EM: Natural Sources

DISC

2017

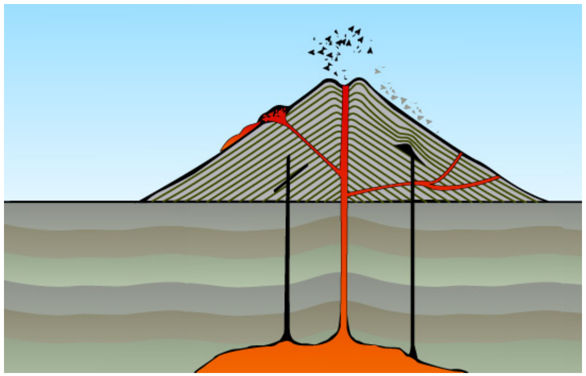
Electromagnetics
Fundamentals and Applications

Outline

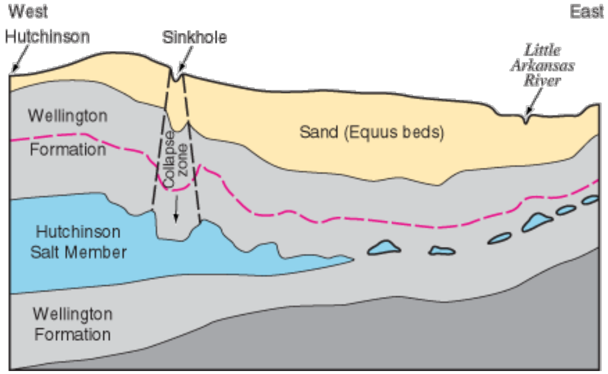
- Background on natural source EM methods
- Magnetotellurics
- Case histories: Geothermal, Minerals
- Z-axis tipper electromagnetics
- Case histories (ZTEM): Geologic Mapping, Minerals

Motivation

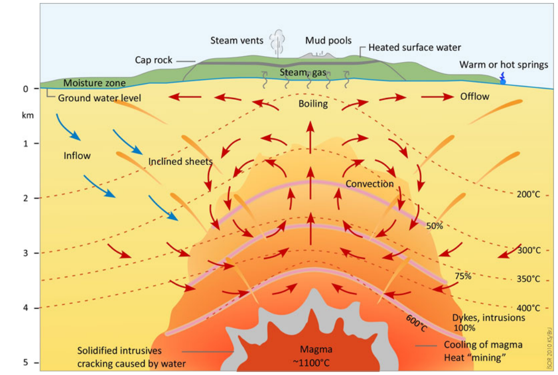
Volcanoes



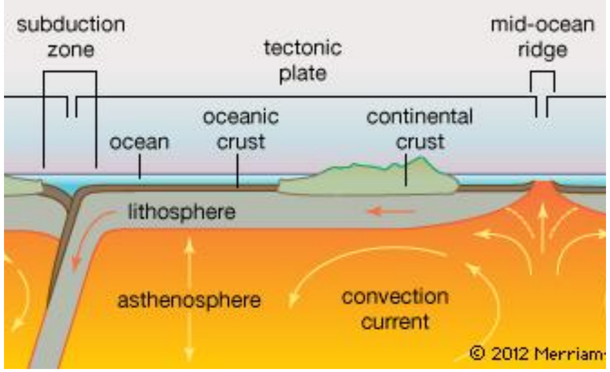
Base of salt



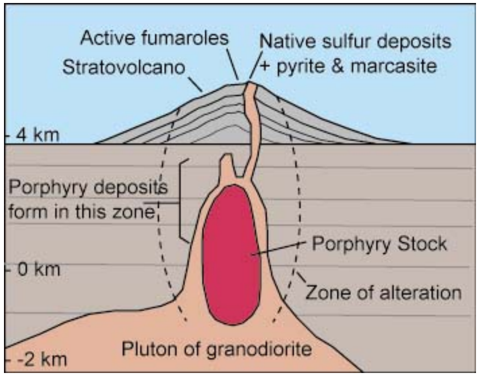
Geothermal



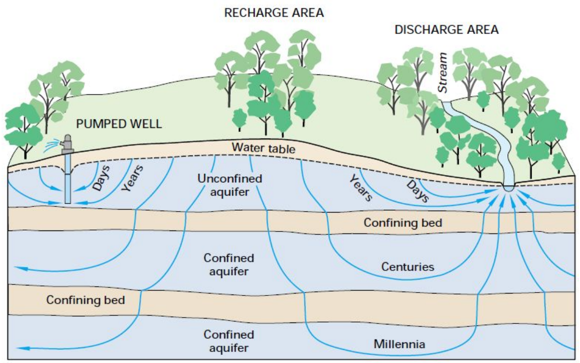
Tectonic settings of top few km



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

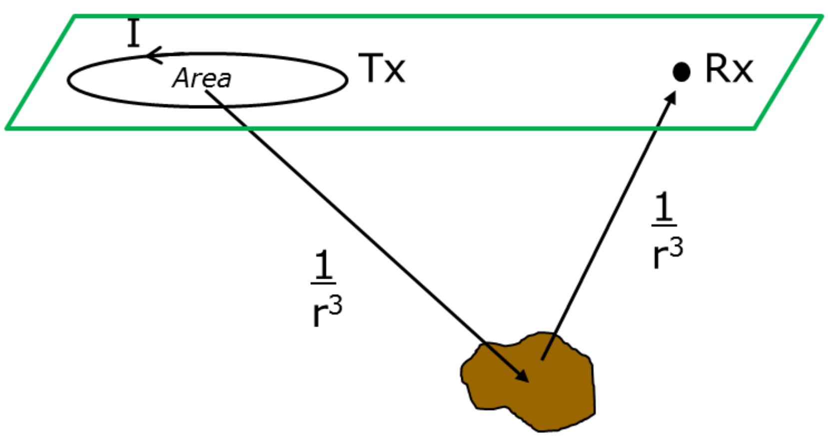
$$m = IA$$

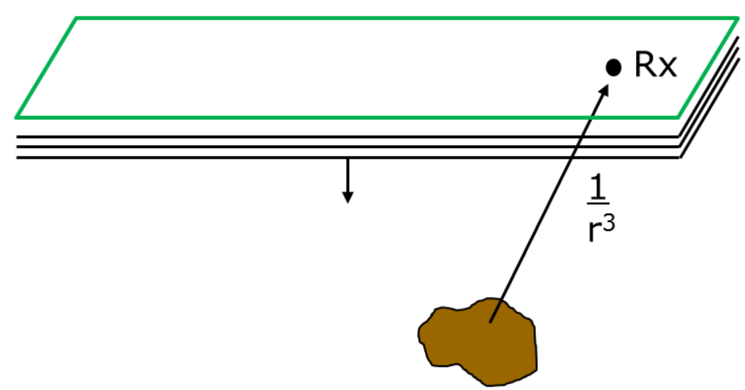
  - Total geometric decay

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

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

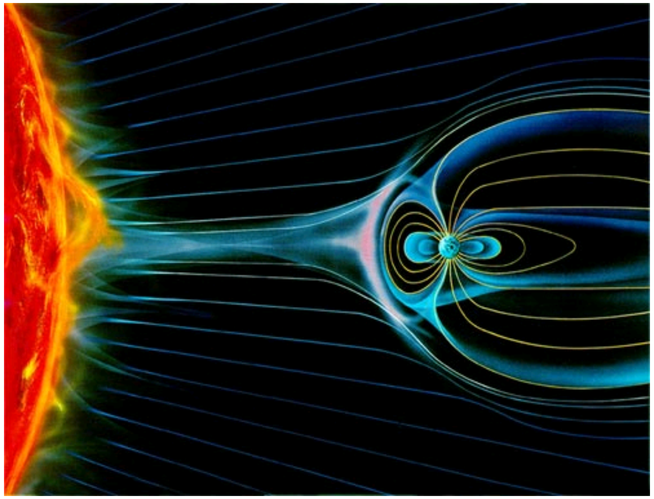
$$\sim \frac{1}{r^3}$$





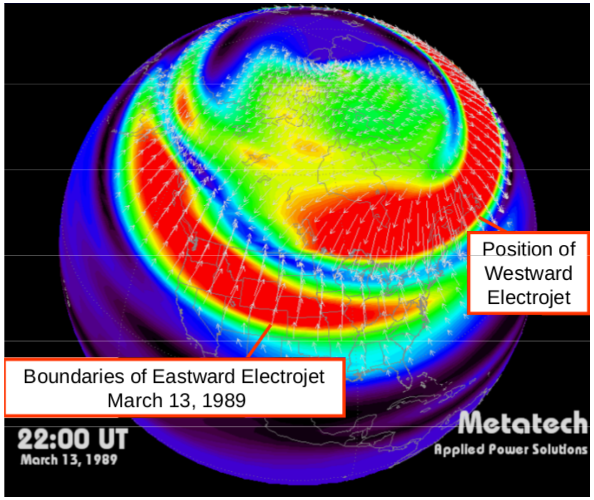
Natural EM sources

Sun and magnetosphere, solar storms

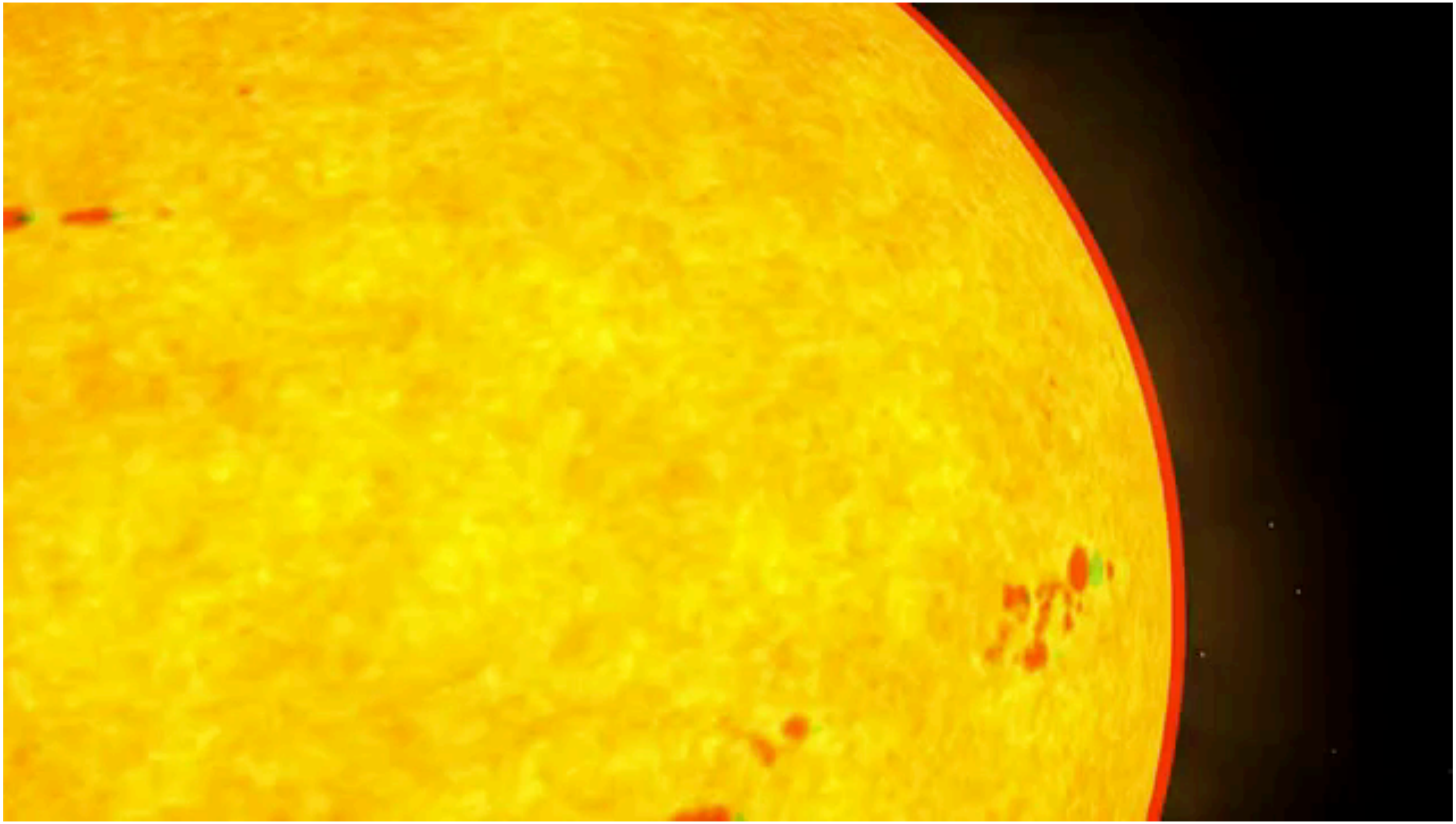


Lightning

Auroral electrojet; aurora

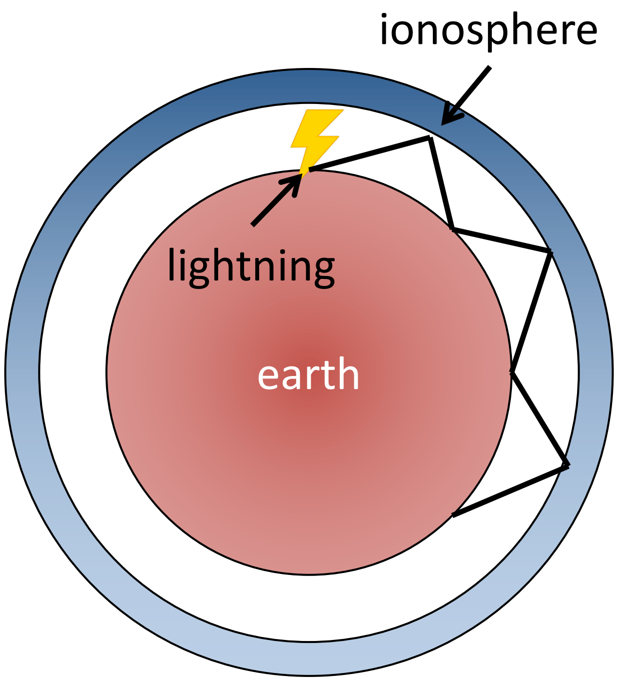


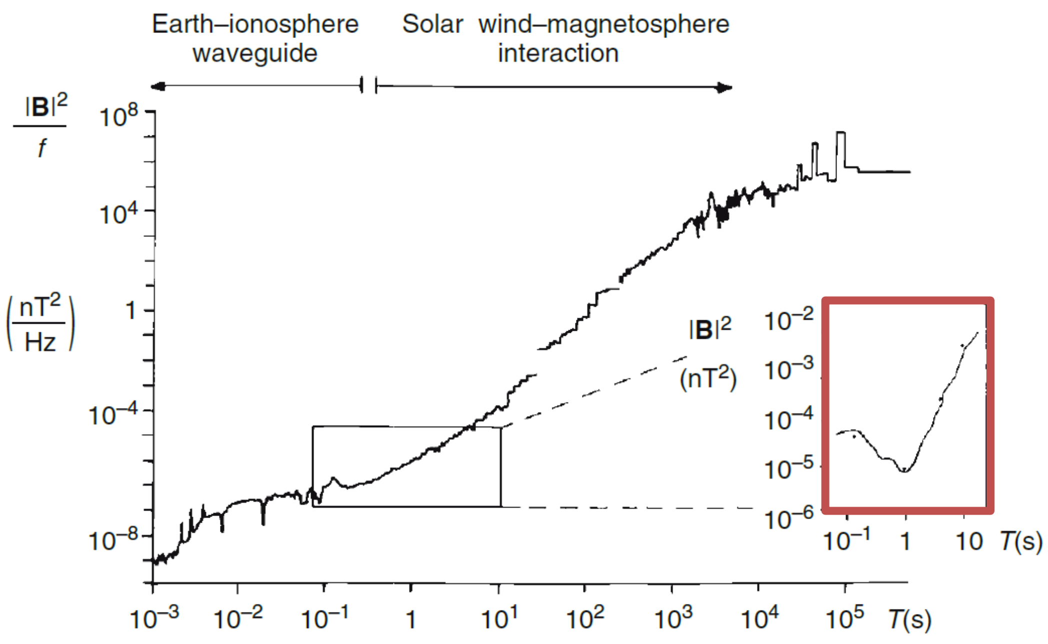
Aurora movie



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

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

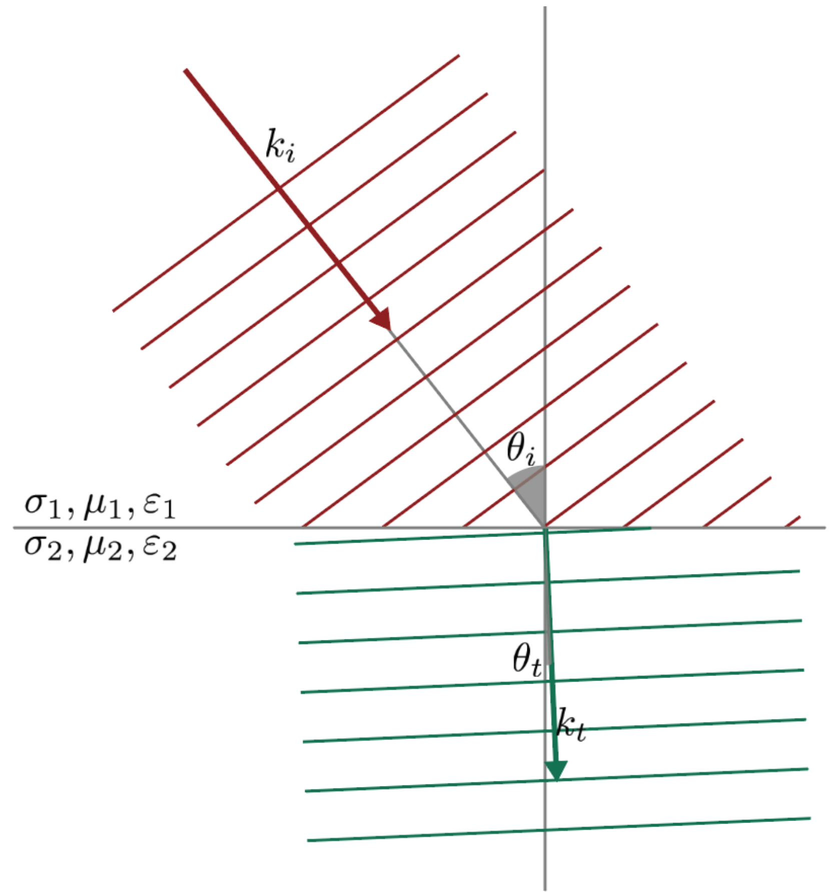
- k is complex wave number

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

- 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 $\theta_t = 1.35°$

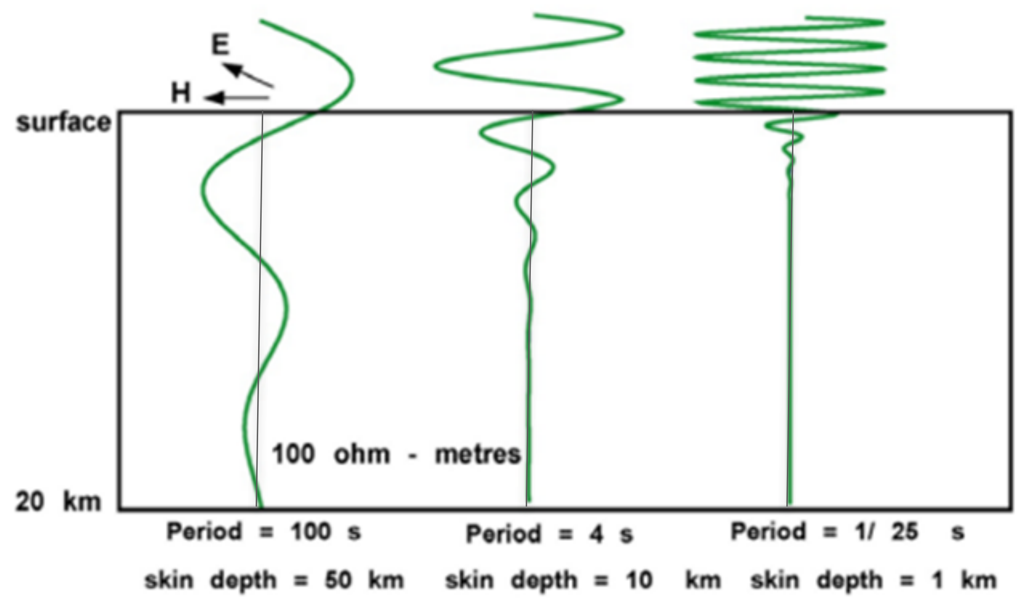
Plane waves and skin depth

- Skin depth (meters)

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

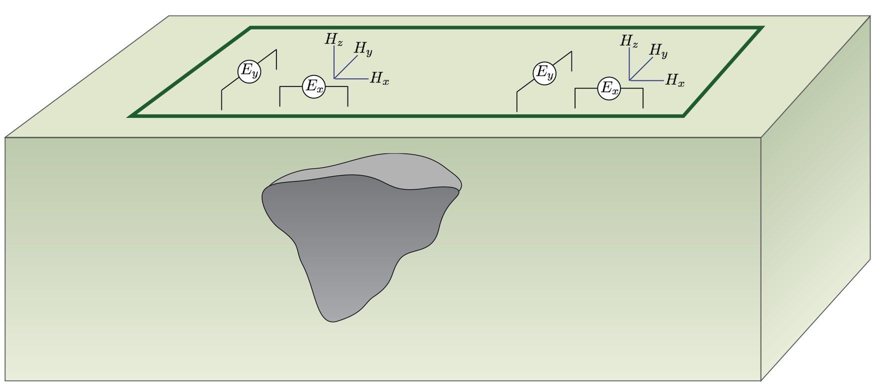
- Low frequency waves propagate further

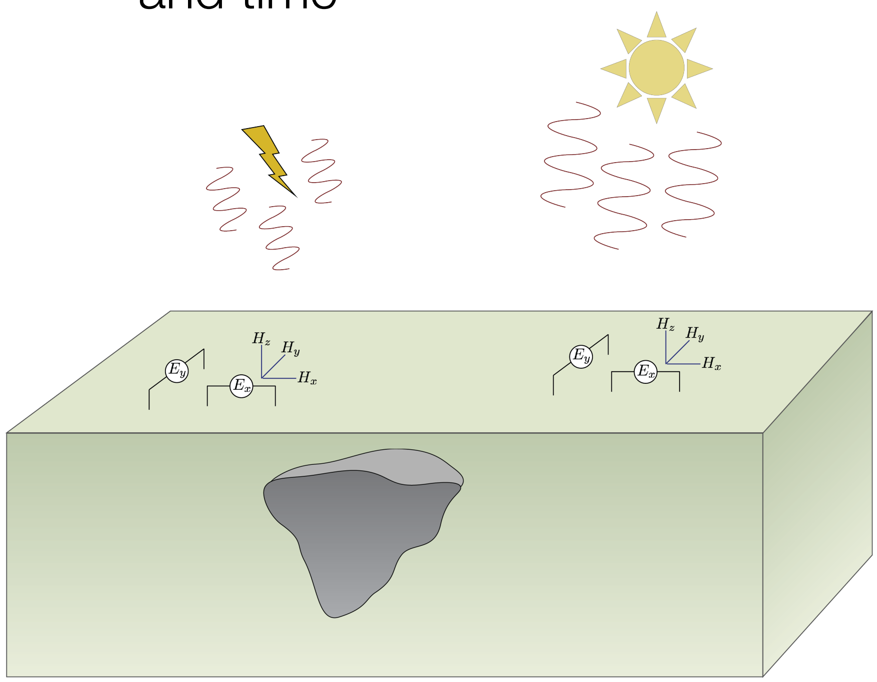
- Depth of propagation
  - A few skin depths
  - Only a portion of a wavelength



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

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

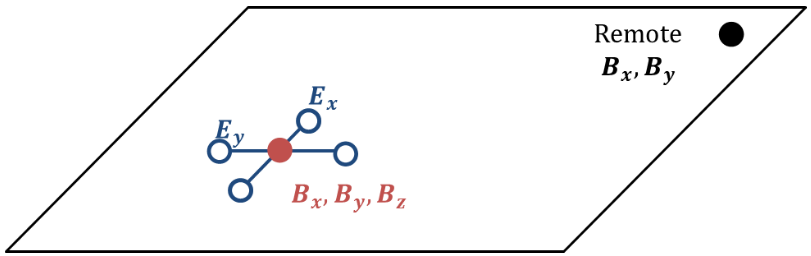
- Effects of unknown source removed by taking ratio

- Transfer function

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

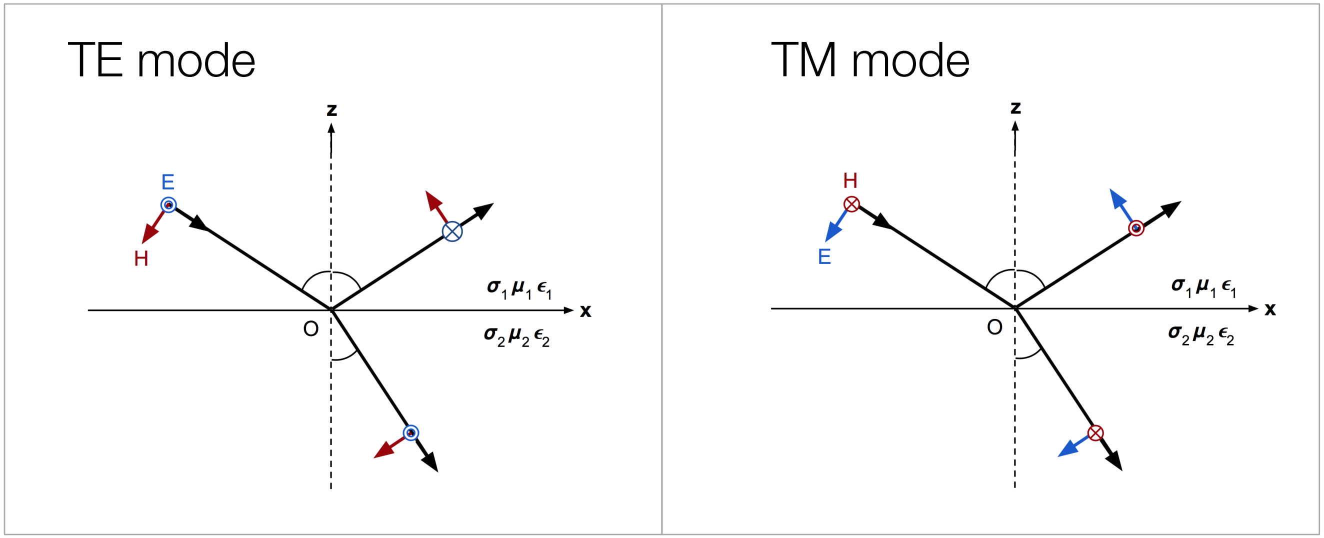
impedance (matrix)

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



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:

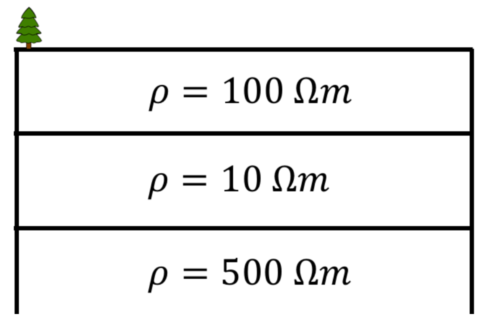
$$\Phi = \tan^{-1}\left(\frac{Im(Z_{xy})}{Re(Z_{xy})}\right)$$

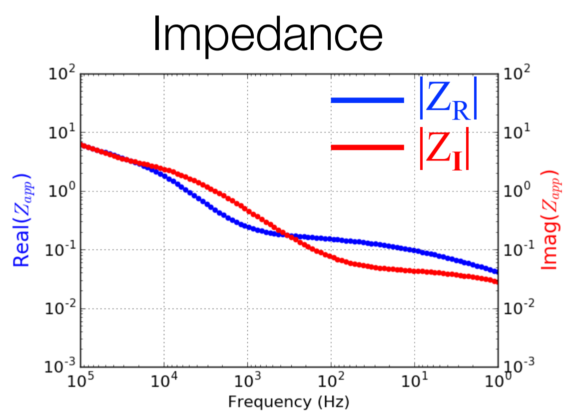
- In 1D:

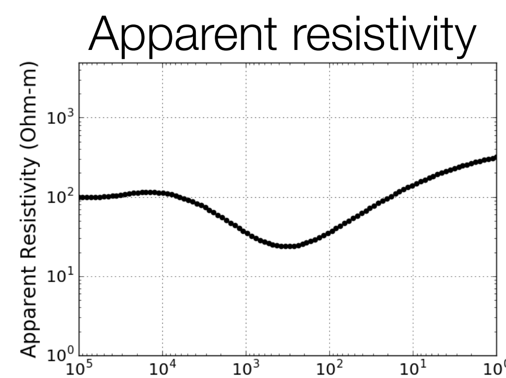
$$Z = \begin{pmatrix} 0 & Z_{xy} \\ Z_{yx} & 0 \end{pmatrix}$$

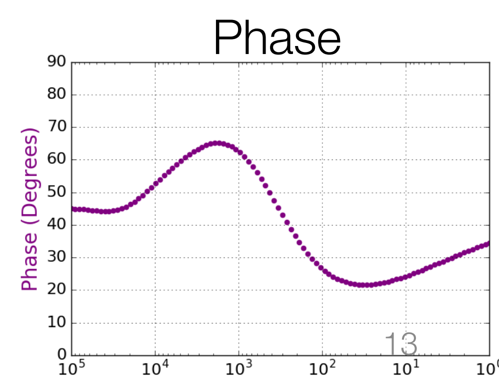
$$Z_{xy} = \frac{E_x}{H_y}$$

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





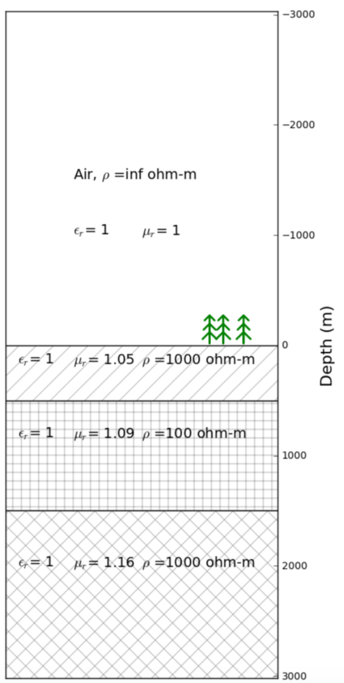


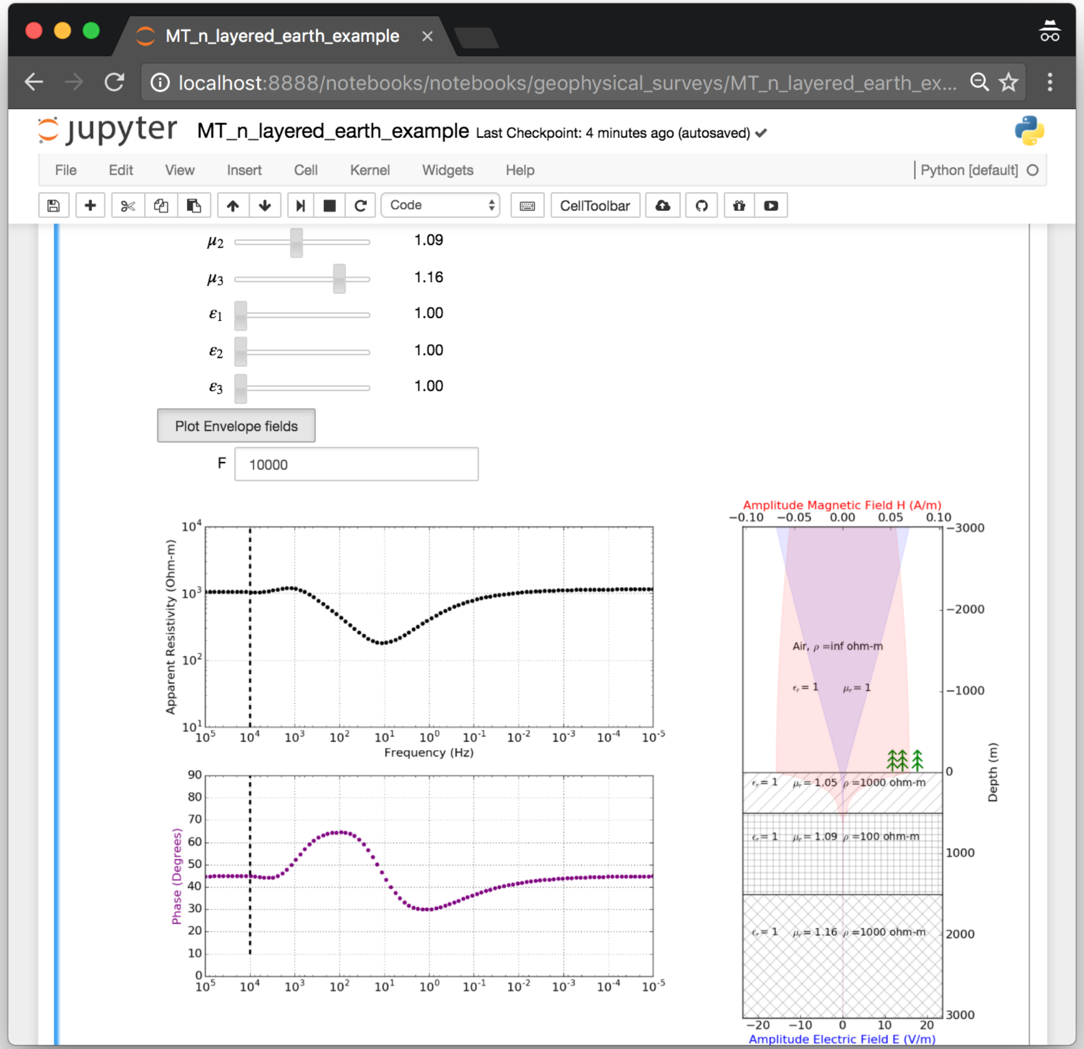


1D MT app

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

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





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

MT soundings in 2D

- In general:

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

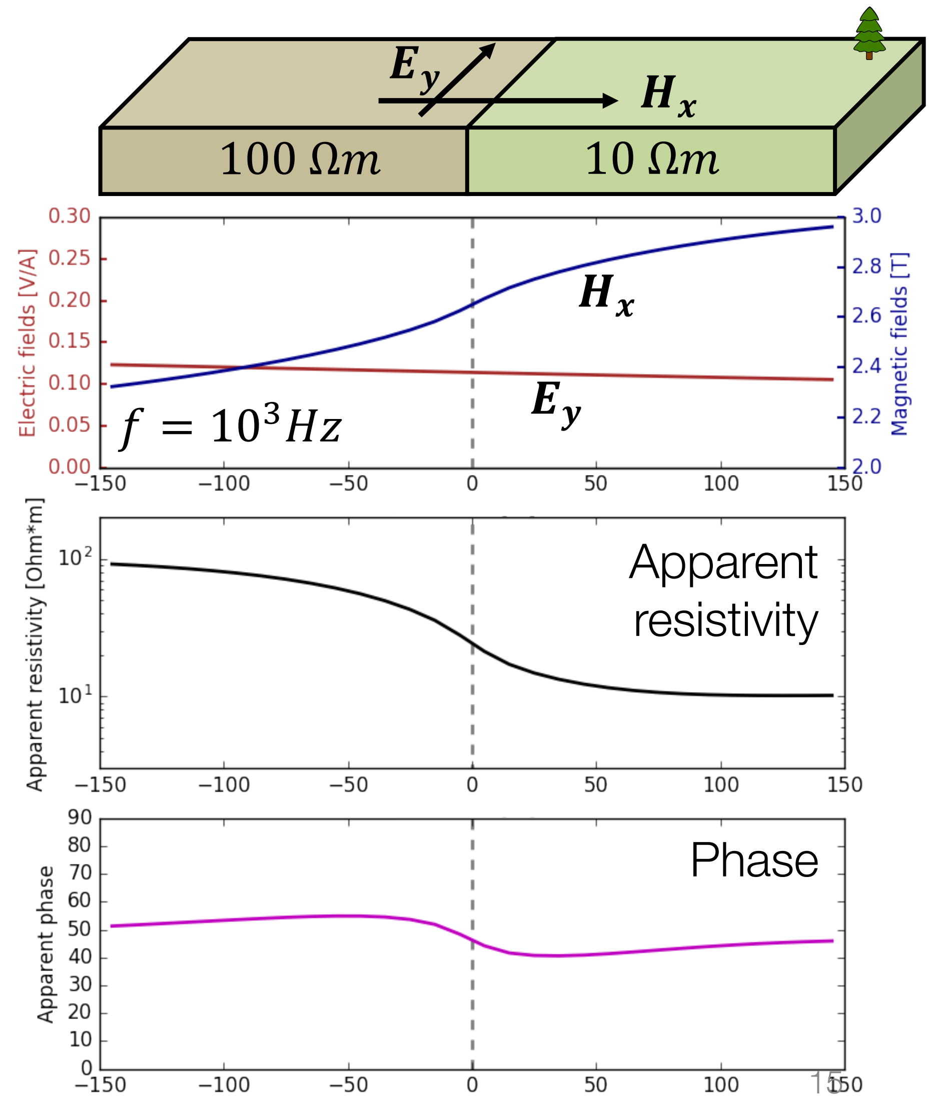
- In 2D:

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

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

- TE mode
  - E-field parallel to structure

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



MT soundings in 2D

- In general:

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

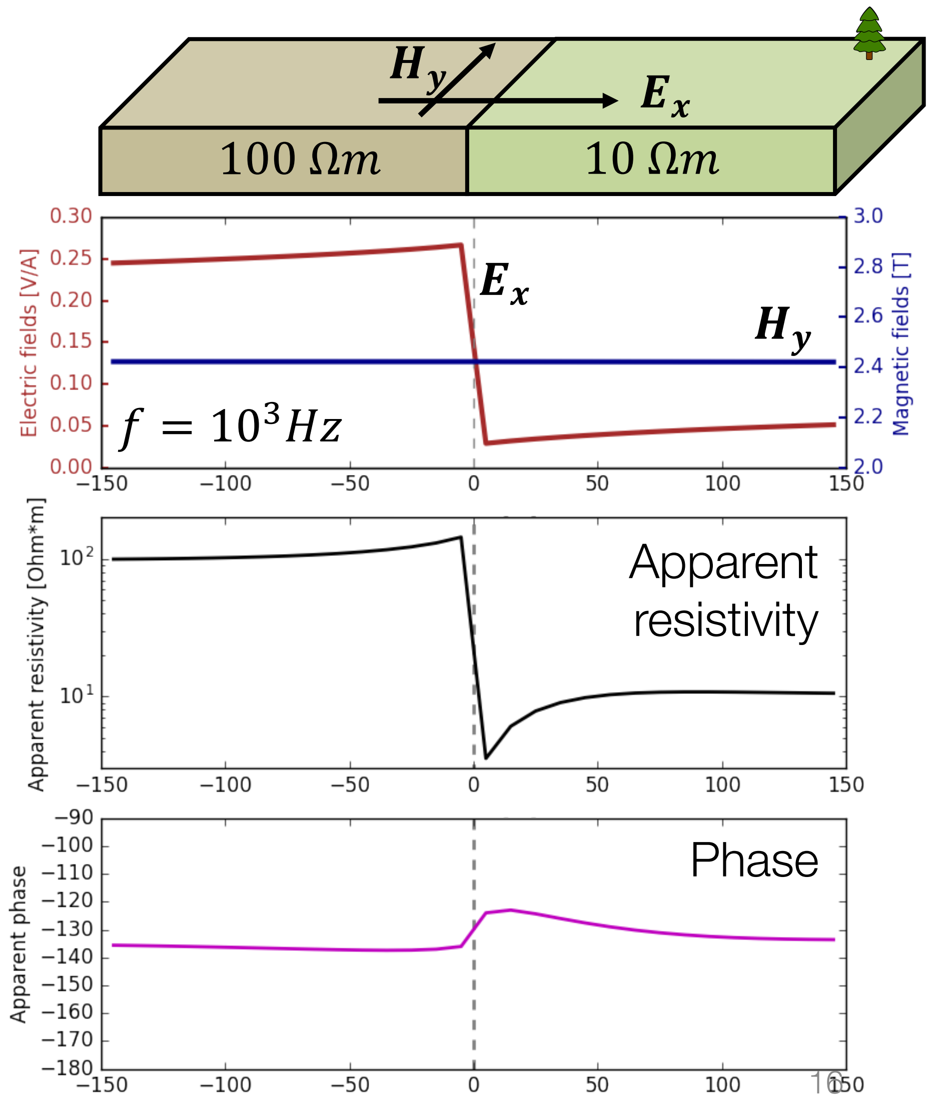
- In 2D:

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

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

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

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



MT soundings in 3D

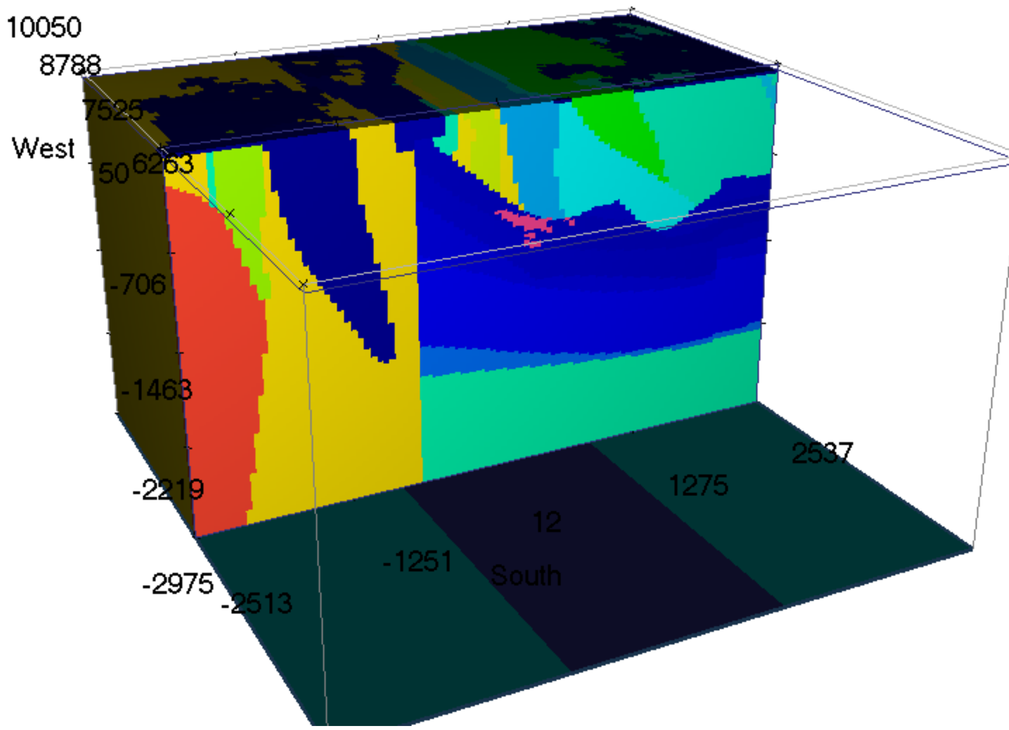
- In general:

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

- In 3D:

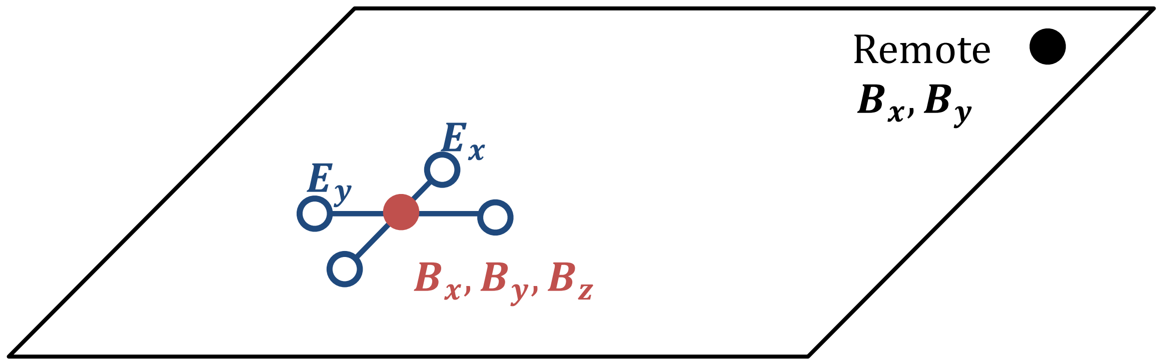
$$Z = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$$

- No symmetry or special conditions



Measuring MT data

- Basic acquisition

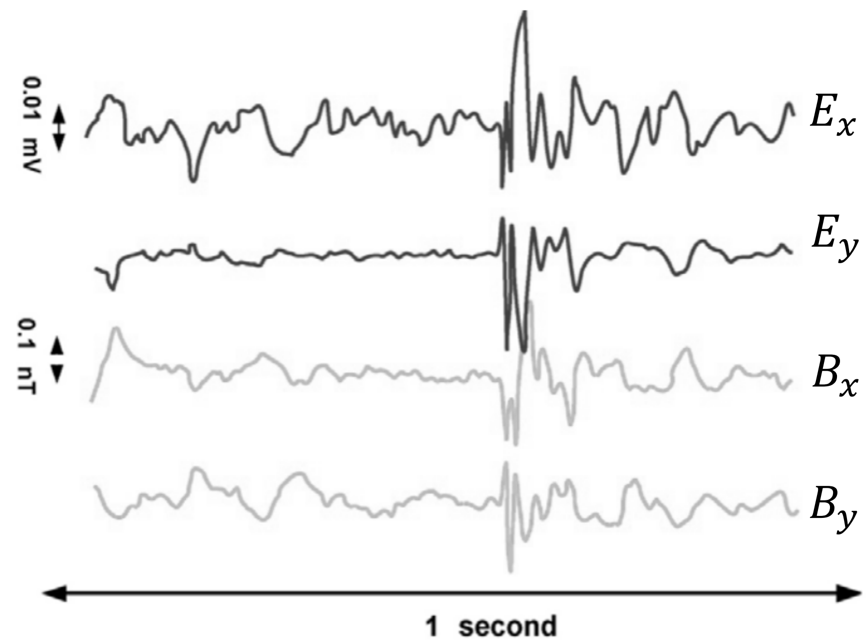


- At each station, measure:

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

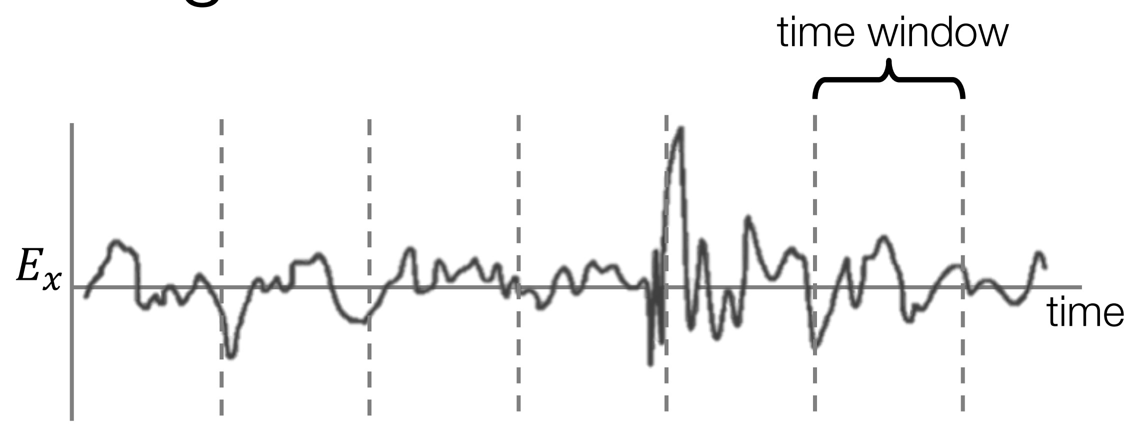
- At remote reference, measure:

$$B_x, B_y$$



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

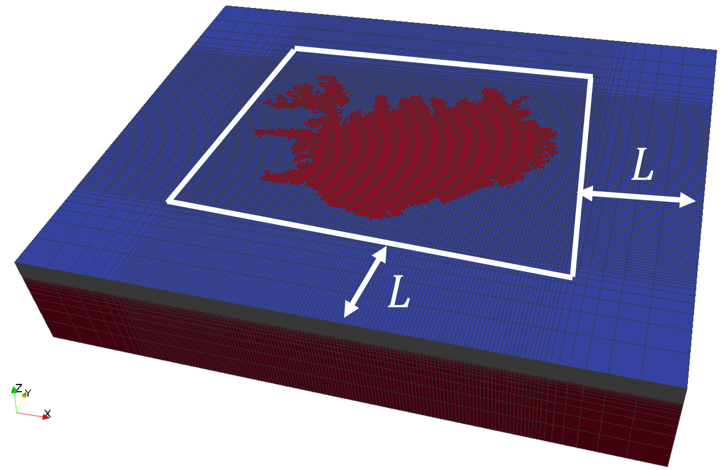
- Boundary conditions important for modelling

- 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

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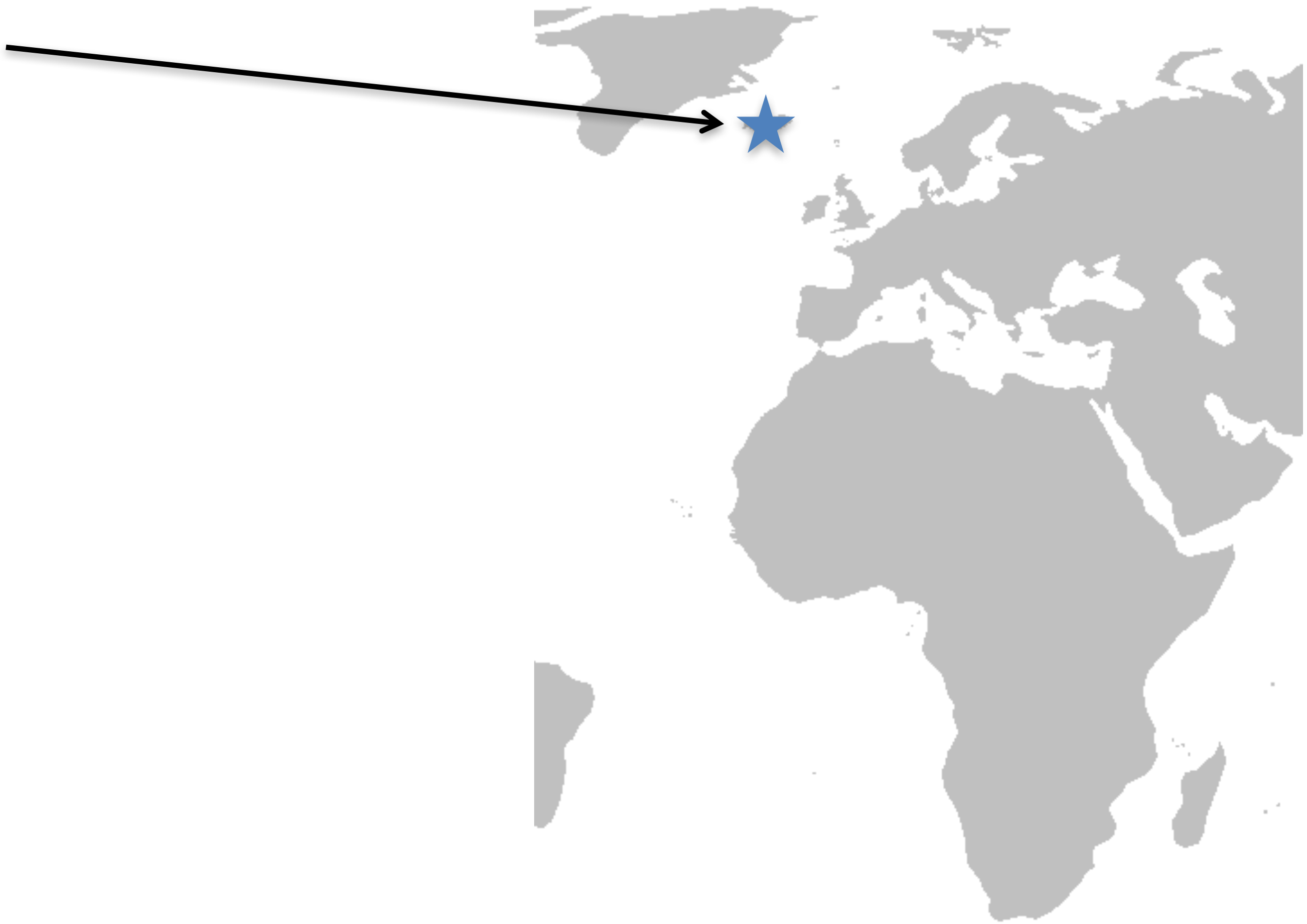
- Magnetotellurics
- Case histories: Geothermal, Minerals
- Z-axis tipper electromagnetics
- Case histories (ZTEM): Geologic Mapping, Minerals

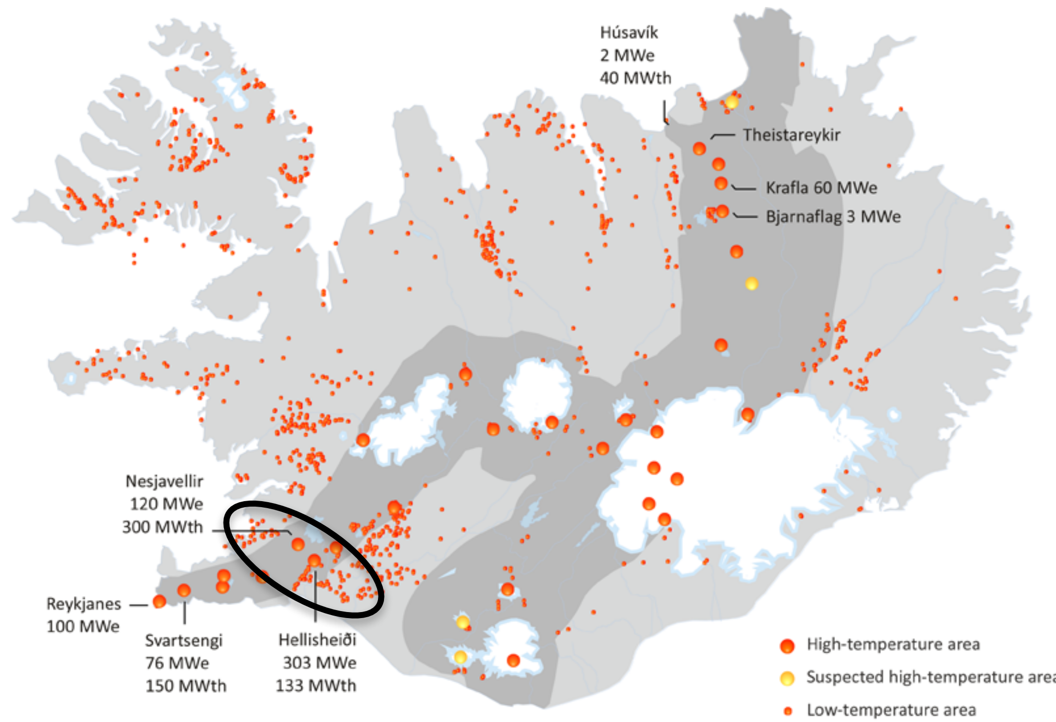
MT case history

- Iceland



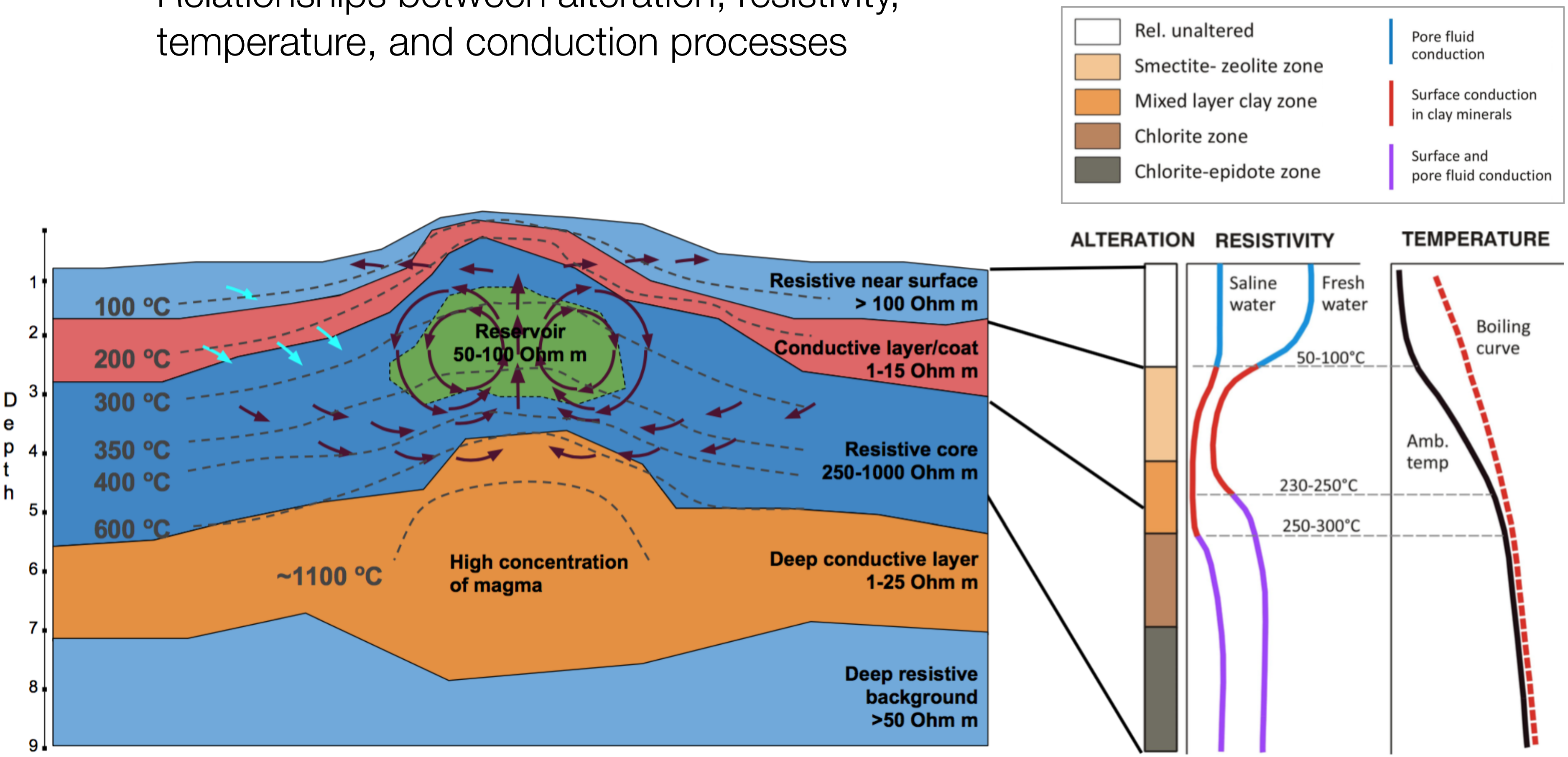
Hengill geothermal region: setup

- Iceland: geothermal hot spot
  - On the mid-Atlantic ridge
  - Hosts multiple high temperature geothermal systems
- Hengill geothermal area
  - Supplies majority of hot water in Reykjavik
  - Contributes ~450 Mwe to National power grid

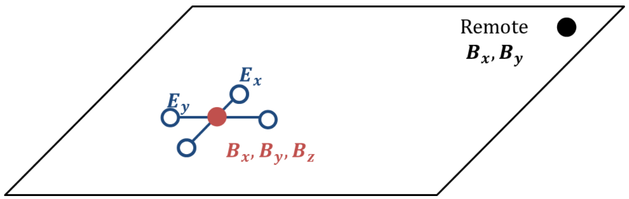


Physical properties

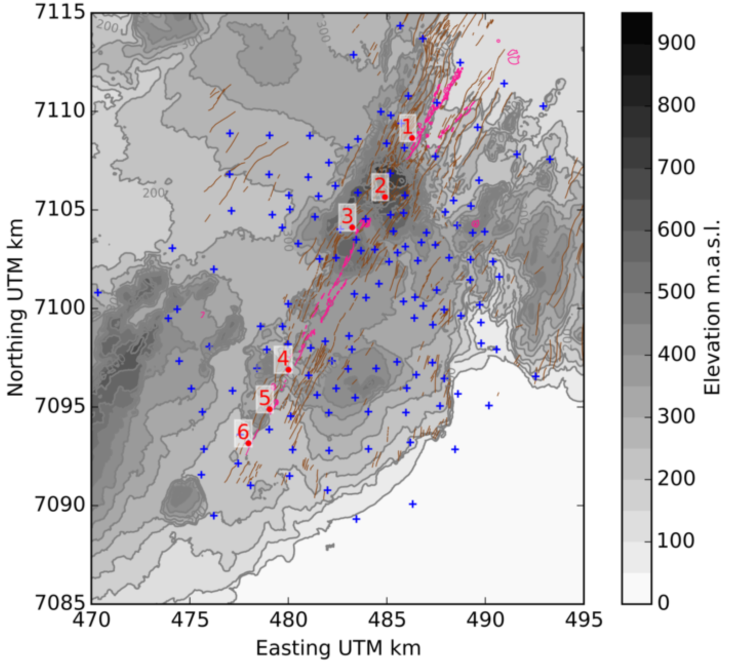
- Relationships between alteration, resistivity, temperature, and conduction processes



Survey

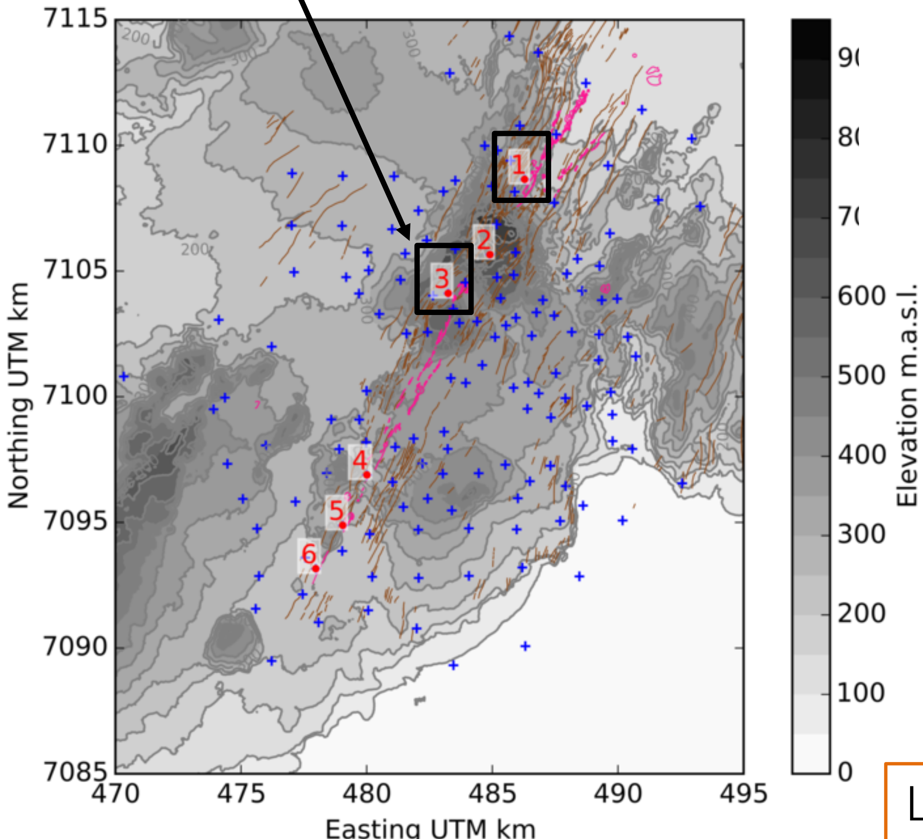


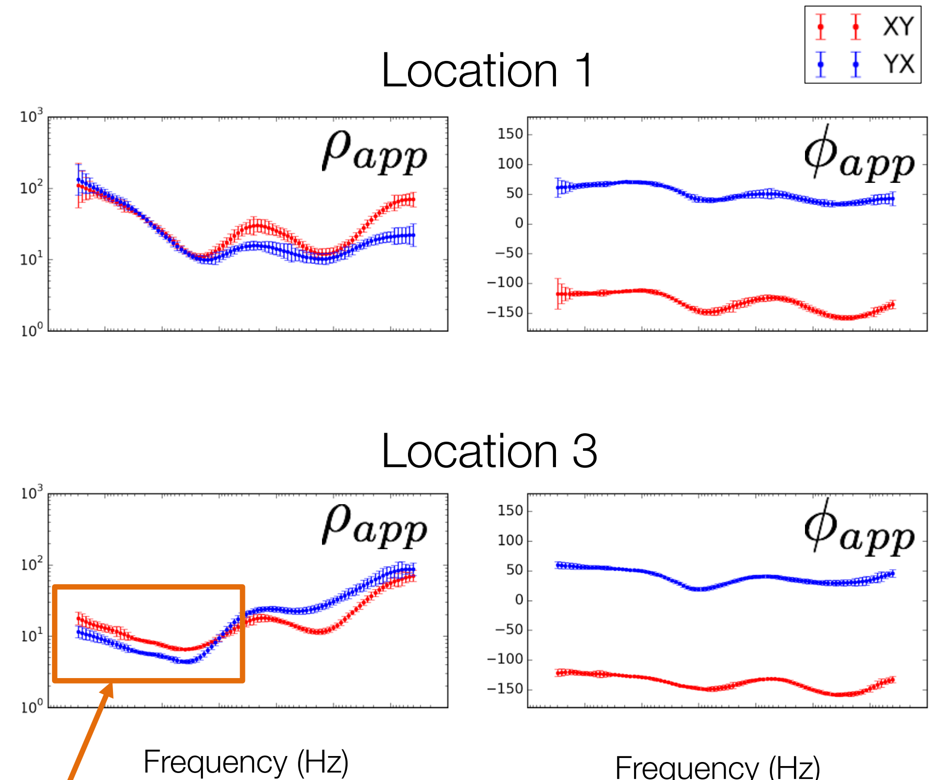
- MT instrumentation
  - Phoenix MTU5's
- Survey
  - 133 stations used
  - Combination of 2E and 2E+3H setup
  - Frequencies: 300 – 0.001 Hz
- Remote reference
  - About 40 km away
- Raw data processing using Phoenix software



Data

Surface alteration, hot water, fumaroles

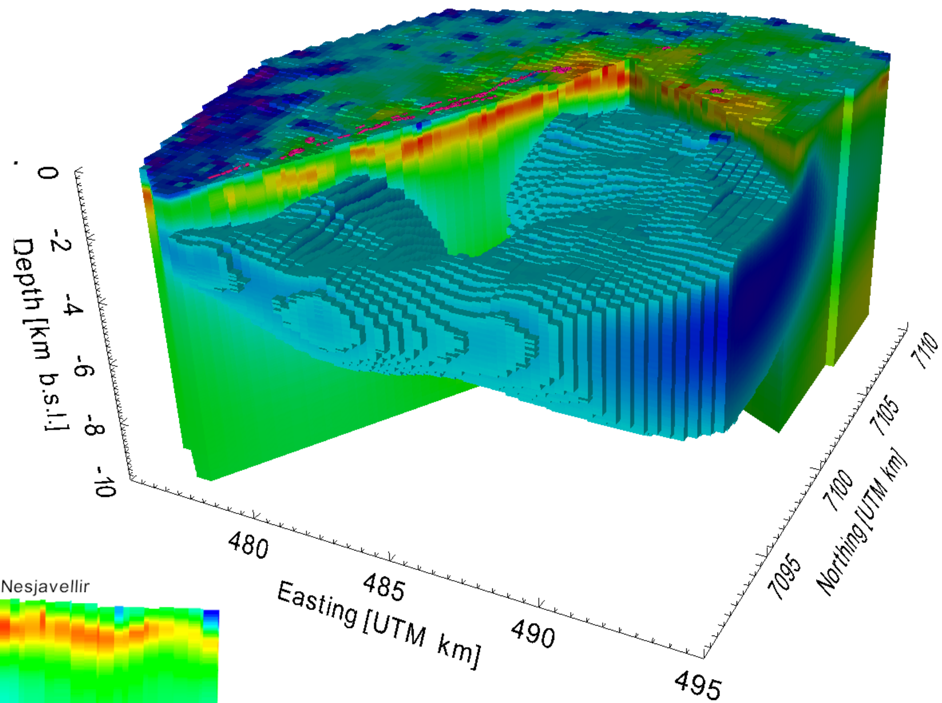


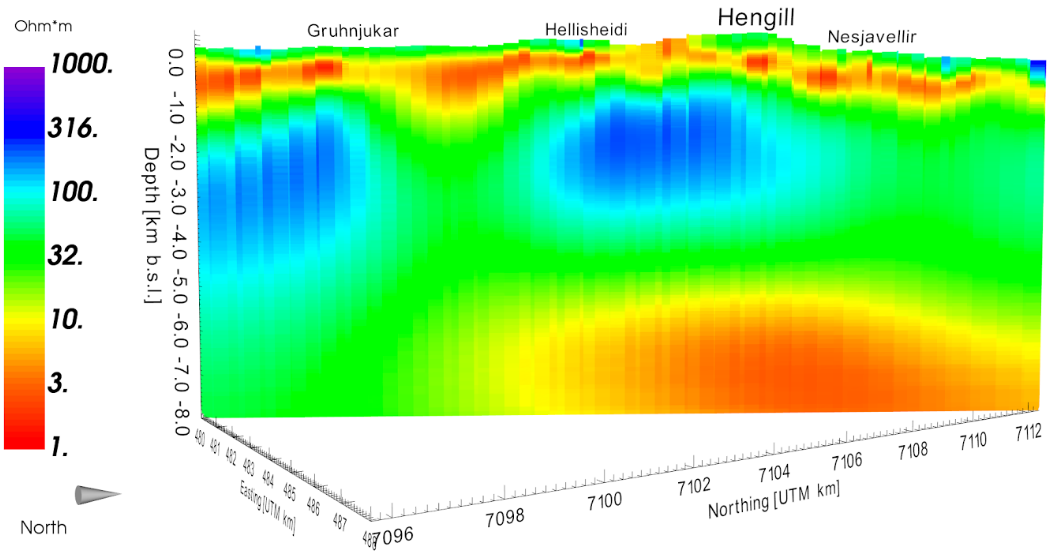


Low apparent resistivity

3D inversion

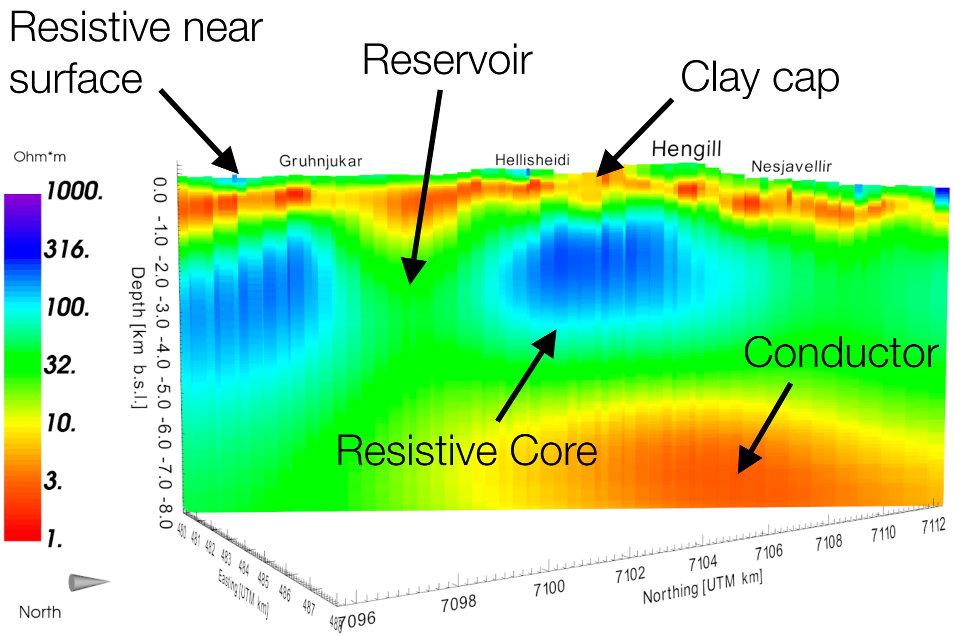
- Off-diagonal impedance (Z_{xy} and Z_{yx}) used
- Combined multi-frequency inversion (300 Hz – 0.001 Hz)

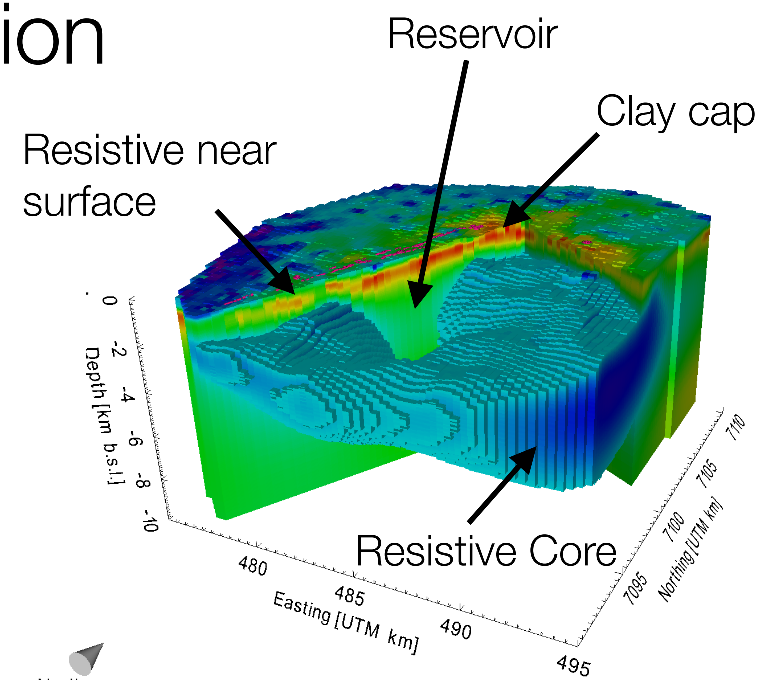


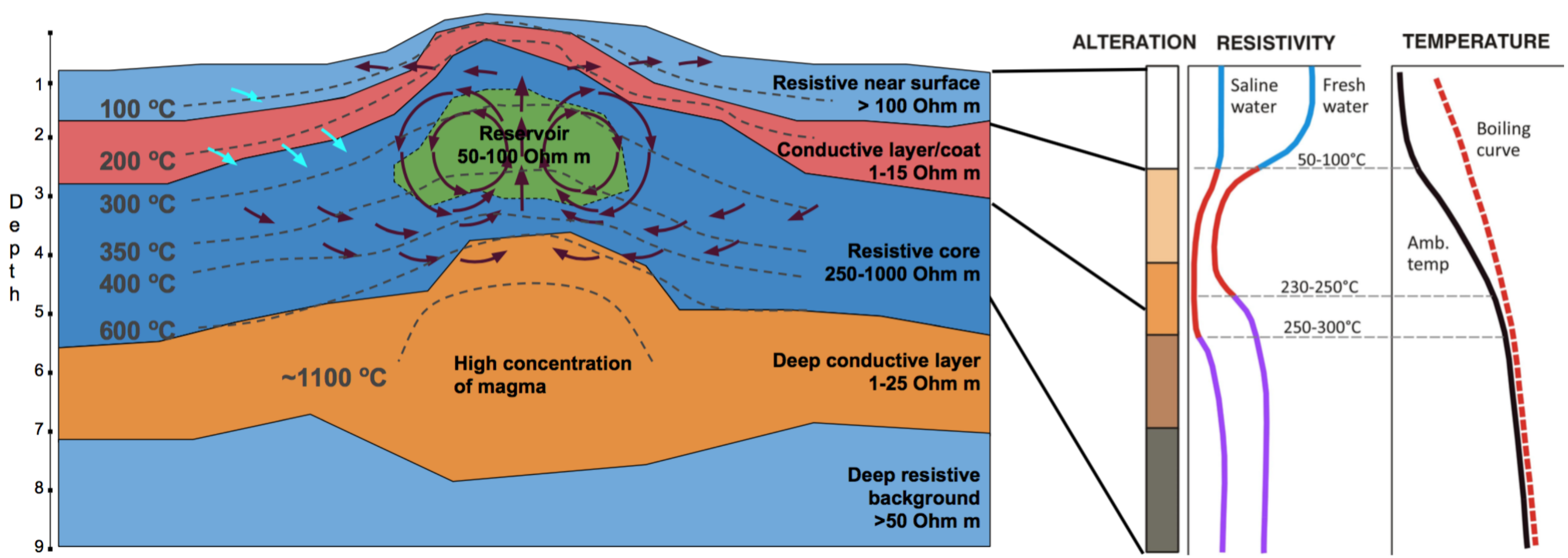


Rosenkjaer et al, 2015

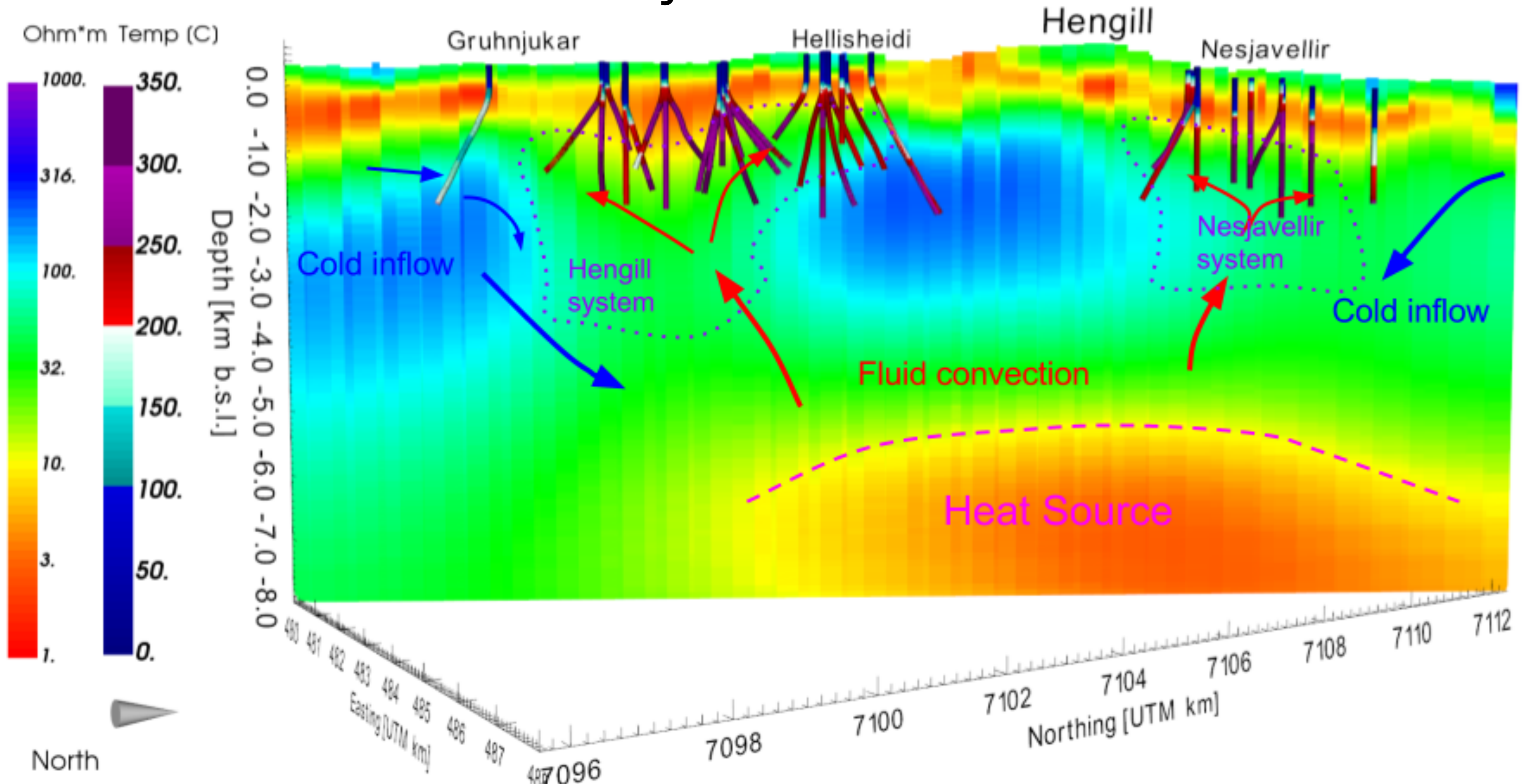
Interpretation







Synthesis

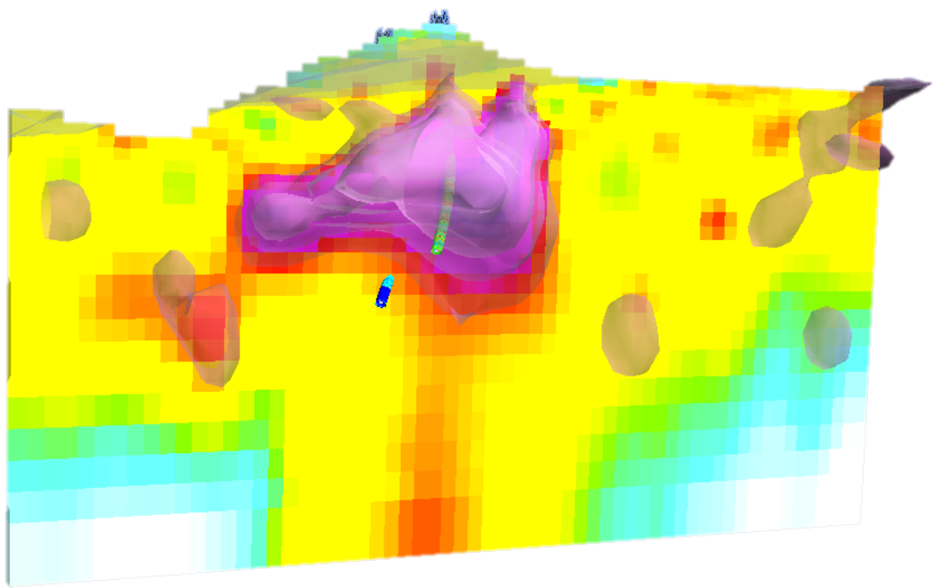


- Conductive layer corresponds with formation temperature
- Two main production fields: Hengill and Nesjavellir
- Deep conductive heat source

Case History:

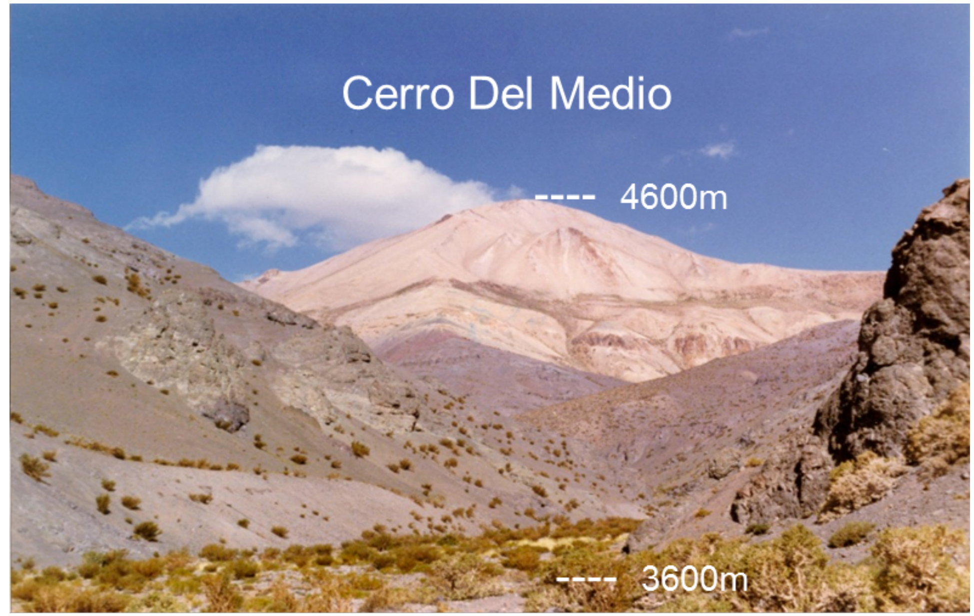
Santa Cecilia Porphyry System, Chile

Bournas and Thomson, 2013



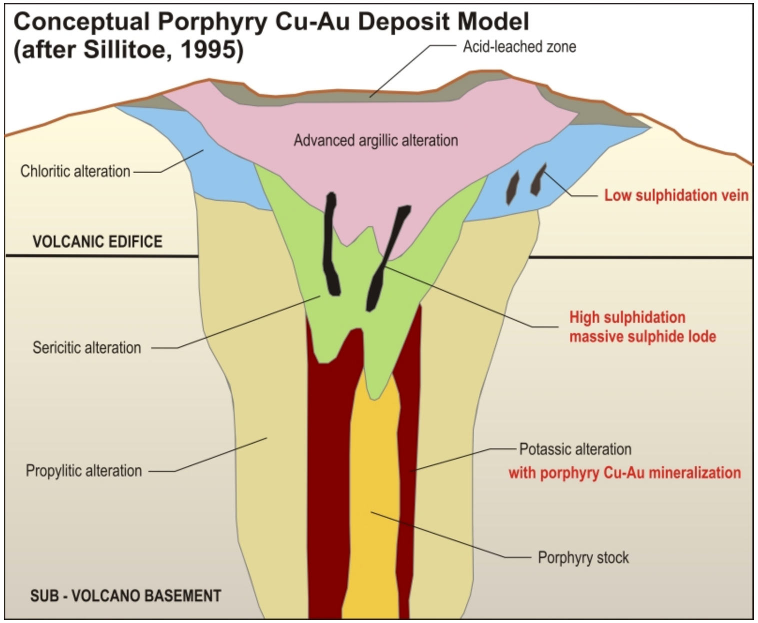
Thanks to Rob Hearst at [Quantec]

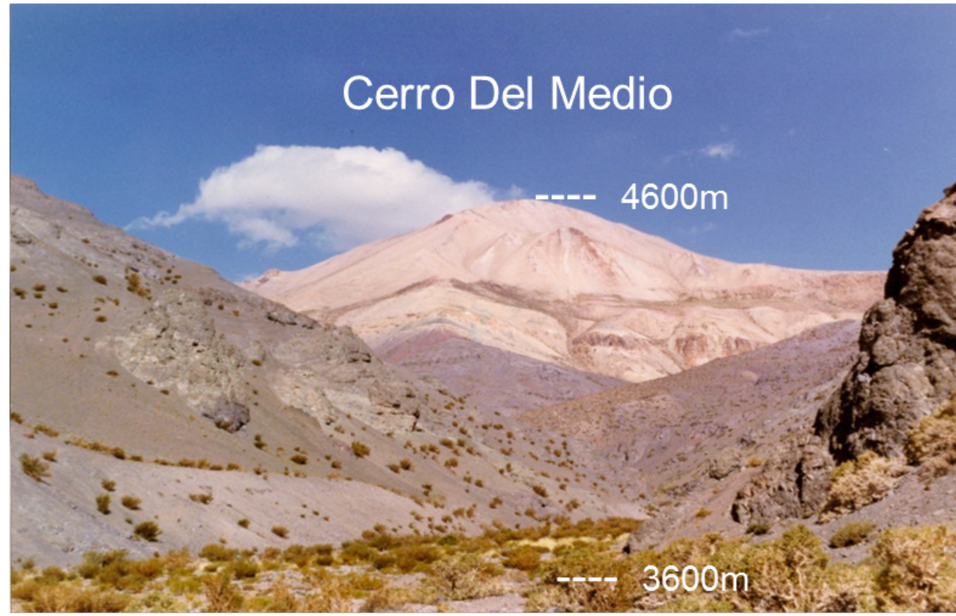
Setup



- Within the Maricunga Metallogenic Belt which hosts known gold-copper deposits
- Intense hydrothermal alteration (elevation between 3600 – 4600 m)
- Main mineralization: gold, silver, and copper

Setup





- Within the Maricunga Metallogenic Belt which hosts known gold-copper deposits
- Intense hydrothermal alteration (elevation between 3600 – 4600 m)
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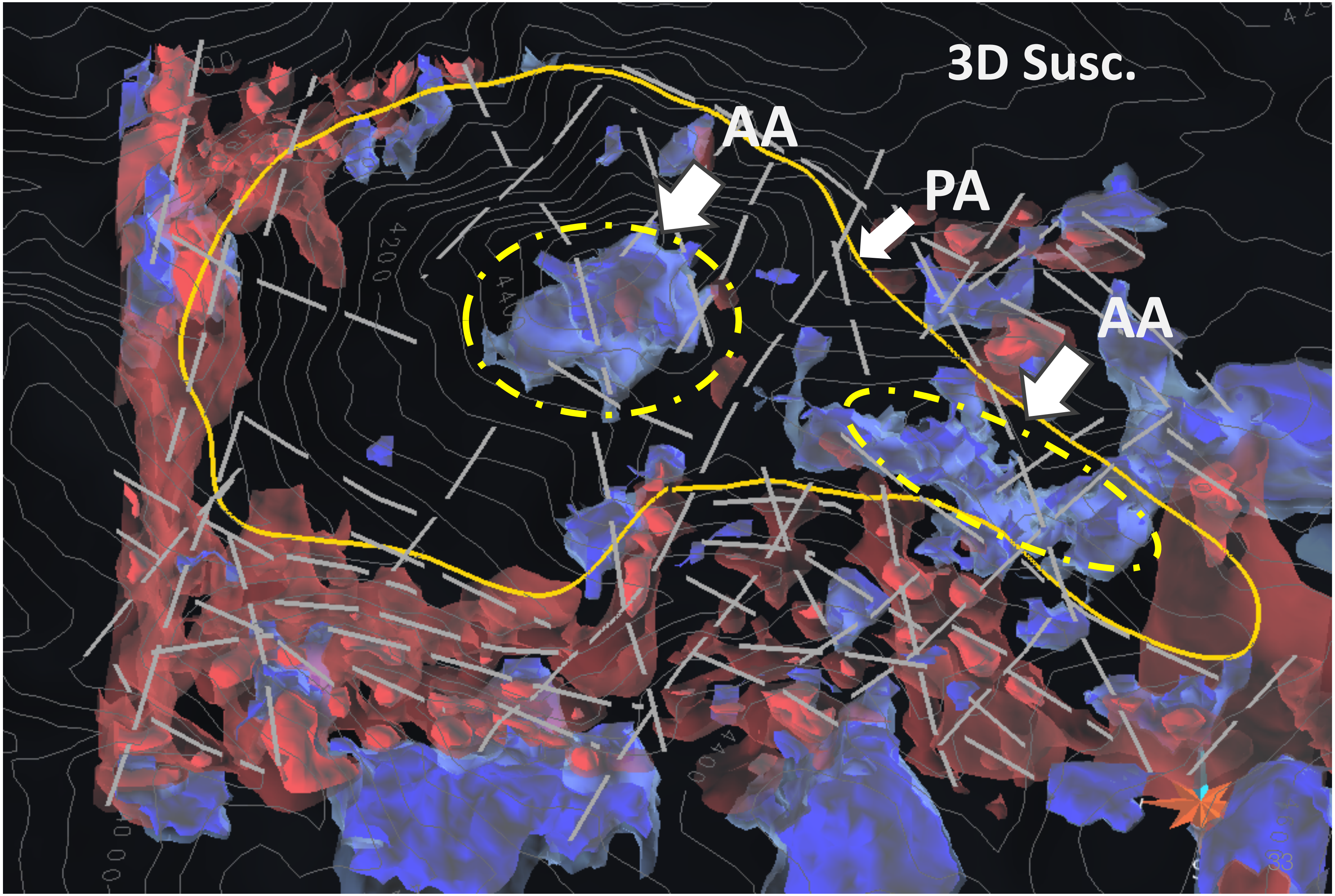
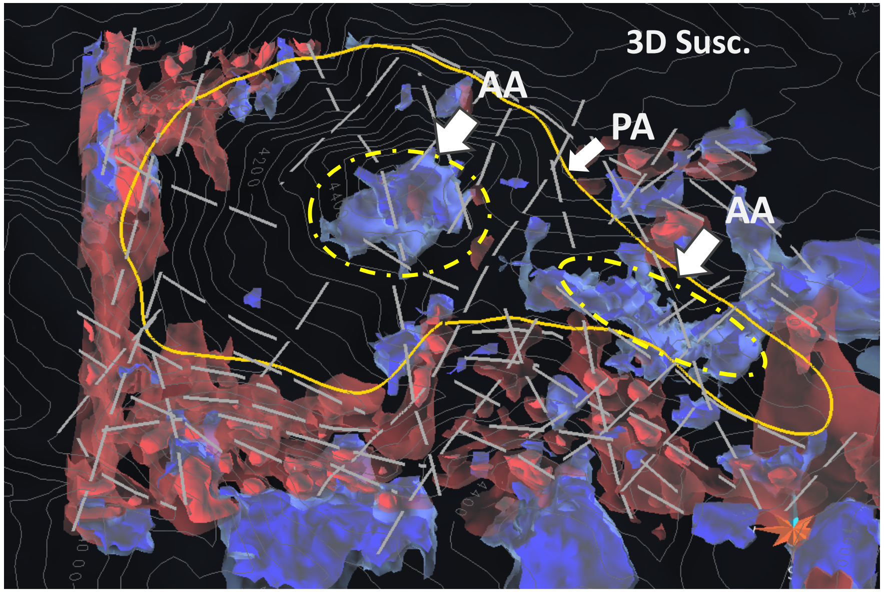
Can we image the porphyry system?

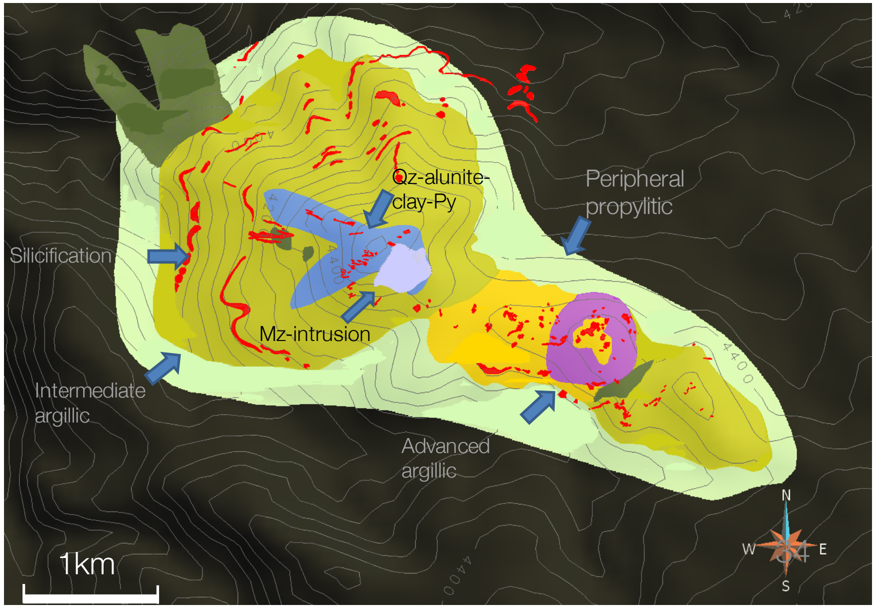
Setup: Ground Magnetics Inversion



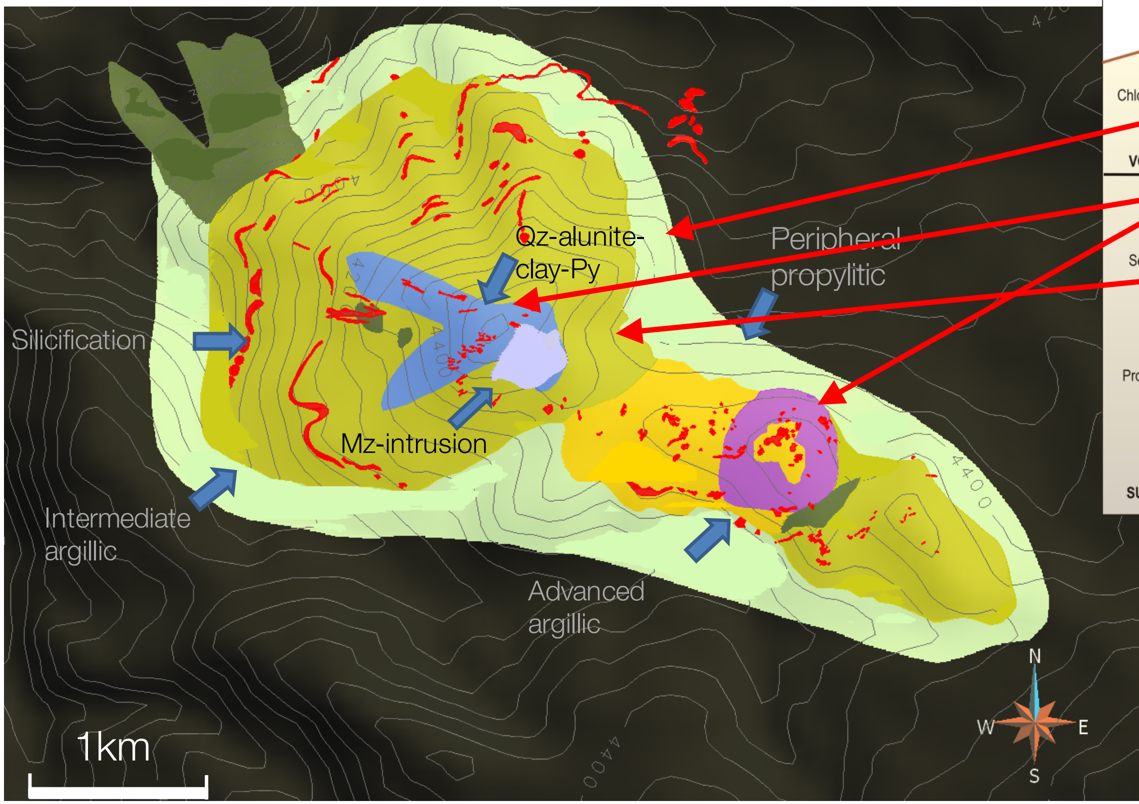
Setup: Discovery

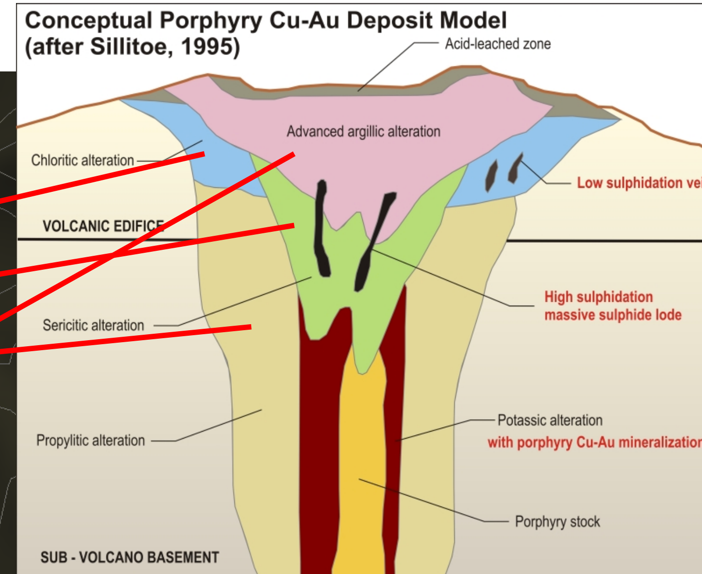
- Ground magnetic data
  - Delineate alteration zones
- Mobile Metal Ion (MMI)
  - Gold and copper anomalies
- CSAMT
  - To test MMI
  - Found large conductor
- Two discovery holes
- ORION 3D: DC/IP & MT





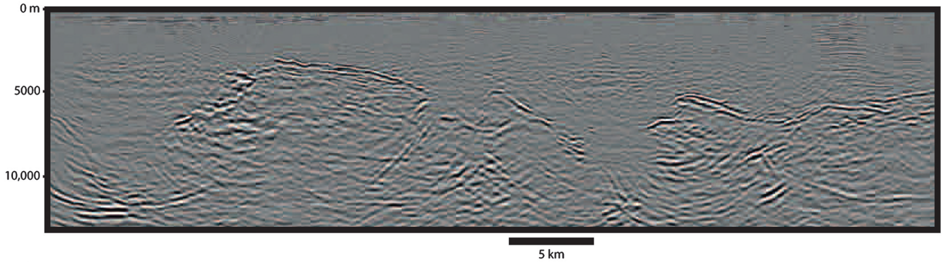
Properties

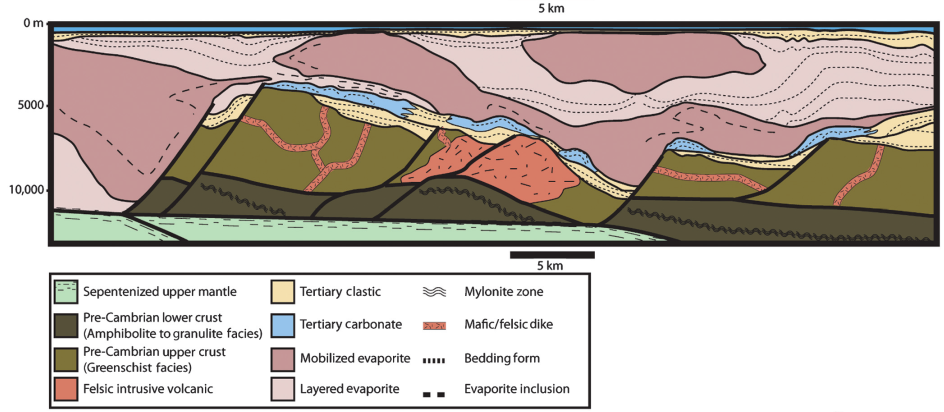




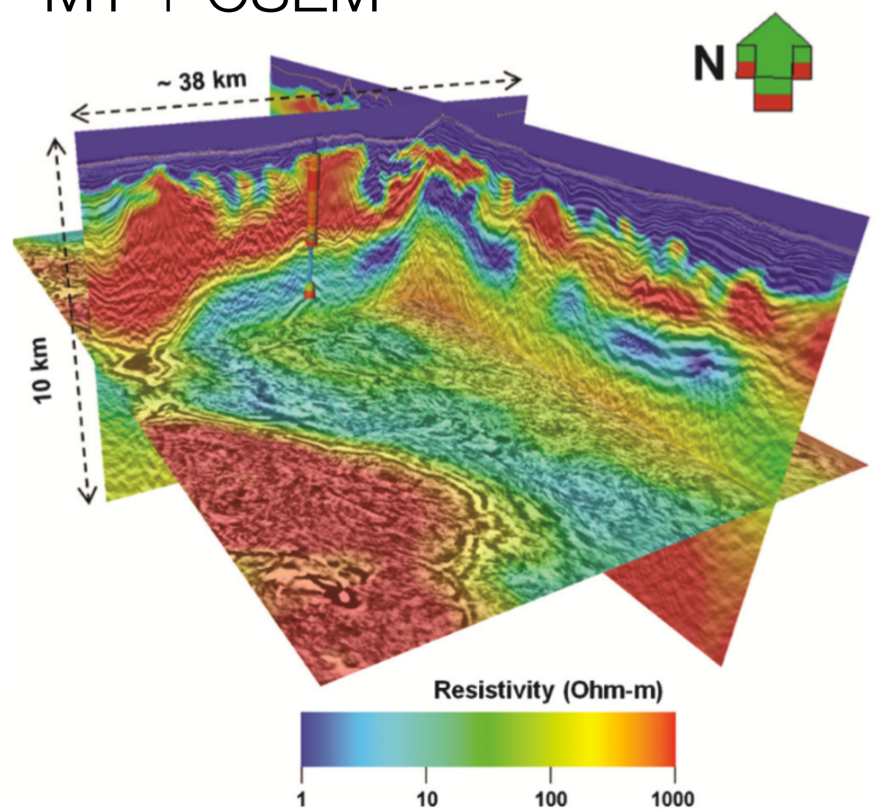
Units	Resistivity	Chargeability	Susceptibility
Host rock	High	None	Moderate
Stock	Moderate	Low	Moderate
Alteration zones	Low - Mod.	Mod. - High	Low

Additional Case History: Red Sea

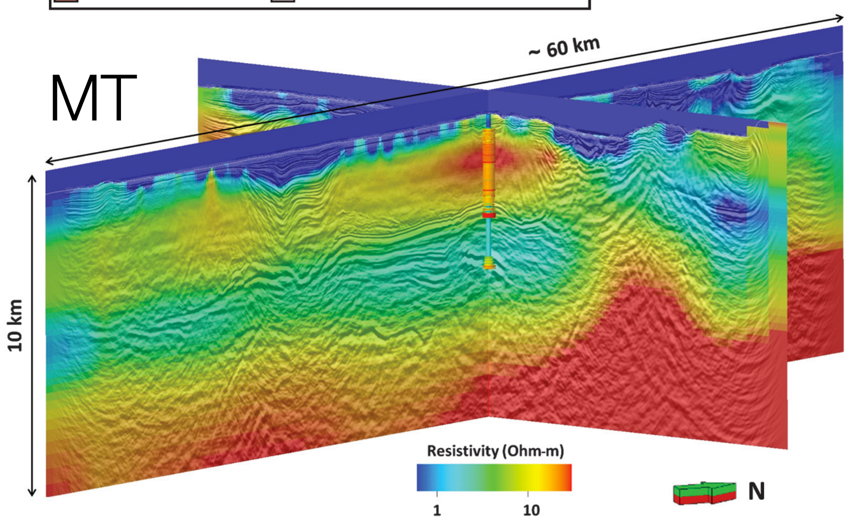




MT + CSEM

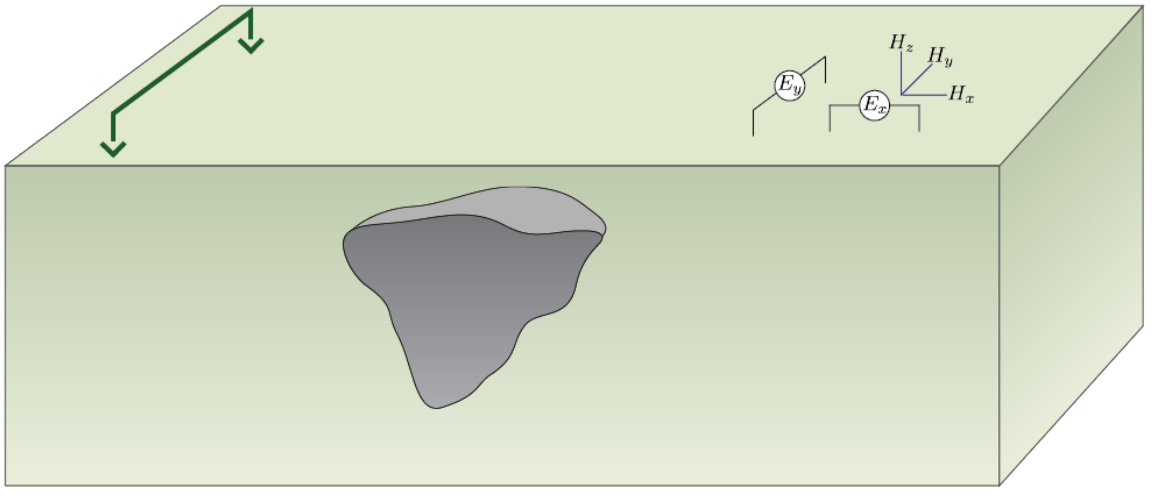


MT



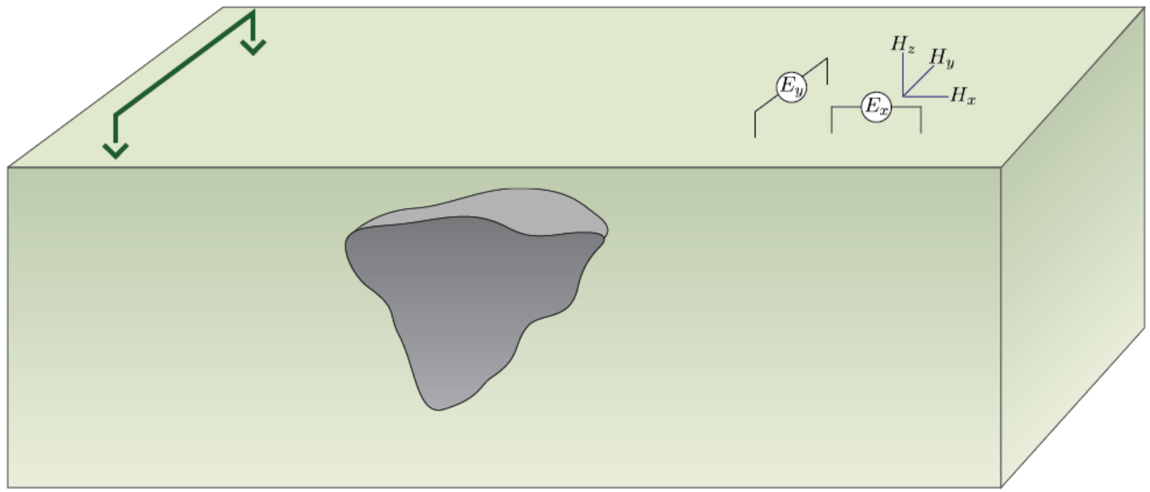
https://em.geosci.xyz/content/case_histories/red_sea

CSAMT



- Controlled Source Audio Magnetotellurics
- Plane wave assumption
  - Receivers need to be far away from source (several skin depths)
- Uses MT inversion algorithm

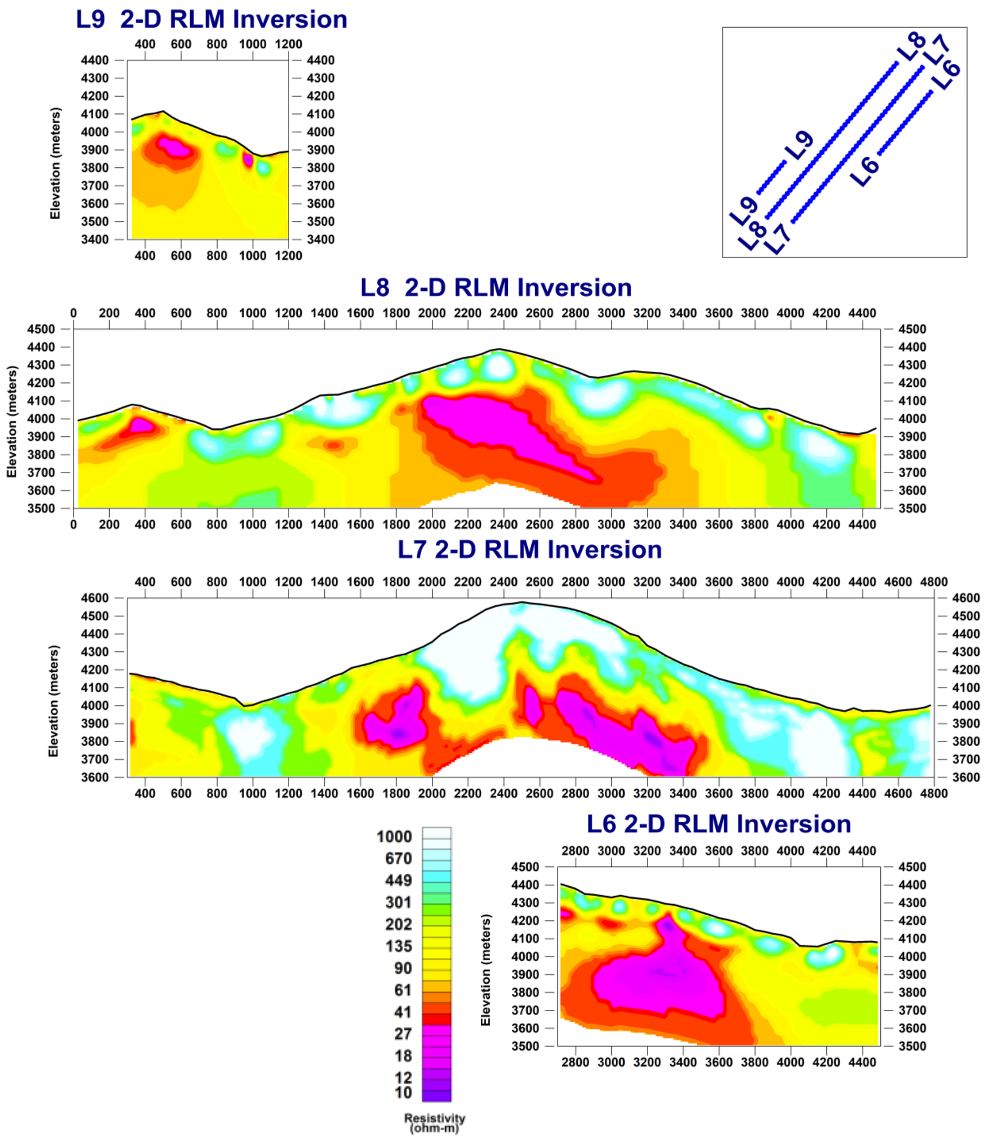
Survey: Discovery



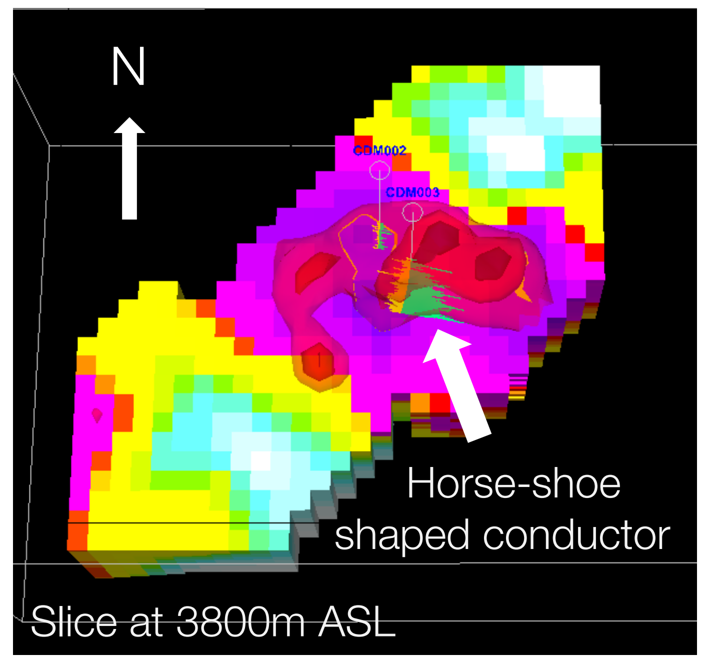
- Controlled Source Audio Magnetotellurics
- Transmitter
  - 3.5 km dipole
  - Frequencies: 2-9000 Hz
- Receivers
  - 10 km from source

Processing: Discovery

2D resistivity sections

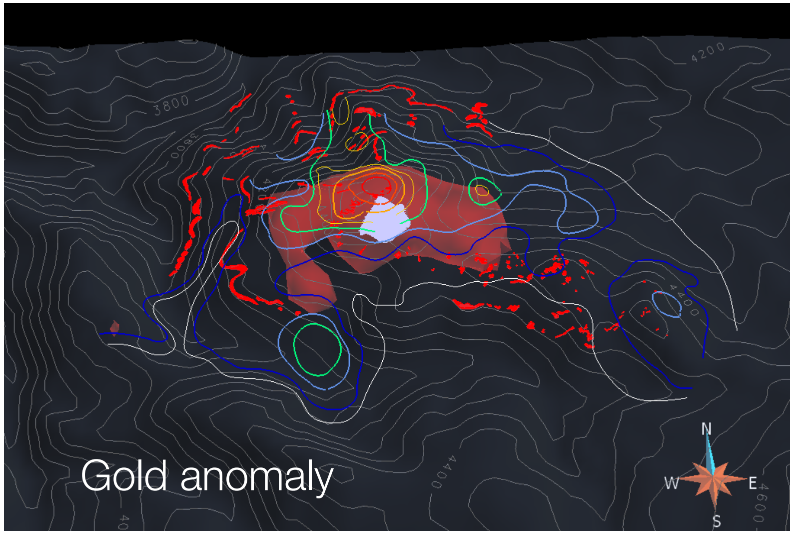


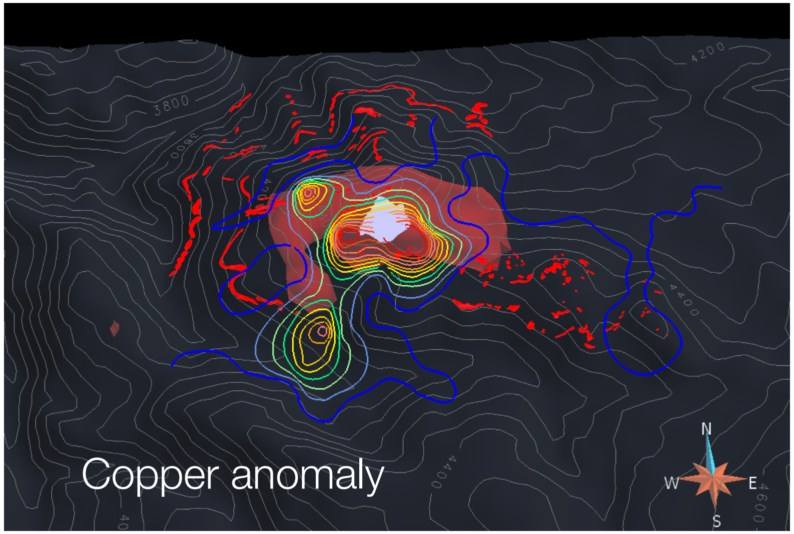
- Recovered horse-shoe shaped conductor



Interpretation and Synthesis: Discovery

3D cut-off volume from CSAMT

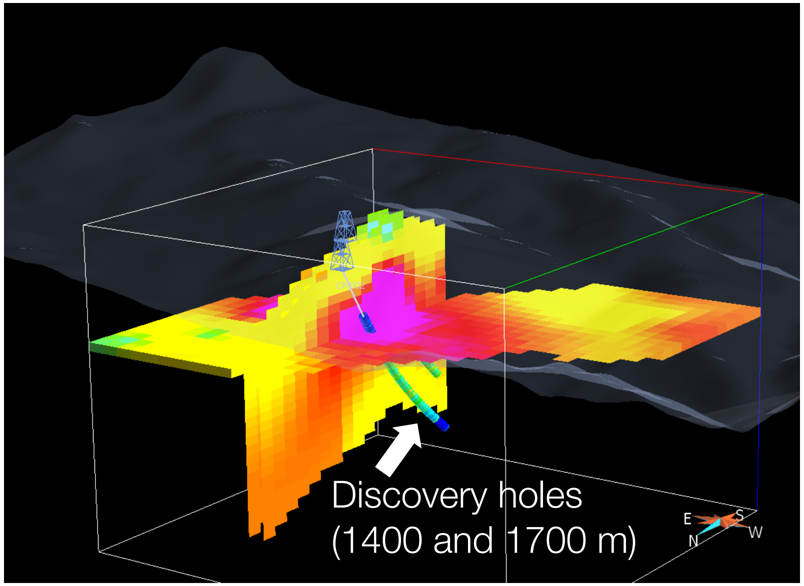


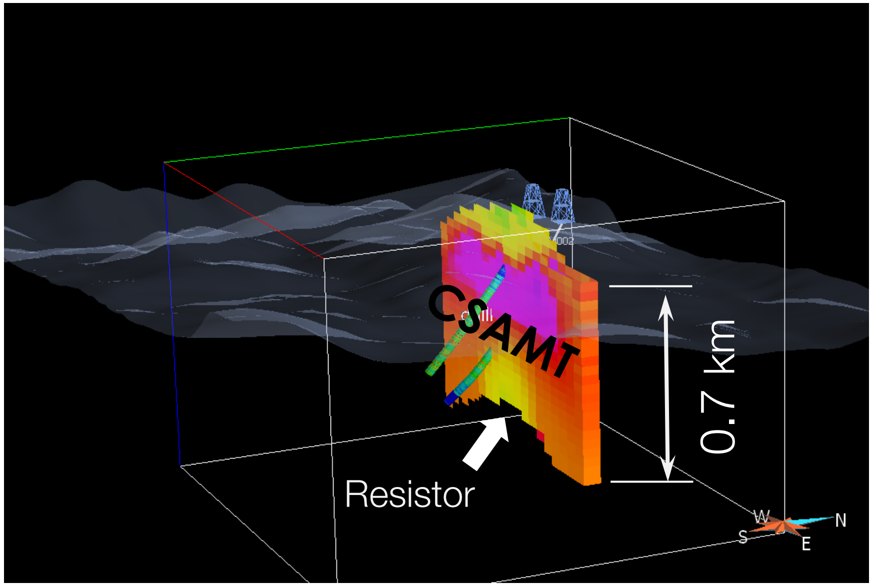


- Recovered conductor consistent with Au and Cu anomalies from MMI

Interpretation and Synthesis: Discovery

2D resistivity sections with drill holes



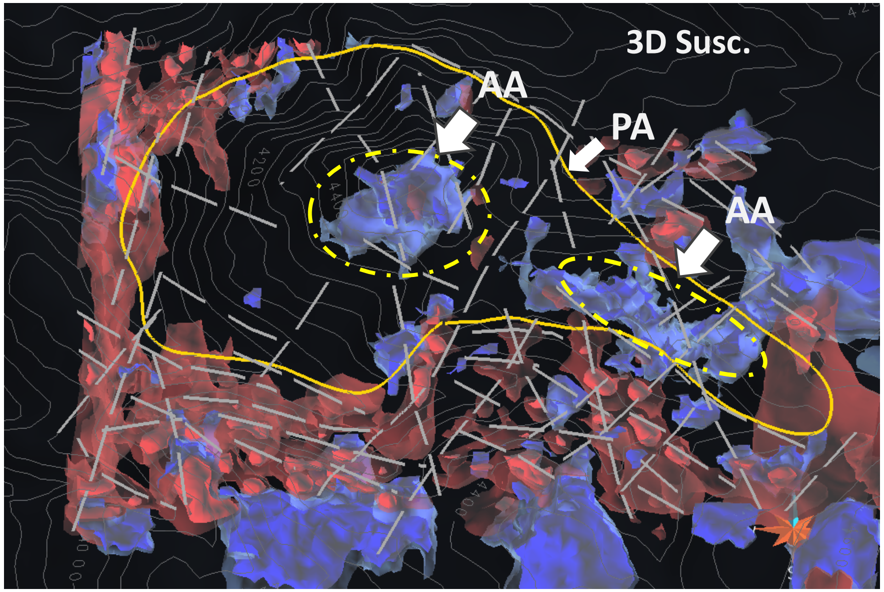


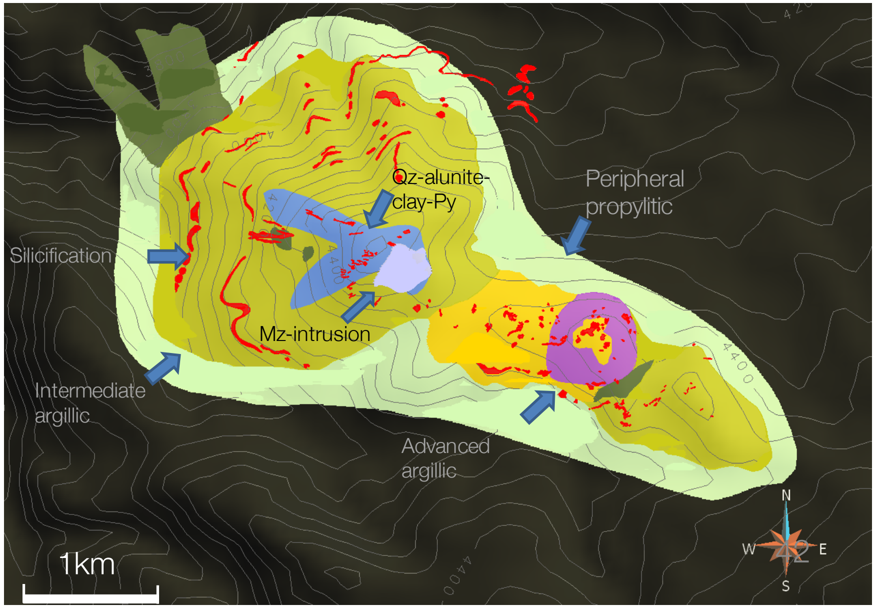
- Two holes are drilled and found mineralized zones (2011)
- Mineralization extends beyond CSAMT conductor
  - Lowest frequency in CSAMT (24 Hz, rho=10 ohm-m)

$$\delta = 500\sqrt{\frac{\rho}{f}} \quad \sim 325 \text{ m}$$

Setup: Evaluation

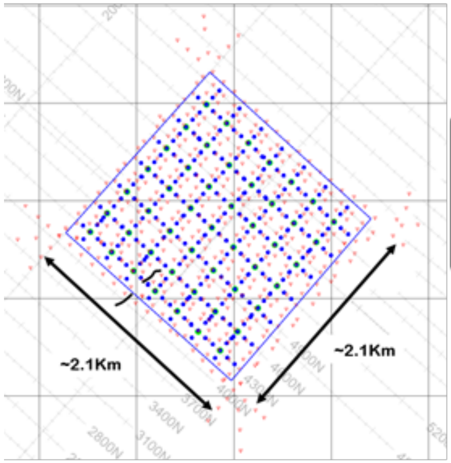
- Ground magnetic data
  - Delineate alteration zones
- Mobile Metal Ion (MMI)
  - Gold and copper anomalies
- CSAMT
  - To test MMI
  - Found large conductor
- Two discovery holes
  - Need to see deeper…
- ORION 3D: DC/IP & MT



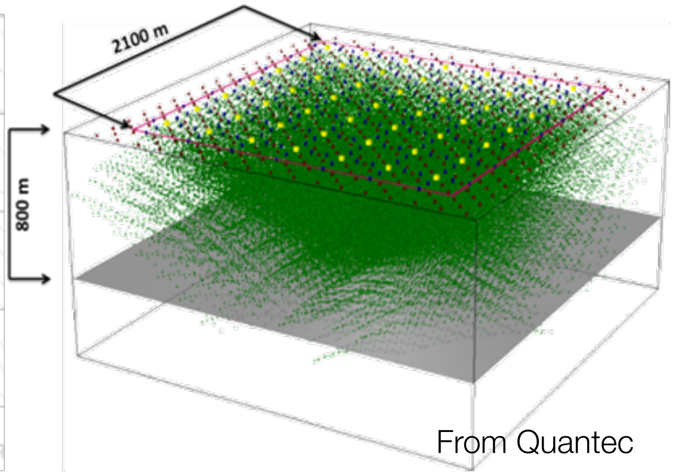


Survey: Evaluation

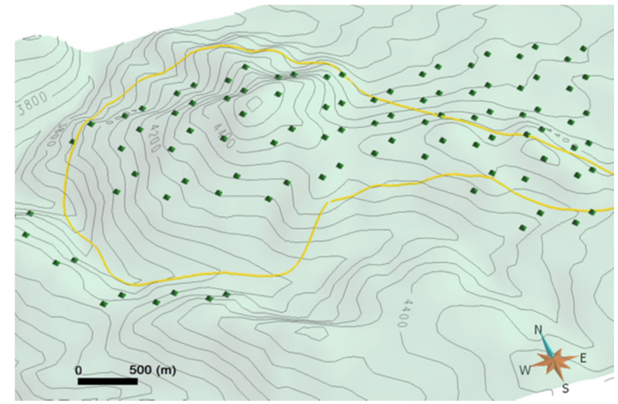
Orion 3D survey



Layout



Coverage

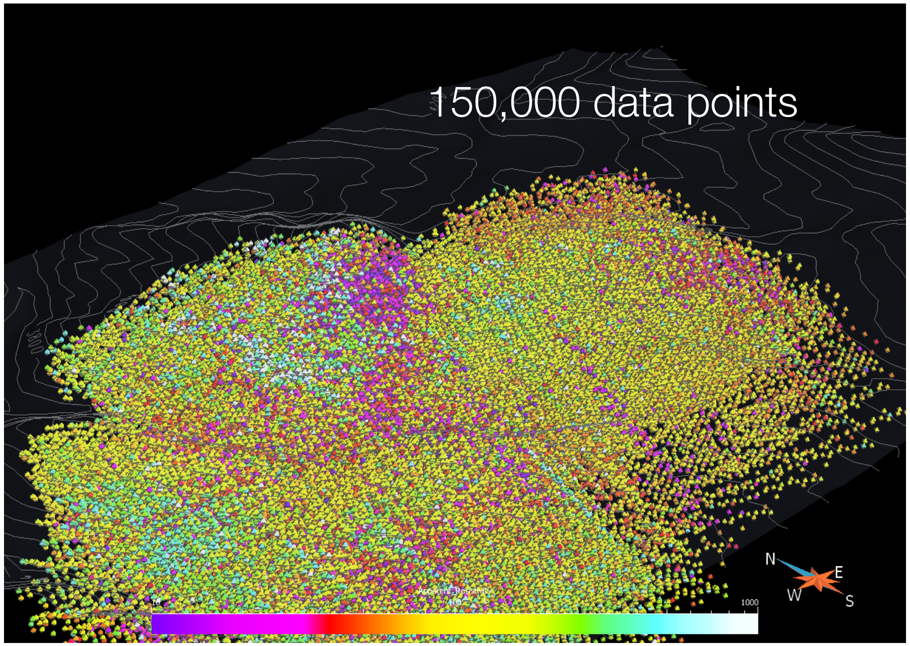


100 MT sites

- DC-IP
  - 539 transmits
  - 200 receiver dipoles
  - Pole-dipole
  - 150 m dipole length
- MT
  - 150 m dipole length
  - Two orthogonal induction coils
  - 450 m spacing
  - Acquired over night
  - Frequency range: 250-0.001 Hz

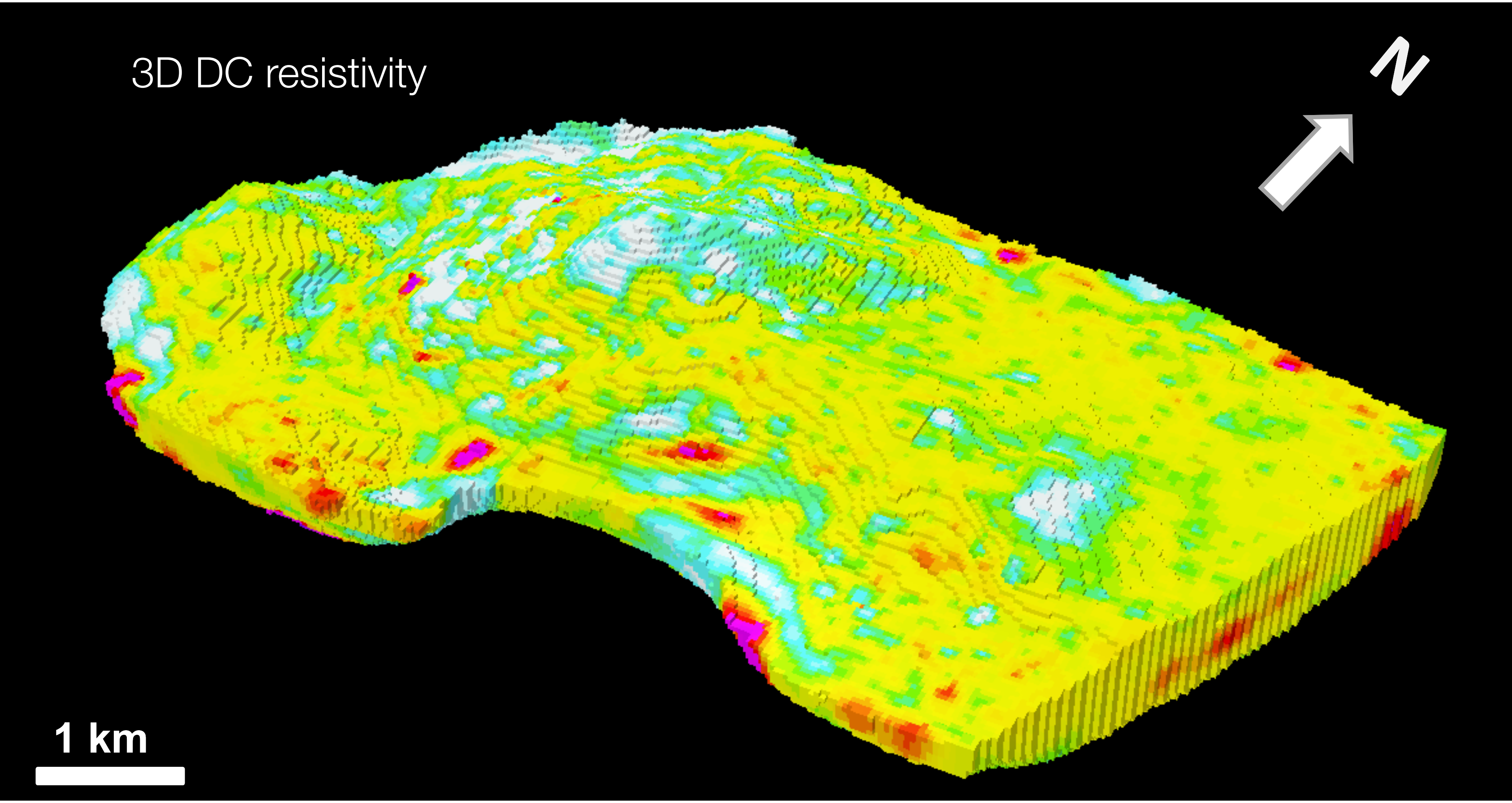
DC Data

Apparent resistivity

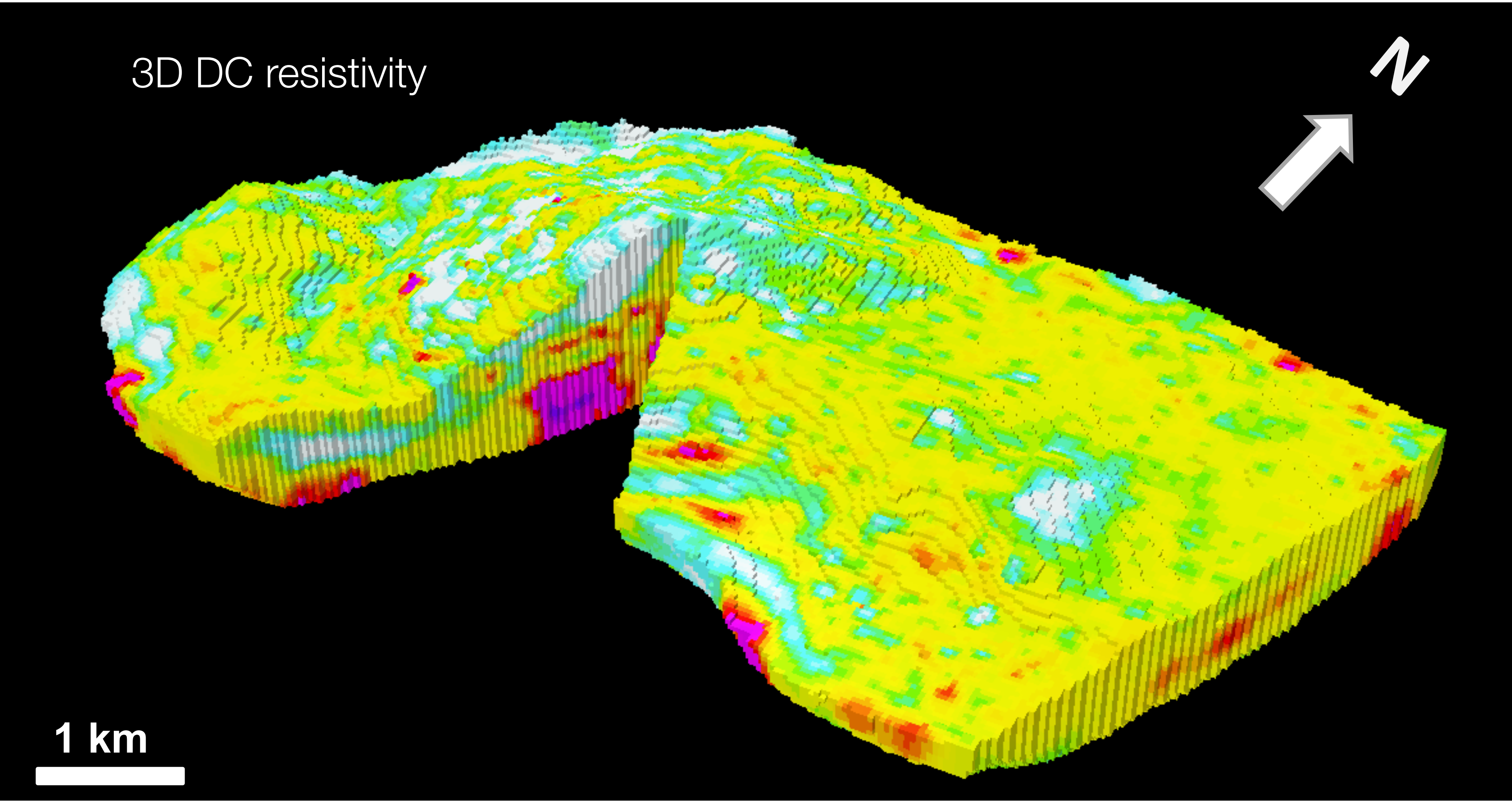


- 150,000 data points from
  - 540 sources
  - 300 dipole receivers
- Hard to visualize and interpret data
- Need to invert

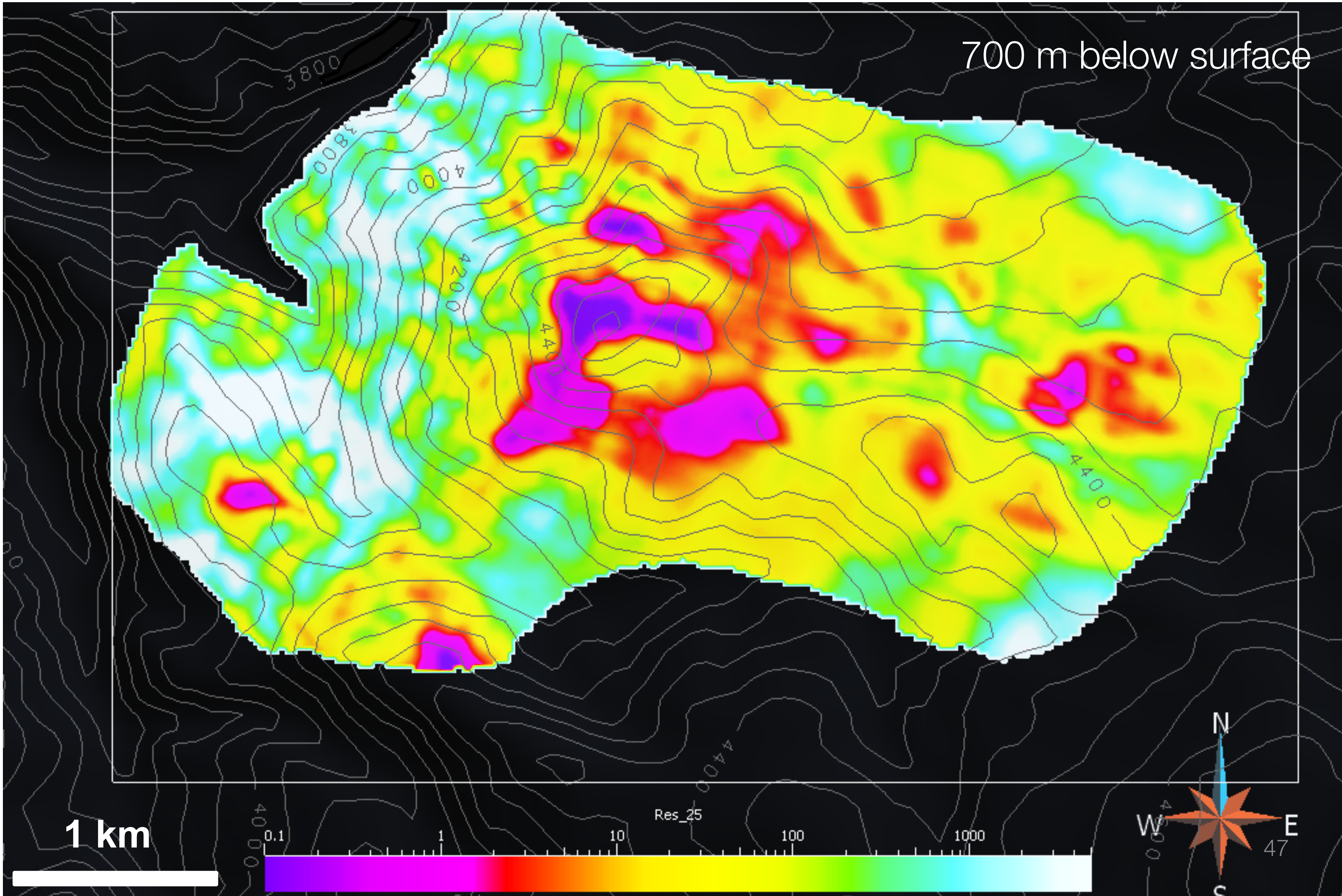
Processing: DC inversion



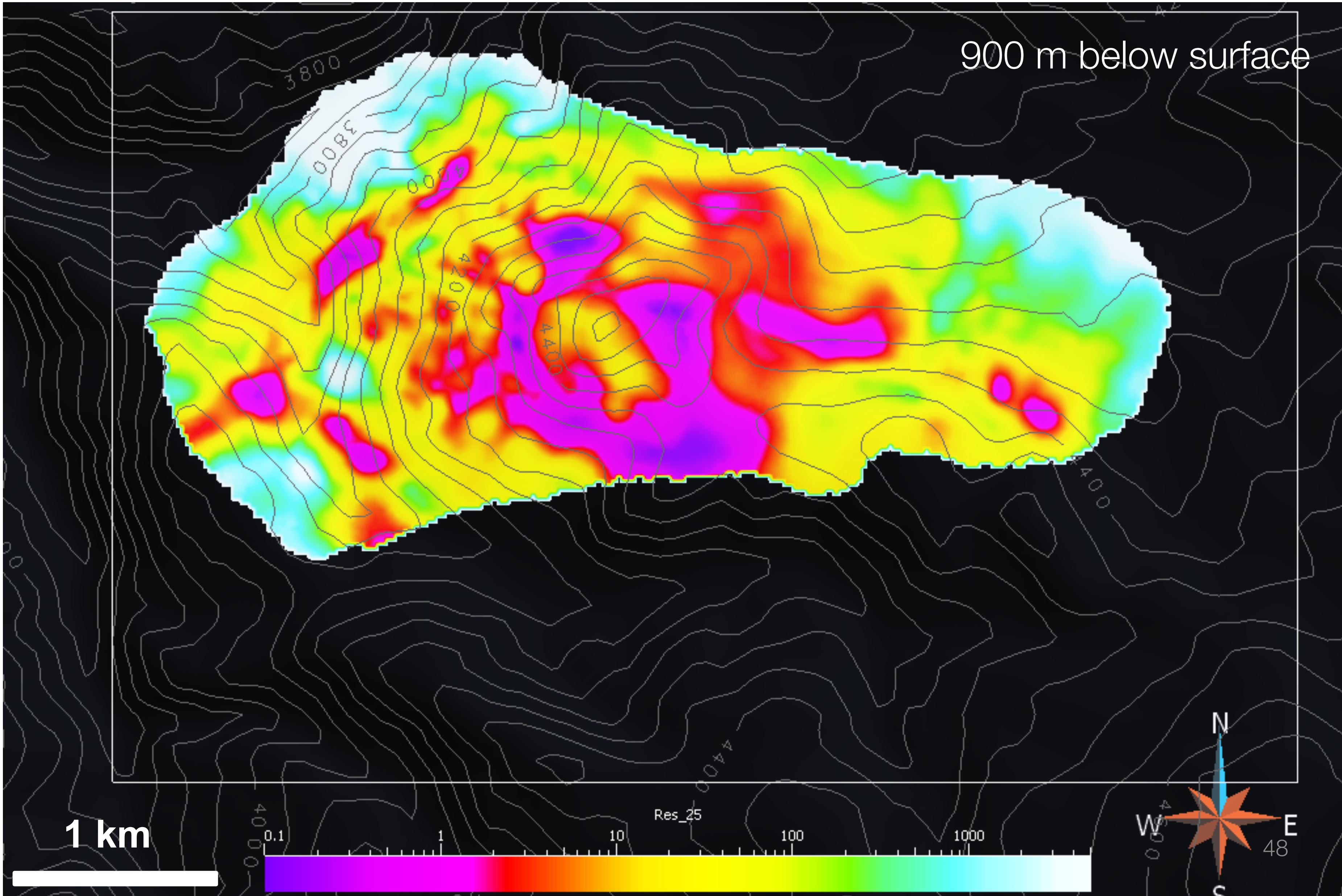
Processing: DC inversion



Processing: DC inversion



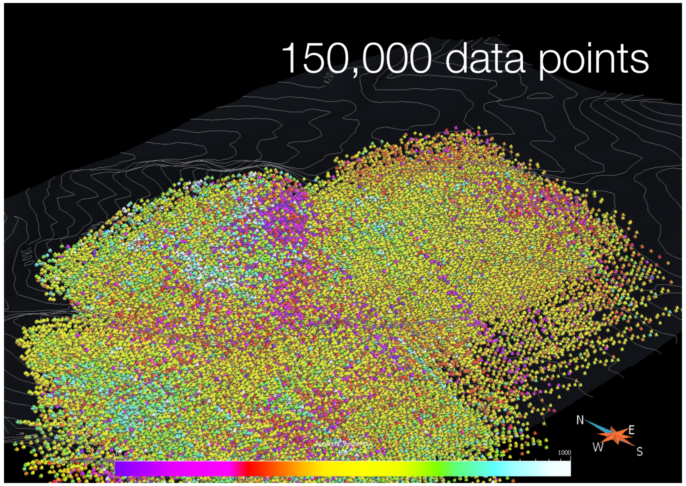
Processing: DC inversion



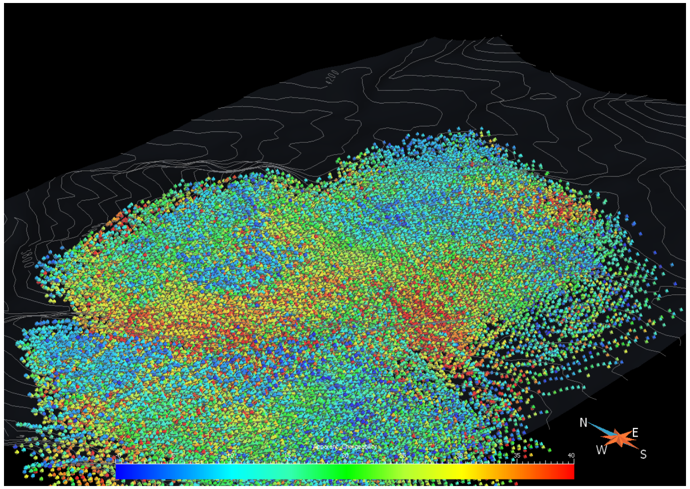
(we also have IP data)

DC-IP Data

DC data



IP data

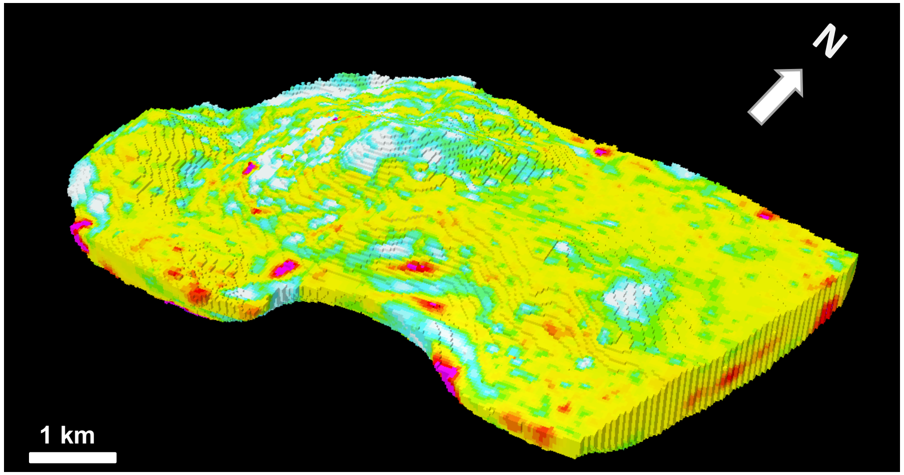


- 150,000 data points from
  - 540 sources
  - 300 dipole receivers
- Hard to visualize and interpret data
- Need to invert

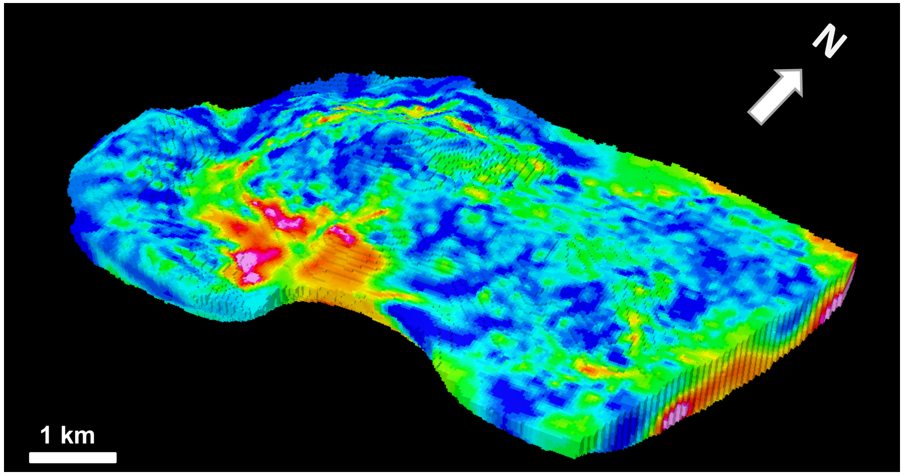
3D DC IP inversion

- Use DC conductivity
- Invert IP data, recover a 3D chargeability
- UBC DCIP3D

Resistivity

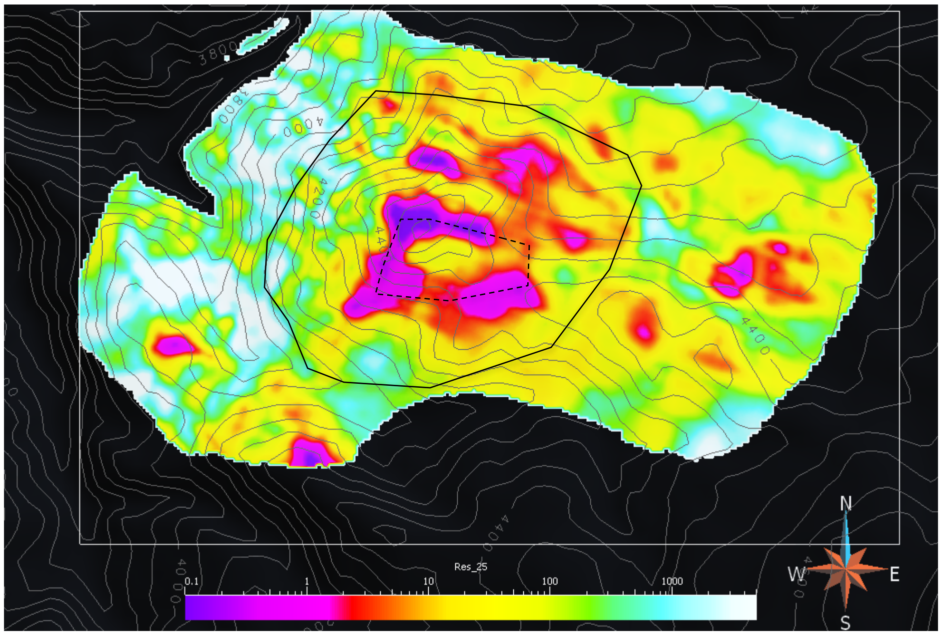


Chargeability

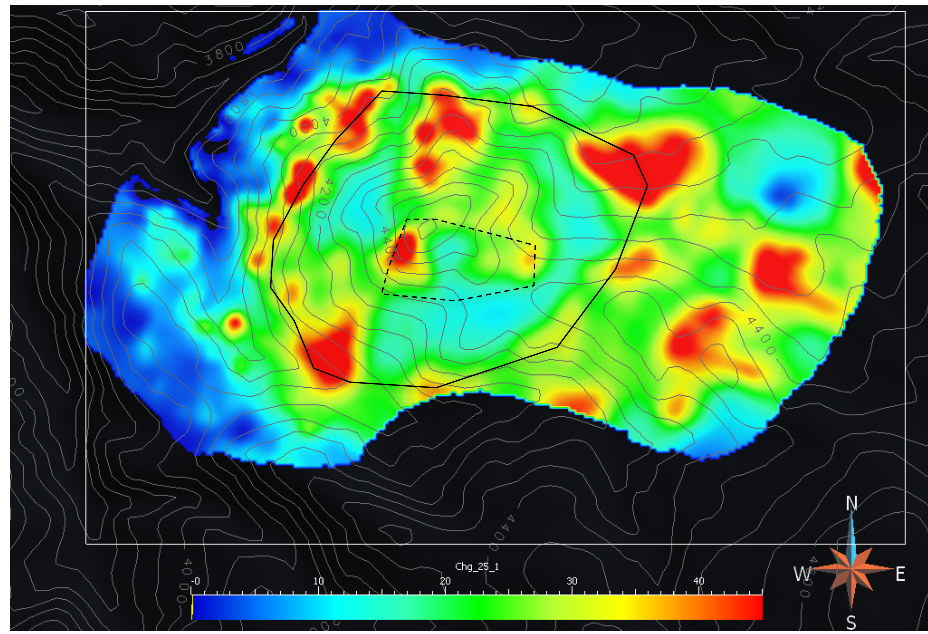


Interpretation: Resistivity & Chargeability

700m below surface



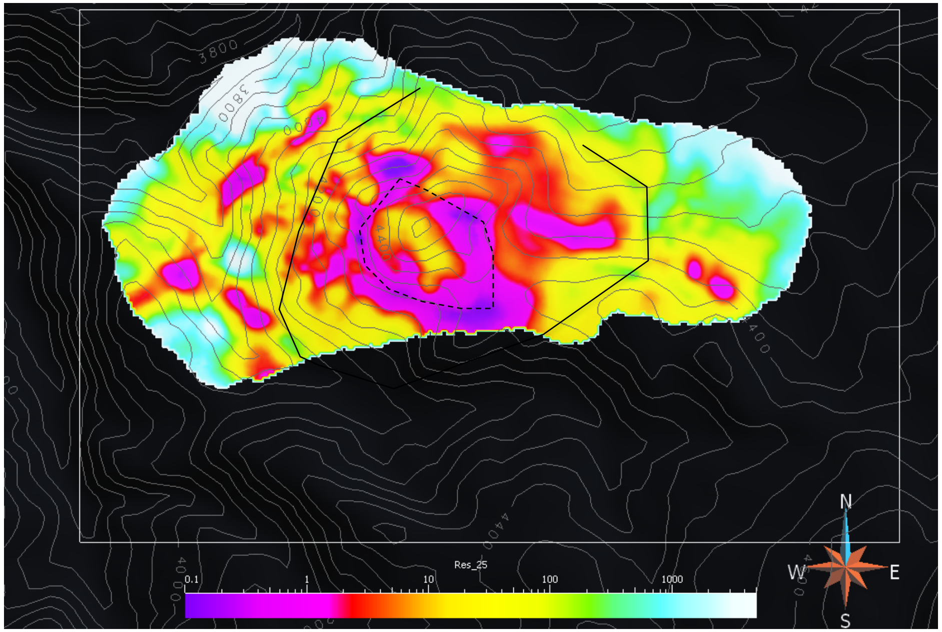
Resistivity



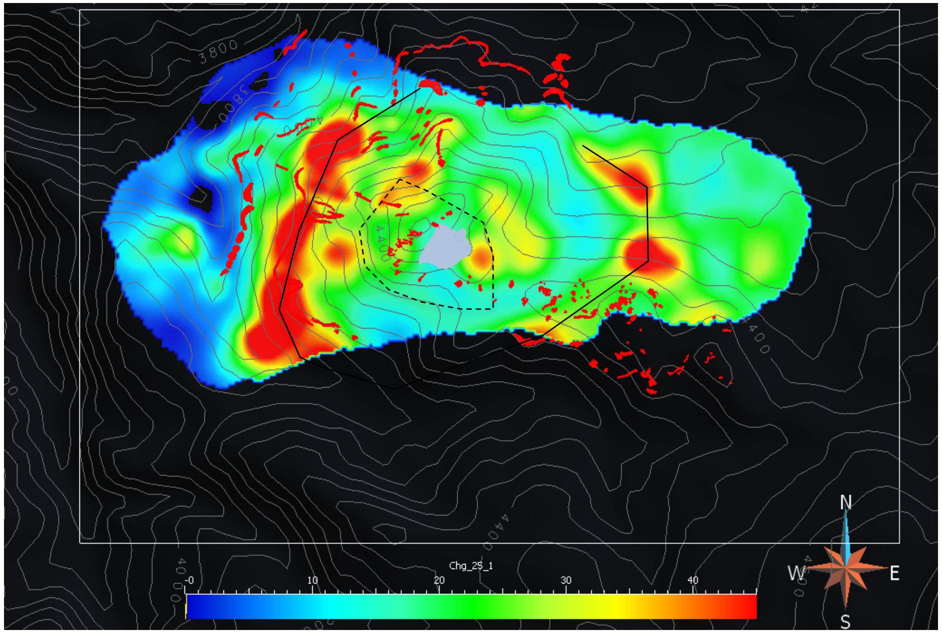
Chargeability

Interpretation: Resistivity & Chargeability

900m below surface

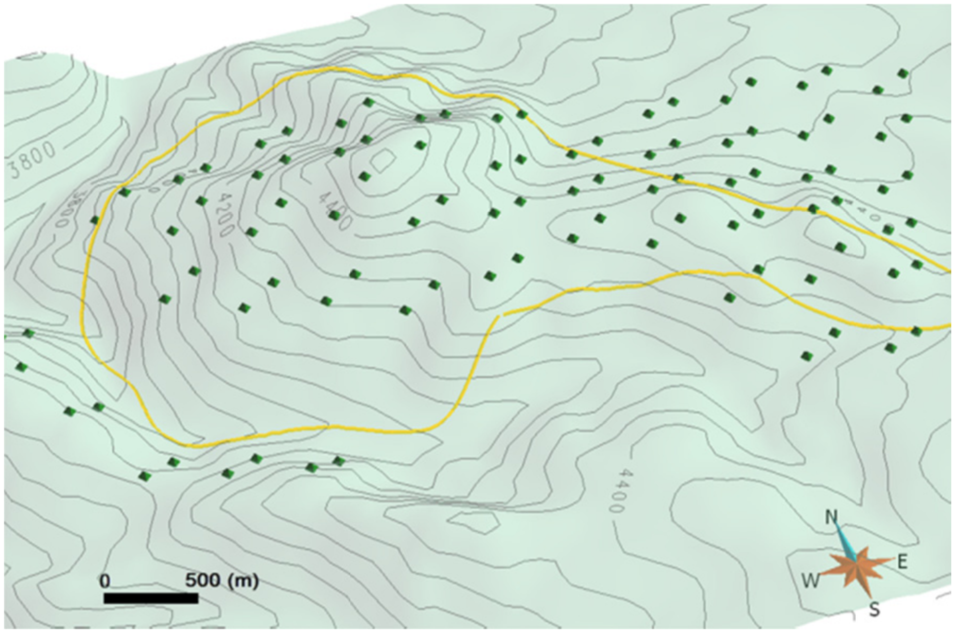


Resistivity



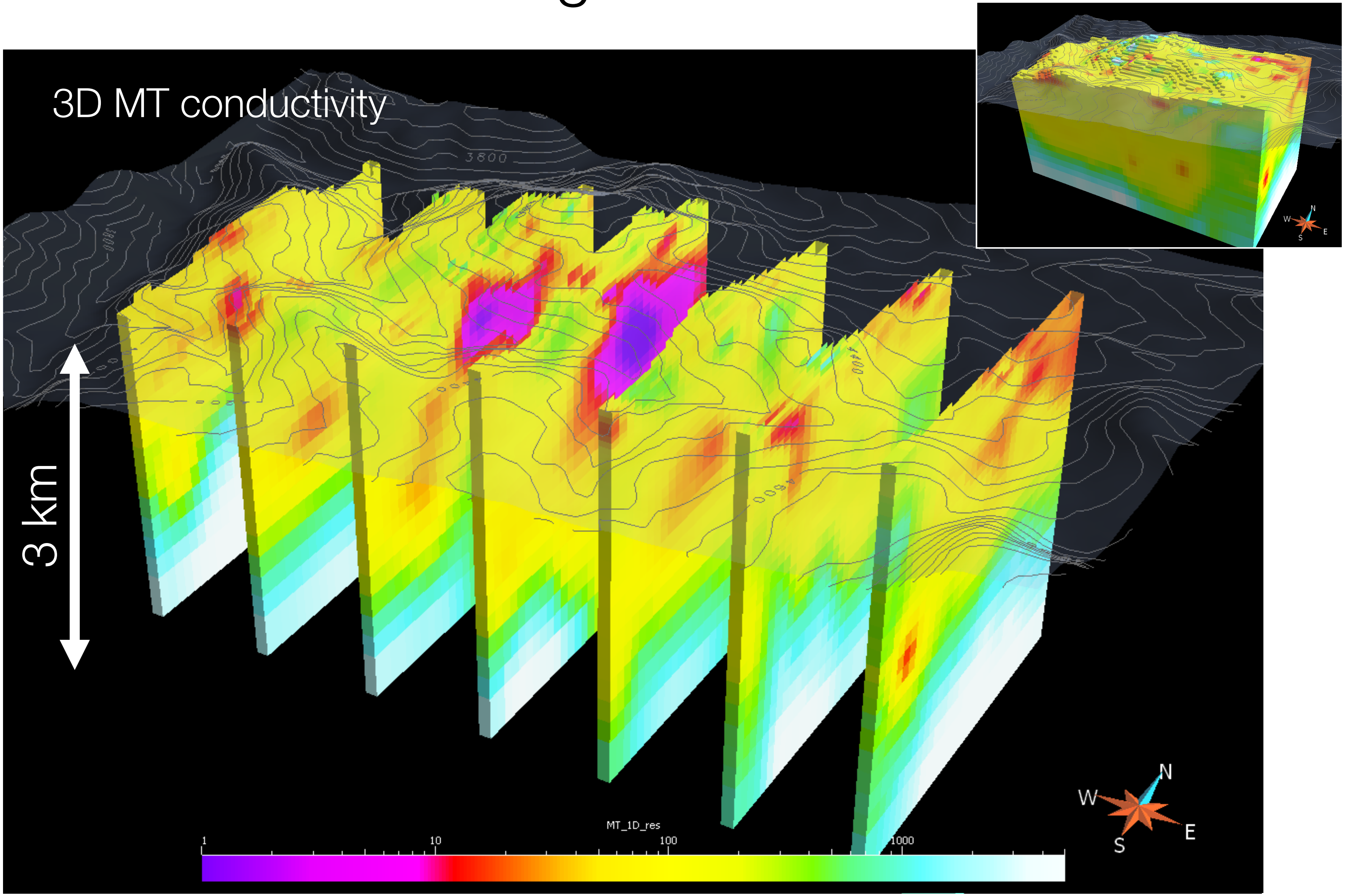
Chargeability

MT Data

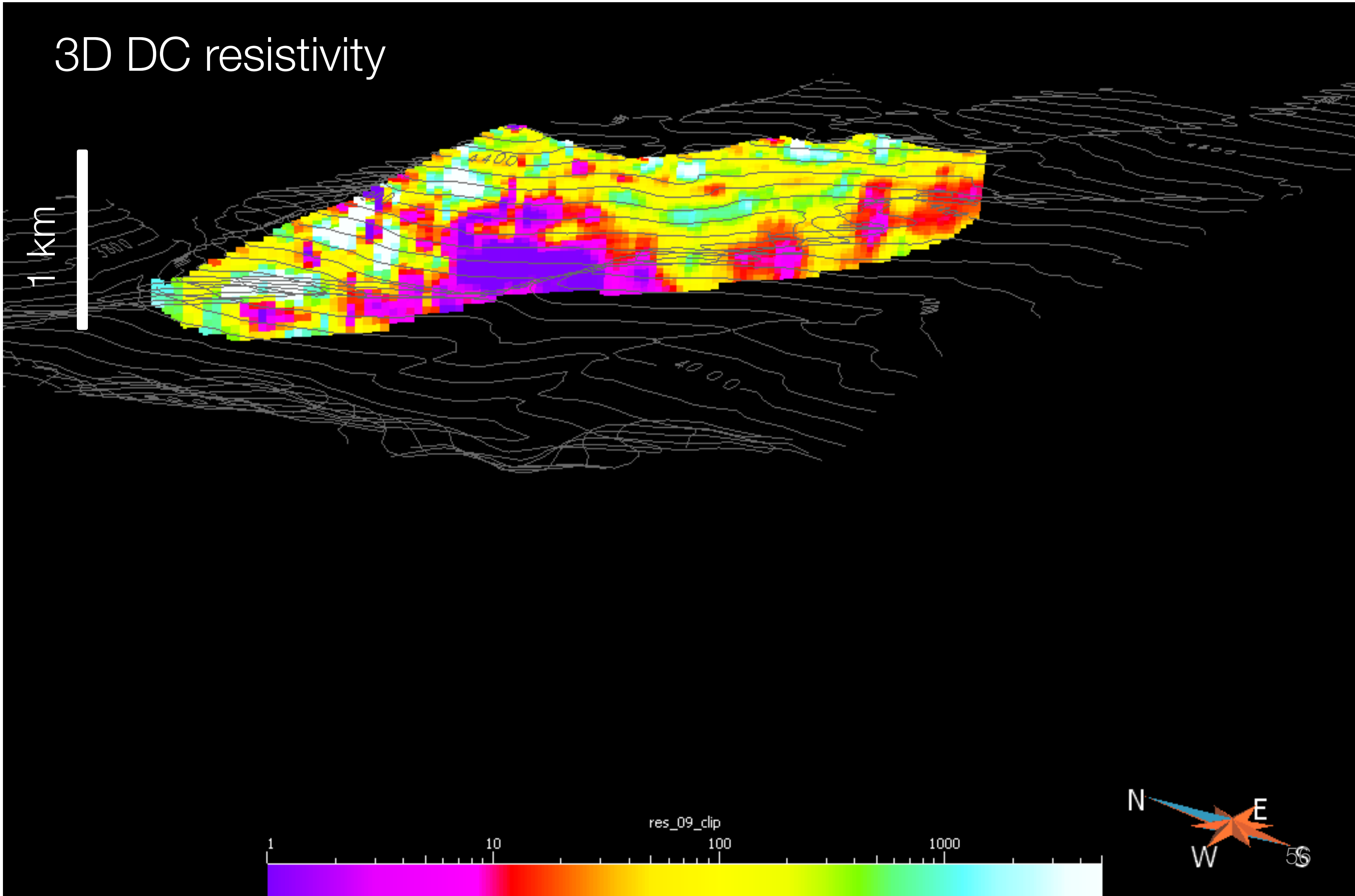


- 100 MT Sites
- 150 m dipole length
- Two orthogonal induction coils
- 450 m spacing
- Acquired over night
- Frequency range: 250-0.001 Hz

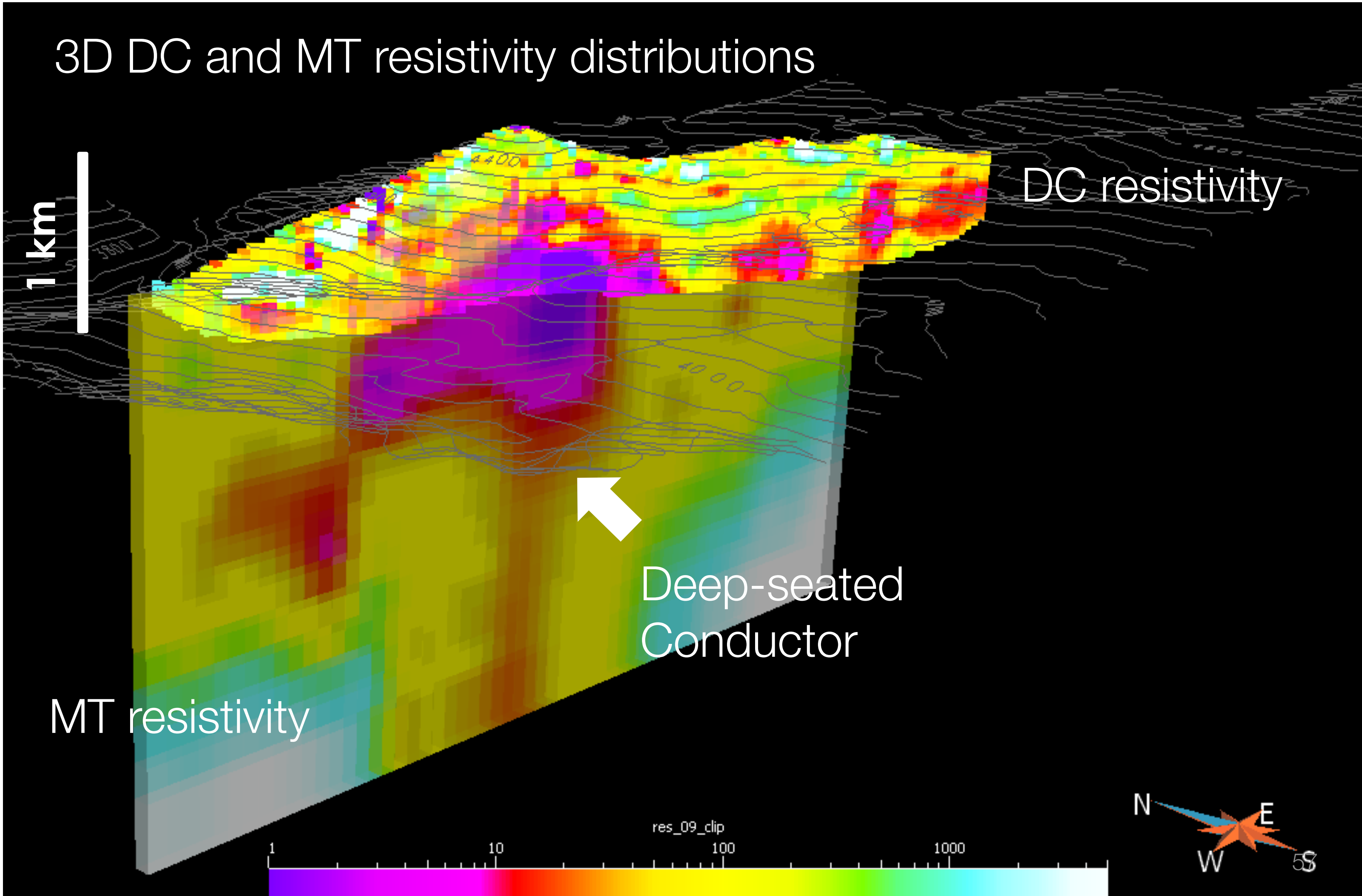
Processing: MT inversion



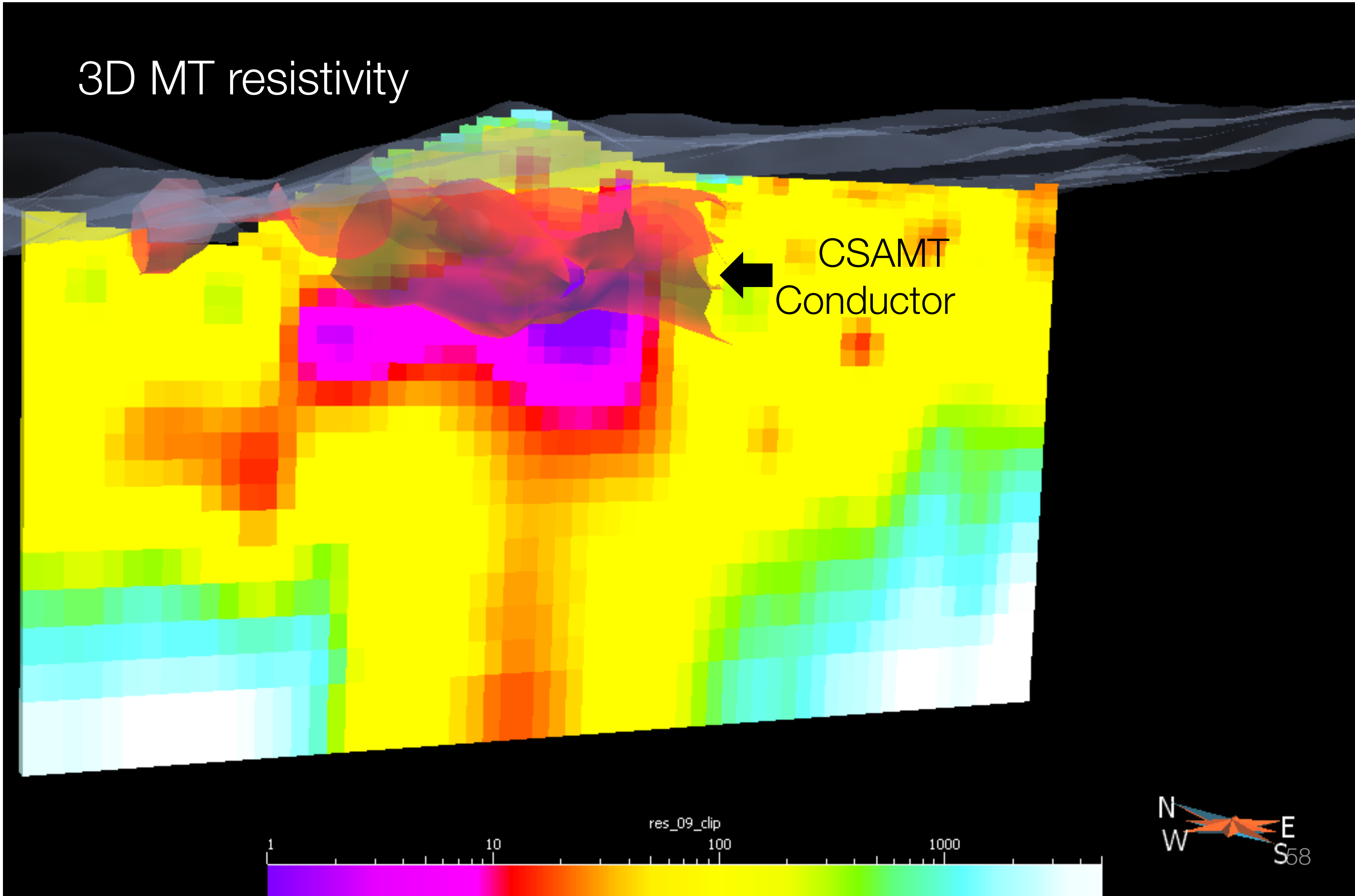
Interpretation



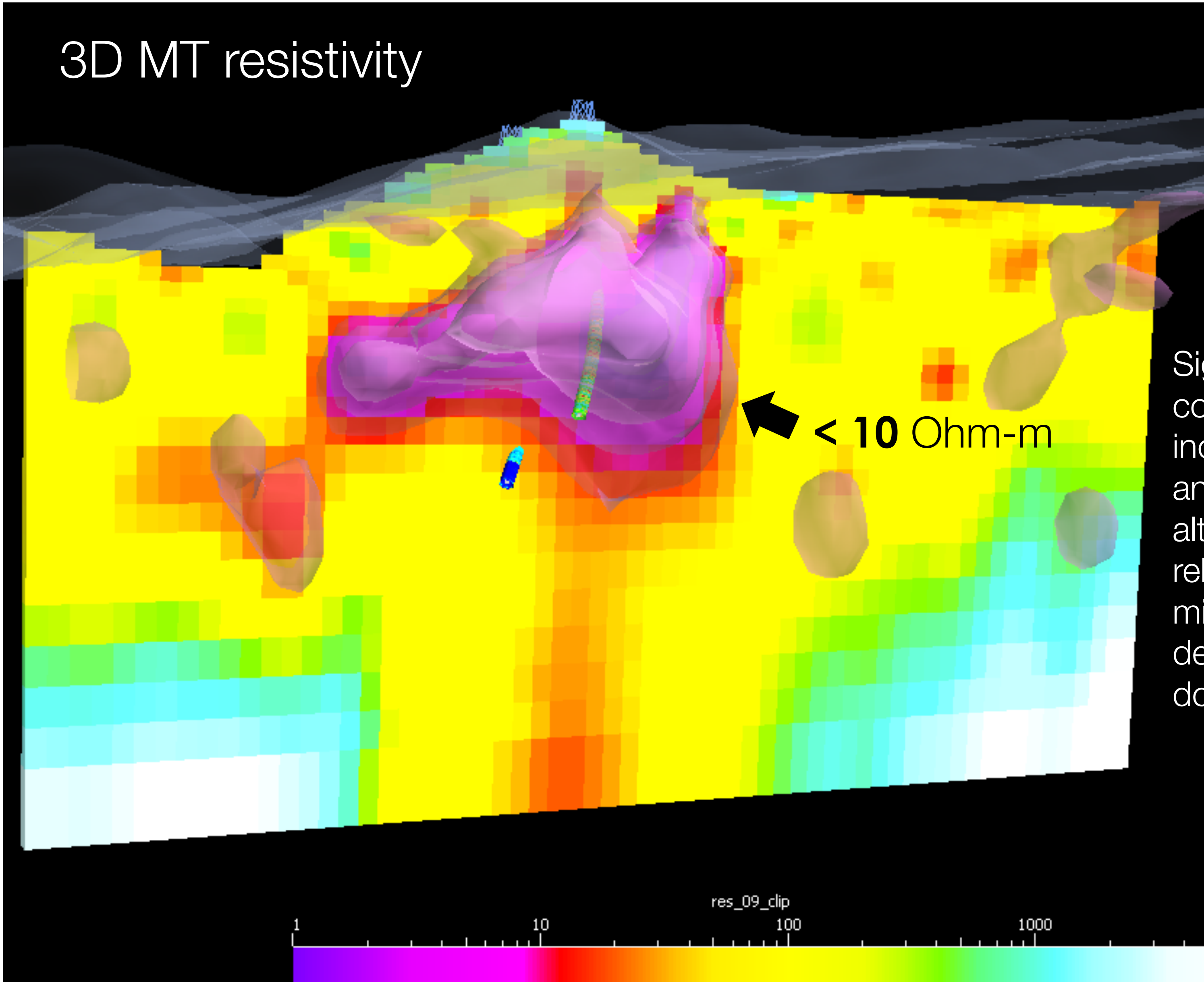
Interpretation



Interpretation



Synthesis



Significant conductor, increases the size and depth of the alteration zone and related mineralization to a depth of 2km in the down dip direction

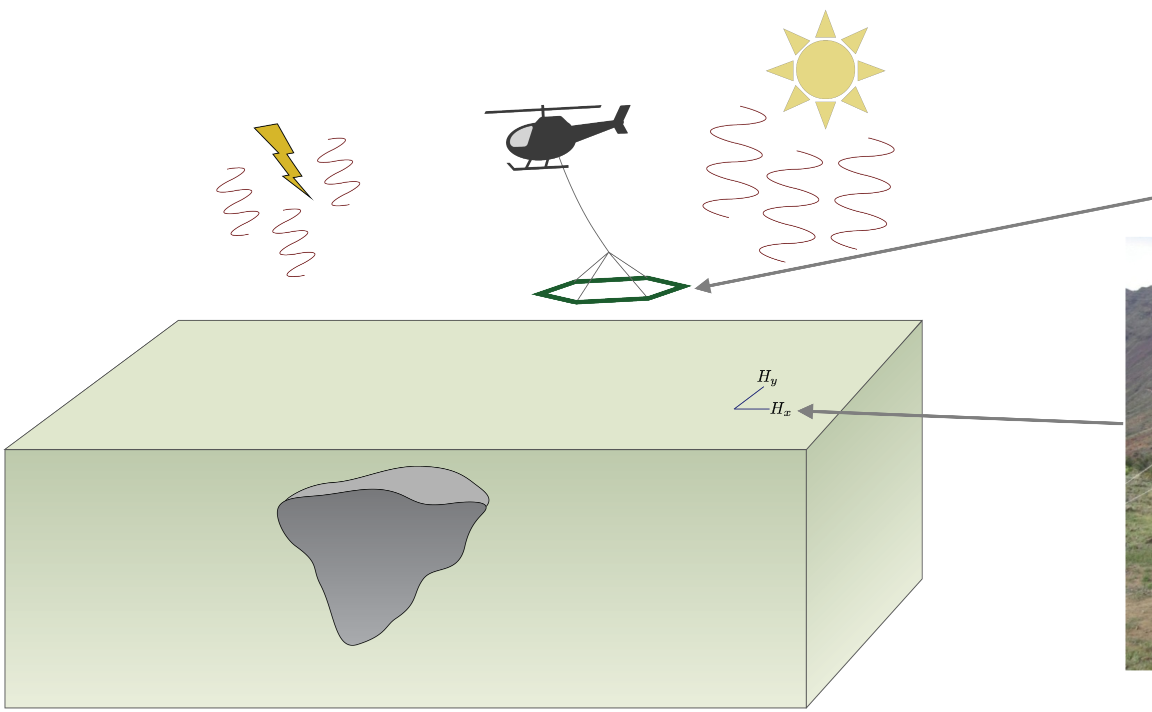
Tipper data (ZTEM)

- Magnetic transfer function

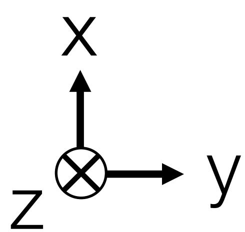
$$H_z = \mathbf{TH}$$

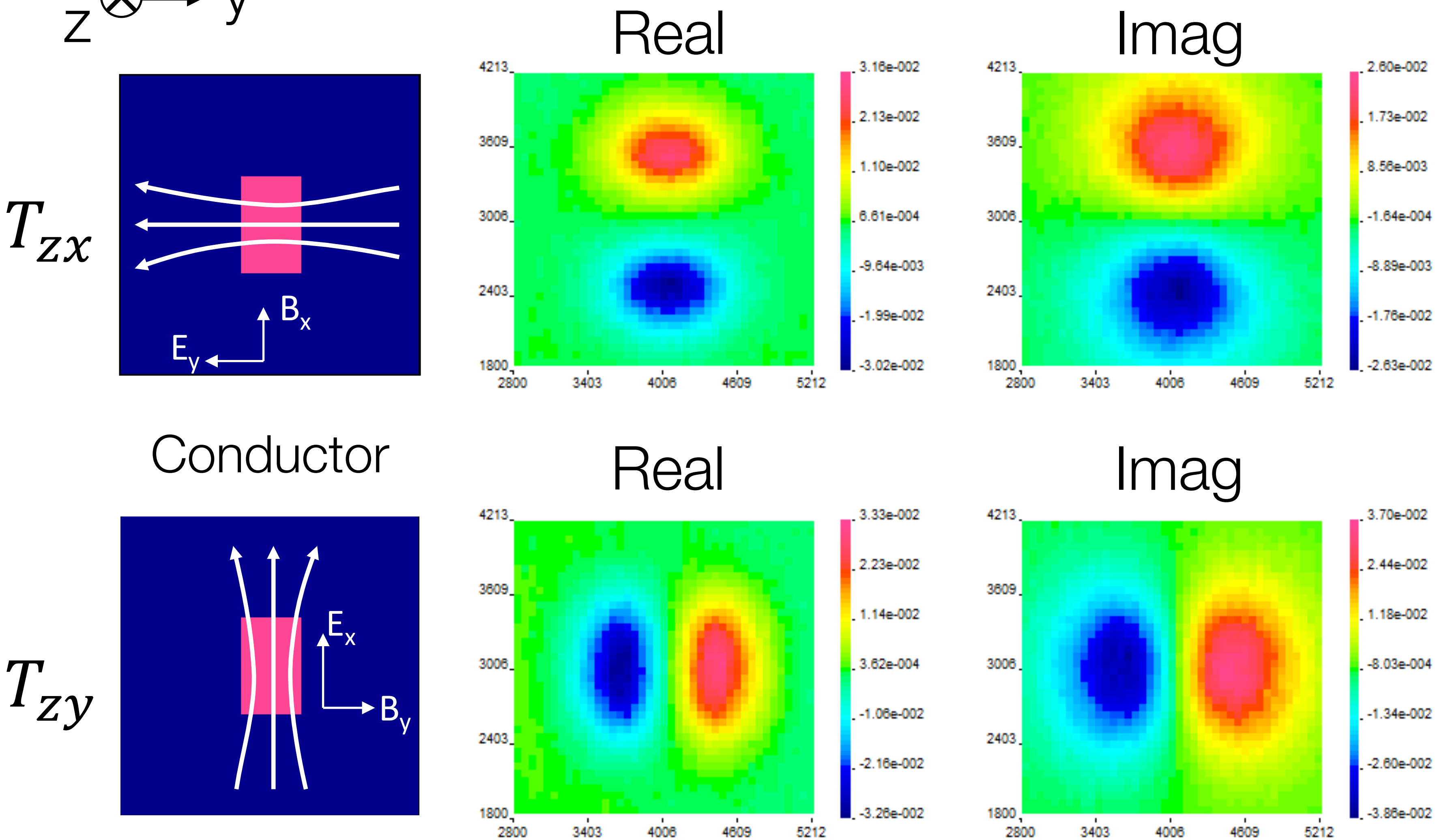
$$H_z(r) = T_{zx}H_x(r_0) + T_{zy}H_y(r_0)$$

- Frequencies 30Hz – 720 Hz



Synthetic example





ZTEM case histories

- Synthetic based on Noranda district

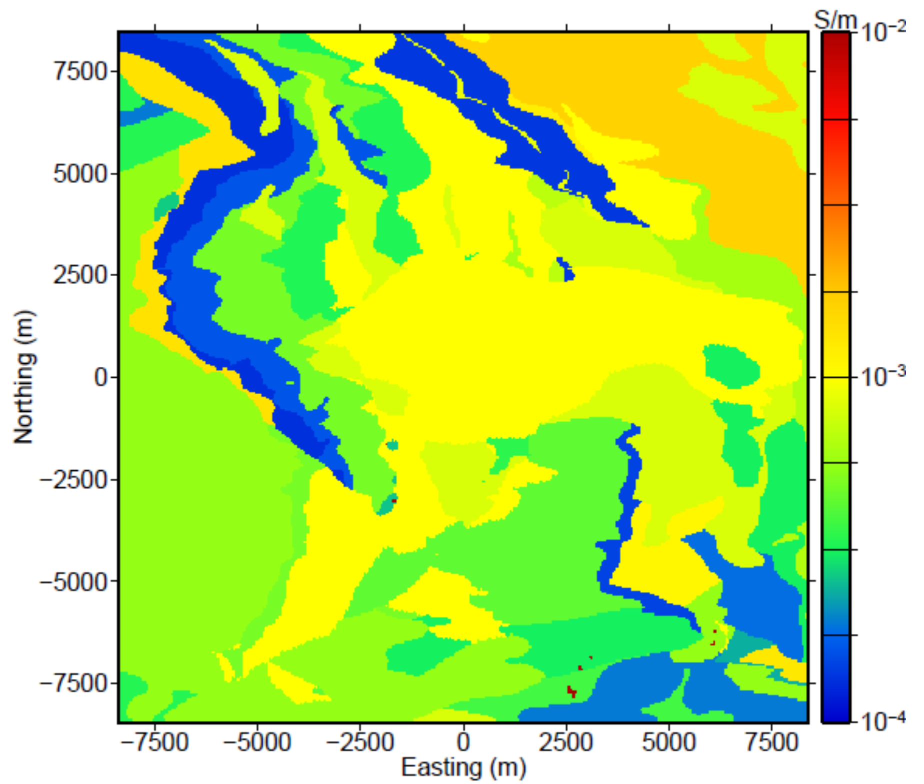
- Balboa copper porphyry deposit

Noranda district, Canada

- Hosts many deposits:
  - 20 economic VMS
  - 19 orogenic gold
  - Several intrusion-hosted Cu-Mo

- Physical properties
  - Synthetic from geologic model
  - 38 geologic units

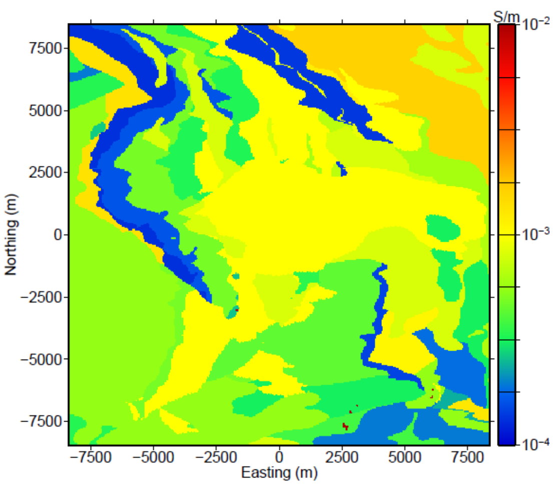
True model at 275m depth



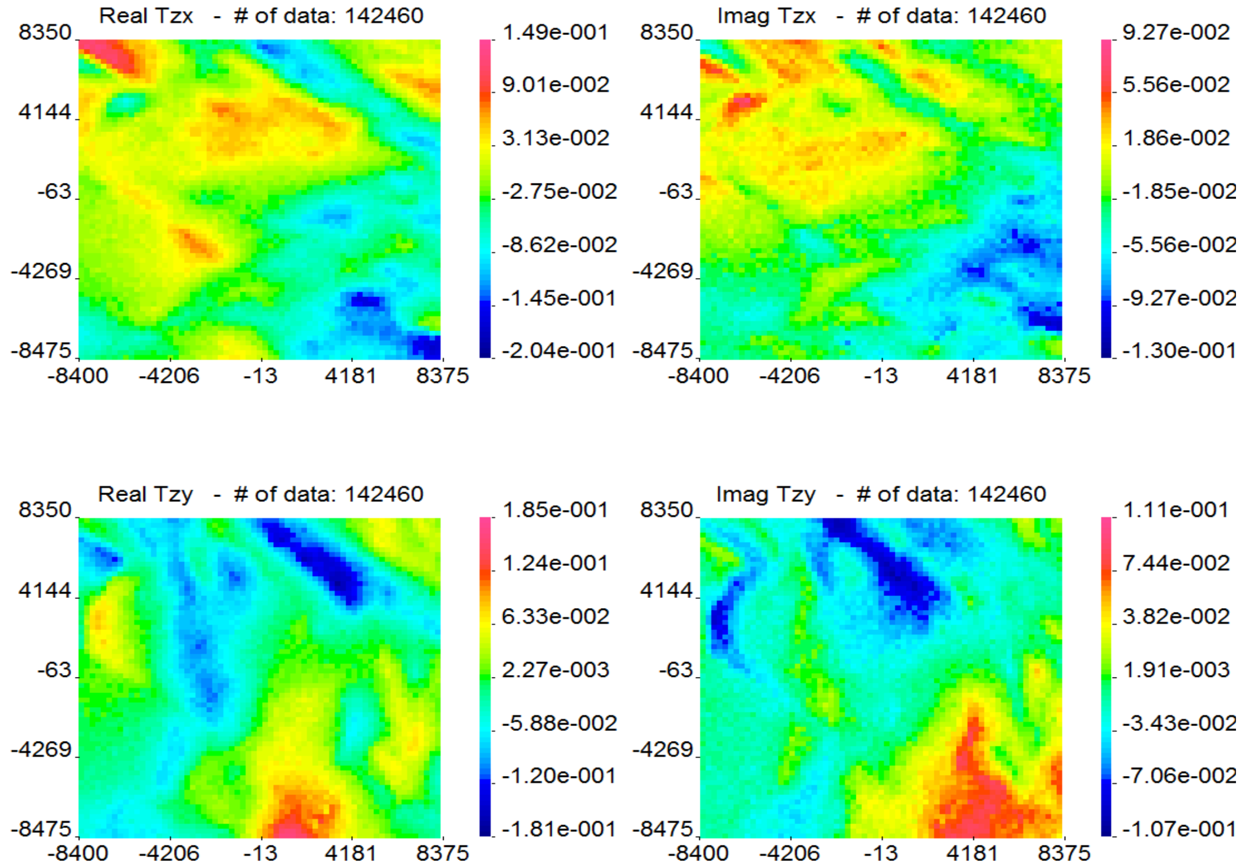
Data

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

True model at 275m depth

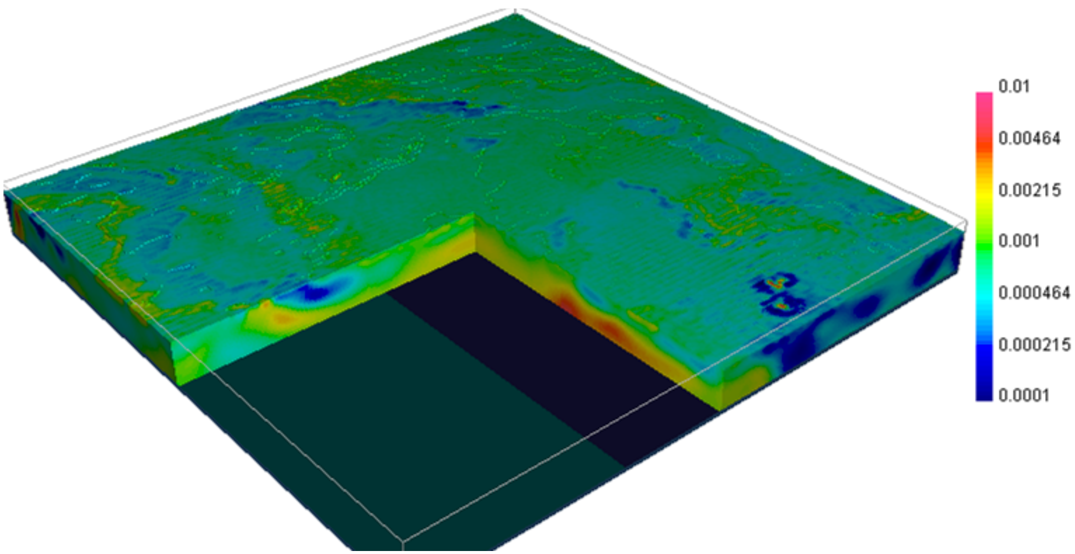


Observed (90 Hz)

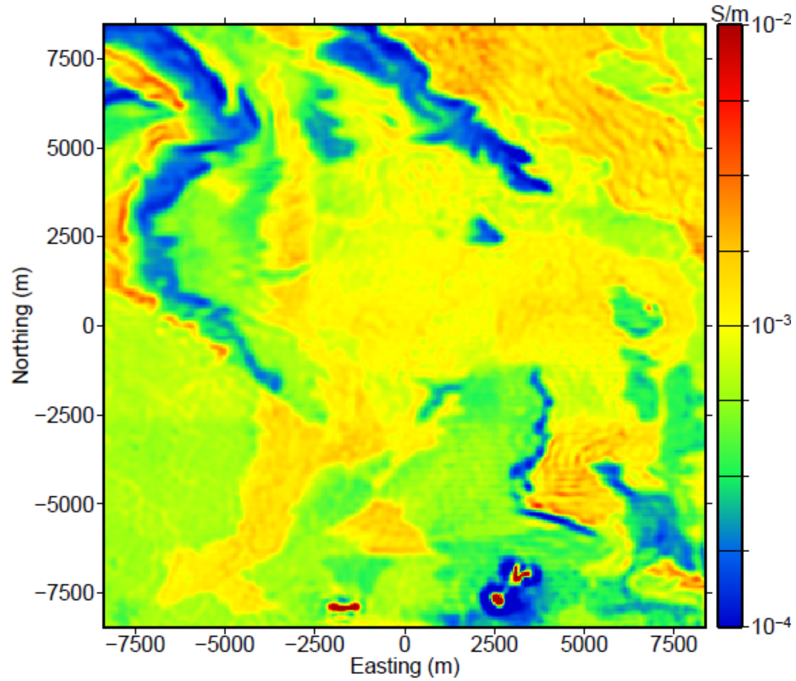


Interpretation

Recovered Model



Model at 275m depth

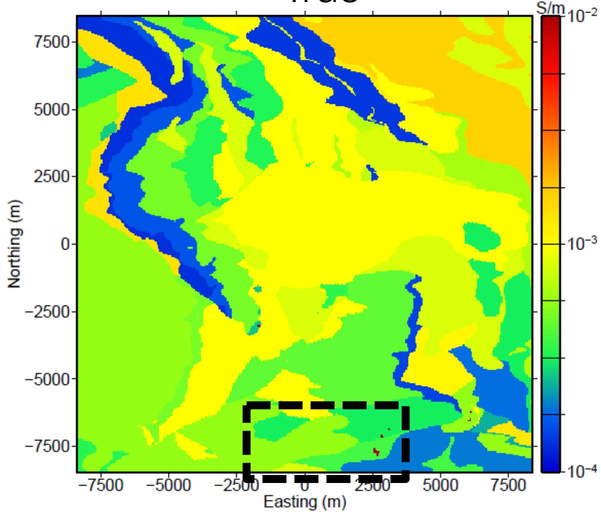


- Geologic units are well mapped
- Some mineralized bodies are located

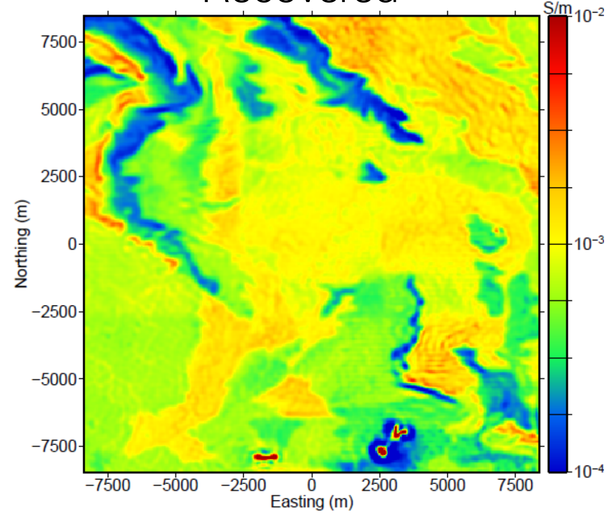
Synthesis

- Recovered model represents the regional geology

True

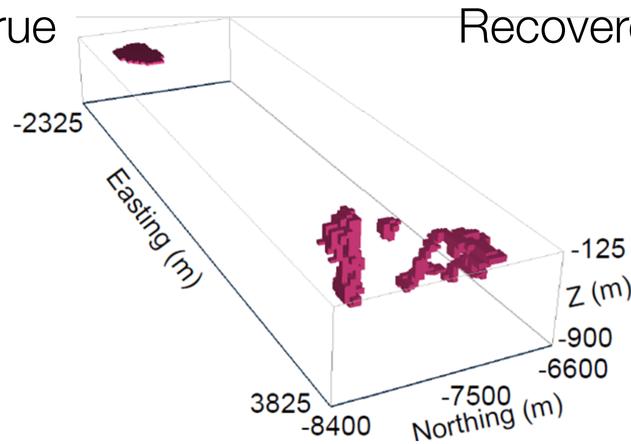


Recovered

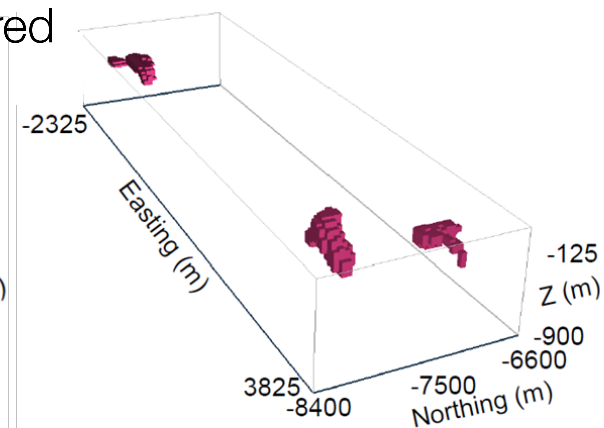


- Mineralized zones are recovered

True



Recovered



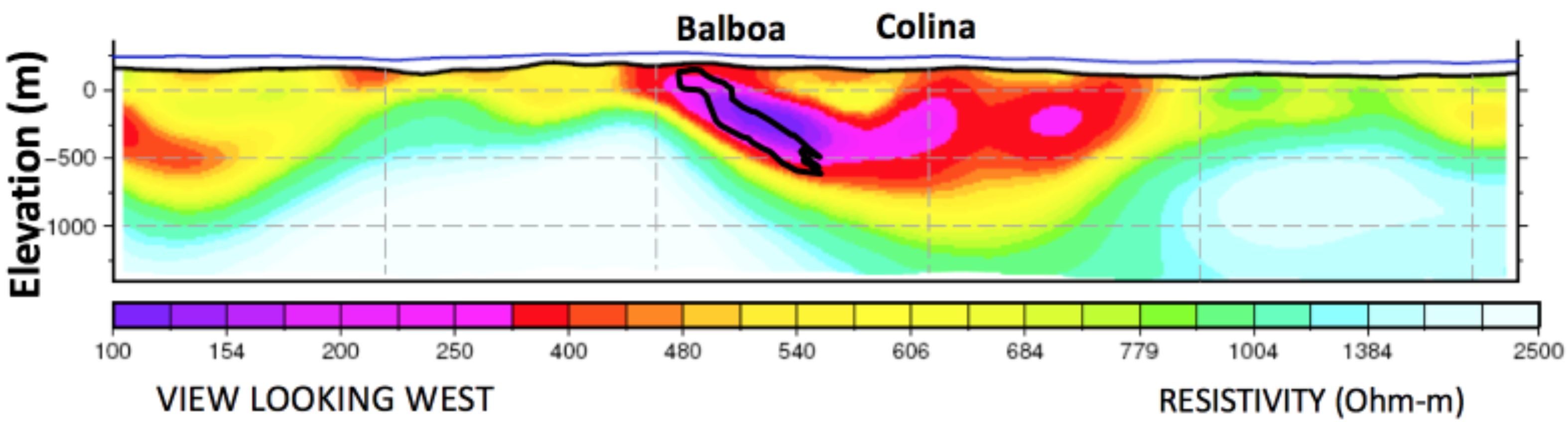
ZTEM case histories

- Synthetic based on Noranda district

- Balboa copper porphyry deposit

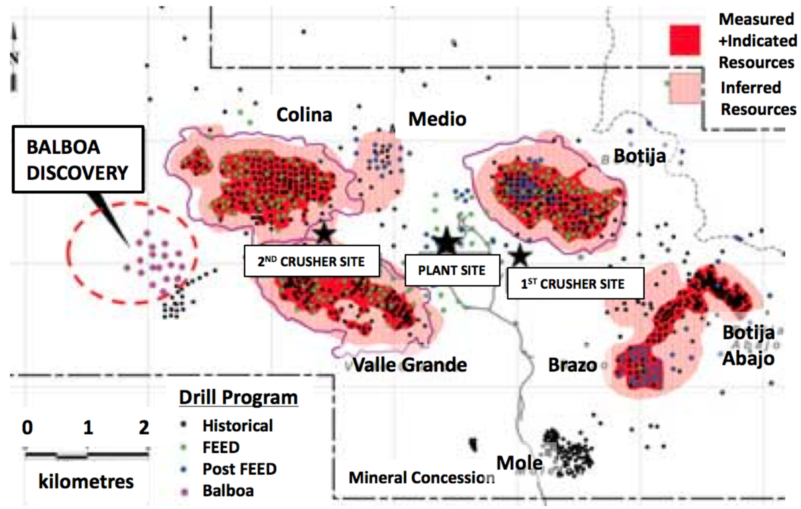
Case History:
The Balboa ZTEM Cu-Mo-Au porphyry discovery at Cobre Panama

Legault et al., 2016



Setup

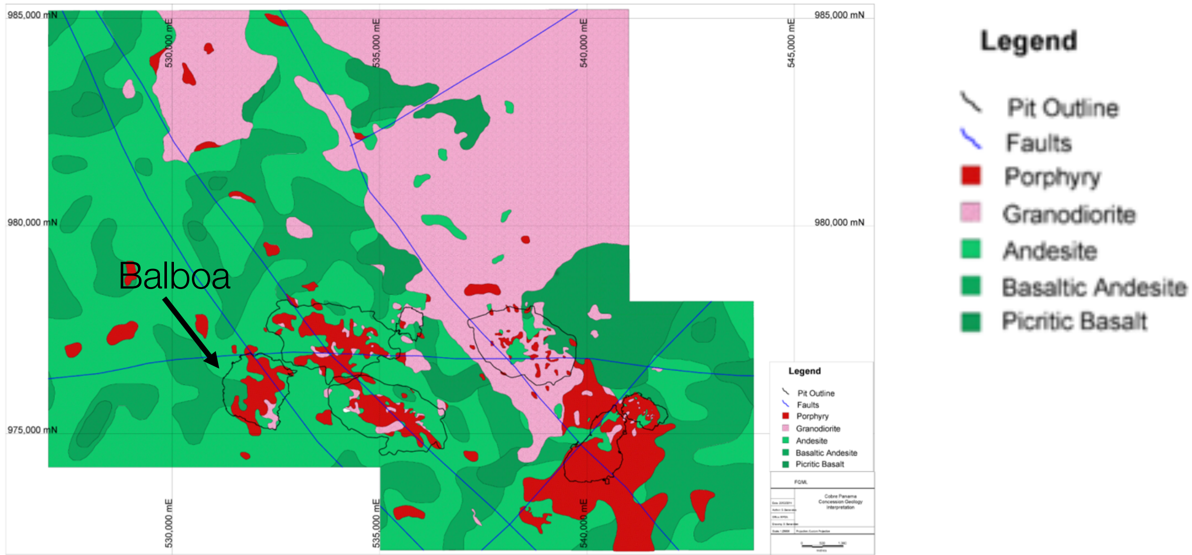
Resource map



- Balboa porphyry Cu-Mo-Au deposit
  - Located 1-2 km from known deposits: Colina, Medio, Botija, Valle Grande, Mole, Brazo, Botija Abajo
  - Most known deposits found with soil samples; followed by exploration programs

Setup

Geologic map

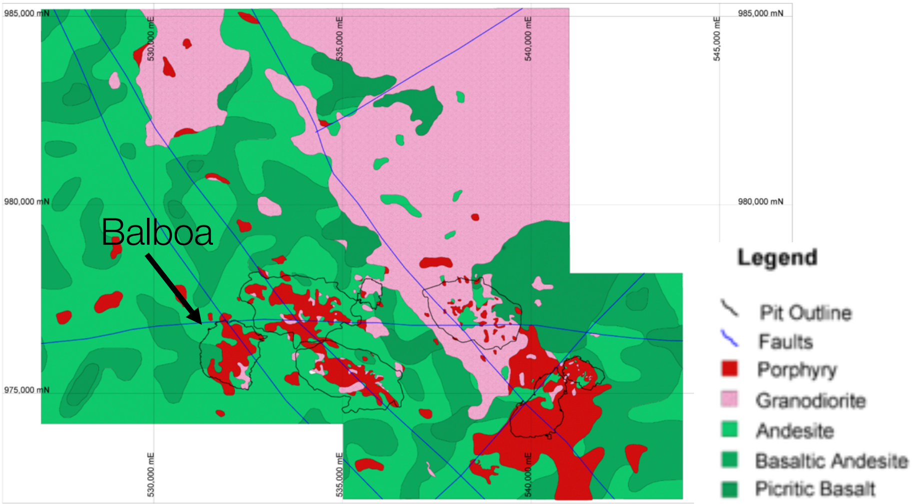


- Overburden: 20-30m of clay-rich saprolite
- Mineralization:
  - Mostly chlorite and chlorite-sericite alteration
  - Abundant disseminated chalcopyrite, pyrite and magnetite
- Previous helicopter TEM survey unsuccessful in detecting mineralized zones

Can ZTEM see mineralized zones below the conductive saprolite layer?

Properties

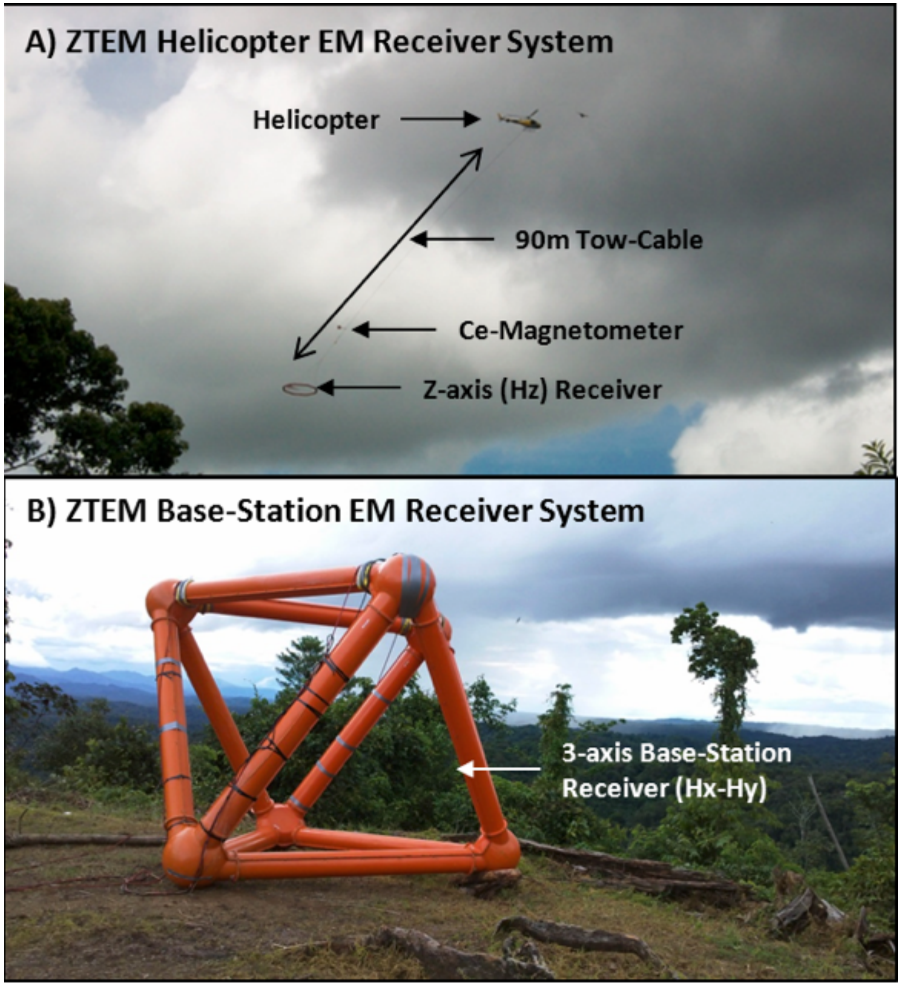
Geologic map

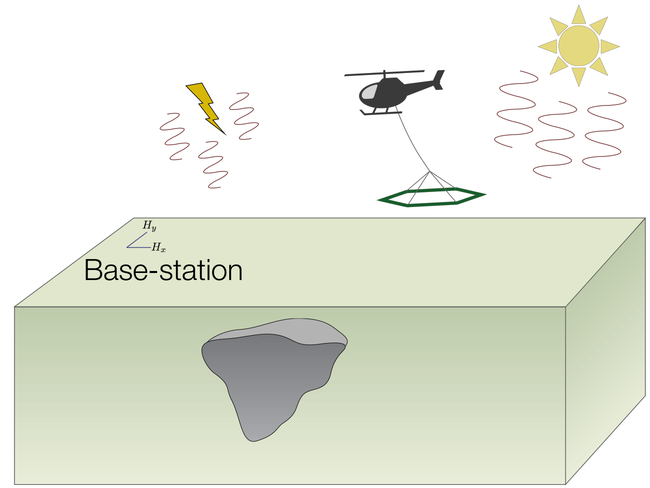


- Mineralized zone
  - High conductivity
  - Low magnetic susceptibility
- Highly conductive saprolite at surface (up to 30m thick)

Rock Unit	Resistivity ($\Omega \cdot m$)	Susceptibility (SI)
Saprolitic overburden	Low	Low
Host rock	High	Moderate
Granodiorite/porphyry (host rock; unmineralized)	Moderate	Moderate
Andesite/basalt (unmineralized)	Moderate	High
Mineralized/clay-altered	Low	Low

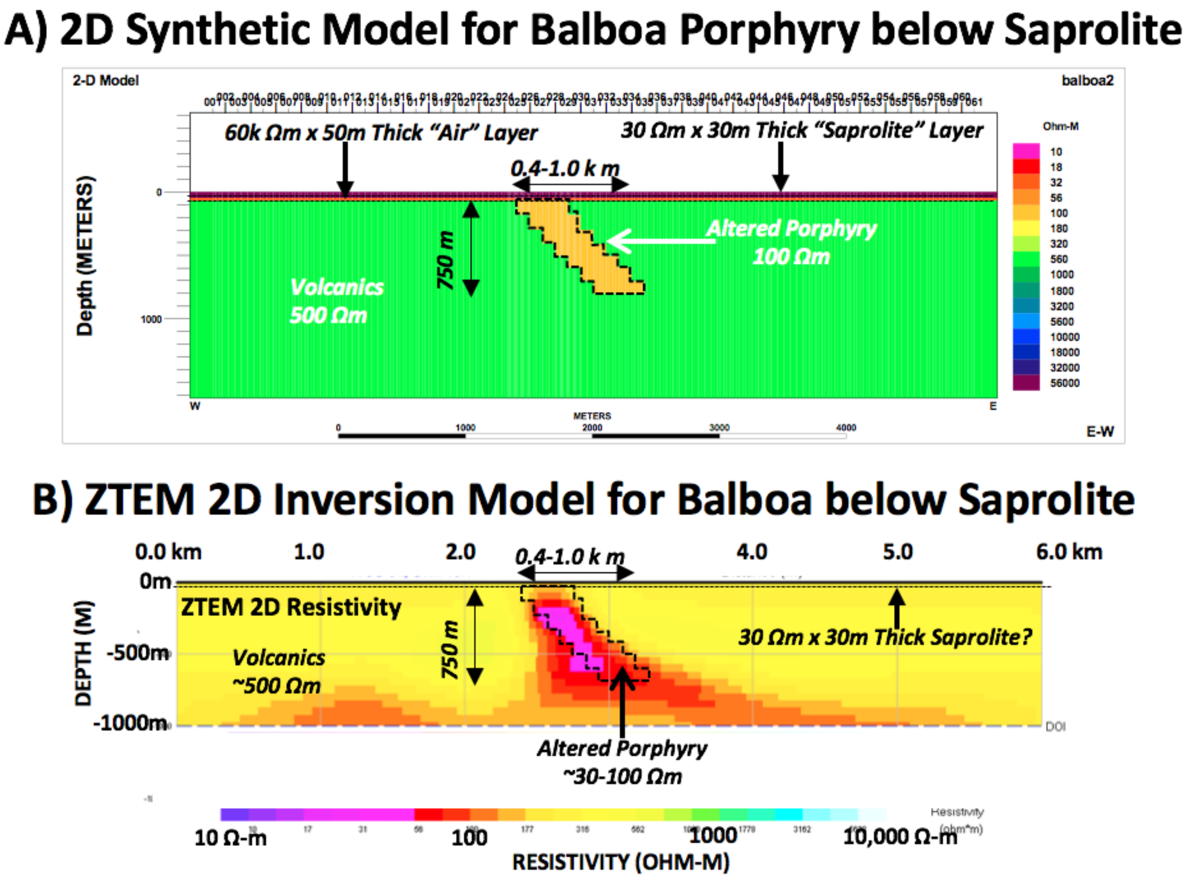
Survey





- System
  - 6 frequencies: 30-720 Hz
  - Hz: airborne receiver
  - Hx and Hy at base-station

Survey design



- Typical AEM survey can't see through conductive saprolite

- ZTEM insensitive to 1D conductivity

ZTEM can see through conductive overburden.

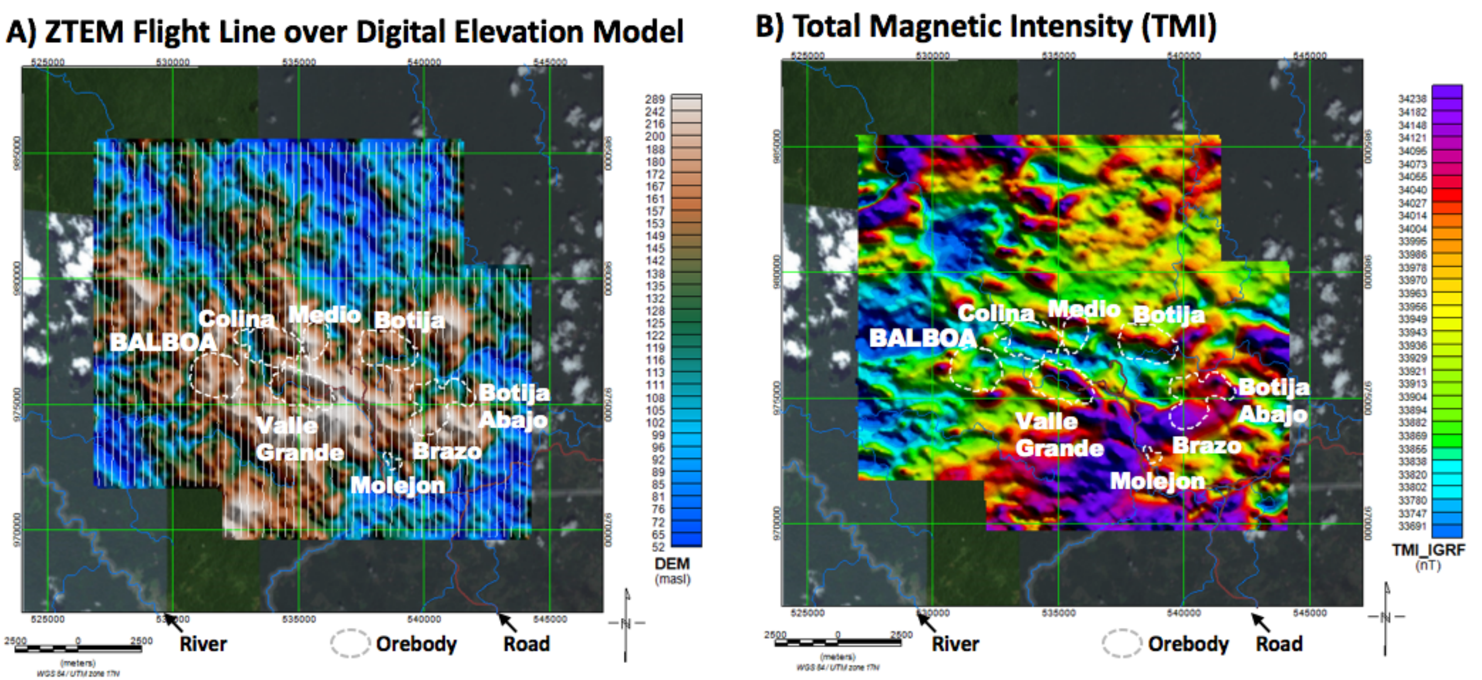
Data

- Tipper transfer function:

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

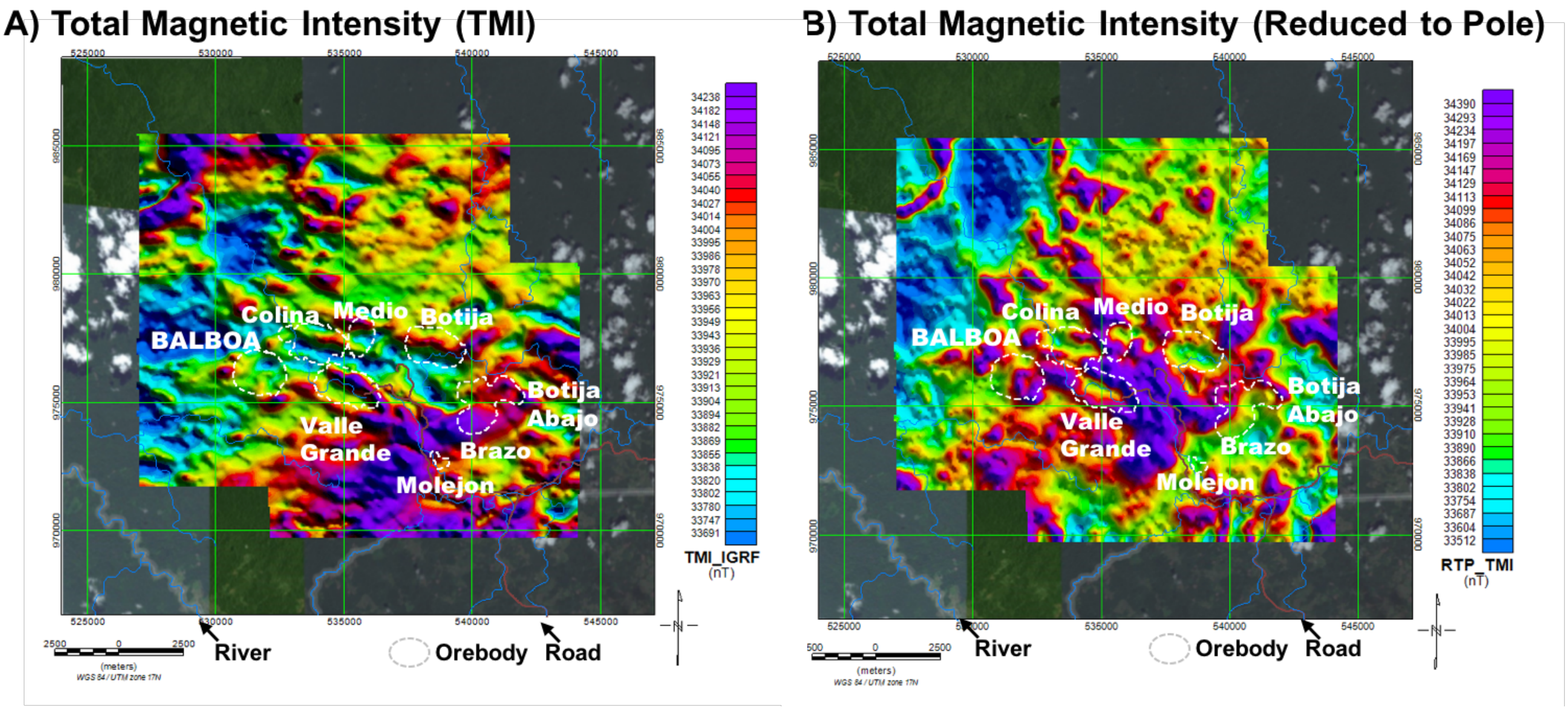
  - Tzx and Tzy obtained using similar processing as MT
  - Hx and Hy obtained from reference site (r_0)

- ZTEM survey also acquires magnetic data



Processing: magnetic data

- Reduced to pole (RTP)

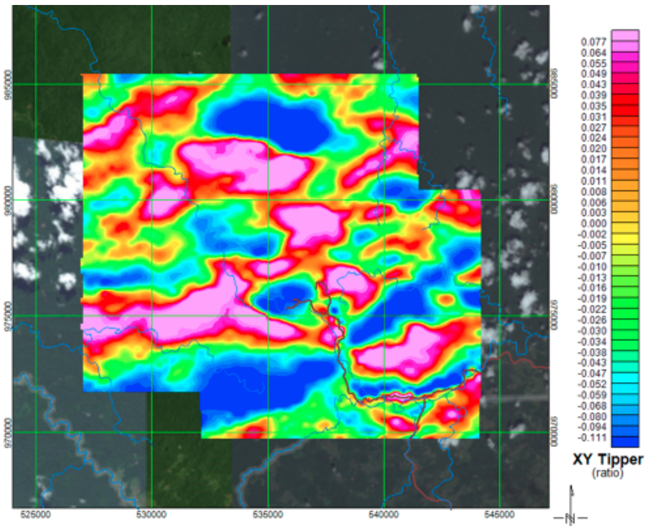


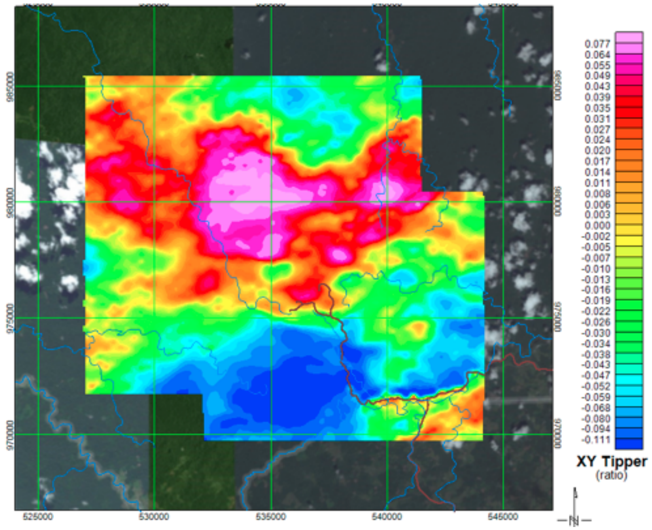
  - Known deposits correlate with magnetic lows (after RTP)
  - Demagnetized areas are due to alteration
  - Balboa not delineated (has both high and low anomalies)

ZTEM data at 90 Hz

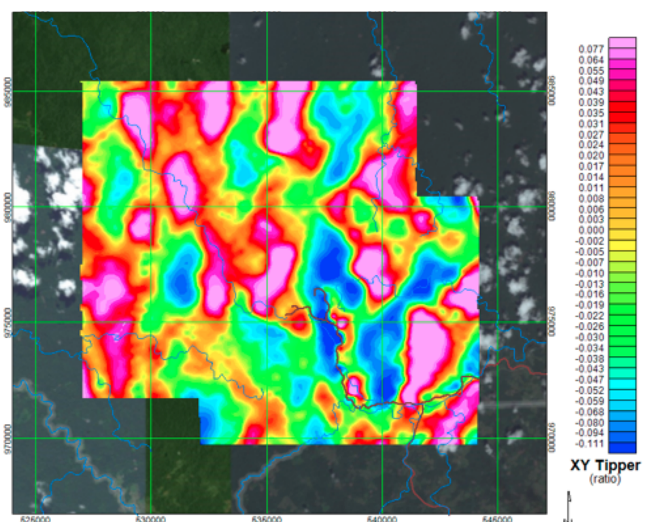
Real | Imag

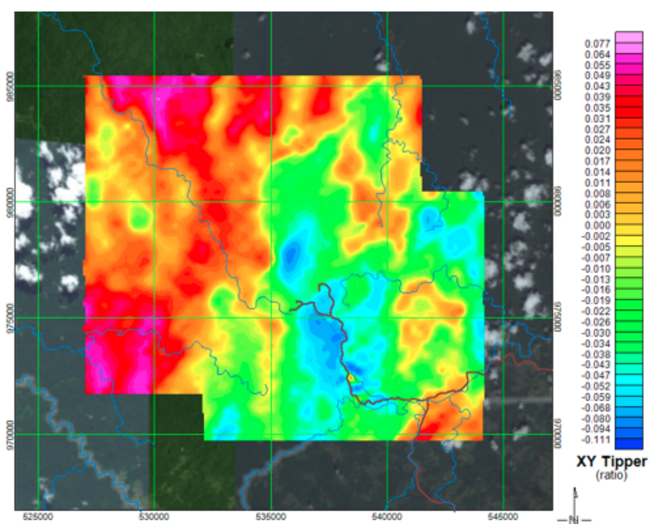
Tzx





Tzy

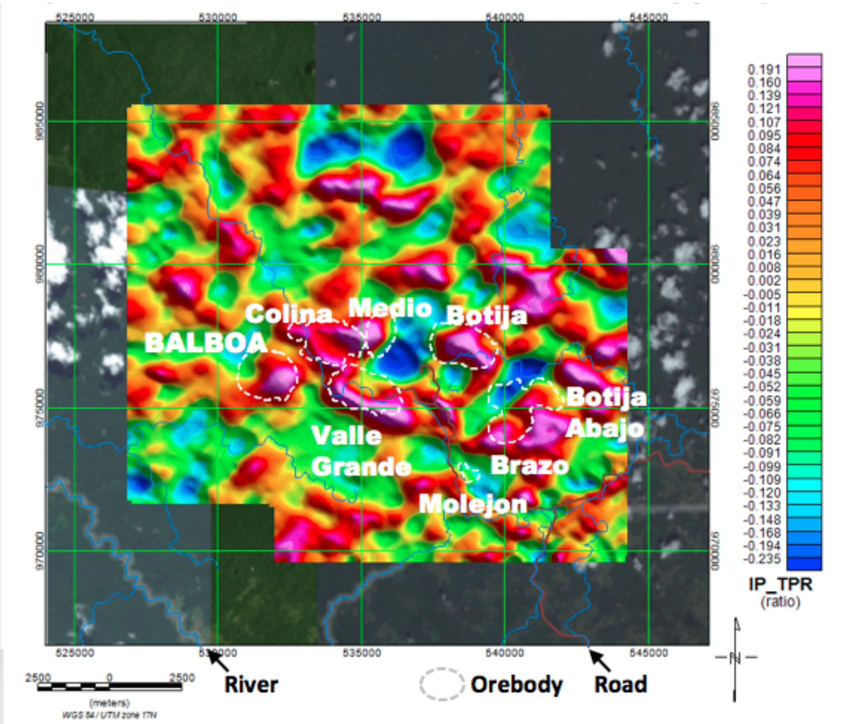




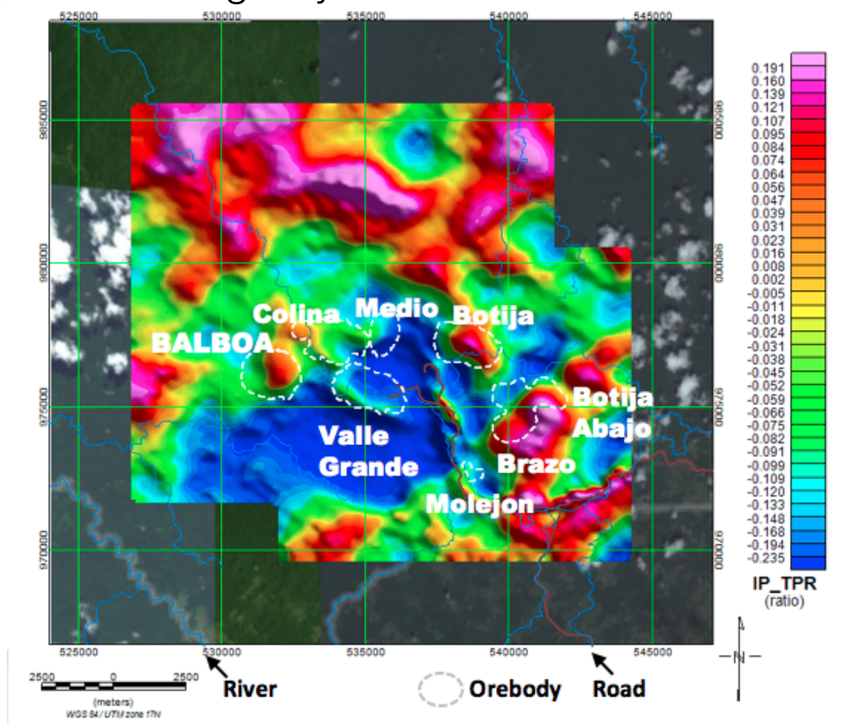
Processing: ZTEM data

- Total phase rotation (TPR)

TPR real at 360 Hz



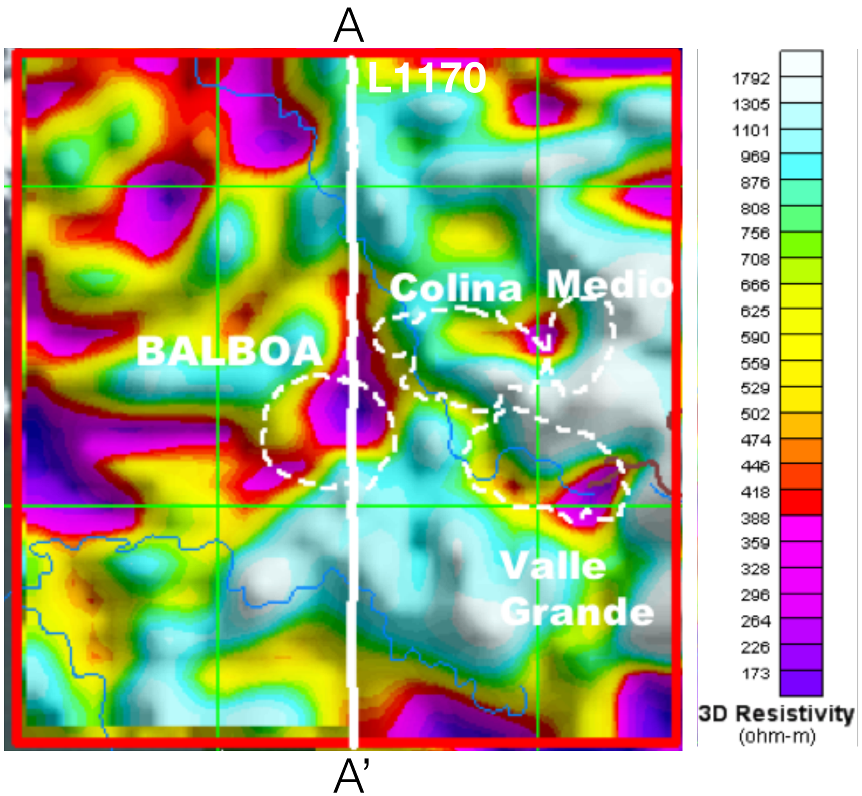
TPR imaginary at 30 Hz



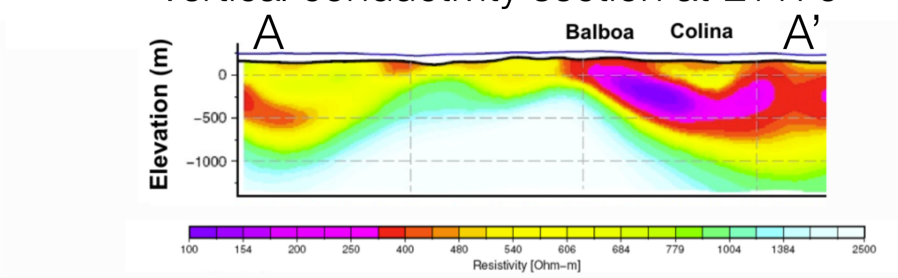
- At 360Hz, high values collocated with known deposits; some false positives
- At 30 Hz, regional resistive structure; deeper conductive structures collocated with some known deposits

Inversion and Interpretation

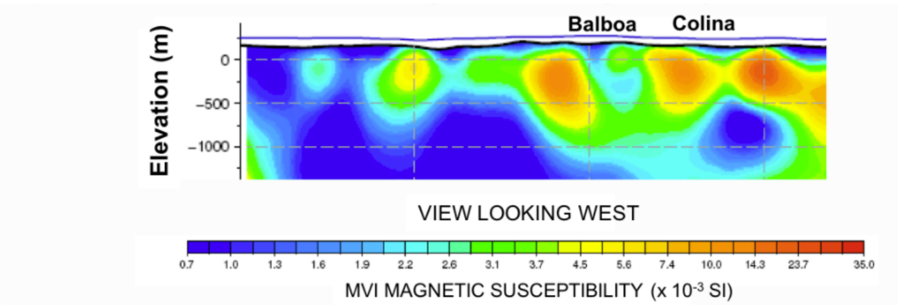
3D conductivity at 500 m depth



Vertical conductivity section at L1170

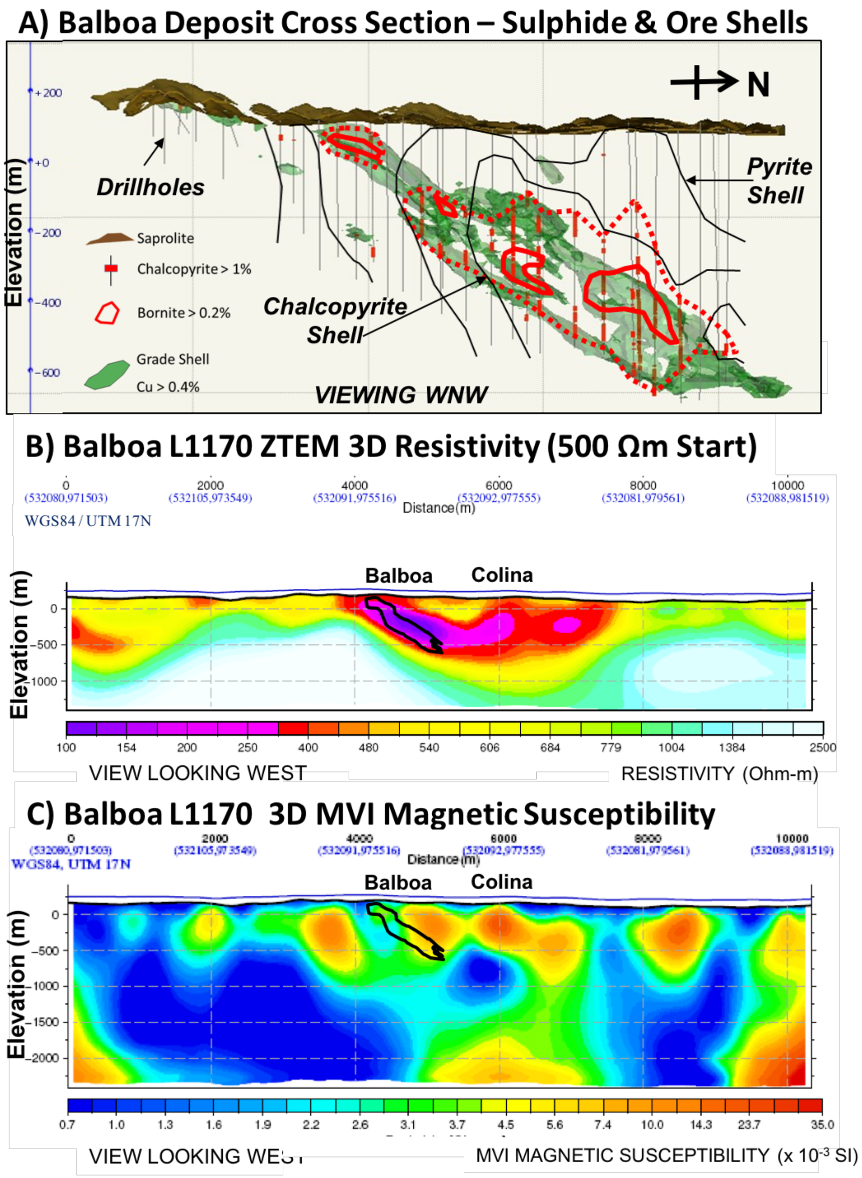


Vertical susceptibility section at L1170



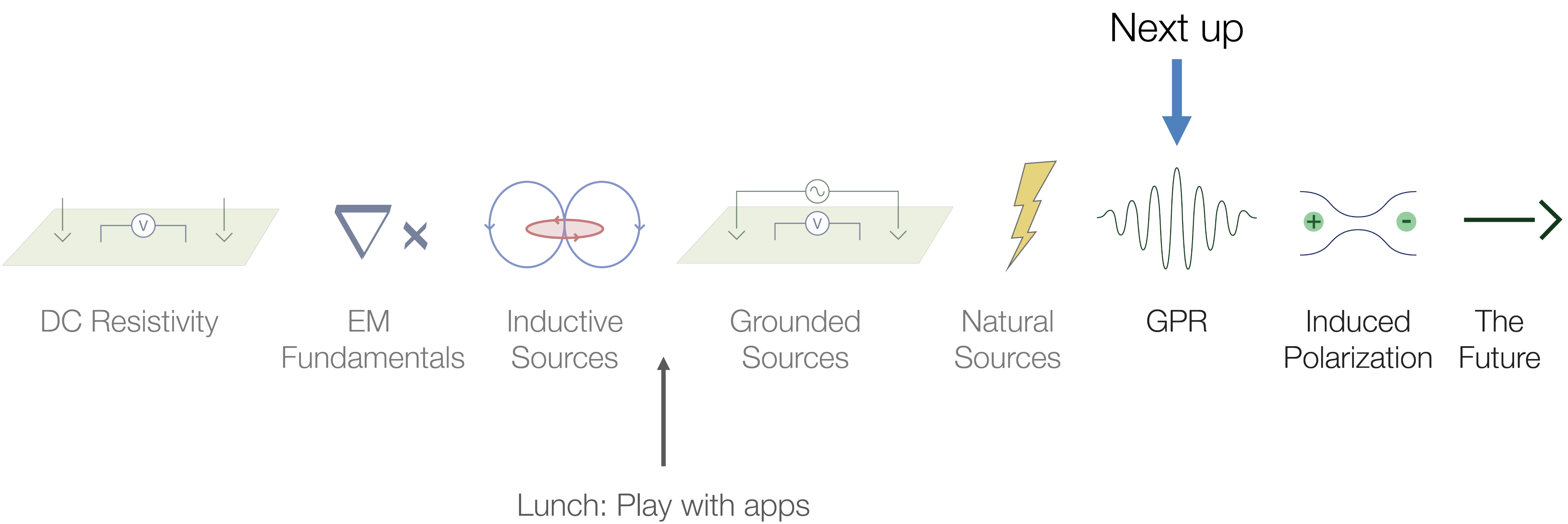
- Balboa deposit
  - Conductor imaged at depth
  - Magnetic low at depth

Synthesis



- Exploration and drilling motivated by soil sampling failed to identify Balboa
- Helicopter TDEM could not see through conductive saprolite
- Conductive anomaly collocated with Balboa deposit agrees with boundary of higher-grade zones from drilling

End of Natural Sources

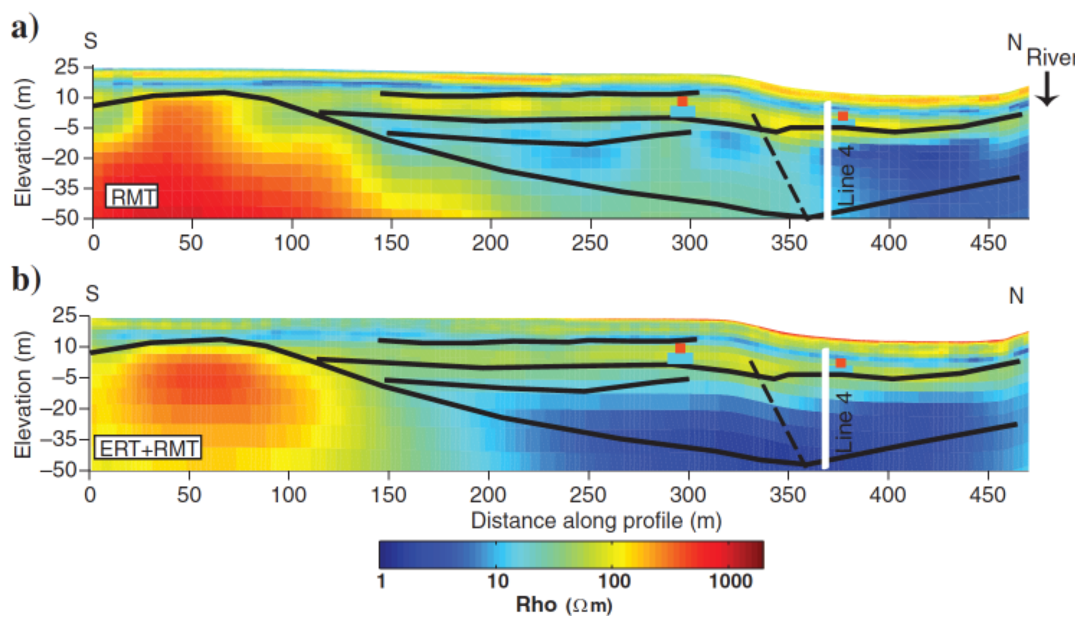


Additional Material

- Case History: Landslides

Case History: Landslides, Sweden

Shan et al., 2014



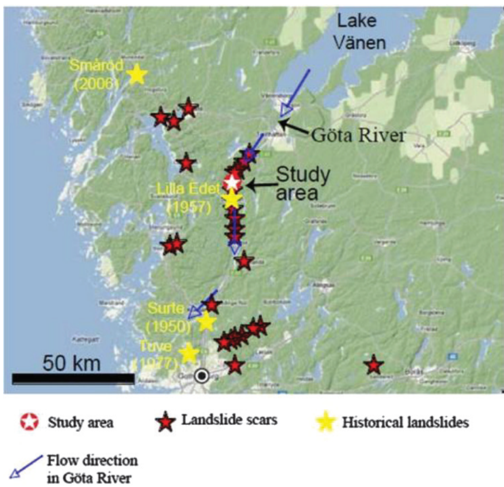
Landslides in Sweden

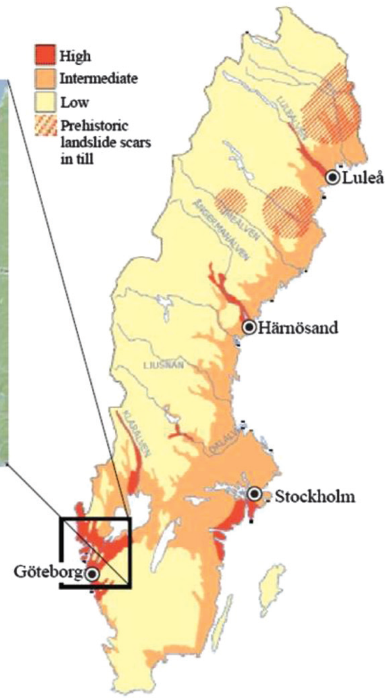

Photo: C Fredén, 1977, Tuve


Photo: Mats Engdahl, 2006, Munkedal

Setup

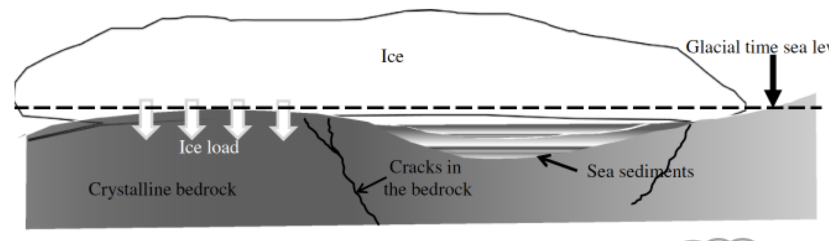
Location map



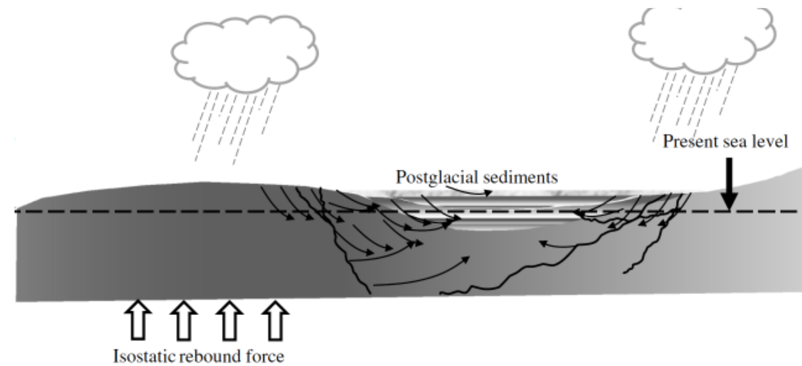


Formation of quick clays

The last glacial period



Land uplift and formation of quick clays



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

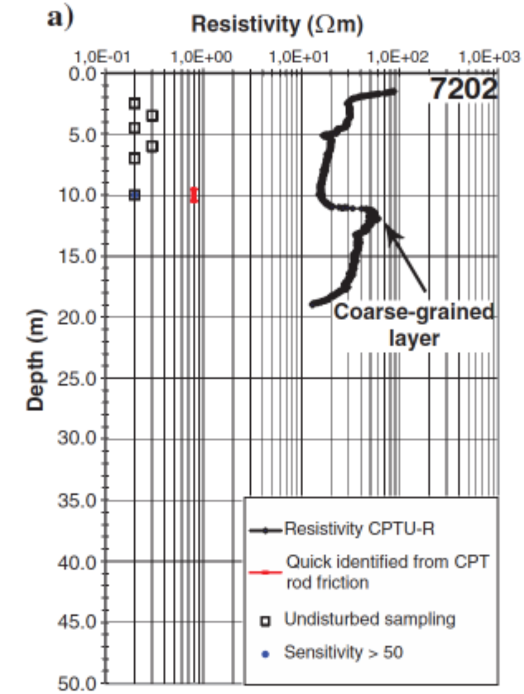
Can we detect quick clays?

Properties

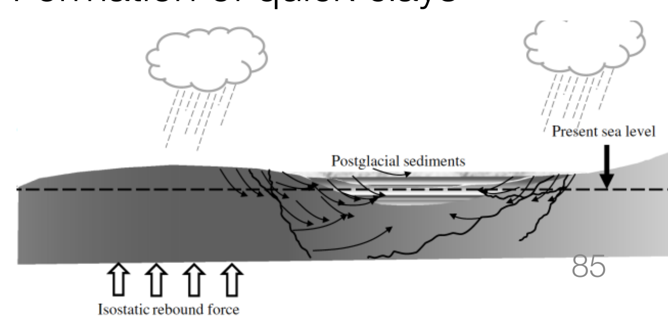
Soil material	Resistivity interval
Salt/intact marine clay	1–10 Ωm
Leached, possible quick clay	10–80 Ωm
Dry crust clay, slide deposits, coarser	>80 Ωm

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

Resistivity (induction log)

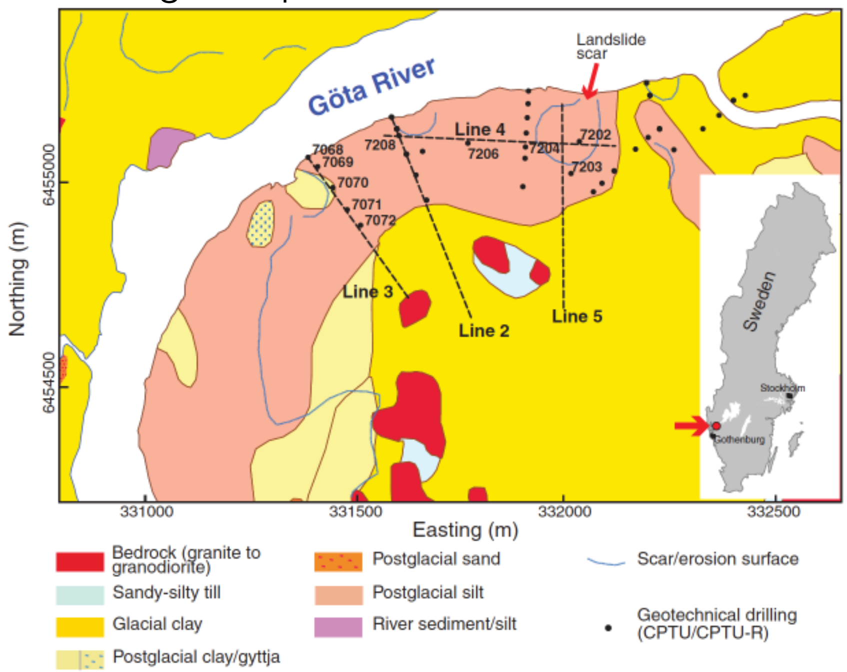


Formation of quick clays

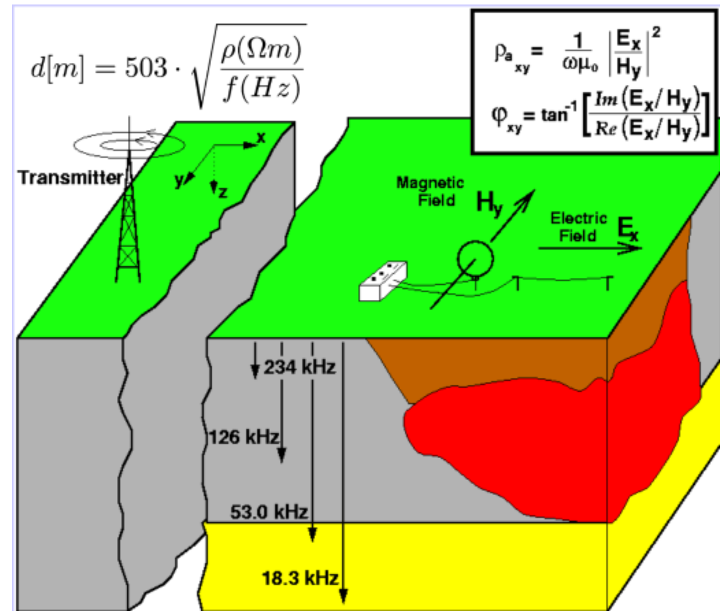


Surveys

Geologic map



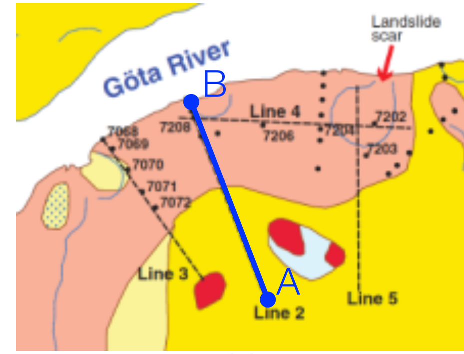
RMT survey



From Bulent (2017)

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

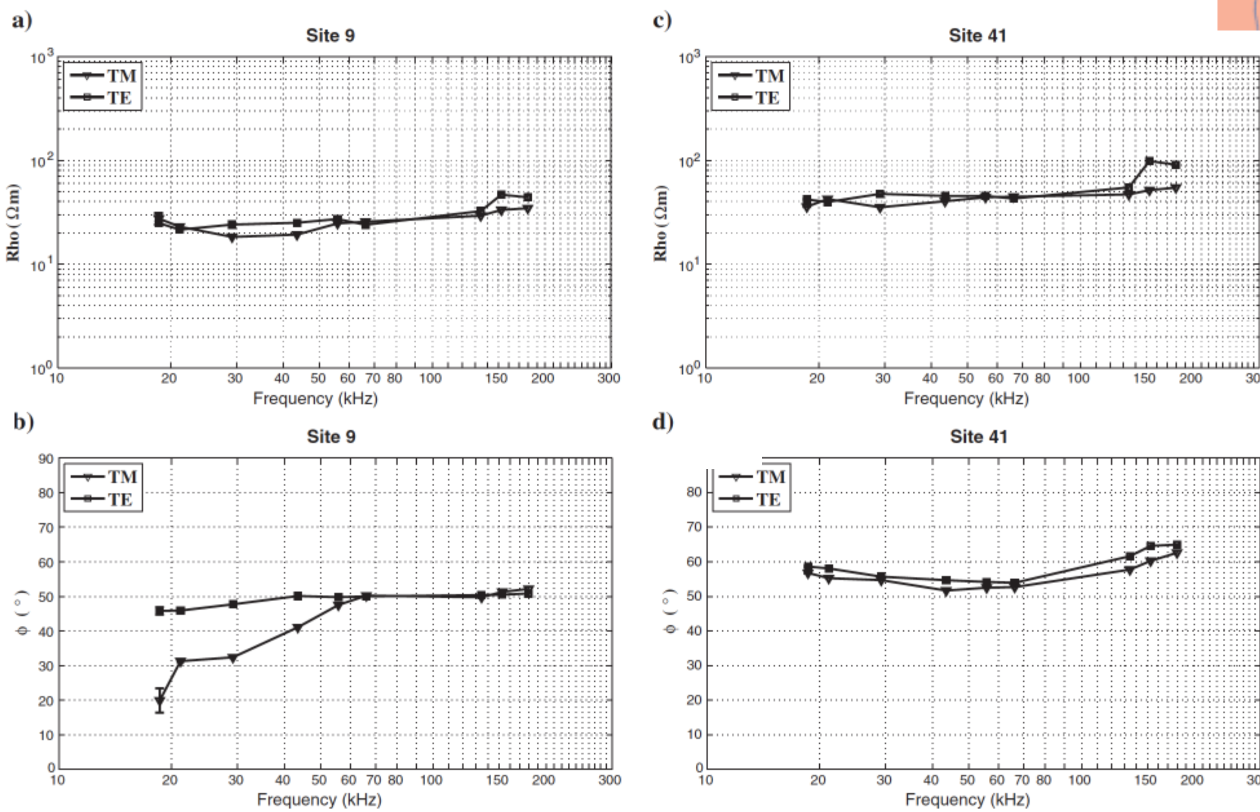
RMT: sounding curves



Line 2

Apparent resistivity

Phase

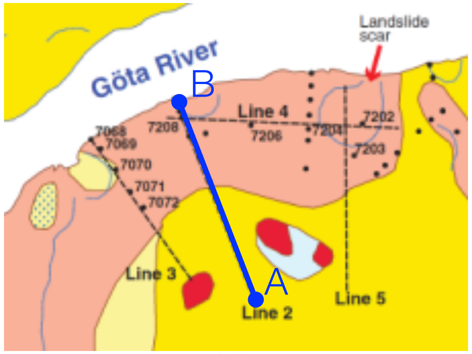


Computed using determinant of impedance tensor at two stations along Line 2

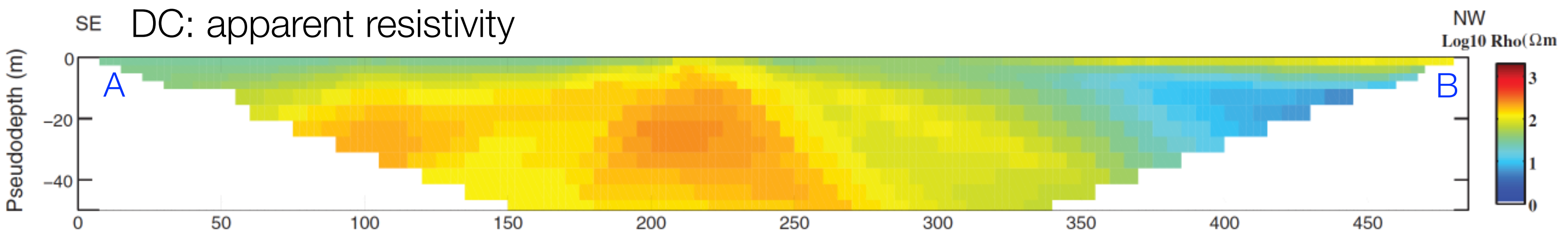
Impedance tensor: $\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix}$

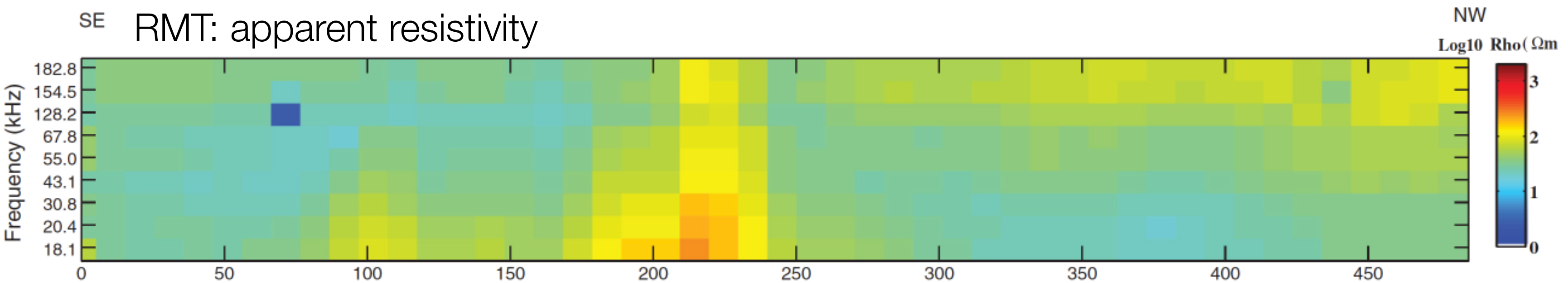
Determinant: (complex-valued) $Z_{\text{det}} = \sqrt{Z_{xx}Z_{yy} - Z_{xy}Z_{yx}}$

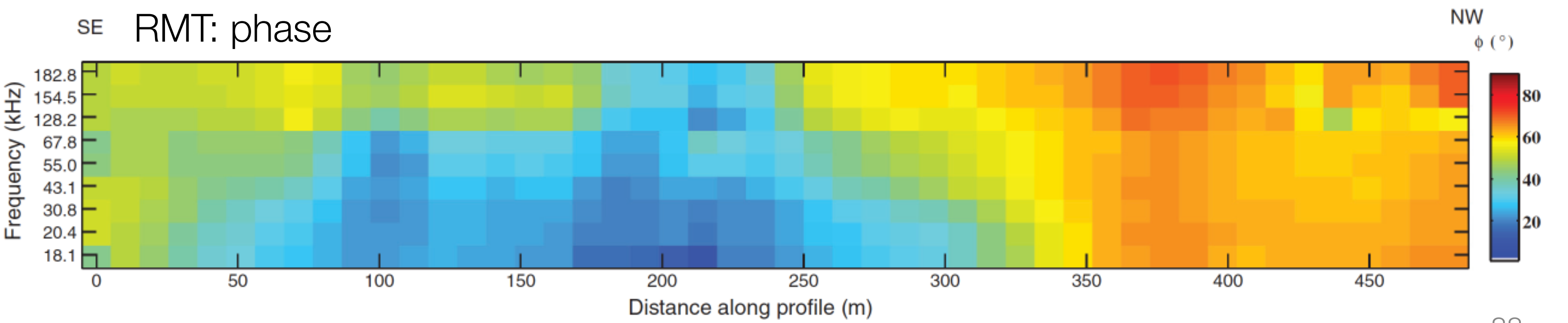
Pseudosections



Line 2







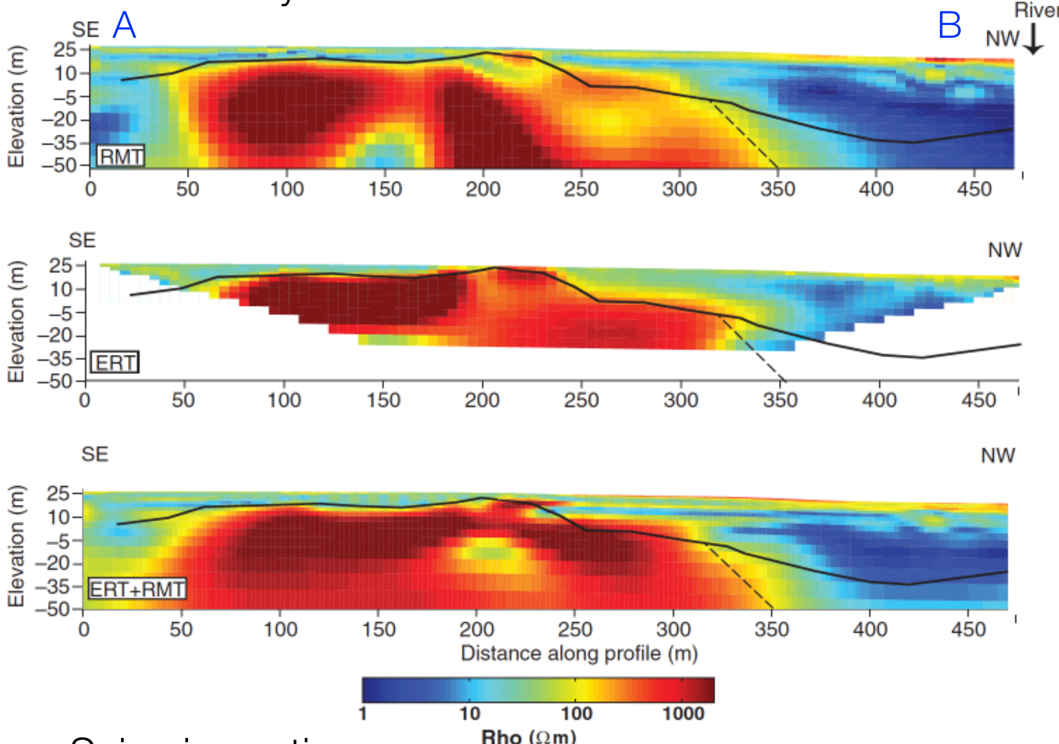
Processing and inversion

2D resistivity sections

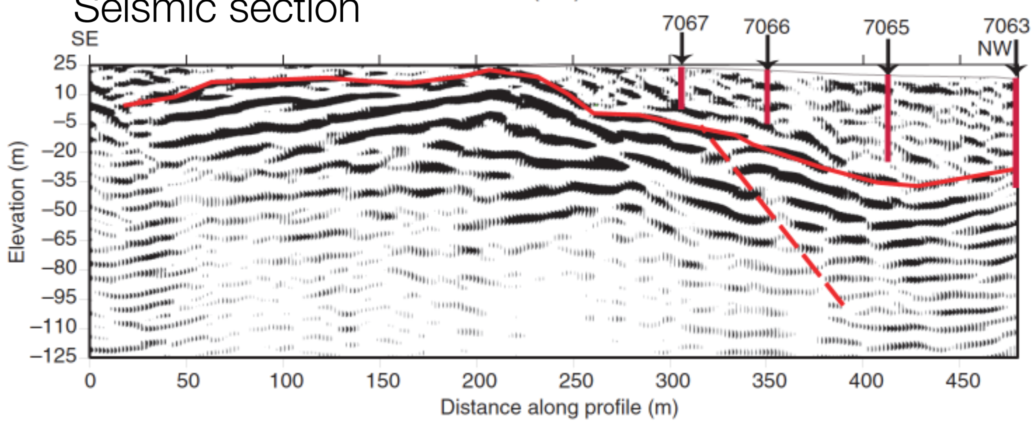
RMT

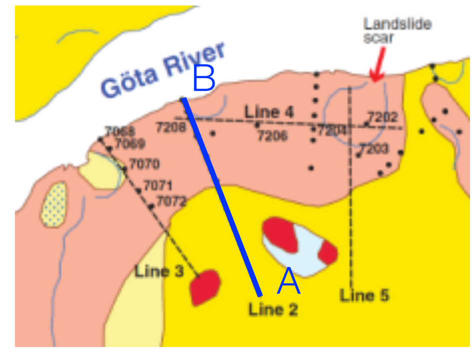
ERT

ERT + RMT



Seismic section





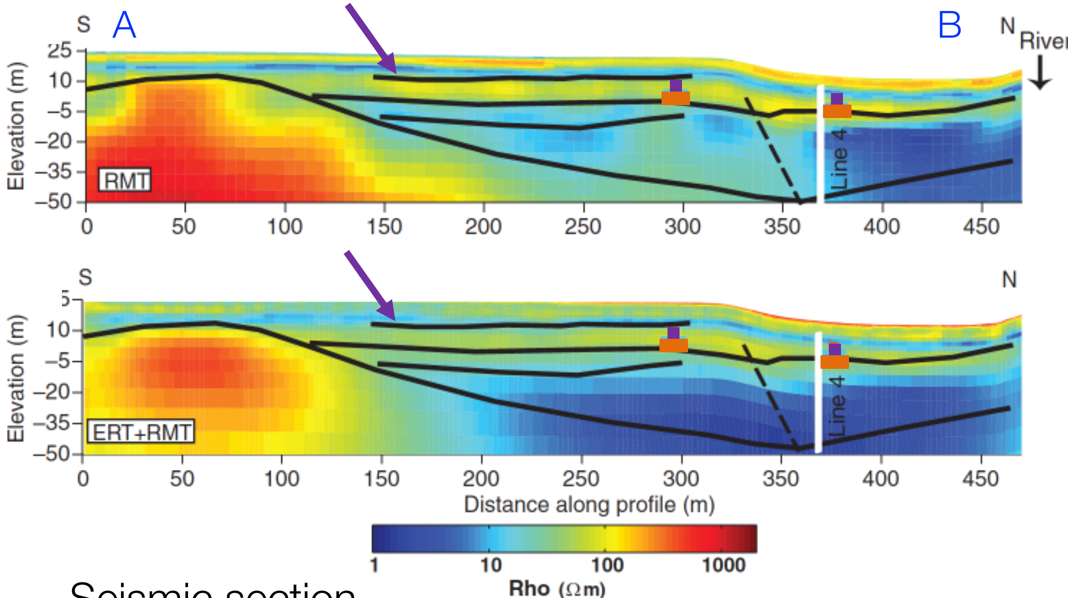
- ERT and RMT yield similar images
- Jointly invert ERT and RMT
- Correlates with seismic

Processing and inversion

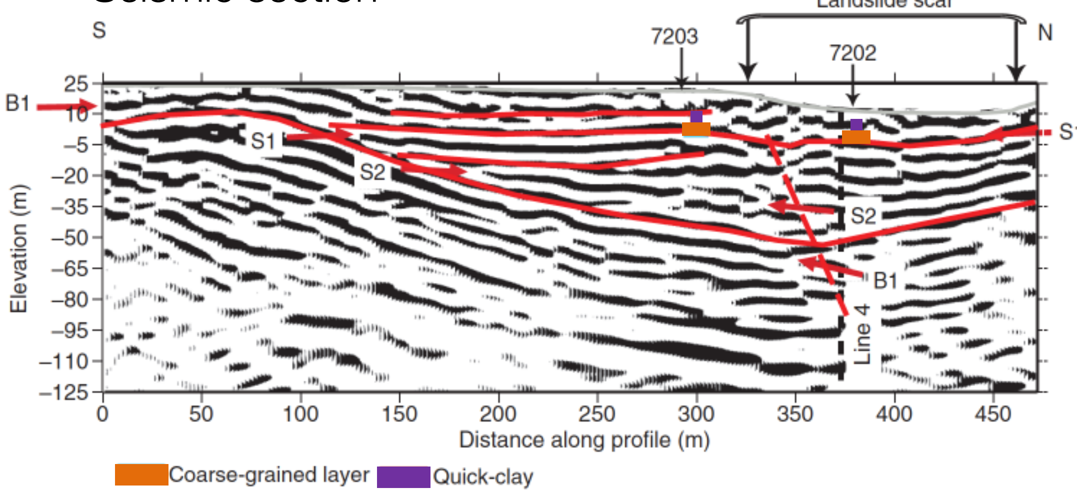
2D resistivity sections

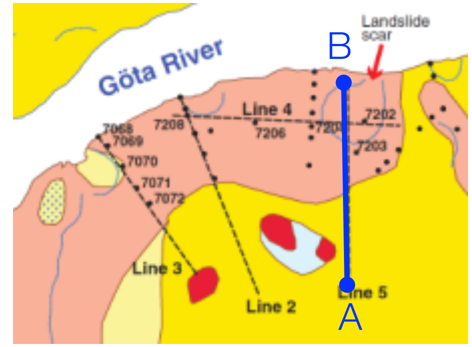
RMT

ERT
+
RMT



Seismic section

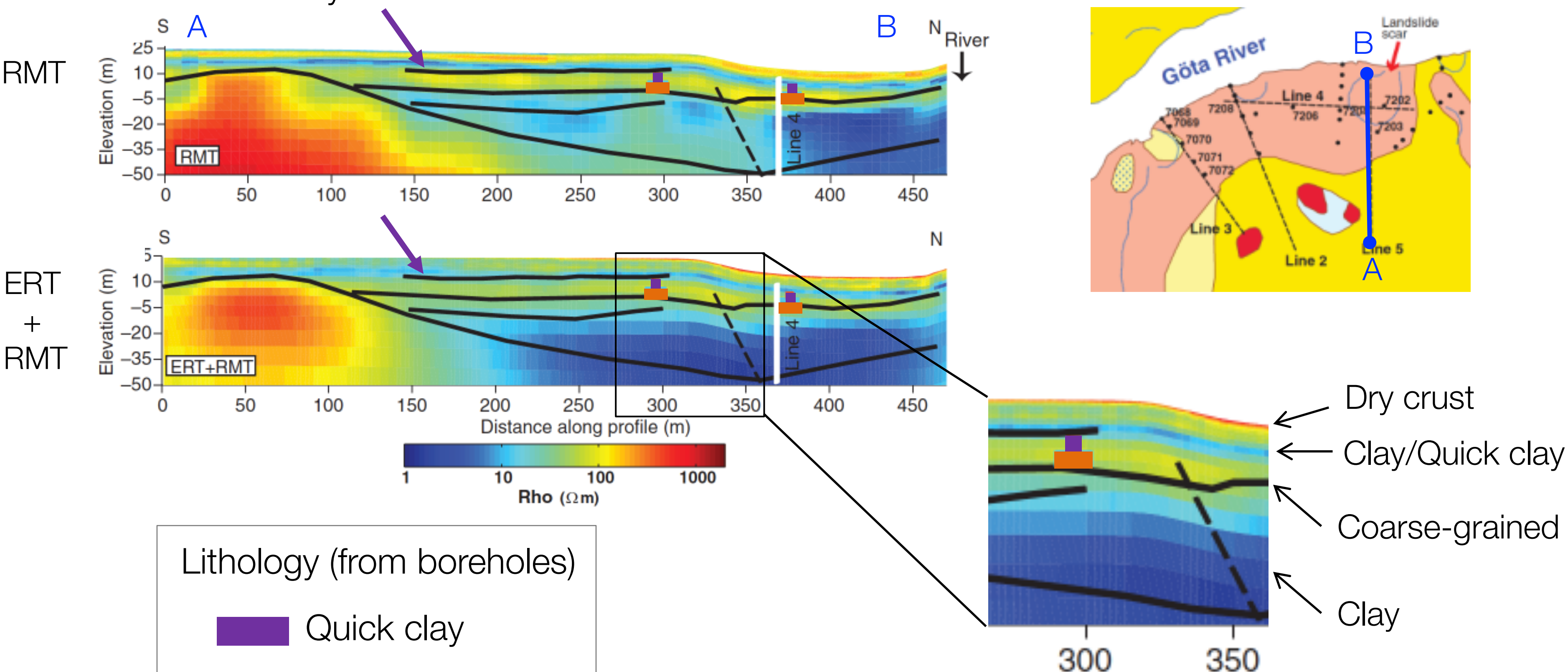




- Inverted RMT, ERT+RMT interpreted with seismic

Processing and inversion

2D resistivity sections



Lithology (from boreholes)

- Quick clay
- Coarse layer

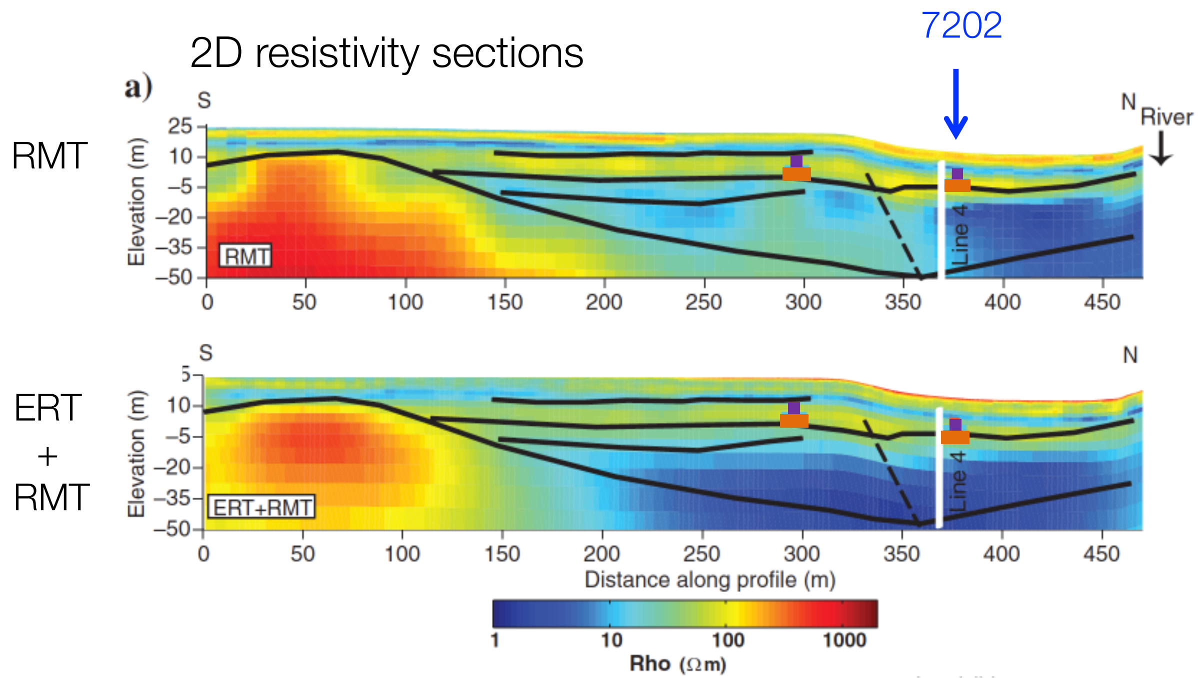
Soil material	Resistivity interval
Salt/intact marine clay	1–10 Ωm
Leached, possible quick clay	10–80 Ωm
Dry crust clay, slide deposits, coarser	>80 Ωm

Quick clay

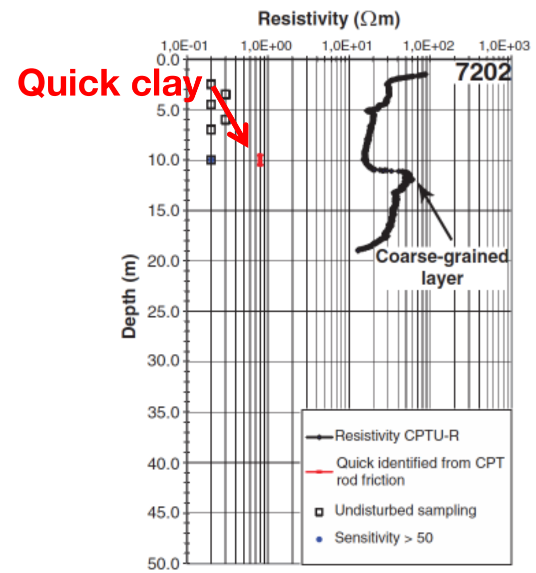
- Top interface: conductor to resistor
- Thickness difficult to estimate

Synthesis

2D resistivity sections



Resistivity log



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