Electromagnetics for Minerals Exploration: Principles and some inversion examples

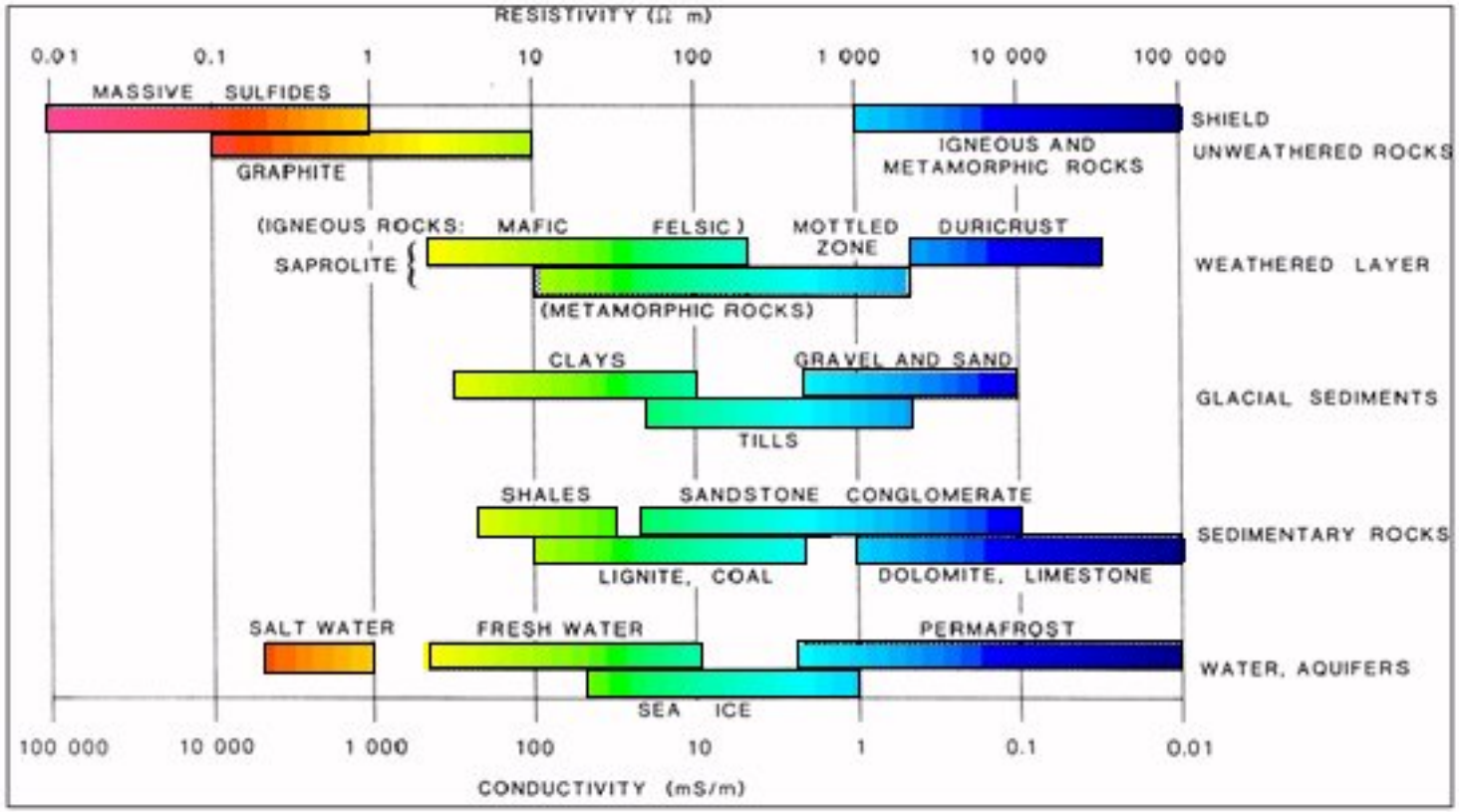
Doug Oldenburg

BCGS Workshop
January 24, 2009

Outline:

- Electromagnetics: (Some basics)
- Frequency domain surveys
- Time domain surveys
- Some inversion examples throughout

Electrical conductivity

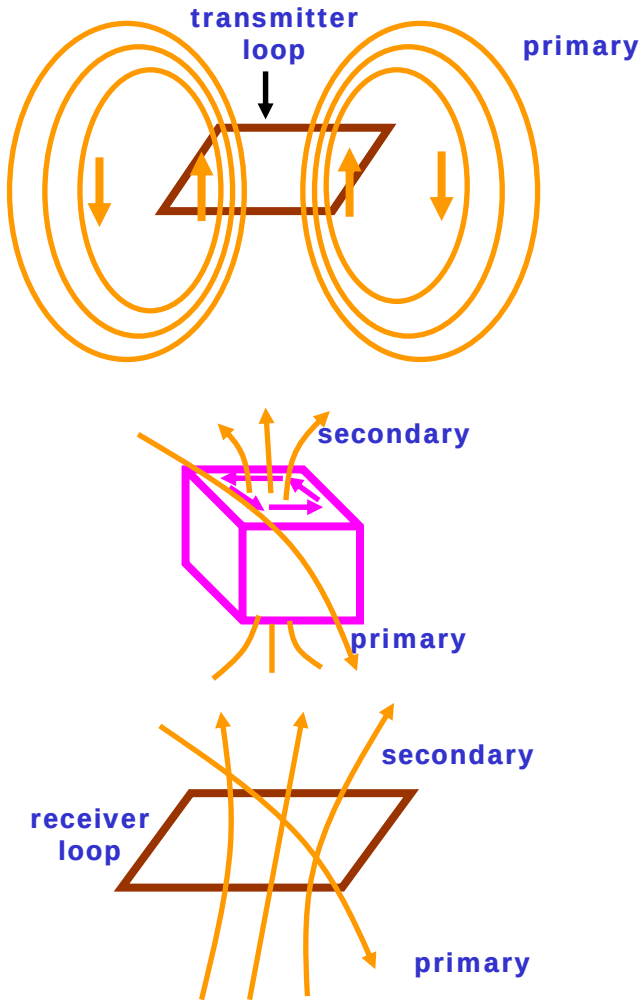


σ Conductivity S/m

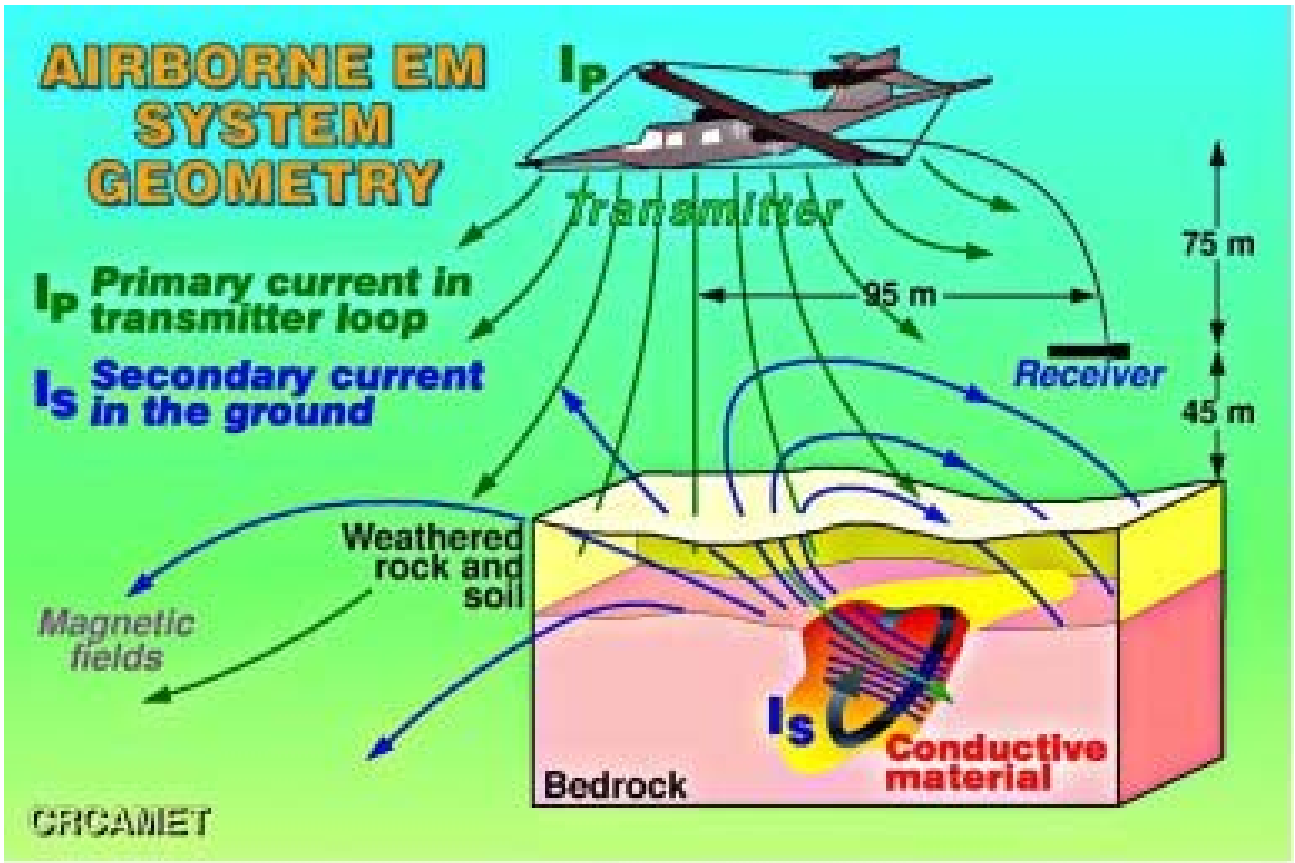
ρ Resistivity Ω-m

Basic principles of EM induction

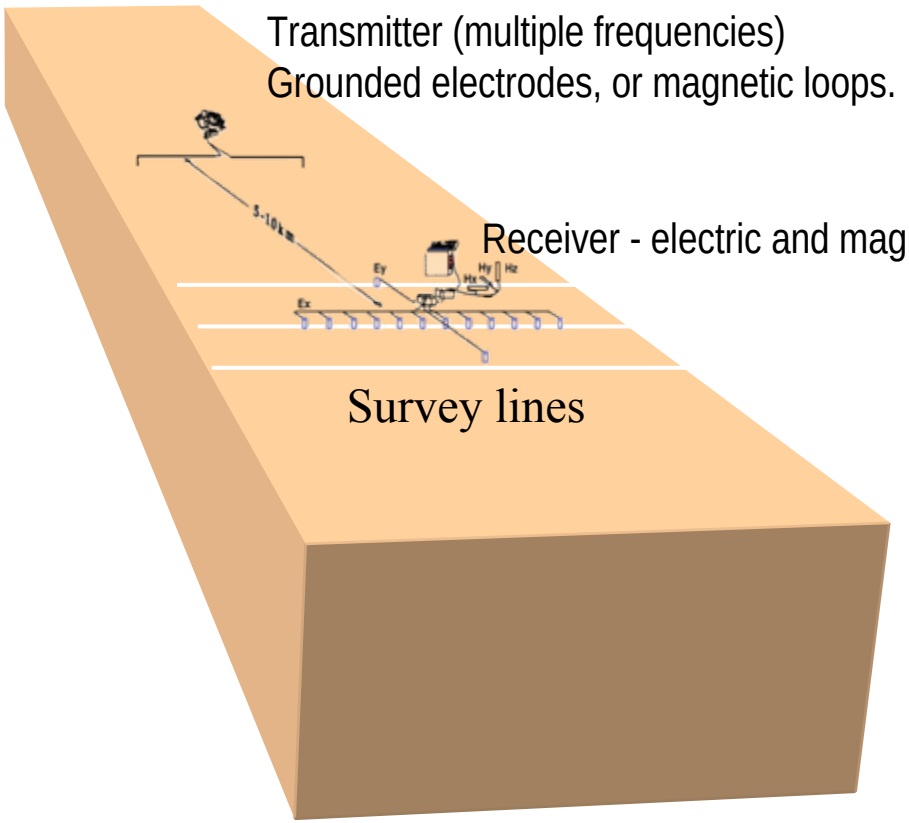
- Time varying transmitter current generates a time varying magnetic field.
- Time varying magnetic field generate an EMF (ie. electric field) in the earth.
- Currents are generated ($J=\sigma E$).
- The currents in the conductor generate magnetic fields.
- We measure these (secondary) fields and the (primary) fields of the transmitter



Airborne (Inductive source)



Grounded source (CSAMT)

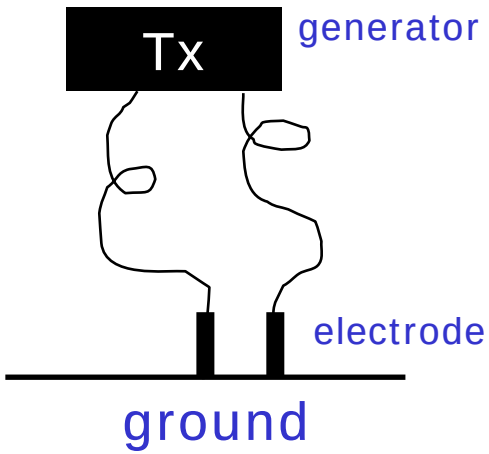


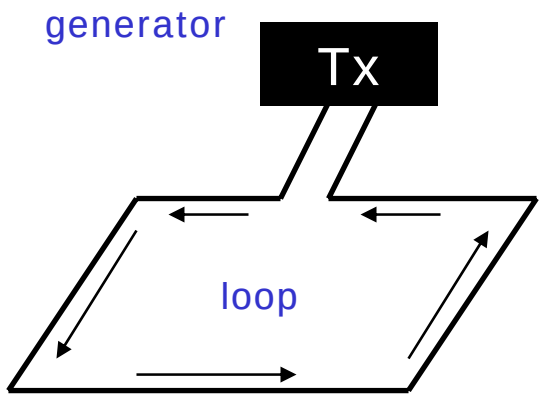
Important elements

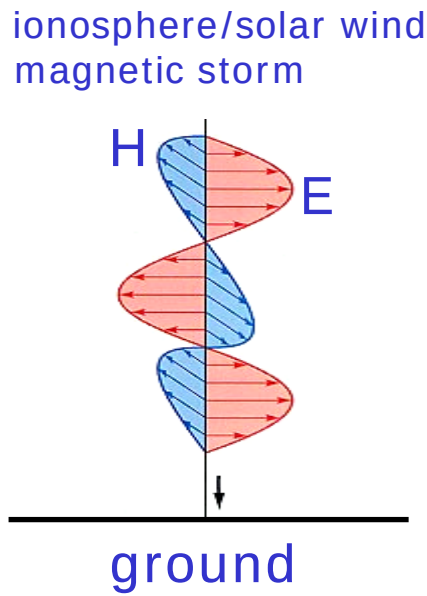
- Primary field must couple with the target
- Strength of the induced currents must be big enough to generate signal
- Need to choose which fields to measure

Why are there so many types of surveys?

Source types: grounded, inductive, natural



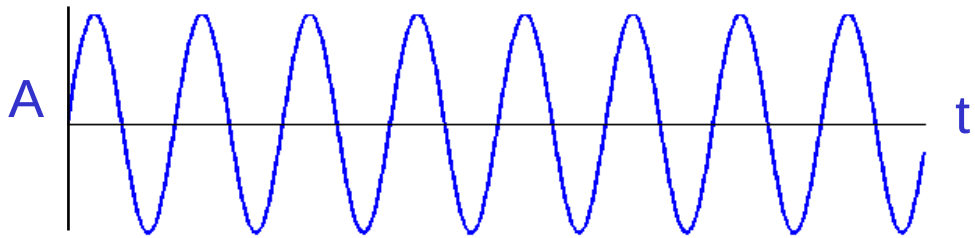




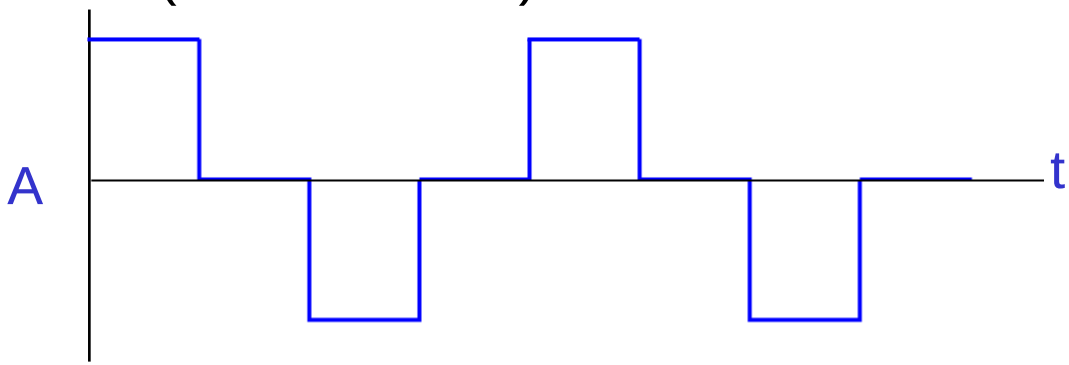
Why are there so many types of surveys?

Source waveform:

- Harmonic (frequency domain)

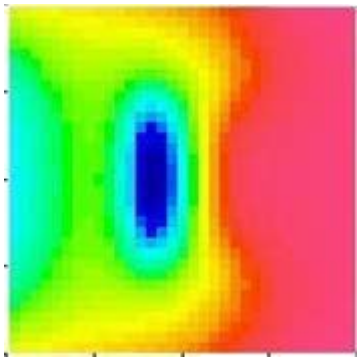


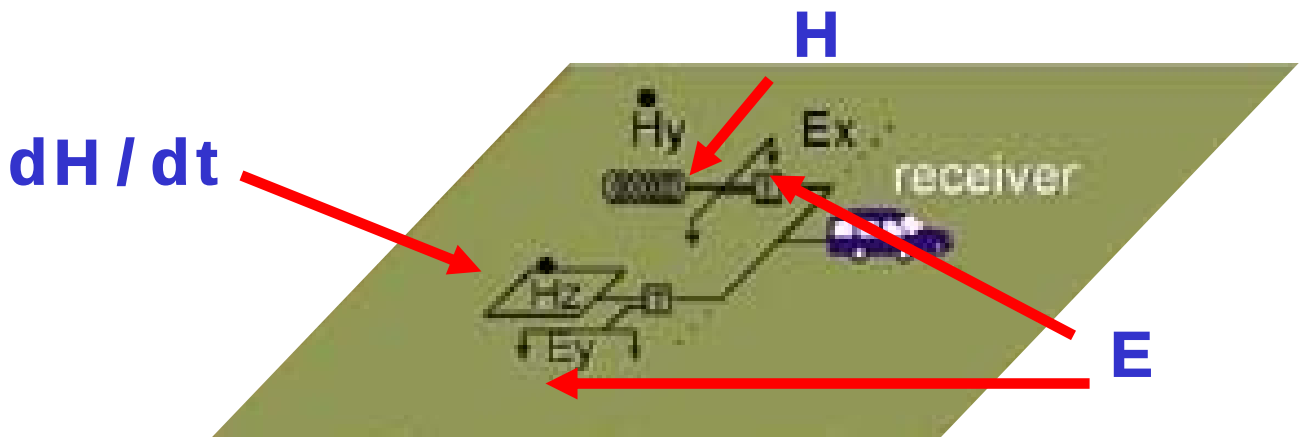
- Impulsive (time domain)



Why are there so many types of surveys?

Data

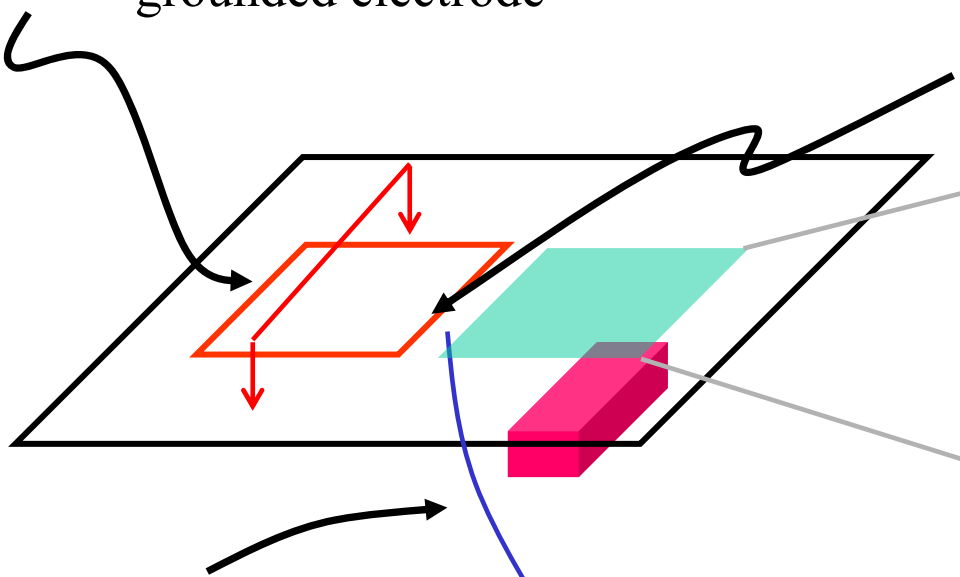




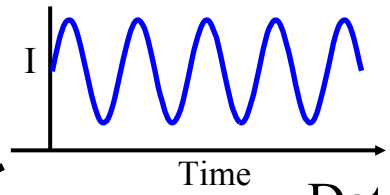
Each scenario (transmitter, receiver, ground, airborne,...) gives rise to different survey equipment, data and analysis. BUT they all want to provide information about conductivity

3D EM: Frequency Domain

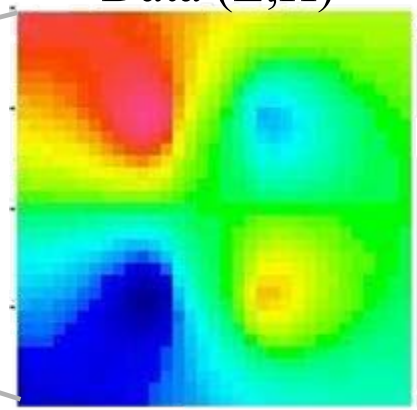
Source: Loop or grounded electrode



Waveform

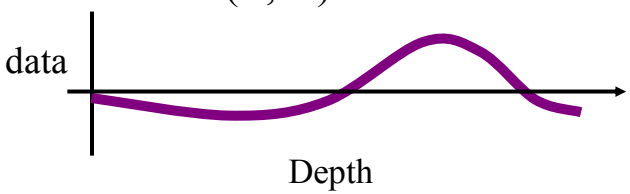


Data (E,H)



Borehole Data

(E, H)



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

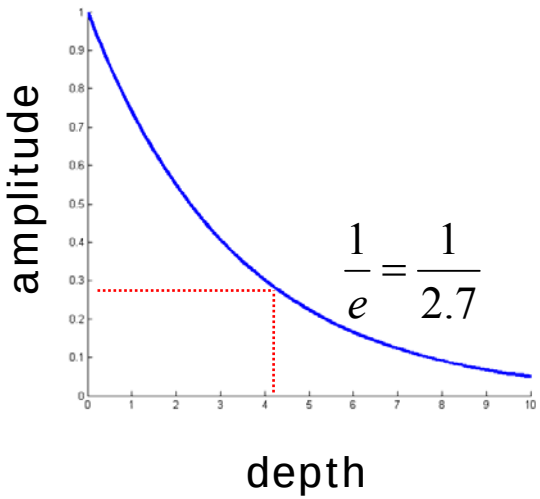
$$\nabla \times \mathbf{H} - (\sigma - i\omega\varepsilon)\mathbf{E} = \mathbf{J}^e$$

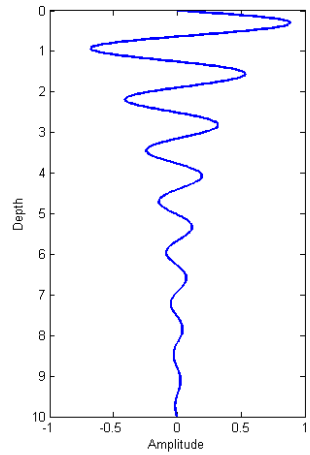
Frequency Domain

- EM waves decay when propagating in a conducting earth

- Skin depth

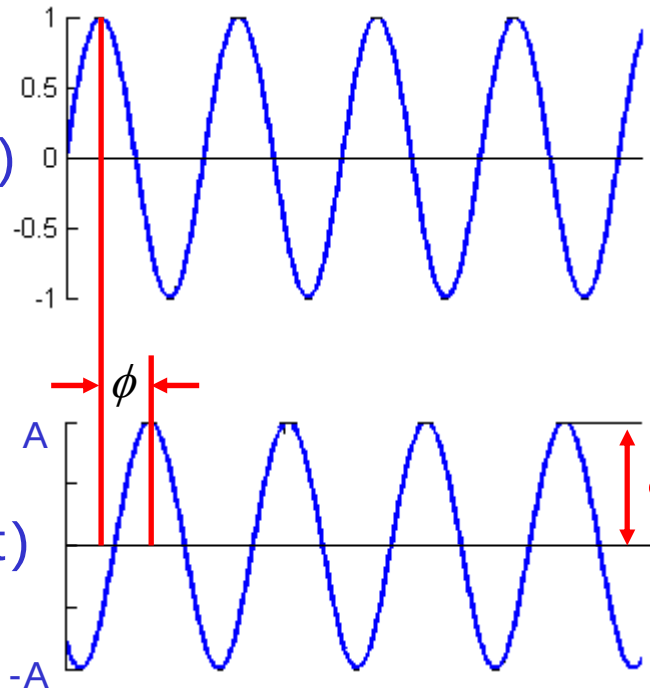
$$\delta = 506\sqrt{\frac{\rho}{f}} \quad \text{meter}$$





where ρ is resistivity in Ωm
and f is frequency in Hz.

Frequency domain EM data



Measure amplitude and phase (A, ϕ)

Or $A\cos(\omega t+\phi)=(A\cos\phi)\cos\omega t+(A\sin\phi)\sin\omega t$

In-phase
Real

Out-of-phase
Imaginary

Frequency domain EM data

Or ratio of fields

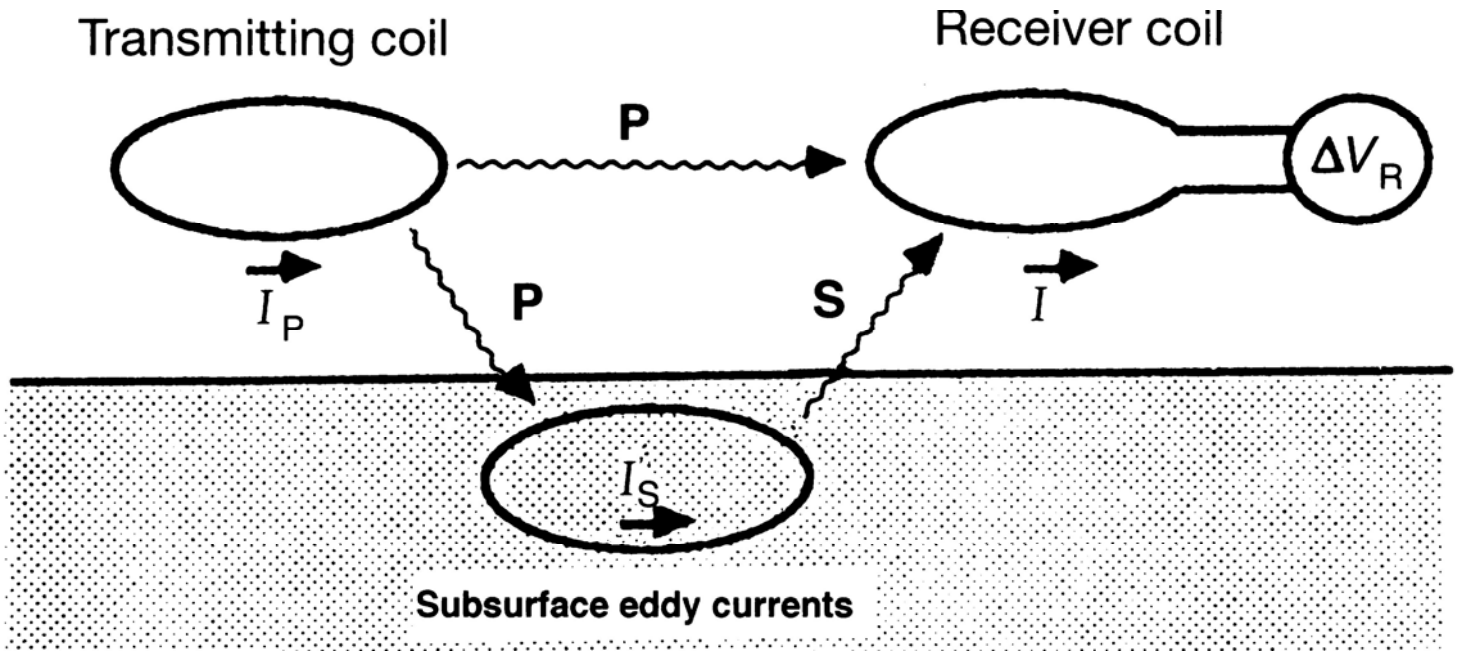
impedance $$Z = \frac{E}{H} = \frac{\text{electric field}}{\text{magnetic field}}$$

or $$R = \frac{H_S}{H_P} = \frac{\text{secondary magnetic}}{\text{primary magnetic}}$$

$$\rho_a = \frac{1}{\mu_0 \omega} |Z|^2$$ Apparent Resistivity

$$\phi = \tan^{-1} \frac{\text{Im}\, Z}{\text{Re}\, Z}$$ Phase

Airborne or ground system



Depth of investigation depends upon

skin depth

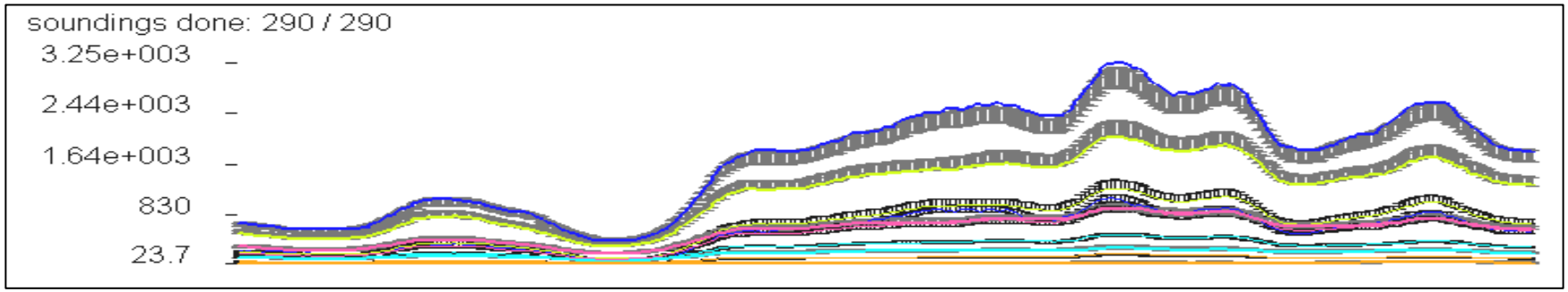
source receiver geometry

Frequency domain

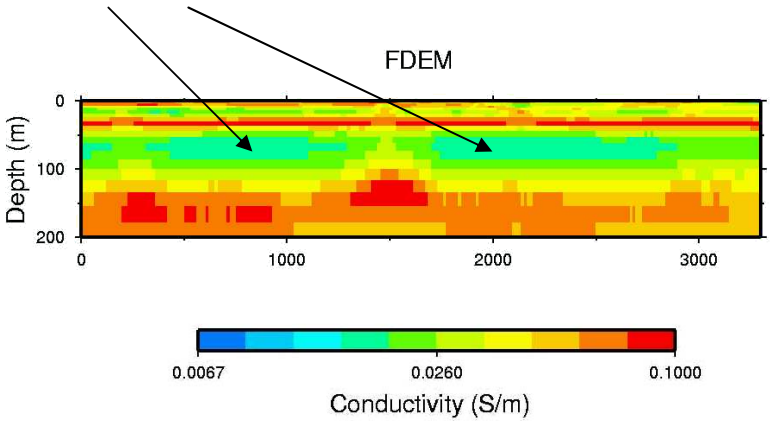
1D modelling

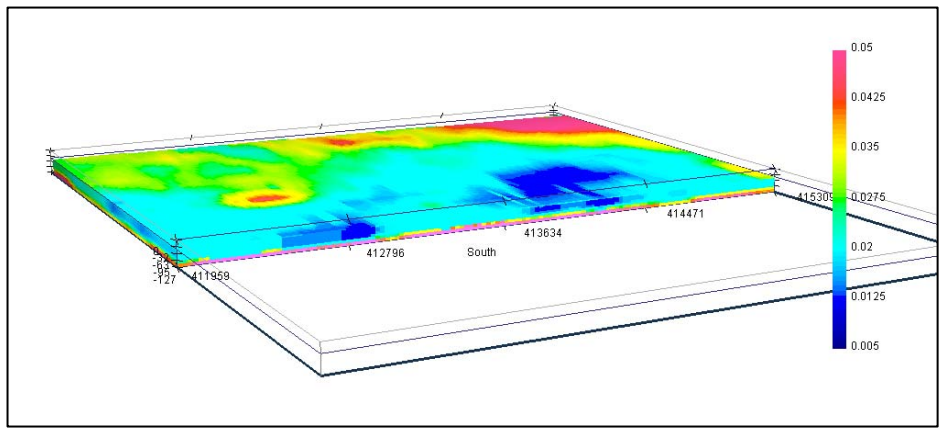
- Delineate background conductivity
- Use for target picking when looking for anomalies

1D FDEM Results

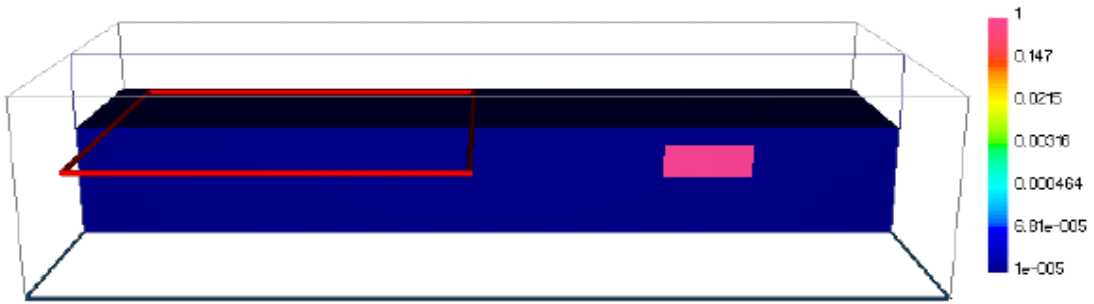


Resistive channels

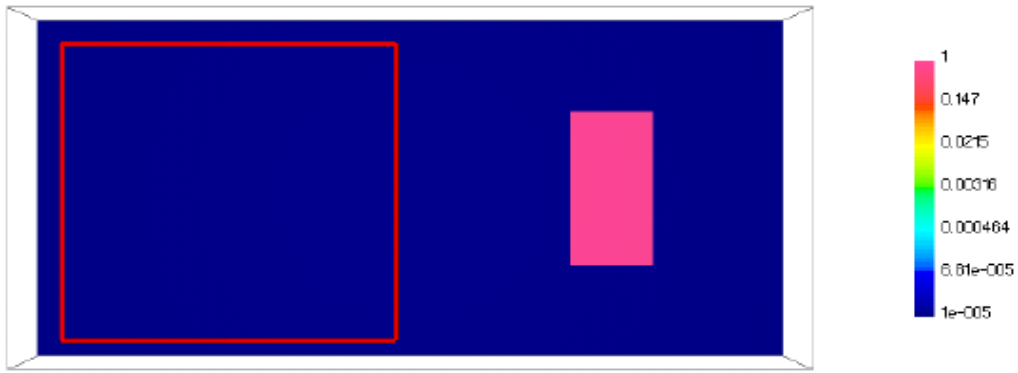




Inductive source: A 3D Model



Cross section

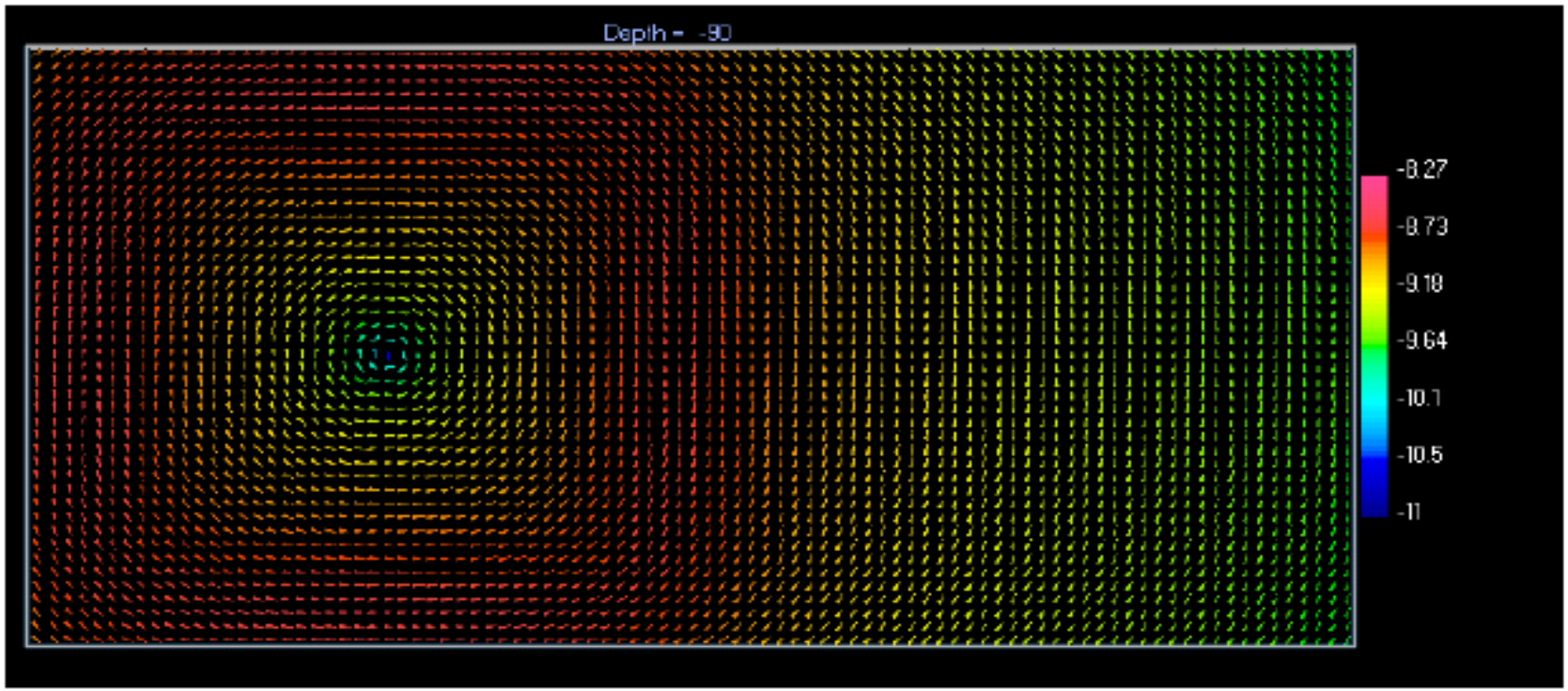


Plan view

Currents at 90 meters depth: Example of induction

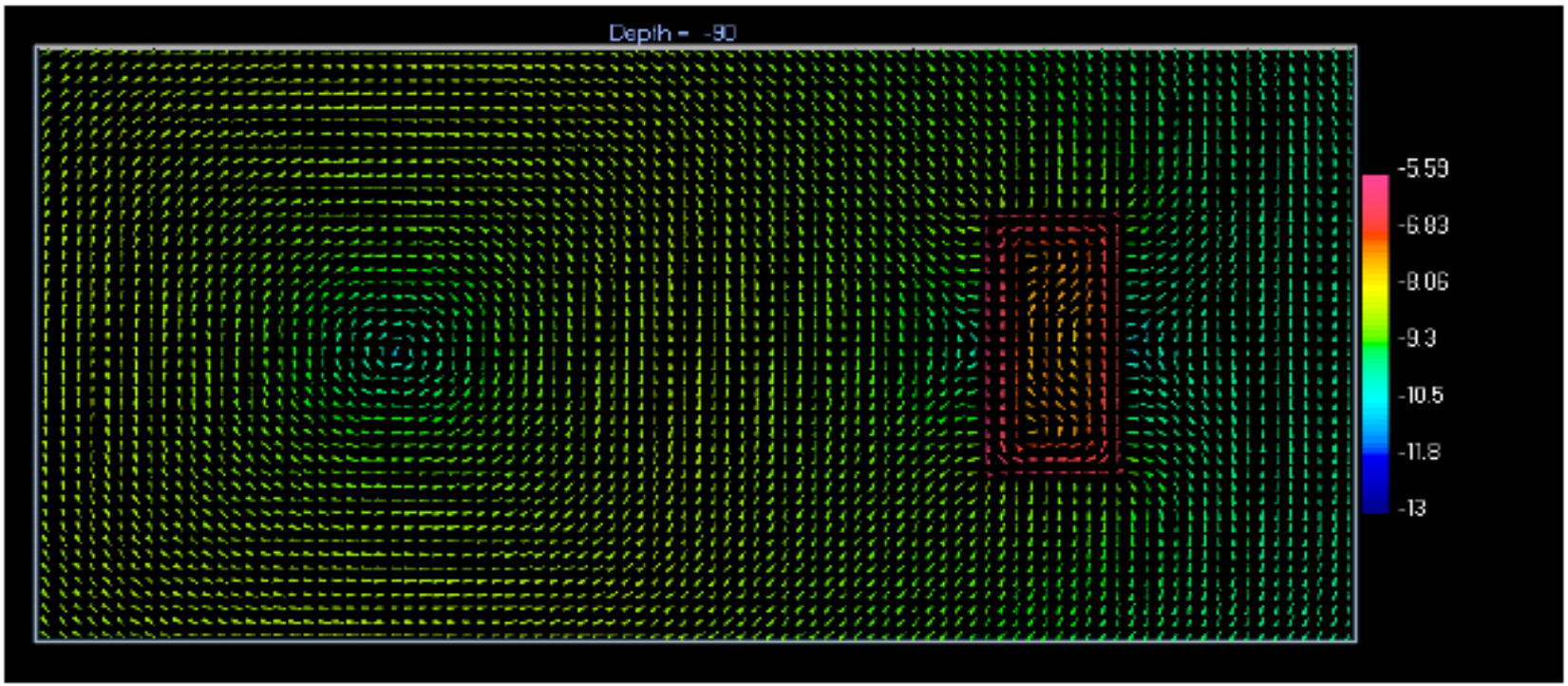
Primary Currents: uniform earth

primary



Currents at 90 meters depth: Example of induction

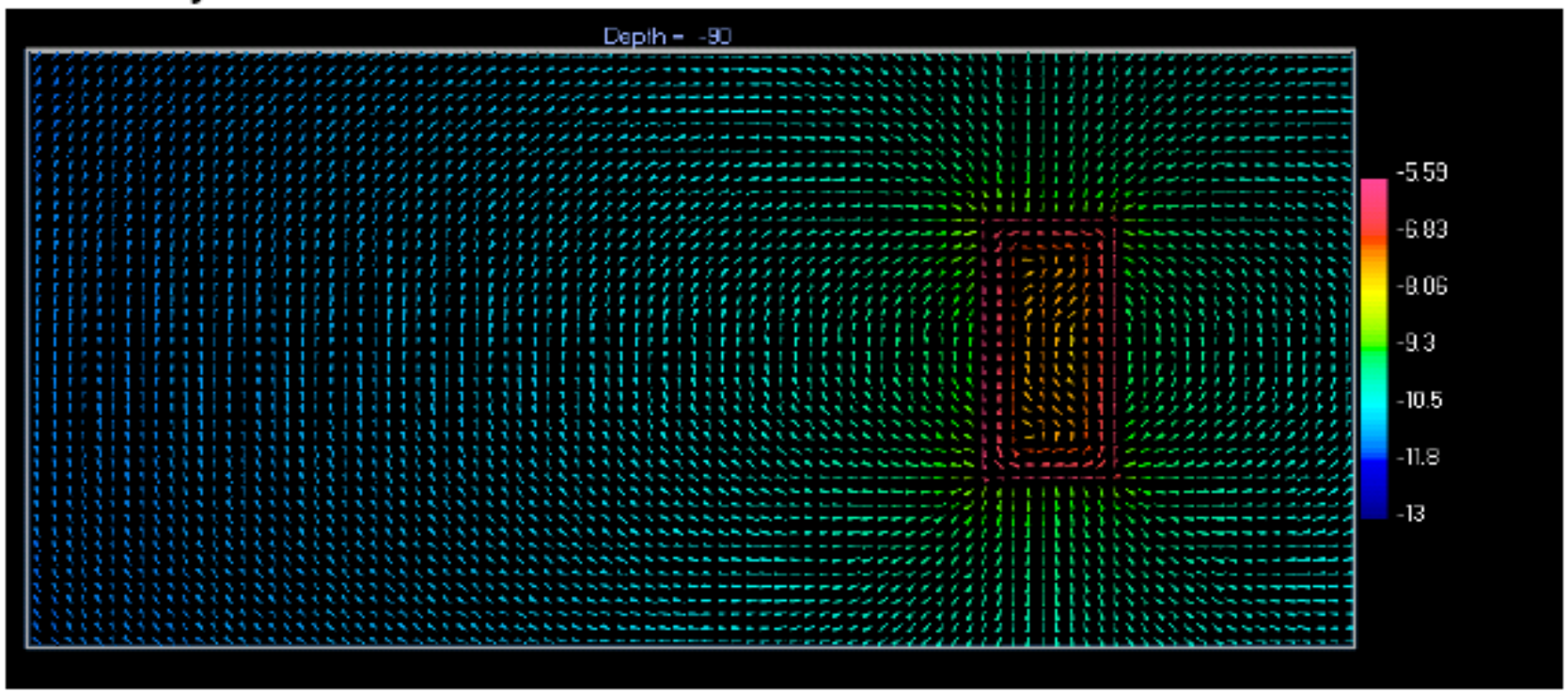
Total currents: with a block



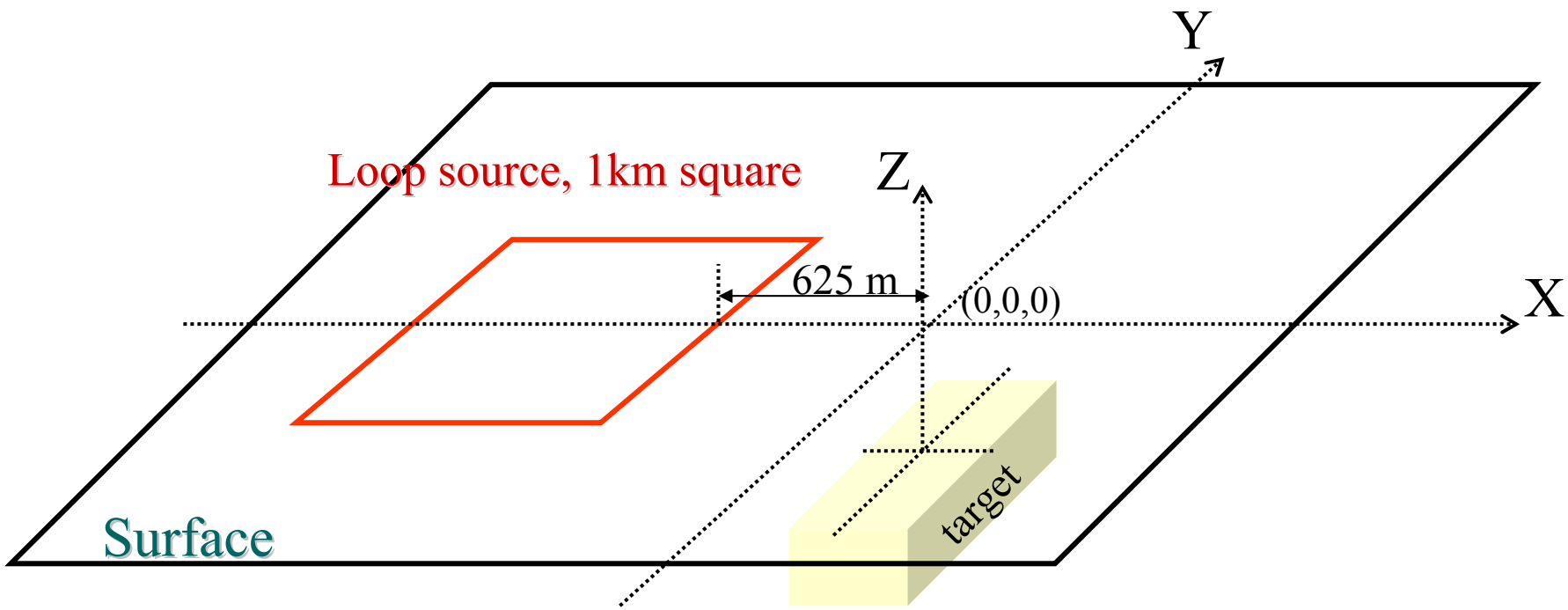
Currents at 90 meters depth: Example of induction

Secondary currents: Total currents – primary currents

secondary



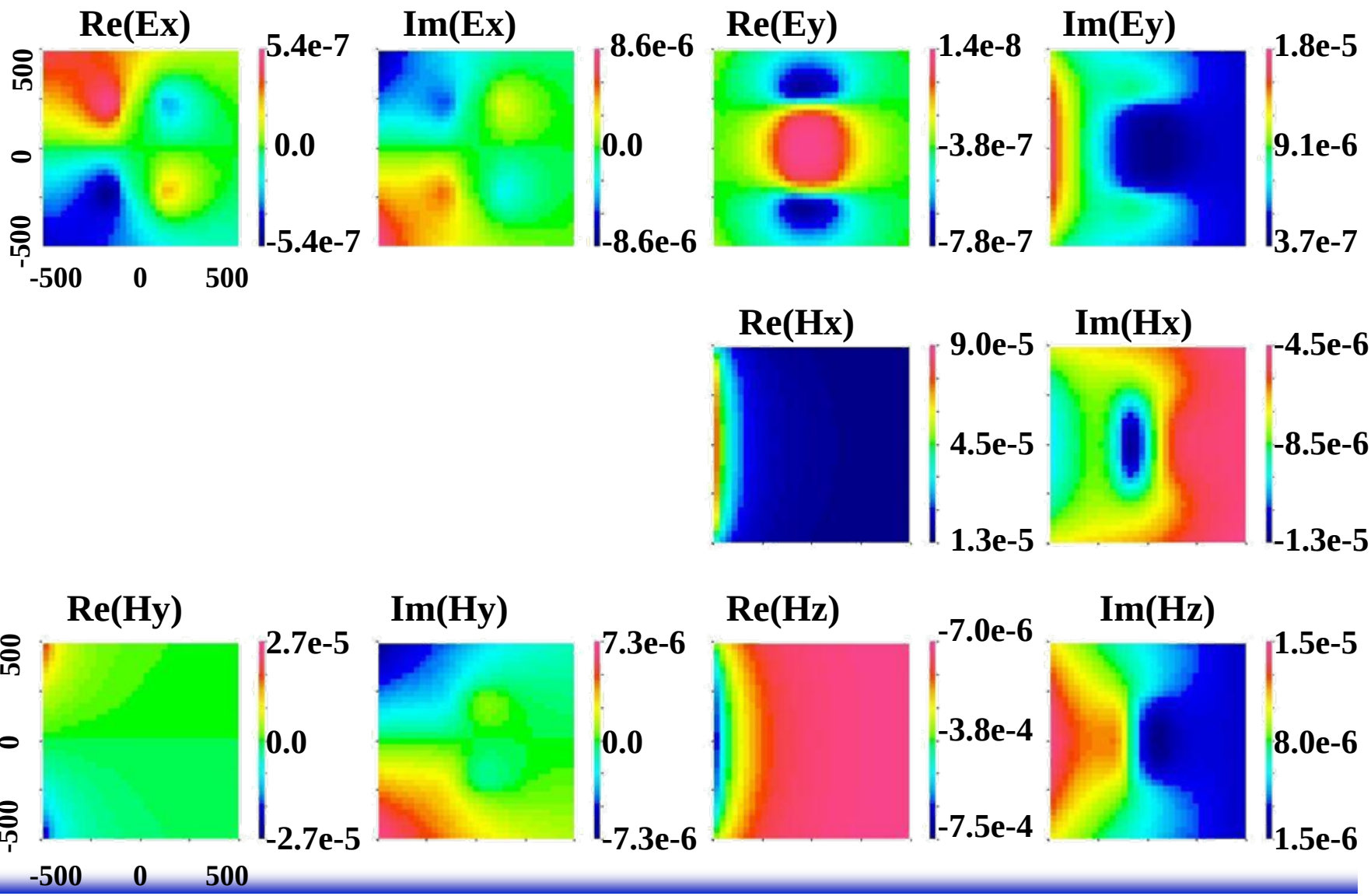
• The "*Cominco*" model : Loop source, conductive target in a host



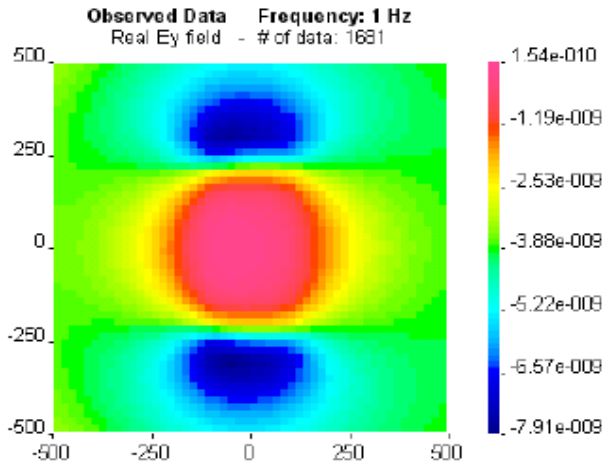
Host resistivity = 200 Ohm-m

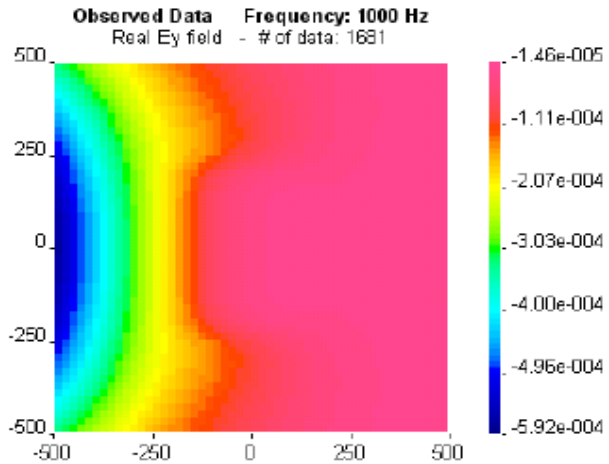
Target (x, y, z) = (250, 500, 100)
Conductivity = 1.0 S/m

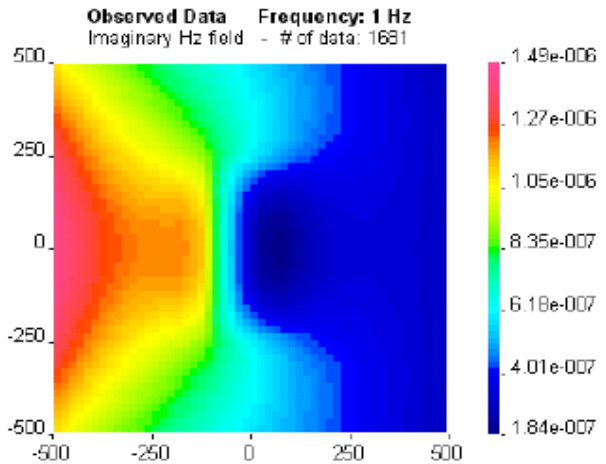
Data: Frequency = 10 Hz

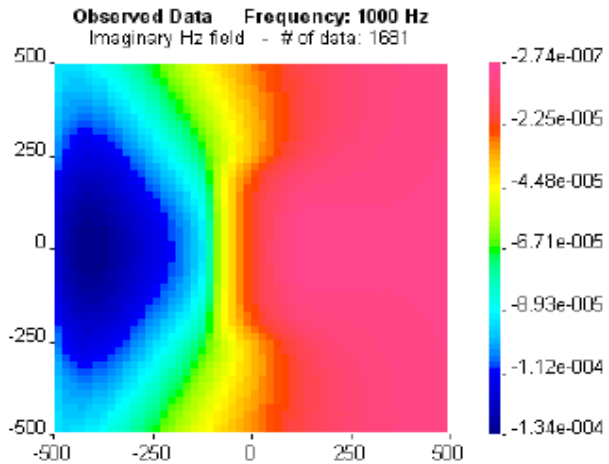


Fields depend upon frequency







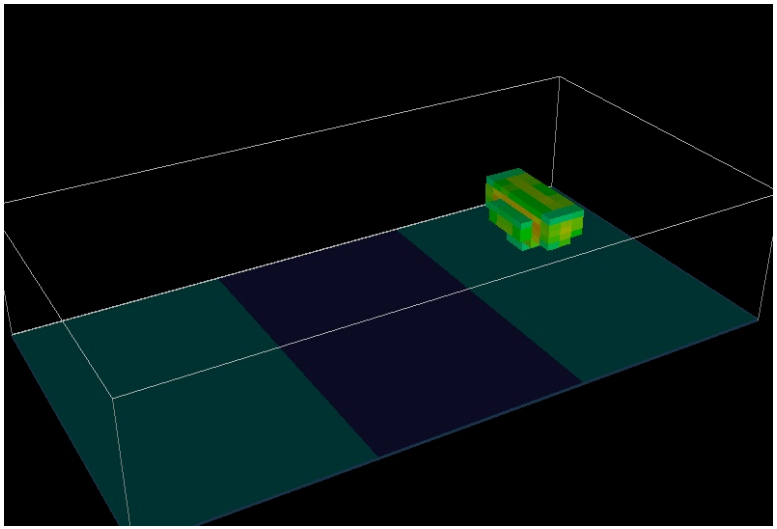


3D inversion

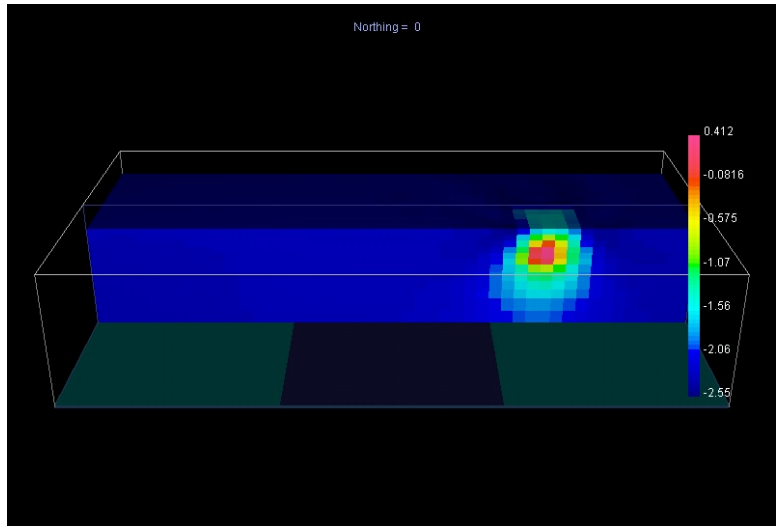
Inversion methodology is same as for DC resistivity but implementation is harder!

Invert E and H fields at 5 frequencies 0.1 – 1000 Hz

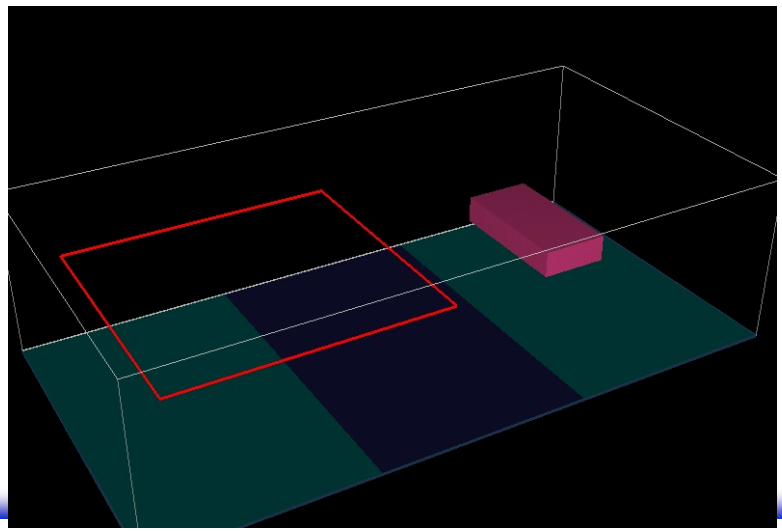
Recovered iso-surface



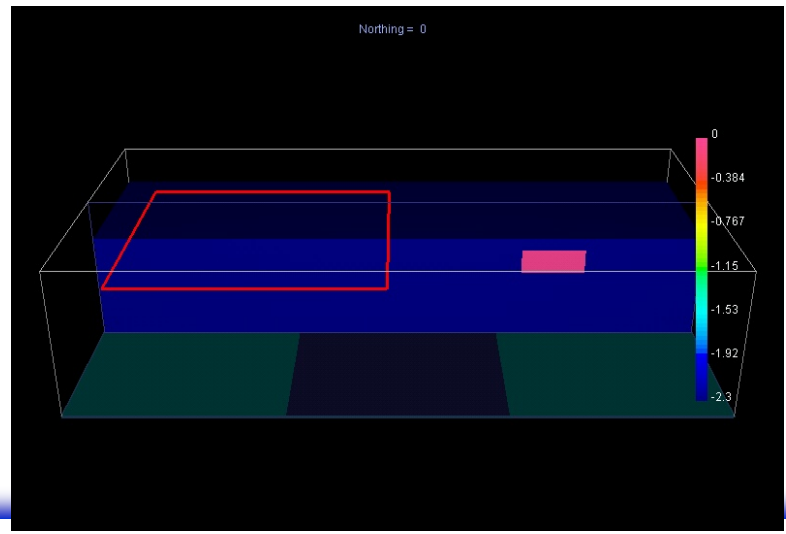
Recovered cross-section



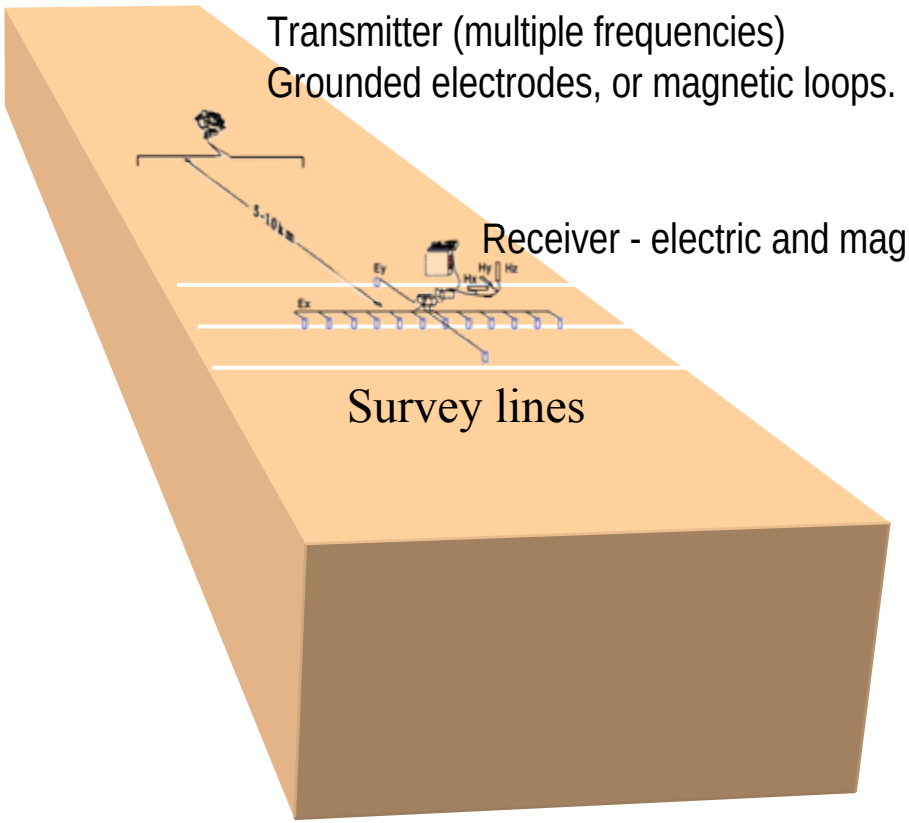
True iso-surface



True cross-section



Grounded source (CSAMT)

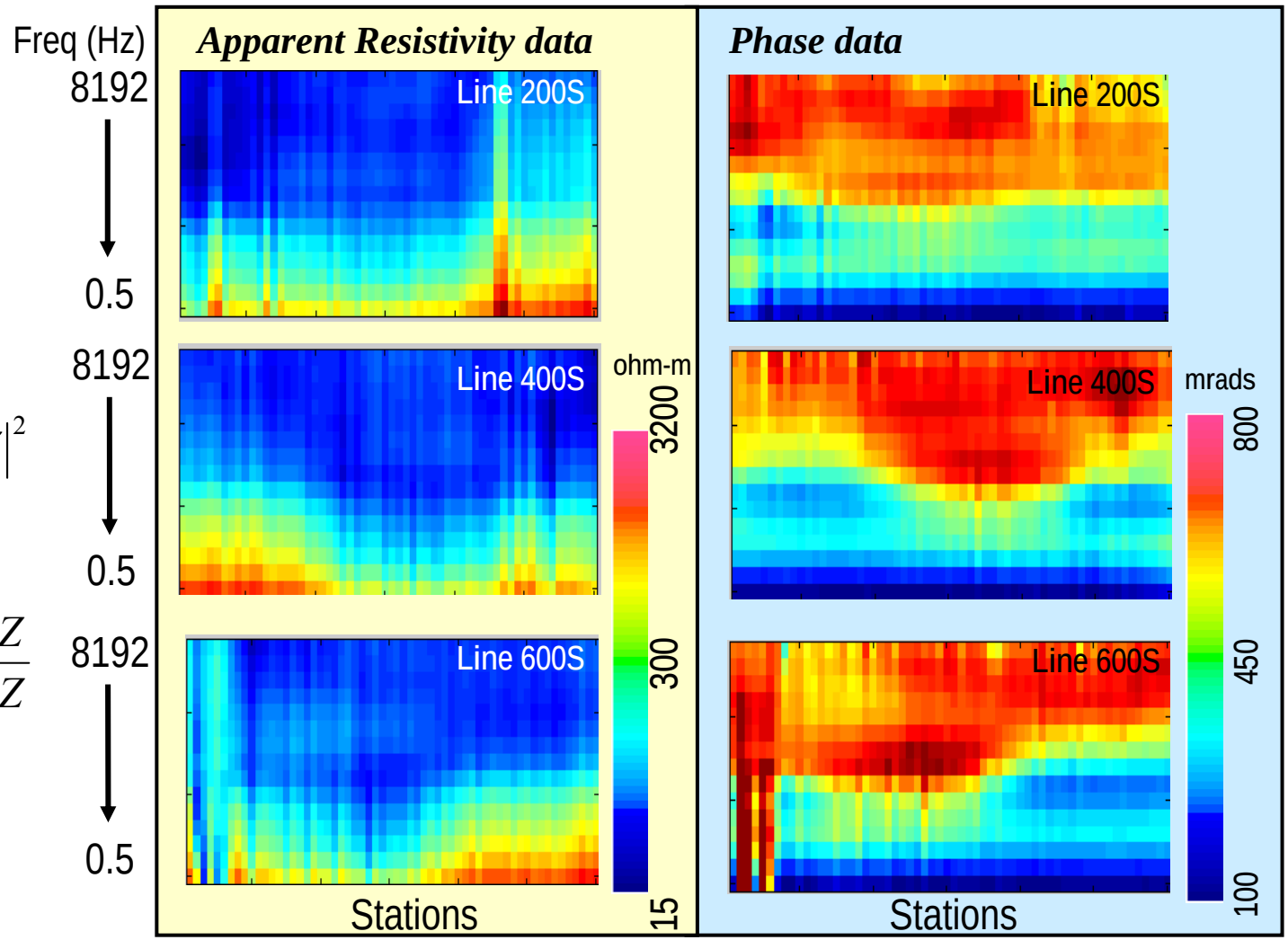


San Nicolás: 3 lines of CSAMT raw data

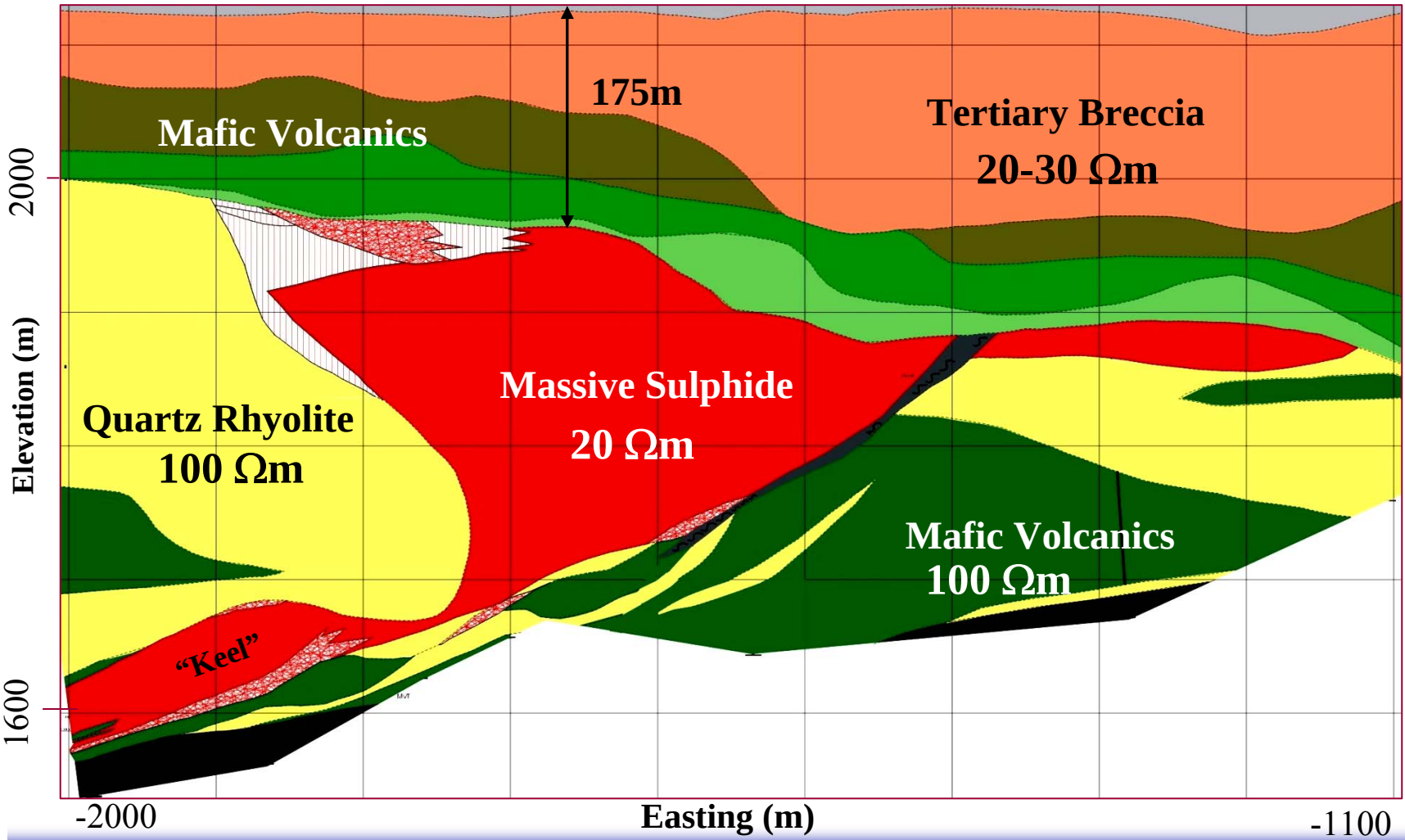
$$Z = \frac{E}{H}$$

$$\rho_a = \frac{1}{\mu_0 \omega} |Z|^2$$

$$\phi = \tan^{-1} \frac{\mathrm{Im}\, Z}{\mathrm{Re}\, Z}$$



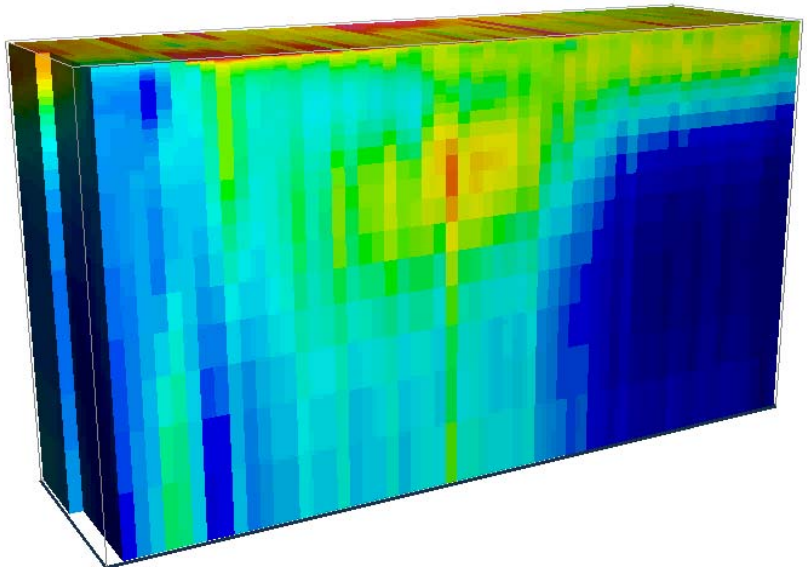
Geology and Physical Properties:
San Nicolas deposit

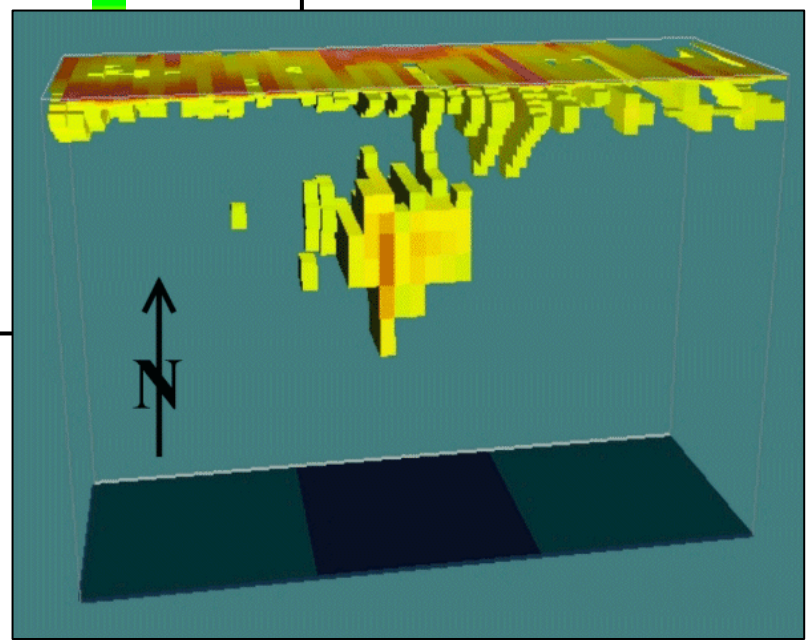


* Geologic Cross section by Nigel Philips

San Nicolás: CSAMT 1D inversion results

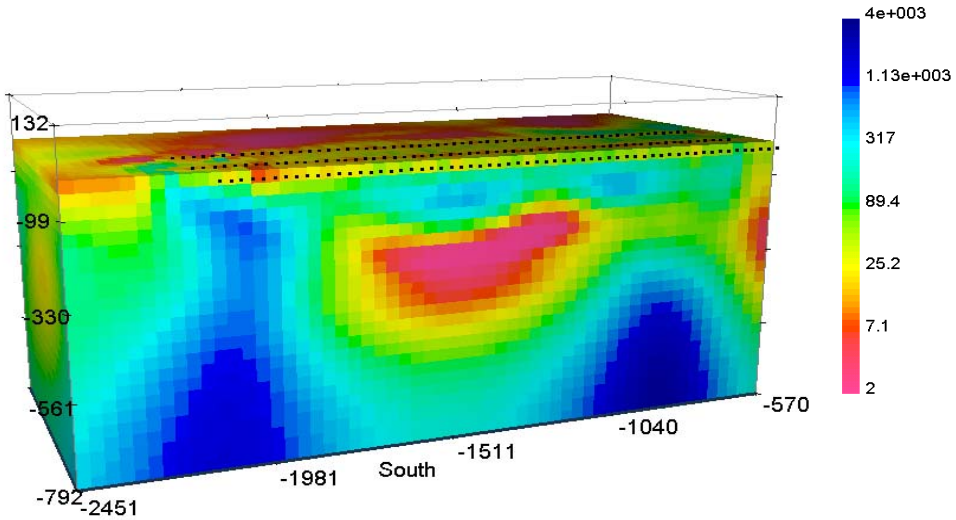
3D model from many 1D column-models



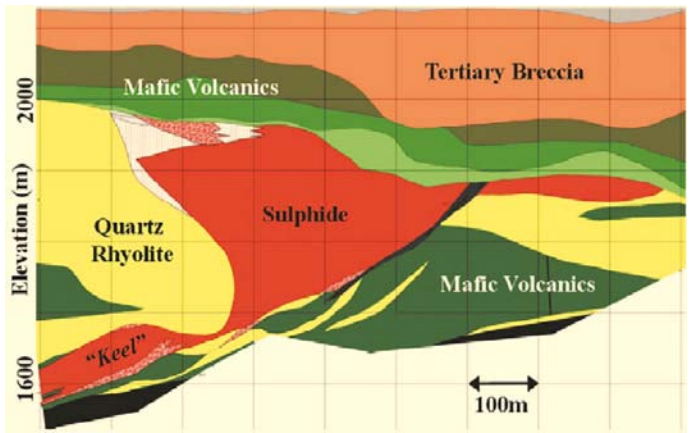


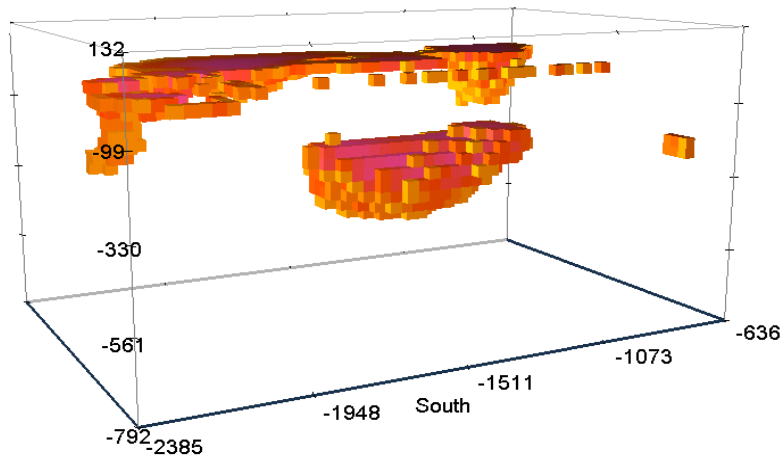
Isosurface view of the same 3D conductivity model

3D CSEM Inversion



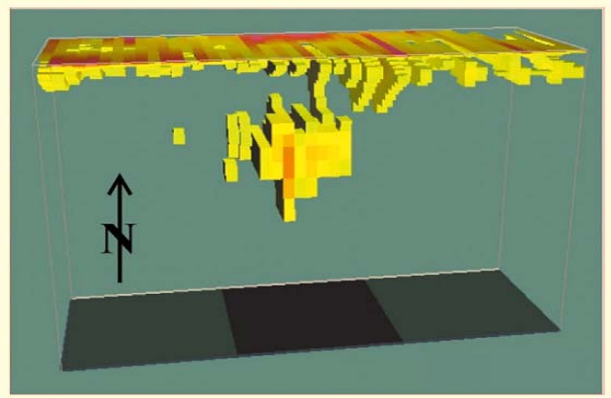
Frequencies
0.5, 8, 64, 256 Hz

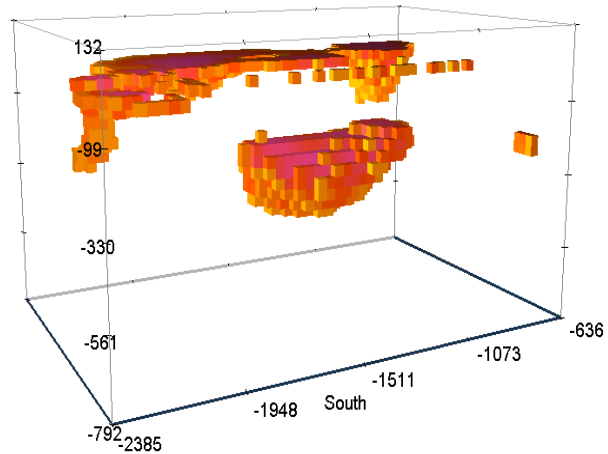


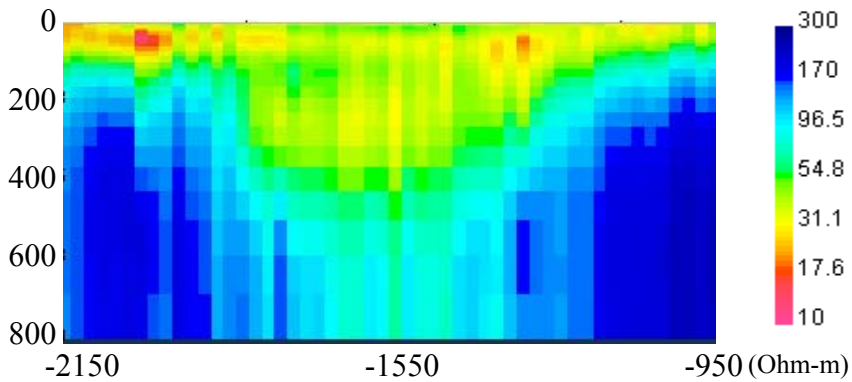


Iso-surface cutoff 10 Ohm-m

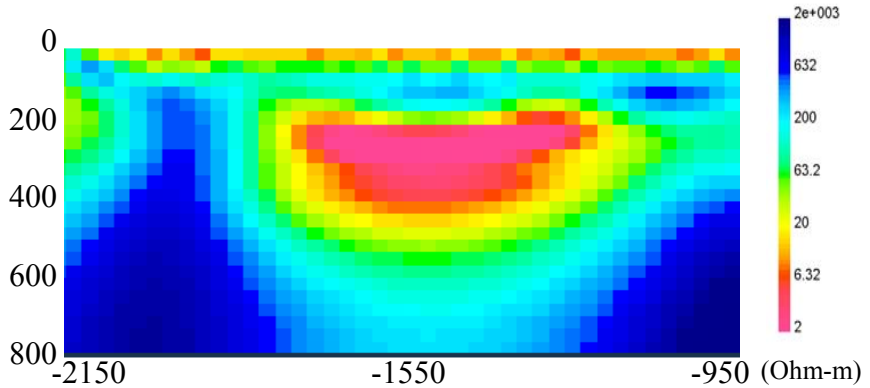
Comparison of 1D and 3D





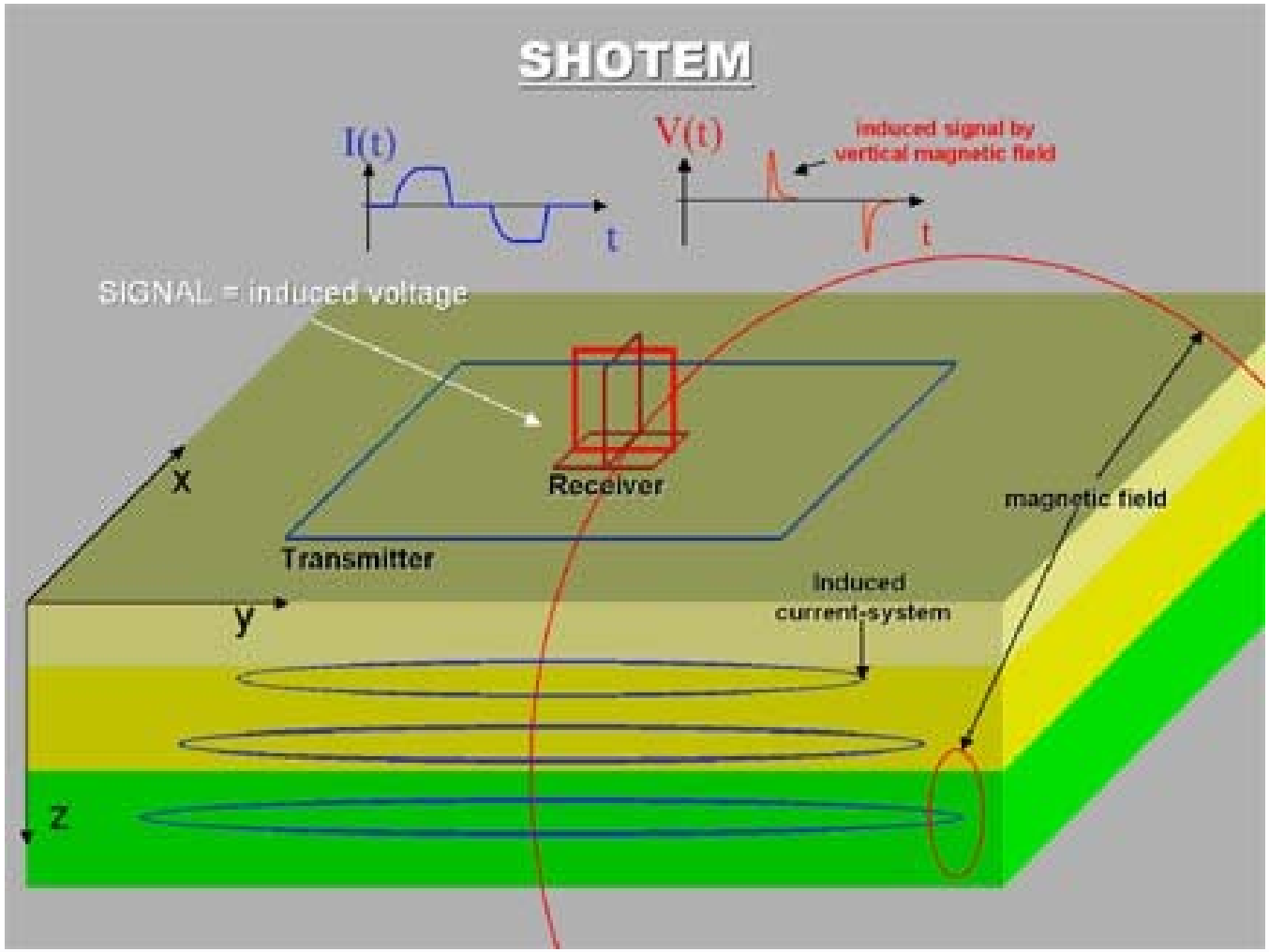


1D CSEM



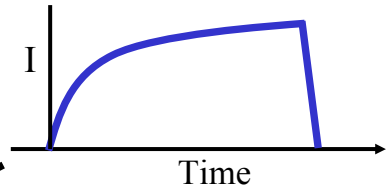
3D CSEM

Time domain EM: typical system



3D TEM Setup

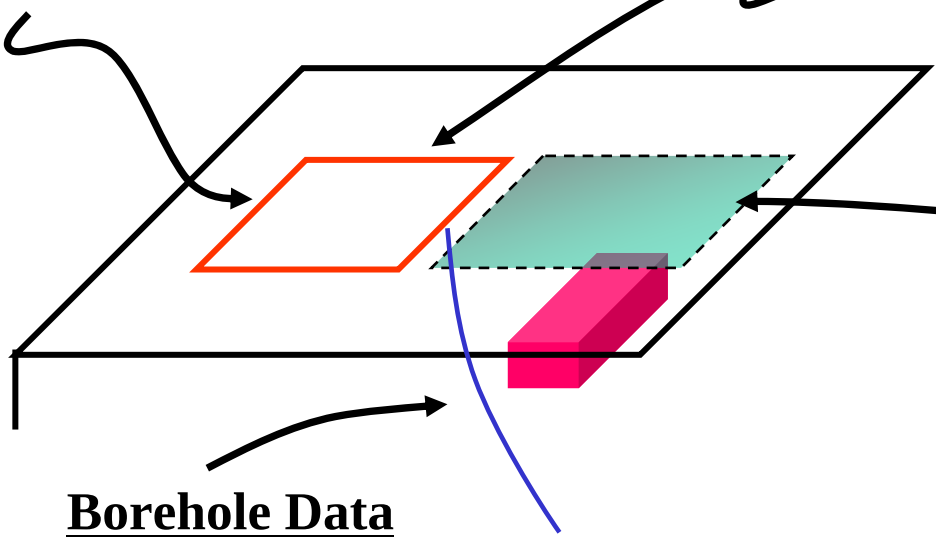
Waveform



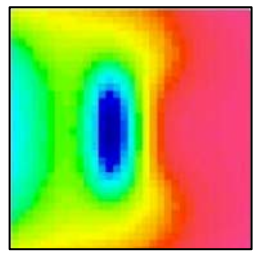
(half sine, step…)

Source

(Loop or grounded electrode)



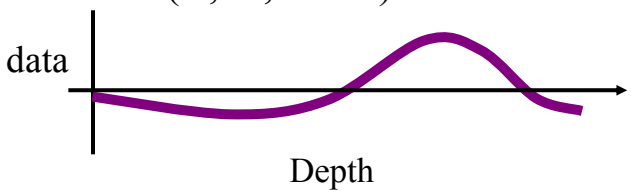
Surface Data



(**E**, **H**, d**B**/dt)

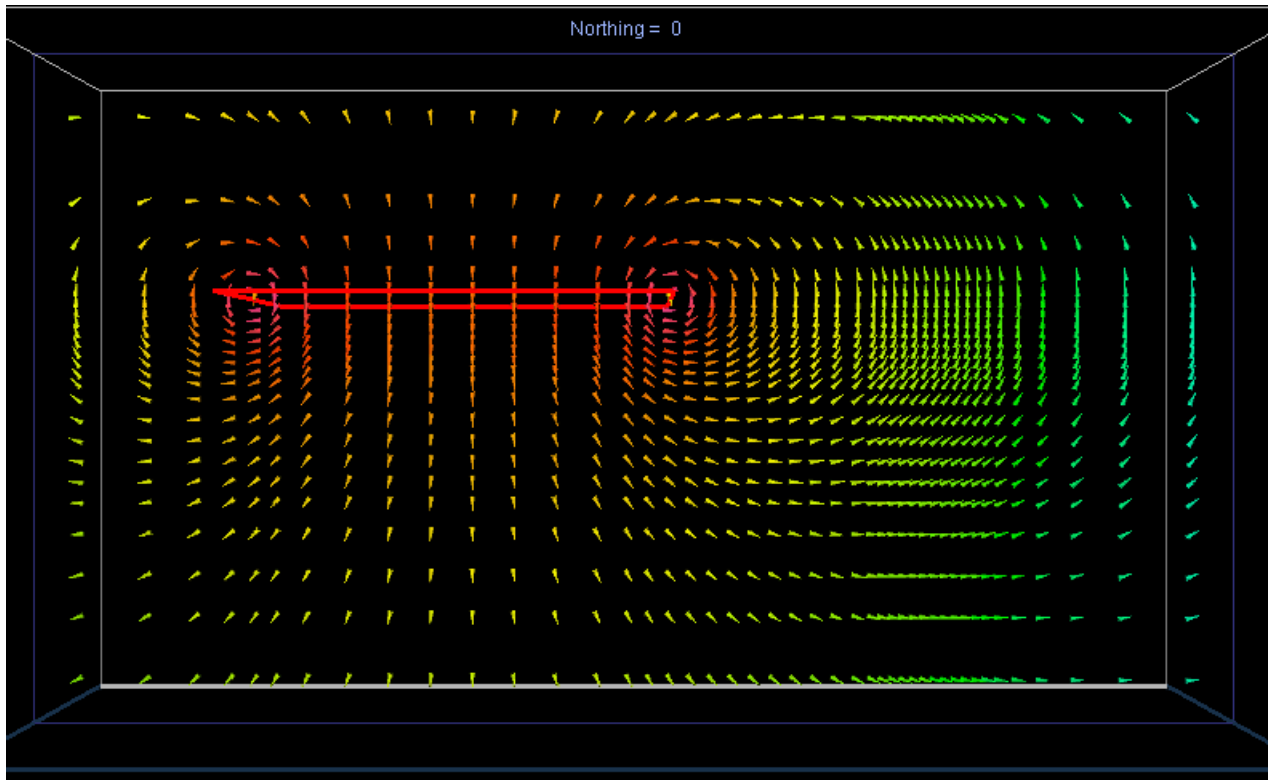
Borehole Data

(**E**, **H**, d**B**/dt)

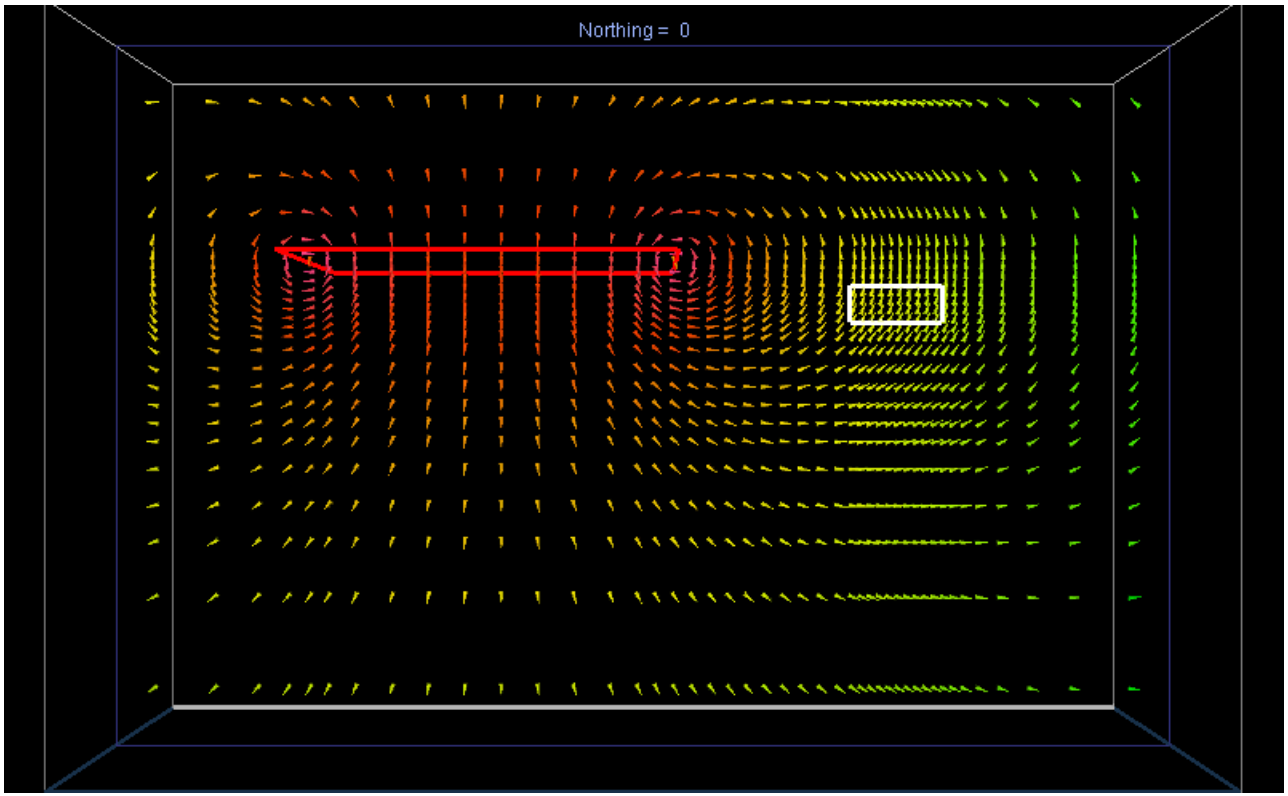


$$\nabla \times \mathbf{E} + \mu \mathbf{H}_t = 0$$
$$\nabla \times \mathbf{H} - \sigma \mathbf{E} - \epsilon \mathbf{E}_t = \mathbf{s}_r(t)$$

Time Domain EM: Currents

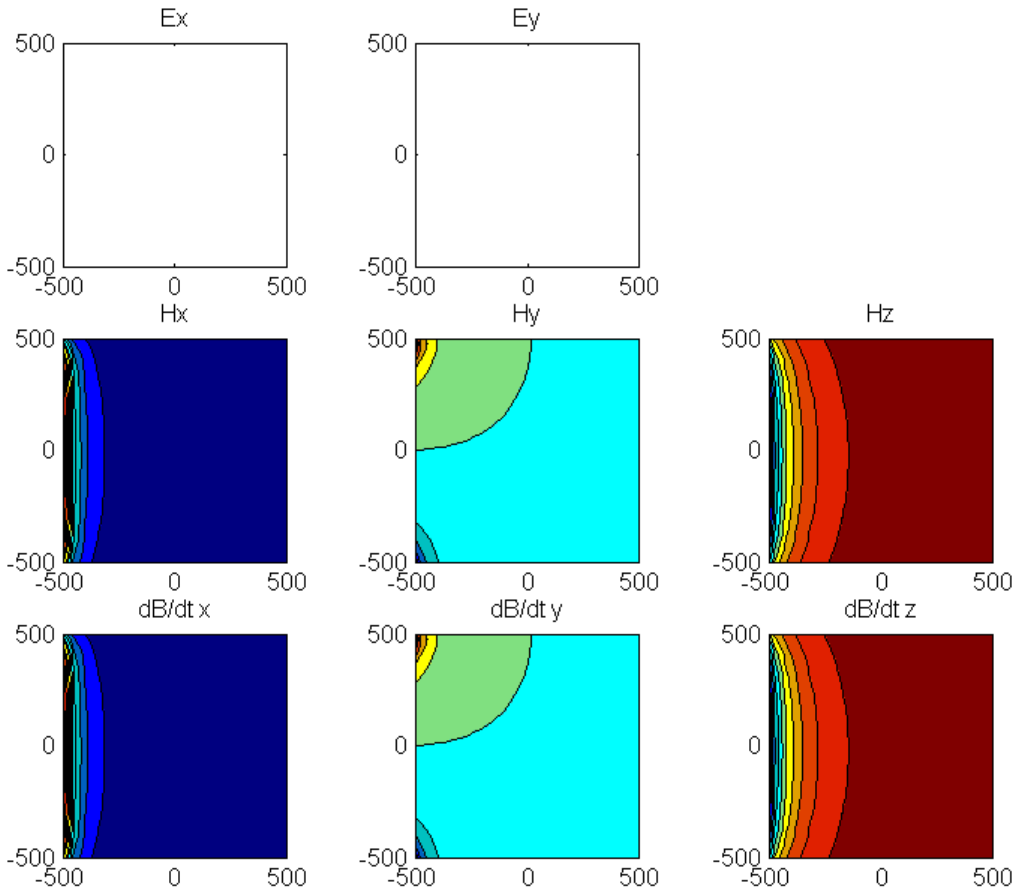


Time Domain EM: Currents

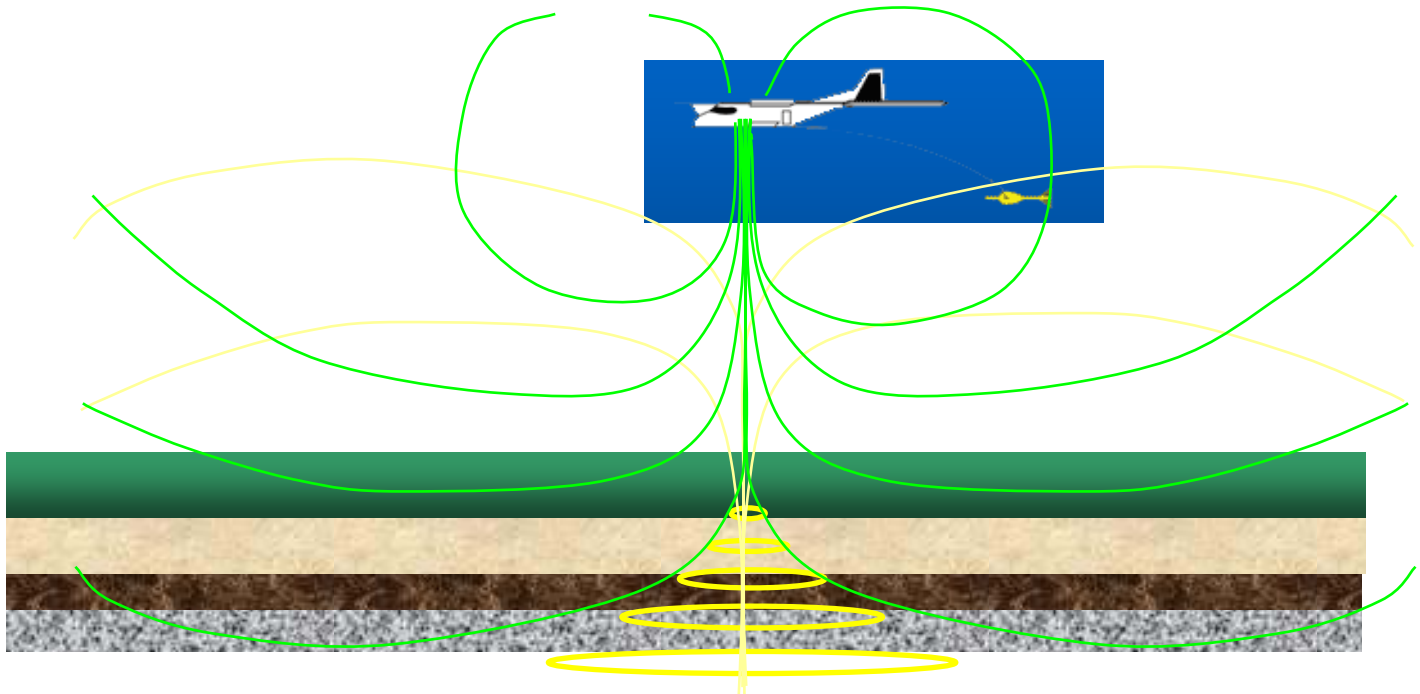


Data

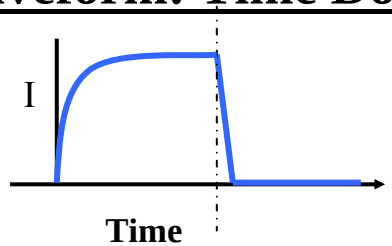
- E, H, or dB/dt
- Measure on-time or off-time



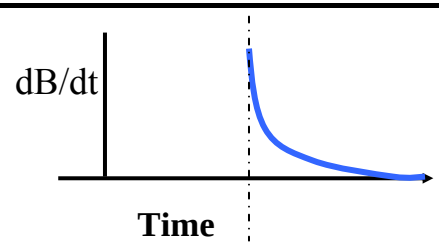
Airborne Time Domain EM Surveying:



Waveform: Time Domain



Inverted Data: Time Domain

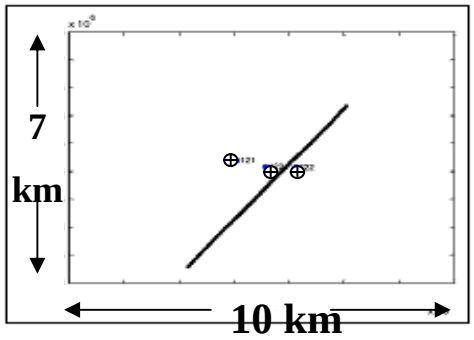


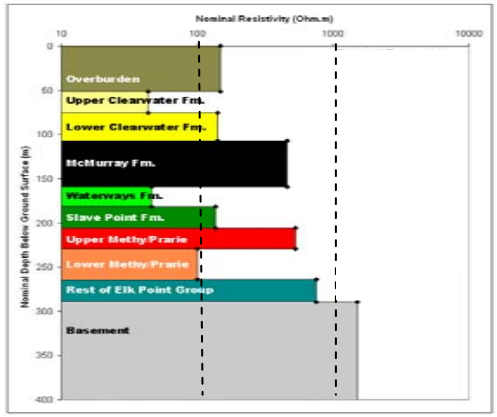
Time Domain EM:

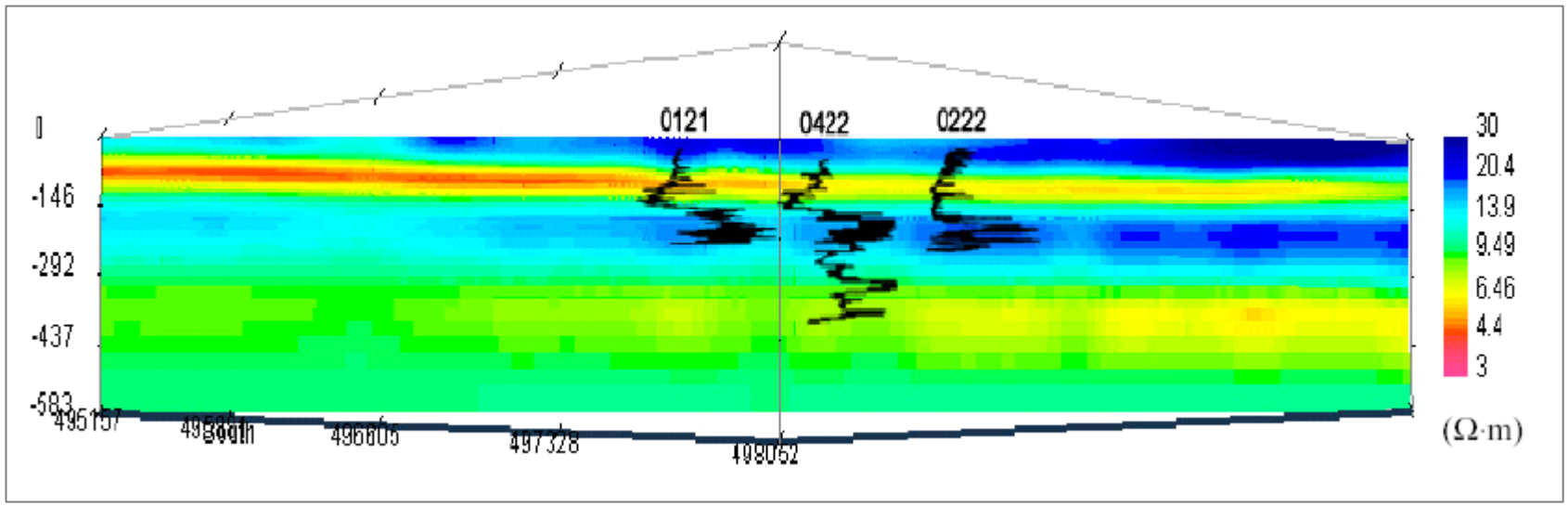
Advantages

- No primary field during recording stage
  - secondary fields only
- Depth of investigation
  - (maximum 150-400 m)
- Large areas at low cost
  - low environmental impact

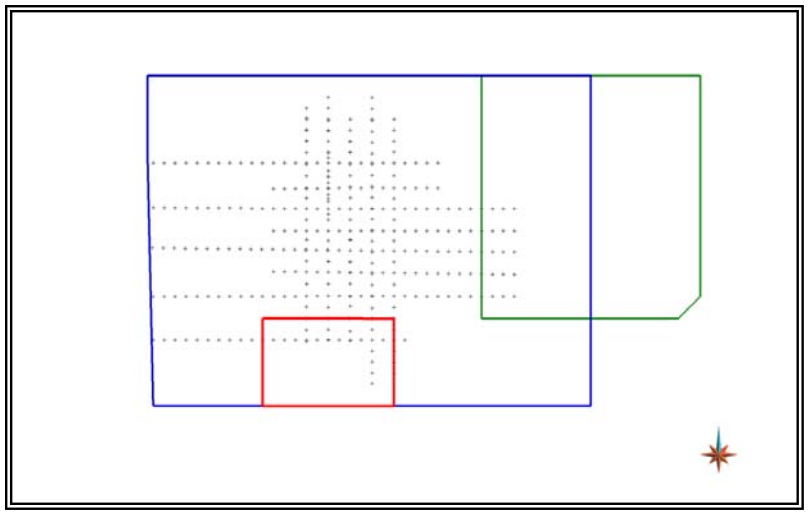
Inversion: McMurray Tar Sands





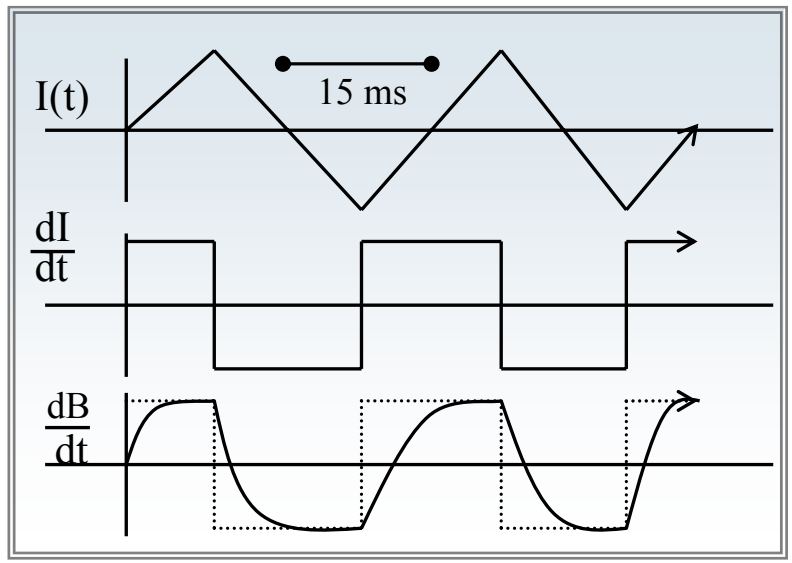


UTEM data at San Nicolas

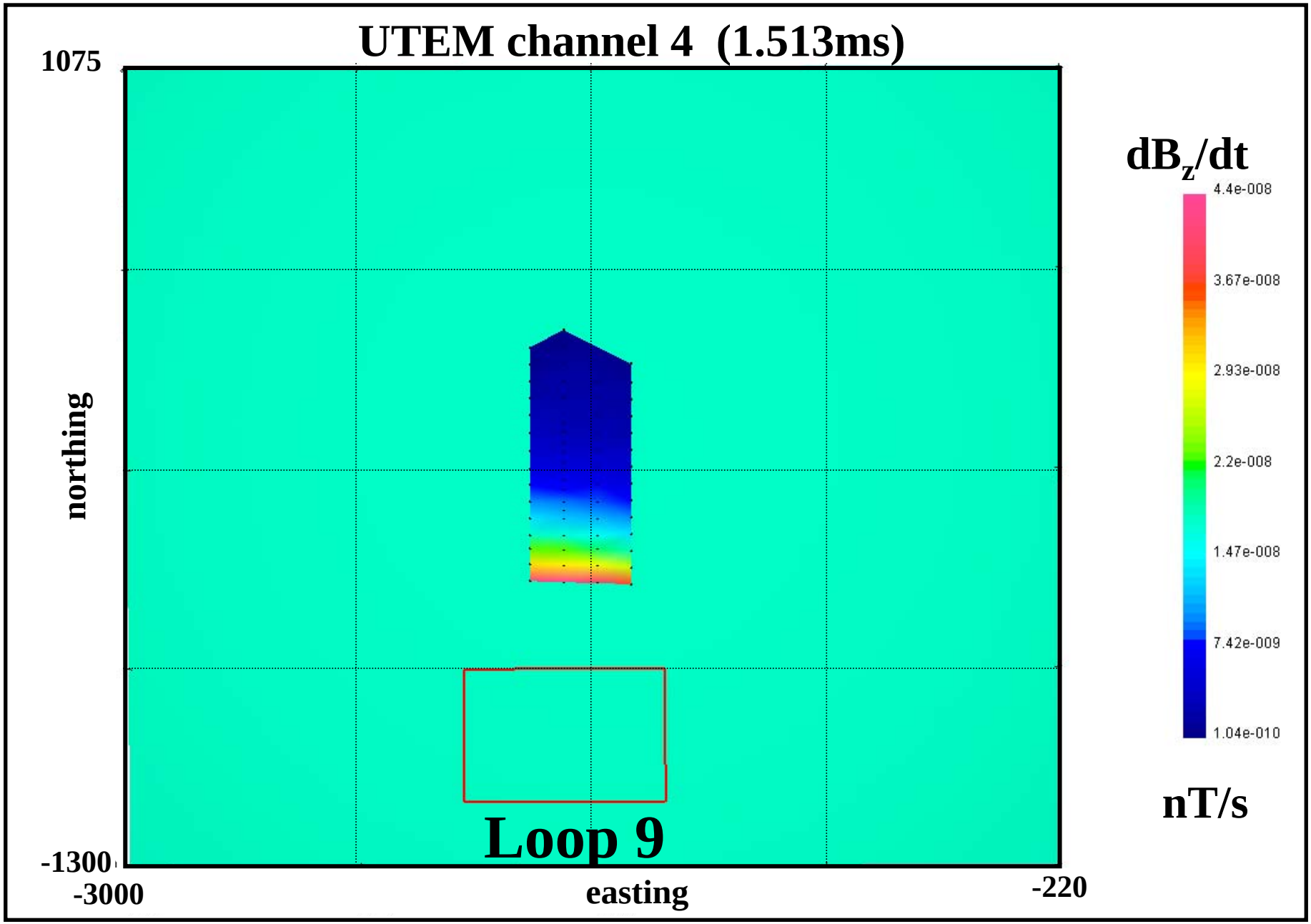


- 3 large loop transmitters
  - 2 km by 1.5 km
- d**B**/dt receivers
  - mainly z component

- transmitter waveform
  - 30 Hz sawtooth wave
  - dI/dt constant over half cycle
- Rx measures d**B**/dt

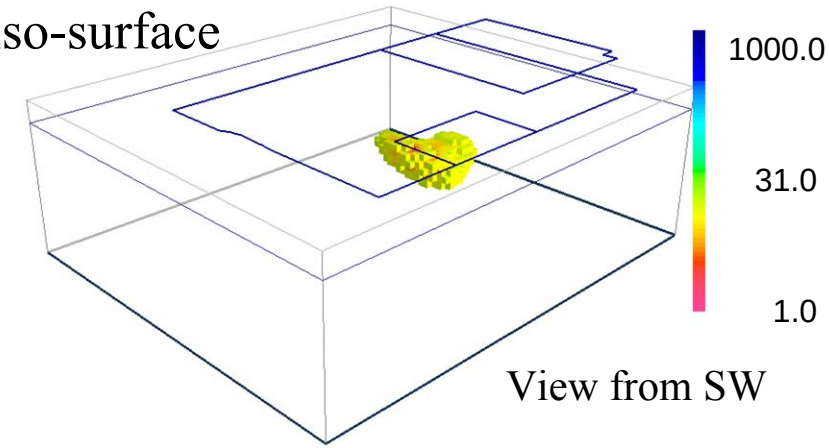


San Nicolas UTEM data

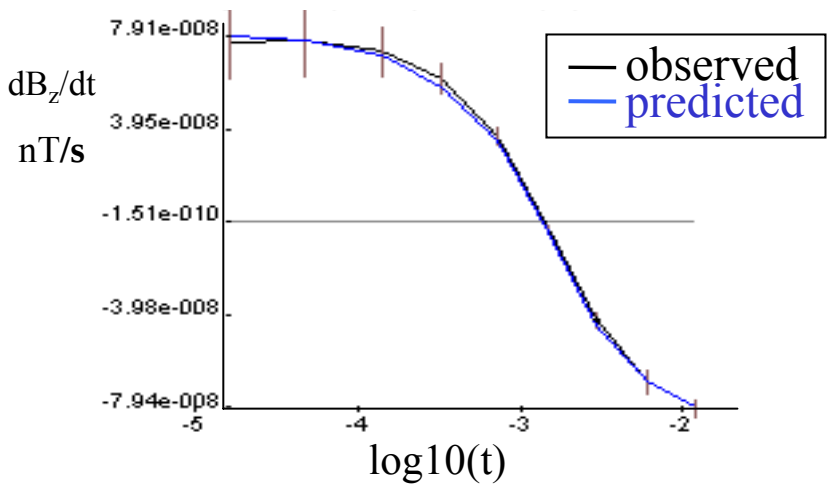


Fitting the data

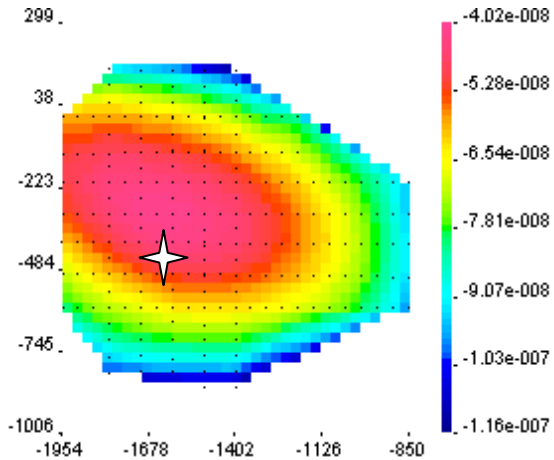
Observed 15 Ωm iso-surface



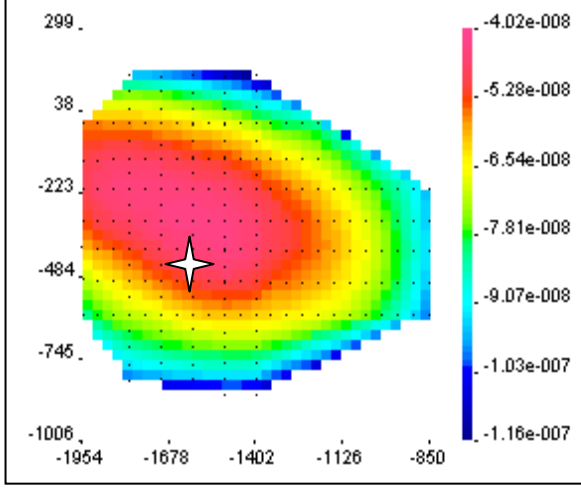
One decay curve: Observed and predicted



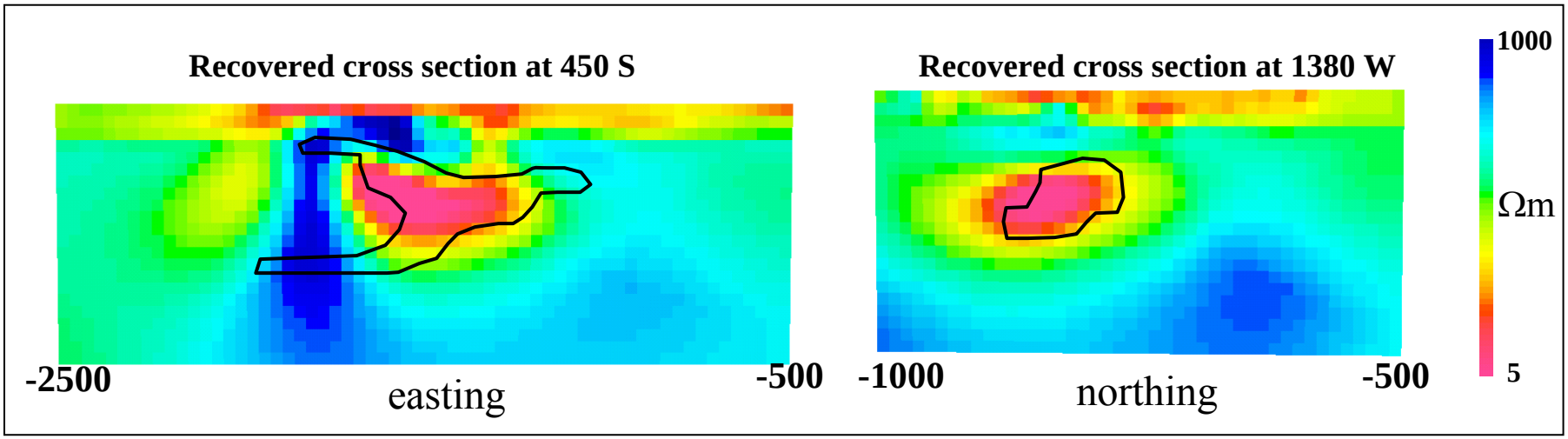
Observed

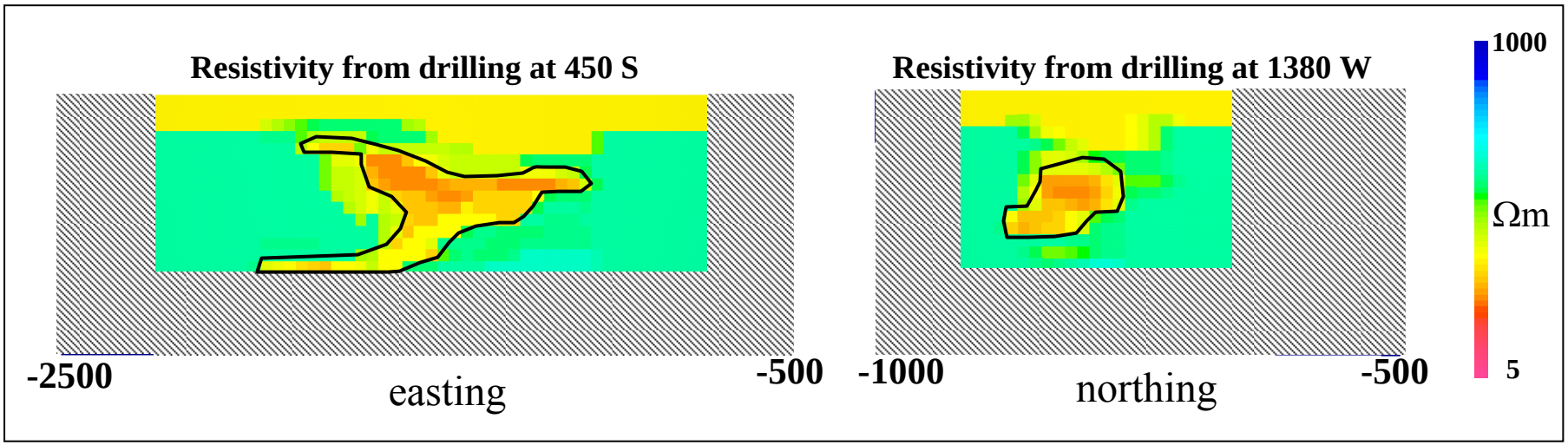


Predicted

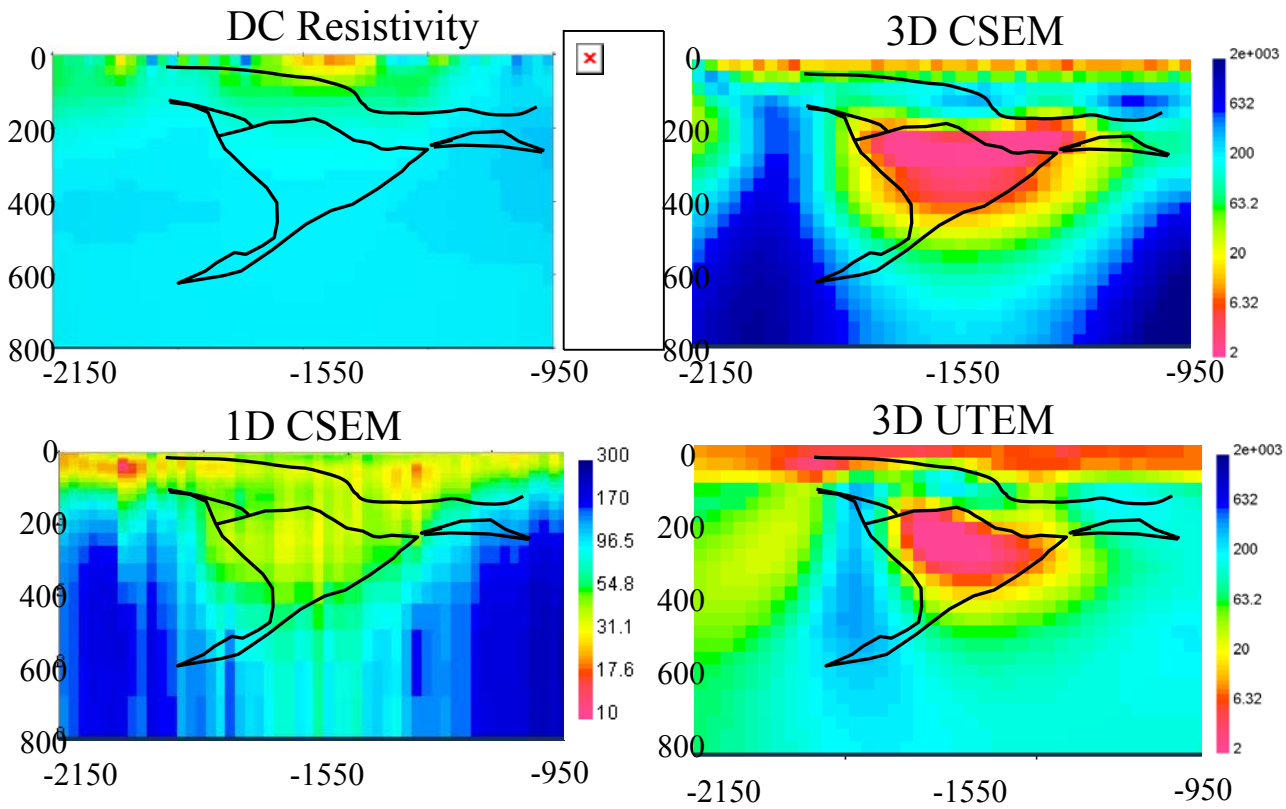


San Nicolas inversion results:





Four conductivity models at San Nic

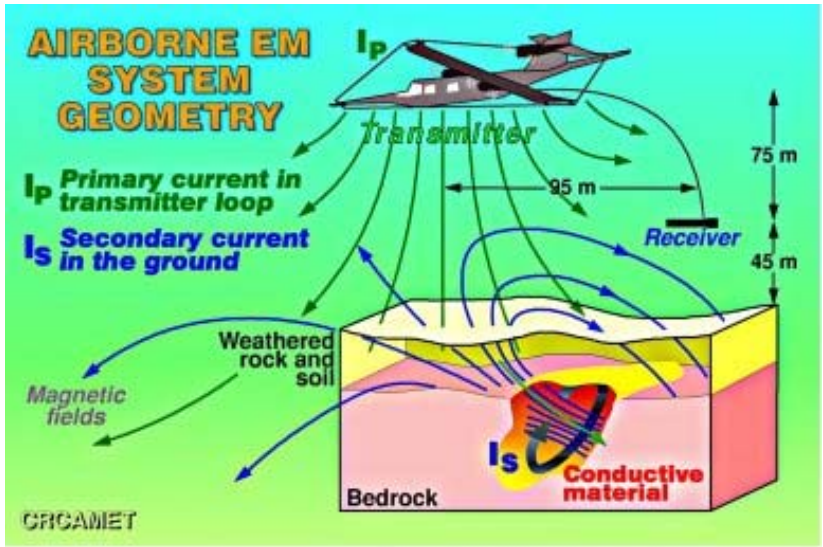


- 3D (frequency and time domain) conductivities show deposit at the same location and same conductivities

Summary:

Principles of EM induction

- Frequency domain
- Time domain



Main applications:

- anomaly detection (particularly airborne 1D)
- background delineation (particularly airborne 1D)
- detailing structure (3D ground or borehole surveys)

Acknowledgments

- Roman Shekhtman
- Dikun Yang
- UBC-GIF Researchers who have contributed to the results shown
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    - Rob Eso
    - Nigel Phillips
    - Eldad Haber
    - Colin Farquharson