EM: Natural Sources

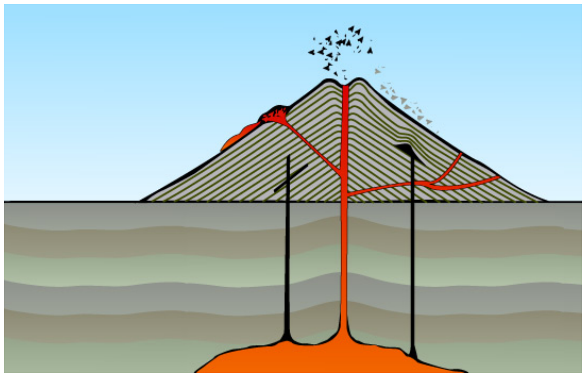
DISC 2017
Electromagnetics
Fundamentals and Applications

Outline

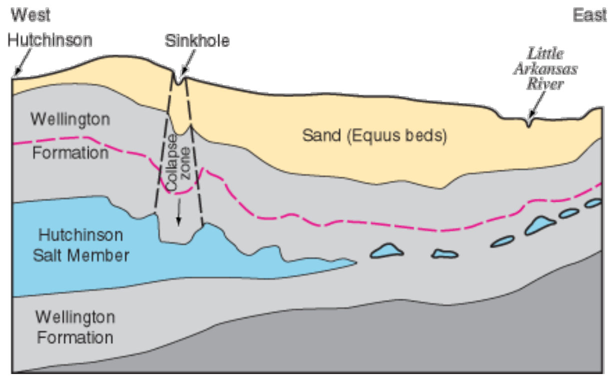
- Background on natural source EM methods
- Magnetotellurics
- MT case history
- Z-axis tipper electromagnetics
- ZTEM case history

Motivation

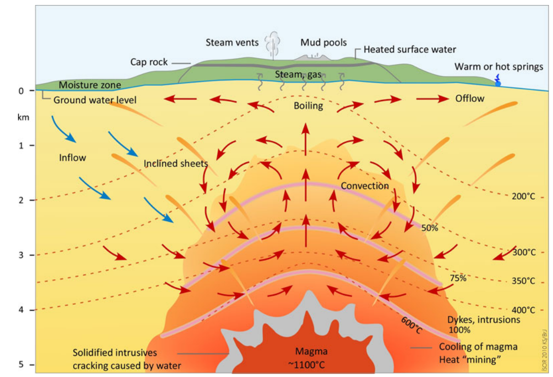
Volcanoes



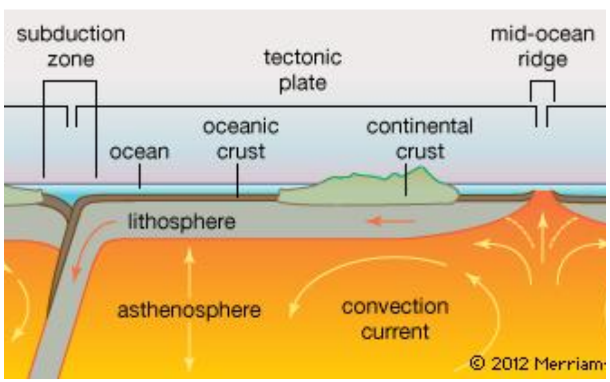
Base of salt



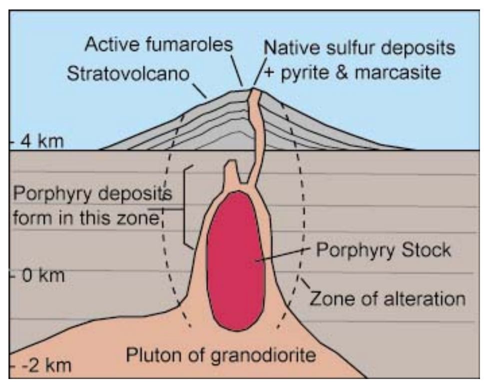
Geothermal



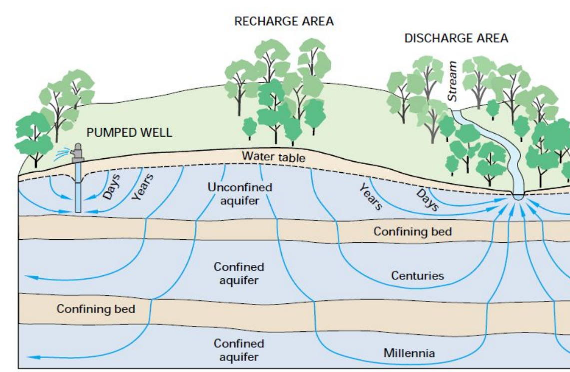
Tectonic settings of top few km



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

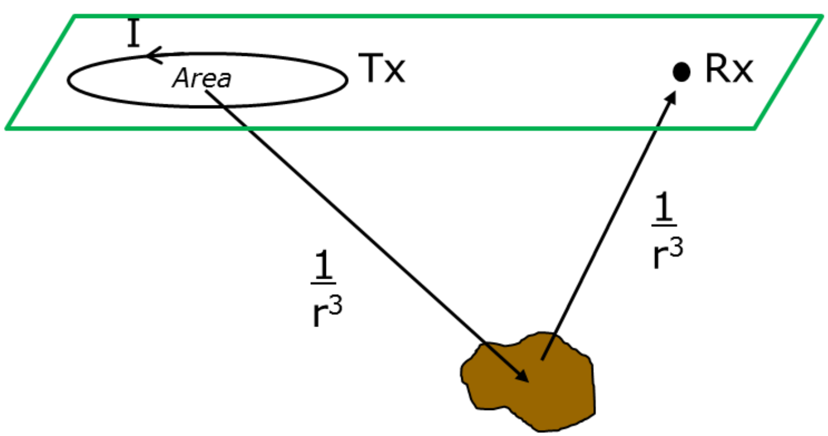
$$m = IA$$

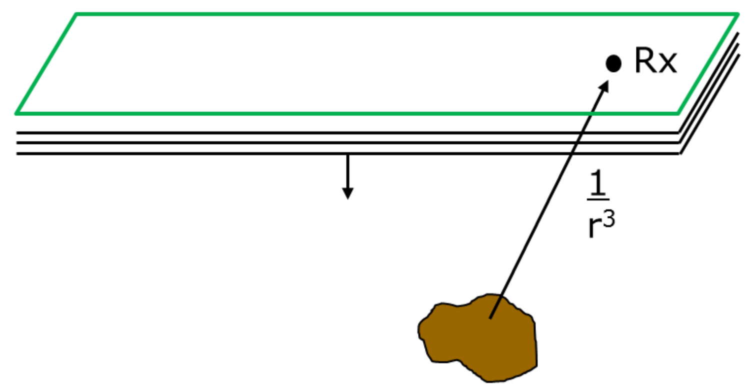
  - Total geometric decay

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

- Infinitely large loop source
  - Sheet currents generate plane waves
  - Total geometric decay

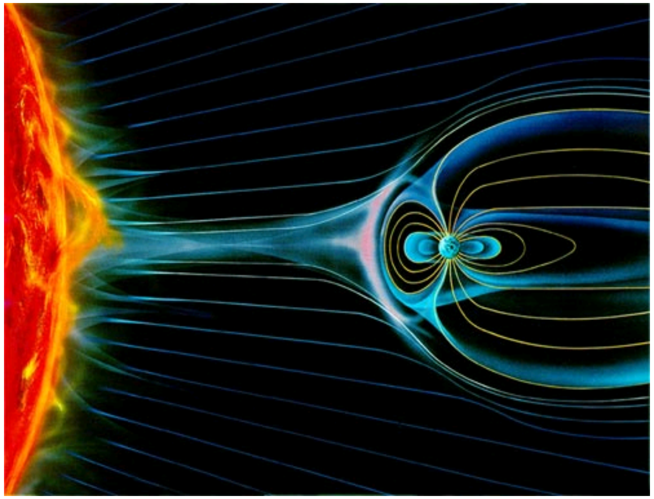
$$\sim \frac{1}{r^3}$$





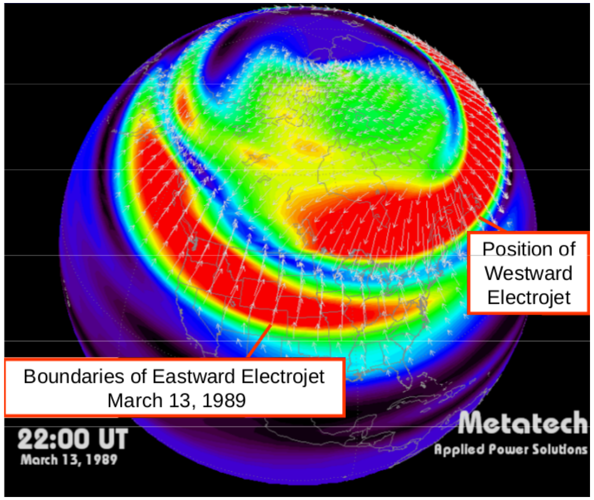
Natural EM sources

Sun and magnetosphere, solar storms

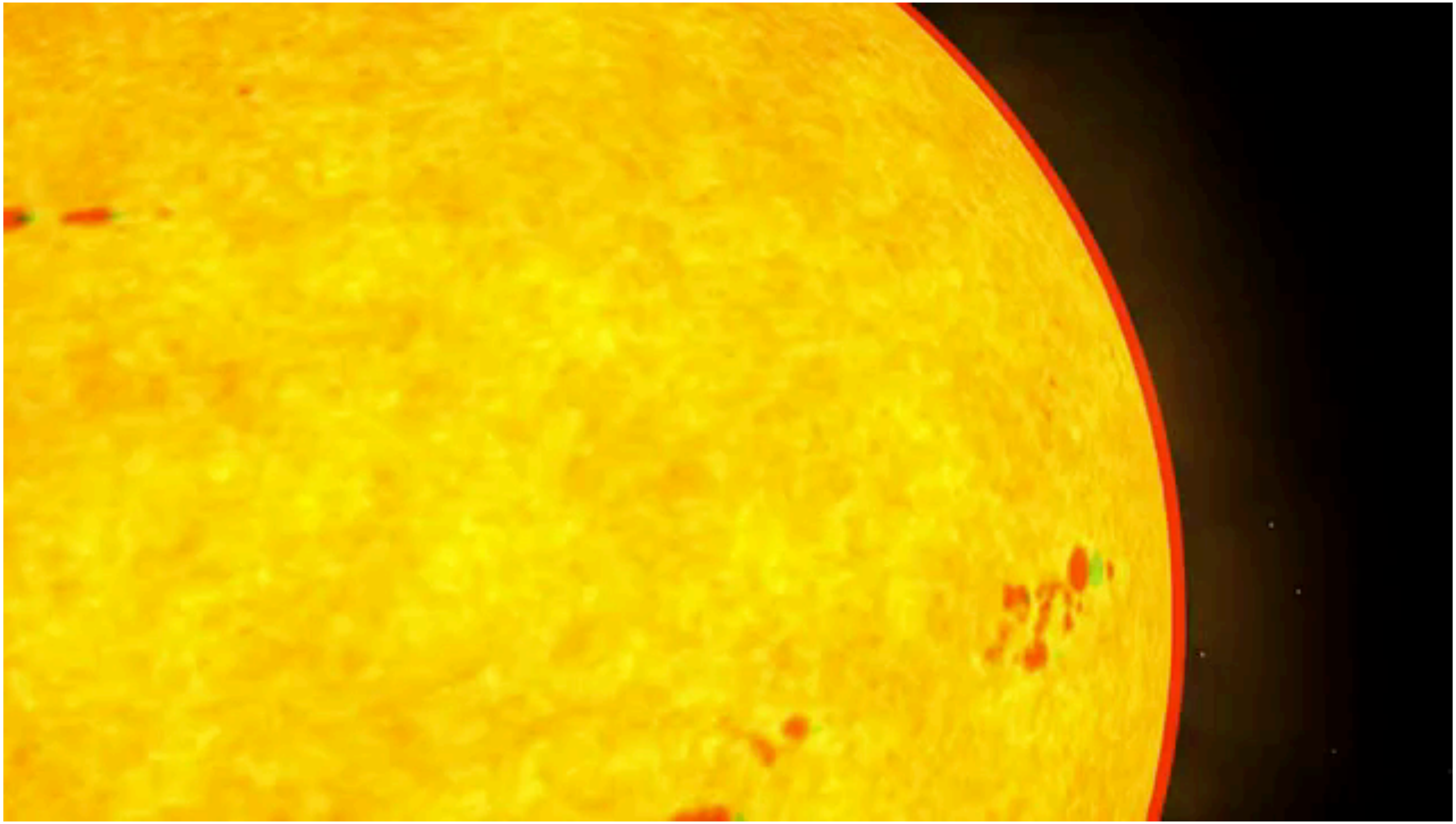


Lightning

Auroral electrojet; aurora

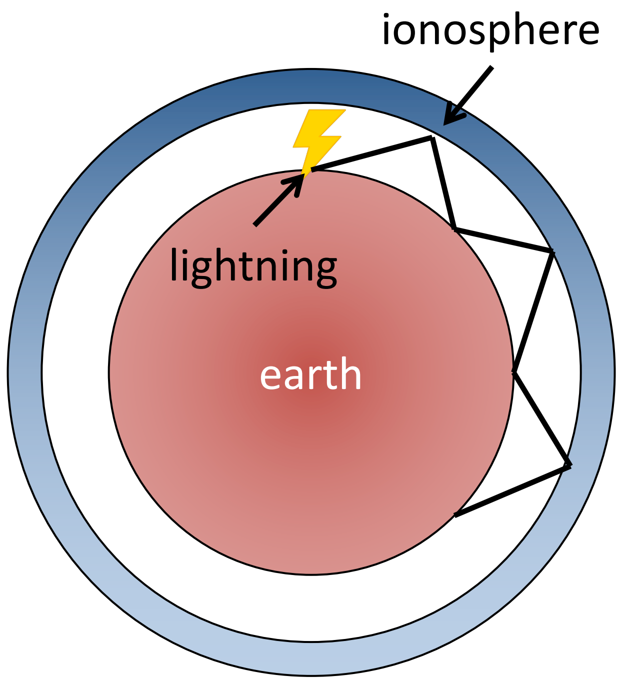


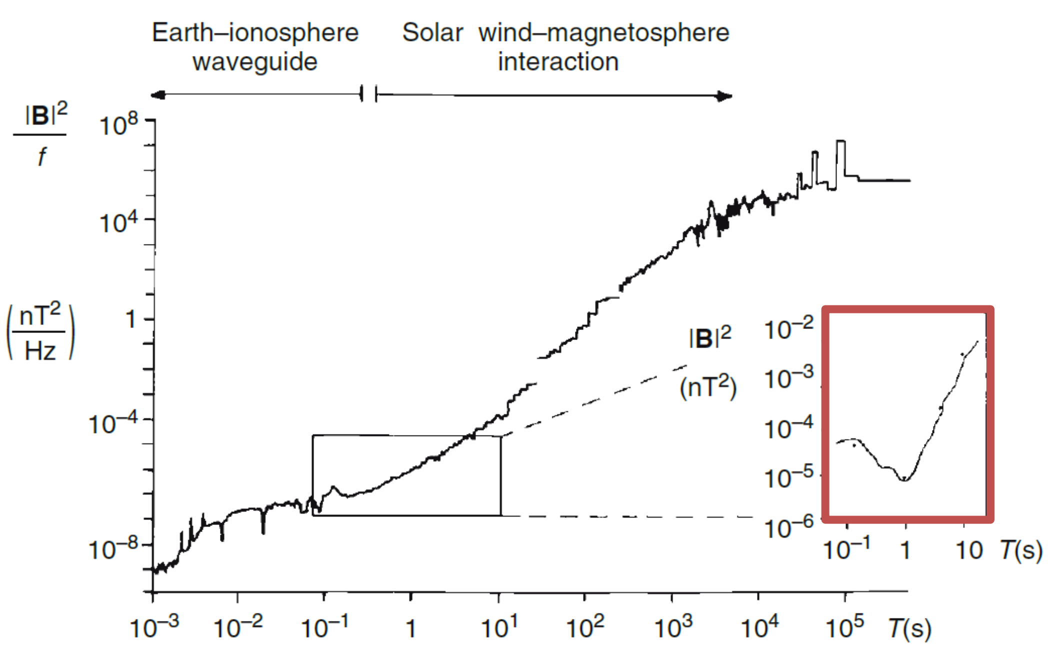
Aurora movie



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

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

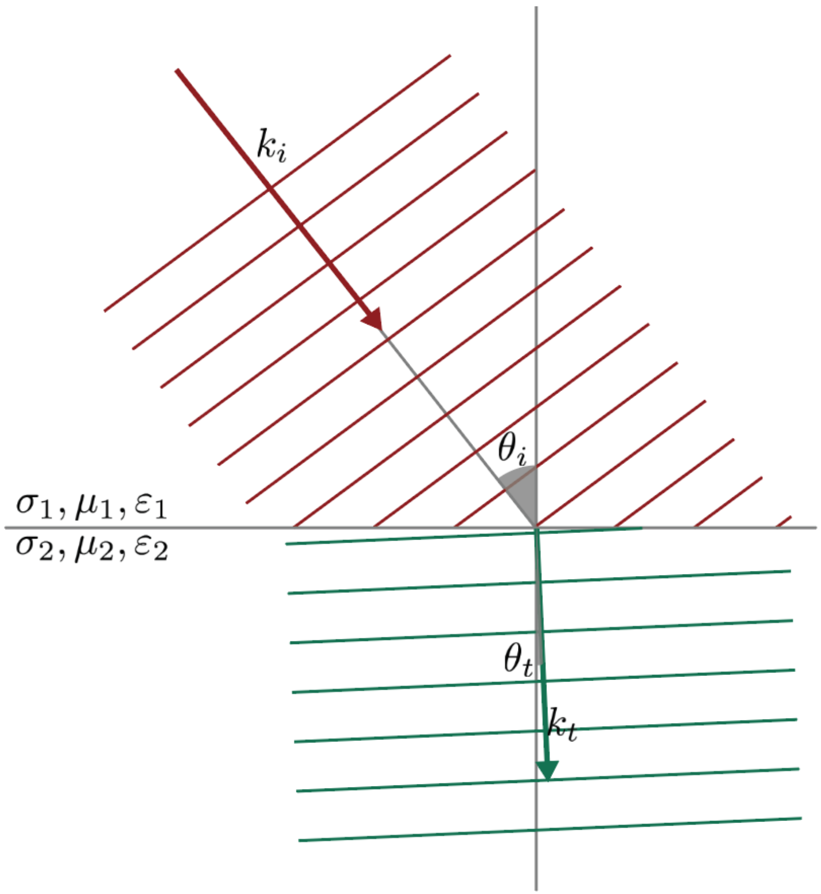
- k is complex wave number

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

- 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 $\theta_t = 1.35°$

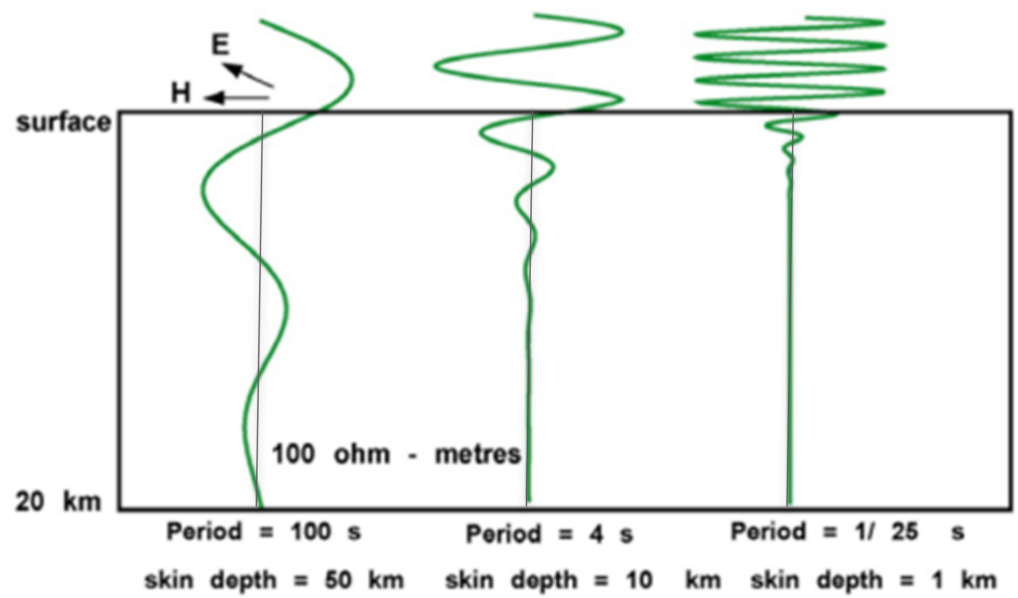
Plane waves and skin depth

- Skin depth (meters)

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

- Low frequency waves propagate further

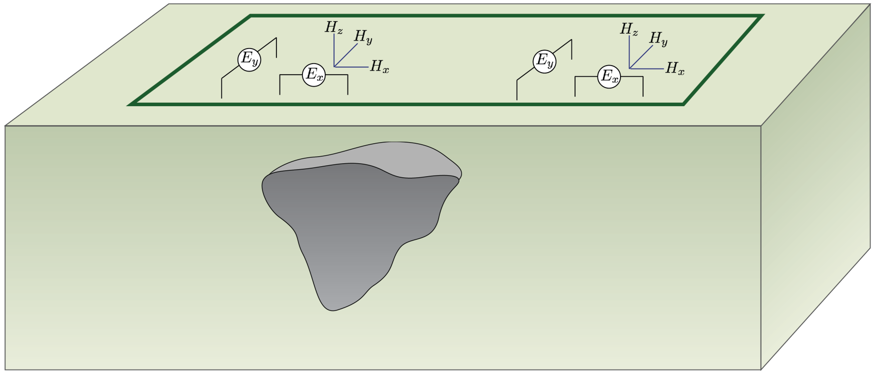
- Depth of propagation
  - A few skin depths
  - Only a portion of a wavelength

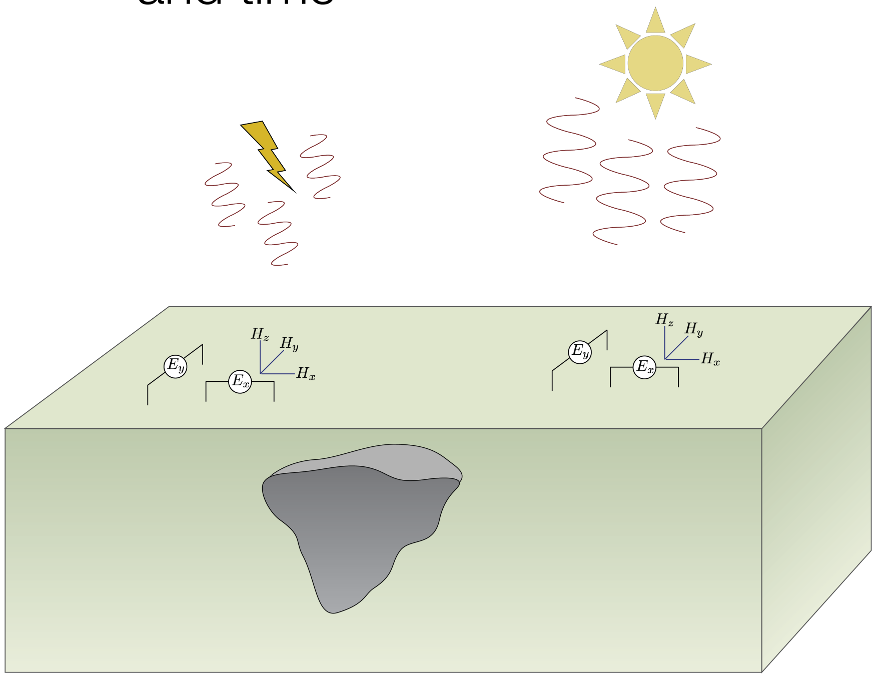


Control source vs Natural source

- 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

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

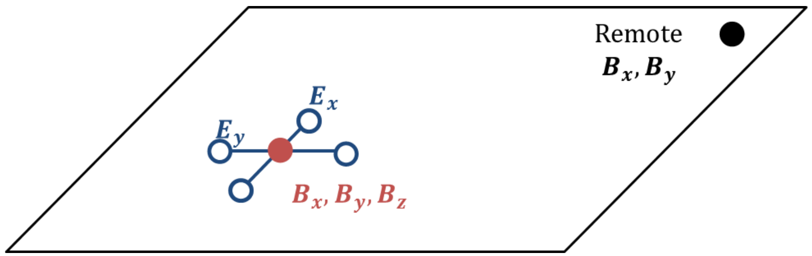
- Effects of unknown source removed by taking ratio

- Transfer function

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

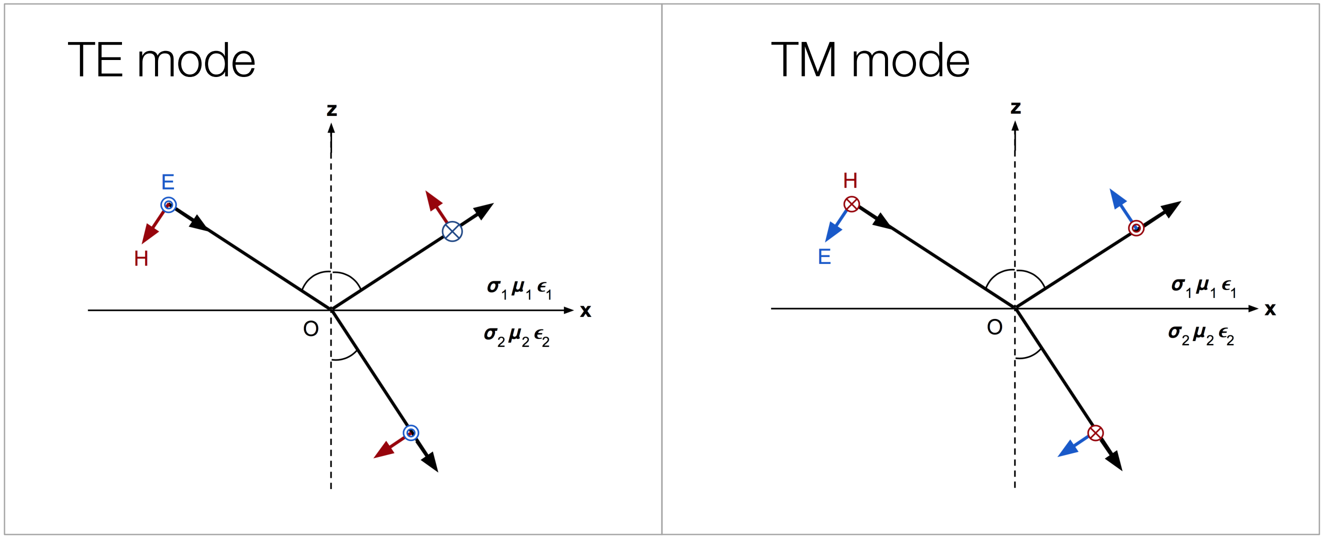
impedance (matrix)

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



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:

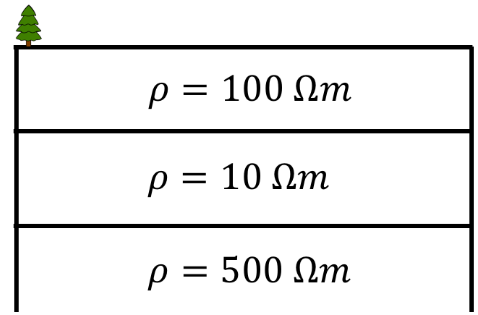
$$\Phi = \tan^{-1}\left(\frac{Im(Z_{xy})}{Re(Z_{xy})}\right)$$

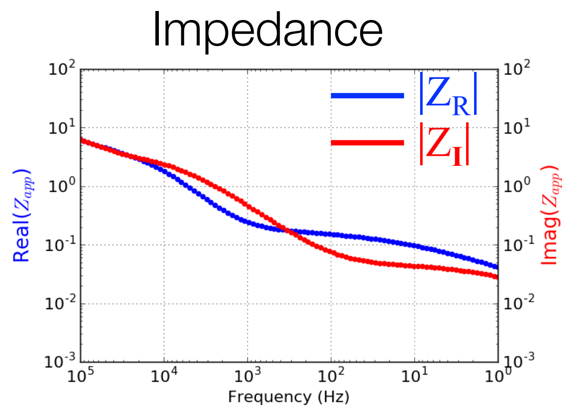
- In 1D:

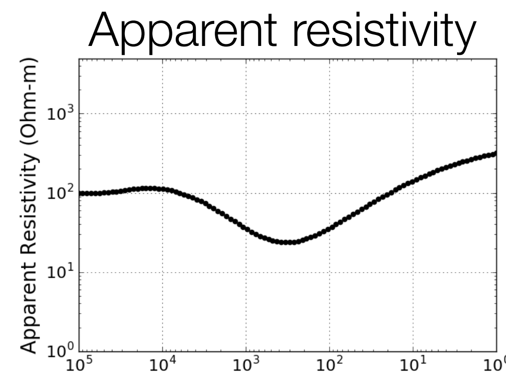
$$Z = \begin{pmatrix} 0 & Z_{xy} \\ Z_{yx} & 0 \end{pmatrix}$$

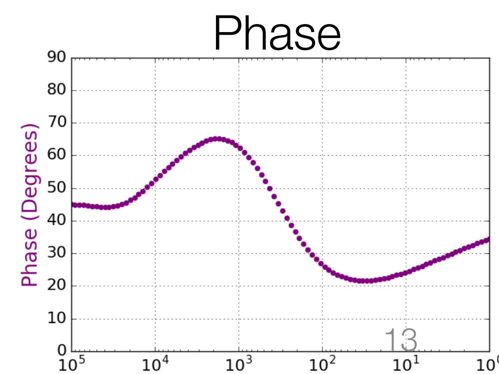
$$Z_{xy} = \frac{E_x}{H_y}$$

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





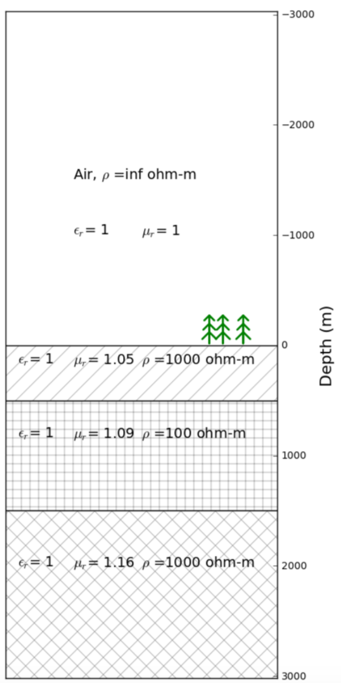


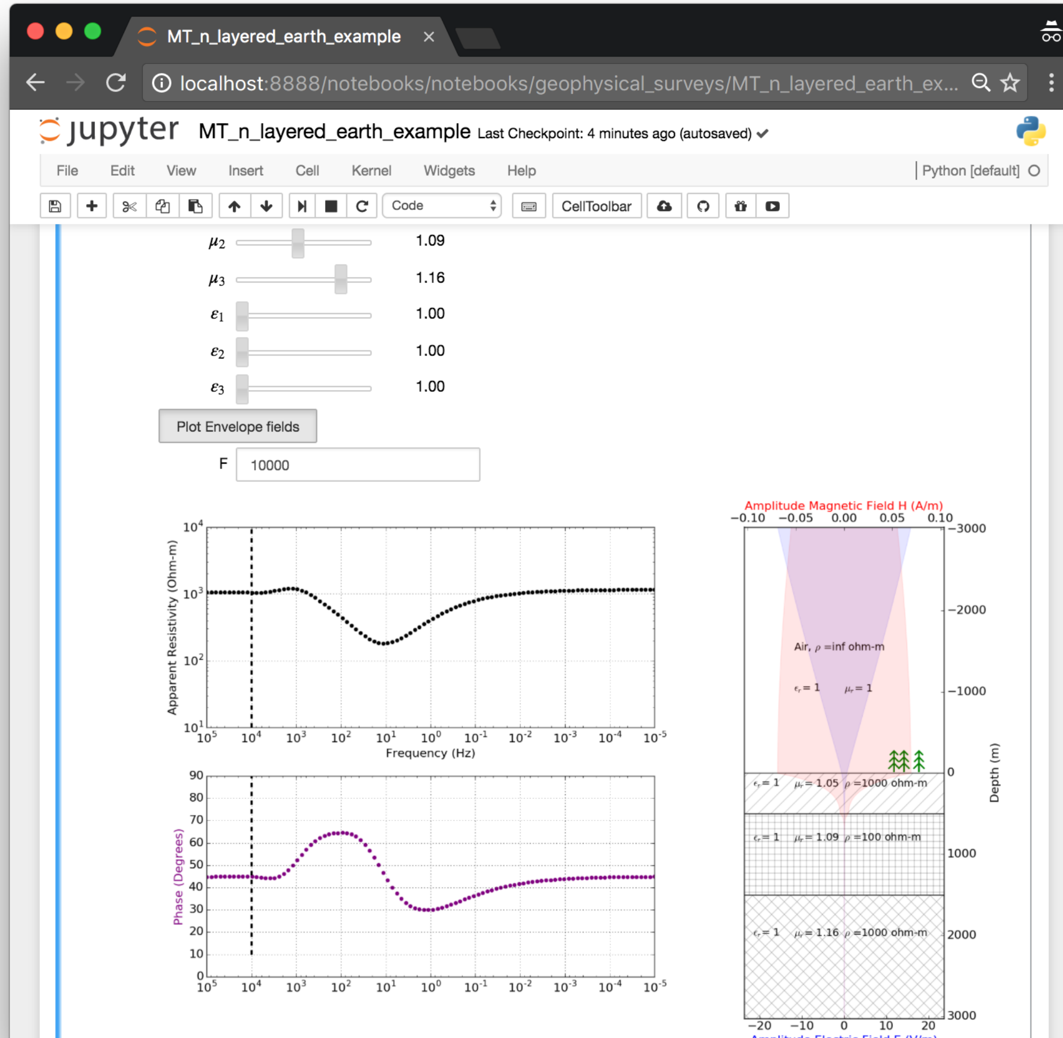


1D MT app

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

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





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

MT soundings in 2D

- In general:

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

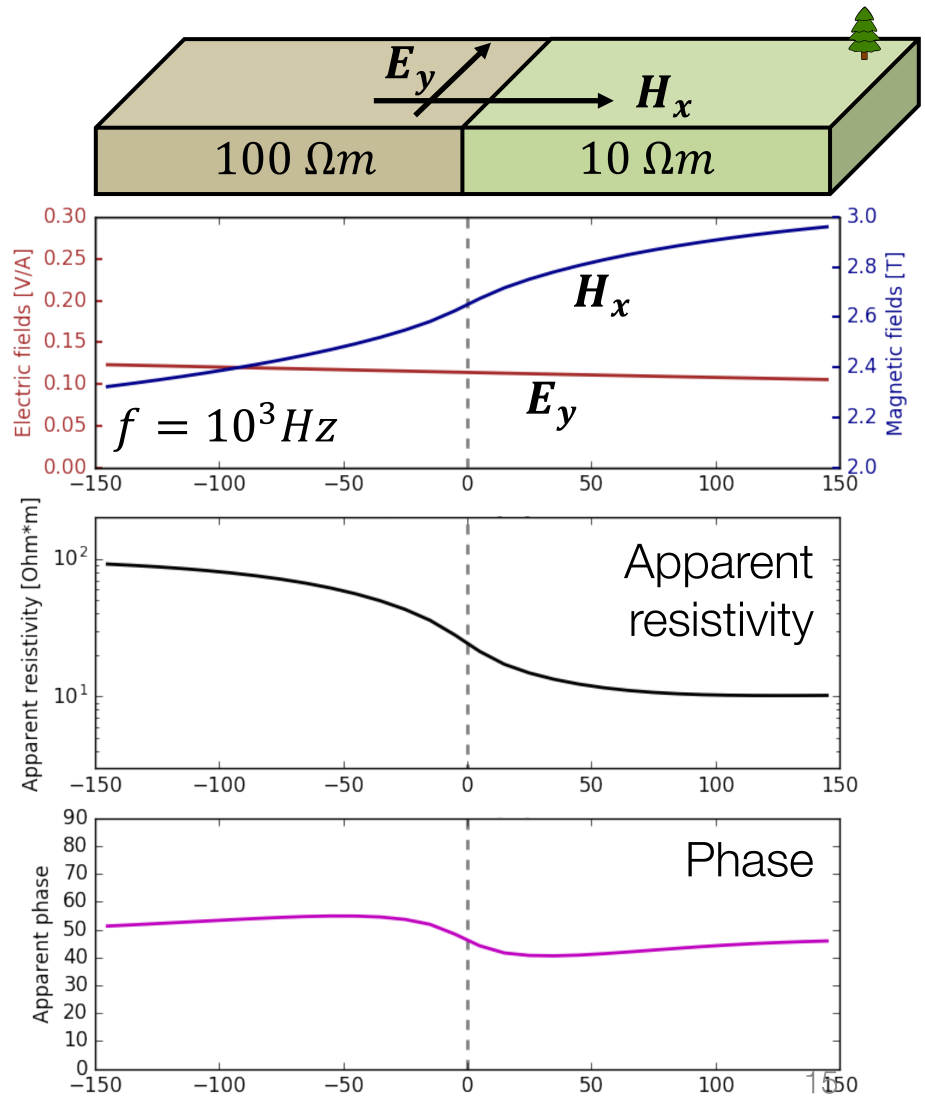
- In 2D:

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

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

- TE mode
  - E-field parallel to structure

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



MT soundings in 2D

- In general:

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

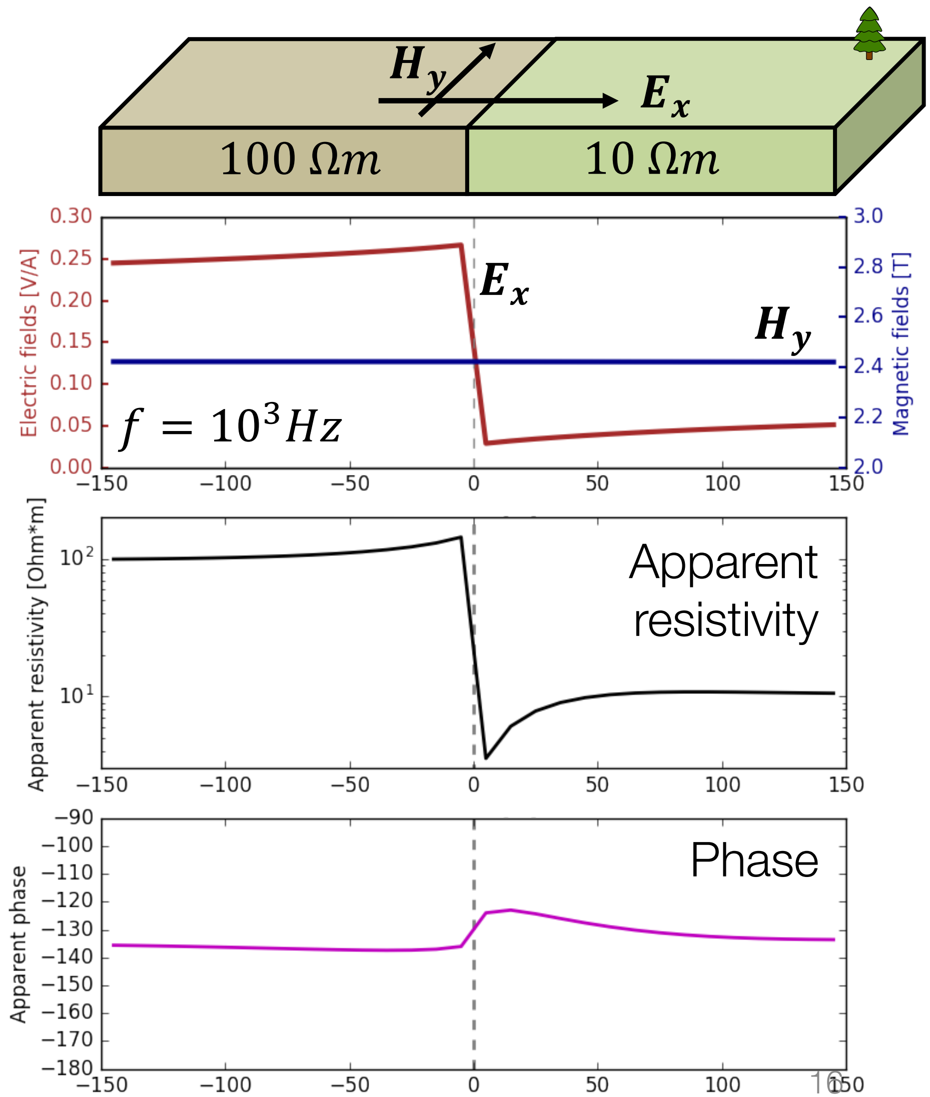
- In 2D:

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

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

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

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



MT soundings in 3D

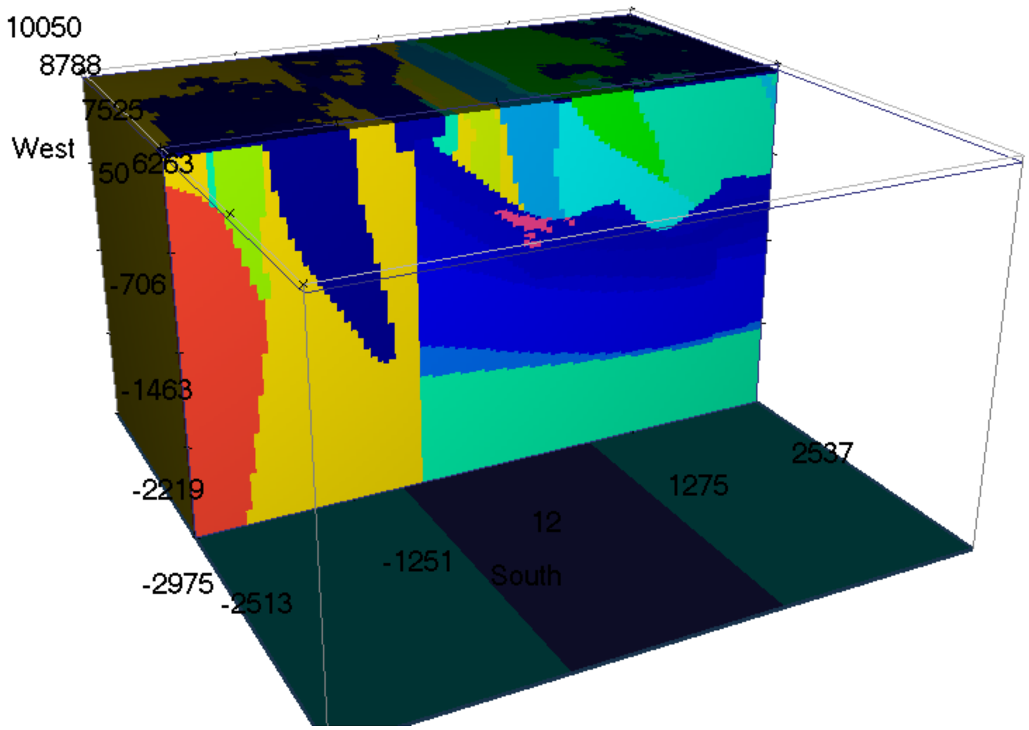
- In general:

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

- In 3D:

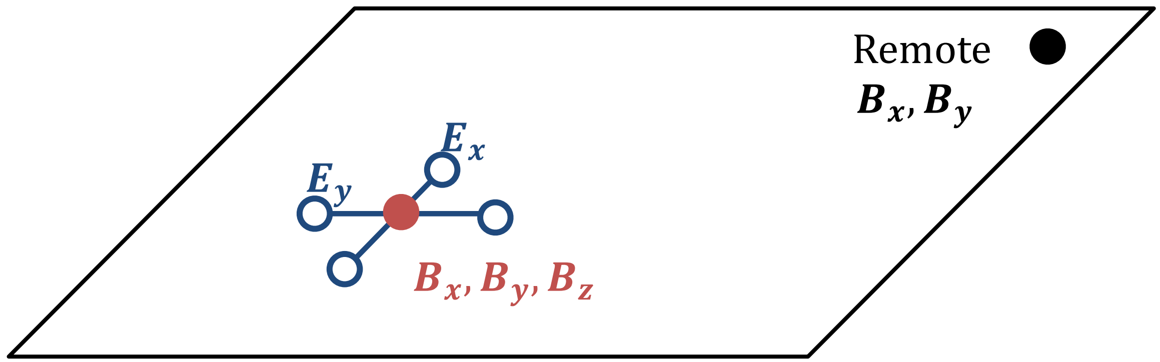
$$Z = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$$

- No symmetry or special conditions



Measuring MT data

- Basic acquisition

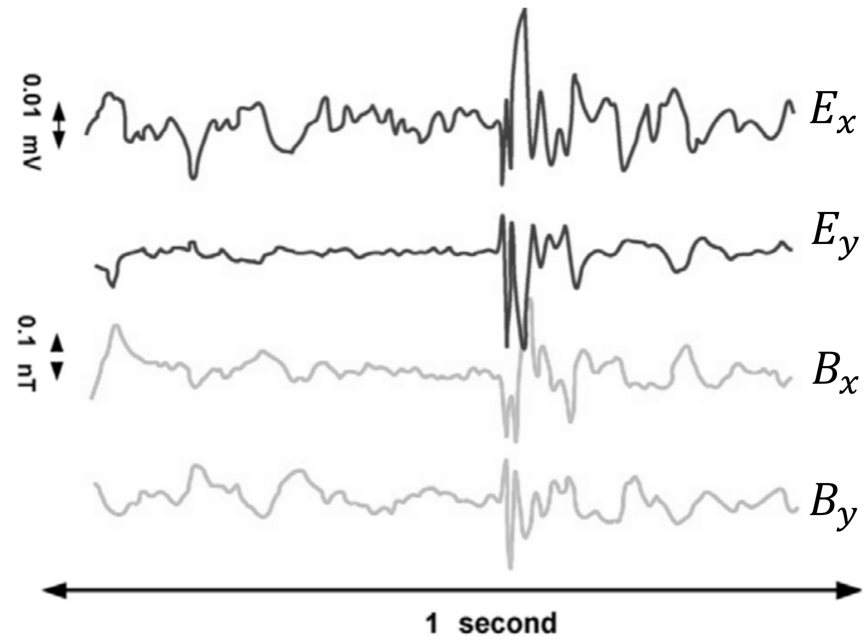


- At each station, measure:

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

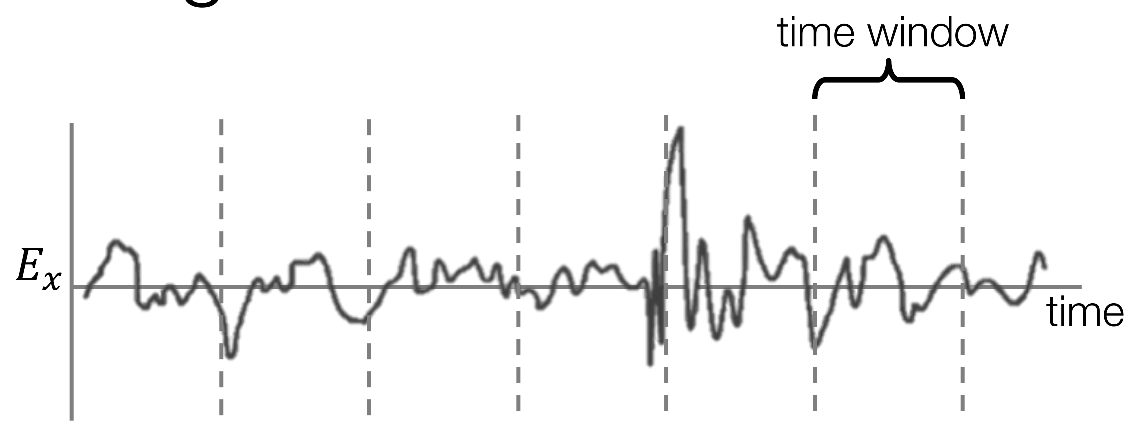
- At remote reference, measure:

$$B_x, B_y$$



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:

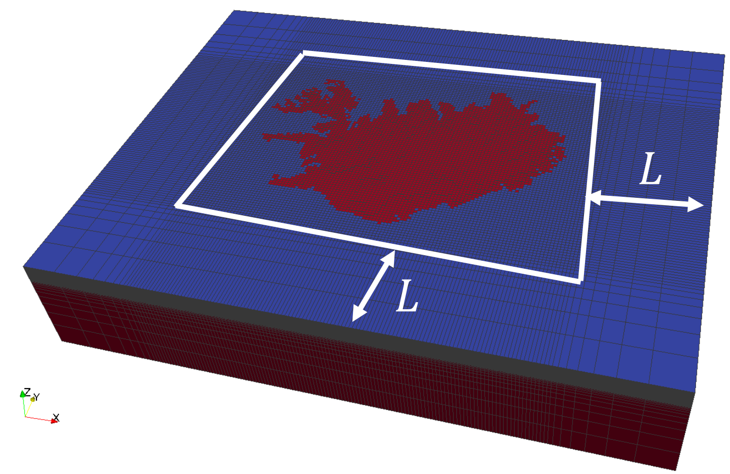
$$Z_{xy}(\omega) = \frac{\langle E_x(\omega) H_y^{R*}(\omega) \rangle}{\langle H_y(\omega) H_y^{R*}(\omega) \rangle}$$

(*) 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

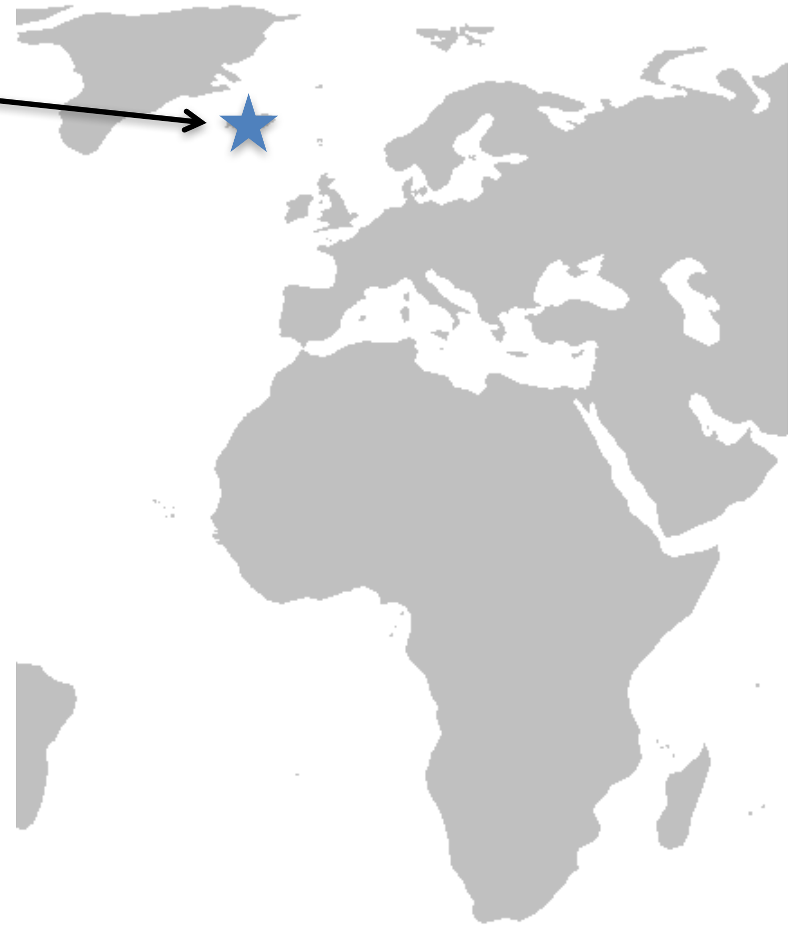
- Background on natural source EM methods
- Magnetotellurics

- Questions?

- MT case histories
- Z-axis tipper electromagnetics
- ZTEM case histories

MT case history

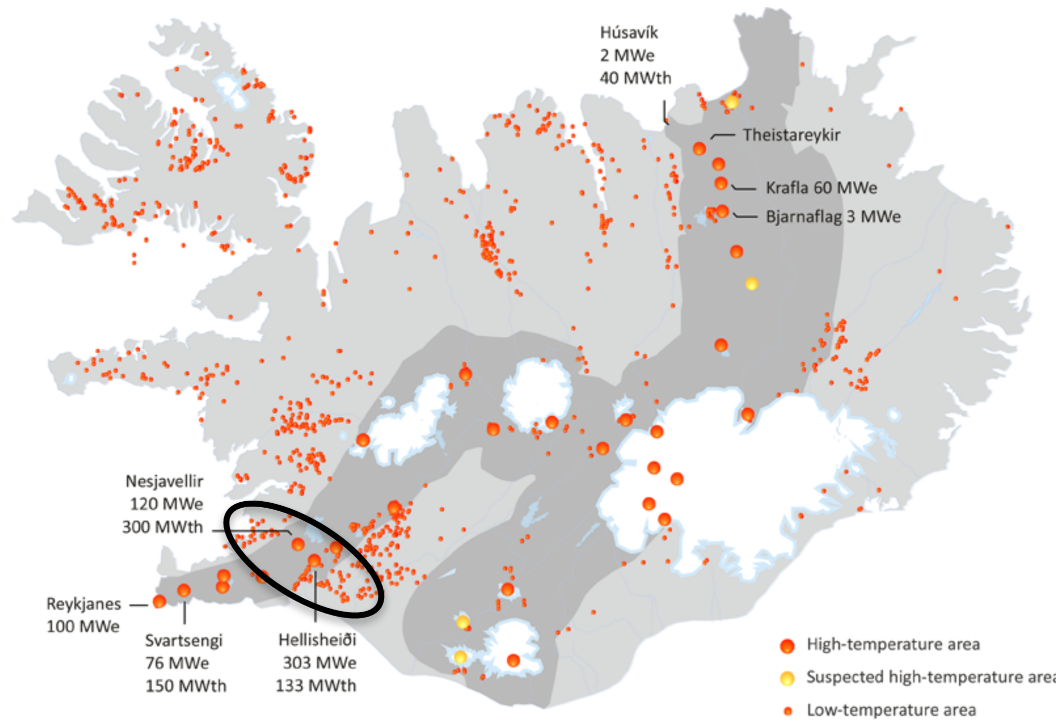
- Iceland



Hengill geothermal region: setup

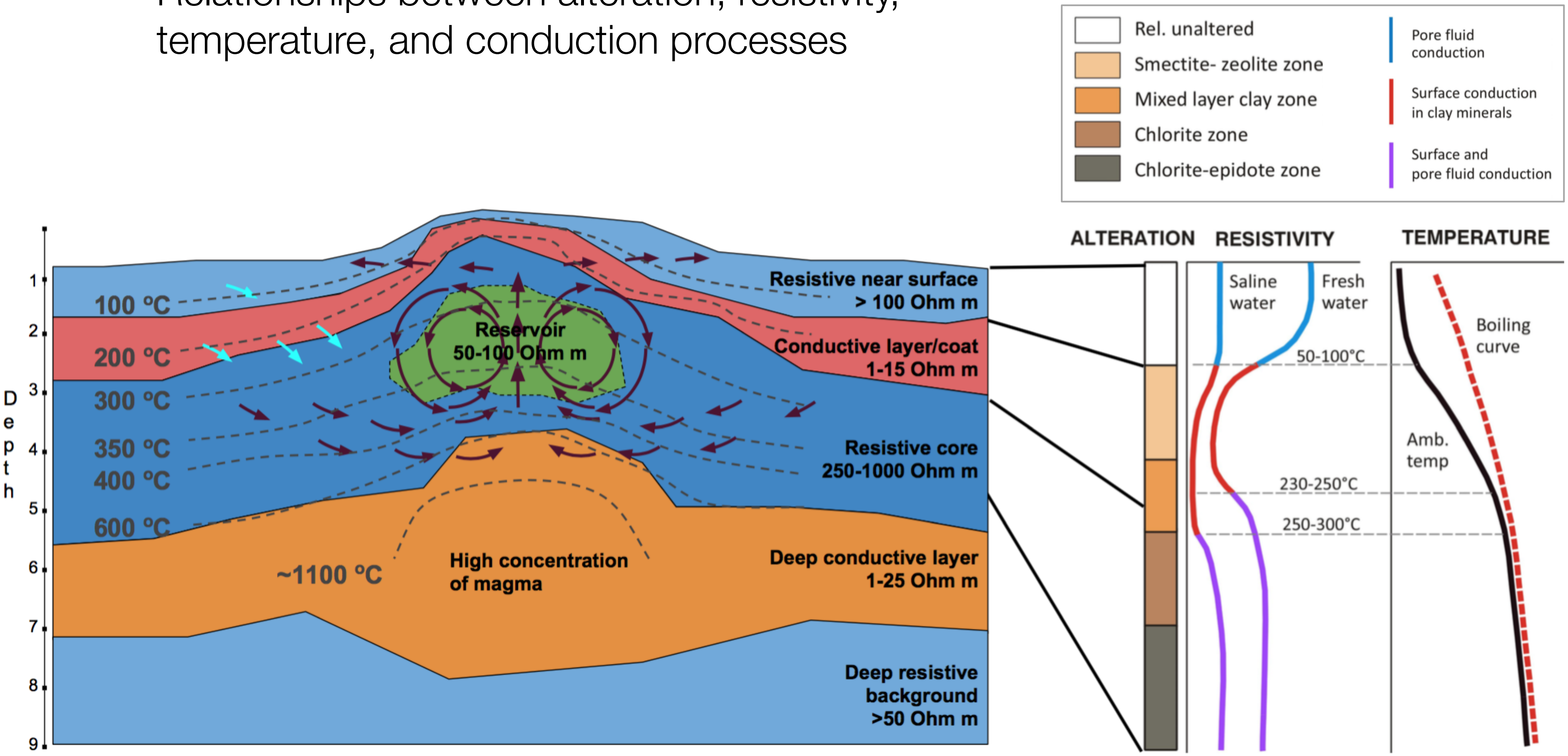
- Iceland: geothermal hot spot
  - On the mid-Atlantic ridge
  - Hosts multiple high temperature geothermal systems

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

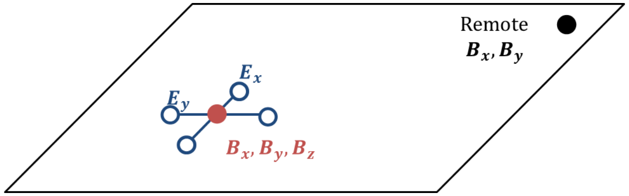


Physical properties

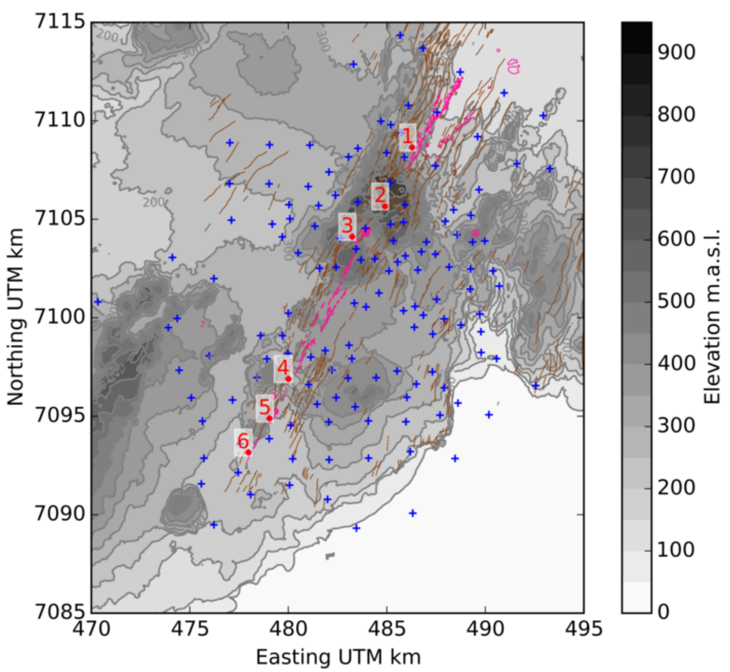
- Relationships between alteration, resistivity, temperature, and conduction processes



Survey

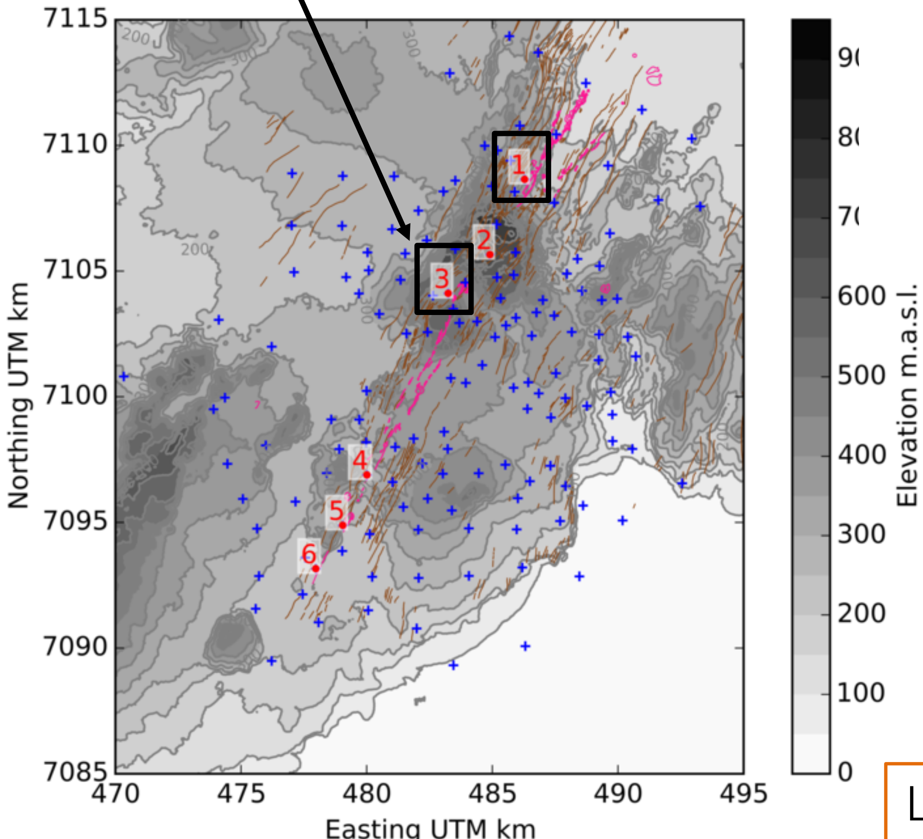


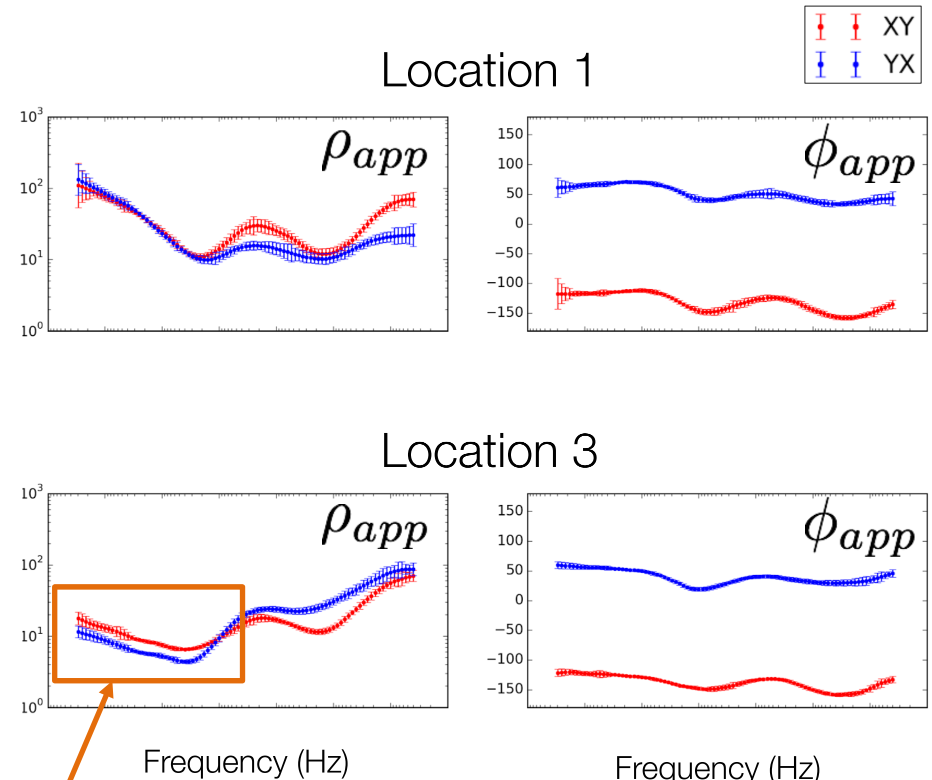
- MT instrumentation
  - Phoenix MTU5's
- Survey
  - 133 stations used
  - Combination of 2E and 2E+3H setup
  - Frequencies: 300 – 0.001 Hz
- Remote reference
  - About 40 km away
- Raw data processing using Phoenix software



Data

Surface alteration, hot water, fumaroles

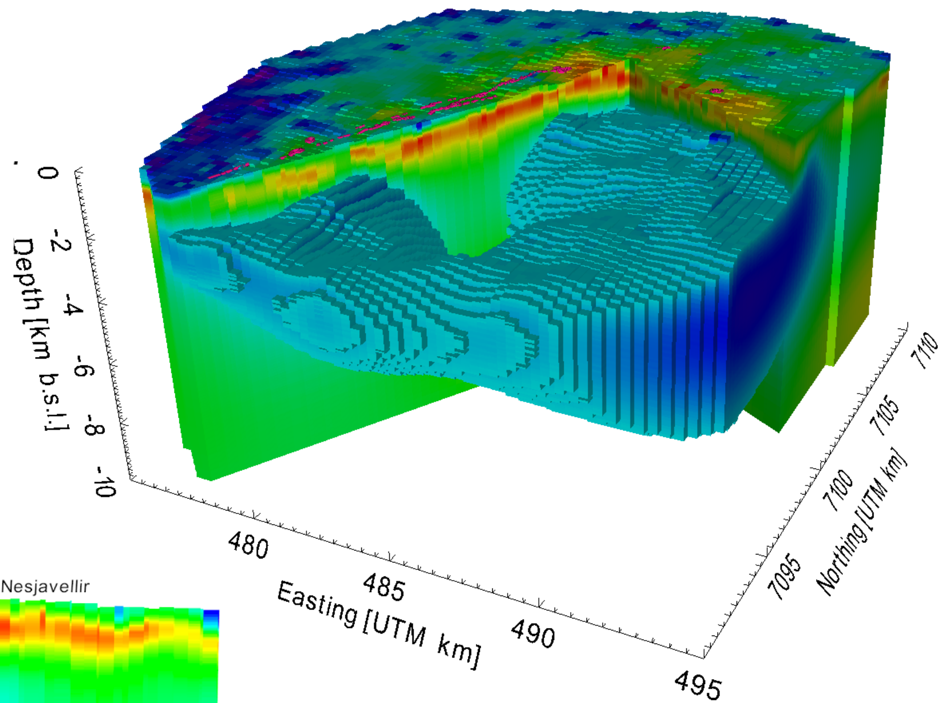


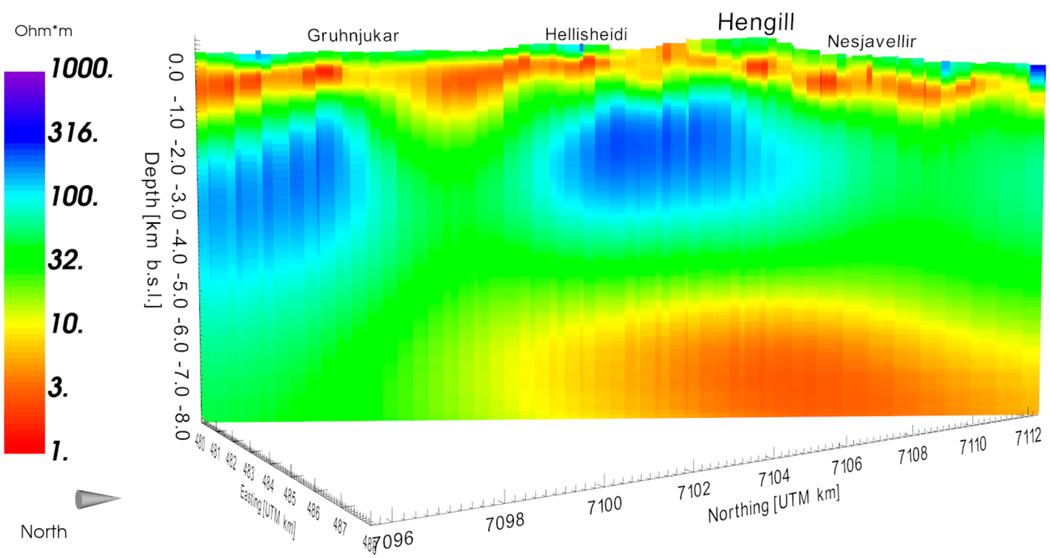


Low apparent resistivity

3D inversion

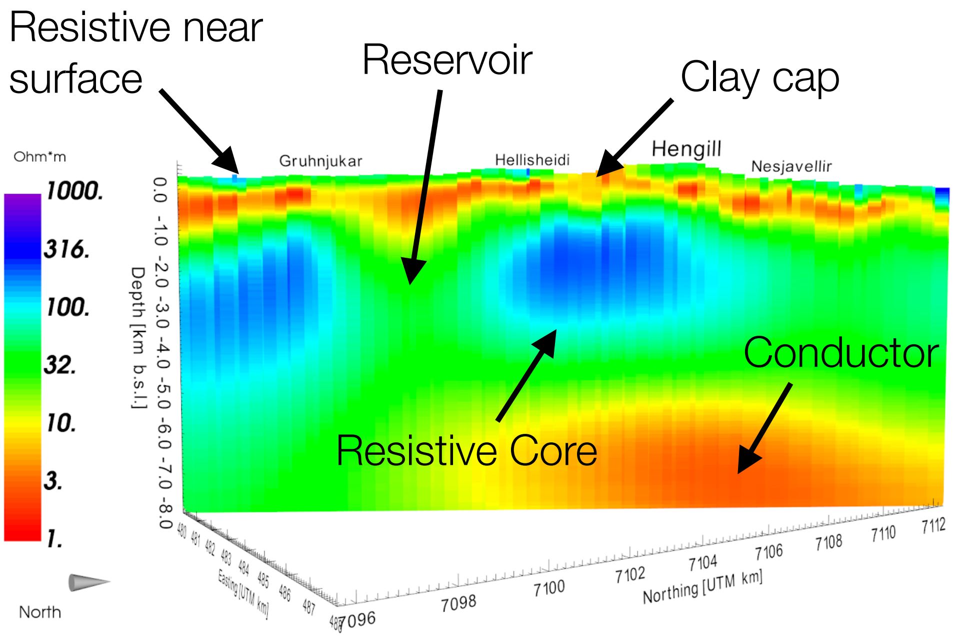
- Off-diagonal impedance (Z_{xy} and Z_{yx}) used
- Combined multi-frequency inversion (300 Hz – 0.001 Hz)

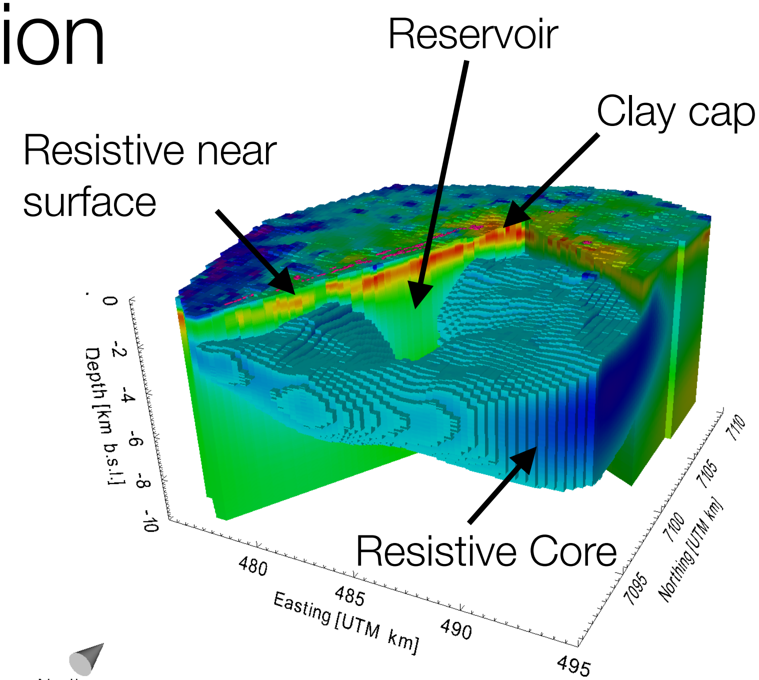


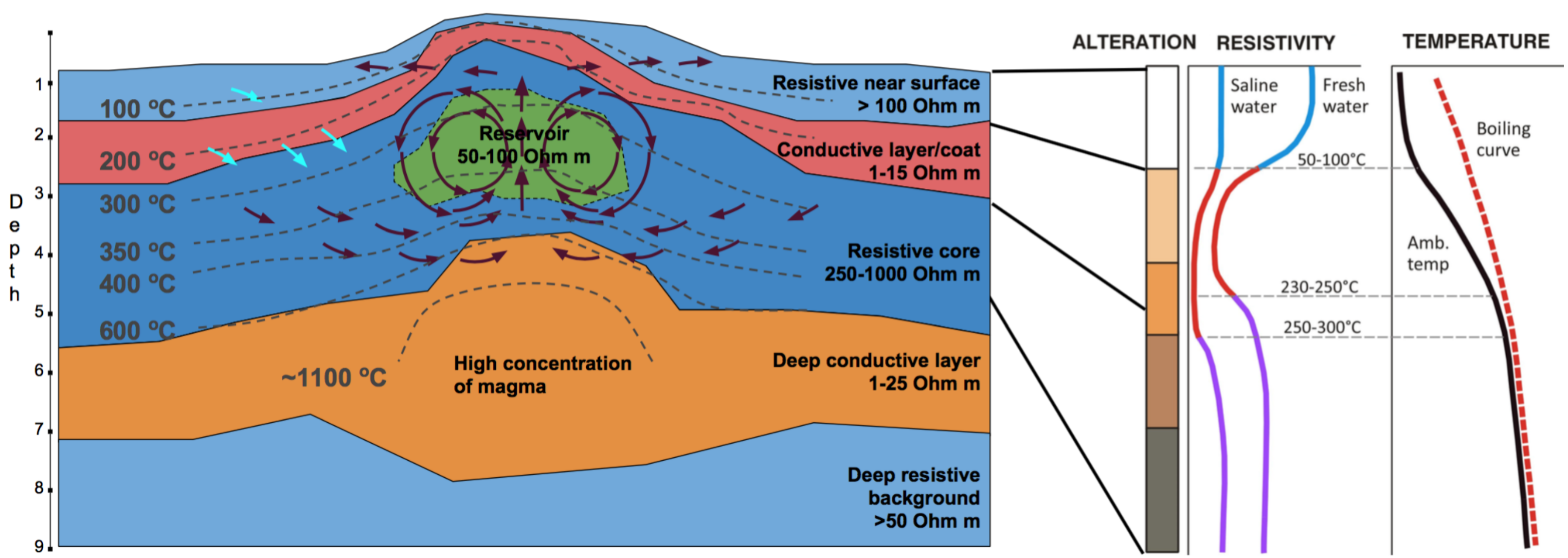


Rosenkjaer et al, 2015

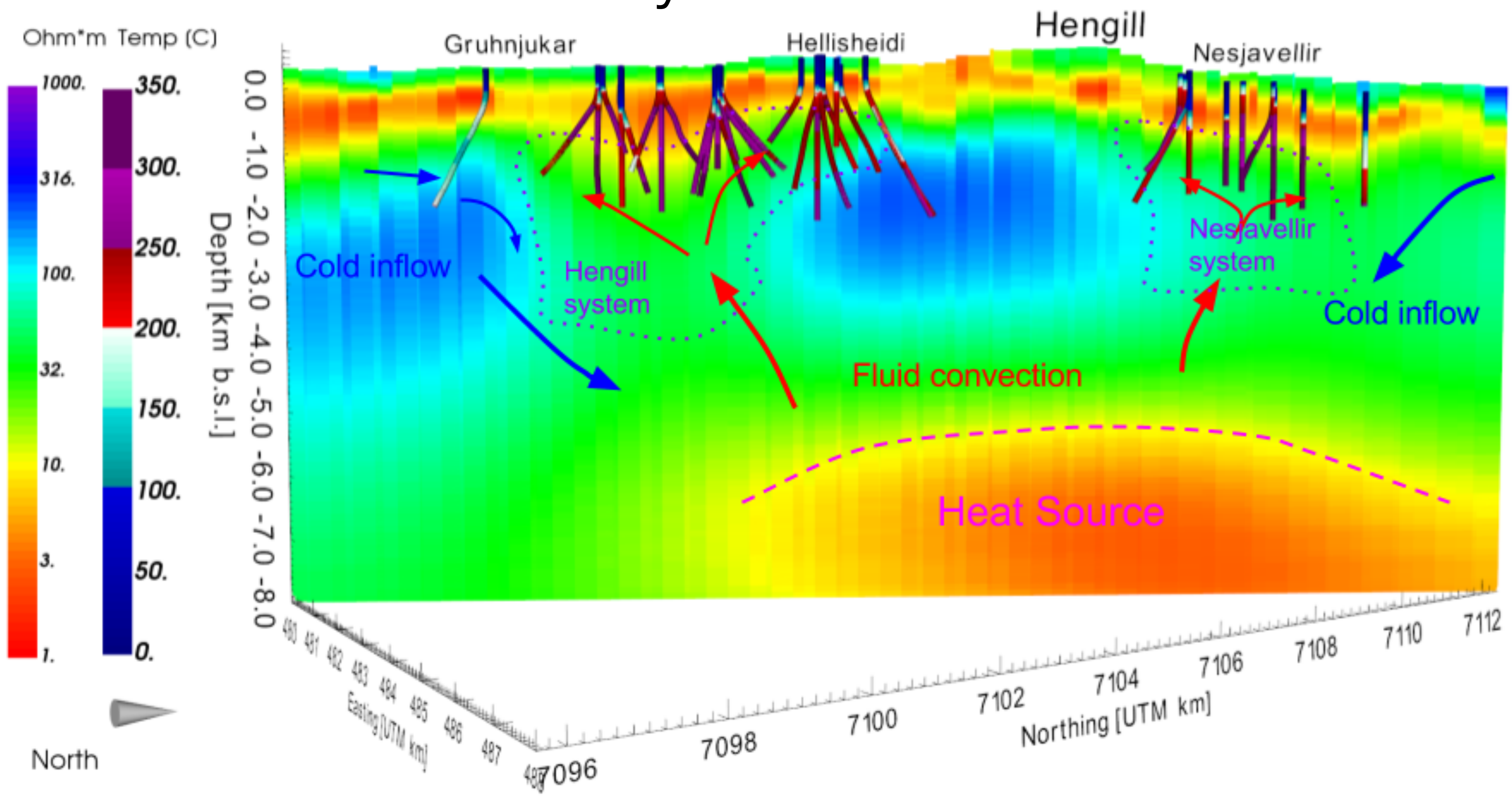
Interpretation







Synthesis



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

Summary

- Background on natural source EM methods
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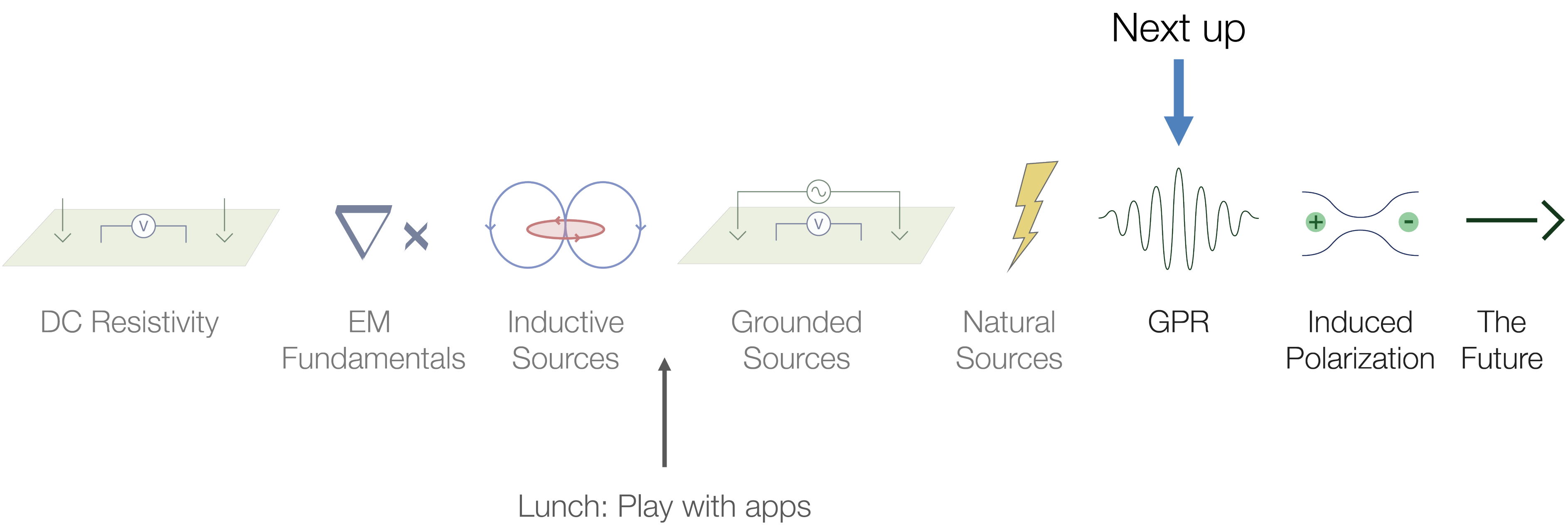
End of Natural Sources



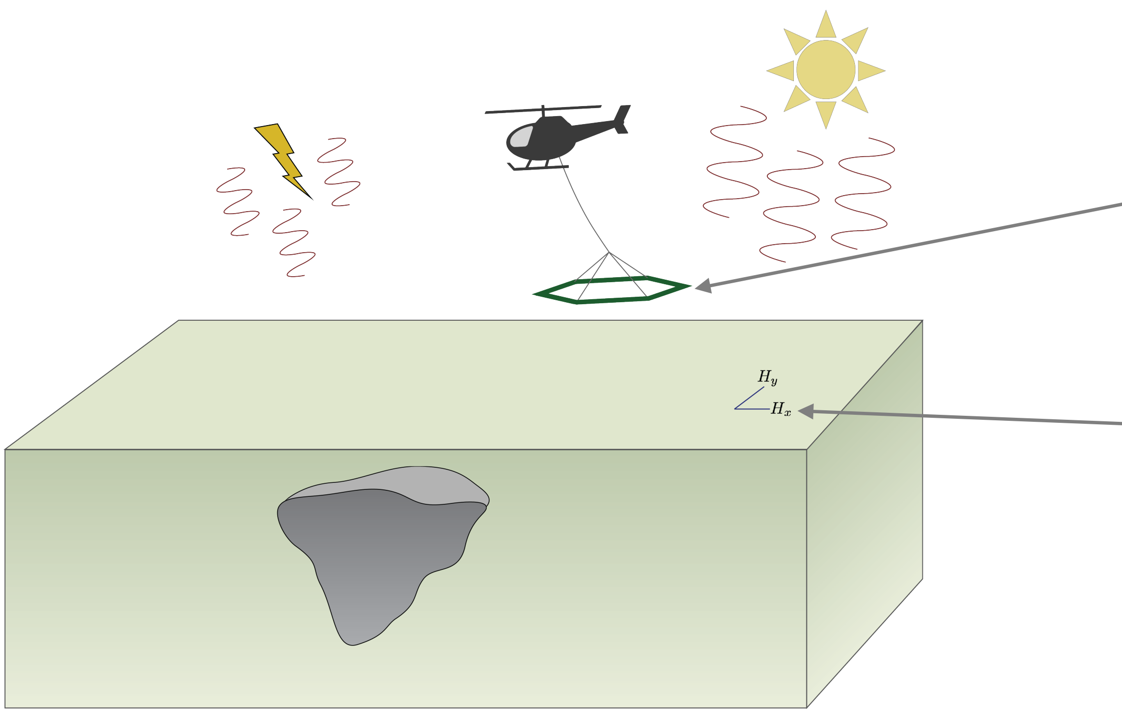
Tipper data (ZTEM)

- Magnetic transfer function

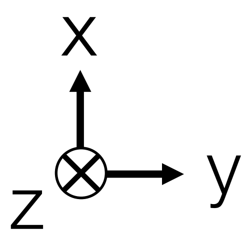
$$H_z = \mathbf{TH}$$

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

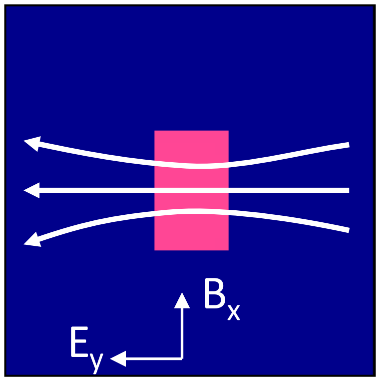
- Frequencies 30Hz – 720 Hz



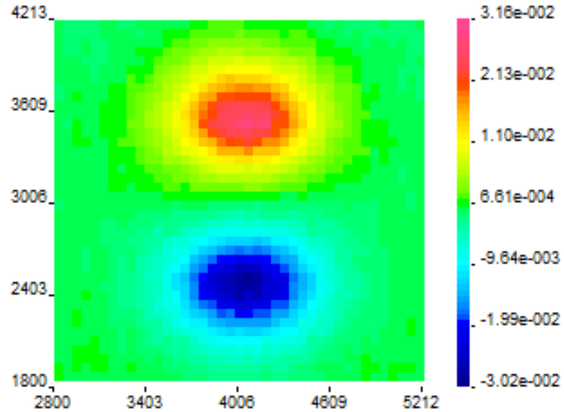
Synthetic example



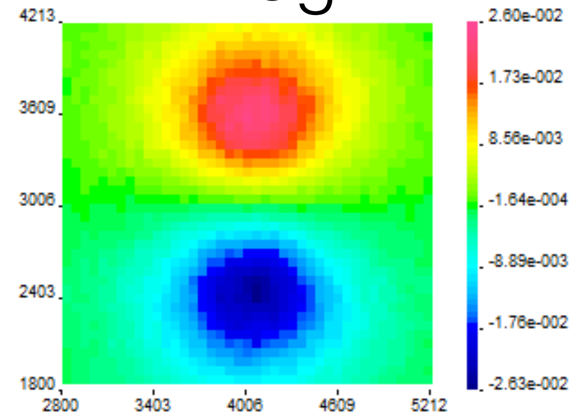
T_{zx}



Real

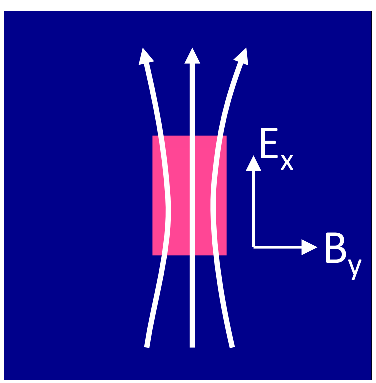


Imag

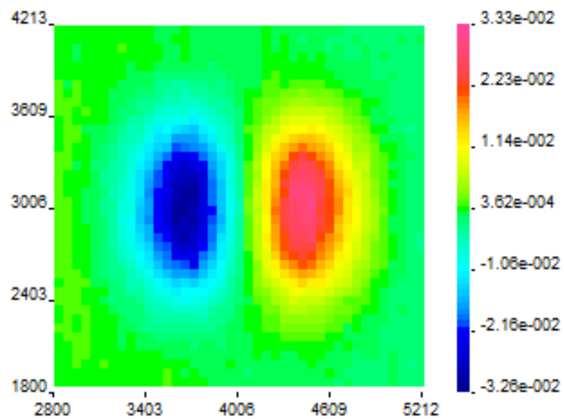


Conductor

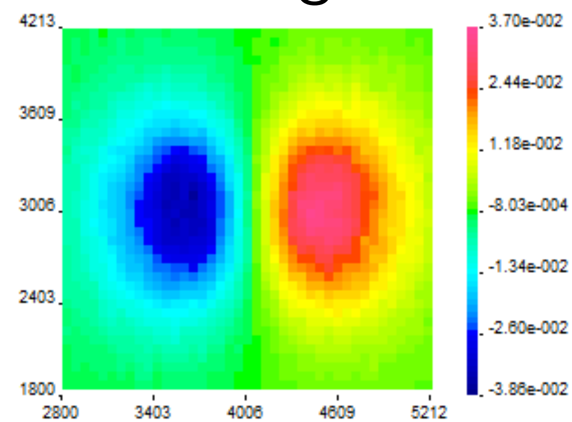
T_{zy}



Real



Imag



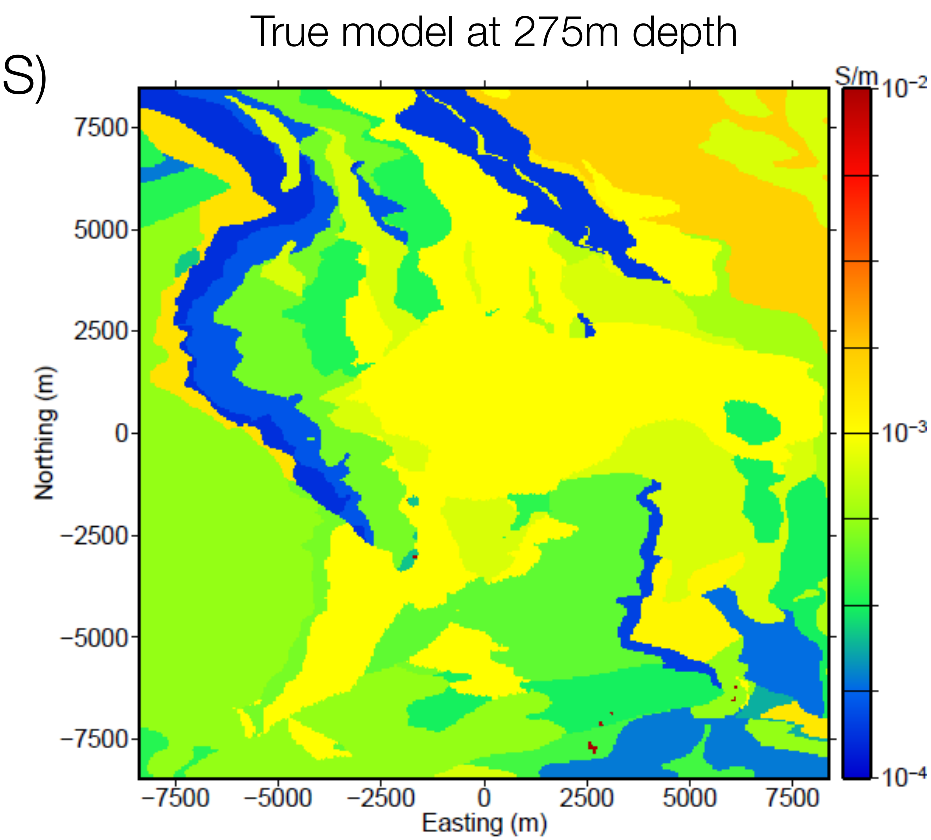
ZTEM case histories

- **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

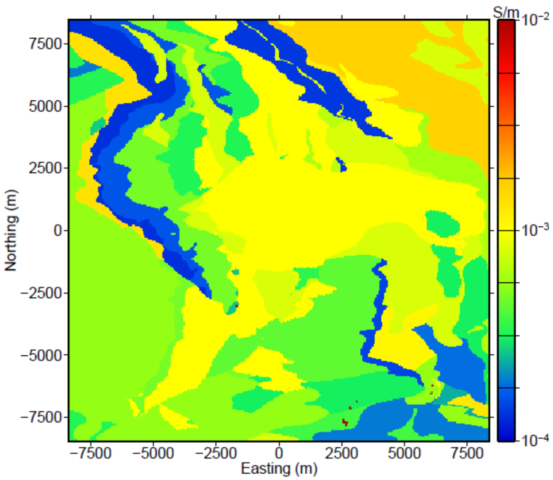
- Physical properties
  - Synthetic example from geologic model
  - 38 geologic units converted into expected conductivities



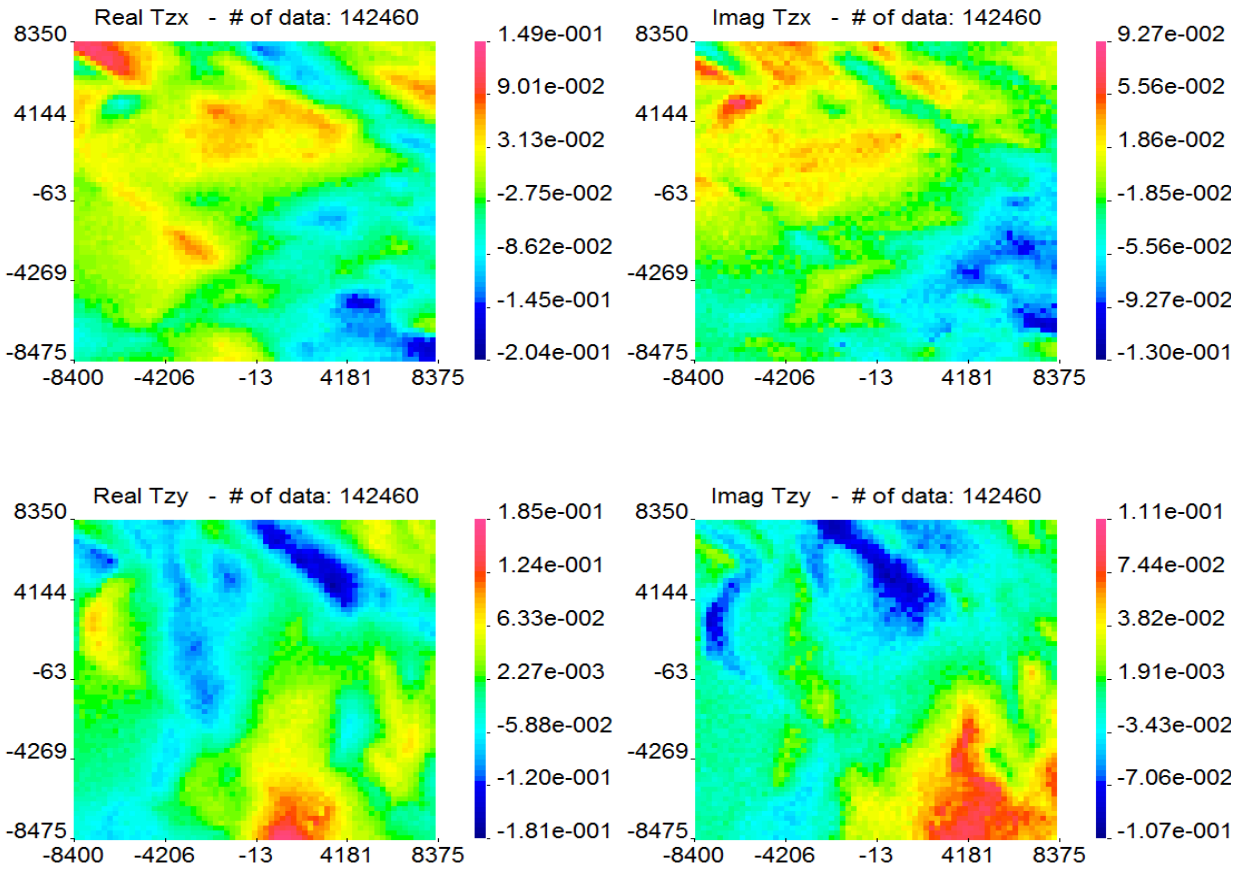
Data

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

True model at 275m depth

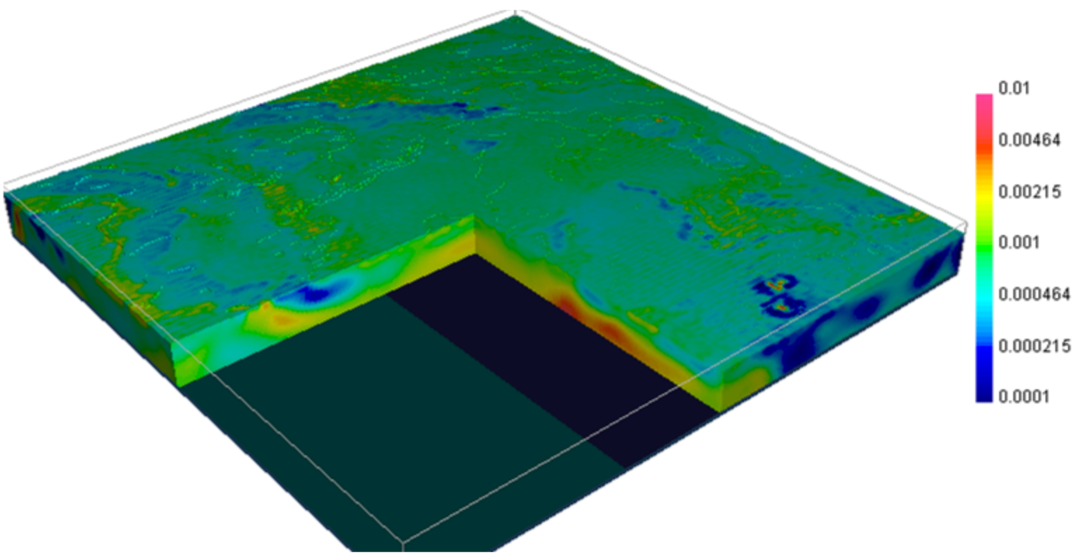


Observed (90 Hz)

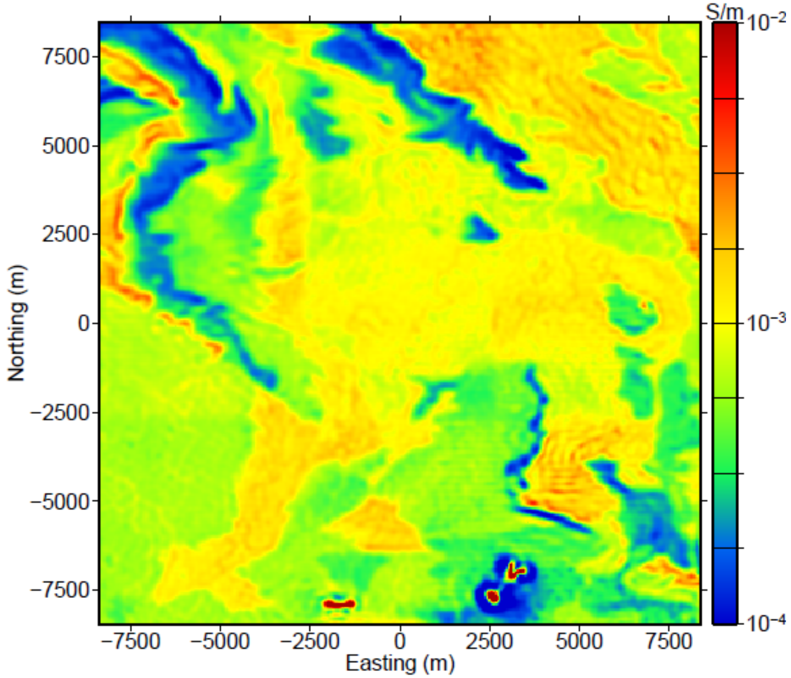


Interpretation

Recovered Model



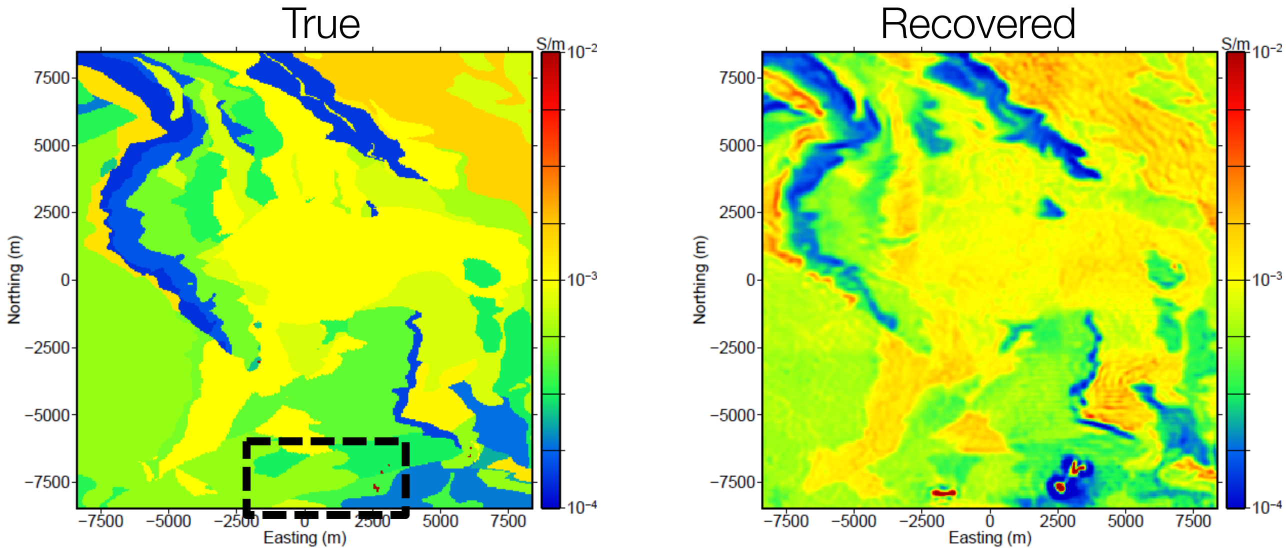
Model at 275m depth



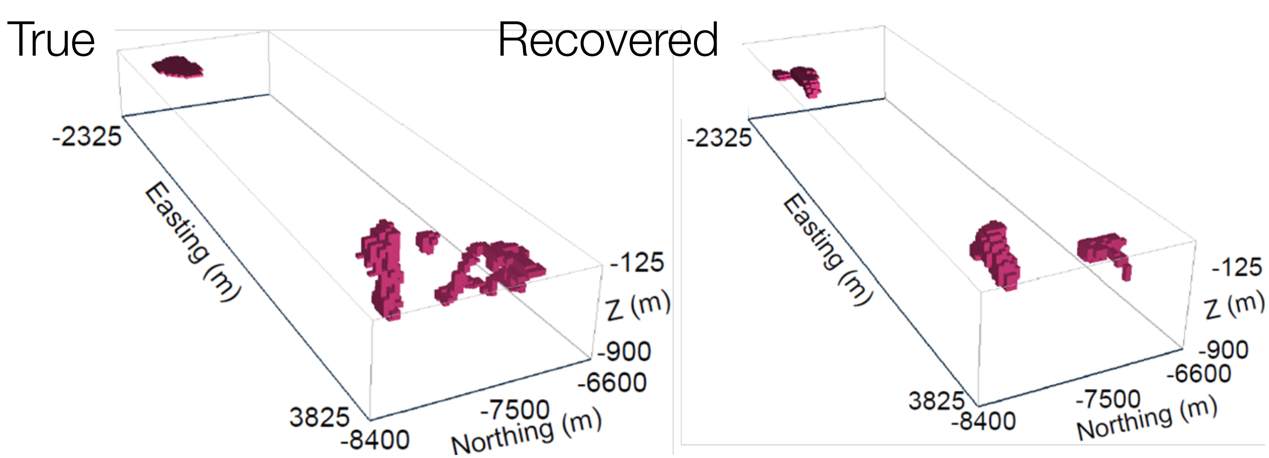
- Geologic units are well mapped
- Some mineralized bodies are located

Synthesis

- Recovered model represents the regional geology

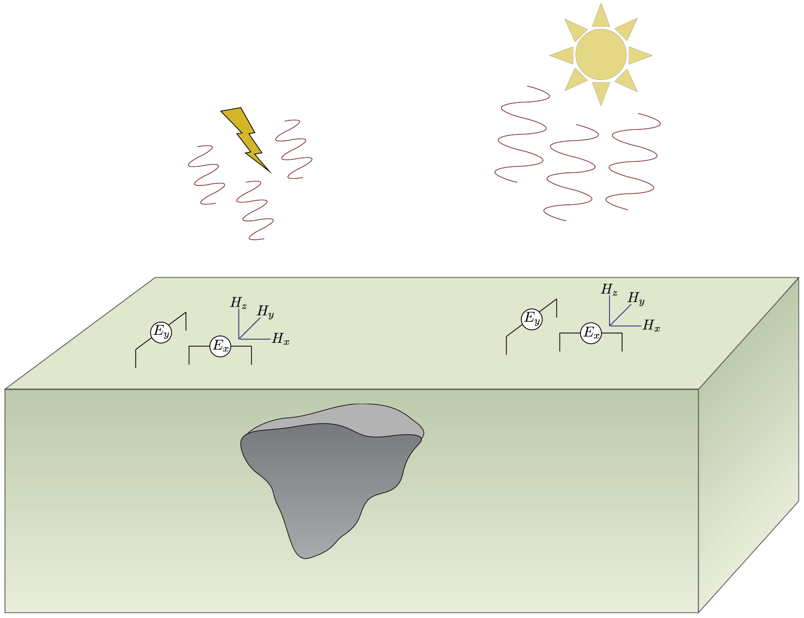


- Mineralized zones are recovered



Summary

- Background on natural source EM methods
- Magnetotellurics
- MT case history
- Z-axis tipper electromagnetics
- ZTEM case history



End of Natural Sources