EM: Natural Sources

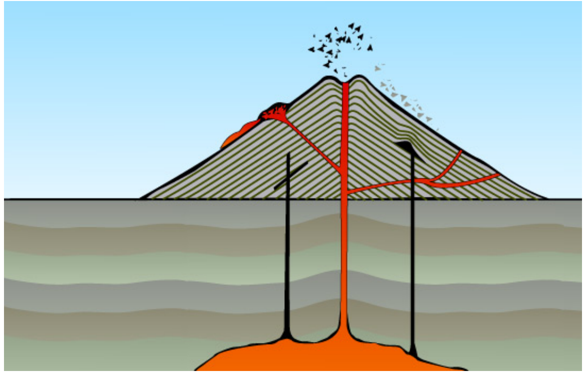
GeoSci.xyz

Outline

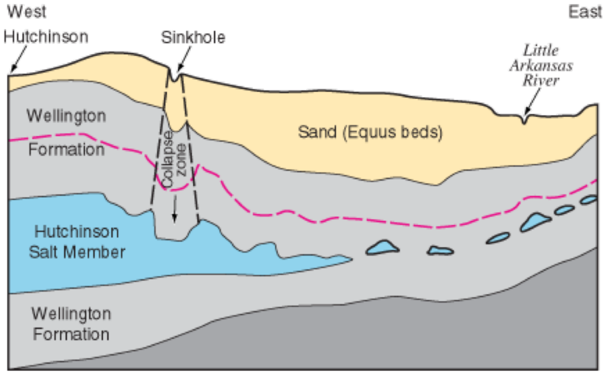
- Background on natural source EM methods
- Magnetotellurics
- Case histories: Geothermal, Minerals, Hydrocarbons
- Z-axis tipper electromagnetics
- Case histories (ZTEM): Geologic Mapping, Minerals

Motivation

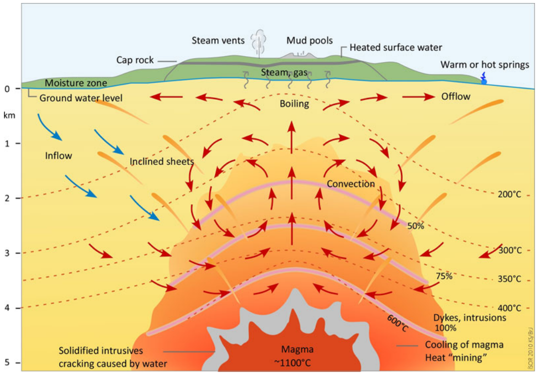
Volcanoes



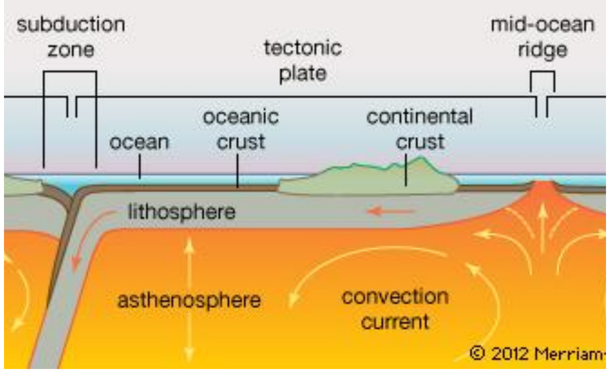
Base of salt



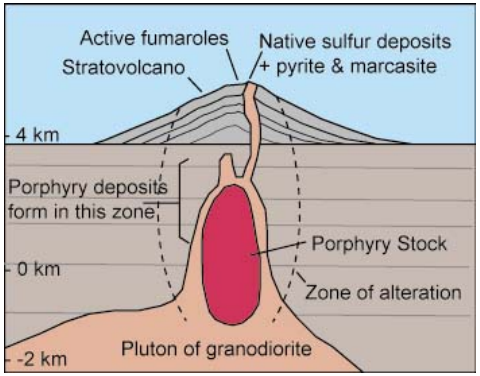
Geothermal



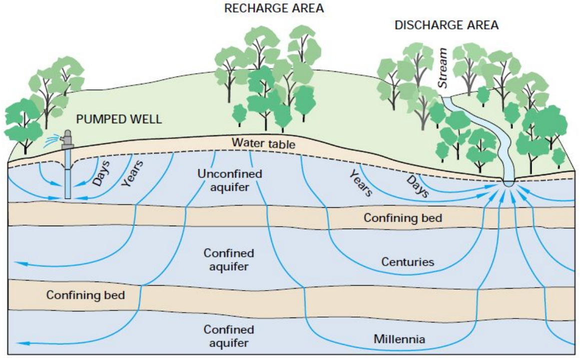
Tectonic settings of top few km



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

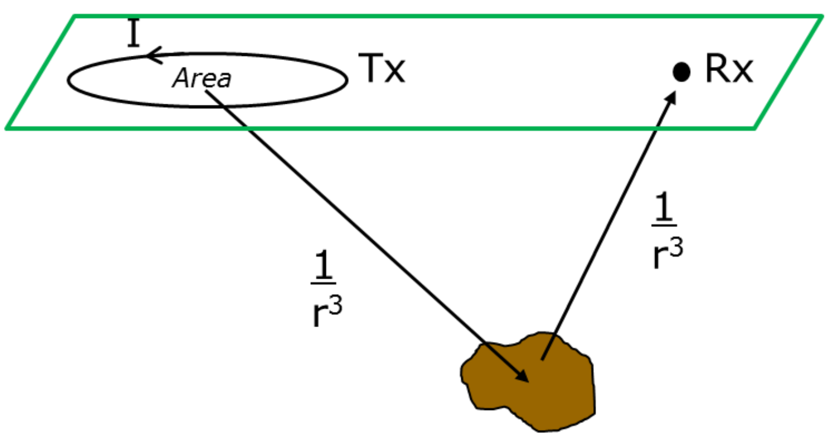
$$m = IA$$

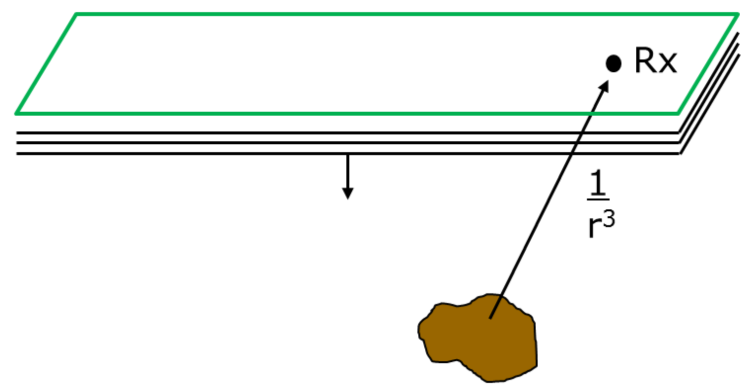
  - Total geometric decay

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

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

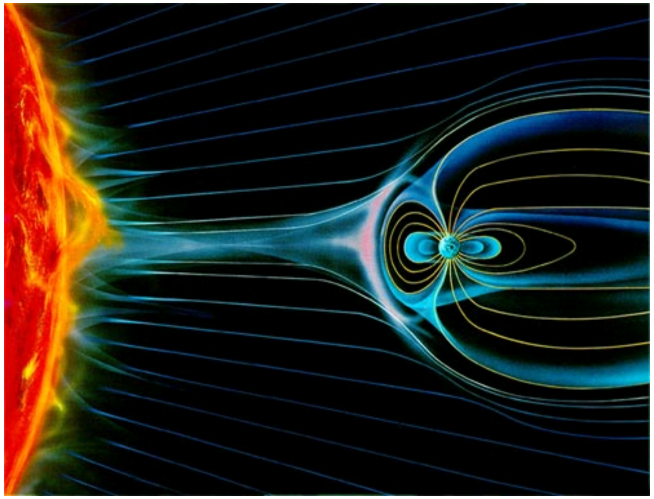
$$\sim \frac{1}{r^3}$$





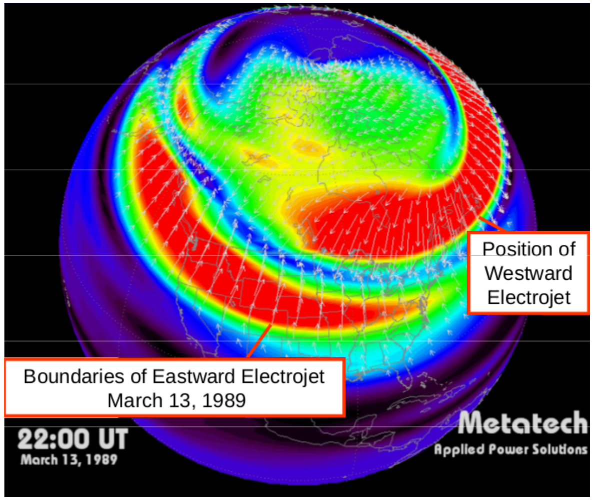
Natural EM sources

Sun and magnetosphere, solar storms

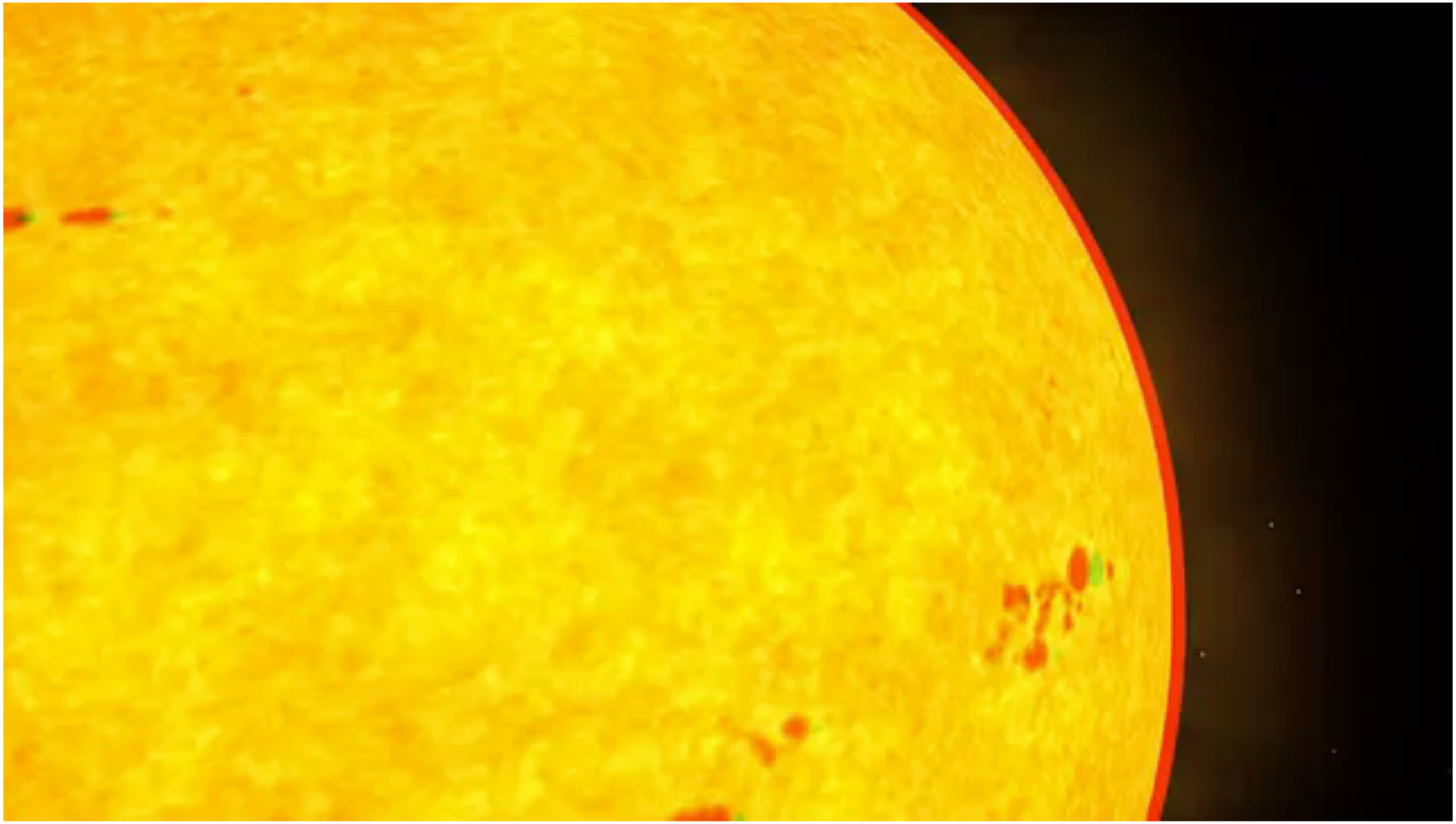


Lightning

Auroral electrojet; aurora

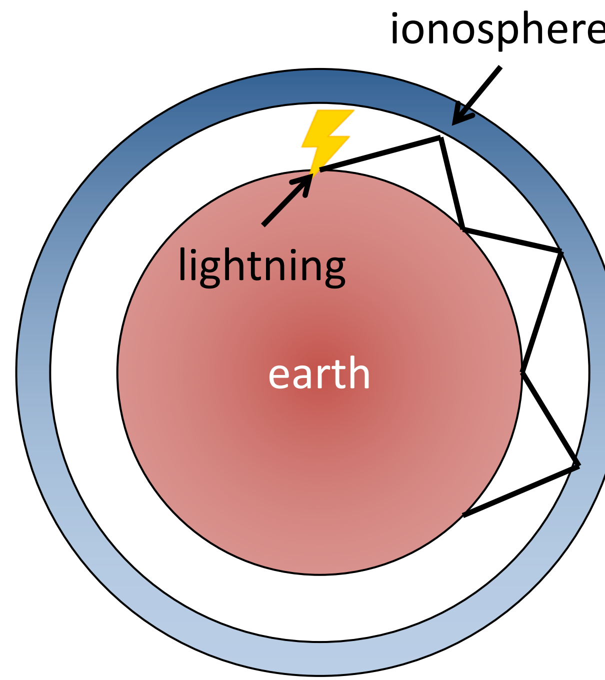


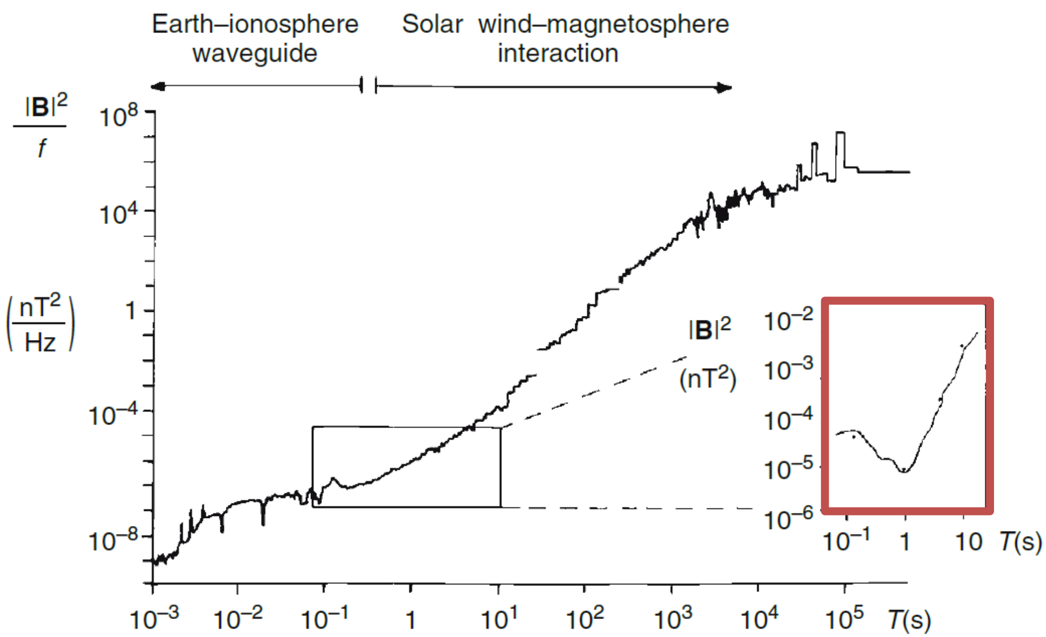
Aurora movie



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

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

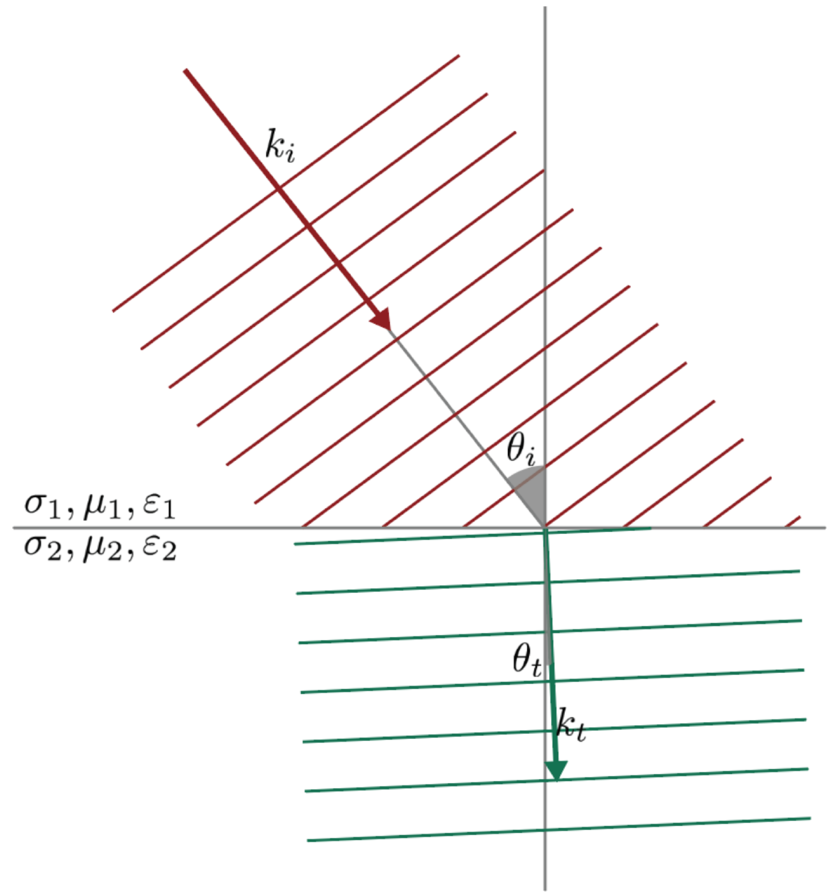
- k is complex wave number

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

- 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 $\theta_t = 1.35°$

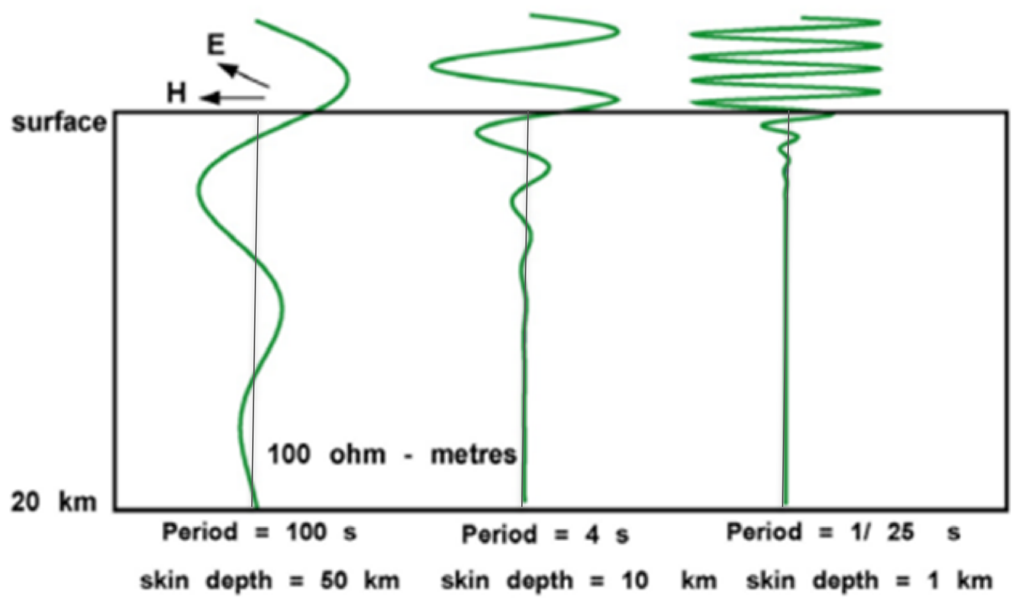
Plane waves and skin depth

- Skin depth (meters)

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

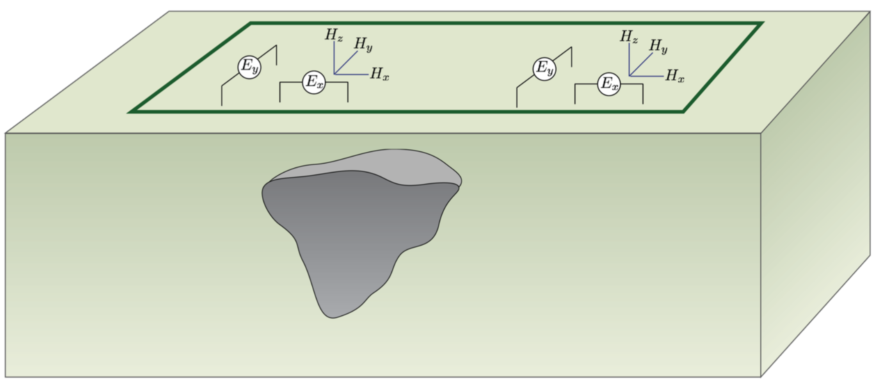
- Low frequency waves propagate further

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

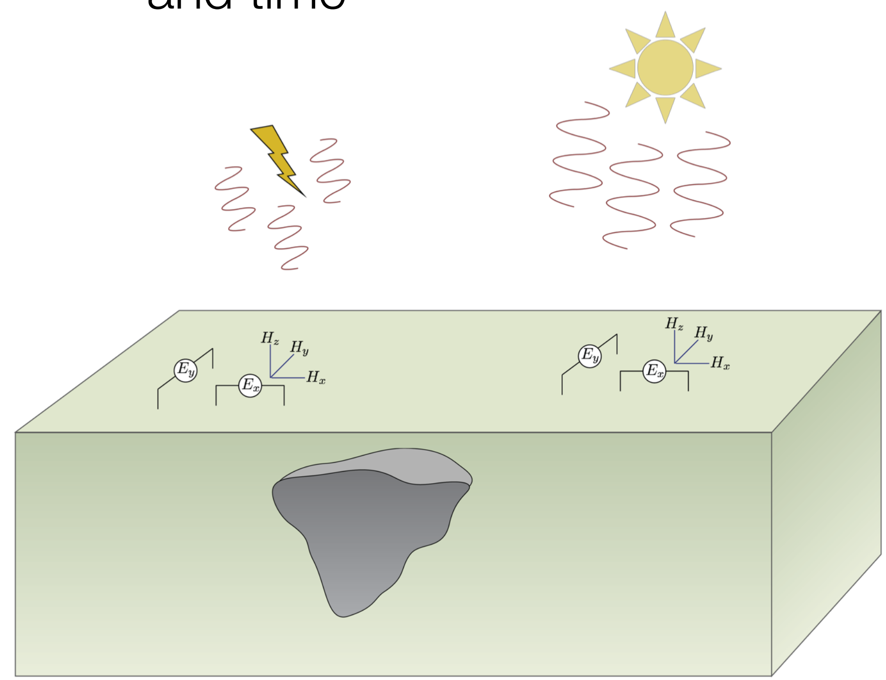


Control source vs Natural source

- 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

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

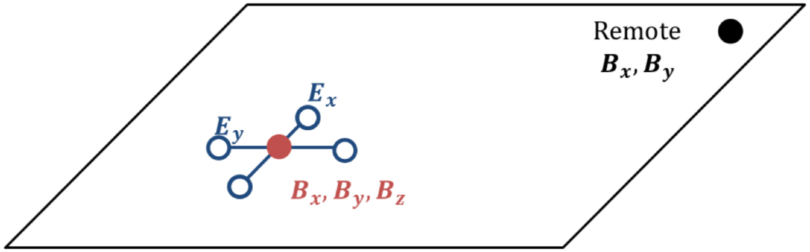
- Effects of unknown source removed by taking ratio

- Transfer function

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

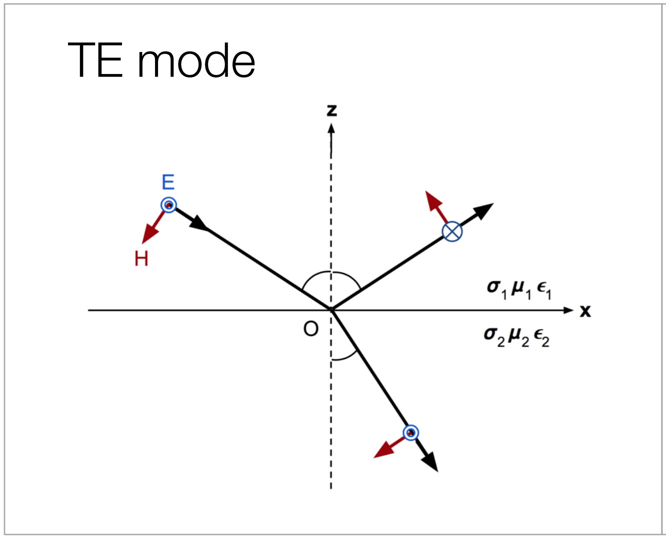
impedance (matrix)

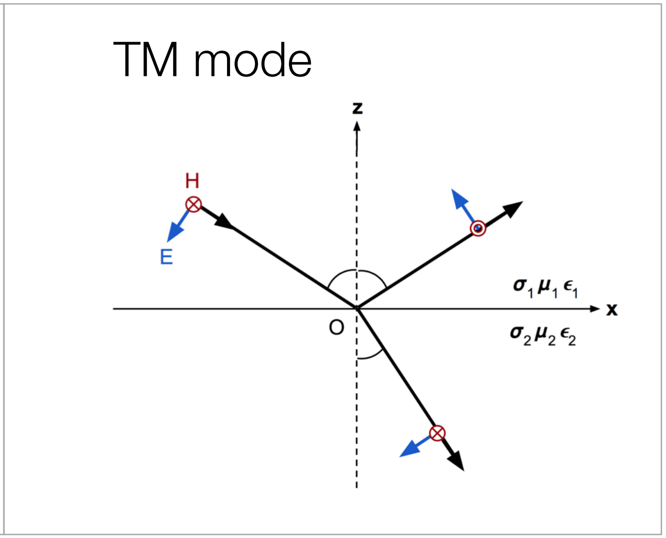
$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \begin{pmatrix} H_x \\ H_y \end{pmatrix}$$



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:

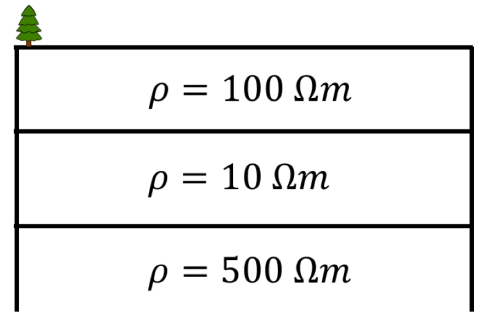
$$\Phi = \tan^{-1}\left(\frac{Im(Z_{xy})}{Re(Z_{xy})}\right)$$

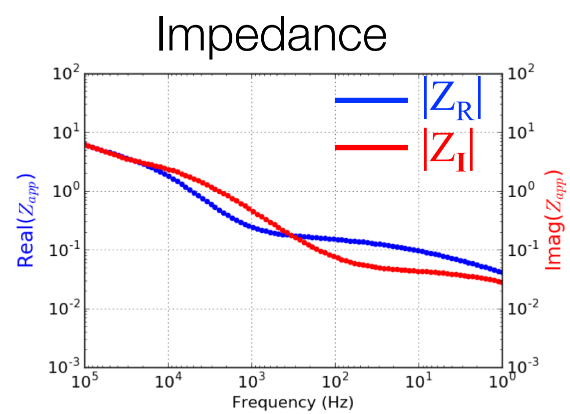
- In 1D:

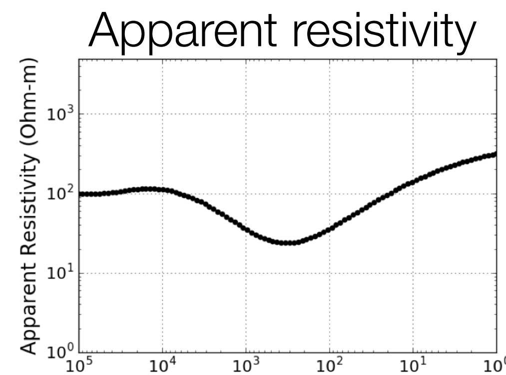
$$Z = \begin{pmatrix} 0 & Z_{xy} \\ Z_{yx} & 0 \end{pmatrix}$$

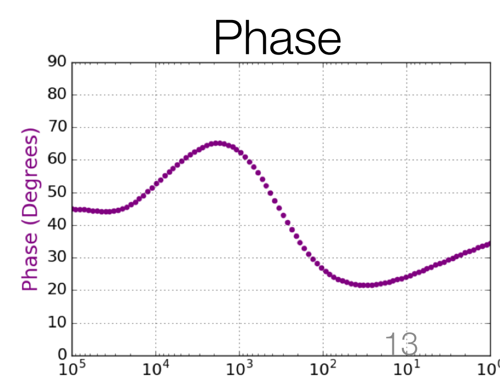
$$Z_{xy} = \frac{E_x}{H_y}$$

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





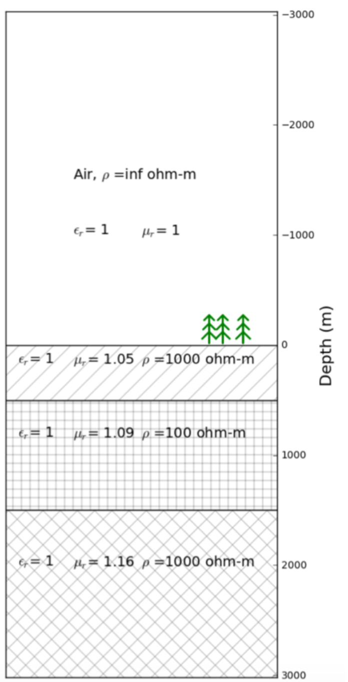


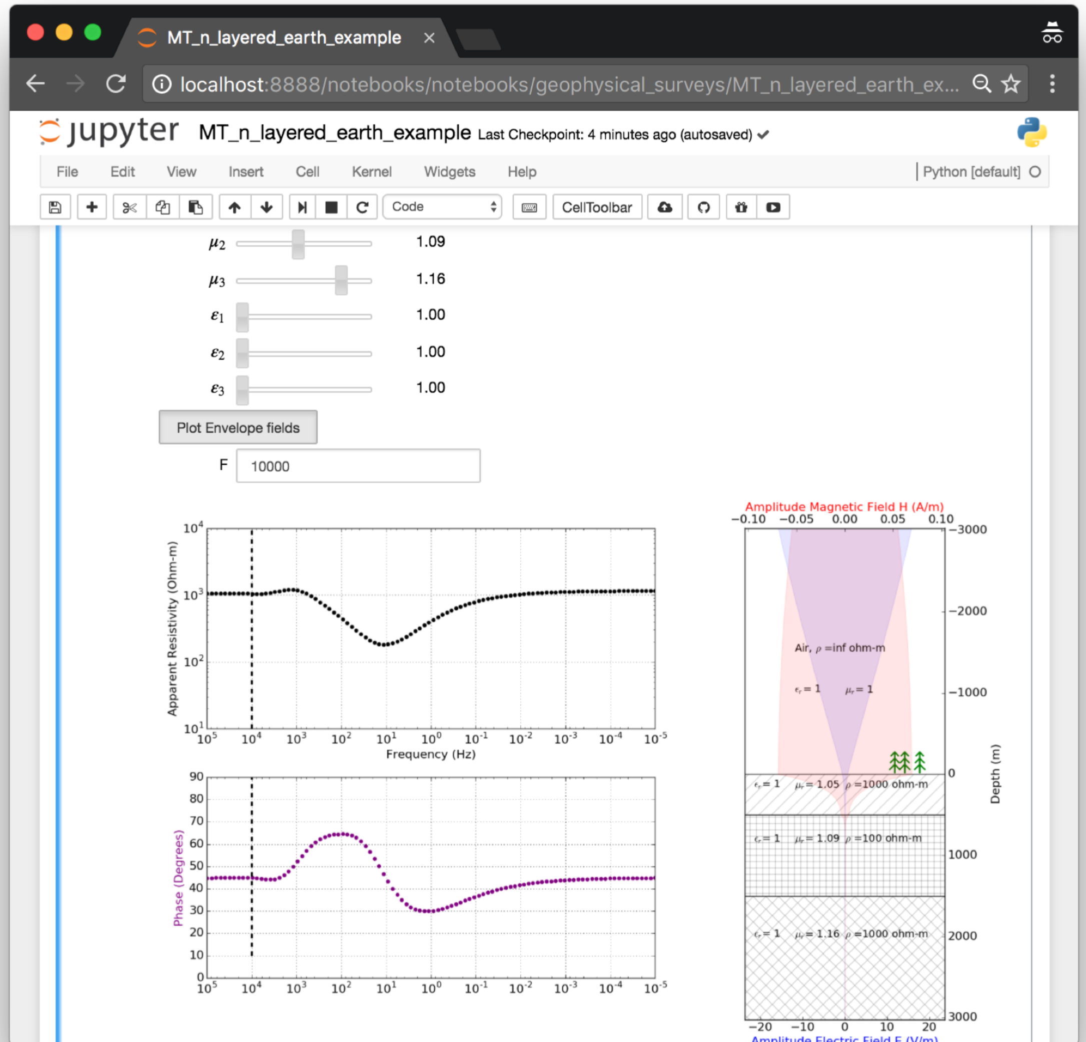


1D MT app

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

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





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

MT soundings in 2D

- In general:

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

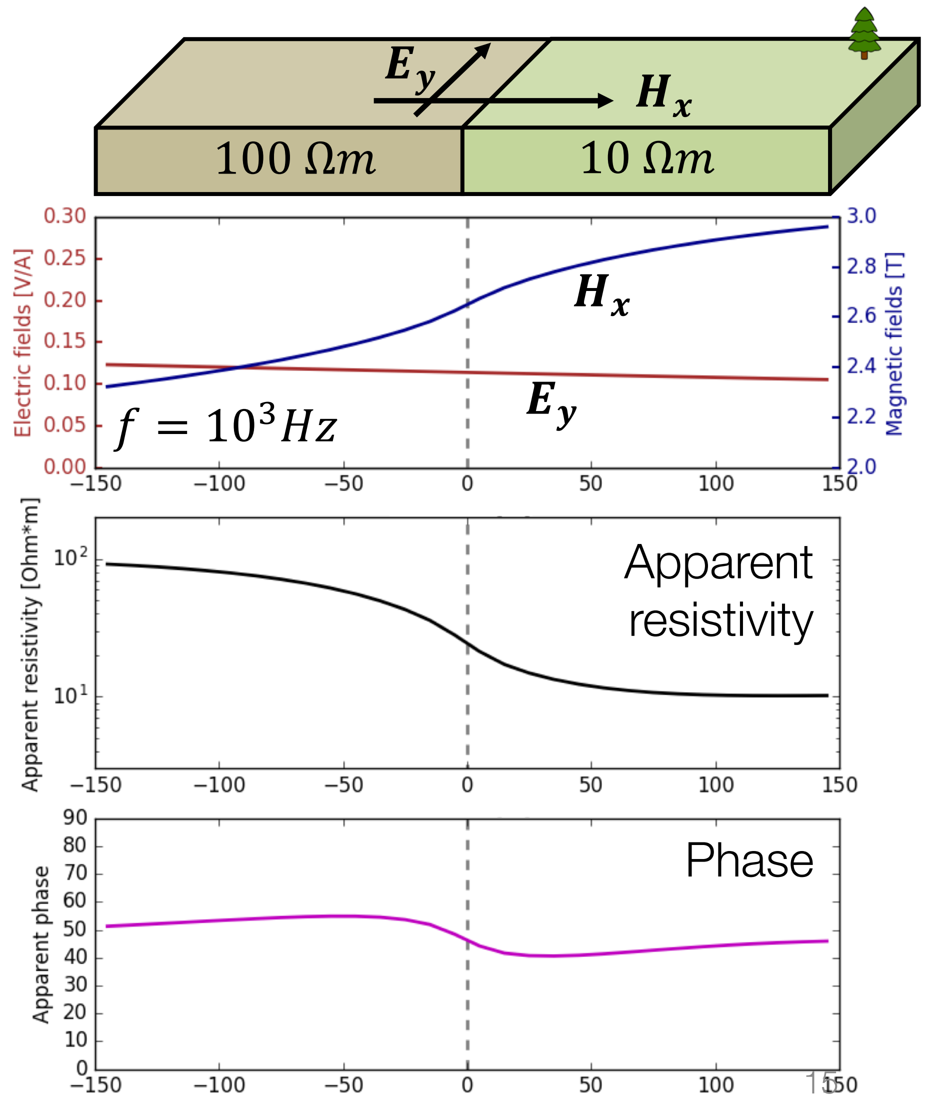
- In 2D:

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

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

- TE mode
  - E-field parallel to structure

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



MT soundings in 2D

- In general:

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

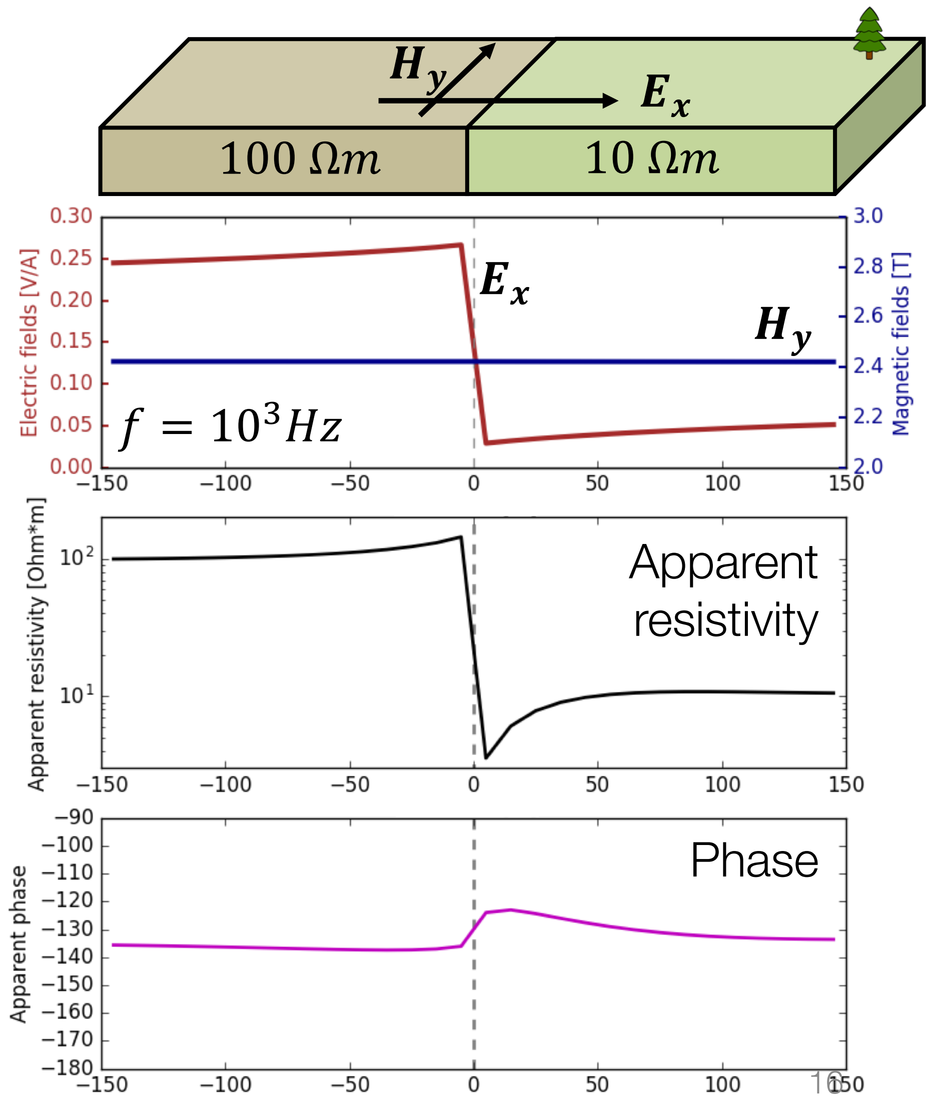
- In 2D:

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

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

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

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



MT soundings in 3D

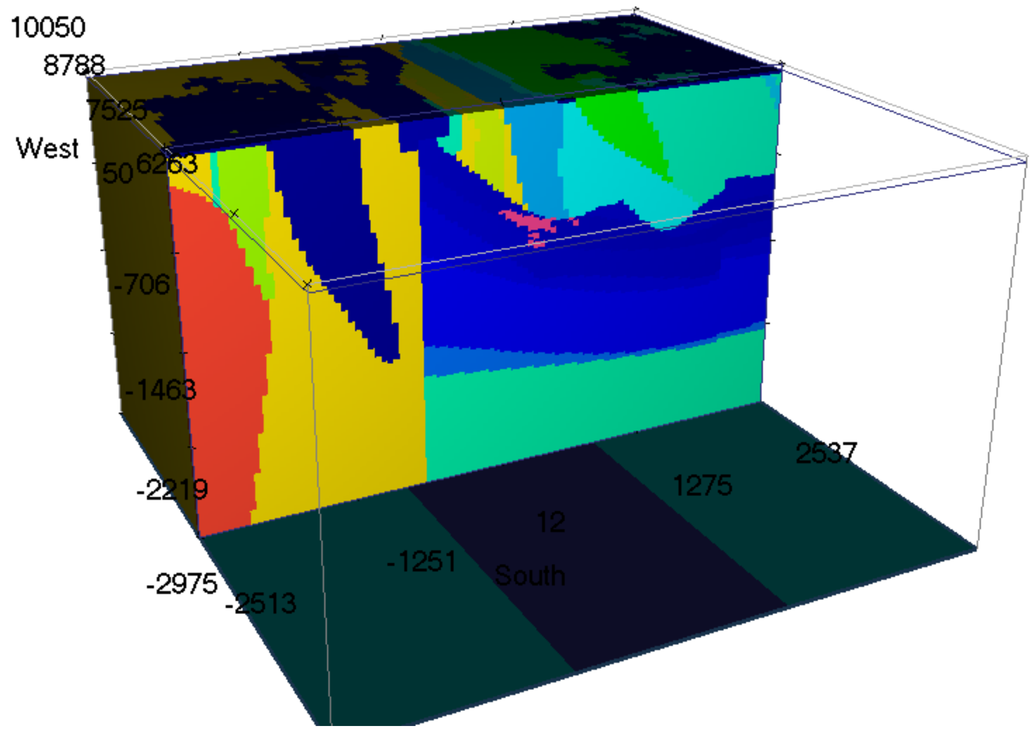
- In general:

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

- In 3D:

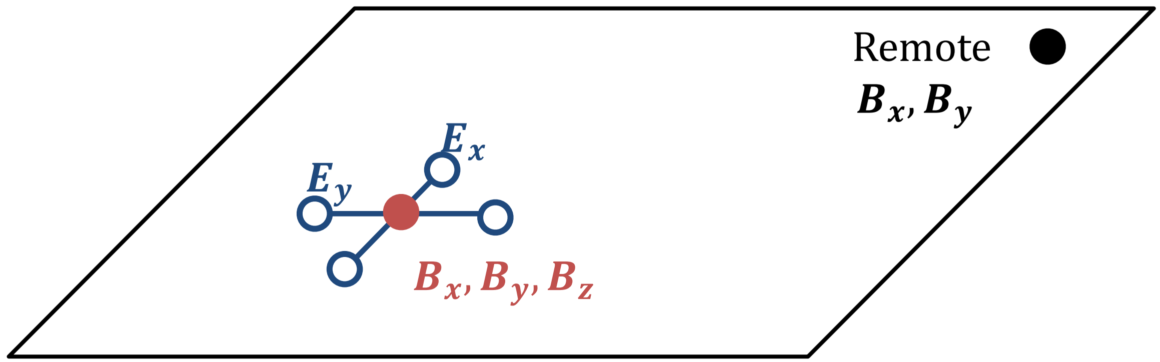
$$Z = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$$

- No symmetry or special conditions



Measuring MT data

- Basic acquisition

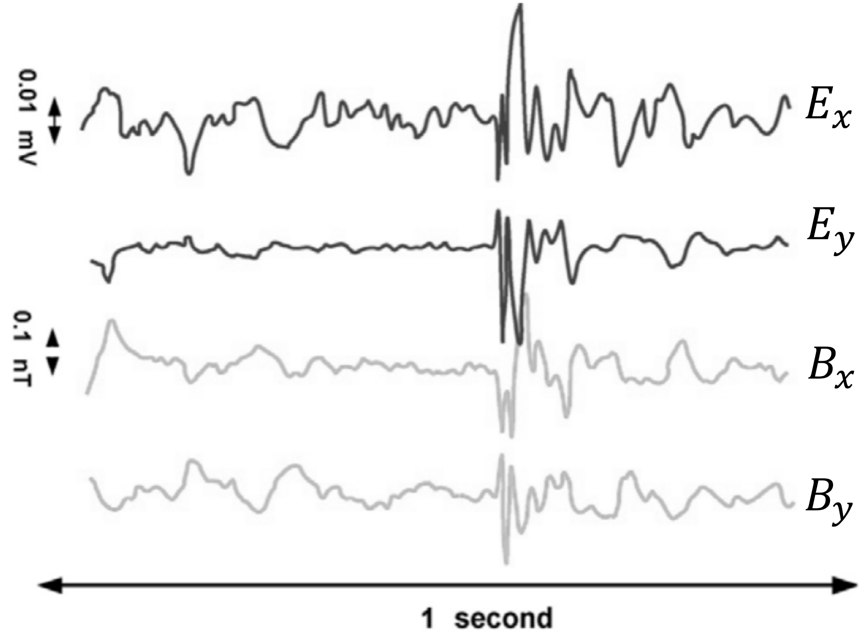


- At each station, measure:

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

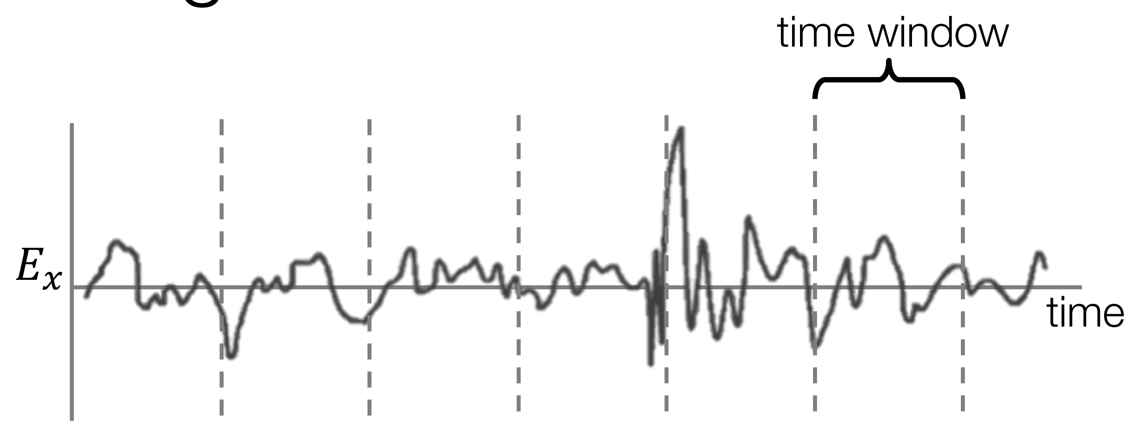
- At remote reference, measure:

$$B_x, B_y$$



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

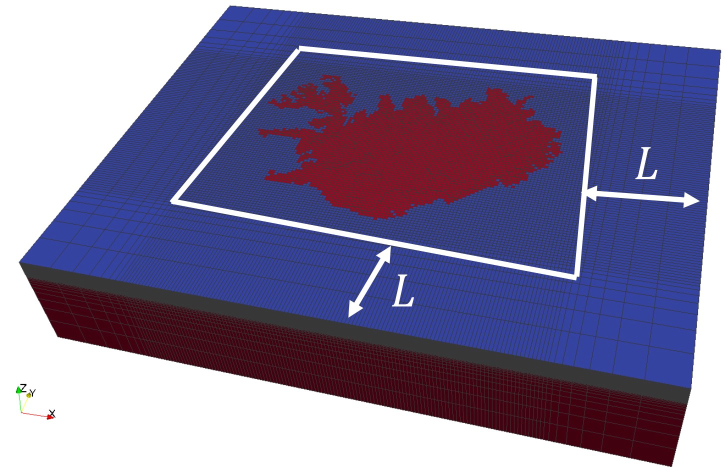
- Boundary conditions important for modelling

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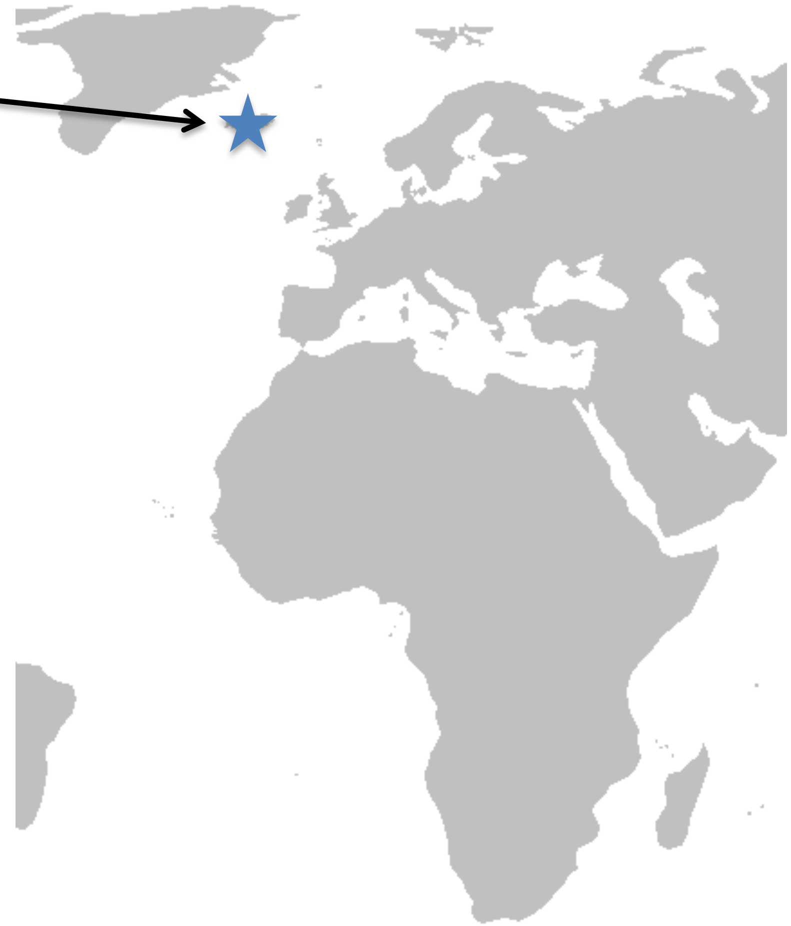
- Magnetotellurics
- Case histories: Geothermal, Minerals, Hydrocarbons
- Z-axis tipper electromagnetics
- Case histories (ZTEM): Geologic Mapping, Minerals

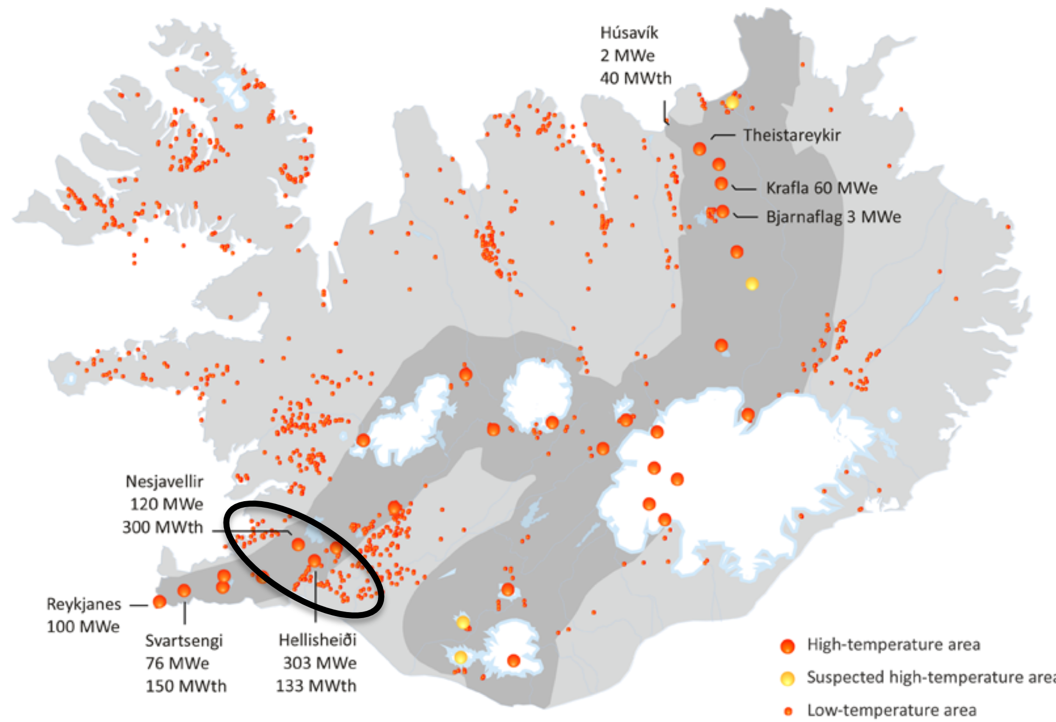
MT case history

- Iceland



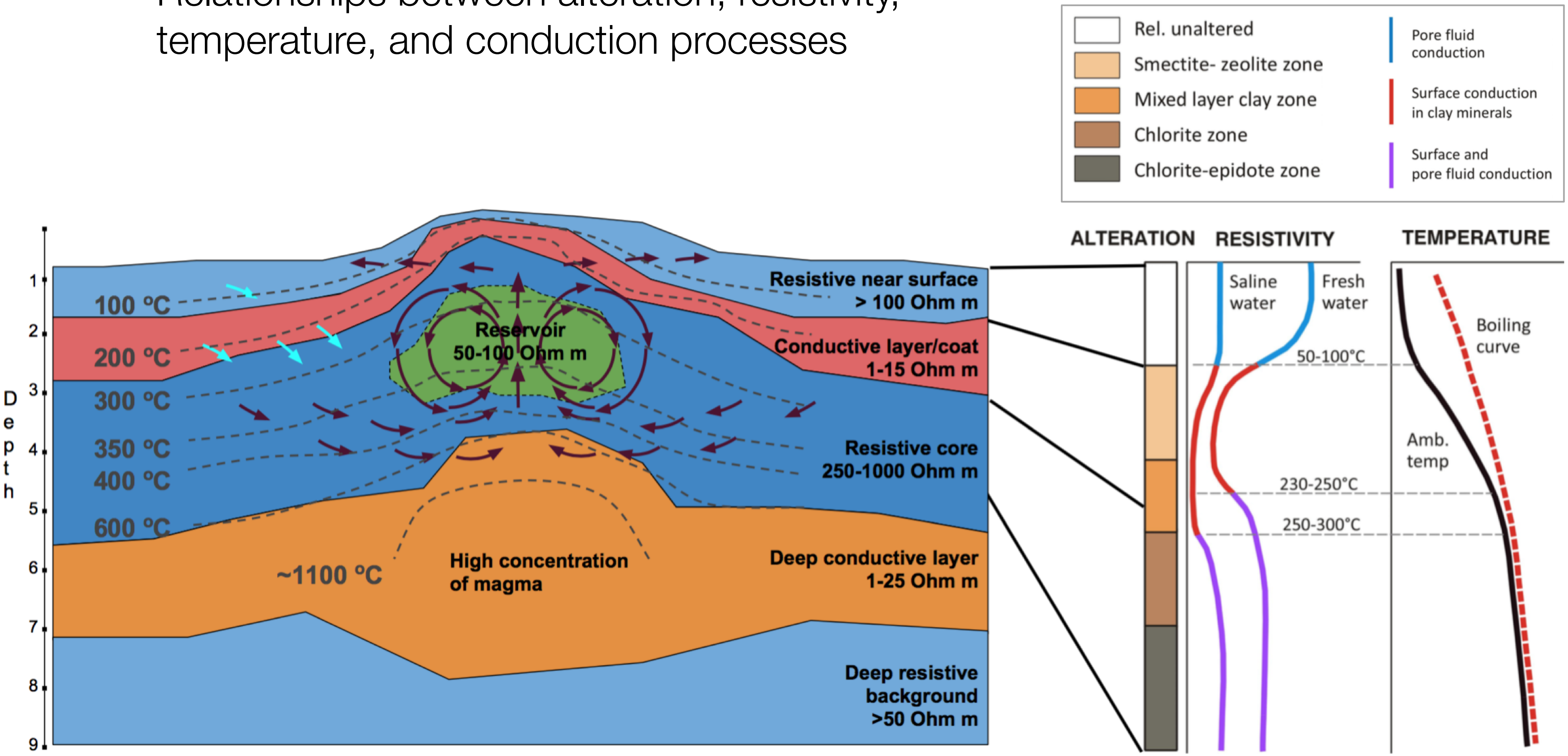
Hengill geothermal region: setup

- 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

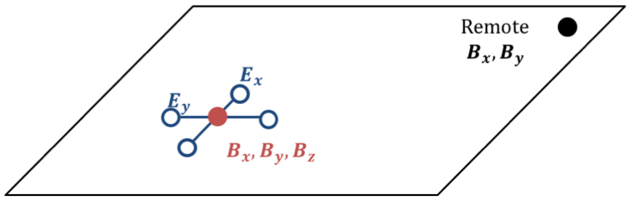


Physical properties

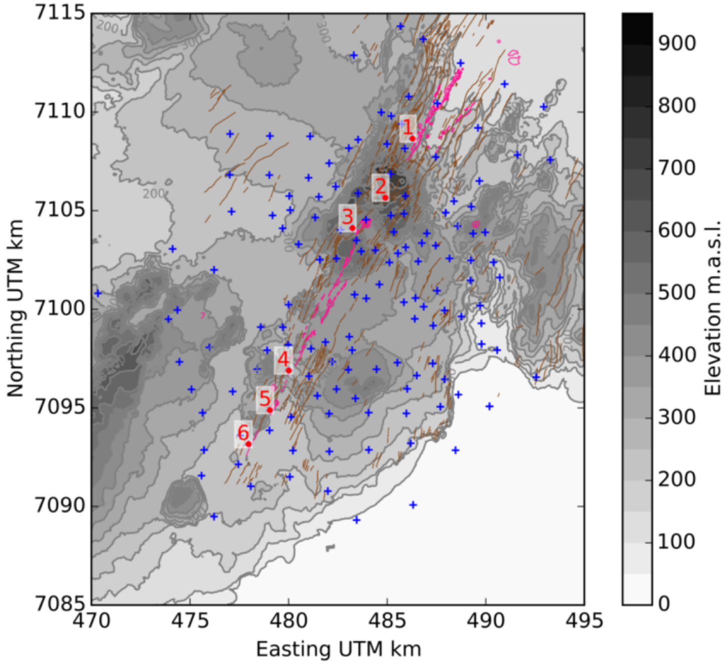
- Relationships between alteration, resistivity, temperature, and conduction processes



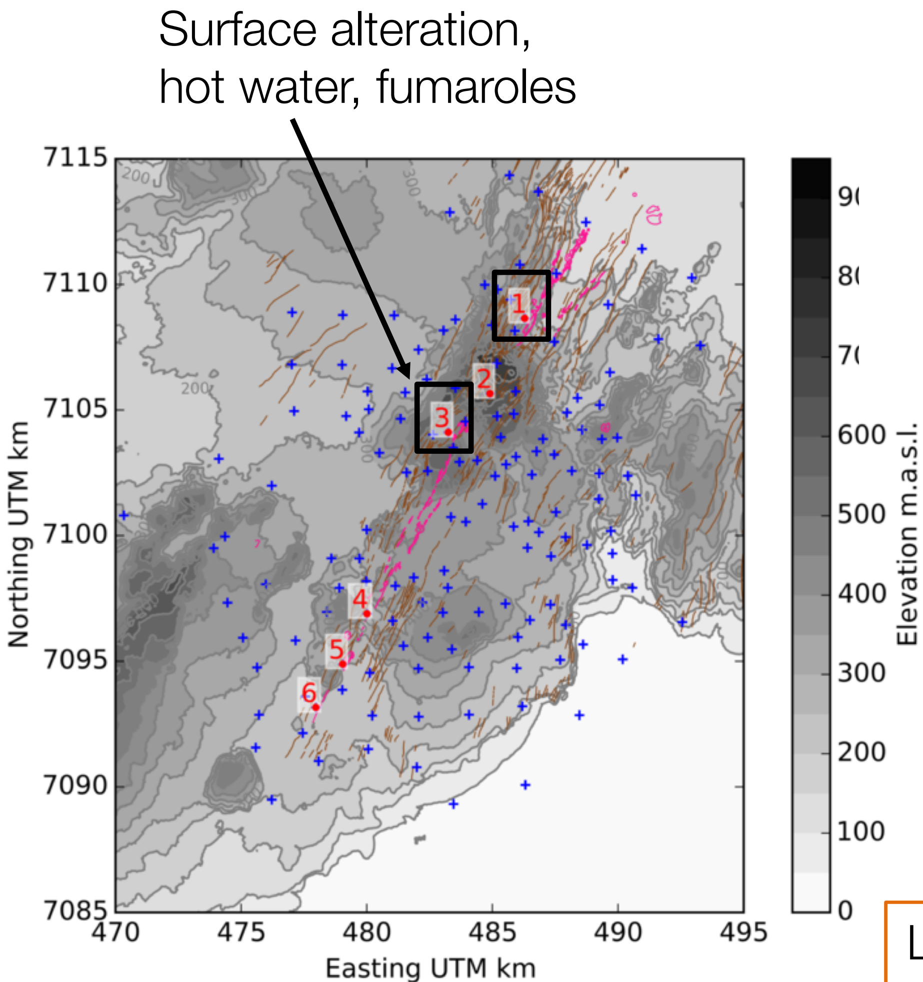
Survey

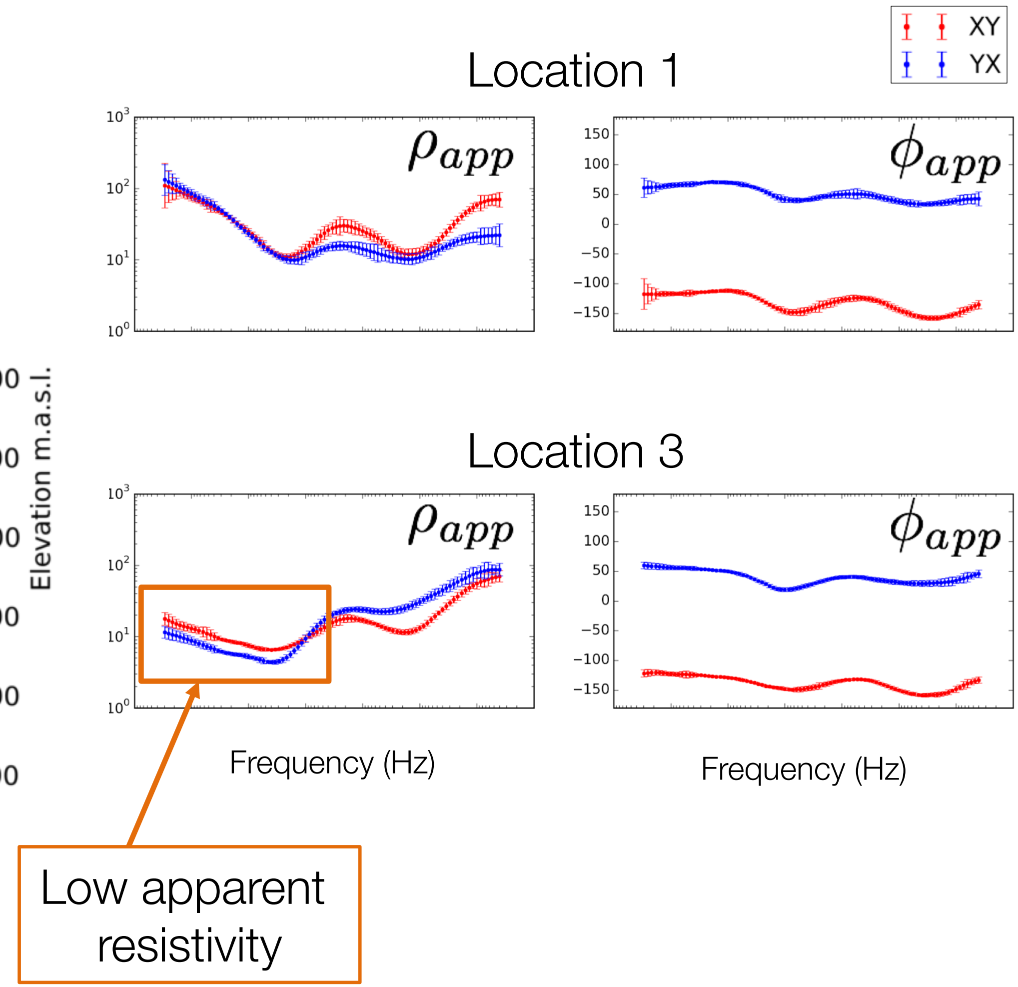


- MT instrumentation
  - Phoenix MTU5's
- Survey
  - 133 stations used
  - Combination of 2E and 2E+3H setup
  - Frequencies: 300 – 0.001 Hz
- Remote reference
  - About 40 km away
- Raw data processing using Phoenix software



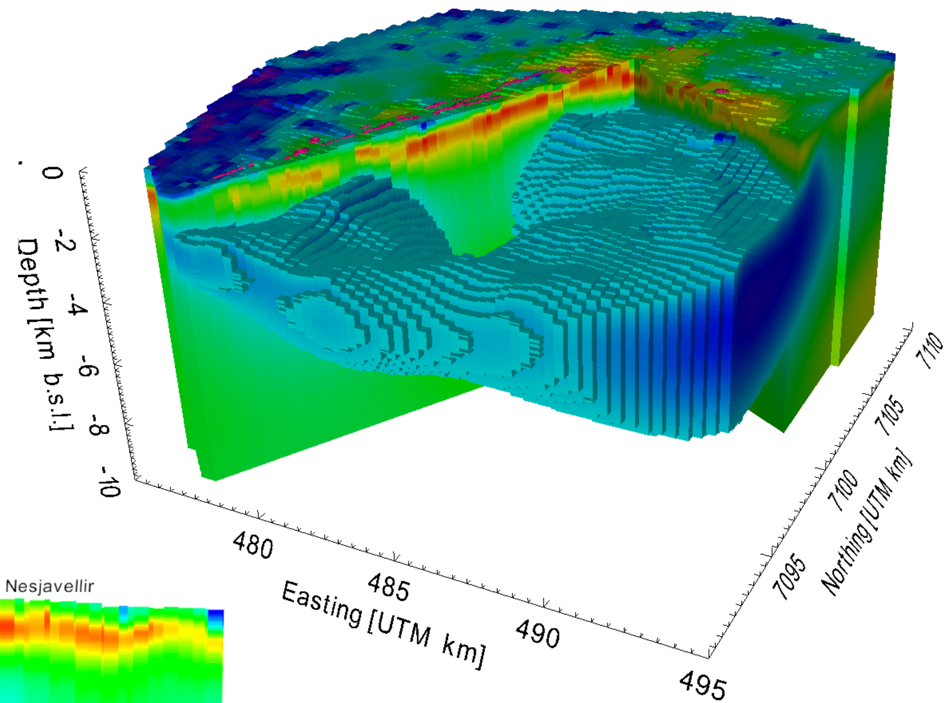
Data

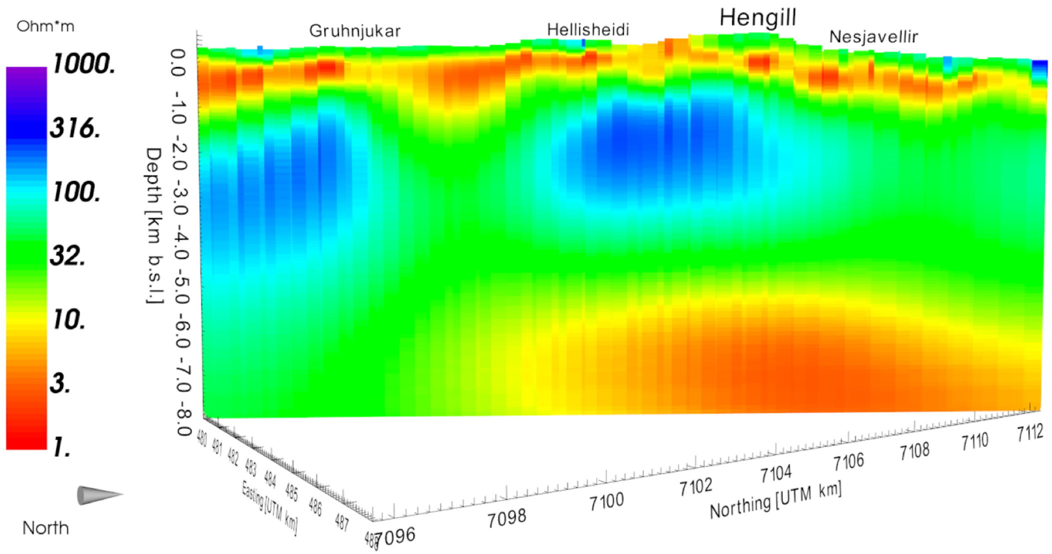

Surface alteration,
hot water, fumaroles
Northing UTM km
7115
7110
7105
7100
7095
7090
7085
470
475
480
485
490
495
Easting UTM km
1
2
3
4
5
6
Elevation m.a.s.l.
600
500
400
300
200
100
0


XY
YX
Location 1
ρ_{app}
ϕ_{app}
Location 3
ρ_{app}
ϕ_{app}
Frequency (Hz)
Frequency (Hz)
Low apparent
resistivity

3D inversion

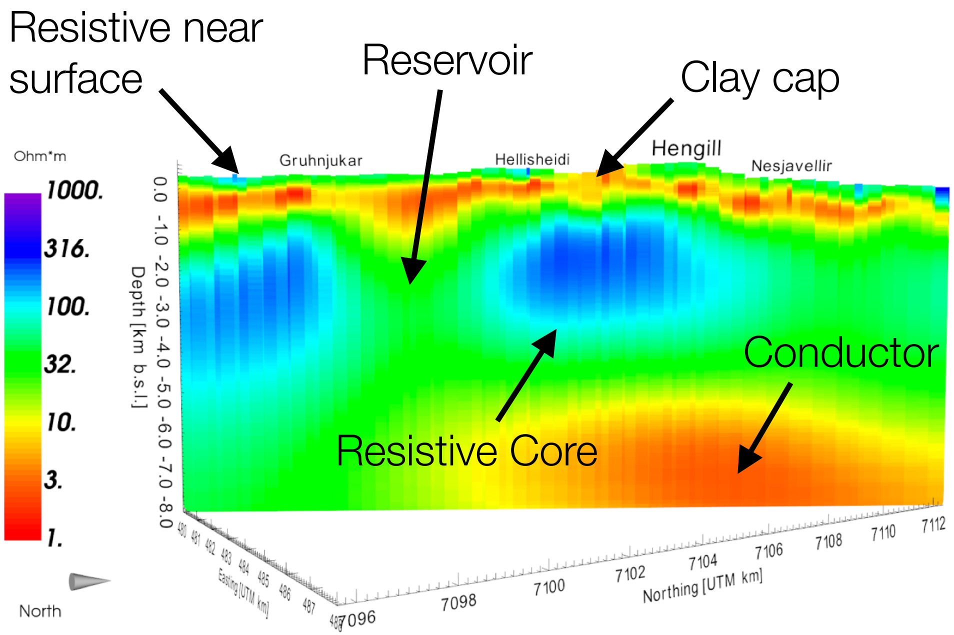
- Off-diagonal impedance (Z_{xy} and Z_{yx}) used
- Combined multi-frequency inversion (300 Hz – 0.001 Hz)

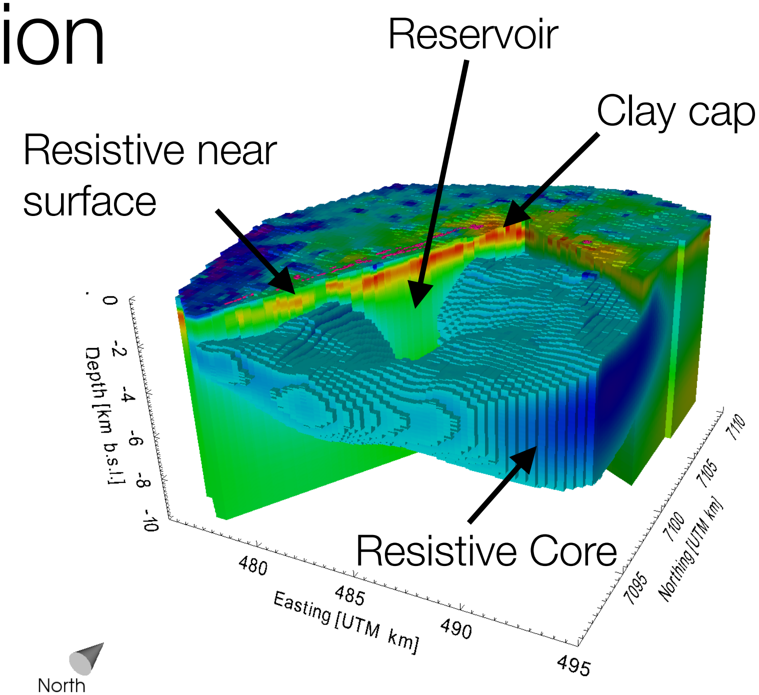


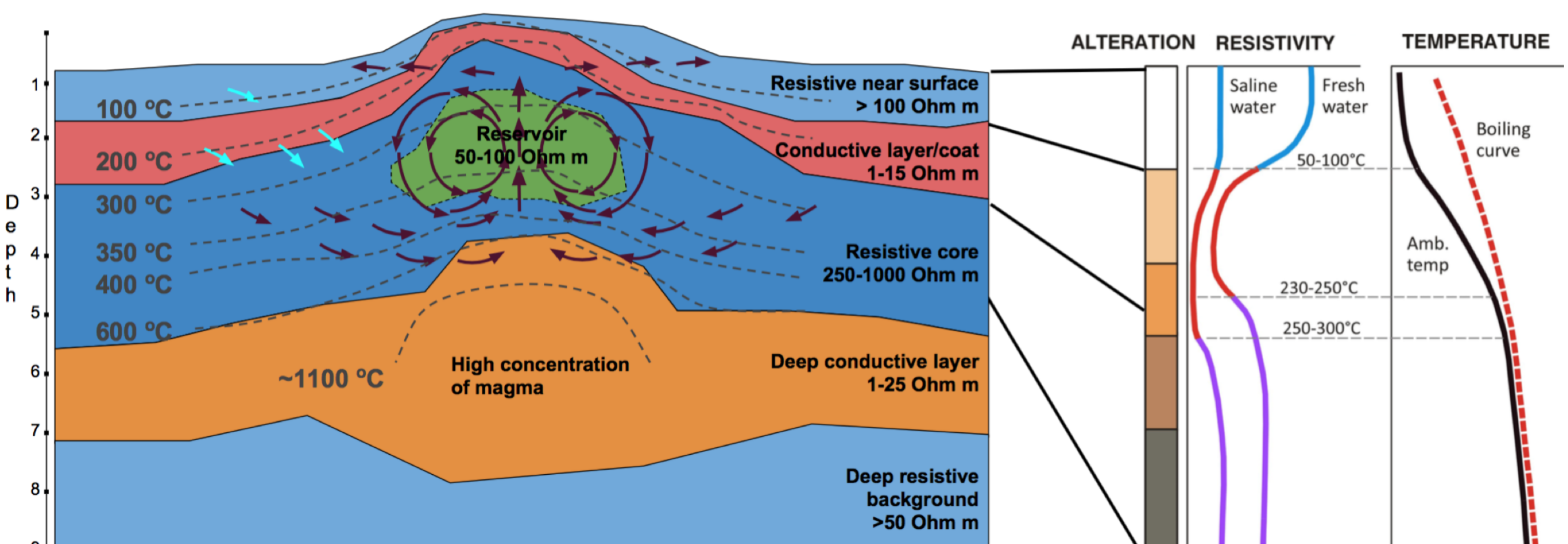


Rosenkjaer et al, 2015

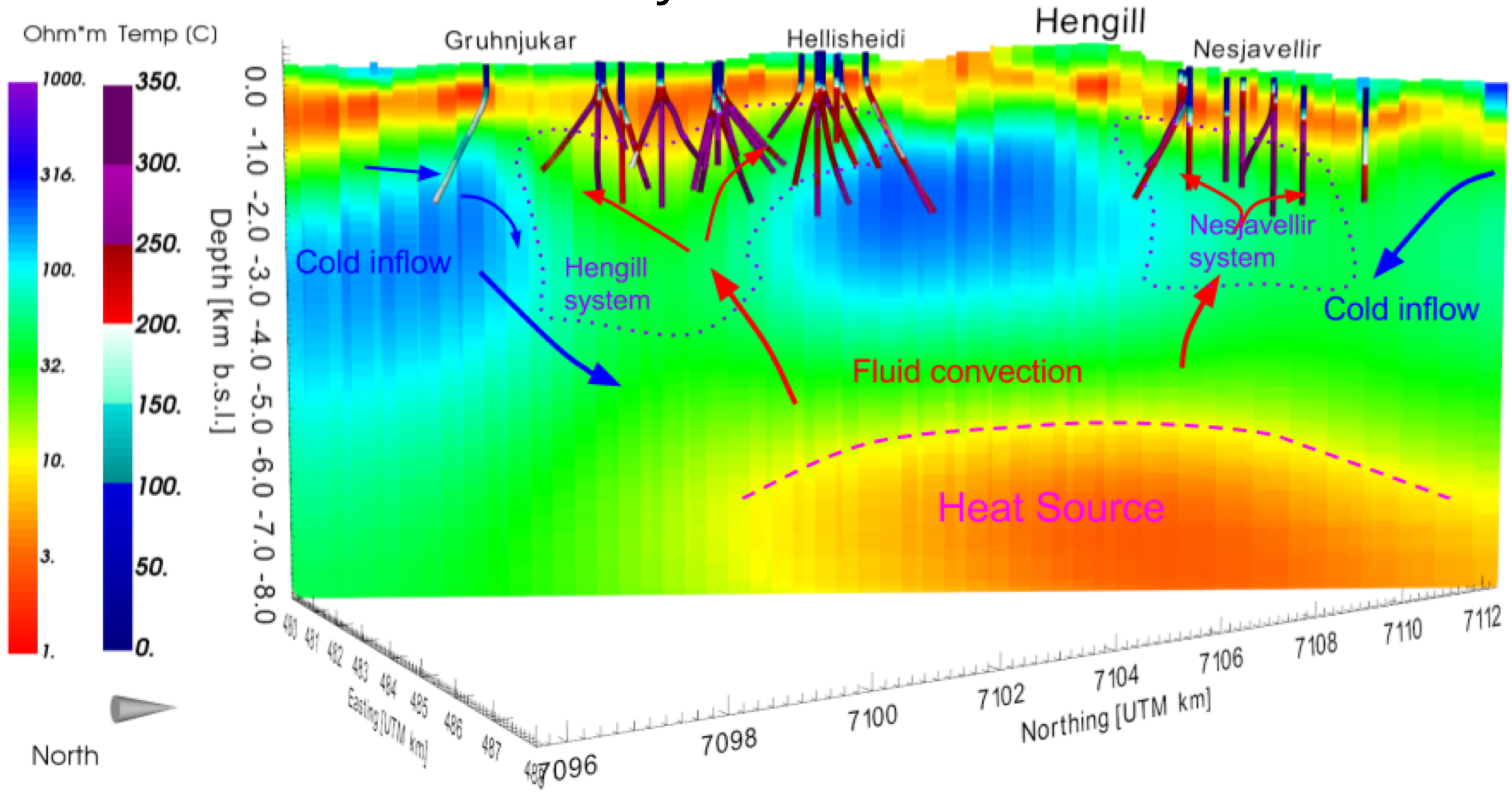
Interpretation







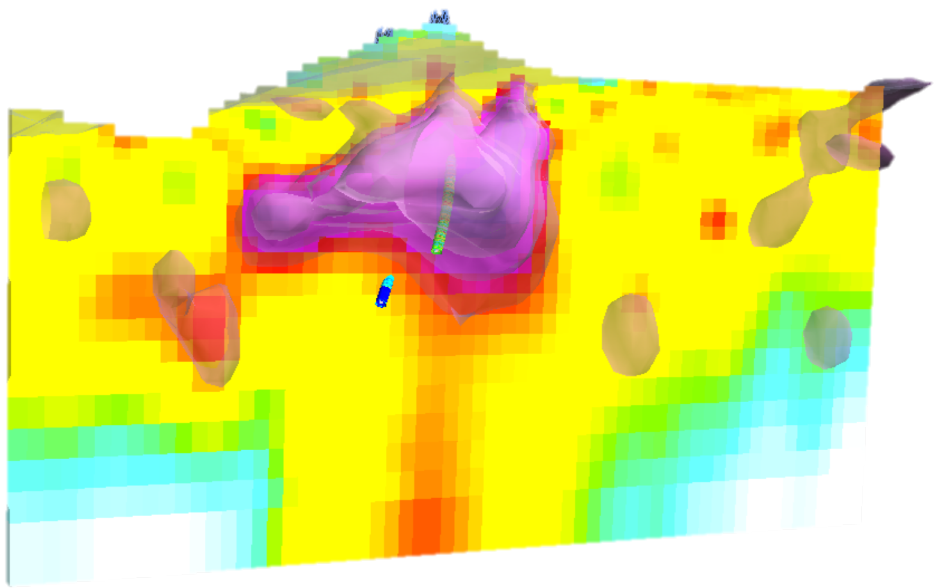
Synthesis



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

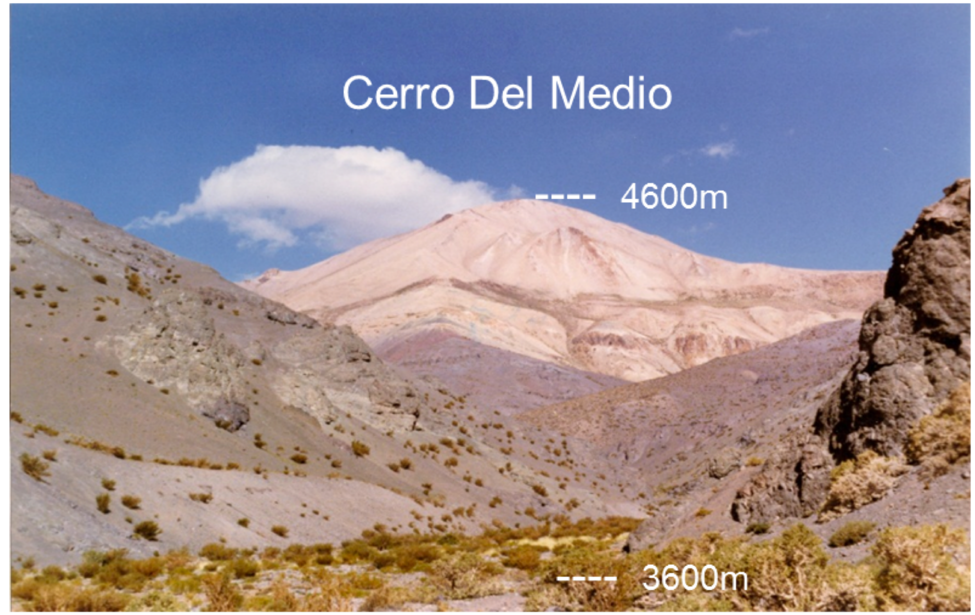
Case History:
Santa Cecilia Porphyry System, Chile

Bournas and Thomson, 2013



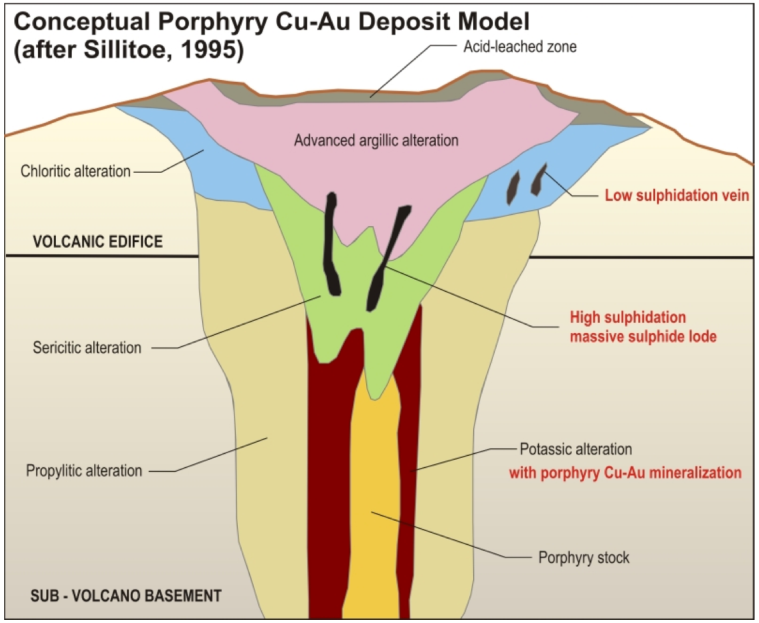
Thanks to Rob Hearst at [Quantec]

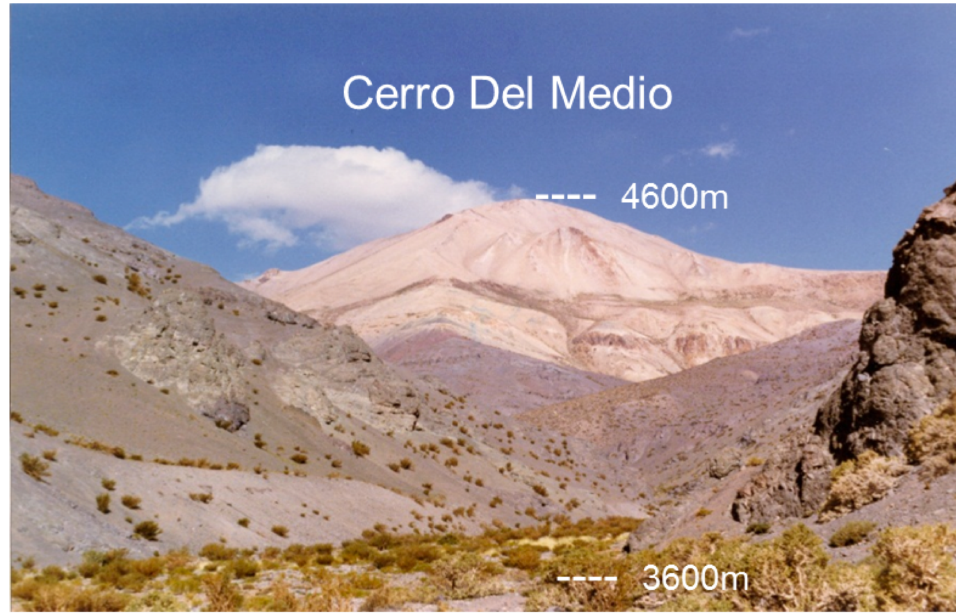
Setup



- 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
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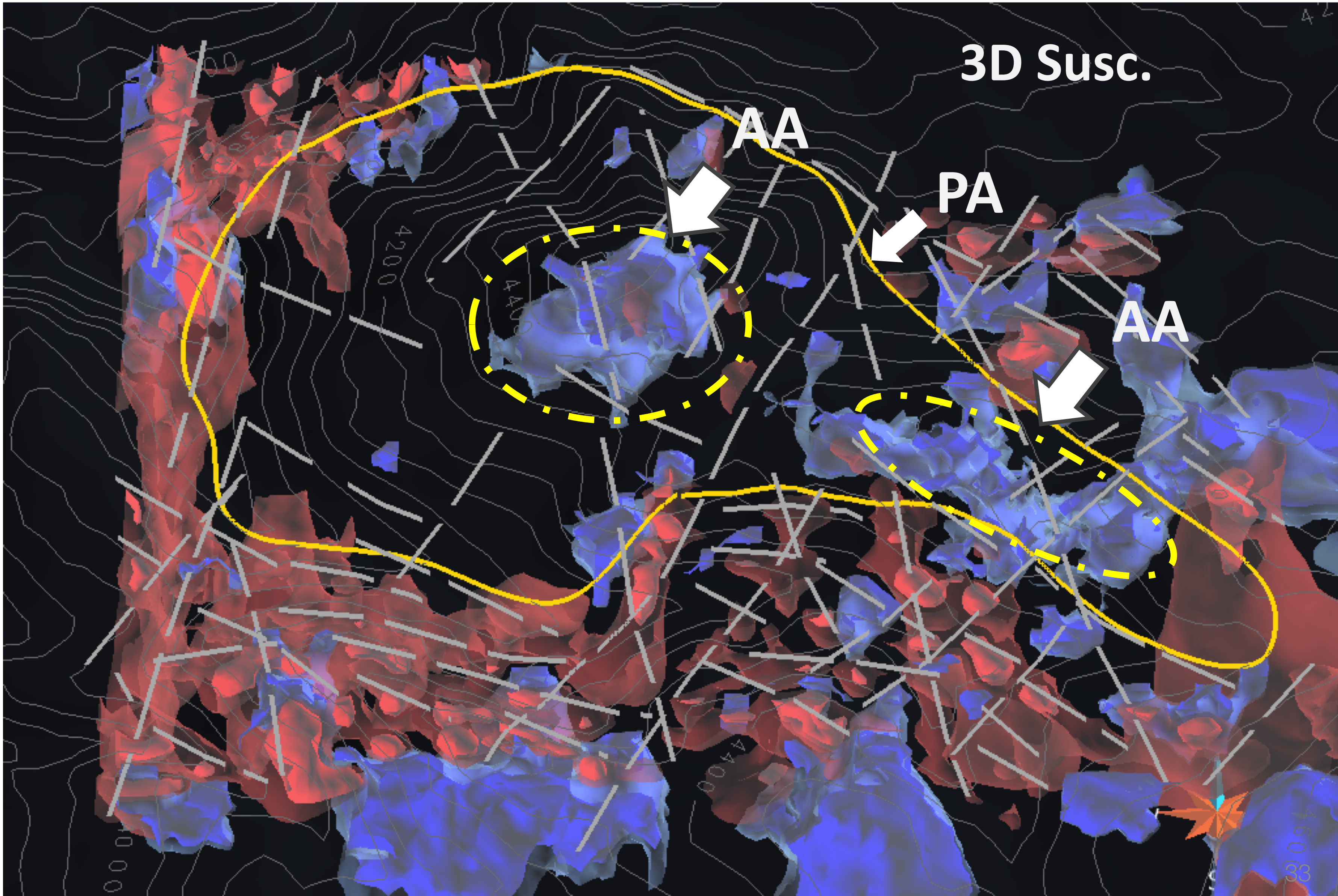
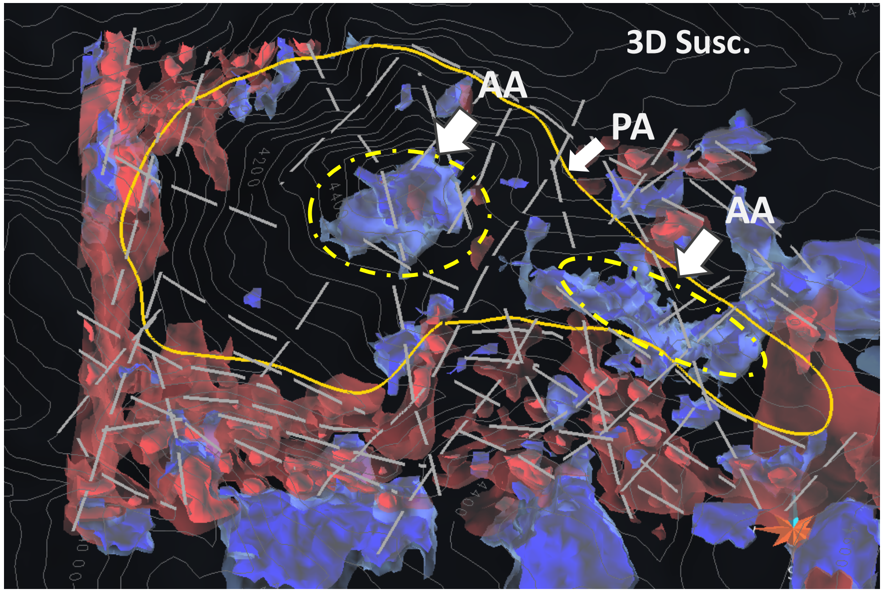
Can we image the porphyry system?

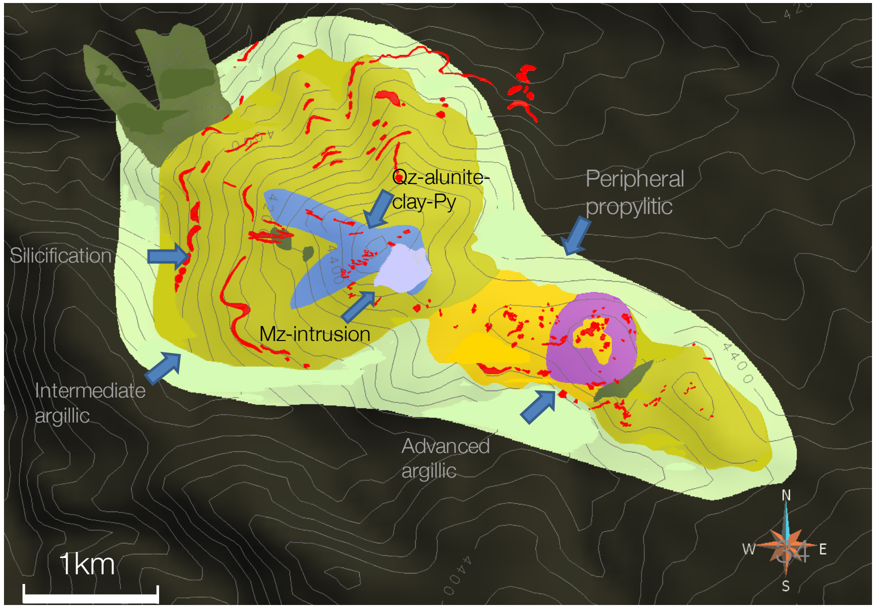
Setup: Ground Magnetics Inversion



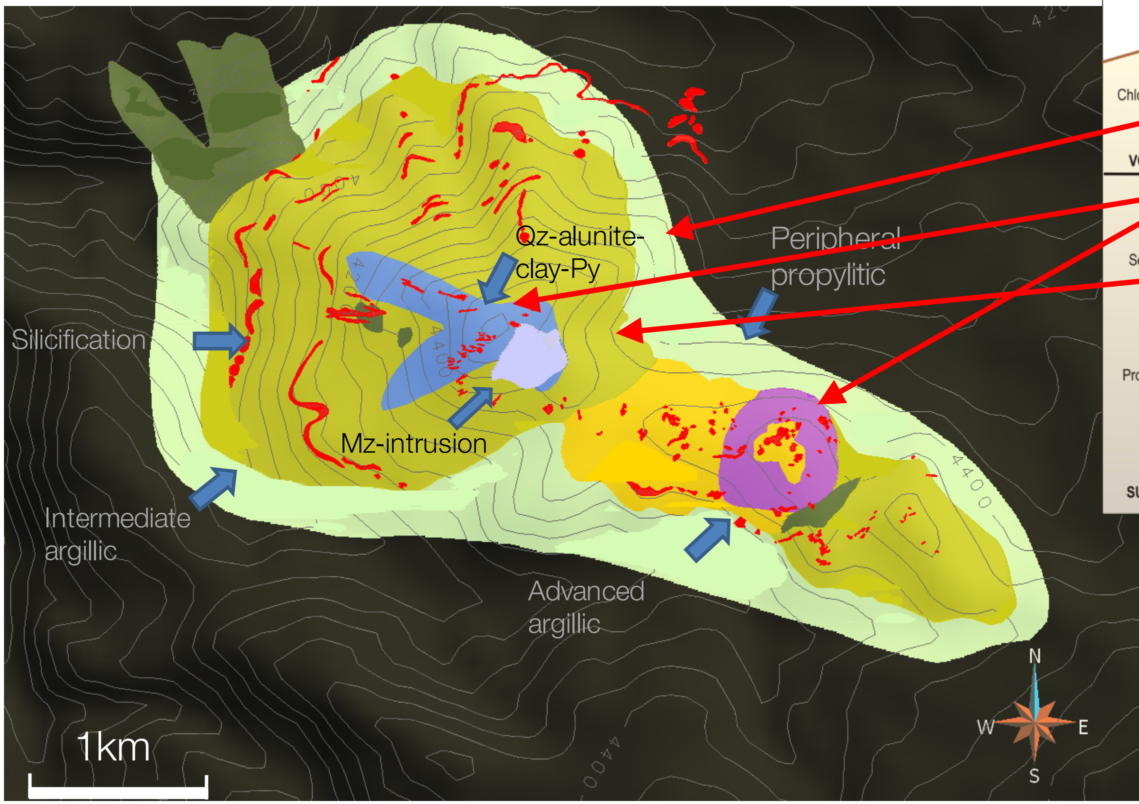
Setup: Discovery

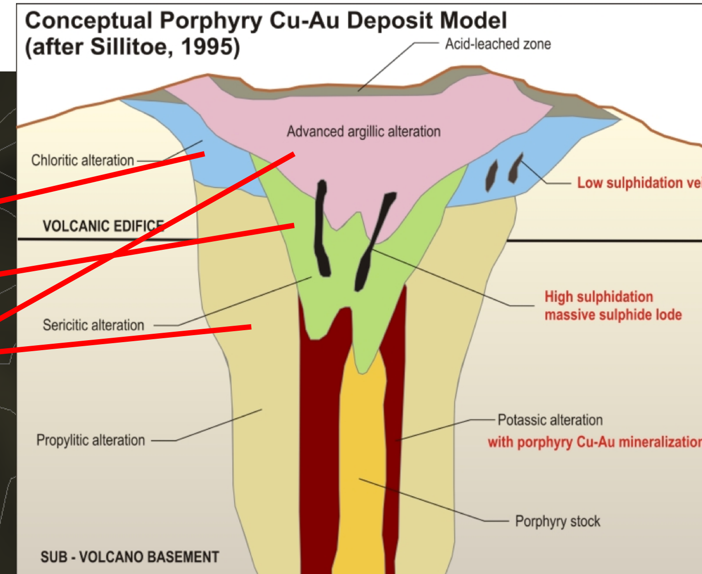
- Ground magnetic data
  - Delineate alteration zones
- Mobile Metal Ion (MMI)
  - Gold and copper anomalies
- CSAMT
  - To test MMI
  - Found large conductor
- Two discovery holes
- ORION 3D: DC/IP & MT





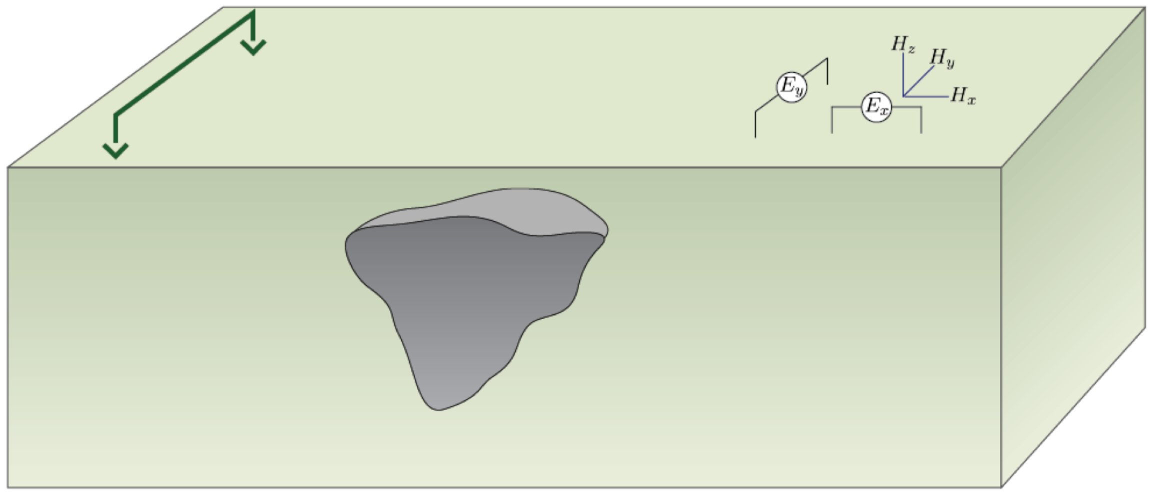
Properties





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

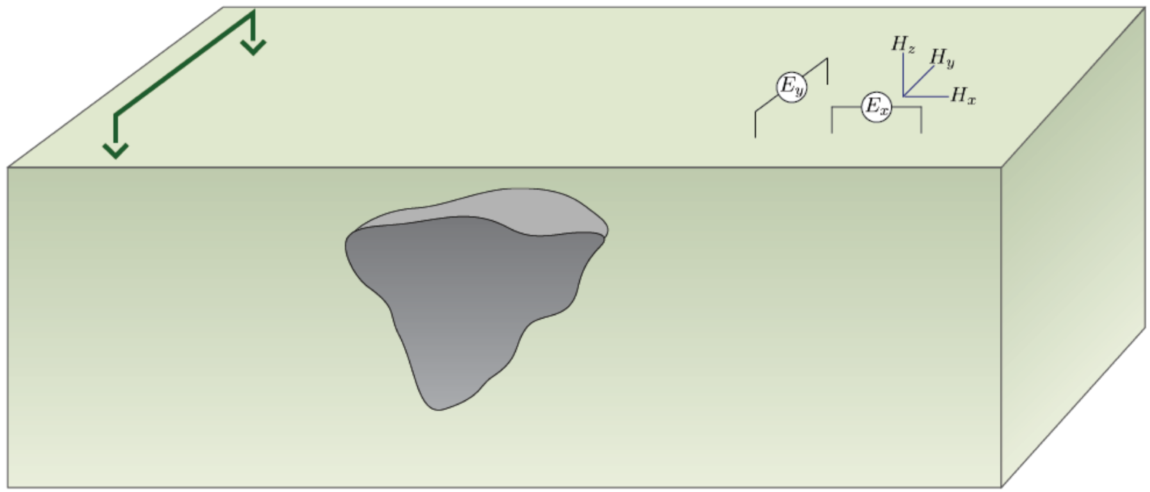
CSAMT



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

- Detail about CSAMT experiment
- Apparent resistivity curve in the far field, transition and near-field.

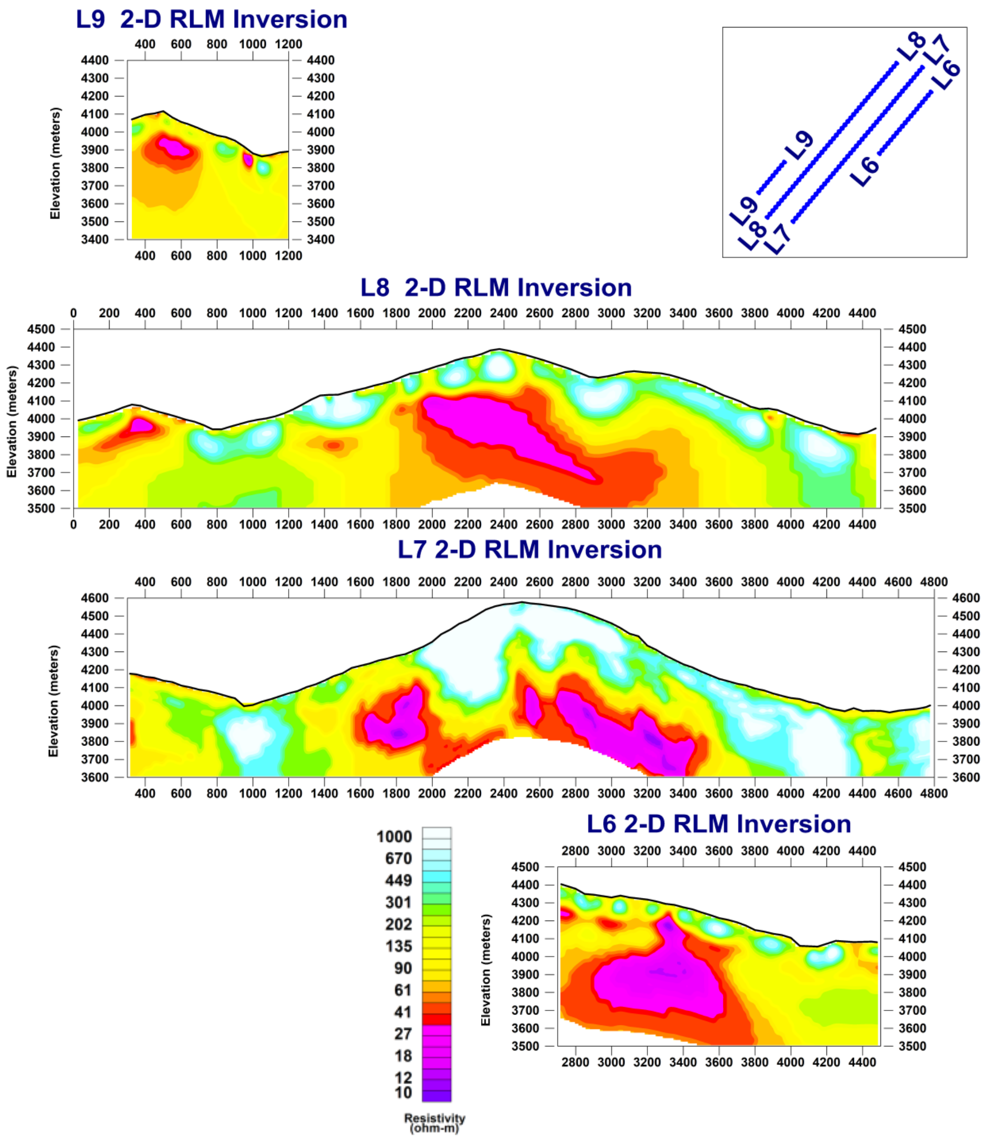
Survey: Discovery



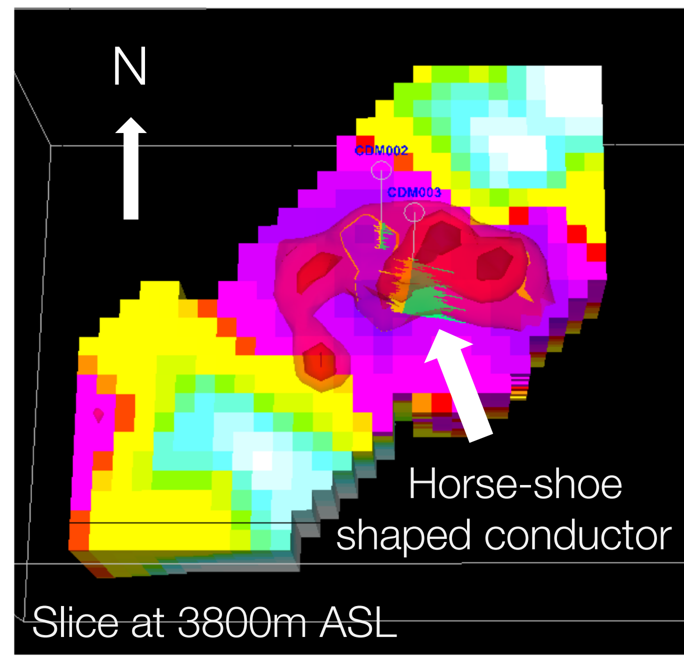
- Controlled Source Audio Magnetotellurics
- Transmitter
  - 3.5 km dipole
  - Frequencies: 2-9000 Hz
- Receivers
  - 10 km from source

Processing: Discovery

2D resistivity sections

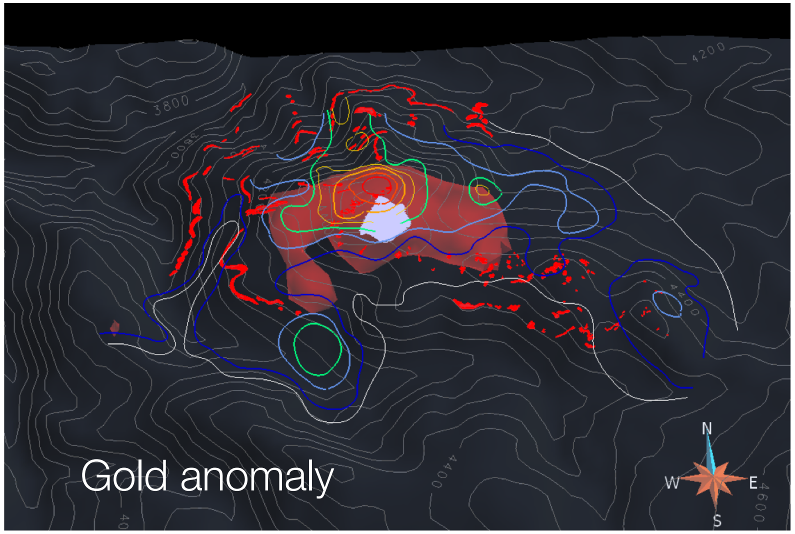


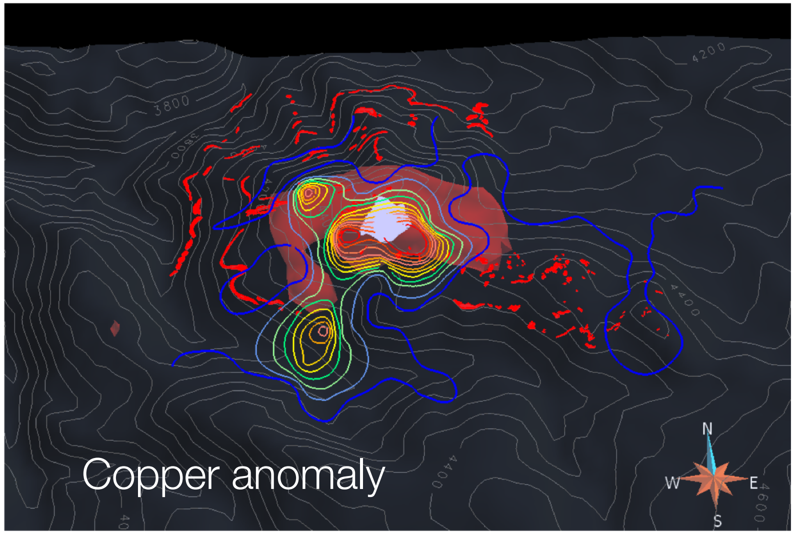
- Recovered horse-shoe shaped conductor



Interpretation and Synthesis: Discovery

3D cut-off volume from CSAMT

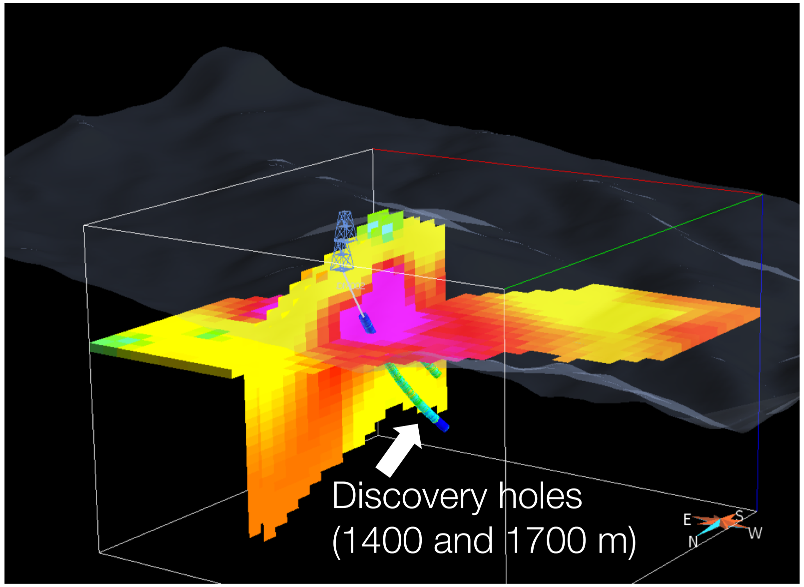


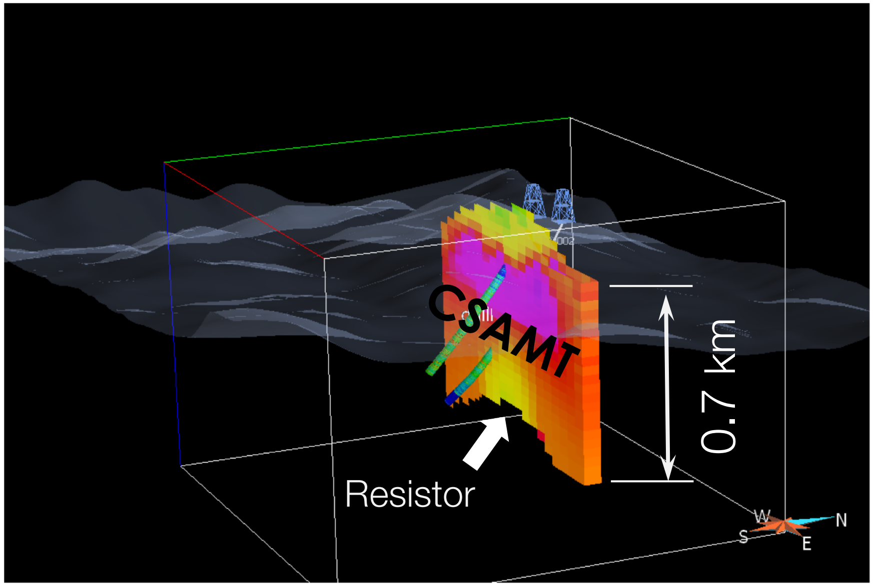


- Recovered conductor consistent with Au and Cu anomalies from MMI

Interpretation and Synthesis: Discovery

2D resistivity sections with drill holes



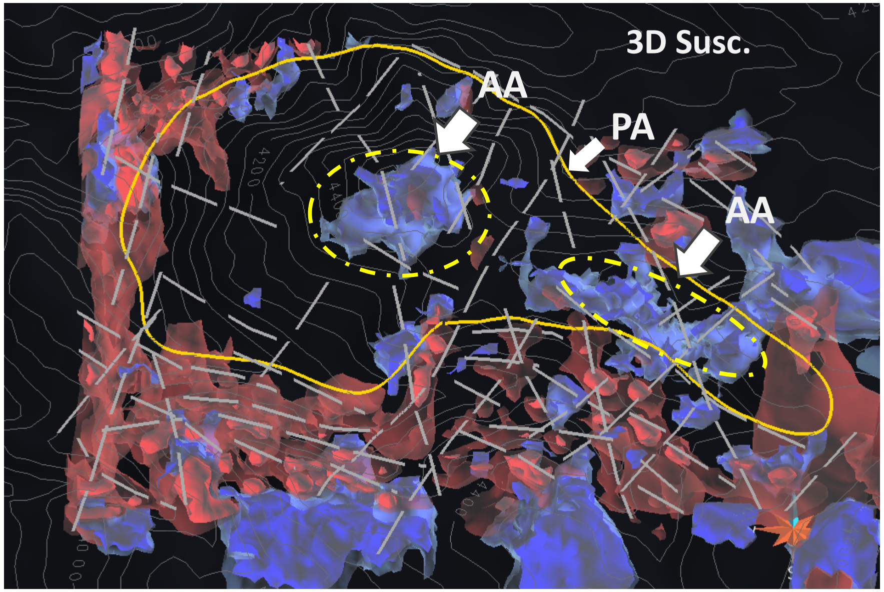


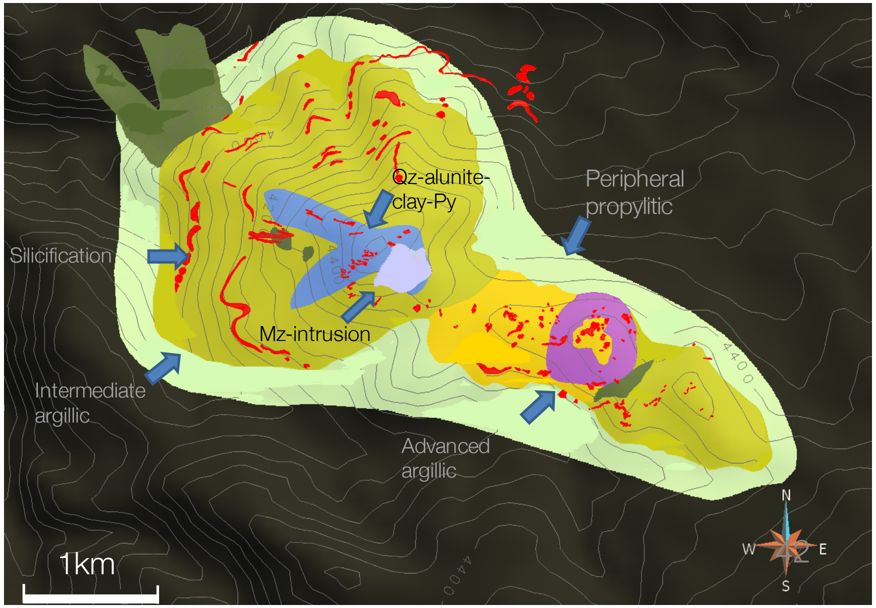
- Two holes are drilled and found mineralized zones (2011)
- Mineralization extends beyond CSAMT conductor
  - Lowest frequency in CSAMT (24 Hz, rho=10 ohm-m)

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

Setup: Evaluation

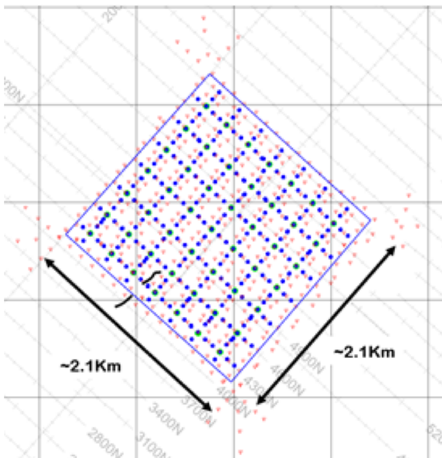
- Ground magnetic data
  - Delineate alteration zones
- Mobile Metal Ion (MMI)
  - Gold and copper anomalies
- CSAMT
  - To test MMI
  - Found large conductor
- Two discovery holes
  - Need to see deeper…
- ORION 3D: DC/IP & MT



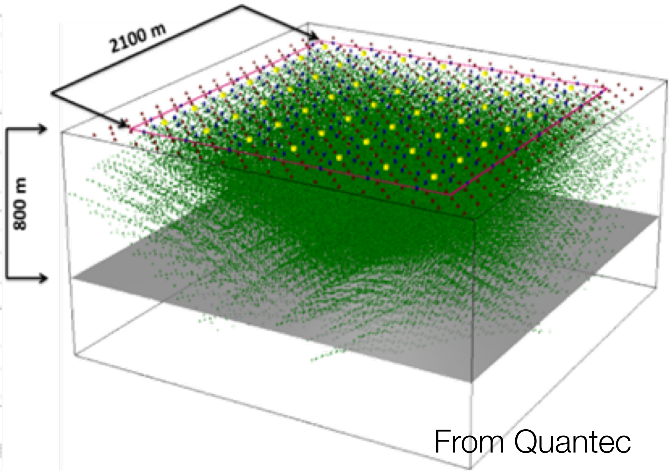


Survey: Evaluation

Orion 3D survey

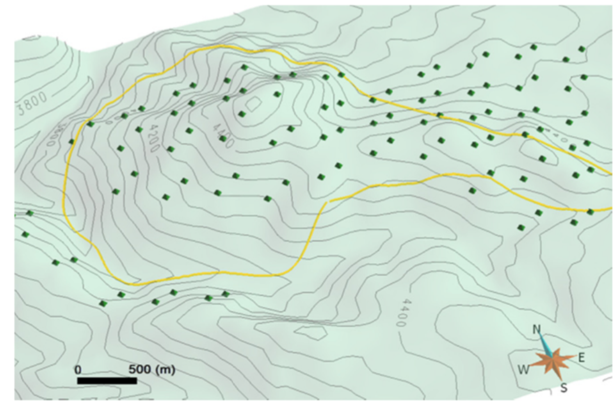


Layout



From Quantec

Coverage

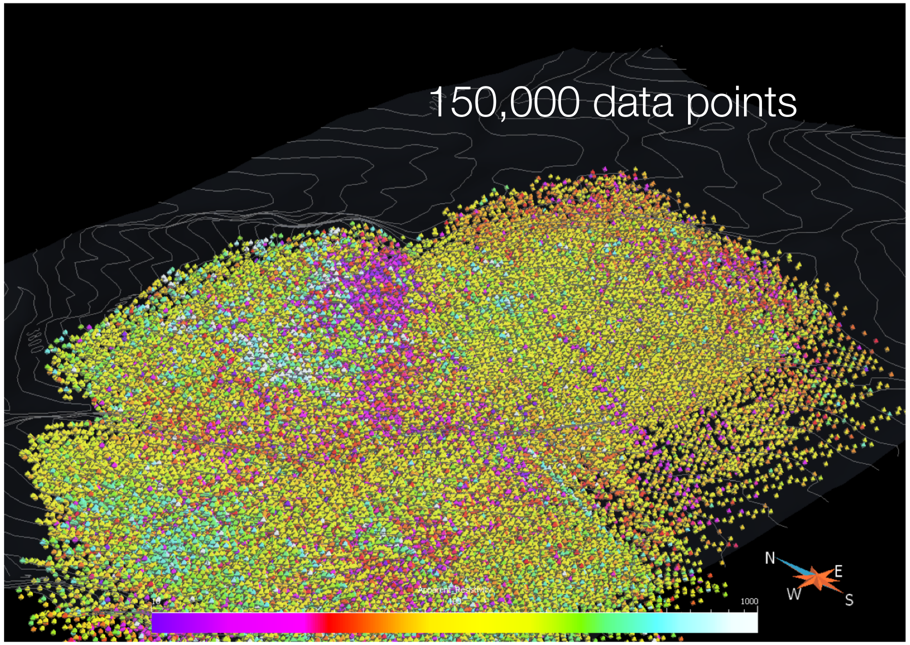


100 MT sites

- DC-IP
  - 539 transmitters
  - 300 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

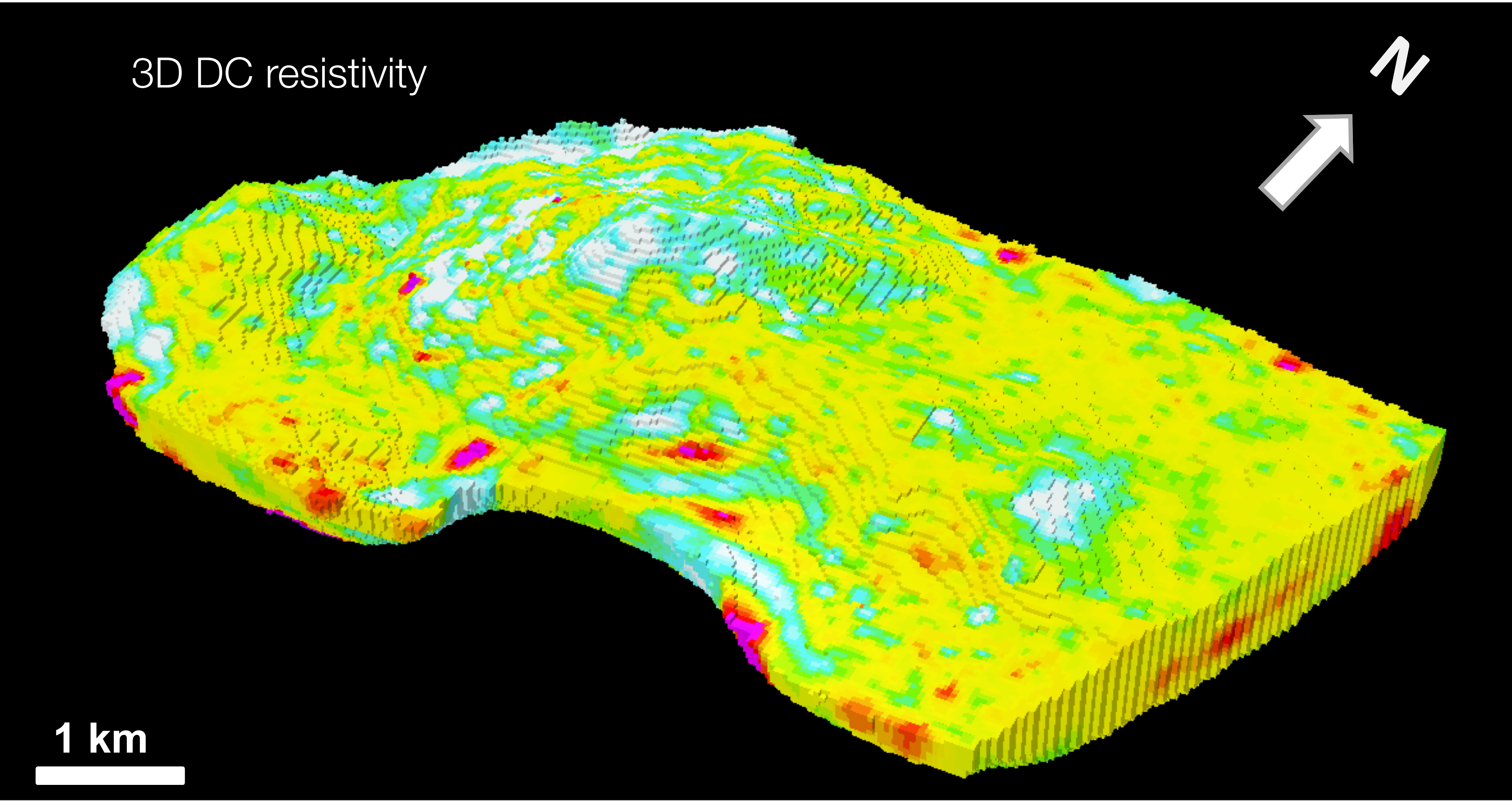
DC Data

Apparent resistivity

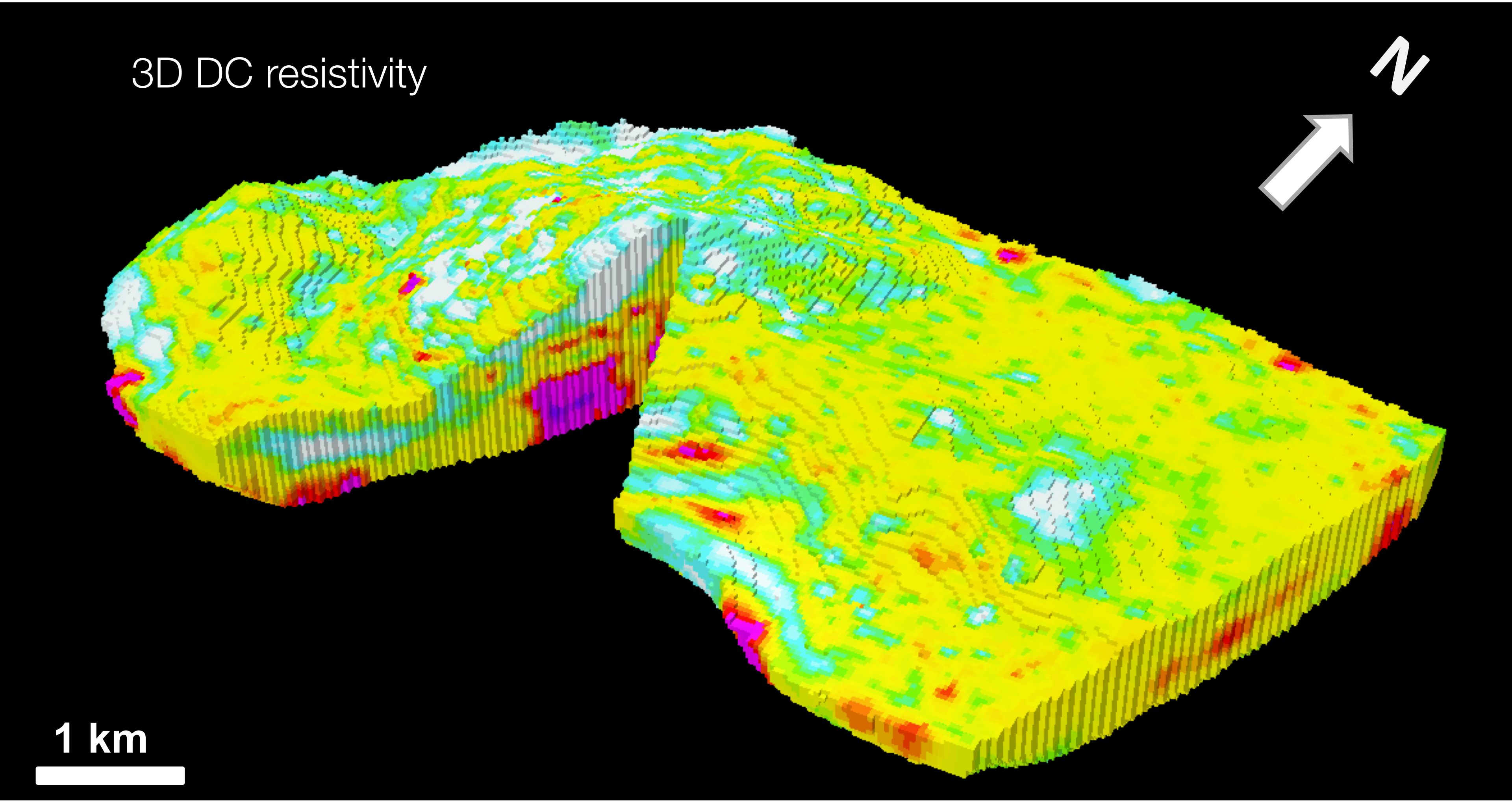


- 150,000 data points from
  - 539 sources
  - 300 receiver dipoles
- Hard to visualize and interpret data
- Need to invert

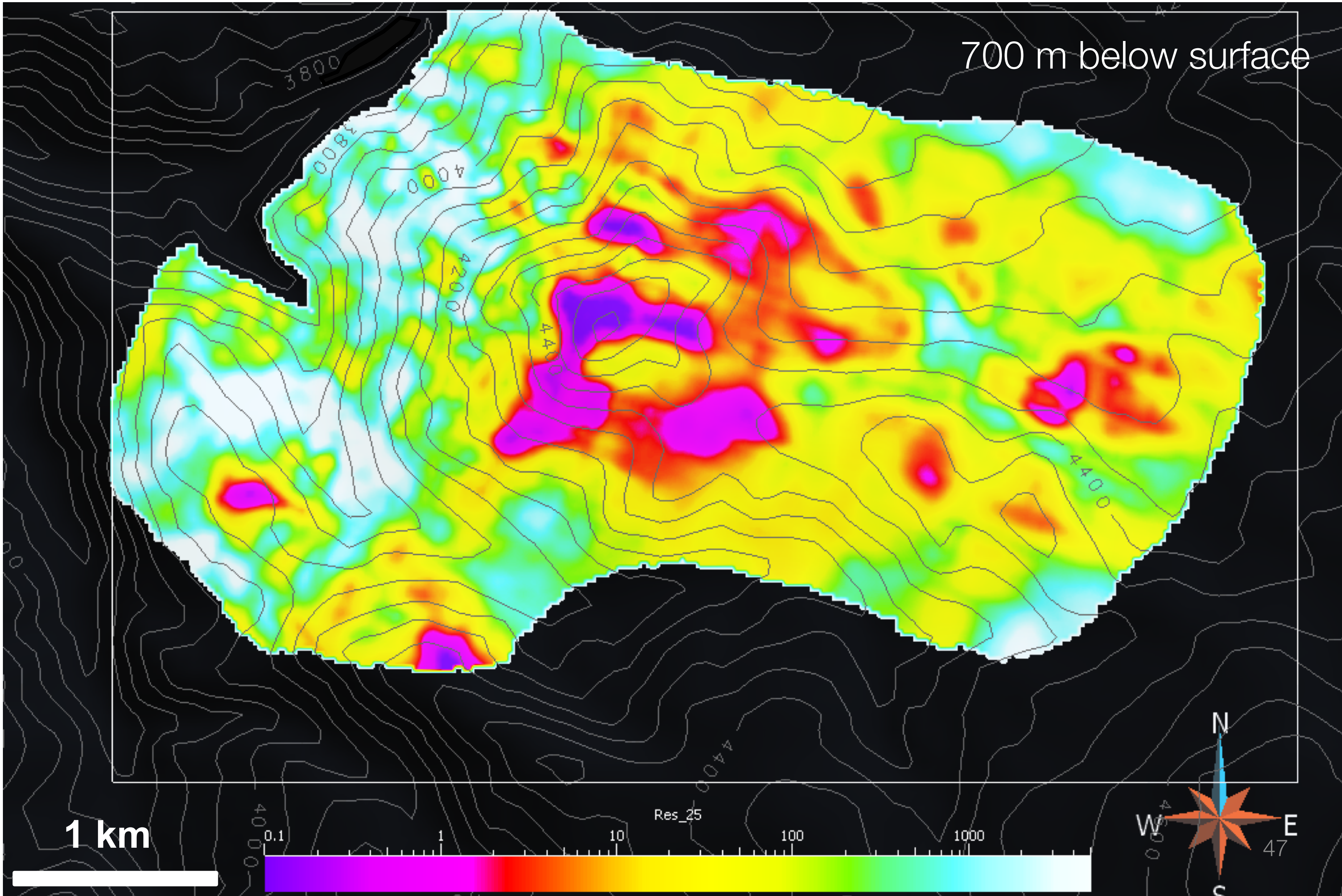
Processing: DC inversion



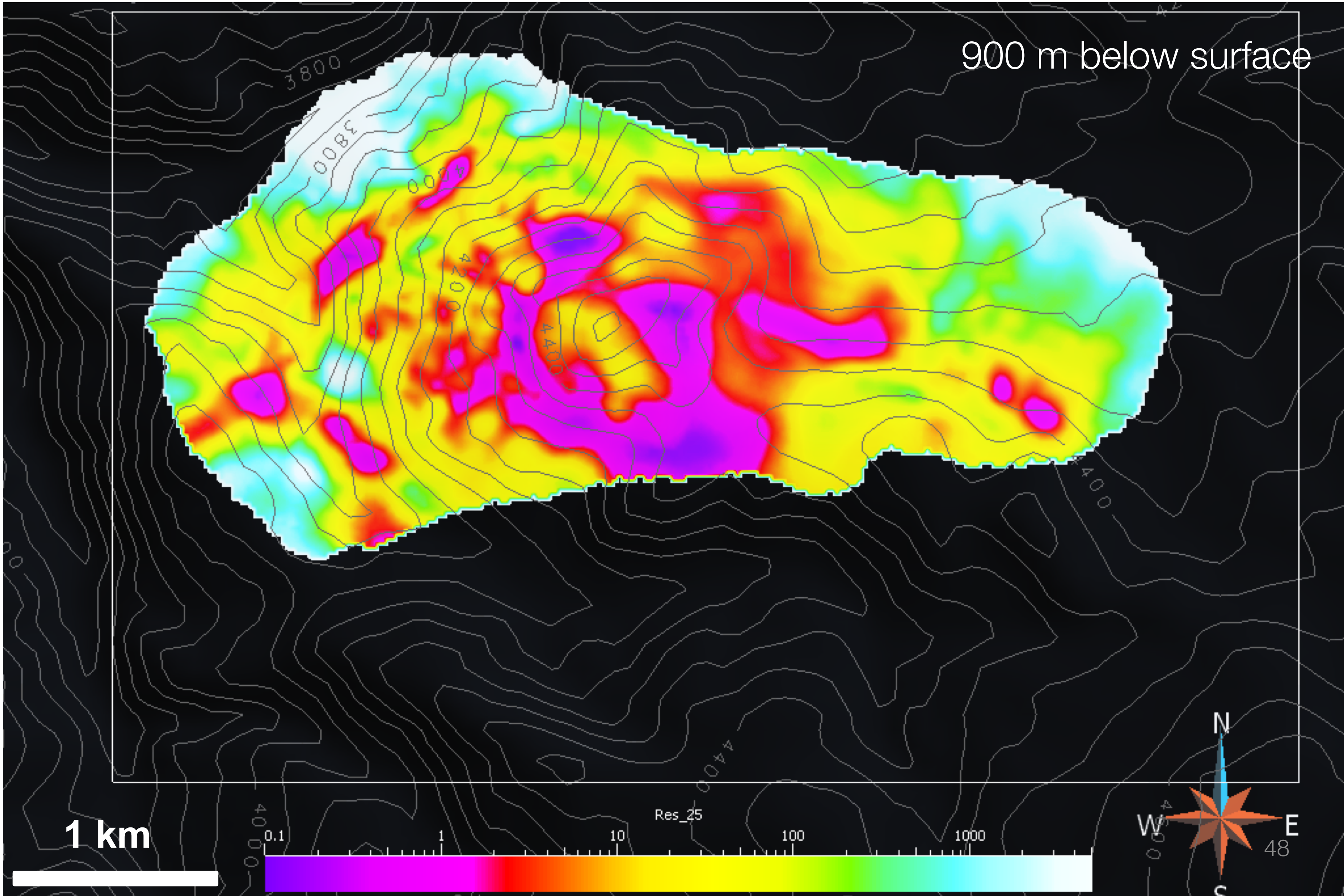
Processing: DC inversion



Processing: DC inversion



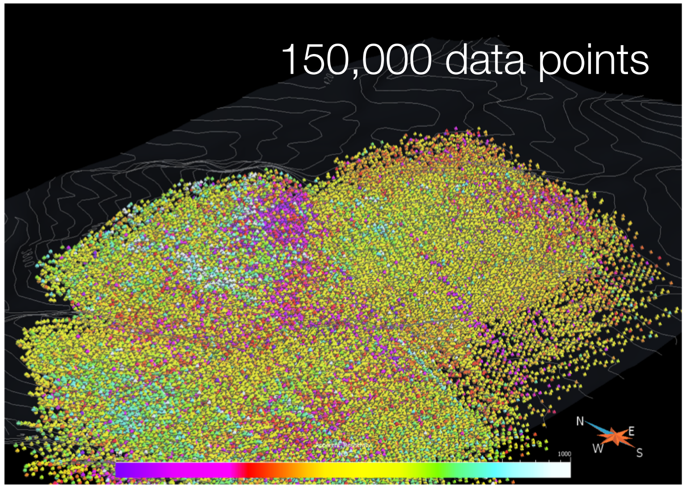
Processing: DC inversion



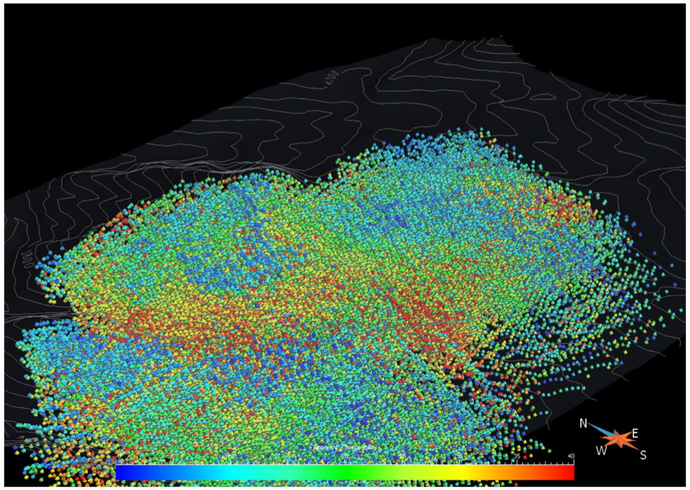
(we also have IP data)

DC-IP Data

DC data



IP data

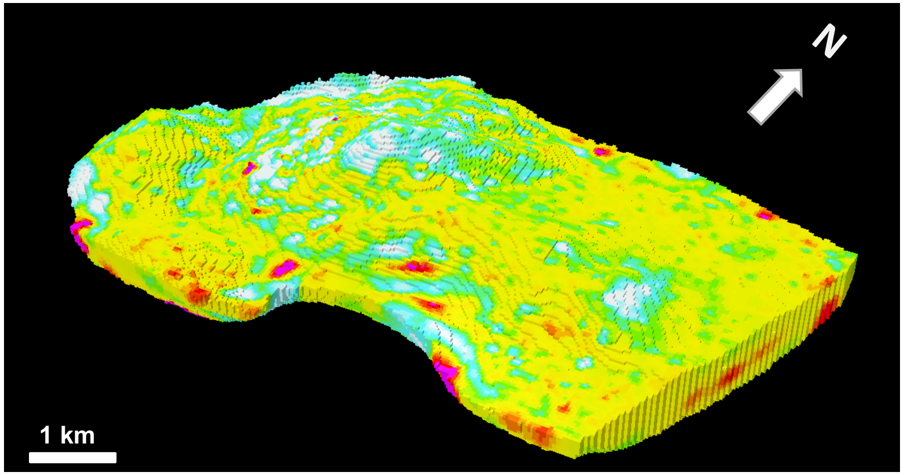


- 150,000 data points from
  - 539 sources
  - 300 receiver dipoles
- Hard to visualize and interpret data
- Need to invert

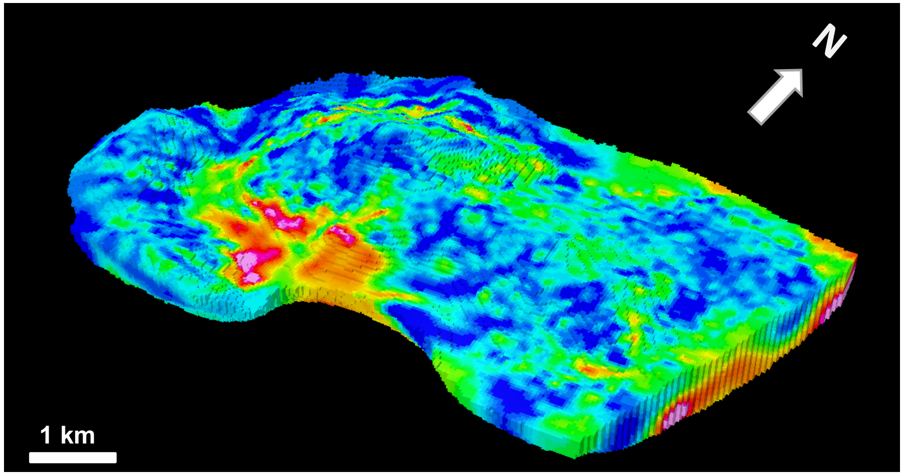
3D DC IP inversion

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

Resistivity

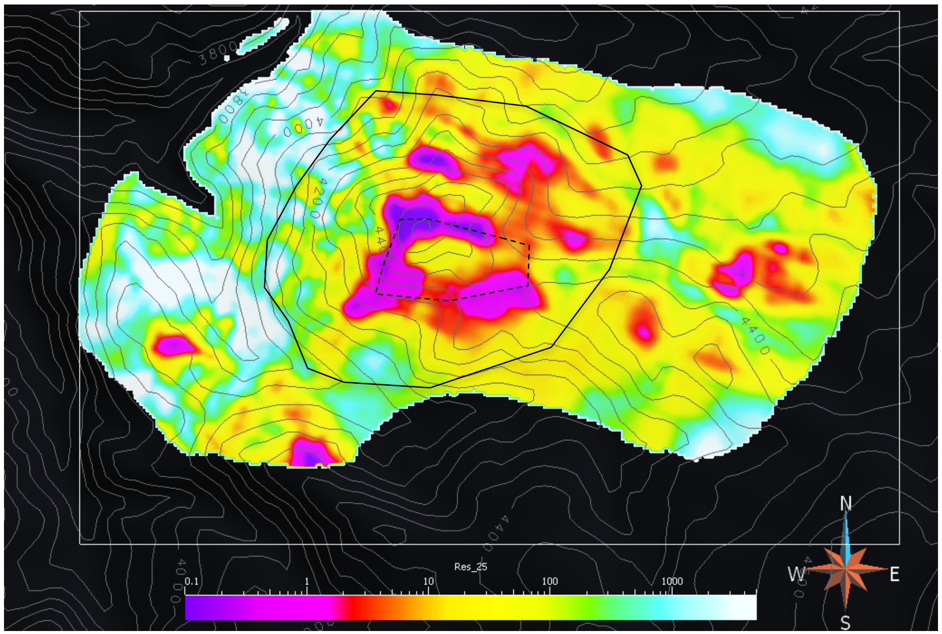


Chargeability

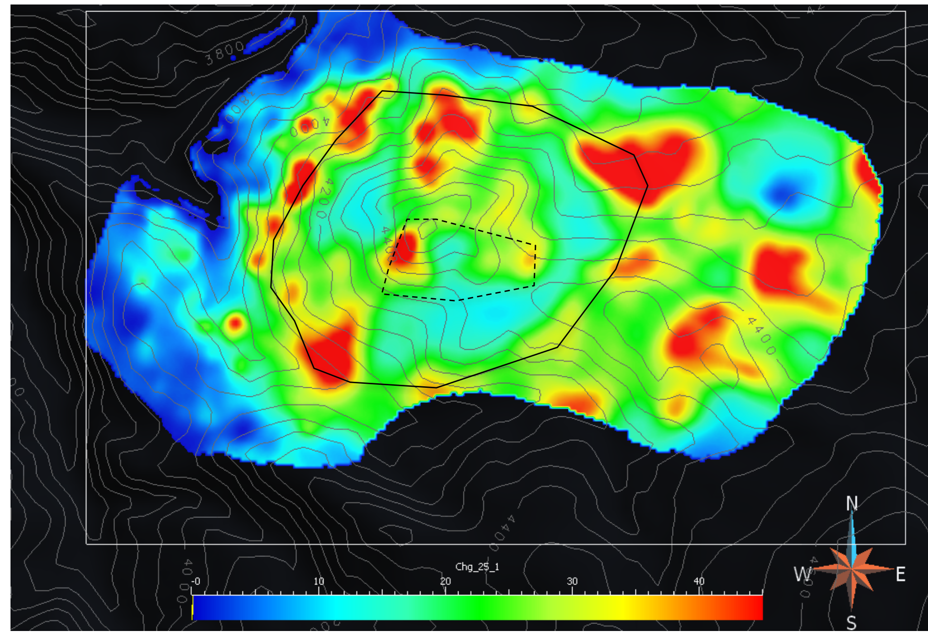


Interpretation: Resistivity & Chargeability

700m below surface



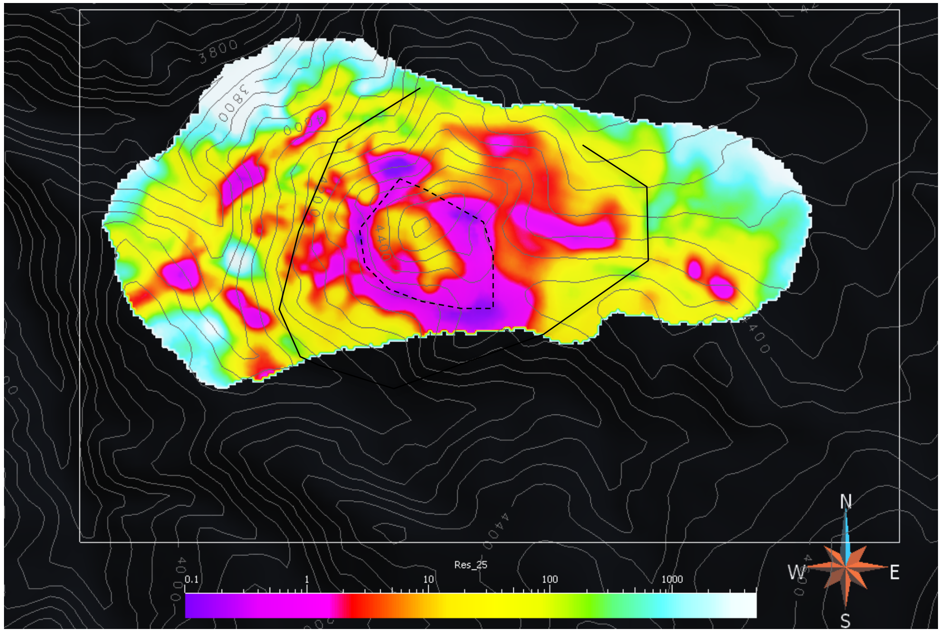
Resistivity



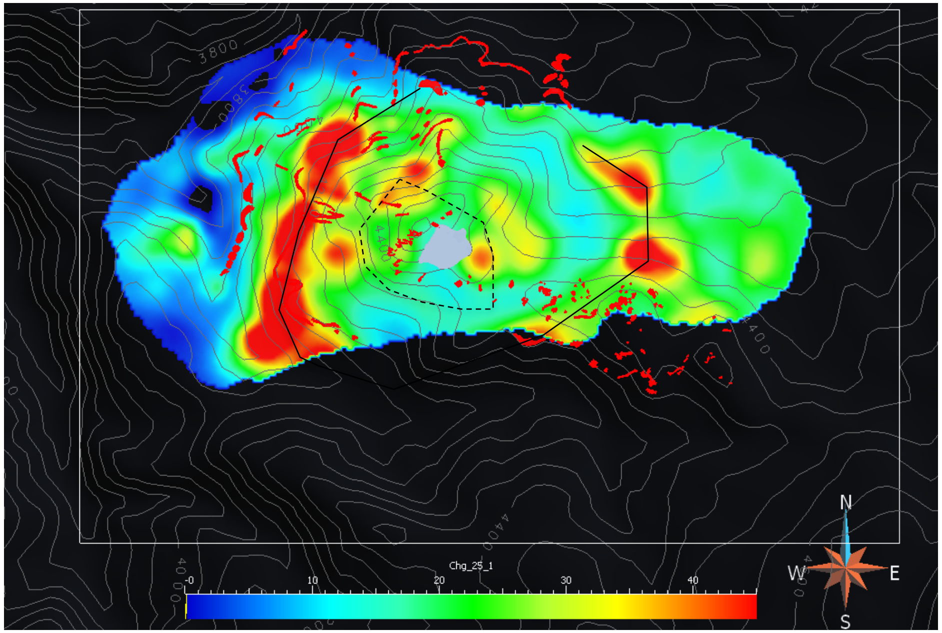
Chargeability

Interpretation: Resistivity & Chargeability

900m below surface

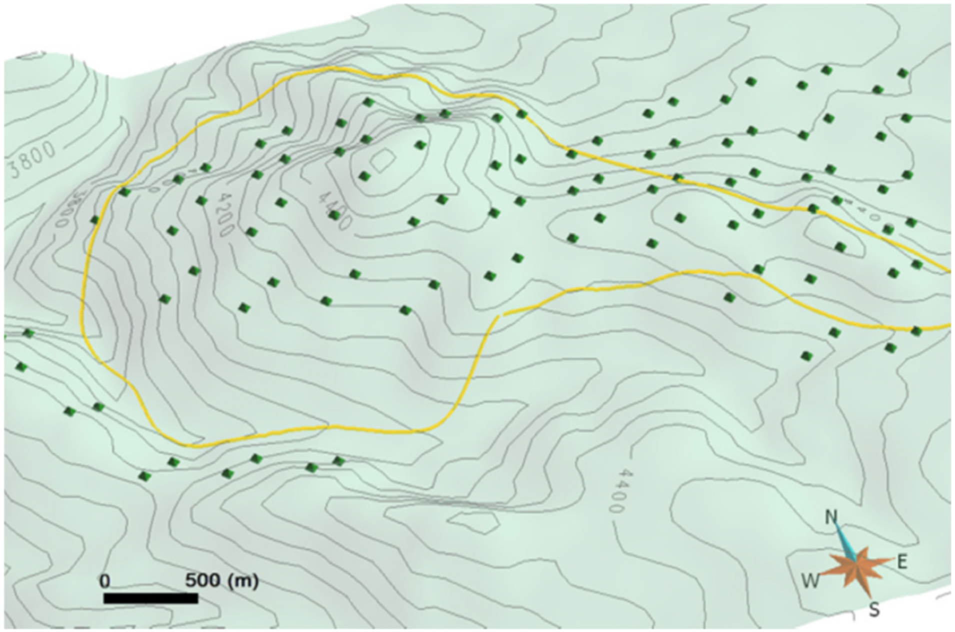


Resistivity



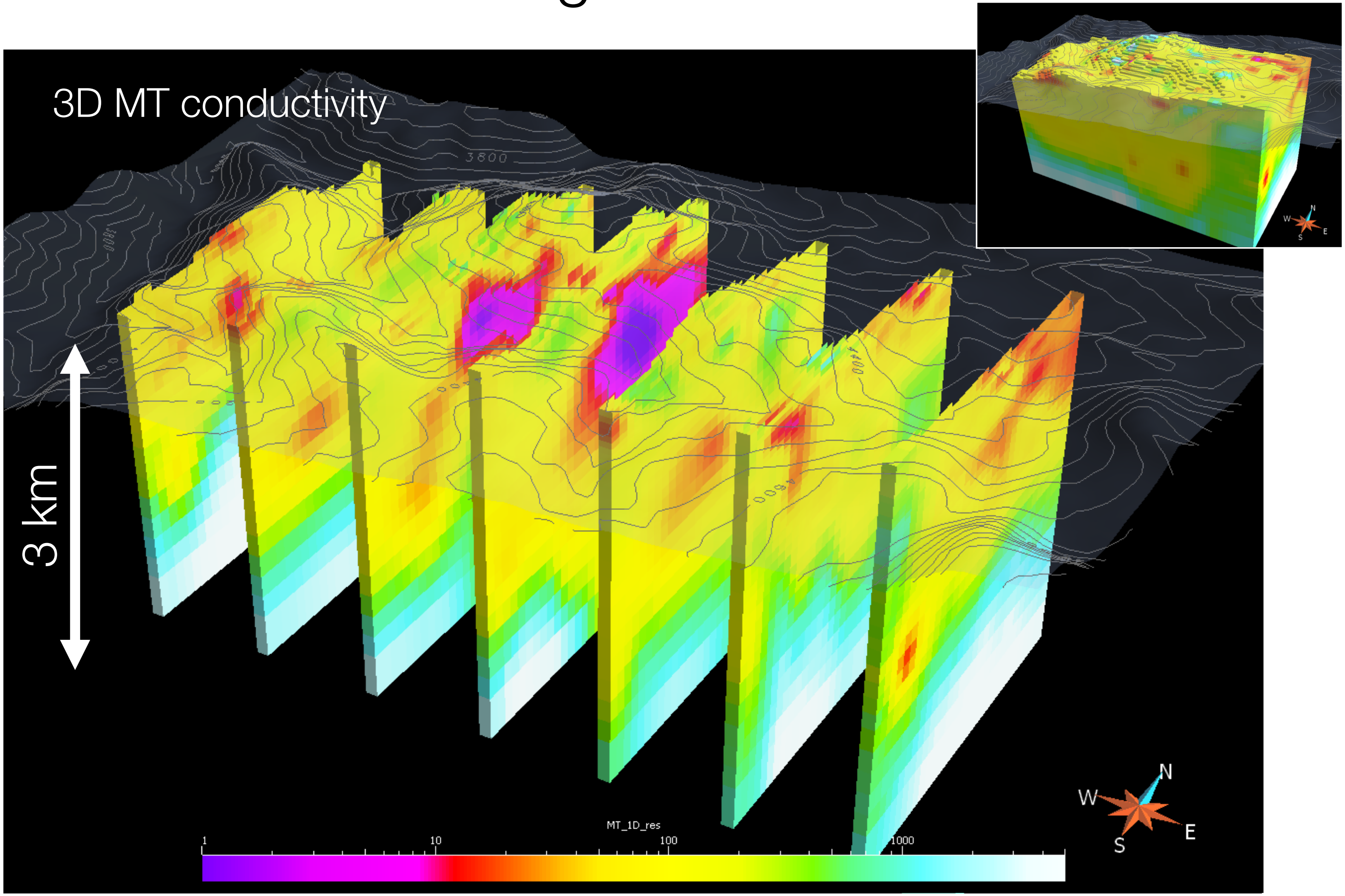
Chargeability

MT Data

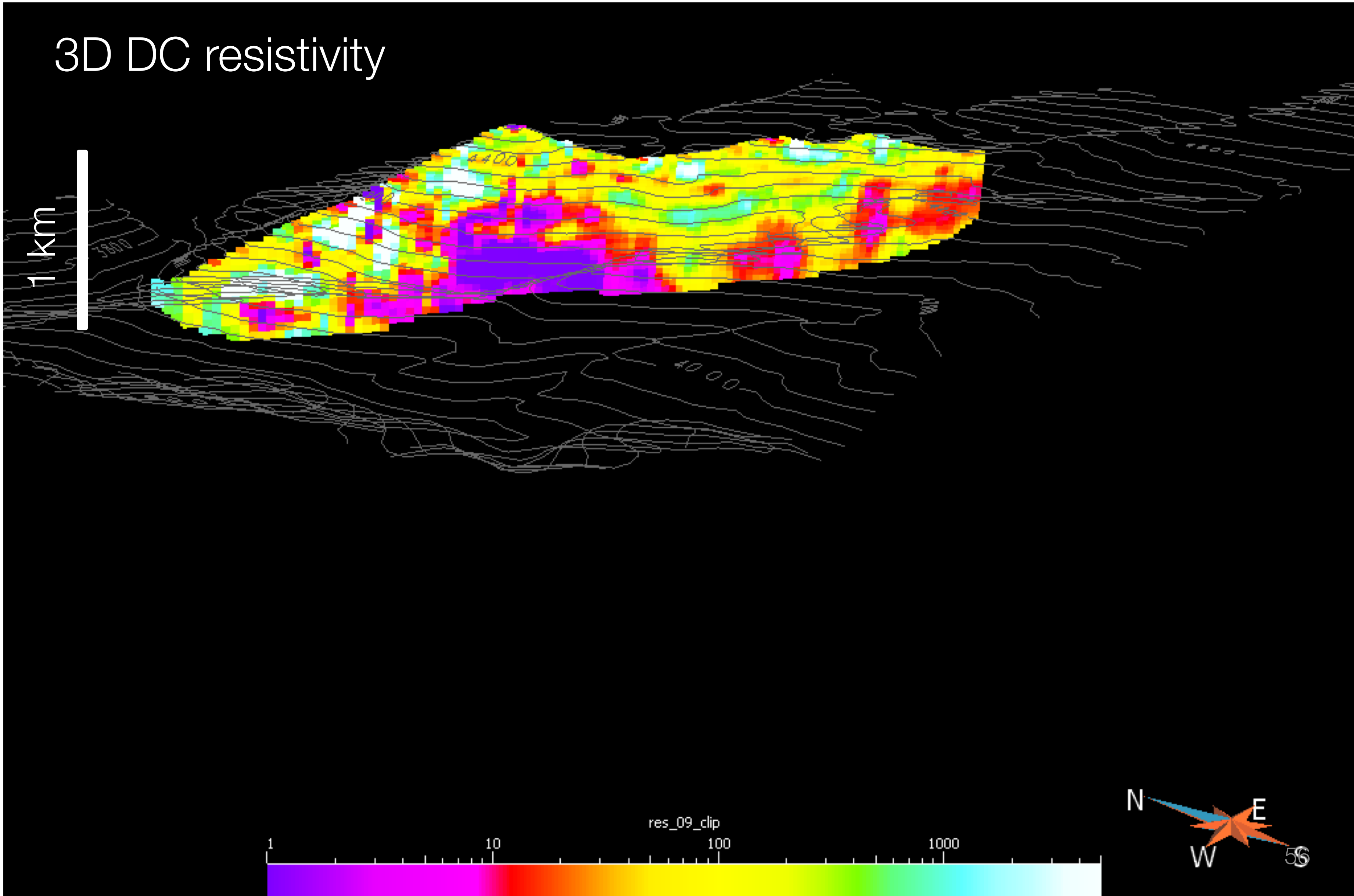


- 100 MT Sites
- 150 m dipole length
- Two orthogonal induction coils
- 450 m spacing
- Acquired over night
- Frequency range: 250-0.001 Hz

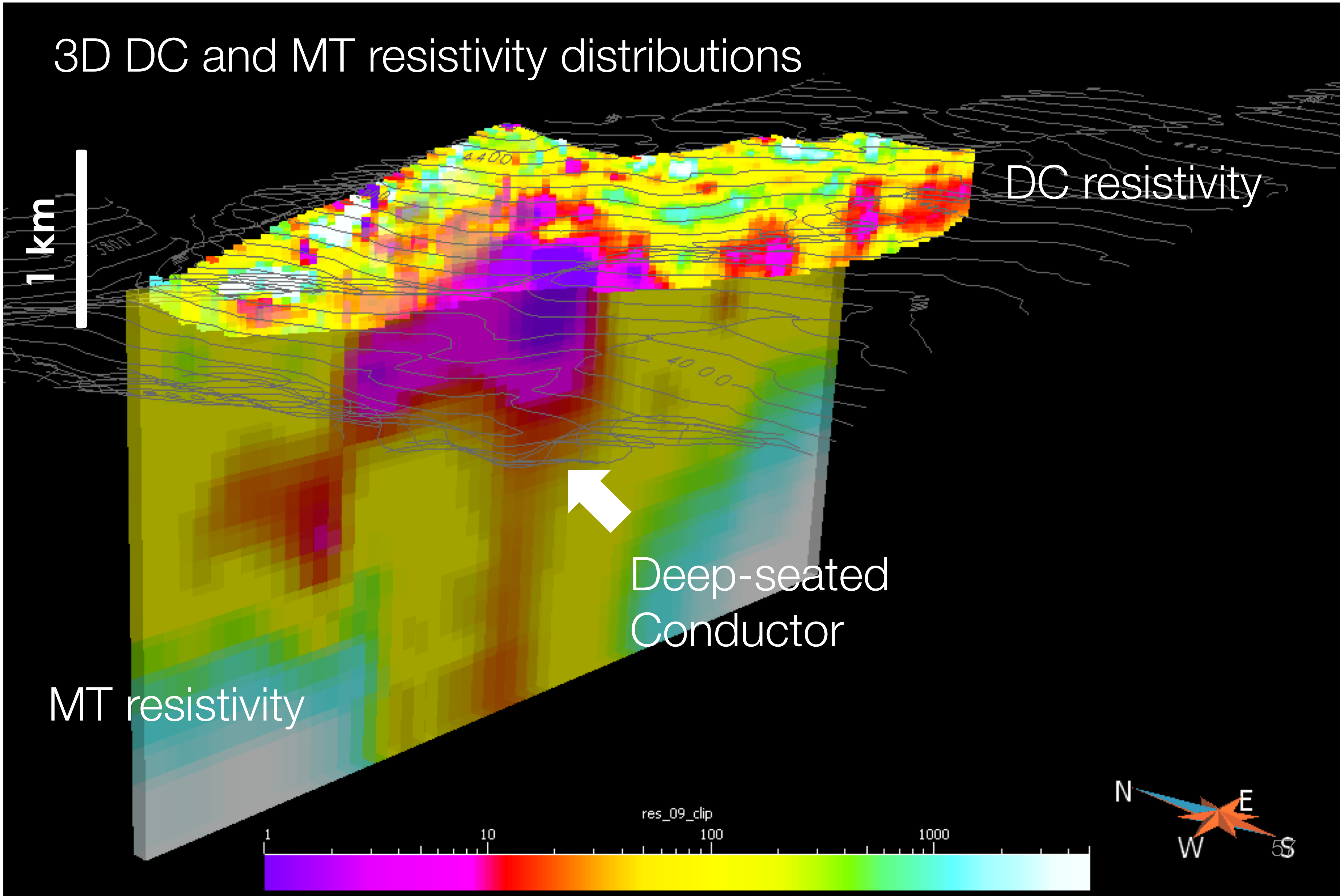
Processing: MT inversion



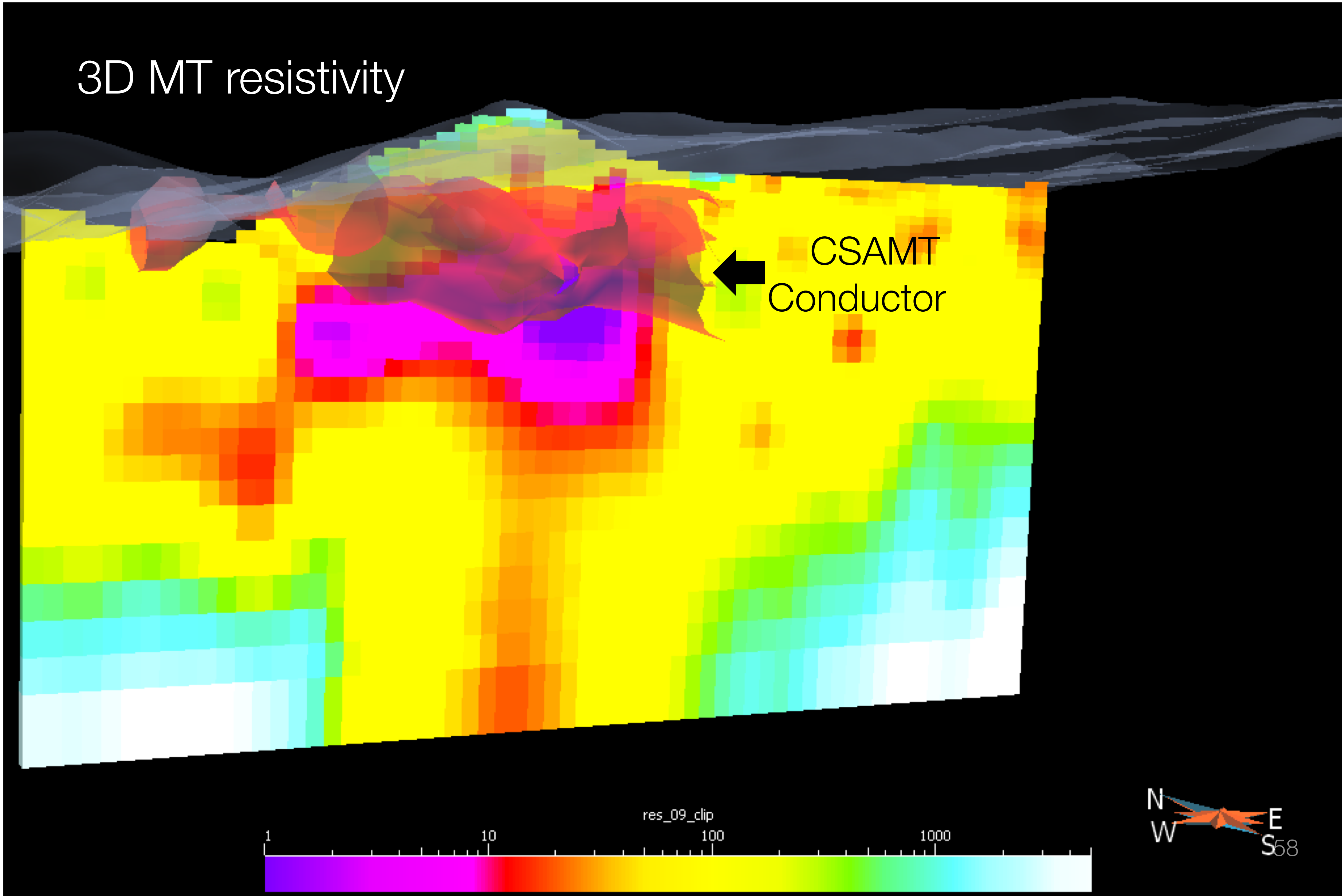
Interpretation



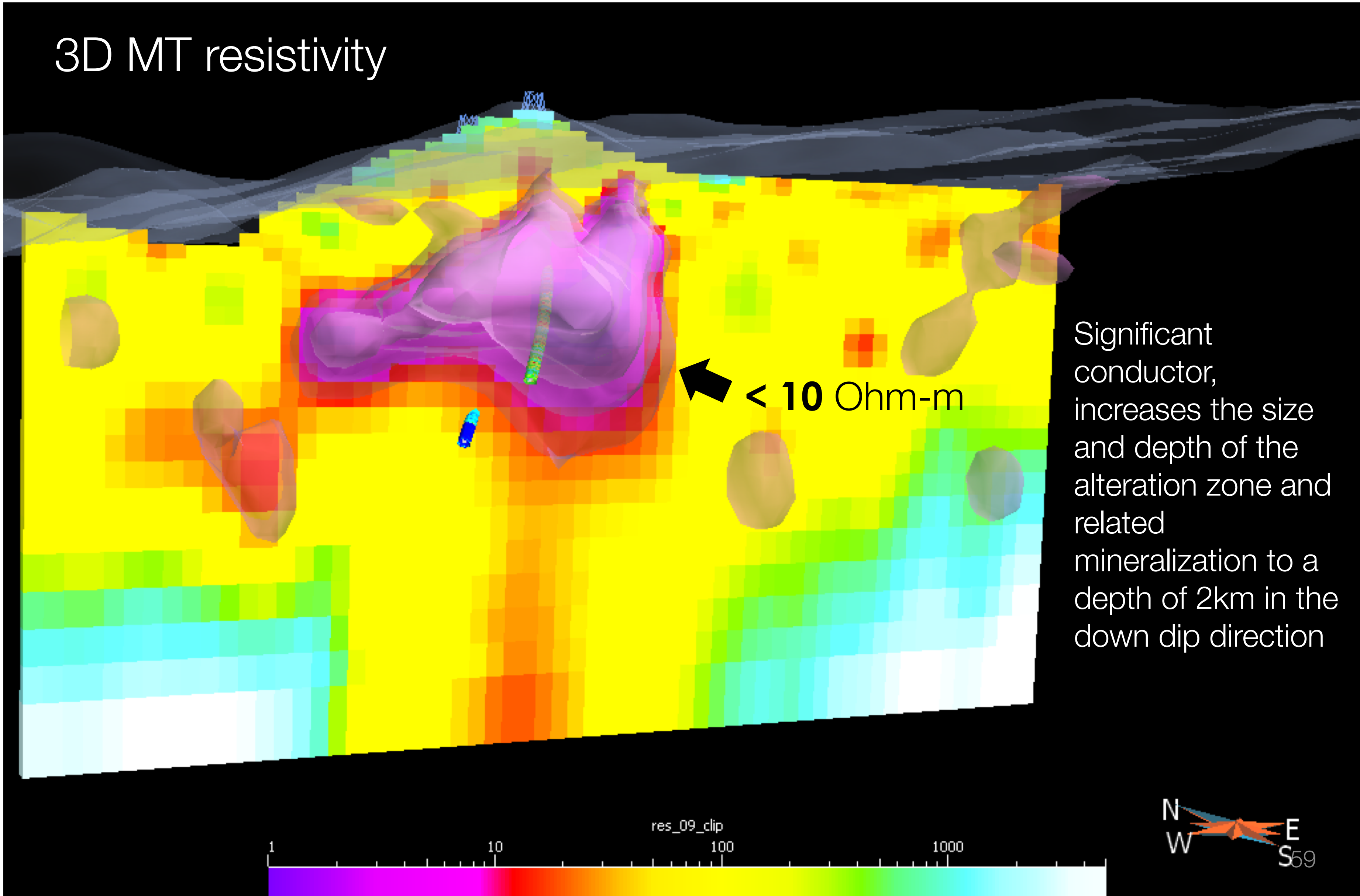
Interpretation



Interpretation

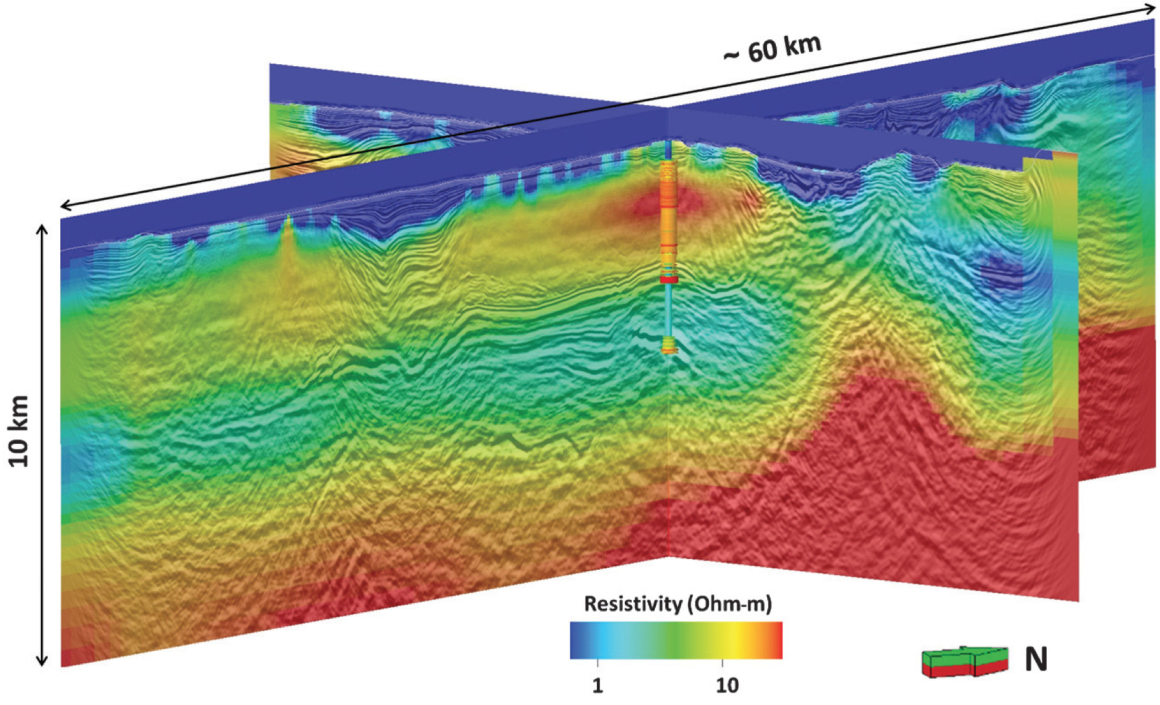


Synthesis


3D MT resistivity
< 10 Ohm-m
Significant conductor, increases the size and depth of the alteration zone and related mineralization to a depth of 2km in the down dip direction
res_09_clip
1
10
100
1000
N
E
W
S

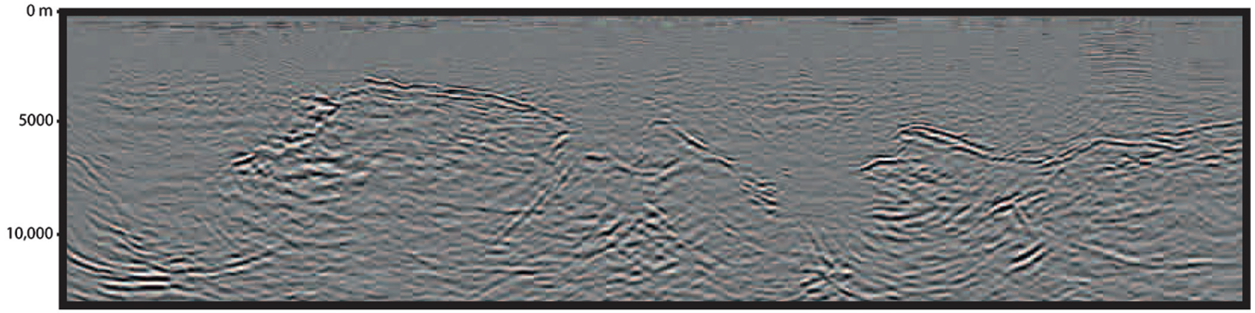
Case History: Red sea

Colombo et al. 2014



Setup

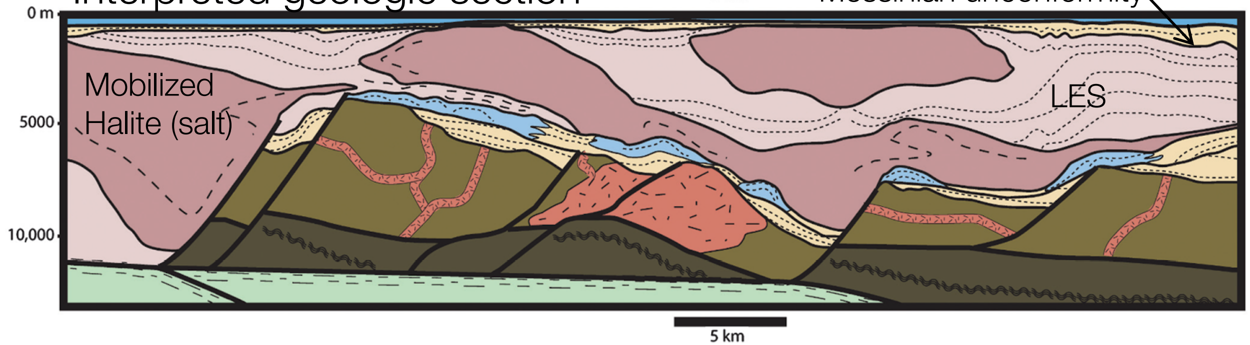
Uninterpreted seismic depth section



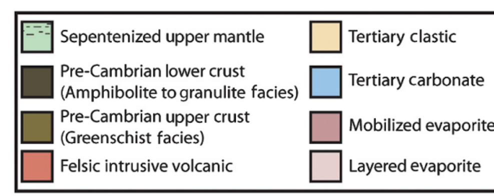
5 km

Interpreted geologic section

Messinian unconformity



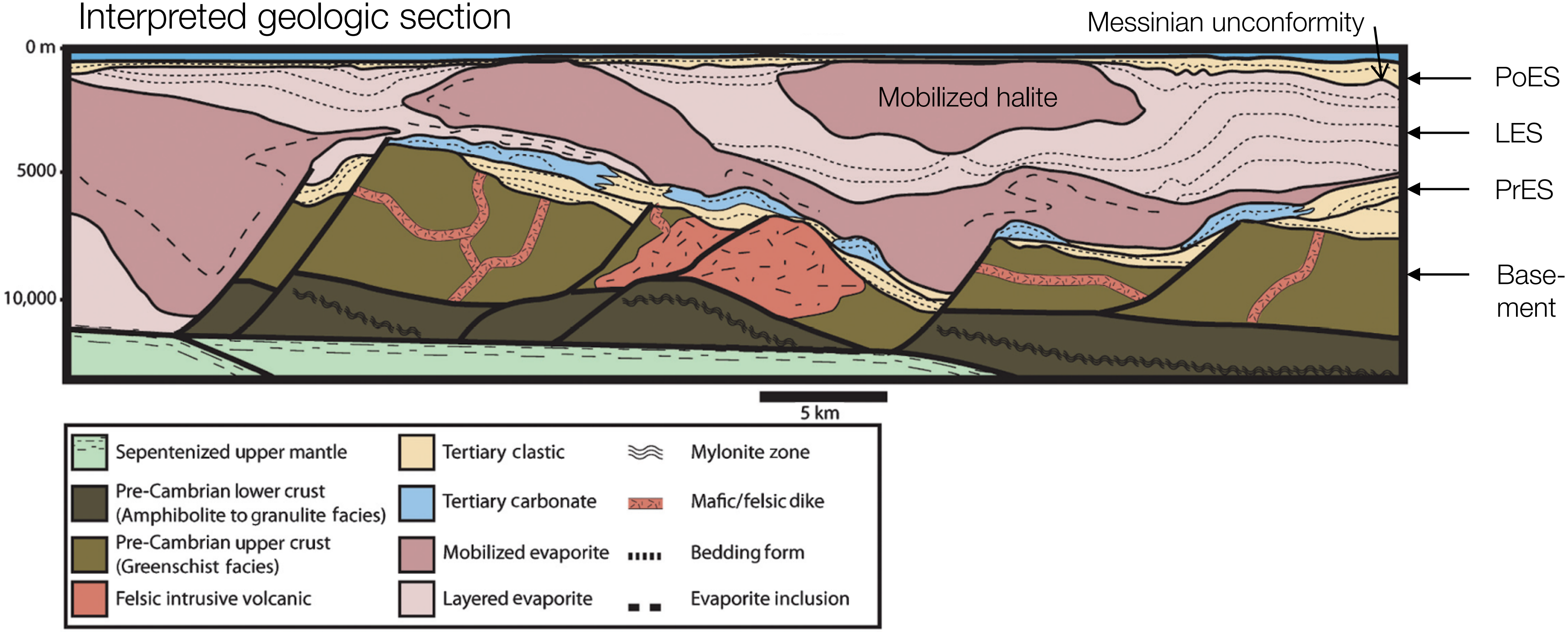
Location of Res Sea



- Thick salt sequences: a seal for potential hydrocarbon accumulations
- Mobilized halite (salt) → vertical and lateral velocity variations
  - challenges for seismic imaging
- Highly deformed basement
  - complicates interpretation

Geology

Interpreted geologic section



- Post-Evaporite Sediment (PoES)
  - Consists of interbedded, deep-marine siltstones and mudstone
- Layered Evaporite Sequence (LES)
  - Layered sedeiments + halite (salt)
  - Mobilization: due to on-going tectonic rifting
- Pre-Evaporite Sediment (PrES)
  - few well penetrations
- Pre-Cambrian Basement
  - Highly deformed

Goals

- How 3D conductivity models from EM methods can be used to better constrain migration results from wide-azimuth (WAZ) seismic data
  - Magnetotelluric (MT)
  - Controlled-source EM (CSEM)
- Assess the ability of MT and CSEM methods to subsurface structures independently
- Compare resulting conductivity models to a density model from gravity gradiometry data

Properties

Interpreted geologic section

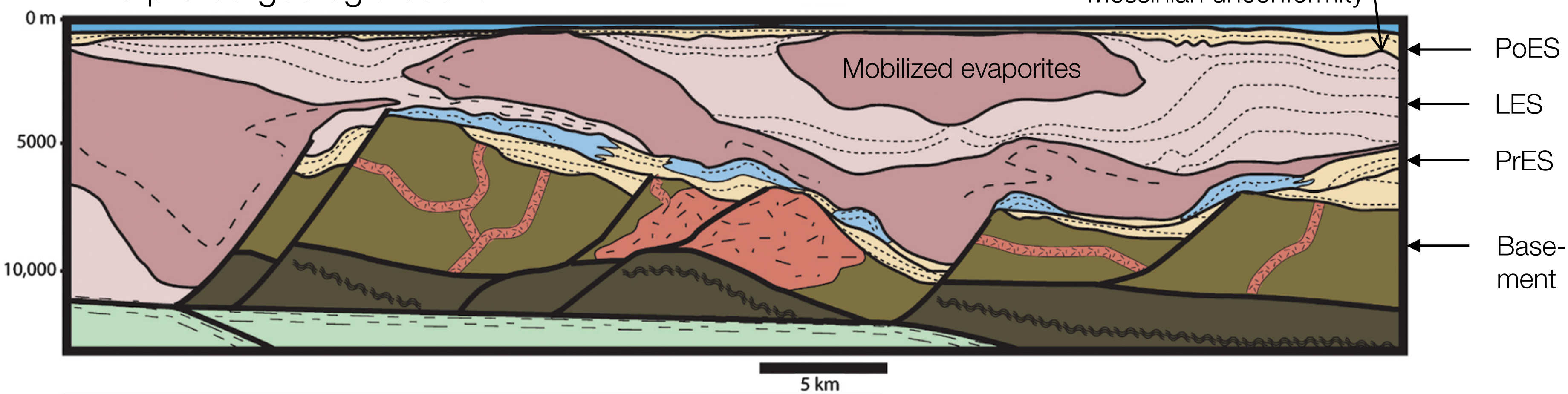


Table of physical properties

Unit	Seismic Velocity (m/s)	Density (kg/m^3)	Resistivity (Ωm)	Anisotropy (Rv/Rh)
PoES	2,200*	2,100*	0.5*	1.5
LES	2,200*	2,100*	230*	1.5
Halite (within LES)	~5,000	~2,050	~10^4<	1*
PrES	2,200*	2,100*	1.5*	1.5*
Basement	6,000*	2,750*	400*	1*

Obtained from paper (*)
Common values (~)

Survey design

Synthetic 3D models

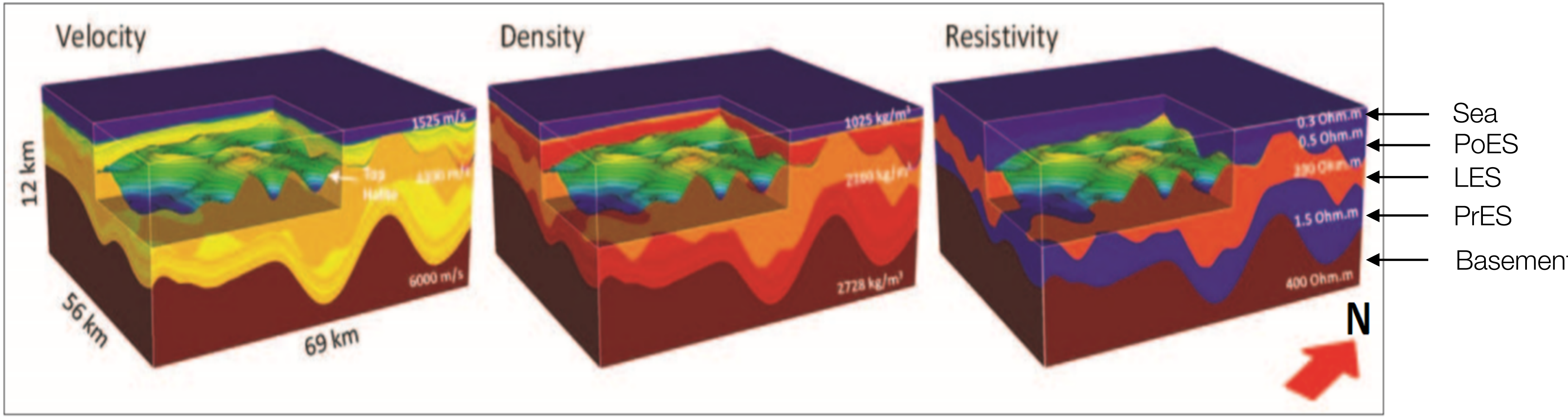
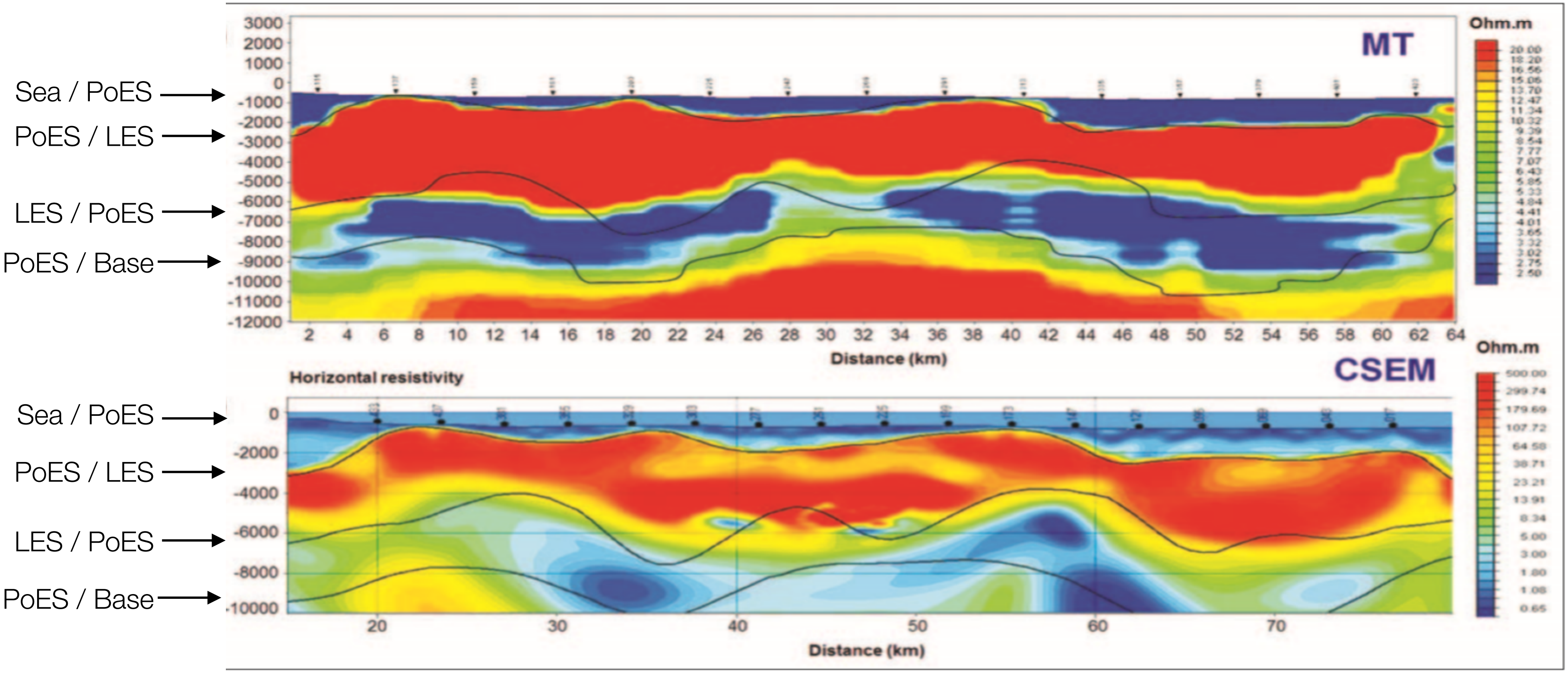


Table of physical properties

Unit	Seismic Velocity (m/s)	Density (kg/m^3)	Resistivity (Ωm)	Anisotropy (Rv/Rh)
Sea	1,525	1,025	0.3	1
PoES	2,200	2,100	0.5	1.5
LES	2,200	2,100	230	1.5
PrES	2,200	2,100	1.5	1.5
Basement	6,000	2,728	400	1

Synthetic 2D inversions

Recovered resistivity sections



- Both inversions resolve the base of LES (salt)
- Only MT inversion resolves the basement

Survey details

Location map

Acquisition parameters

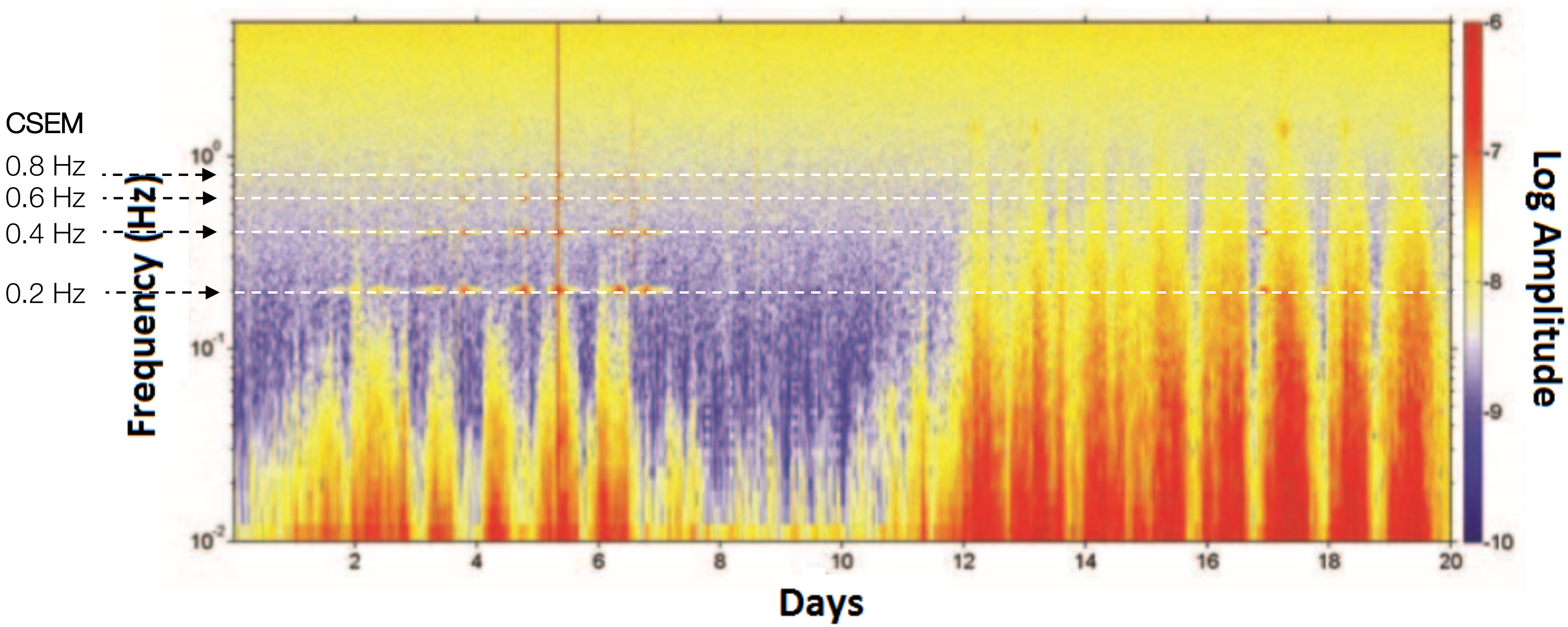
Item	Specification
Blocks	3
Surface	Average of 2000 square km per block
Number of stations	650 ←
Spacing	3 km (staggered grid)
Sea bottom recording time	Up to 20 days of continuous recording
Inline offset	30 km
Crossline offset	12 km (four azimuthal lines)
Measured components	Ex, Ey, Bx, By
CSEM transmitted frequency	0.2 Hz
CSEM harmonics	0.4, 0.6, 0.8, 1.4, 2.0 Hz

- Focus on Area1
- World largest marine EM and MT survey

Processing and Interpretation: Data-driven

Data

Spectogram

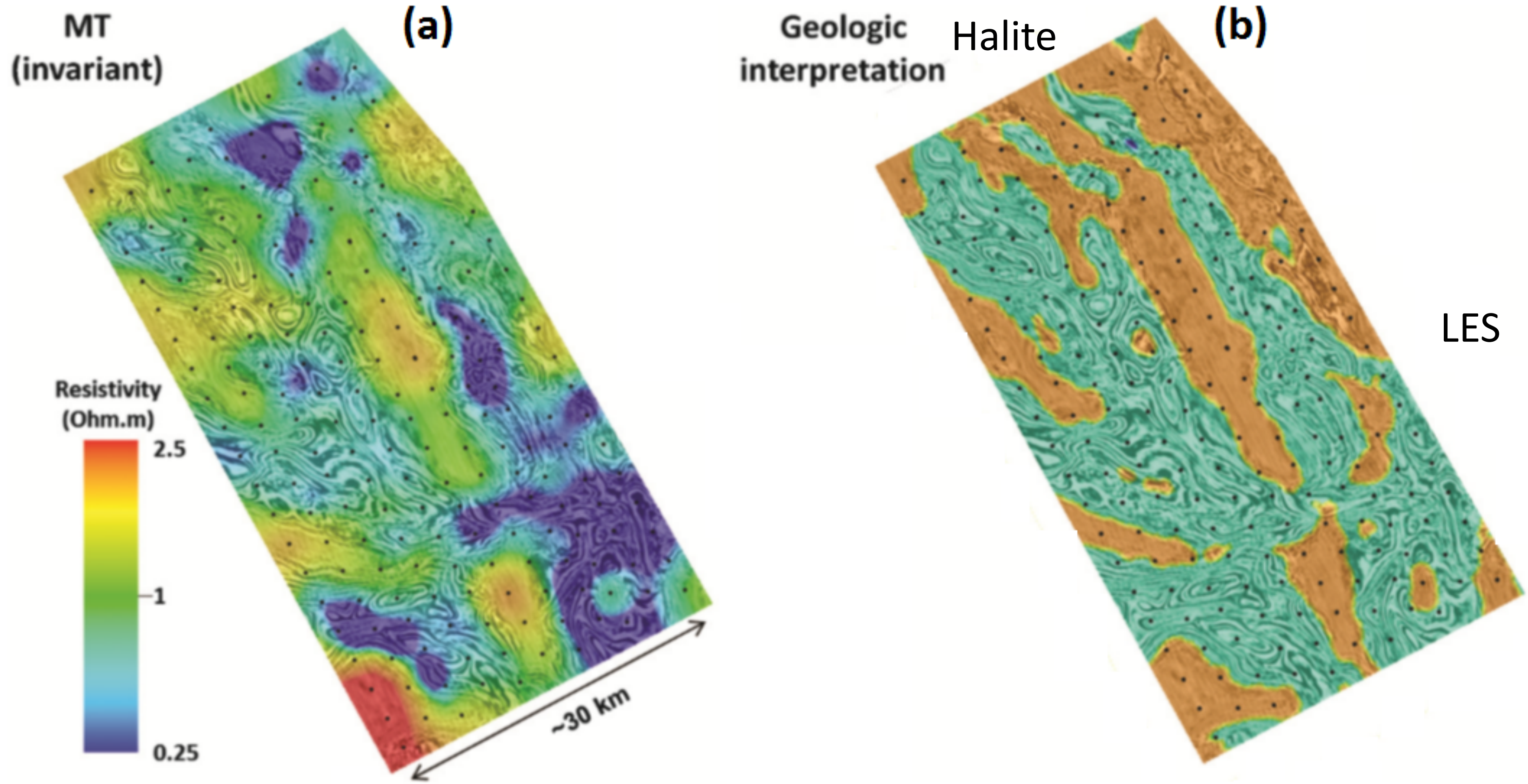


- EM data were recorded for 12 days up to 20 days
- Frequency band: 0.2 mHz – 2.0 Hz
- Diurnal variations / Solar activities

MT data

0.1 Hz

From seismic and well logs

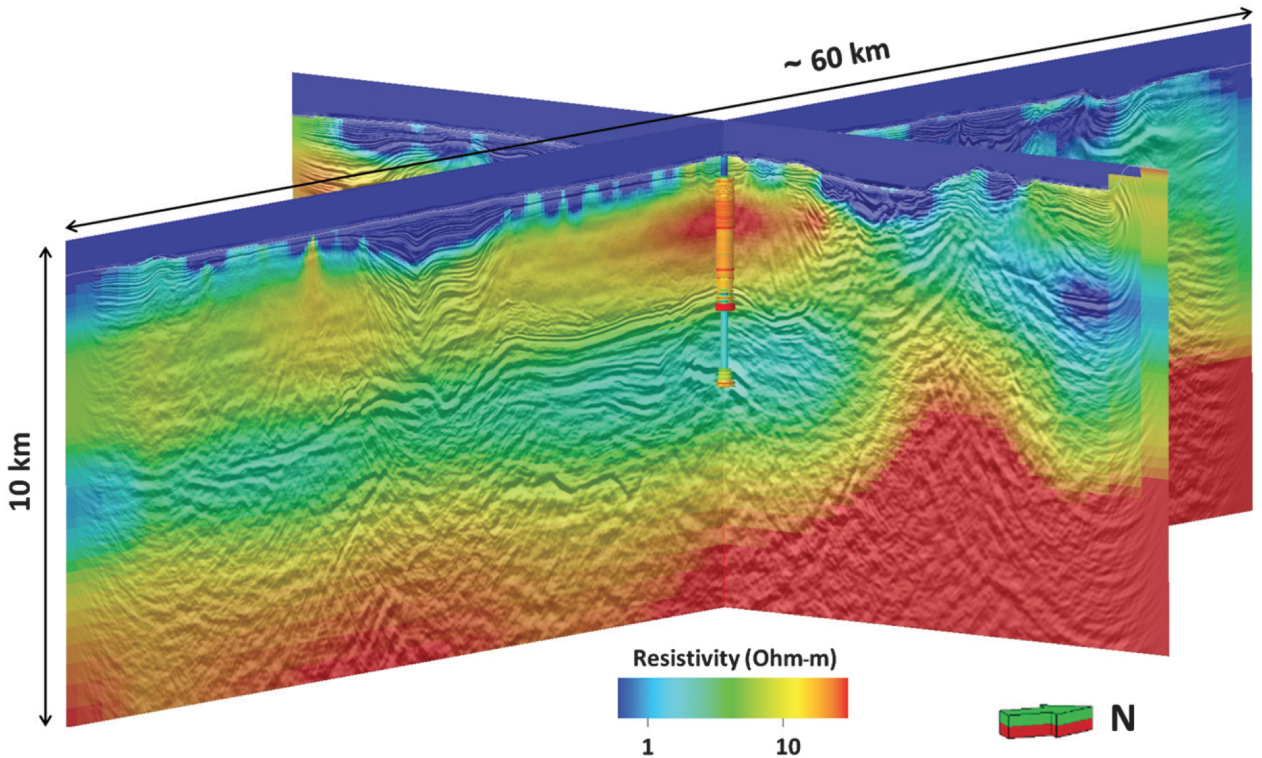


- Apparent resistivity

$$\rho = \frac{1}{\omega\mu}\left|Z_{xy}\right|^2 \qquad Z_{xy} = \frac{E_x}{H_y}$$

3D MT inversion

3D resistivity model



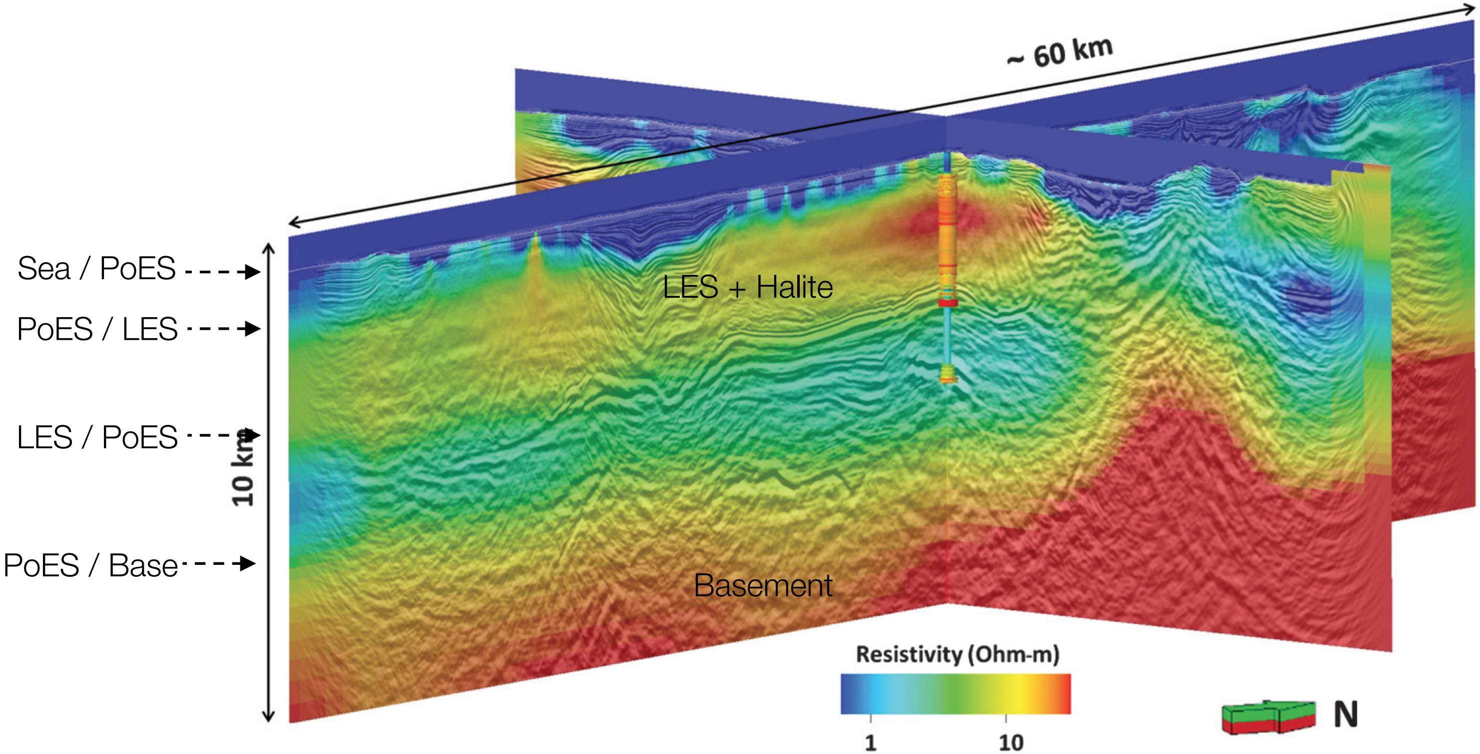
Model parameters

X-Y cell spacing	Z min size	N. of cells	N. receivers
200×200 m	50 m	8.7 million	198

- Initial guess: salt flood model
  - Generated from seismic horizon

Interpretation

3D resistivity model



- Good recovery of the main salt body: LES + halite
- Recovered salt body matches well with drillings
- Able to recover the deep basement

Survey details

Location map

Acquisition parameters

Item	Specification
Blocks	3
Surface	Average of 2000 square km per block
Number of stations	650 ←
Spacing	3 km (staggered grid)
Sea bottom recording time	Up to 20 days of continuous recording
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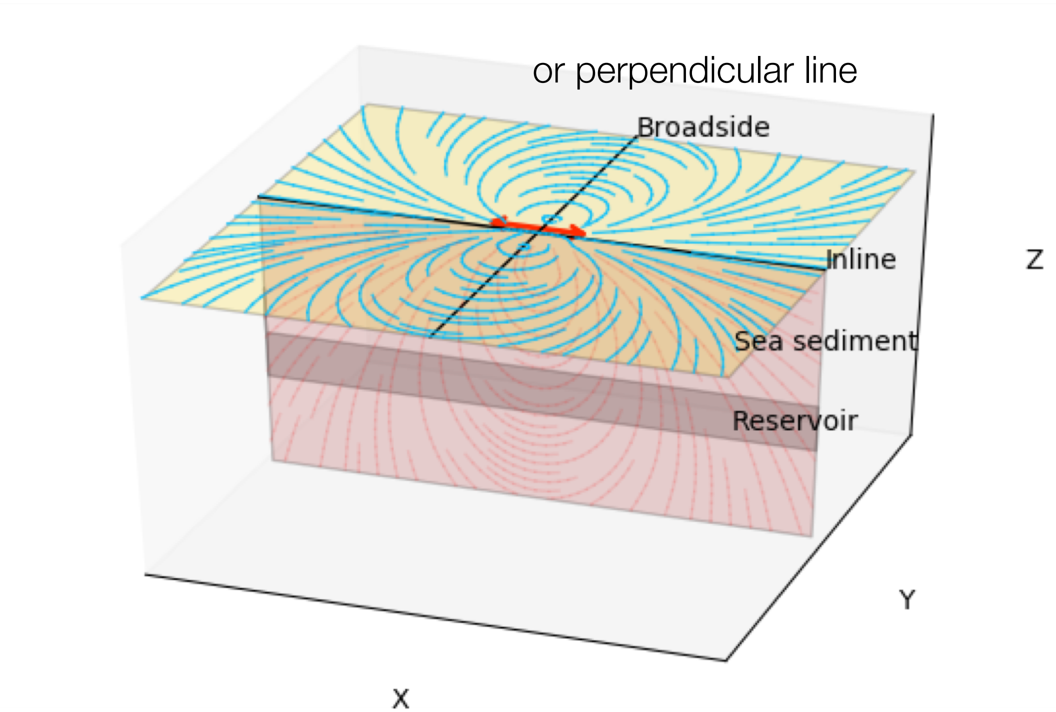
CSEM transmitted frequency	0.2 Hz
CSEM harmonics	0.4, 0.6, 0.8, 1.4, 2.0 Hz

- Focus on Area1

CSEM survey

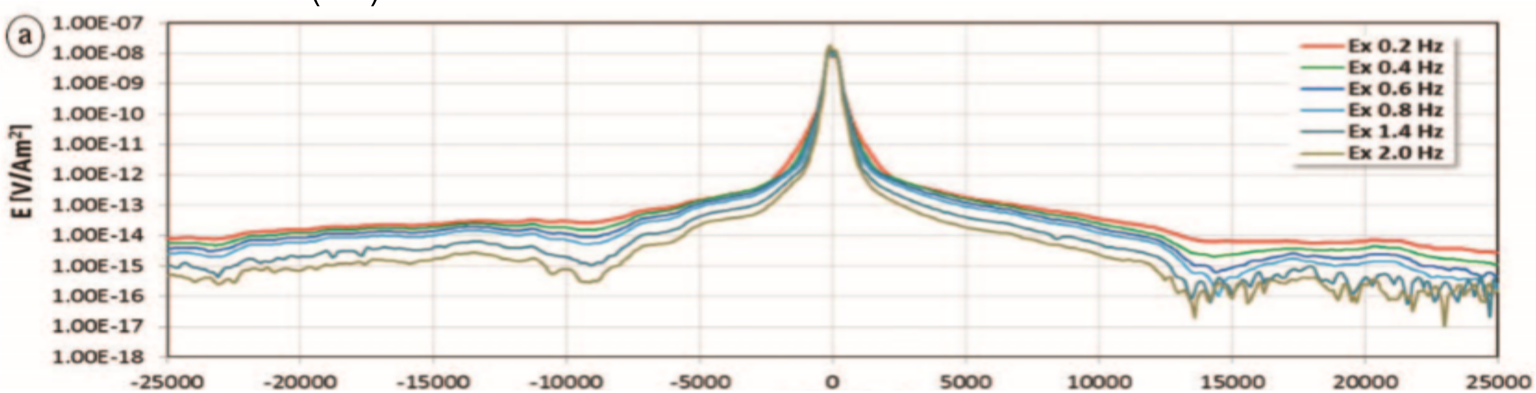


- Assuming 1D structure
- Inline
  - Only Ex, Ez / Hy
  - No vertical magnetic field
  - Sensitive Rv

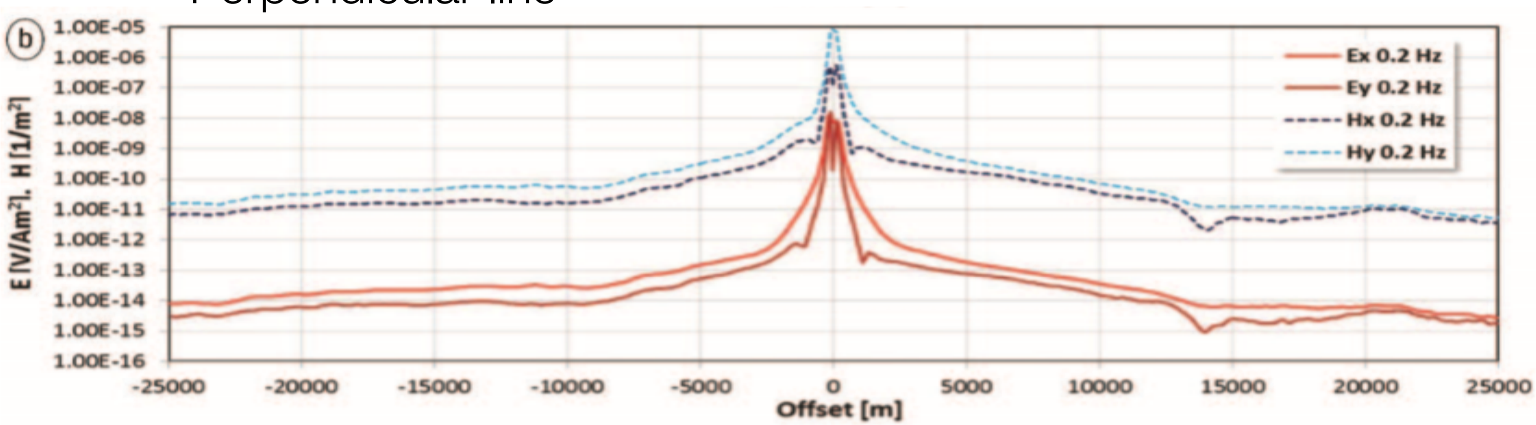
- Broadside
  - Only Ex / Hy, Hz
  - No vertical electric field
  - Sensitive Rh

CSEM data: EM fields (Ex, Ey, Hx, and Hy)

Inline (Ex)



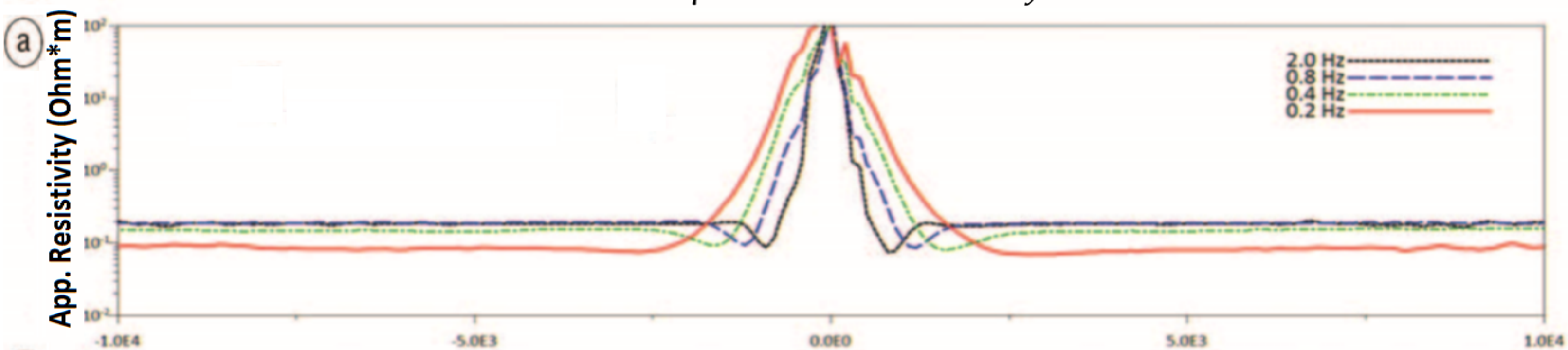
Perpendicular line



- Good S/N ratio at whole offset of 25 km (except 2 Hz ~20 km)
- Significant signals in Ey and Hx on perpendicular line
  - Presence of 2D or 3D structures

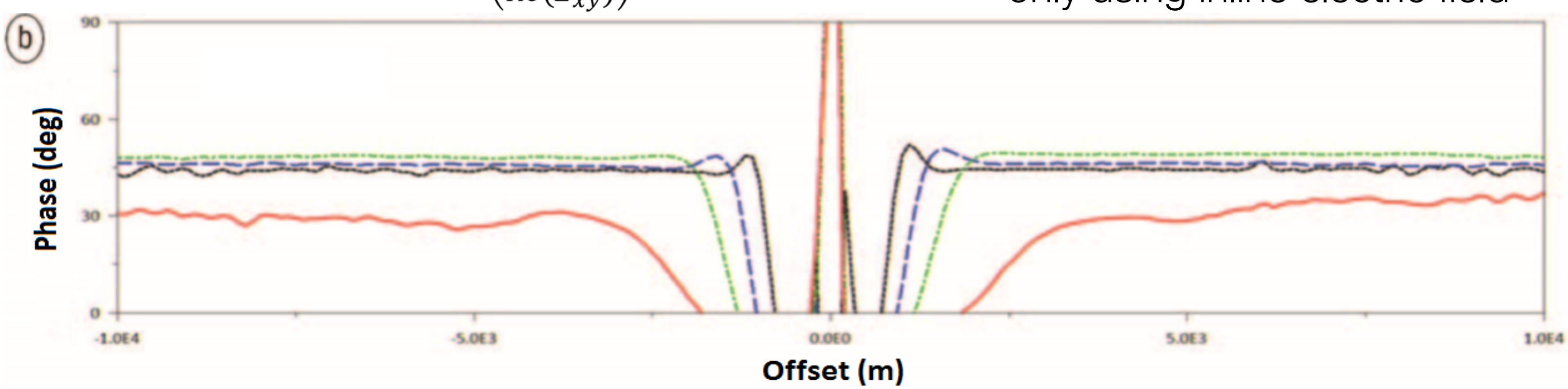
CSEM data: apparent resistivity and phase

Apparent resistivity: $\rho = \frac{1}{\omega\mu}\left|Z_{xy}\right|^2 \qquad Z_{xy} = \frac{E_x}{H_y}$



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

*only using inline electric field



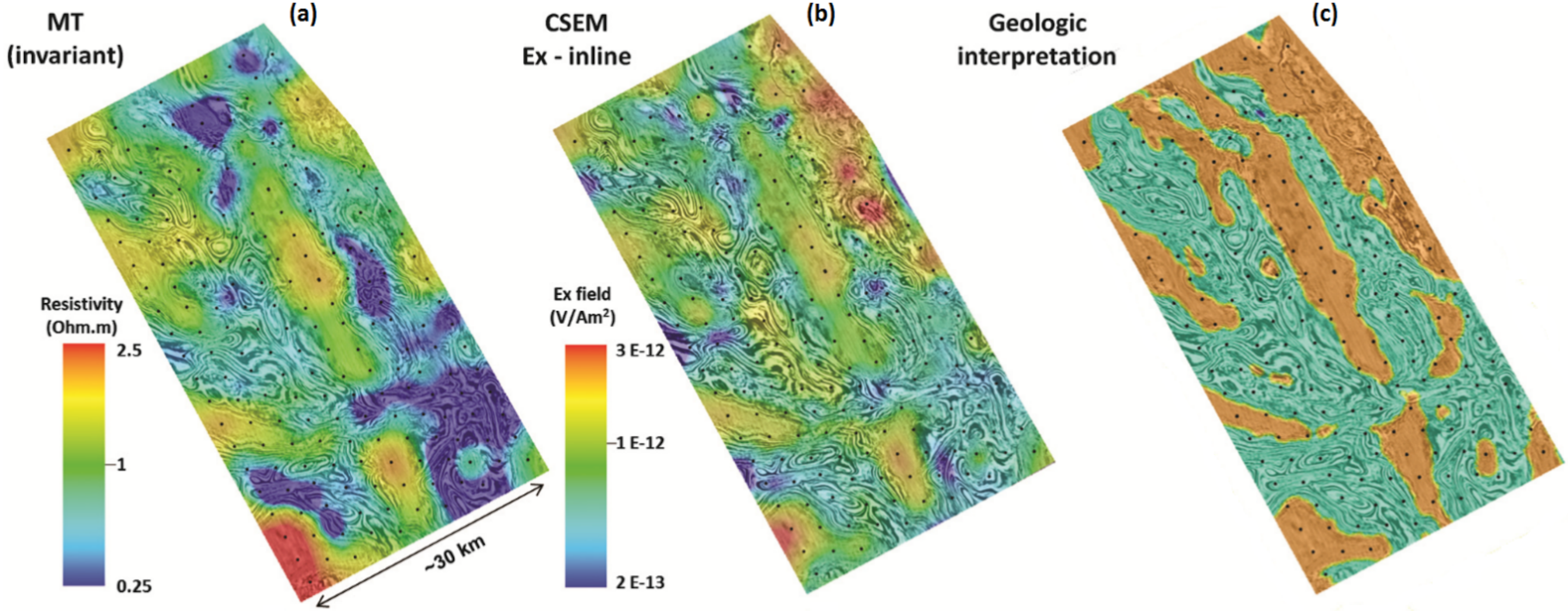
- Near field and far field behaviors:
  - Far field: the plane wave approximation (after 1 to 2.5 km)

CSEM and MT data

0.1 Hz

0.4 Hz

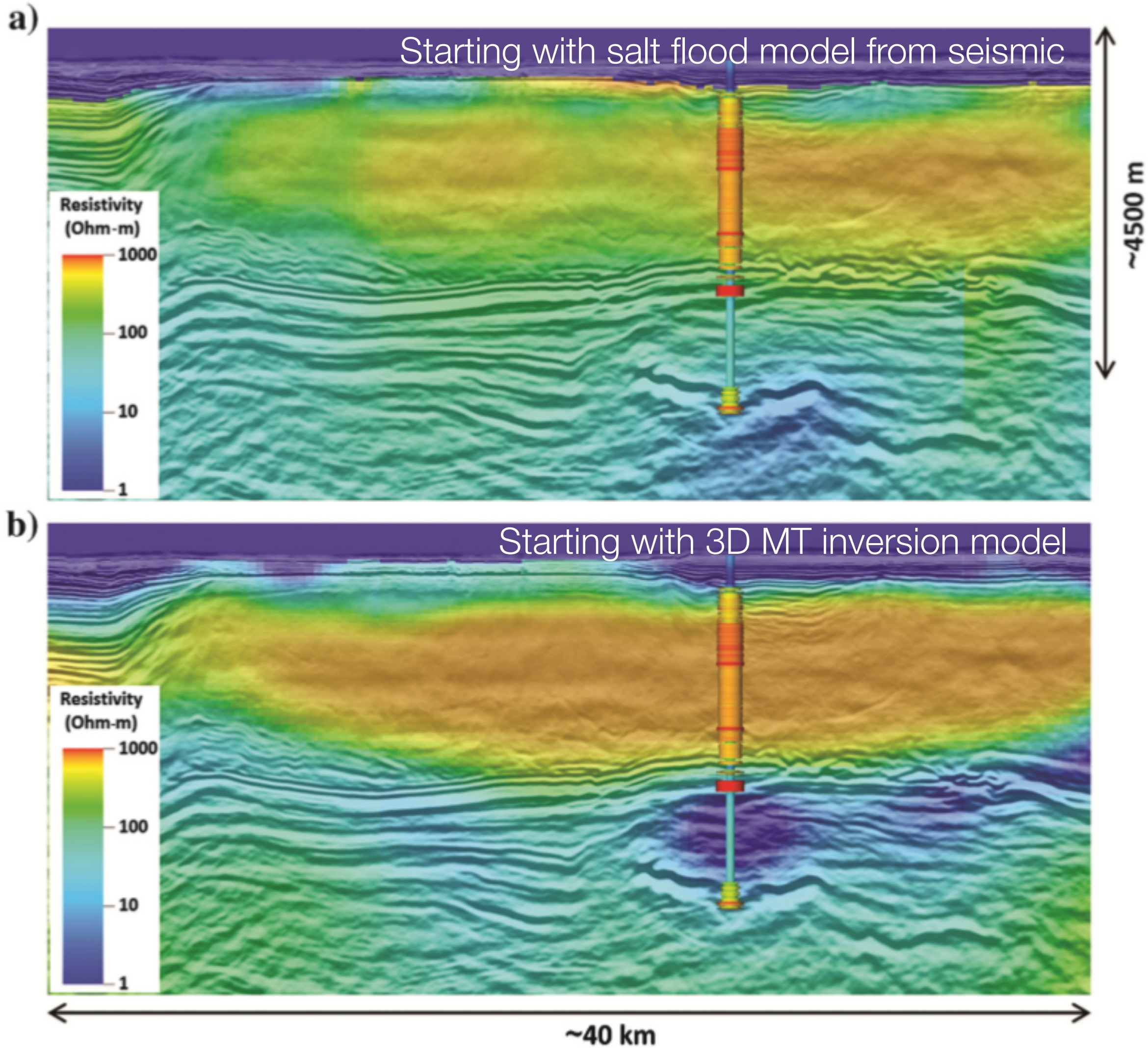
From seismic and well logs



- Correlate reasonably well to subsurface geologic structures:
  - Top of halite and the top of the LES

3D CSEM inversion

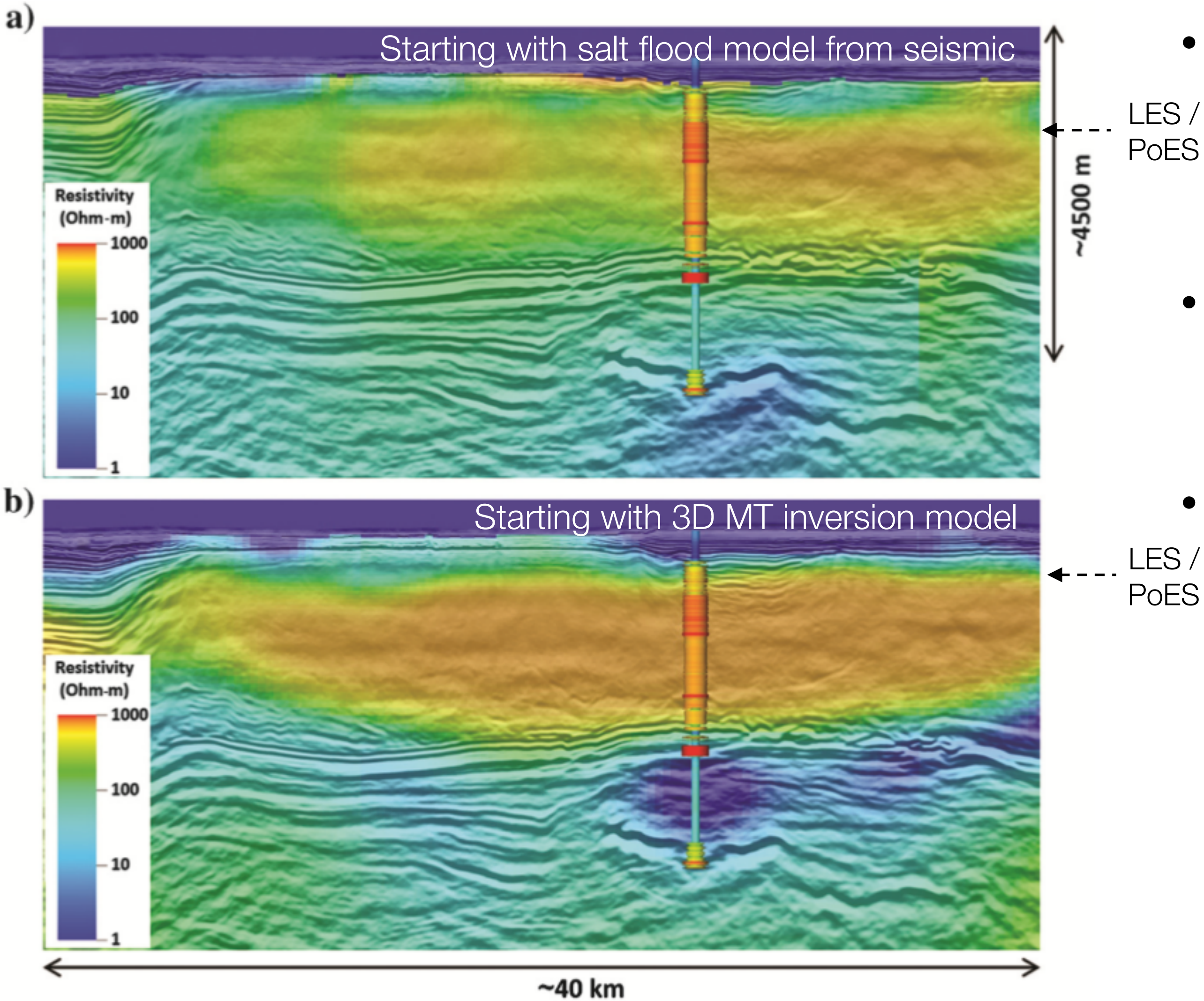
3D resistivity sections



- Assume isotropic case
- Inversion workflow:
  - First inverting 0.4 Hz (only inline)
  - Add additional frequencies, and broad-side data
- Try two different initial models:
  - Salt flood model from WAZ seismic
  - 3D MT resistivity

Interpretation

3D resistivity sections

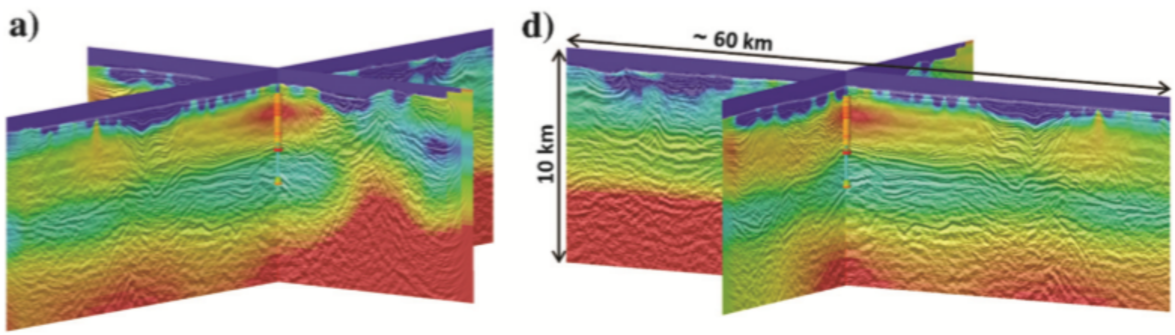


- CSEM inversion is able to resolve the base of the LES
- Not sensitive to the basement
- Did not converge
  - May be anisotropy needs to be considered

Processing and Interpretation: Model-driven

3D MT inversions

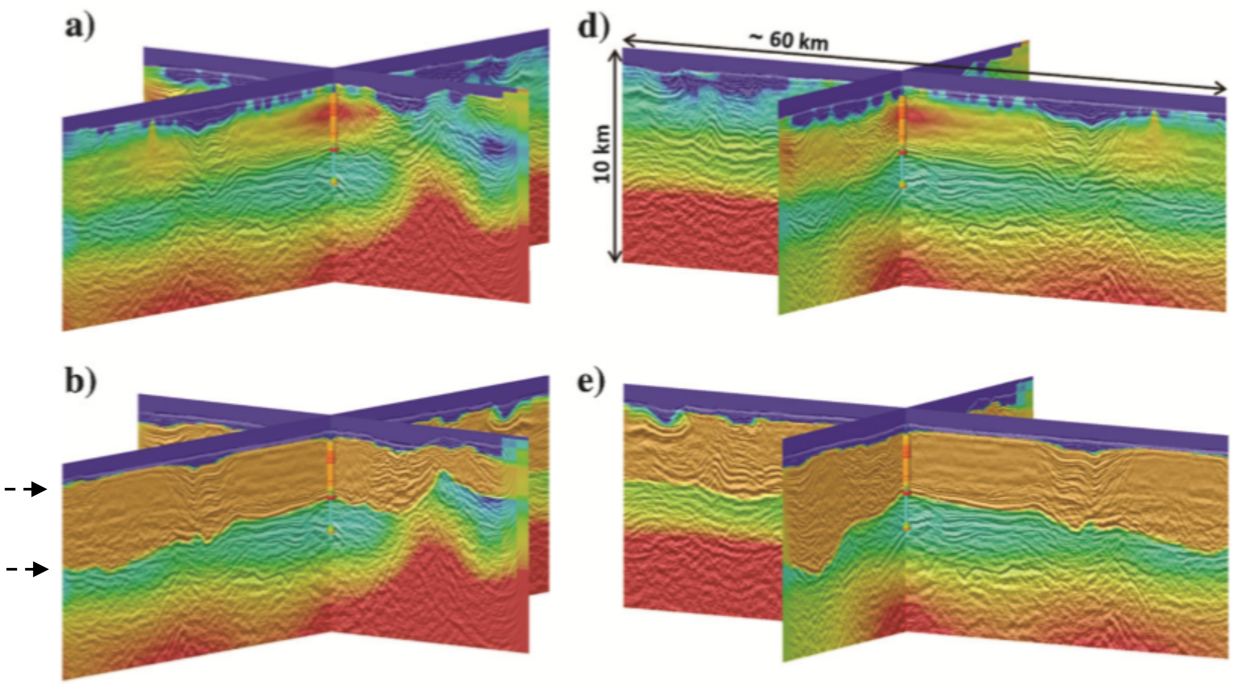
3D resistivity sections



- Data-driven:
  - Excellent match with well data for the base of the salt layer
  - Basement structures
  - Poor shallow resistivity

3D MT inversions

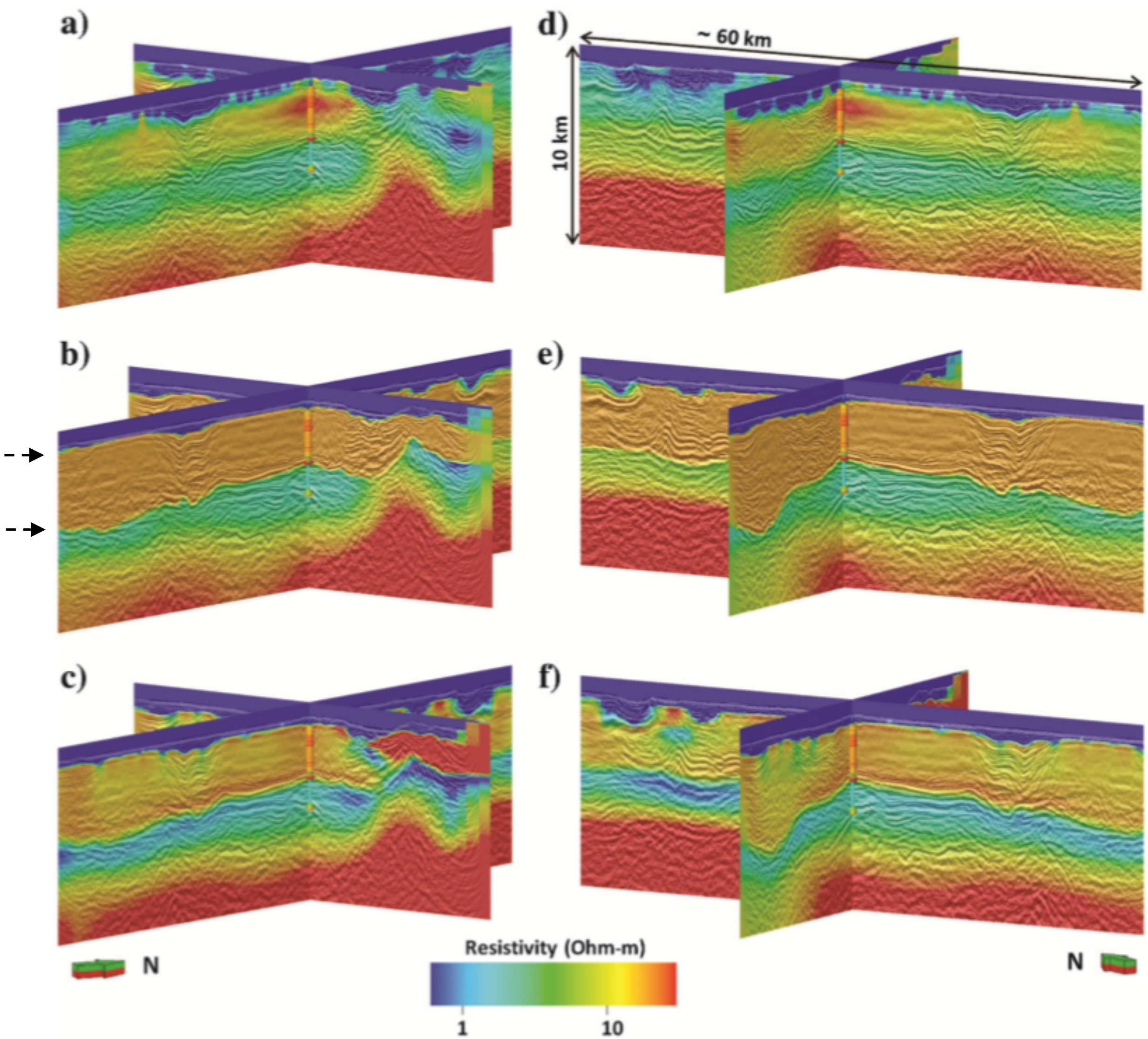
3D resistivity sections



- Data-driven:
  - Excellent match with well data for the base of the salt layer
  - Basement structures
  - Poor shallow resistivity
- Model-driven #1:
  - A priori knowledge of the top and bottom of the LES
  - Fixed resistivity of PoEs and LES

3D MT inversions

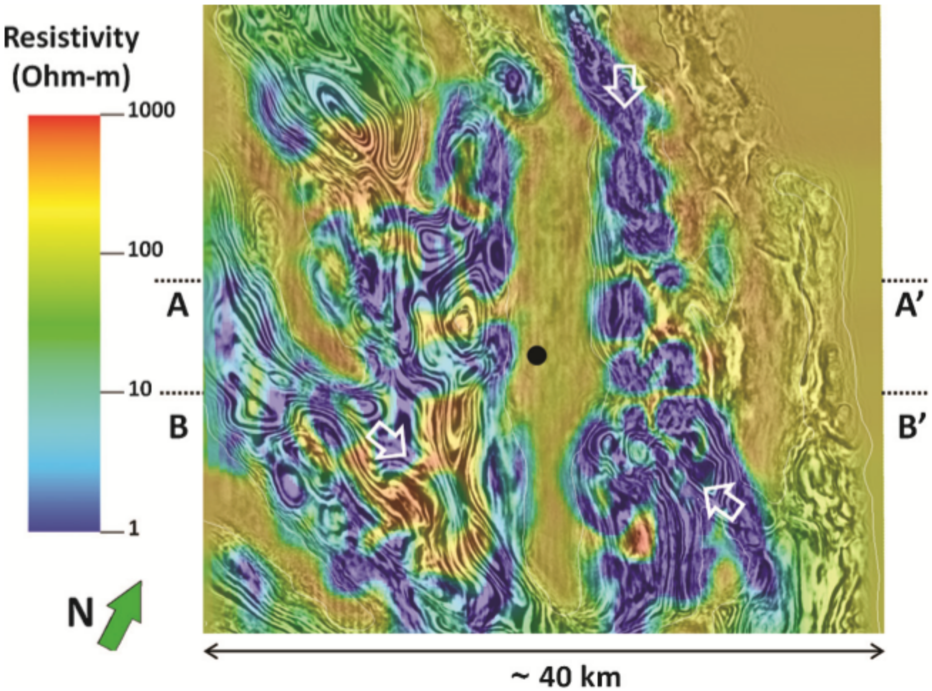
3D resistivity sections



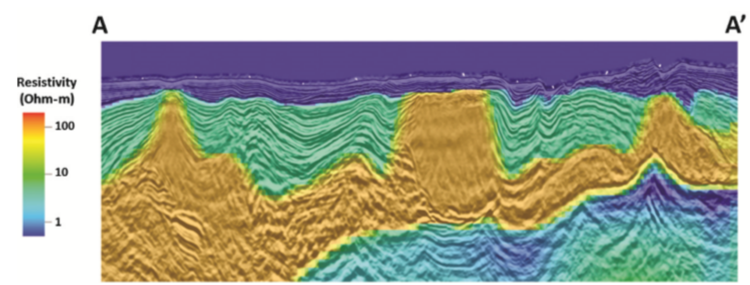
- Data-driven:
  - Excellent match with well data for the base of the salt layer
  - Basement structures
  - Poor shallow resistivity
- Model-driven #1:
  - A priori knowledge of the top and bottom of the LES
  - Fixed resistivity of PoEs and LES
- Model-driven #2:
  - Use above as a starting and reference models

3D CSEM inversion

Resistivity (Rh) slice at -1800 m



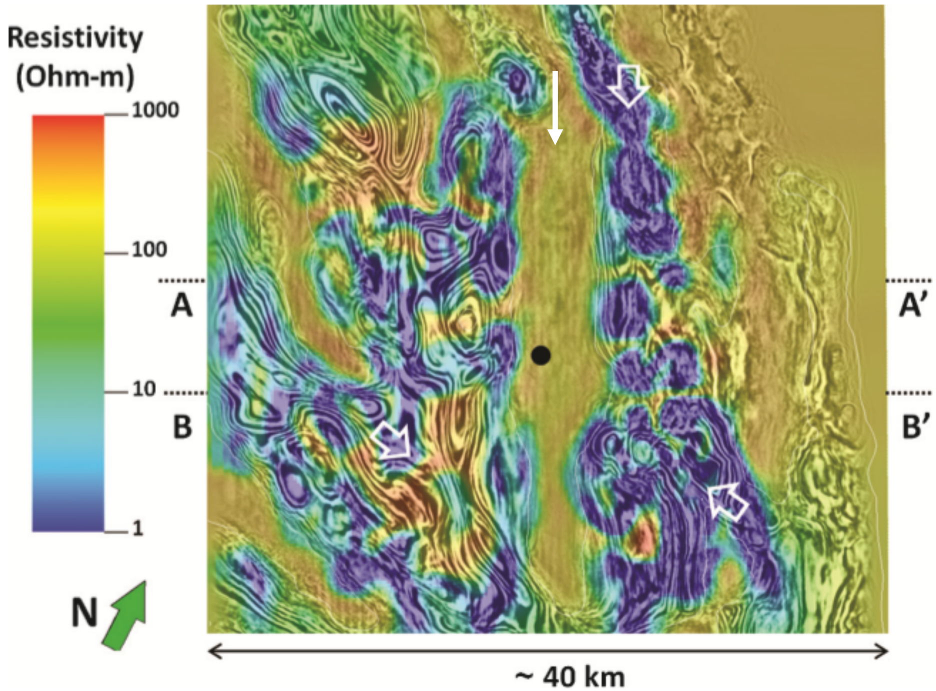
- Initial model:
  - Final resistivity model from MT inversion
  - Additional surfaces: a) top LES and b) top halite layer picked by seismic interpreters



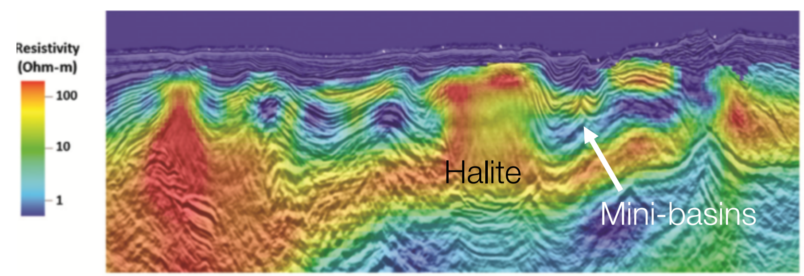
- Consider anisotropic resistivity:
  - Vertical and horizontal

Interpretation

Resistivity (Rh) slice at -1800 m

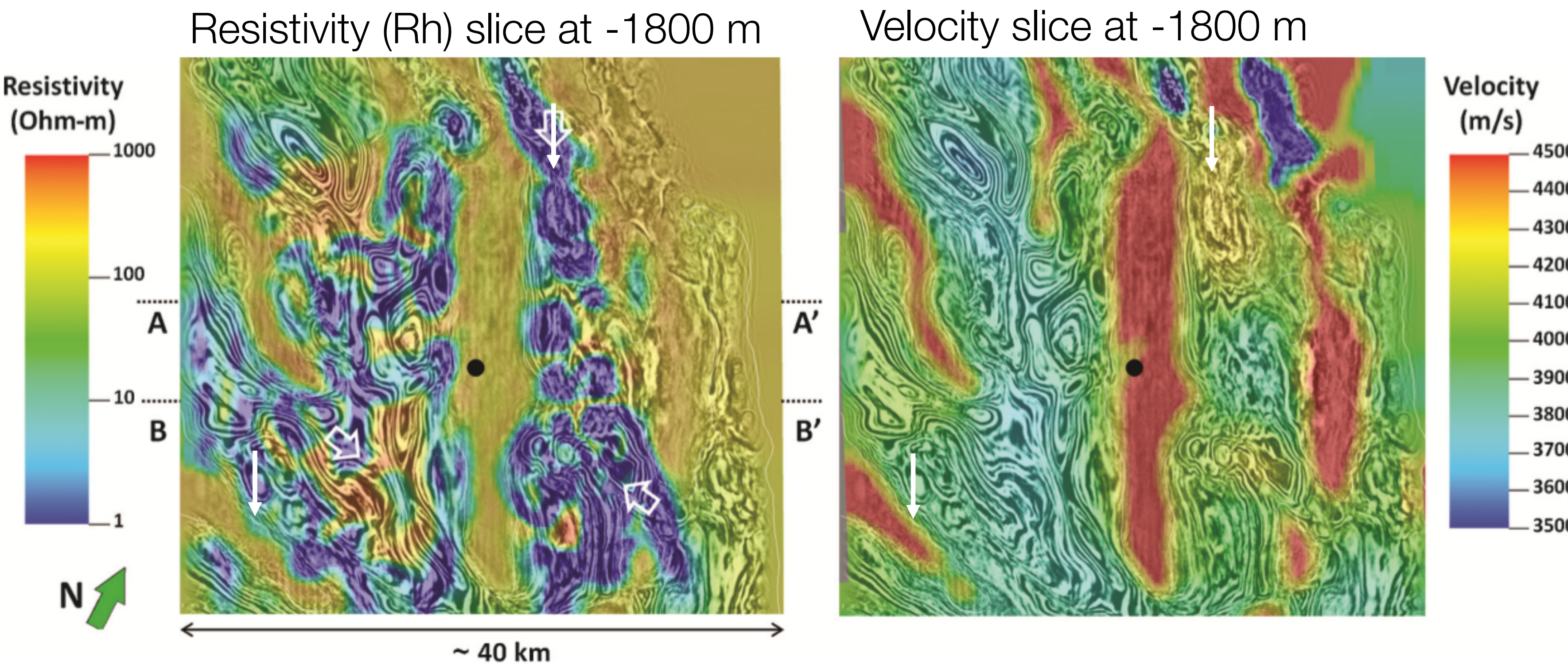


Vertical section at A-A'



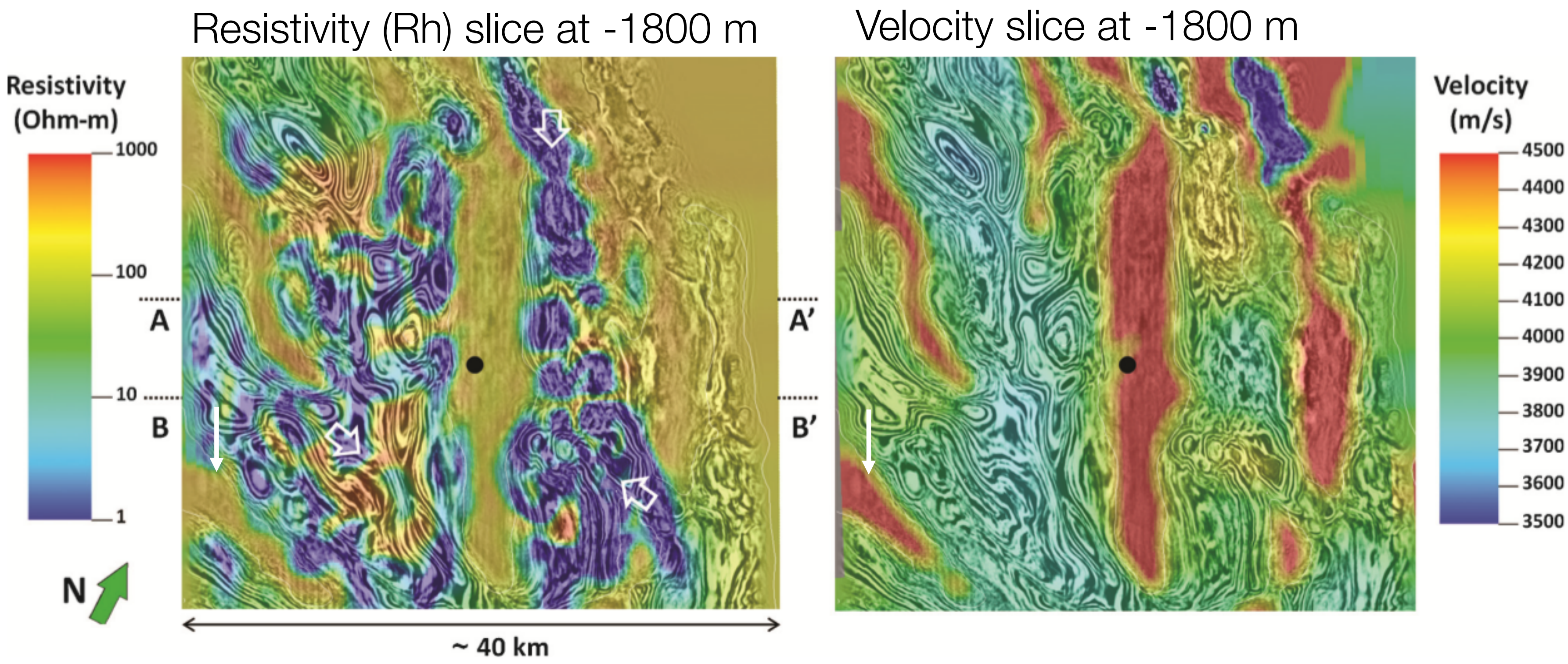
- Images main structures (halite bodies and mini-basins) well:
  - uncertainty in velocity model building arises from here

Interpretation



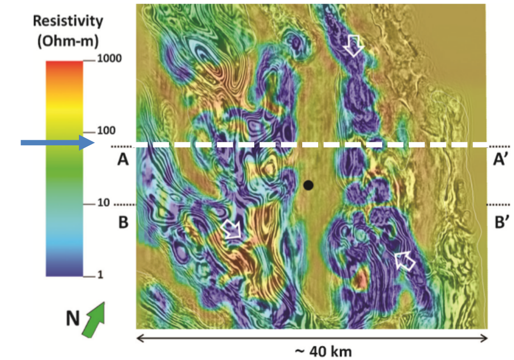
- Images main structures (halite bodies and mini-basins) well:
  - uncertainty in velocity model building arises from here
- North-eastern block: high velocity and low resistivity (Rh)
  - Initial seismic interpretation may overestimate the velocity in the mini-basins

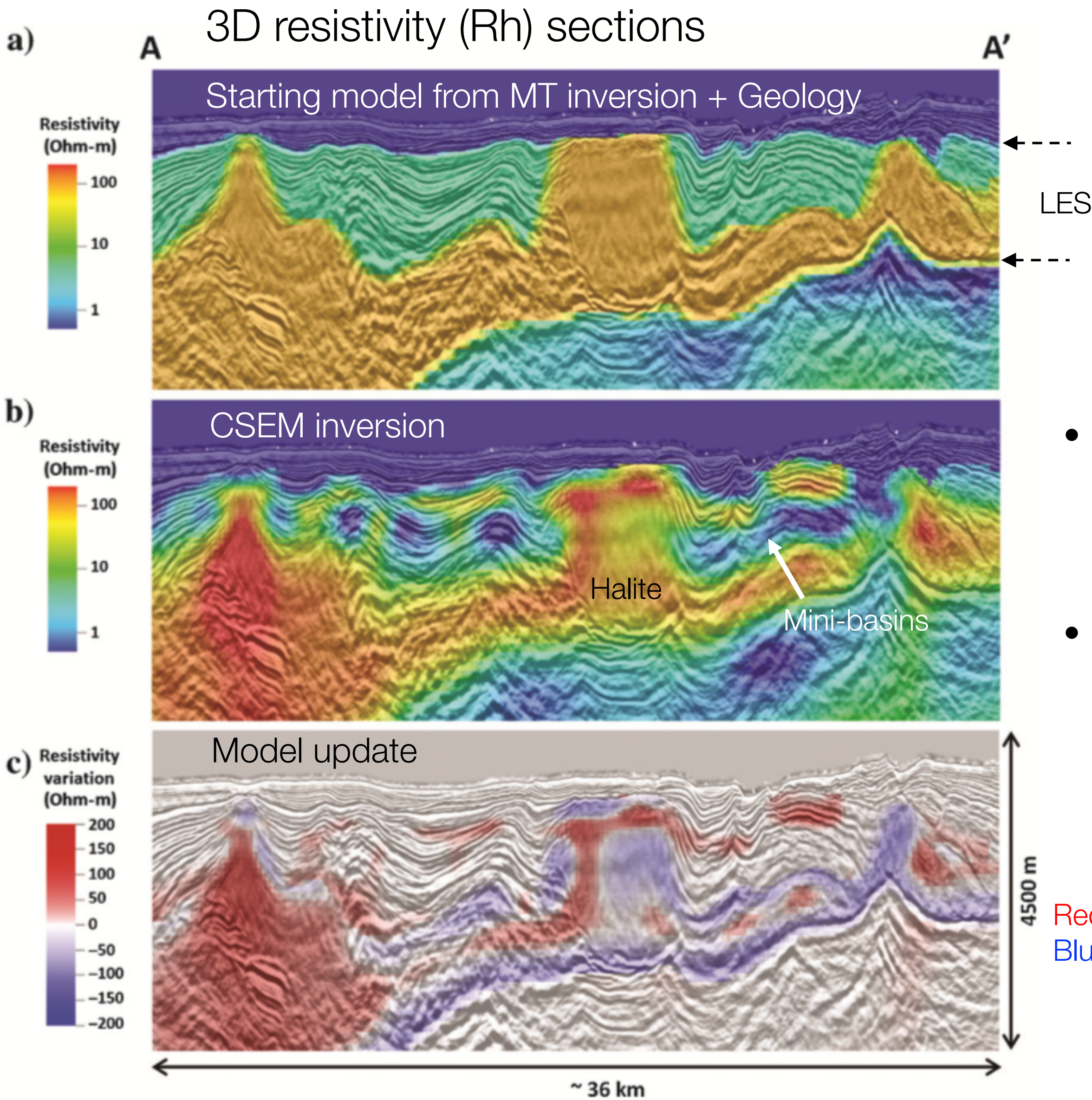
Interpretation



- Images main structures (halite bodies and mini-basins) well:
  - uncertainty in velocity model building arises from here
- North-eastern block: high velocity and low resistivity (Rh)
  - Initial seismic interpretation may overestimate the velocity in the mini-basins
- South-western corner: high velocity and high resistivity (Rh)
  - high velocities due to evaporite concentrations

Interpretation

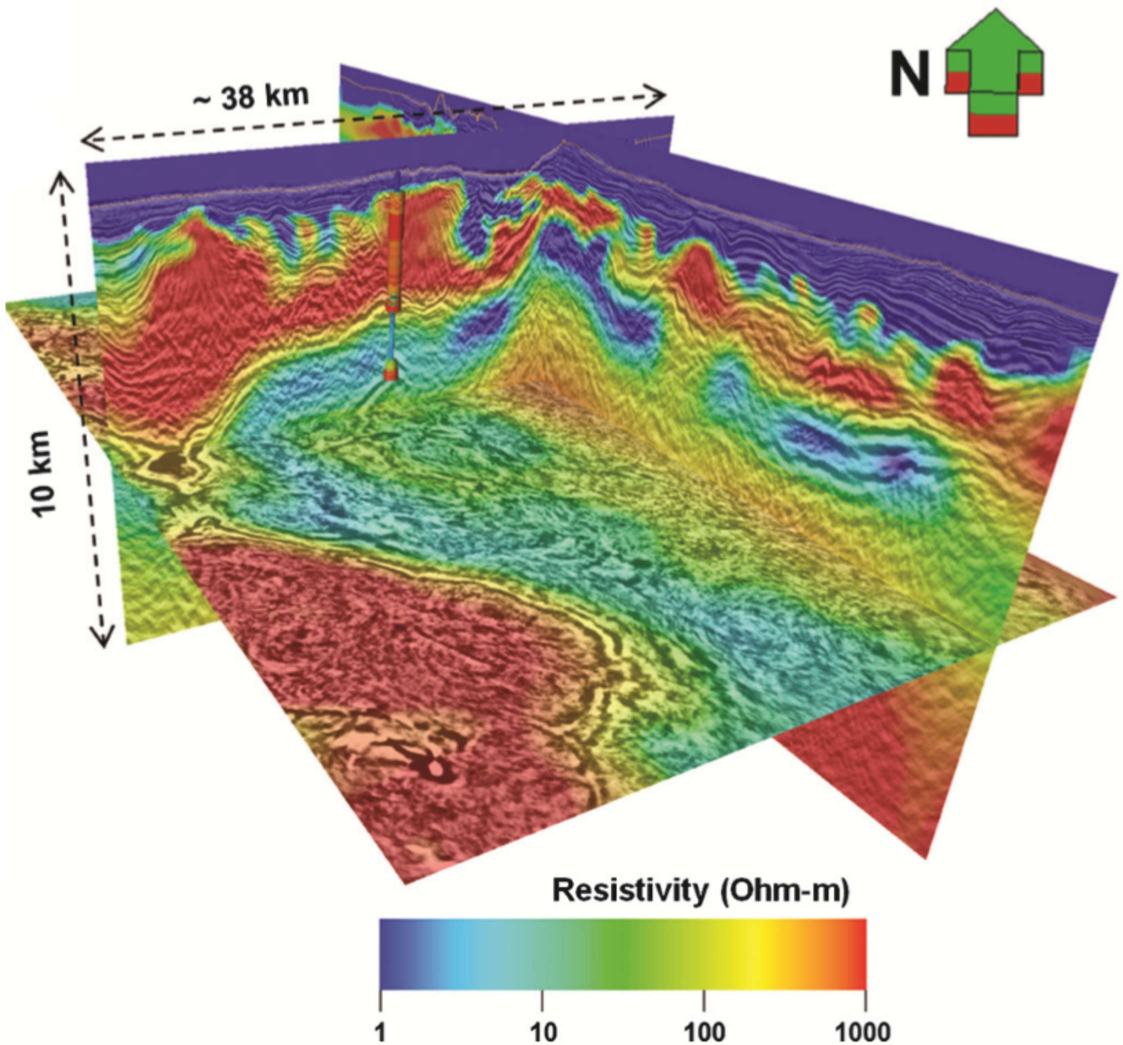




- Refine the structure of the main halite bodies
- Consistent with RTM image
  - with the reflections off the flanks of the structures

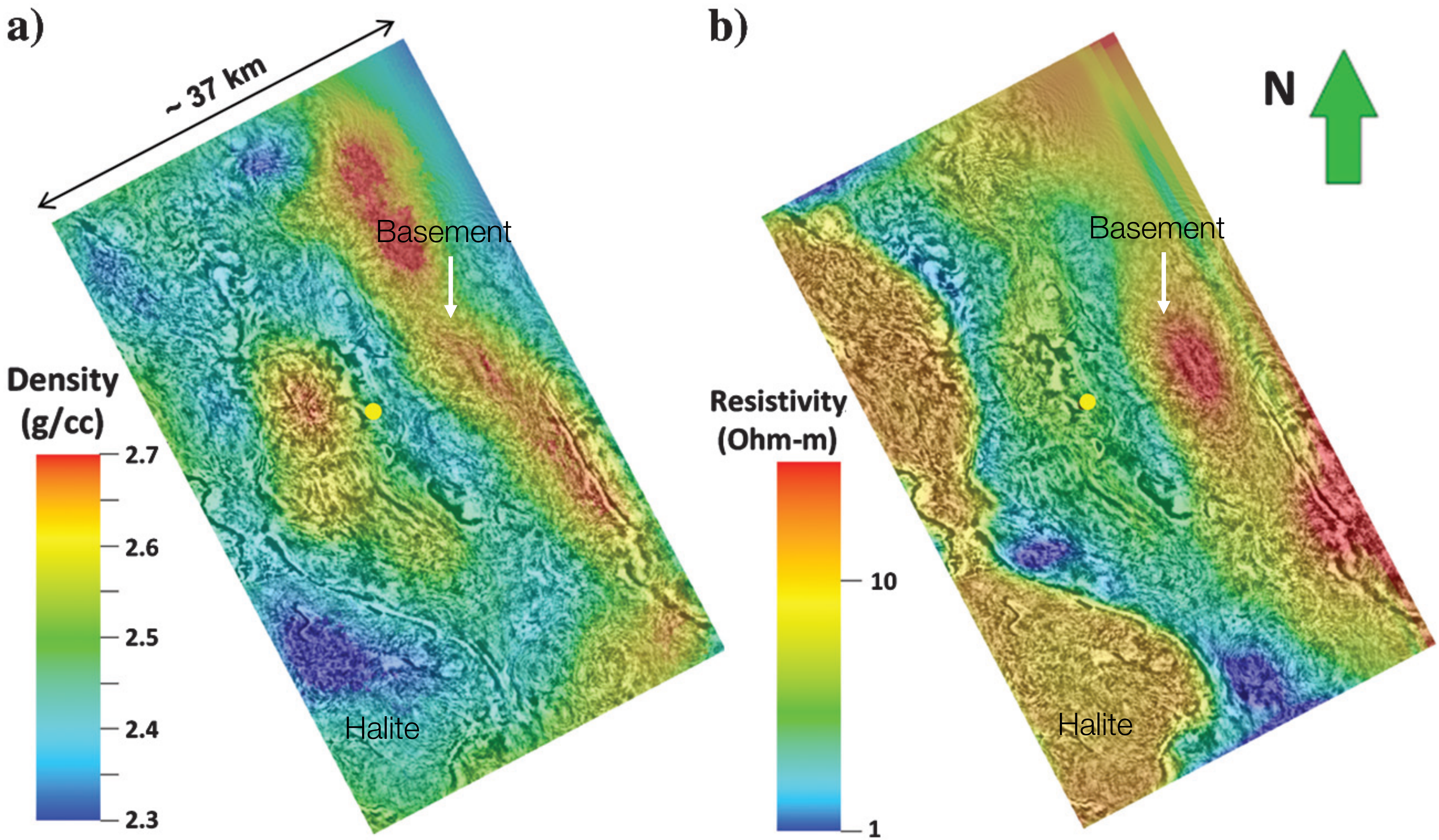
Red: halite concentrations (more resistive)
Blue: larger clastic content (more conductive)

Synthesis: MT and CSEM

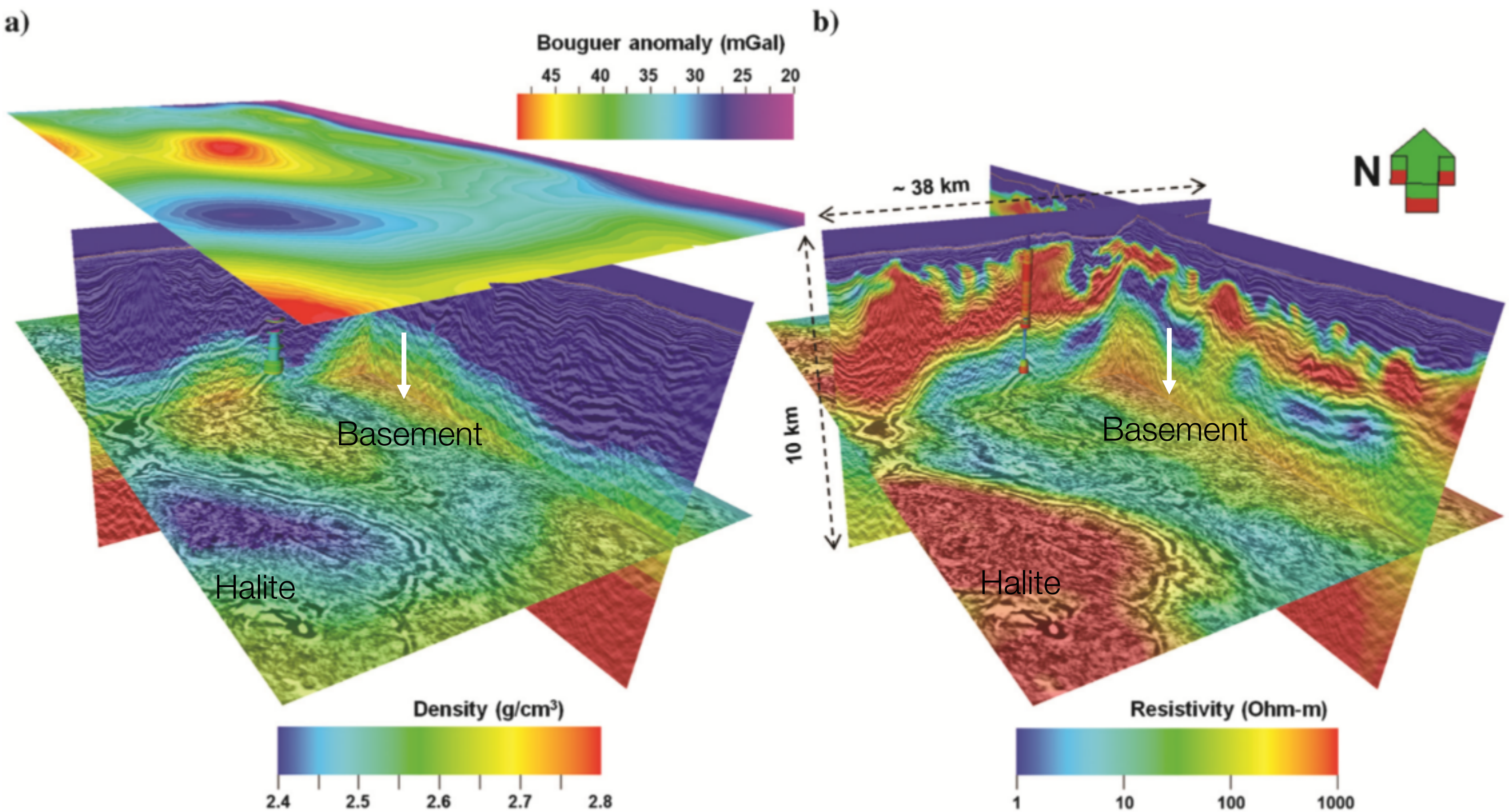


- Data-driven inversions of MT and CSEM derive the main geologic features
  - the base of the salt,
  - the thickness of the conductive subsalt sediments
  - the main basement structures
- With a priori information from seismic interpretation:
  - Boost the resolution of the MT and CSEM inversions

Synthesis: MT and Gravity gradiometry



Synthesis: MT and Gravity gradiometry



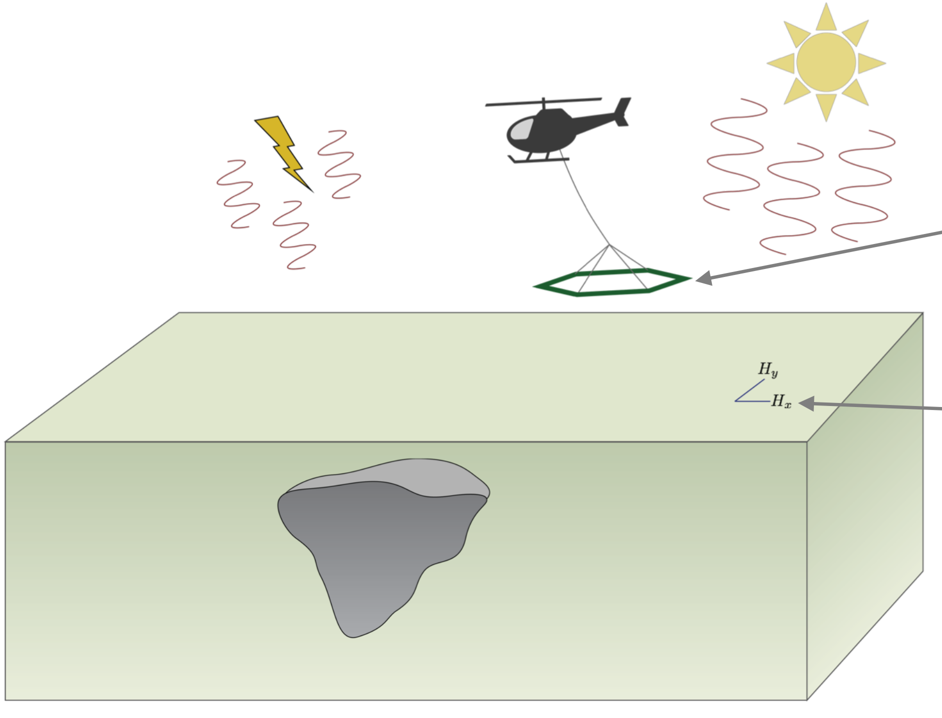
Tipper data (ZTEM)

- Magnetic transfer function

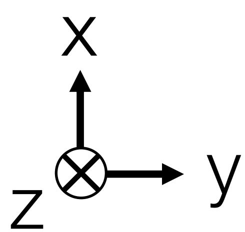
$$H_z = \mathbf{TH}$$

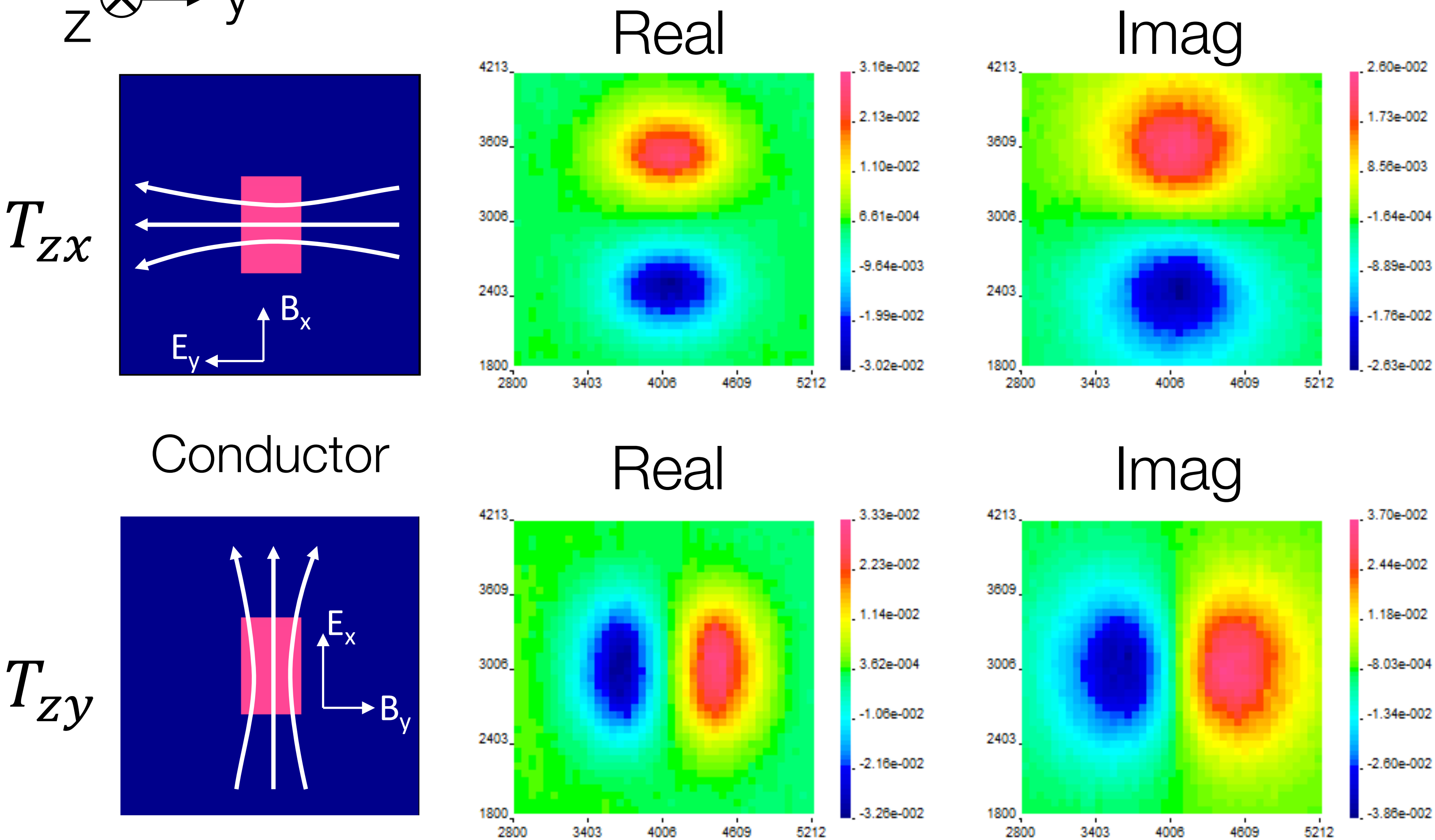
$$H_z(r) = T_{zx}H_x(r_0) + T_{zy}H_y(r_0)$$

- Frequencies 30Hz – 720 Hz



Synthetic example





ZTEM case histories

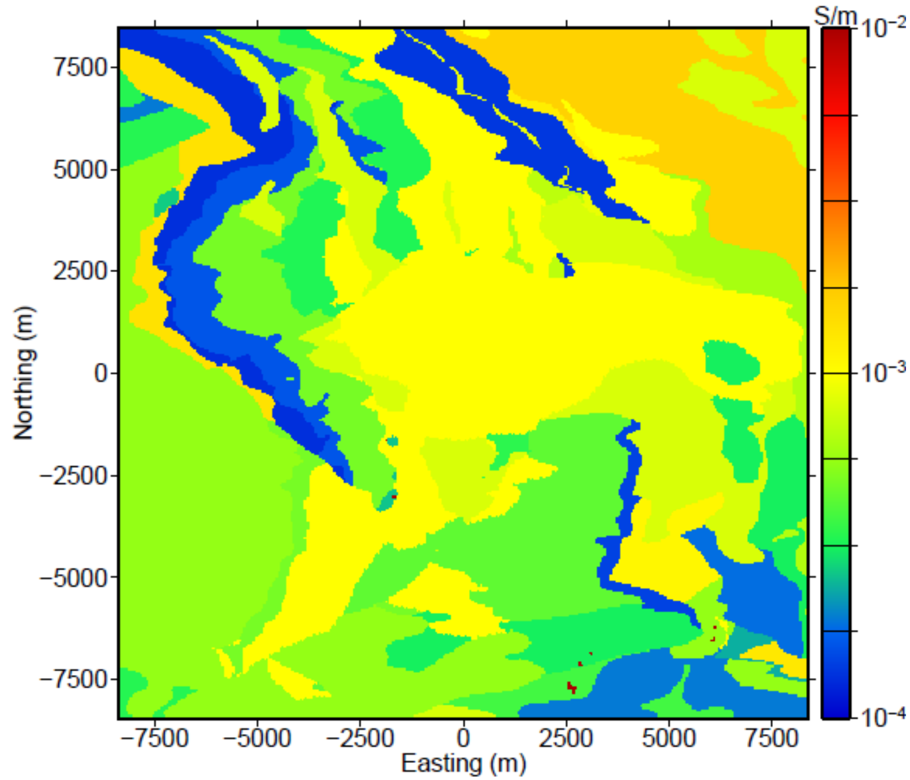
- Synthetic based on Noranda district

- 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

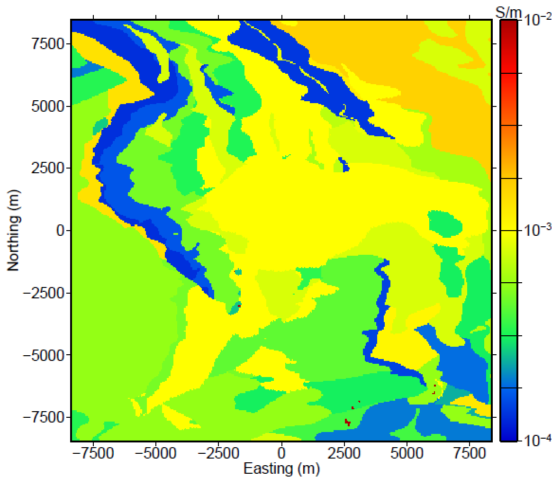
True model at 275m depth



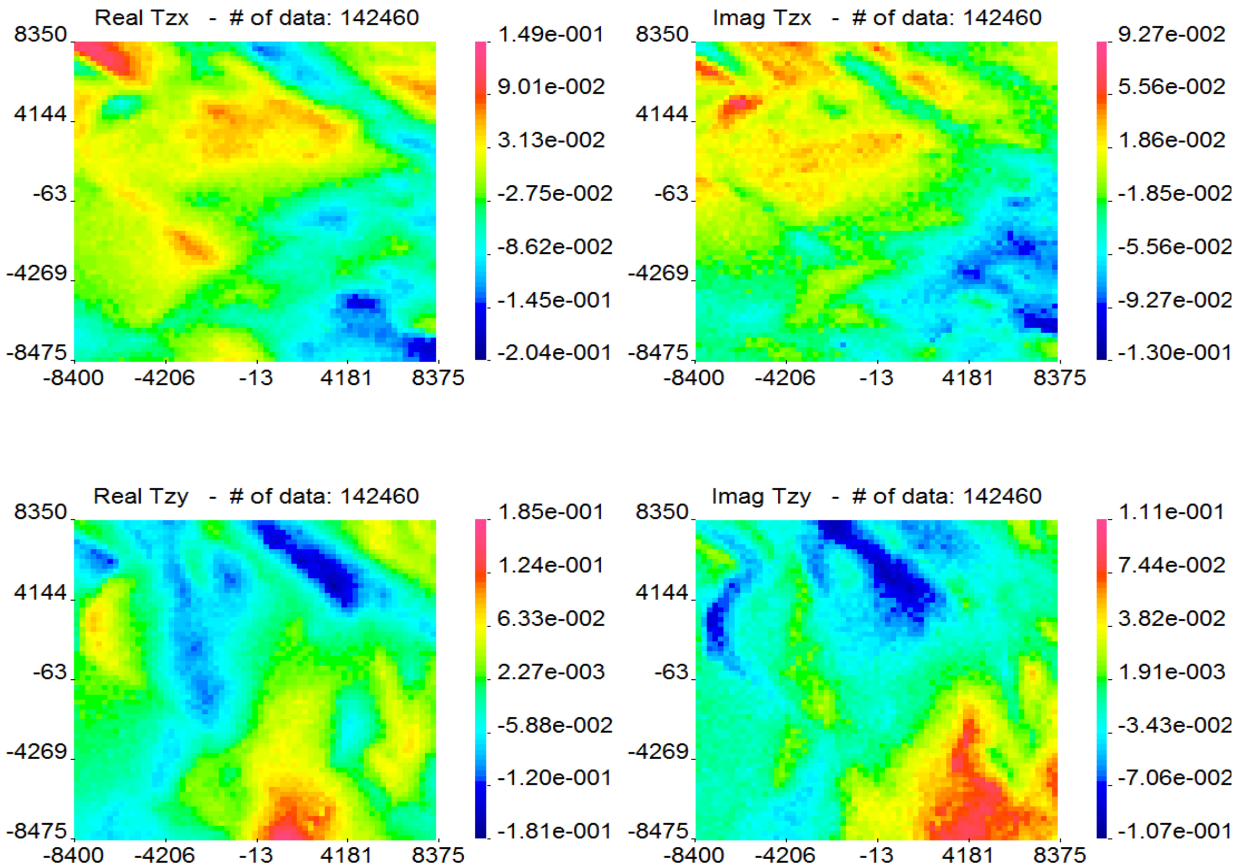
Data

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

True model at 275m depth

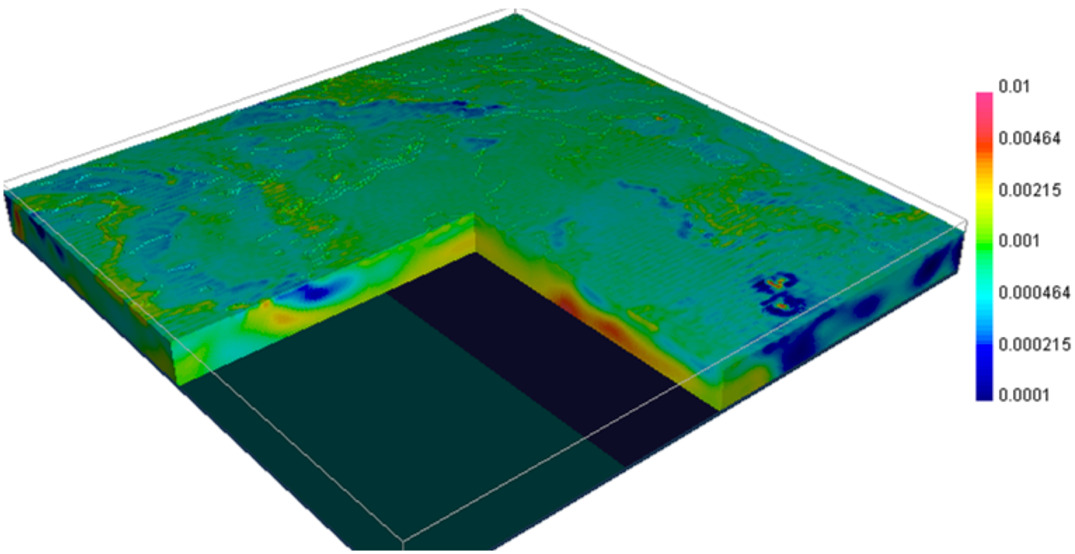


Observed (90 Hz)

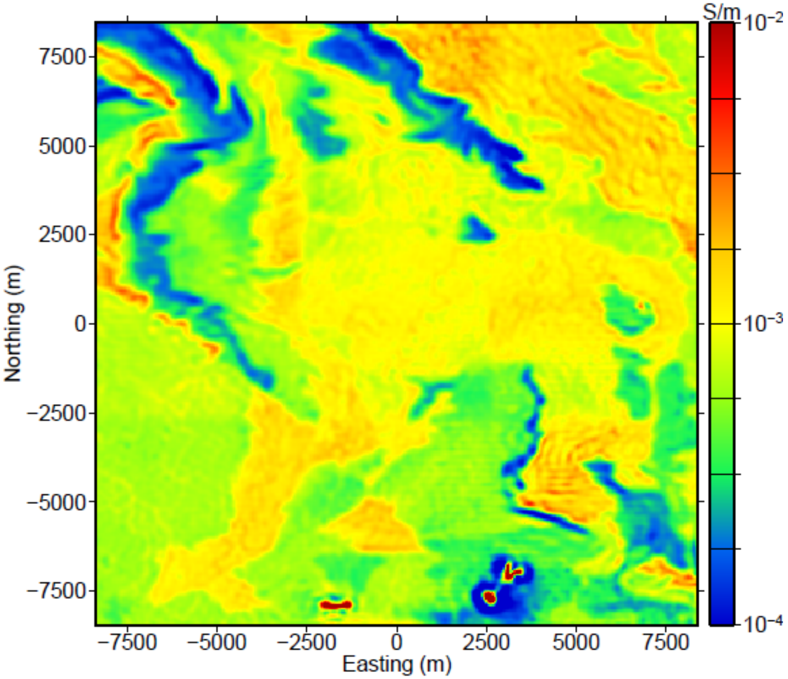


Interpretation

Recovered Model



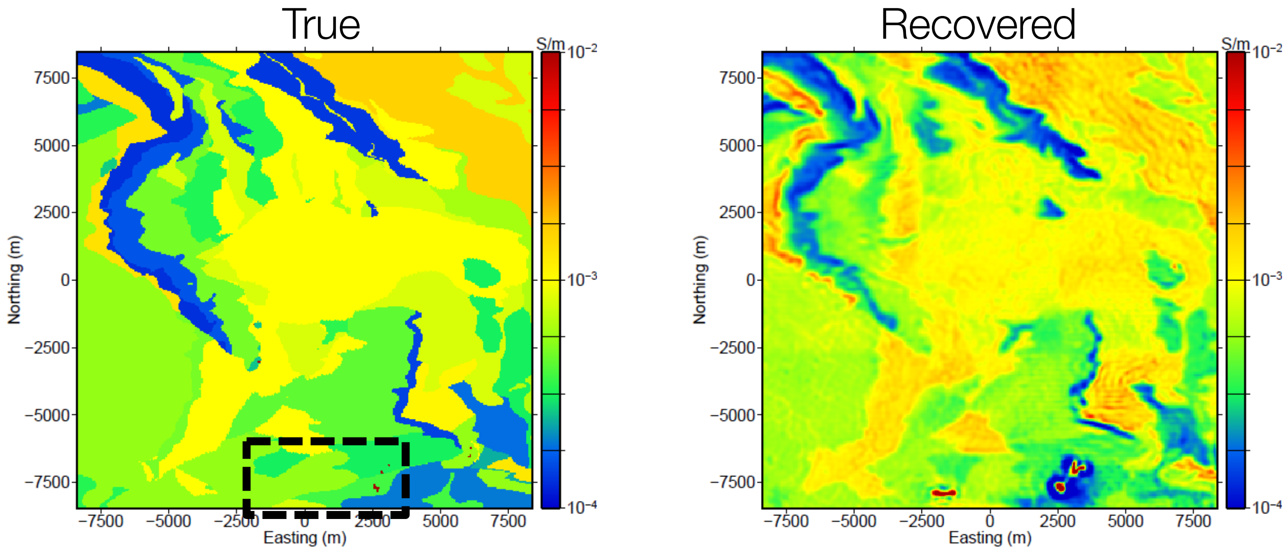
Model at 275m depth



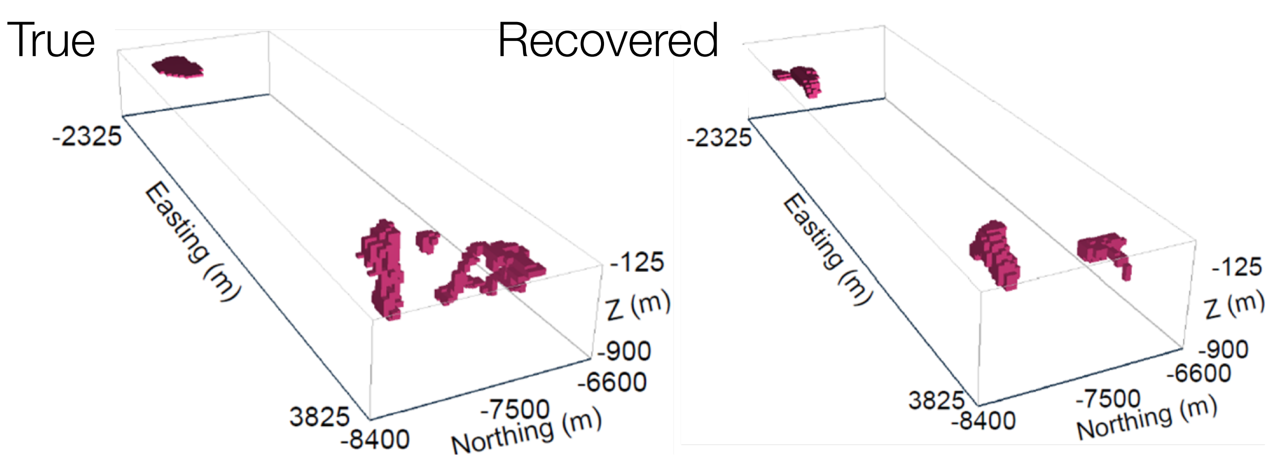
- Geologic units are well mapped
- Some mineralized bodies are located

Synthesis

- Recovered model represents the regional geology



- Mineralized zones are recovered



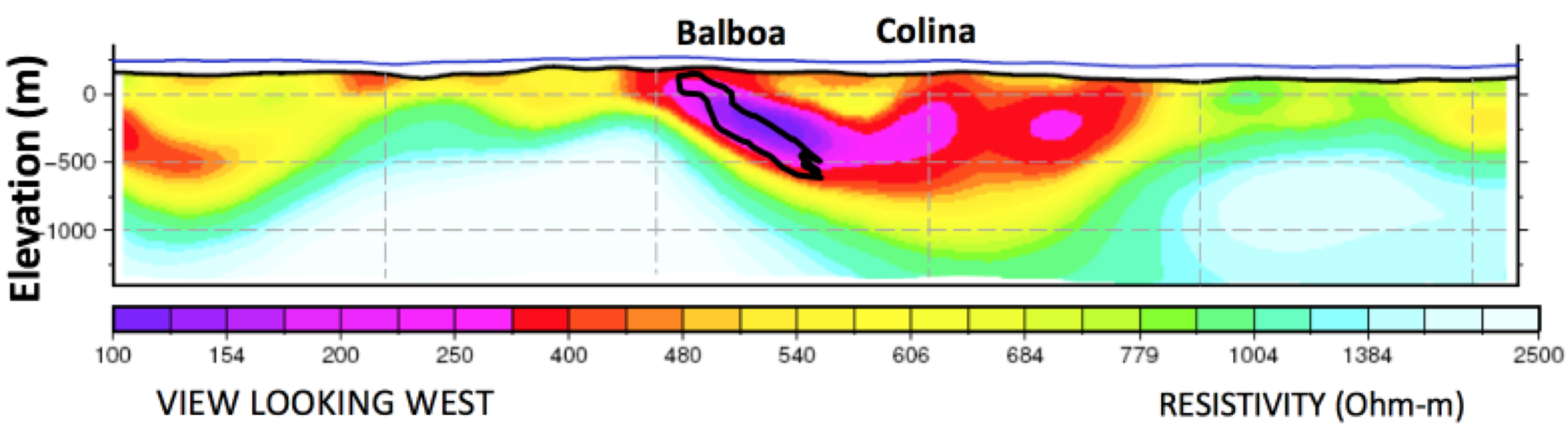
ZTEM case histories

- Synthetic based on Noranda district

- Balboa copper porphyry deposit

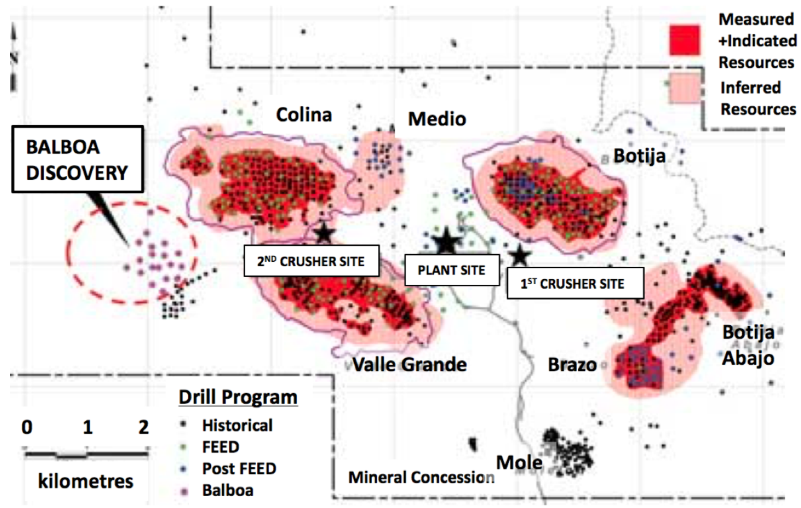
Case History:
The Balboa ZTEM Cu-Mo-Au porphyry discovery at Cobre Panama

Legault et al., 2016



Setup

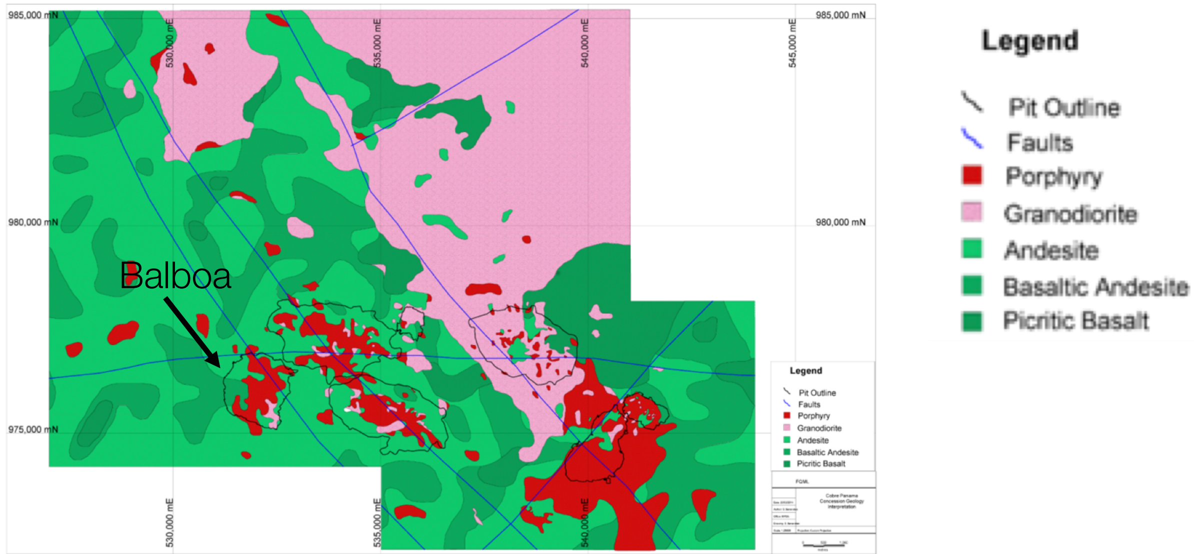
Resource map



- 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

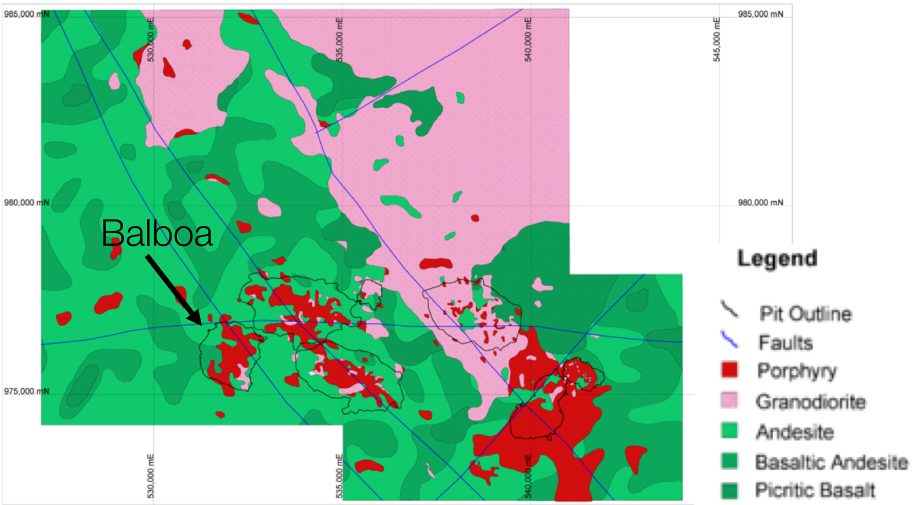


- Overburden: 20-30m of clay-rich saprolite
- Mineralization:
  - Mostly chlorite and chlorite-sericite alteration
  - Abundant disseminated chalcopyrite, pyrite and magnetite
- Previous helicopter TEM survey unsuccessful in detecting mineralized zones

Can ZTEM see mineralized zones below the conductive saprolite layer?

Properties

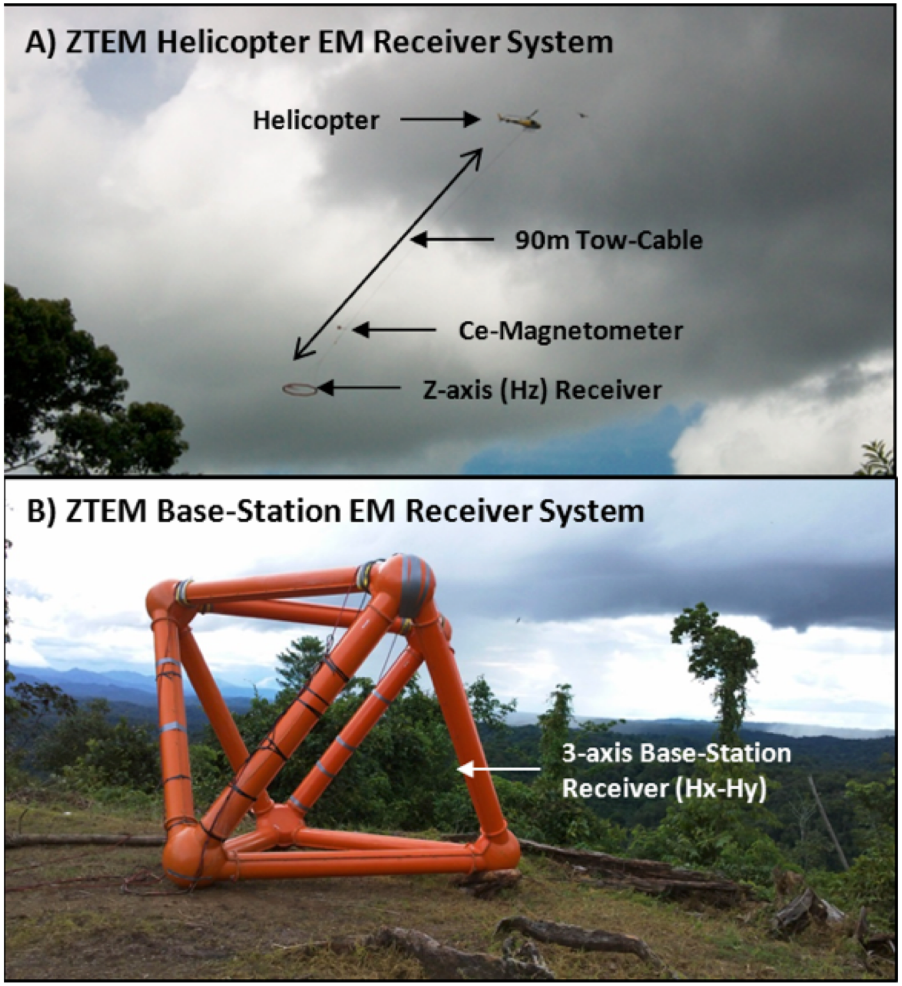
Geologic map

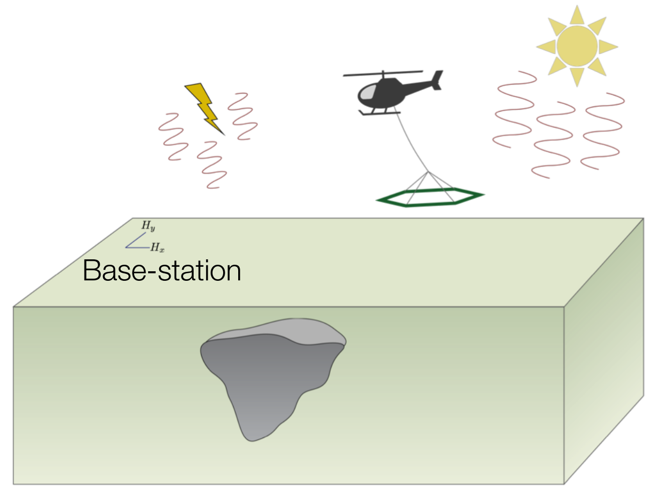


- Mineralized zone
  - High conductivity
  - Low magnetic susceptibility
- Highly conductive saprolite at surface (up to 30m thick)

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



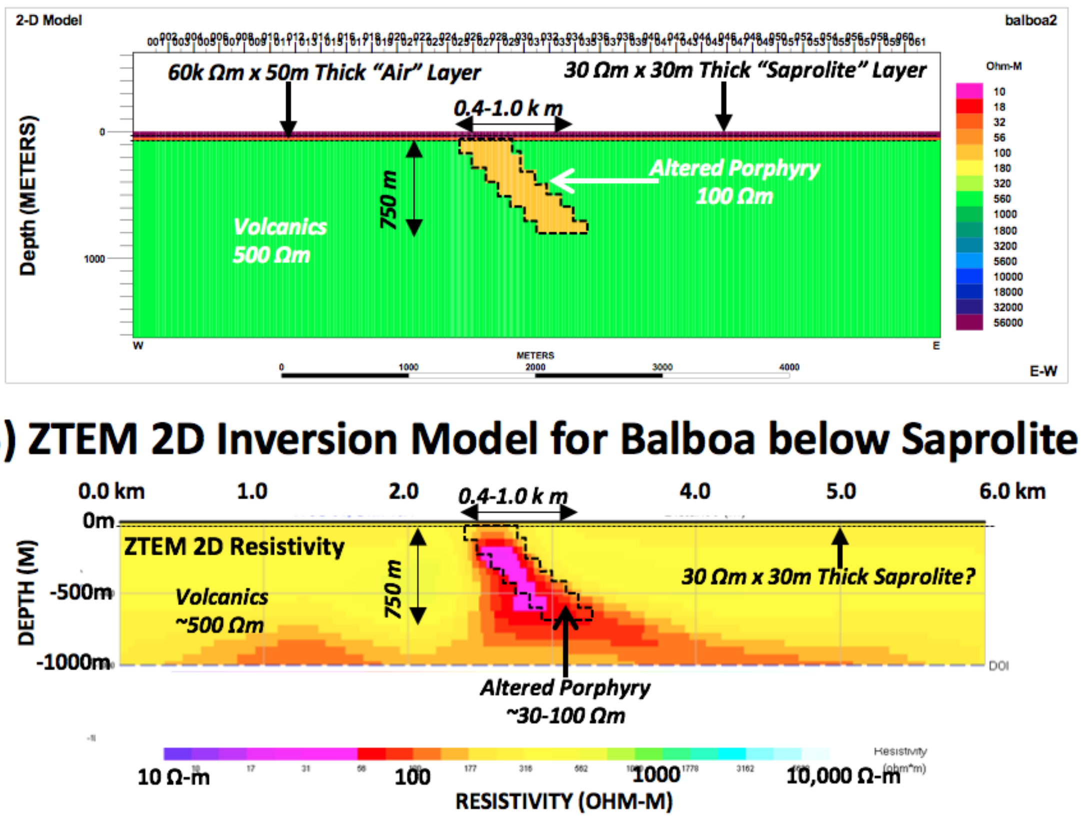


- System
  - 6 frequencies: 30-720 Hz
  - Hz: airborne receiver
  - Hx and Hy at base-station

Survey design

A) 2D Synthetic Model for Balboa Porphyry below Saprolite

B) ZTEM 2D Inversion Model for Balboa below Saprolite



- Typical AEM survey can't see through conductive saprolite

- ZTEM insensitive to 1D conductivity

ZTEM can see through conductive overburden.

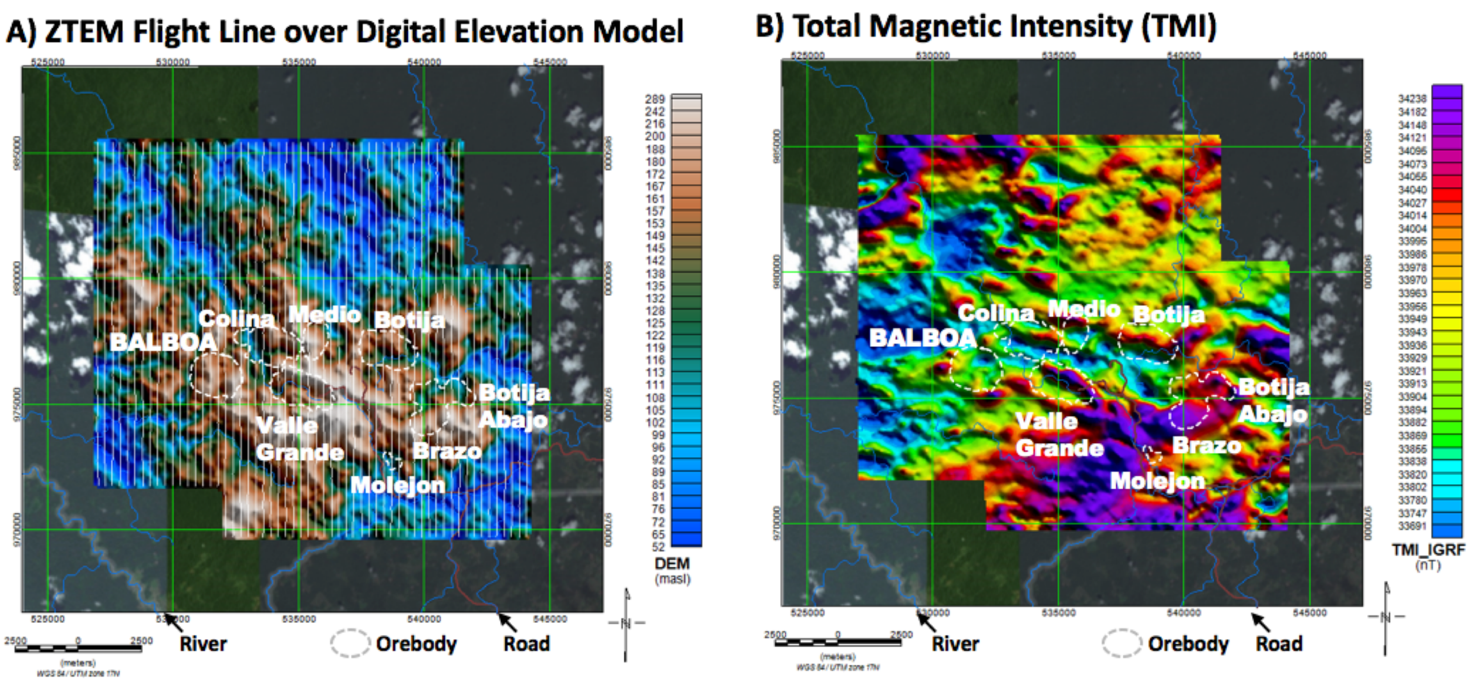
Data

- Tipper transfer function:

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

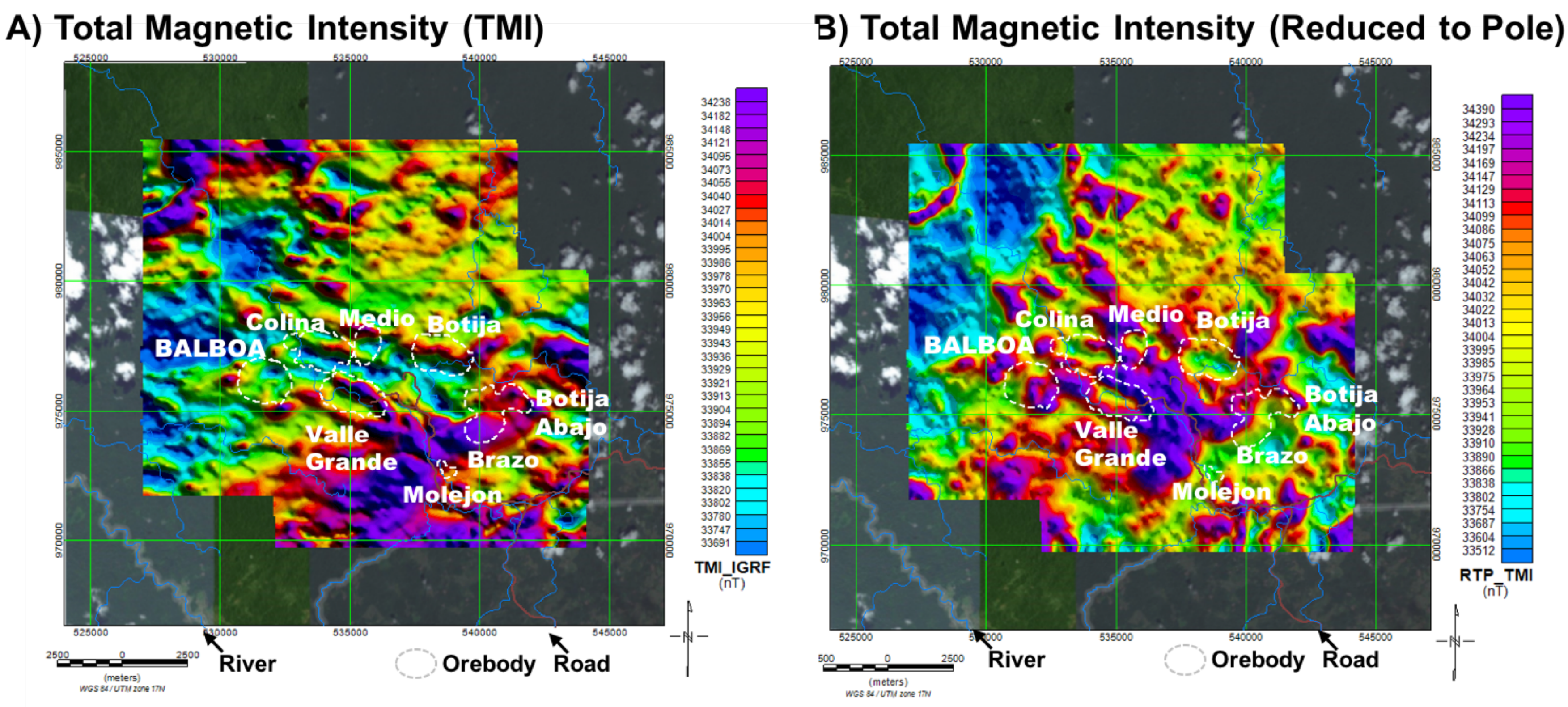
  – Tzx and Tzy obtained using similar processing as MT
  – Hx and Hy obtained from reference site (r_0)

- 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)

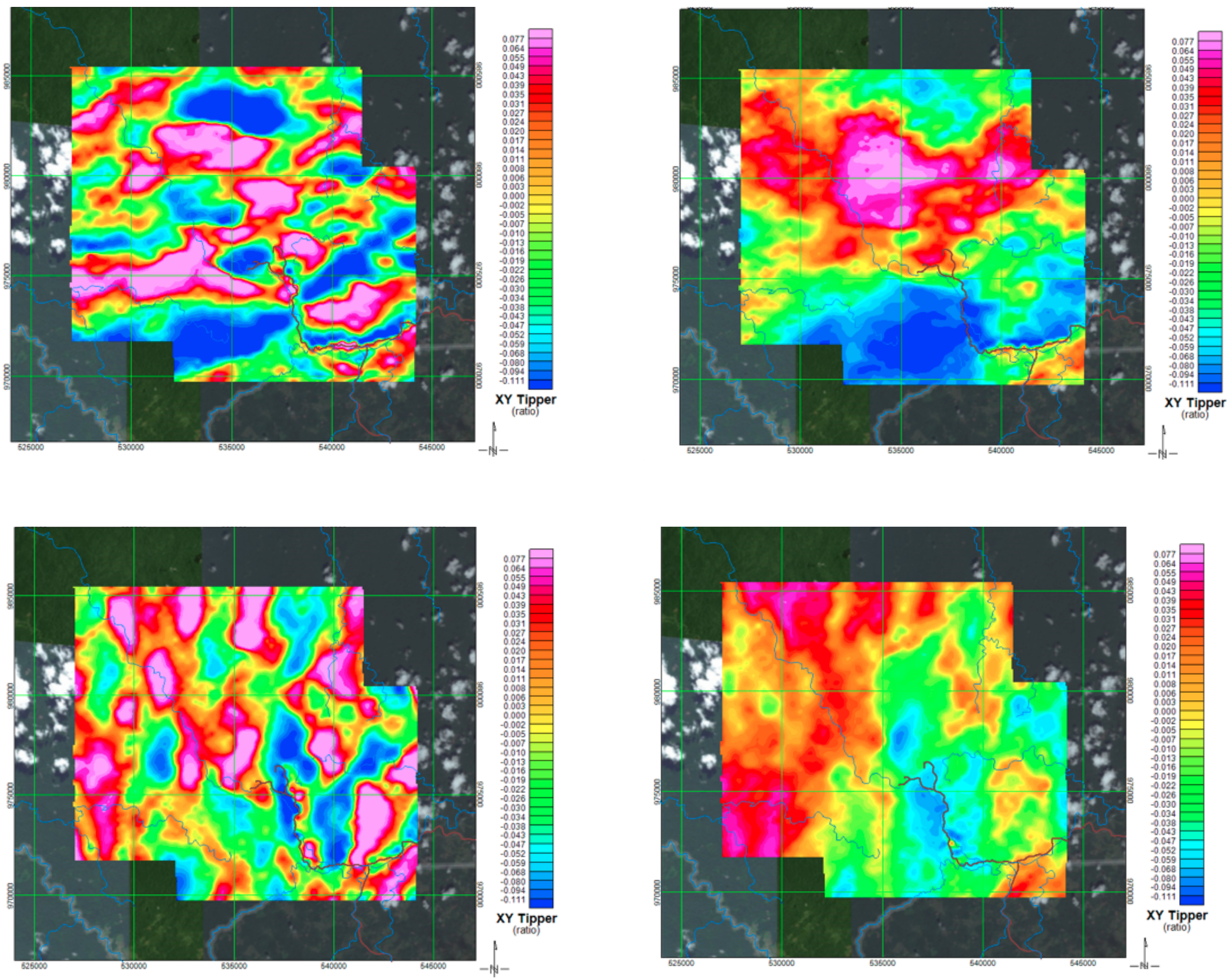
ZTEM data at 90 Hz

Real

Imag

Tzx

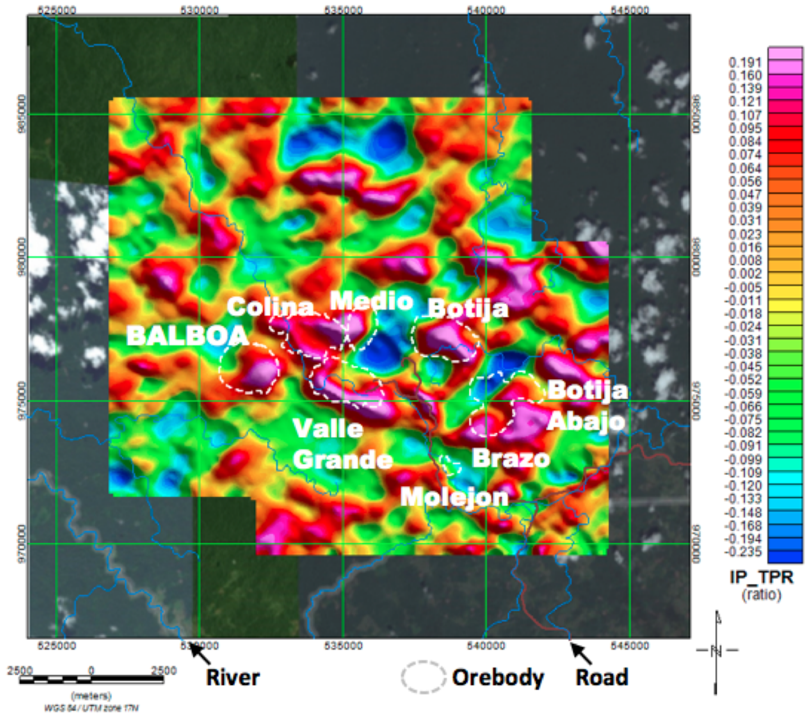
Tzy



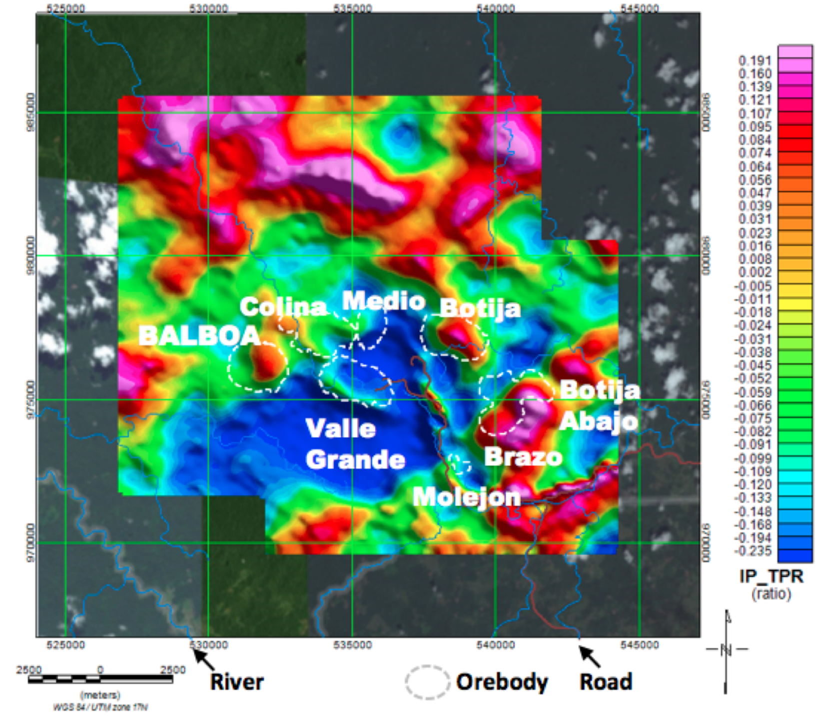
Processing: ZTEM data

- Total phase rotation (TPR)

TPR real at 360 Hz



TPR imaginary at 30 Hz

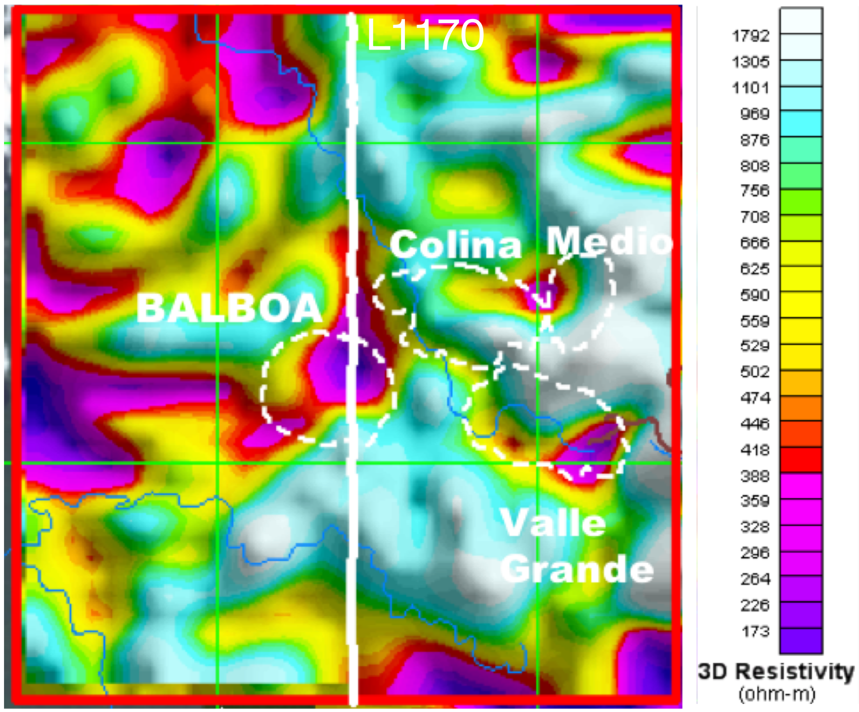


  – At 360Hz, high values collocated with known deposits; some false positives
  – At 30 Hz, regional resistive structure; deeper conductive structures collocated with some known deposits

Inversion and Interpretation

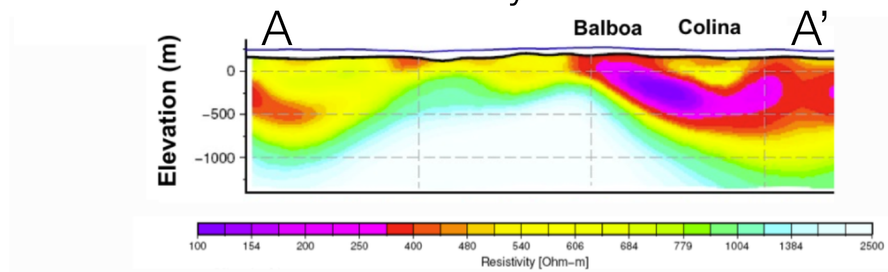
3D conductivity at 500 m depth

A

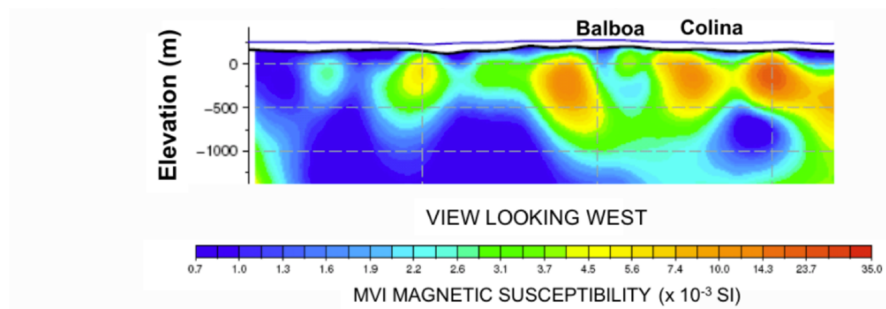


A'

Vertical conductivity section at L1170

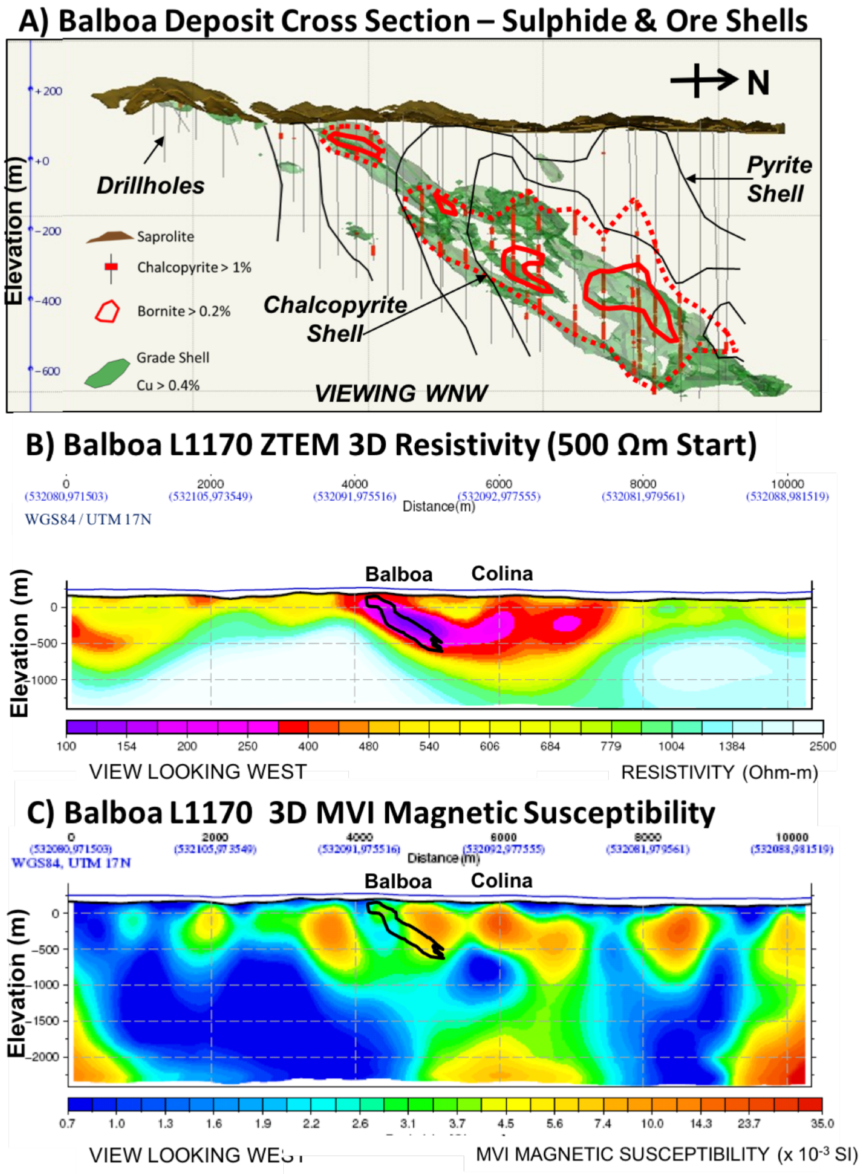


Vertical susceptibility section at L1170



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

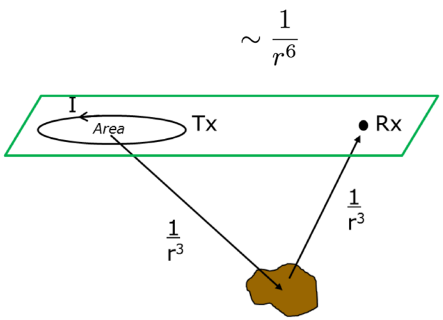
Synthesis

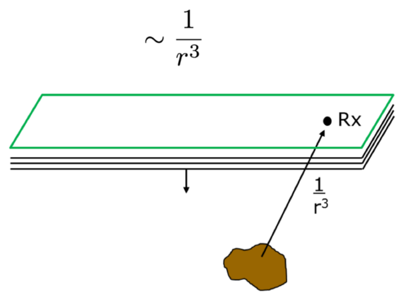


- Exploration and drilling motivated by soil sampling failed to identify Balboa
- Helicopter TDEM could not see through conductive saprolite
- Conductive anomaly collocated with Balboa deposit agrees with boundary of higher-grade zones from drilling

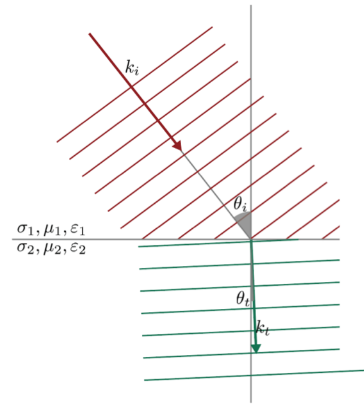
Summary

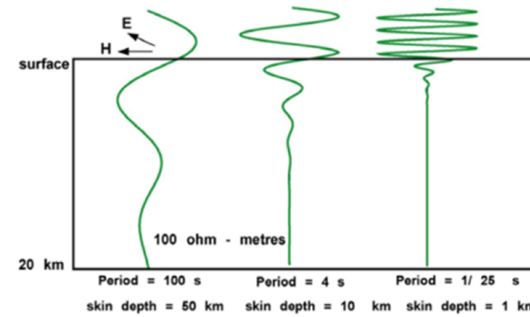
Seeing deeper



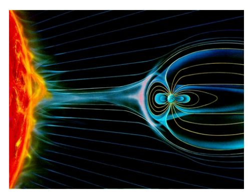


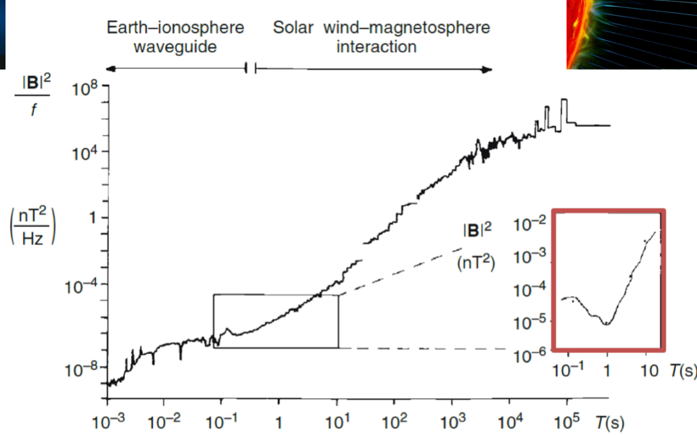
Plane waves and depth of propagation



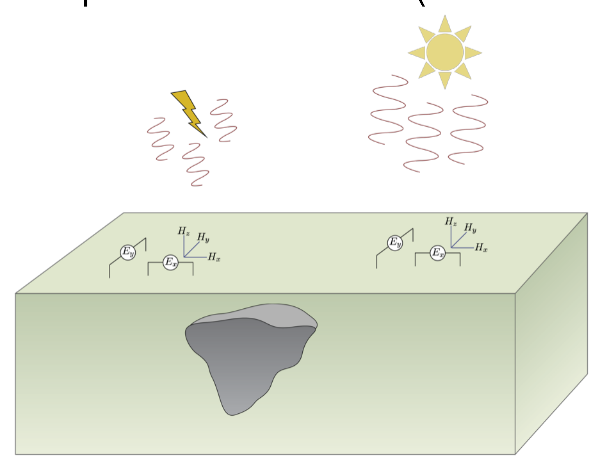


EM Sources



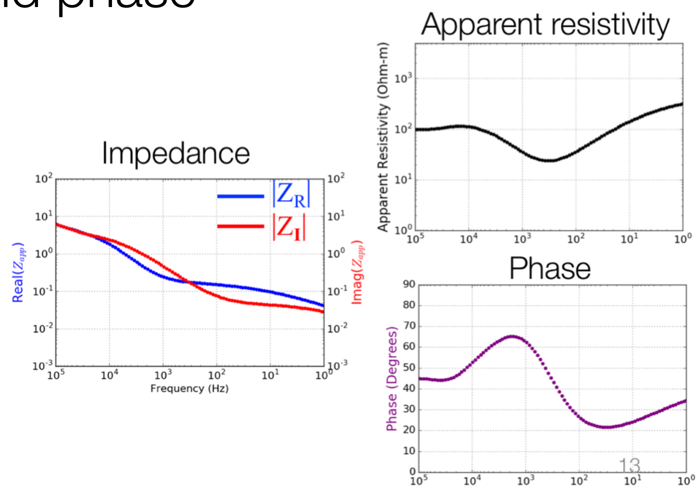


Source random in space and time, collect impedance data (ratio of fields)

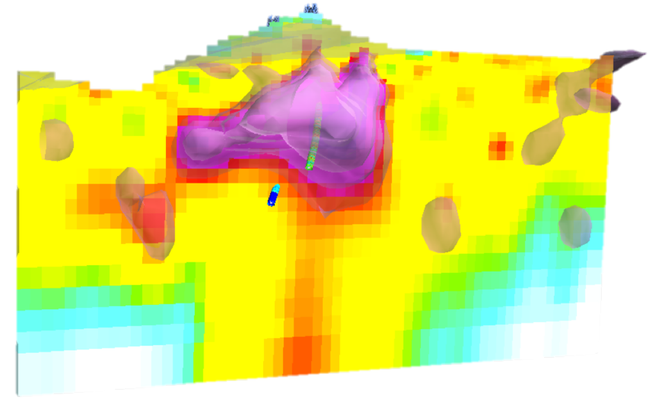


Summary

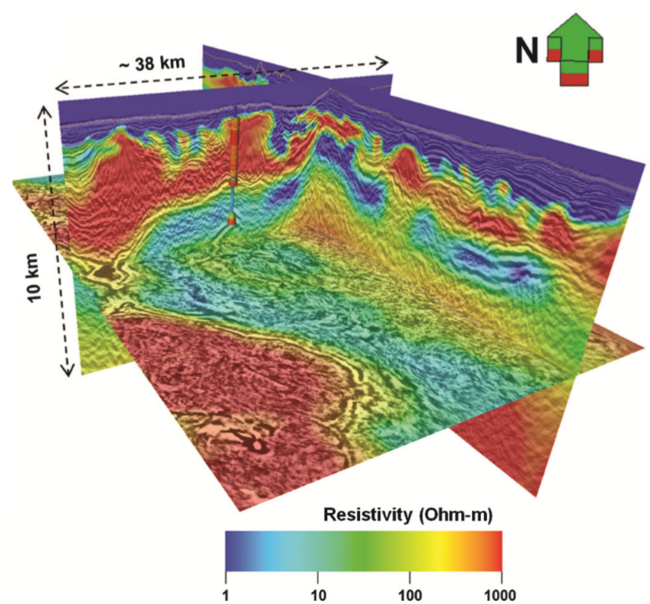
Impedance, apparent resistivity and phase



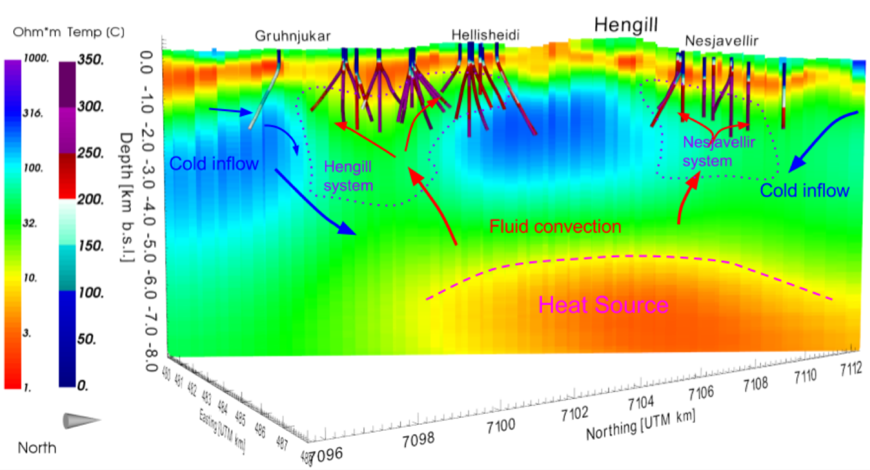
Case History: Mining



Case History: Hydrocarbons

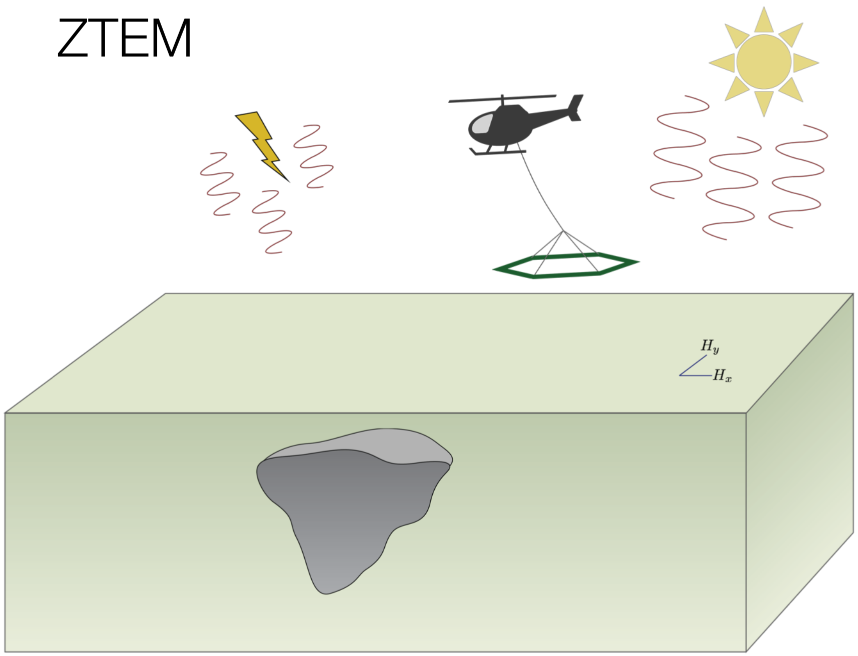


Case History: Geothermal

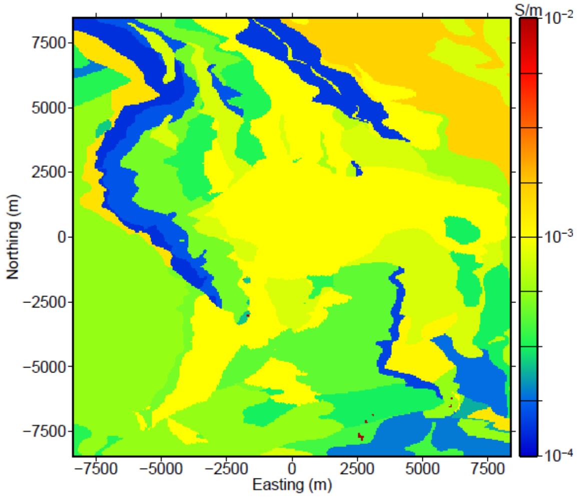


Summary

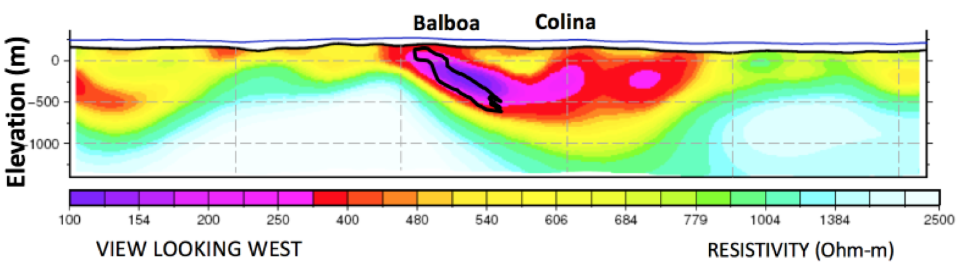
ZTEM



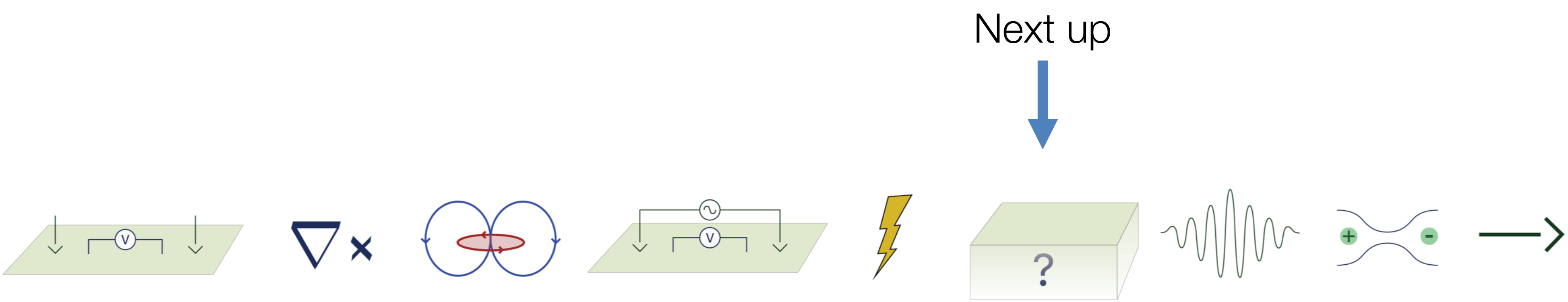
Case history: Geologic Mapping



Case history: minerals



End of Natural Sources

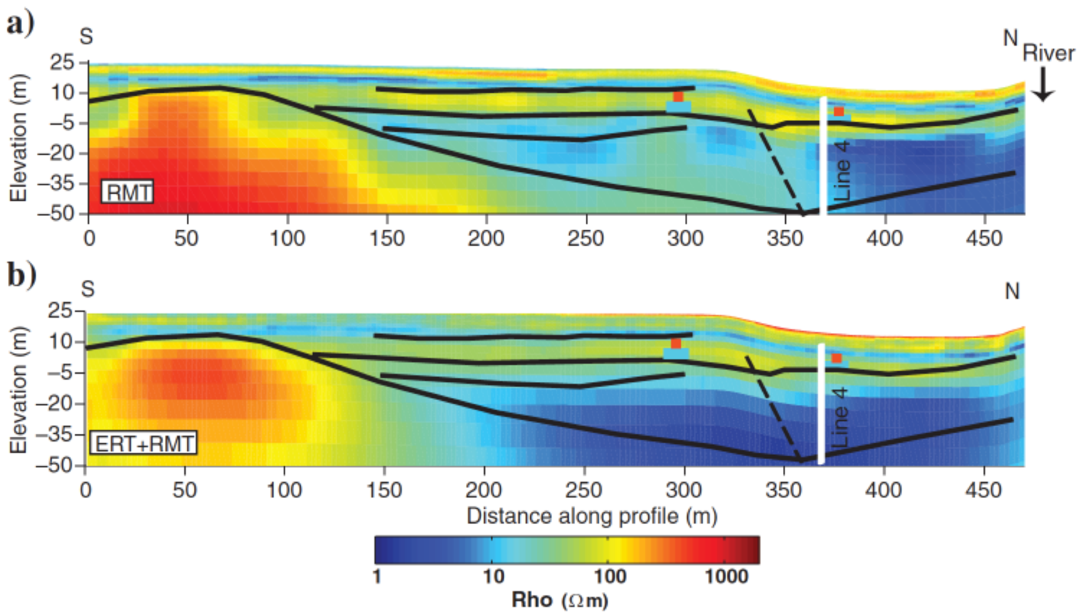


Additional Material

- Case Histories:
  - Landslides

Case History: Landslides, Sweden

Shan et al., 2014



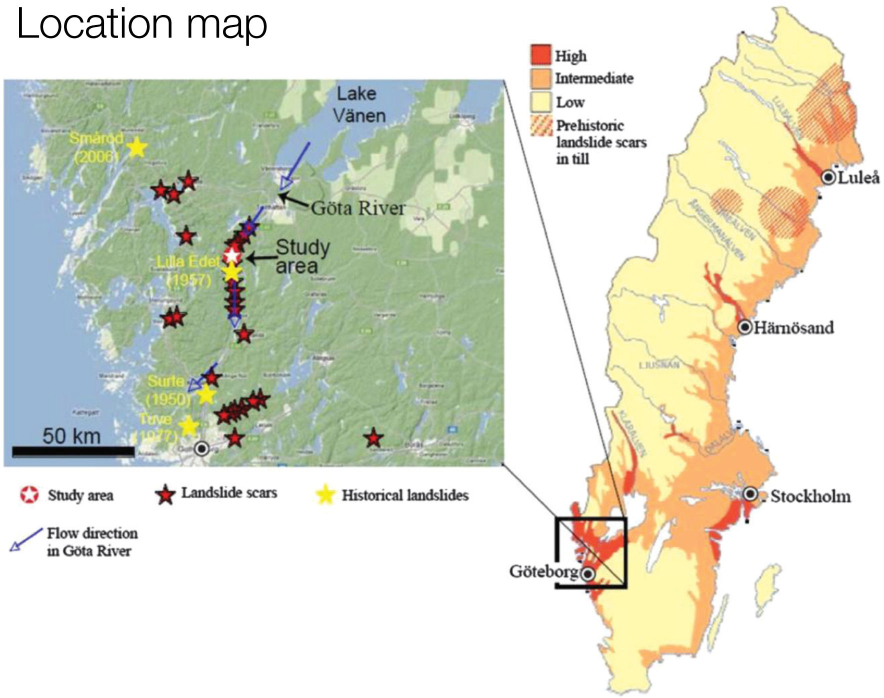
Landslides in Sweden

Photo: C Fredén, 1977, Tuve

Photo: Mats Engdahl, 2006, Munkedal

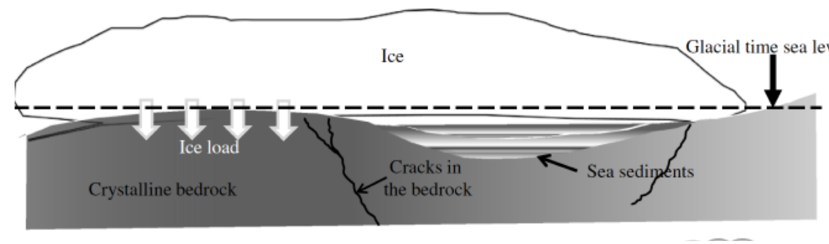
Setup

Location map

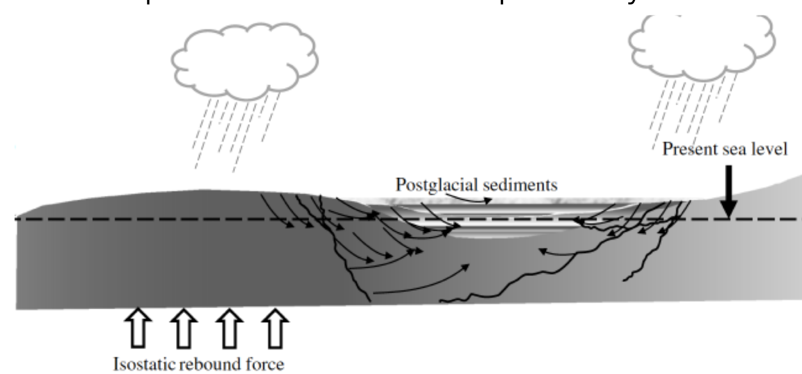


Formation of quick clays

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

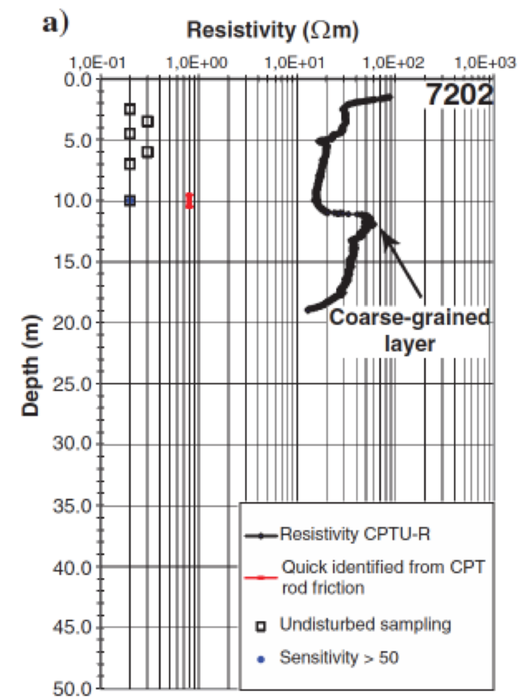
Can we detect quick clays?

Properties

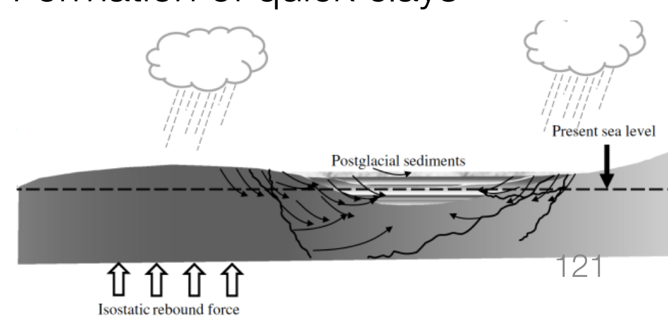
Soil material	Resistivity interval
Salt/intact marine clay	1–10 Ωm
Leached, possible quick clay	10–80 Ωm
Dry crust clay, slide deposits, coarser	>80 Ωm

- 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)

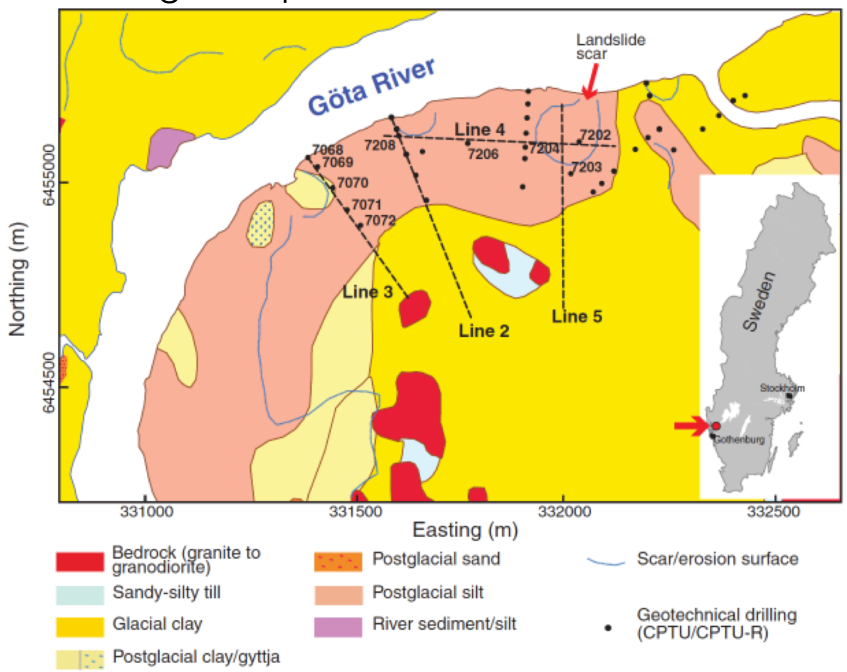


Formation of quick clays

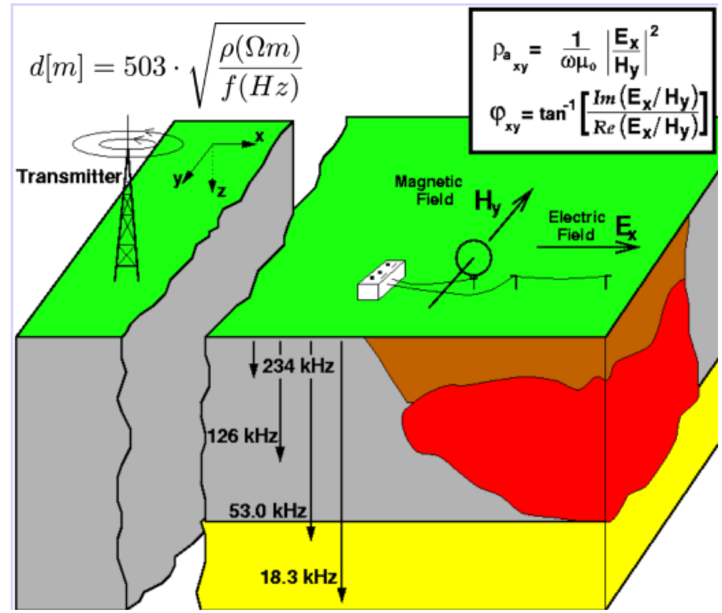


Surveys

Geologic map



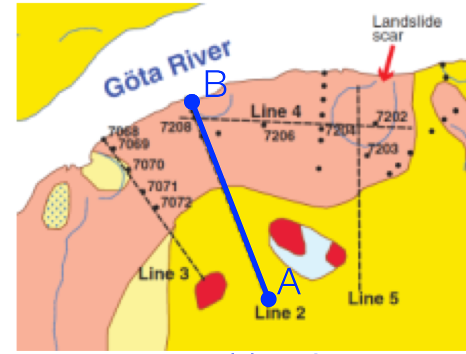
RMT survey



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

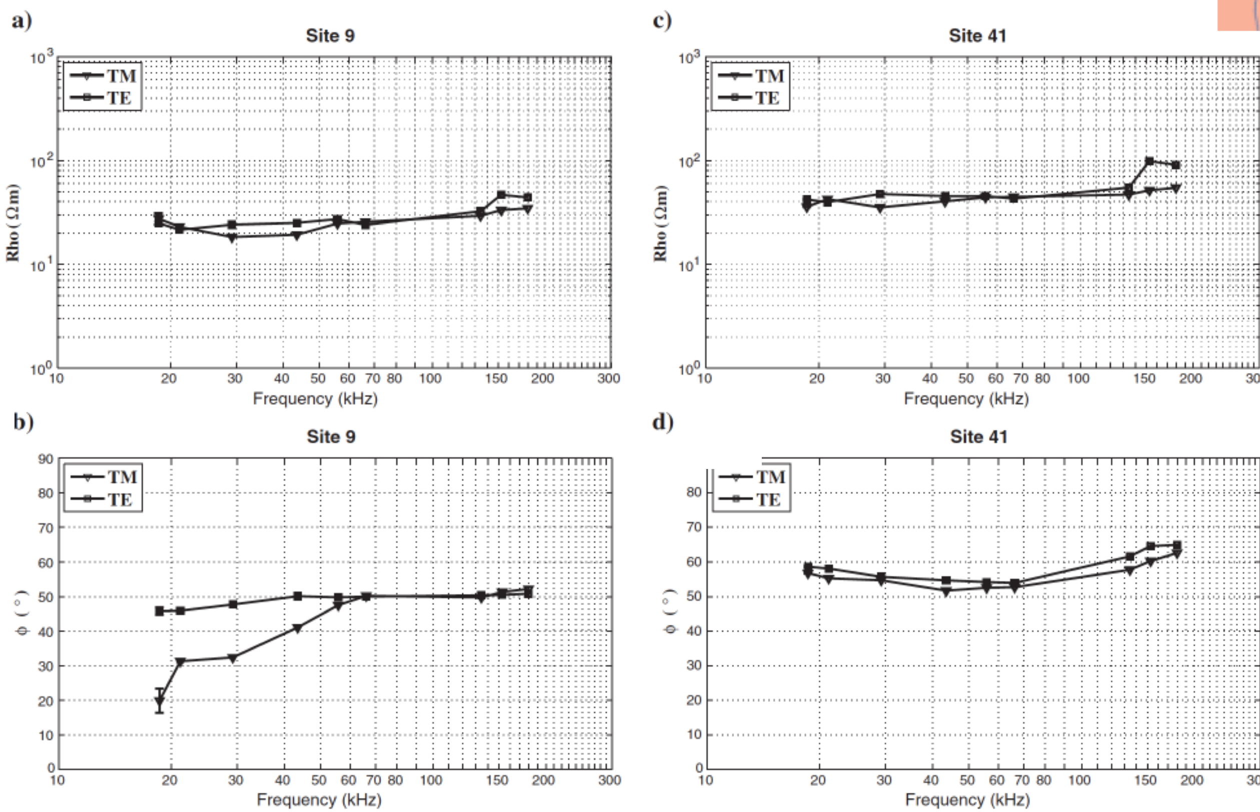
RMT: sounding curves



Line 2

Apparent resistivity

Phase

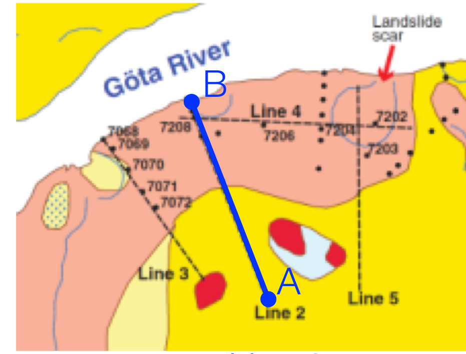


Computed using determinant of impedance tensor at two stations along Line 2

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

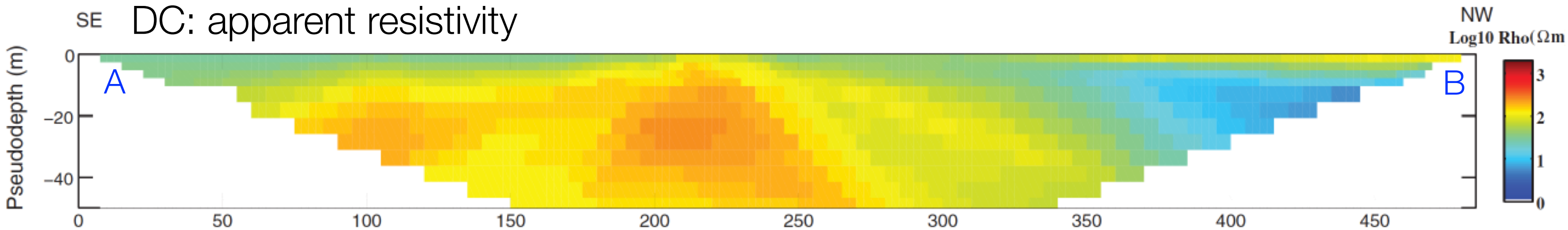
Determinant: (complex-valued) $Z_{\text{det}} = \sqrt{Z_{xx}Z_{yy} - Z_{xy}Z_{yx}}$

Pseudosections

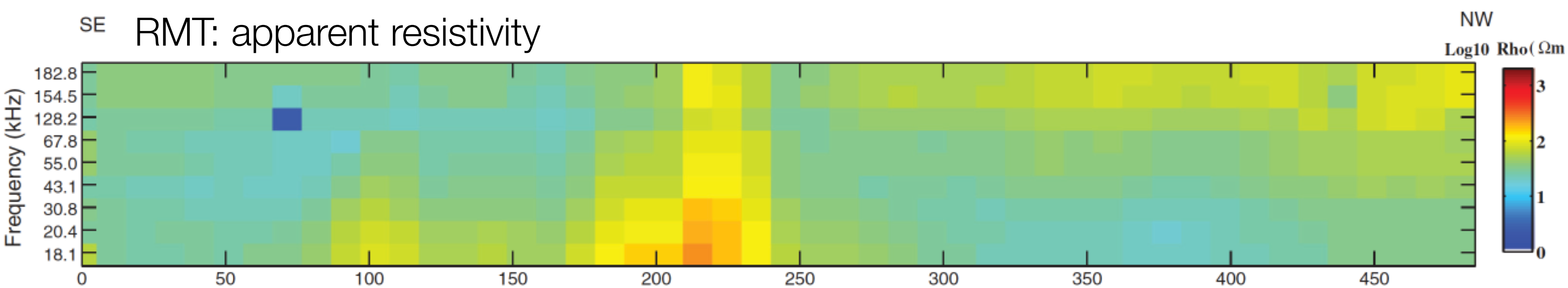


Line 2

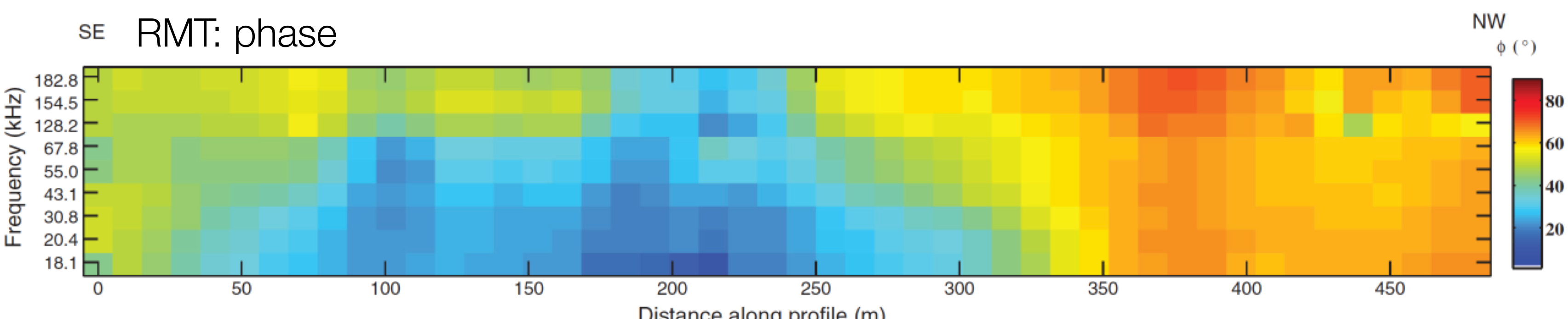
DC: apparent resistivity



RMT: apparent resistivity



RMT: phase



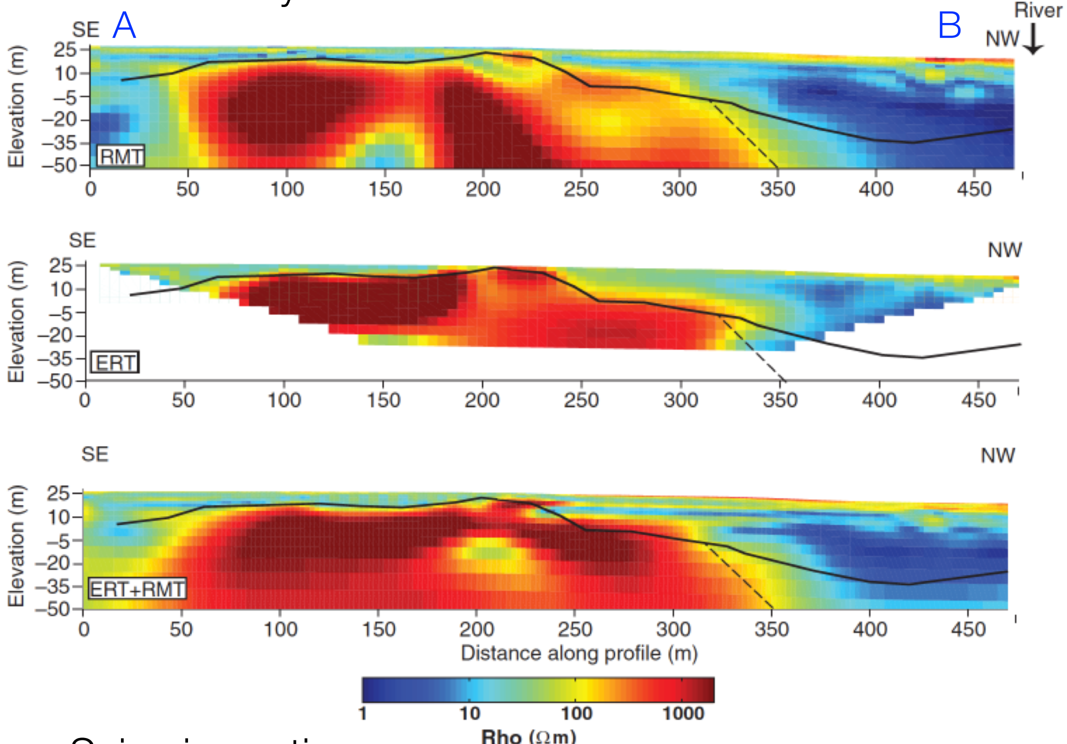
Processing and inversion

2D resistivity sections

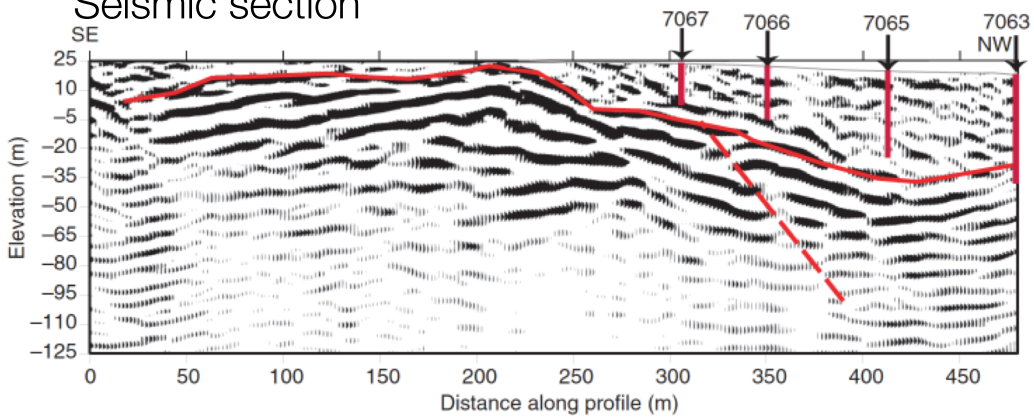
RMT

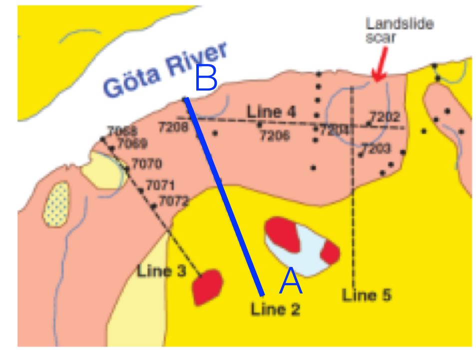
ERT

ERT
+
RMT



Seismic section

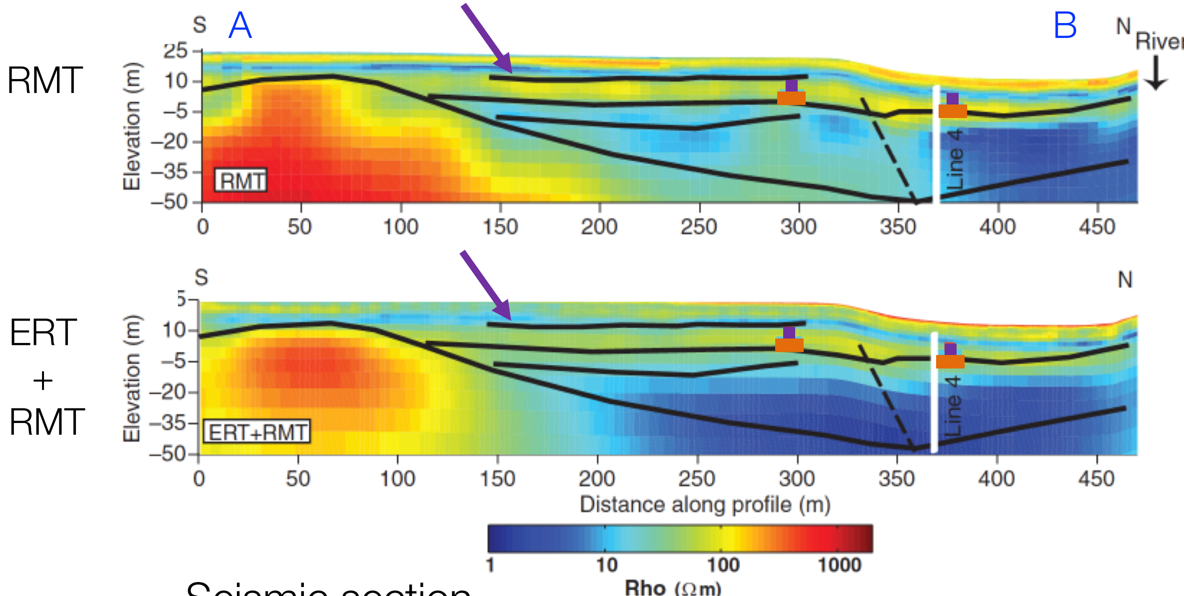


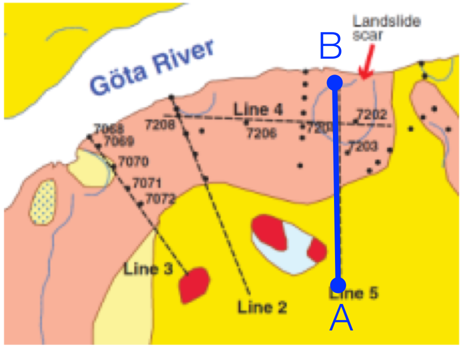


- ERT and RMT yield similar images
- Jointly invert ERT and RMT
- Correlates with seismic

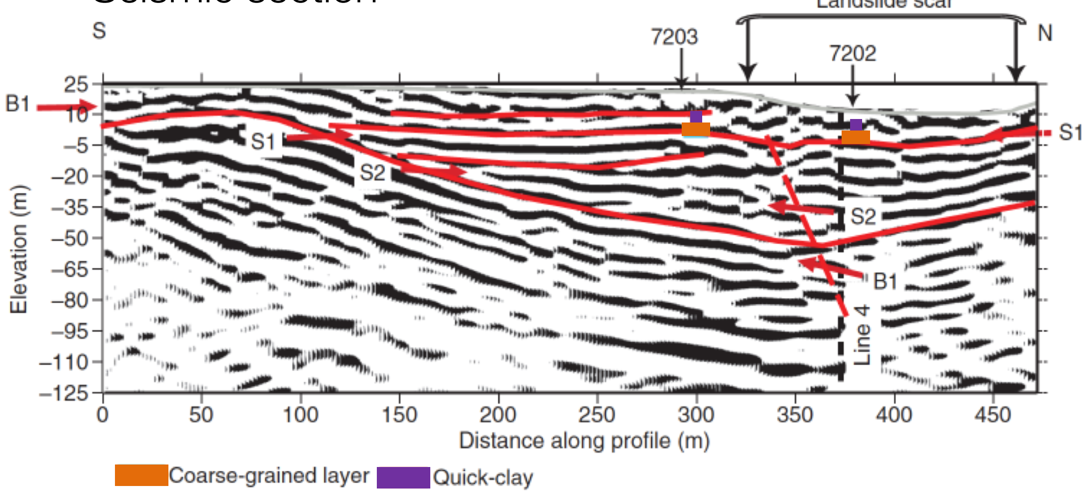
Processing and inversion

2D resistivity sections





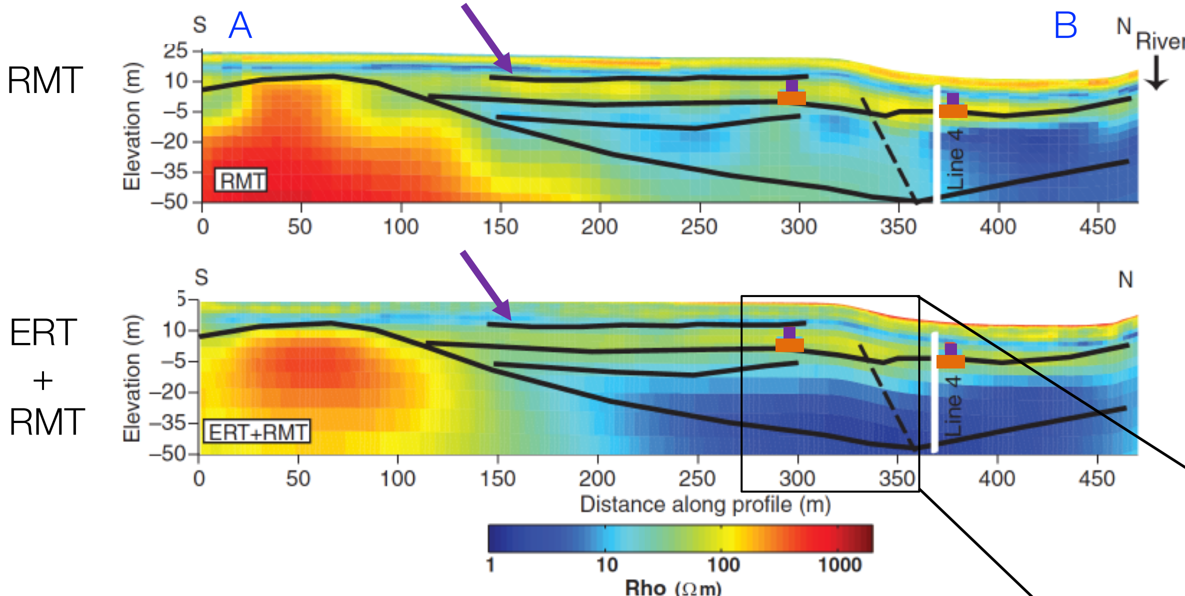
Seismic section

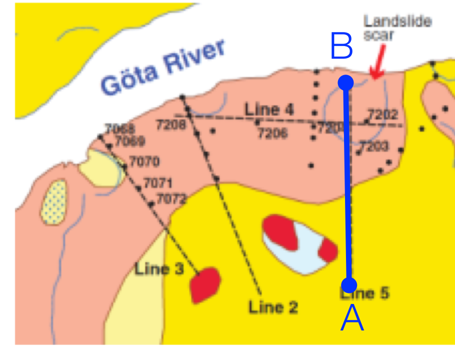


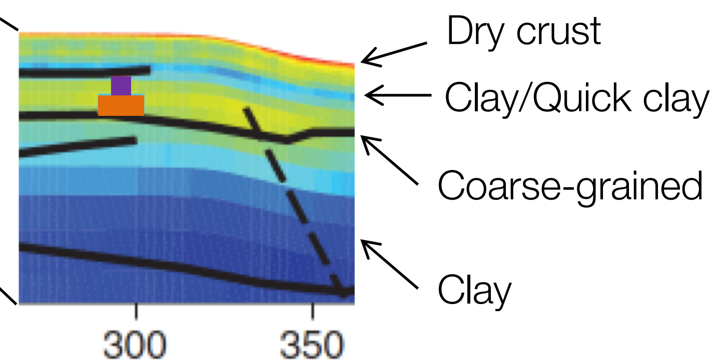
- Inverted RMT, ERT+RMT interpreted with seismic

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

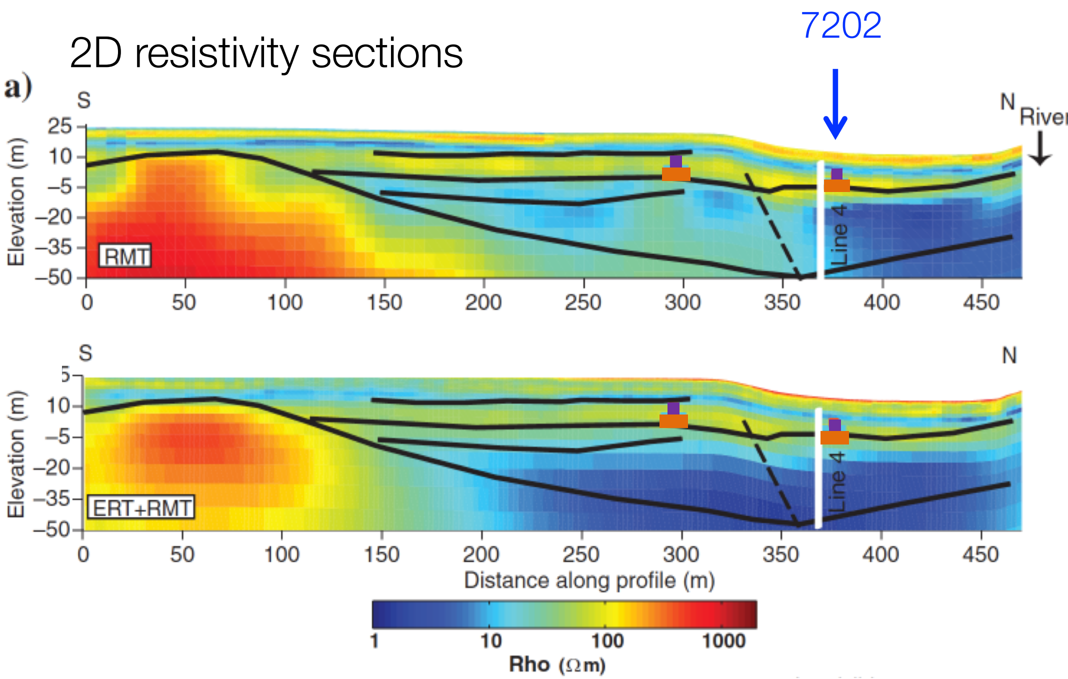
- Top interface: conductor to resistor
- Thickness difficult to estimate

Synthesis

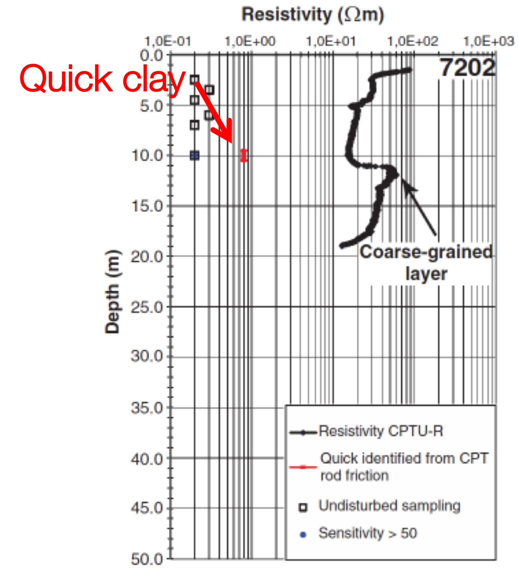
2D resistivity sections

RMT

ERT + RMT



Resistivity log



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