EM: Natural Sources

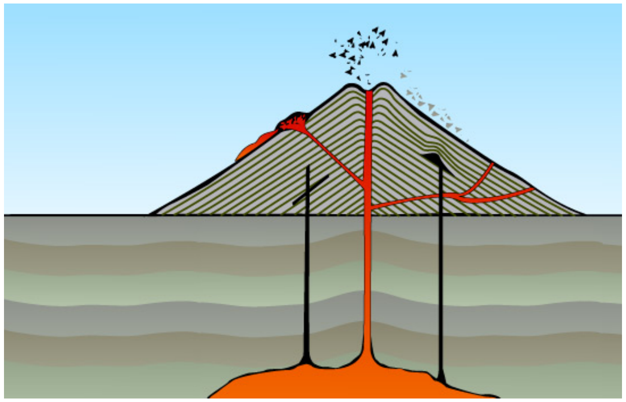
DISC
2017
Electromagnetics
Fundamentals and Applications

Outline

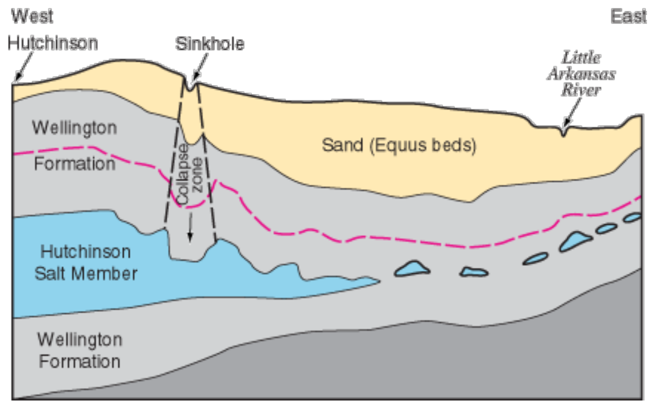
- Background on natural source EM methods
- Magnetotellurics
- MT case history
- Z-axis tipper electromagnetics
- ZTEM case history

Motivation

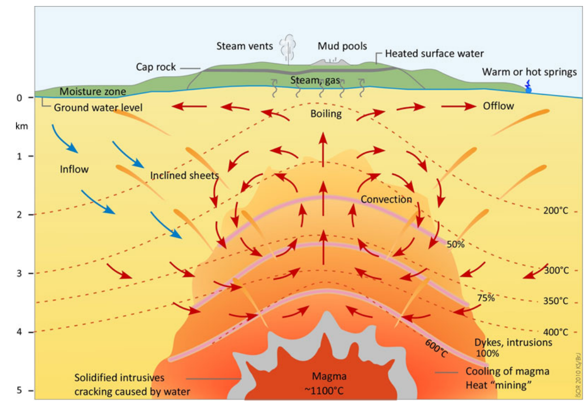
Volcanoes



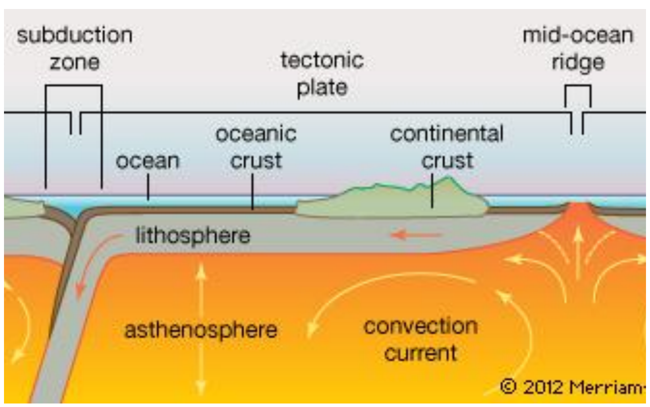
Base of salt



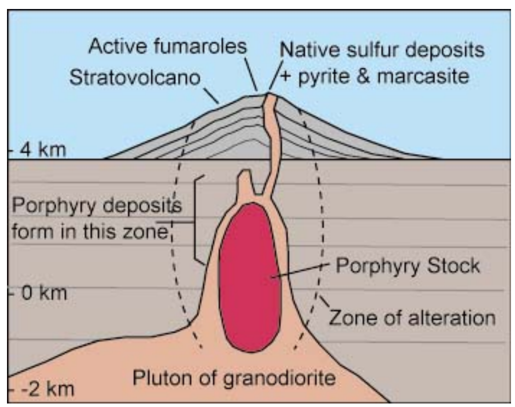
Geothermal



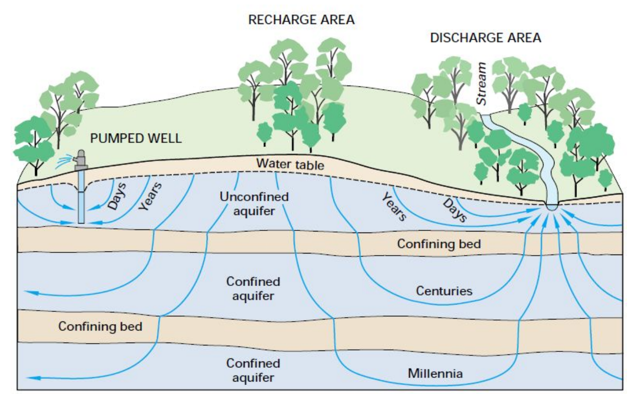
Tectonic settings of top few km



Mineral targets



Groundwater



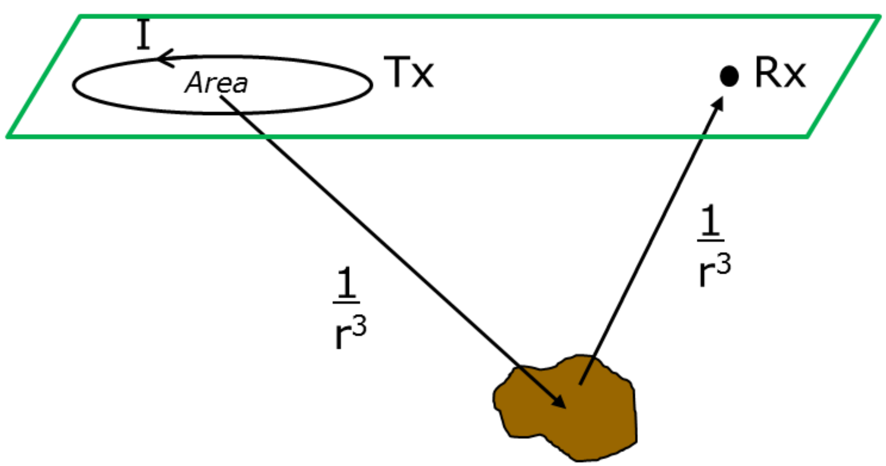
Common challenge: getting enough energy into the ground

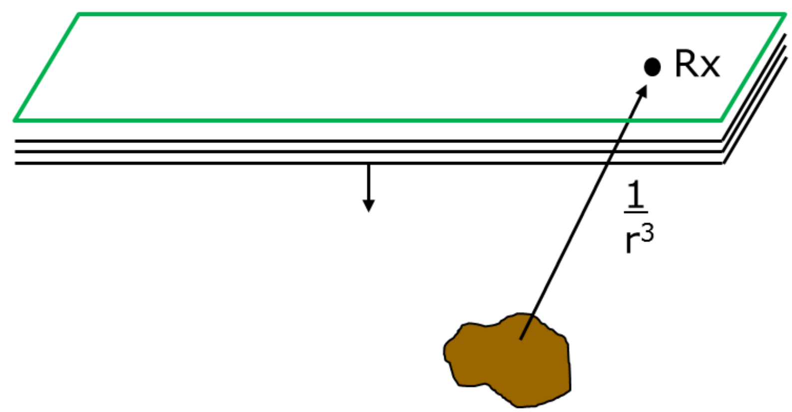
What is required to see deeper?

- Penetration depth depends upon system power

- Controlled source:
  - Using a small loop
  - Magnetic moment = $I * Area$
  - Total geometric decay = $\frac{1}{r^6}$

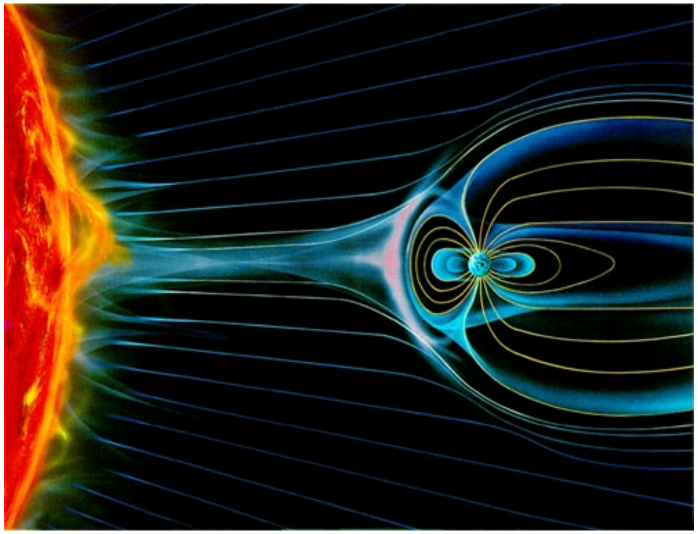
- Infinitely large loop source
  - Sheet currents generate plane waves



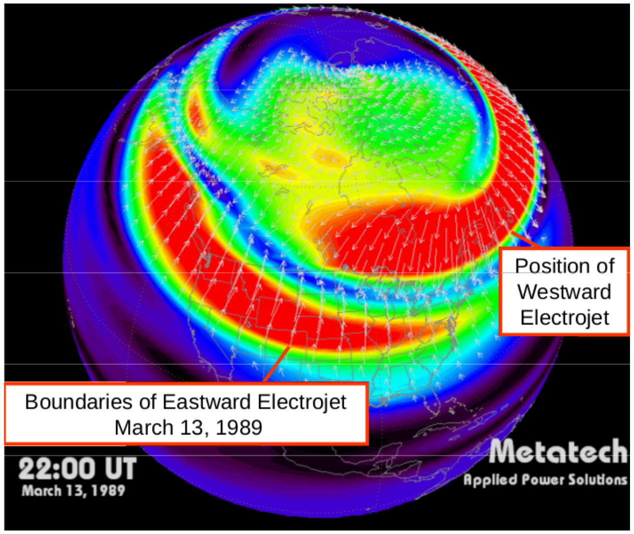


Natural EM sources

Sun and magnetosphere, solar storms



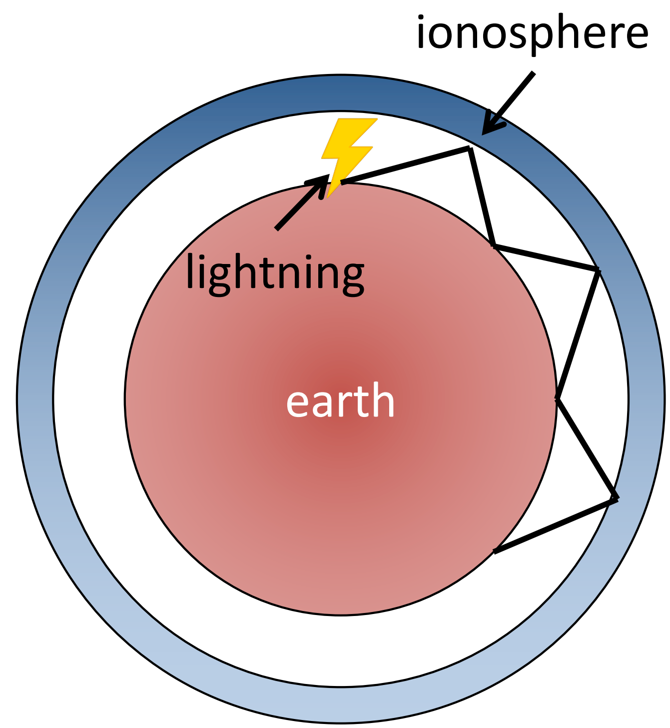
Auroral electrojet; aurora

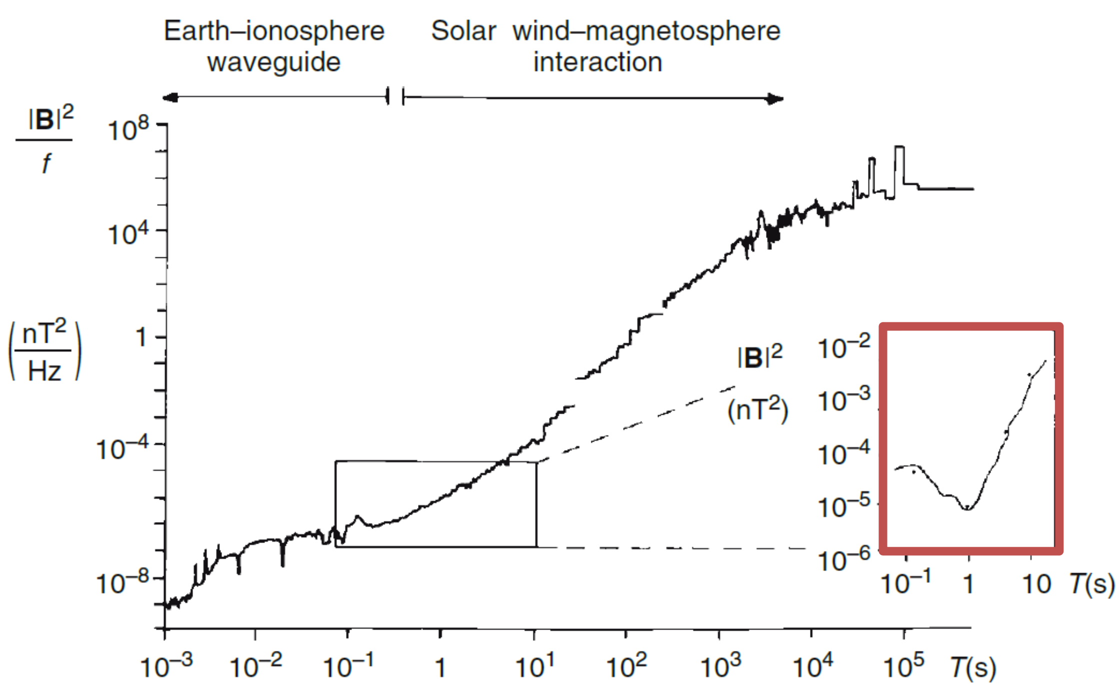


Lightning

Earth as a waveguide

- EM waves bounce between earth surface and highly conductive ionosphere
- And travel as plane waves





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

Refraction of waves

- Snell's law

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

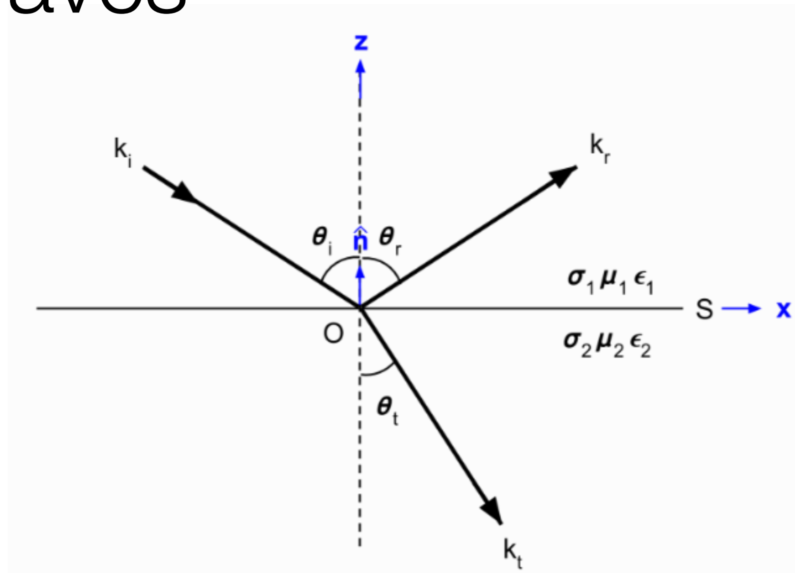
- k is complex wave number

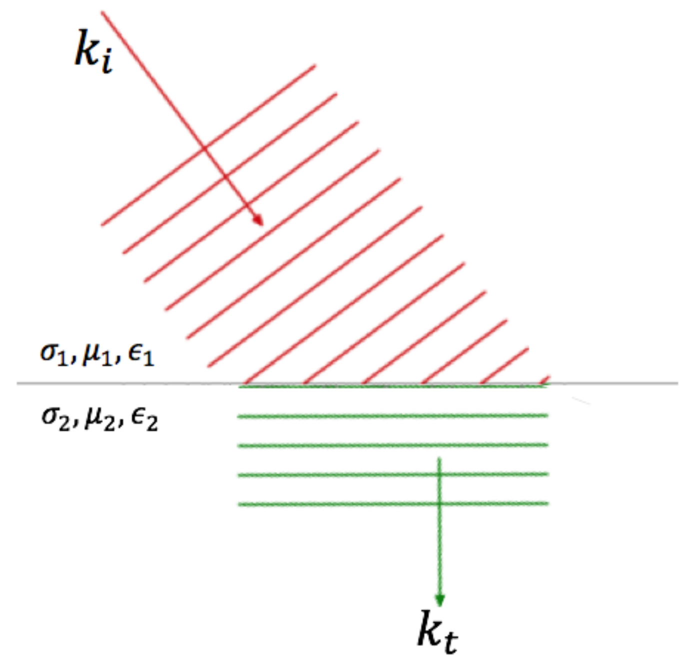
$$k^2 = \omega^2 \mu \epsilon - \imath \omega \mu \sigma$$

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

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

- 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 $\theta_R = 1.35°$





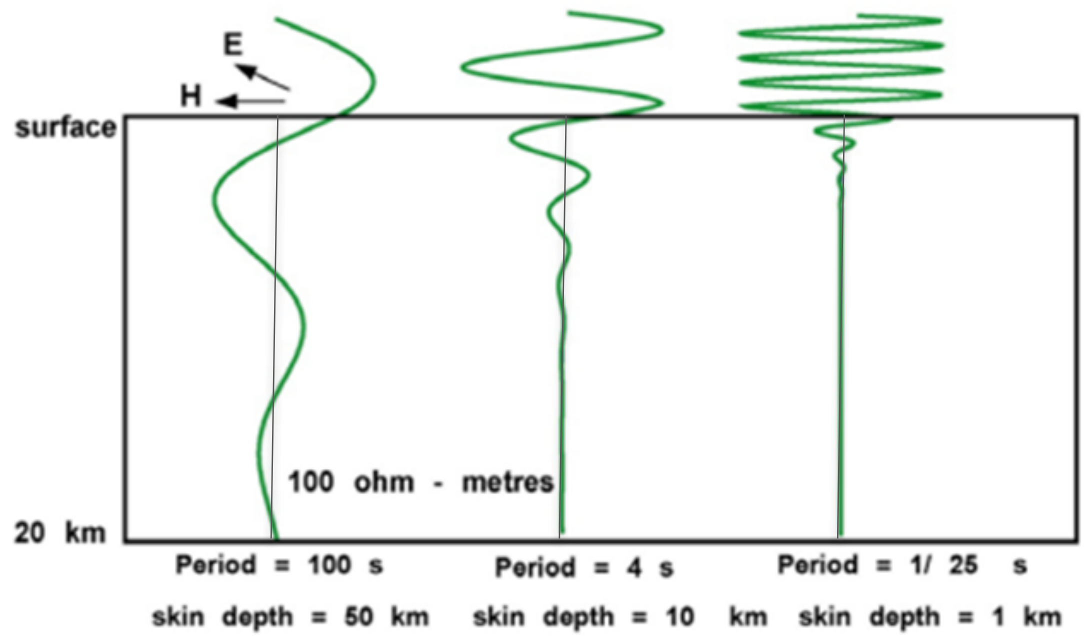
Plane waves and skin depth

- Skin depth (meters)

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

- Low frequency waves propagate further

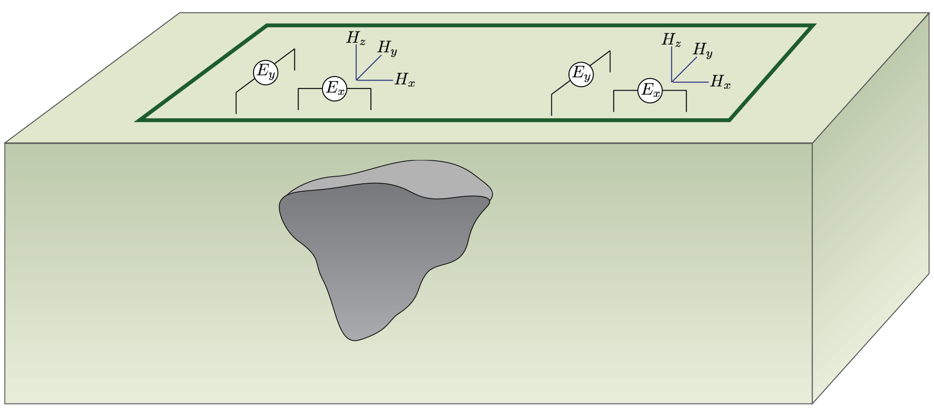
- Depth of propagation
  - A few skin depths
  - Only a portion of a wavelength

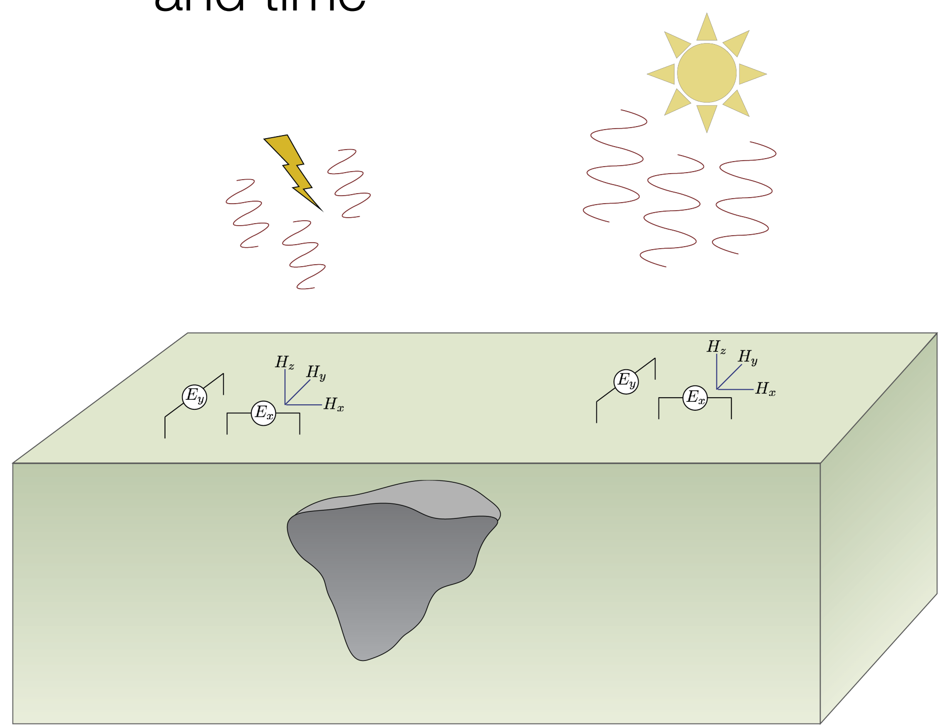


Control source vs Natural source

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

- Natural sources
  - Sources are random in space and time





MT Station

- Maxwell's equations:
  - Equations are linear in J_s
  - Both E and H are affected in the same way

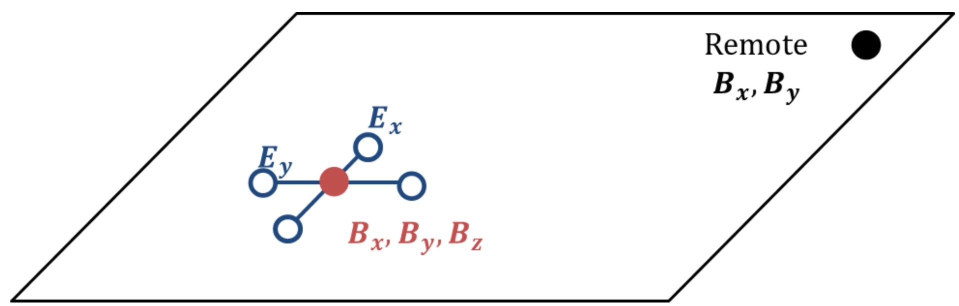
$$\nabla \times \mathbf{E} + \imath\omega\mu\mathbf{H} = 0$$

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

- Effects of unknown source removed by taking ratio
- Transfer function: relationship between fields.

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

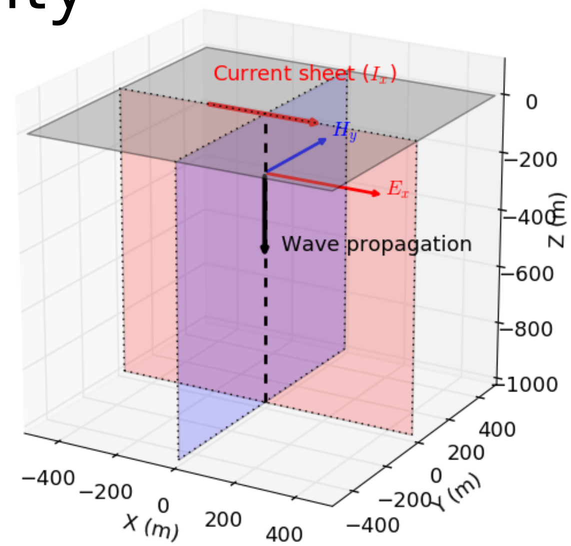
- **Z** is the impedance (matrix)



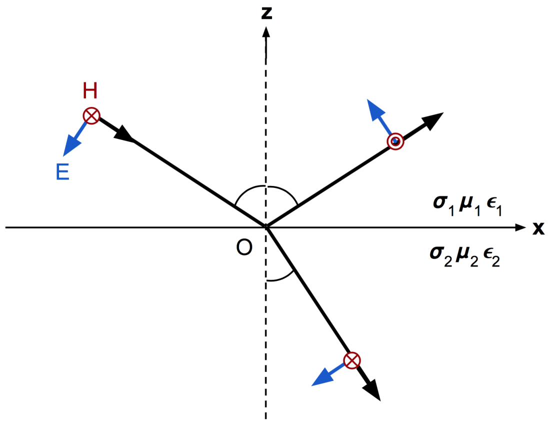
$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \begin{pmatrix} H_x \\ H_y \end{pmatrix}$$

Impedance and resistivity

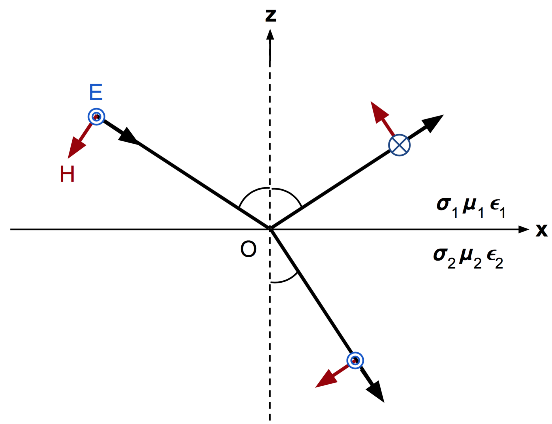
- Plane wave in homogenous media:
  - E and H fields are perpendicular

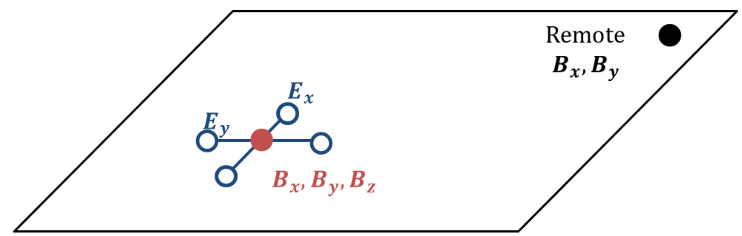


TE mode



TM mode





Homogeneous half space

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

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:

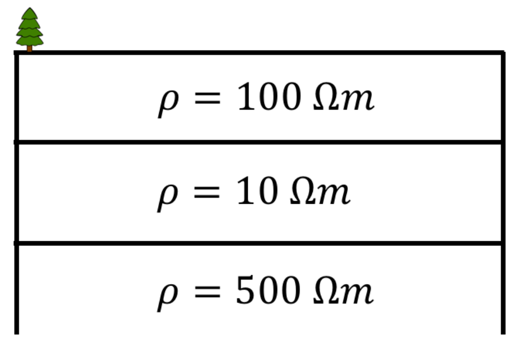
$$\Phi = \tan^{-1}\left(\frac{Im(Z_{xy})}{Re(Z_{xy})}\right)$$

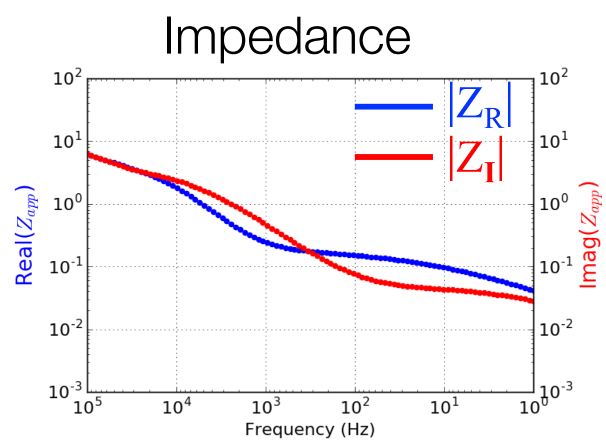
- In 1D:

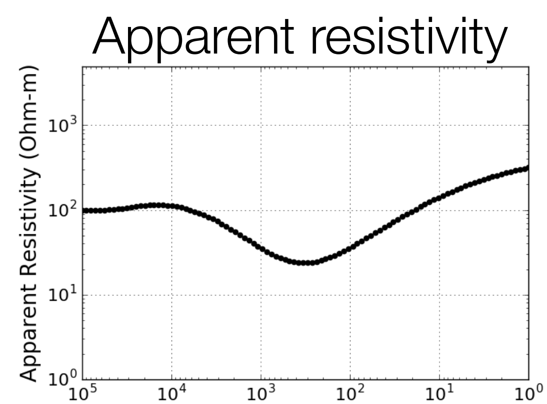
$$Z = \begin{pmatrix} 0 & Z_{xy} \\ Z_{yx} & 0 \end{pmatrix}$$

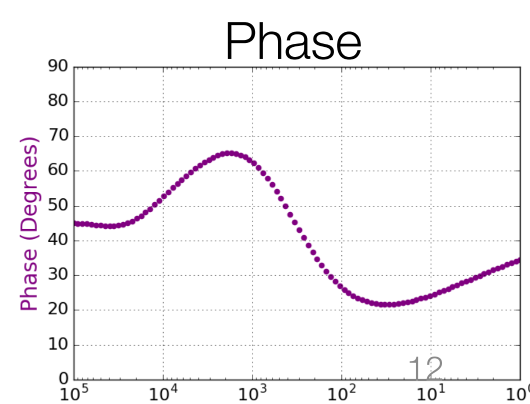
$$Z_{xy} = \frac{E_x}{H_y}$$

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



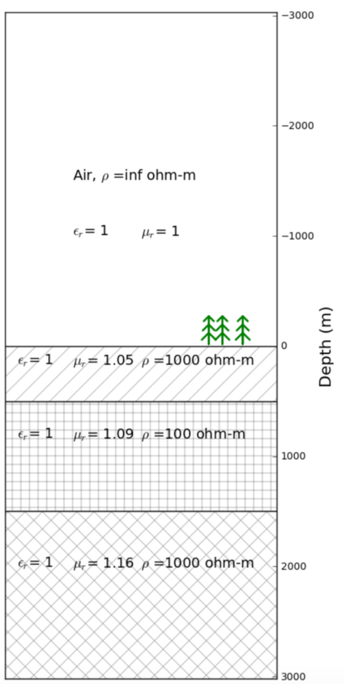


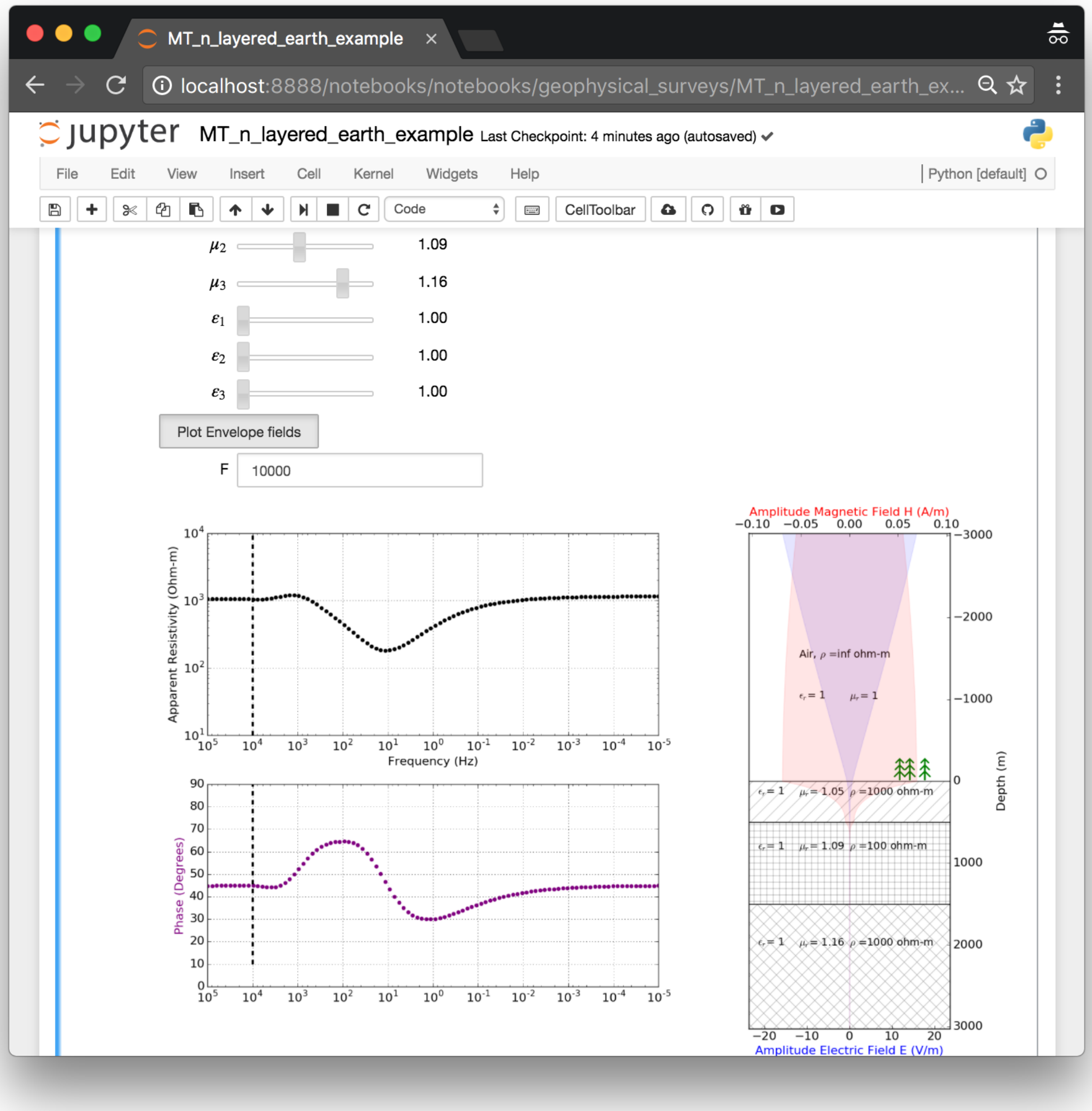




1D MT app

- Forward model MT data for layered Earth (1 to 3 layers)
- Choose physical properties for each layer
- Observe skin depth, apparent resistivity, phase





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

MT soundings in 2D

- In general:

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

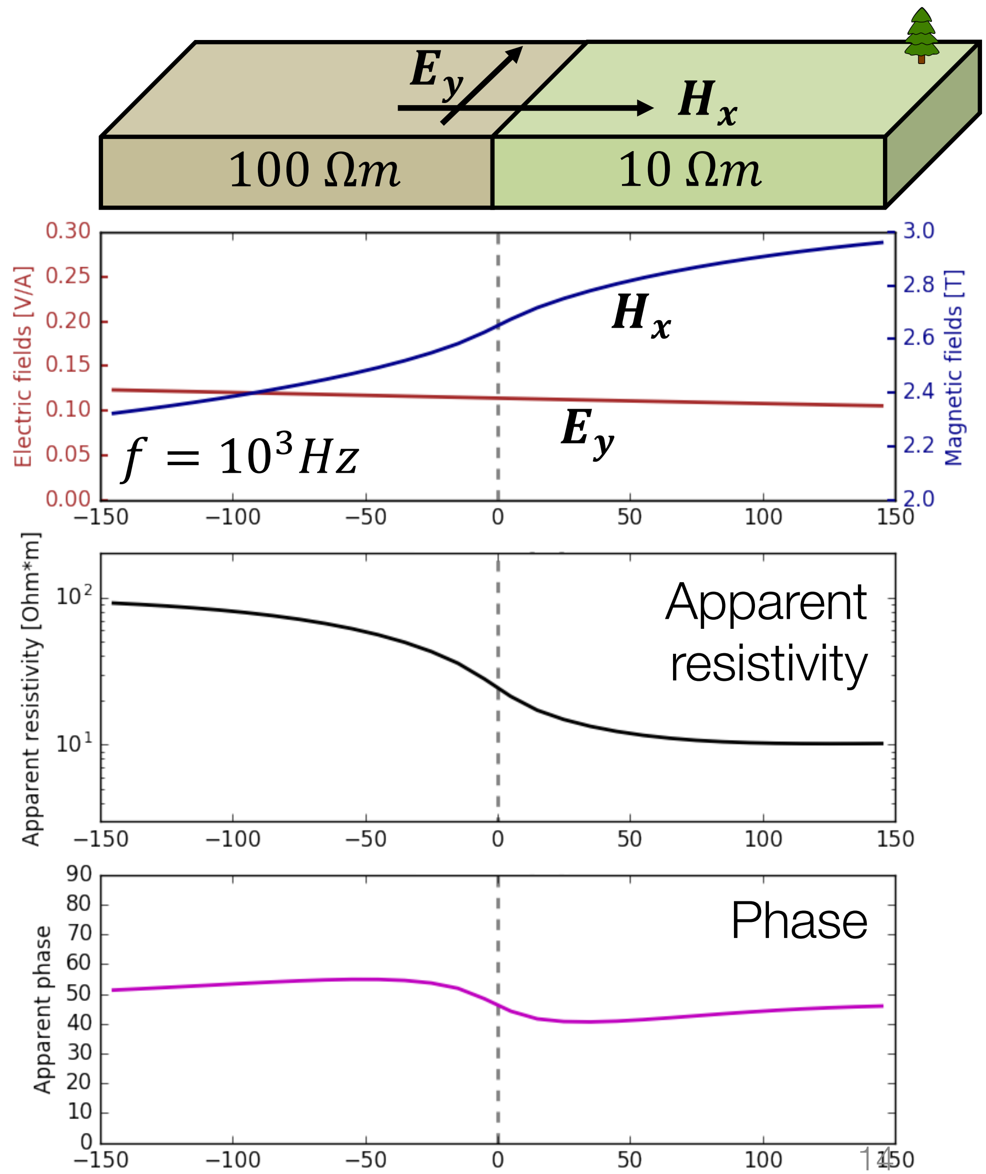
- In 2D:

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

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

- TE mode
  - E-field parallel to structure

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



MT soundings in 2D

- In general:

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

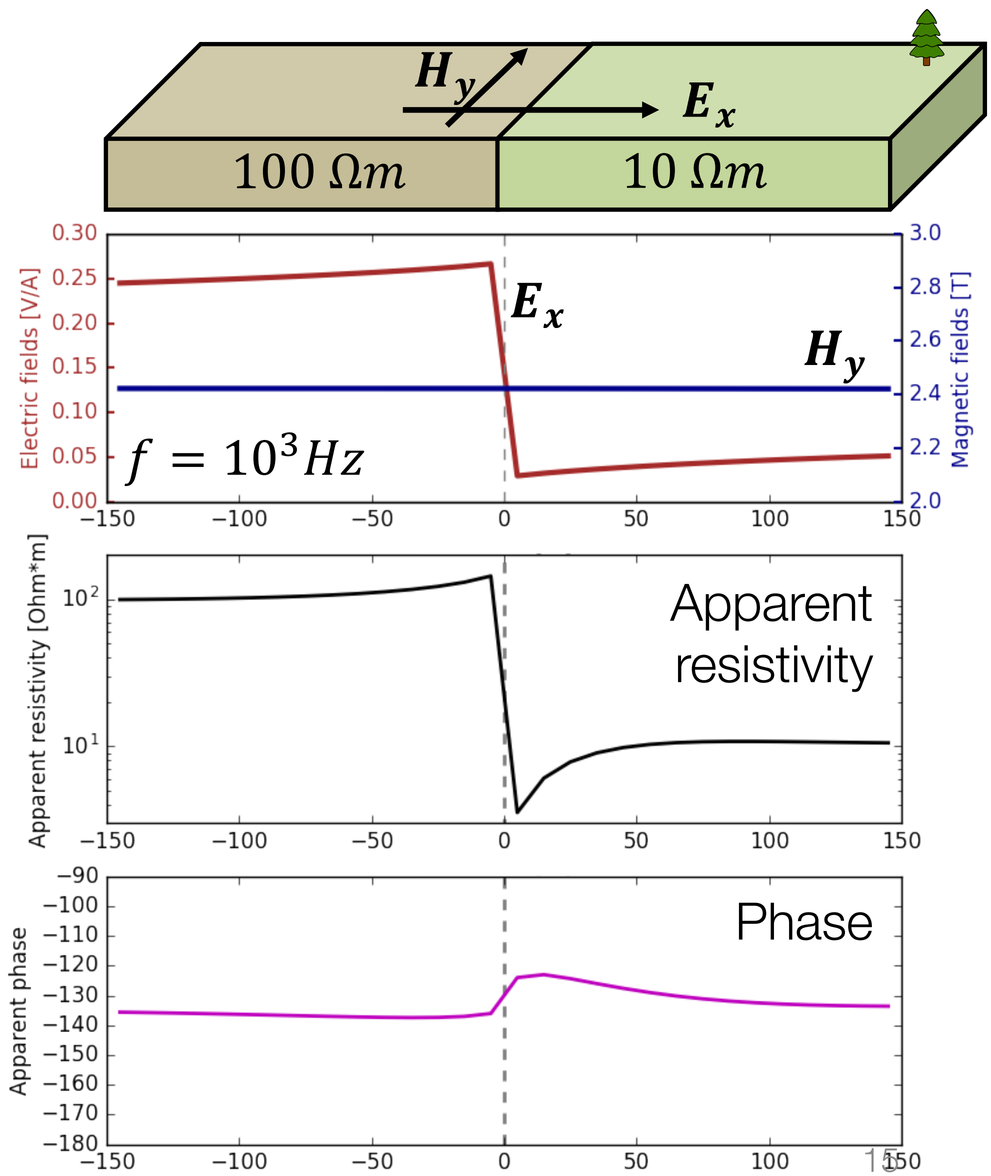
- In 2D:

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

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

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

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



MT soundings in 3D

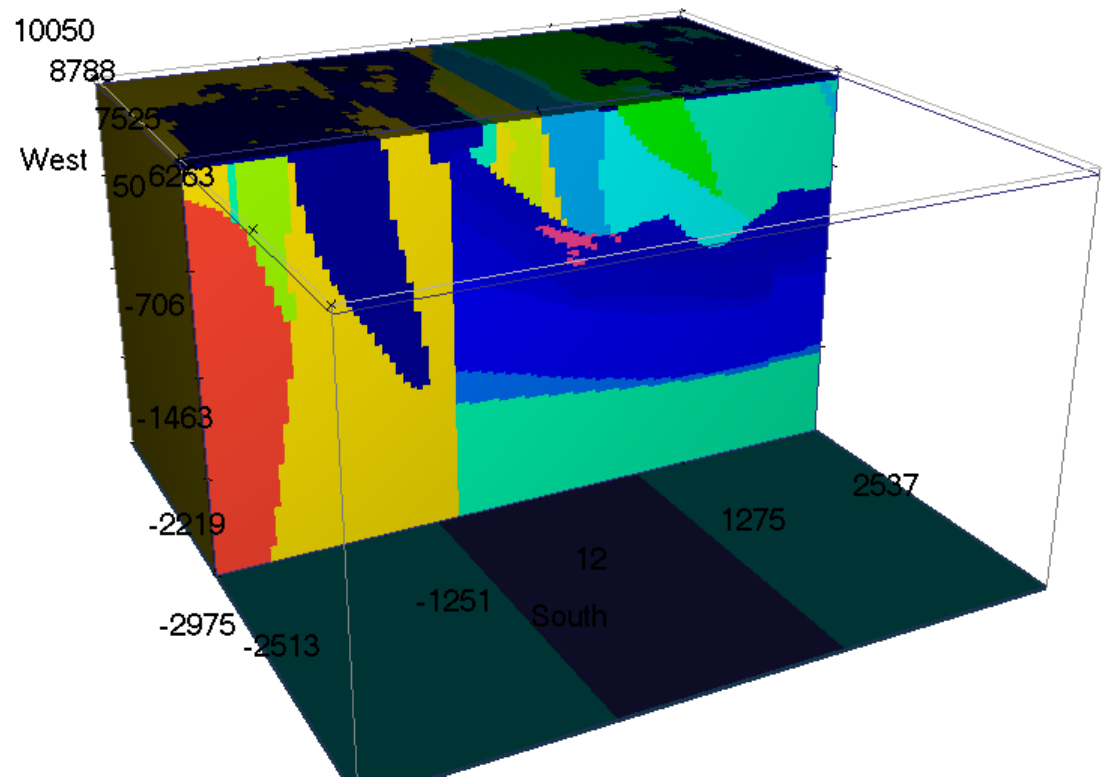
- In general:

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

- In 3D:

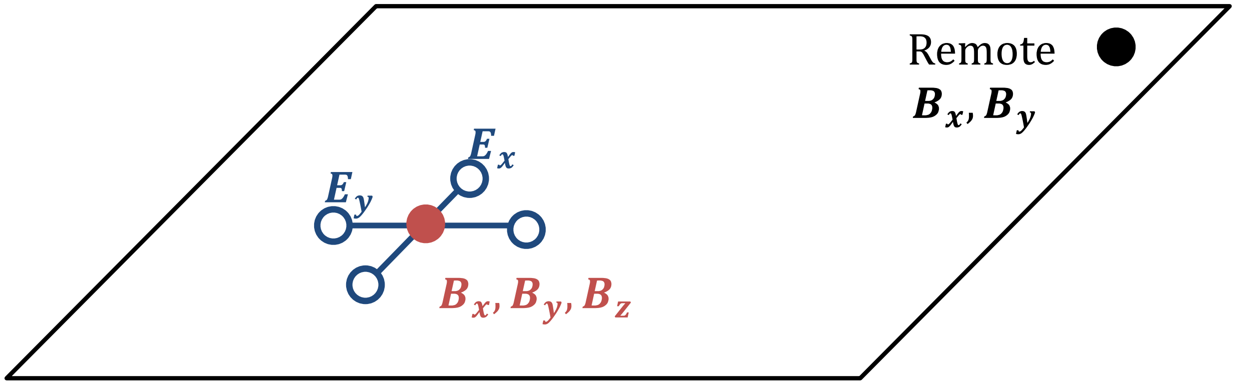
$$Z = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$$

- No symmetry or special conditions



Measuring MT data

- Basic acquisition

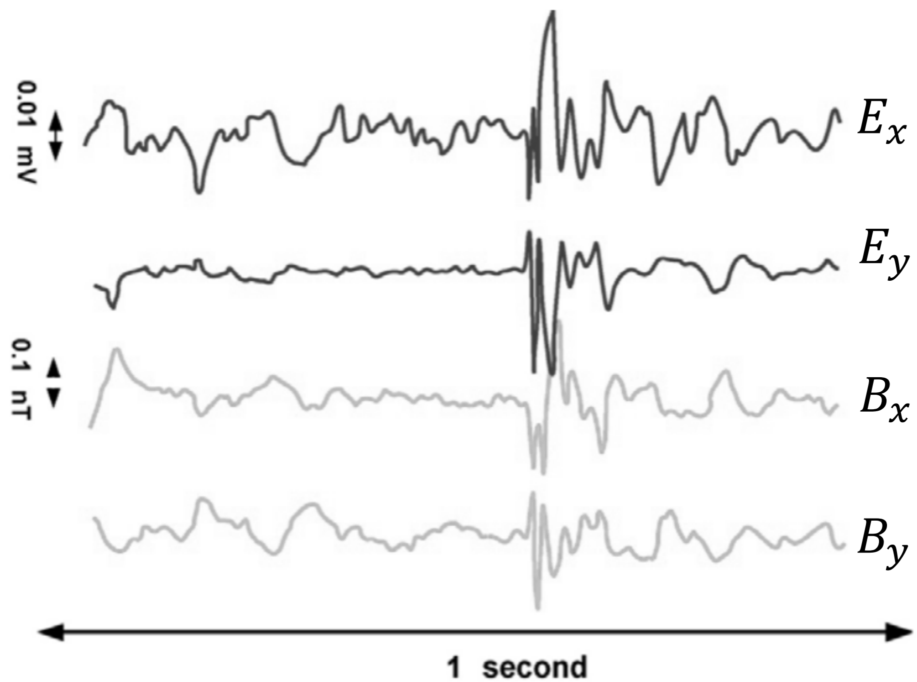


- At each station, measure:

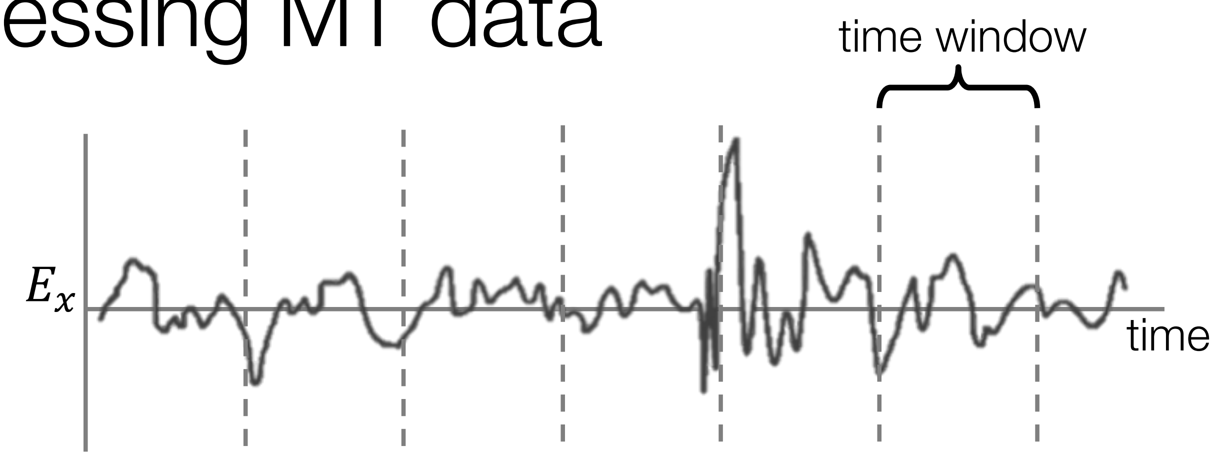
$$E_x, E_y, B_x, B_y, B_z$$

- 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:

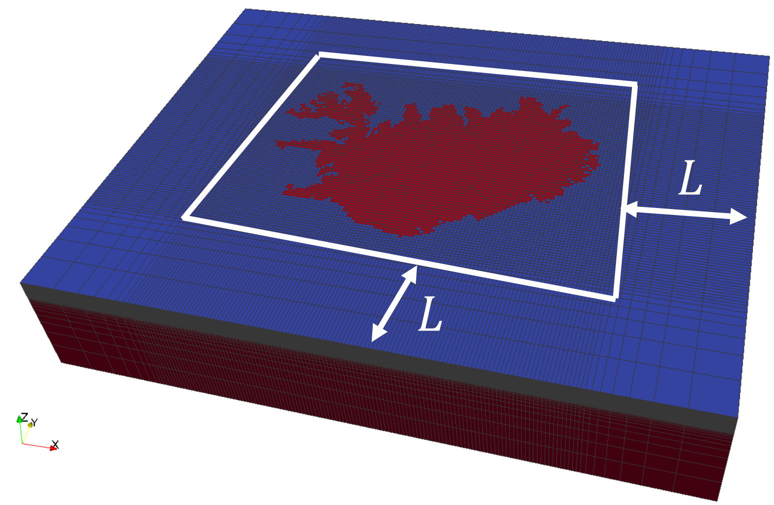
$$Z_{xy}(\omega) = \frac{\langle E_x(\omega) H_y^{R*}(\omega) \rangle}{\langle H_y(\omega) H_y^{R*}(\omega) \rangle}$$

(*) complex conjugate
<> average over multiple samples

Inverting MT data

- Important: boundary conditions 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?

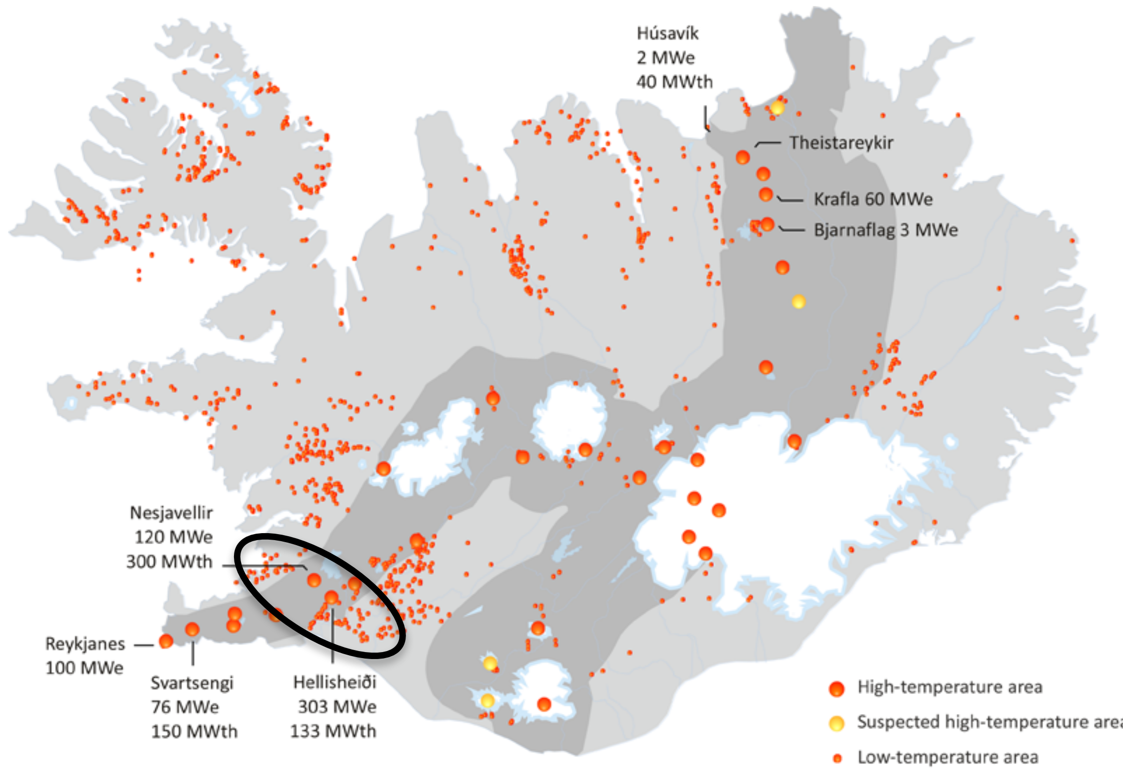
- MT case histories
- Z-axis tipper electromagnetics
- ZTEM case histories

MT case history

- Iceland

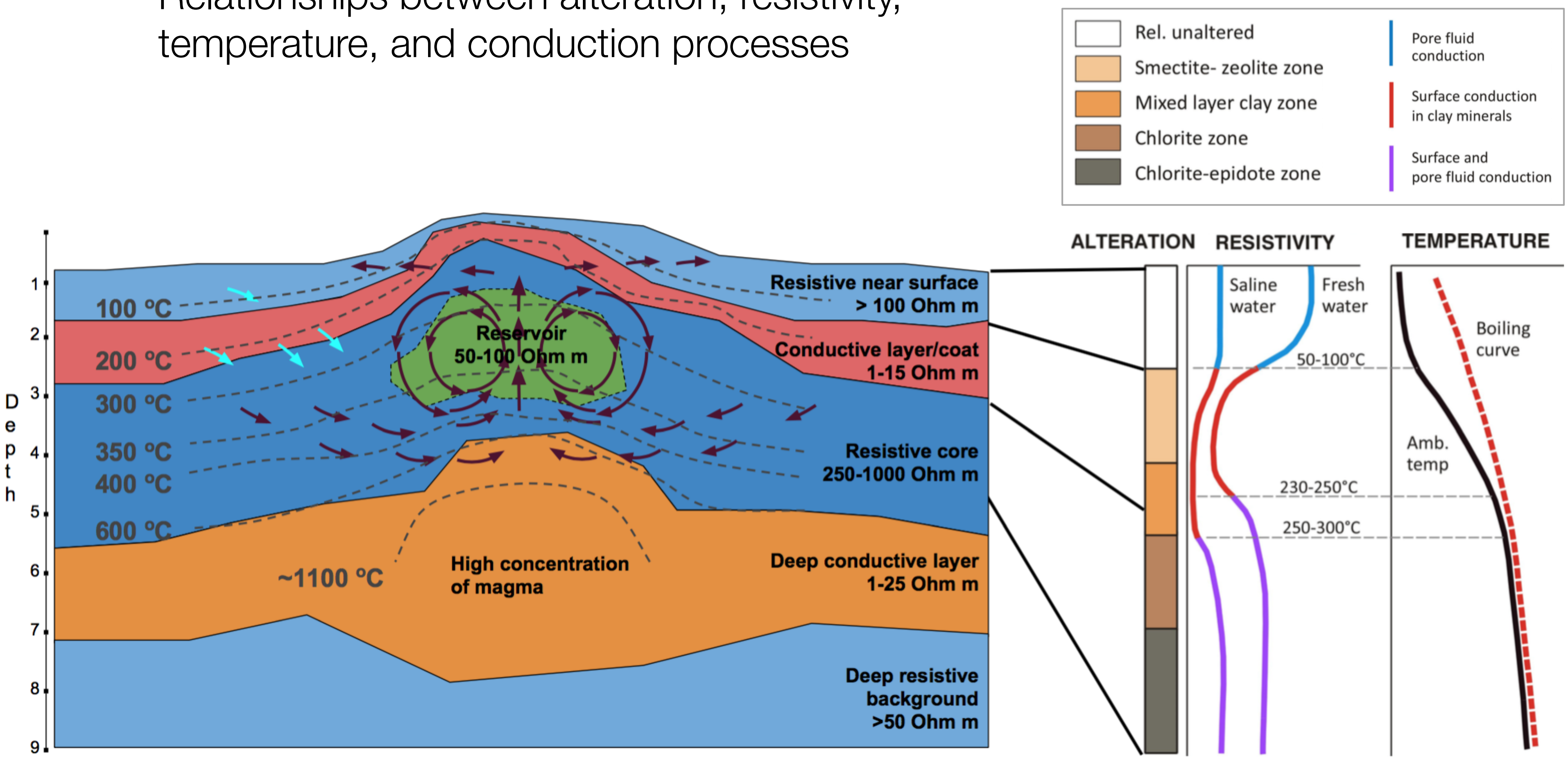
Hengill geothermal region: setup

- 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

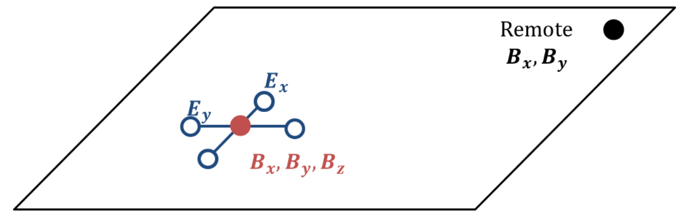


Physical properties

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

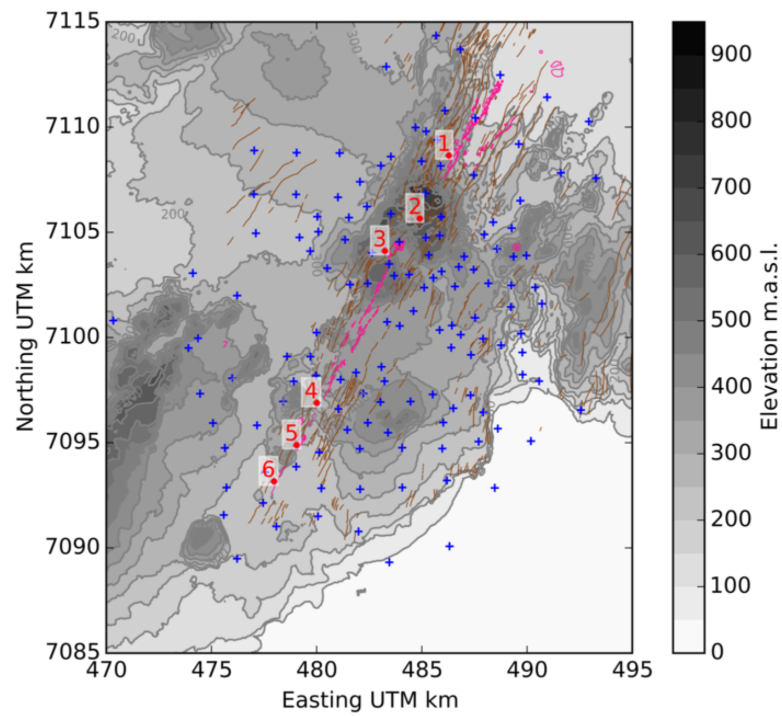


Survey



- MT instrumentation
  - Phoenix MTU5's

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

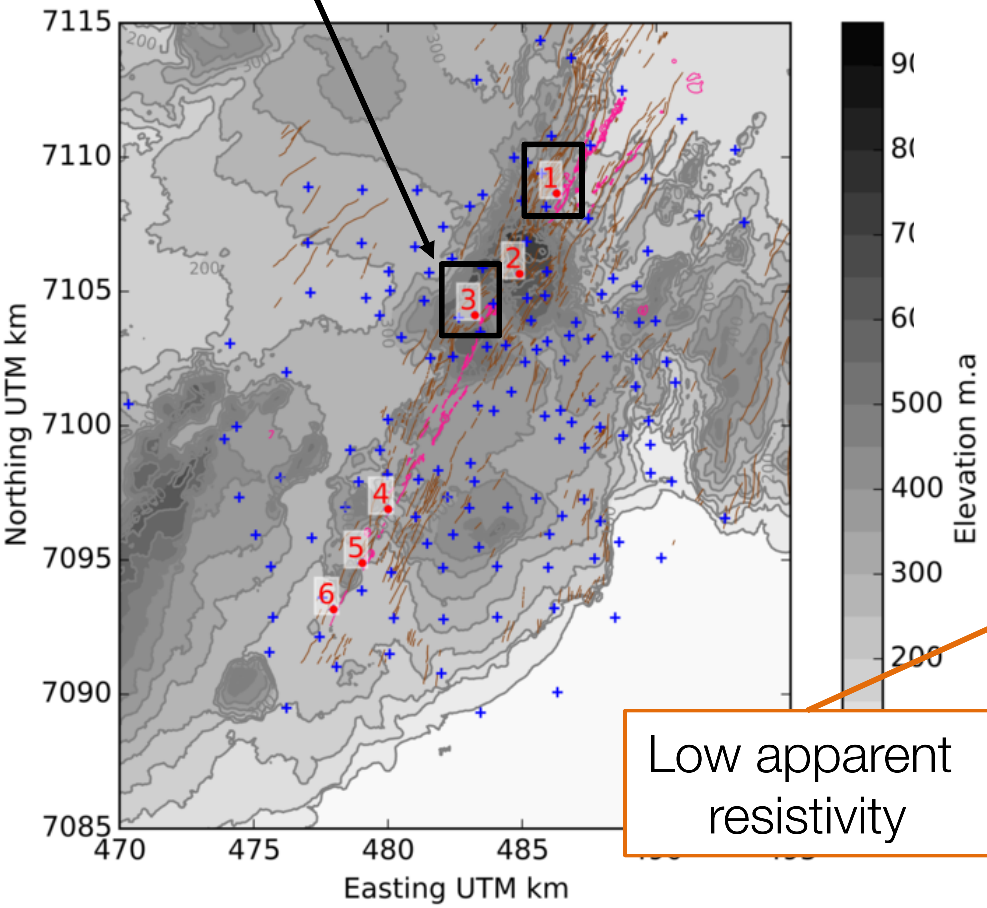


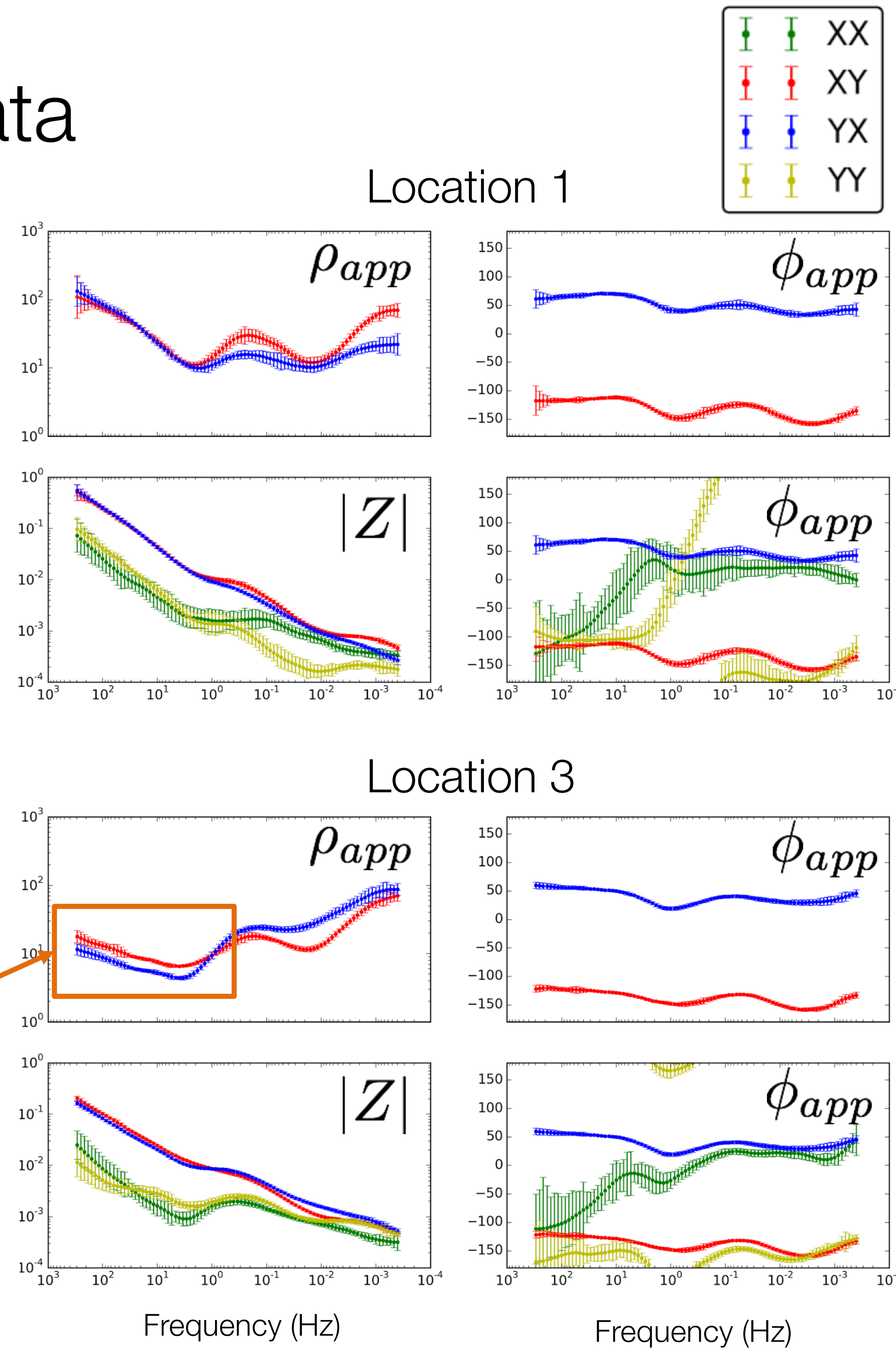
- Remote reference
  - About 40 km away

- Raw data processing using Phoenix's SSMT2000 software

Data

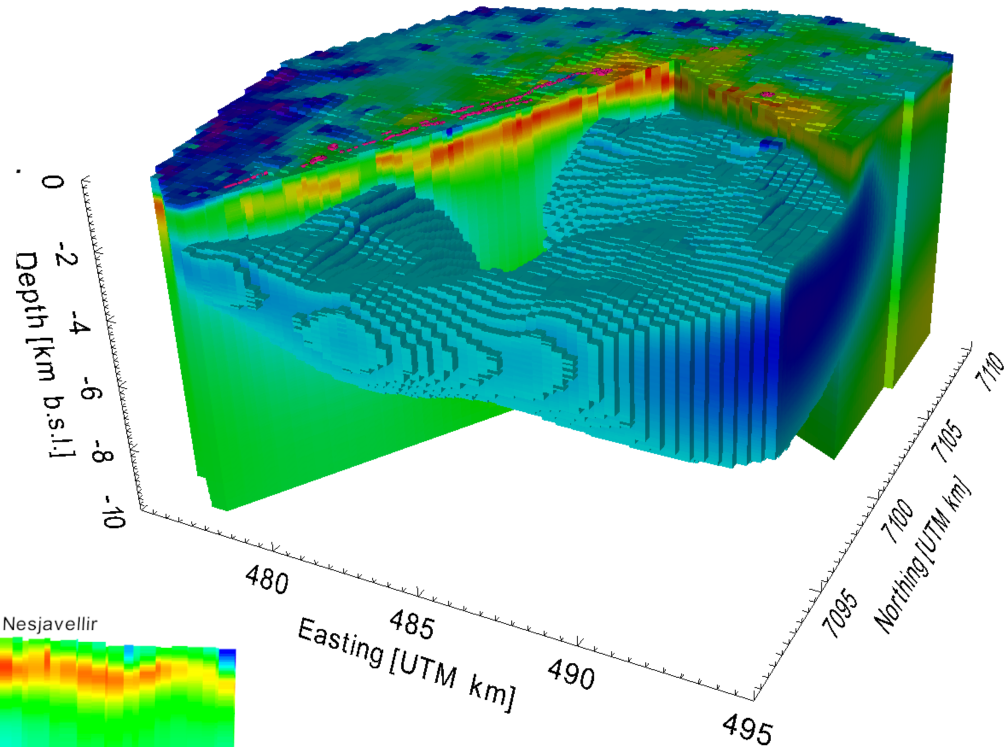
Surface alteration, hot water, fumaroles

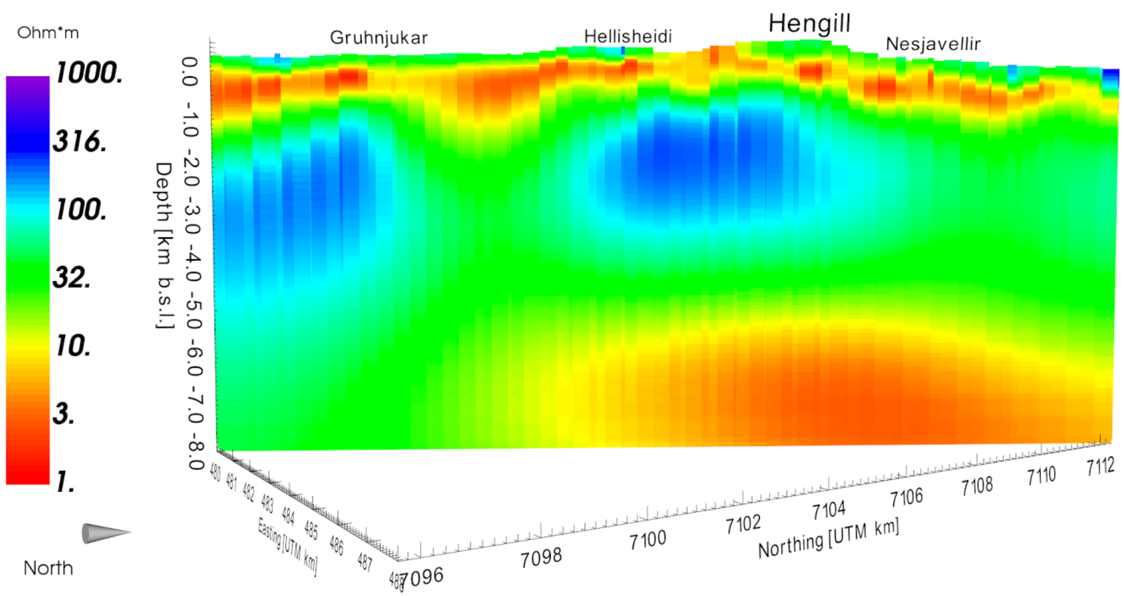




3D inversion

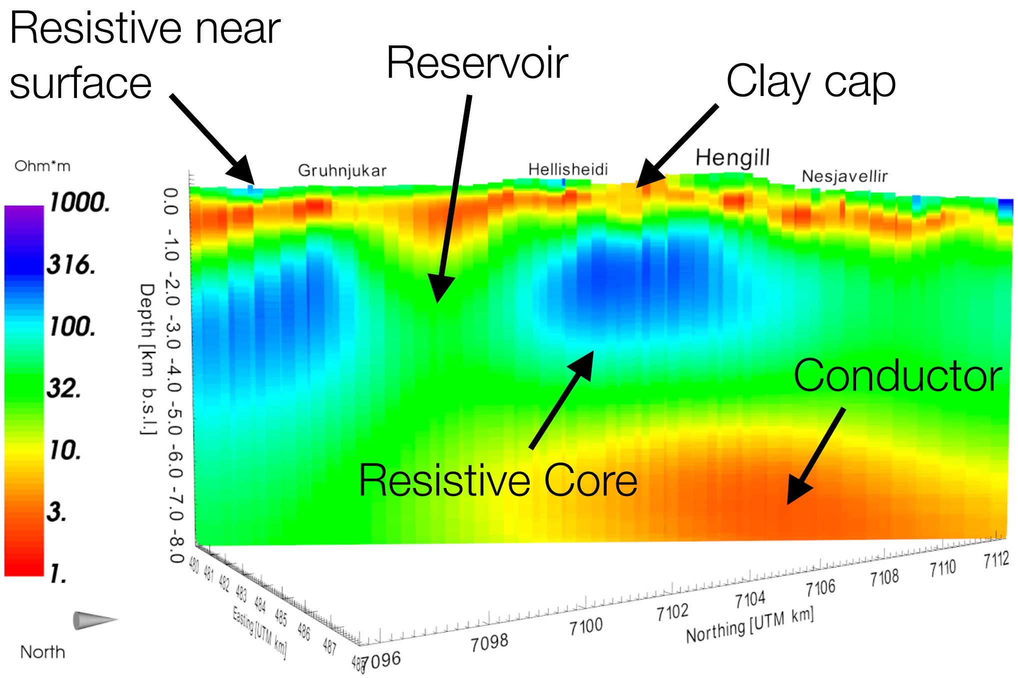
- Off-diagonal impedance (Z_{xy} and Z_{yx}) used
- Combined multi-frequency inversion (300 Hz – 0.001 Hz)

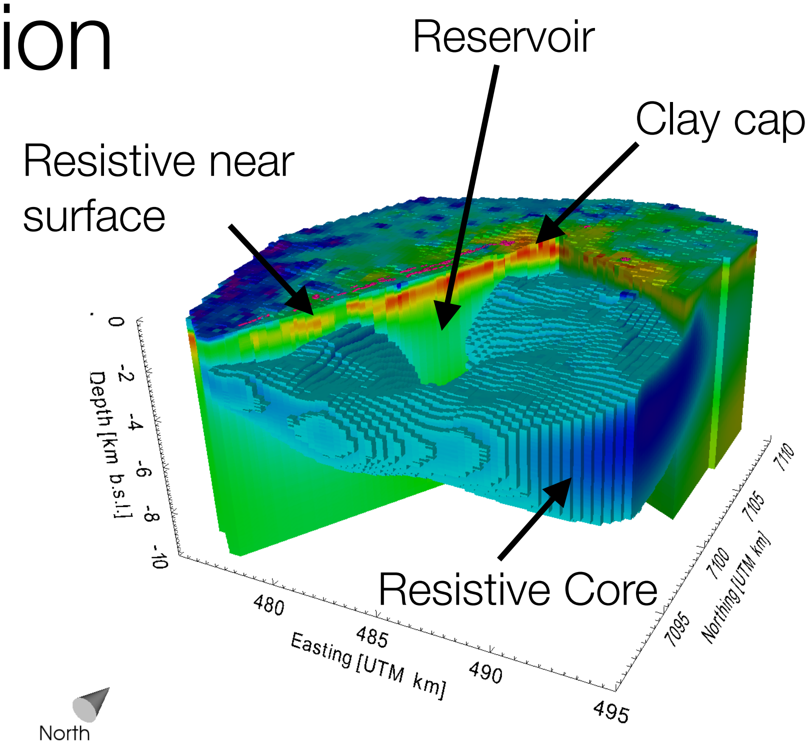


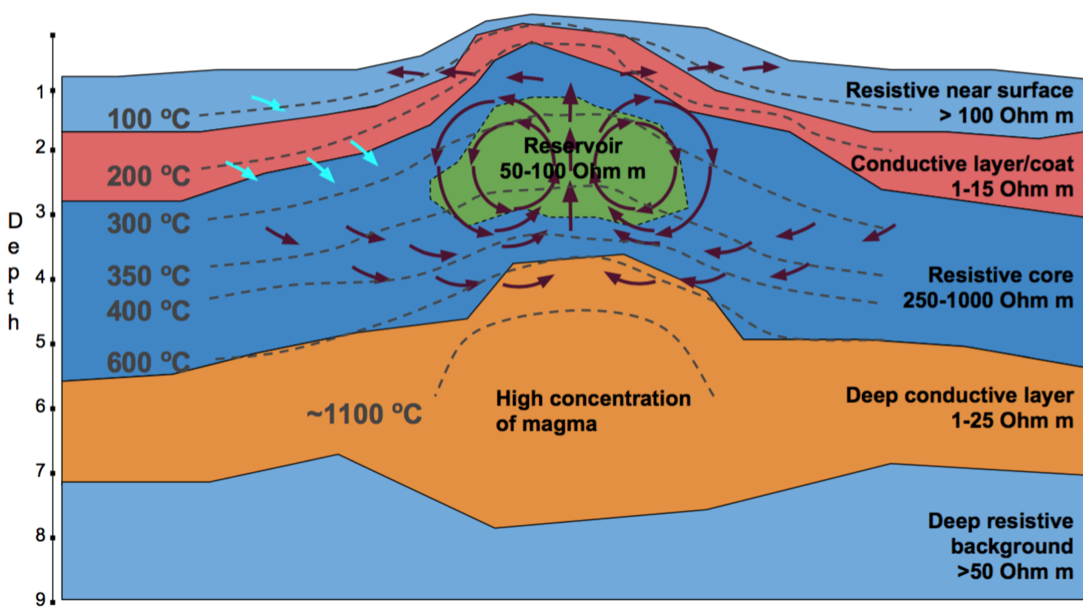


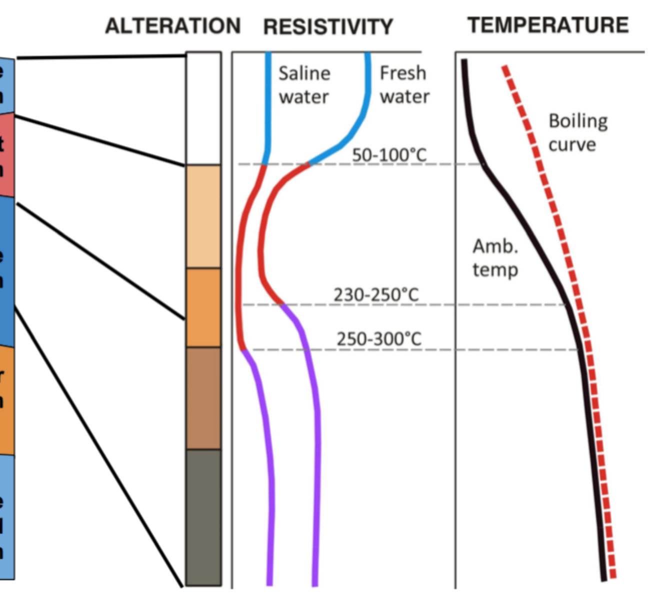
Rosenkjaer et al, 2015

Interpretation

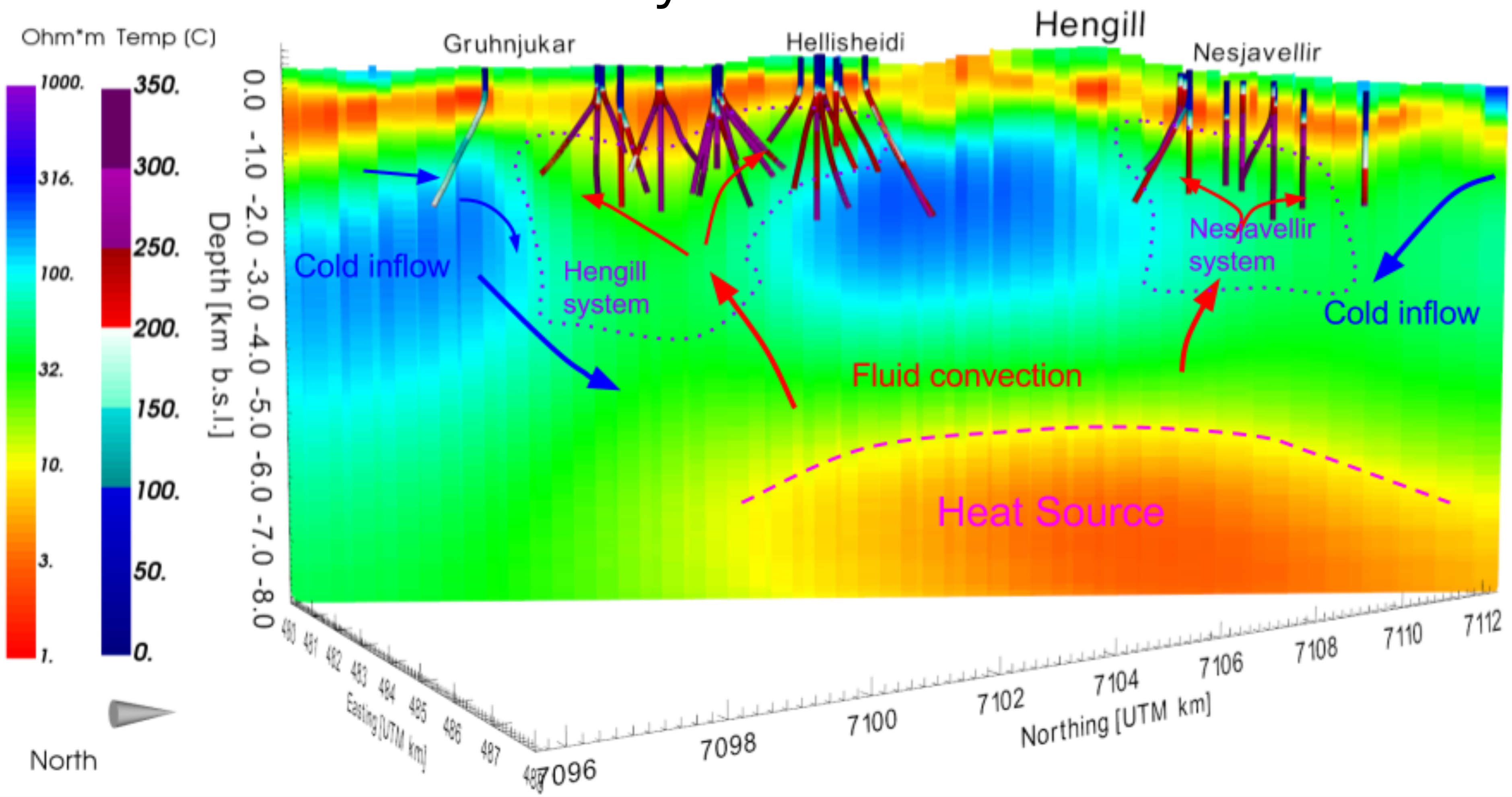








Synthesis



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

Summary

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

Tipper data (ZTEM)

- Transfer functions = relationship between two different fields.

- For MT relationship

$$E = ZH$$

- Relationships between magnetic fields

$$H_z = TH$$

- ZTEM: Z-axis tipper EM

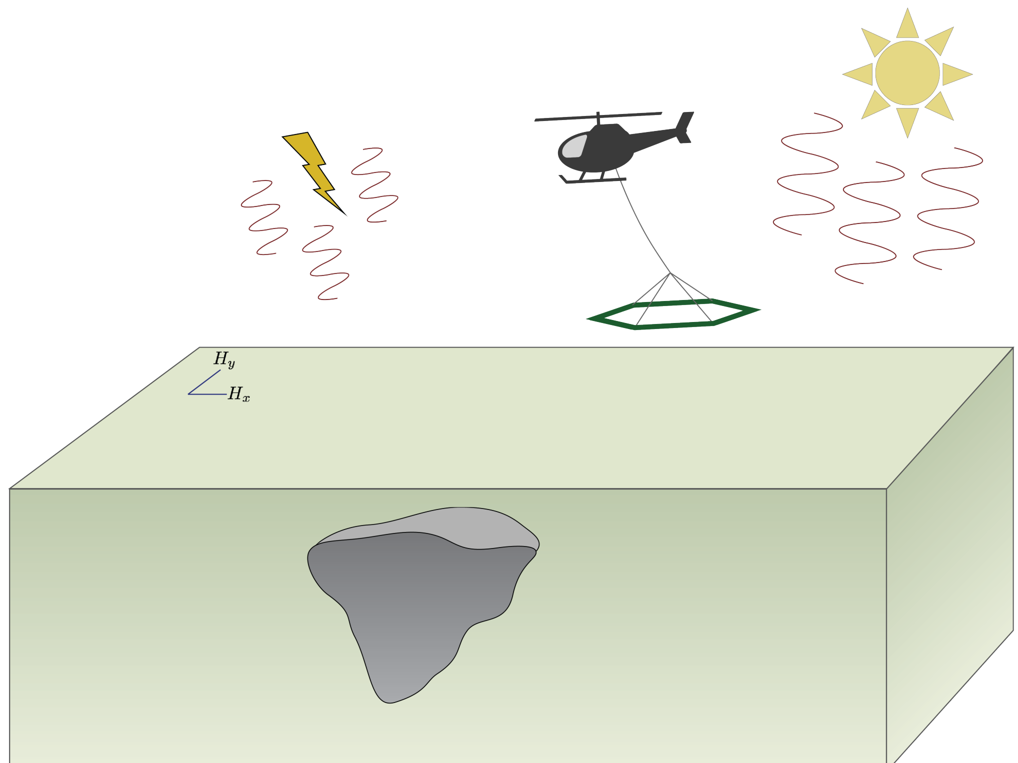
ZTEM data

- H_z recorded over survey area
- H_x and H_y at a ground reference station
- Frequencies: 30-720 Hz
- Complex transfer functions

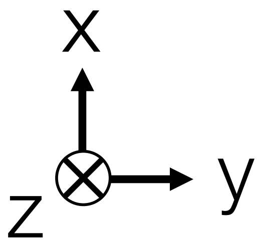
$$H_z(r) = T_{zx}H_x(r_o) + T_{zy}H_y(r_0)$$

$H_z(r)$

$H_x(r_0)$, $H_y(r_0)$



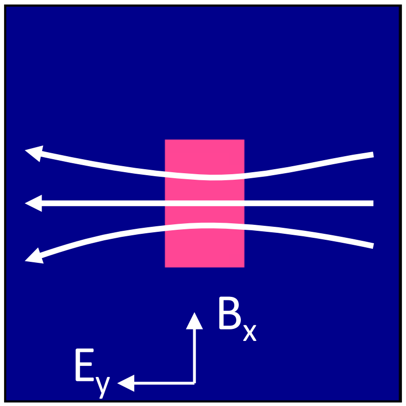
Synthetic example

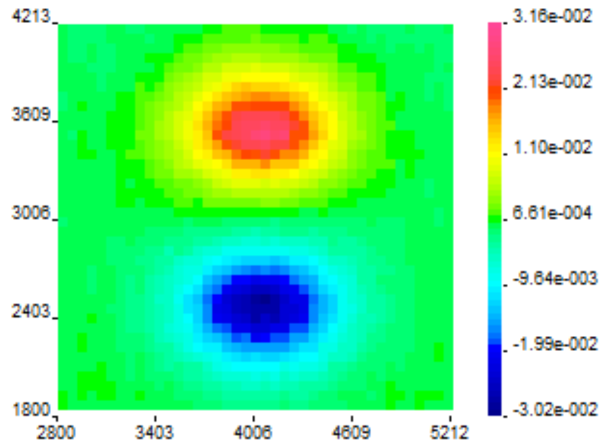


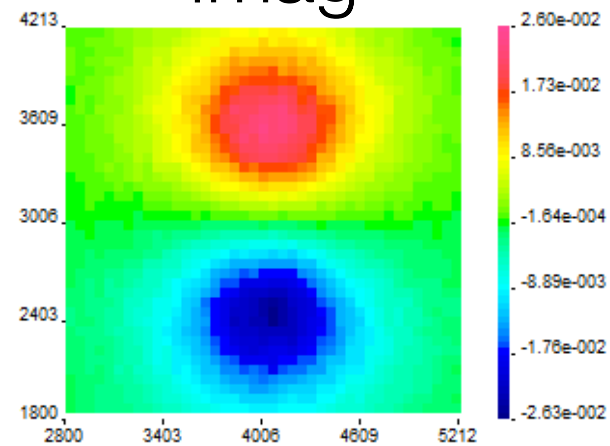
Real

Imag

T_{zx}





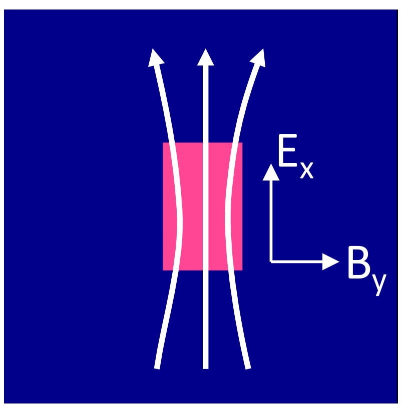


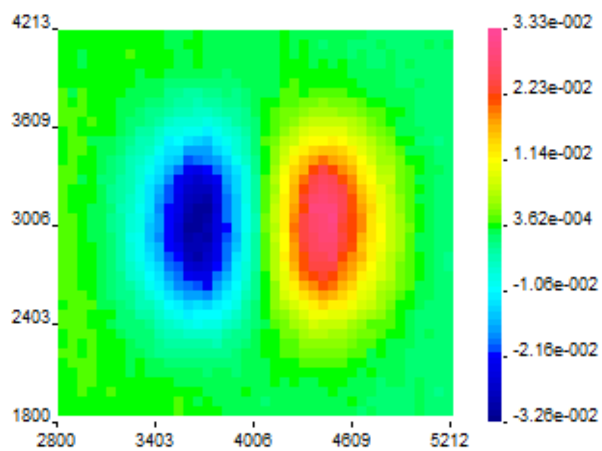
Conductor

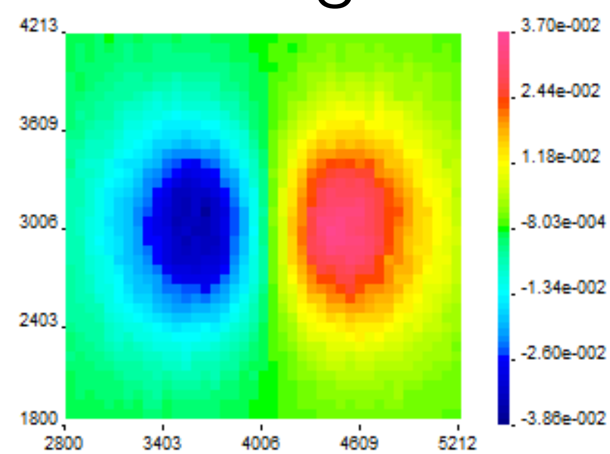
Real

Imag

T_{zy}

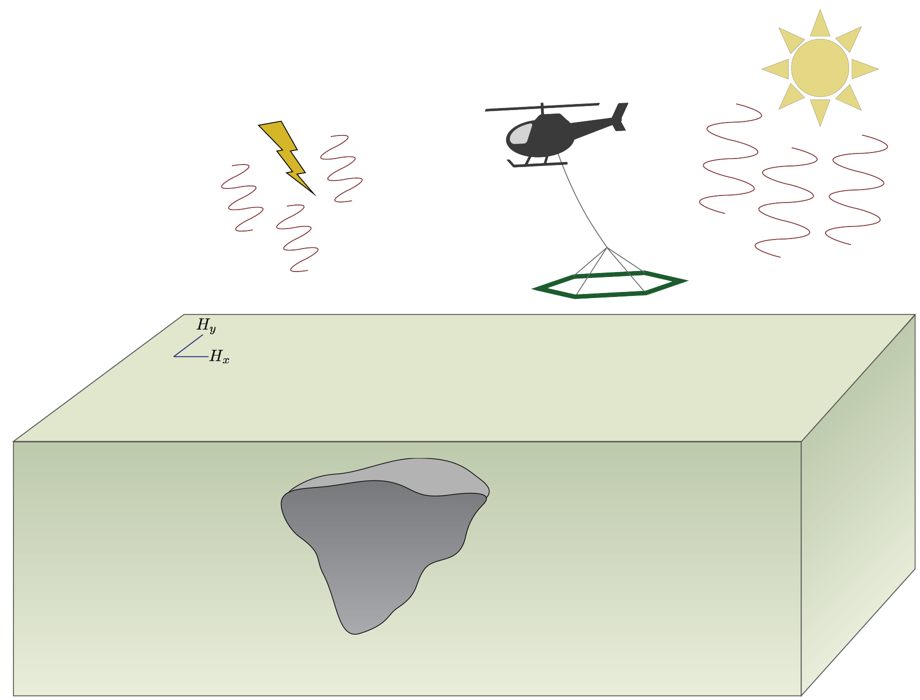






ZTEM: some comments

- Can explore the “difficult to see” depth range 200-1000m
- Fast and economical
- Good geologic mapper
- Can be basis for follow-up ground survey



ZTEM case histories

- **Noranda district**

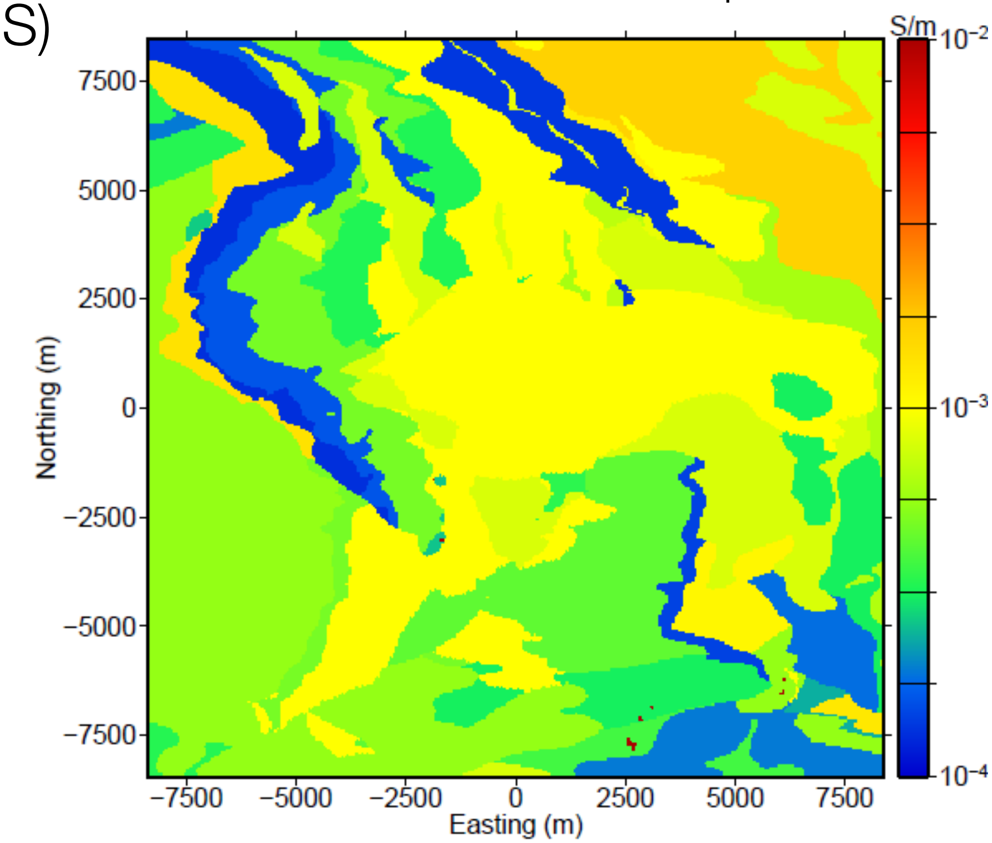
- Elevenmile Canyon geothermal area
- Balboa copper porphyry deposit

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

True model at 275m depth

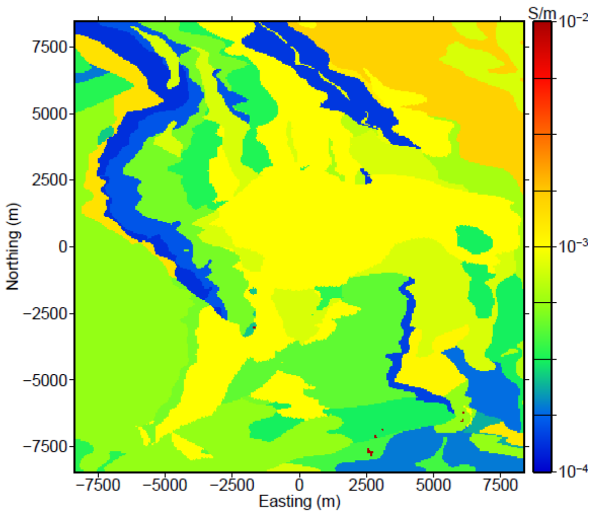


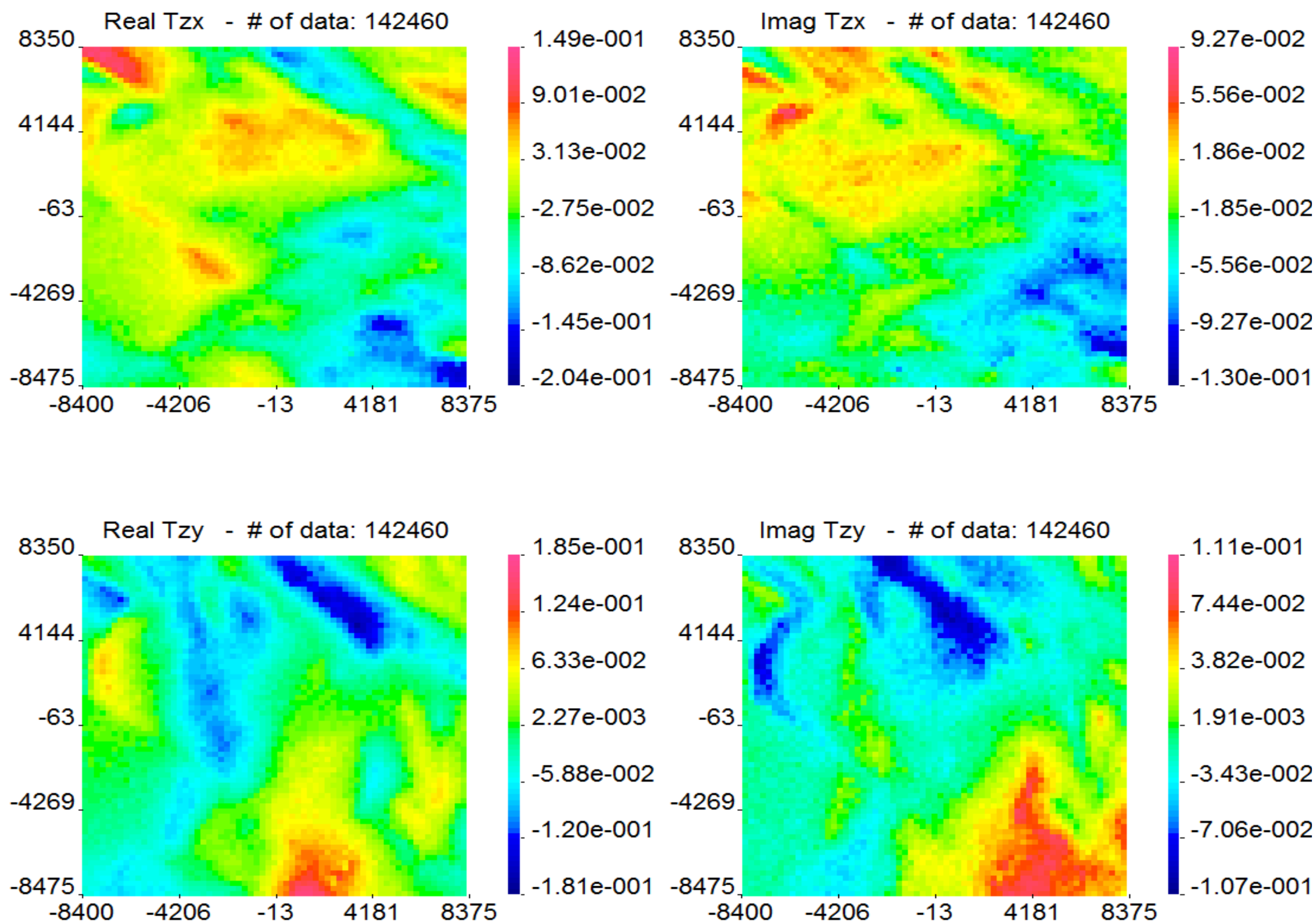
Data

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

Observed (90 Hz)

True model at 275m depth

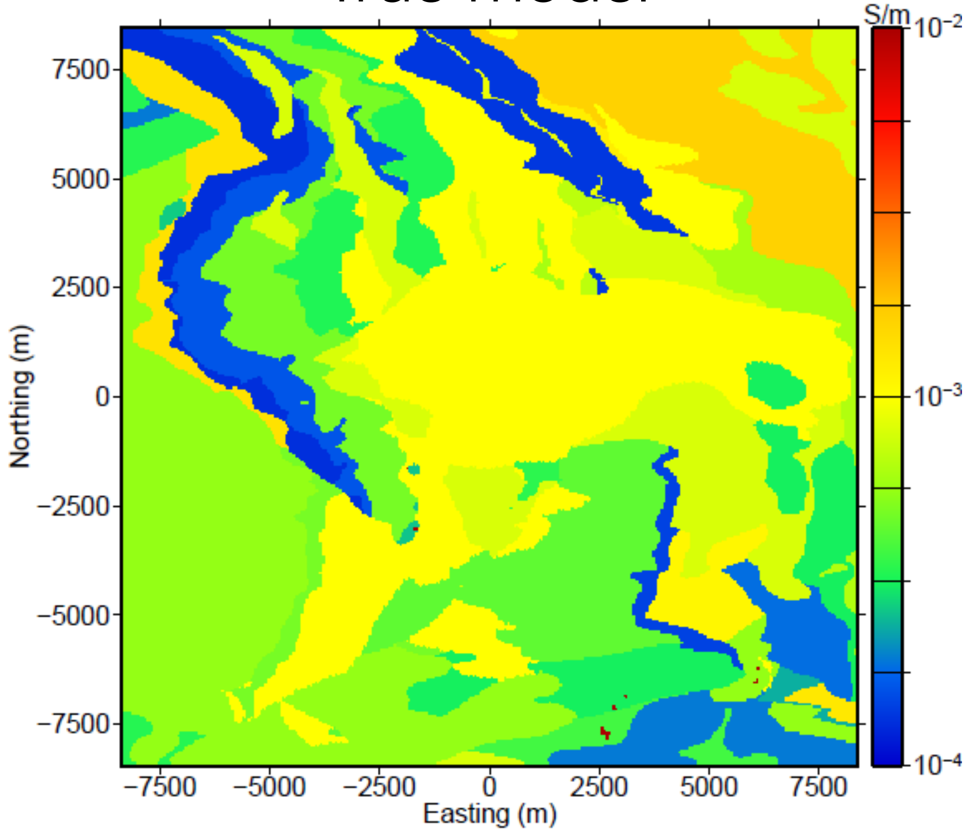




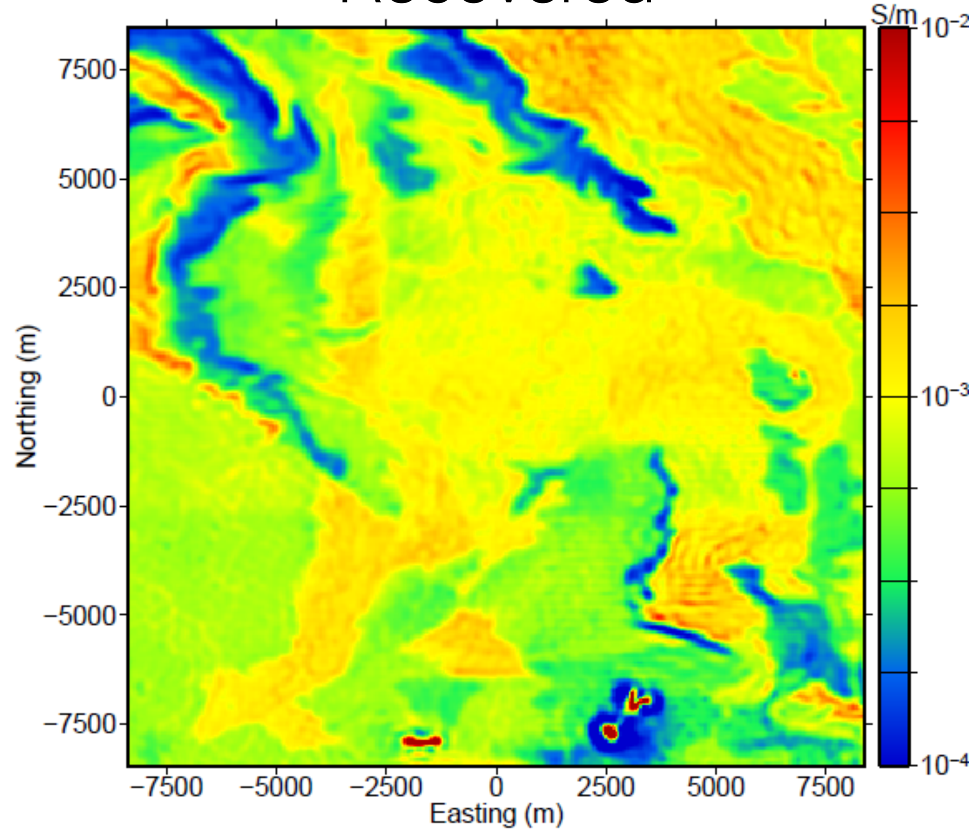
- Need to invert

Interpretation

True model



Recovered

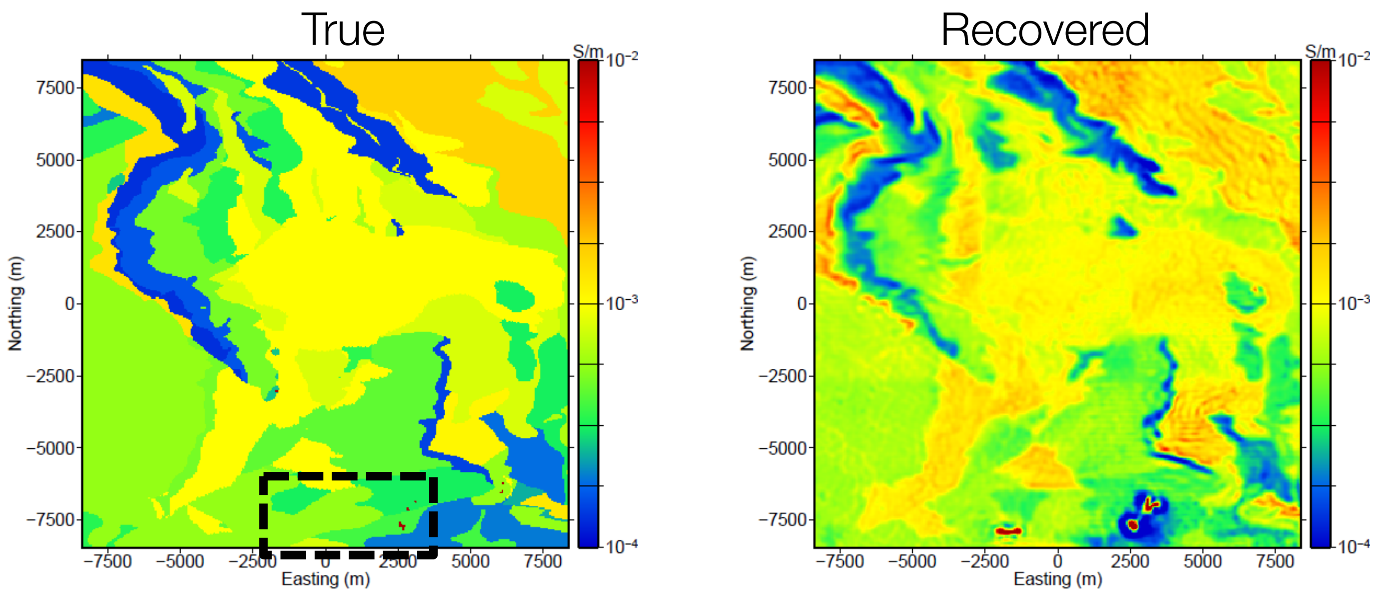


Model at 275m depth

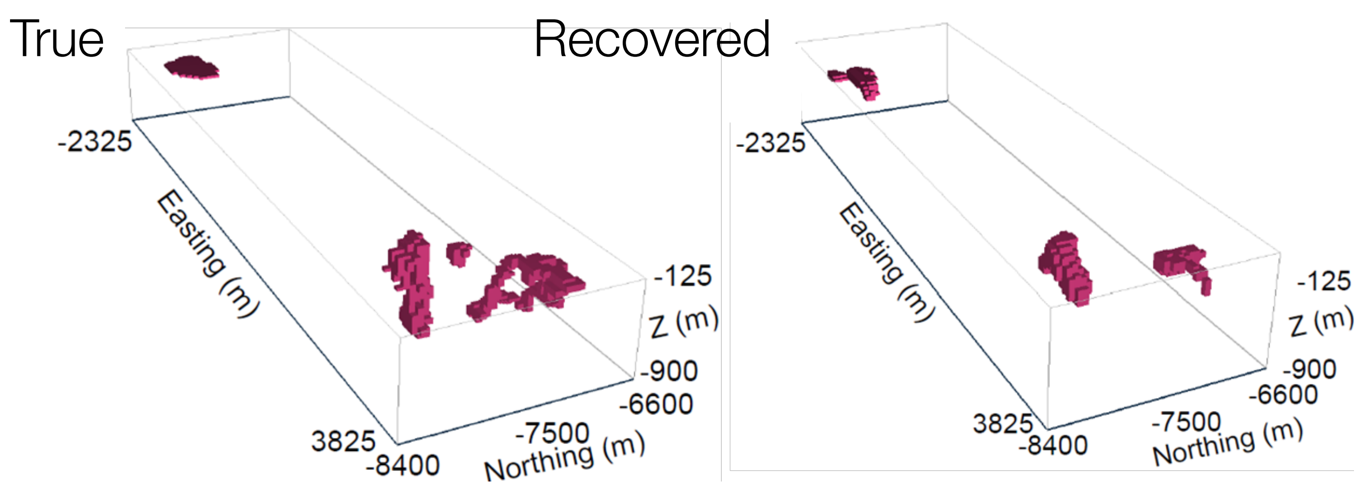
- Geologic units are well mapped
- Some mineralized bodies are located

Synthesis

- Recovered model represents the regional geology

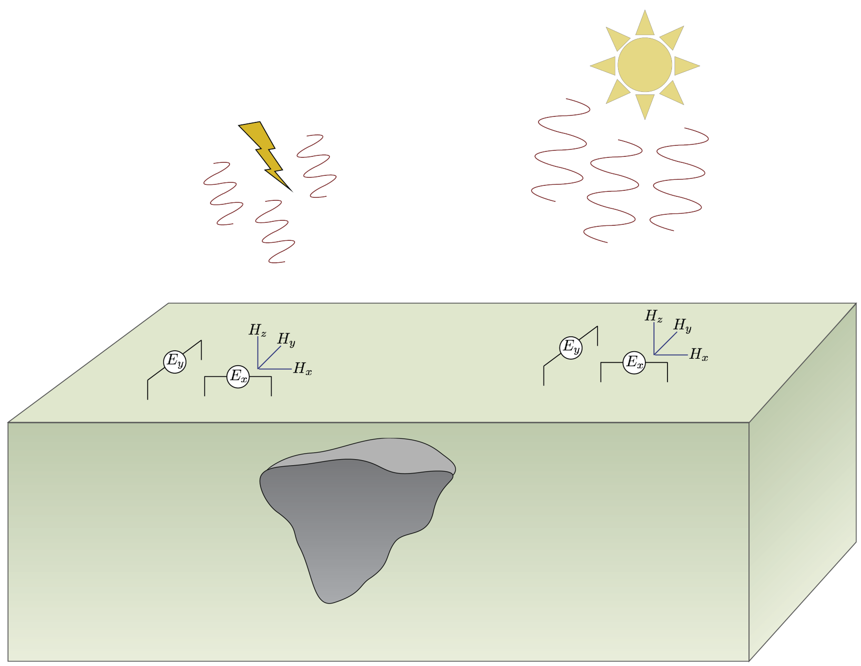


- Mineralized zones are recovered



Summary

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



End of Natural Sources

- Introduction to EM
- DCR
- EM Fundamentals
- Inductive sources
    - Lunch: Play with apps
- Grounded sources
- Natural sources
- Next up → GPR
- Induced polarization
- The Future