

EM: Natural Sources

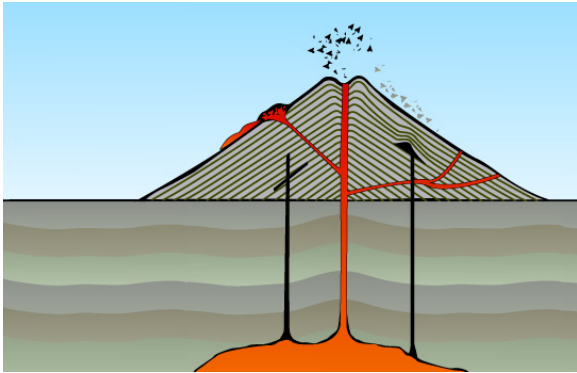


Outline

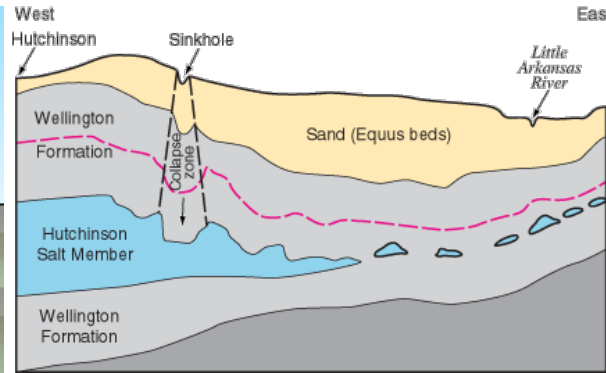
- Background on natural source EM methods
- Magnetotellurics
- Case history: Geothermal
- Case history: Landfill
- Z-axis tipper electromagnetics
- ZTEM case history

Motivation

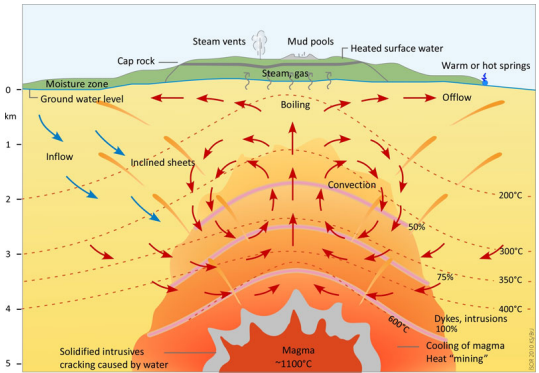
Volcanoes



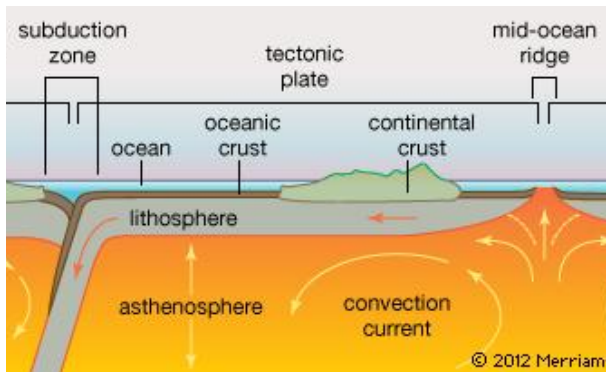
Base of salt



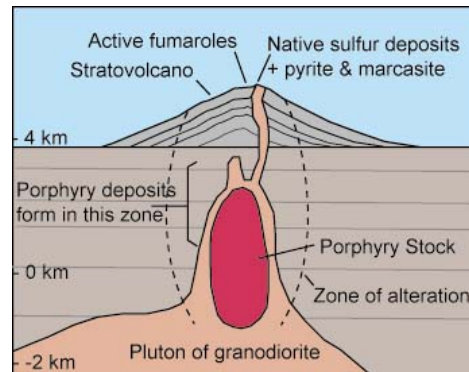
Geothermal



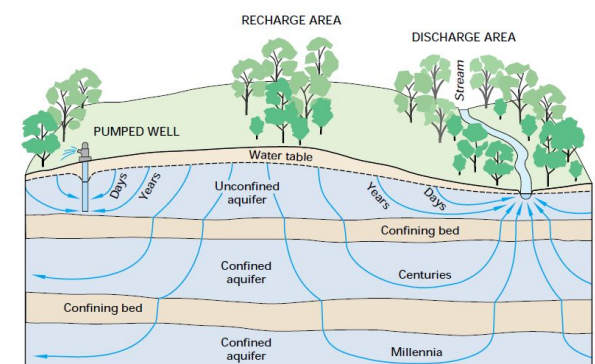
Tectonic settings of top few km



Mineral targets



Groundwater



Common challenge: getting enough energy into the ground

What is required to see deeper?

- Penetration depth depends upon system power

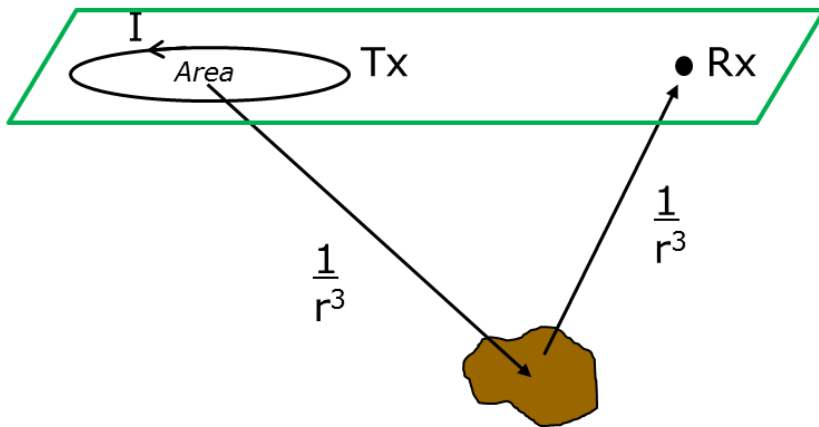
- Controlled source:

- Using a small loop
- Magnetic moment

$$m = IA$$

- Total geometric decay

$$\sim \frac{1}{r^6}$$

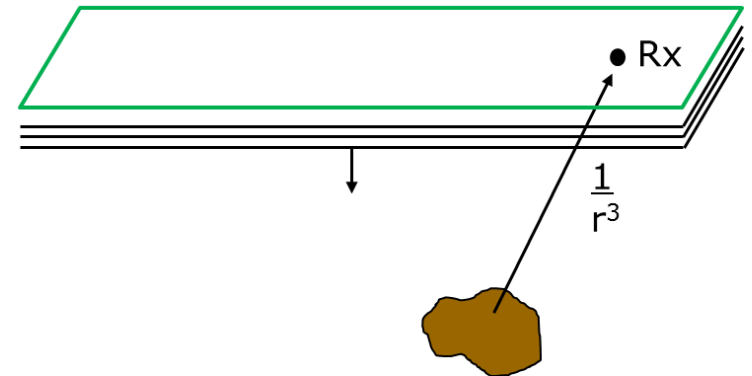


- Infinitely large loop source

- Sheet currents generate plane waves

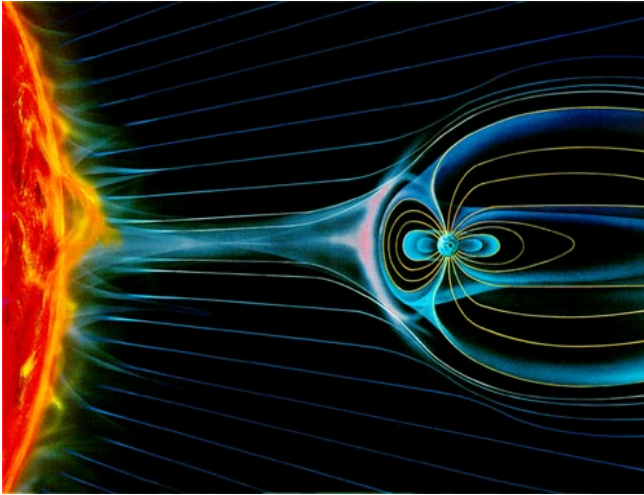
- Total geometric decay

$$\sim \frac{1}{r^3}$$

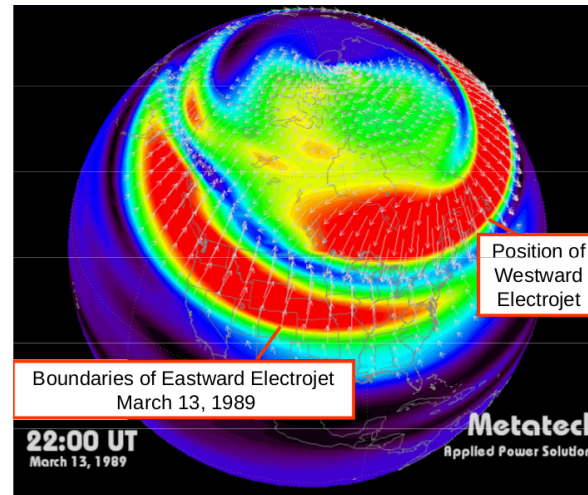


Natural EM sources

Sun and magnetosphere, solar storms



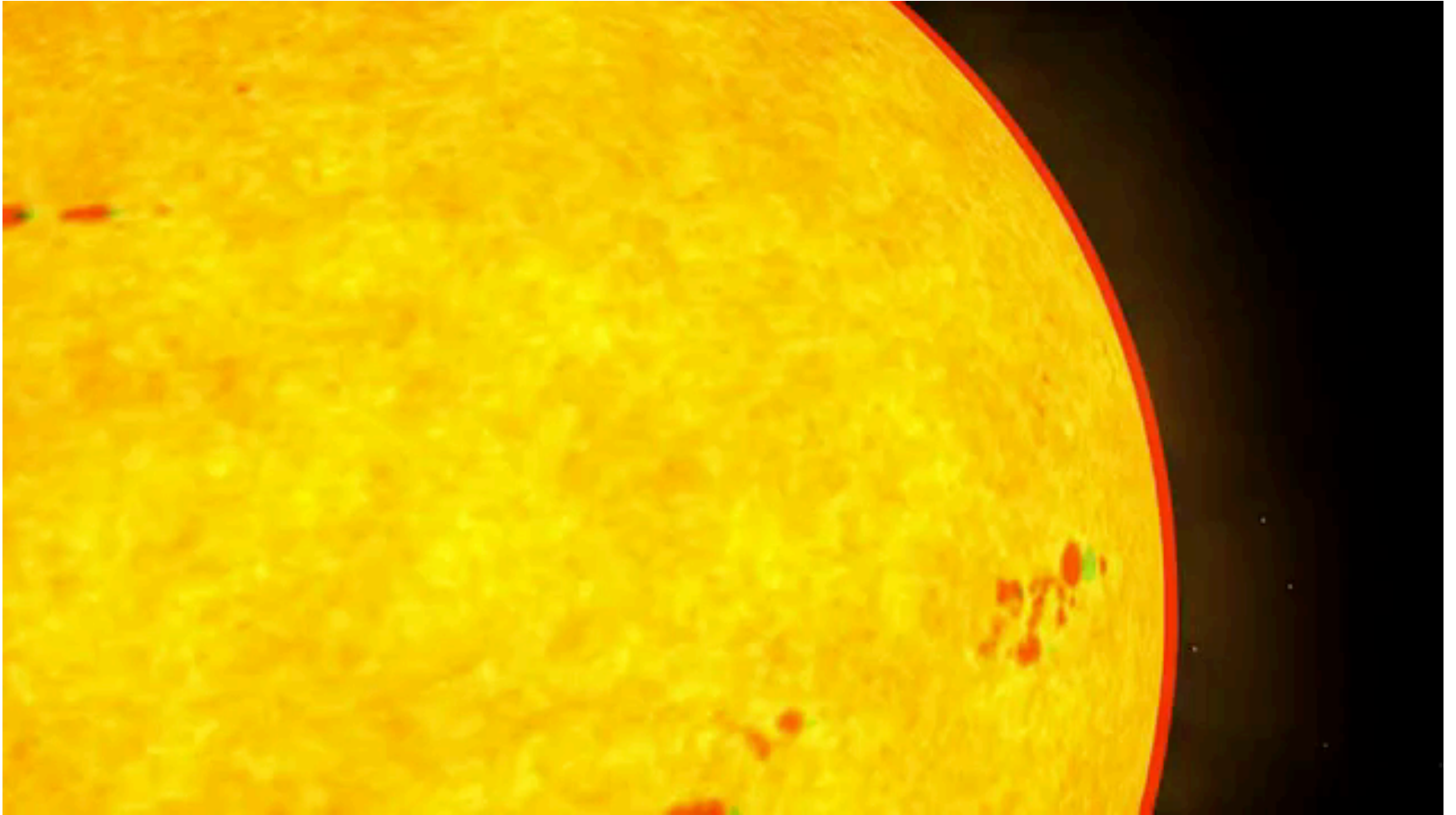
Auroral electrojet; aurora



Lightning

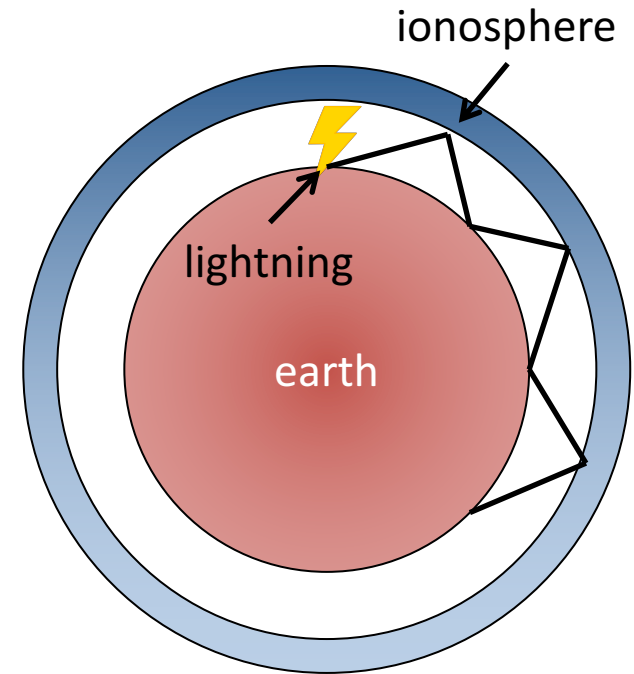


Aurora movie

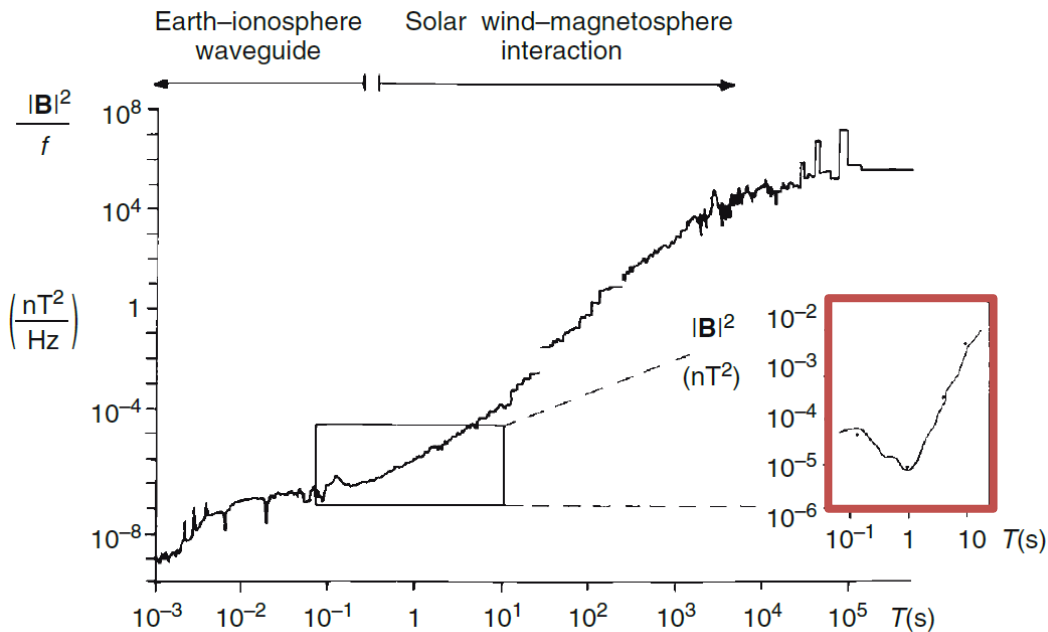


Earth as a waveguide

- 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

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

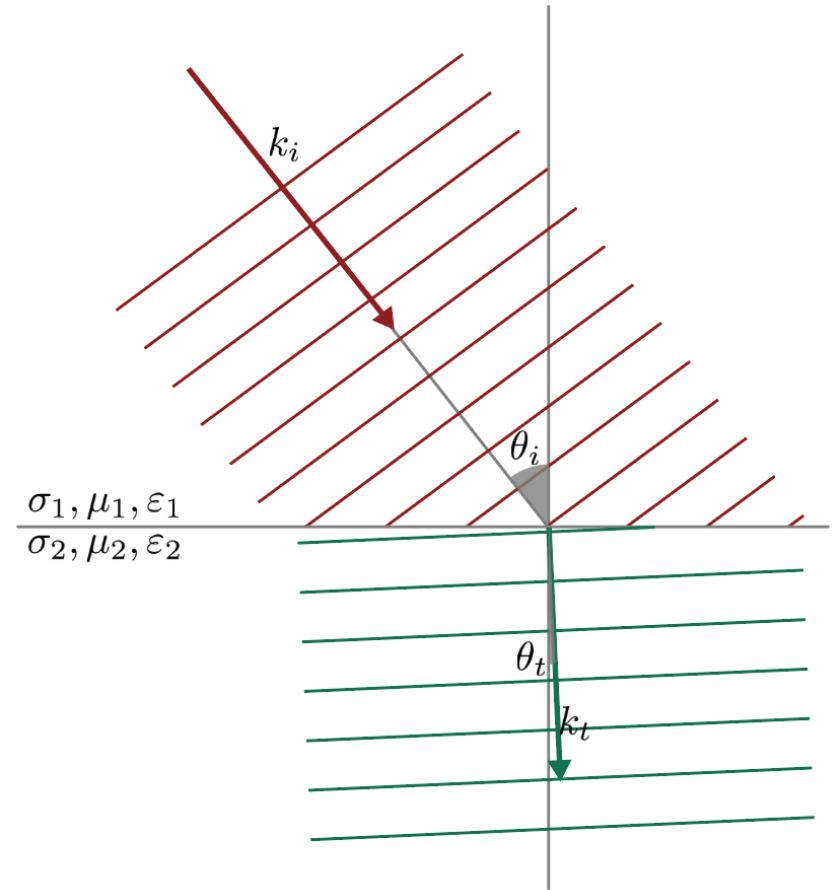
- k is complex wave number

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

- Quasi-static: $\frac{\omega \epsilon_0}{\sigma} \ll 1$

$$\sin \theta_t = \sqrt{\frac{2\omega \epsilon_0}{\sigma}} \sin \theta_i$$

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



Example for 10,000 Hz

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

$$\theta_i = 89^\circ$$

$$\text{Then } \theta_t = 1.35^\circ$$

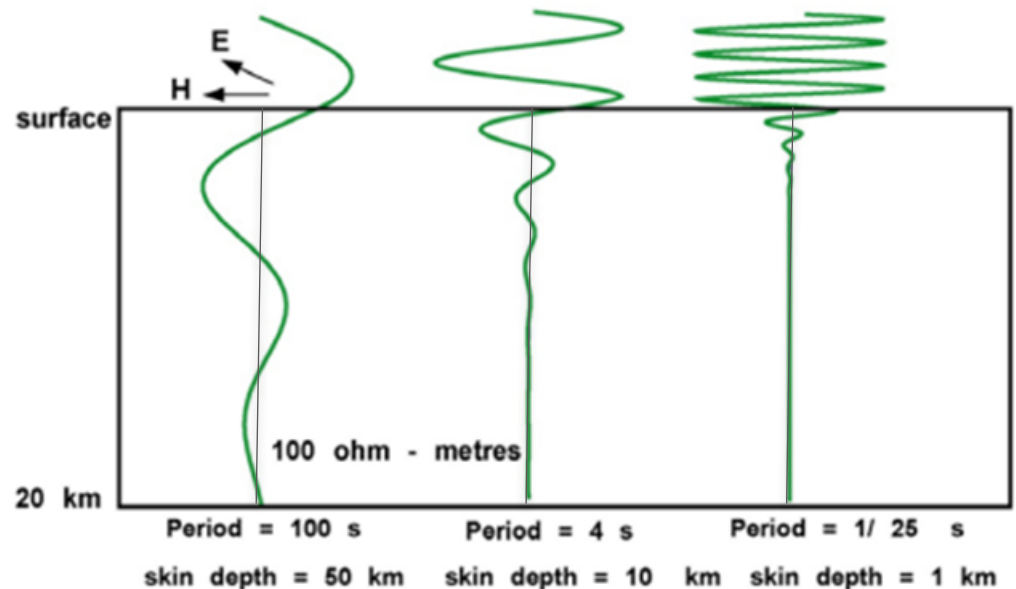
Plane waves and skin depth

- Skin depth (meters)

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

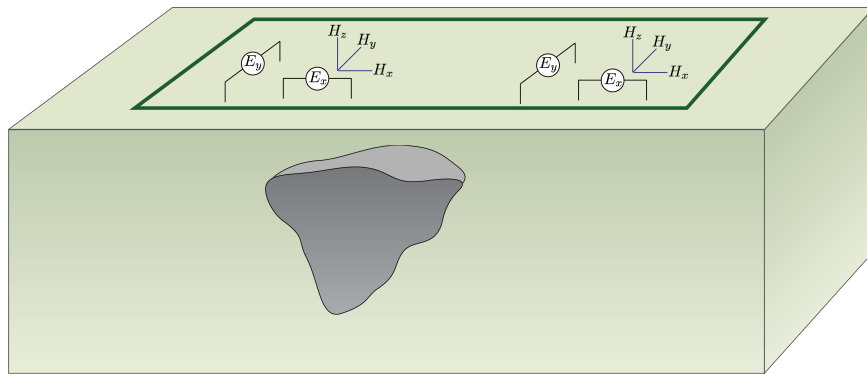
- Low frequency waves propagate further

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

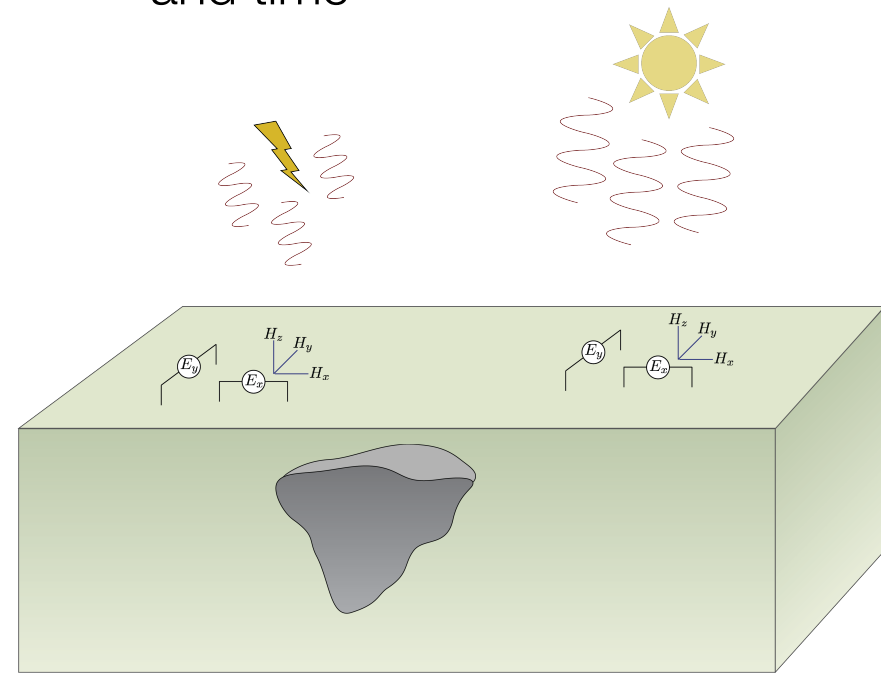


Control source vs Natural source

- 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
- Effects of unknown source removed by taking ratio
- Transfer function

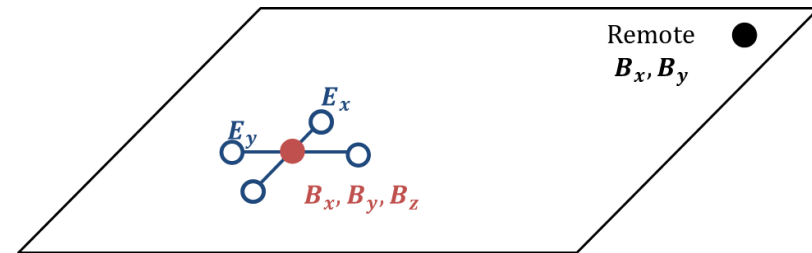
$$\nabla \times \mathbf{E} + i\omega\mu\mathbf{H} = 0$$

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

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

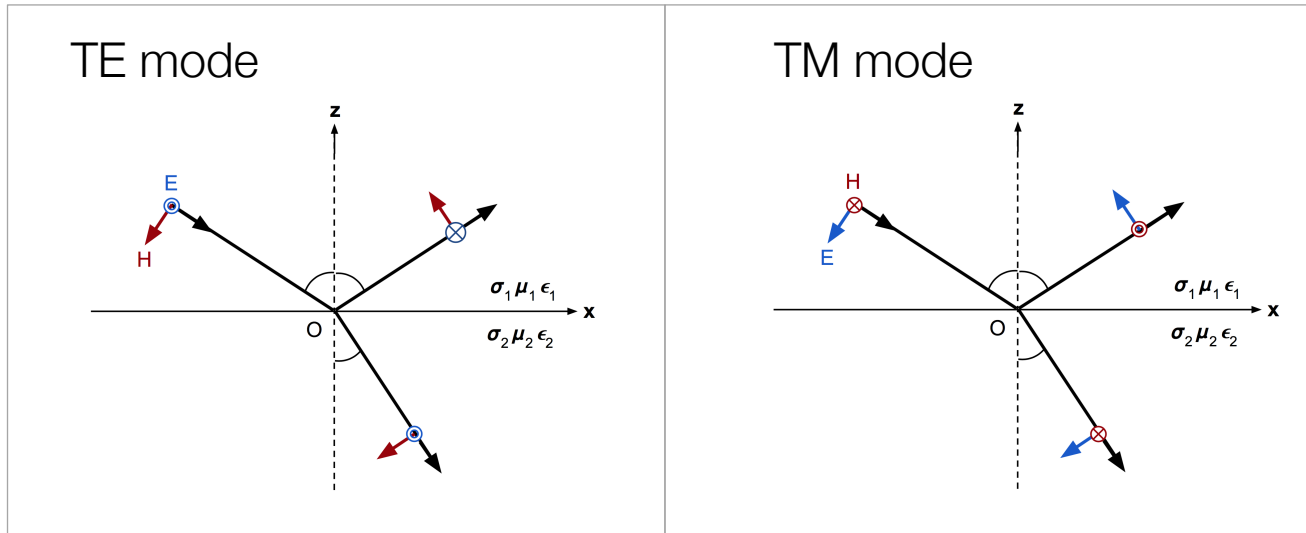
impedance (matrix)

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



Impedance and resistivity

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



Homogeneous half space

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

- In general:

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

- Apparent resistivity:

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

- Phase:

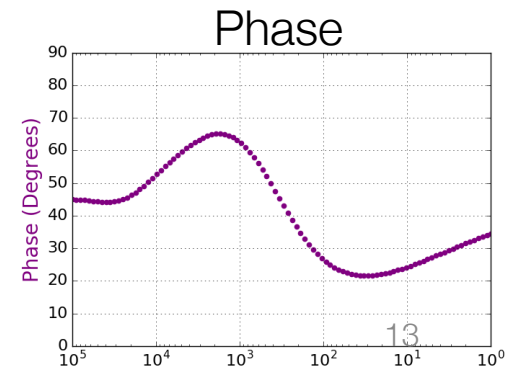
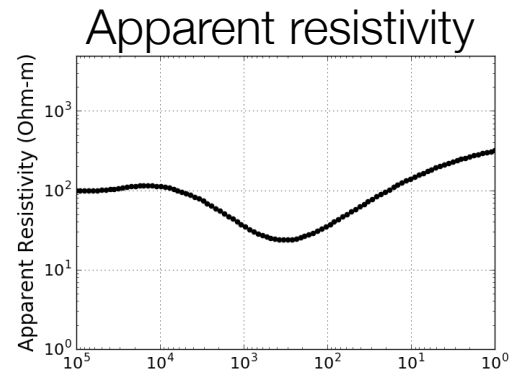
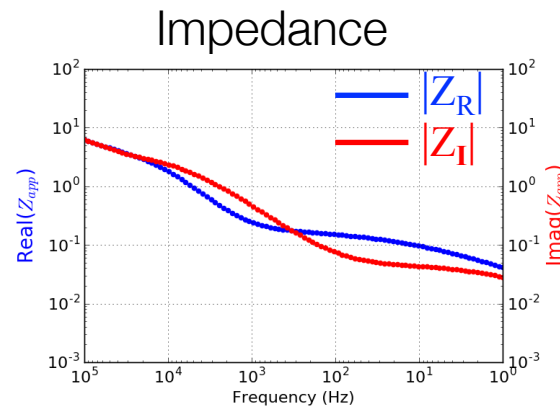
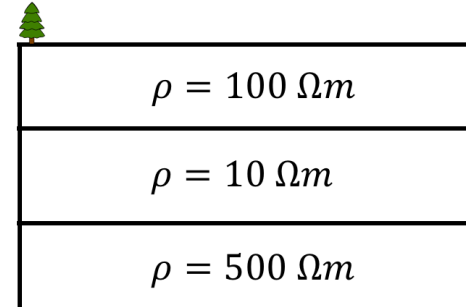
$$\Phi = \tan^{-1} \left(\frac{\text{Im}(Z_{xy})}{\text{Re}(Z_{xy})} \right)$$

- In 1D:

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

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

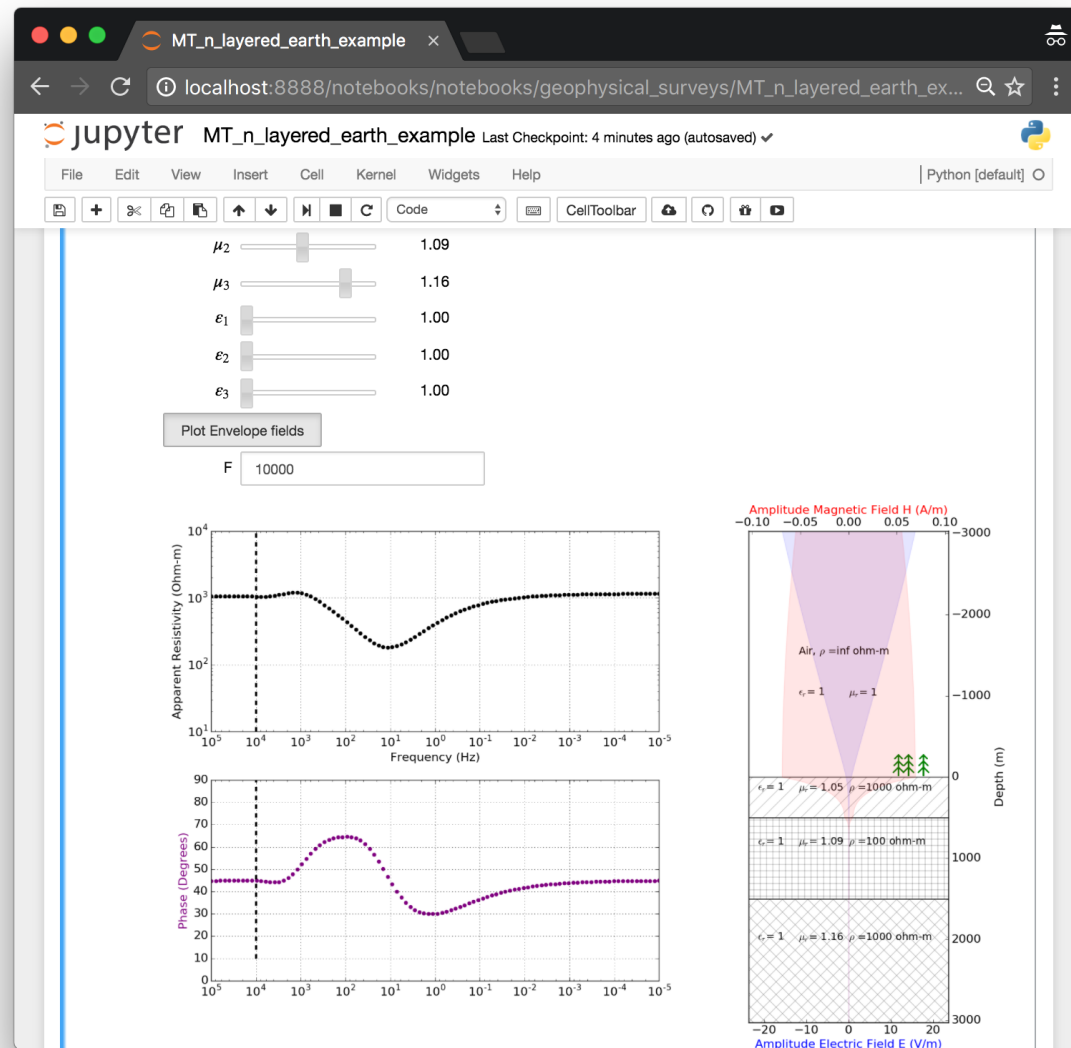
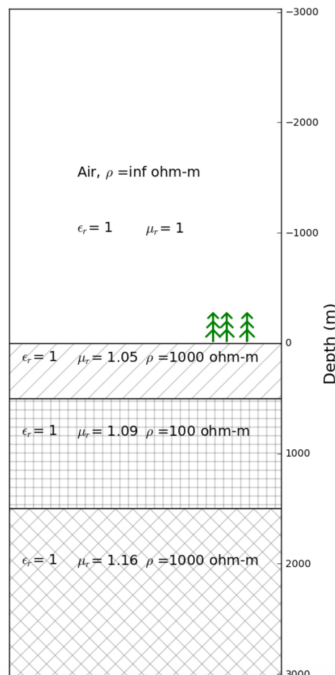
$$Z_{yx} = -Z_{xy}$$



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:

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

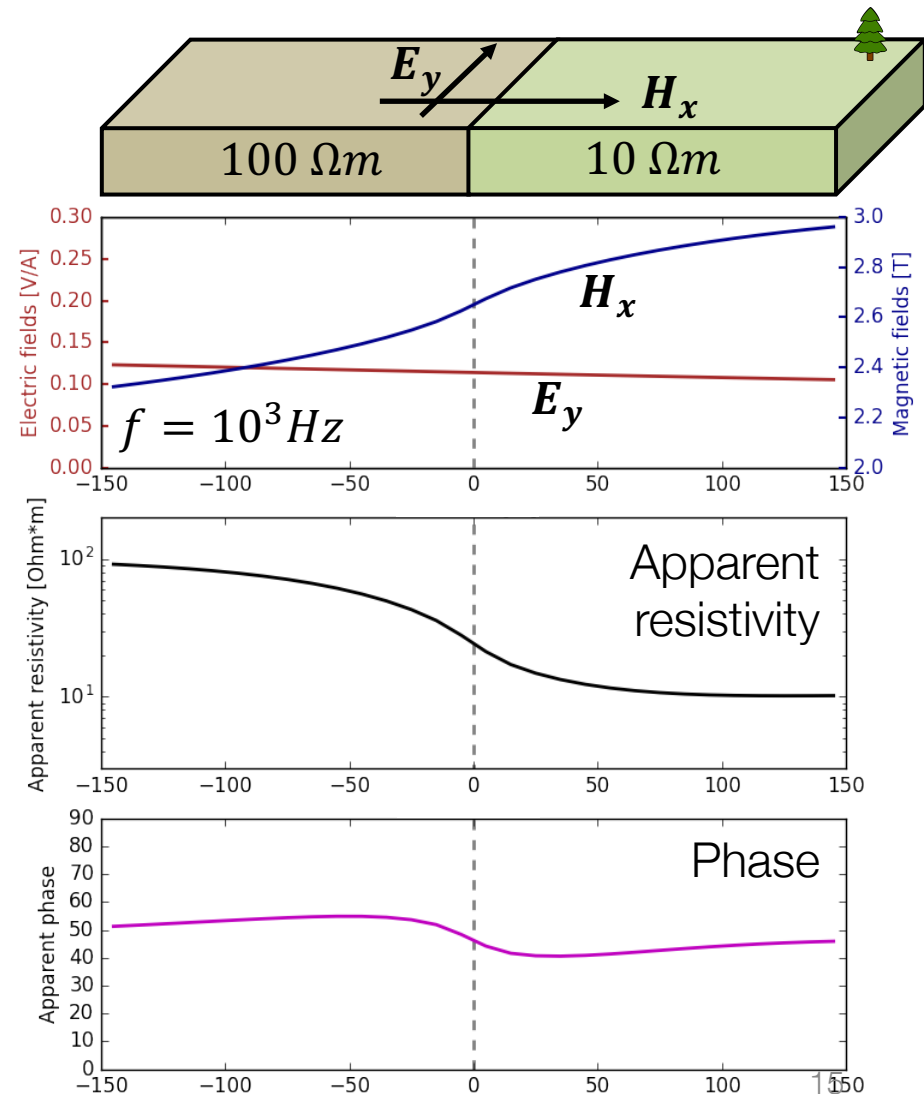
- In 2D:

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

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

- TE mode
 - E-field parallel to structure

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



MT soundings in 2D

- In general:

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

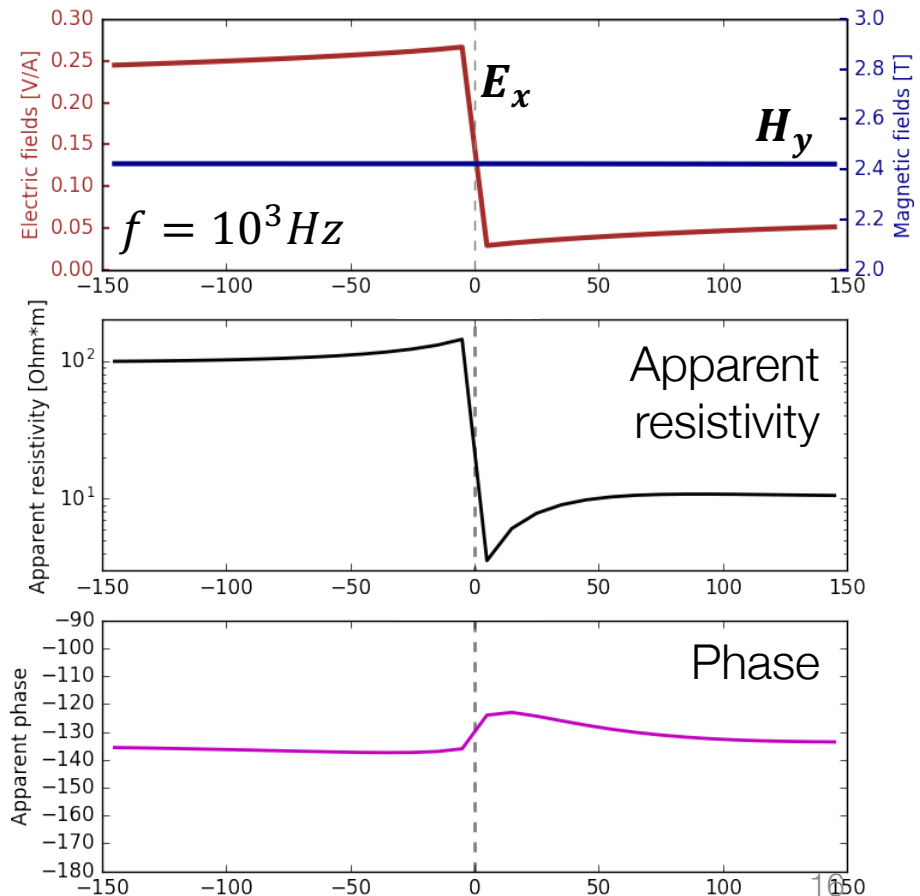
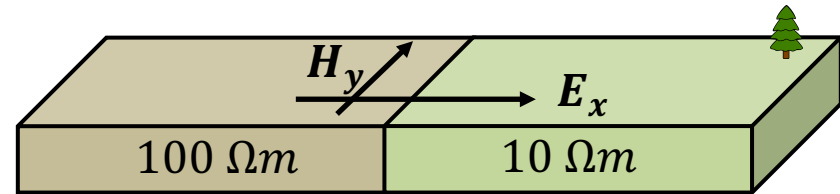
- In 2D:

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

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

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

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



MT soundings in 3D

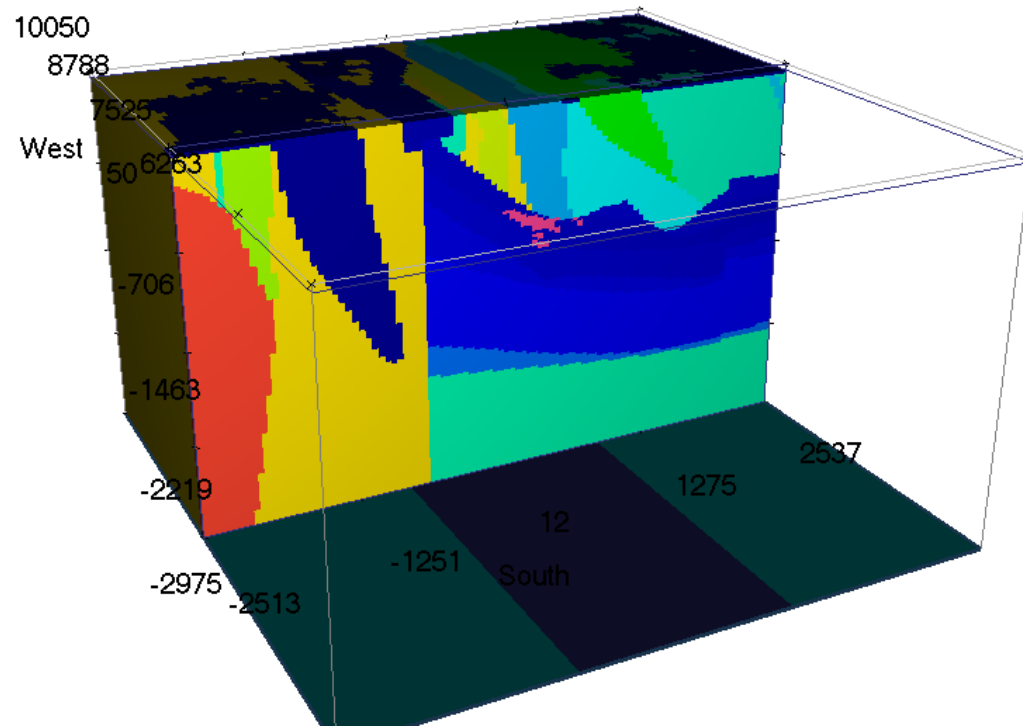
- In general:

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

- In 3D:

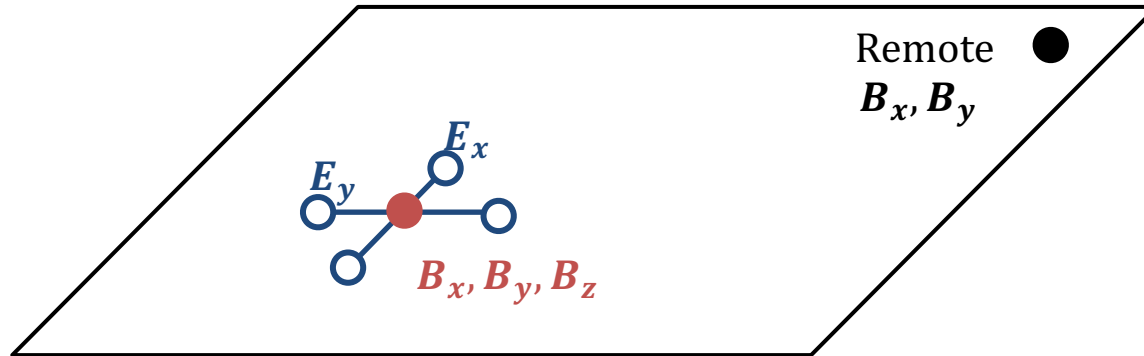
$$Z = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$$

- No symmetry or special conditions



Measuring MT data

- Basic acquisition

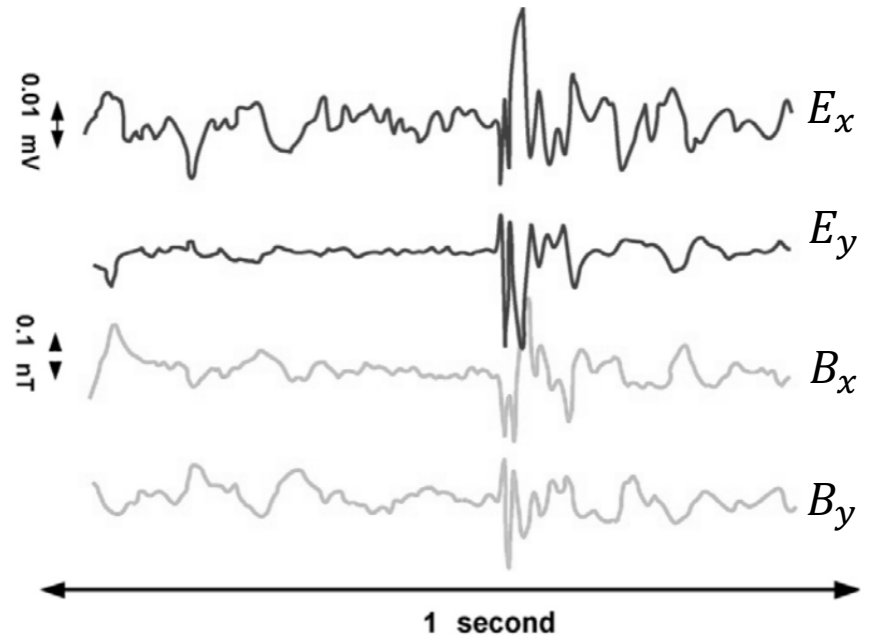


- At each station, measure:

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

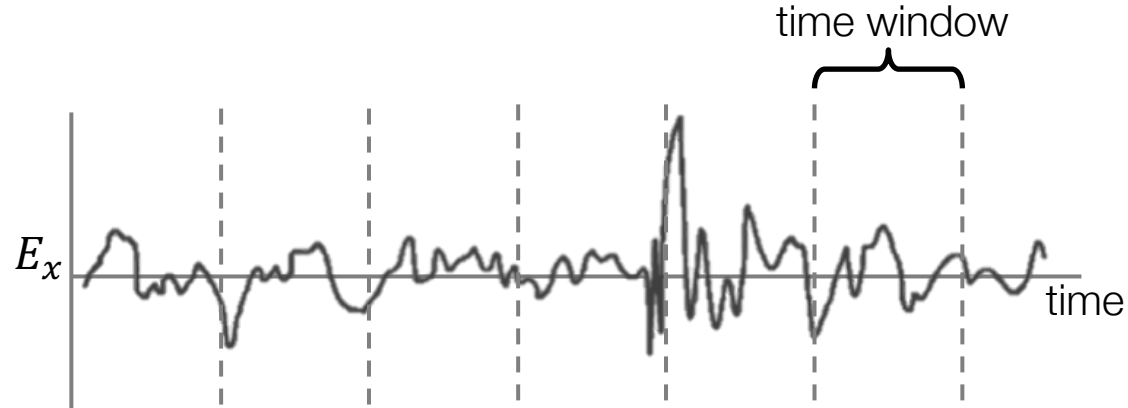
- At remote reference, measure:

$$B_x, B_y$$



Processing MT data

- Divide time series into time windows



- Apply Fourier transform
 - For each station:

$$\begin{aligned} e_x(t) &\rightarrow E_x(\omega) \\ h_y(t) &\rightarrow H_y(\omega) \end{aligned}$$

- For the remote reference:

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

- Form the impedance tensor:

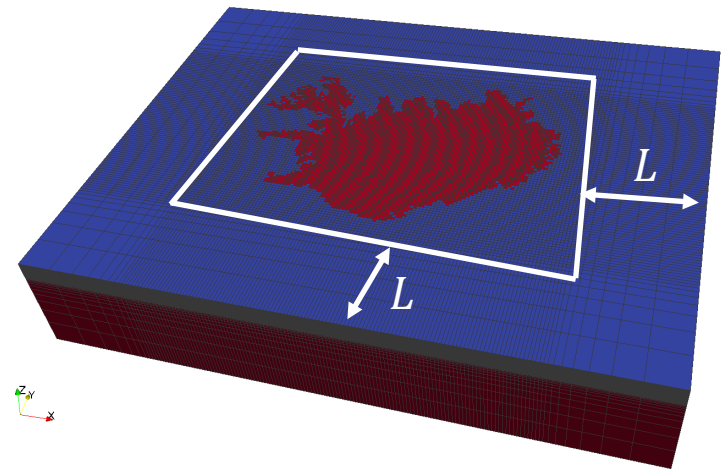
$$Z_{xy}(\omega) = \frac{\langle E_x(\omega) H_y^{R*}(\omega) \rangle}{\langle H_y(\omega) H_y^{R*}(\omega) \rangle}$$

(*) 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

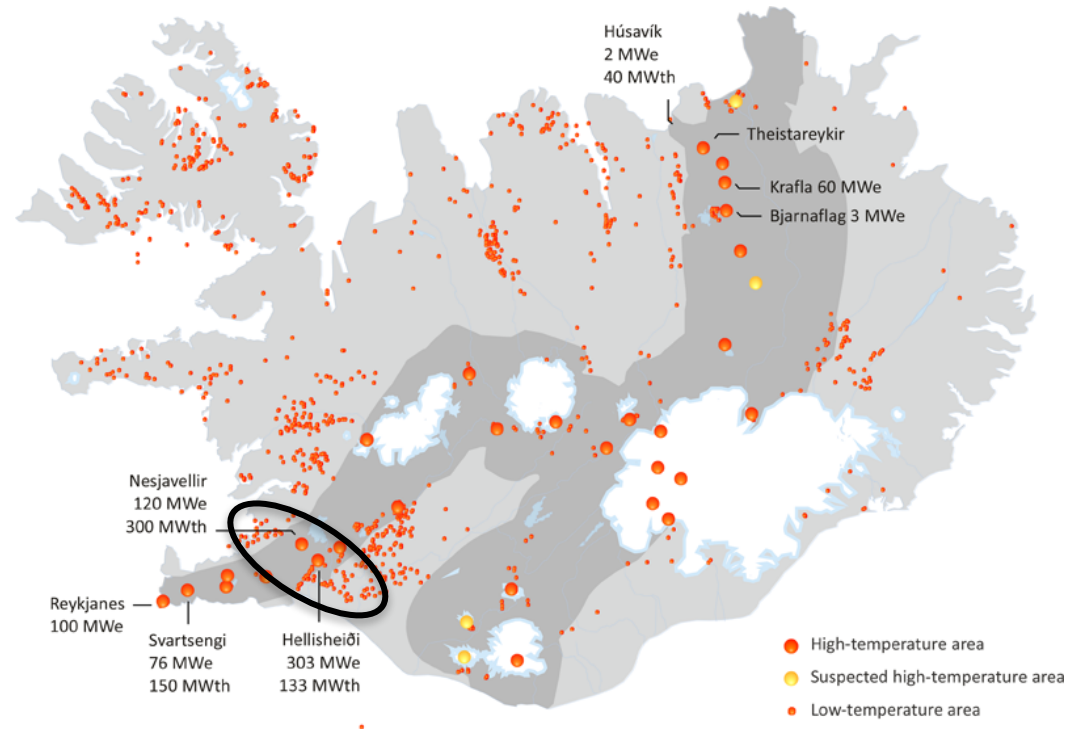
MT case history

- Iceland



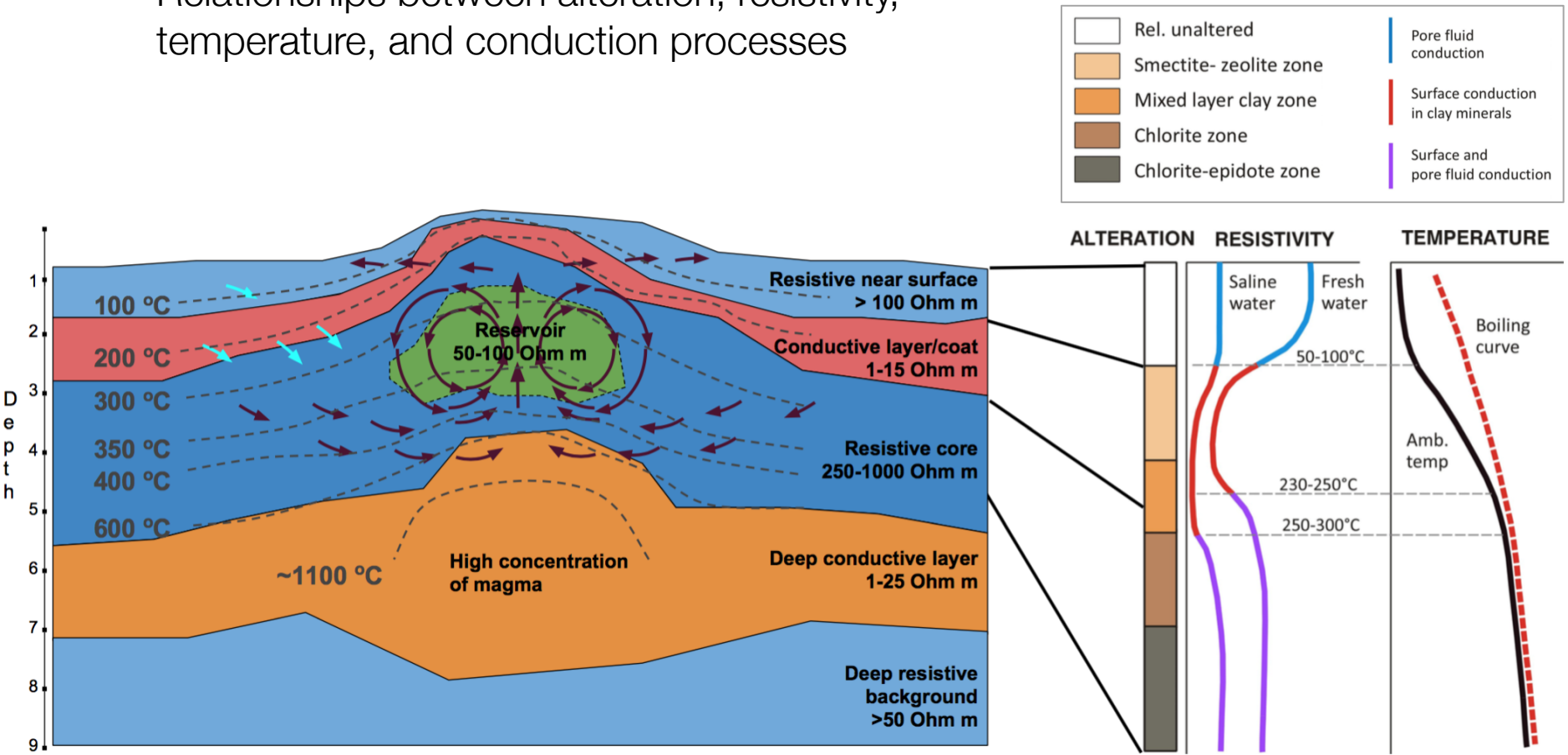
Hengill geothermal region: setup

- 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

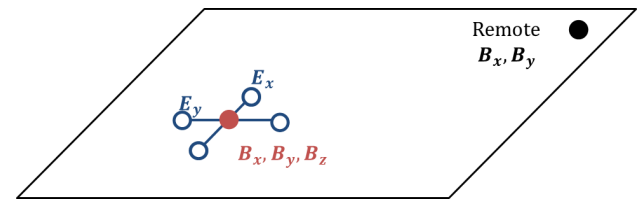


Physical properties

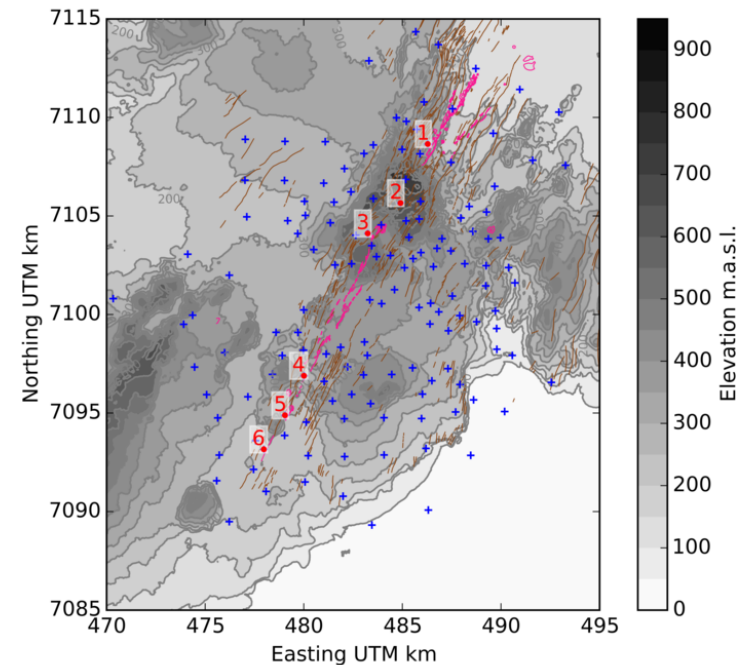
- Relationships between alteration, resistivity, temperature, and conduction processes



Survey

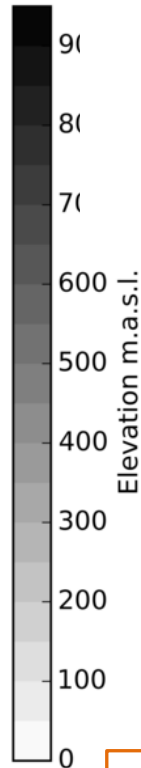
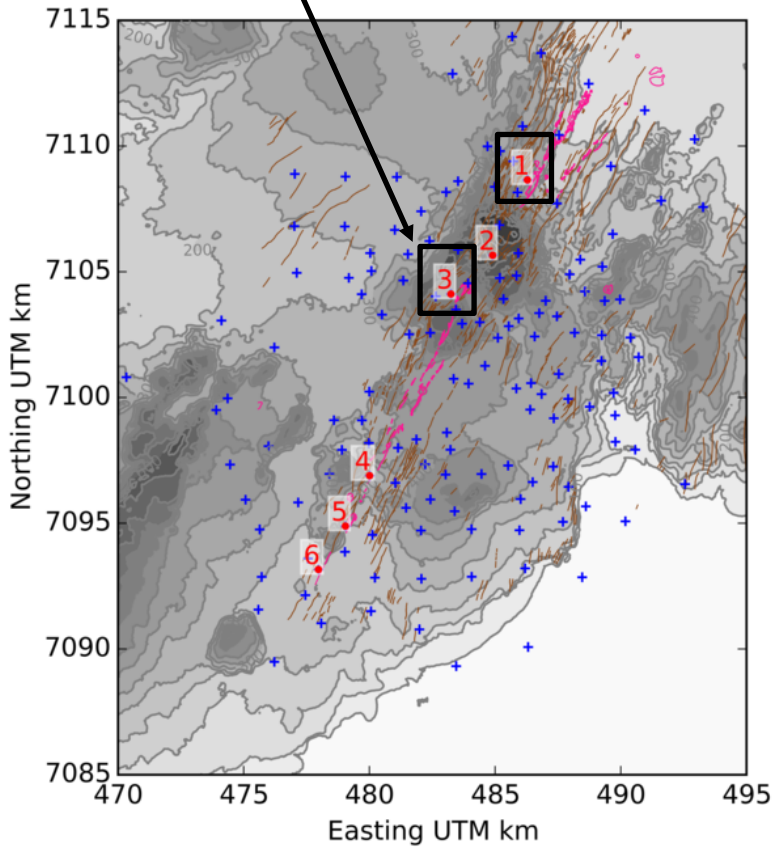


- MT instrumentation
 - Phoenix MTU5's
- Survey
 - 133 stations used
 - Combination of 2E and 2E+3H setup
 - Frequencies: 300 – 0.001 Hz
- Remote reference
 - About 40 km away
- Raw data processing using Phoenix software

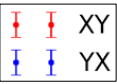
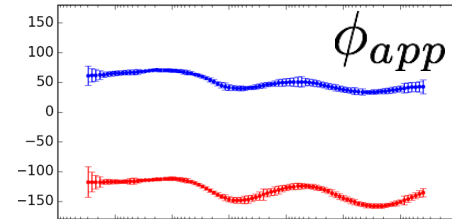
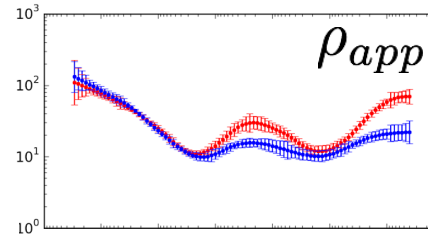


Data

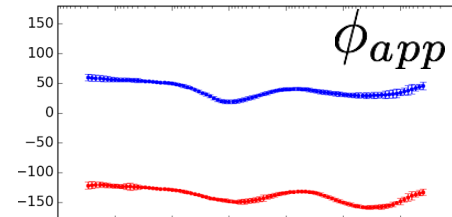
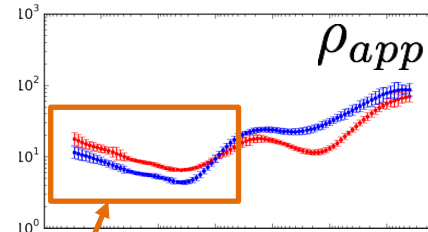
Surface alteration,
hot water, fumaroles



Location 1



Location 3



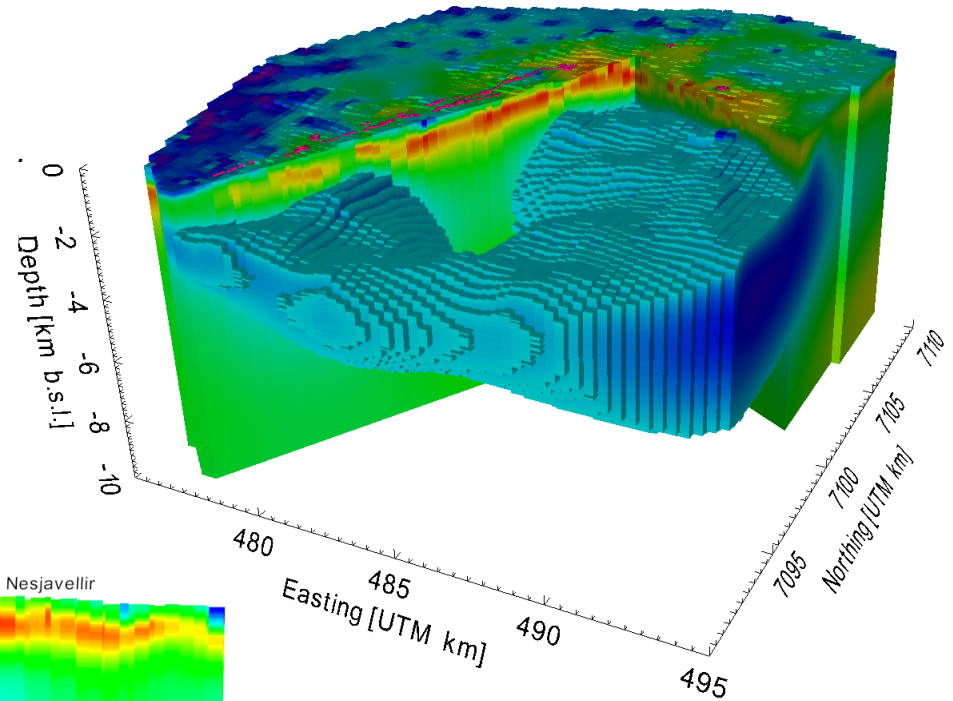
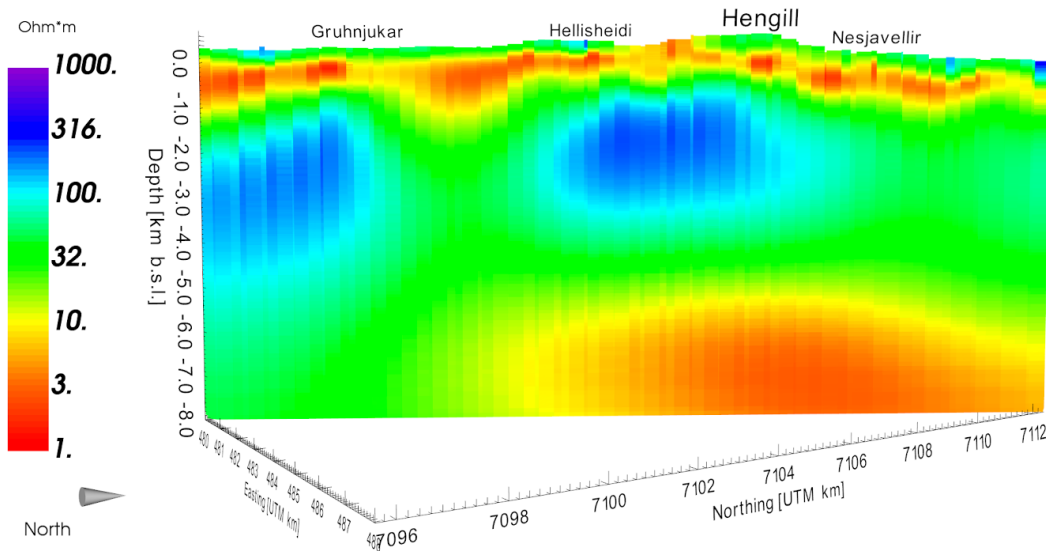
Frequency (Hz)

Frequency (Hz)

Low apparent
resistivity

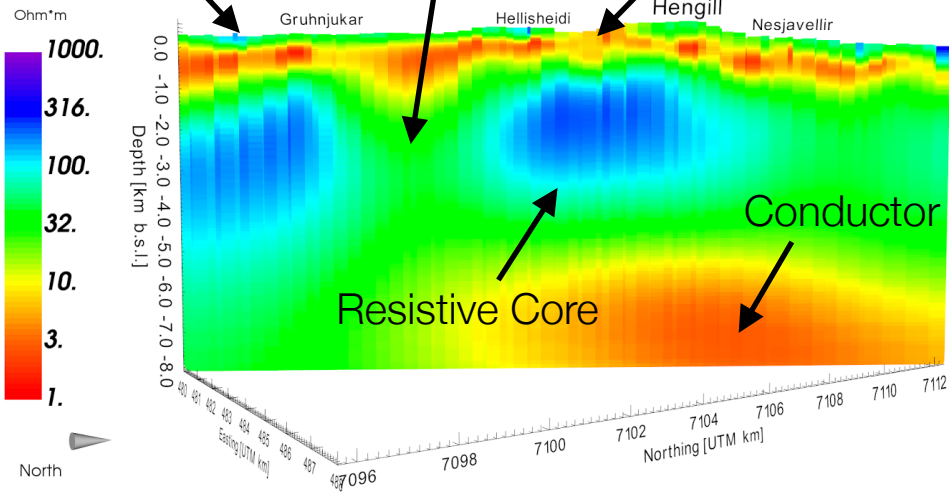
3D inversion

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

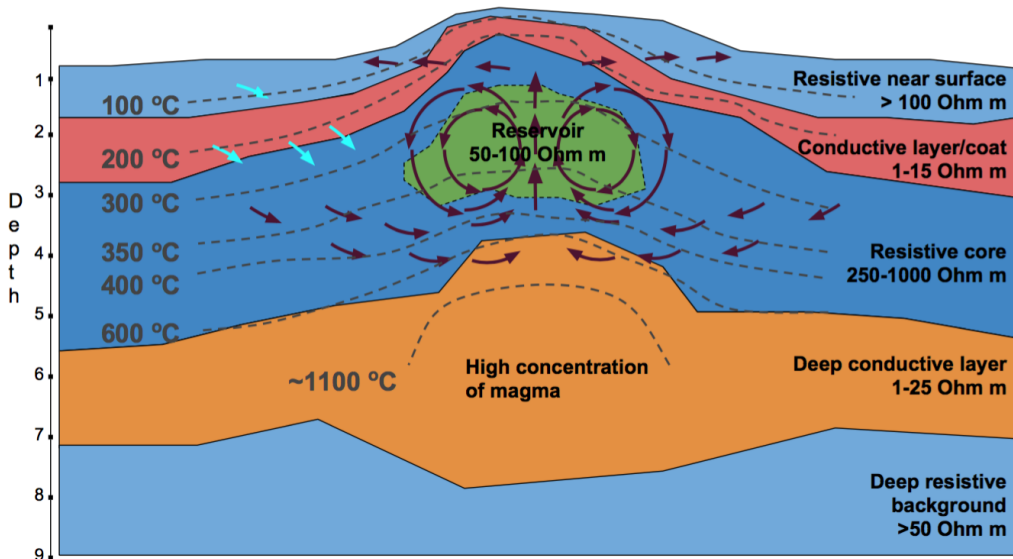
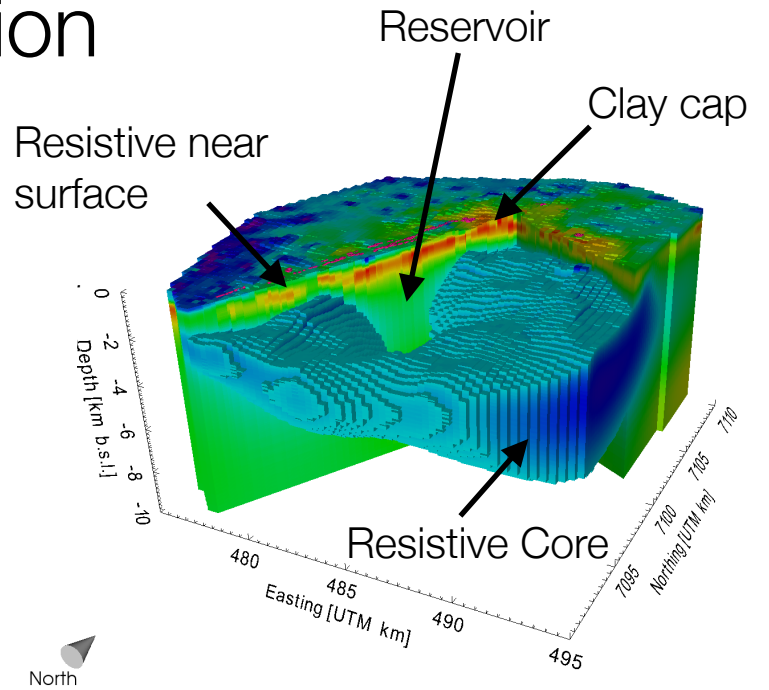


Interpretation

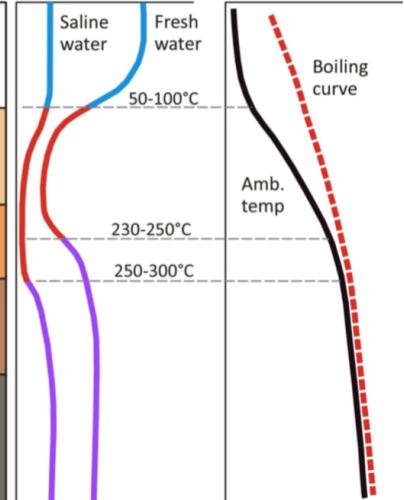
Resistive near surface



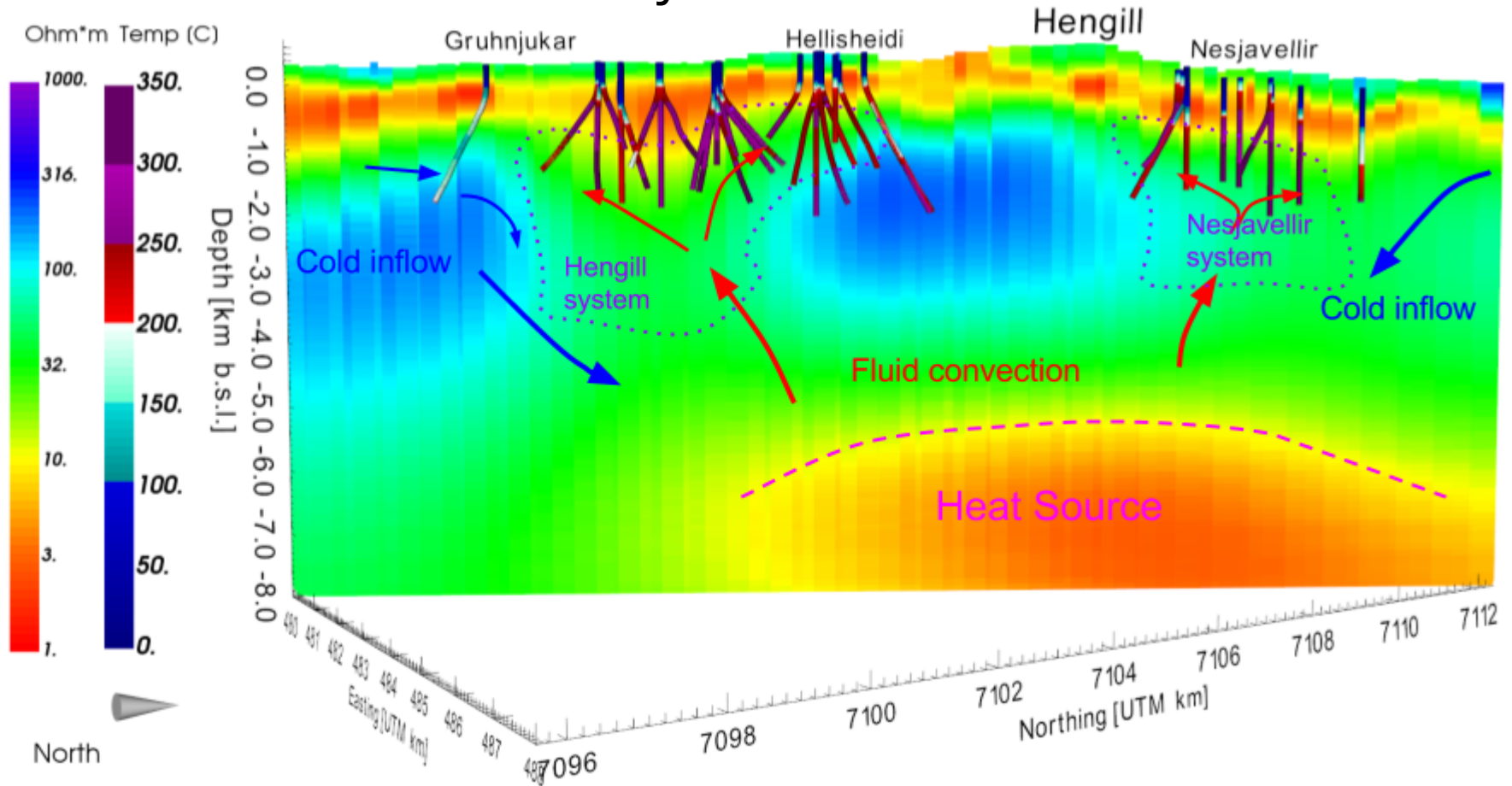
Resistive near surface



ALTERATION RESISTIVITY TEMPERATURE



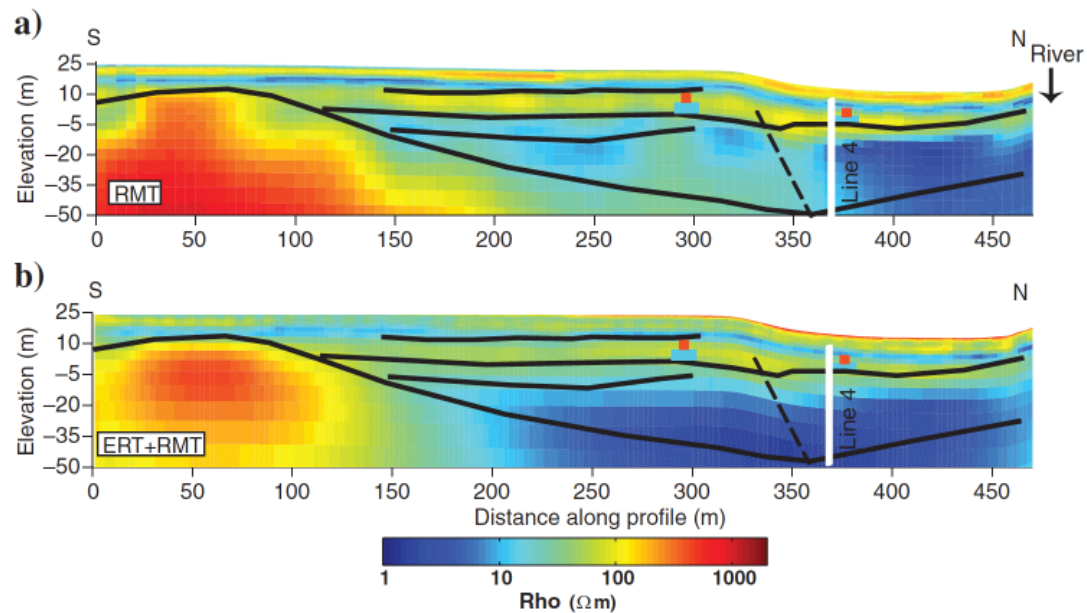
Synthesis



- 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



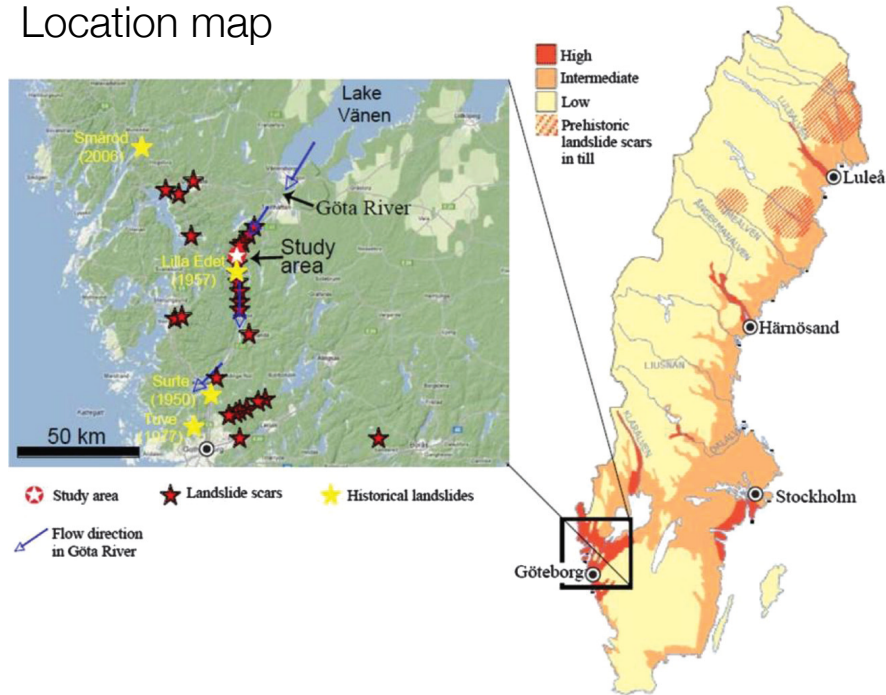
Photo: C Fredén, 1977, Tüve



Photo: Mats Engdahl, 2006, Munkedal

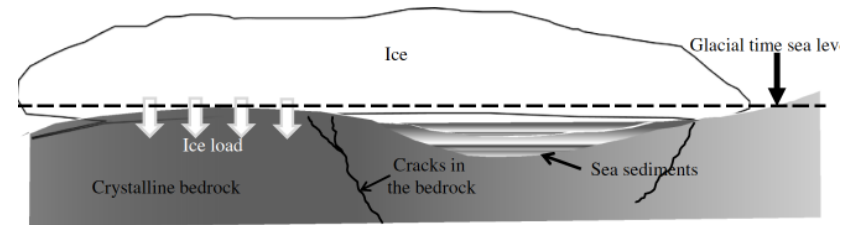
Setup

Location map

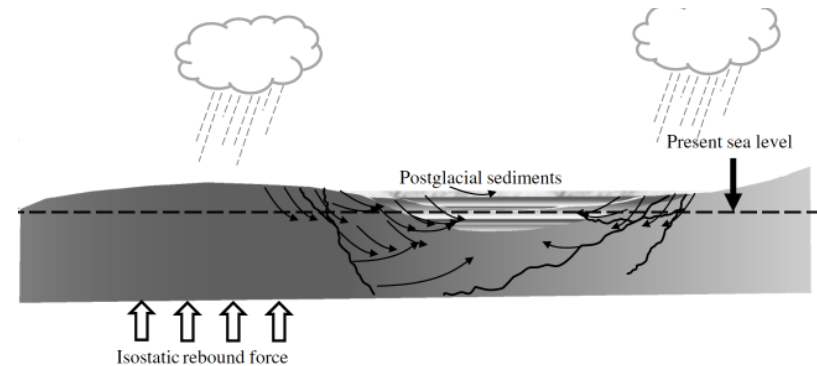


Formation of quick clays

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

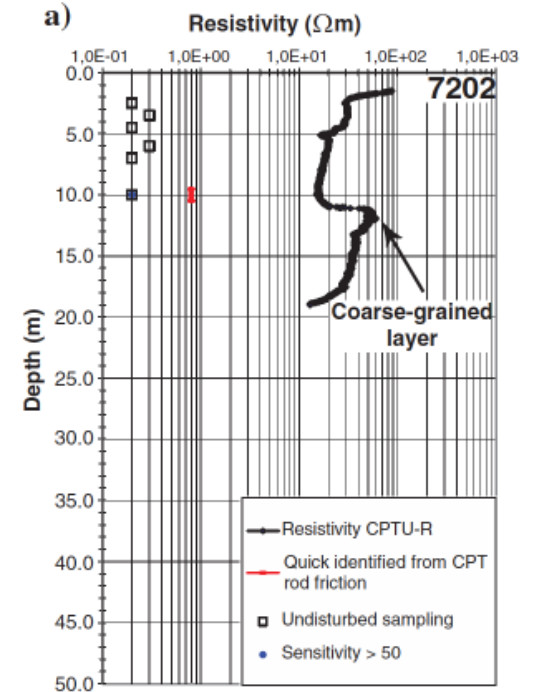
Can we detect quick clays?

Properties

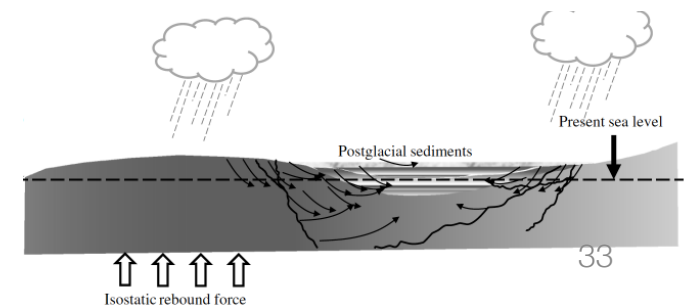
Soil material	Resistivity interval
Salt/intact marine clay	1–10 Ωm
Leached, possible quick clay	10–80 Ωm
Dry crust clay, slide deposits, coarser	>80 Ωm

- 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)

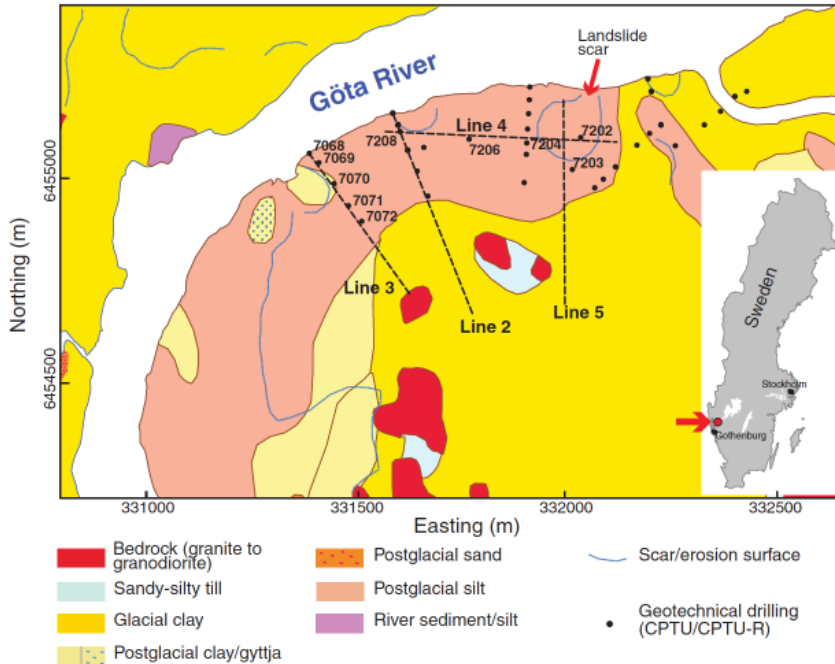


Formation of quick clays

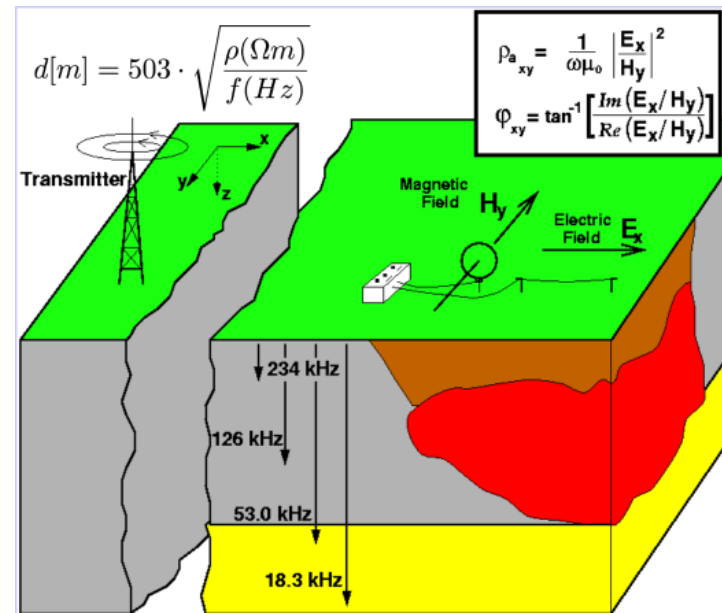


Surveys

Geologic map



RMT survey

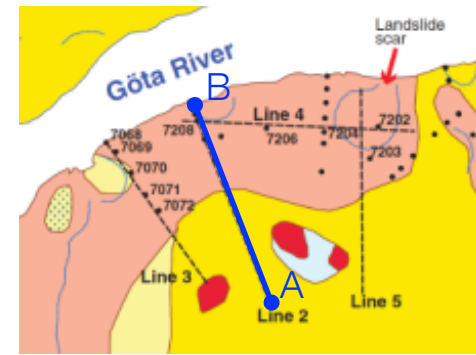


From Bulent (2017)

- DC (ERT)
 - Lines 2-5
 - ABEM system
 - Wenner array (5m spacing)

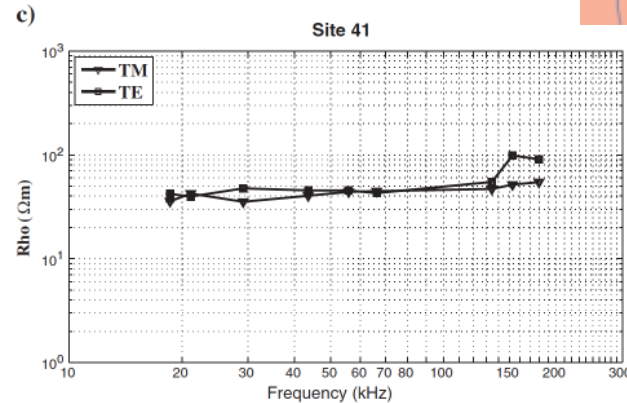
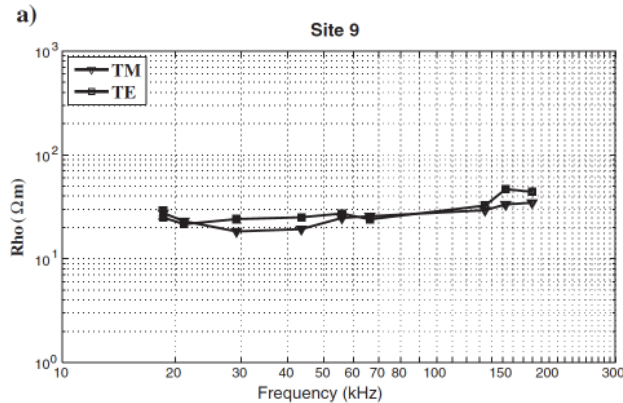
- Radio MT (RMT)
 - Same lines as DC
 - EnviroMT system
 - 21-28 radio transmitters
 - Frequencies: 18.3-183 kHz

RMT: sounding curves

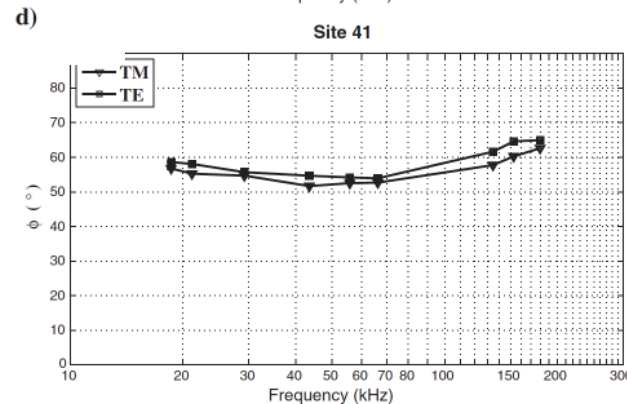
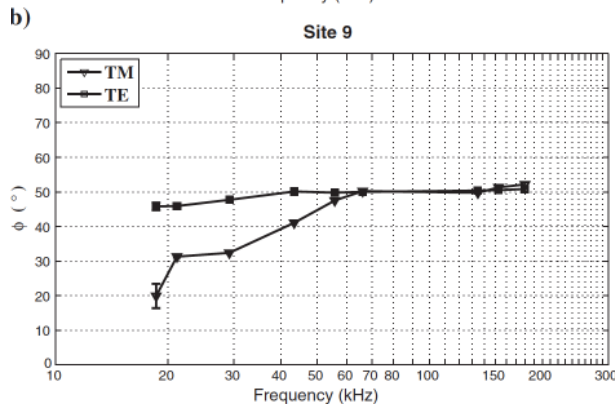


Line 2

Apparent resistivity



Phase

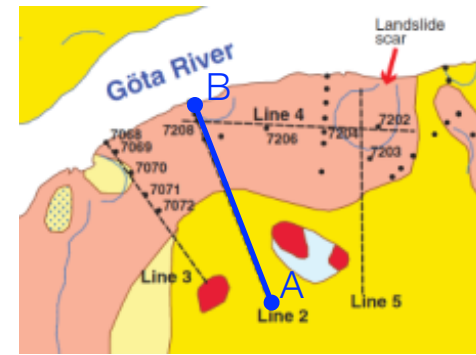


Computed using determinant of impedance tensor at two stations along Line 2

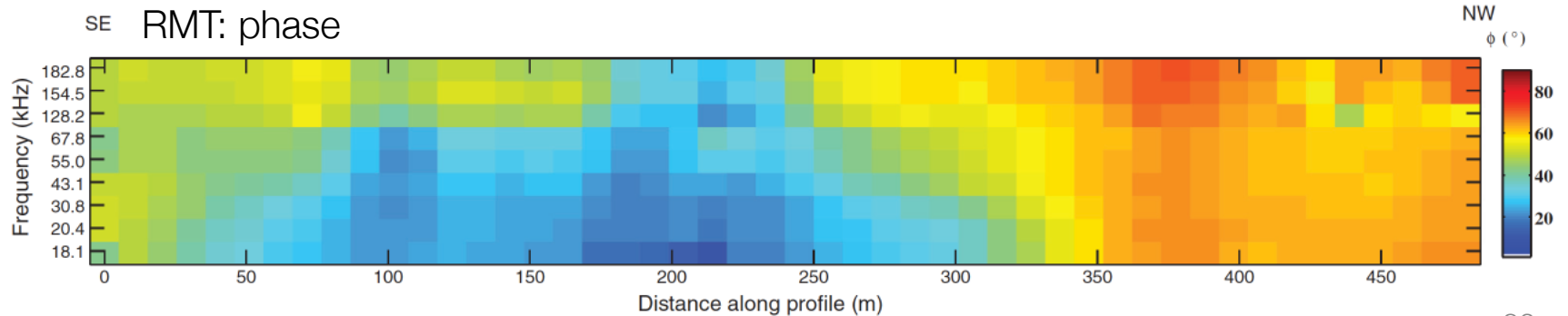
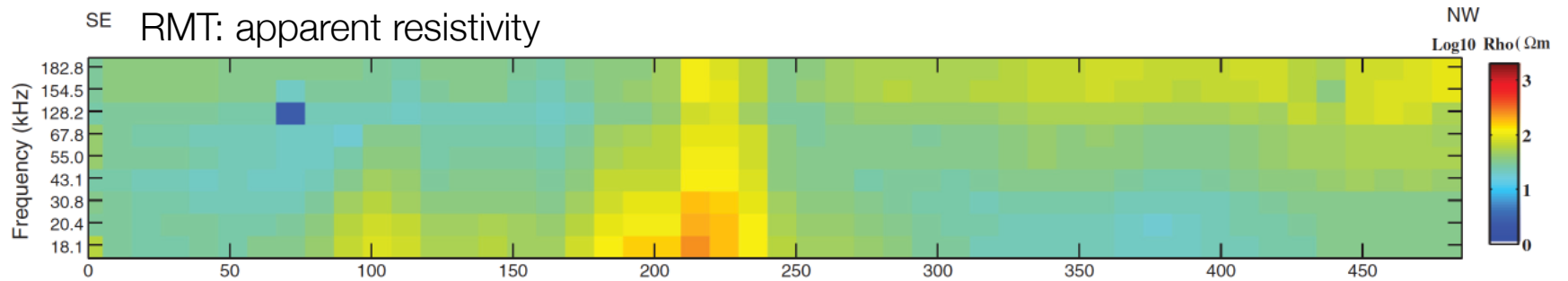
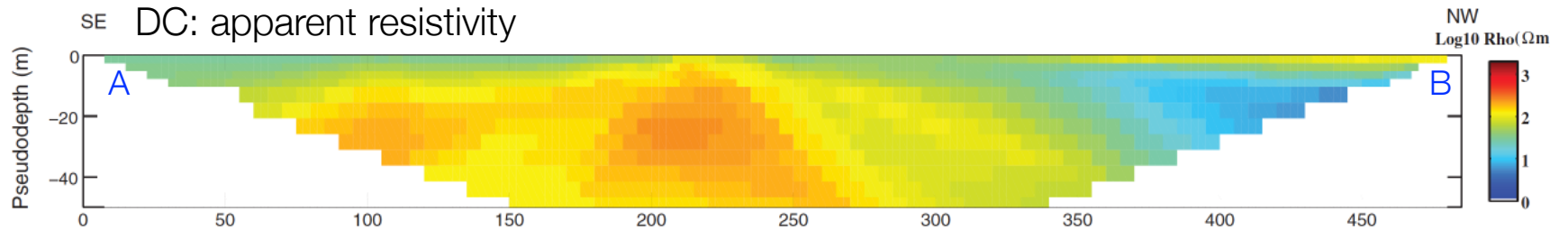
Impedance tensor:
$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix}$$

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

Pseudosections

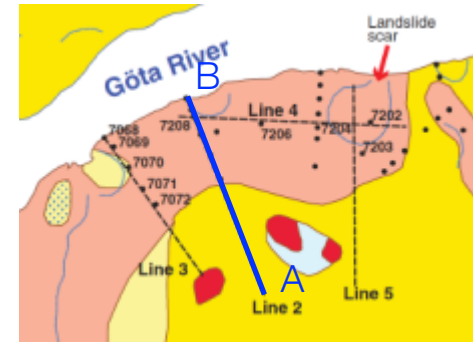
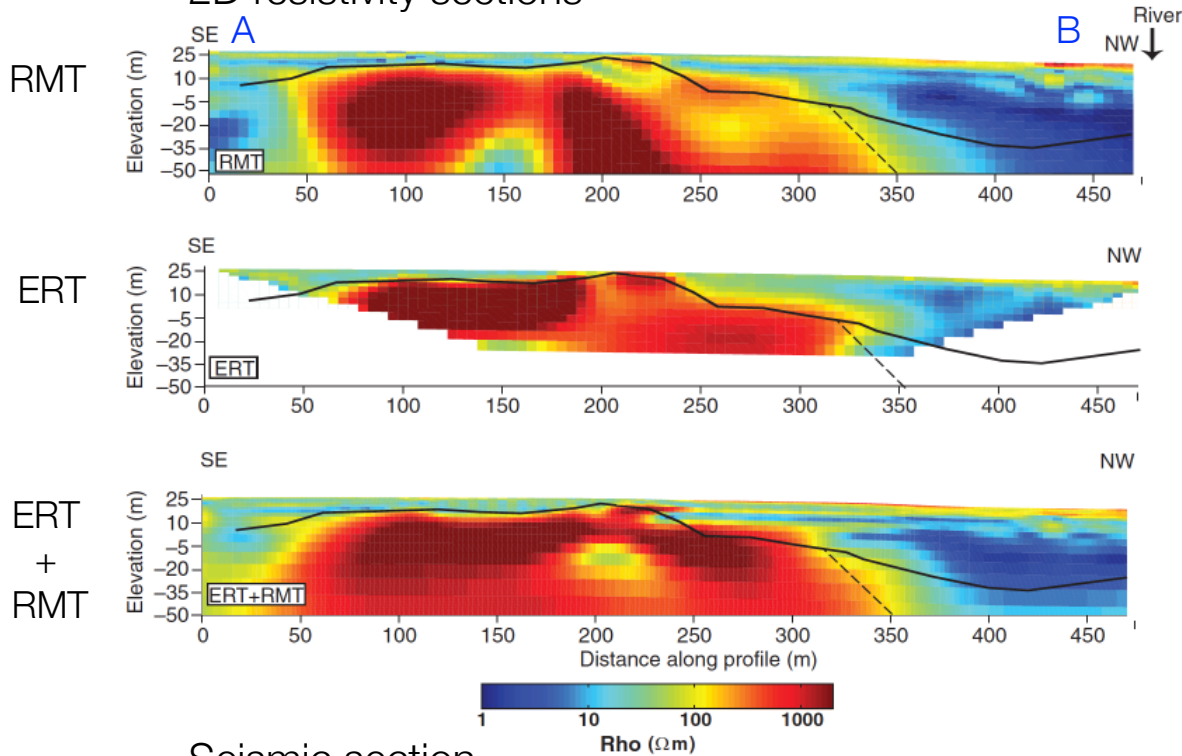


Line 2

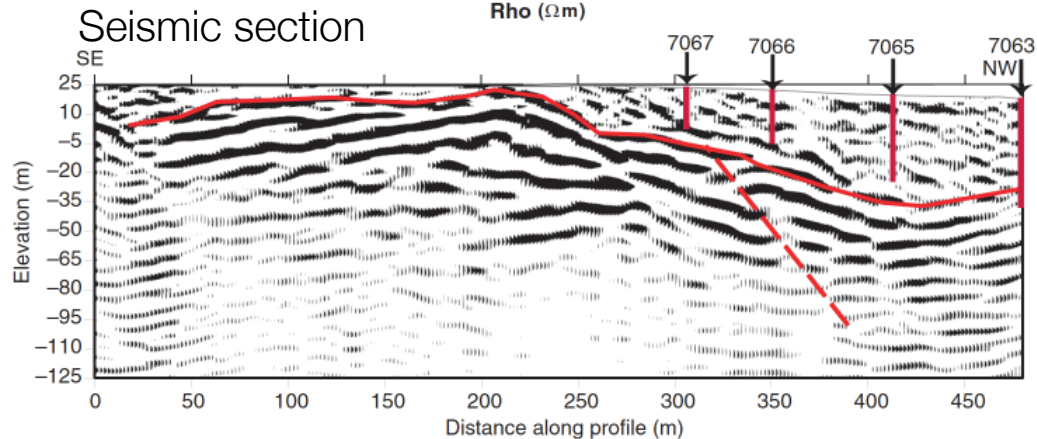


Processing and inversion

2D resistivity sections

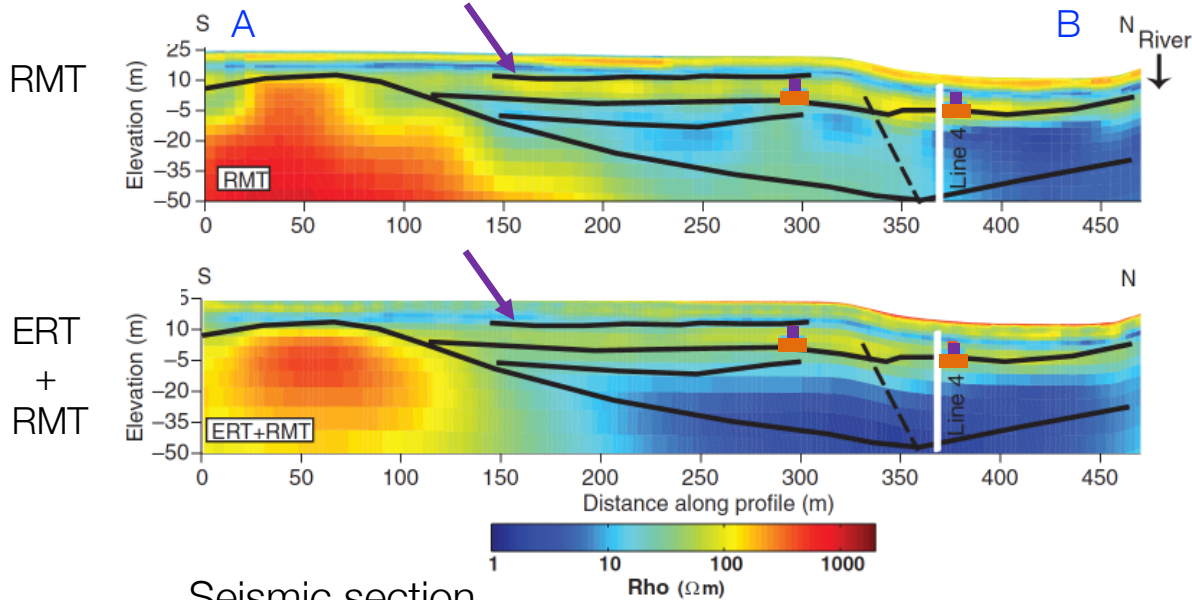


- ERT and RMT yield similar images
- Jointly invert ERT and RMT
- Correlates with seismic

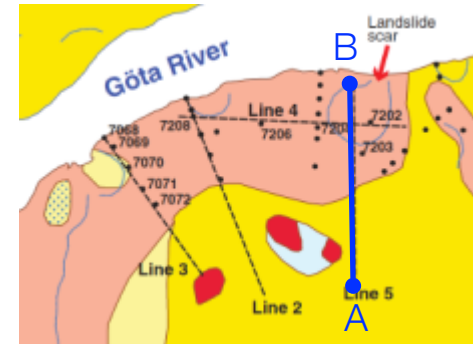
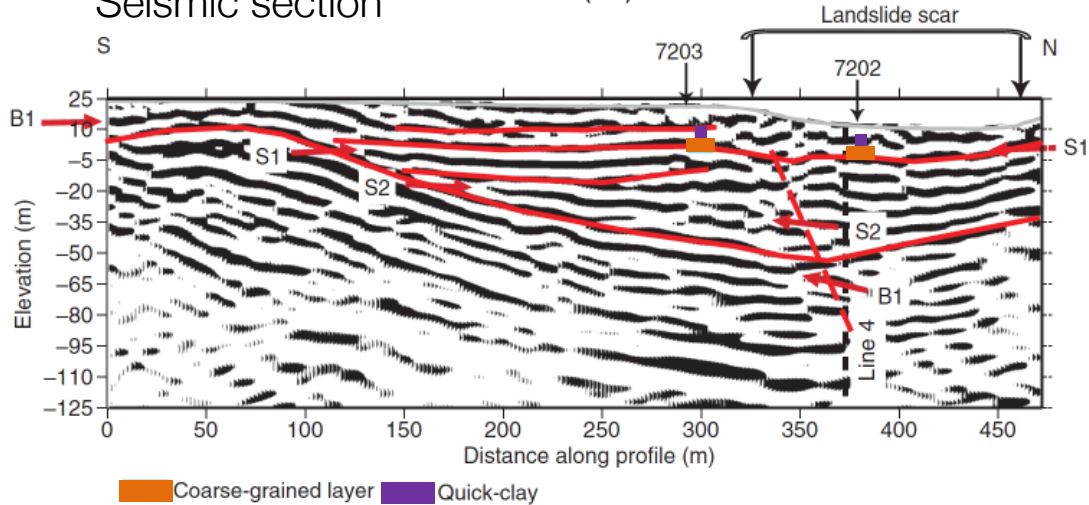


Processing and inversion

2D resistivity sections



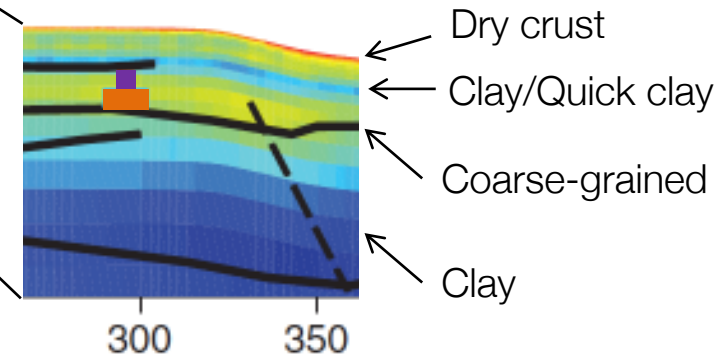
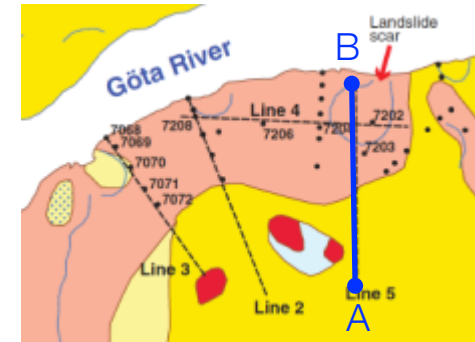
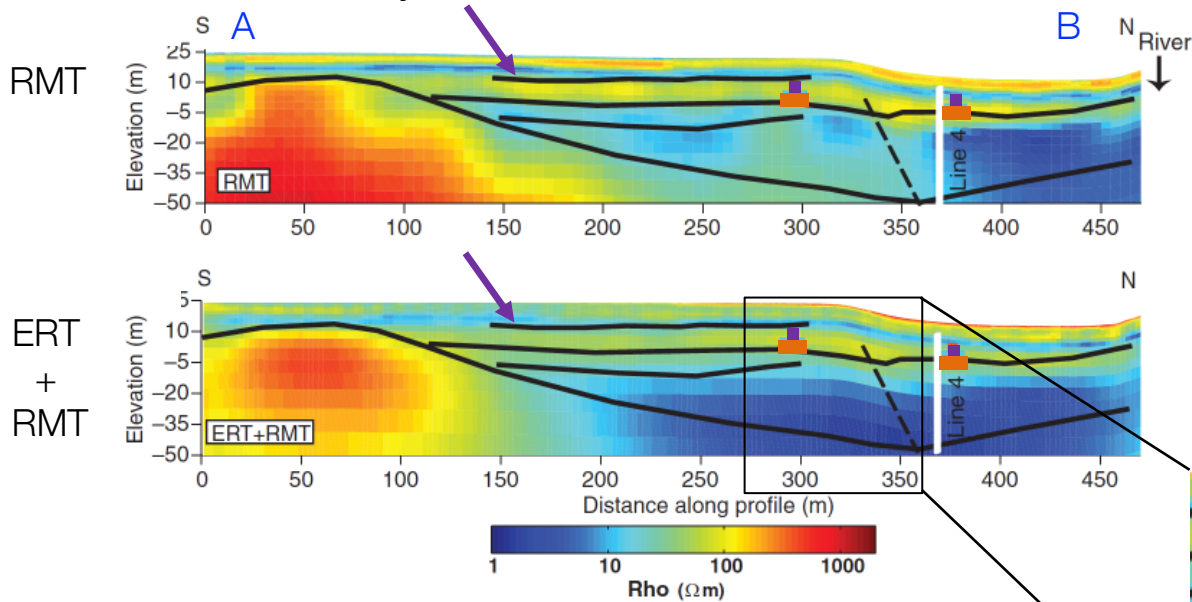
Seismic section



- Inverted RMT, ERT+RMT interpreted with seismic

Processing and inversion

2D resistivity sections



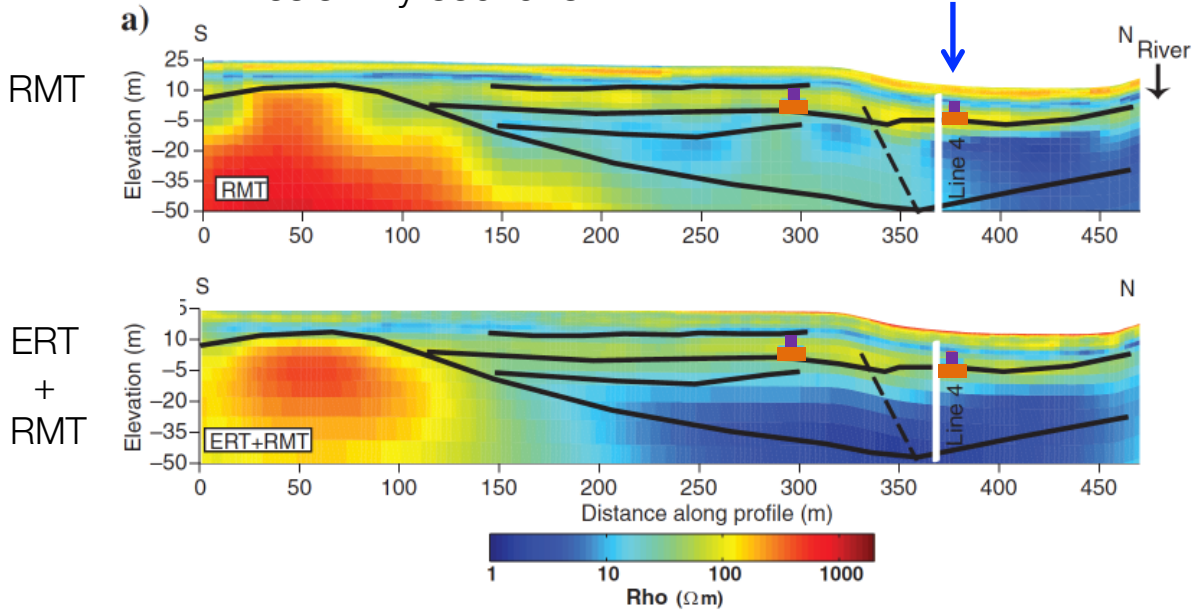
Soil material	Resistivity interval
Salt/intact marine clay	1–10 Ωm
Leached, possible quick clay	10–80 Ωm
Dry crust clay, slide deposits, coarser	>80 Ωm

Quick clay

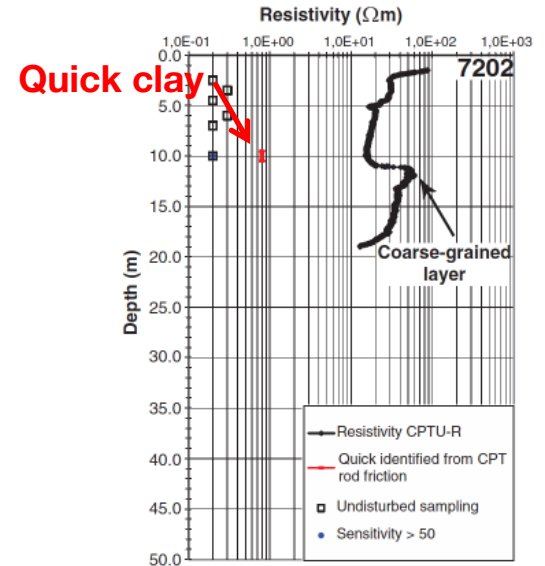
- Top interface: conductor to resistor
- Thickness difficult to estimate

Synthesis

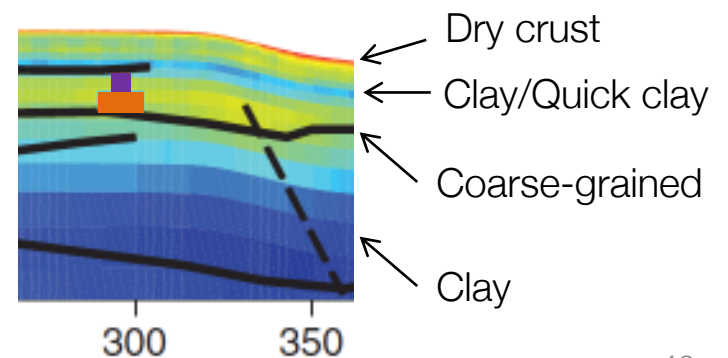
2D resistivity sections



Resistivity log



- 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

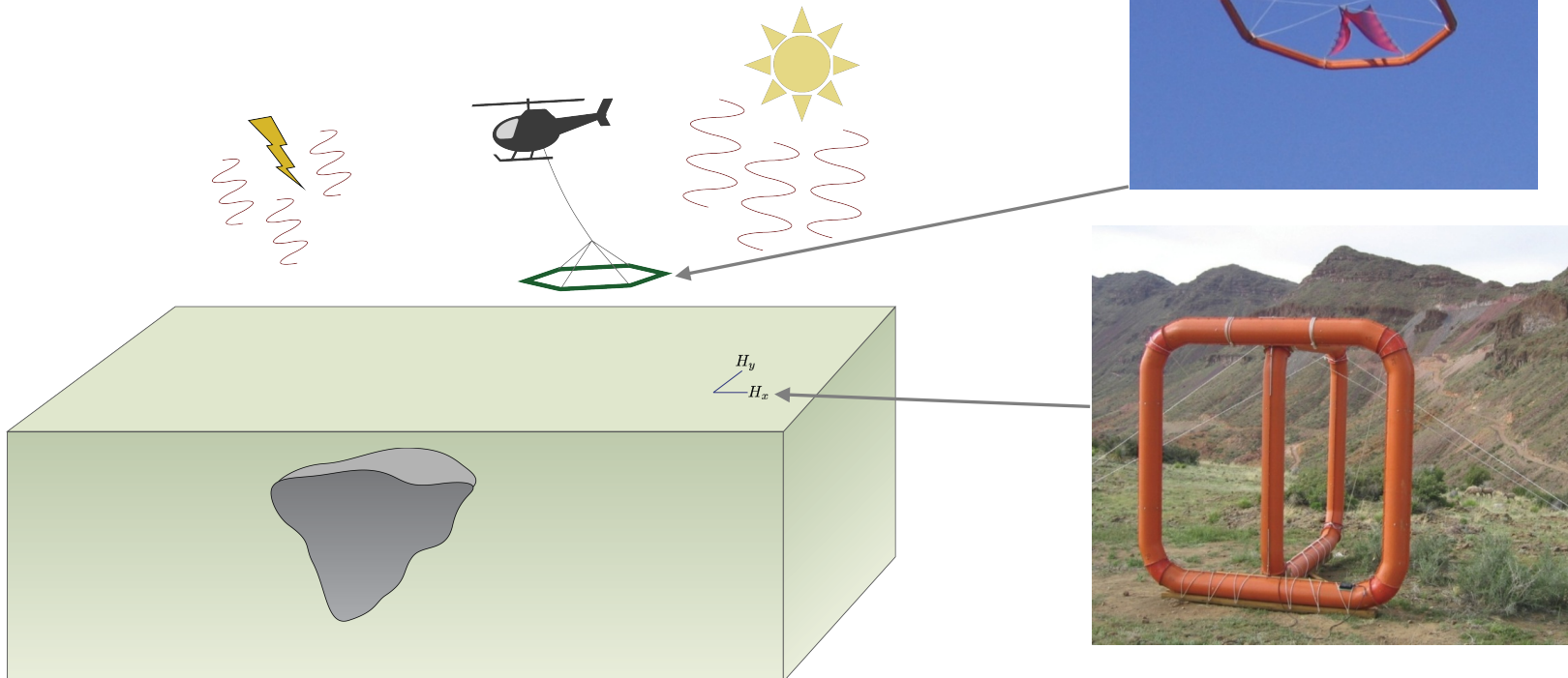
Tipper data (ZTEM)

- Magnetic transfer function

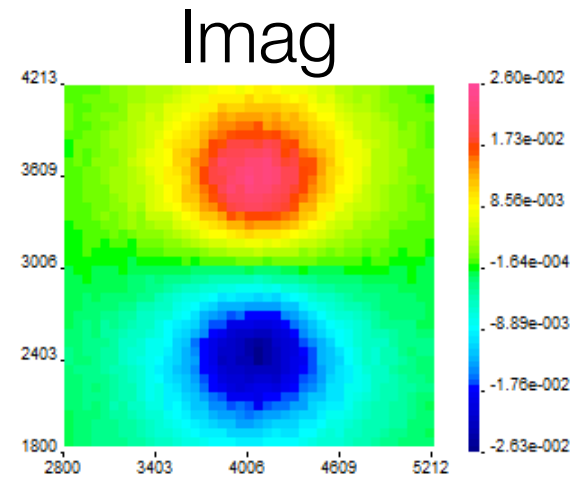
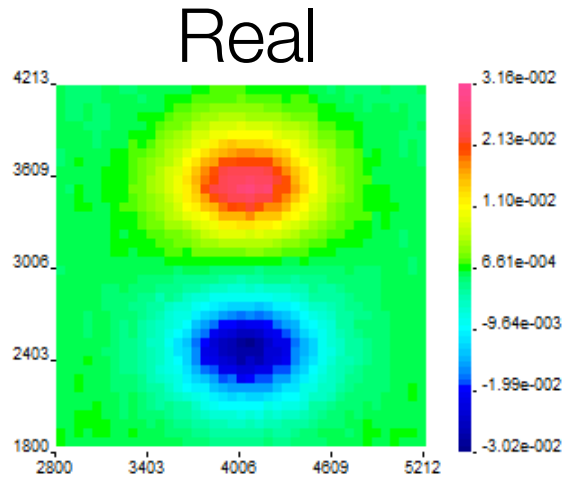
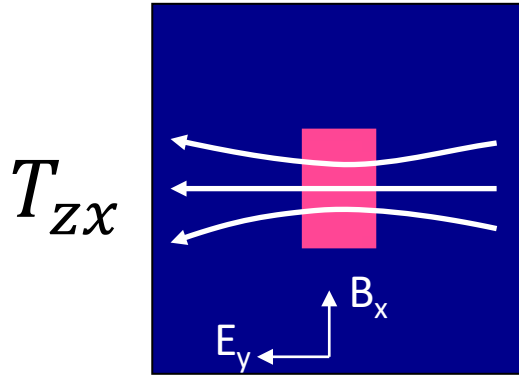
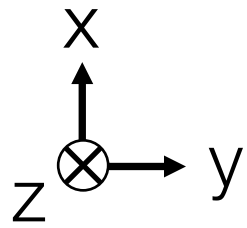
$$H_z = \mathbf{T}\mathbf{H}$$

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

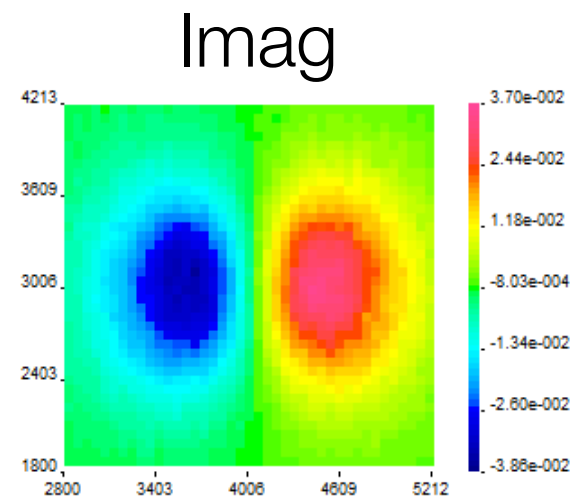
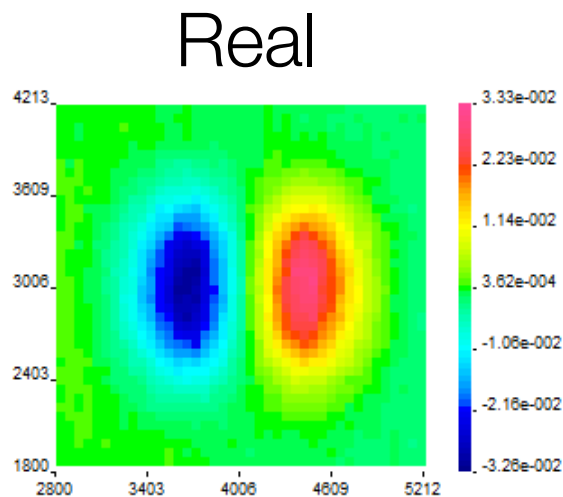
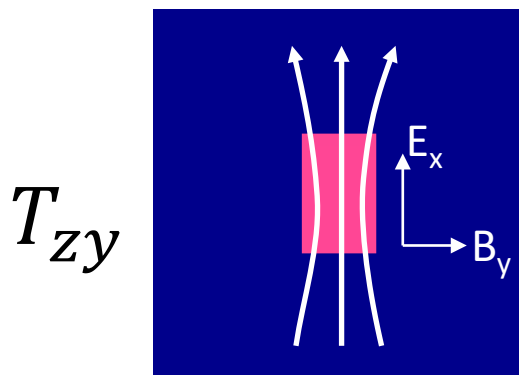
- Frequencies 30Hz – 720 Hz



Synthetic example

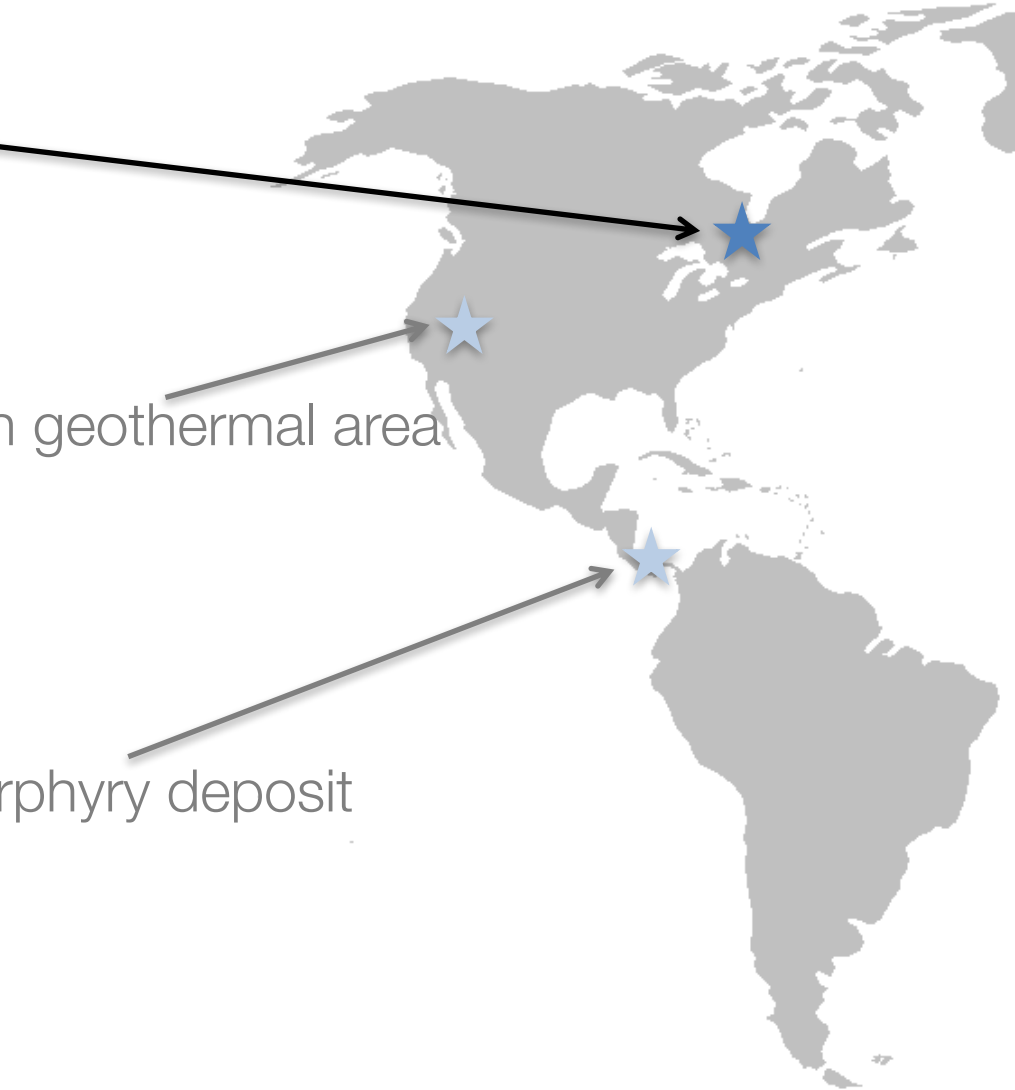


Conductor



ZTEM case histories

- **Noranda district**

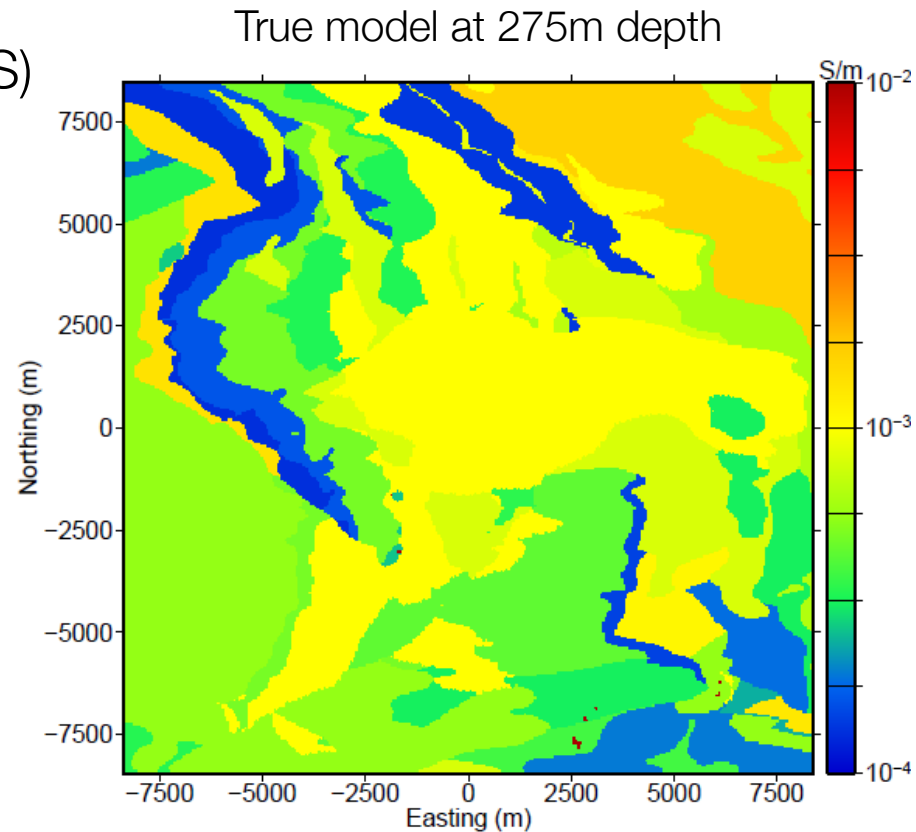


- Elevenmile Canyon geothermal area

- 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

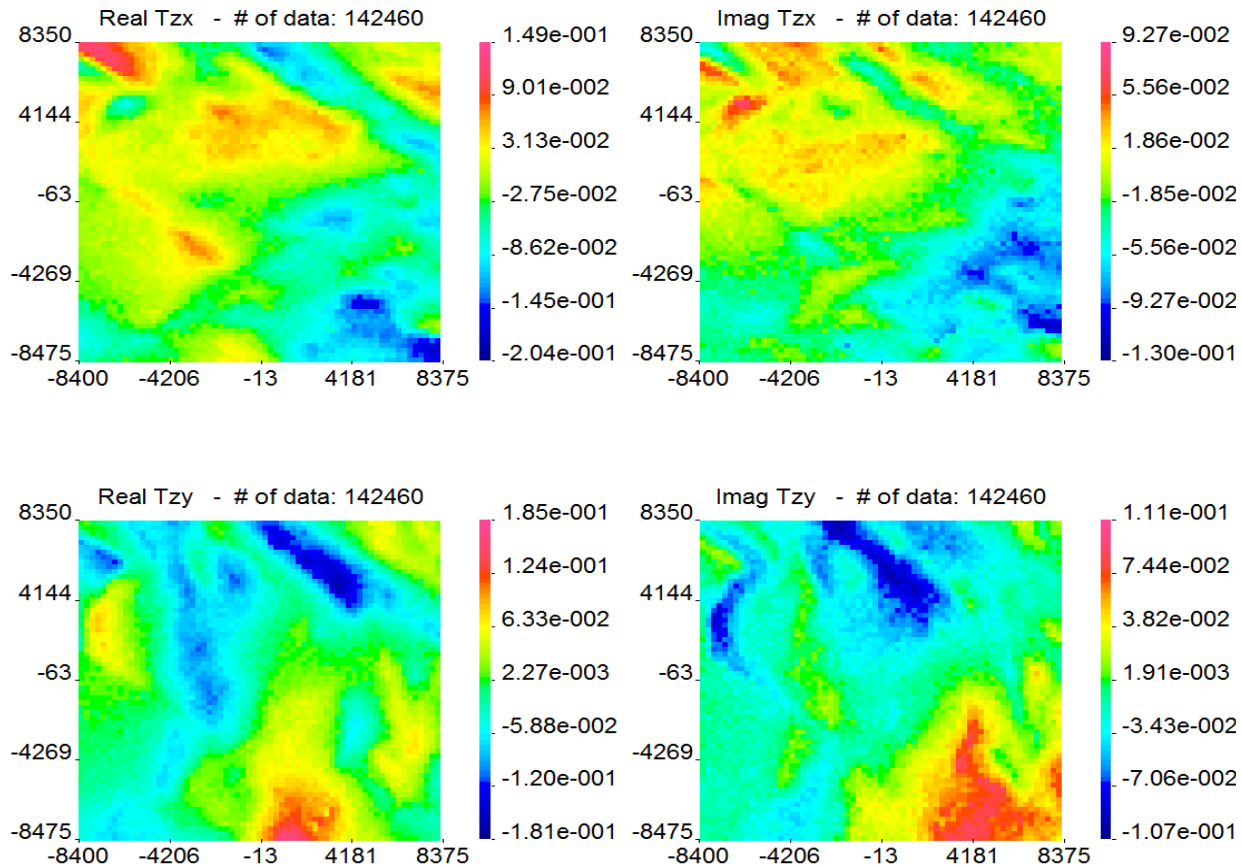
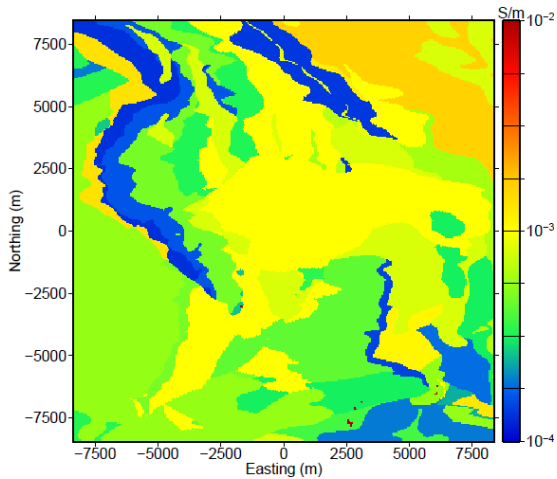


Data

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

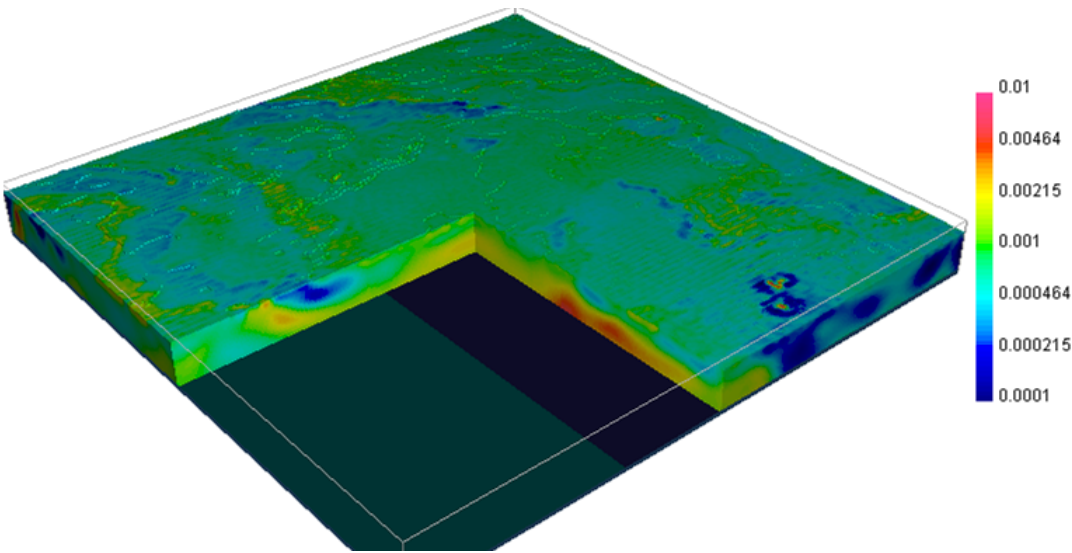
Observed (90 Hz)

True model at 275m depth

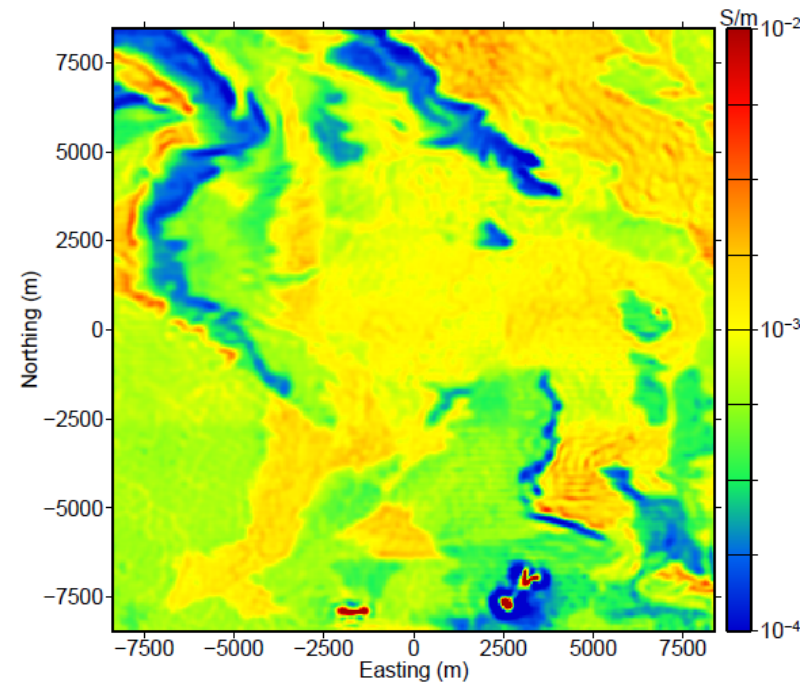


Interpretation

Recovered Model



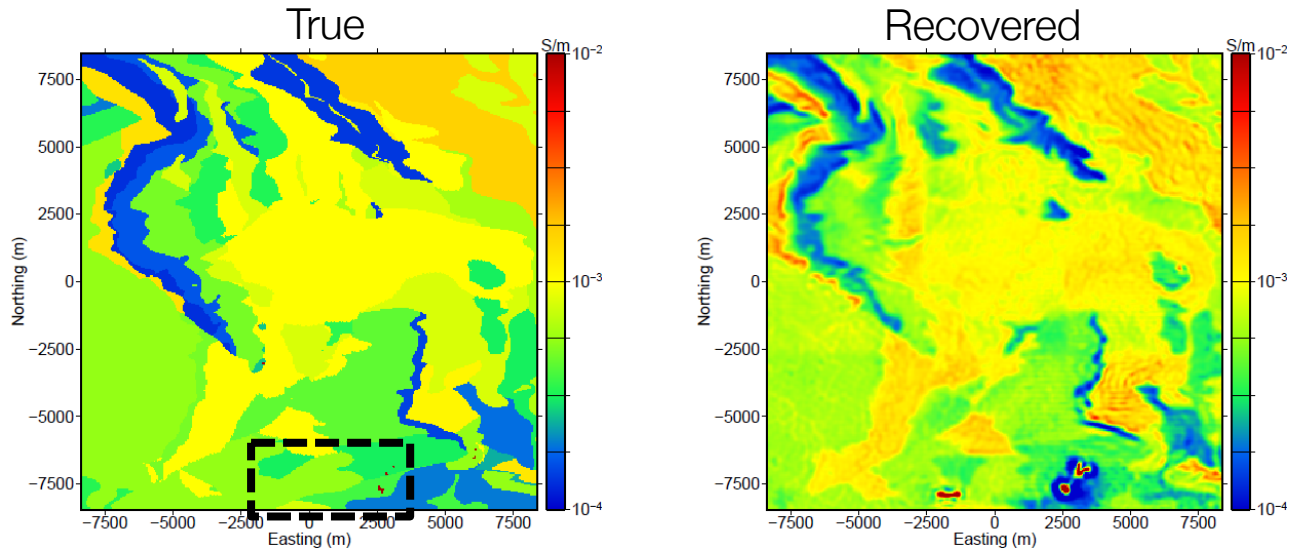
Model at 275m depth



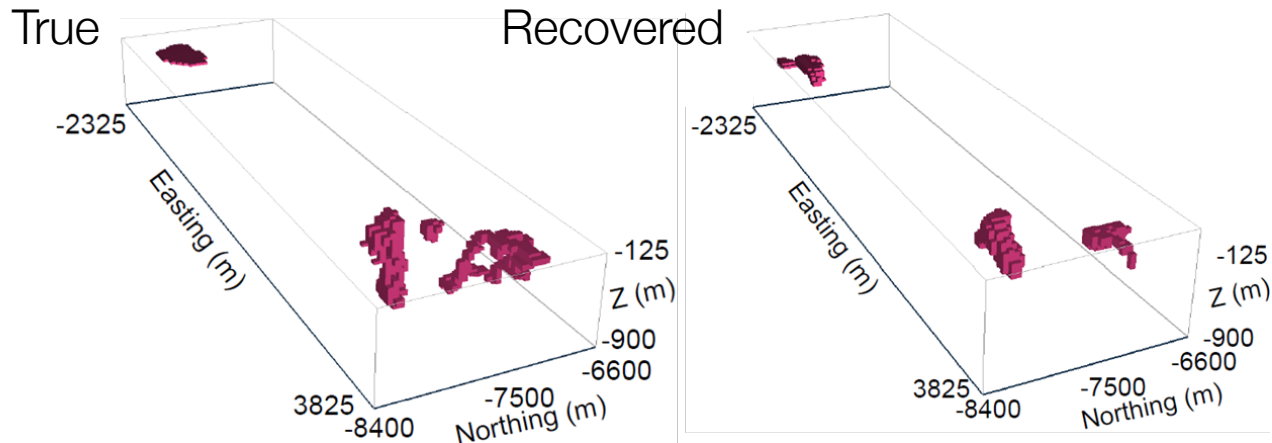
- Geologic units are well mapped
- Some mineralized bodies are located

Synthesis

- Recovered model represents the regional geology

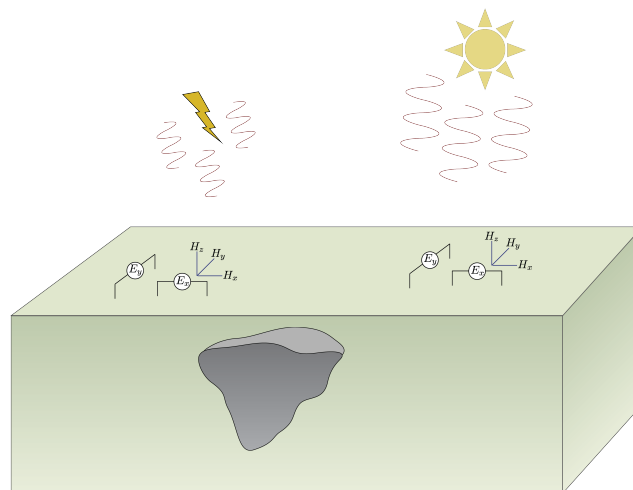


- Mineralized zones are recovered



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

