EM: Natural Sources

DISC

2017

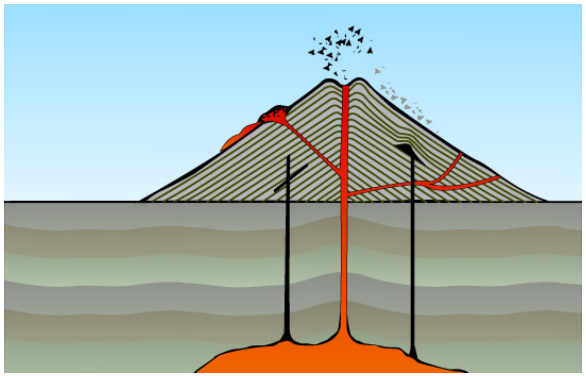
Electromagnetics
Fundamentals and Applications

Outline

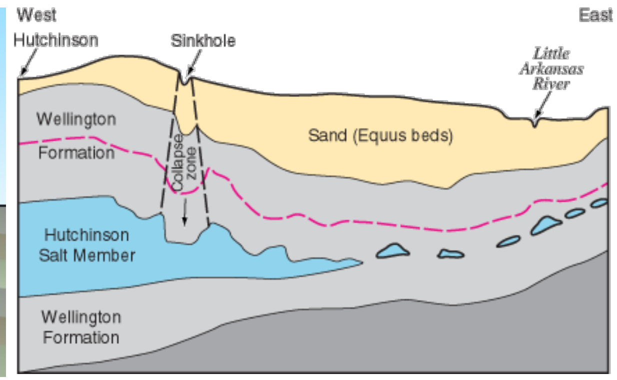
- Background on natural source EM methods
- Magnetotellurics
- Case history: Geothermal
- Case history: Landfill
- Z-axis tipper electromagnetics
- ZTEM case history

Motivation

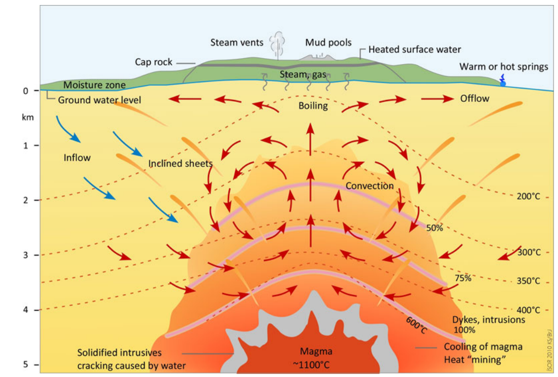
Volcanoes



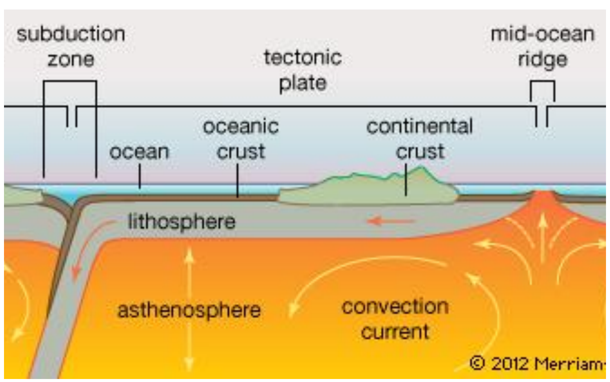
Base of salt



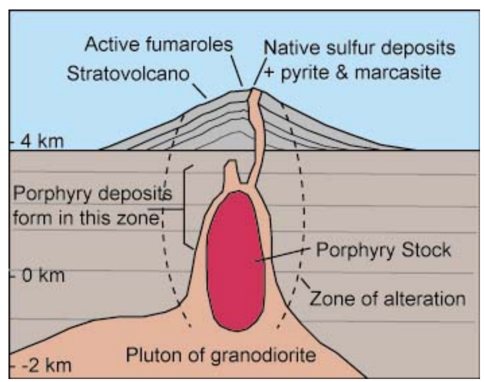
Geothermal



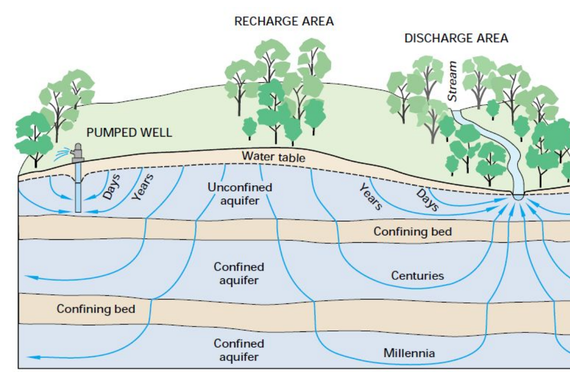
Tectonic settings of top few km



Mineral targets



Groundwater

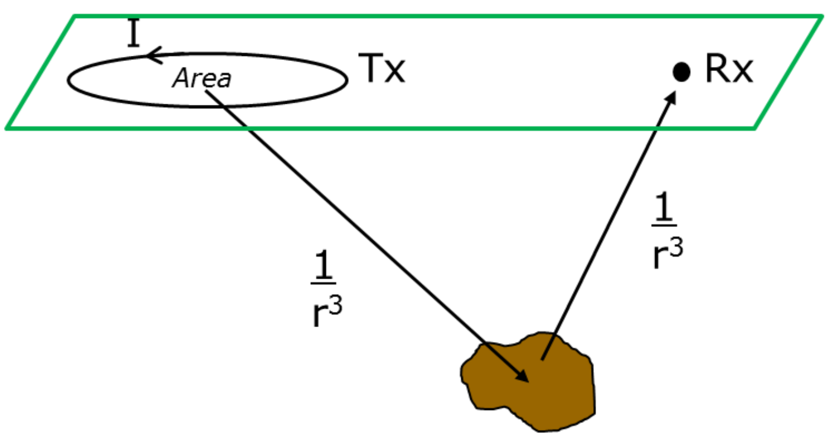


Common challenge: getting enough energy into the ground

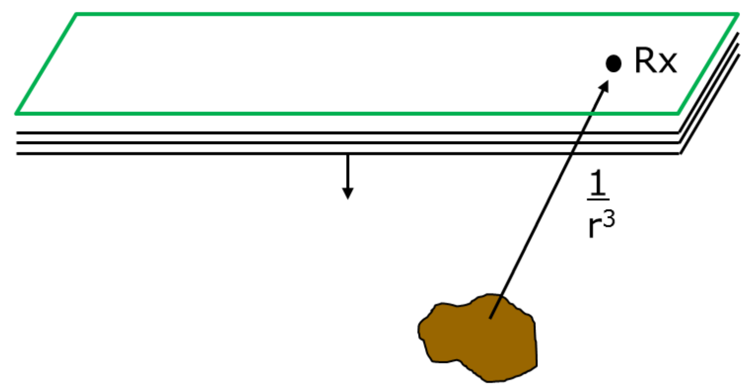
What is required to see deeper?

- Penetration depth depends upon system power

- Controlled source:
  - Using a small loop
  - Magnetic moment
  $$m = IA$$
  - Total geometric decay
  $$\sim \frac{1}{r^6}$$

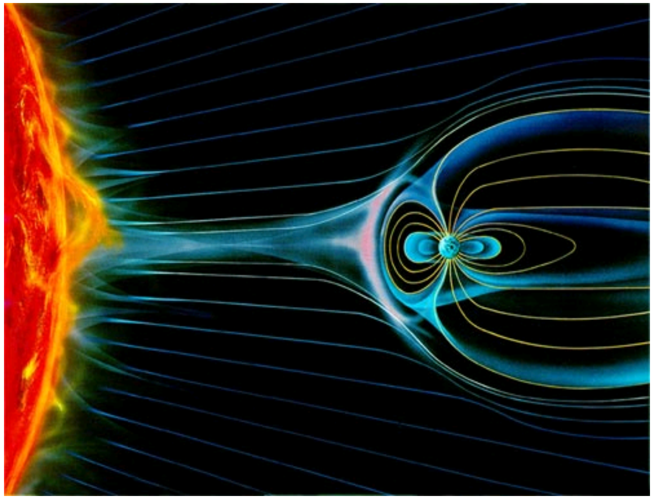


- Infinitely large loop source
  - Sheet currents generate plane waves
  - Total geometric decay
  $$\sim \frac{1}{r^3}$$



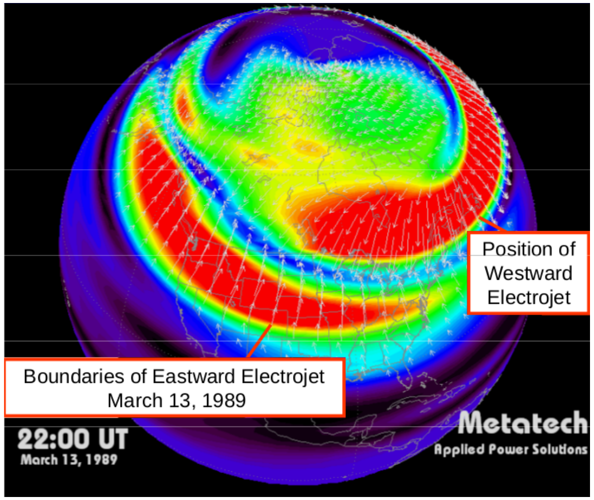
Natural EM sources

Sun and magnetosphere, solar storms

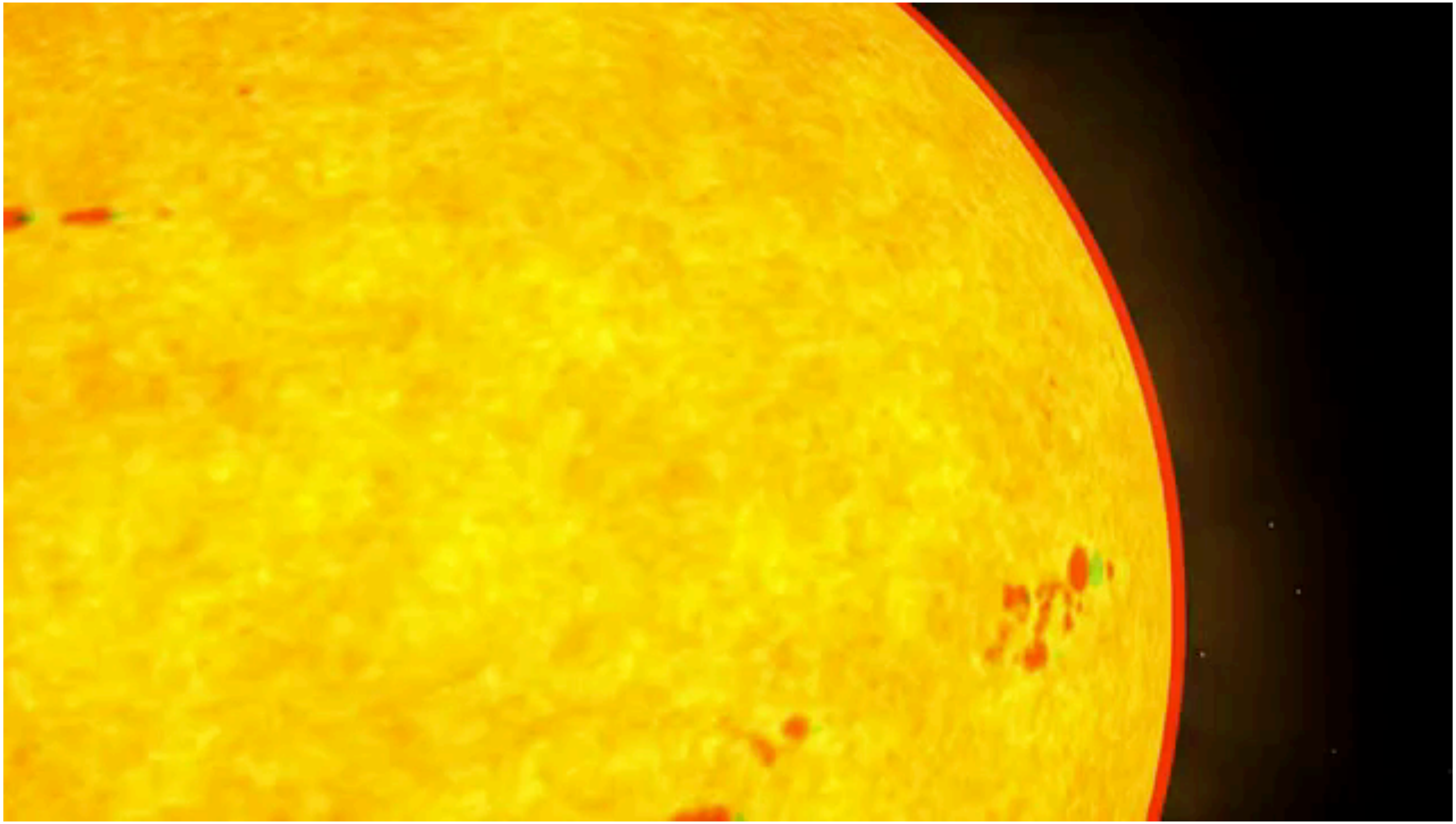


Lightning

Auroral electrojet; aurora

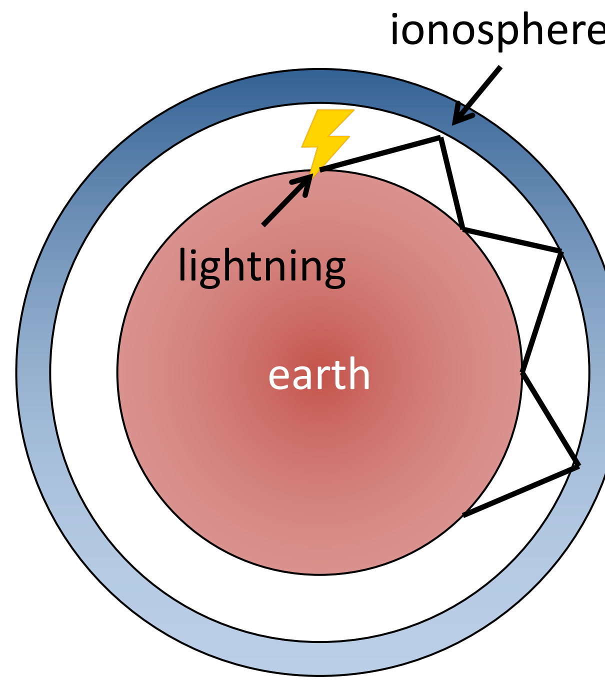


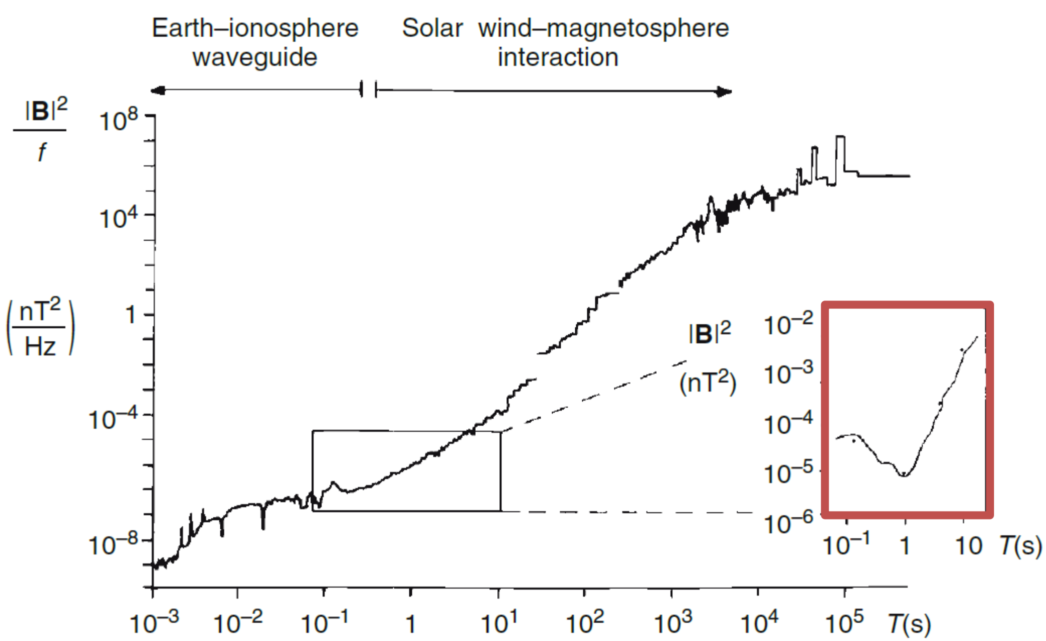
Aurora movie



Earth as a waveguide

- EM waves bounce between earth and highly conductive ionosphere
- Travel as plane waves





- Dead band: difficult to collect frequencies in notch (~1 Hz)

Refraction of waves

- Snell's law

$$k_i \sin\theta_i = k_t \sin\theta_t$$

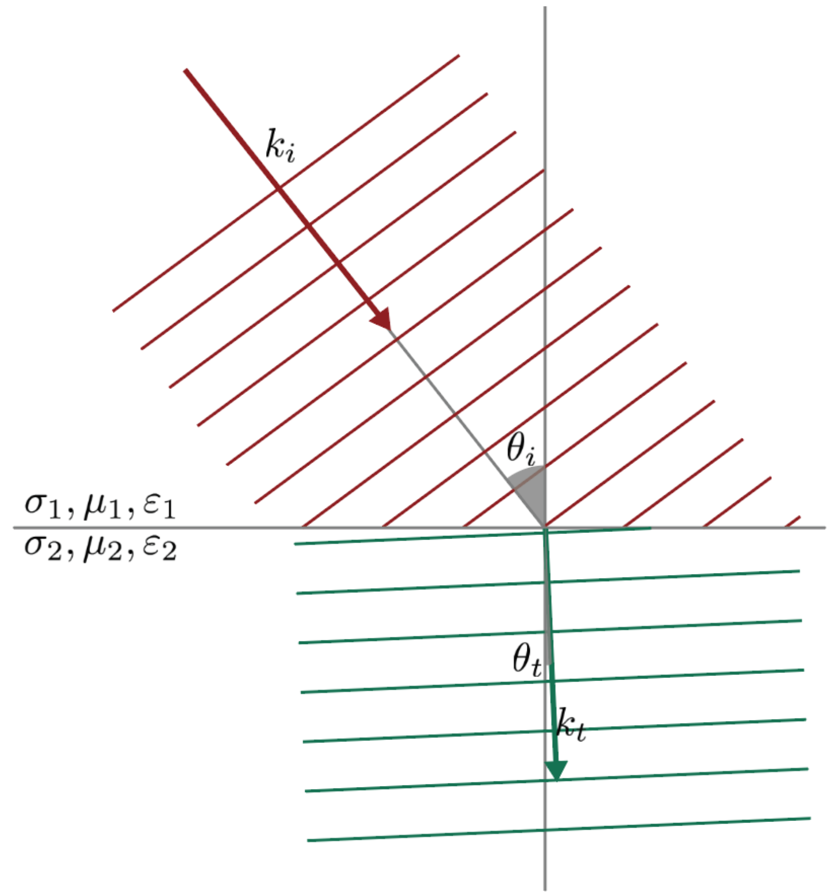
- k is complex wave number

$$k^2 = \omega^2 \mu\varepsilon - i\omega\mu\sigma$$

- Quasi-static: $\frac{\omega\varepsilon_0}{\sigma} \ll 1$

$$\sin\theta_t = \sqrt{\frac{2\omega\varepsilon_0}{\sigma}} \sin\theta_i$$

- Angle of refraction is $\theta_t = 0°$ in almost every instance



Example for 10,000 Hz

$\sigma = 10^{-3}$ S/m

$\theta_i = 89°$

Then $\theta_t = 1.35°$

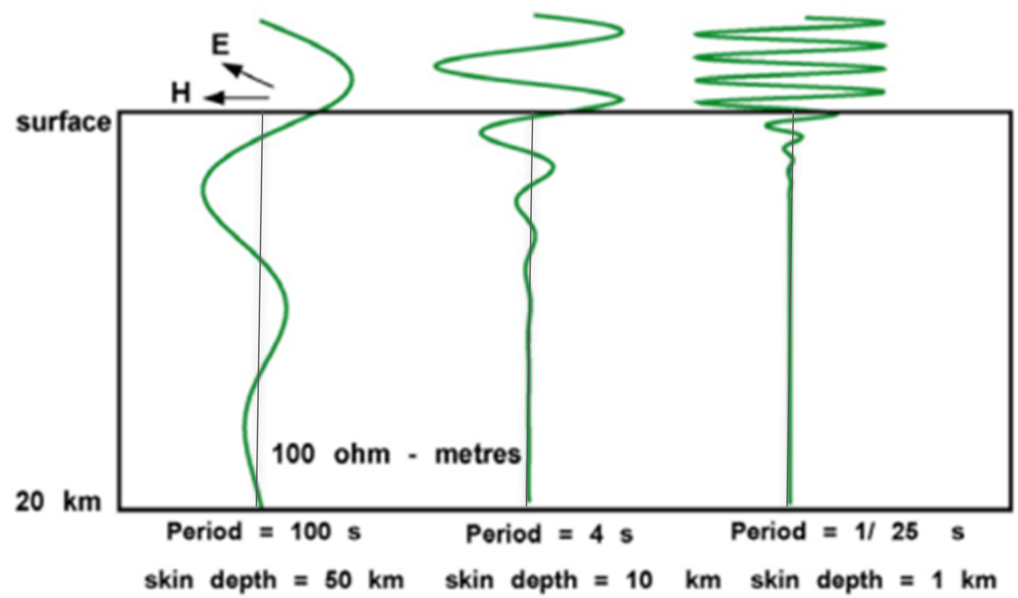
Plane waves and skin depth

- Skin depth (meters)

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} = 503\sqrt{\frac{1}{\sigma f}}$$

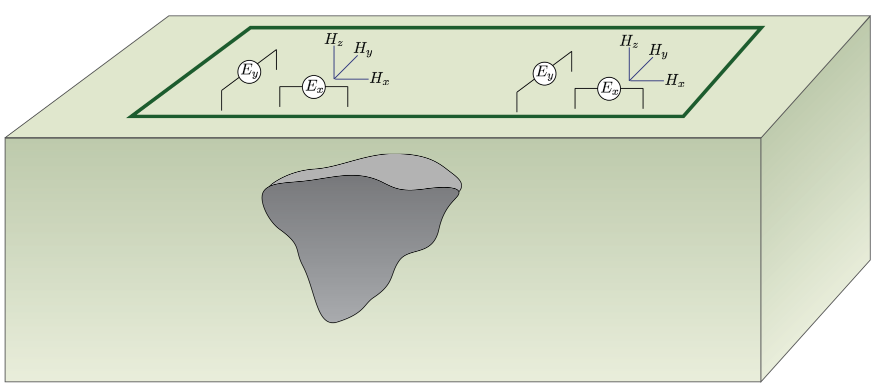
- Low frequency waves propagate further

- Depth of propagation
  - A few skin depths
  - Only a portion of a wavelength

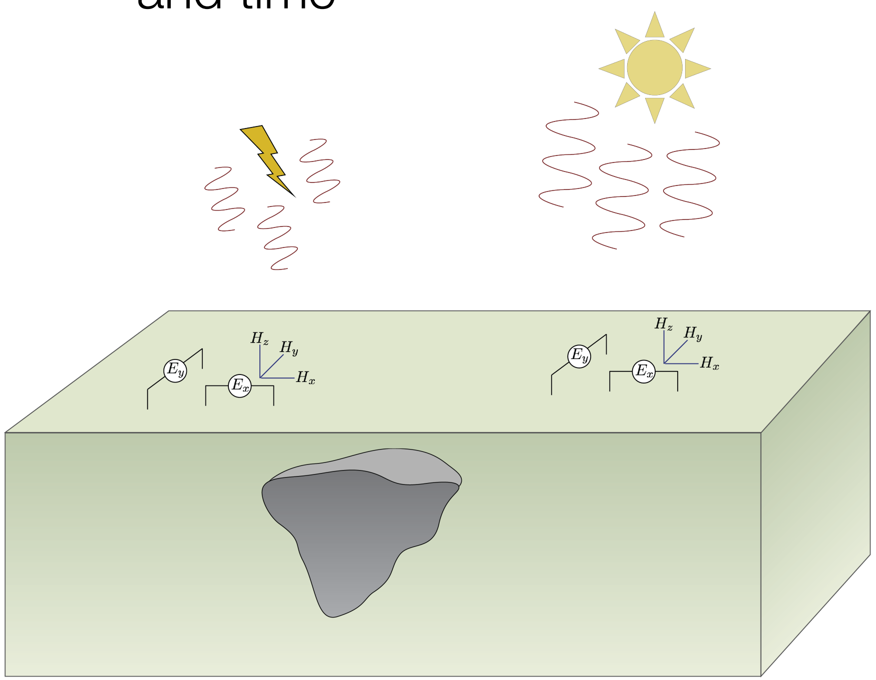


Control source vs Natural source

- Controlled source
  - Well-defined location, geometry, and amplitude



- Natural sources
  - Sources are random in space and time



MT Station

- Maxwell's equations:
  - Linear in J_s
  - E and H affected in the same way

$$\nabla \times \mathbf{E} + i\omega\mu\mathbf{H} = 0$$
$$\nabla \times \mathbf{H} - \sigma\mathbf{E} = \mathbf{J_s}$$

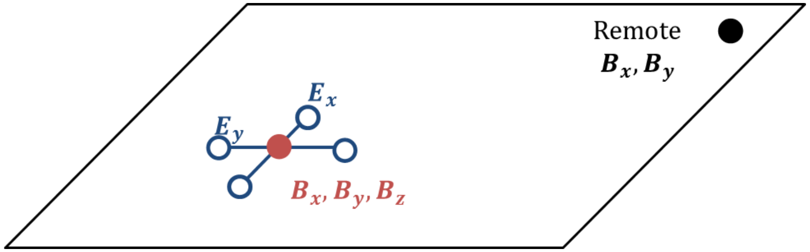
- Effects of unknown source removed by taking ratio

- Transfer function

$$\mathbf{E} = \mathbf{ZH}$$

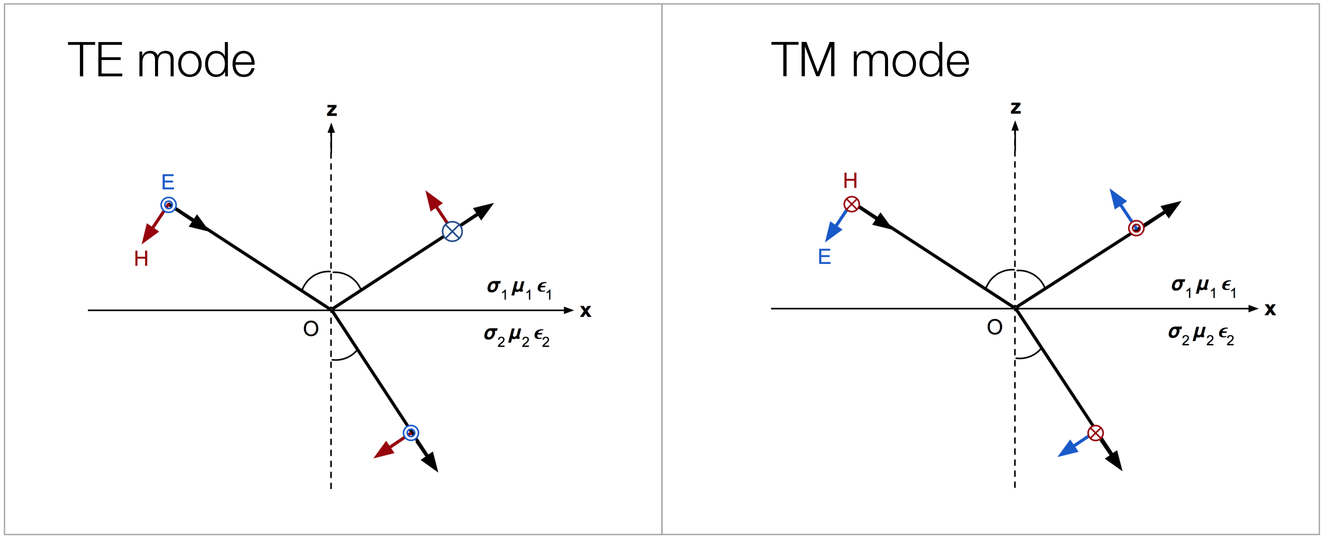
impedance (matrix)

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \begin{pmatrix} H_x \\ H_y \end{pmatrix}$$



Impedance and resistivity

- Plane wave in homogenous media:
  - E and H fields are perpendicular



Homogeneous half space

Impedance	Resistivity	Phase
$Z_{xy} = \frac{E_x}{H_y}$	$\rho = \frac{1}{\omega\mu} \lvert Z_{xy} \rvert^2$	$\Phi = \tan^{-1}\left(\frac{Im(Z_{xy})}{Re(Z_{xy})}\right) = \frac{\pi}{4}$

MT soundings in 1D

- In general:

$$Z = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$$

- Apparent resistivity:

$$\rho_a = \frac{1}{\omega\mu_0}\left|Z_{xy}\right|^2$$

- Phase:

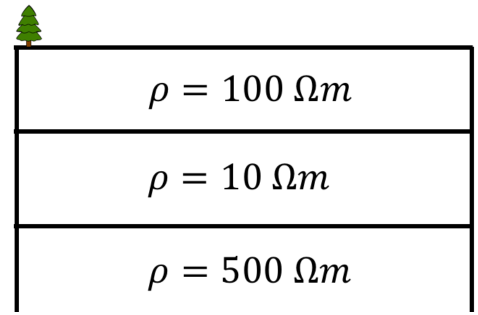
$$\Phi = \tan^{-1}\left(\frac{Im(Z_{xy})}{Re(Z_{xy})}\right)$$

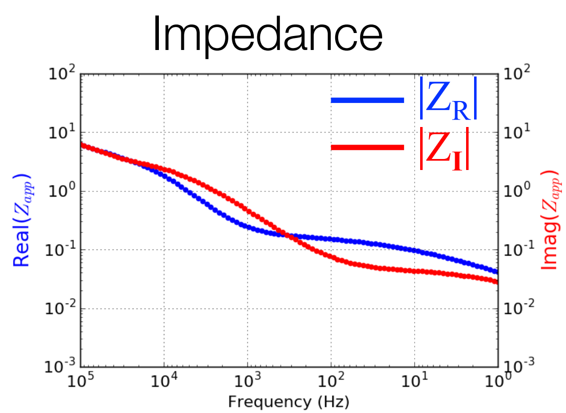
- In 1D:

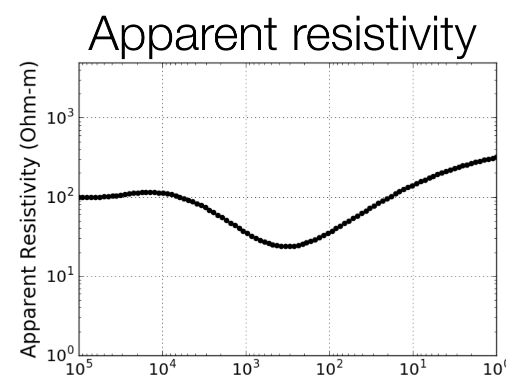
$$Z = \begin{pmatrix} 0 & Z_{xy} \\ Z_{yx} & 0 \end{pmatrix}$$

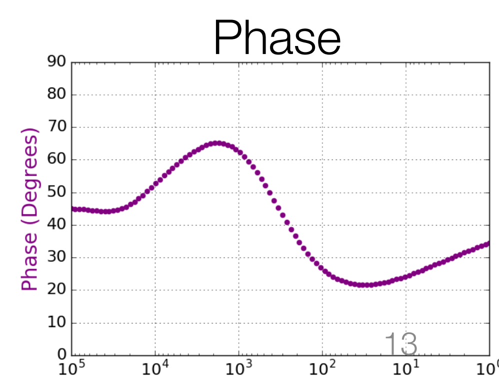
$$Z_{xy} = \frac{E_x}{H_y}$$

$$Z_{xy} = -Z_{yx}$$





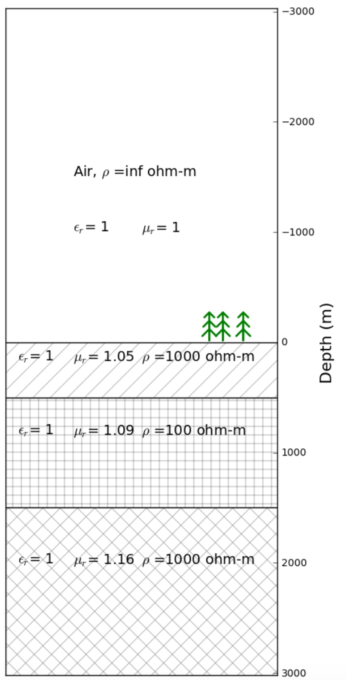


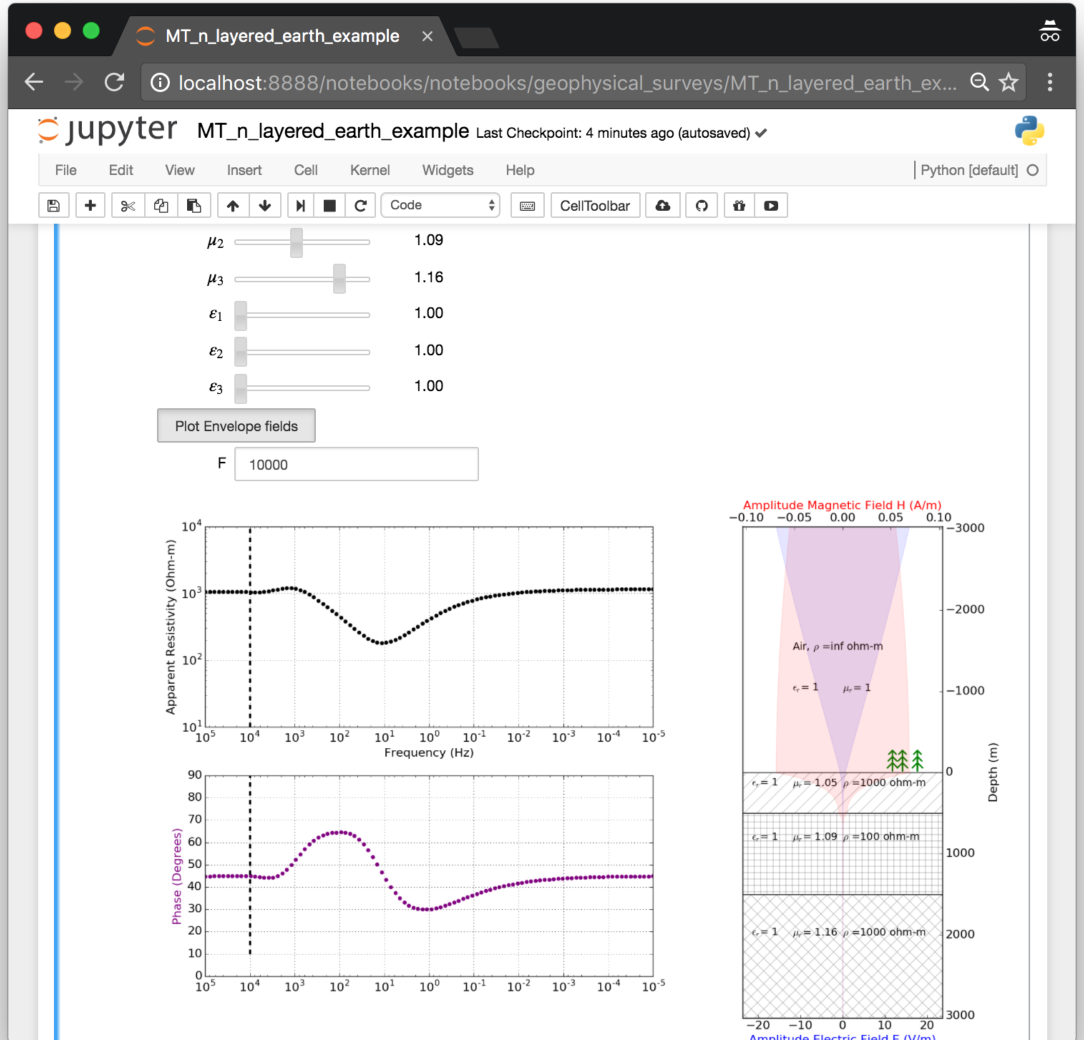


1D MT app

$$\nabla \times \mathbf{E} + i\omega\mu\mathbf{H} = 0$$

$$\nabla \times \mathbf{H} - \sigma\mathbf{E} = \mathbf{J_s}$$





MT soundings in 2D

- In general:

$$Z = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$$

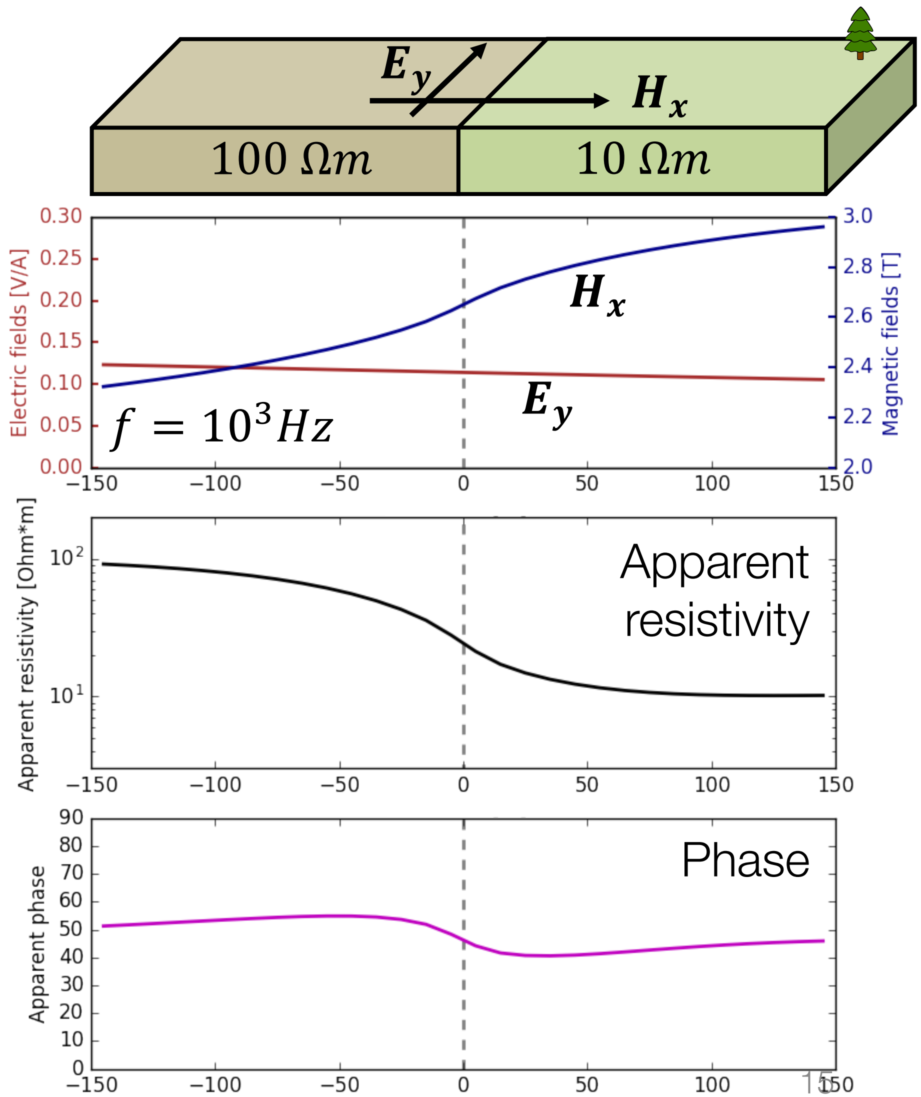
- In 2D:

$$Z = \begin{pmatrix} 0 & Z_{xy} \\ Z_{yx} & 0 \end{pmatrix}$$

$$Z_{xy} \neq Z_{yx}$$

- TE mode
  - E-field parallel to structure

$$Z_{yx} = \frac{E_y}{H_x}$$



MT soundings in 2D

- In general:

$$Z = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$$

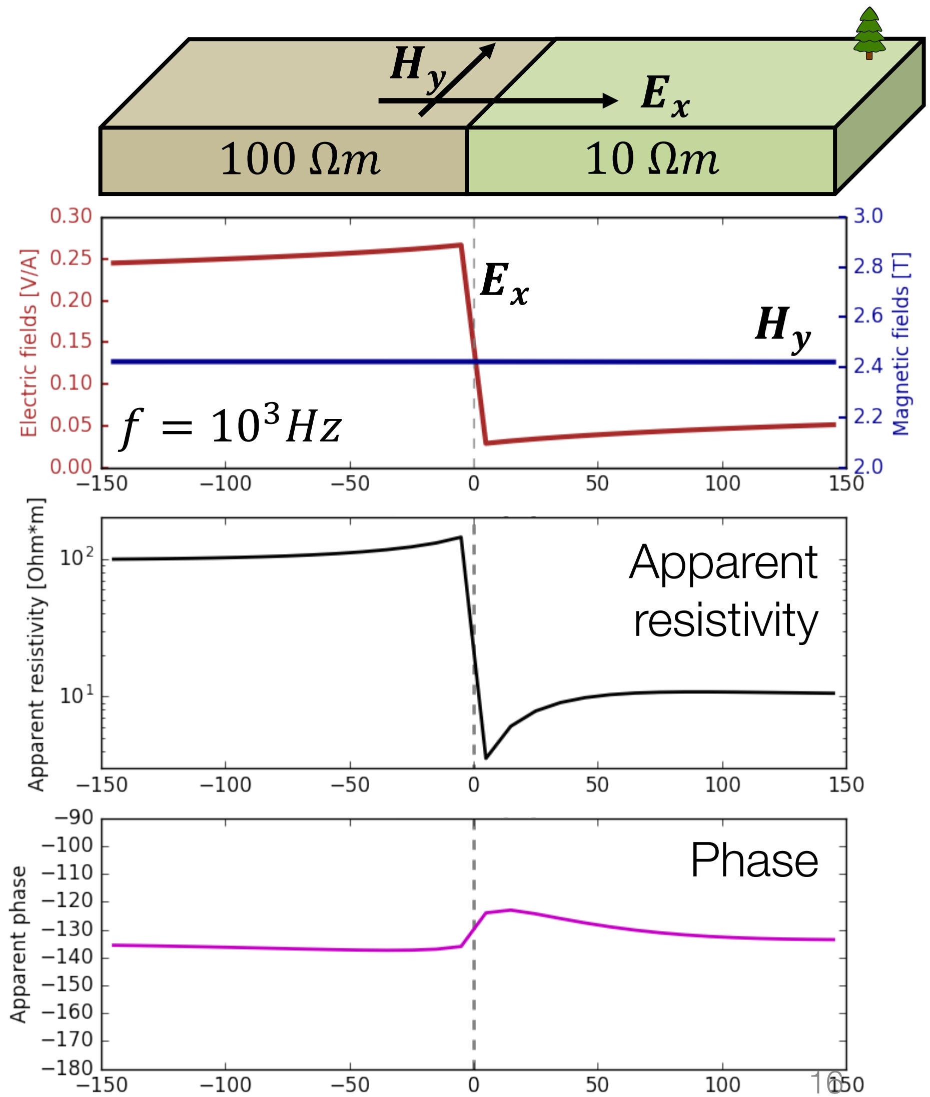
- In 2D:

$$Z = \begin{pmatrix} 0 & Z_{xy} \\ Z_{yx} & 0 \end{pmatrix}$$

$$Z_{xy} \neq Z_{yx}$$

- TM mode
  - H-field parallel to structure
  - E_x discontinuous

$$Z_{xy} = \frac{E_x}{H_y}$$



MT soundings in 3D

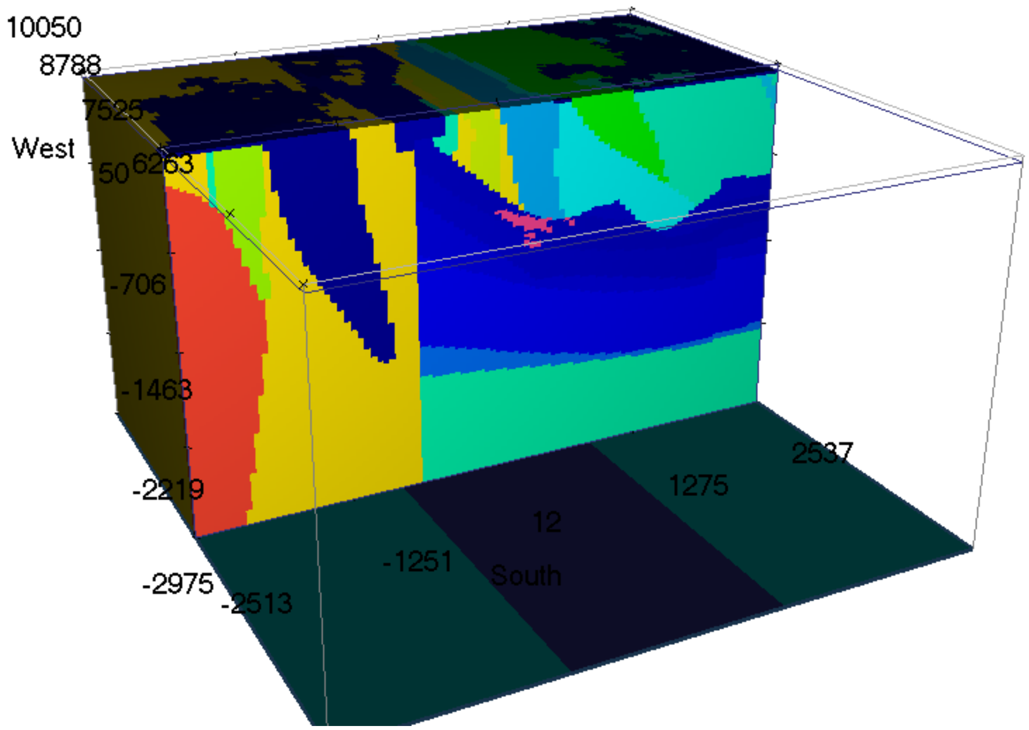
- In general:

$$Z = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$$

- In 3D:

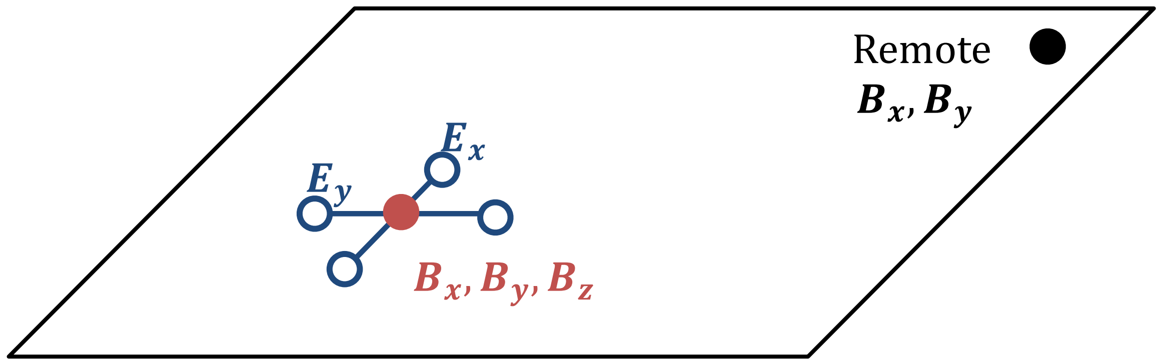
$$Z = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$$

- No symmetry or special conditions



Measuring MT data

- Basic acquisition

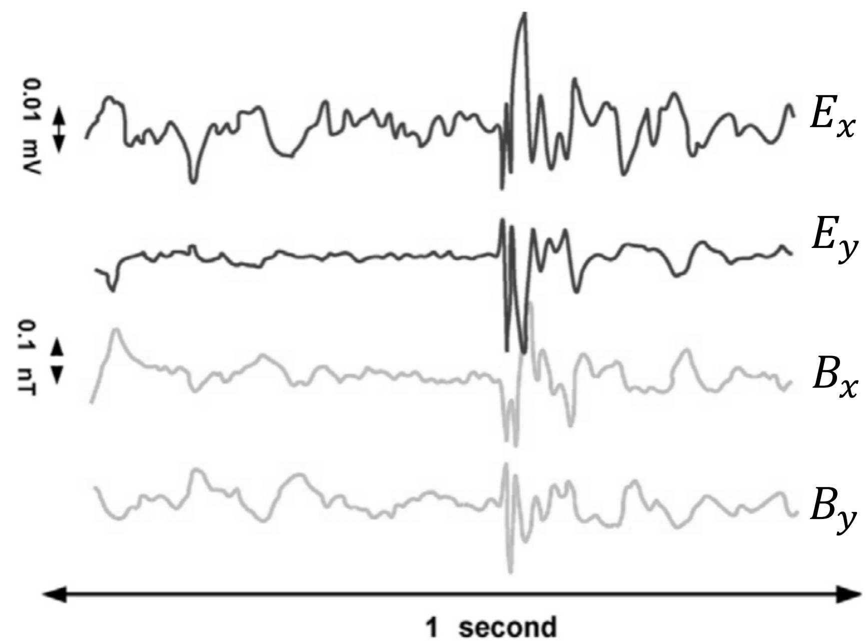


- At each station, measure:

$$E_x, E_y, B_x, B_y, B_z$$

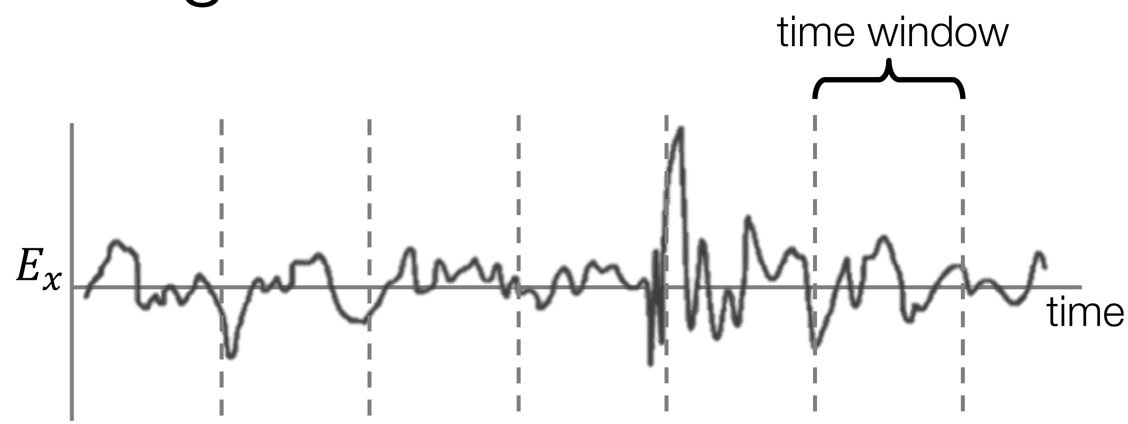
- At remote reference, measure:

$$B_x, B_y$$



Processing MT data

- Divide time series into time windows



- Apply Fourier transform
  - For each station:

$$e_x(t) \rightarrow E_x(\omega)$$
$$h_y(t) \rightarrow H_y(\omega)$$

  - For the remote reference:

$$h_y^R(t) \rightarrow H_y^R(\omega)$$

- Form the impedance tensor:

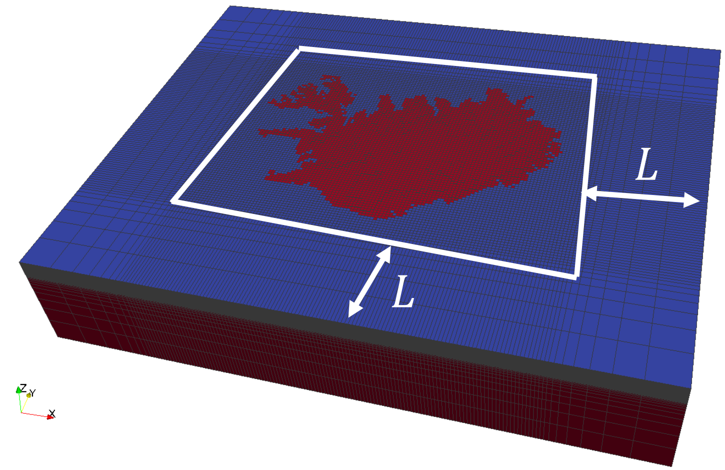
$$Z_{xy}(\omega) = \frac{\langle E_x(\omega) H_y^{R*}(\omega) \rangle}{\langle H_y(\omega) H_y^{R*}(\omega) \rangle}$$

(*) complex conjugate
<> average over multiple samples

Inverting MT data

- Boundary conditions important for modelling
- Mesh size:
  - MT: extended grid

    L: a few skin depths from data area
- Challenge: Unknown boundary conditions
  - Possible channeled currents
  - Data can be affected by distant structures
- Otherwise, inversion of MT is essentially same as CSEM data



Outline

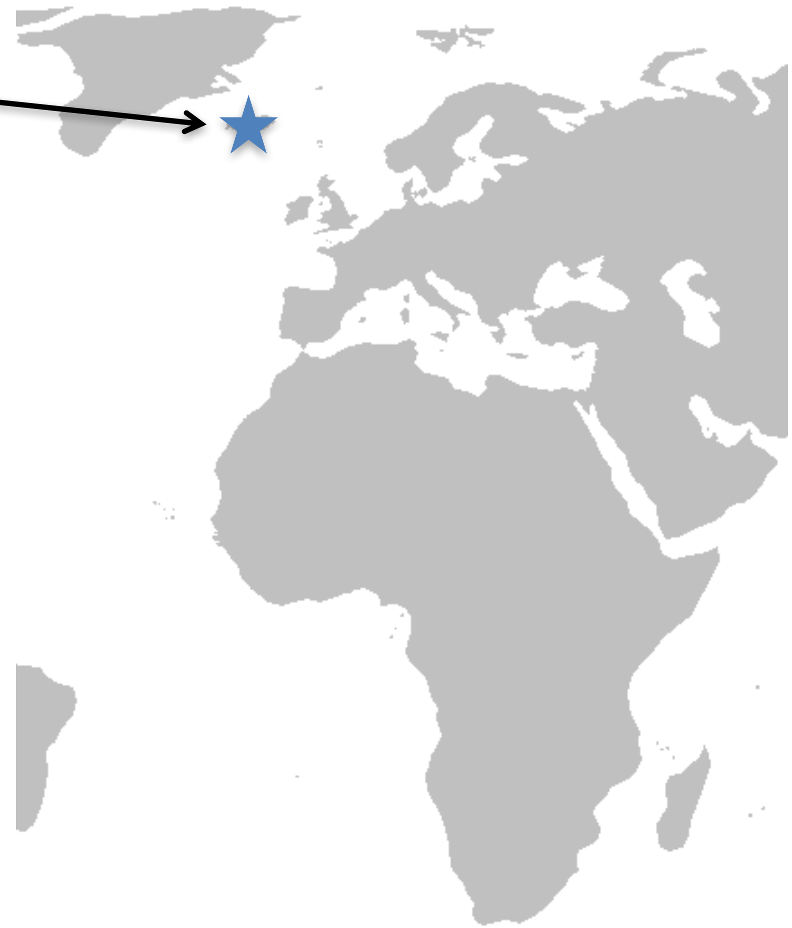
- Background on natural source EM methods
- Magnetotellurics

- Questions?

- Case history: Geothermal
- Case history: Landfill
- Z-axis tipper electromagnetics
- ZTEM case histories

MT case history

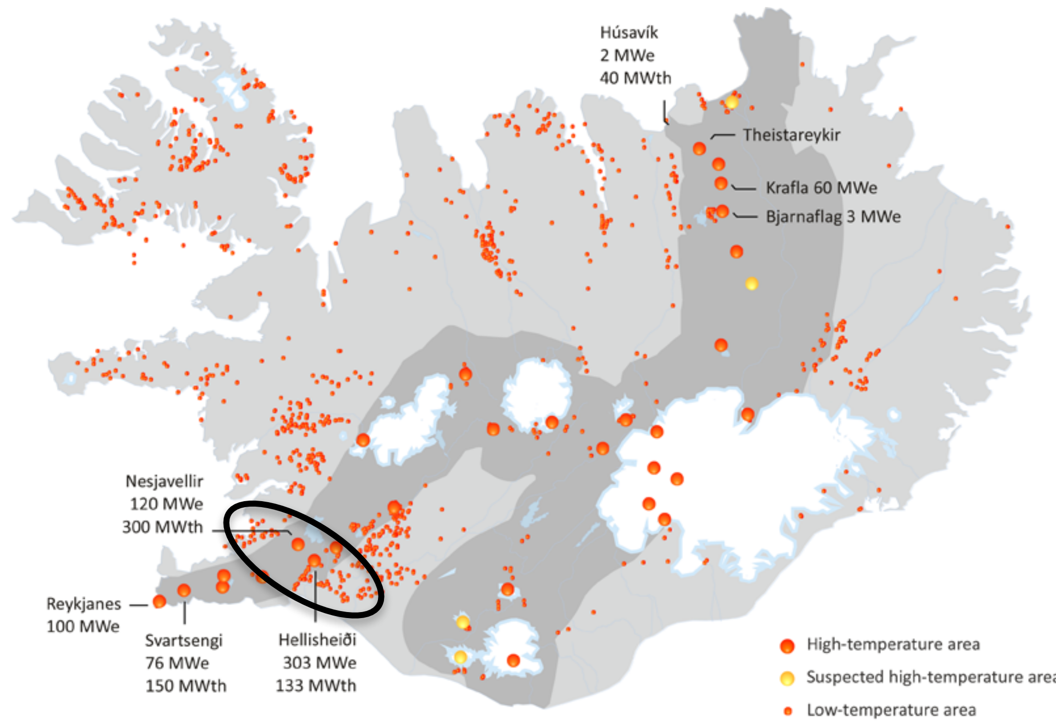
- Iceland



Hengill geothermal region: setup

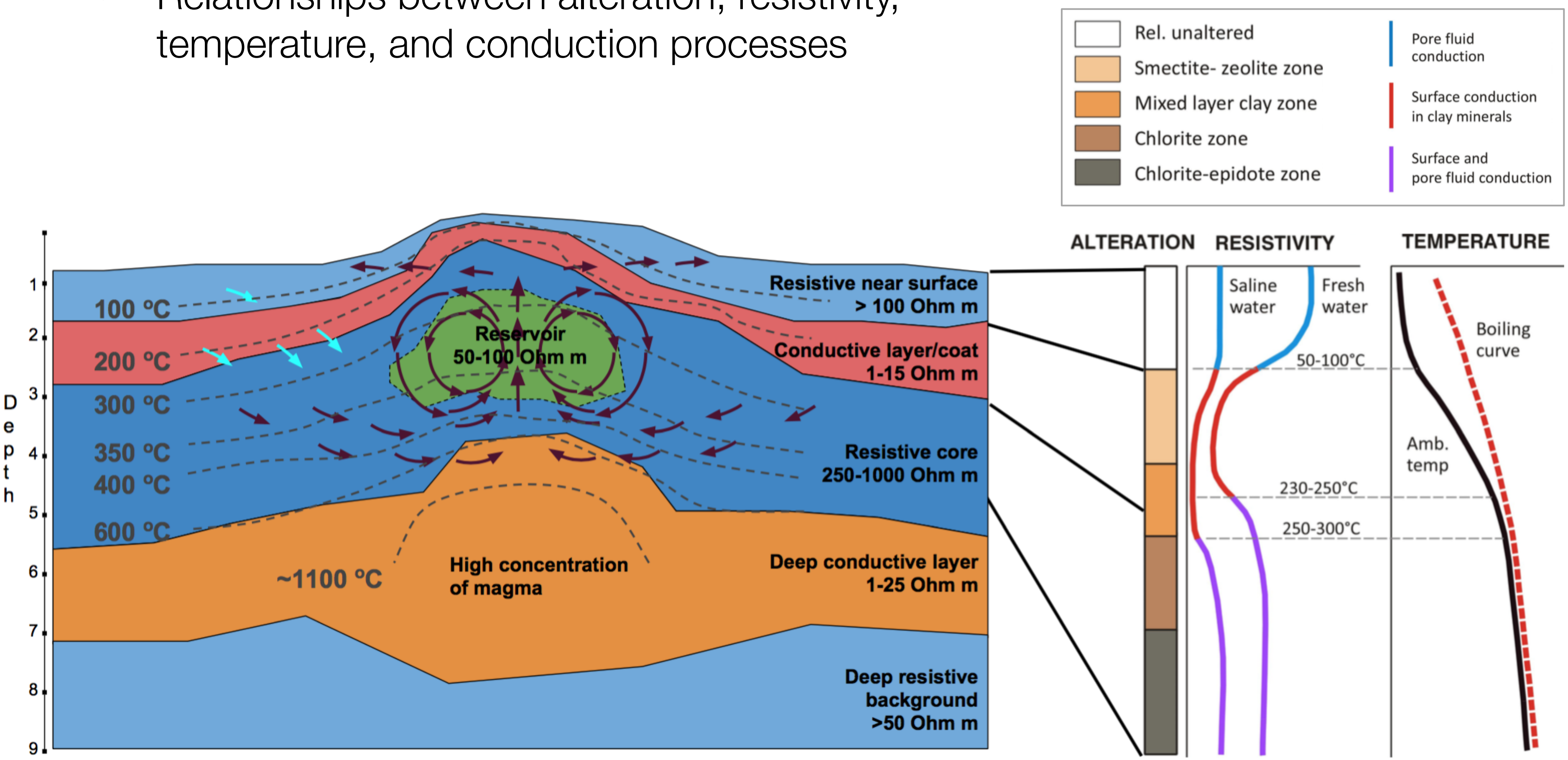
- Iceland: geothermal hot spot
  - On the mid-Atlantic ridge
  - Hosts multiple high temperature geothermal systems

- Hengill geothermal area
  - Supplies majority of hot water in Reykjavik
  - Contributes ~450 Mwe to National power grid

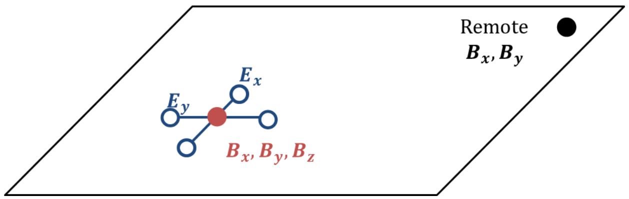


Physical properties

- Relationships between alteration, resistivity, temperature, and conduction processes

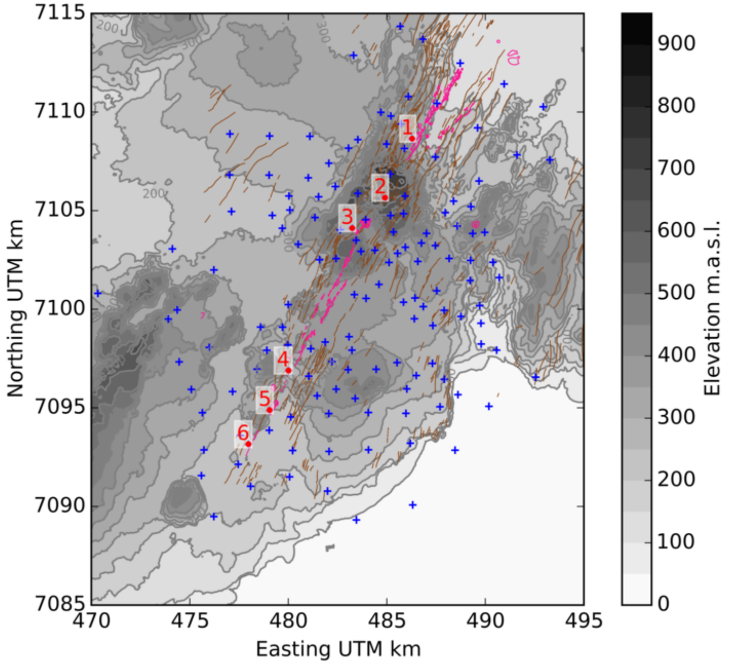


Survey



- MT instrumentation
  - Phoenix MTU5's

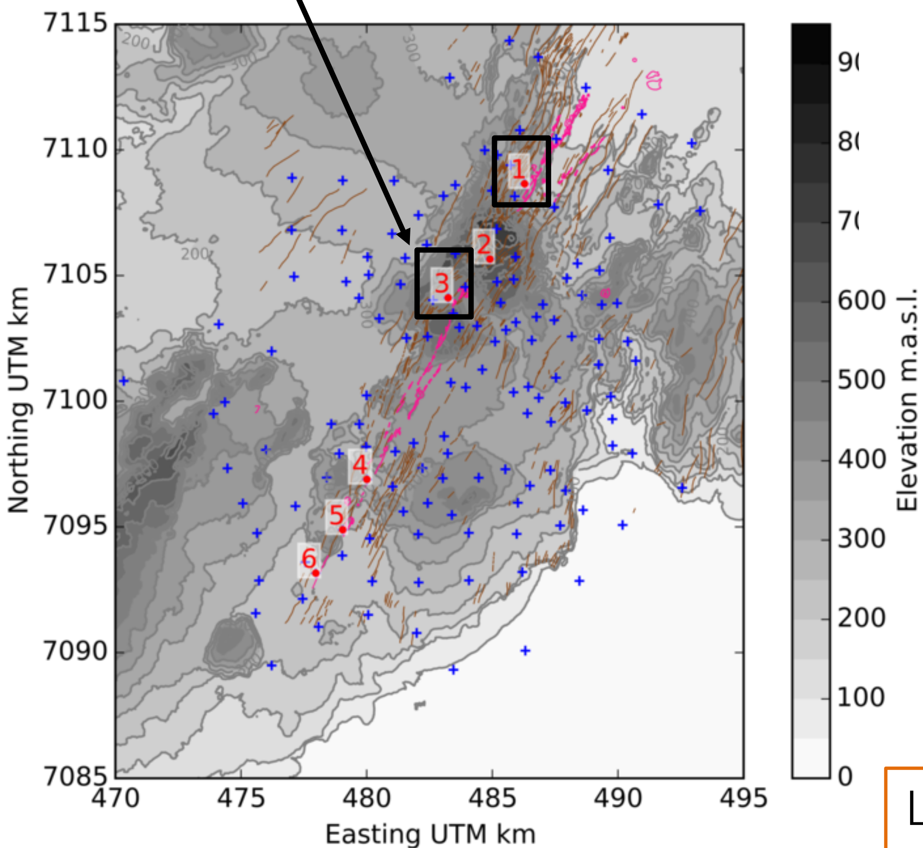
- Survey
  - 133 stations used
  - Combination of 2E and 2E+3H setup
  - Frequencies: 300 – 0.001 Hz

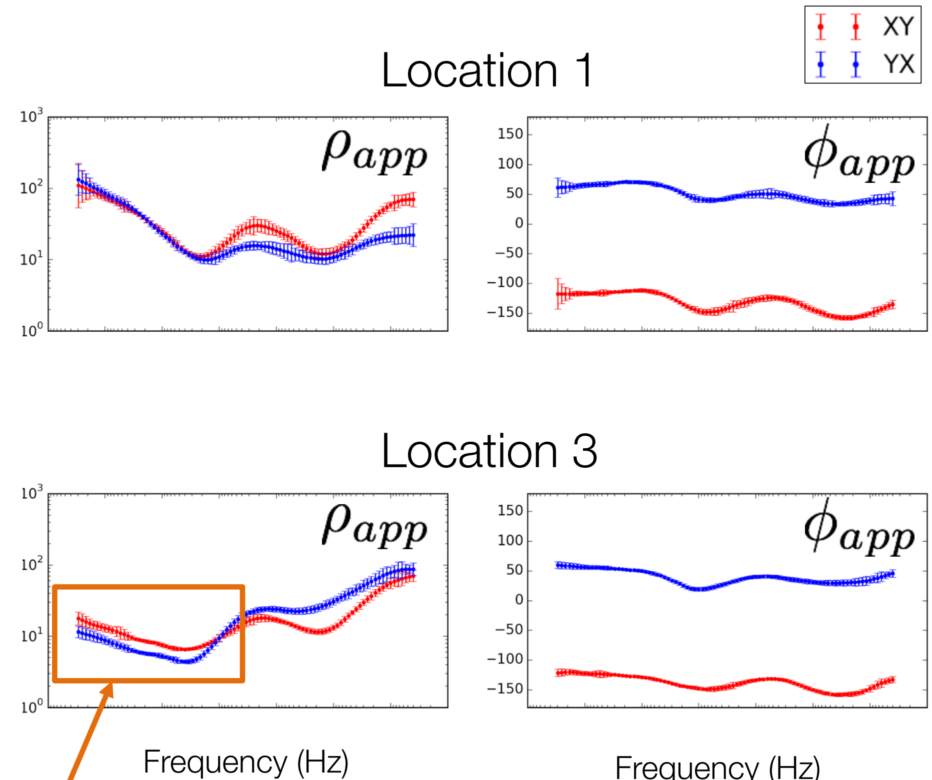


- Remote reference
  - About 40 km away
- Raw data processing using Phoenix software

Data

Surface alteration,
hot water, fumaroles

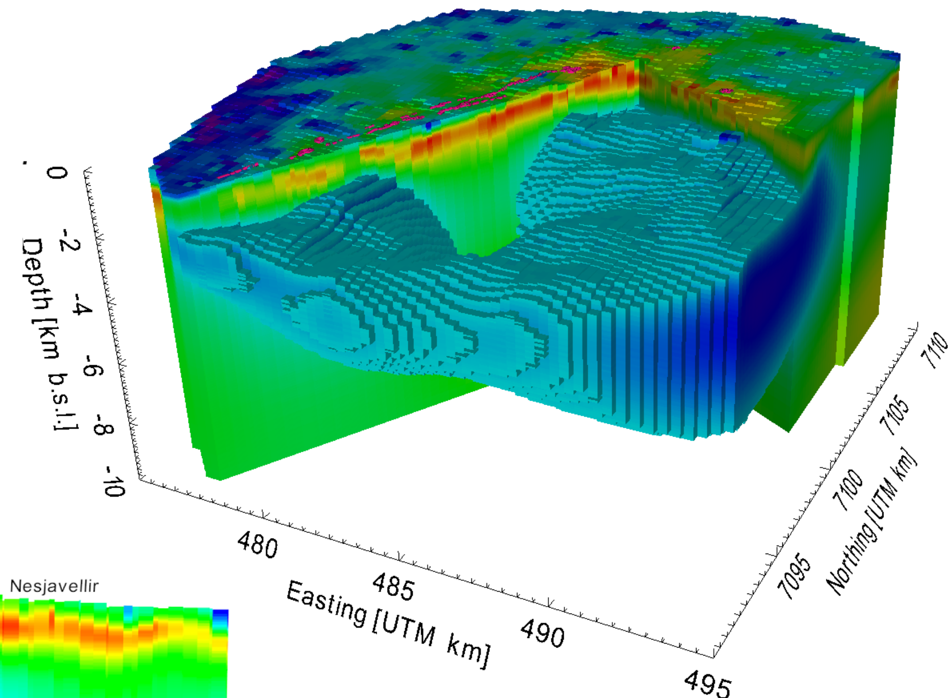


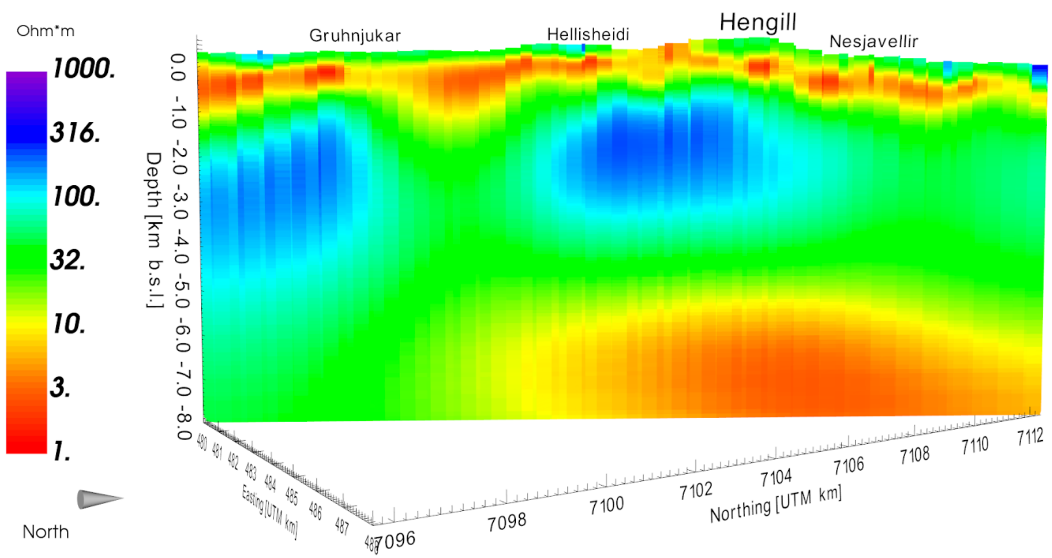


Low apparent
resistivity

3D inversion

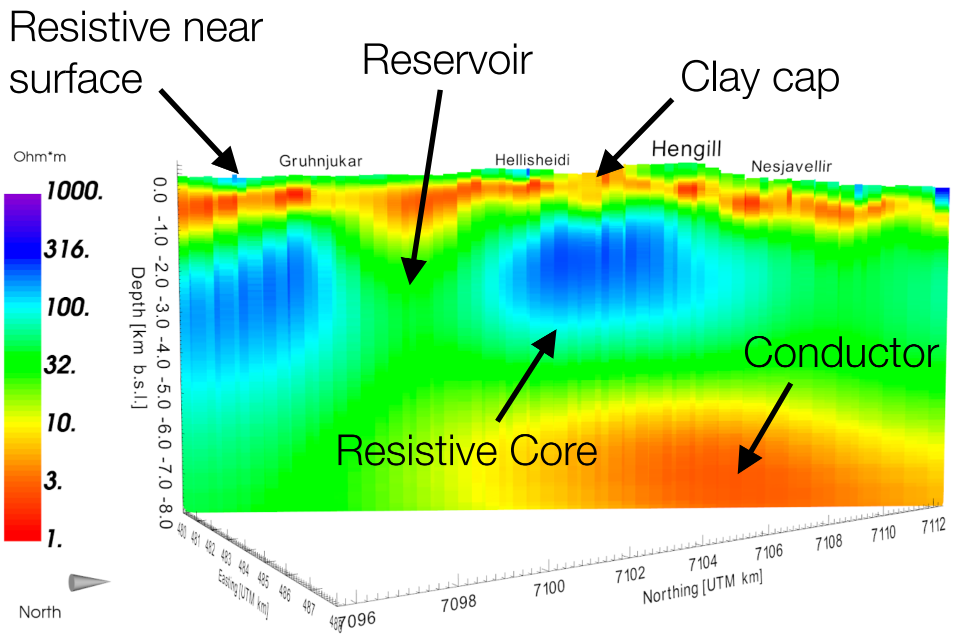
- Off-diagonal impedance (Z_{xy} and Z_{yx}) used
- Combined multi-frequency inversion (300 Hz – 0.001 Hz)

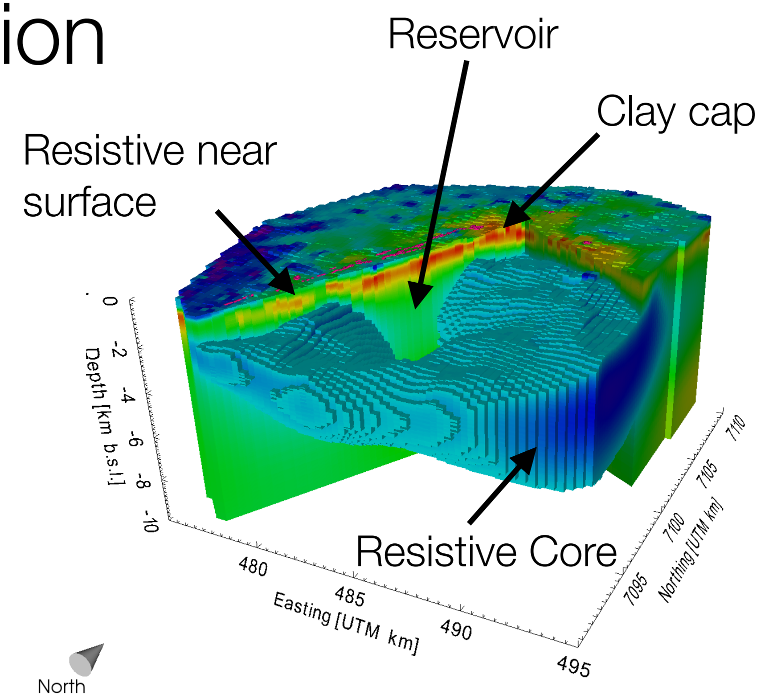


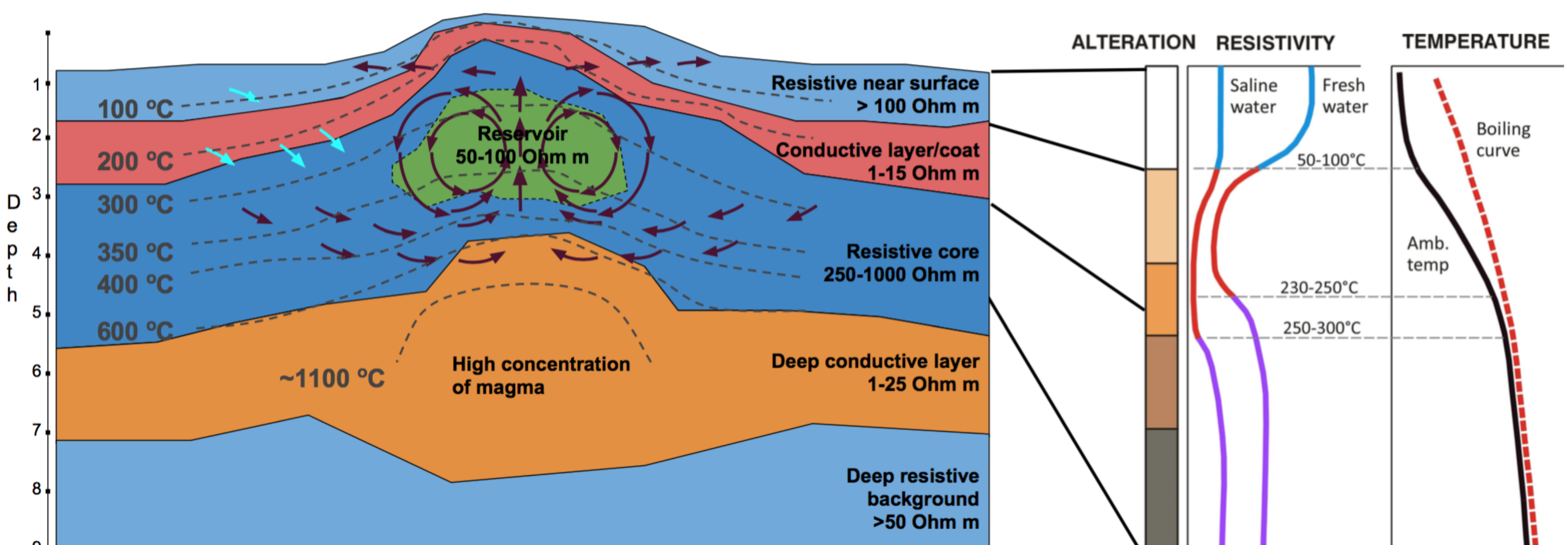


Rosenkjaer et al, 2015

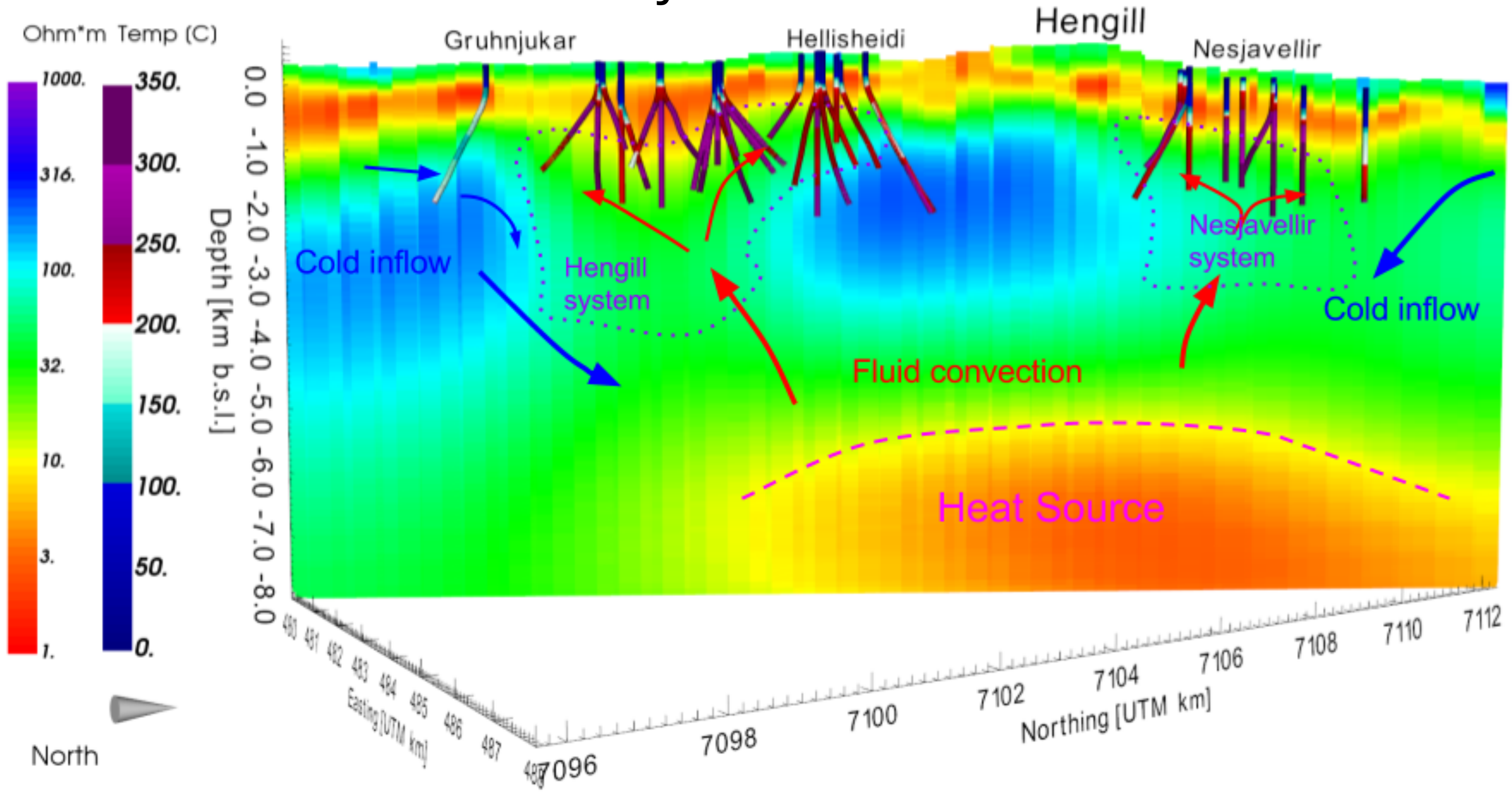
Interpretation







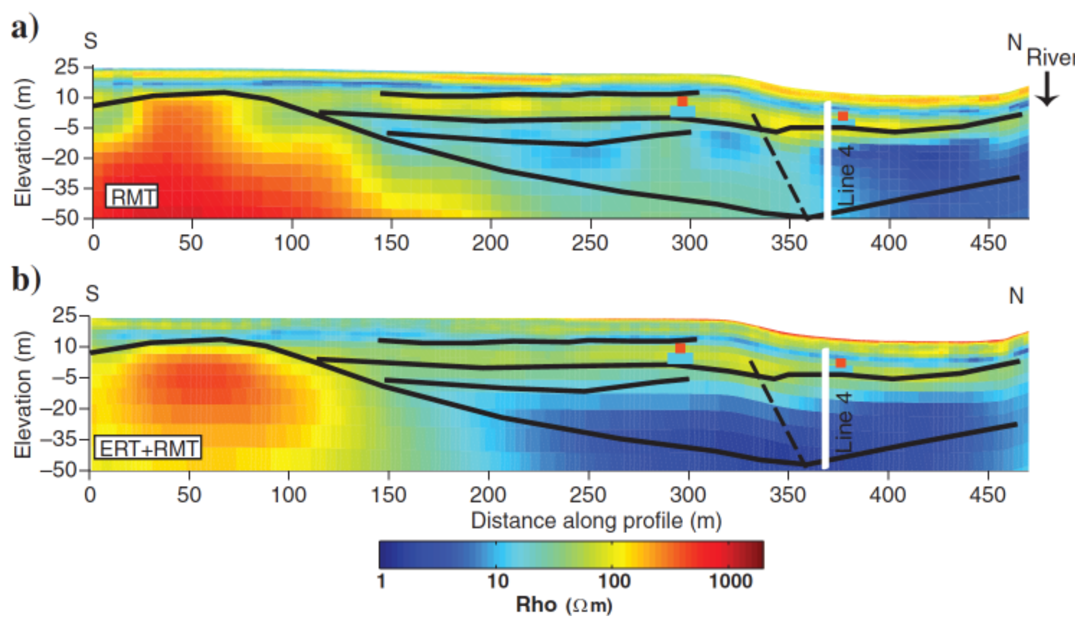
Synthesis



- Conductive layer corresponds with formation temperature
- Two main production fields: Hengill and Nesjavellir
- Deep conductive heat source

Case History: Landslides, Sweden

Shan et al., 2014



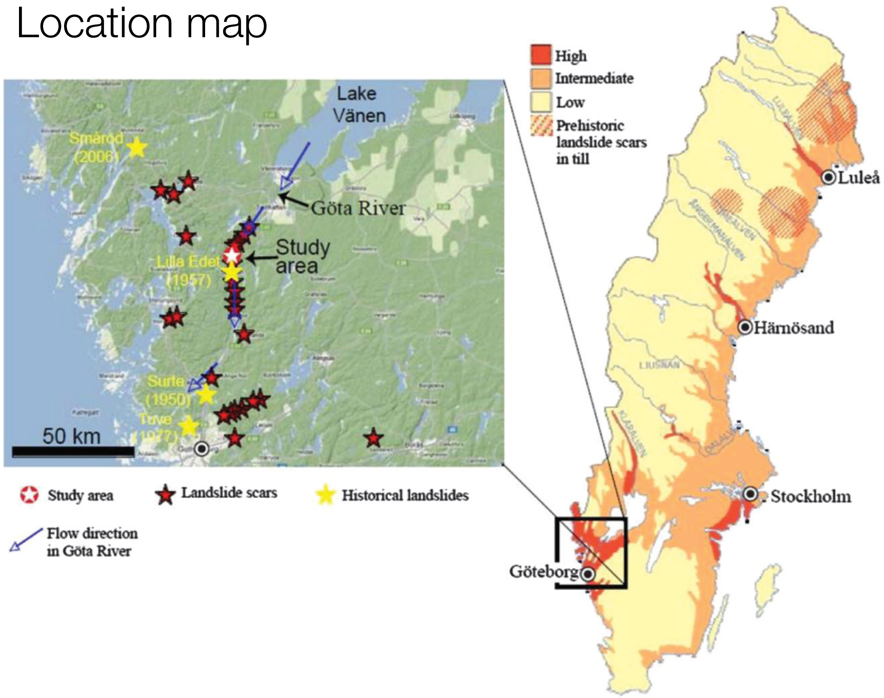
Landslides in Sweden

Photo: C Fredén, 1977, Tuve

Photo: Mats Engdahl, 2006, Munkedal

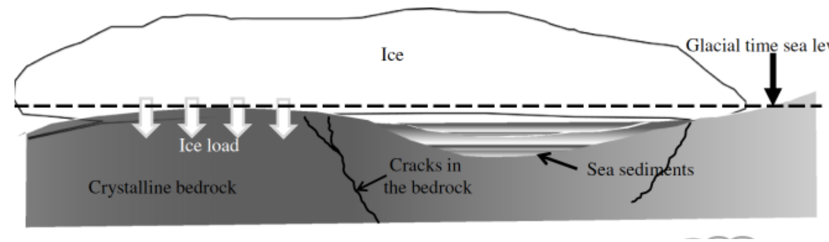
Setup

Location map

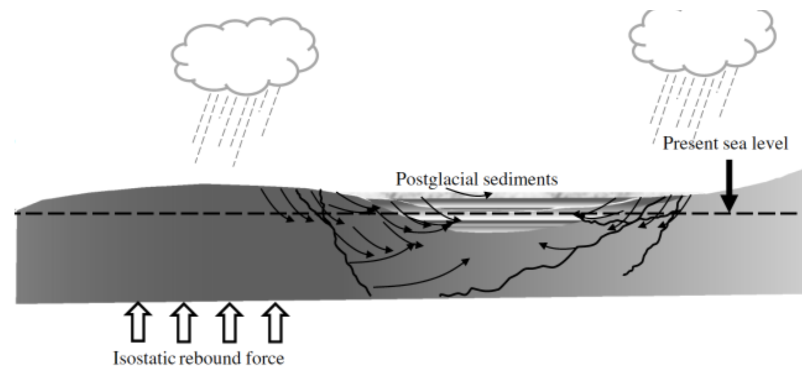


Formation of quick clays

The last glacial period



Land uplift and formation of quick clays



- Marine clay, deposited, uplifted then flushed with freshwater
  - Decreases salinity and reduces strength →quick clays

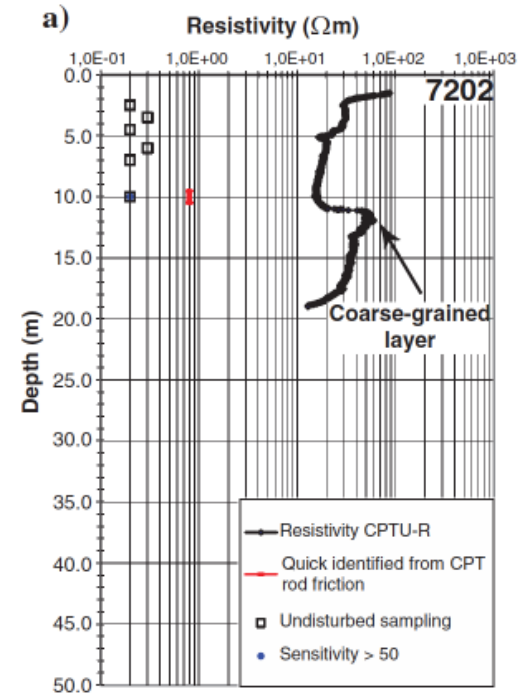
Can we detect quick clays?

Properties

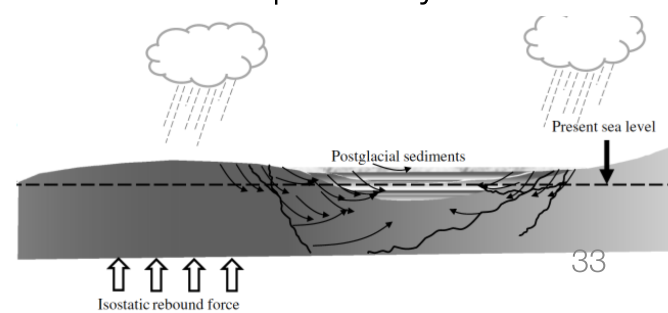
Soil material	Resistivity interval
Salt/intact marine clay	1–10 Ωm
Leached, possible quick clay	10–80 Ωm
Dry crust clay, slide deposits, coarser	>80 Ωm

- Clays
  - Conductive
  - Usually overlay sand / gravel
- Quick clays
  - Infiltration of water removes salt
  - More resistive than typical clays
- Coarse-grained layer
  - Resistive
  - Sand and gravel (porous)

Resistivity (induction log)

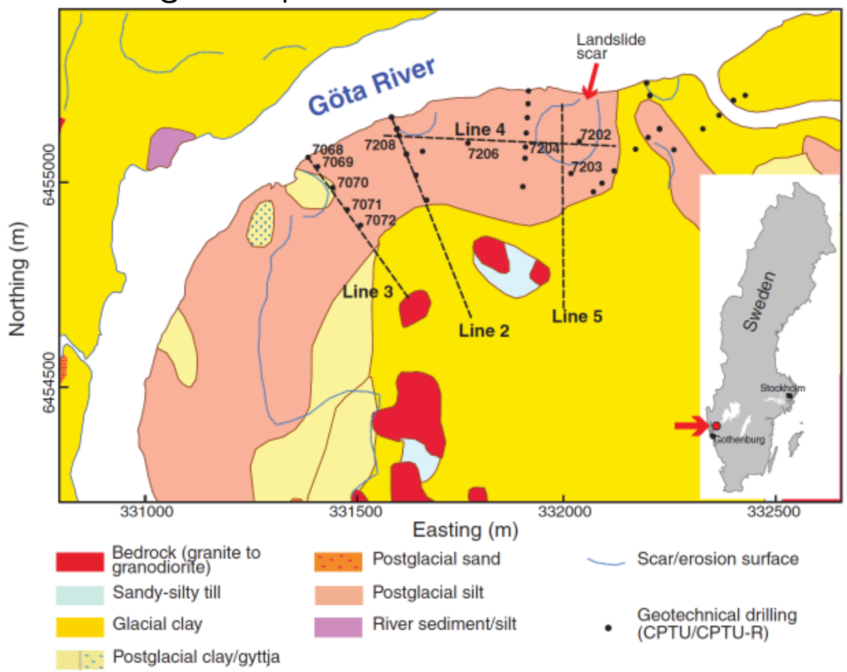


Formation of quick clays

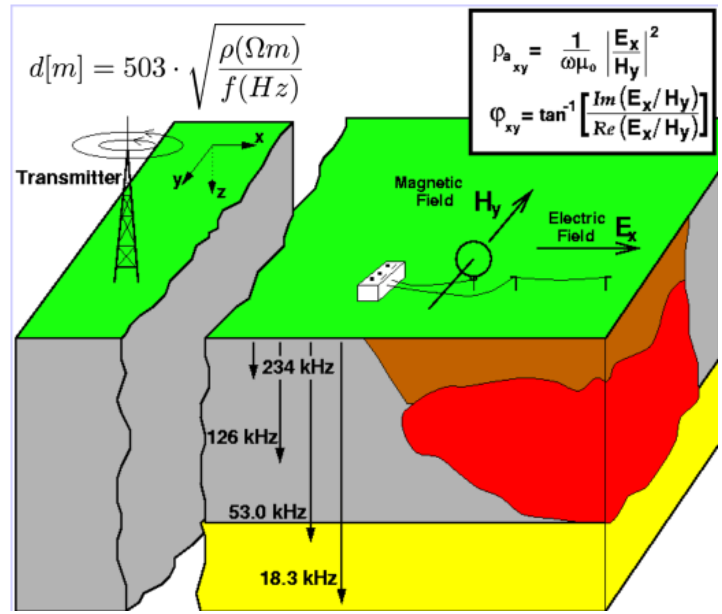


Surveys

Geologic map



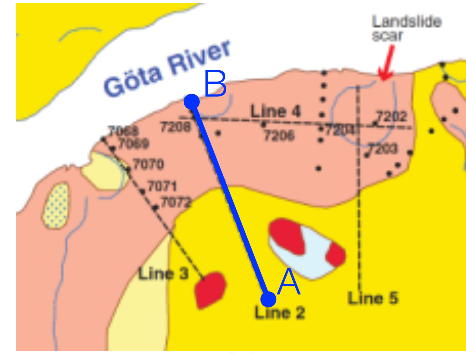
RMT survey



From Bulent (2017)

- DC (ERT)
  - Lines 2-5
  - ABEM system
  - Wenner array (5m spacing)
- Radio MT (RMT)
  - Same lines as DC
  - EnviroMT system
  - 21-28 radio transmitters
  - Frequencies: 18.3-183 kHz

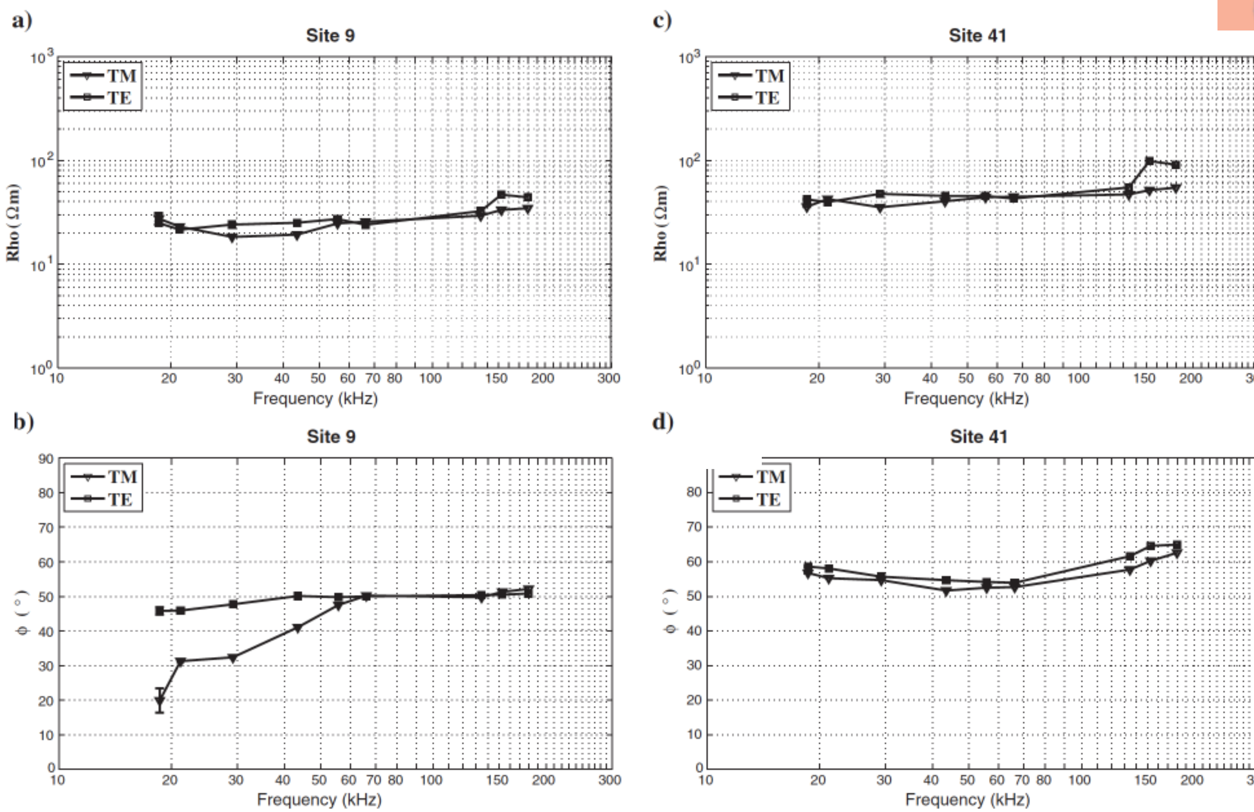
RMT: sounding curves



Line 2

Apparent resistivity

Phase

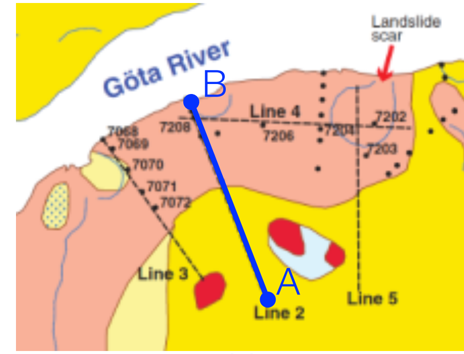


Computed using determinant of impedance tensor at two stations along Line 2

Impedance tensor: $$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix}$$

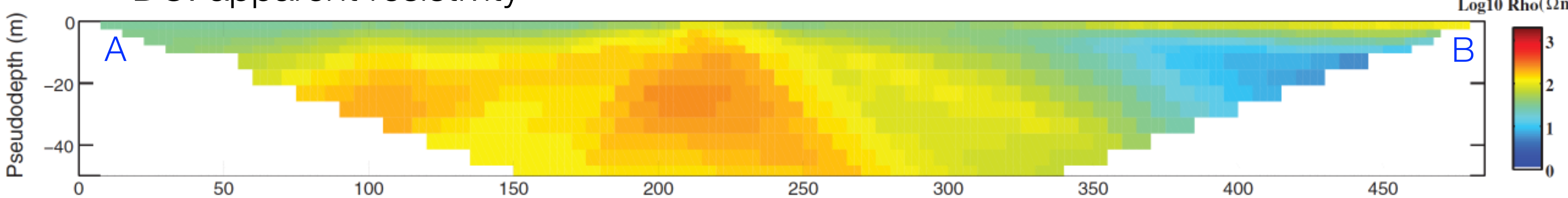
Determinant: (complex-valued) $$Z_{\text{det}} = \sqrt{Z_{xx}Z_{yy} - Z_{xy}Z_{yx}}$$

Pseudosections

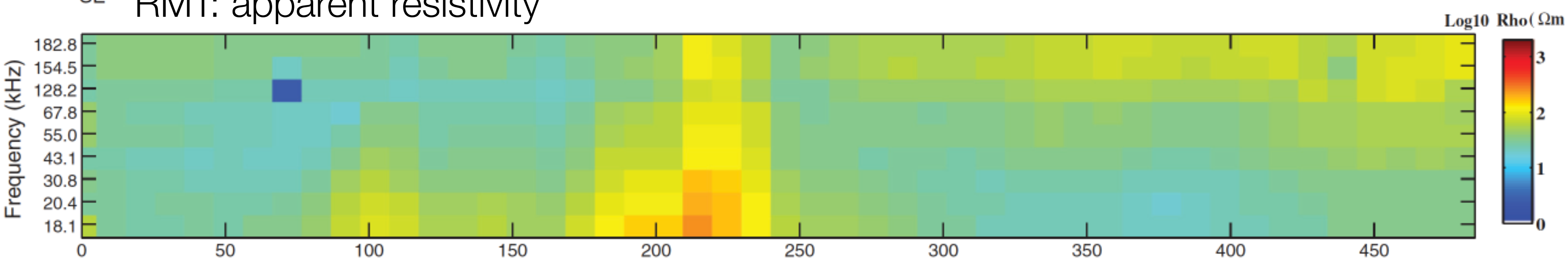


Line 2

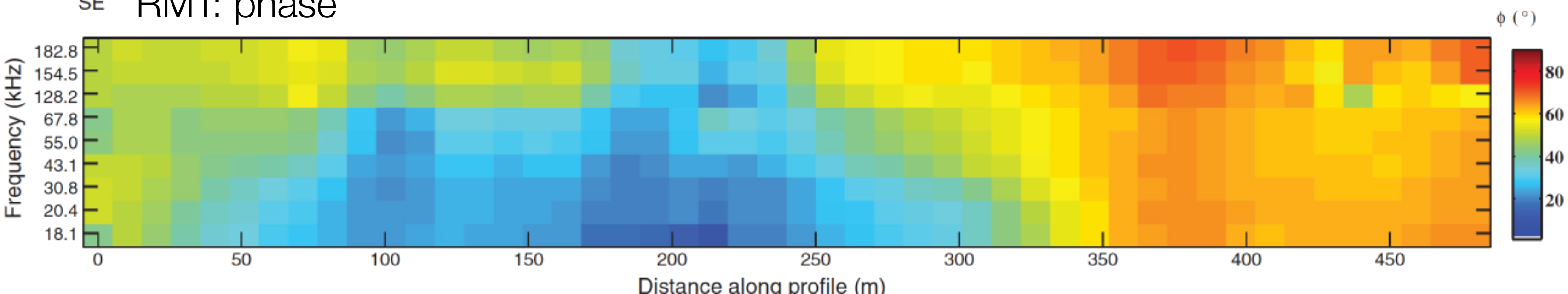
SE DC: apparent resistivity NW



SE RMT: apparent resistivity NW



SE RMT: phase NW



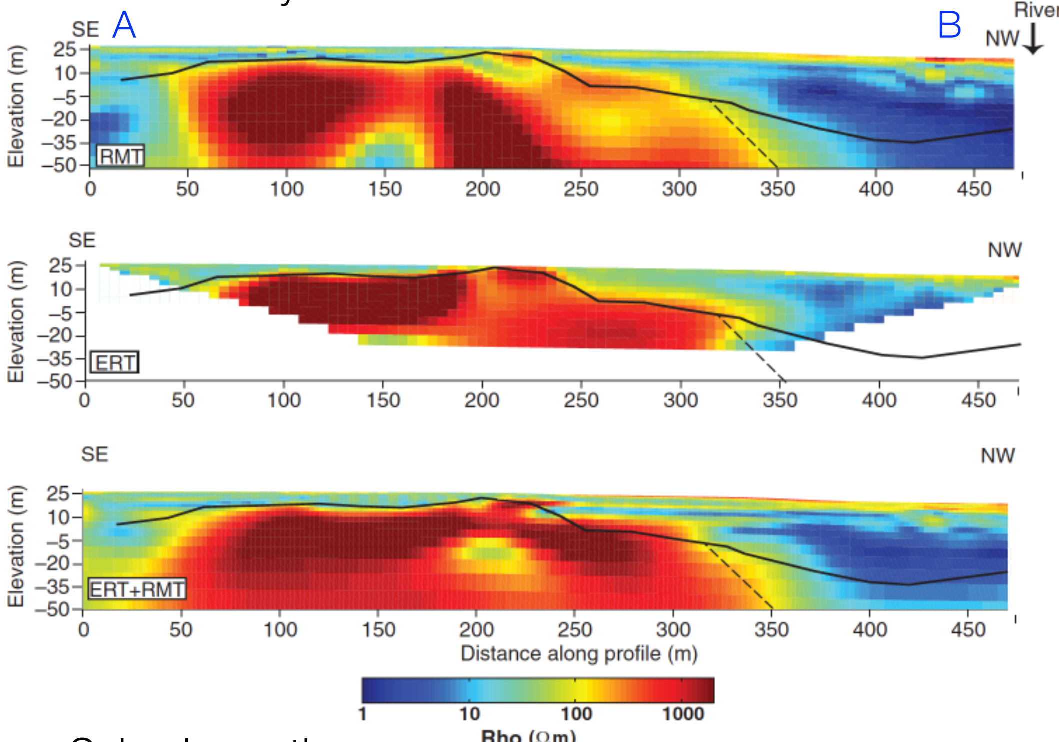
Processing and inversion

2D resistivity sections

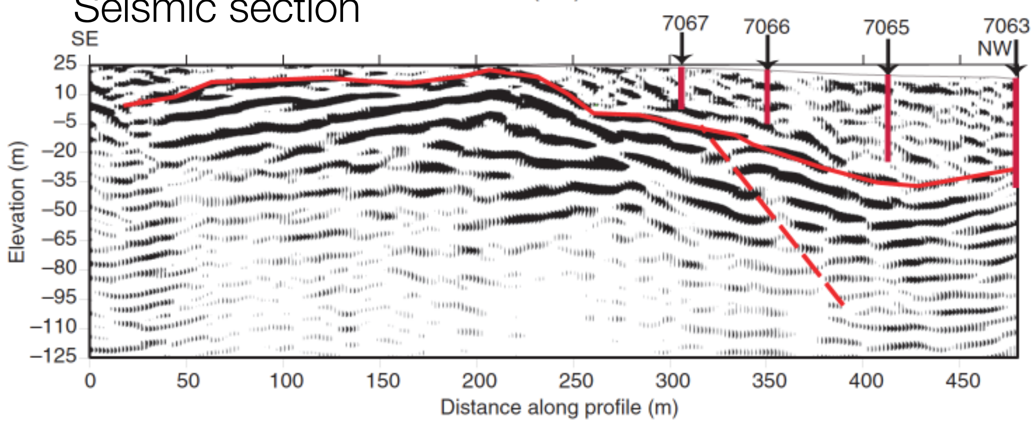
RMT

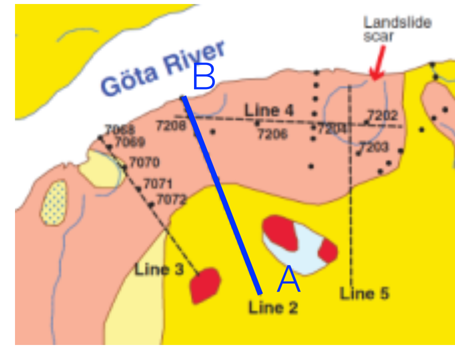
ERT

ERT
+
RMT



Seismic section





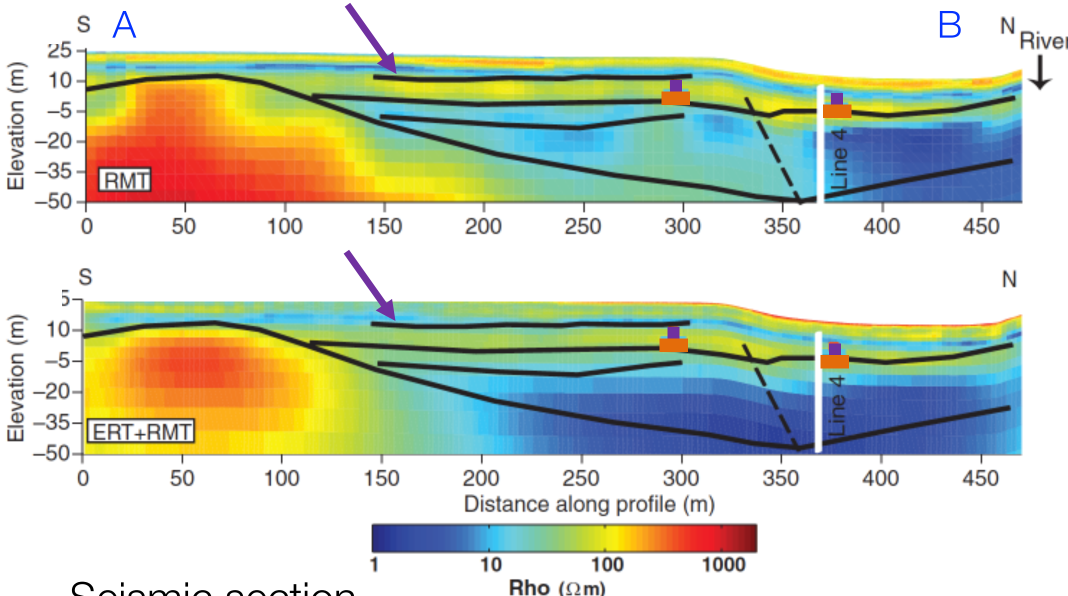
- ERT and RMT yield similar images
- Jointly invert ERT and RMT
- Correlates with seismic

Processing and inversion

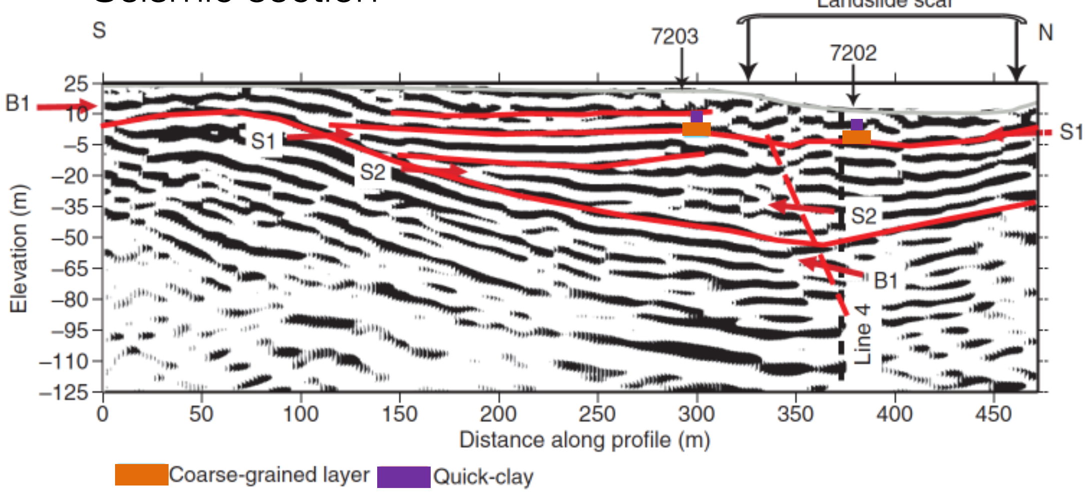
2D resistivity sections

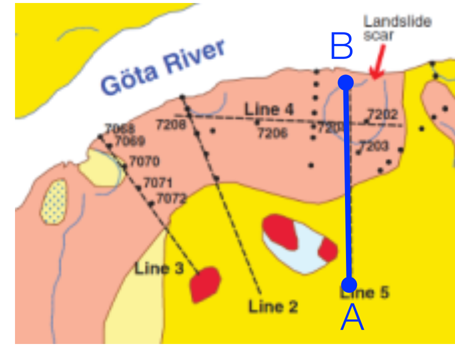
RMT

ERT
+
RMT



Seismic section

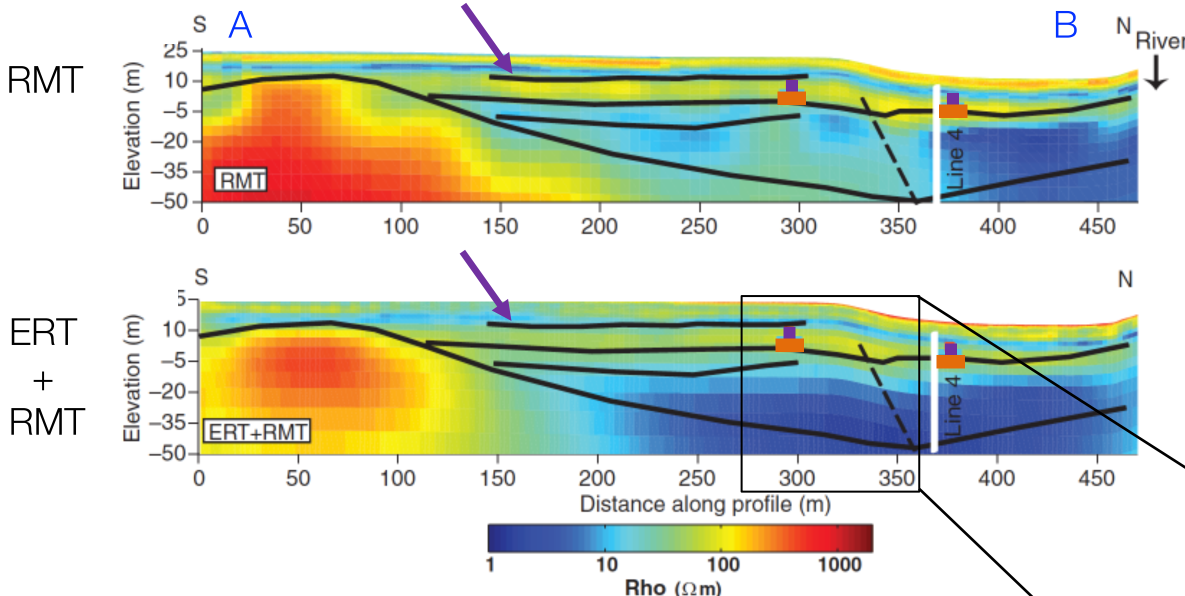


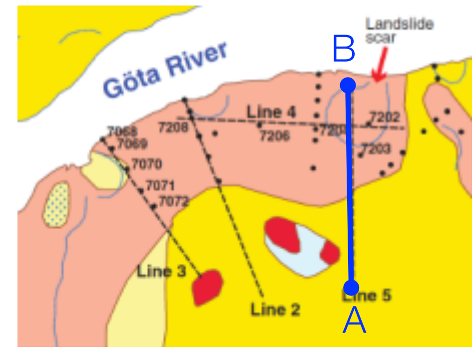


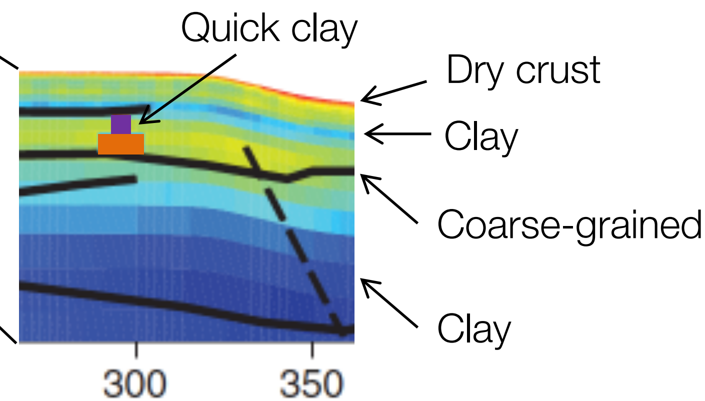
- Inverted RMT, ERT+RMT interpreted with seismic

Processing and inversion

2D resistivity sections







Lithology (from boreholes)

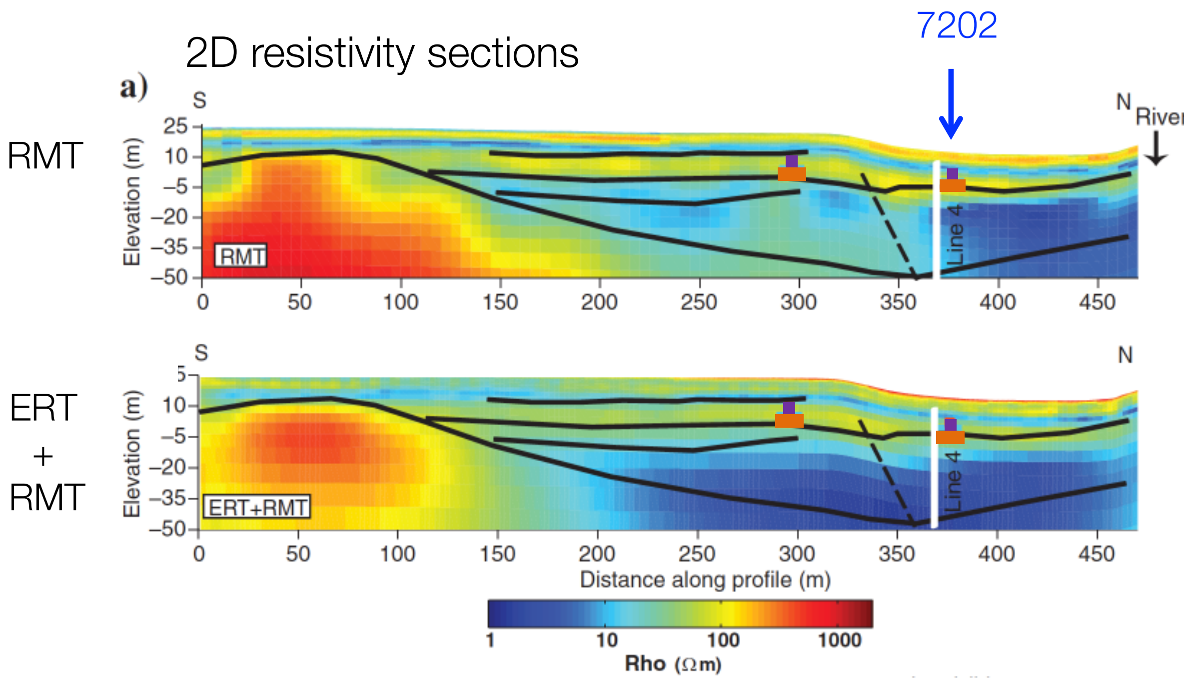
- Quick clay
- Coarse layer

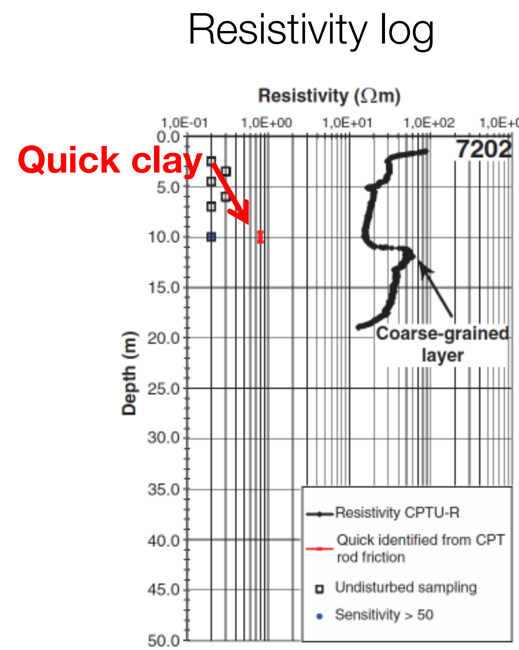
Soil material	Resistivity interval
Salt/intact marine clay	1–10 Ωm
Leached, possible quick clay	10–80 Ωm
Dry crust clay, slide deposits, coarser	>80 Ωm

Quick clay

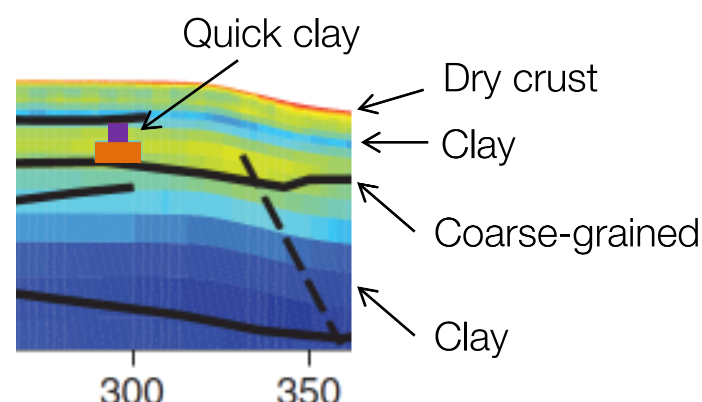
- Top interface: conductor to resistor
- Thickness difficult to estimate

Synthesis





- Resistivity is indicative of lithologic units → identify possible quick clays
  - Corresponds with seismic
  - Determining thickness is challenging



Summary

- Background on natural source EM methods
- Magnetotellurics
- Case history: Geothermal
- Case history: Landfill
- Z-axis tipper electromagnetics
- ZTEM case history

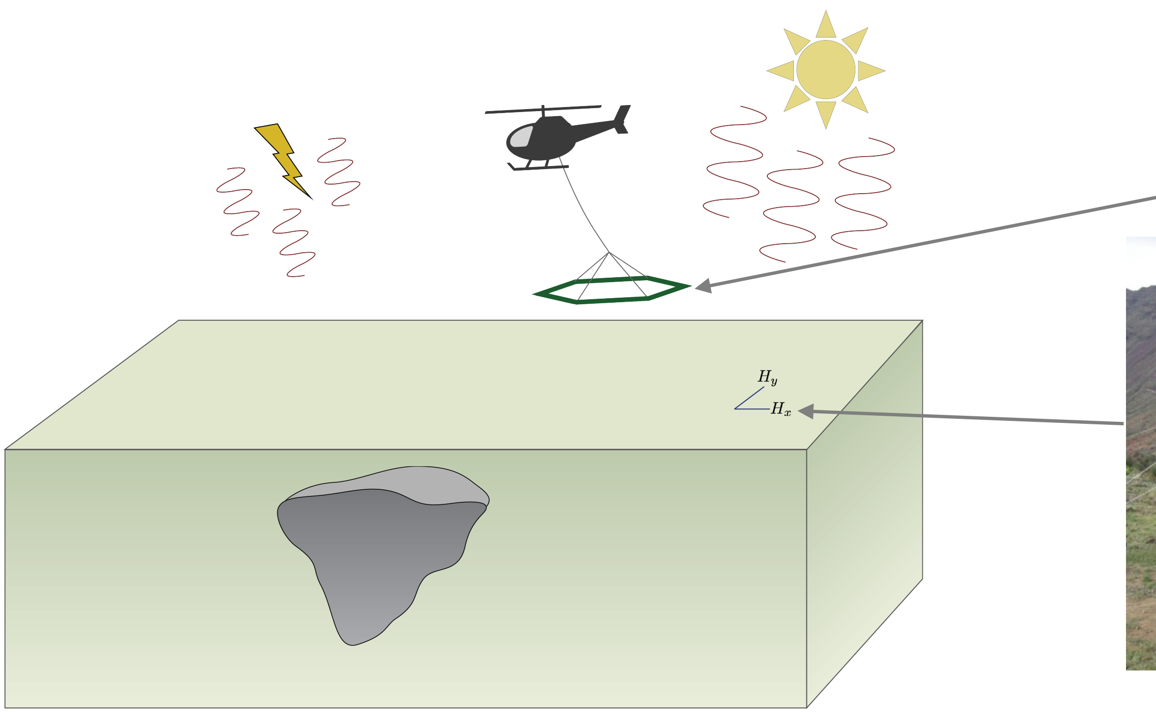
Tipper data (ZTEM)

- Magnetic transfer function

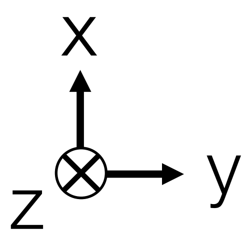
$$H_z = \mathbf{TH}$$

$$H_z(r) = T_{zx}H_x(r_0) + T_{zy}H_y(r_0)$$

- Frequencies 30Hz – 720 Hz



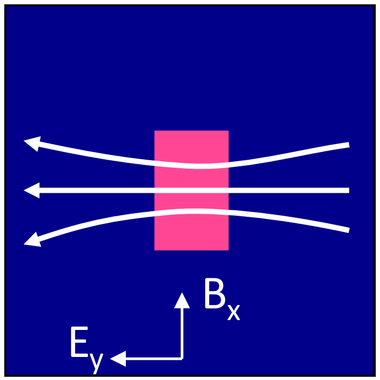
Synthetic example

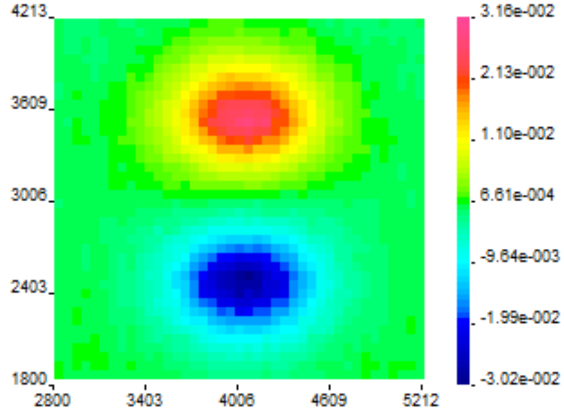


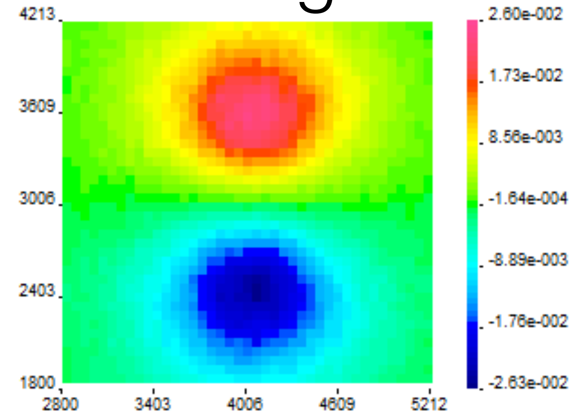
Real

Imag

T_{zx}





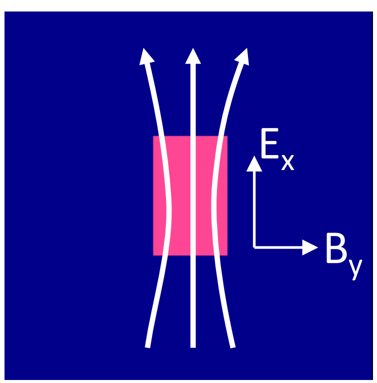


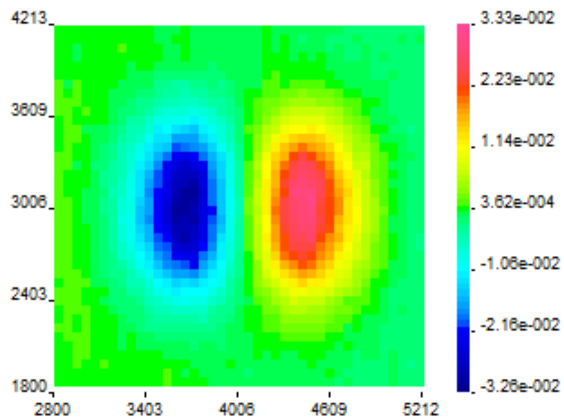
Conductor

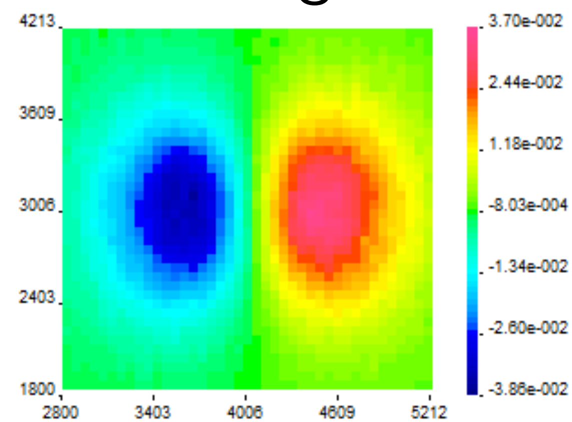
Real

Imag

T_{zy}







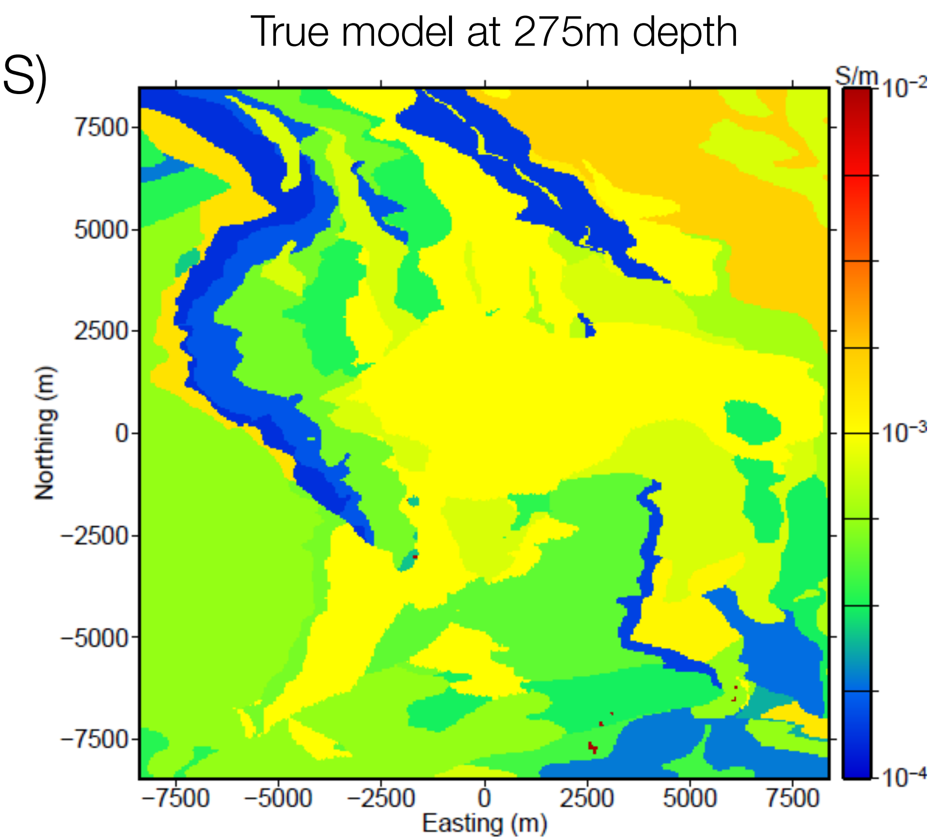
ZTEM case histories

- **Noranda district**
- Elevenmile Canyon geothermal area
- Balboa copper porphyry deposit

Noranda district, Canada

- Hosts many deposits:
  - 20 economic volcanogenic massive sulphide deposits (VMS)
  - 19 orogenic gold deposits
  - Several intrusion-hosted Cu-Mo deposits

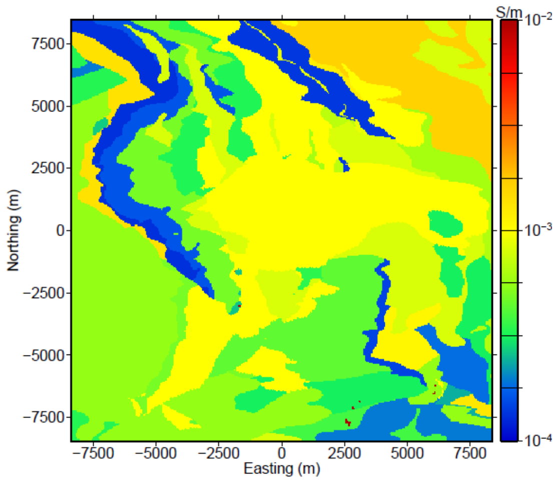
- Physical properties
  - Synthetic example from geologic model
  - 38 geologic units converted into expected conductivities



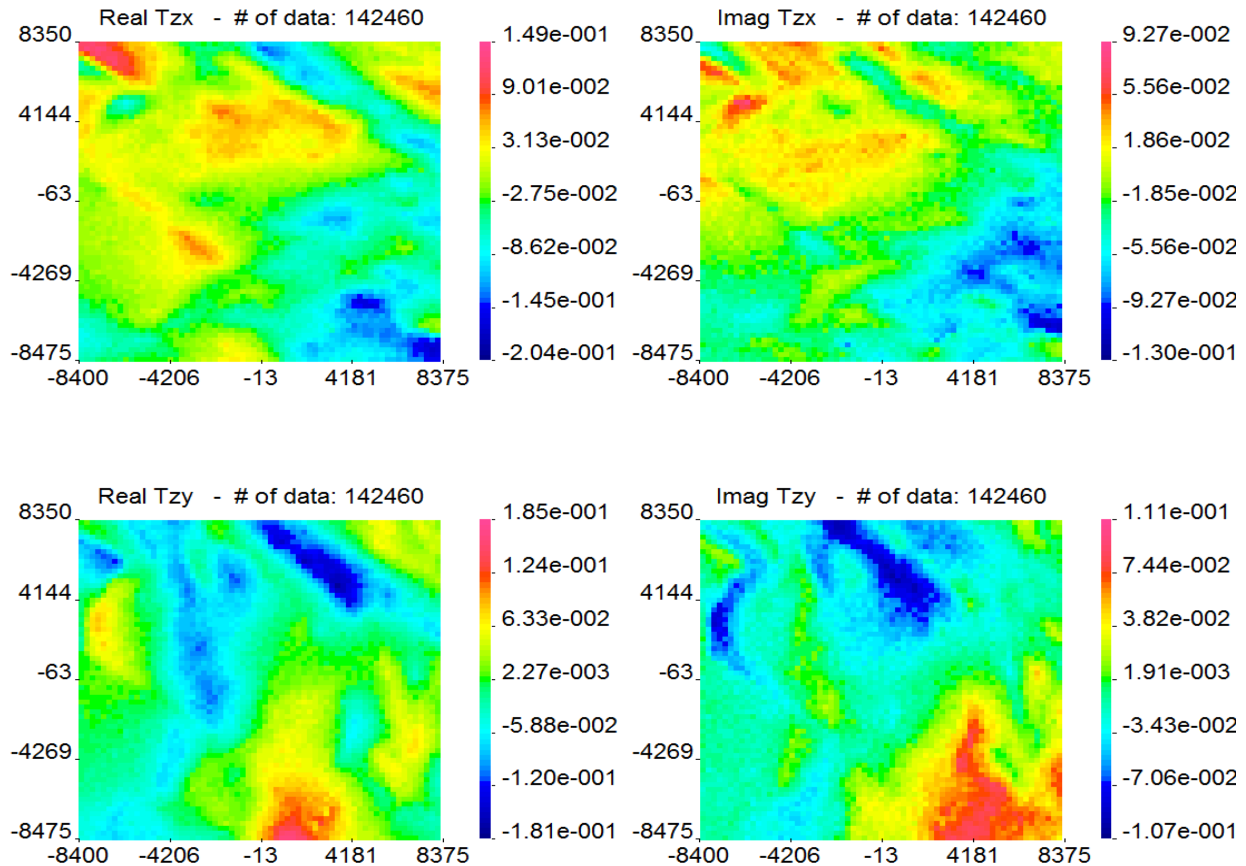
Data

- Forward model data at 6 frequencies
  - 30, 45, 90, 180, 360, and 720 Hz
- Need to invert data

True model at 275m depth

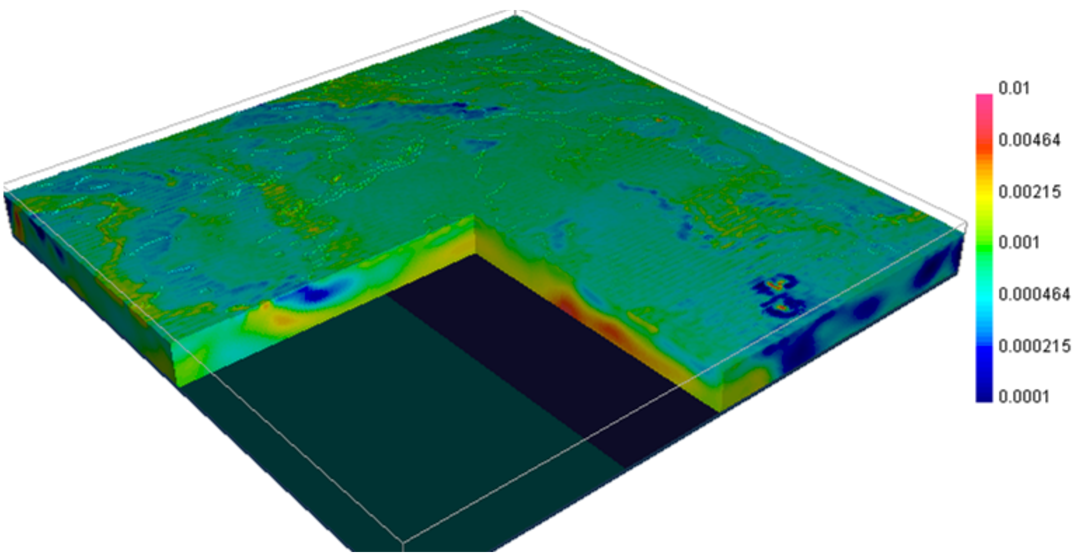


Observed (90 Hz)

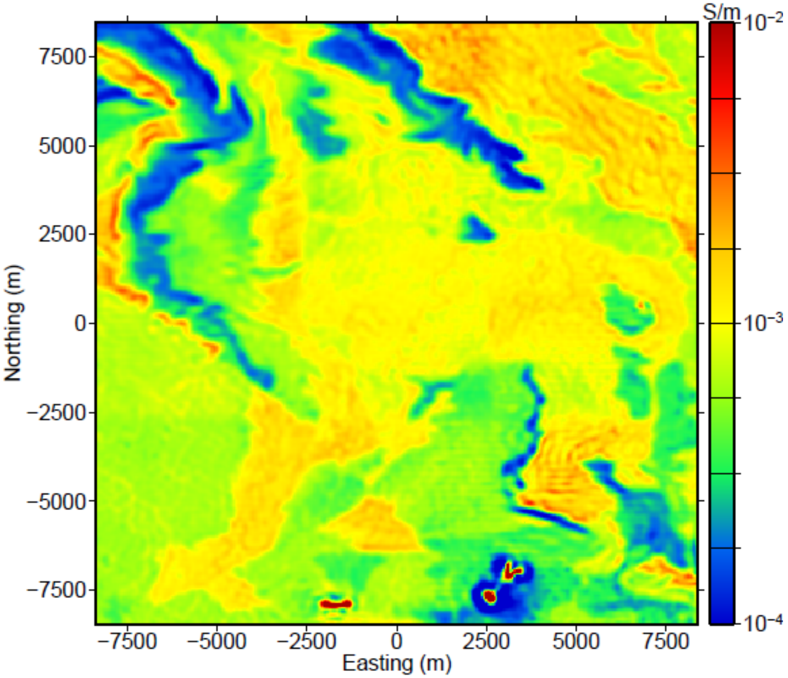


Interpretation

Recovered Model



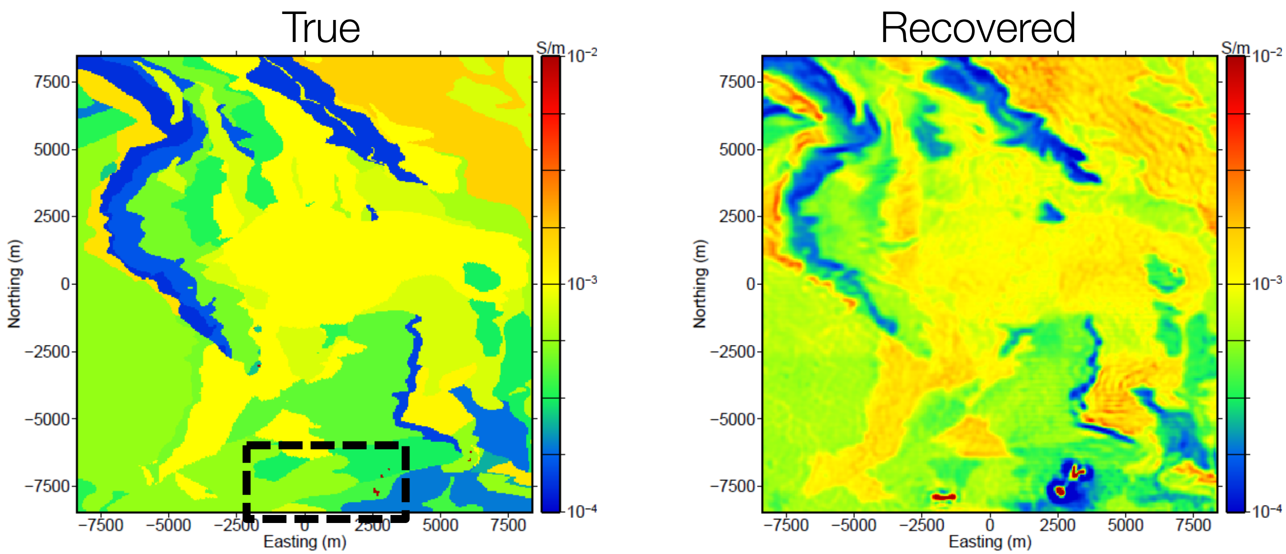
Model at 275m depth



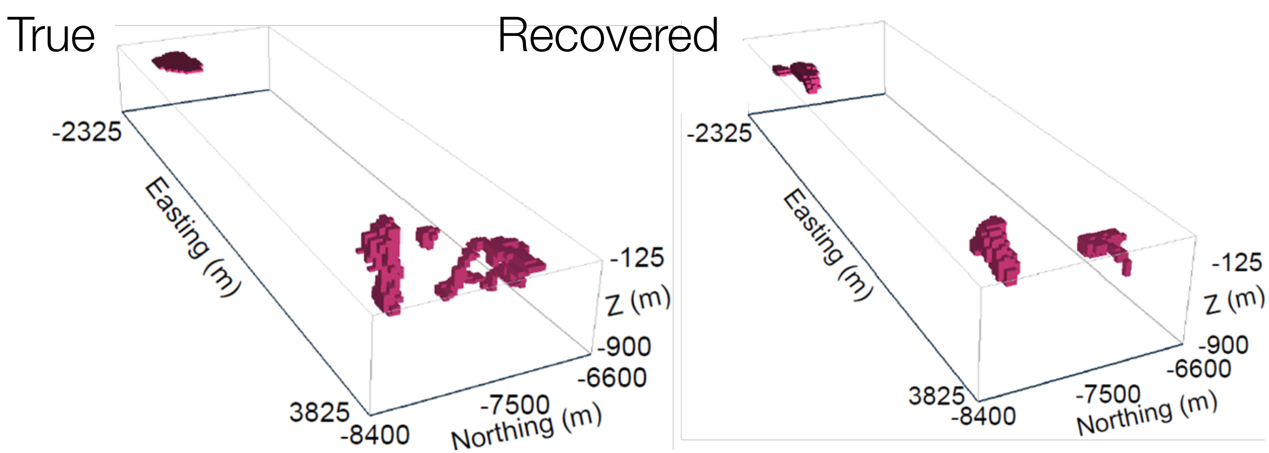
- Geologic units are well mapped
- Some mineralized bodies are located

Synthesis

- Recovered model represents the regional geology

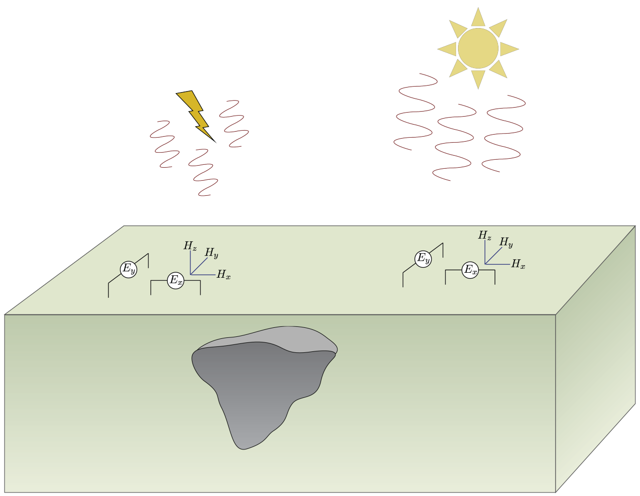


- Mineralized zones are recovered



Summary

- Background on natural source EM methods
- Magnetotellurics
- Case history: Geothermal
- Case history: RMT for landslides
- Z-axis tipper electromagnetics
- Case history: ZTEM for minerals



End of Natural Sources