The University of British Columbia
Geophysical Inversion Facility

UBC-GIF: Capabilities for EM Modelling and Inversion of LSBB data

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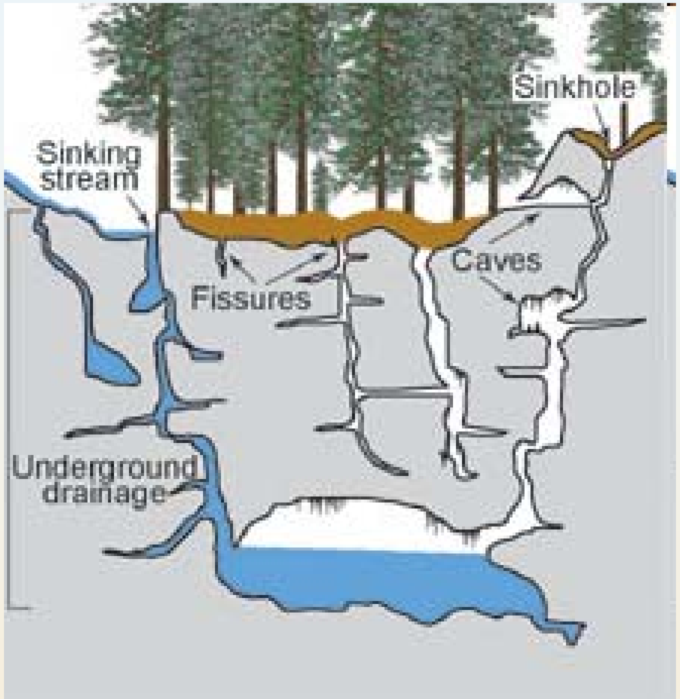
June 12, 2009

LSBB: Karst Aquifer Characterization

- Principle Questions:
  - What is the underground matrix
  - Hydrogeologic properties
  - Storage capacity
  - Production capacity
  - Potential for pollution
  - Sustainability



- What is the role of geophysics?

Framework for Applied Geophysics

- What is the question to be answered?
- What are the diagnostic physical properties?

Density
Magnetic susceptibility
Electrical conductivity

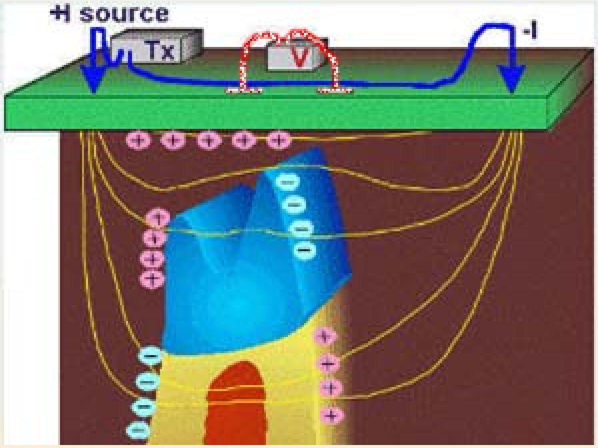
Electrical permittivity
Elastic parameters

- Choose survey type
- Collect data
- **Invert data** to get physical property model
- Interpret model and synthesize with other data

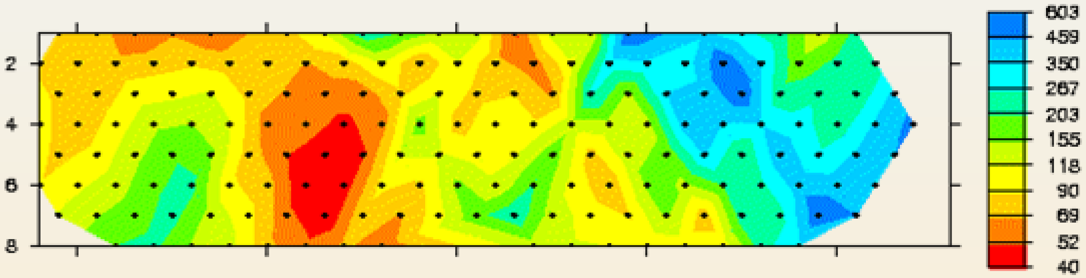
Geophysical Experiment

- Physical property: Electrical conductivity
- Survey: DC Resistivity
- Collect data

DC survey

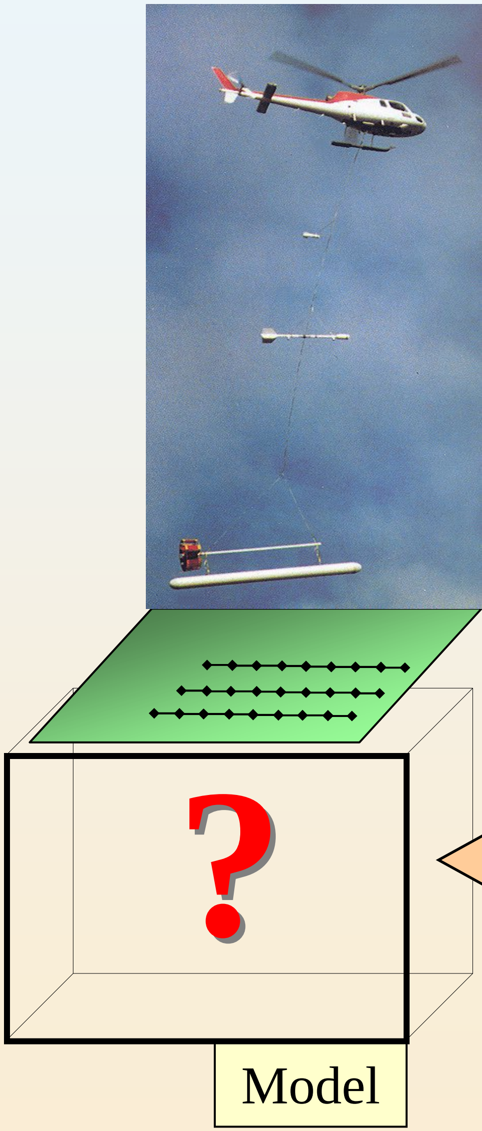


Data: "pseudosection"

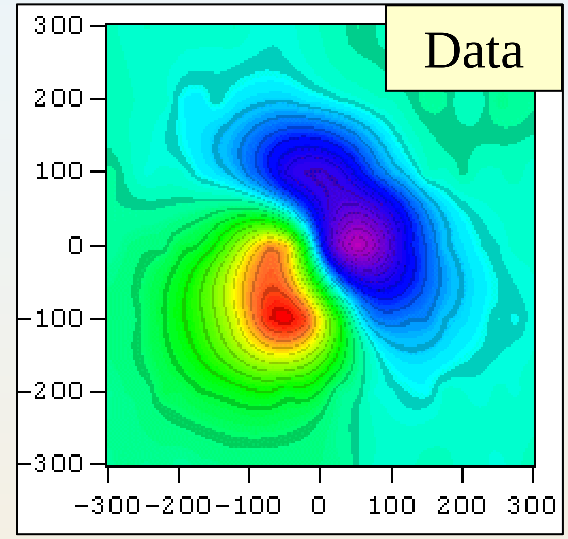


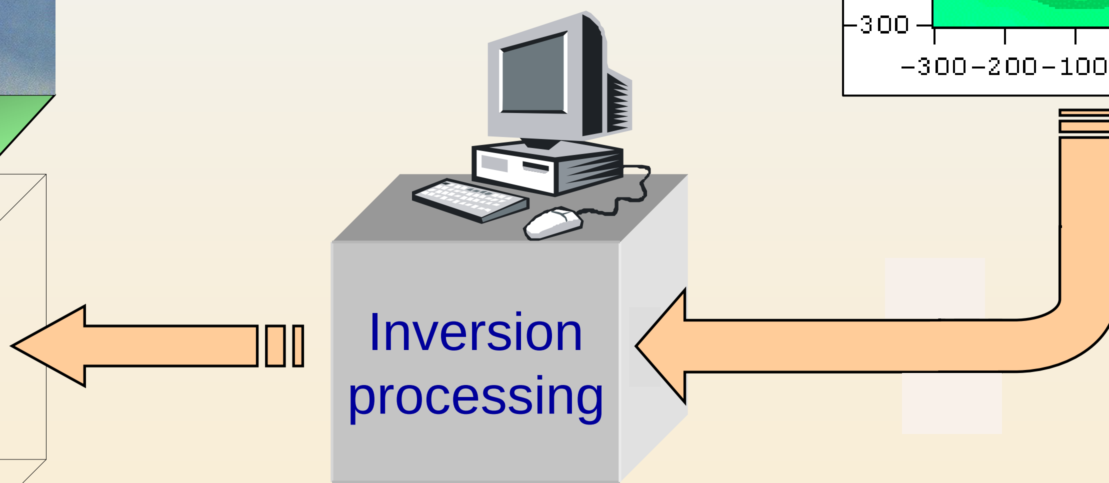
Data images cannot be directly interpreted in terms of geology
Data must be inverted

What is Inversion?



Measurements over the Earth are **data**.

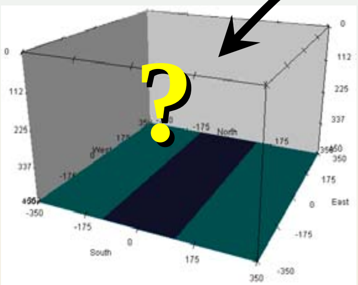




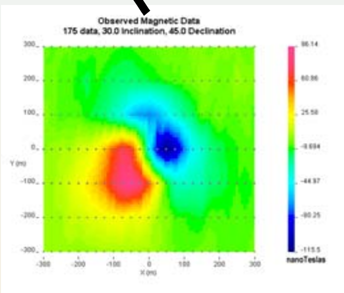
Inversion estimates Earth **models** based upon data and prior knowledge.

The inverse problem

- Geophysical data are: $\mathbf{F}[\mathbf{m}] + \in = \mathbf{d}$
  - **m**: model --- unknown
  - **F**: forward mapping operator
  - $\in$: errors
  - **d**: observations (data)



$\mathbf{F}^{-1}$



- **Given:**
  - data, errors, a forward modelling method
- **Find:**
  - the model that generated measurements.
- **Major Difficulty:** Nonuniquenes

Inversion as optimization: 3 parts

Misfit:

$$\phi_d = \sum_{i=1}^{N} \left(\frac{F_i[m] - d_i^{obs}}{\varepsilon_i} \right)^2$$

- ε_i : standard deviation

A priori information: reference model, structural detail...

Model objective function:

$$\phi_m(m) = \alpha_s \int_S (m - m_0)^2 dv + \alpha_x \int_S \left(\frac{\partial (m - m_0)}{\partial x} \right)^2 dv + \ldots$$

- α_s, α_x ... constants
- m_0 : reference model

Inversion as optimization:

$$\phi = \phi_d + \beta \, \phi_m.$$

$0 < \beta < \infty$ is a constant

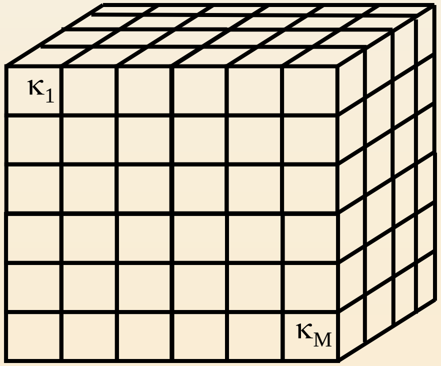
Choose β such that $\phi_d < Tolerance$

Numerical solution

- Discretize: Divide the earth into M cells of constant physical property (M>>N).
- Minimize

$$\phi = \phi_d + \beta\phi_m$$
$$= \left\| W_d (F[m] - d^{obs}) \right\|^2 + \beta \left\| W_m (m - m_0) \right\|^2$$

- Use the Gauss-Newton method for solution.
- Solving for β:
  - Discrepancy principle.
  - GCV.
  - L-Curve.



Numerical solution (Gauss-Newton method)

- Minimize $\phi = \phi_d + \beta\phi_m$

$$= \left\| F[m] - d^{obs} \right\|^2 + \beta \left\| W(m - m_0) \right\|^2$$

- set

$$g(m) \equiv \frac{\partial \phi}{\partial m} = J(m)^T (F[m] - d^{obs}) + \beta W^T W (m - m_0) = 0$$

J is the sensitivity matrix: $J_{ij} = \dfrac{\partial d_i}{\partial m_j}$

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- Expand forward operator (dropping higher order terms):

$$F[m + \delta m] \approx F[m] + J(m)\delta m$$

Numerical solution (Gauss-Newton method)

- Minimize $$\phi = \phi_d + \beta\phi_m$$
$$= \left\| F[m] - d^{obs} \right\|^2 + \beta \left\| W(m - m_0) \right\|^2$$
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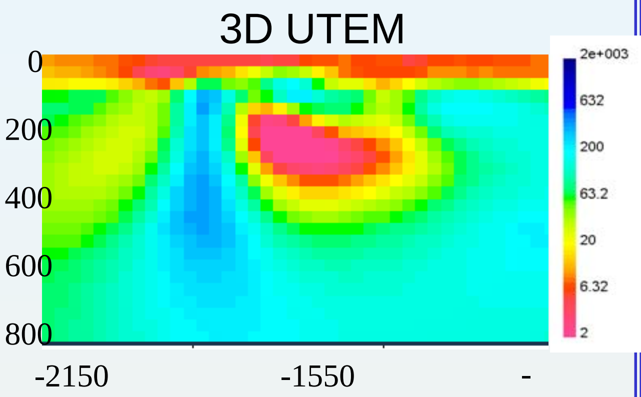
J is the sensitivity matrix: $J_{ij} = \frac{\partial d_i}{\partial m_j}$

- Expand forward operator (dropping higher order terms):
$$F[m + \delta m] \approx F[m] + J(m)\delta m$$
- Solve: $$\left(J(m_k)^T J(m_k) + \beta W^T W \right) \delta m = g(m_k)$$
    - where m_k is the model at the k^th iteration.
    - This is an M x M system of equations.

(*M* = # model parameters, or cells)

Inversion Capabilities



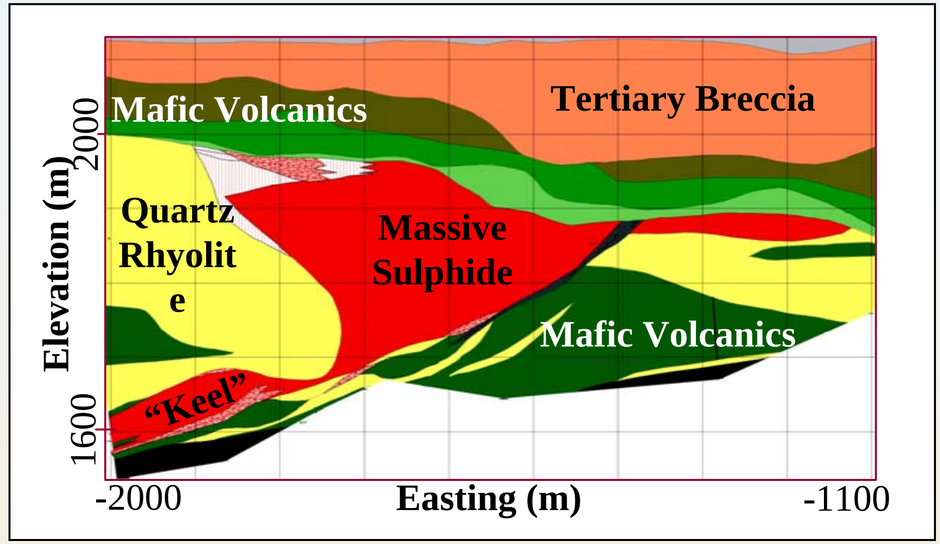
- Gravity (3D)
- Magnetics (3D)
- DC resistivity and IP (2D and 3D)
- Frequency domain EM (1D and 3D)
- Time domain EM (1D and 3D)

Software for inversion is distributed world wide through UBC and third party vendors

Field Example: San Nicolas Deposit

Location

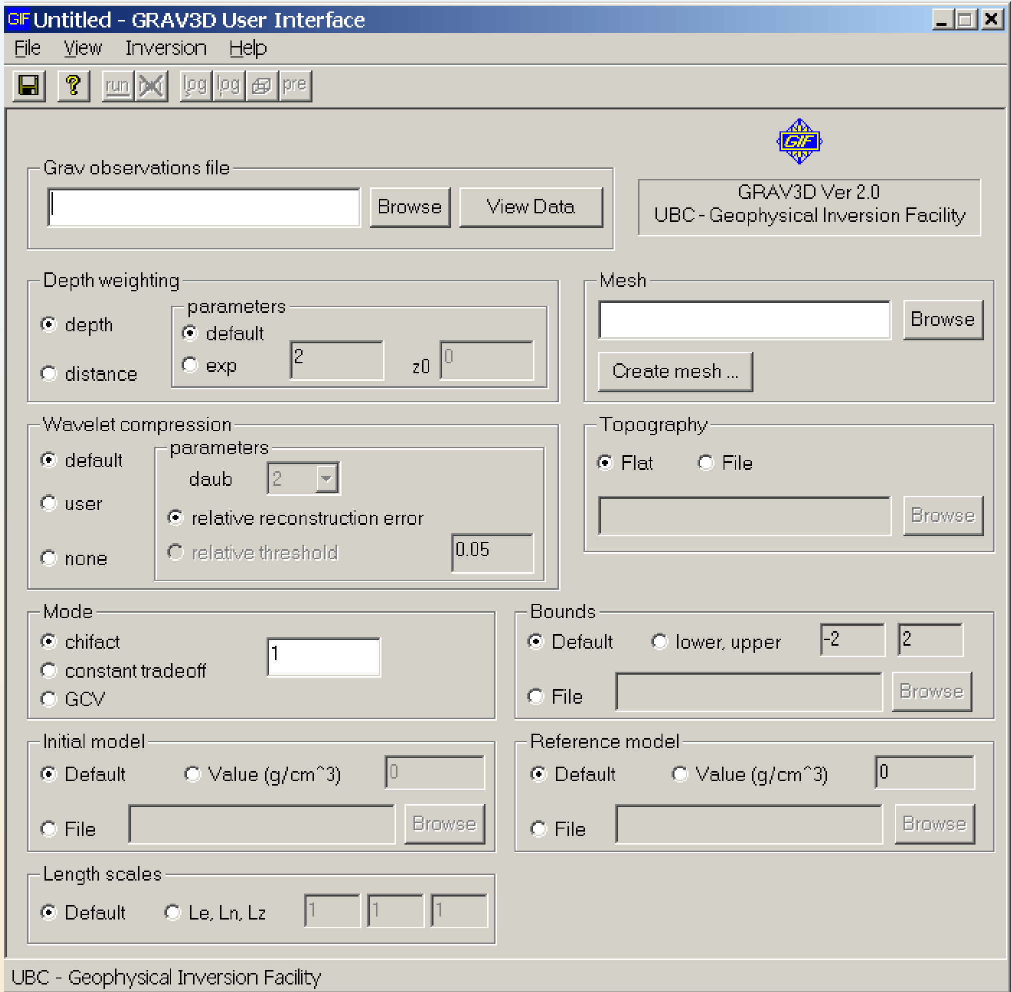
Geologic cross section



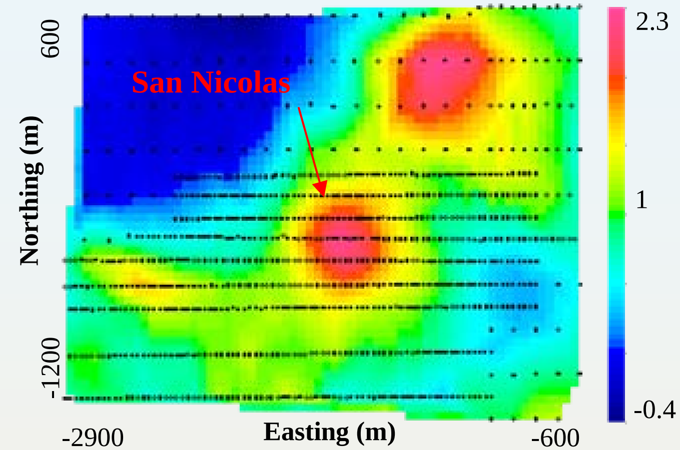
Physical properties

Unit	Density (g/cc)	Susceptibility (S.I. x10^3)	Resistivity (ohm- m)	Chargeability (msec)
Qal	2	0 - 10	50	5
Tv	2.3	0 (20)	20 -30	10 - 30
Mst./Lst	2.4	0	150	20 - 40
Mafic Vol.	2.7	0 - 5	80	30 - 50
Mafic/IntVol.	2.7	0 - 5	80	30 - 50
Sulphide	**3.5**	**10**	**20**	**200**
Qtz Rhyolite	2.4	0 - 10	100	10 - 20
GraphiticMst.	2.4	0 - 5	100+	30 - 70

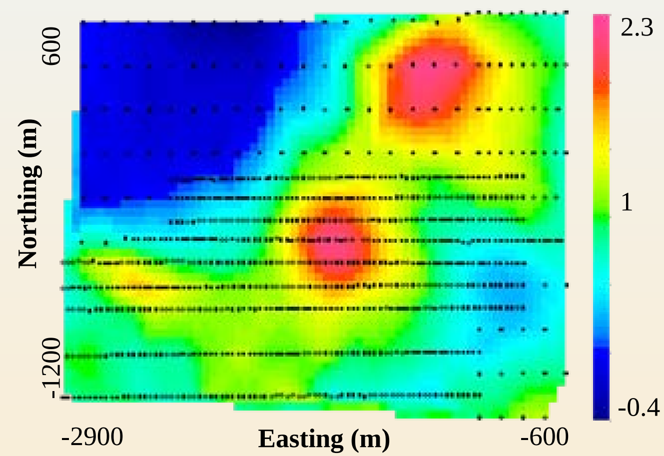
Gravity



Observed Data

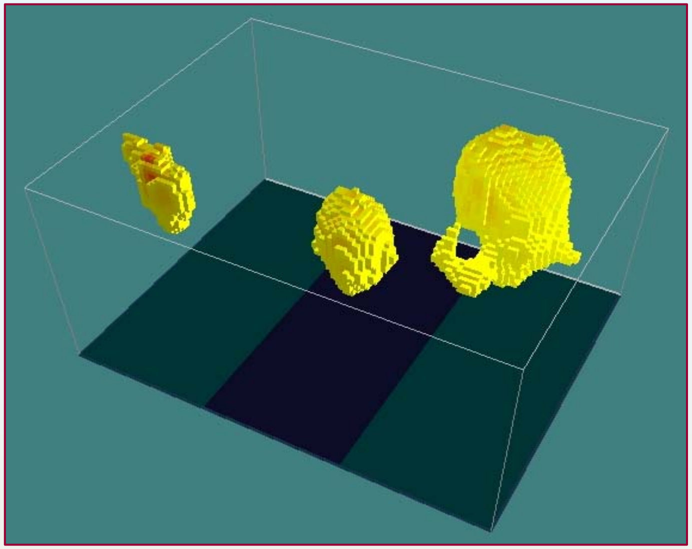


Predicted Data

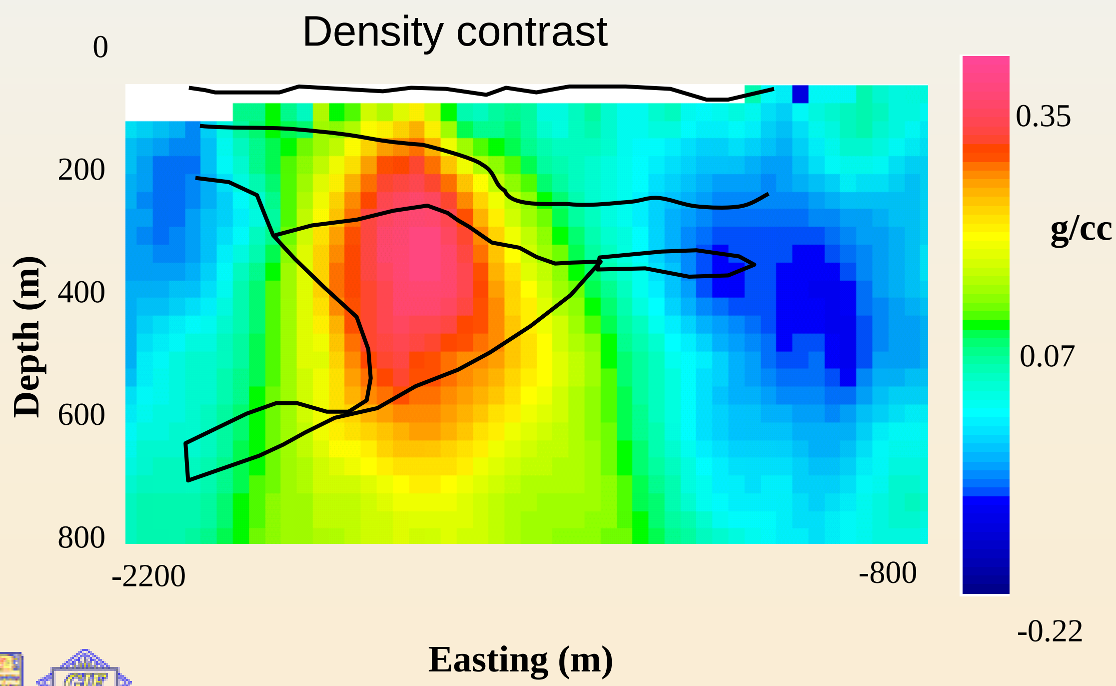


Gravity data collected at the San Nicholas deposit.

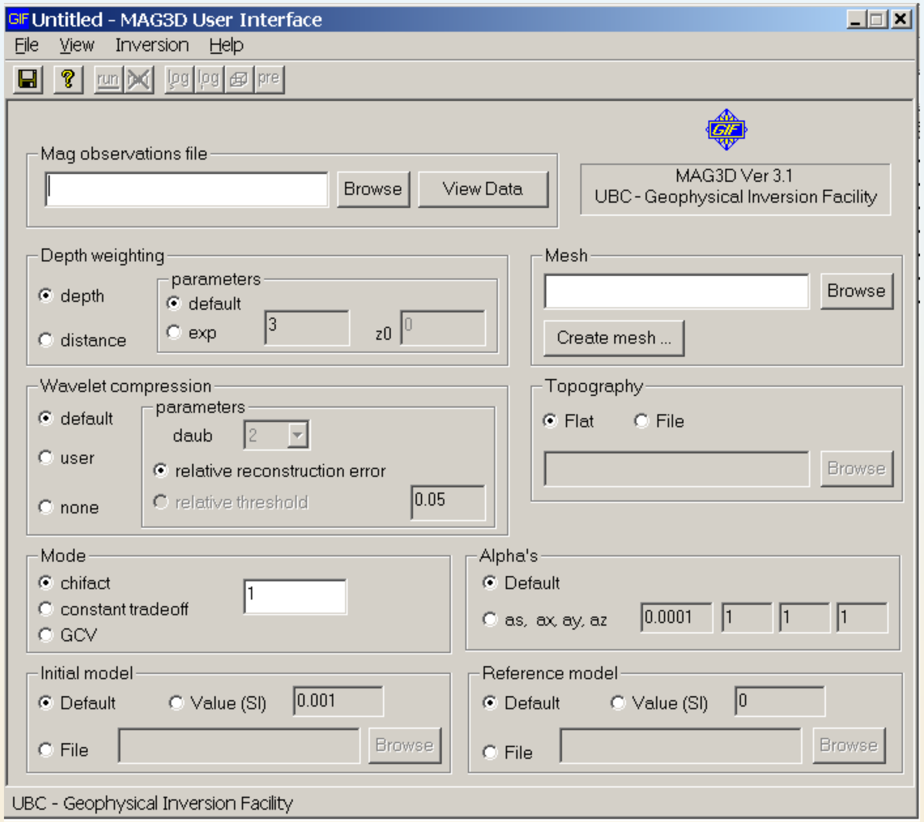
Gravity Inversion Results



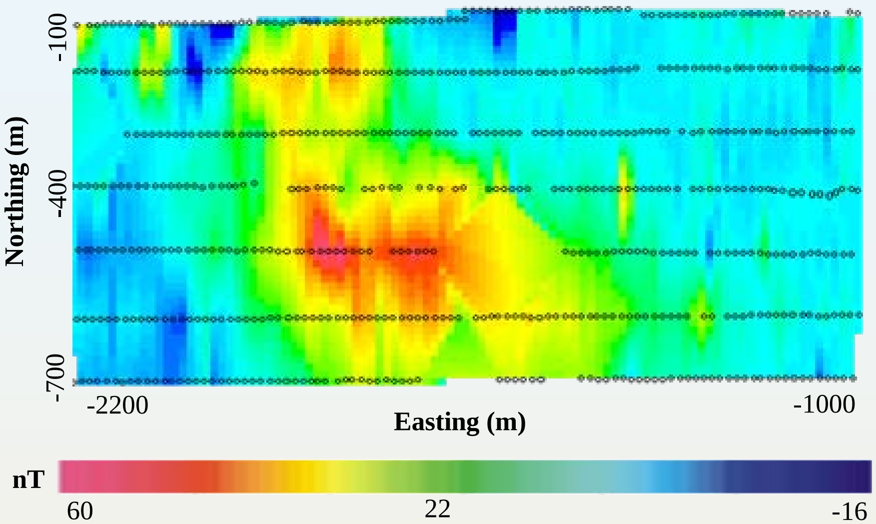
Cross-section of Density Contrast Model with Geology



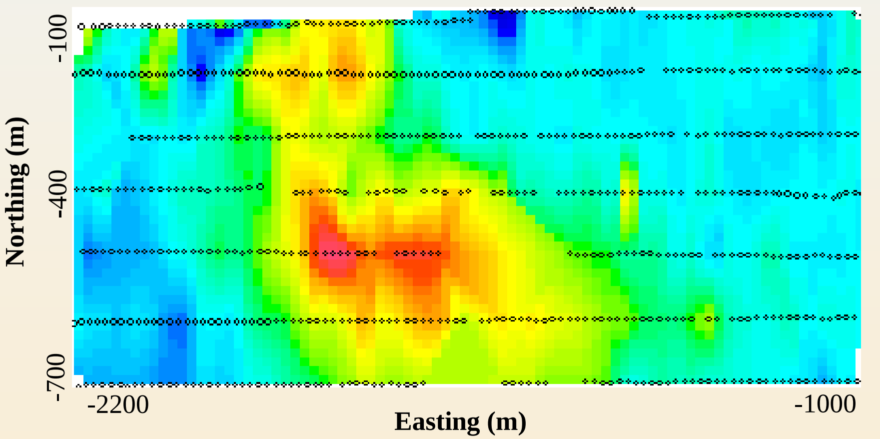
Magnetics



Observed Data

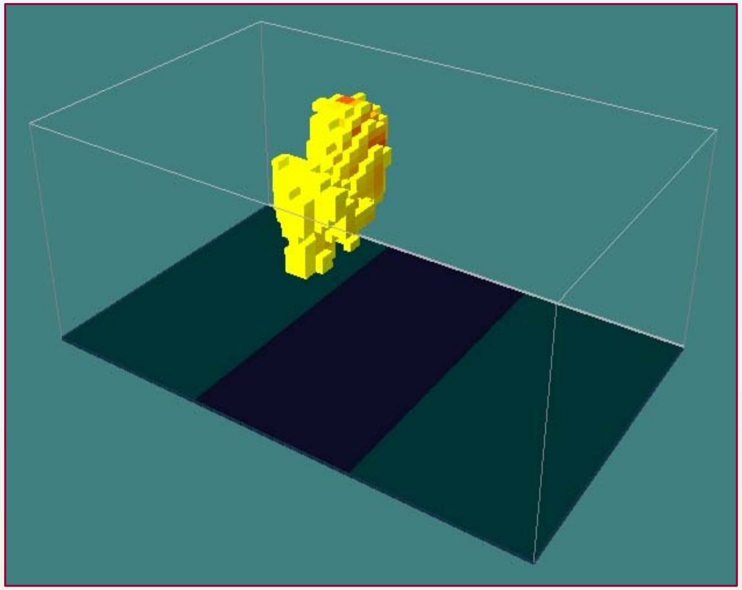


Predicted Data

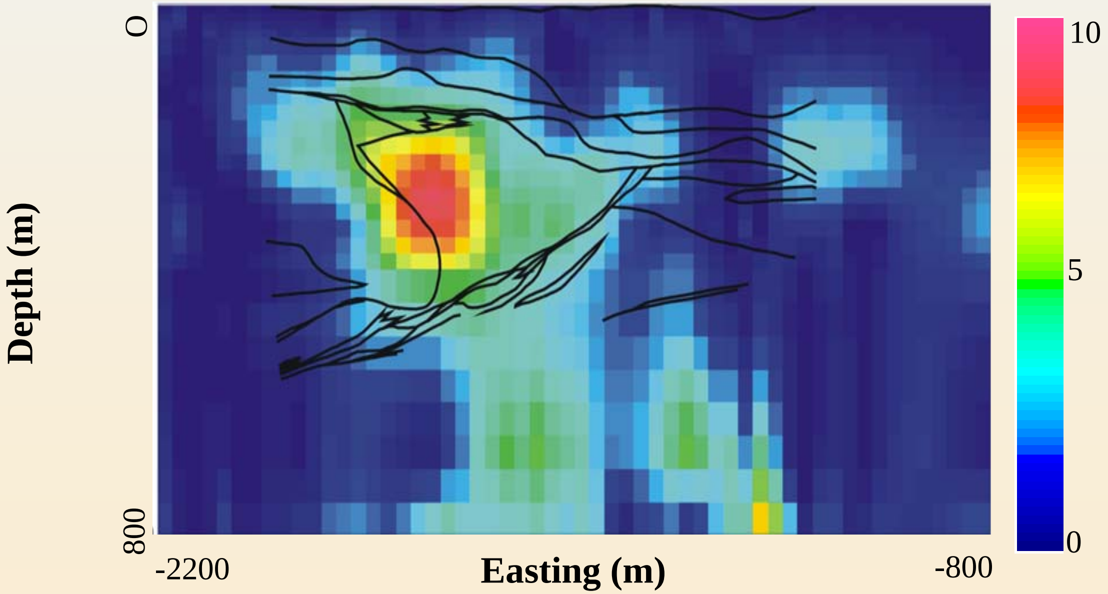


Magnetic data collected at the San Nicholas deposit.

Magnetic Inversion Results

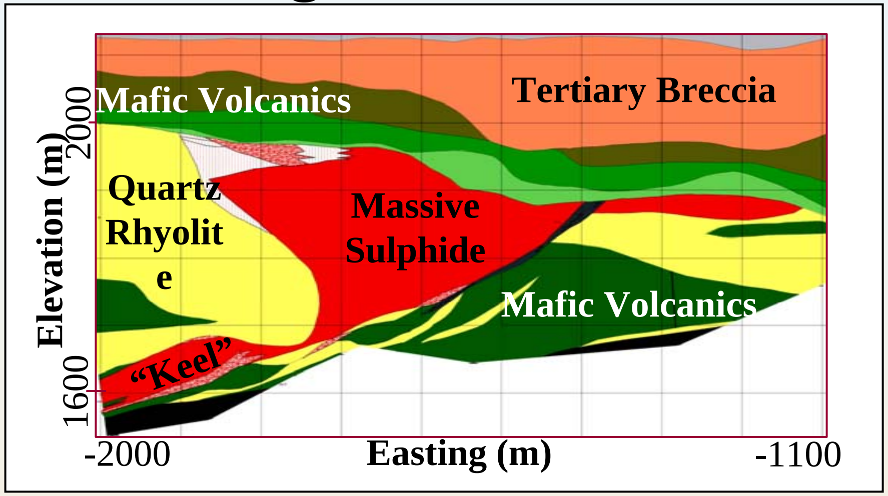


Cross-section of Magnetic Susceptibility Model with Geology



Field Example: San Nicolas Deposit

Geologic cross section



- ✓ Density
- ✓ Magnetic Susceptibility
- • Electrical Conductivity
- • Chargeability

Physical properties

Unit	Density (g/cc)	Susceptibility (S.I. x10^3)	Resistivity (ohm- m)	Chargeability (msec)
Qal	2	0 - 10	50	5
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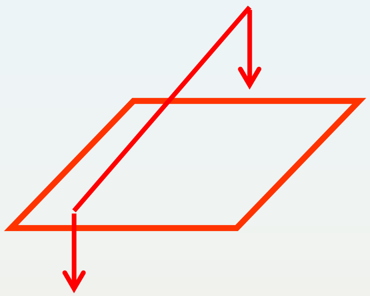
Electrical Conductivity: Different Surveys

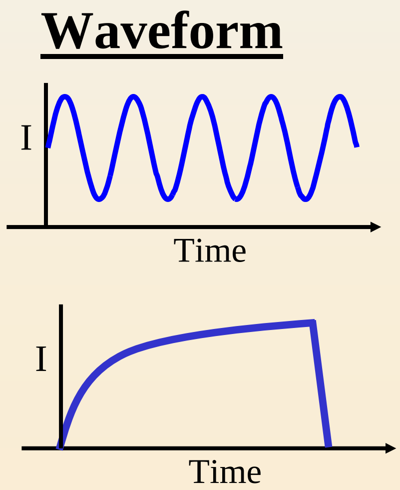
Sources:

- Galvanic (grounded electrodes)
- Inductive (current loops)

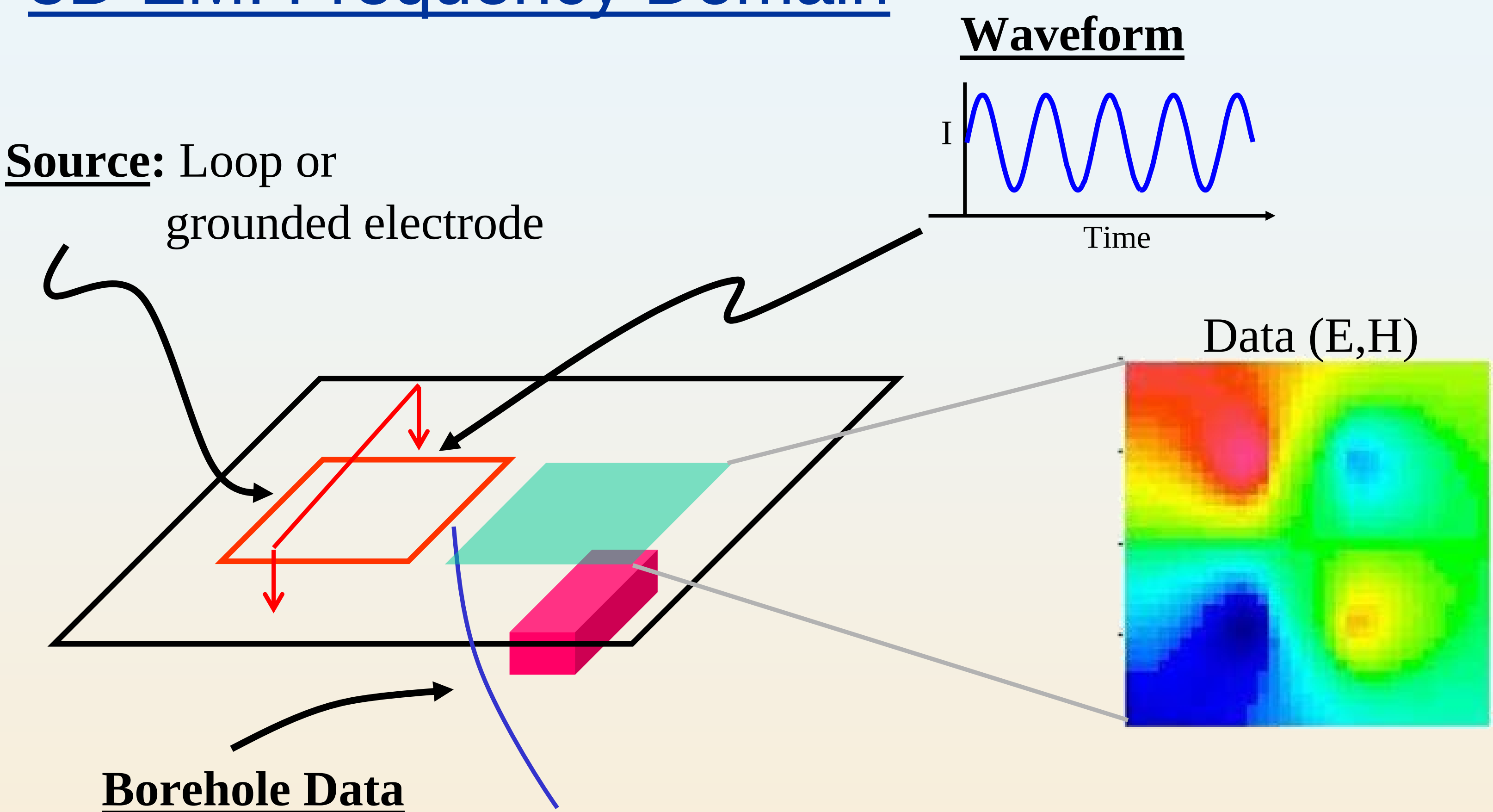


Waveforms

- Sinusoidal (Frequency domain
- Time waveforms (Time domain)

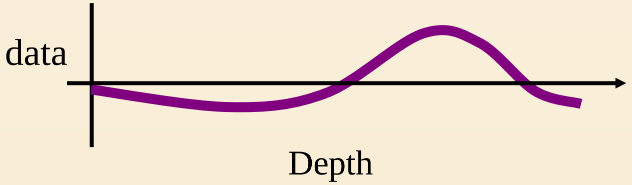


3D EM: Frequency Domain



Borehole Data

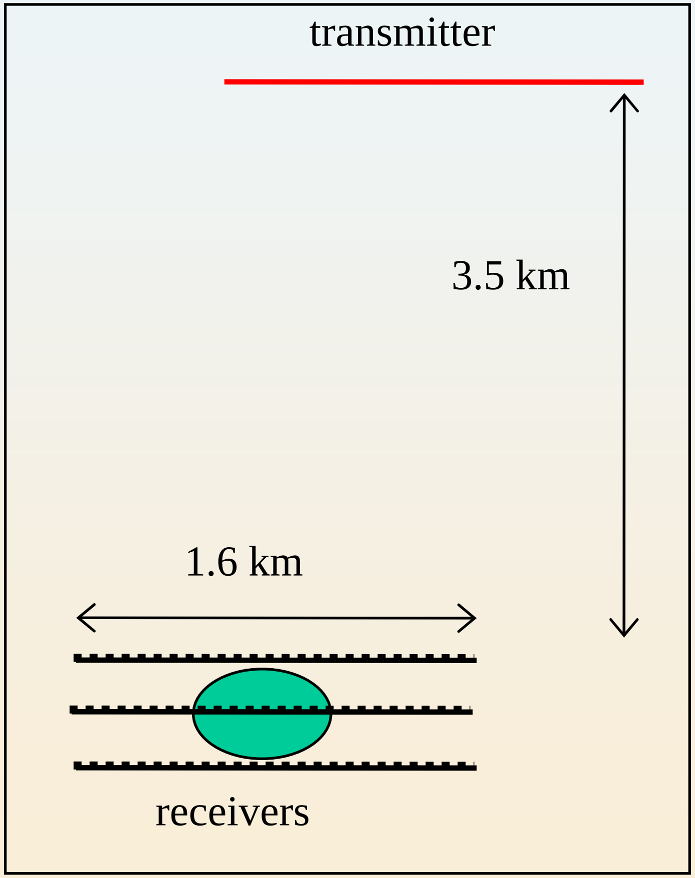
(E, H)



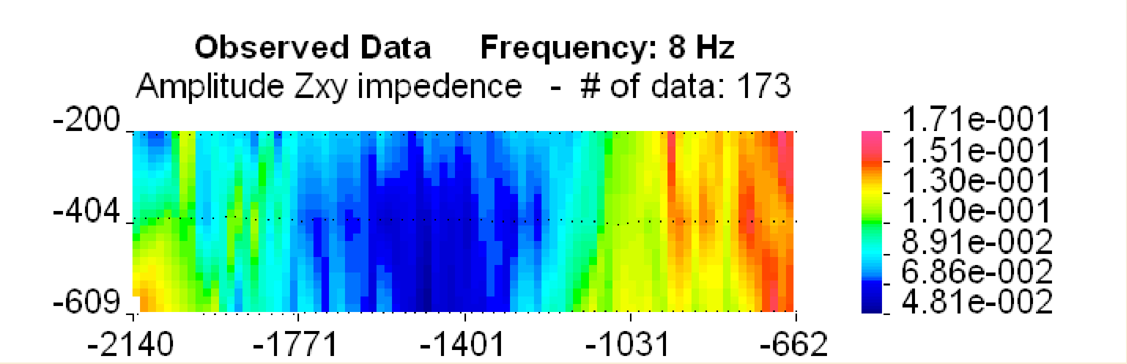
$$\nabla \times \mathbf{E} - i\omega\mu\mathbf{H} = 0$$

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

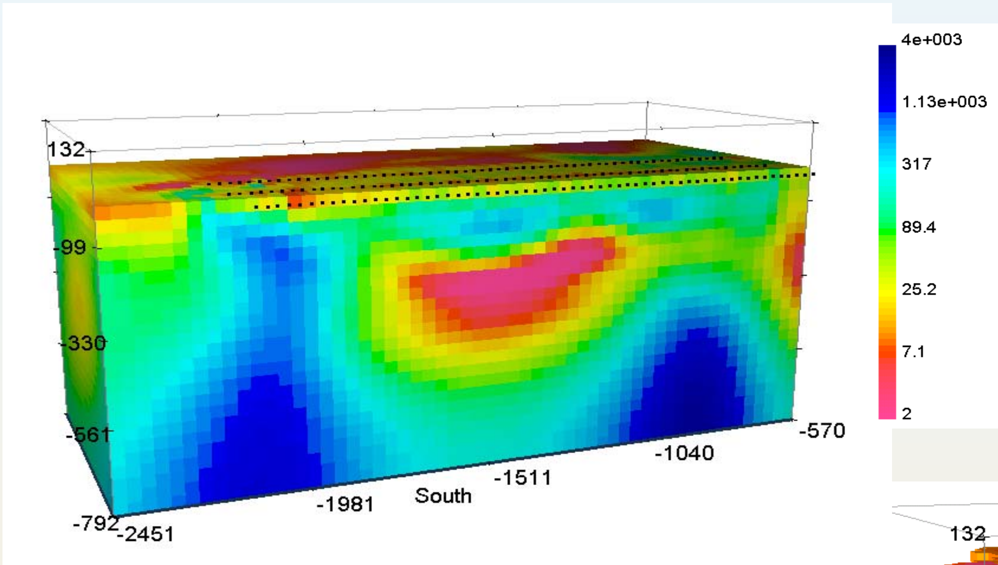
CSEM Survey



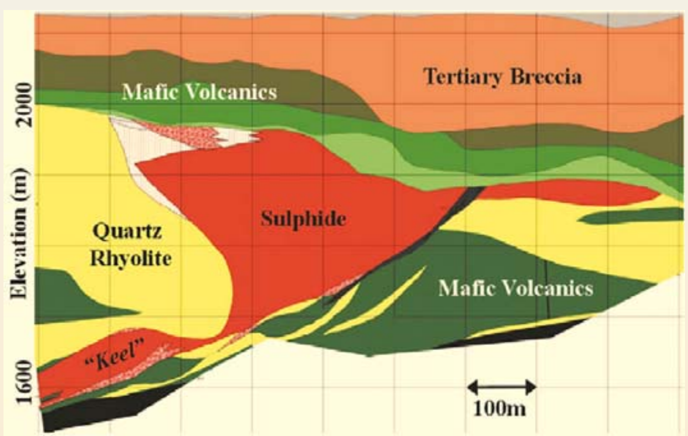
- 15 Frequencies between 0.5Hz, 8192 Hz
- 3 lines, 1.6km long, 200m apart
- 25 meter station spacing
- single transmitter
- data are scalar impedances (Ex/Hy)
- data collected with the goal of MT interpretation

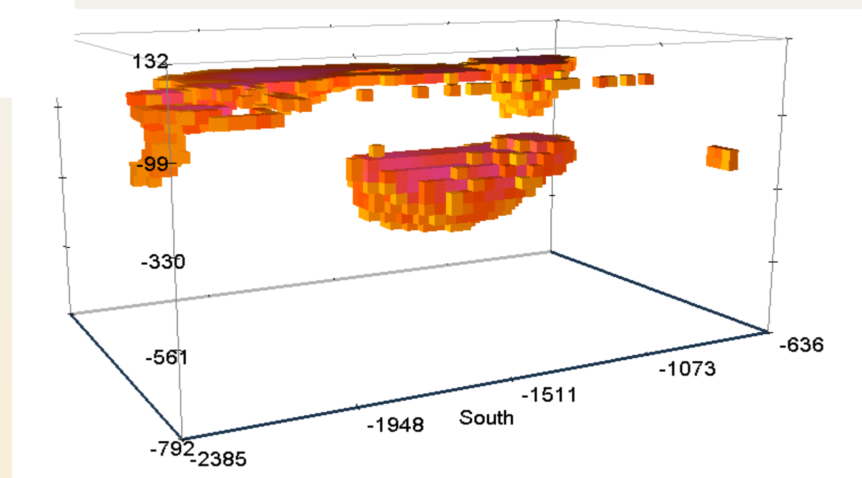


3D CSEM Inversion



Frequencies
0.5, 8, 64, 256 Hz

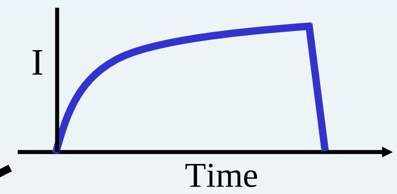




Iso-surface cutoff 10 Ohm-m

3D TEM Setup

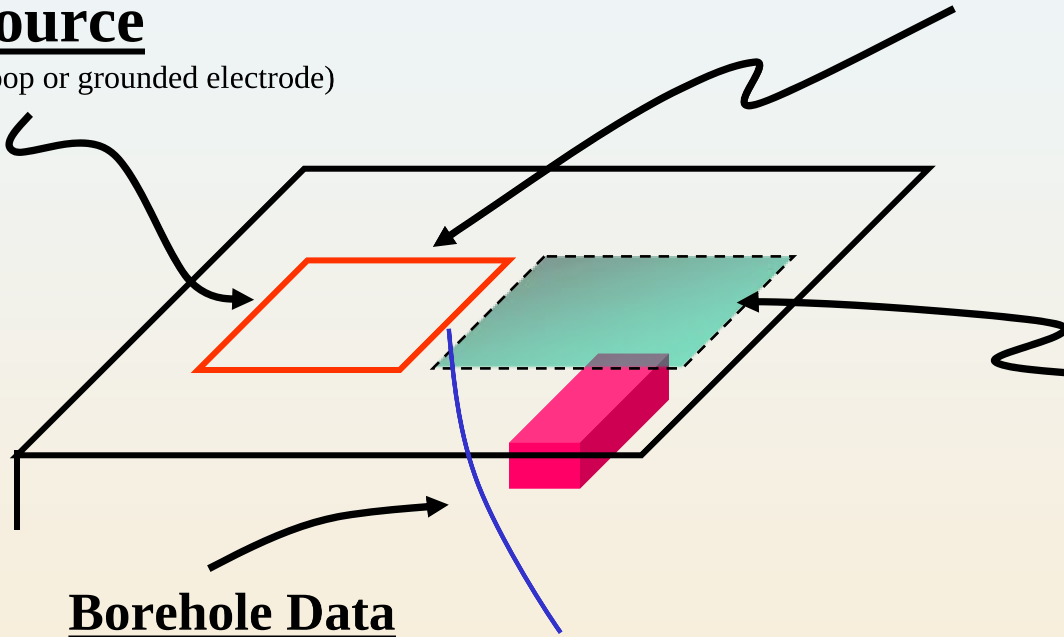
Waveform



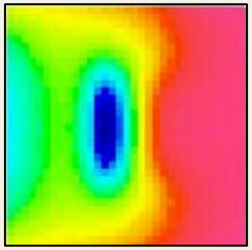
(half sine, step…)

Source

(Loop or grounded electrode)



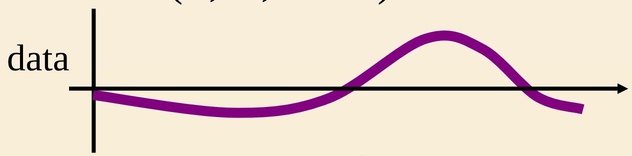
Surface Data



(E, H, dB/dt)

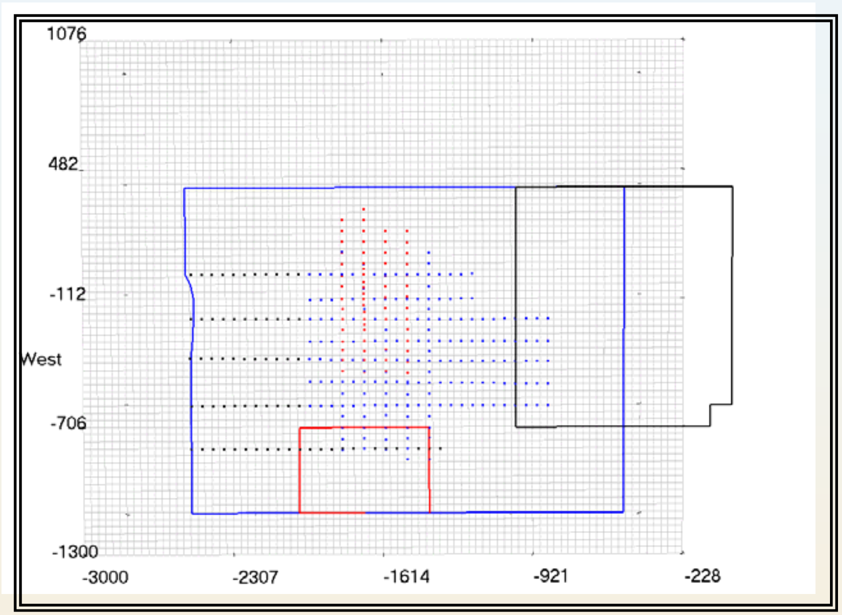
Borehole Data

(E, H, dB/dt)

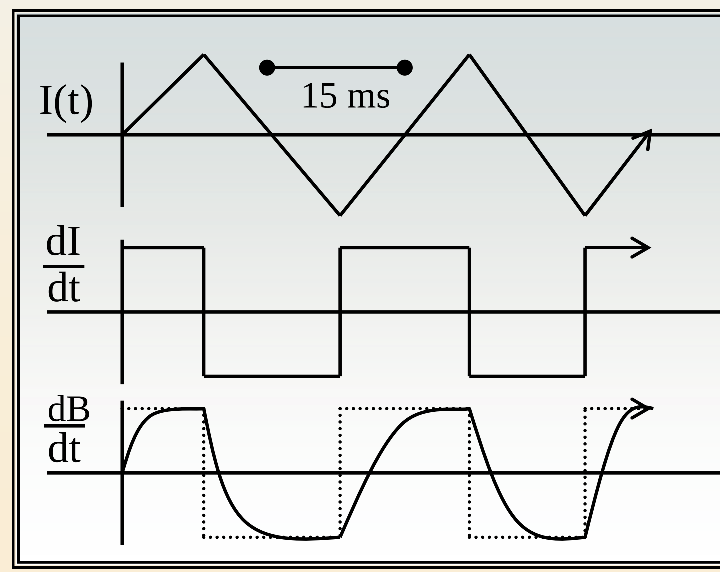


$$\begin{aligned} \nabla \times \mathbf{E} + \mu \mathbf{H}_t &= 0 \\ \nabla \times \mathbf{H} - \sigma \mathbf{E} - \epsilon \mathbf{E}_t &= \mathbf{s}_r(t) \end{aligned}$$

Introduction to UTEM data at San Nicolas

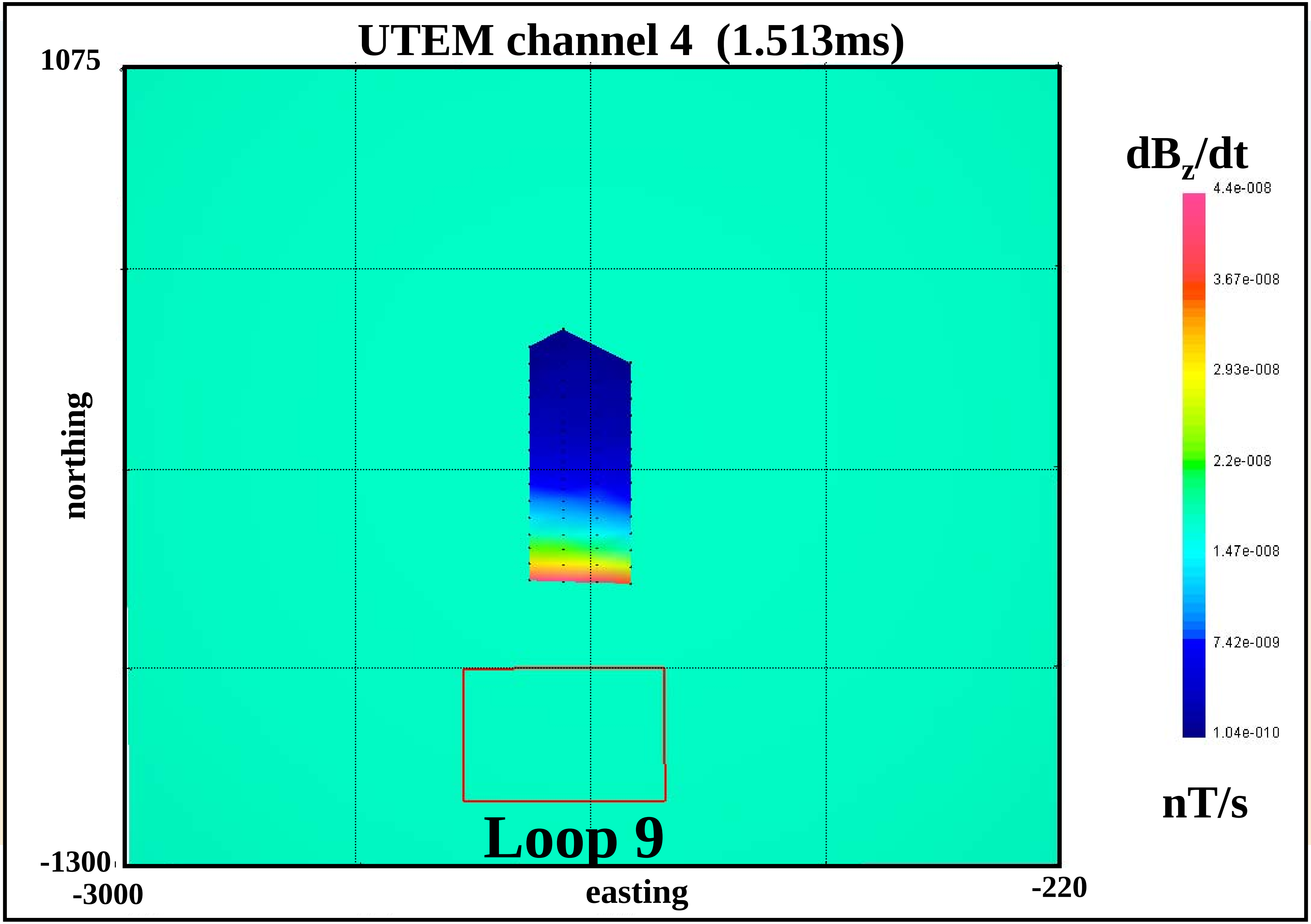


- 3 large loop transmitters
  - 2 km by 1.5 km
- d**B**/dt receivers
  - mainly z component



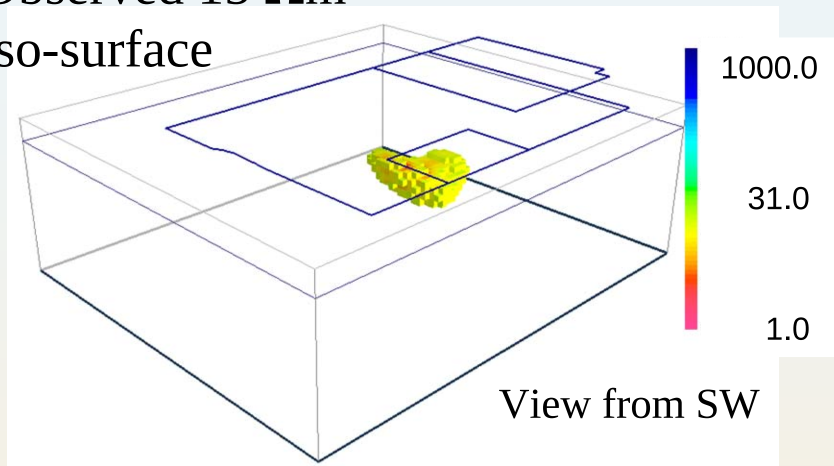
- transmitter waveform
  - 30 Hz sawtooth wave
  - dI/dt constant over half cycle

San Nicolas UTEM data

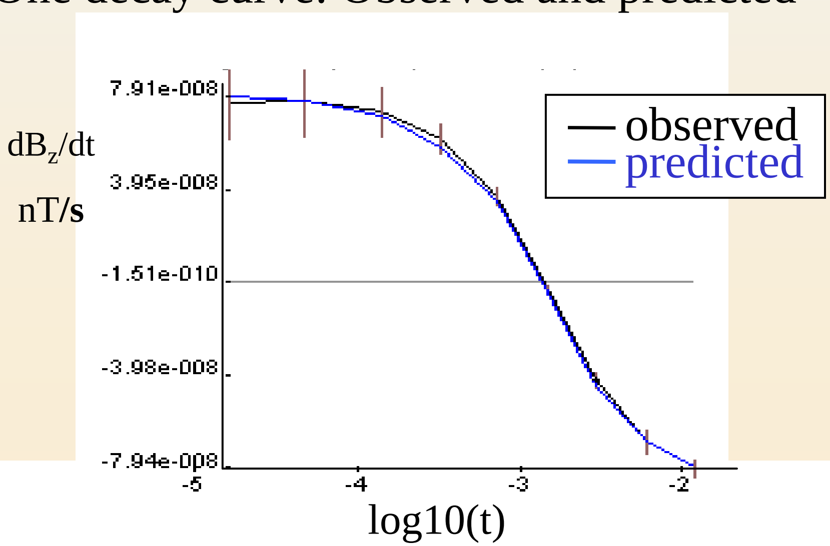


Fitting the data

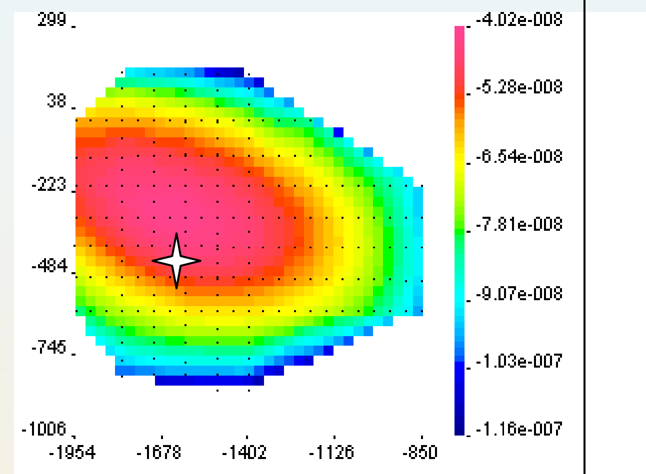
Observed 15 Ωm iso-surface



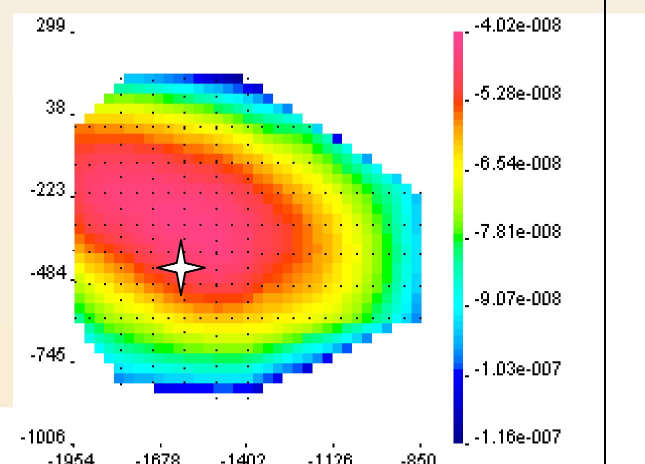
One decay curve: Observed and predicted



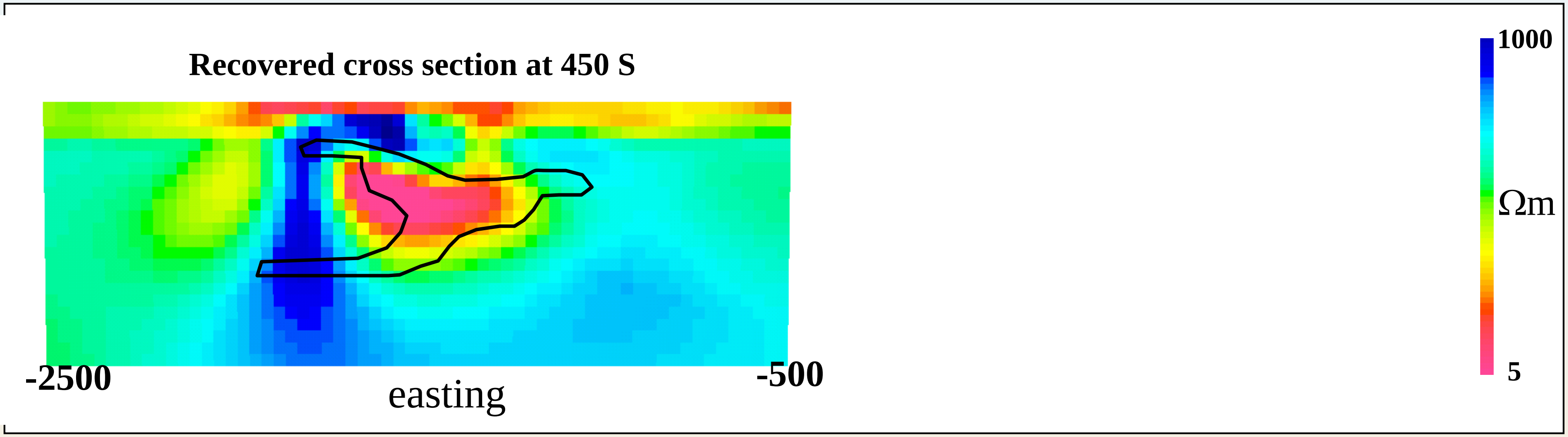
Observed

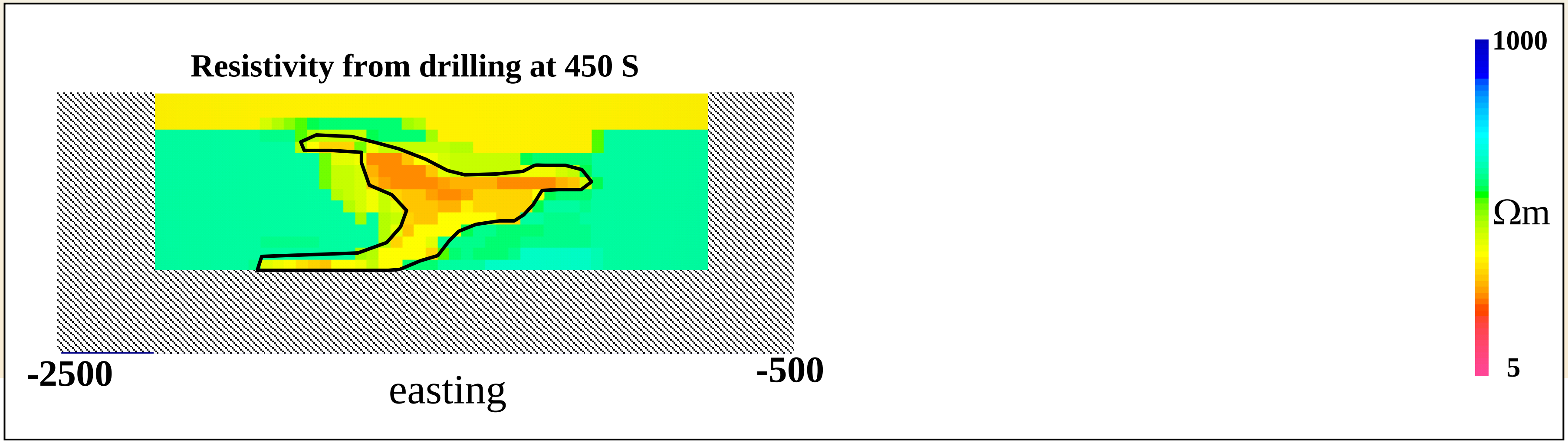


Predicted

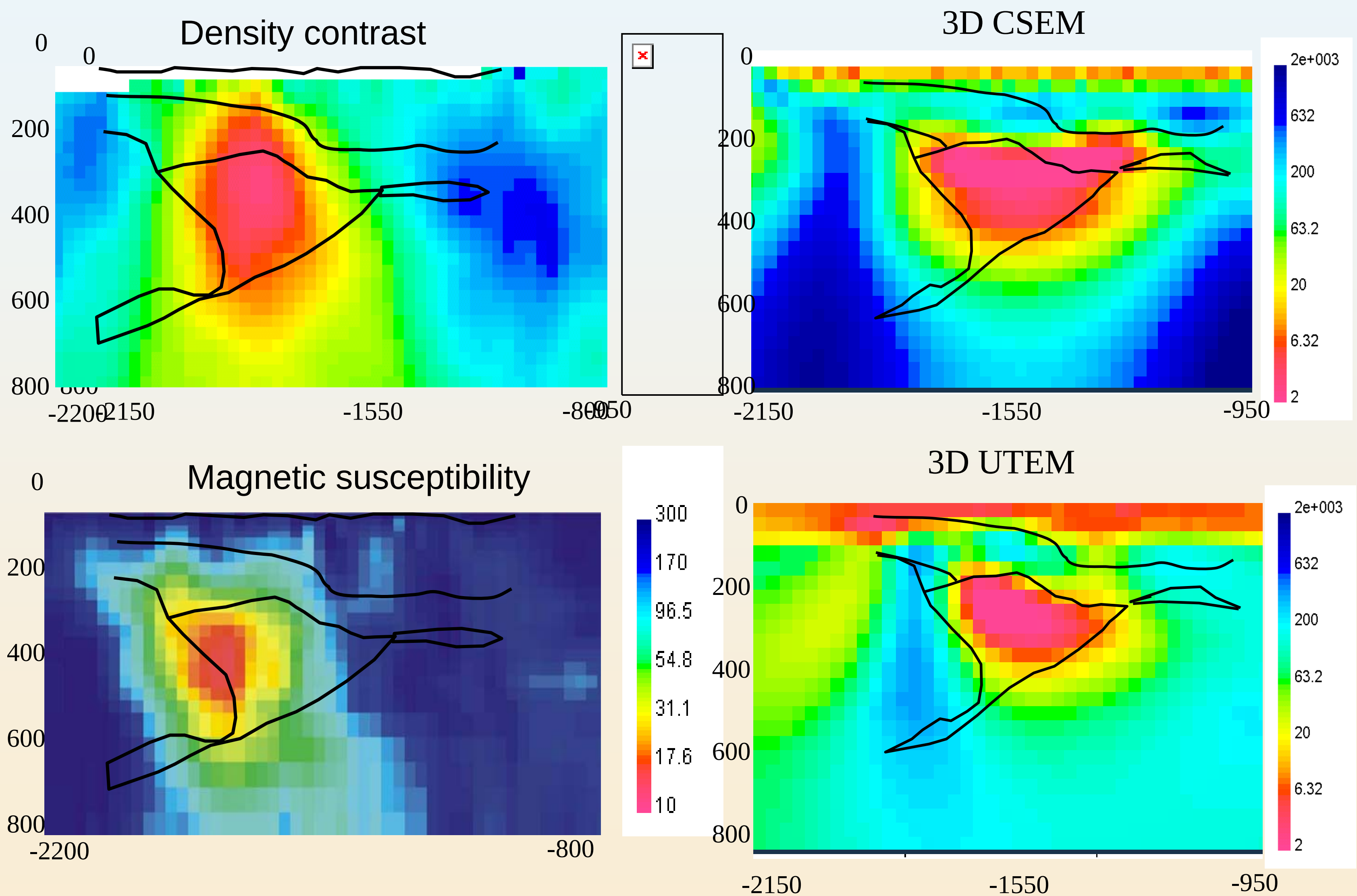


San Nicolas inversion results:



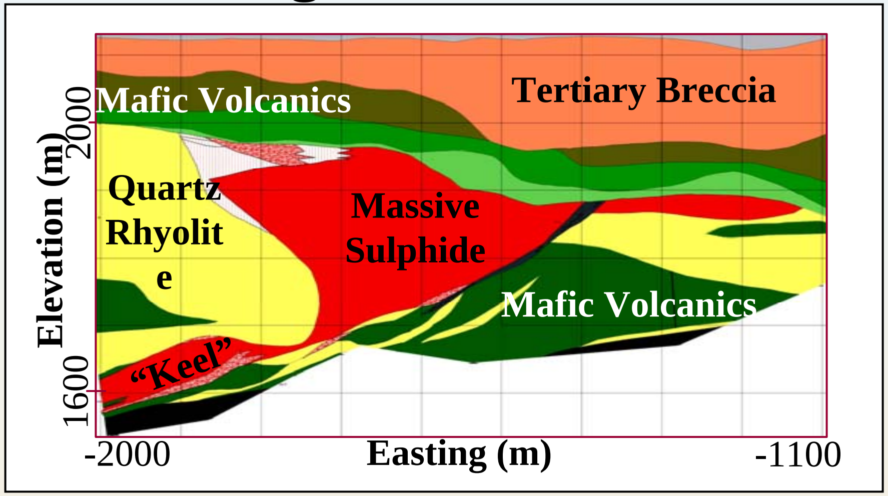


Density, Magnetic susceptibility, Conductivity



Field Example: San Nicolas Deposit

Geologic cross section



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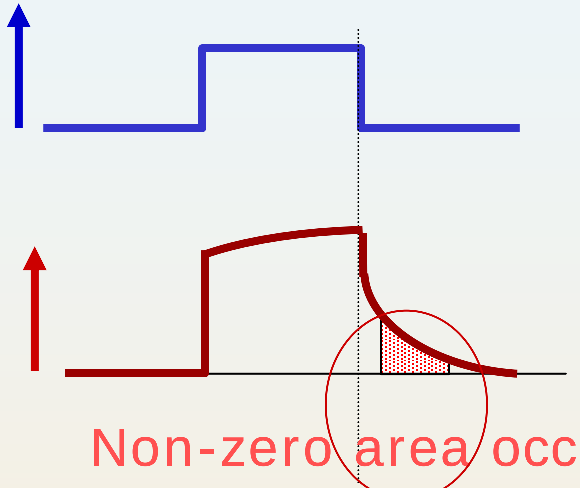
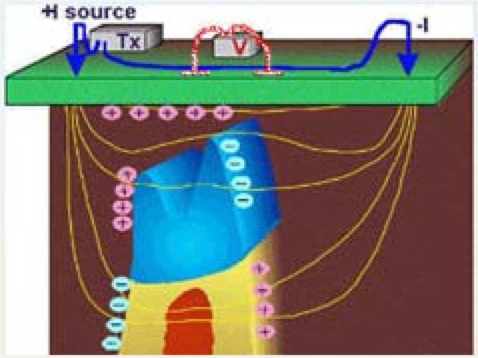
Qtz Rhyolite	2.4	0 - 10	100	10 - 20
GraphiticMst.	2.4	0 - 5	100+	30 - 70

Induced Polarization

Source Current (Amps)

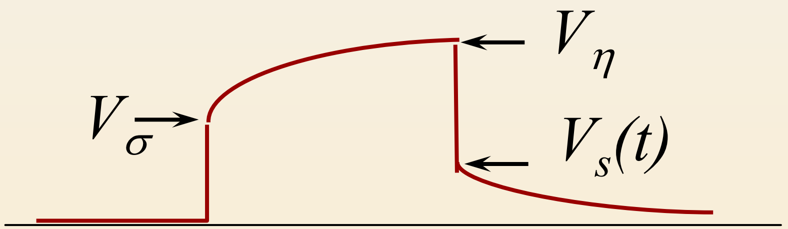
Measured Voltage (Volts)





Non-zero area occurs because charges took time to equilibrate.

IP datum: Vs/Vn

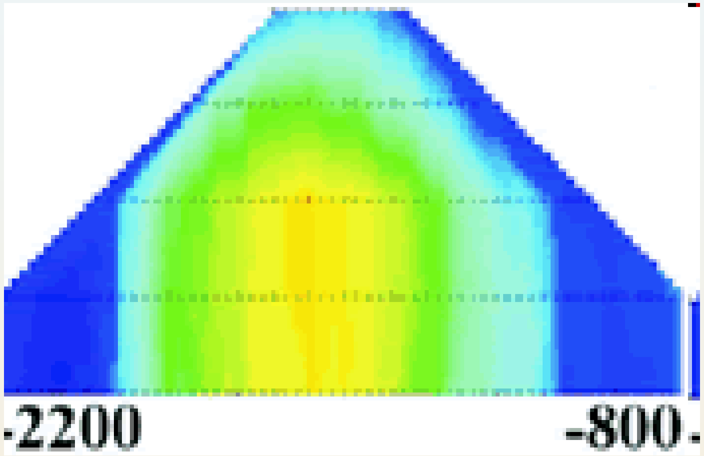


Collect IP data along with DC resistivity data

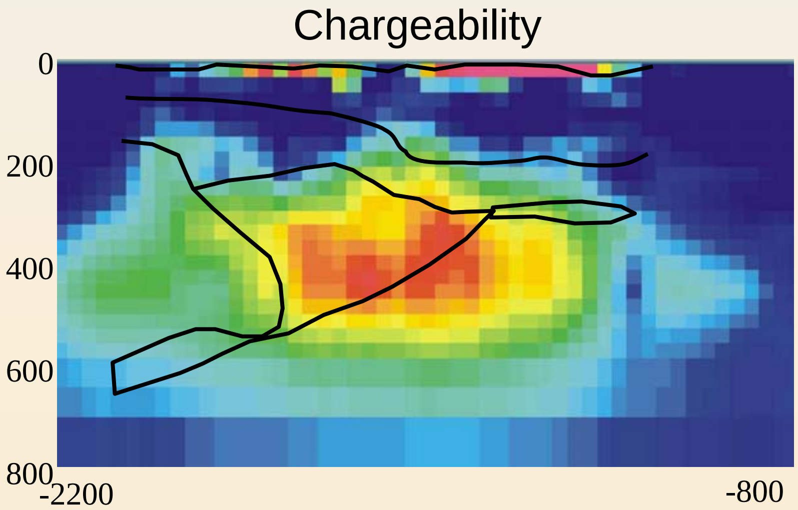
DC/IP data at San Nicolas

- Pole-dipole
- Real Section

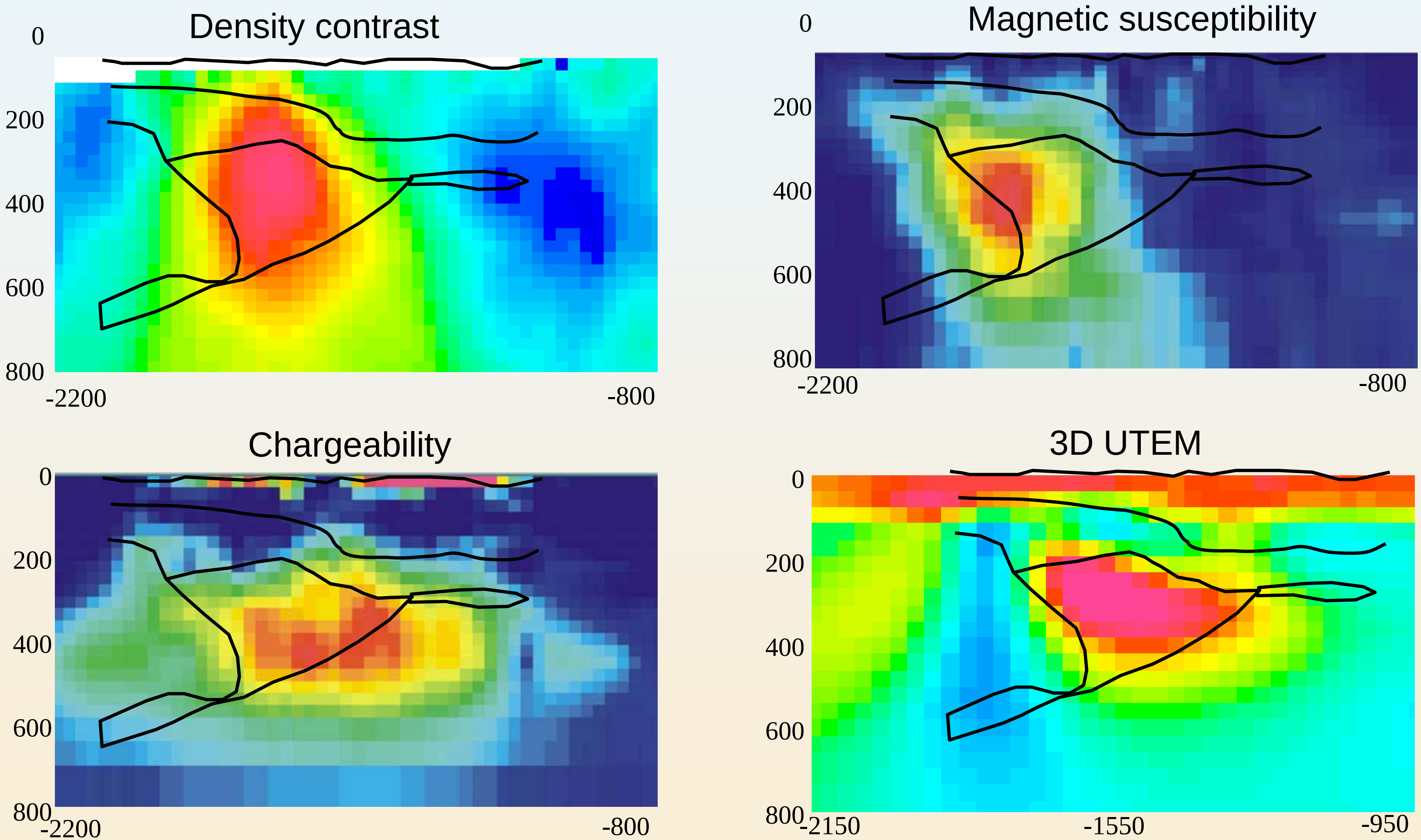
Pseudo-section



3D Inversion

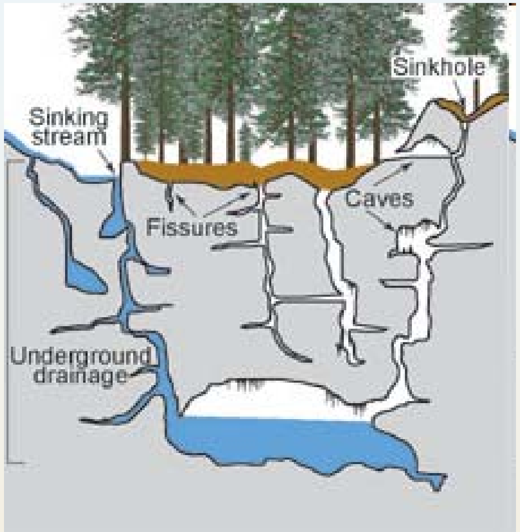


Summary of physical property inversion at San Nicolás

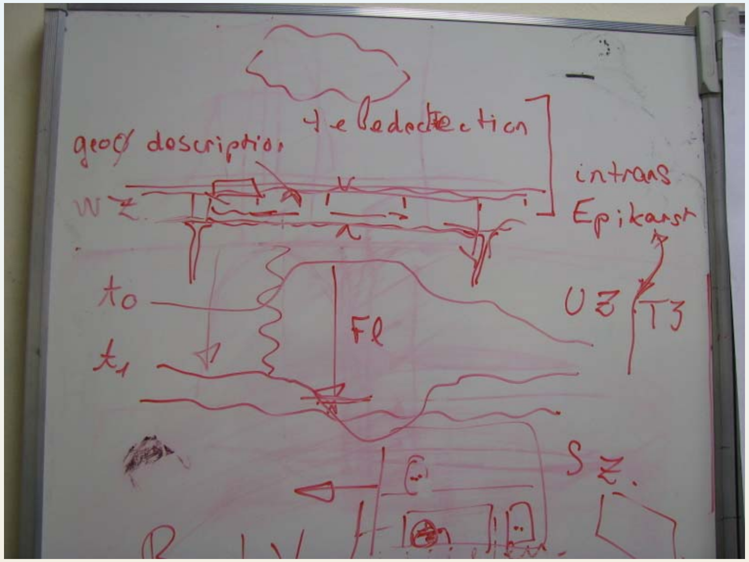


Sulfide: dense, chargeable, susceptible, conductive.

Back to Karst Aquifers: LSBB

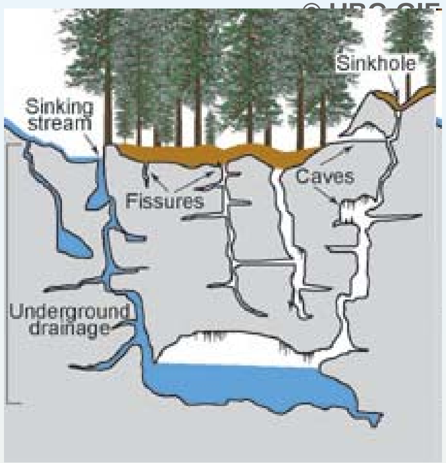


- Soil
- Epikarst
- Unsaturated
- Saturate



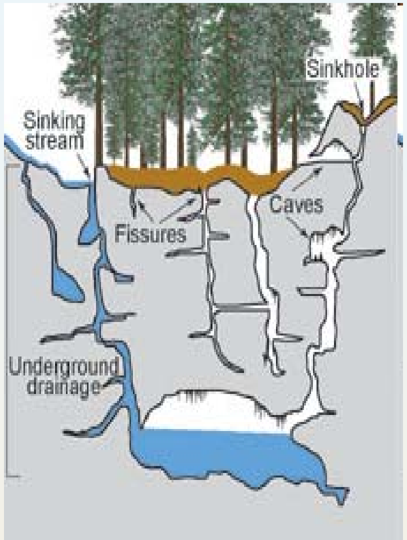
- What scale?
- Which physical properties?

Back to Karst Aquifers: LSBB



- Tunnel Scale (meters to km):
  - Conductivity (indicative of water)
    (DC resistivity, FEM or TEM)
  - IP might be useful for clay layers if they are chargeable
  - Time-lapse DC (EM) resistivity can provide information about hydraulic conductivity
  - Electrical permittivity (GPR)

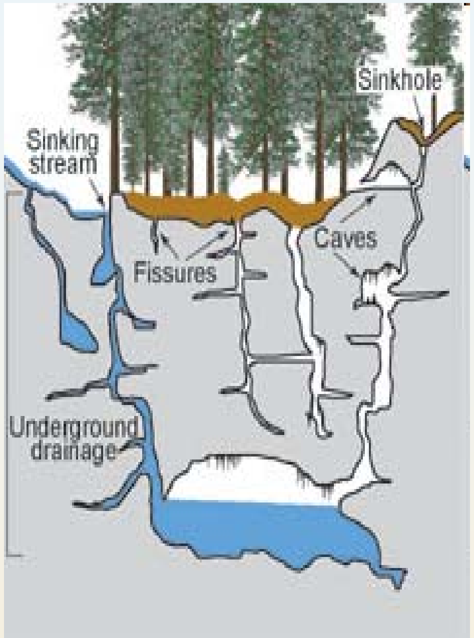
Geophysics for large scale aquifer



- Conductivity
  - Airborne EM for 200 meters (Epikarst delineation)
  - ZTEM or MT for deeper structure (large voids/conduits, depth of saturated zone)

Geophysics for large scale aquifer

- Density: (Change in water volume)
- Magnetics ??
- Self-potential (from fluid motion)
- Chargeability ??
- Self-potential, MRI, Seismic



Good news from geophysics side: We can invert most types of survey data to recover 3D distribution of physical properties.

Thank you!