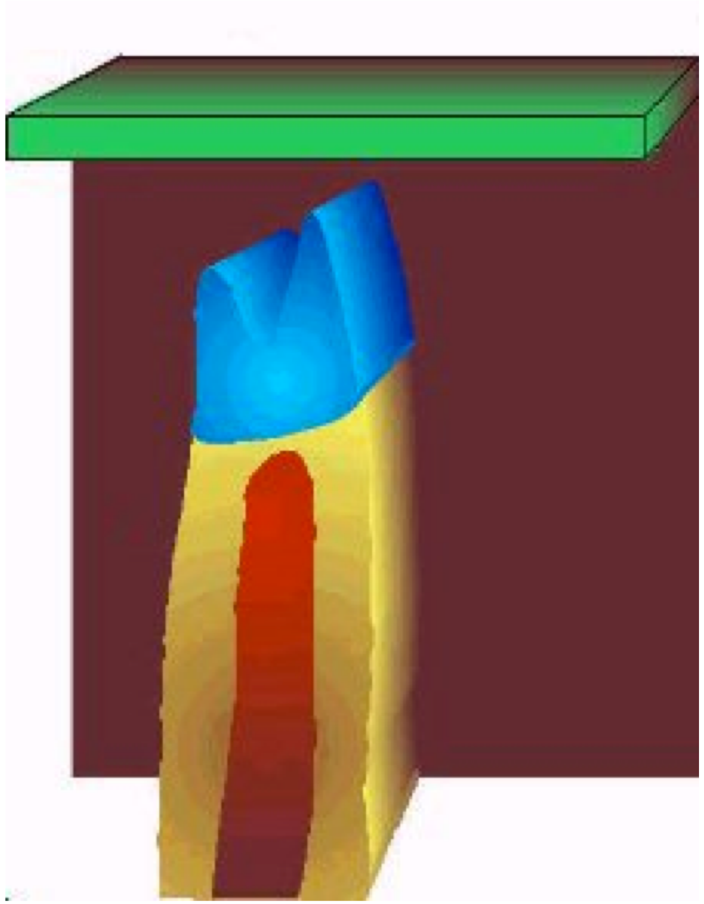


Basic Experiment

- 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



Basic Experiment

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

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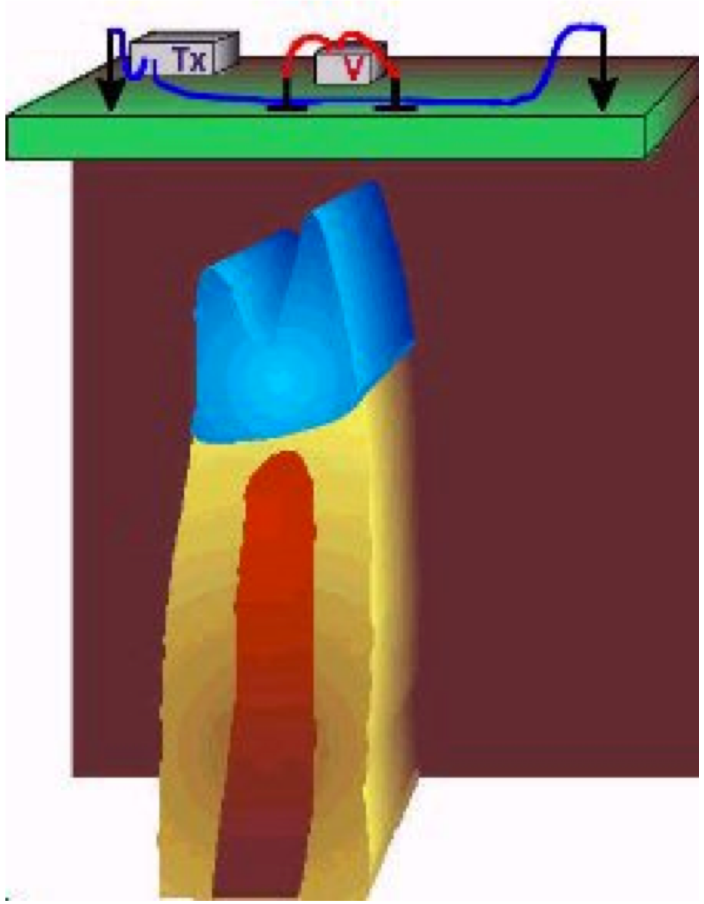

Basic Experiment

- **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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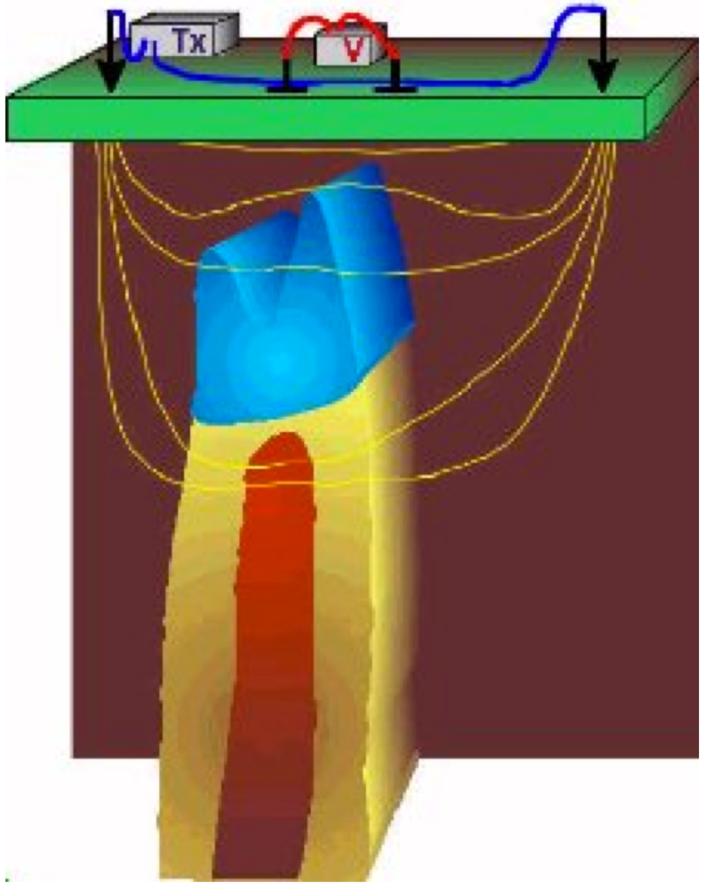

Basic Experiment

- **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

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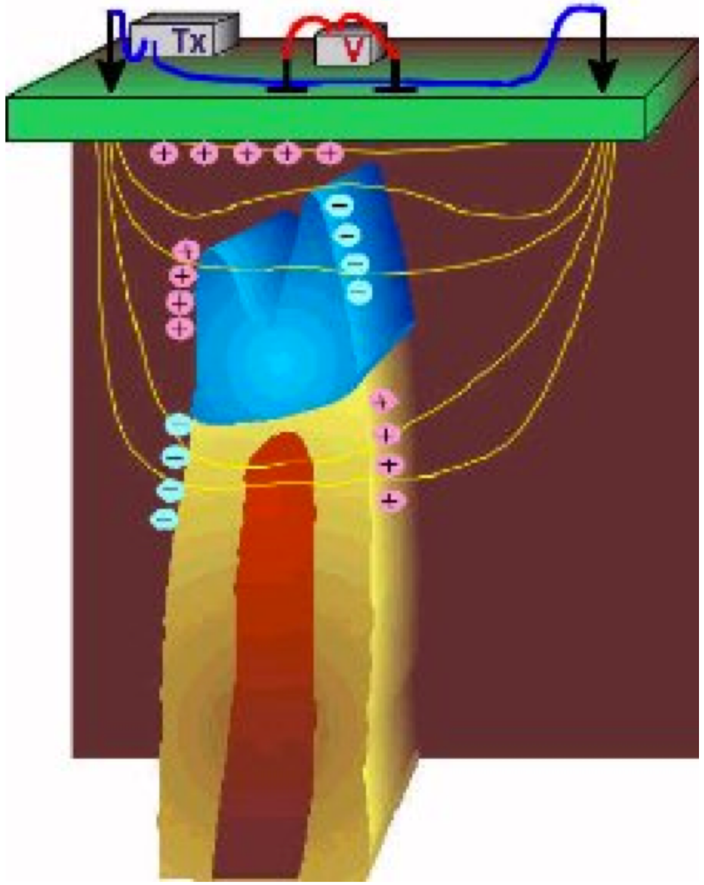

Basic Experiment

- 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

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Gossan	420
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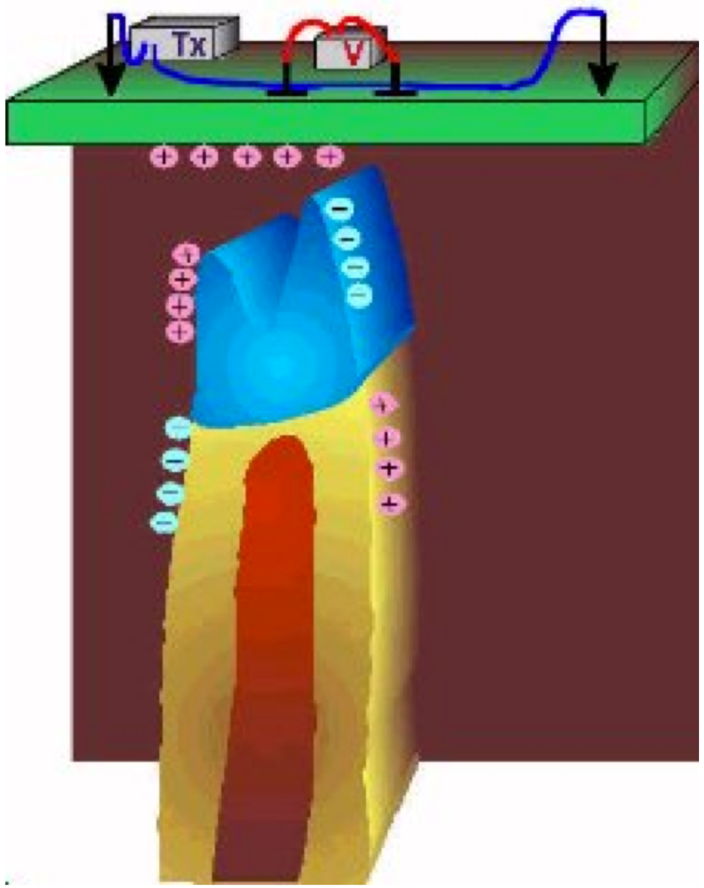
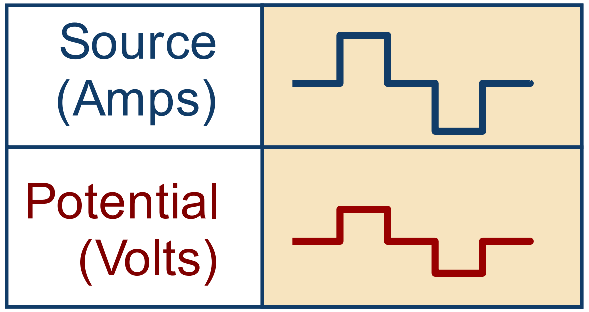
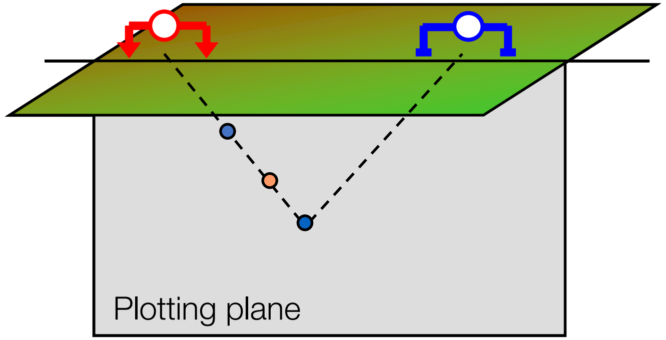
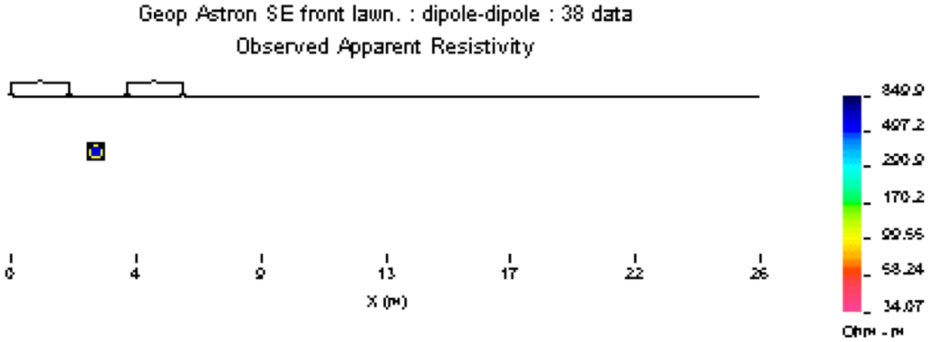


DC resistivity data



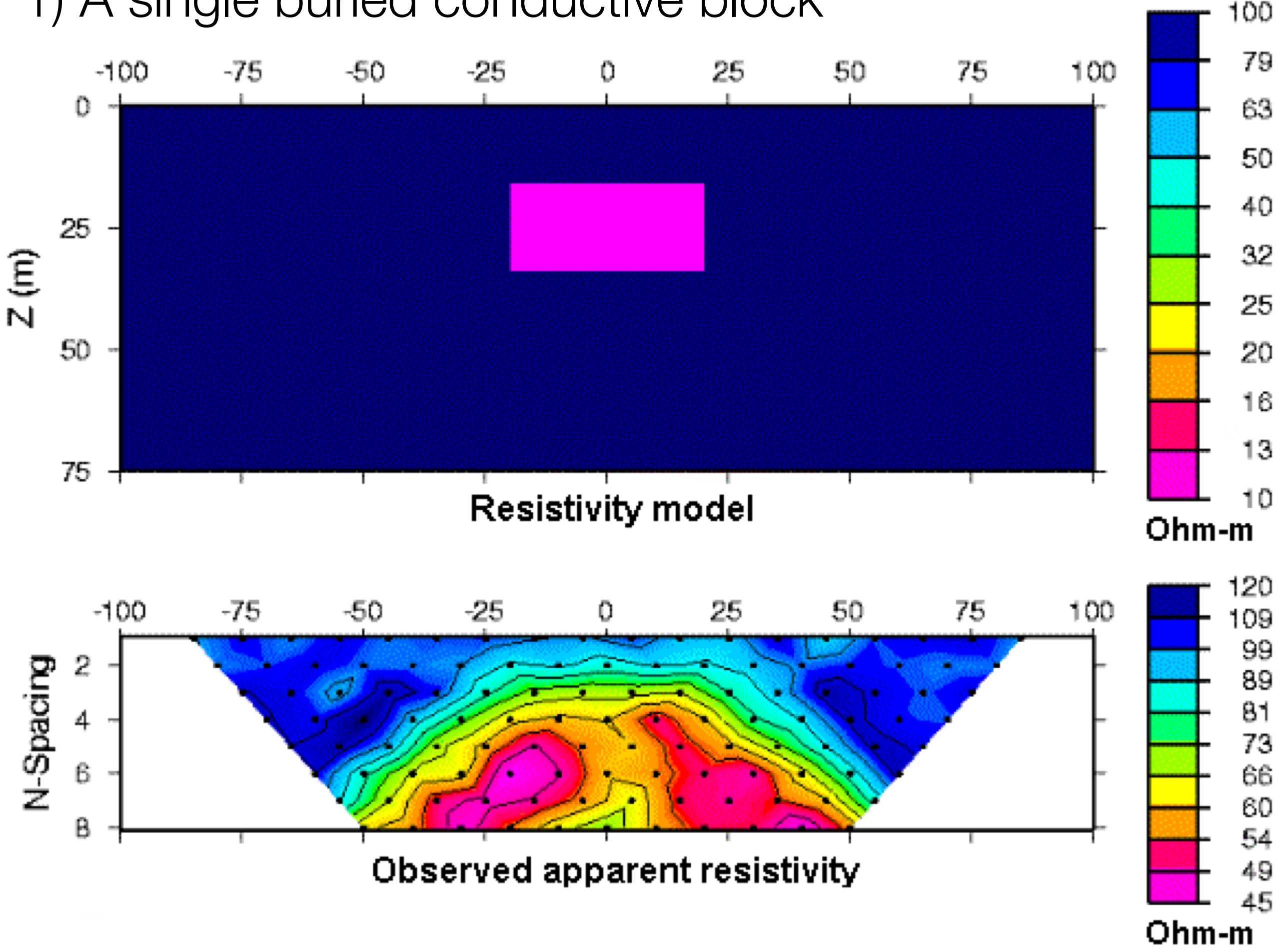


Each data point is an apparent resistivity: $$\rho_a = \frac{2\pi \Delta V}{IG}$$



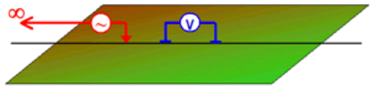
Example pseudosections

1) A single buried conductive block



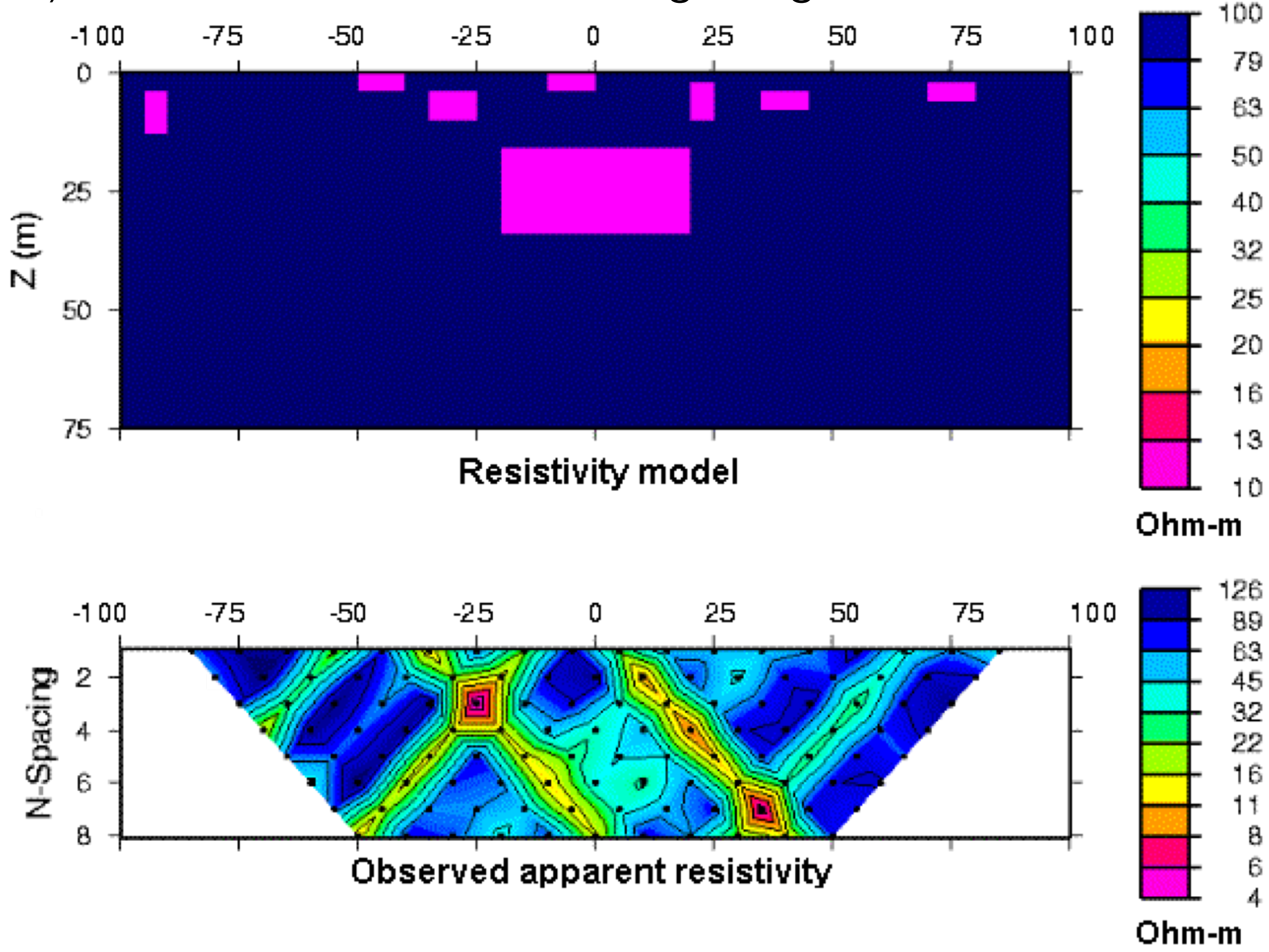
- Pole-dipole; n=1,8; a=10m; N=316

Pole-Dipole

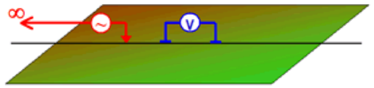


Example pseudosections

2) The conductive block with geologic noise.

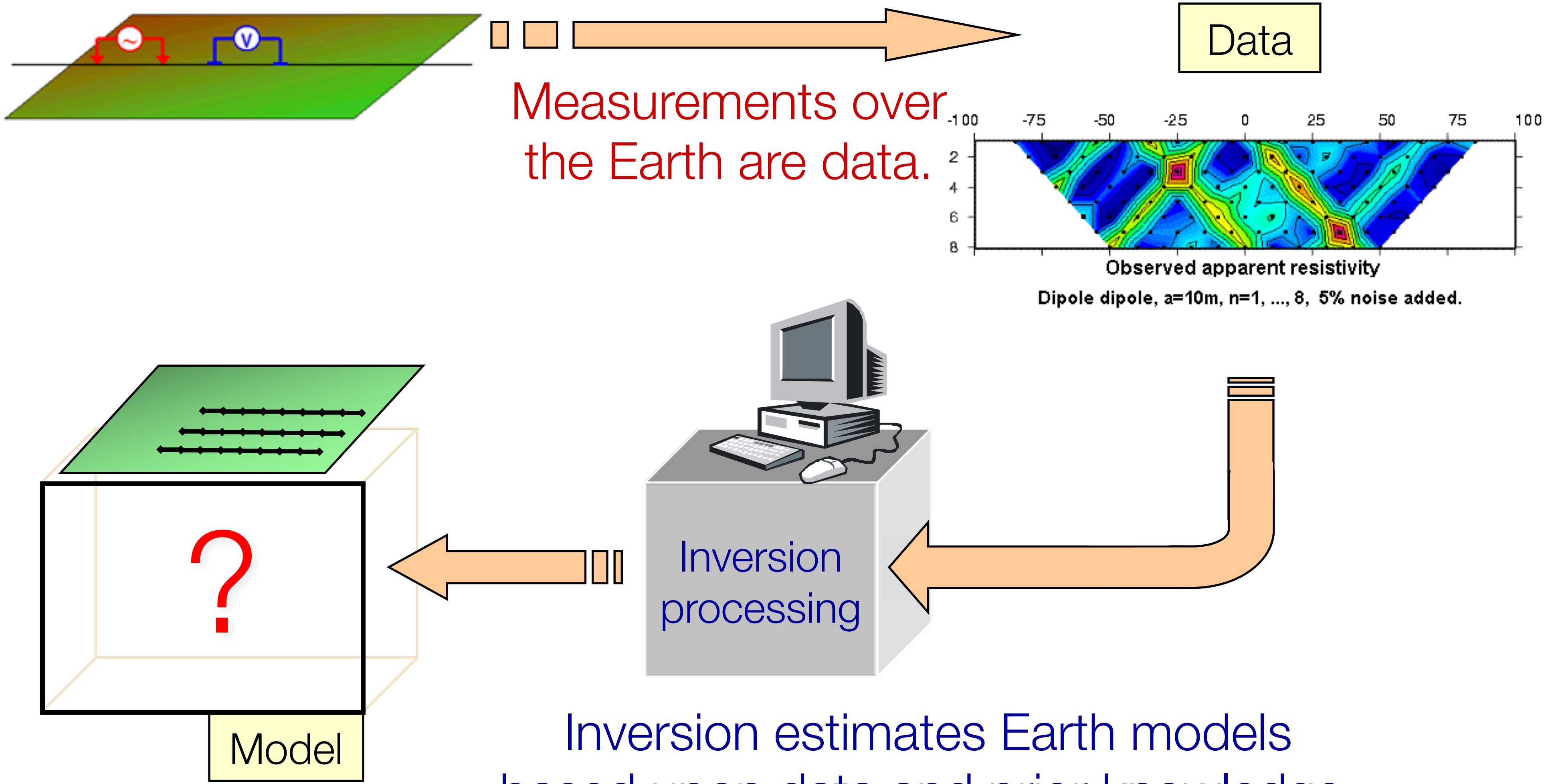


Pole-Dipole



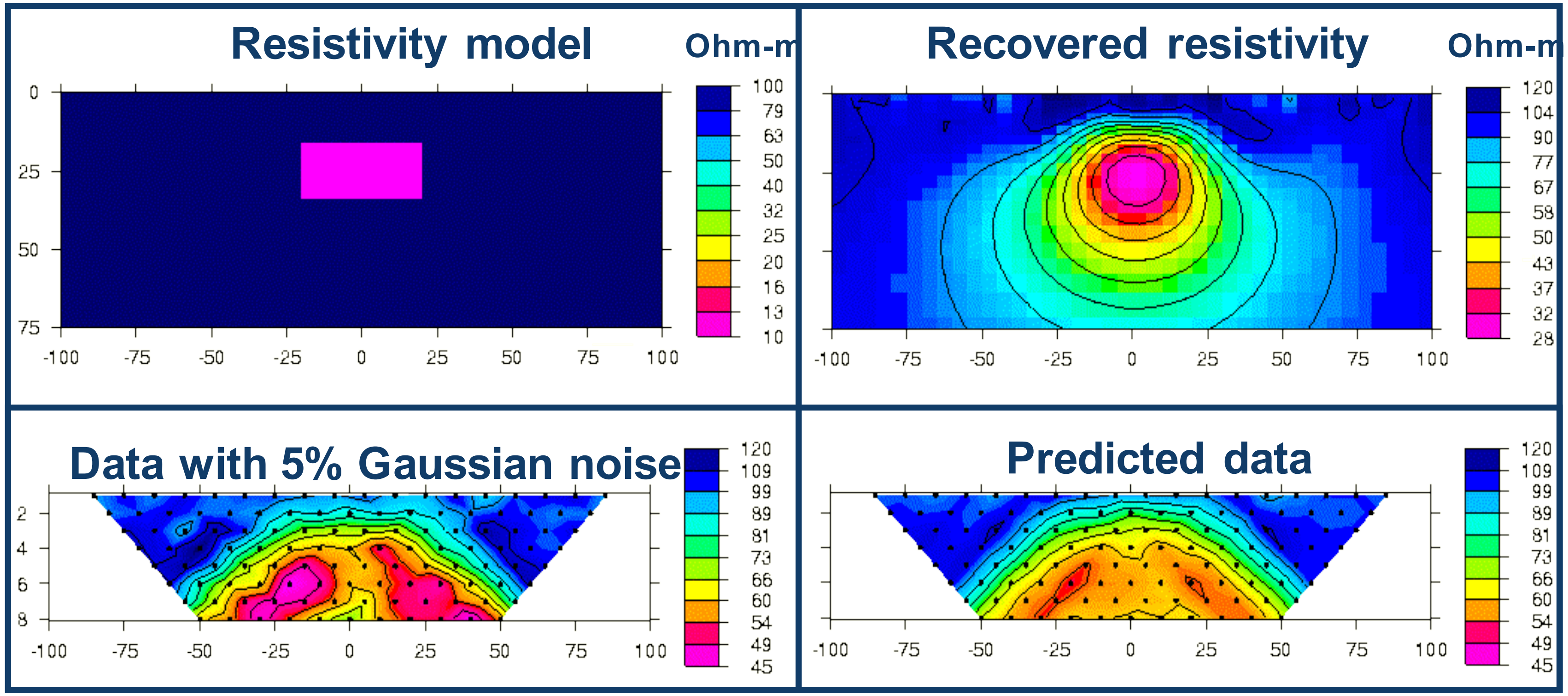
- Pole-dipole; n=1,8; a=10m; N=316

Inversion



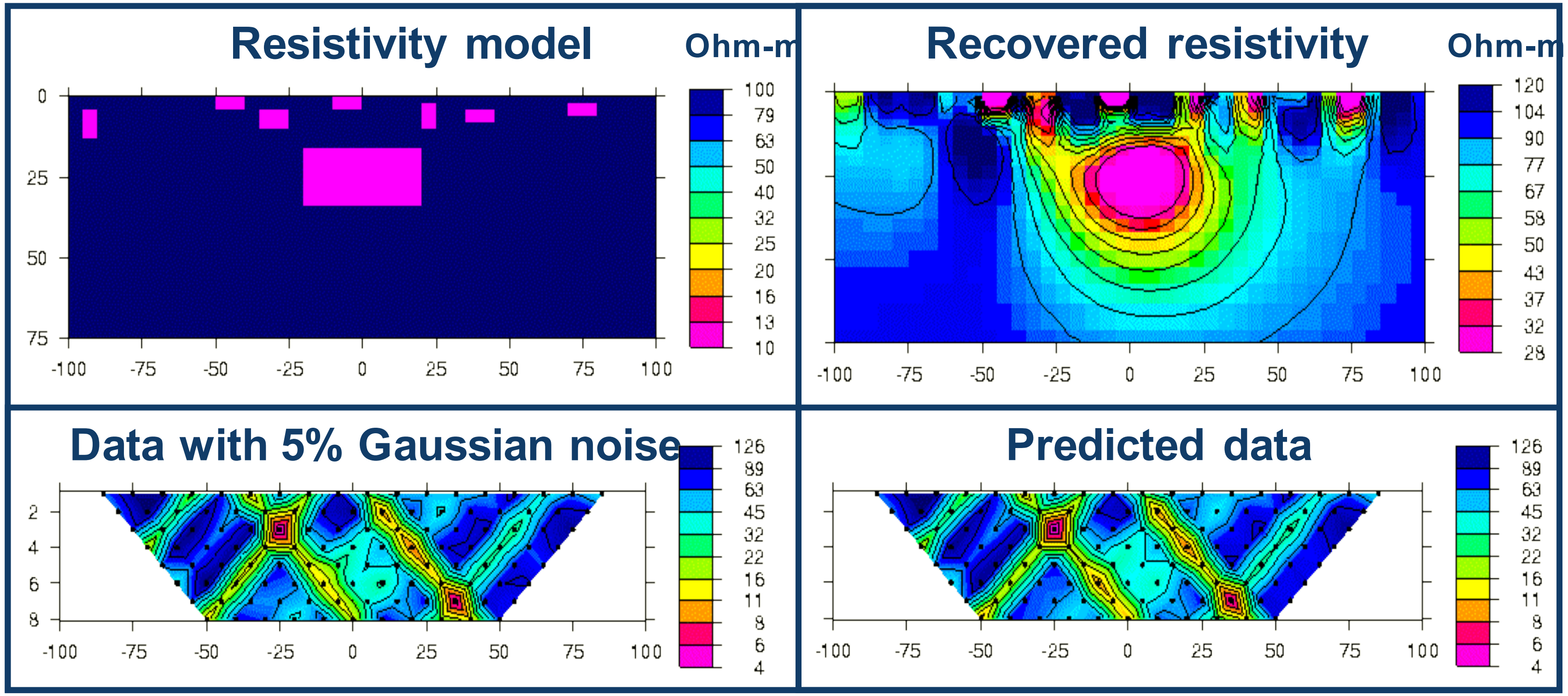
Inversion estimates Earth models based upon data and prior knowledge.

Example 1: buried prism



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

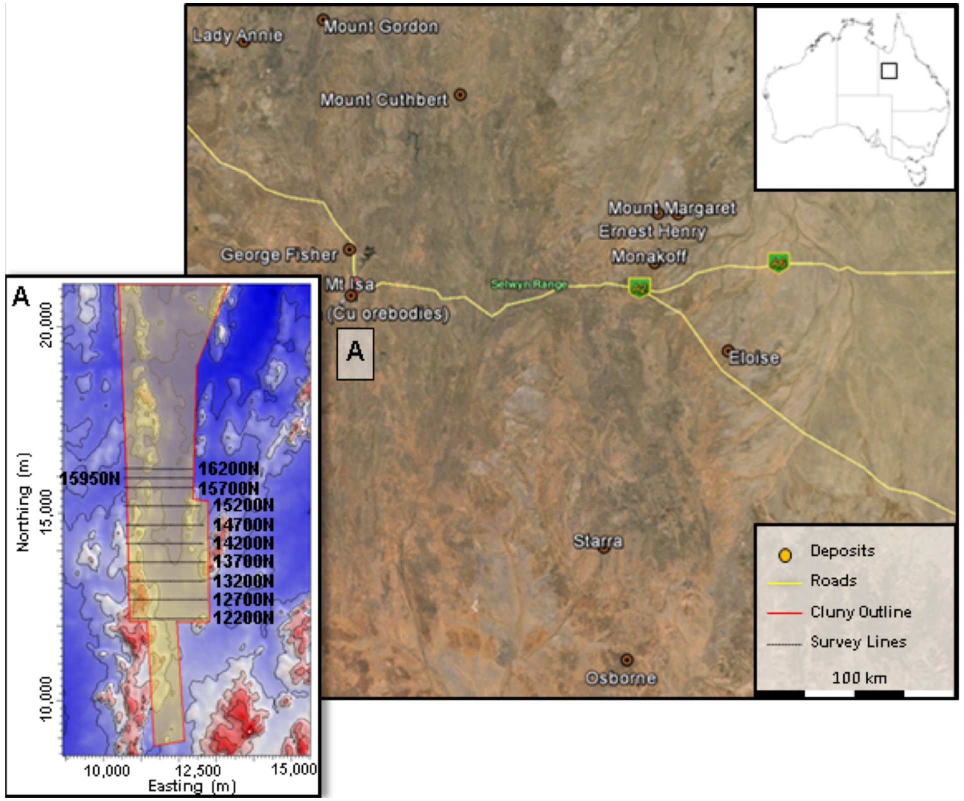
Example 2: prism with geologic noise



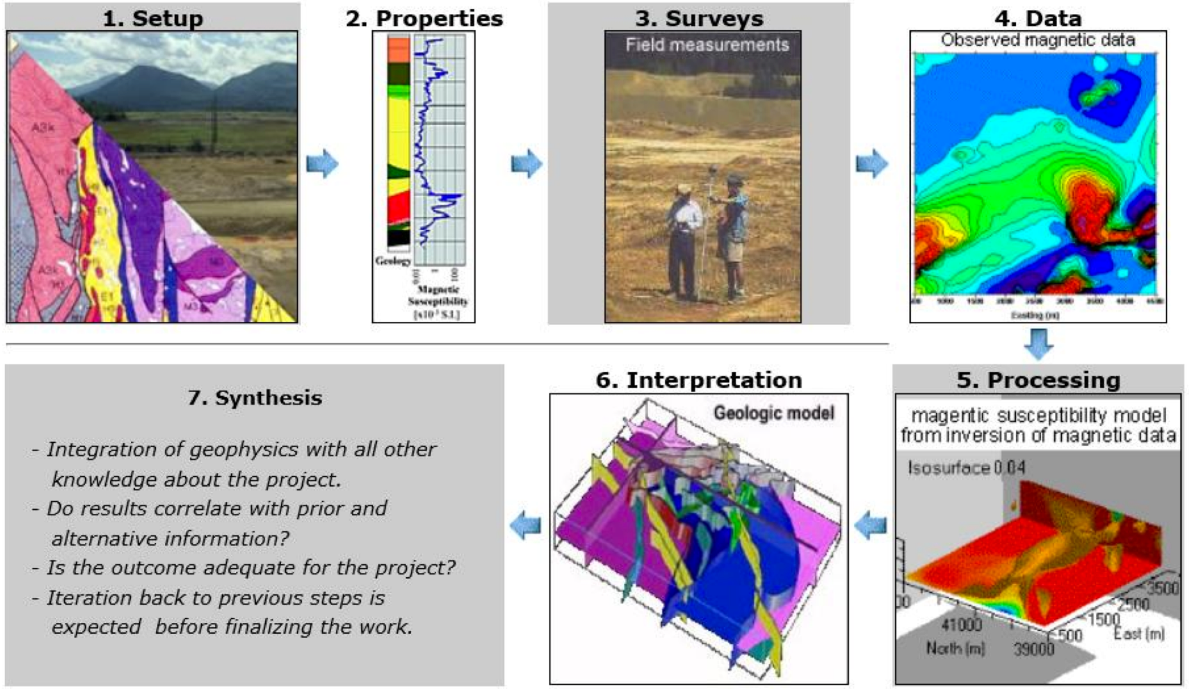
- Pole-dipole; n=1,8; a=10m; N=316; $(\alpha_s, \alpha_x, \alpha_z)$=(.001, 1.0, 1.0)

DCR Case History: Mt. Isa

Mt. Isa (Cluny prospect)

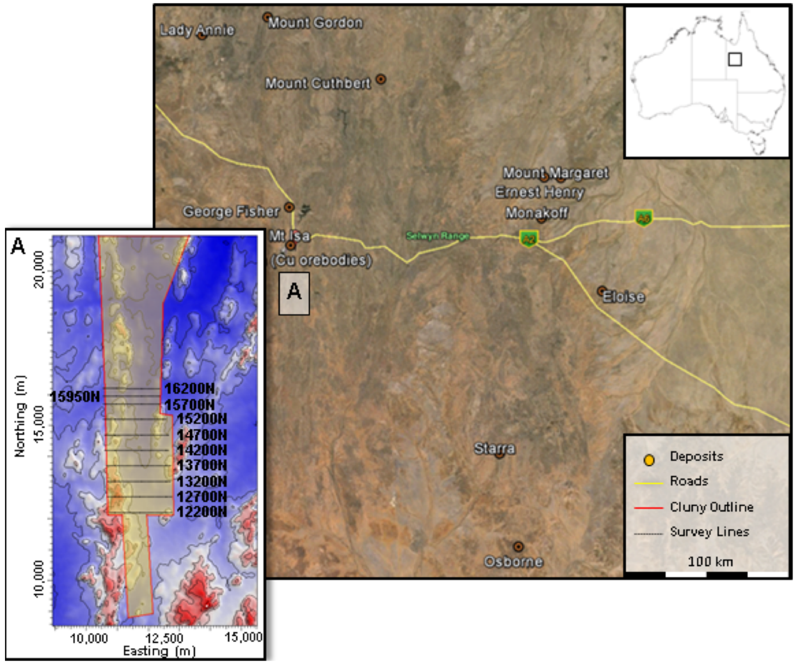


Seven Steps

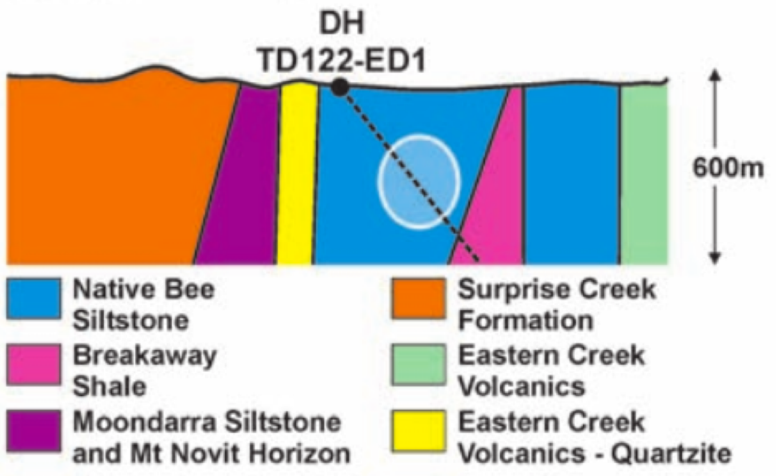


Setup

Mt. Isa (Cluny prospect)



Geologic model

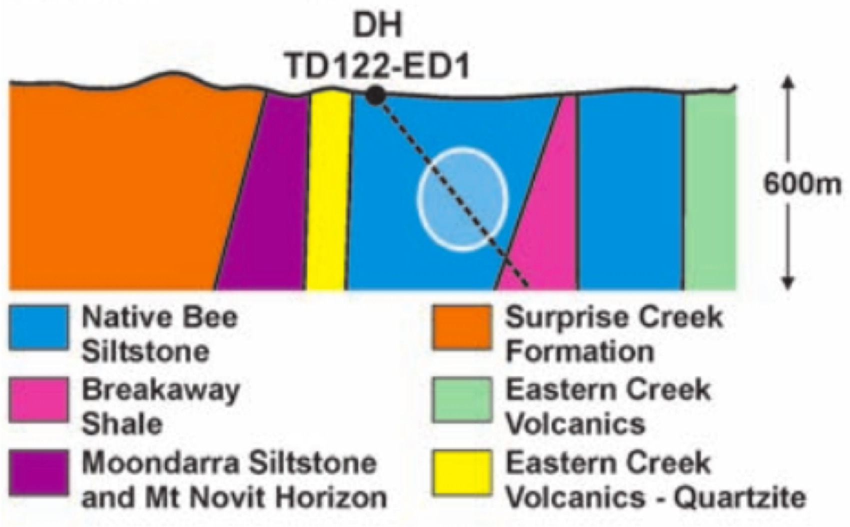


Question

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

Properties

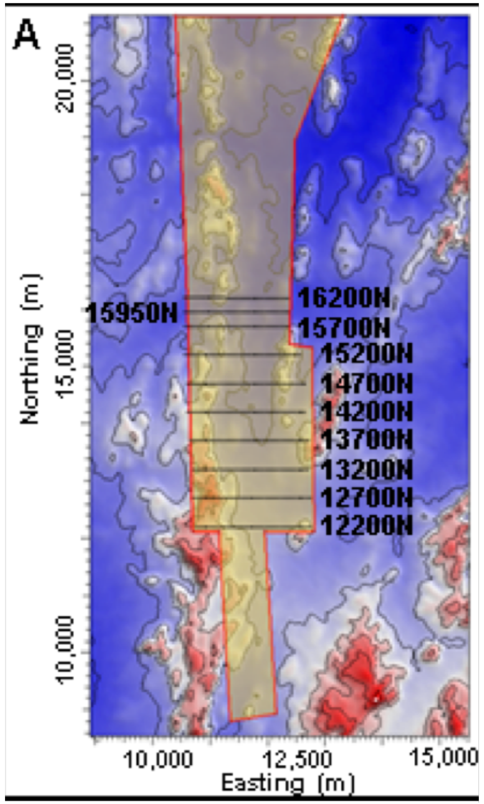
Geologic model



Conductivity table

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

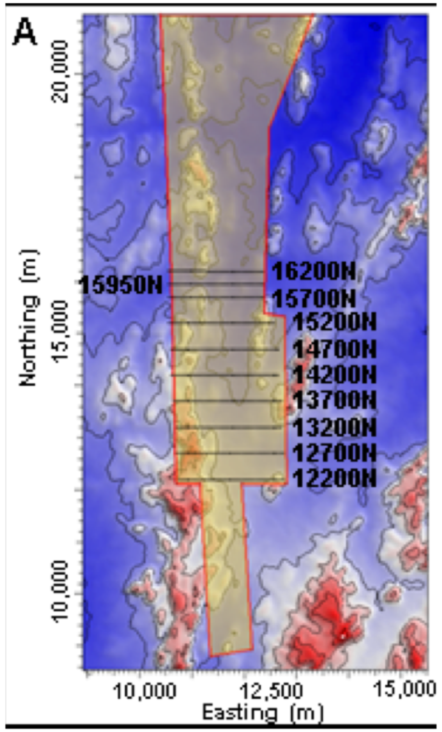
Surface topography



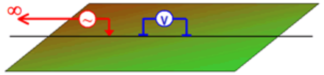
Survey and Data

- Eight survey lines
- Two survey configurations.

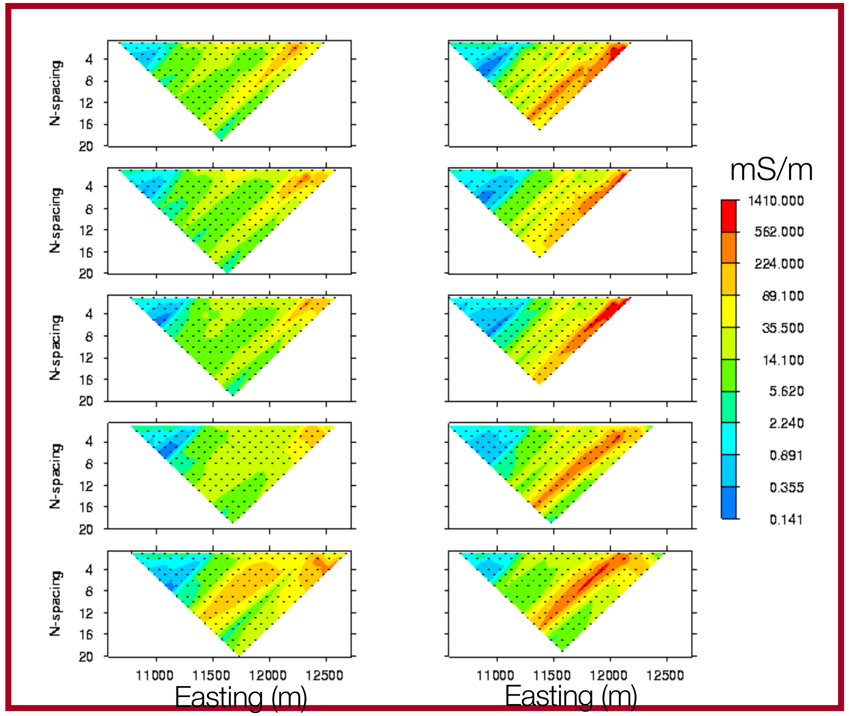
Surface topography



Data set #1:



Apparent resistivity, pole - dipole.



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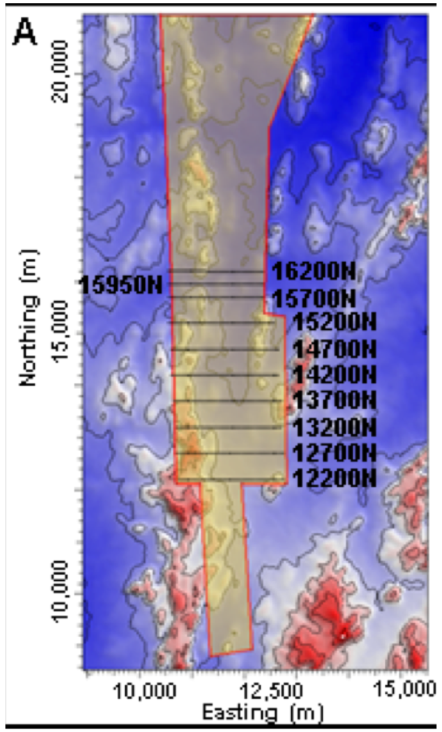
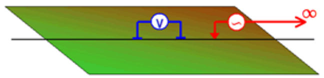
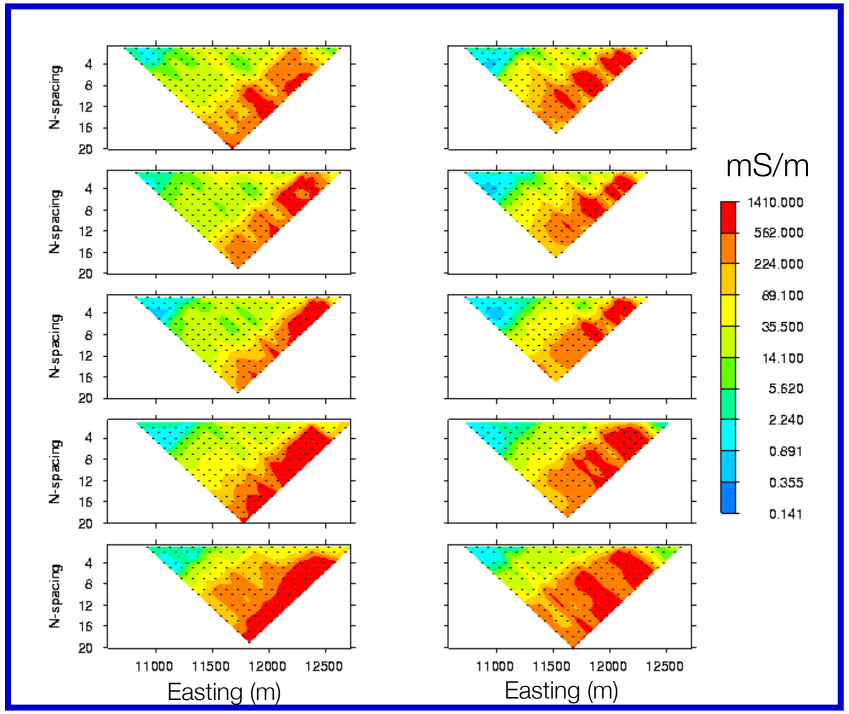


Data set #2:

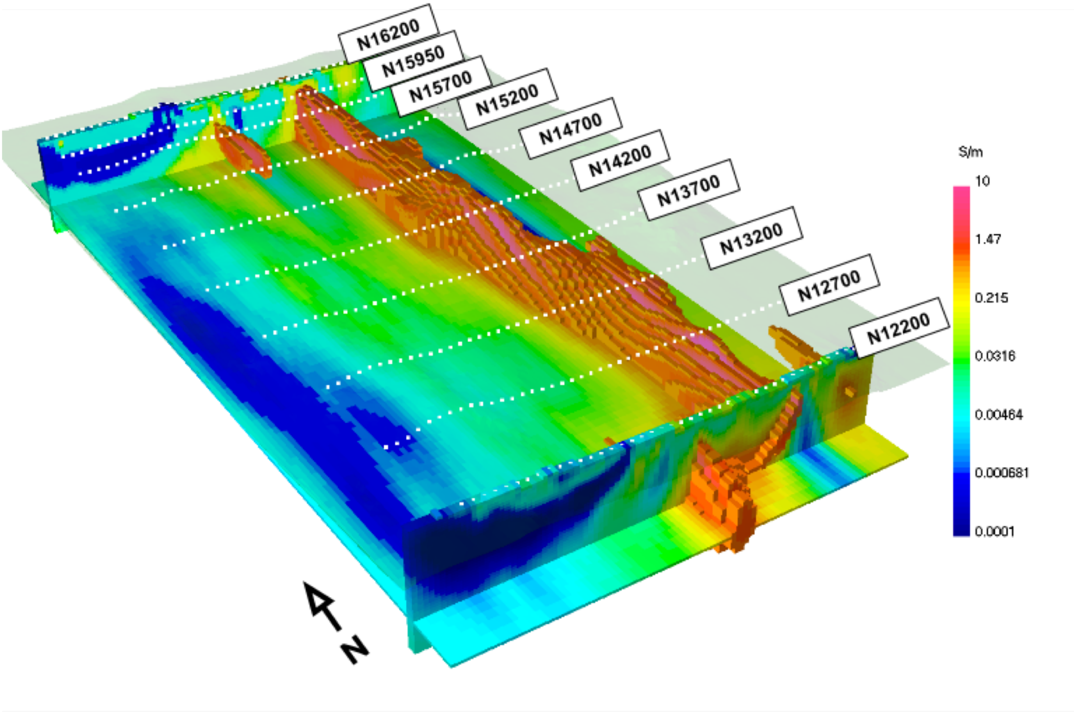
Apparent resistivity, dipole - pole



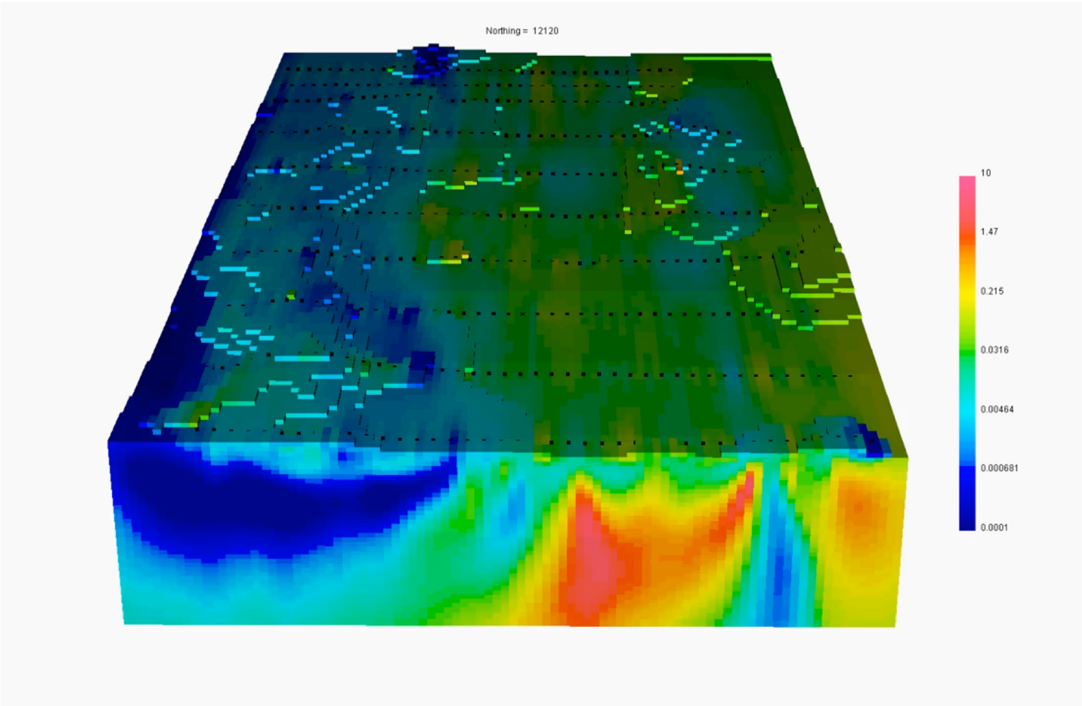


Processing and interpretation

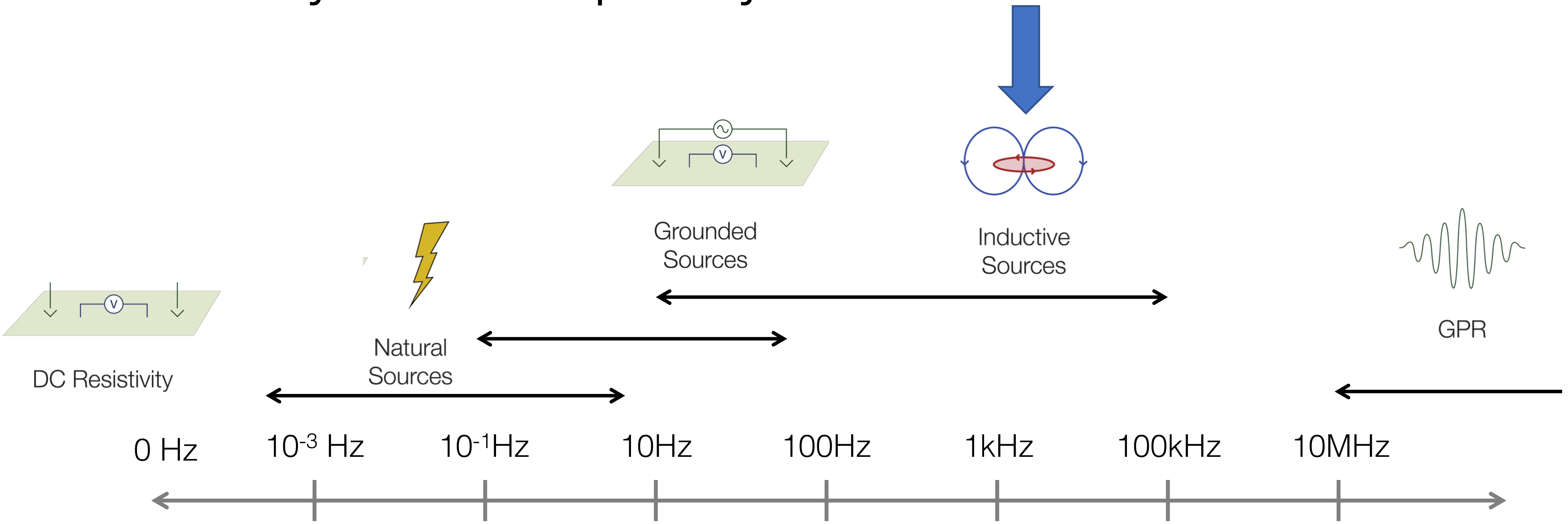
3D resistivity model



Animation



EM Surveys and frequency



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$$\nabla \times \nabla \times \vec{E} + \mu\sigma \frac{\partial \vec{E}}{\partial t} = 0$$

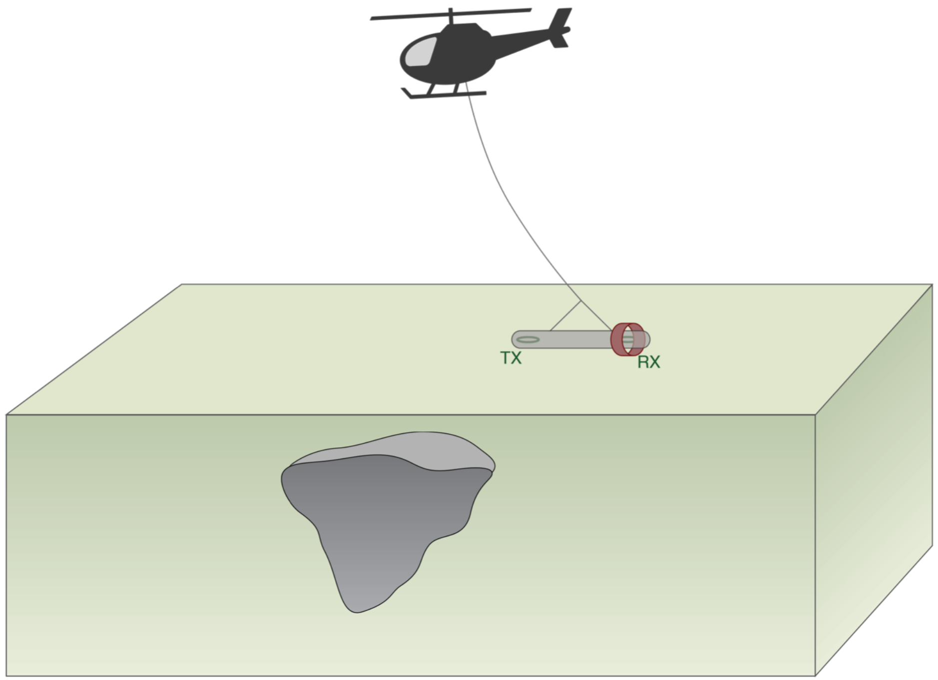
$$\nabla \times \nabla \times \vec{E} + \mu\sigma \frac{\partial \vec{E}}{\partial t} + \mu\epsilon \frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

Inductivity source EM survey

Basic Experiment

- **Setup:**

  transmitter and receiver are in a towed bird



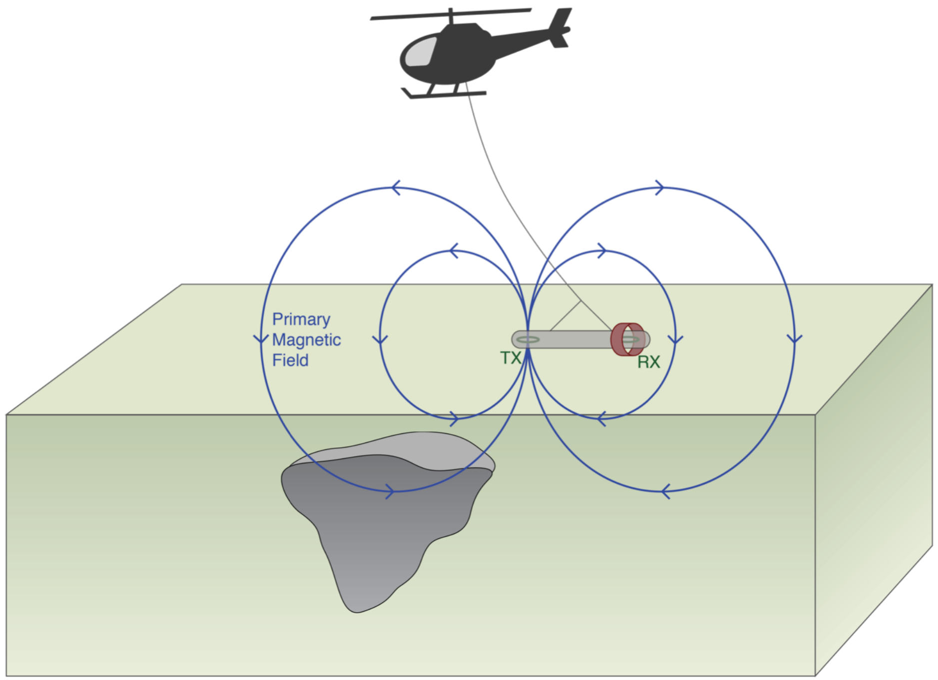
Basic Experiment

- **Setup:**

  transmitter and receiver are in a towed bird

- **Primary:**

  Transmitter produces a primary magnetic field



Basic Experiment

- **Setup:**
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- **Primary:**
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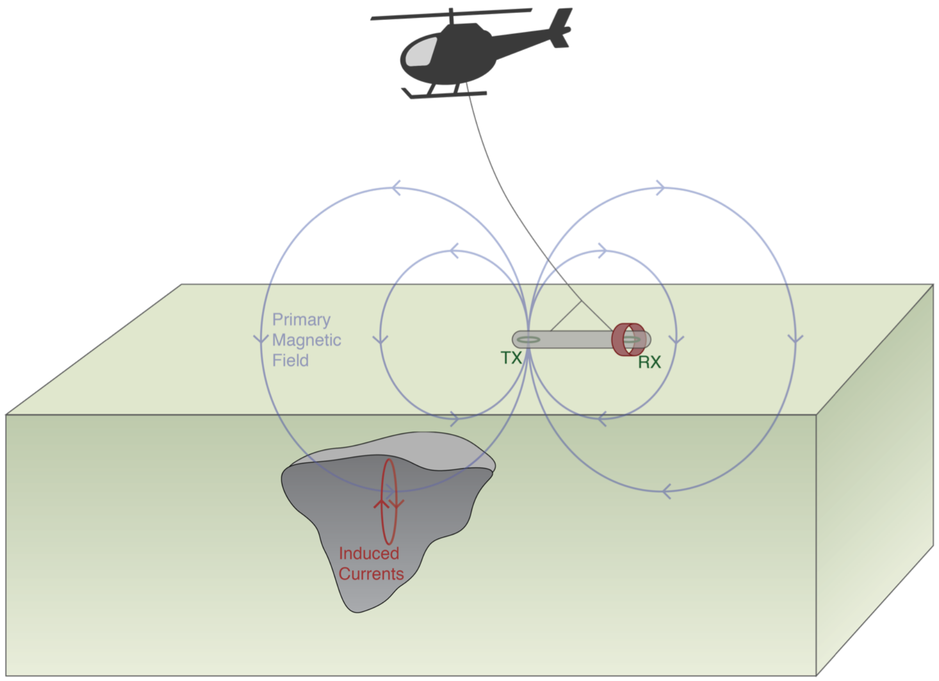
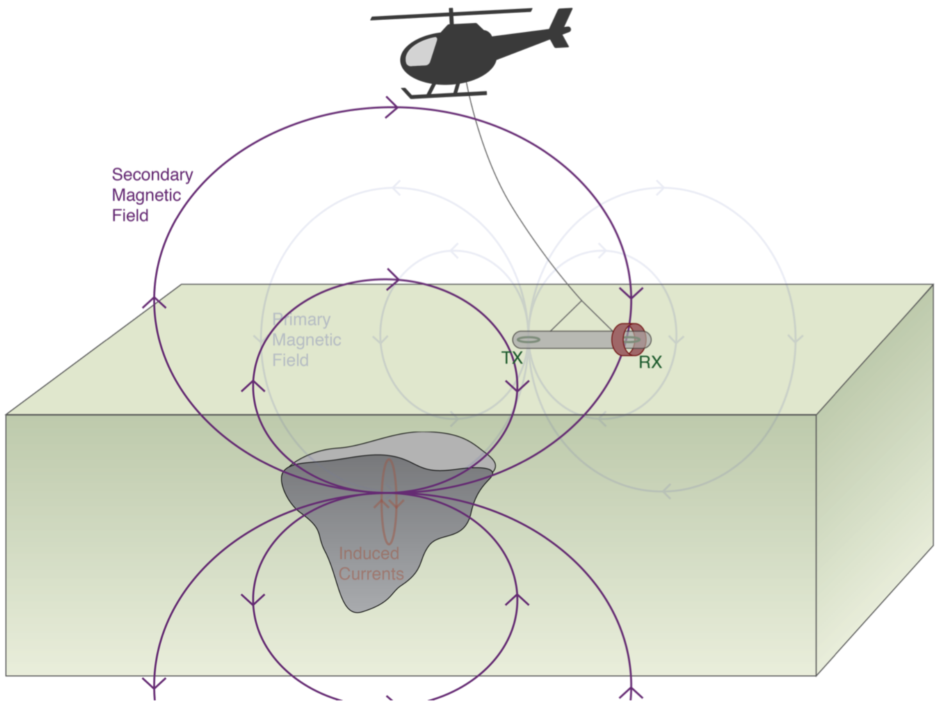
- **Induced Currents:**
  Time varying magnetic fields generate electric fields everywhere and currents in conductors

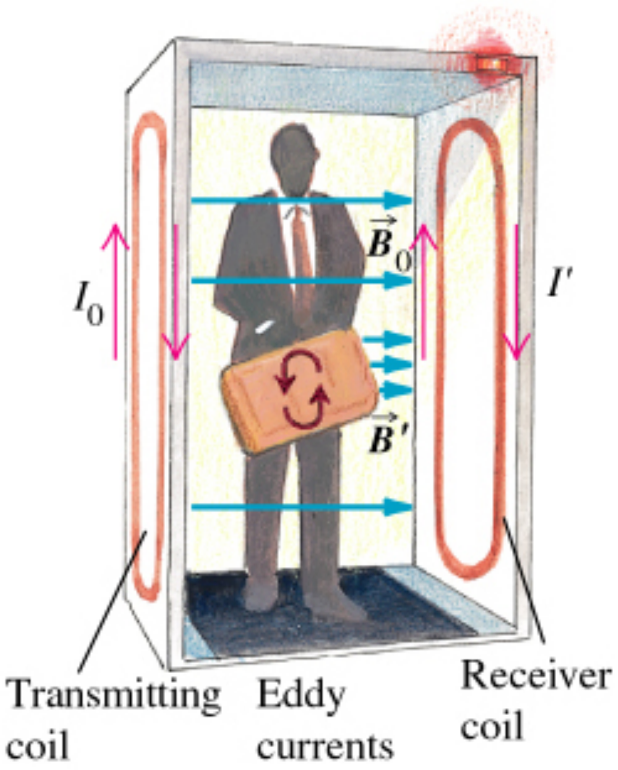


Basic Experiment

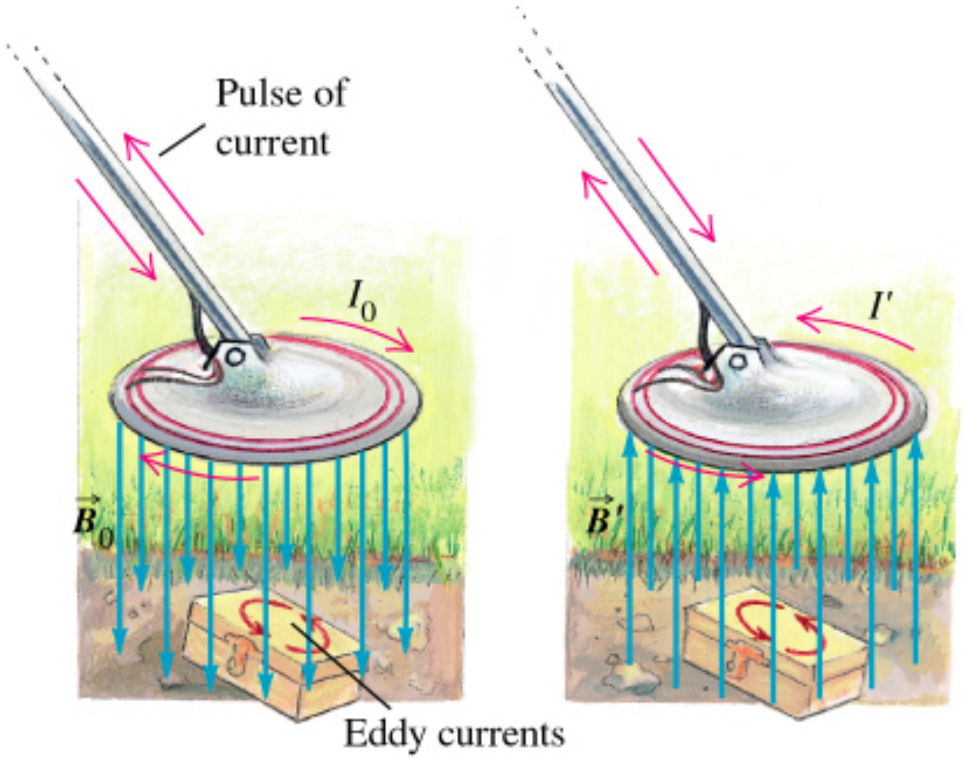
- **Setup:**
  transmitter and receiver are in a towed bird
- **Primary:**
  Transmitter produces a primary magnetic field
- **Induced Currents:**
  Time varying magnetic fields generate electric fields everywhere and currents in conductors
- **Secondary Fields:**
  The induced currents produce a secondary magnetic field.



Electromagnetic Induction



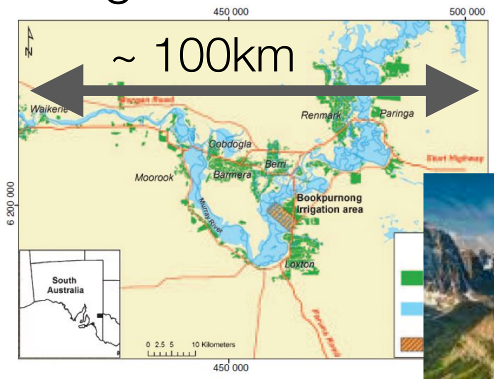
Security scan



Metal detector

Why airborne EM?

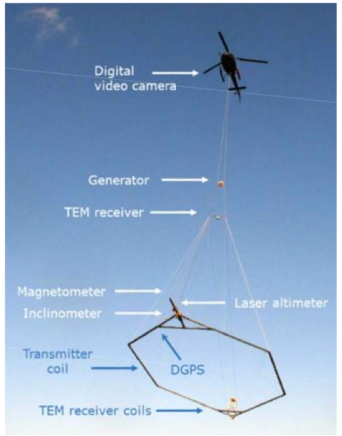
Large areas



Rugged terrain

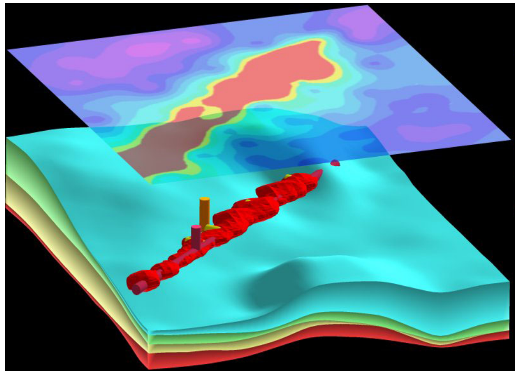
Airborne Survey

Resolve

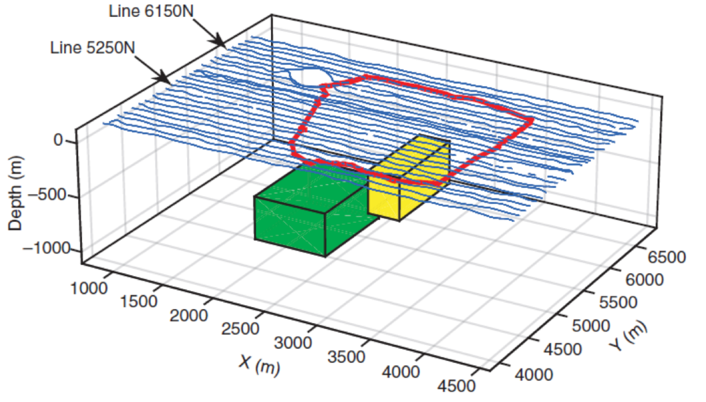


SkyTEM

Deep Targets



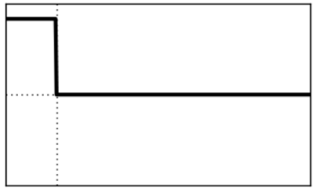
Large Loop



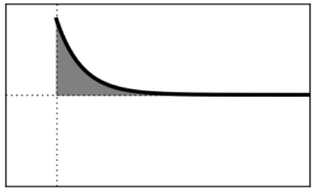
Receiver: Time Domain

- Primary field has off-time
- Measure secondary fields
- Receivers can be mounted on transmitter loop or above it

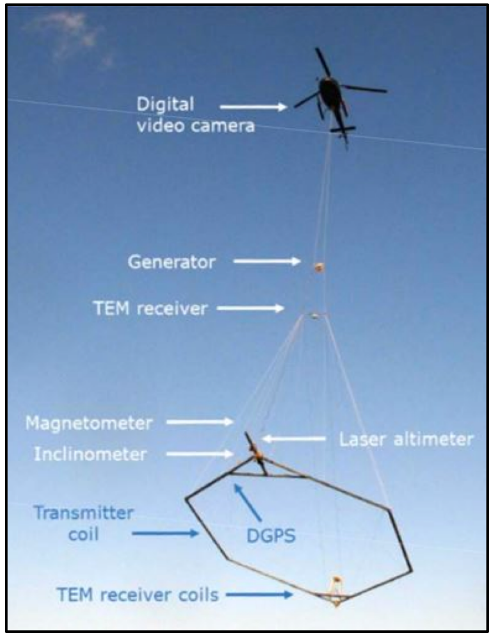
Current



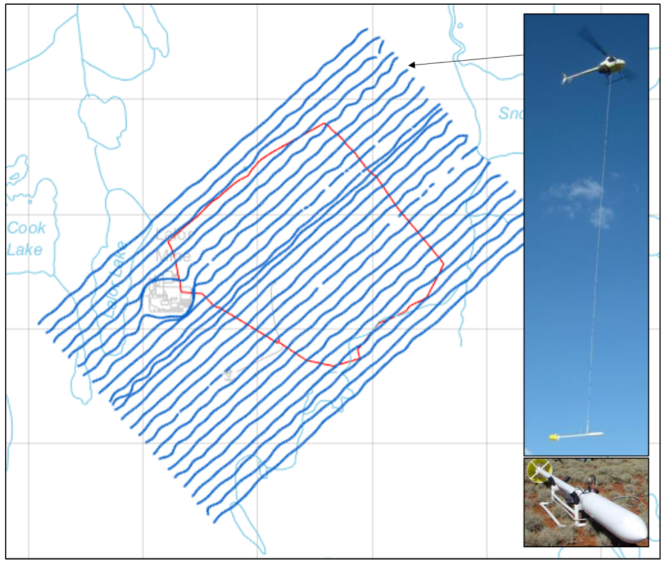
Response



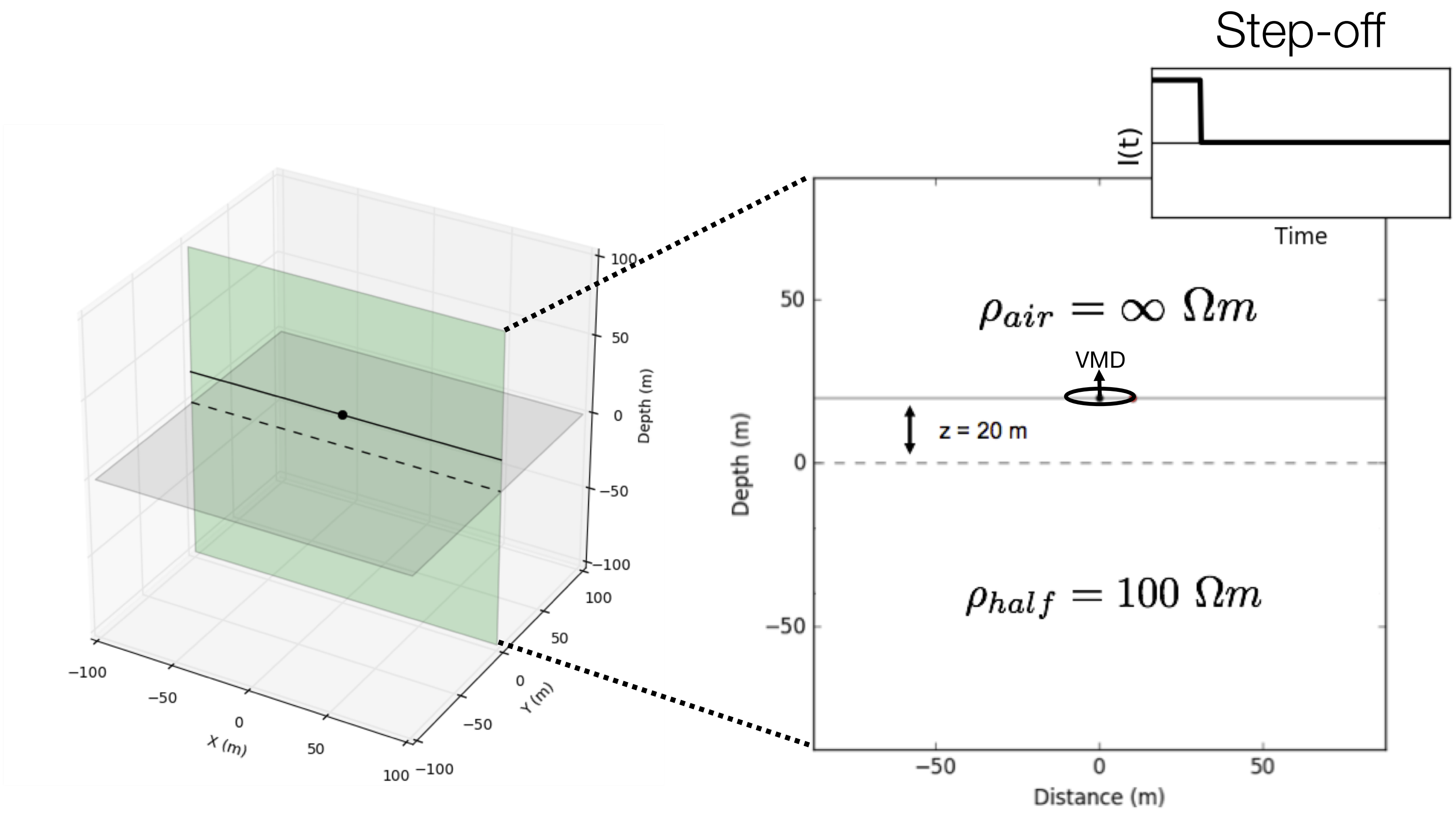
SkyTEM



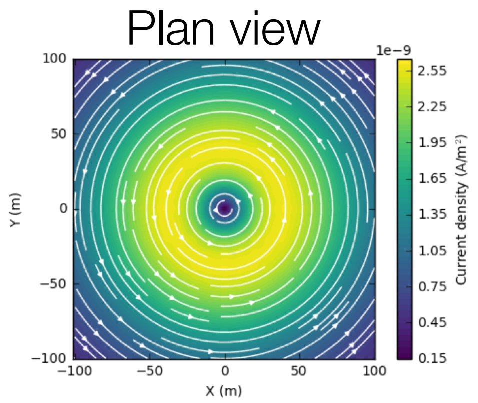
HeliSAM



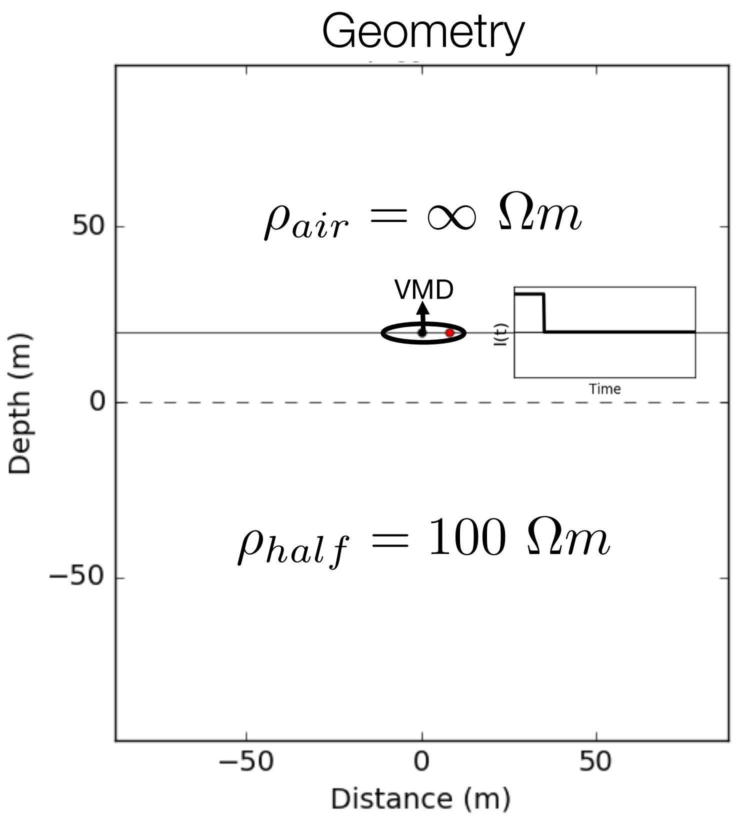
Vertical Magnetic Dipole over a halfspace (TDEM)

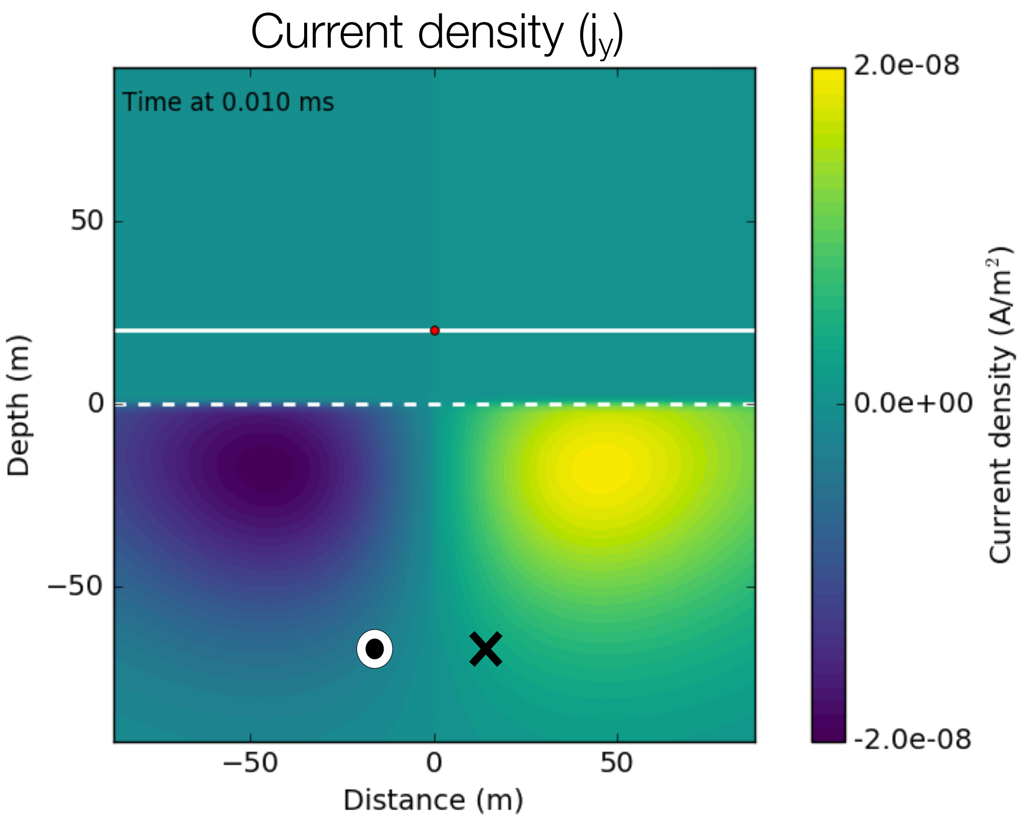


Current Density

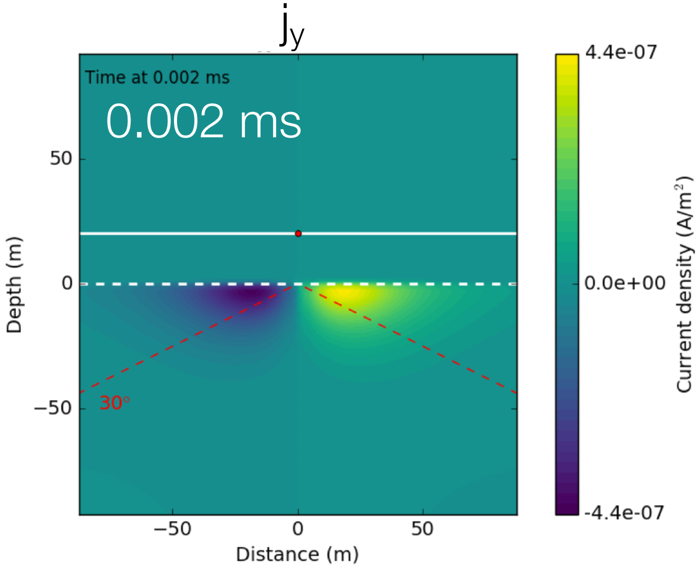


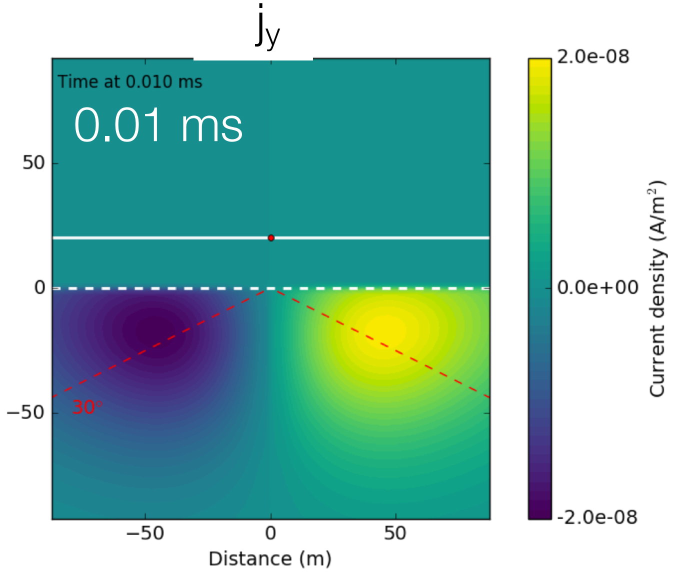
Time: 0.01ms

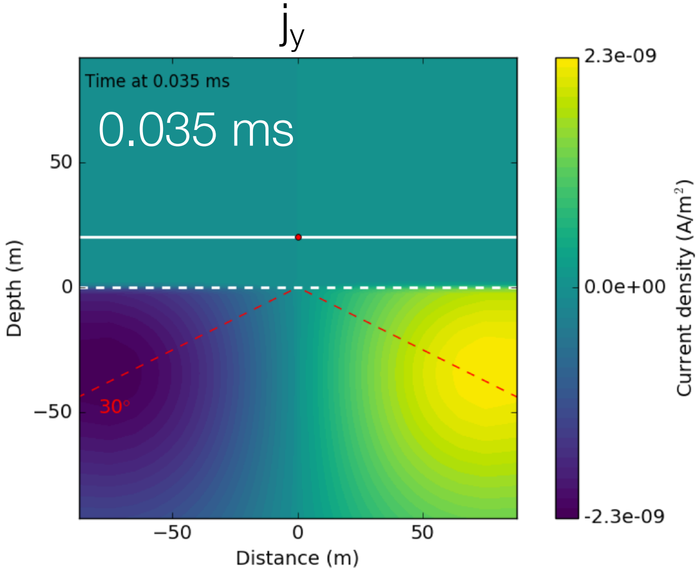




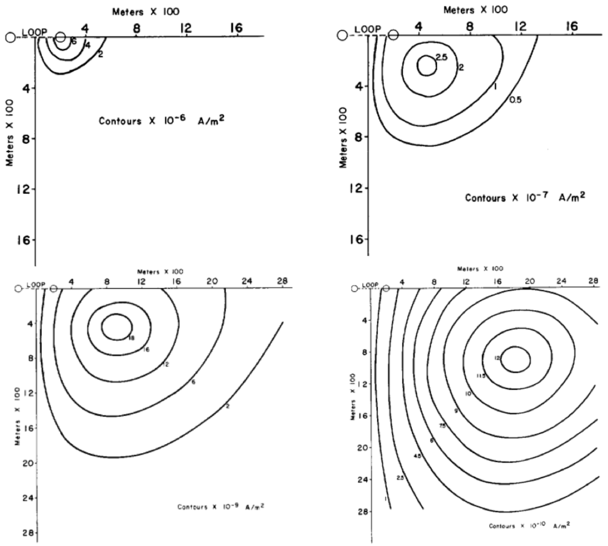
Summary: propagation through time







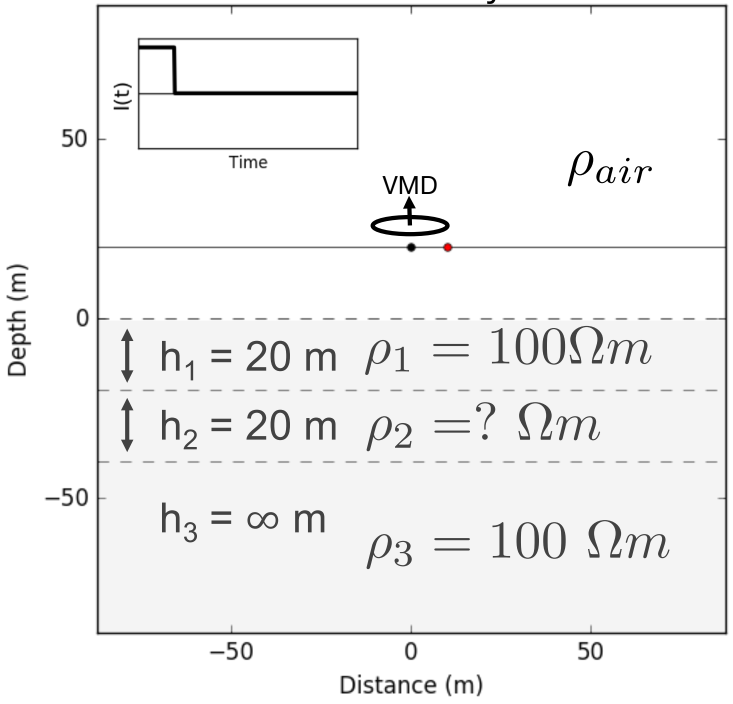
Nabighian (1979)



Layered earth

- 3 layers + air,
- ρ_2 varies

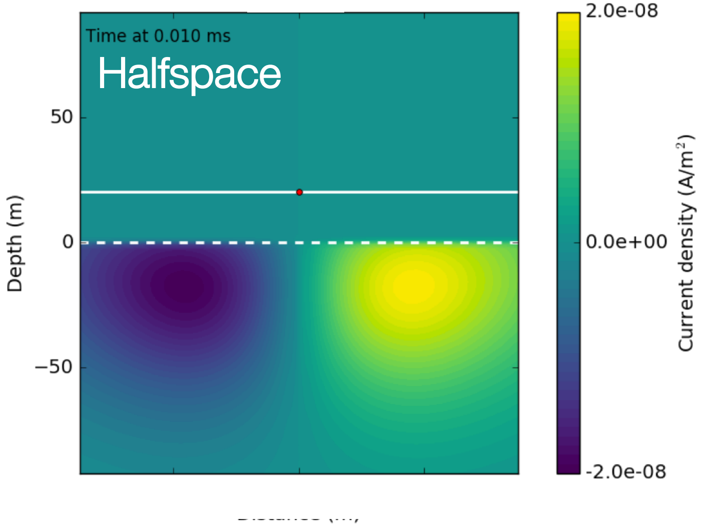
Geometry



- Four different cases:
  - Halfspace
    $\rho_2 = 100\ \Omega\mathrm{m}$
  - Resistive
    $\rho_2 = 1000\ \Omega\mathrm{m}$
  - Conductive
    $\rho_2 = 10\ \Omega\mathrm{m}$
  - Very conductive
    $\rho_2 = 1\ \Omega\mathrm{m}$
- Fields
  - j_y off-time
  - **b** off-time

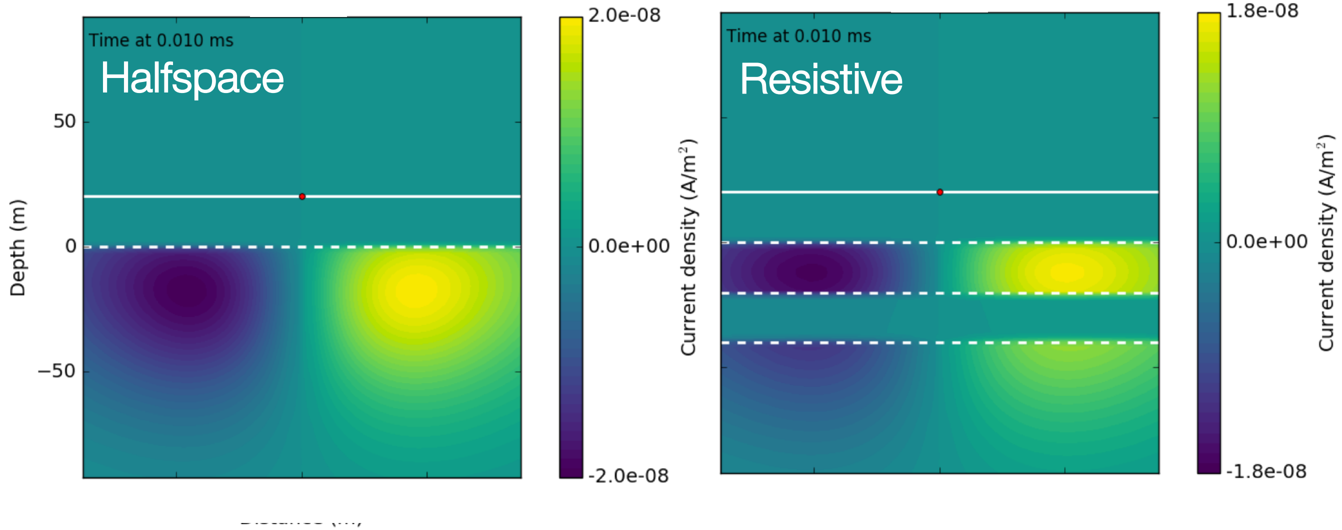
Layered earth currents (j_y)

$\rho_2 = 100\ \Omega m$



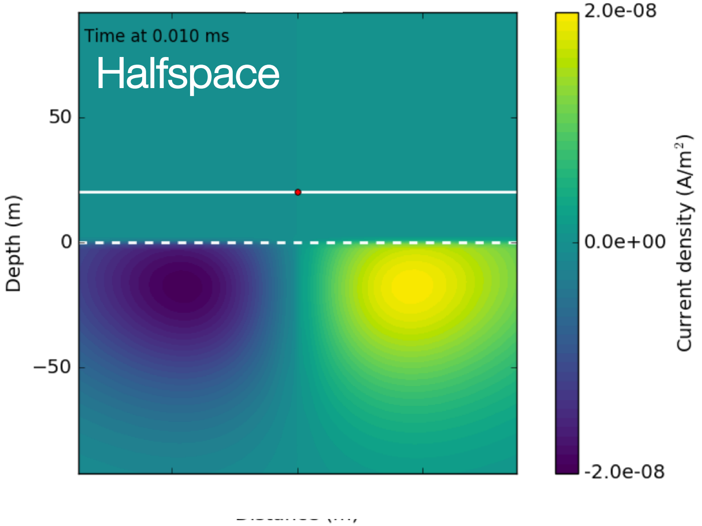
Layered earth currents (j_y)

$\rho_2 = 100\ \Omega m$ $\rho_2 = 1000\ \Omega m$

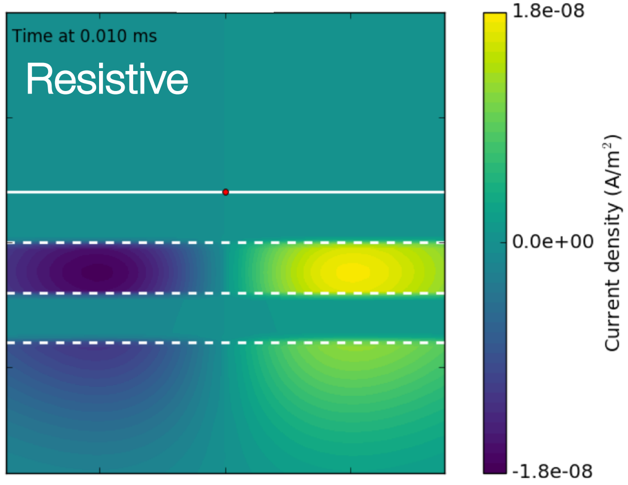


Layered earth currents (j_y)

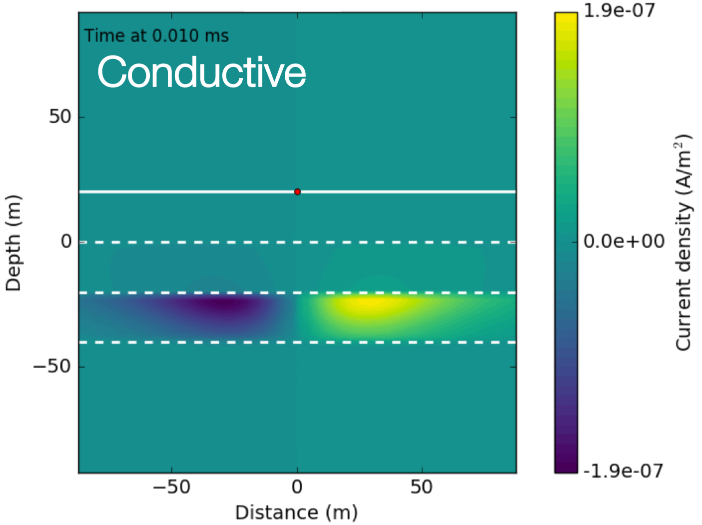
$\rho_2 = 100\ \Omega m$



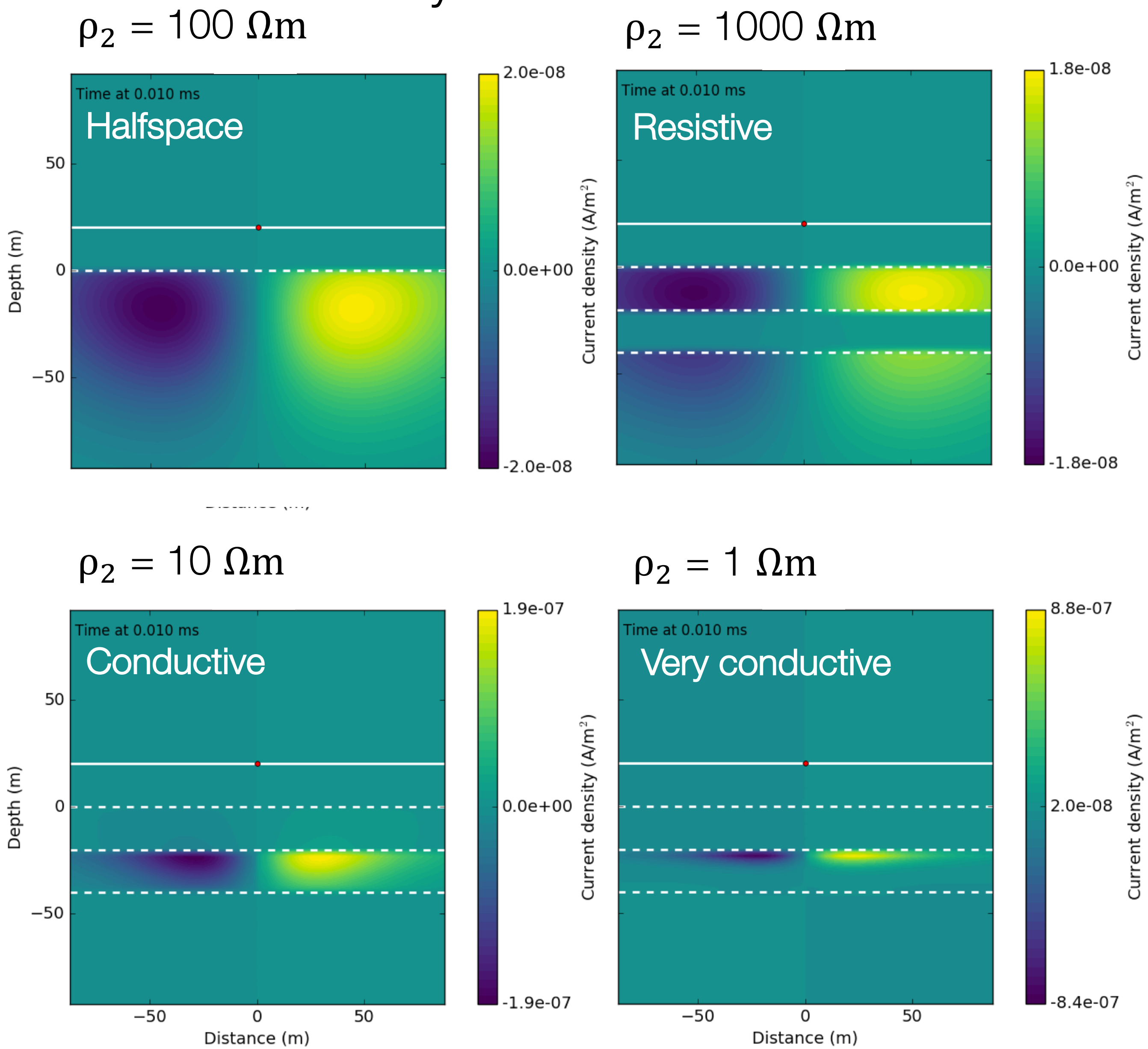
$\rho_2 = 1000\ \Omega m$



$\rho_2 = 10\ \Omega m$

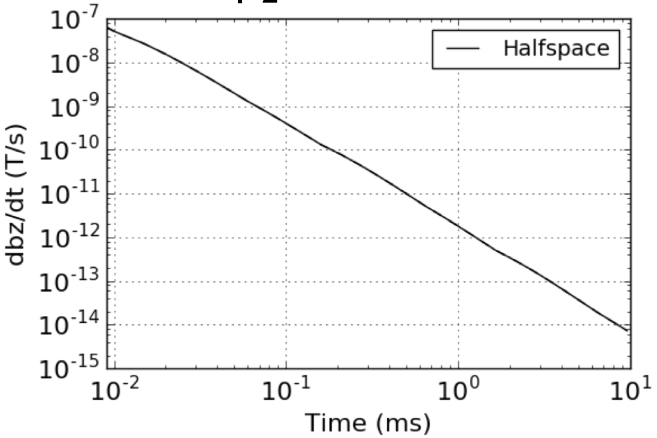


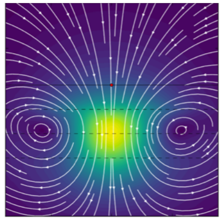
Layered earth currents (j_y)



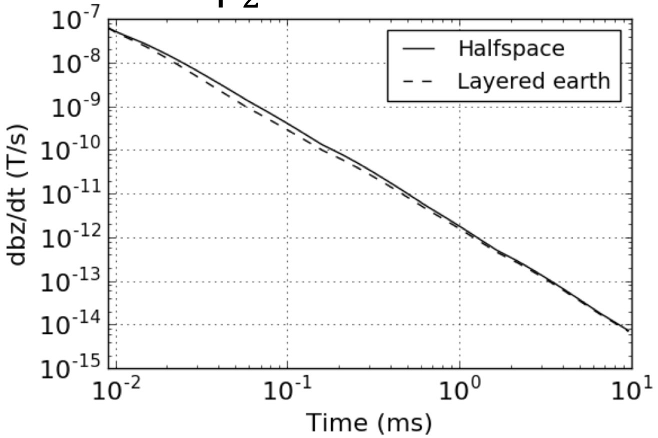
db_z/dt sounding curves

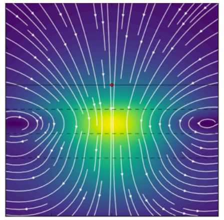
$\rho_2 = 100\ \Omega m$





$\rho_2 = 1000\ \Omega m$





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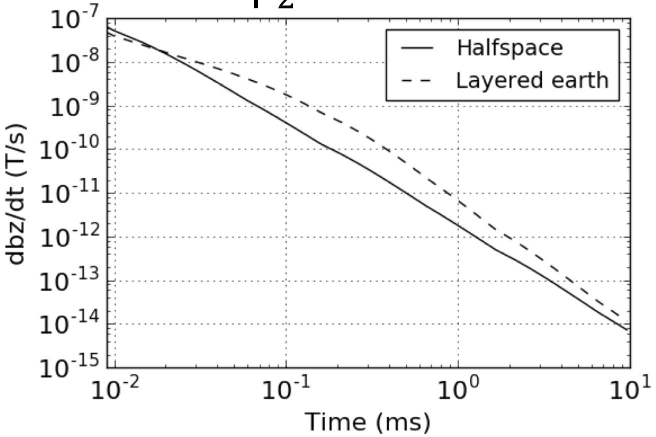
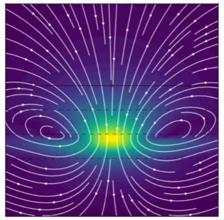
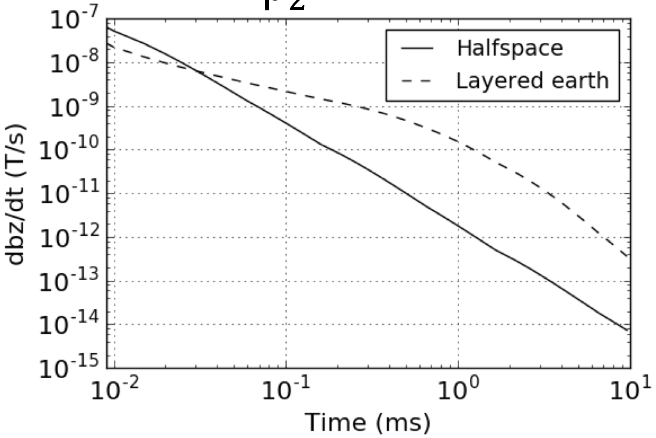
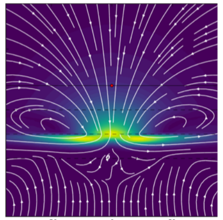




$\rho_2 = 1\ \Omega m$





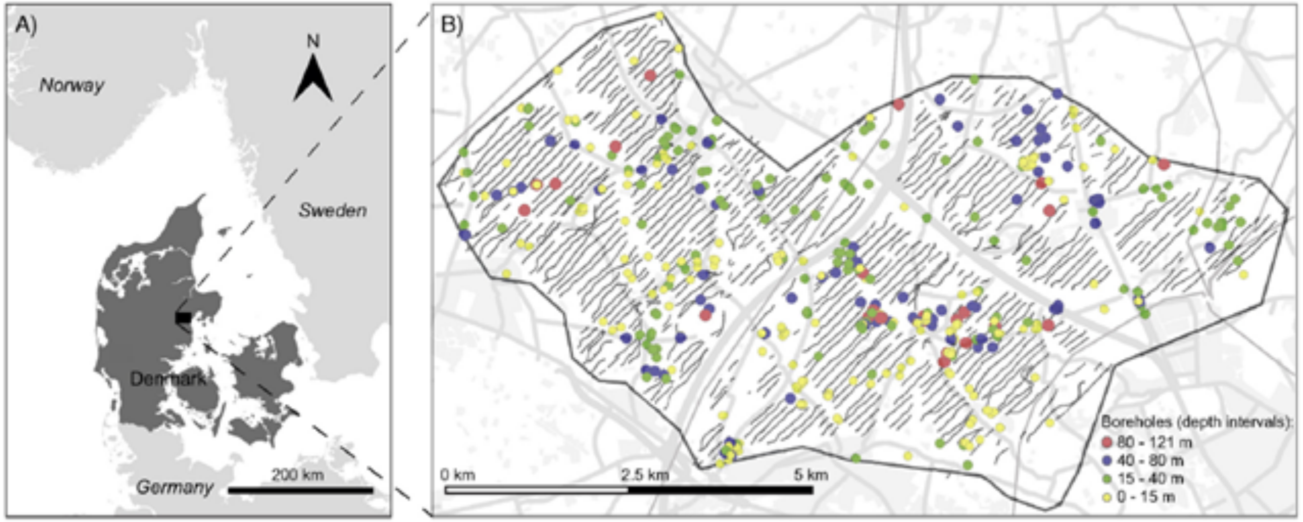
Case History: Kasted

Vilhelmsen et al. (2016)

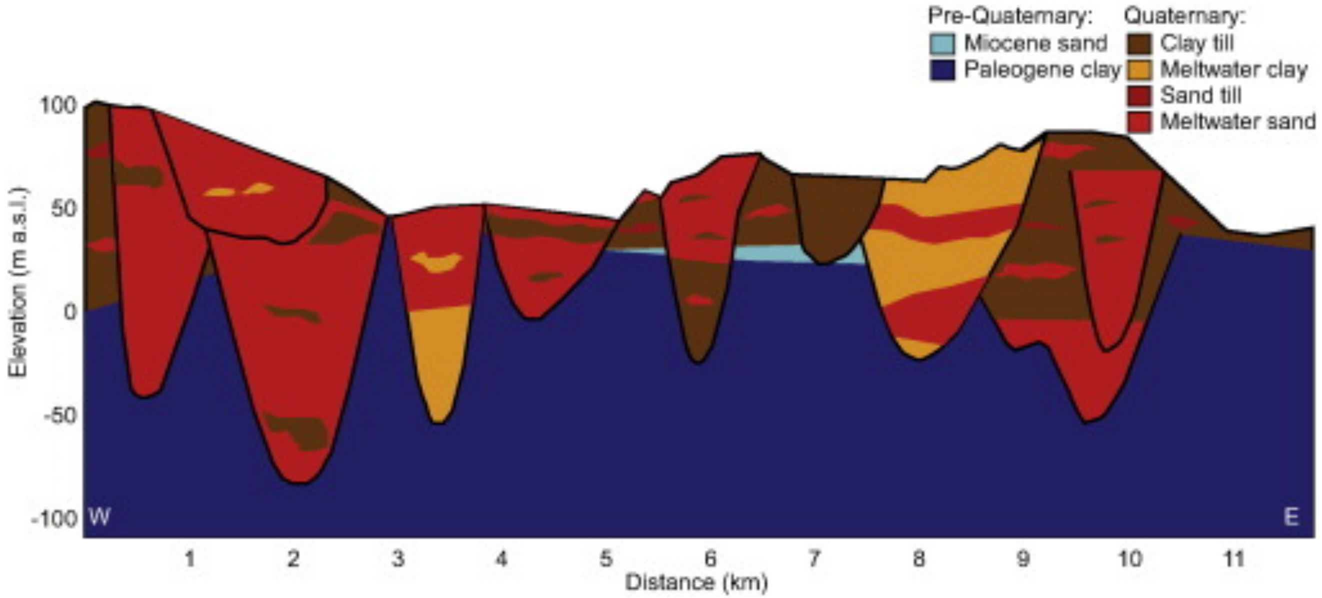
Setup

A) Survey Area: Kasted, Demark

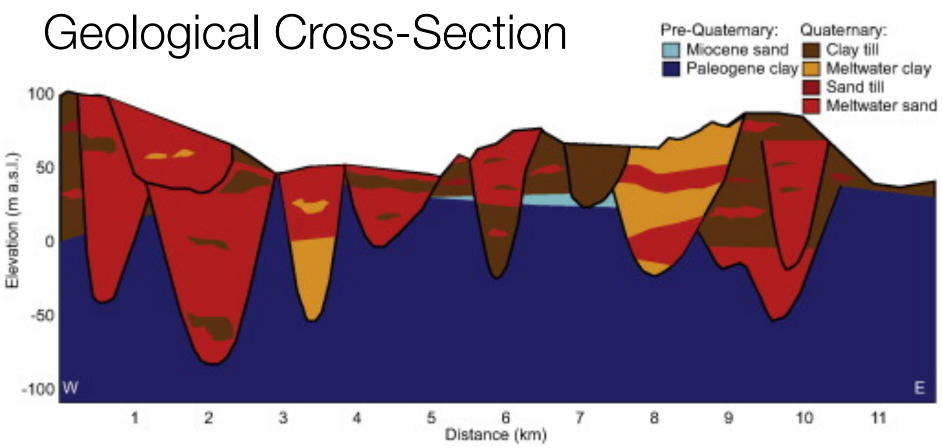
B) Borehole locations



Local Geology:
W-E cross-section



Properties

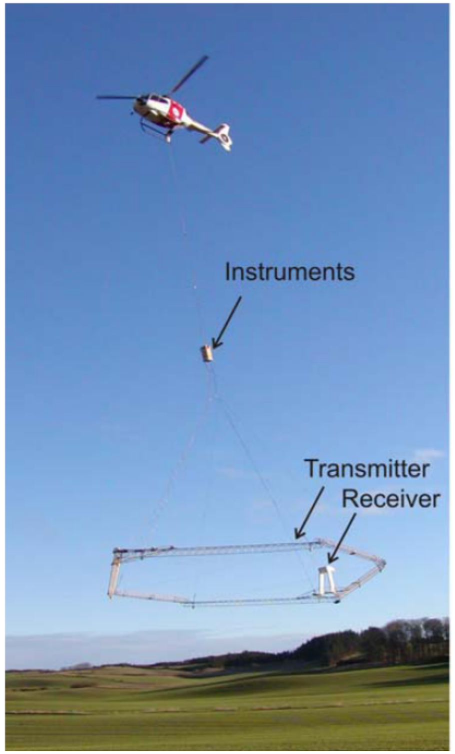


Geological Units	Resistivity (Ωm)
Palaeogene Clay	1-10
Clay Till	25-60
Sand Till	>50
Meltwater Sand and Gravel	>60
Glaciolacustrine Clay	10-40
Miocene Silt and Sand	>40
Miocene Clay	10-40
Sand	>40
Clay	1-60

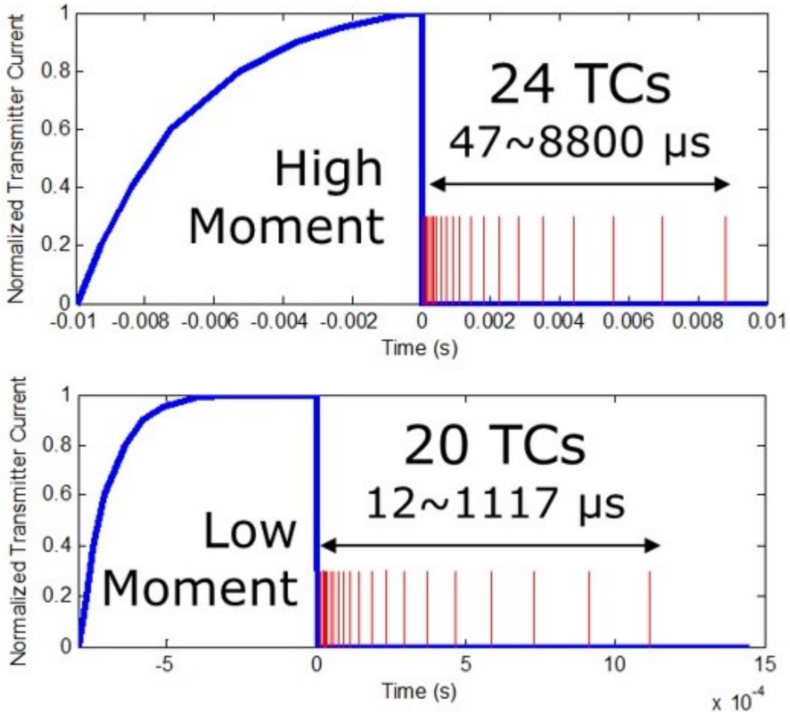
- Buried valleys with clays beneath
- Infill (water-bearing): coarse sand and gravel
- Clays are conductive (1-40 Ωm)
- Water-bearing sands and gravels are more resistive (>40 Ωm)

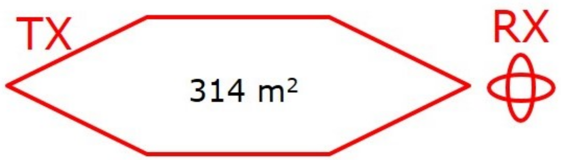
Survey

SkyTEM System



System Configuration

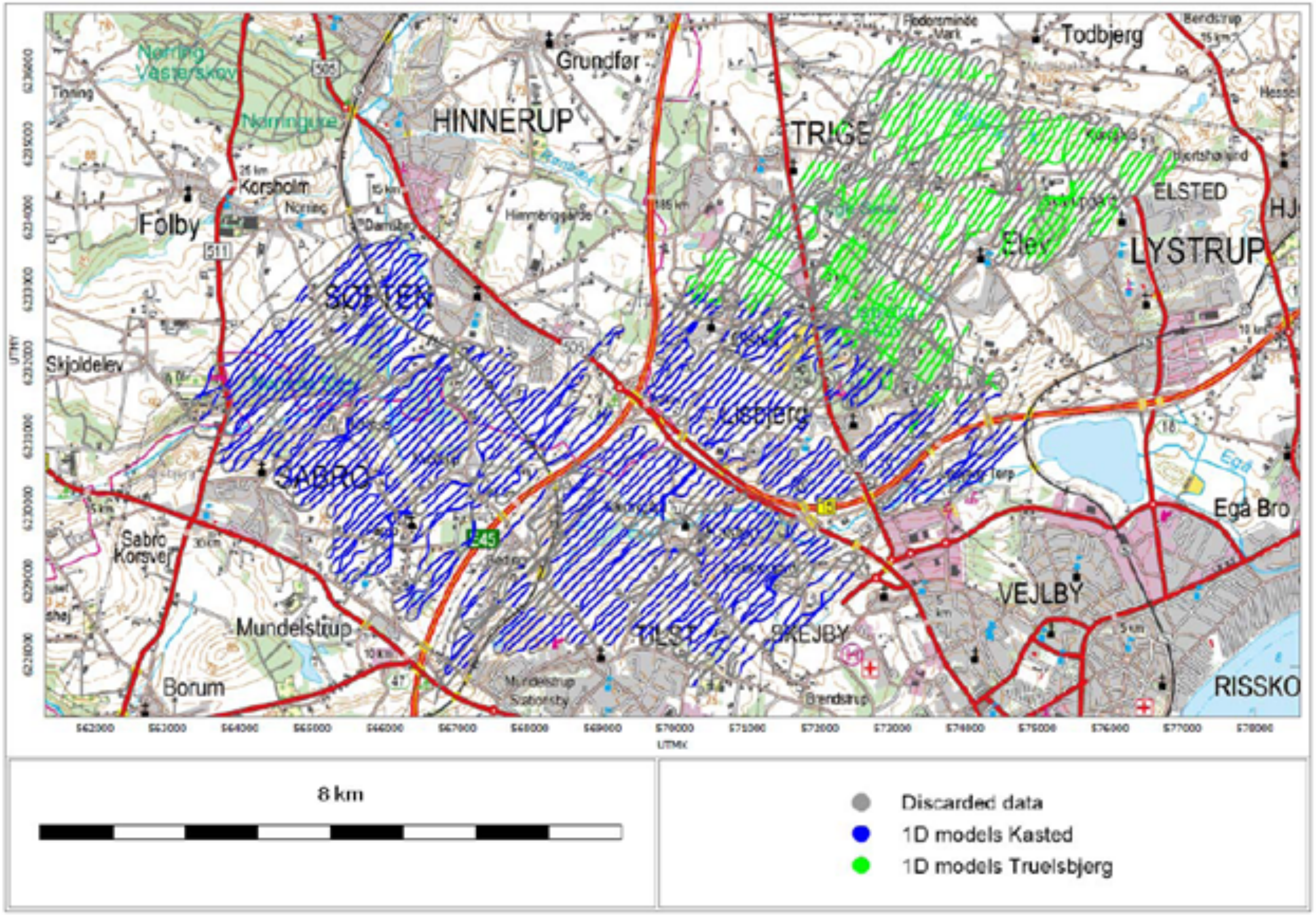




- Low moment (LM) used to image near surface structures
- High moment (HM) used to image deeper structures

Data

Blue: data used for Kasted study

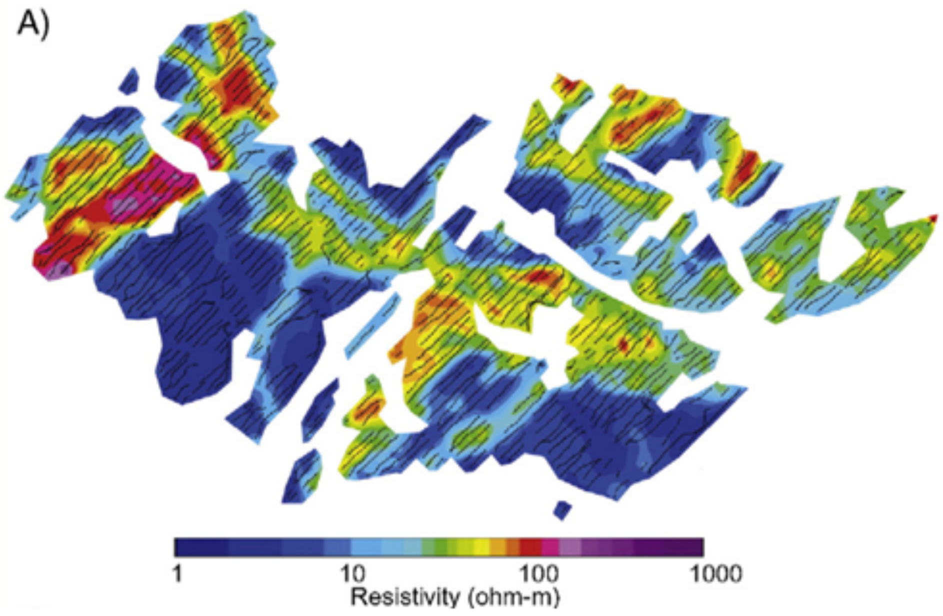


- 333 line km of data, 100 m line-spacing
- Data points with strong coupling to cultural noise were removed (~30%)

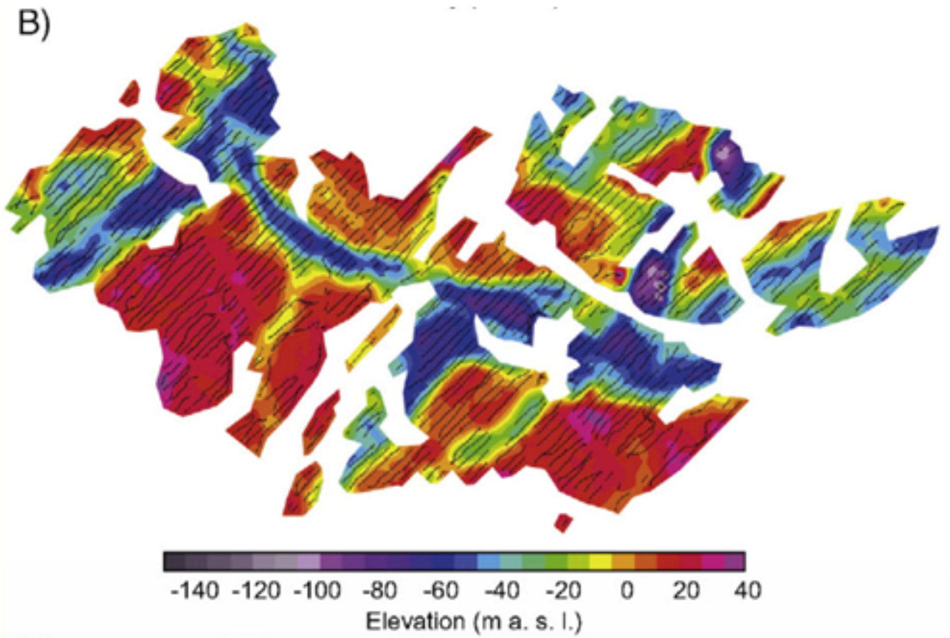
Processing (inversion)

- Spatially constrained 1D inversion → quasi-3D approach
- 9,500 soundings were inverted using 25 layers

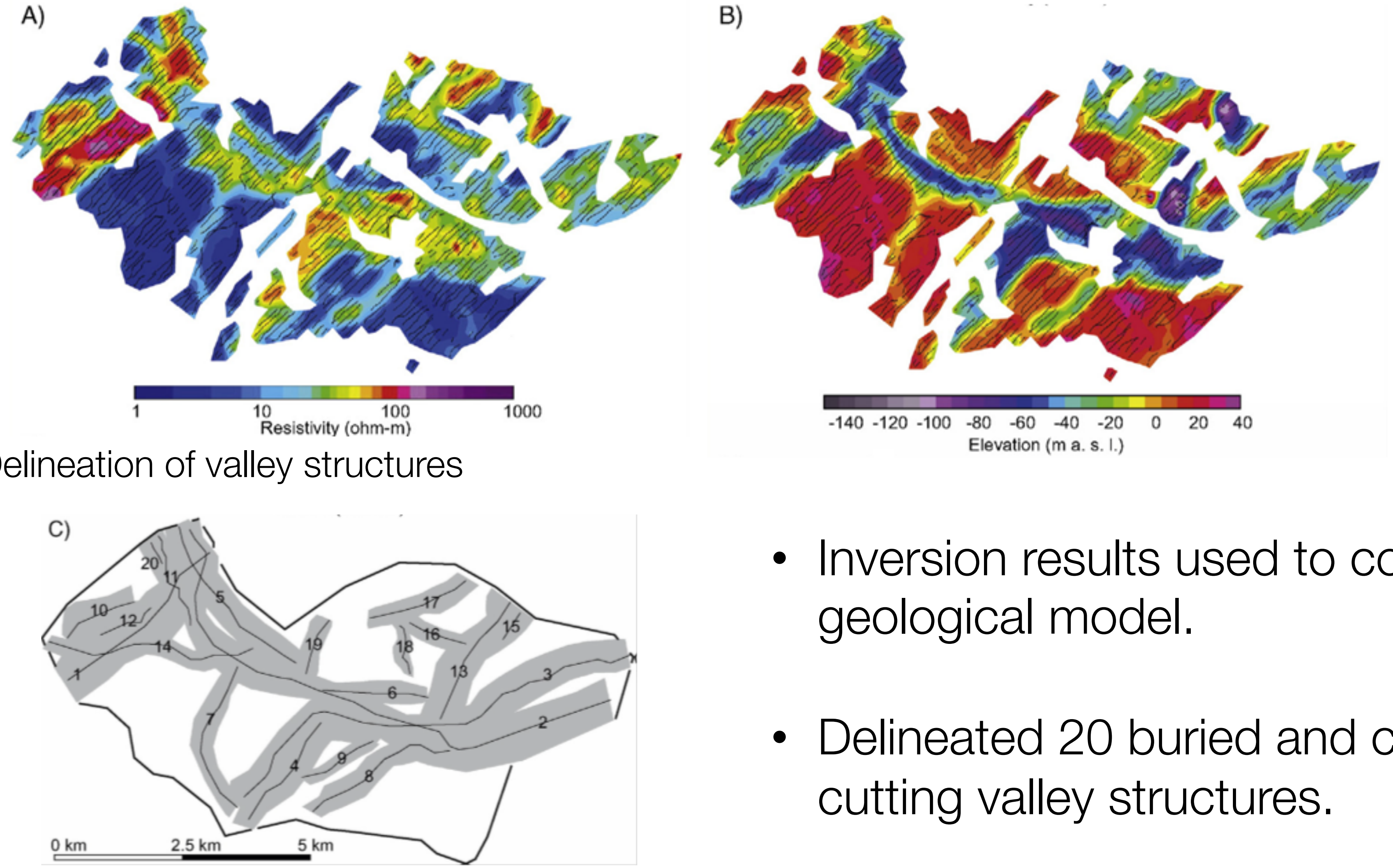
Depth slice 5 m above sea-level



Approximate depth to the top of Paleogene clay layer



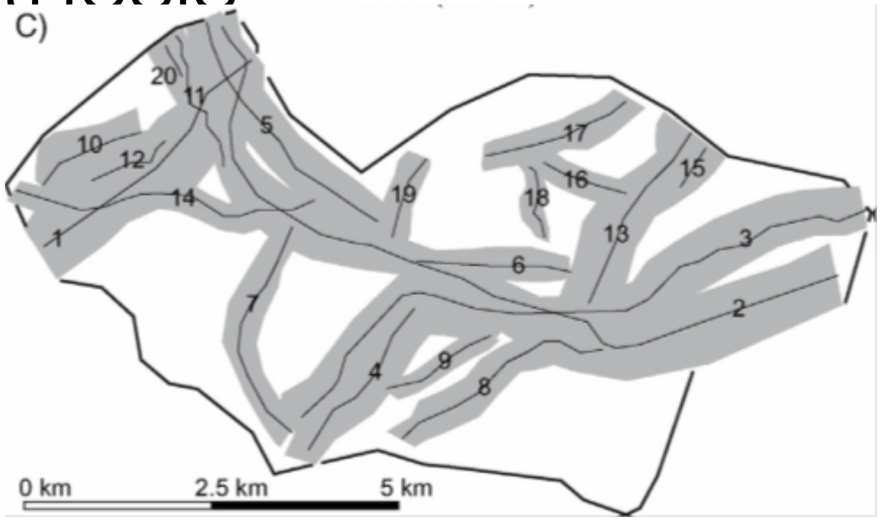
Interpretation



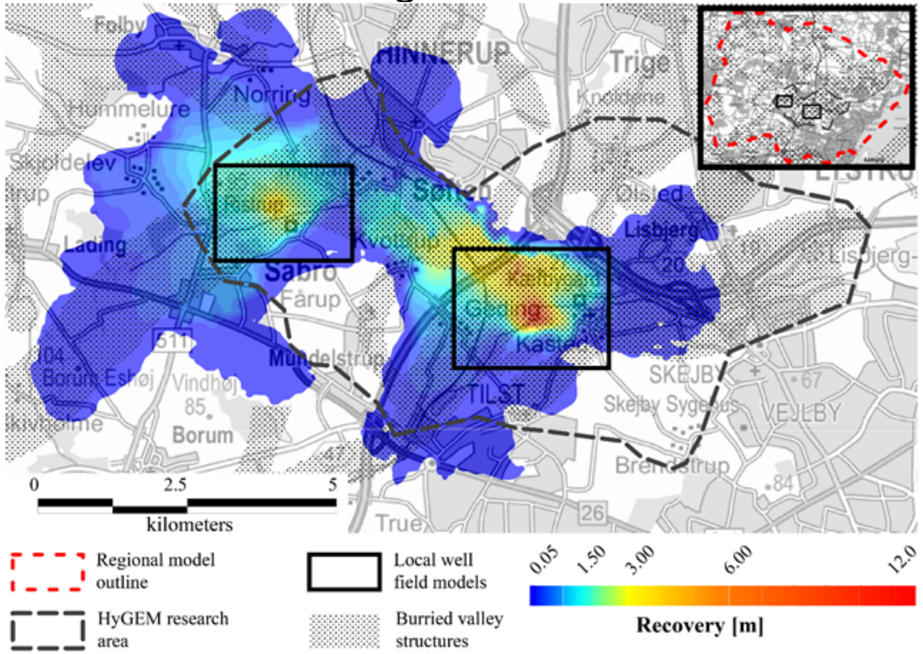
Delineation of valley structures

- Inversion results used to construct geological model.
- Delineated 20 buried and cross-cutting valley structures.

Synthesis



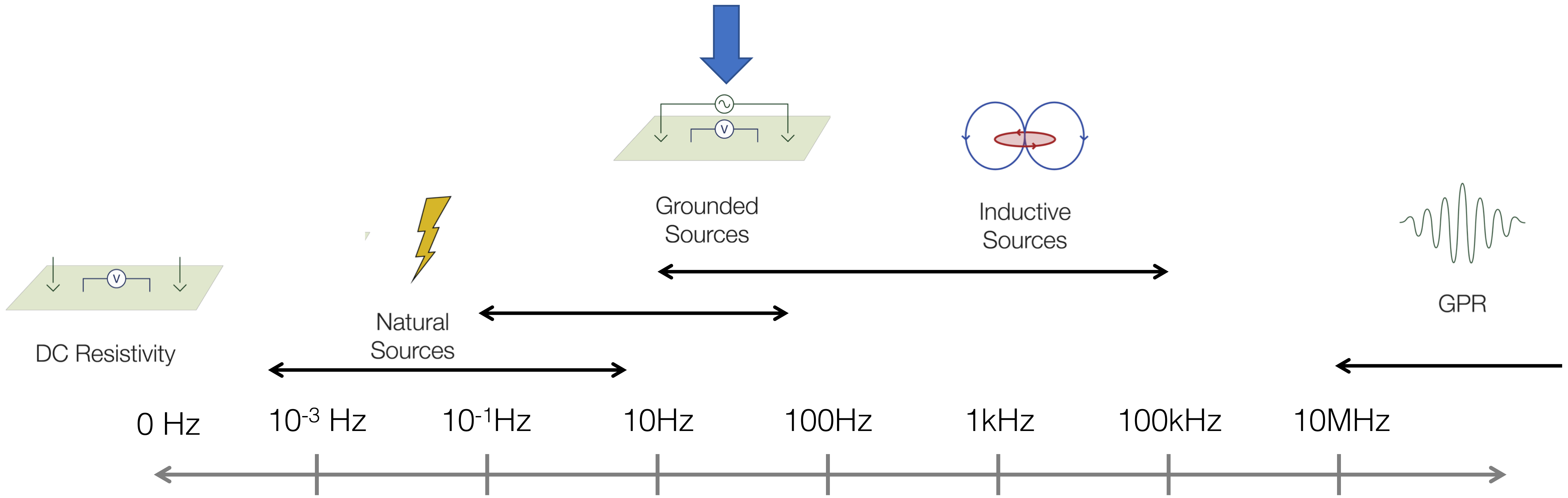
MODFLOW-USG groundwater model



- 3D geologic model incorporated into MODFLOW-USG groundwater modeling tool
- Extracted water from 2 wells.
- Downdraw between the two wells correlated with the resistive valley structures

Other EM surveys

Other EM surveys



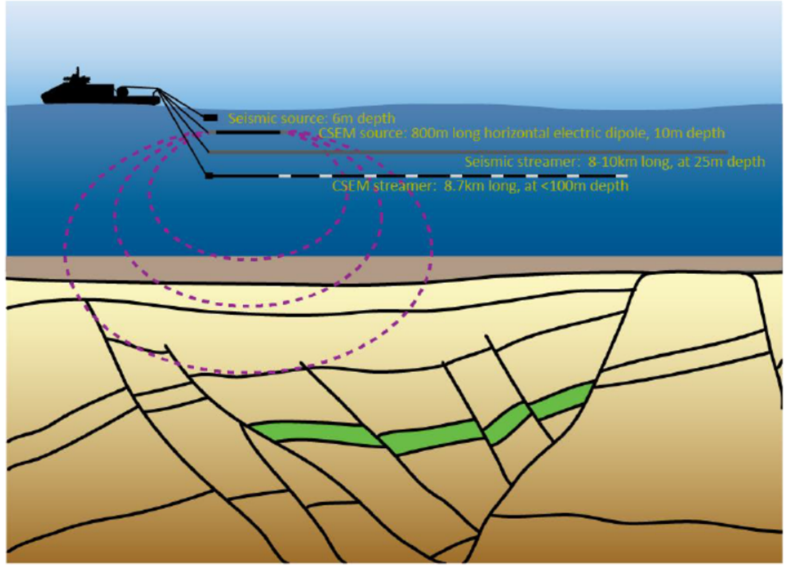
$$\nabla \cdot \sigma \nabla \phi = q$$

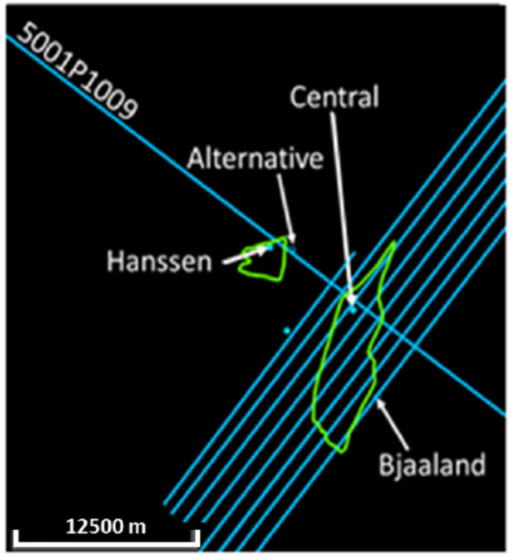
$$\nabla \times \nabla \times \vec{E} + \mu\sigma \frac{\partial \vec{E}}{\partial t} = 0$$

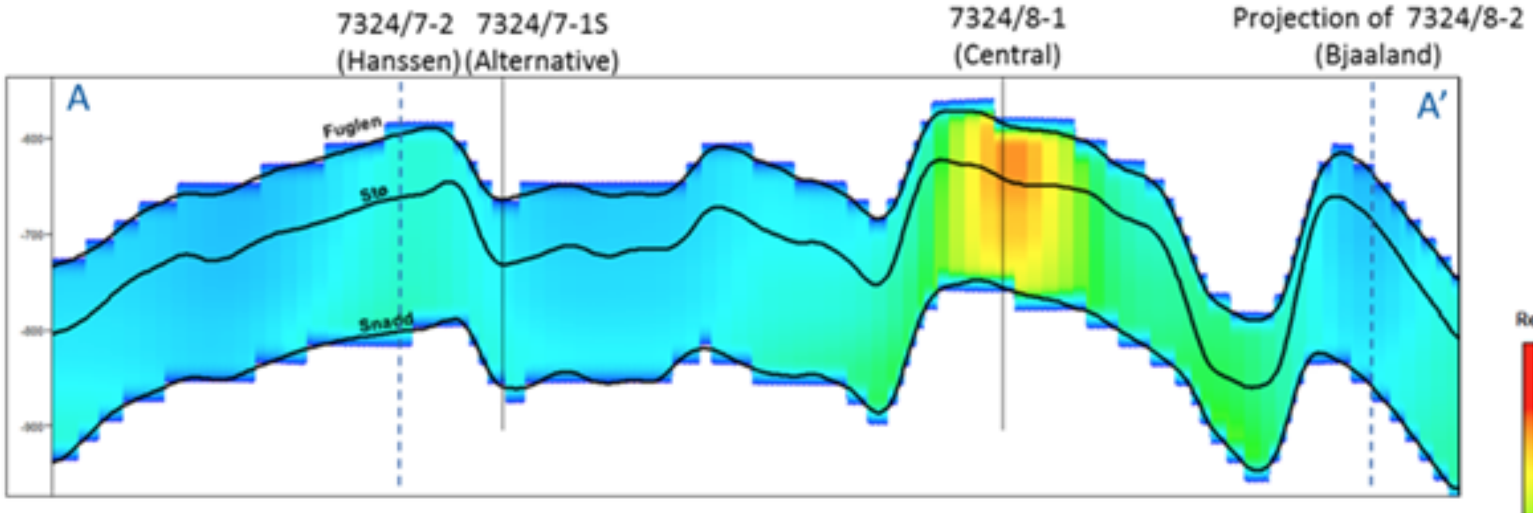
$$\nabla \times \nabla \times \vec{E} + \mu\sigma \frac{\partial \vec{E}}{\partial t} + \mu\epsilon \frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

Electromagnetics at sea

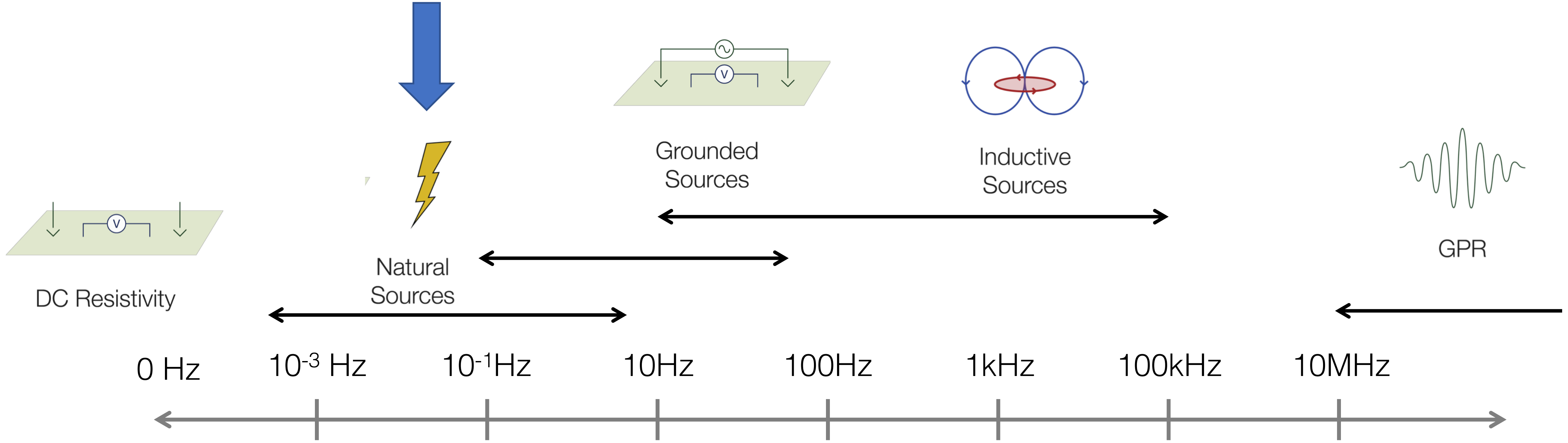
- Other uses
  - Hydrocarbons
  - Gas hydrates
  - Sea floor mining
  - Tectonic







EM Surveys and frequency



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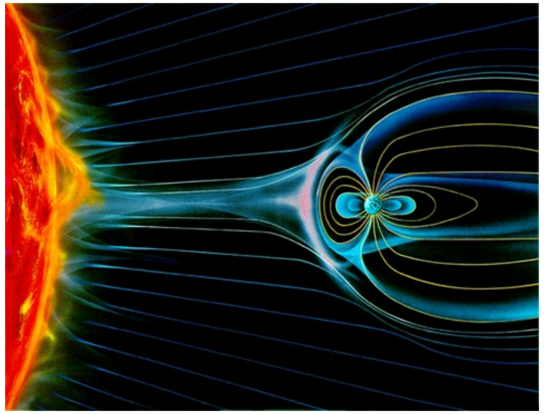
$$\nabla \times \nabla \times \vec{E} + \mu\sigma \frac{\partial \vec{E}}{\partial t} + \mu\epsilon \frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

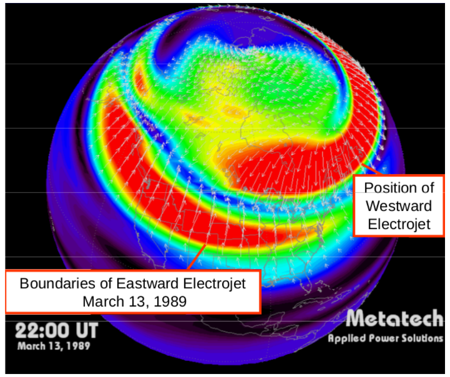
Natural EM sources

Sun and magnetosphere, solar storms

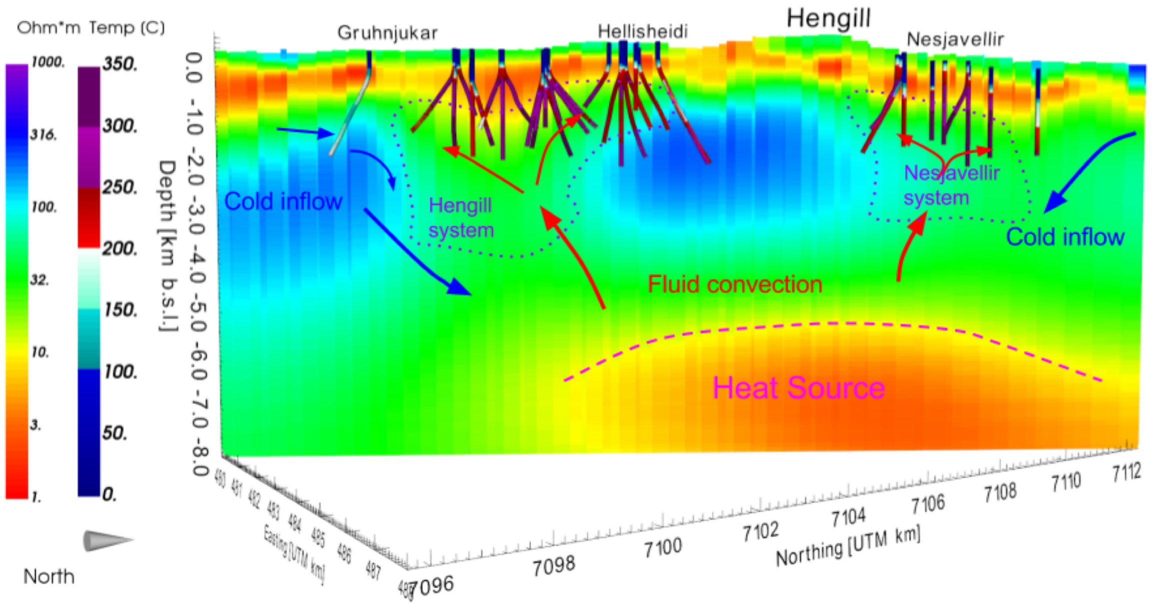


Lightning

Auroral electrojet; aurora



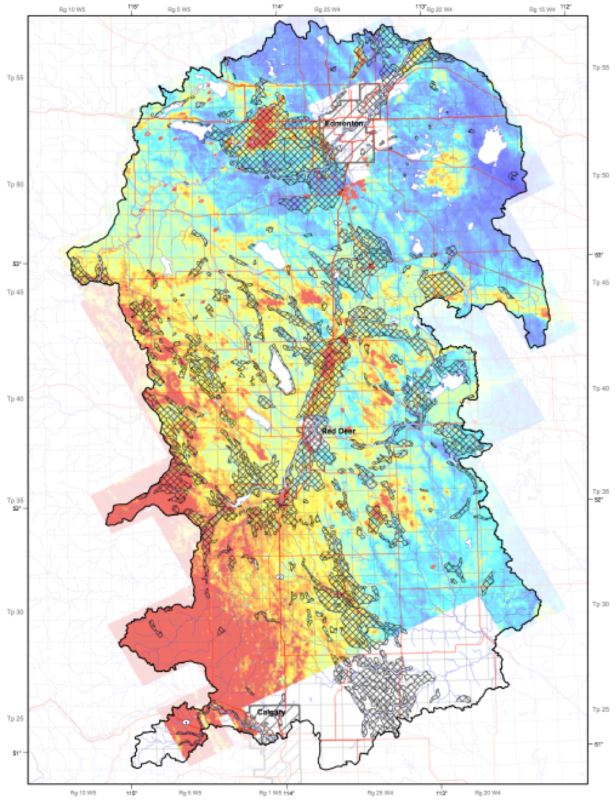
3D resistivity at Iceland



Future problem: groundwater

- Consider Edmonton-Calgary Corridor (ECC)
  - Large scale problem
  - But conductivity itself is not completely informative
- Questions
  - Where are the aquifers and aquitards?
  - What is the water quality (e.g. arsenic, salt water)?
  - What is the storage capacity, flow rate?
  - How are the aquifers recharged (or not)?
  - Are losing water or gaining water? (water balance)
- Stake holder
  - Farmers
  - Government and industry
  - Public
  - Hydrogeologists, engineers, geophysicists

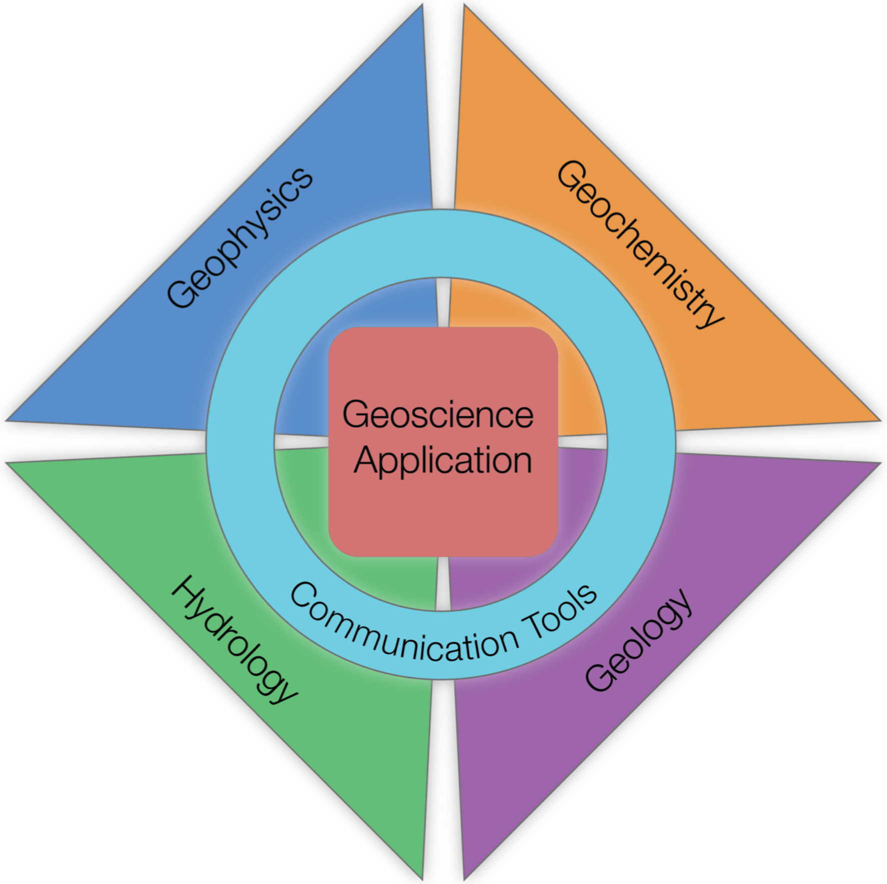
AEM resistivity Alberta Corridor



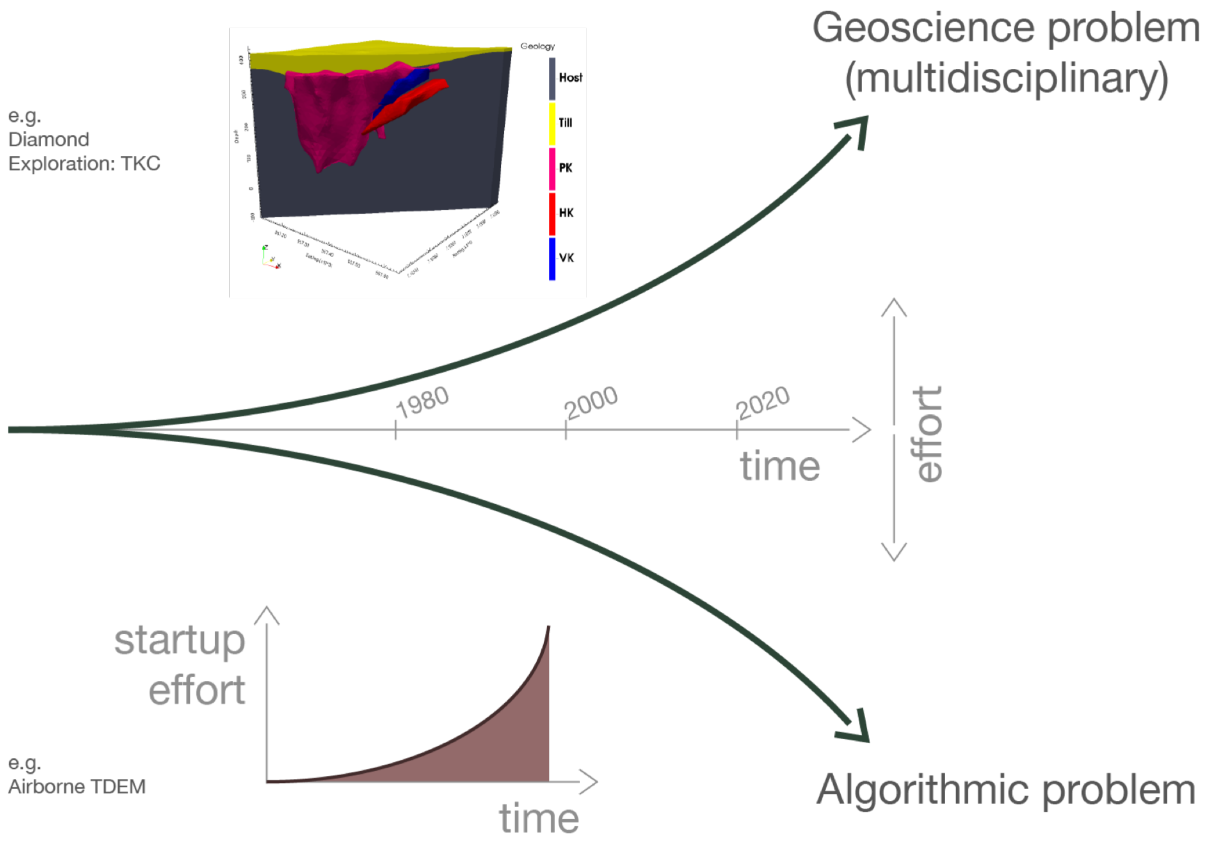
Baker (2011)

Next Generation of Geoscience Problems

- Multi-disciplinary
- Geophysics has a support role
- Inversion needed in multiple places
- Interaction is needed

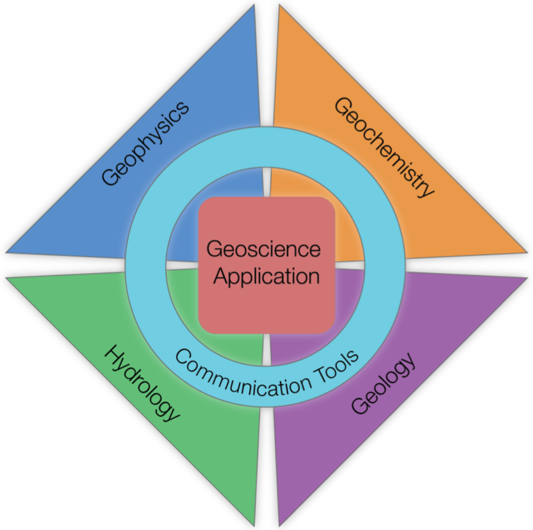


Research challenges keep increasing

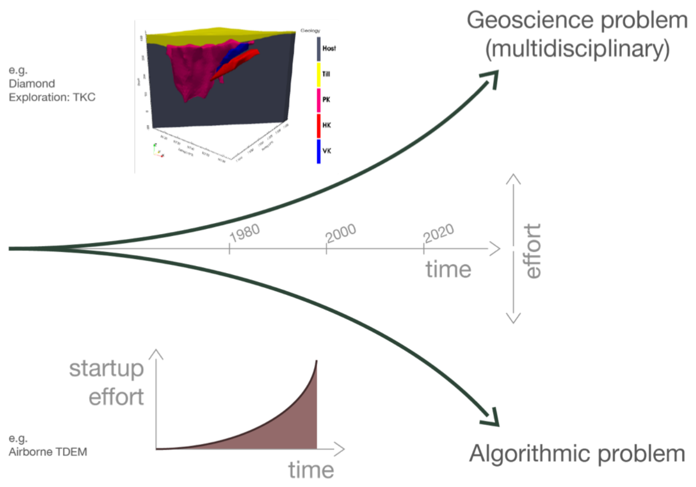


Next Generation of Geoscience Problems

- How to extract information about physical properties from data
- How to integrate that to help solve the geoscience problem?



- Who are the researchers?
  - Industry
  - Academia
- Tools for cooperation: Open Source



Open Source

Open source communities already doing this:

- Collaboration
  - Development of software
  - Implementing and applying
- Development practices
  - Shared repository
  - Version control
  - Automated testing
  - User and developer documentation
  - Peer review of code
  - Issue tracking
  - Attribution for contributors
  - Licensing

astropy
A Community Python Library for Astronomy
253 contributors

scikit learn
machine learning in Python
1,095 contributors

SciPy
Scientific Computing with Python
612 contributors

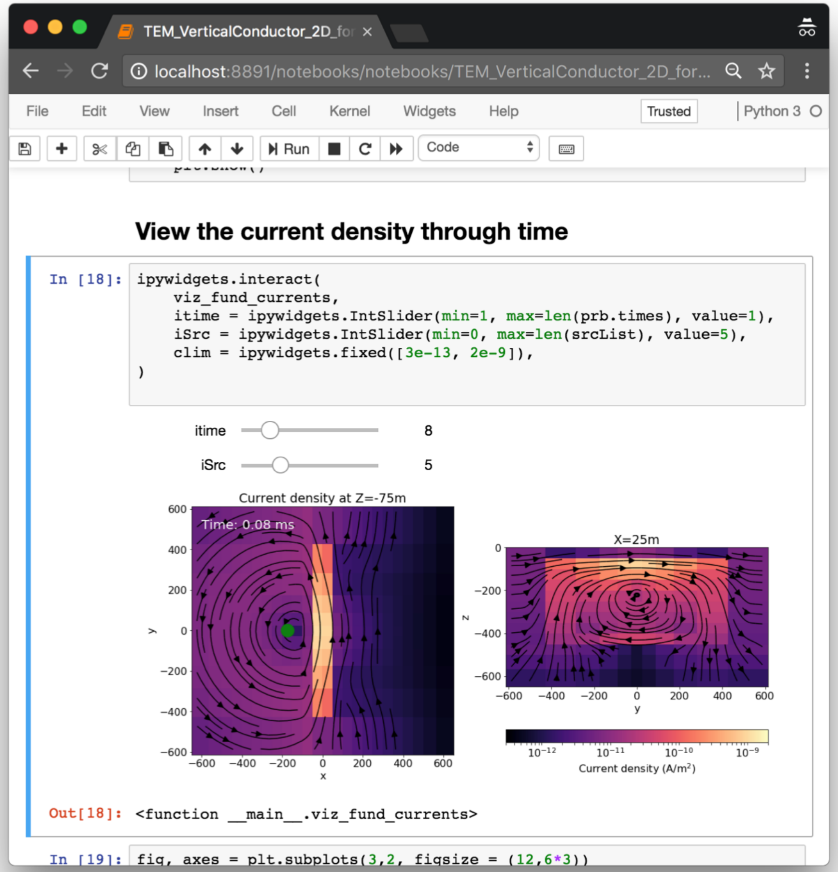
Sampling of modern open-source projects

- For EM
  - empymod
  - jInv
  - Geoscience Australia
  - pyGIMLi
  - Fatiando
  - SimPEG
  - …

- They differ in objectives, capabilities, structure, interactivity, license, and language

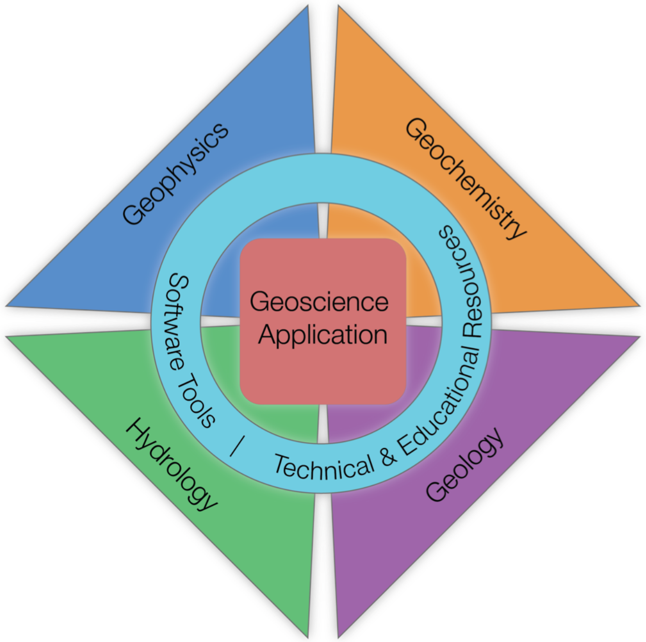
simpeg

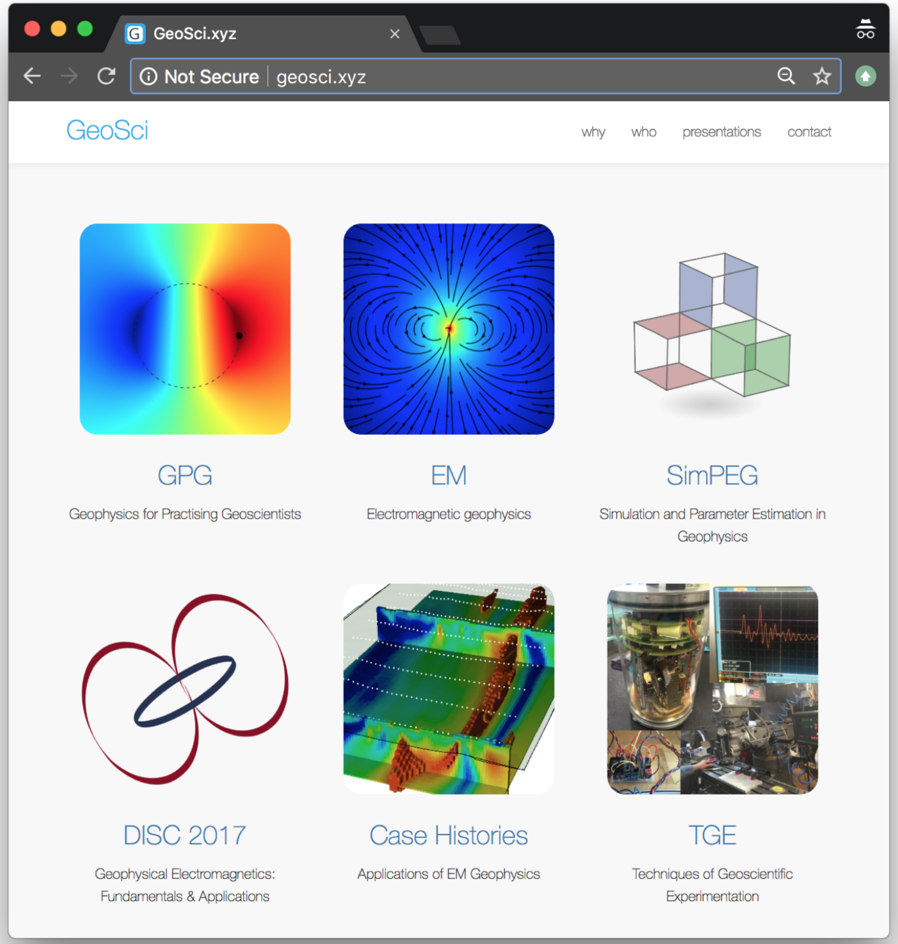
- Modular framework for simulation and inversion of geophysical data
    - gravity, magnetics, vadose flow, DC/IP, FDEM, TDEM
- Open source
- Written in Python
- Specific to electromagnetics
    - Quasi-static Maxwell
    - Tensor, OcTree, Curvilinear and Cylindrical meshes
    - Easily visualize fields, fluxes, charges



http://simpeg.xyz

GeoSci.xyz


Geophysics
Geochemistry
Hydrology
Geology
Geoscience Application
Software Tools / Technical & Educational Resources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GPG
Geophysics for Practising Geoscientists
EM
Electromagnetic geophysics
SimPEG
Simulation and Parameter Estimation in Geophysics
DISC 2017
Geophysical Electromagnetics: Fundamentals & Applications
Case Histories
Applications of EM Geophysics
TGE
Techniques of Geoscientific Experimentation

Thank You

Resources

geosci.xyz

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slack.simpeg.xyz

courses.geosci.xyz/aem2018

SimPEG Team

Thank you