EM: Natural Sources

DISC
2017
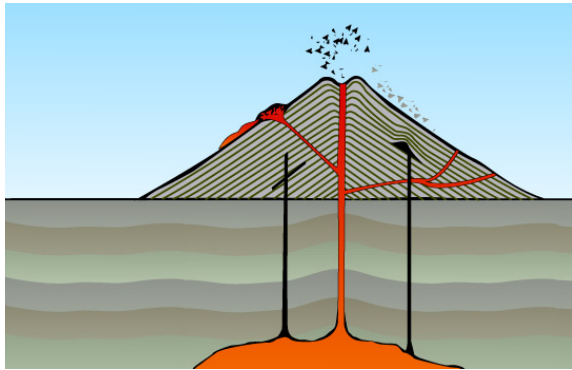Electromagnetics
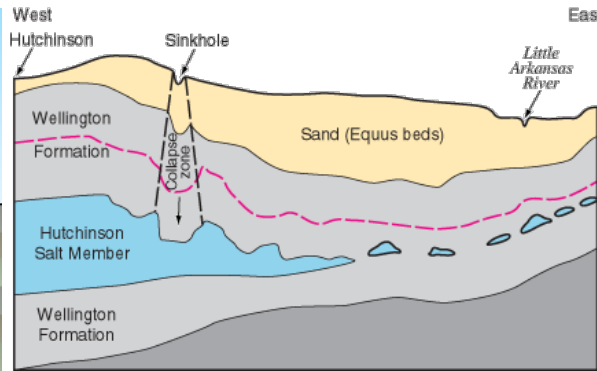Fundamentals and Applications

Outline

- Background on natural source EM methods

- Magnetotellurics

- MT case history

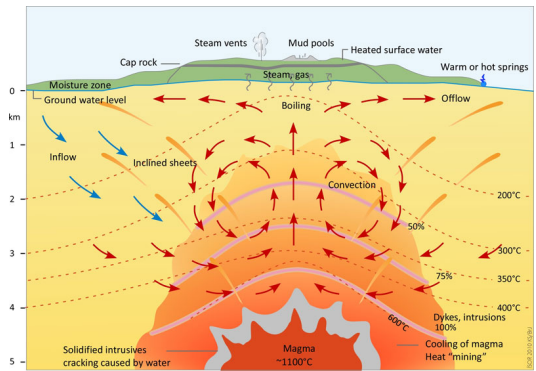- Z-axis tipper electromagnetics

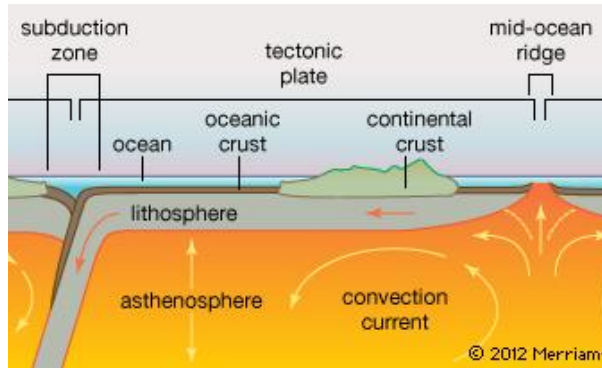- ZTEM case history

Motivation
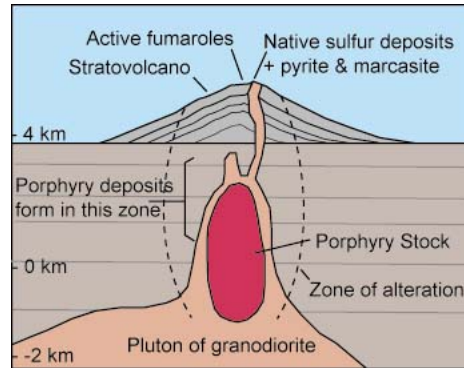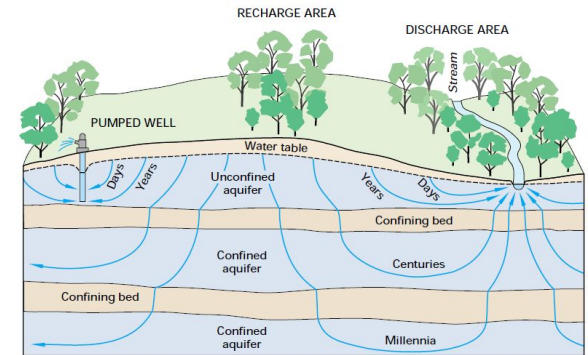
Volcanoes

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?

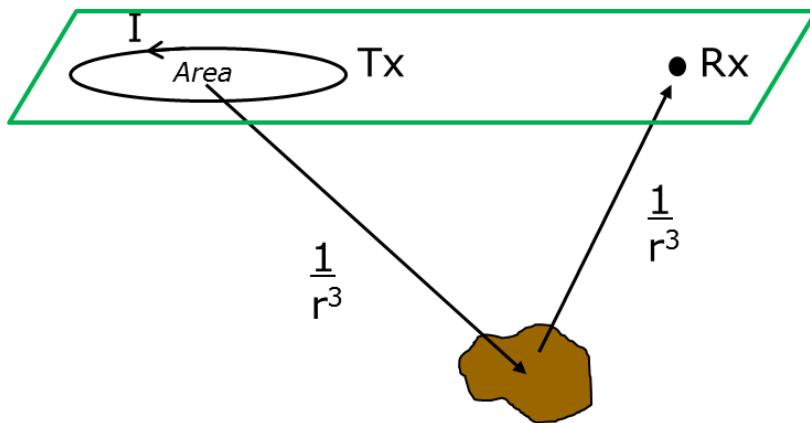- Penetration depth depends upon system power

- Controlled source:
  - Using a small loop
  - Magnetic moment

$$m = IA$$

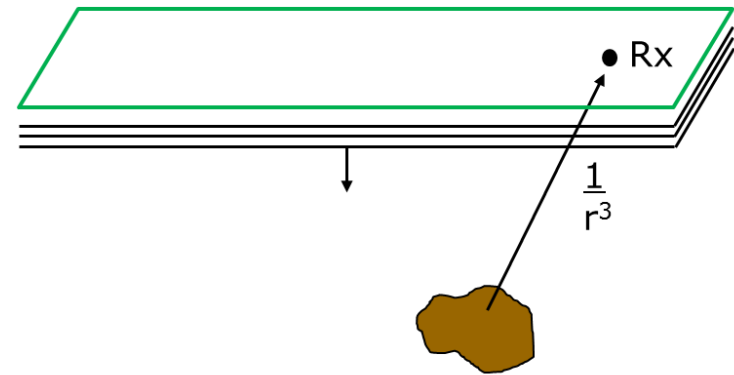 - Total geometric decay

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

- Infinitely large loop source
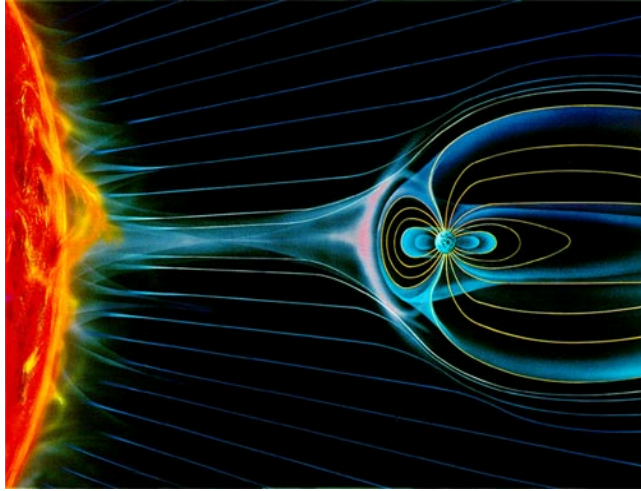 - Sheet currents generate plane waves

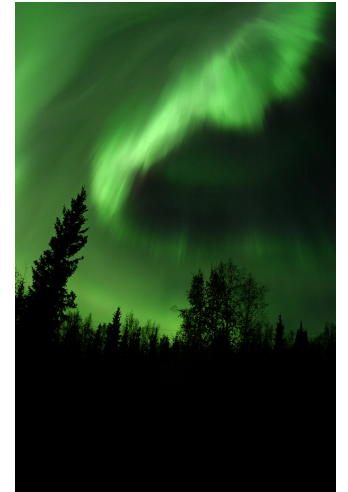 - Total geometric decay

$$\sim \frac{1}{r^3}$$
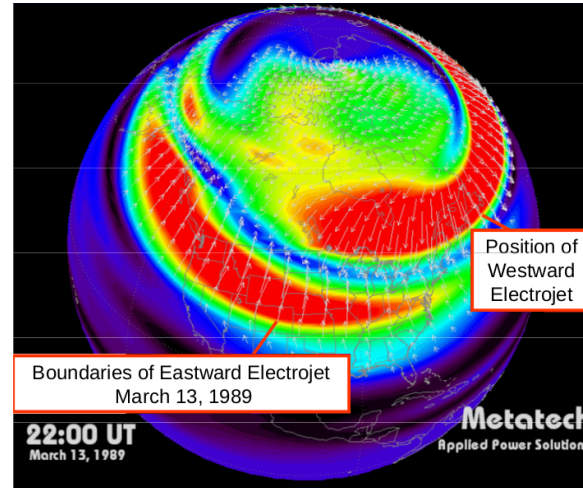
Natural EM sources

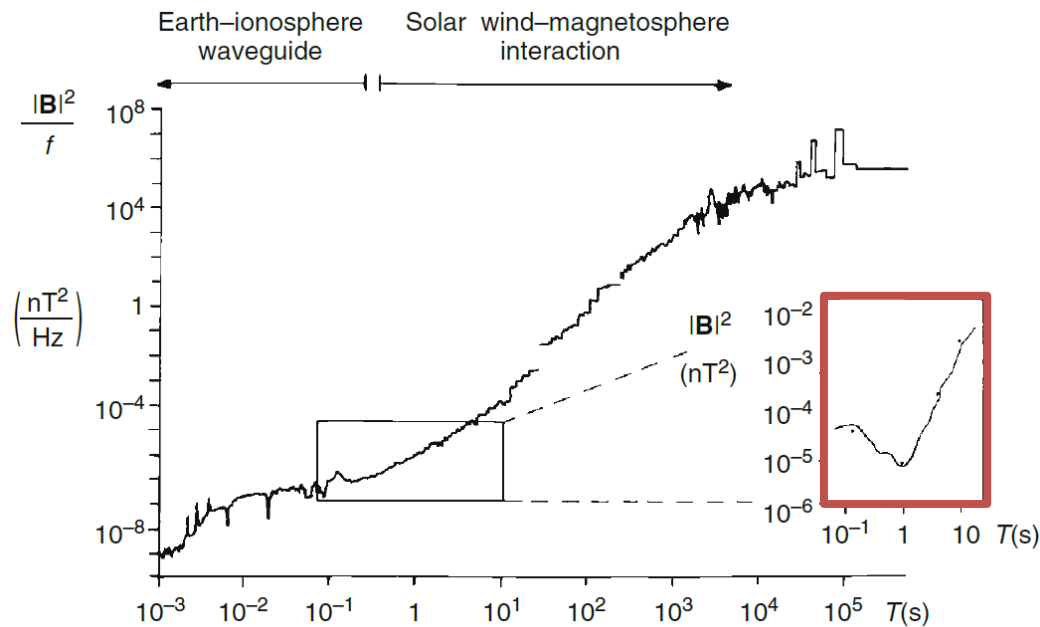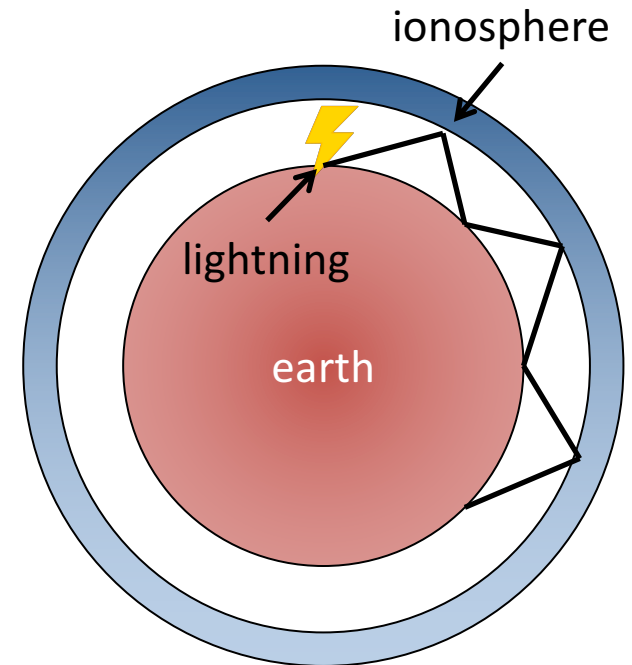Sun and magnetosphere, solar storms

Auroral electrojet; aurora

Lightning

Aurora movie

Earth as a waveguide

- EM waves bounce between earth and highly conductive ionosphere

- Travel as plane waves

ionosphere

lightning

earth

Earth–ionosphere waveguide

Solar wind–magnetosphere interaction

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

Refraction of waves
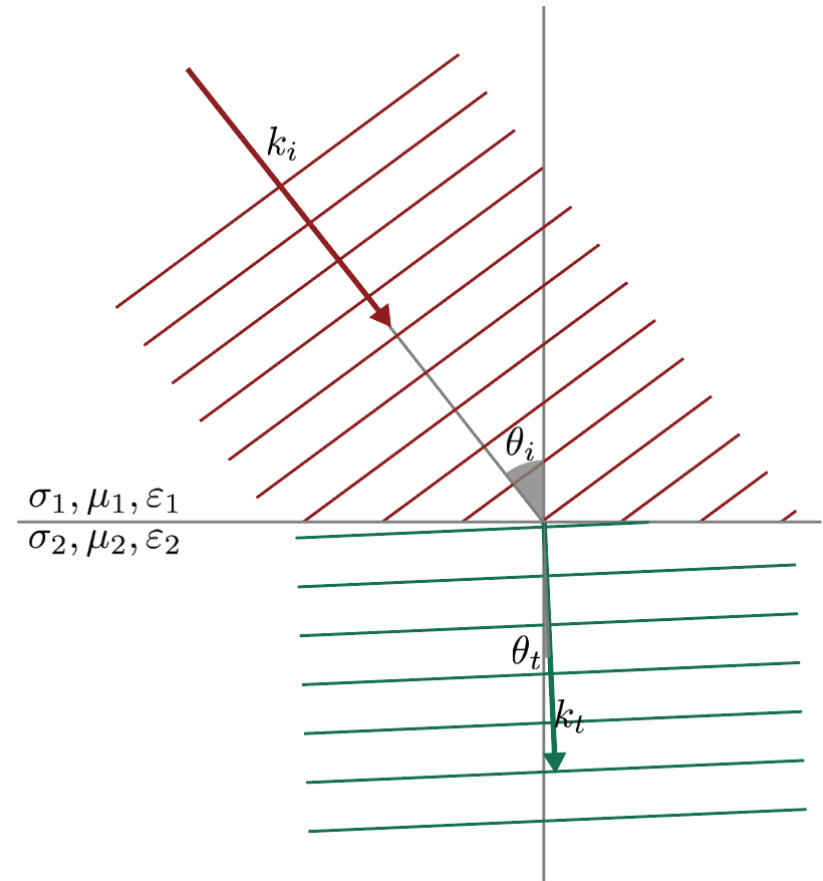
- Snell's law

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

- k is complex wave number

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

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

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

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

Example for 10,000 Hz

$$\sigma = 10^{-3} \text{ S/m}$$
$$\theta_i = 89°$$
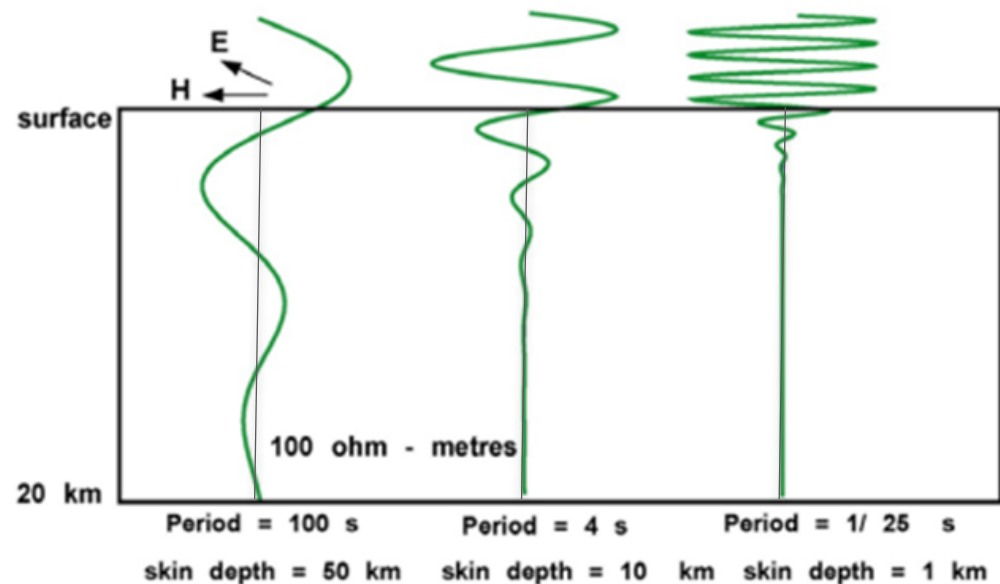$$\text{Then } \theta_t = 1.35°$$

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

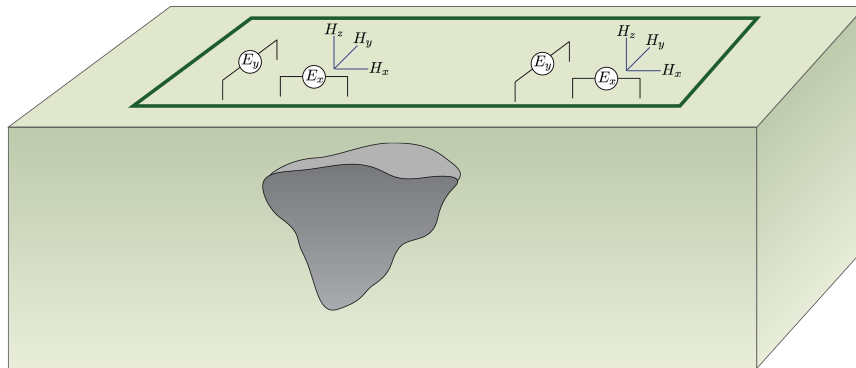- Depth of propagation
  - A few skin depths
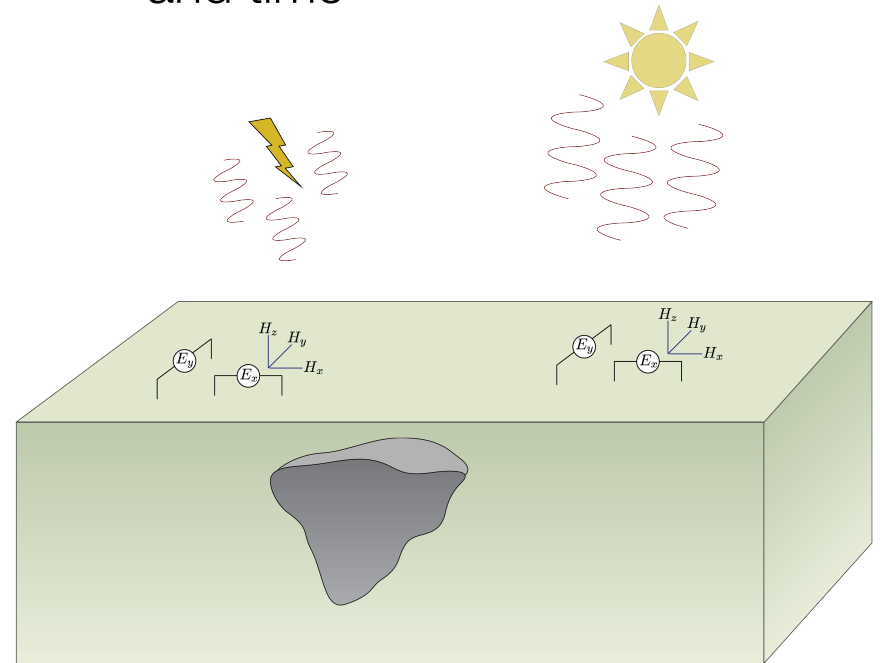 - Only a portion of a wavelength

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Control source vs Natural source

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

- ## Natural sources
  - Sources are random in space and time

MT Station

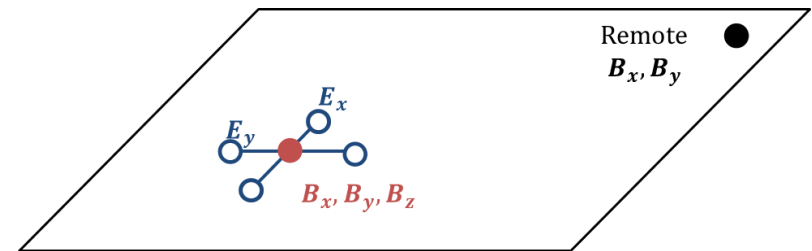- Maxwell's equations:
  - Linear in J_s
  - E and H affected in the same way

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

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

- Effects of unknown source removed by taking ratio

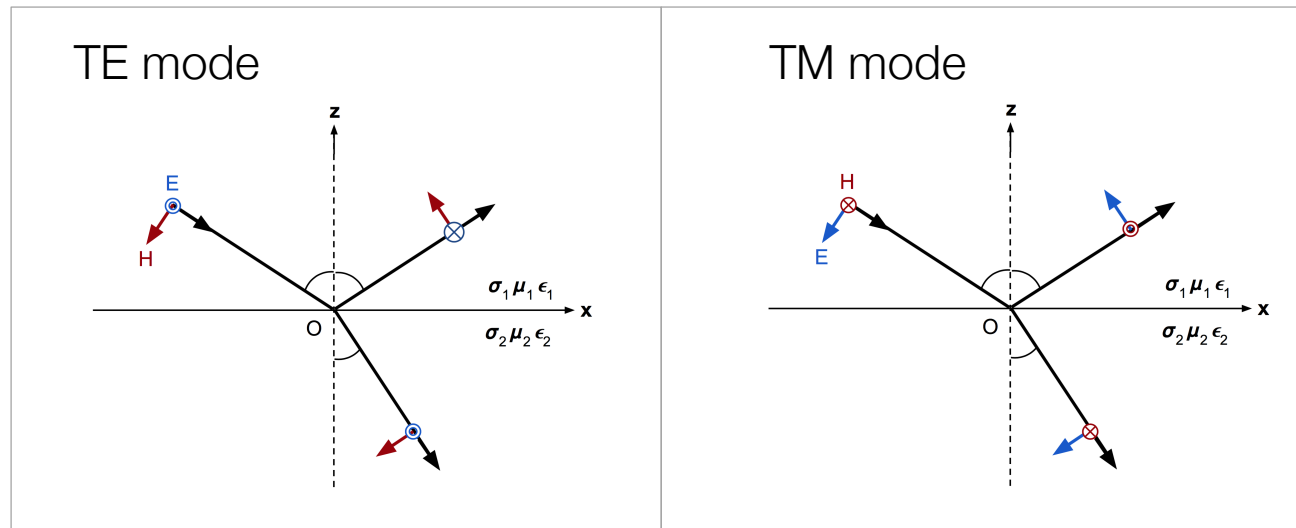- Transfer function

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

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

TE mode	TM mode

Homogeneous half space

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

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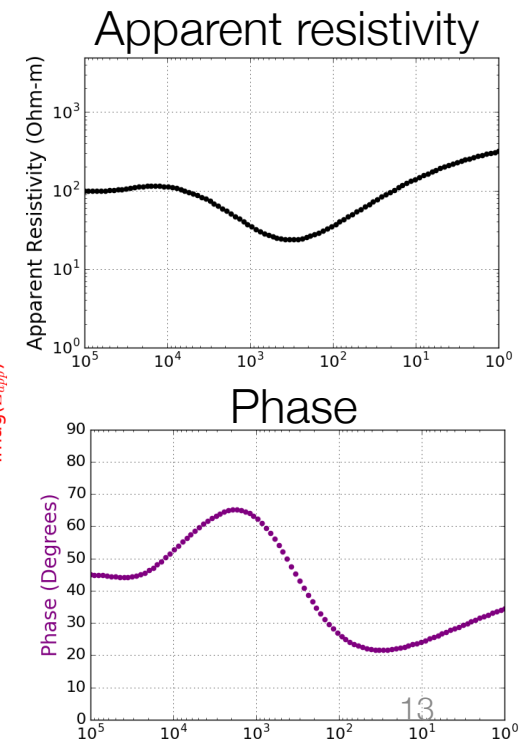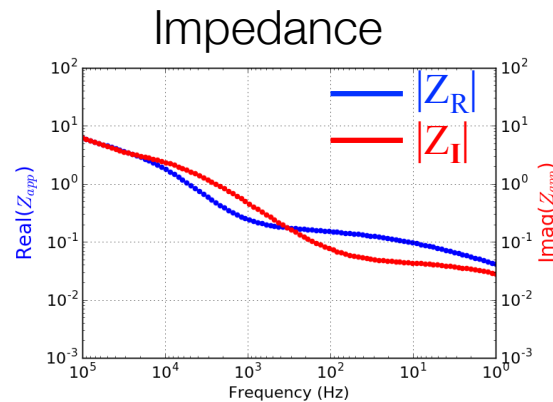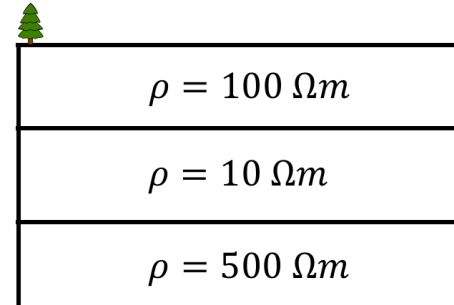
$$\Phi = \tan^{-1}\left(\frac{Im(Z_{xy})}{Re(Z_{xy})}\right)$$

- In 1D:

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

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

$$Z_{xy} = -Z_{yx}$$
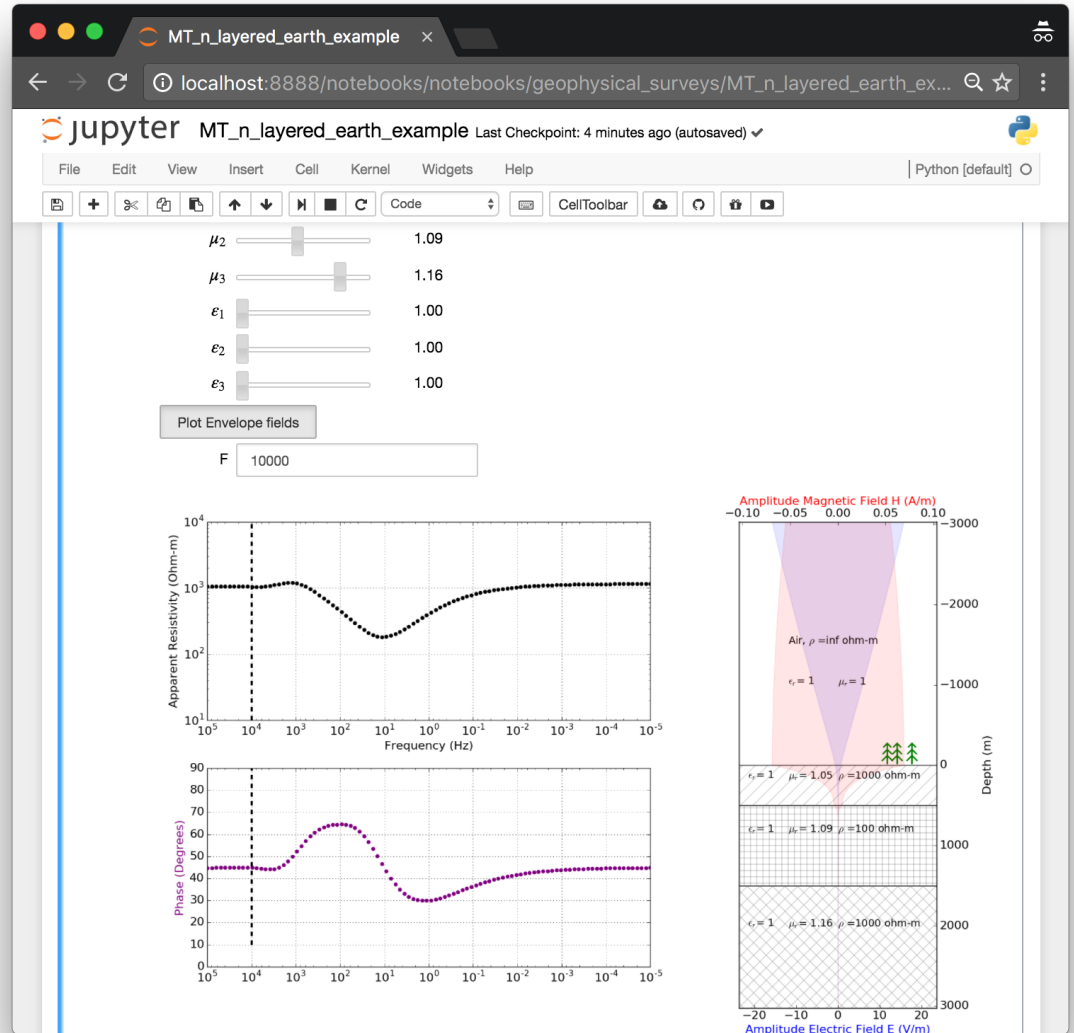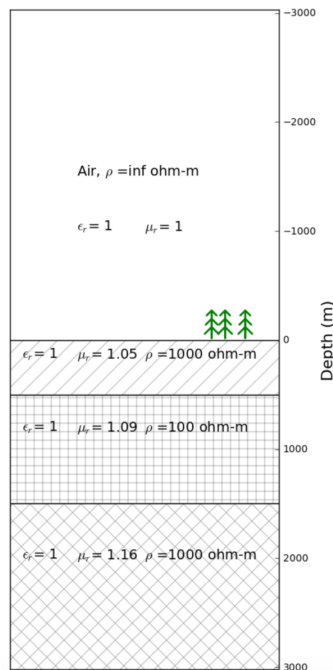
$\rho = 100\ \Omega m$

$\rho = 10\ \Omega m$

$\rho = 500\ \Omega m$

Apparent resistivity

Impedance

$|Z_R|$

$|Z_I|$

Phase

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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

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MT soundings in 2D

- In general:

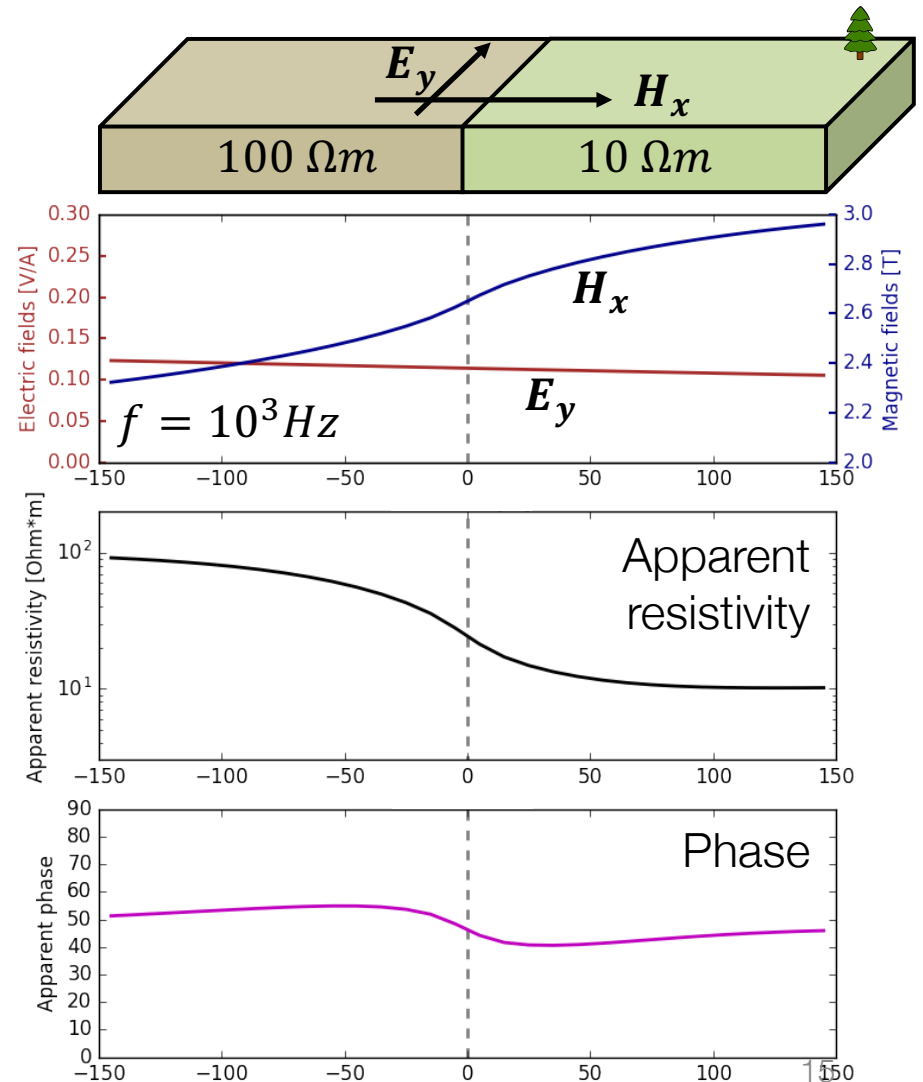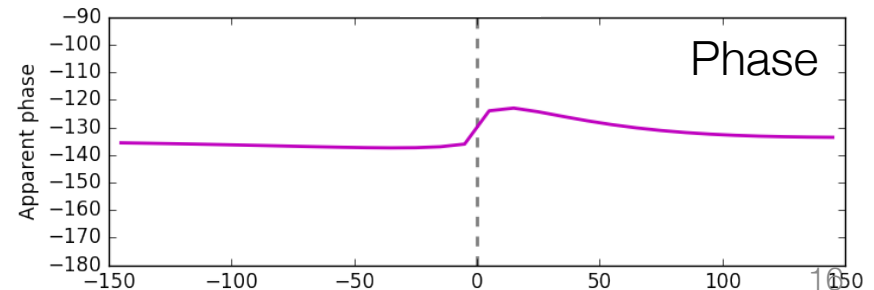$$Z = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$$

- 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

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

E_y H_x

$100\ \Omega m$ $10\ \Omega m$

H_x

E_y

$f = 10^3 Hz$

Apparent resistivity

Phase

MT soundings in 2D

- In general:

$$Z = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$$
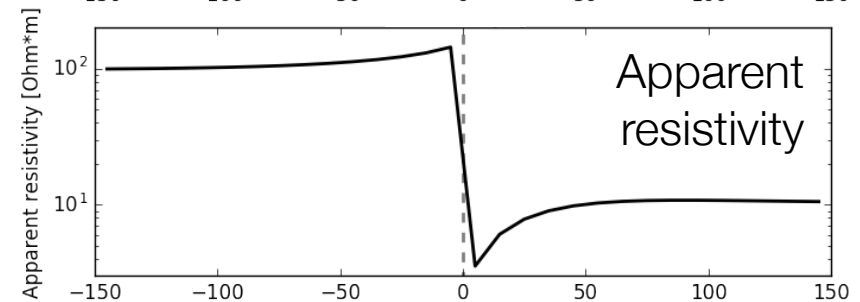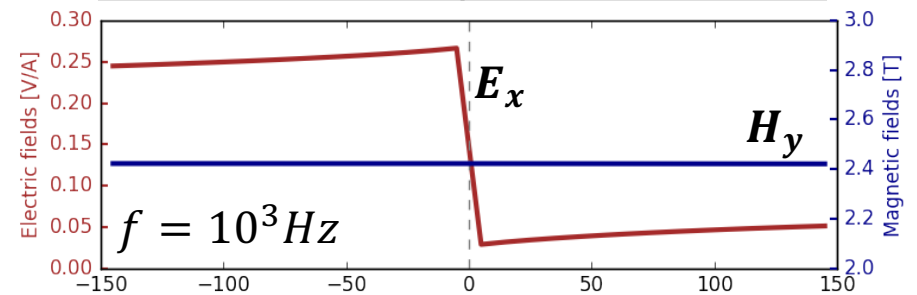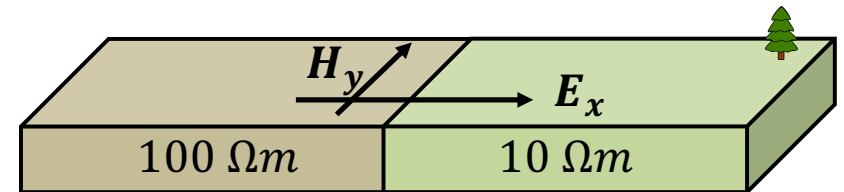
- In 2D:

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

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

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

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

H_y E_x

$100\ \Omega m$ $10\ \Omega m$

E_x

H_y

$f = 10^3 Hz$

Apparent resistivity

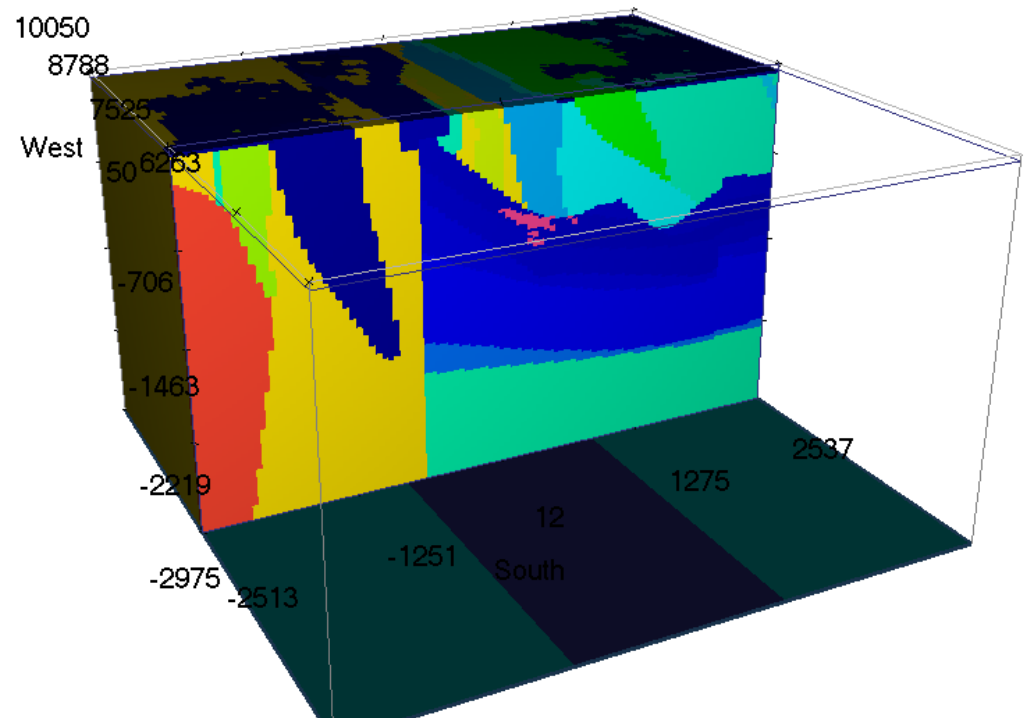Phase

MT soundings in 3D

- In general:

$$Z = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$$
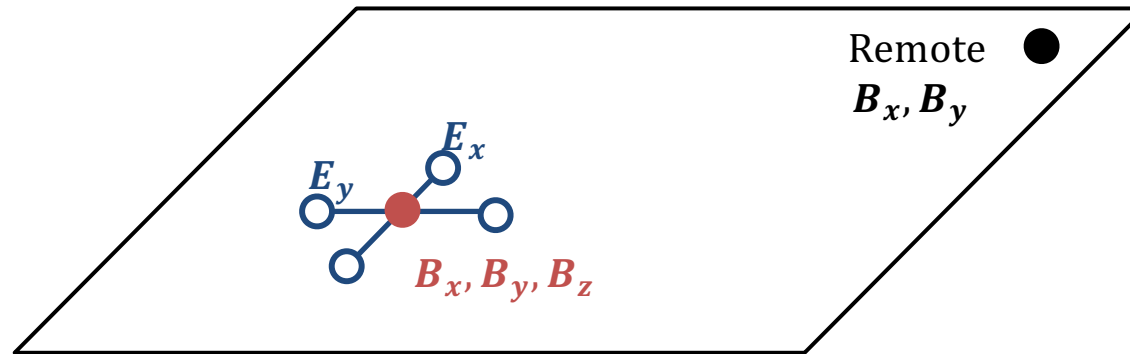
- In 3D:

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

- No symmetry or special conditions
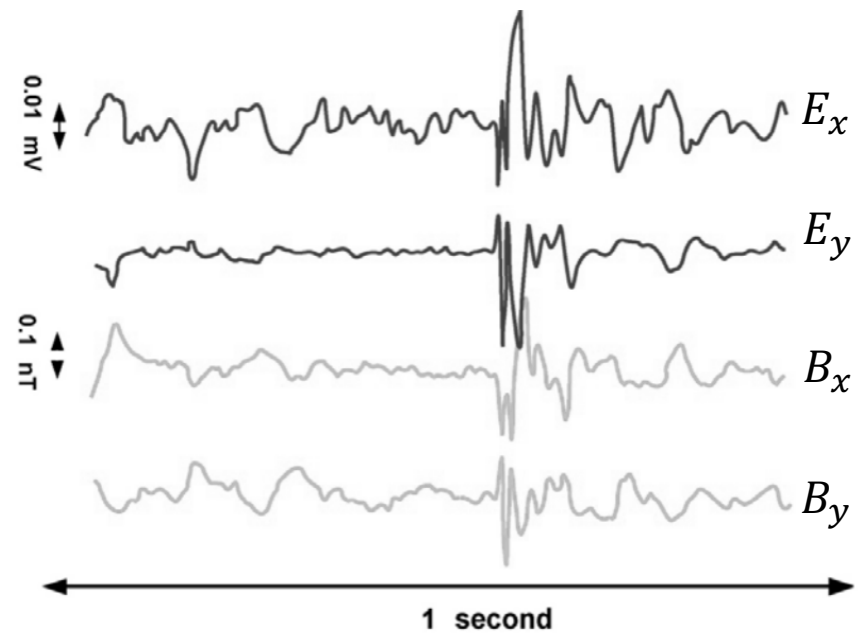
Measuring MT data

- Basic acquisition

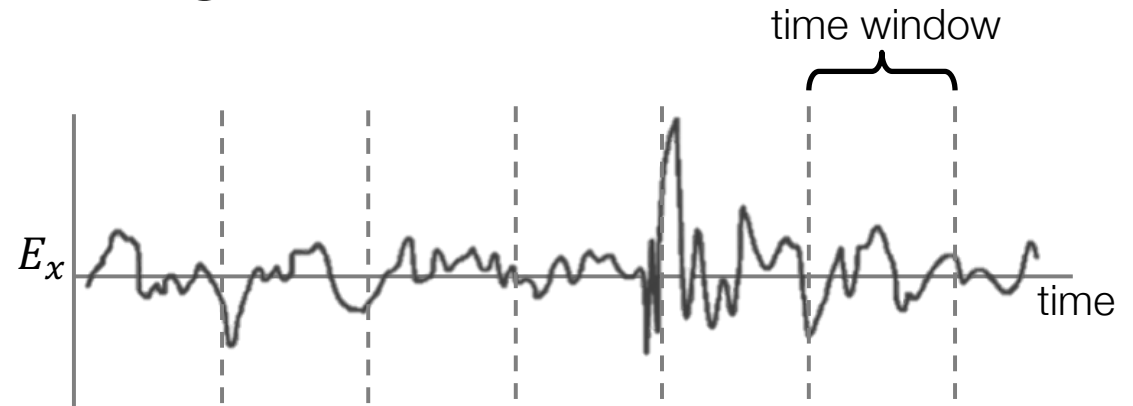- At each station, measure:

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

- At remote reference, measure:

$$B_x, B_y$$

Processing MT data

time window

- Divide time series into time windows

E_x time

- 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

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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

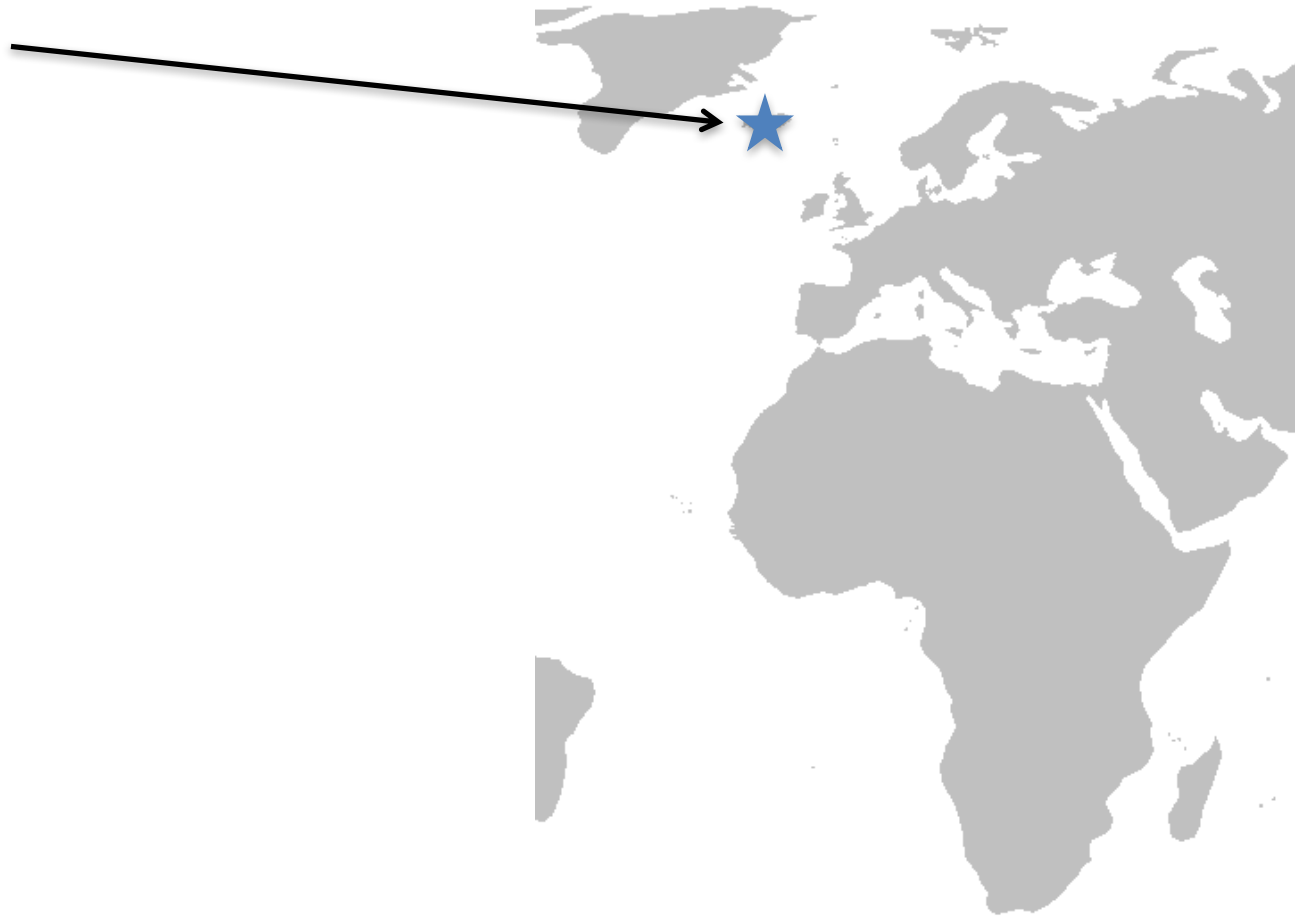- Otherwise, inversion of MT is essentially same as CSEM data
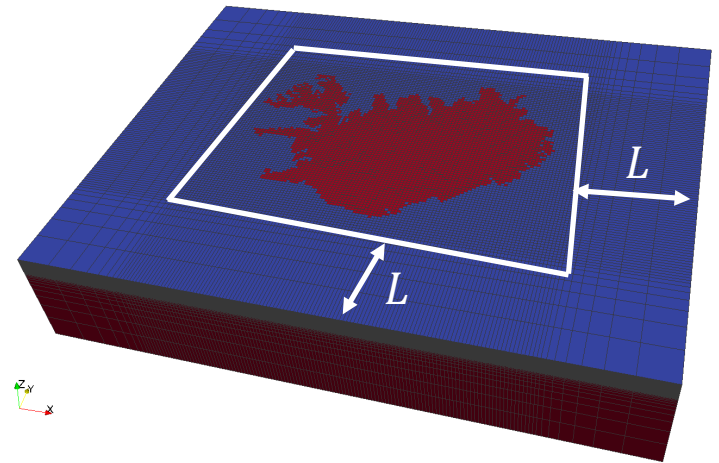
Outline

- Background on natural source EM methods
- Magnetotellurics

- Questions?

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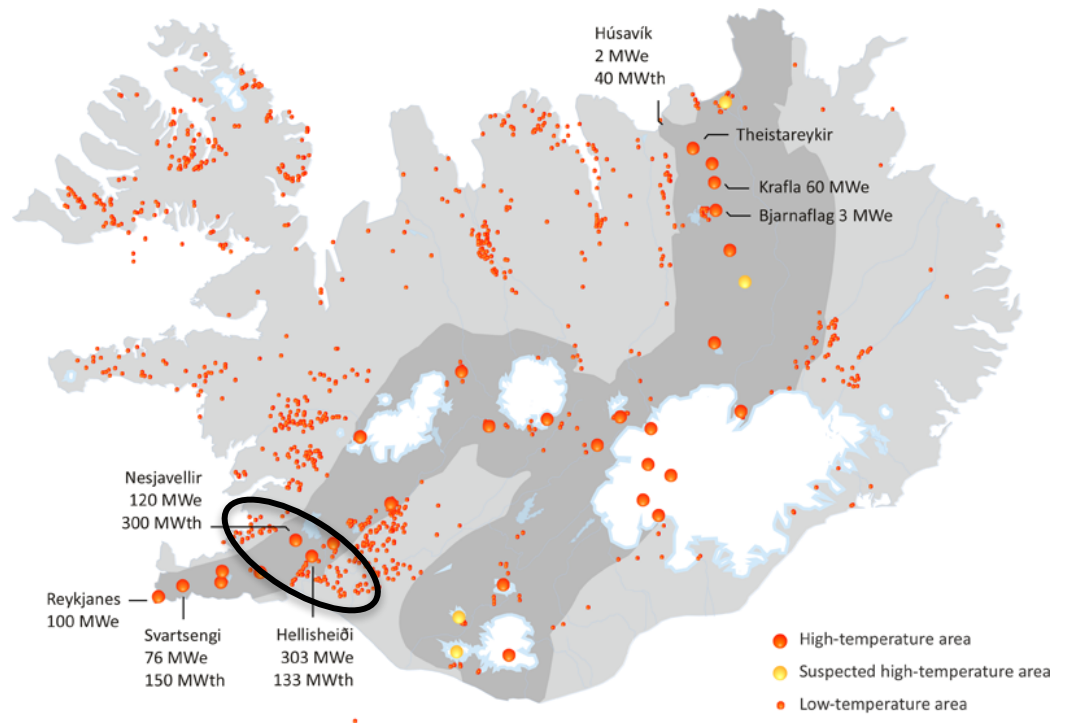- Z-axis tipper electromagnetics
- ZTEM case histories

# 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

Húsavík
2 MWe
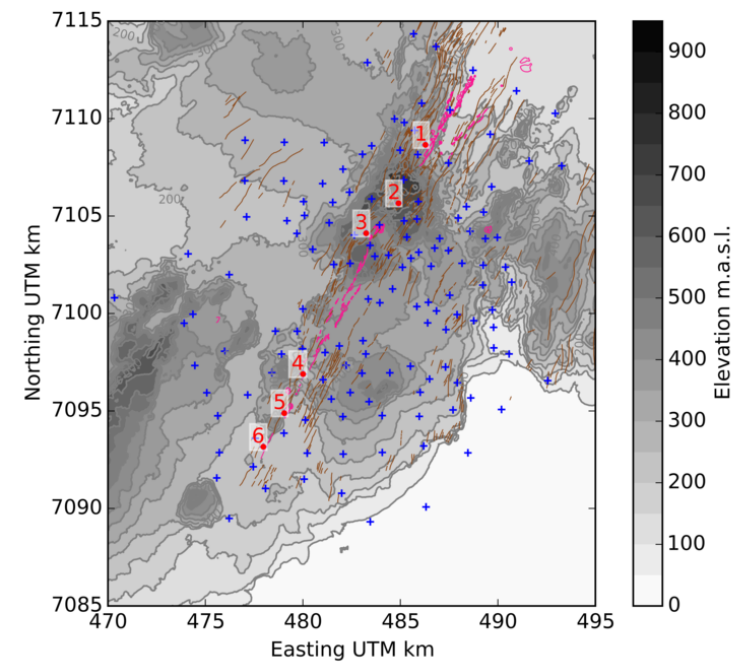40 MWth

Theistareykir

Krafla 60 MWe
Bjarnaflag 3 MWe

Nesjavellir
120 MWe
300 MWth

Reykjanes
100 MWe

Svartsengi
76 MWe
150 MWth

Hellisheiði
303 MWe
133 MWth

High-temperature area
Suspected high-temperature area
Low-temperature area

Physical properties

- Relationships between alteration, resistivity, temperature, and conduction processes
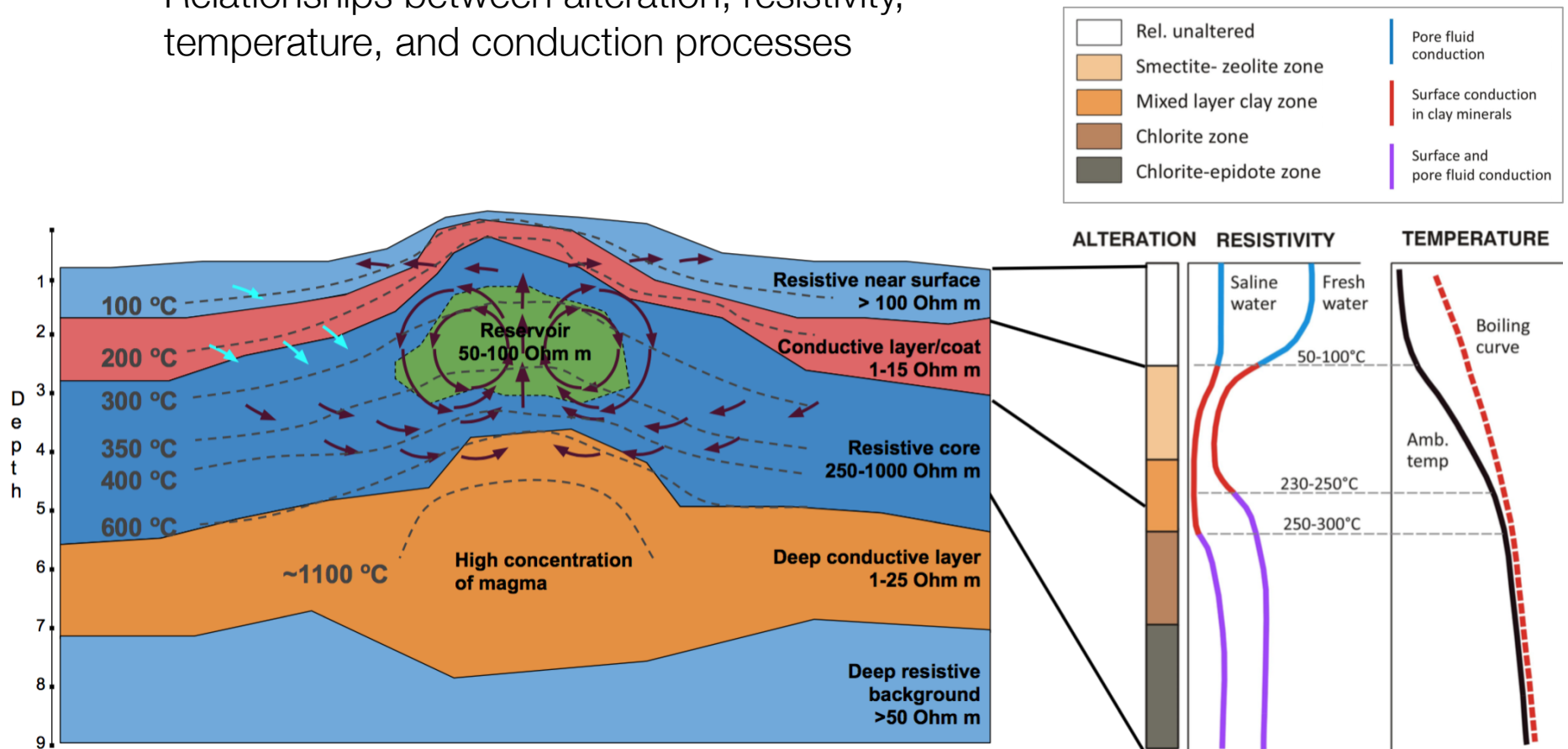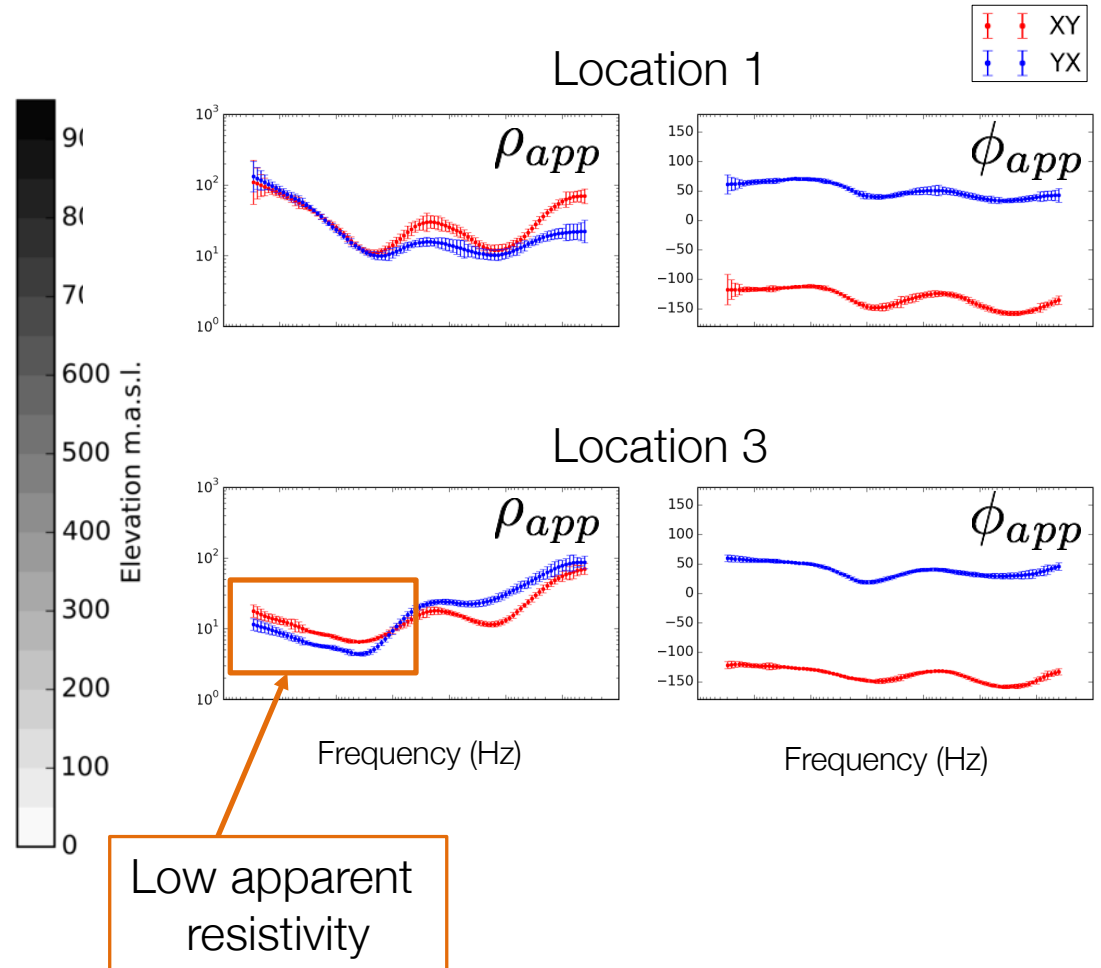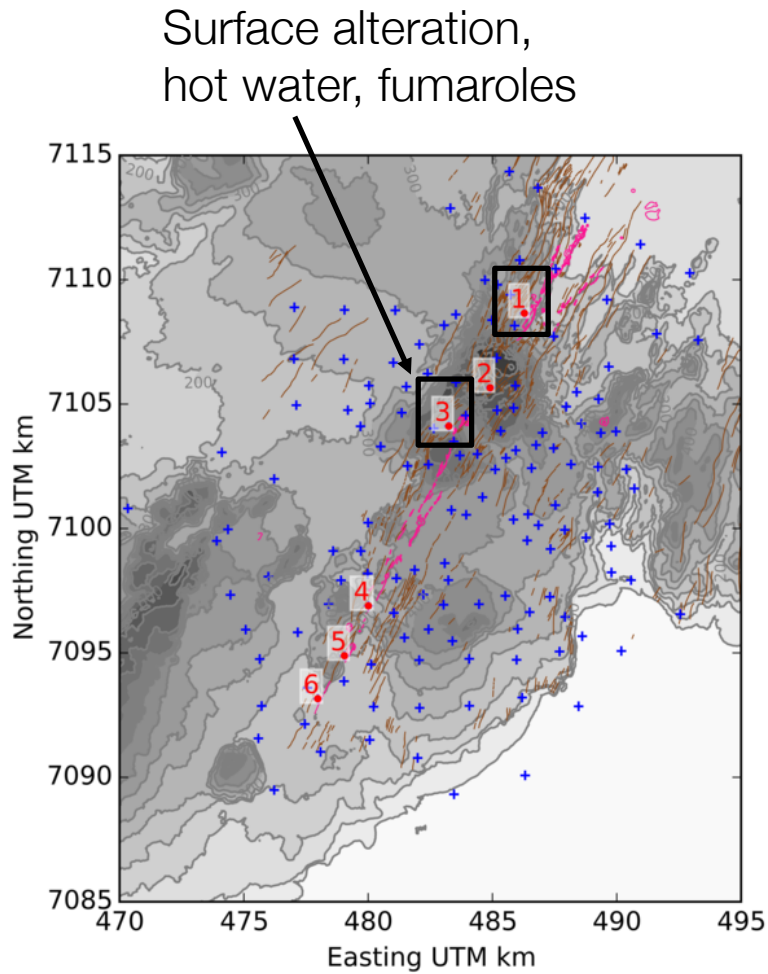
Survey
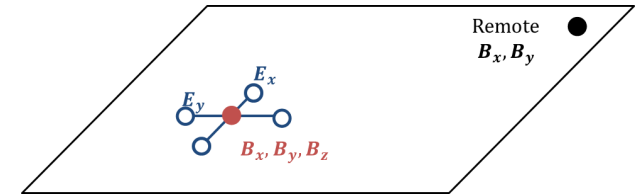
- **MT instrumentation**
  - Phoenix MTU5's

- **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

ρ_{app}

ϕ_{app}

Location 3

ρ_{app}

ϕ_{app}

Frequency (Hz)

Frequency (Hz)

XY
YX

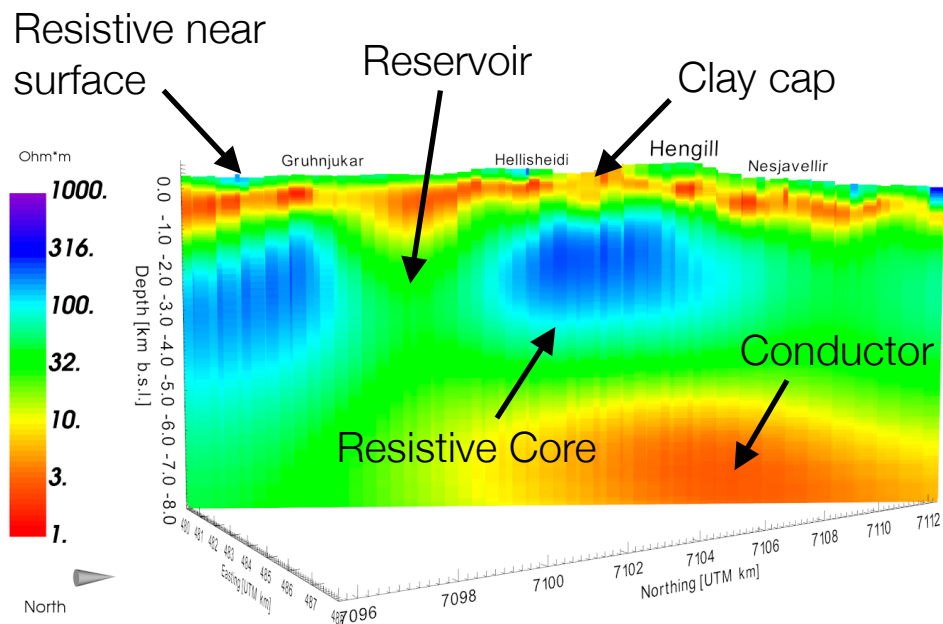Low apparent resistivity

Elevation m.a.s.l.

Northing UTM km

Easting UTM km

3D inversion

- Off-diagonal impedance (Z_{xy} and Z_{yx}) used

- Combined multi-frequency inversion (300 Hz – 0.001 Hz)

Rosenkjaer et al, 2015   27
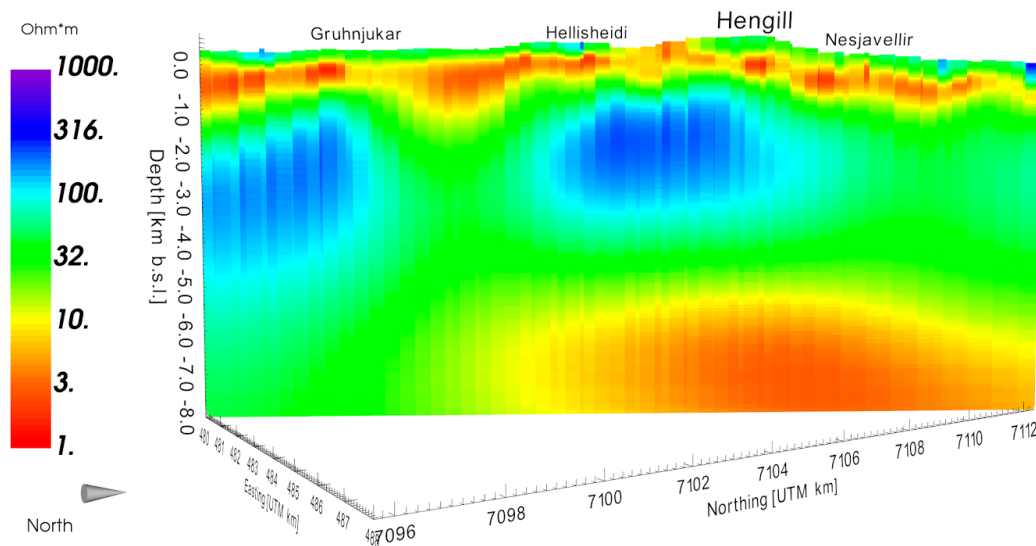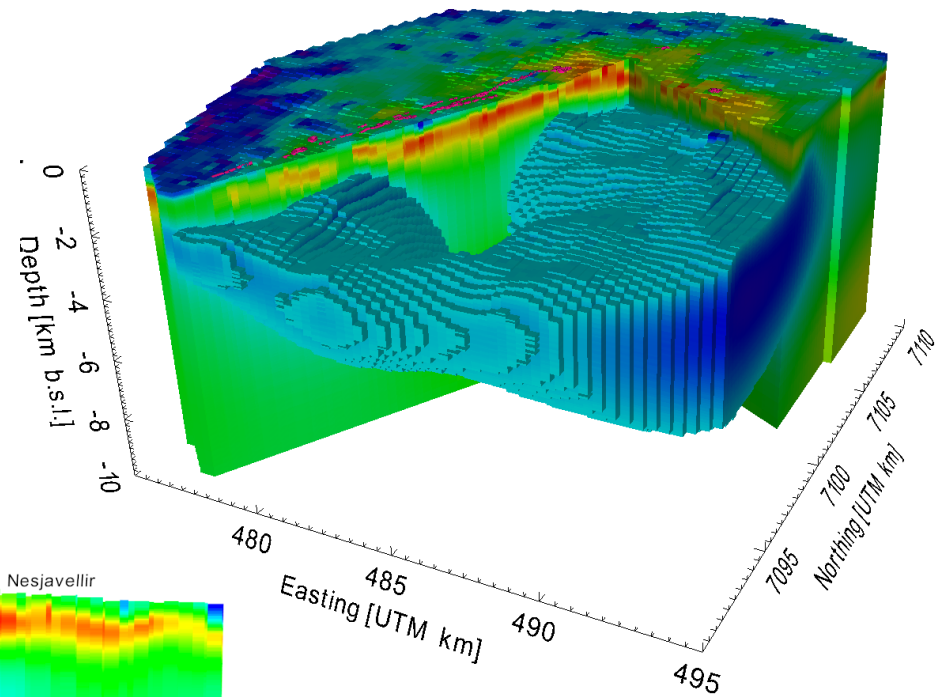
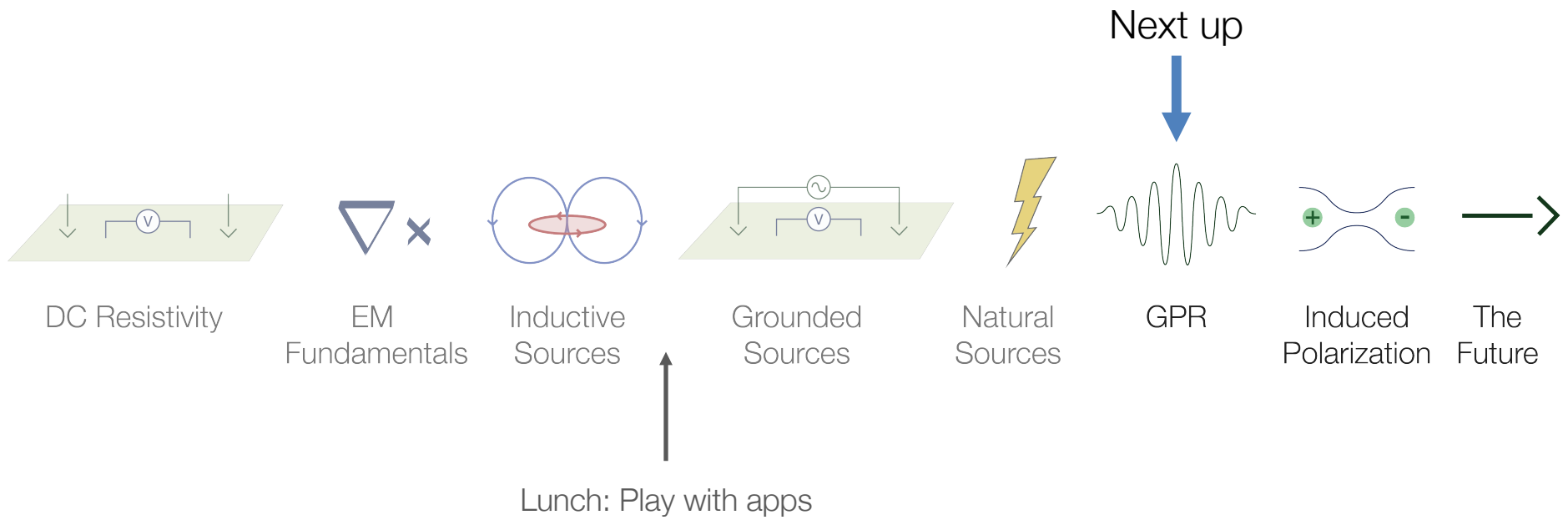# Interpretation
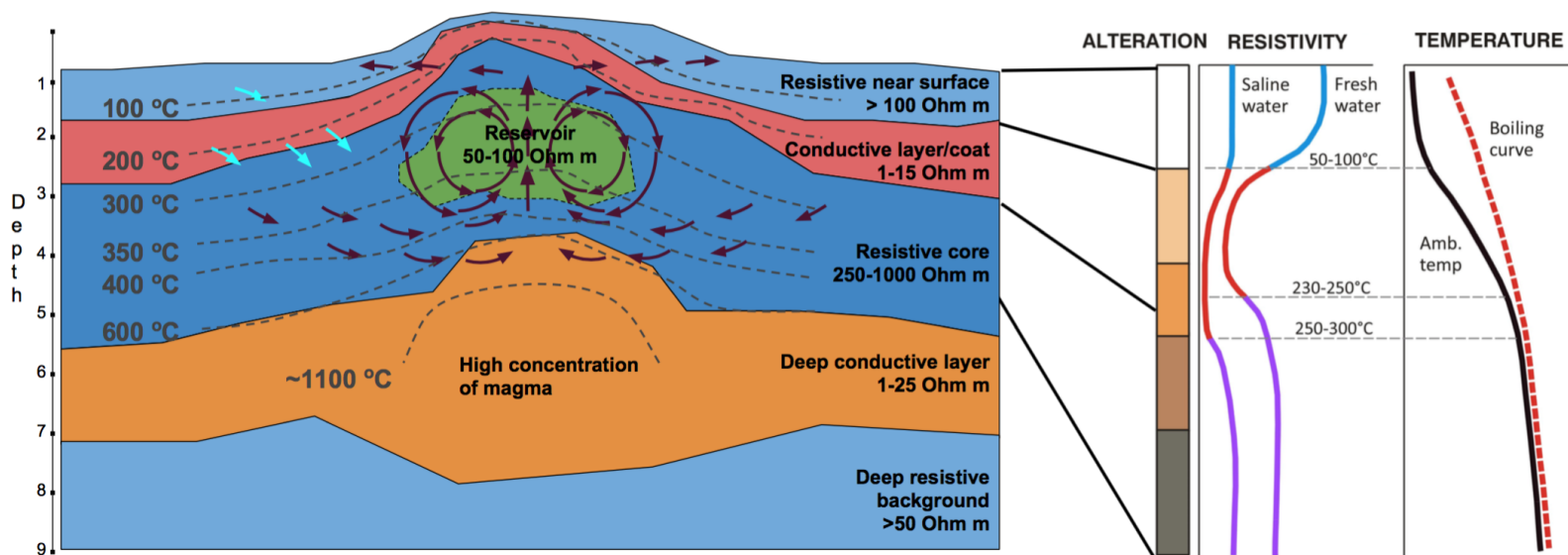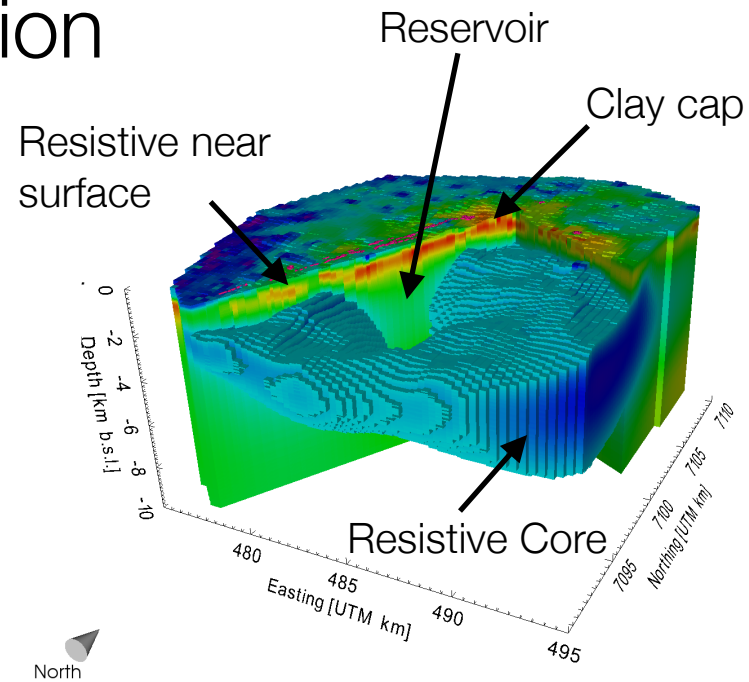
Synthesis
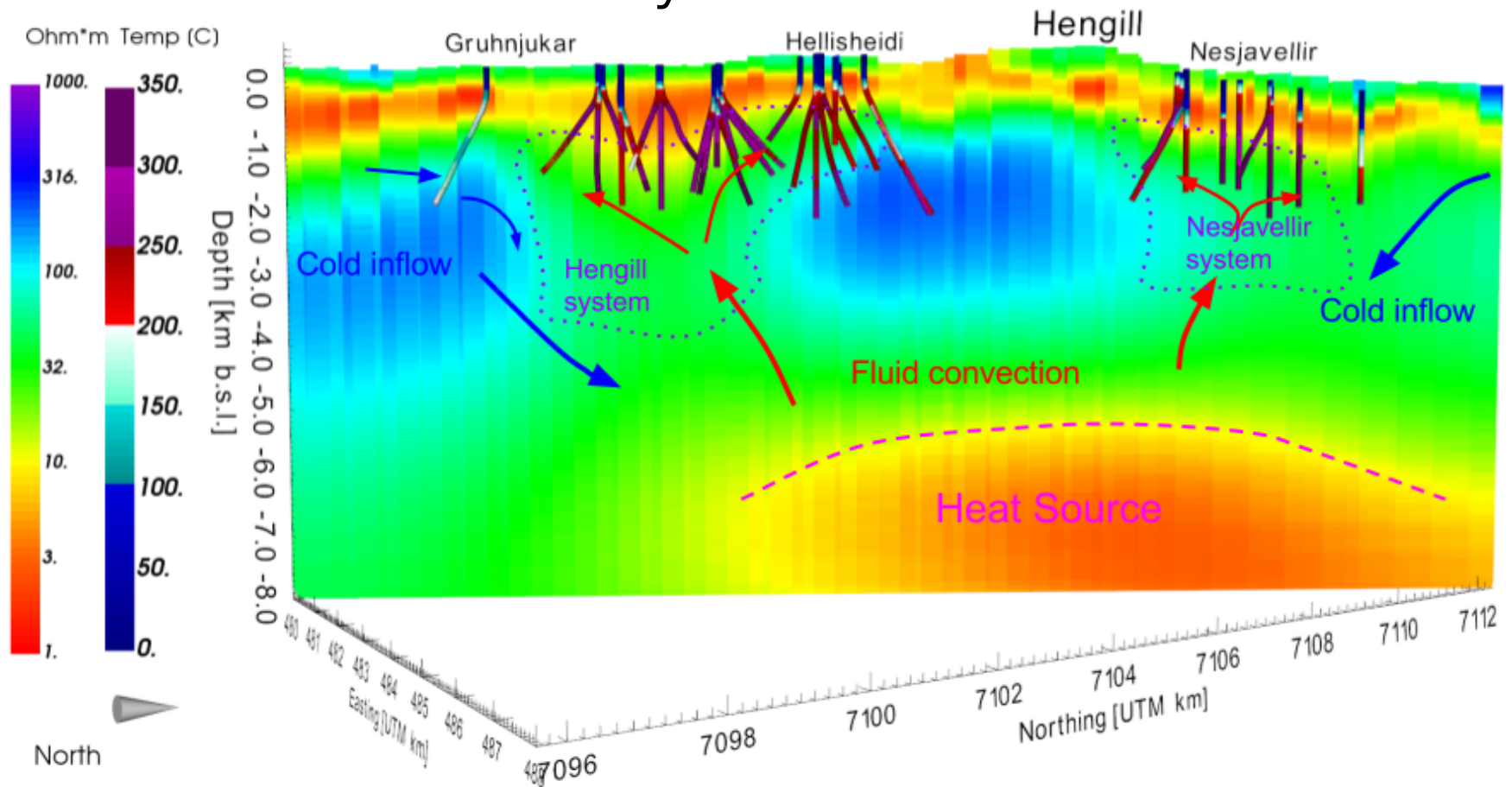
- Conductive layer corresponds with formation temperature
- Two main production fields: Hengill and Nesjavellir
- Deep conductive heat source

Summary

- Background on natural source EM methods

- Magnetotellurics

- MT case history

- Z-axis tipper electromagnetics

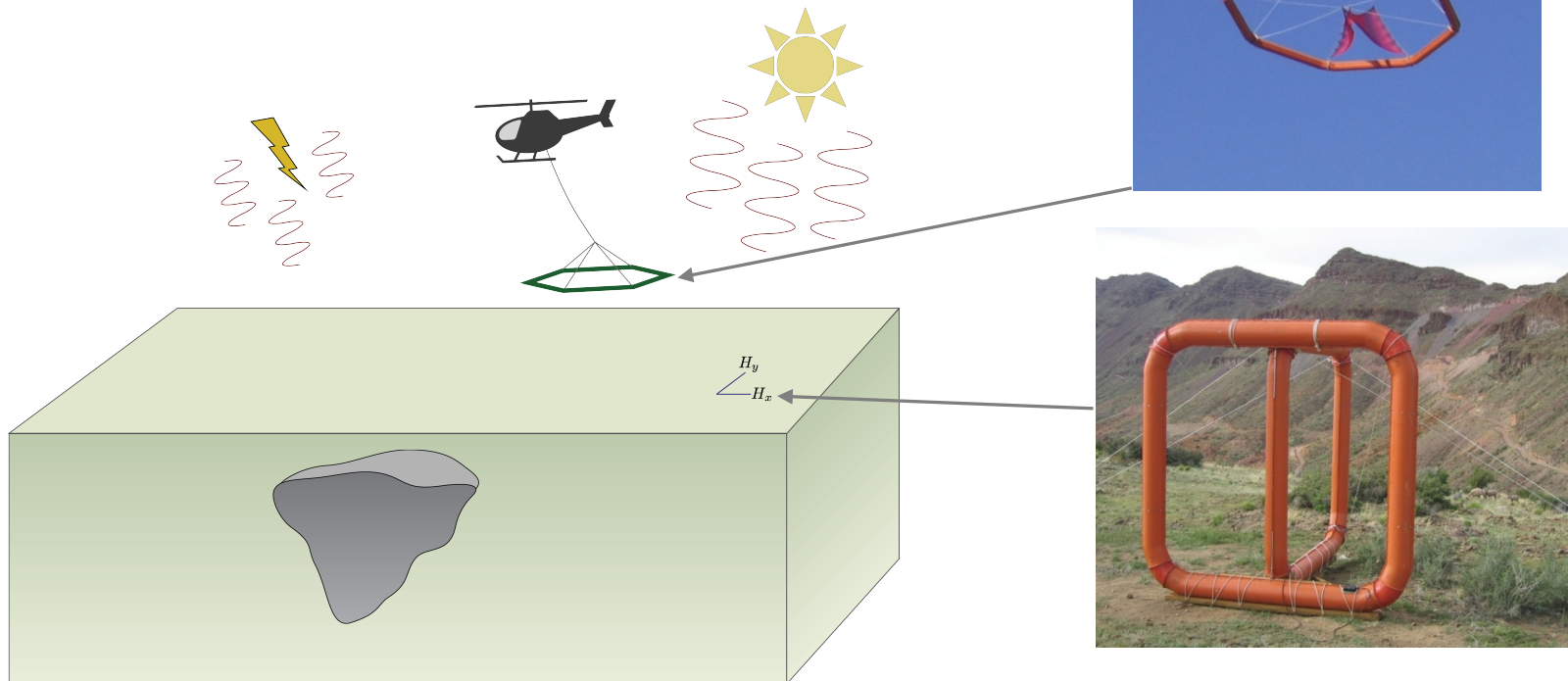- ZTEM case history

End of Natural Sources

Next up

DC Resistivity

EM Fundamentals

Inductive Sources

Grounded Sources

Natural Sources

GPR

Induced Polarization

The Future

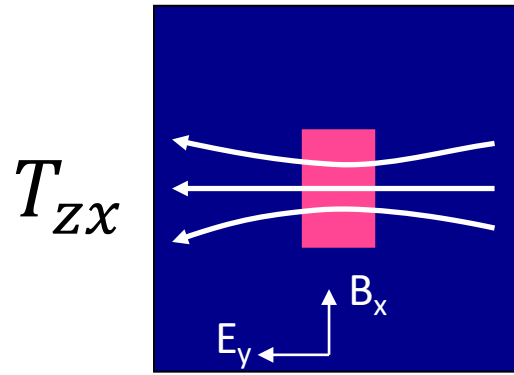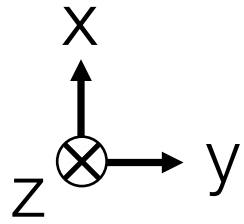Lunch: Play with apps

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
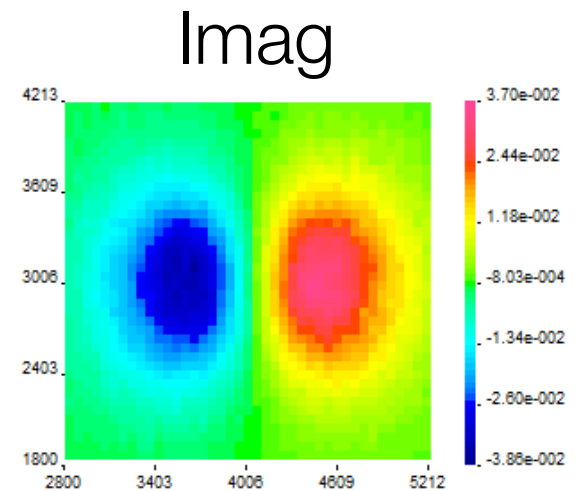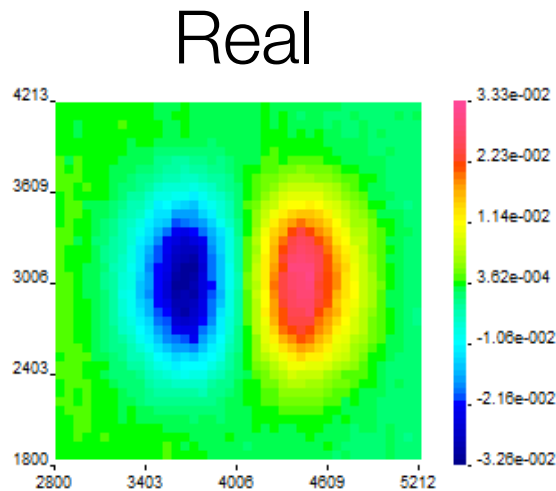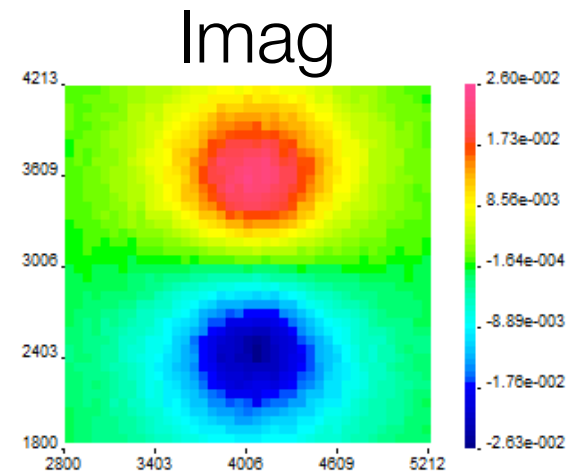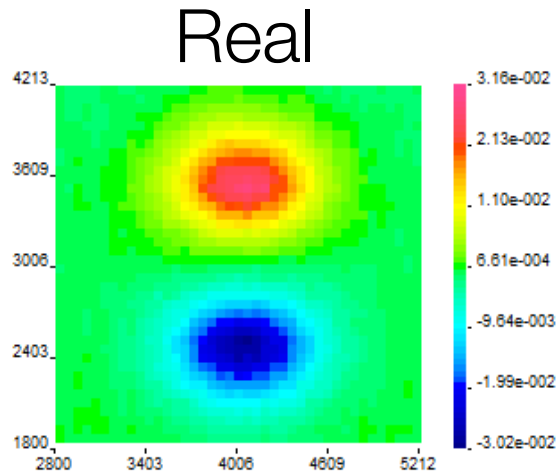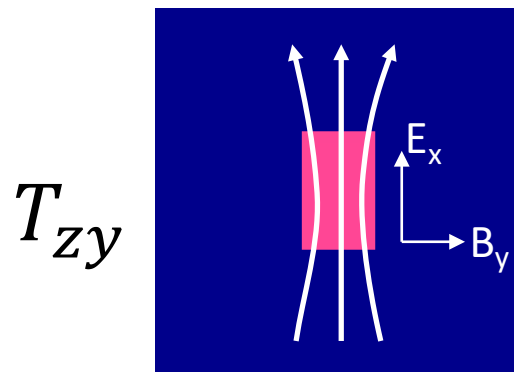

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Synthetic example
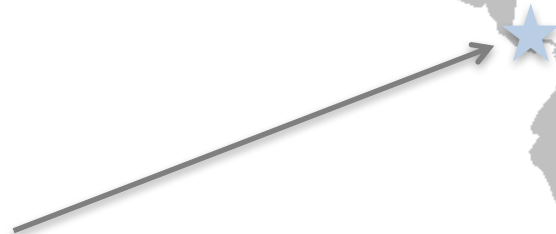
ZTEM case histories

- **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
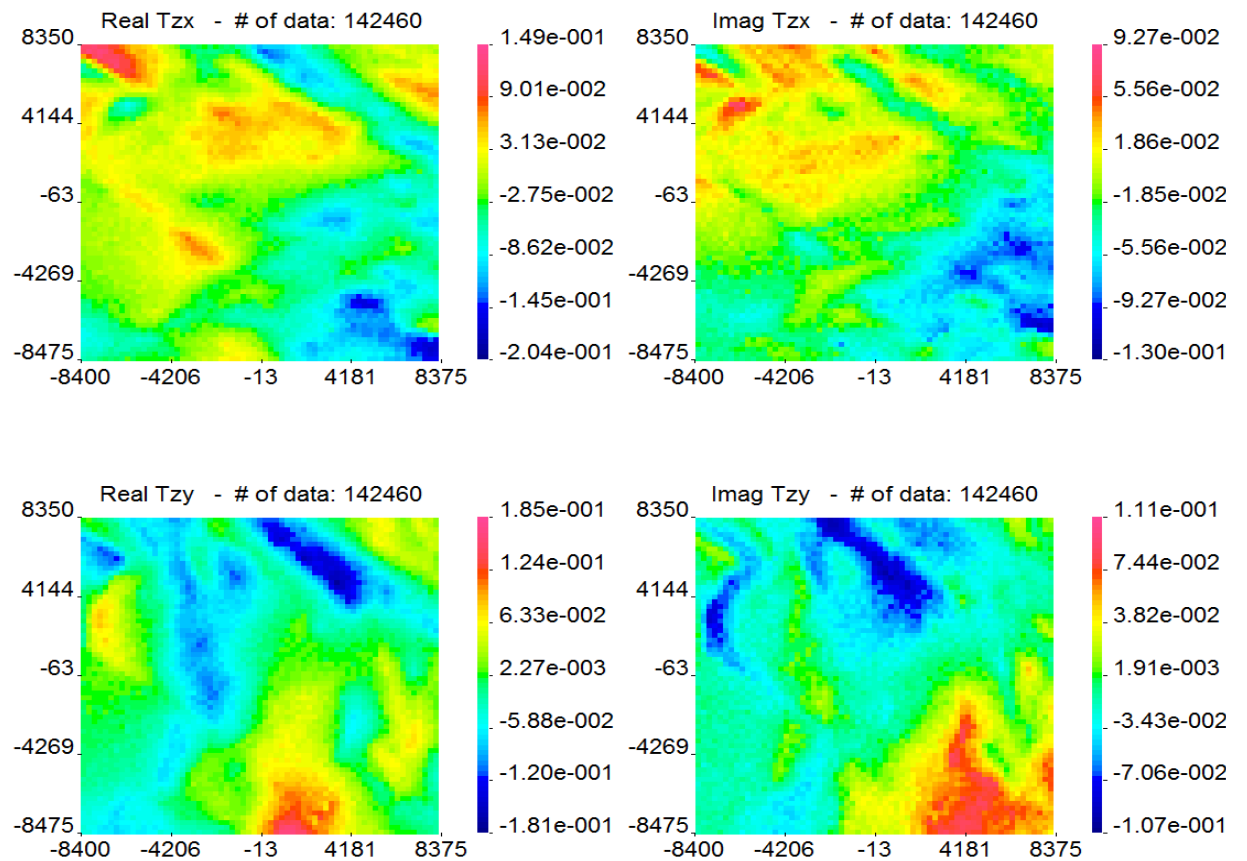
True model at 275m depth
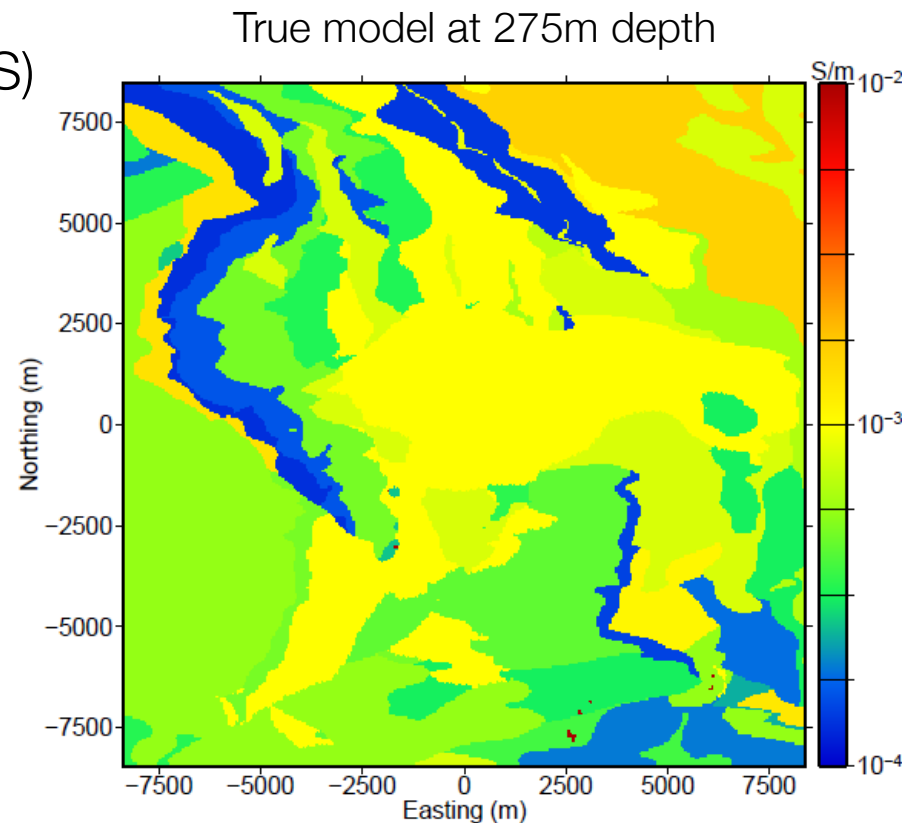
Data

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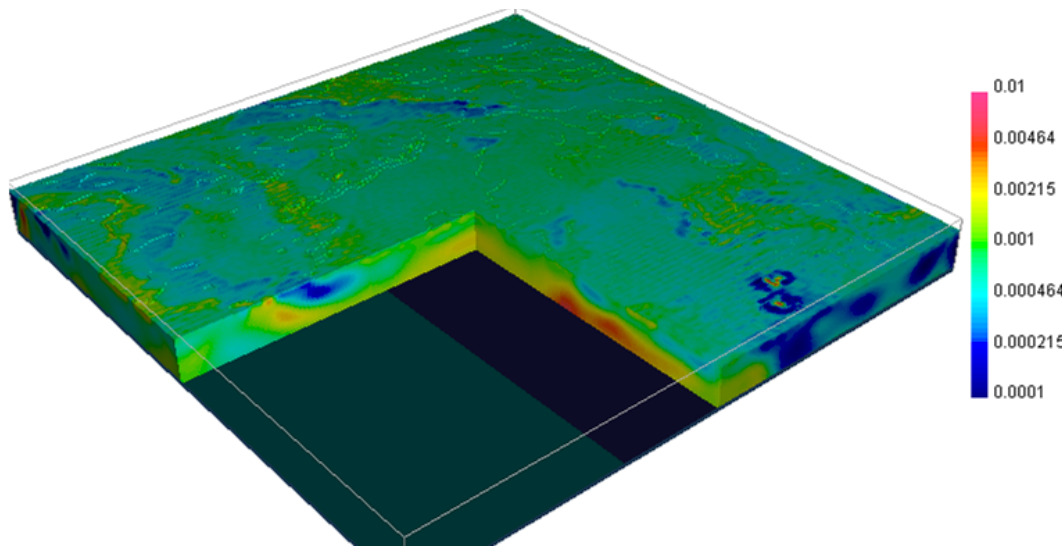
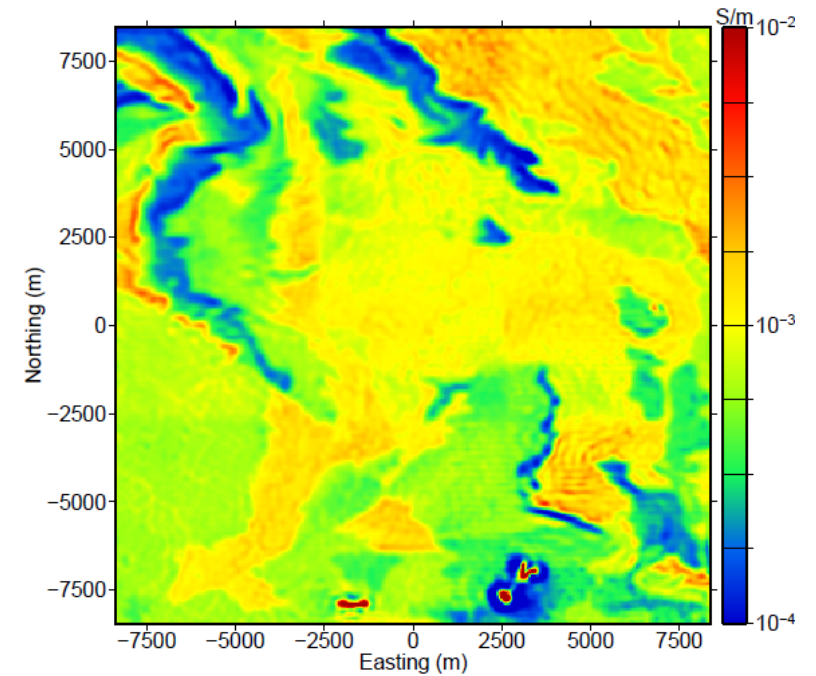- Need to invert data

True model at 275m depth
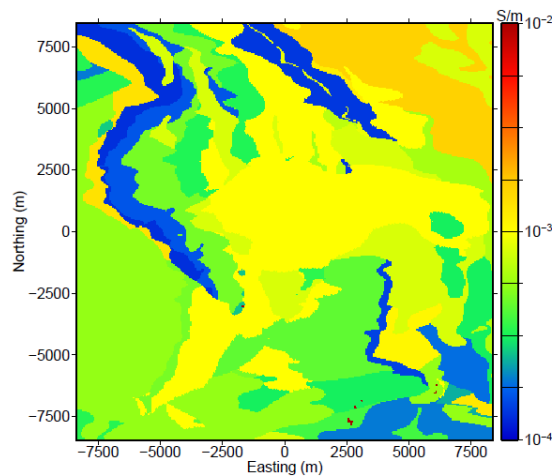
Observed (90 Hz)

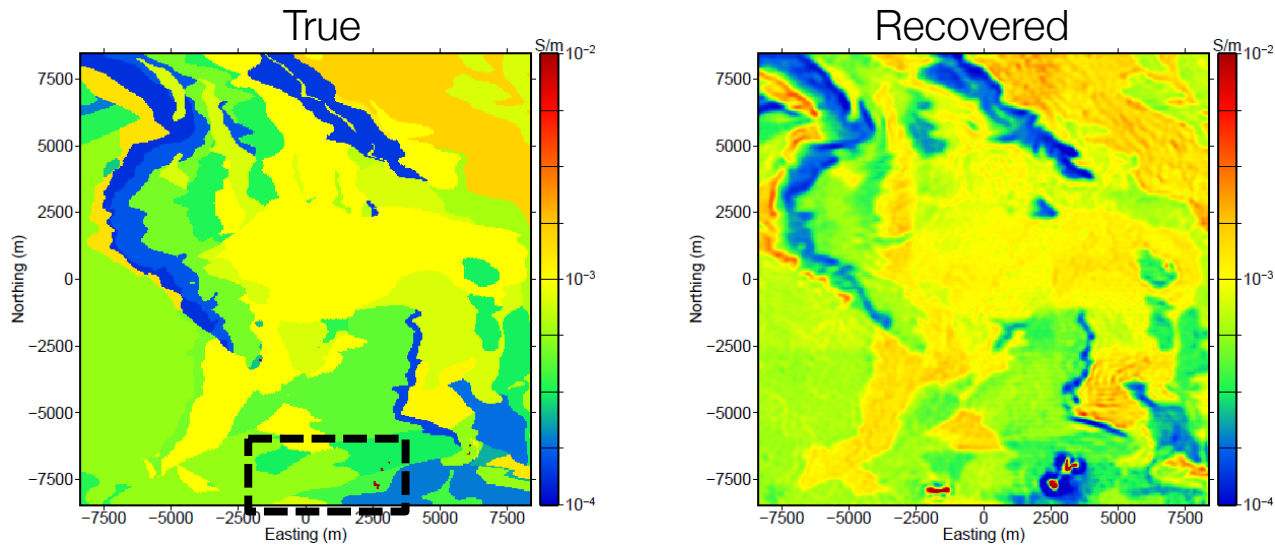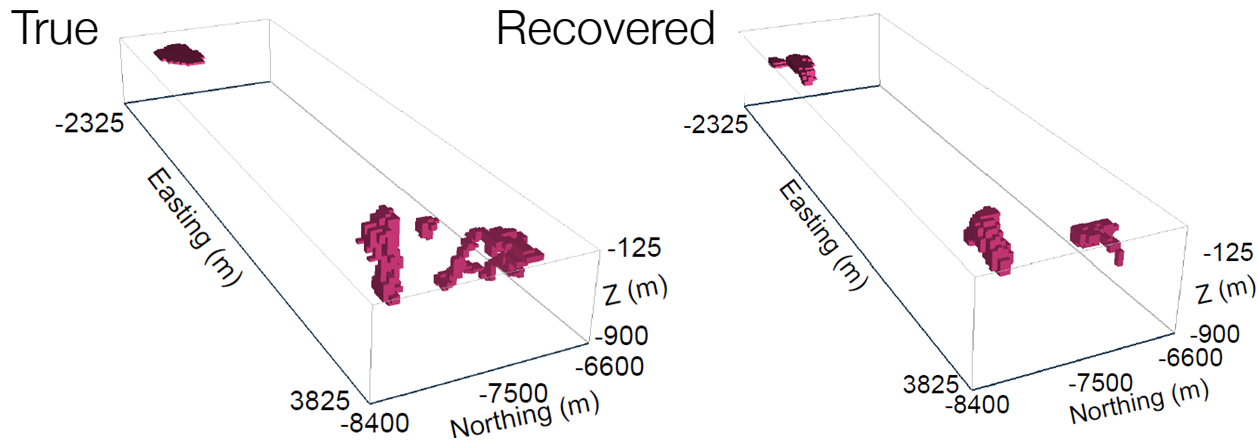# Interpretation

Recovered Model

Model at 275m depth

- Geologic units are well mapped

- Some mineralized bodies are located

Synthesis

- Recovered model represents the regional geology
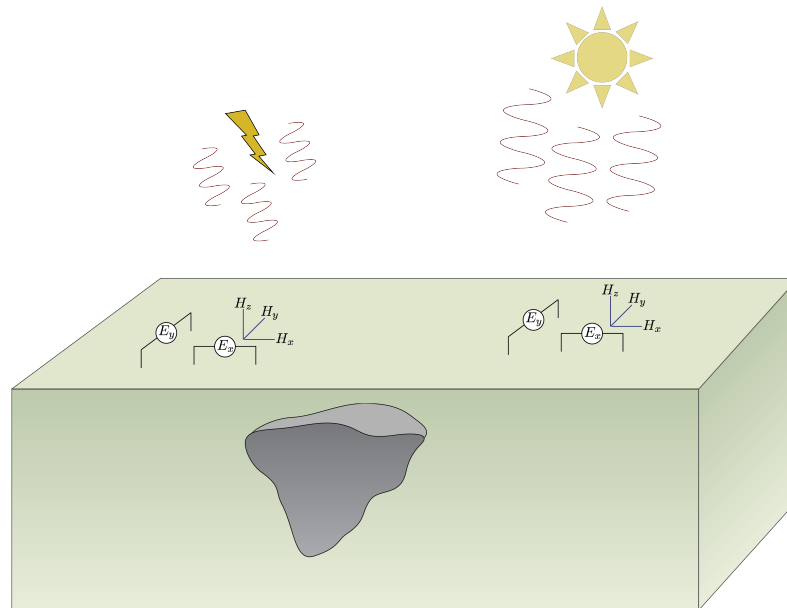

True   Recovered

- Mineralized zones are recovered

True   Recovered

Summary

- Background on natural source EM methods

- Magnetotellurics

- MT case history

- Z-axis tipper electromagnetics

- ZTEM case history

End of Natural Sources

DC Resistivity · EM Fundamentals · Inductive Sources · Grounded Sources · Natural Sources · GPR · Induced Polarization · The Future

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Lunch: Play with apps