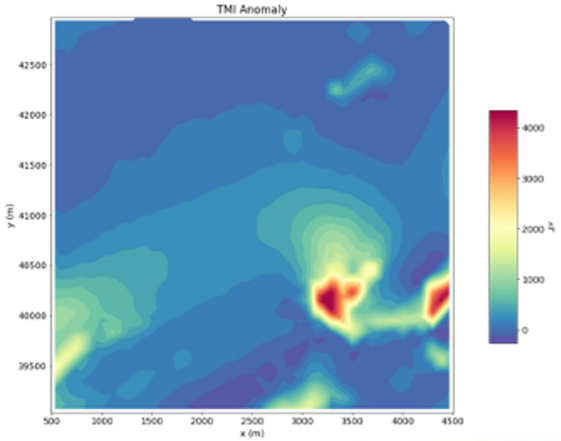
inversion, visualization, and open-source tools

Lindsey Heagy

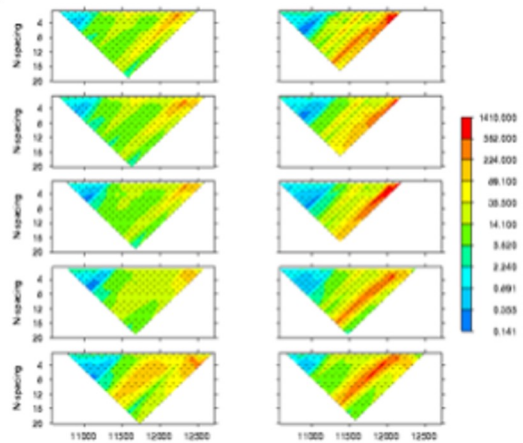
University of British Columbia – Geophysical Inversion Facility

geophysical data

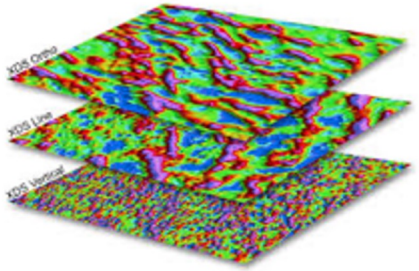
maps (mag, grav, ….)



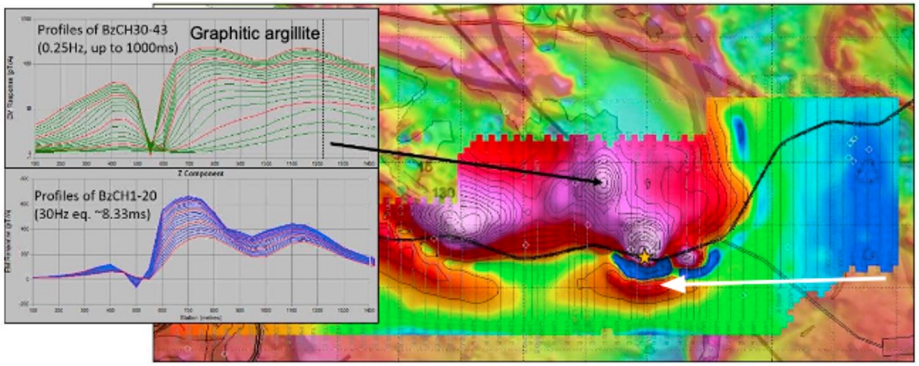
pseudosections (DC, IP)

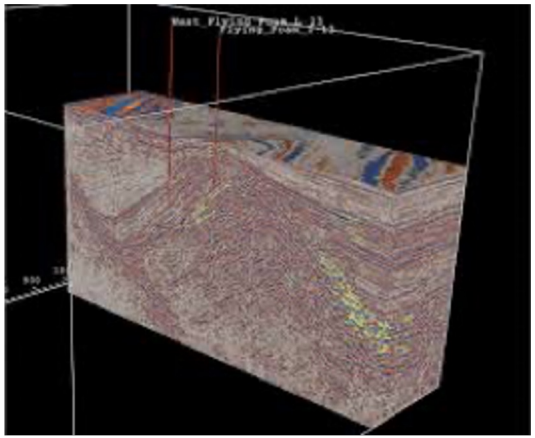


multiple maps, volumes (EM, seismic)



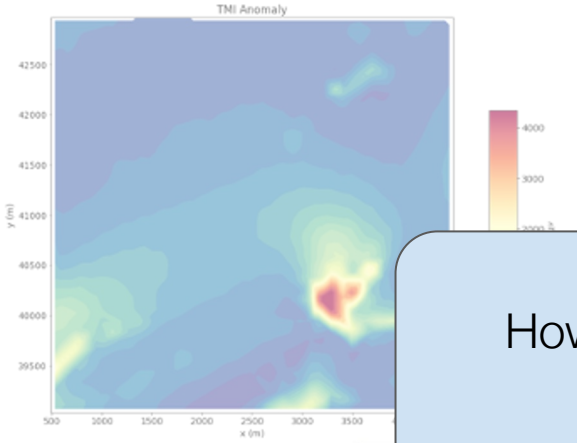
profiles, timeseries (EM)





geophysical data

maps (mag, grav, ….)



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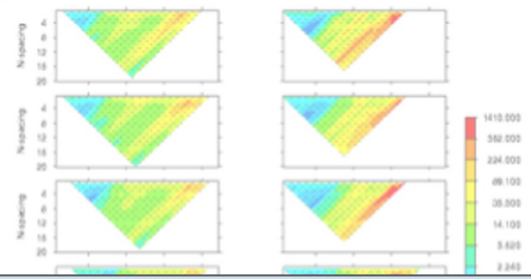
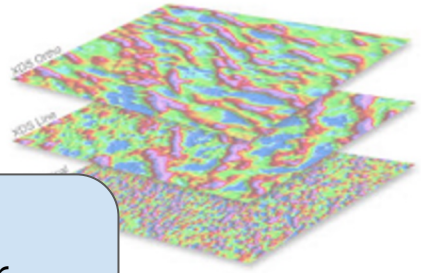
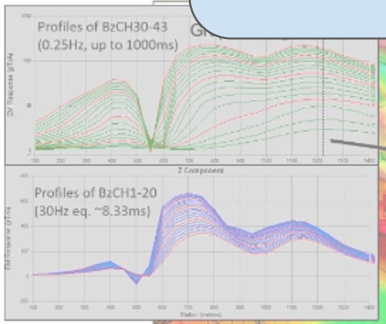


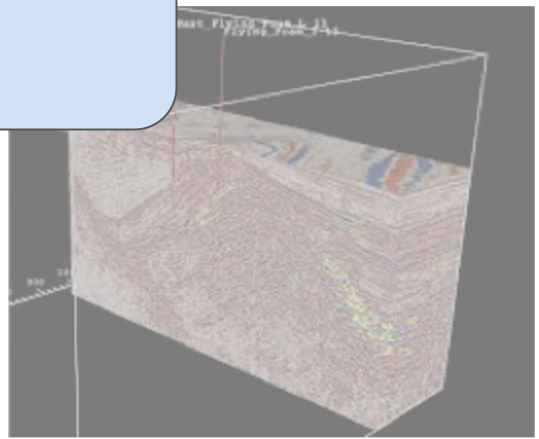
multiple maps, volumes (EM, seismic)



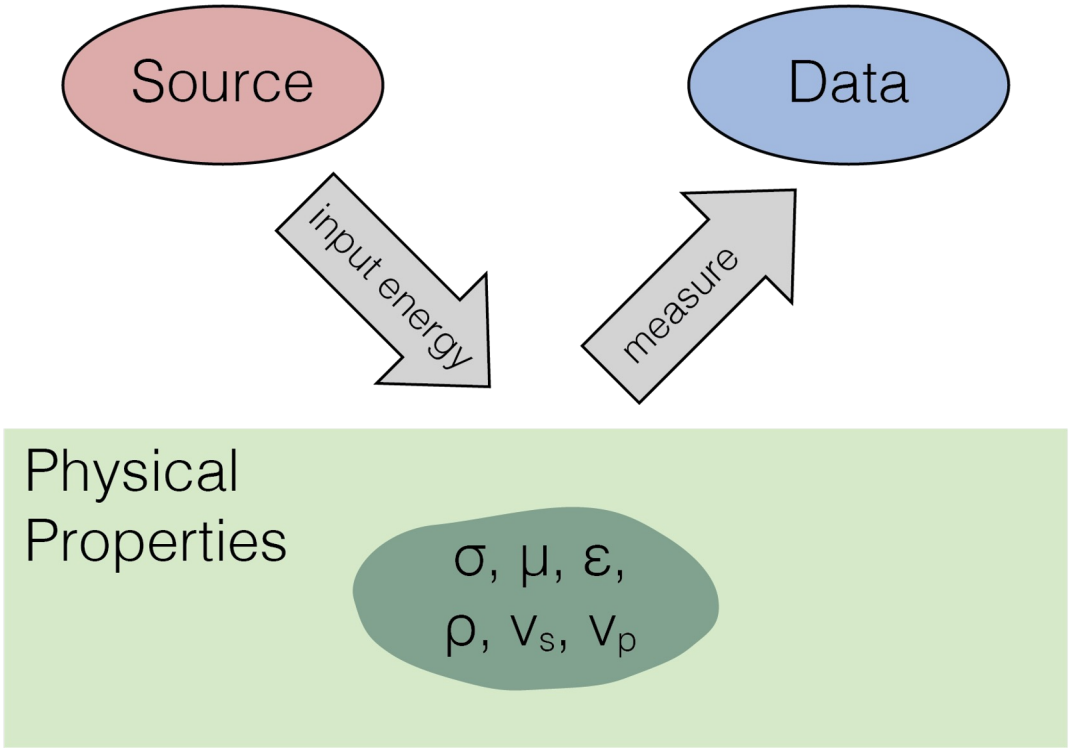
How do we use these data to answer our geologic questions?

profiles, timeseries (EM)

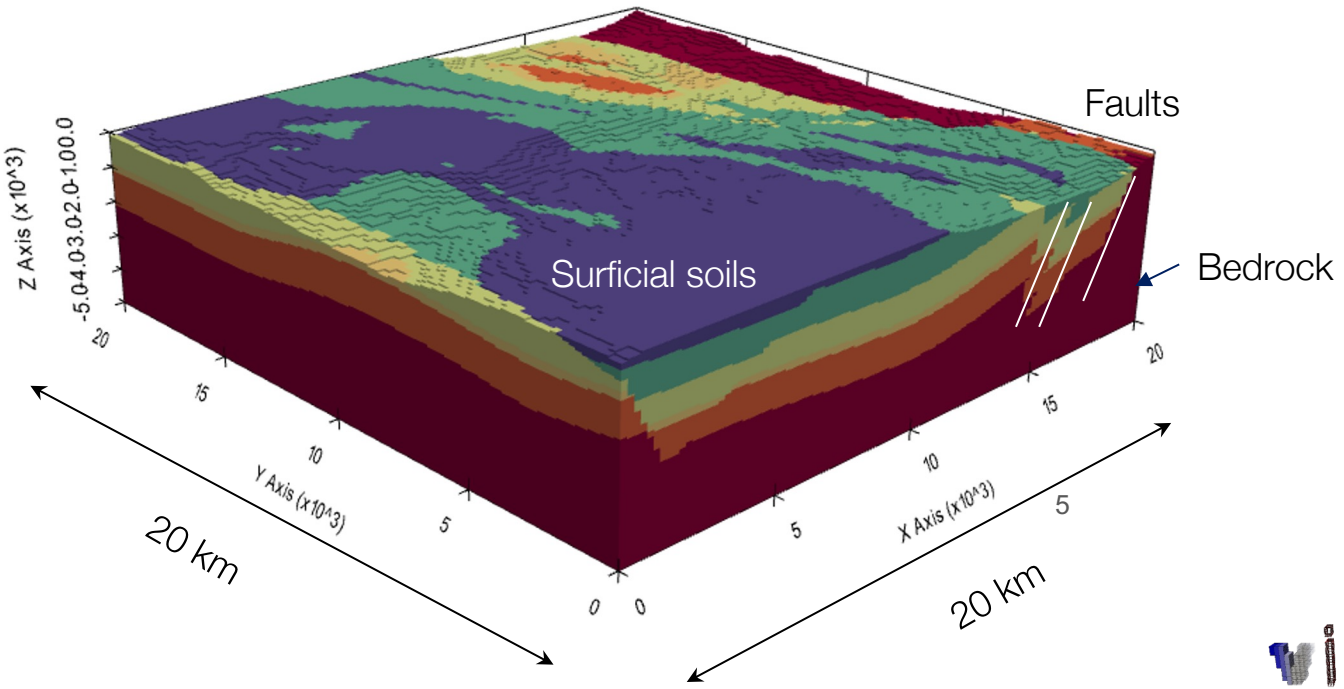




basic geophysical experiment

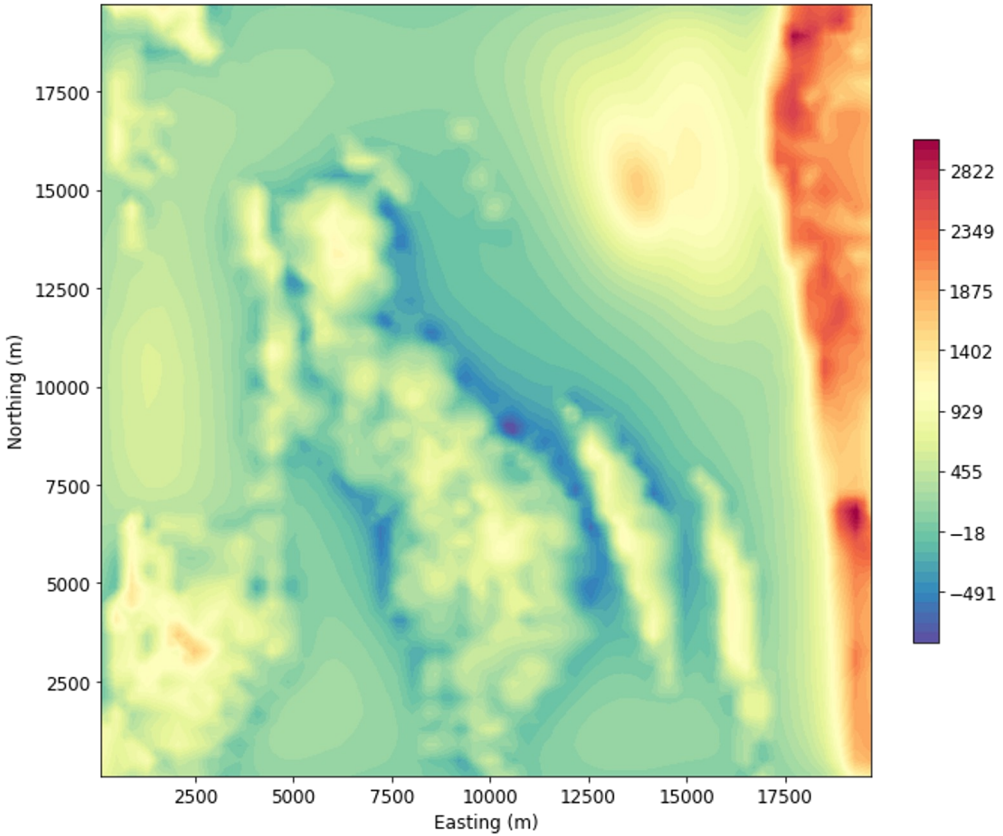


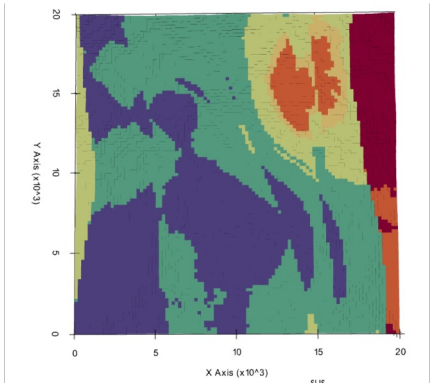
connecting geology and geophysics: why invert data?

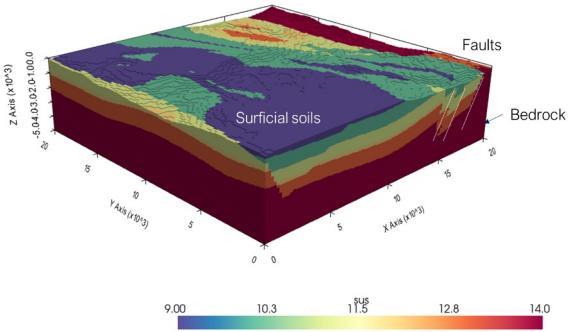


Example from Seogi Kang

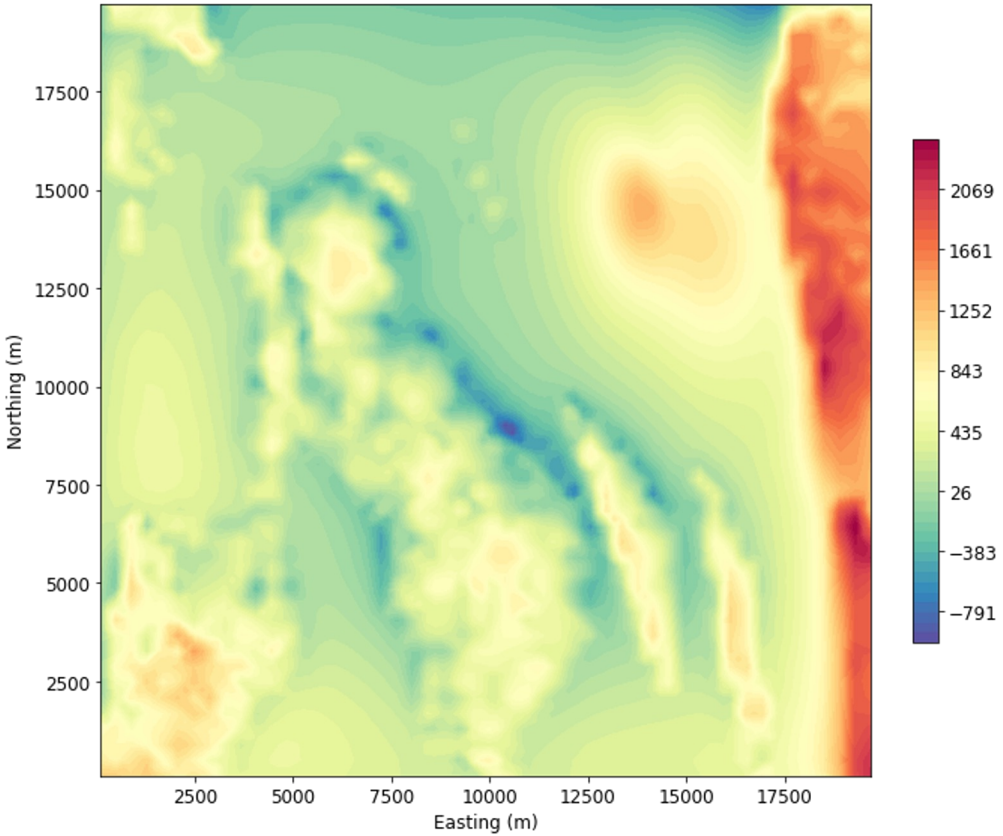
Measured magnetic data at I=90, D=0 (Magnetic pole)

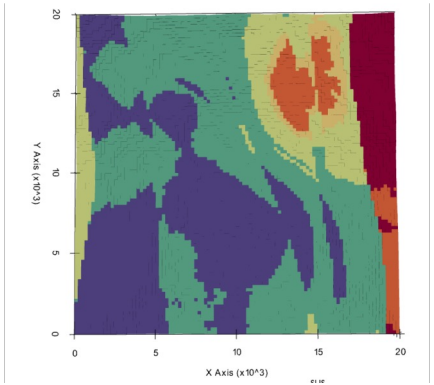


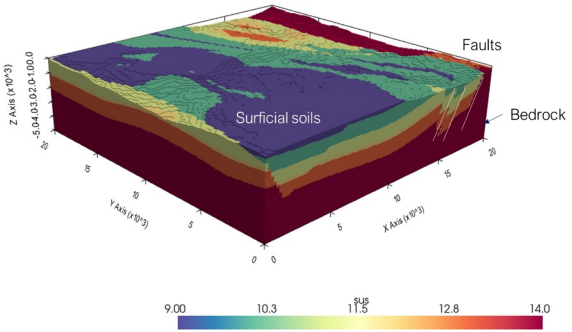




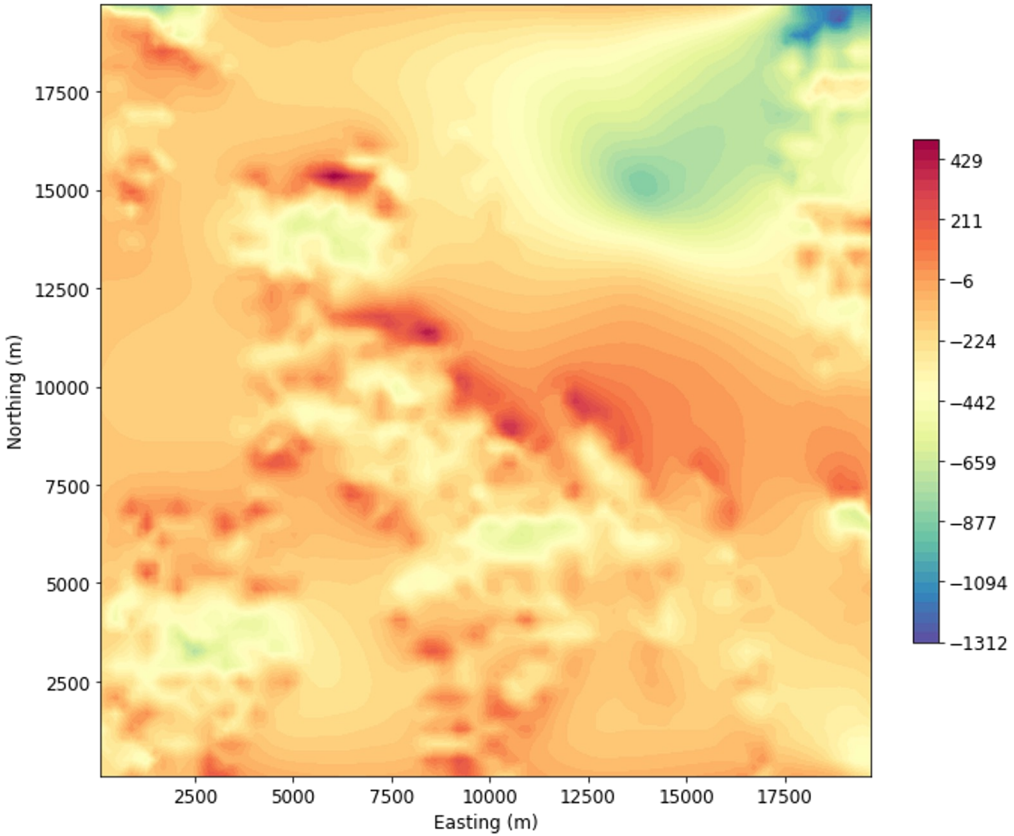
Measured magnetic data at I=66, D=-6 (California)

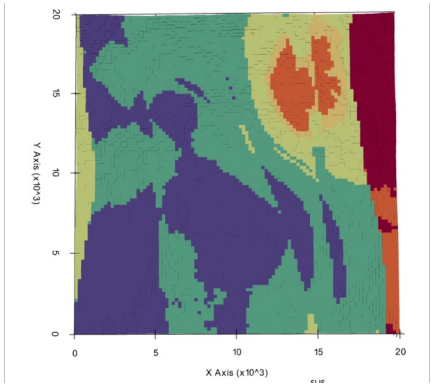


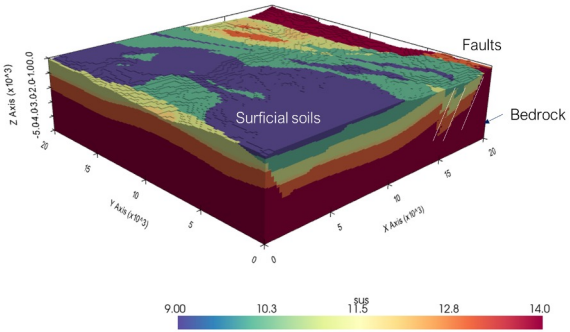




Measured magnetic data at I=0, D=0 (Equator)

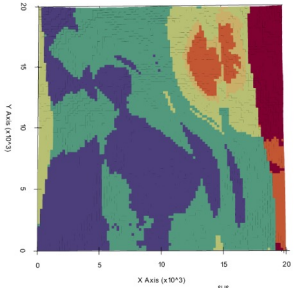




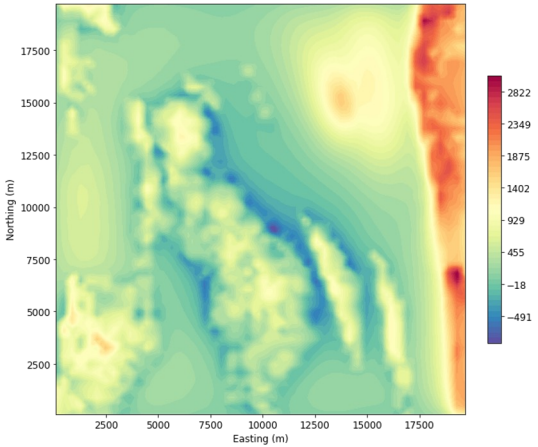


Why invert data?

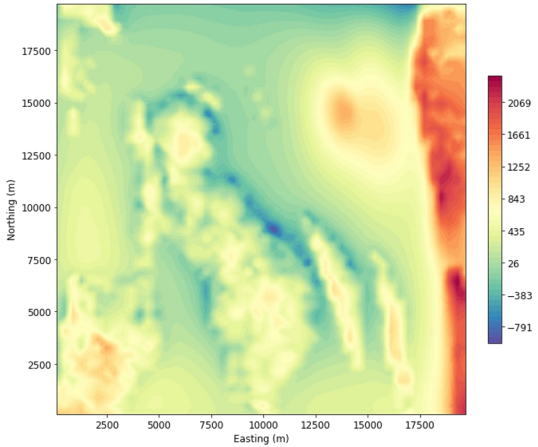
different source → different data (even for the same geology)



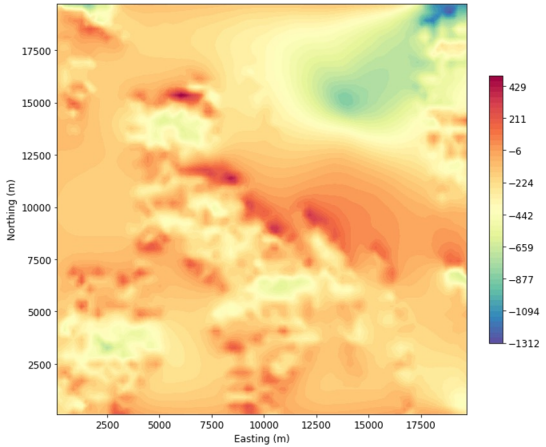
Pole (I=90, D=0)



California (I=66, D=-6)

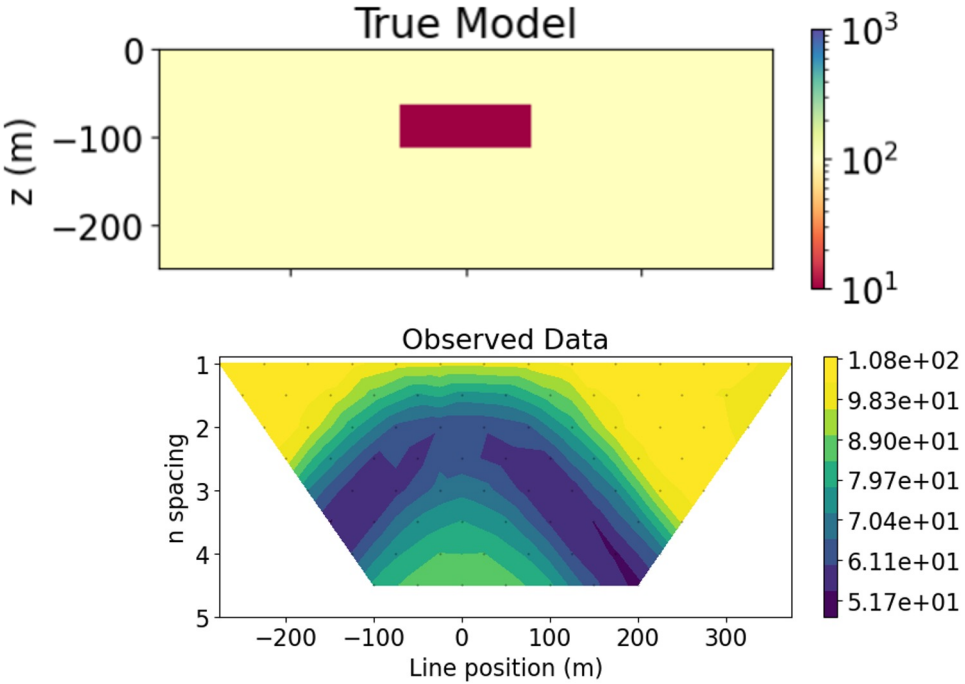


Equator (I=0, D=0)



Why invert data?

data aren't always interpretable directly



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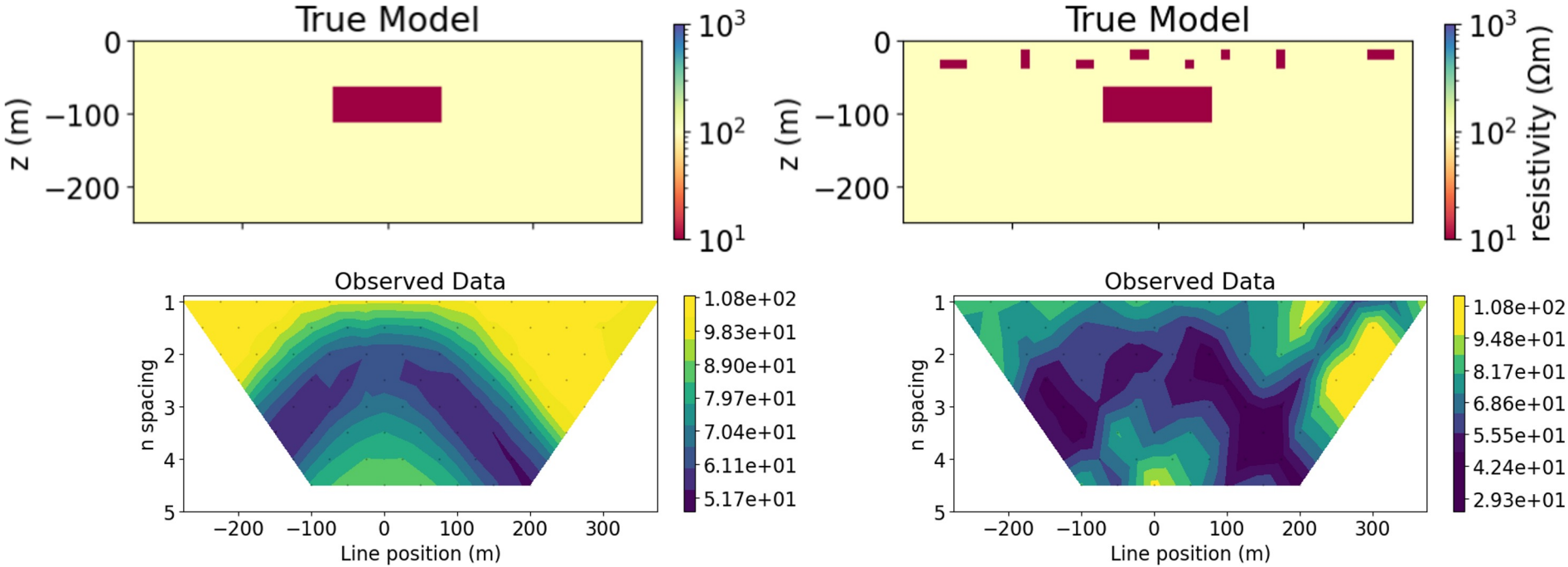

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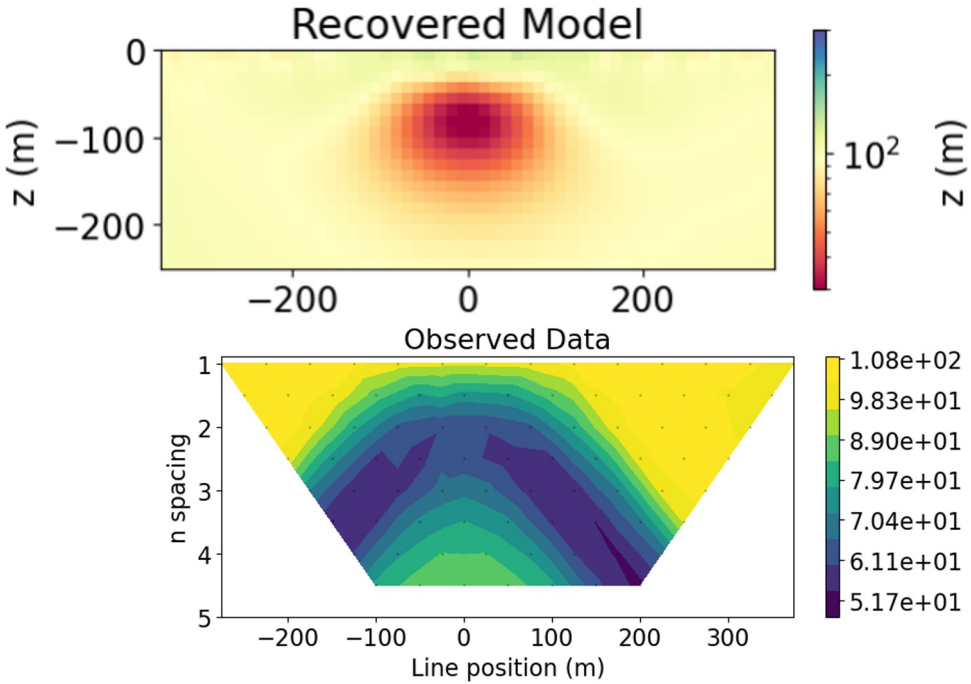
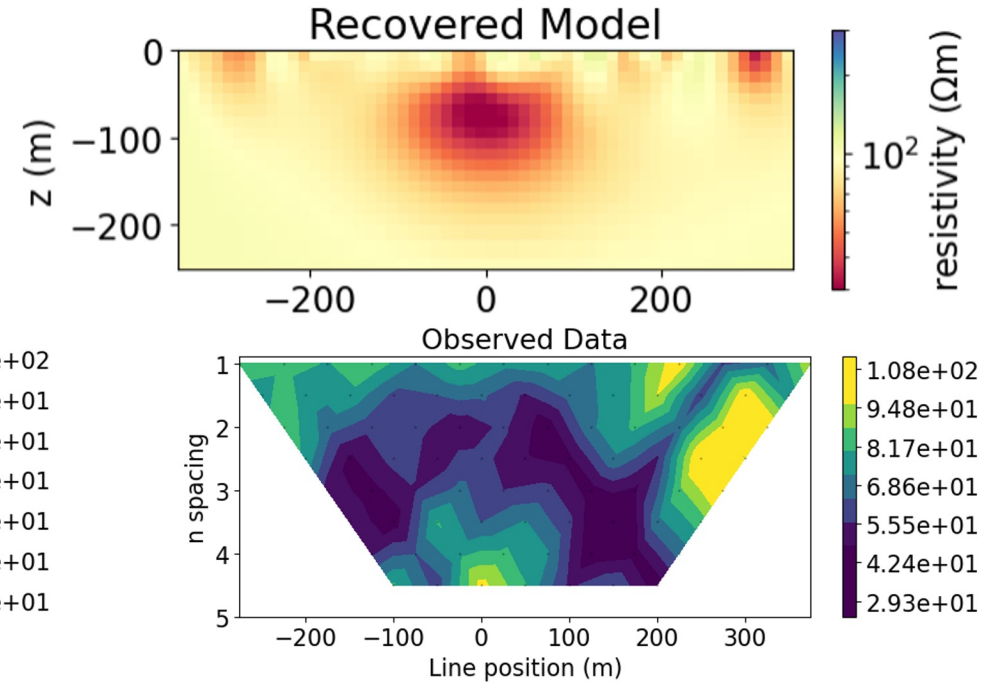
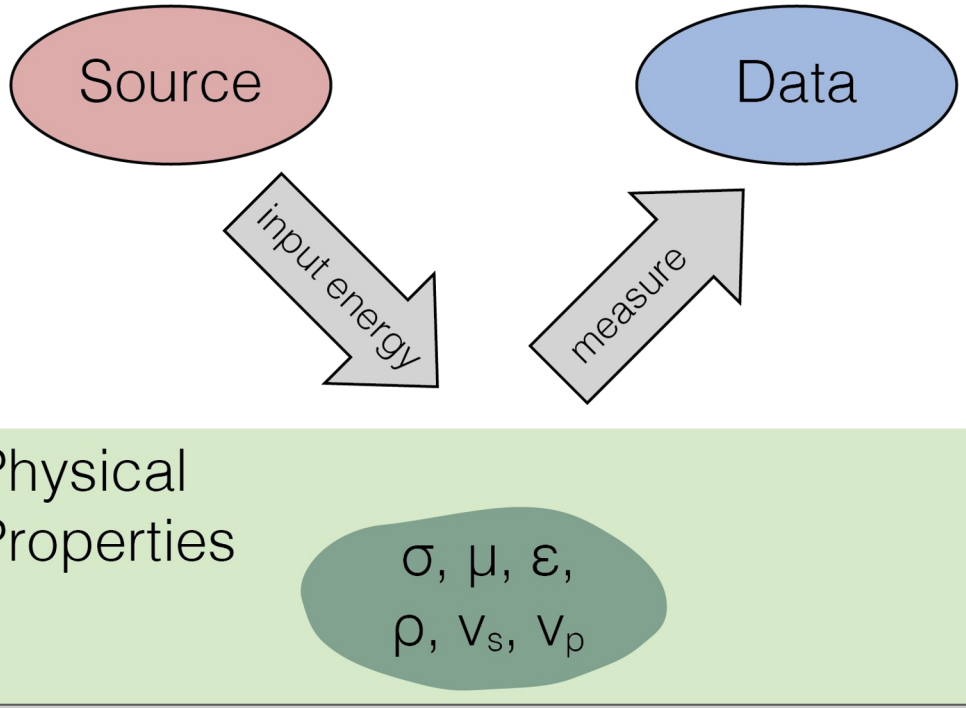




basic geophysical experiment



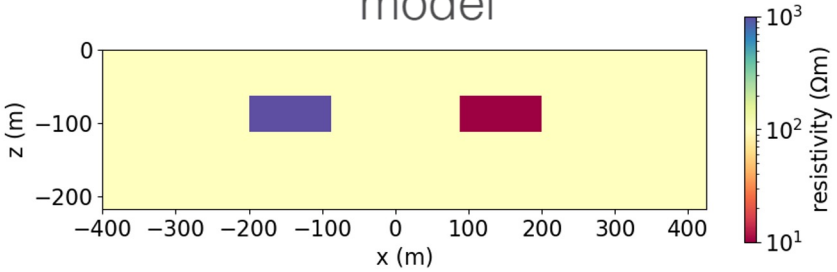
physical properties: connection point between geology and geophysics

Forward and inverse problems

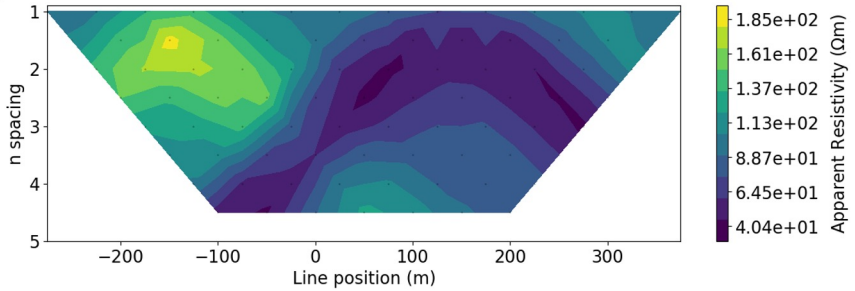
forward problem

$$\mathbf{d} = \mathcal{F}[\mathbf{m}]$$

physical property model



data



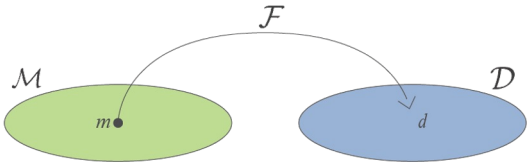
$$\tilde{\mathbf{m}} = \mathcal{F}^{-1}[\mathbf{d}]$$

inverse problem

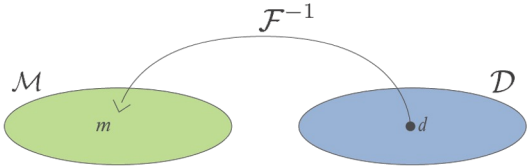
Statement of the inverse problem

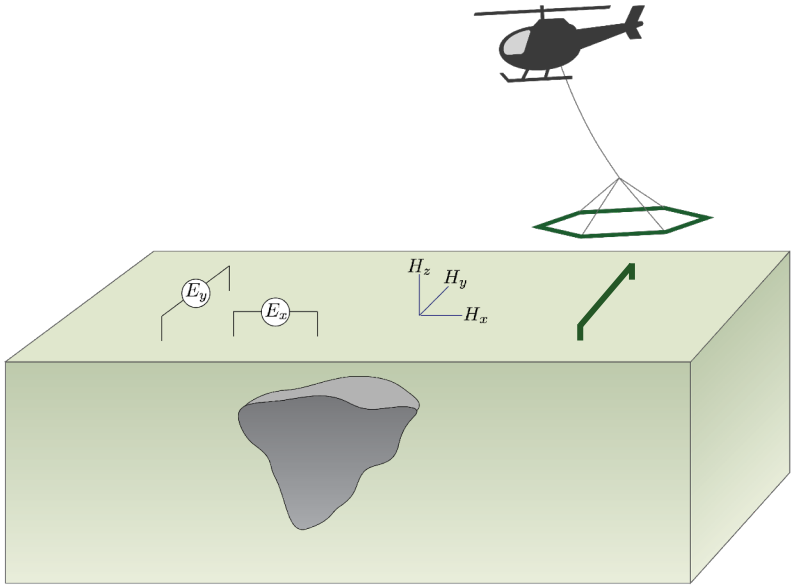
Given

- observations: $d_j^{obs}, \quad j = 1, \ldots, N$
- uncertainties: ϵ_j
- ability to forward model: $\mathcal{F}[m] = d$



Find the Earth model that gave rise to the data

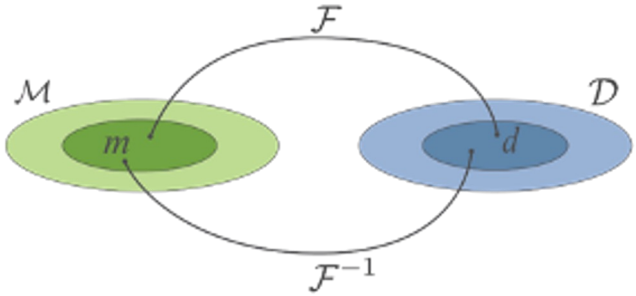




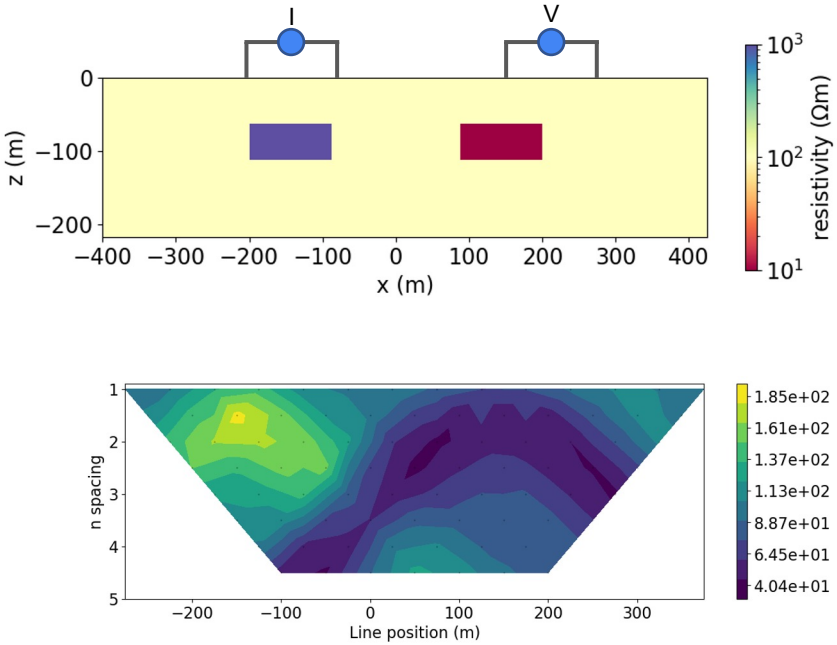
Inverse problems

The inverse problem is non-unique & ill-posed

Many models can fit the data



as an example of extreme non-uniqueness….



Inverse problems

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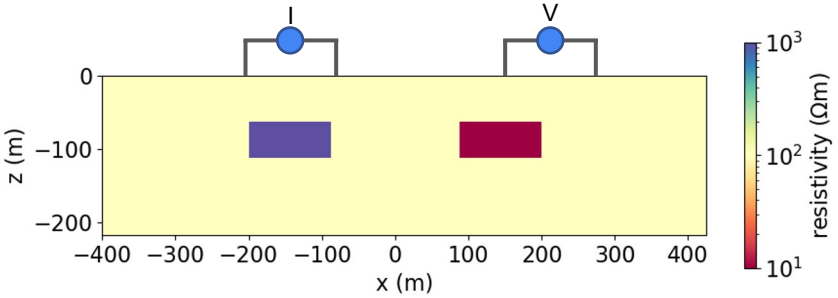
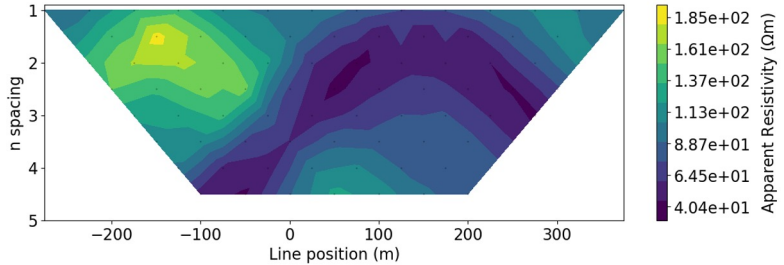
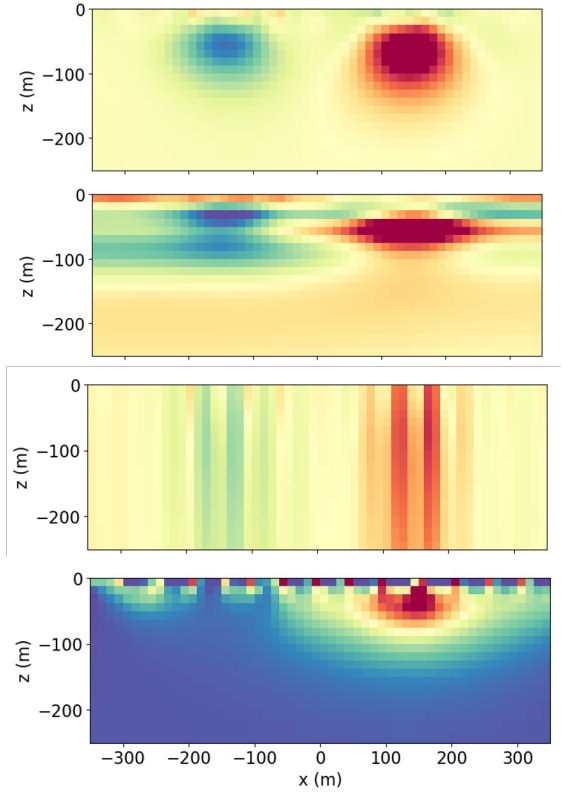




extreme non-uniqueness…

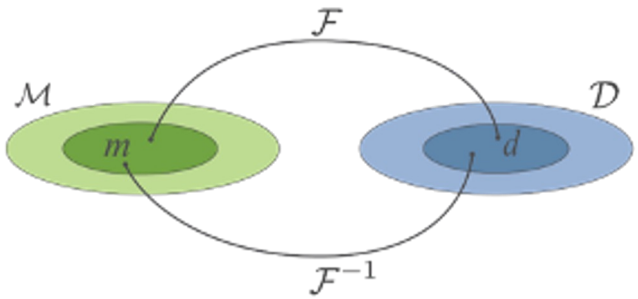
recovered models (all fit the data)



Inverse problems

The inverse problem is non-unique & ill-posed

Many models of the subsurface can fit the data

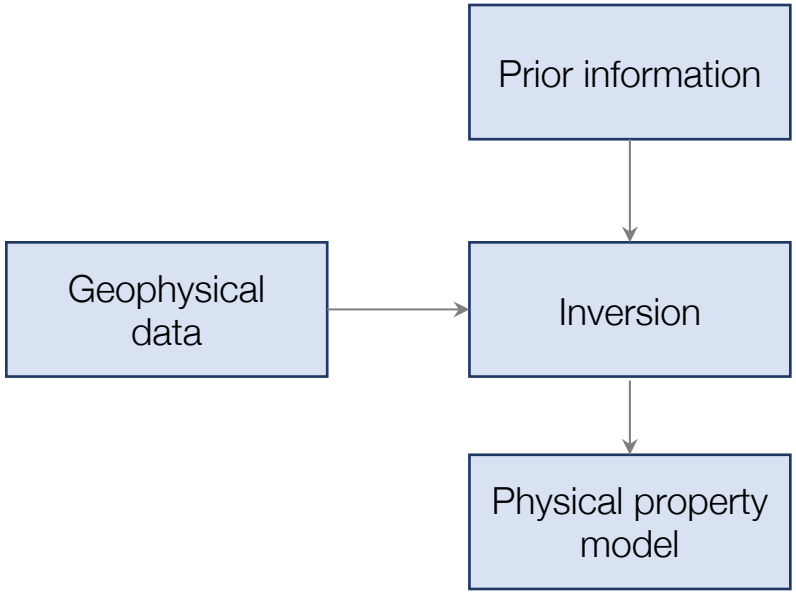


any approach to the inverse problem must address these issues

Constraining the inversion

What information is available?

- Geologic structure
- Geologic constraints
- Reference model
- Bounds
- Multiple data sets
- Physical property measurements
- Additional geophysical data



Our approach to the inverse problem

pose as an optimization problem

$$\underset{\mathbf{m}}{\text{minimize}}\ \phi(\mathbf{m}) = \phi_d(\mathbf{m}) + \beta\phi_m(\mathbf{m})$$

ϕ_d: data misfit
ϕ_m: regularization
β: trade-off parameter

find a model

that fits the data

and respects prior knowledge

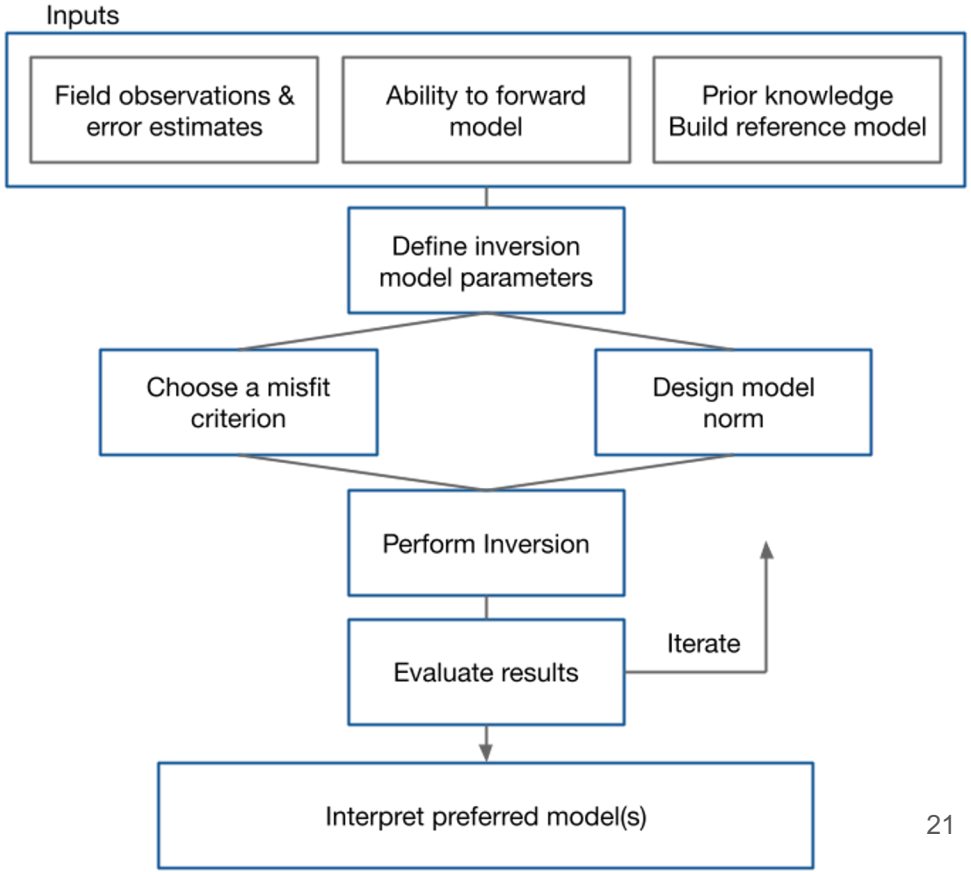
- drill logs
- geophysical logs (e.g. resistivity)
- spatial patterns
- other geophysical data
- …

Flowchart for the inverse problem

How do we solve our problem?

$$\underset{\mathbf{m}}{\text{minimize}}\ \phi(\mathbf{m}) = \phi_d(\mathbf{m}) + \beta\phi_m(\mathbf{m})$$

- Many components to achieving a quality result
- Success is in the details
- Evaluate each step in the box critically before going on



Starting up

Survey and observations

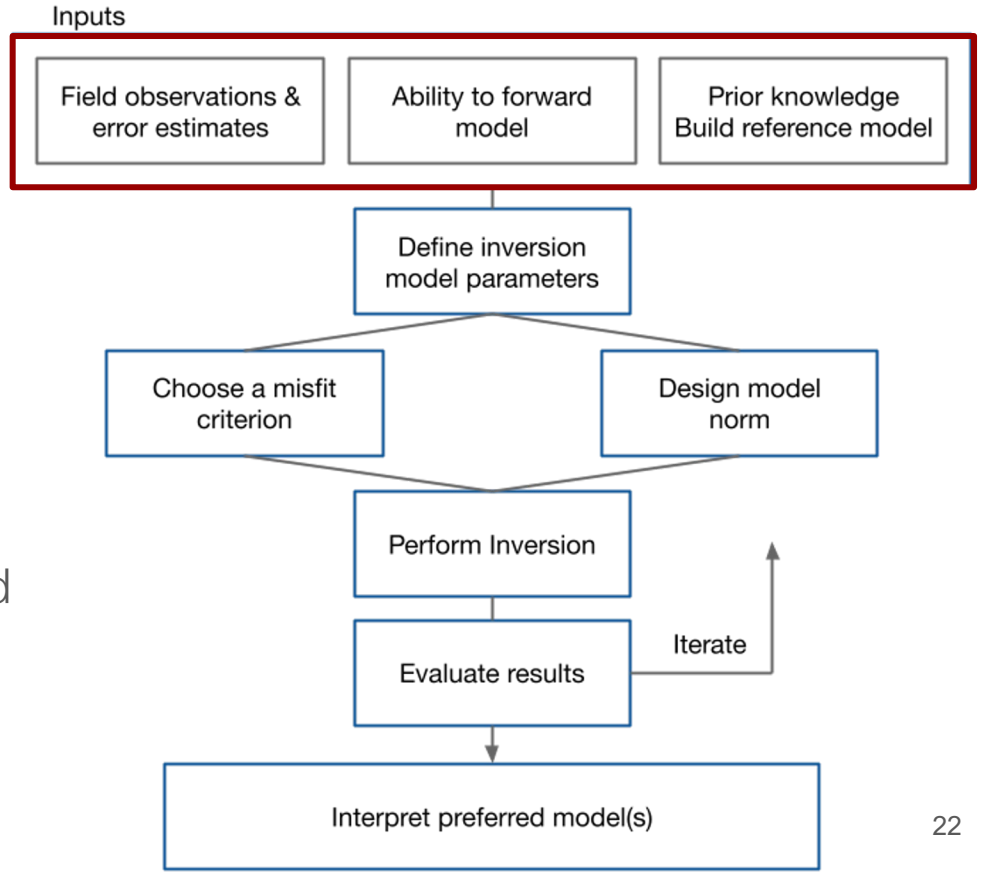
What processing has been done?

Ability for forward model

Assemble geologic, petrophysical information

Build a reference model

What is the question you want answered from the inversion?



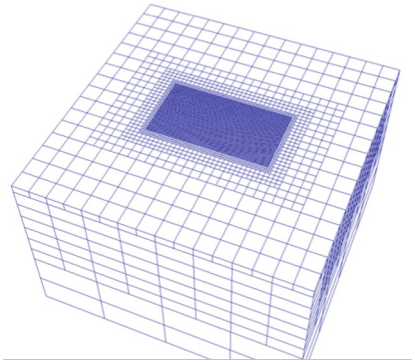
forward modelling

Given a model of the earth → simulate data

$$\mathcal{F}[m] = d$$

General approach

- "discretize" the subsurface
- assign physical properties to each cell
- solve discrete version of governing equations

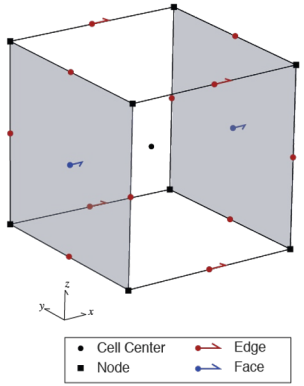


governing equation

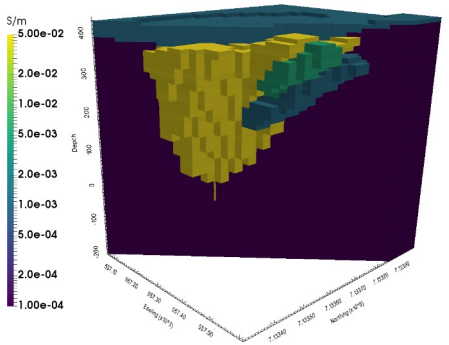
$$\nabla \cdot \sigma \nabla \phi = I\delta(r)$$

discretized equations

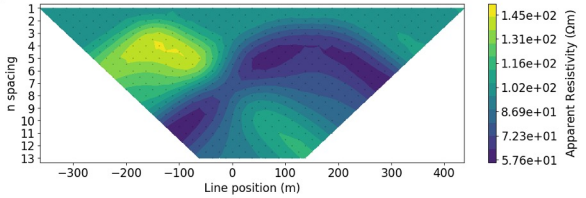
$$\underbrace{\mathbf{G}^\top \mathbf{M}_\sigma^\mathbf{e} \mathbf{G}}_{\mathbf{A(m)}} \phi = \mathbf{q}$$



physical property model



simulated data



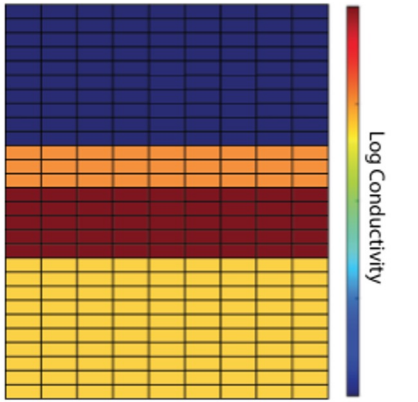
inversion model parameters

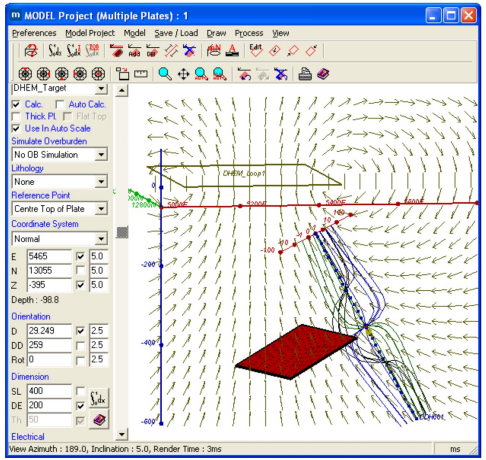
identify relevant physical properties

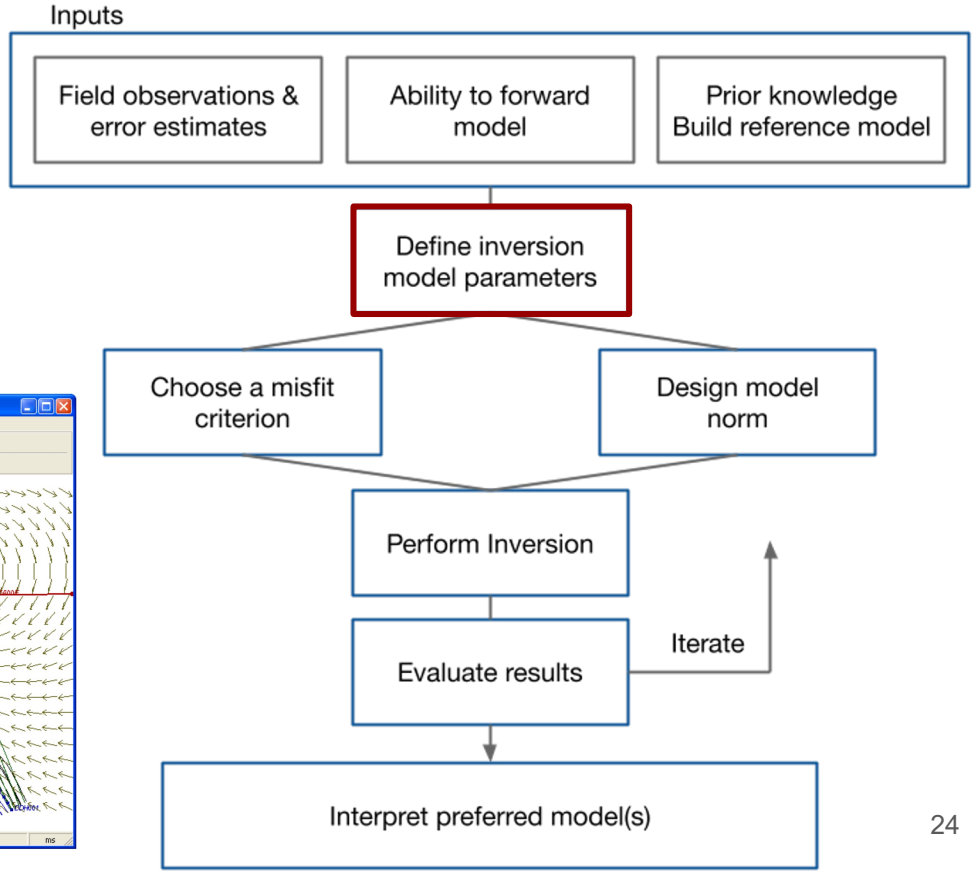
$$\mathcal{F}[m] = d$$

define parameters to invert for

have flexibility: log conductivity, layered earth, parametric….







fitting the data

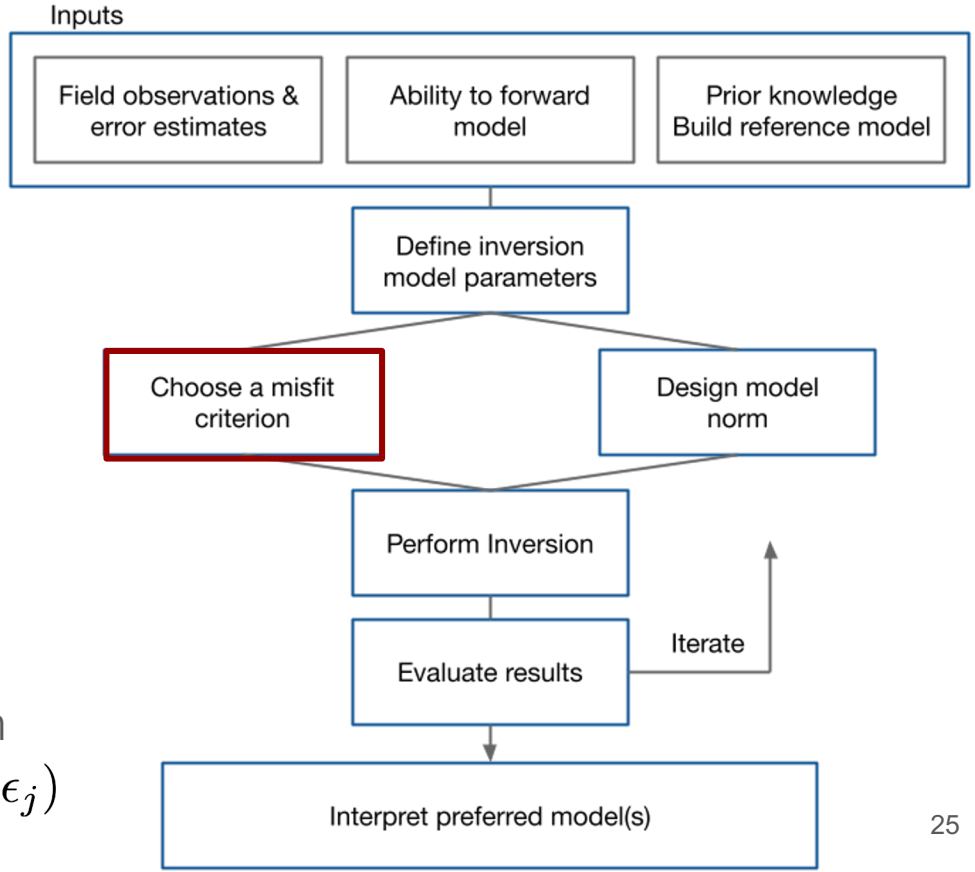
Observed data

$$d_j^{obs} = F_j(m) + n_j$$

Noise n_j includes…

- instrument / sensor noise
- cultural noise, powerlines, wind, …
- inaccuracies in survey parameters
- modelling errors
  - dimensionality errors (1D v. 3D)
  - incomplete physics
  - discretization errors

True statistics of noise is complicated. In practice, assume Gaussian errors $\mathcal{N}(0, \epsilon_j)$



fitting the data

Observed data

$$d_j^{obs} = F_j(m) + n_j$$

Define a metric for data fit that lets us include information about uncertainties

$$\phi_d = \sum_{j=1}^{N} \left(\frac{F_j(m) - d^{obs}}{\epsilon_j} \right)^2$$

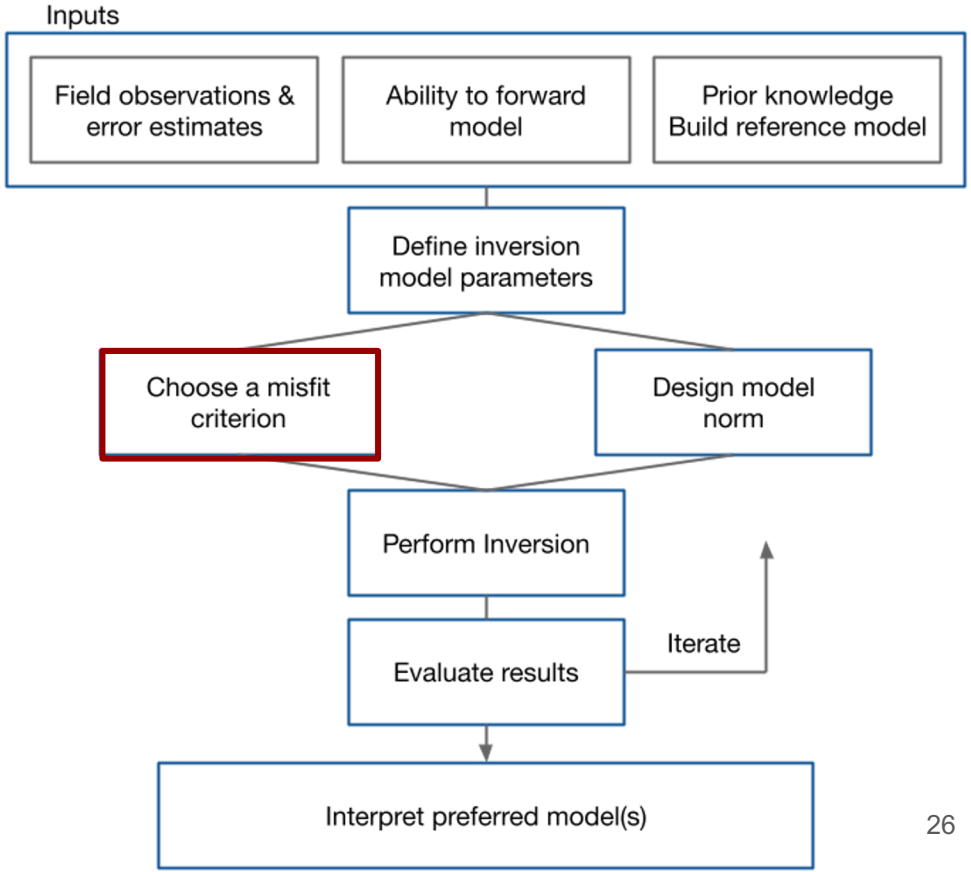
difference: predicted and observed data

weighted by uncertainties

data adequately fit when

$$\phi_d^* \simeq N$$

number of data



defining a model norm

bring in priori knowledge, assumptions

- smallest model: favor model close to a reference model

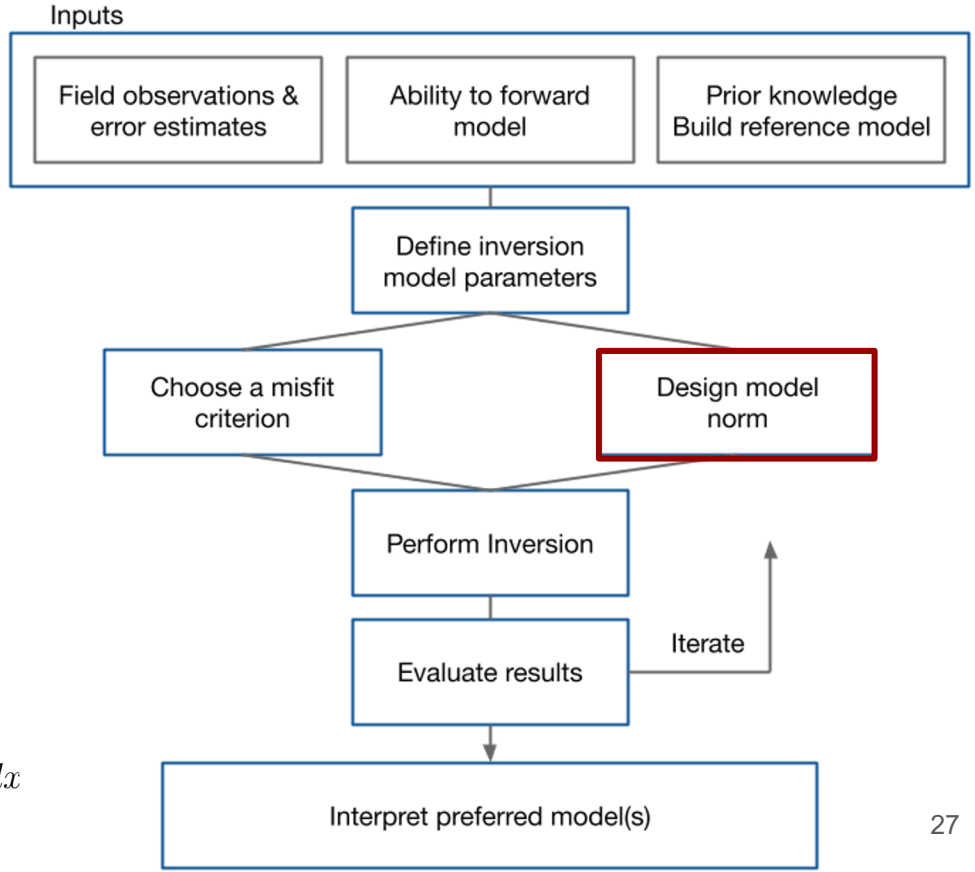
$$\phi_m = \int (m - m_{ref})^2 dx$$

- smooth model: penalize large changes spatially

$$\phi_m = \int \left(\frac{dm}{dx}\right)^2 dx$$

- combination

$$\phi_m = \alpha_s \int (m - m_{ref})^2 dx + \alpha_x \int \left(\frac{dm}{dx}\right)^2 dx$$



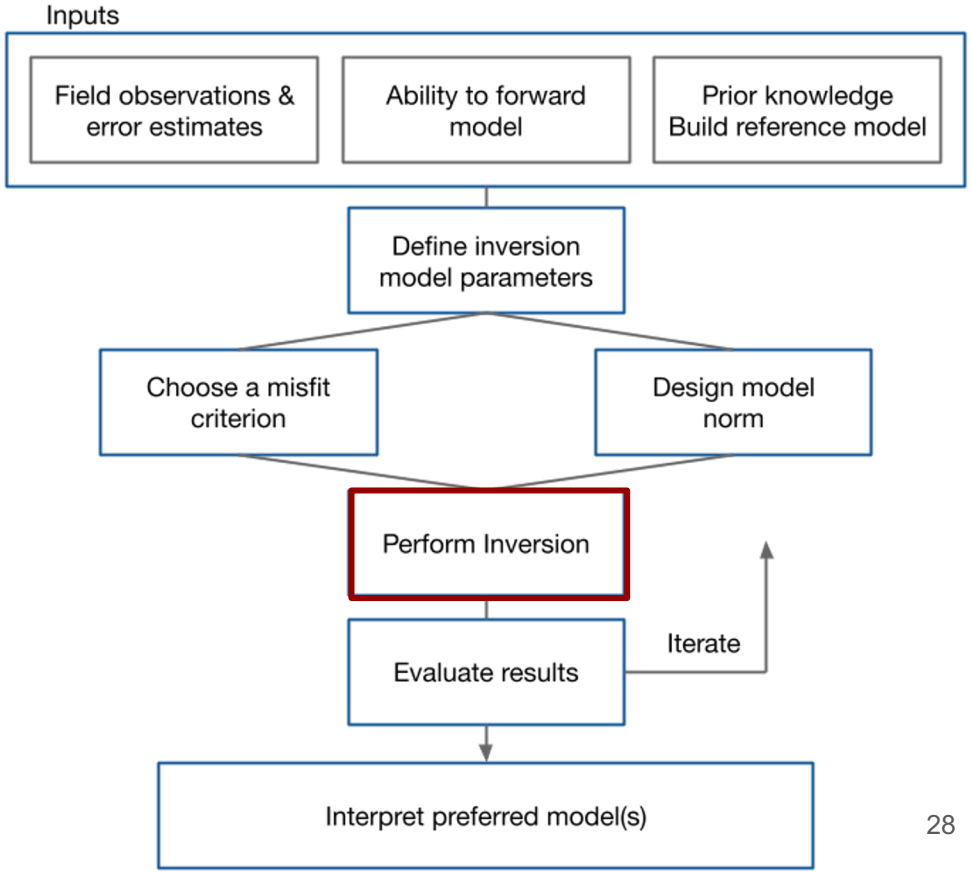
running the inversion

Combine the pieces of the inversion

$$\underset{\mathbf{m}}{\text{minimize}}\ \phi(\mathbf{m}) = \phi_d(\mathbf{m}) + \beta\phi_m(\mathbf{m})$$

Choosing beta?

An example…



Role of β

$$\phi(m) = \phi_d(m) + \beta\phi_m(m)$$

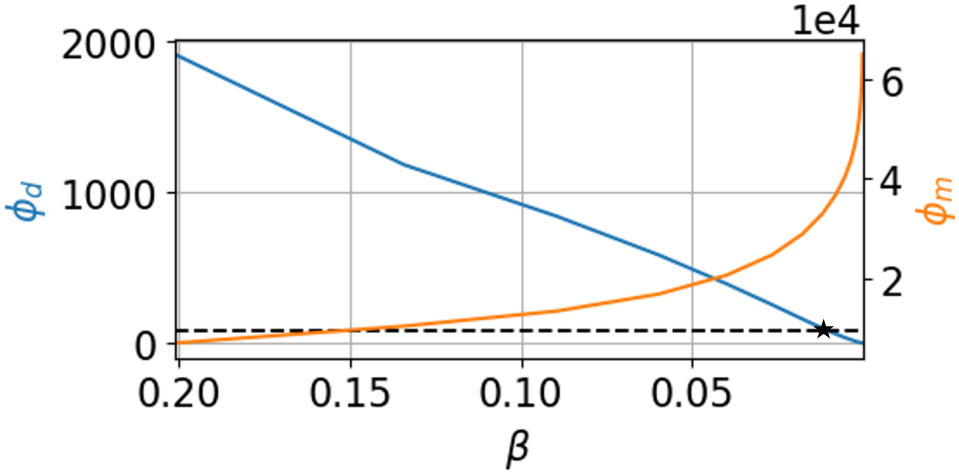
Influence of trade off parameter

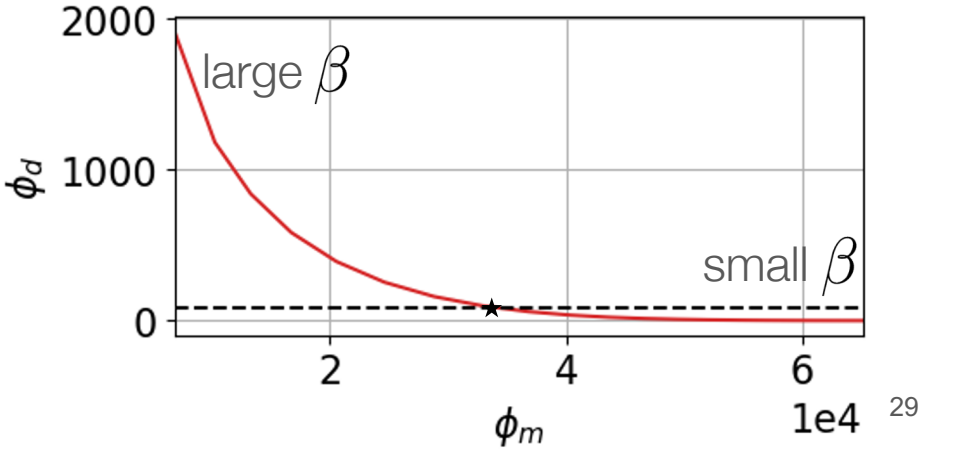
$$\beta \to 0 \quad : \quad \phi \sim \phi_d$$
$$\beta \to \infty : \quad \phi \sim \phi_m$$

Visualize influence with Tikhonov Curve

Desired misfit $\phi_d^* \simeq N$

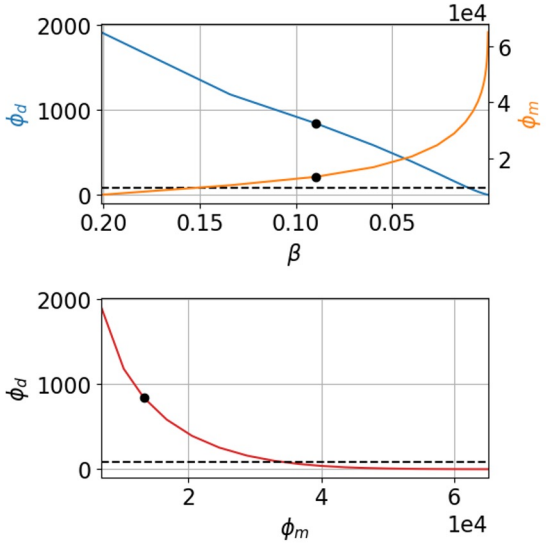
Choose β such that $\phi_d(m) = \phi_d^*$

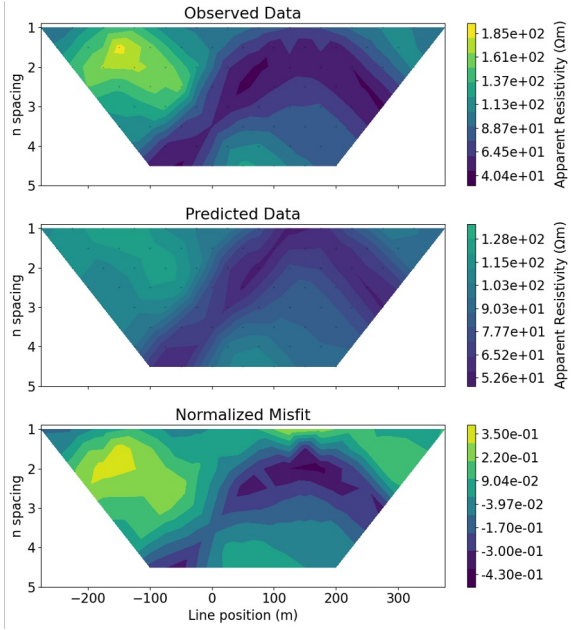


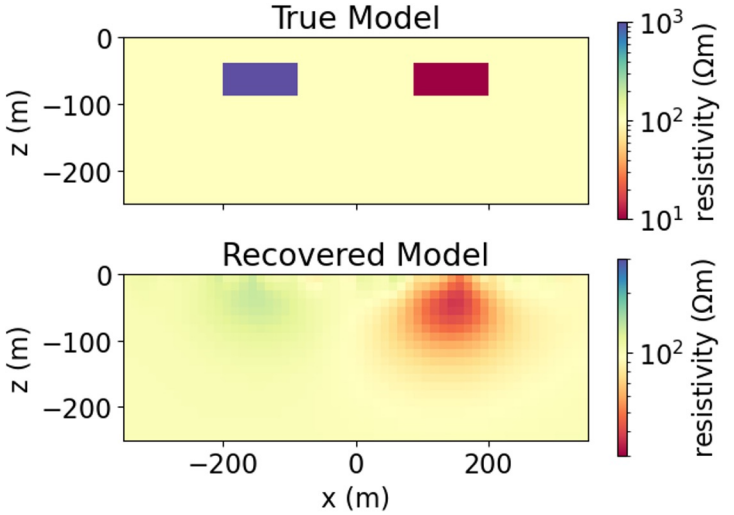


Role of β

Large β : under fit

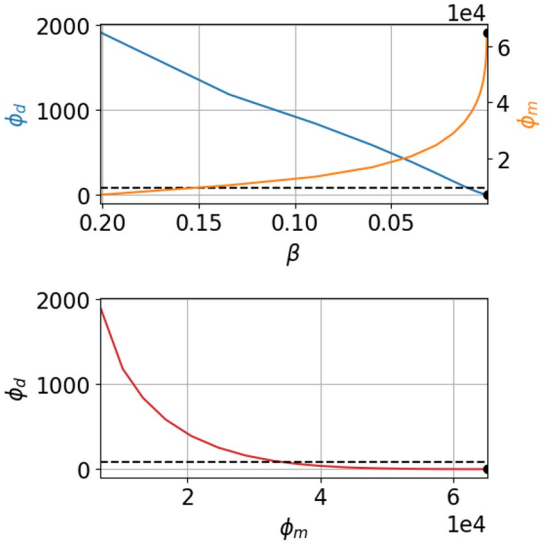


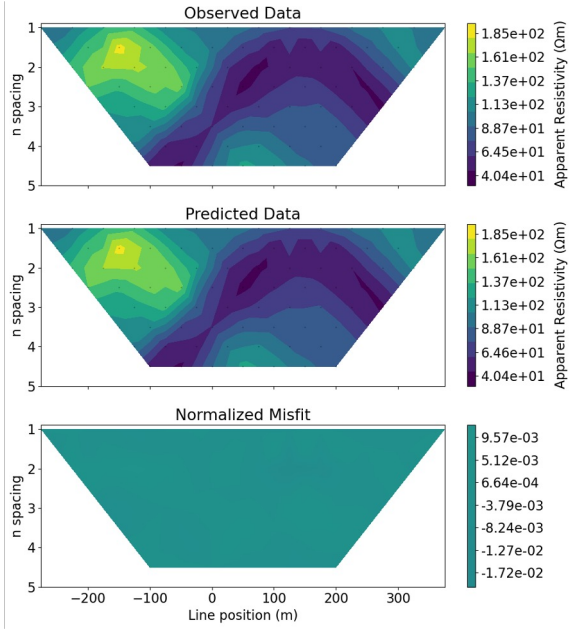


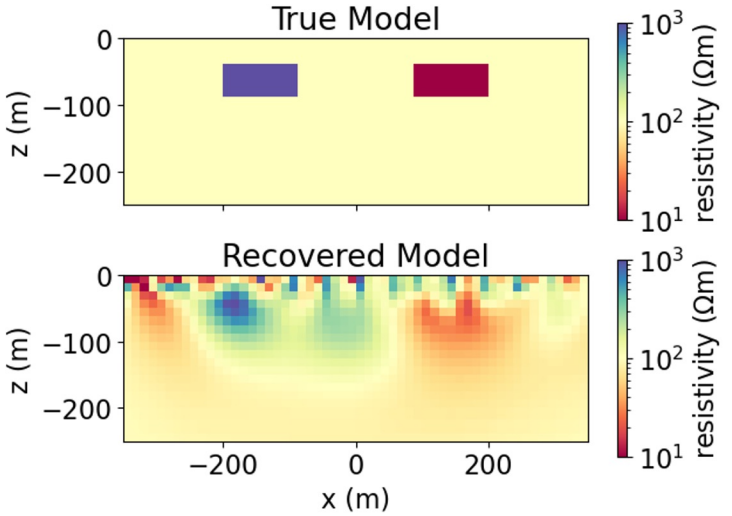


Role of β

Small β : over fit

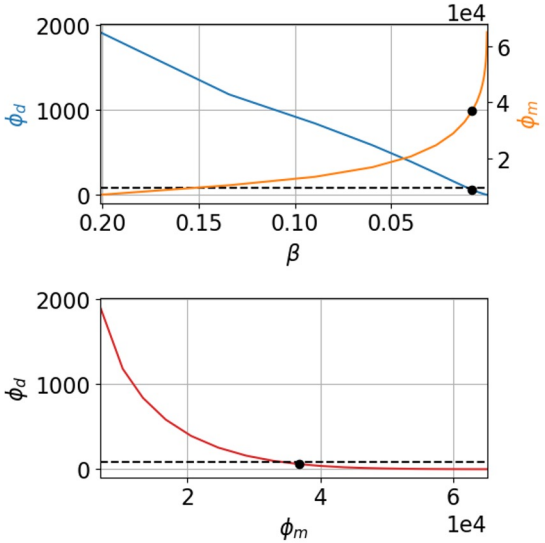


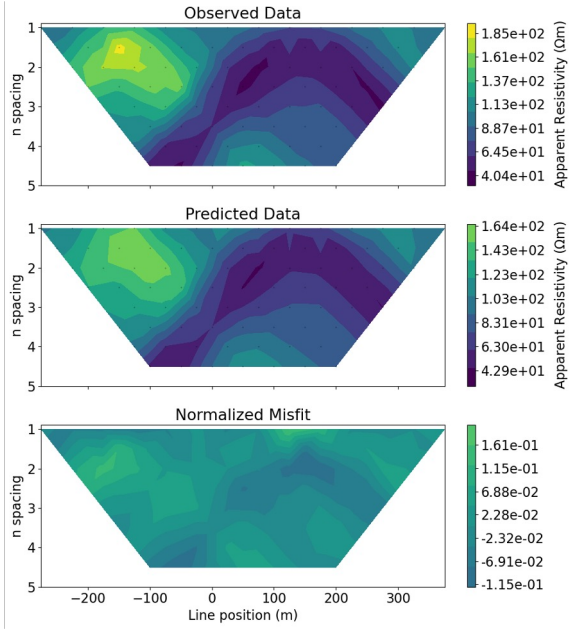


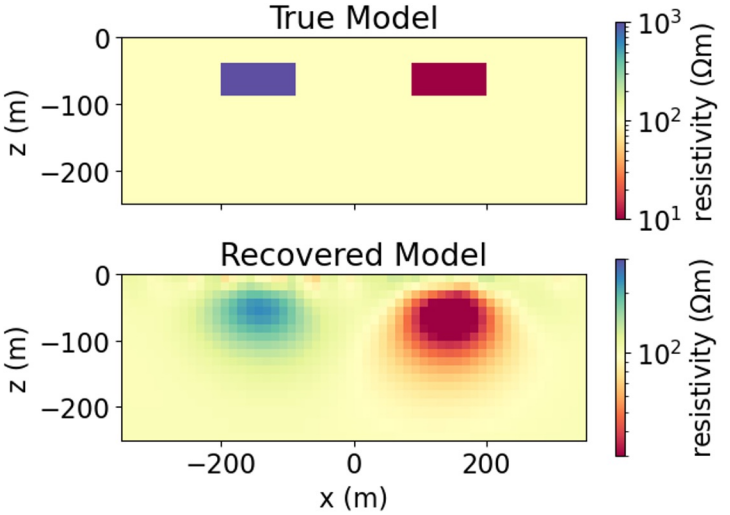


Role of β

β : just right!





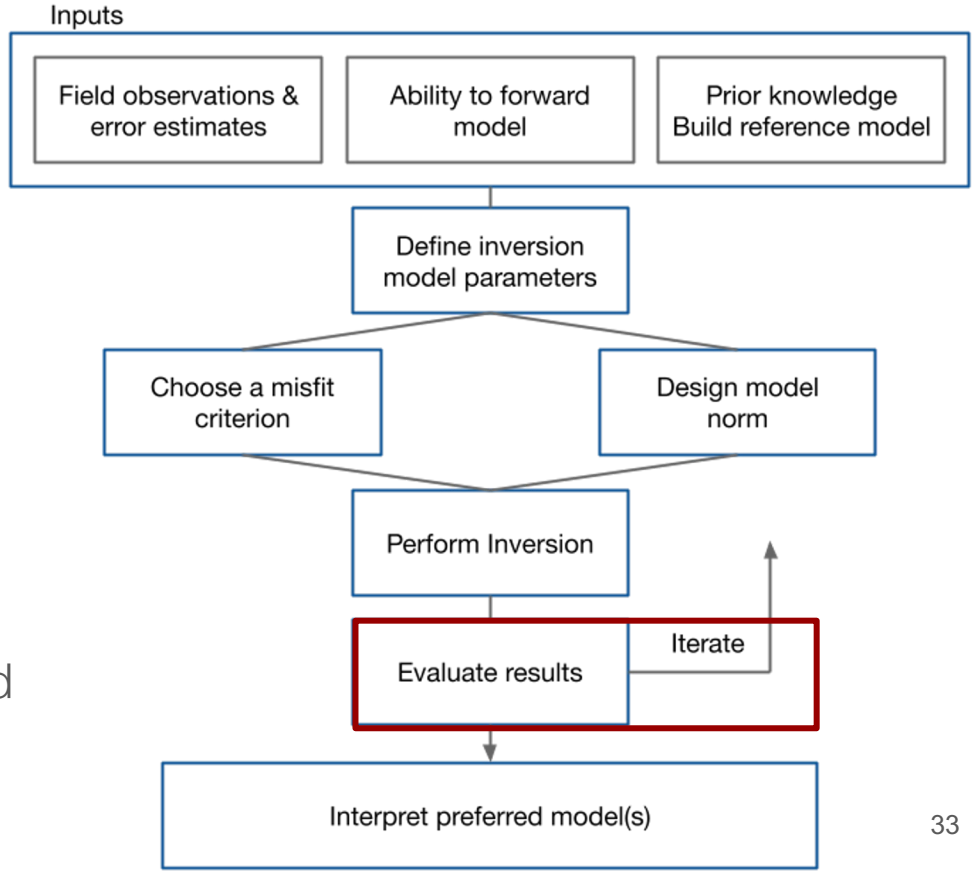


Flowchart for the inverse problem

How do we solve our problem?

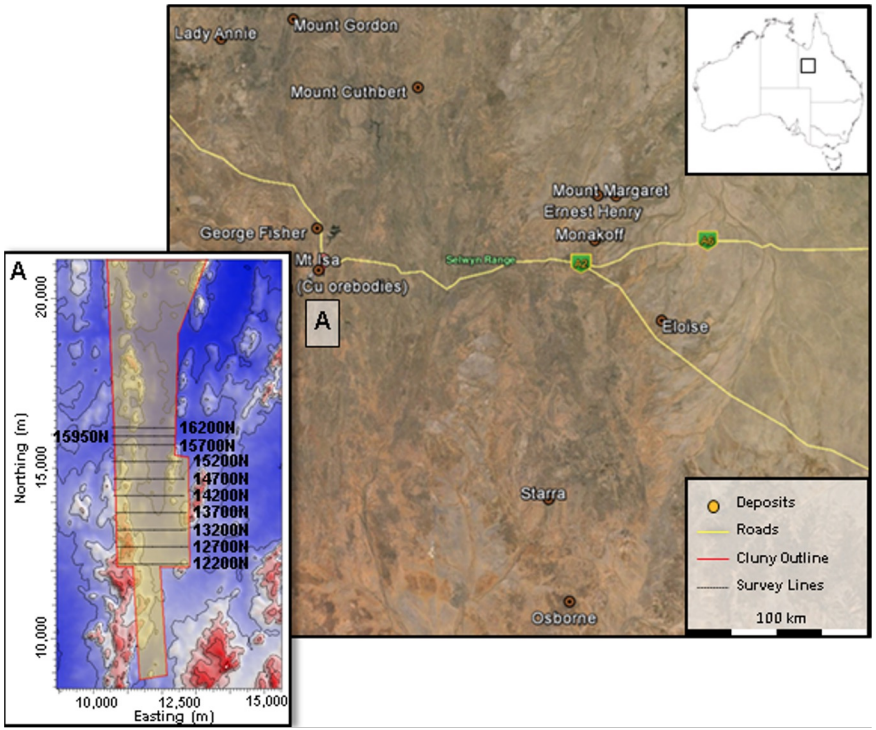
$$\underset{\mathbf{m}}{\text{minimize}}\ \phi(\mathbf{m}) = \phi_d(\mathbf{m}) + \beta\phi_m(\mathbf{m})$$

- often requires multiple inversions to obtain model for interpretation
- iteratively update design of model norm, noise estimates, …
- use geologic knowledge, common features in multiple inversion to build confidence in results

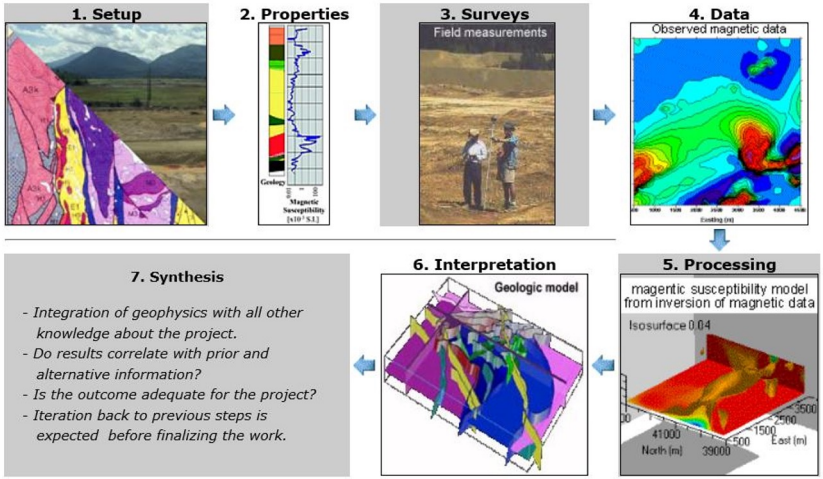


Case study: Mt. Isa

The Cluny copper/lead/zinc deposit, Queensland, Australia



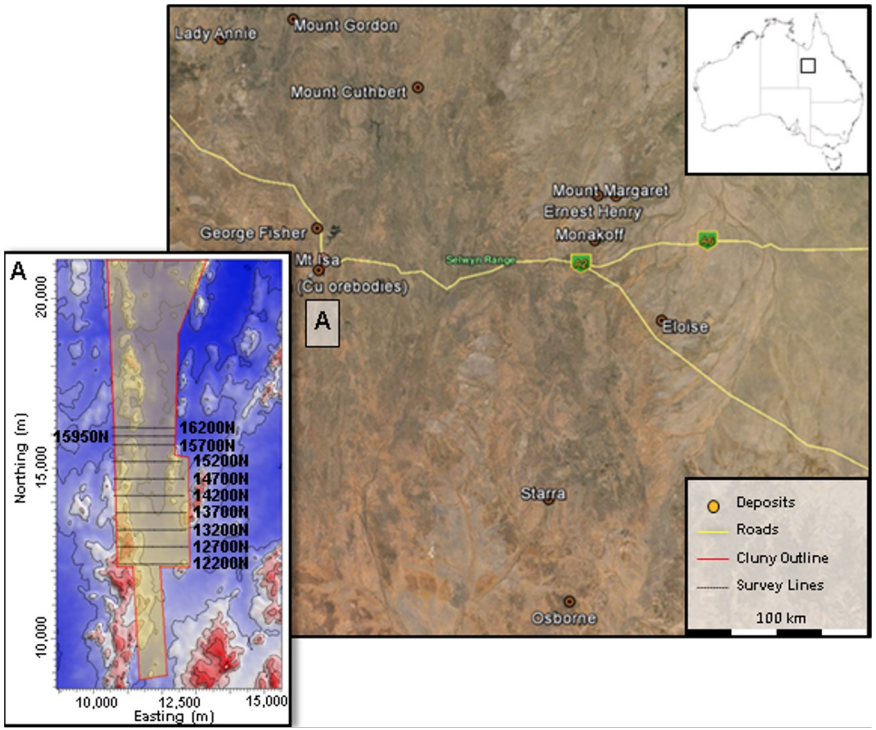
Seven step framework for geophysics



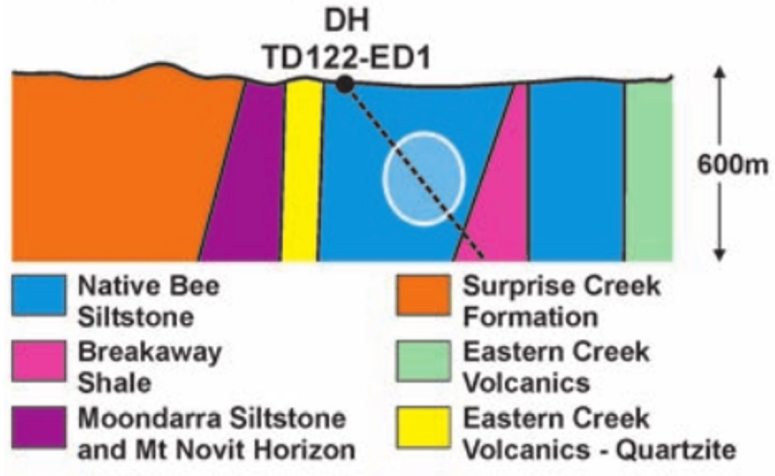
gpg.geosci.xyz

Setup

The Cluny copper/lead/zinc deposit, Queensland, Australia

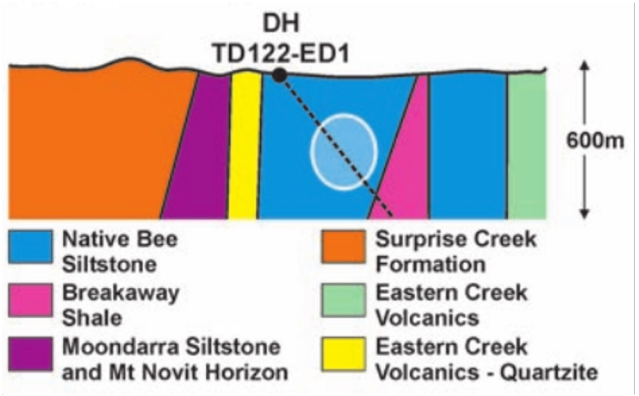


Geological model



Question: Can conductive units, which would be potential targets within the siltstones, be identified with DC?

Properties



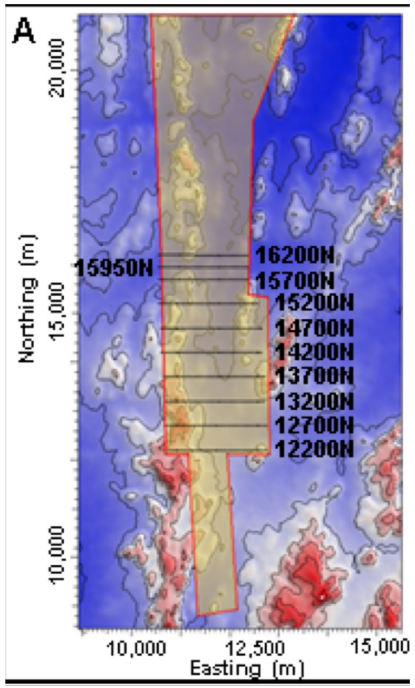
expect mineralized zones to be conductive

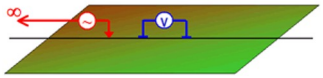
do you anticipate any challenges?

Rock Unit	Conductivity
Native Bee Siltstone	Moderate
Moondarra Siltstone	Moderate
Breakaway Shale	Very High
Mt Novit Horizon	High
Surprise Creek Formation	Low
Eastern Creek Volcanics	Low

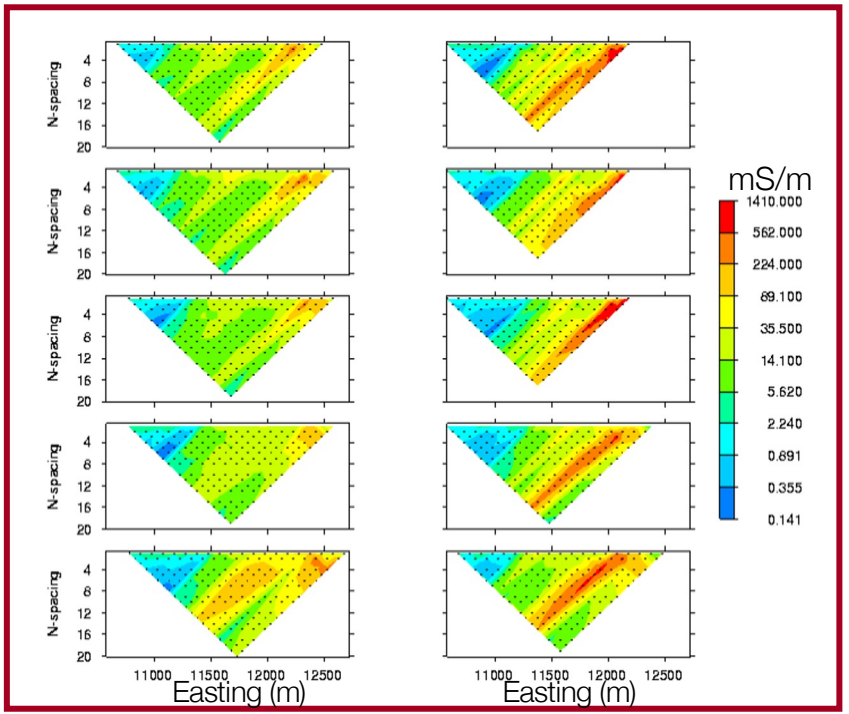
Survey

8 survey lines, 2 configurations



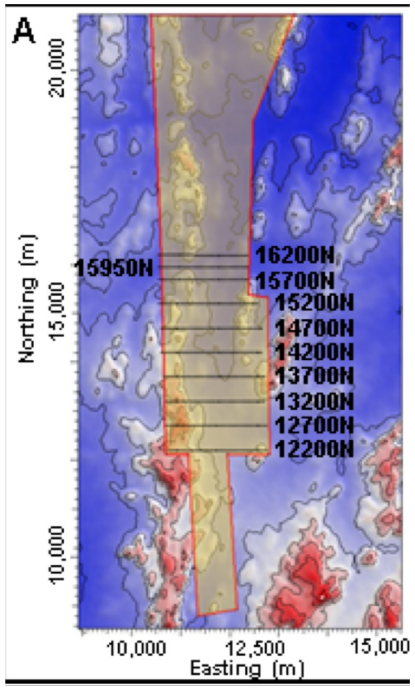


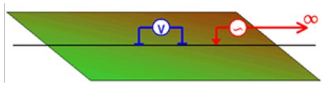
data set 1:
pole-dipole



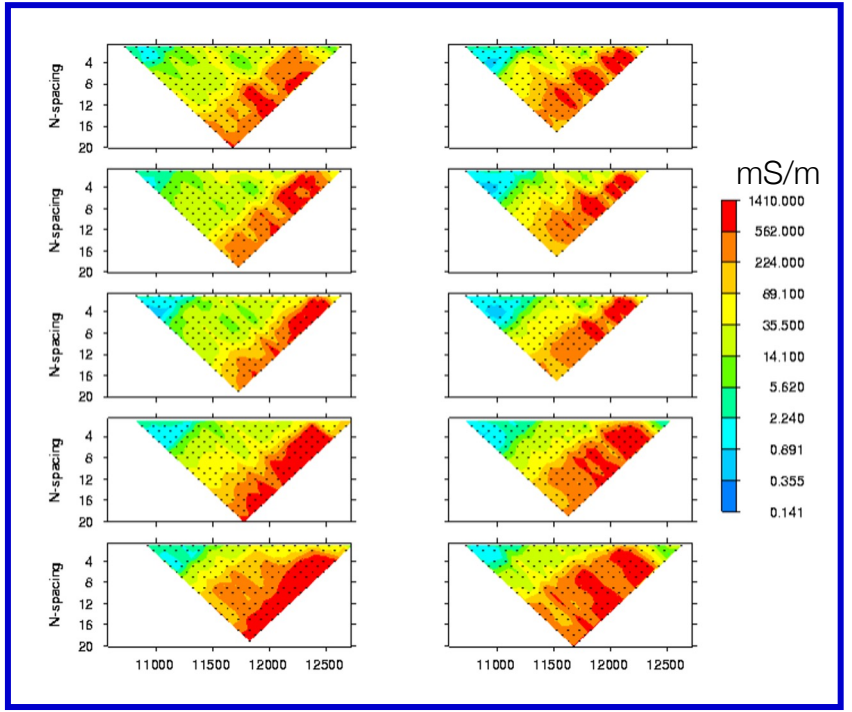
Survey

8 survey lines, 2 configurations



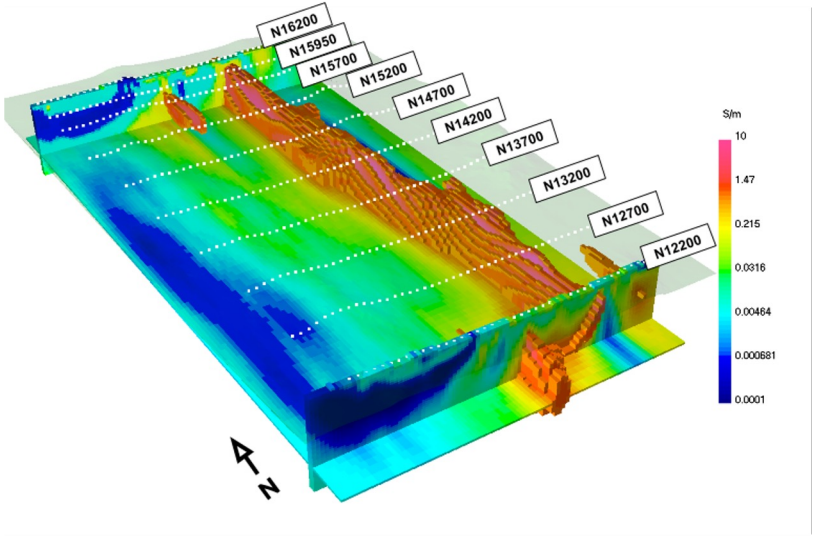


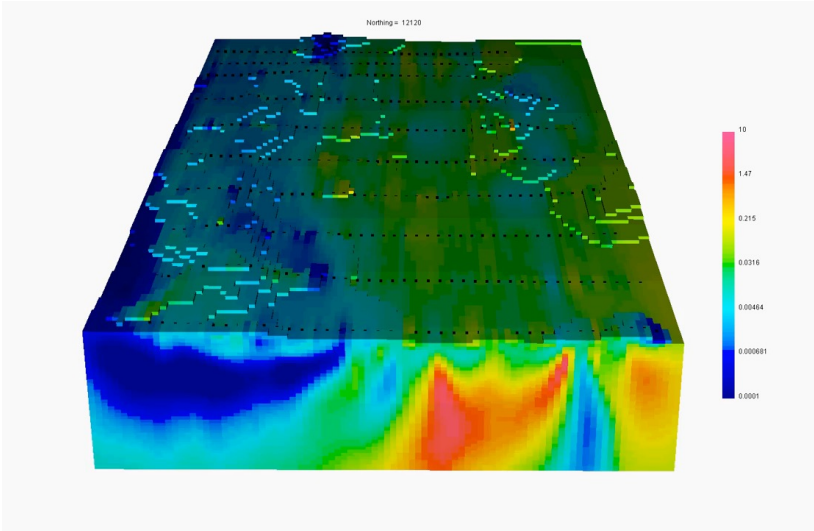
data set 2:
dipole-pole



Processing and interpretation

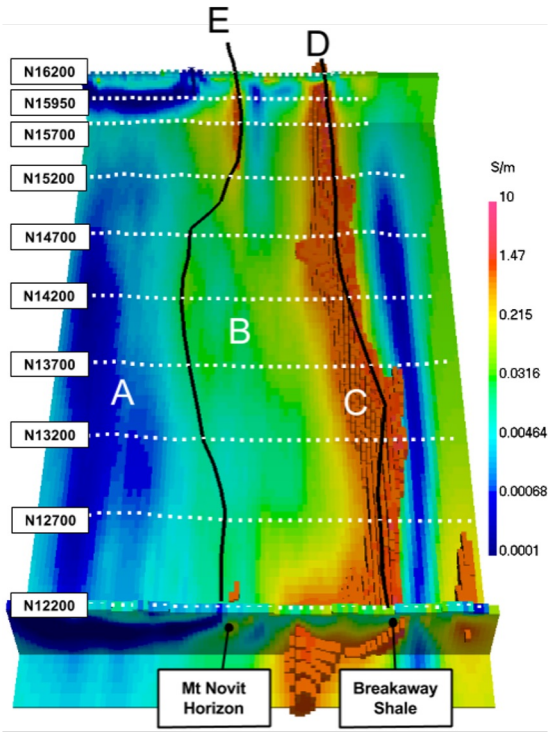
invert to obtain resistivity model



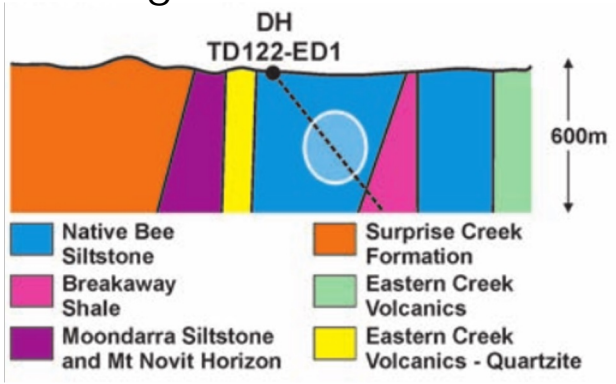


Synthesis

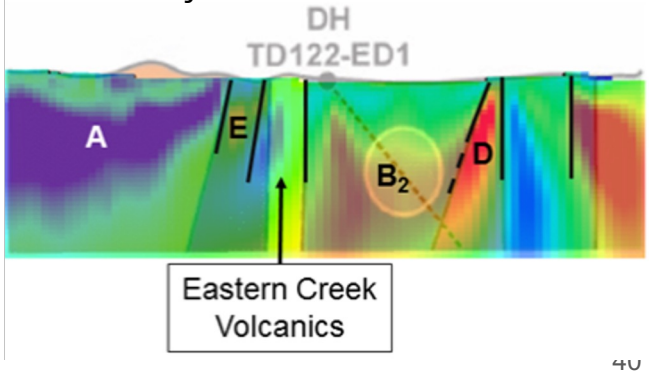
3D resistivity model



Geologic section



Resistivity section

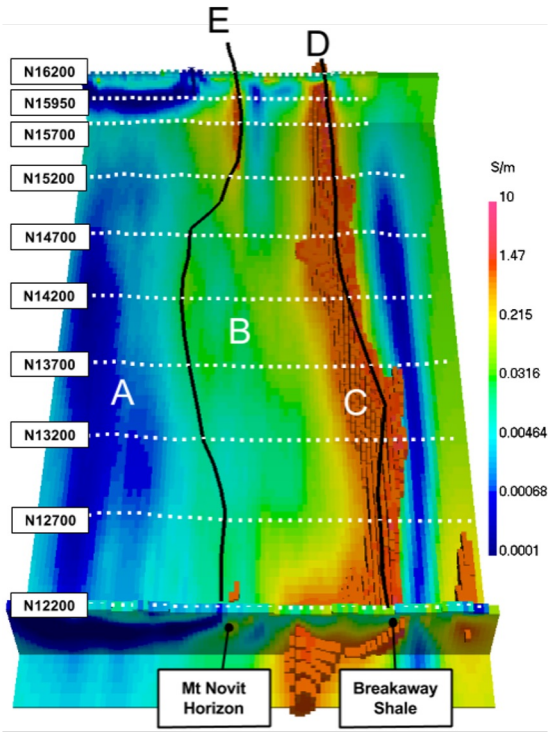


Synthesis

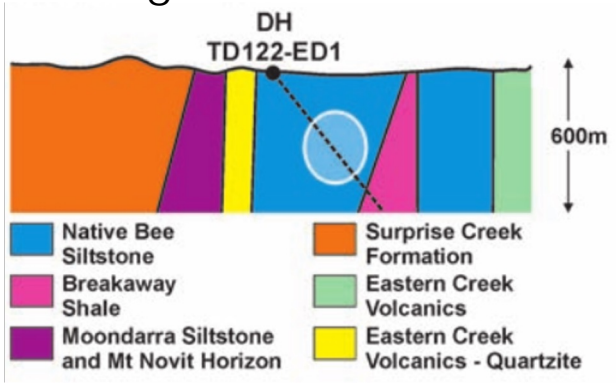
Identified a major conductor → black shale unit

Some indication of a moderate conductor

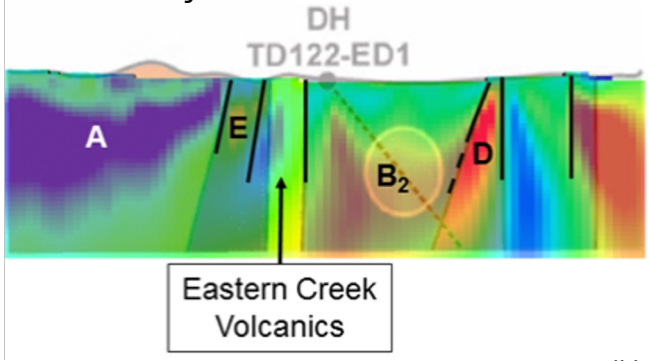
3D resistivity model



Geologic section



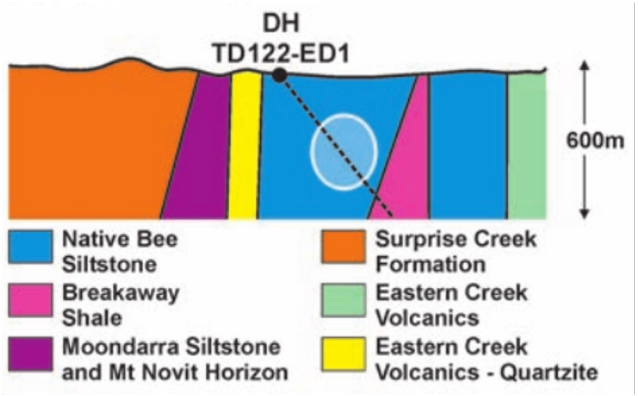
Resistivity section



Can IP help?

Additional physical property: chargeability

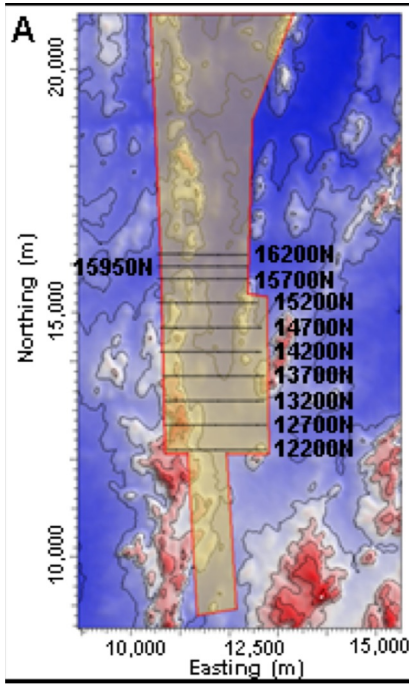
Do you expect mineralization (disseminated sulfides) to be chargeable?

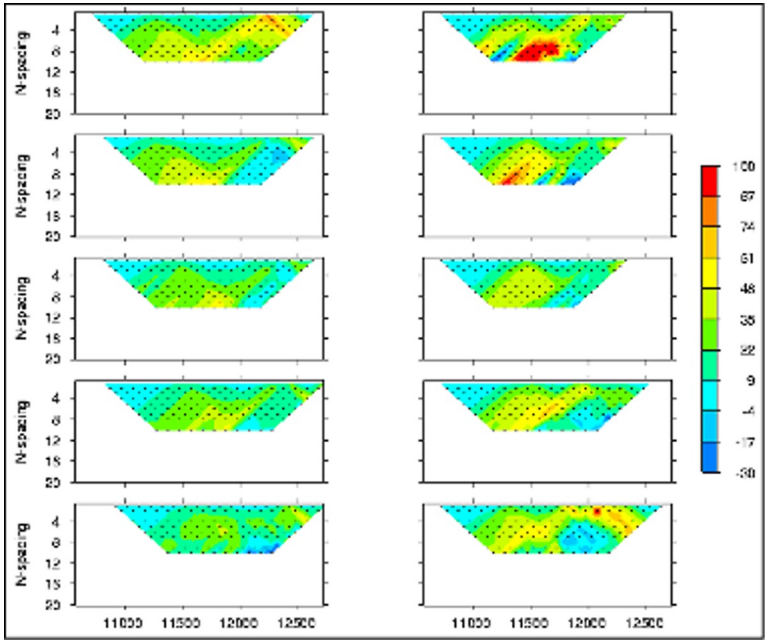


Rock Unit	Conductivity	Chargeability
Native Bee Siltstone	Moderate	Low
Moondarra Siltstone	Moderate	Low
Breakaway Shale	Very High	Low-None
Mt Novit Horizon	High	High
Surprise Creek Formation	Low	None
Eastern Creek Volcanics	Low	None

Survey and Data

IP data collected at same time as DC

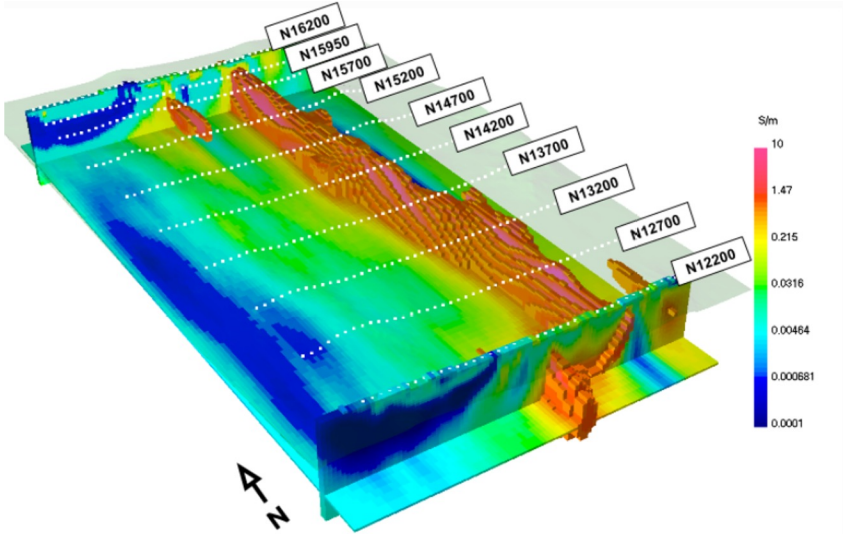




Processing: two step process

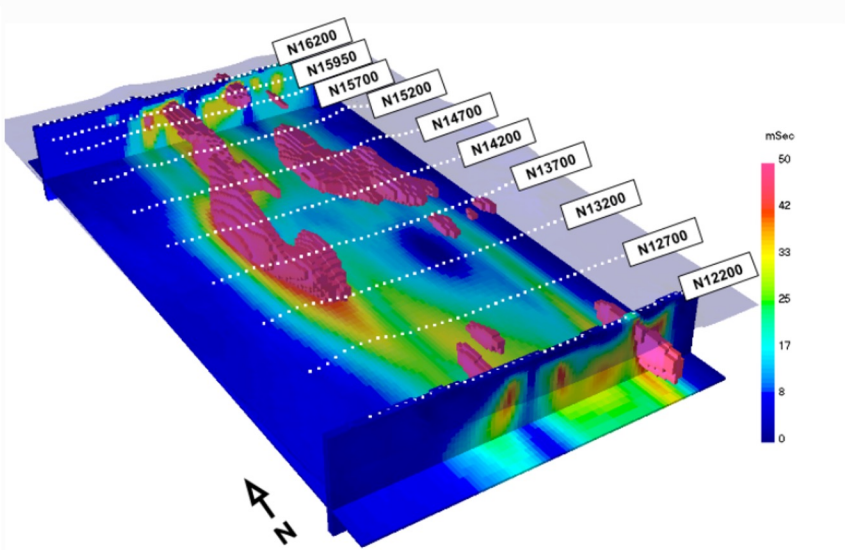
DC data

Resistivity model (ρ)

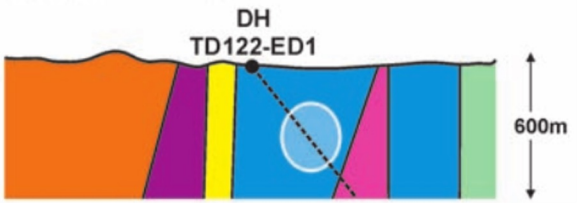


IP data

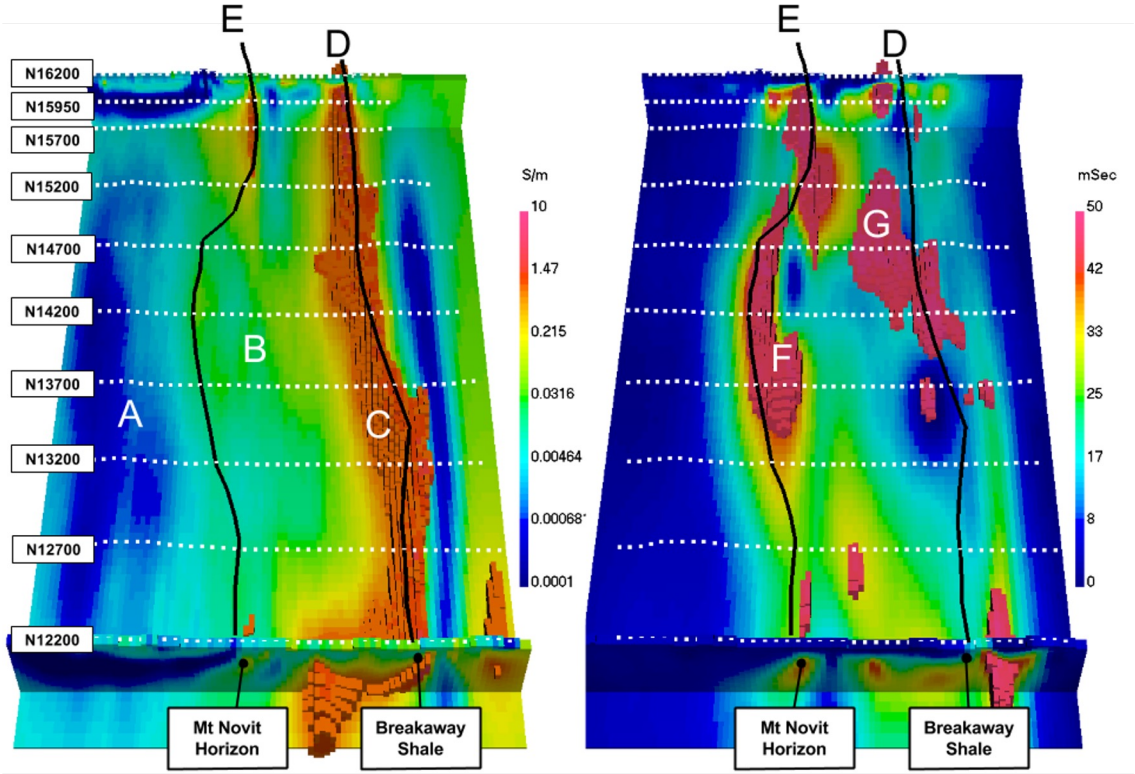
Chargeability model (η)



Interpretation

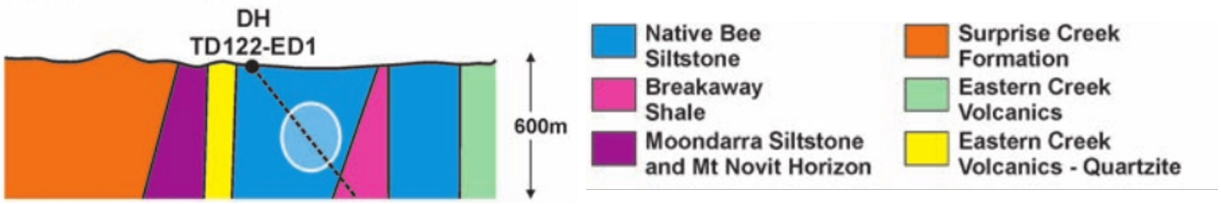


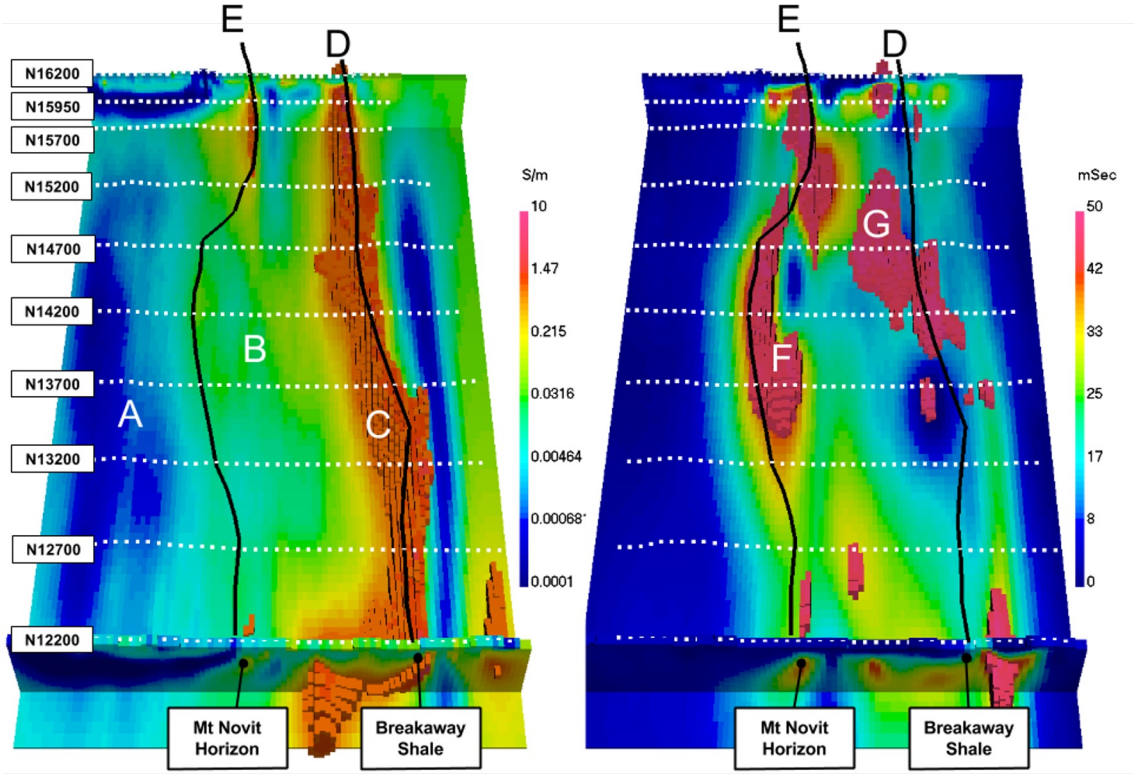
Native Bee Siltstone
Breakaway Shale
Moondarra Siltstone and Mt Novit Horizon
Surprise Creek Formation
Eastern Creek Volcanics
Eastern Creek Volcanics - Quartzite



A: Surprise creek
(low σ, low η)

Interpretation

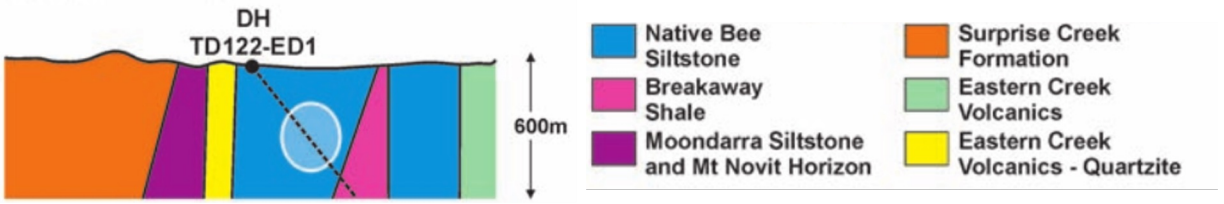


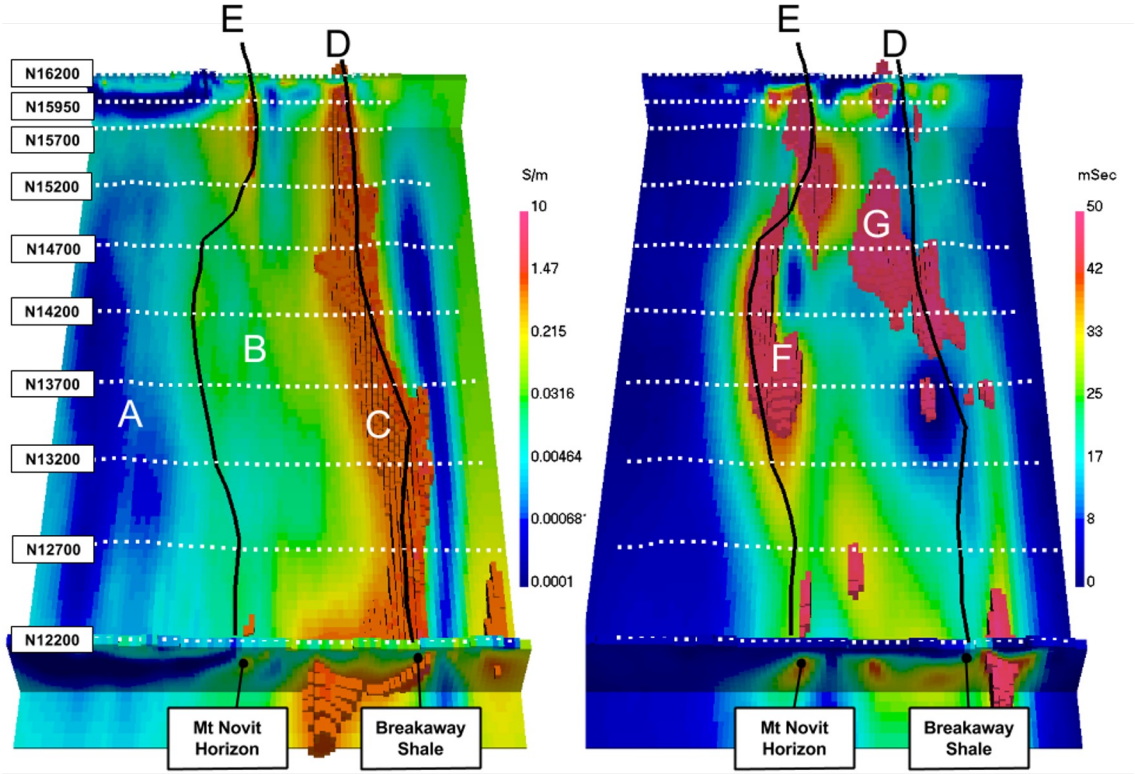


A: Surprise creek
(low σ, low η)

B: Moondarra, Native Bee siltstones
(moderate σ, low η)

Interpretation



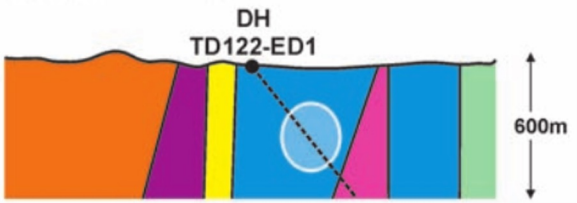


A: Surprise creek
(low σ, low η)

B: Moondarra, Native Bee siltstones
(moderate σ, low η)

C and D: Breakaway shales
(high σ, low η)

Interpretation



Native Bee Siltstone
Breakaway Shale
Moondarra Siltstone and Mt Novit Horizon
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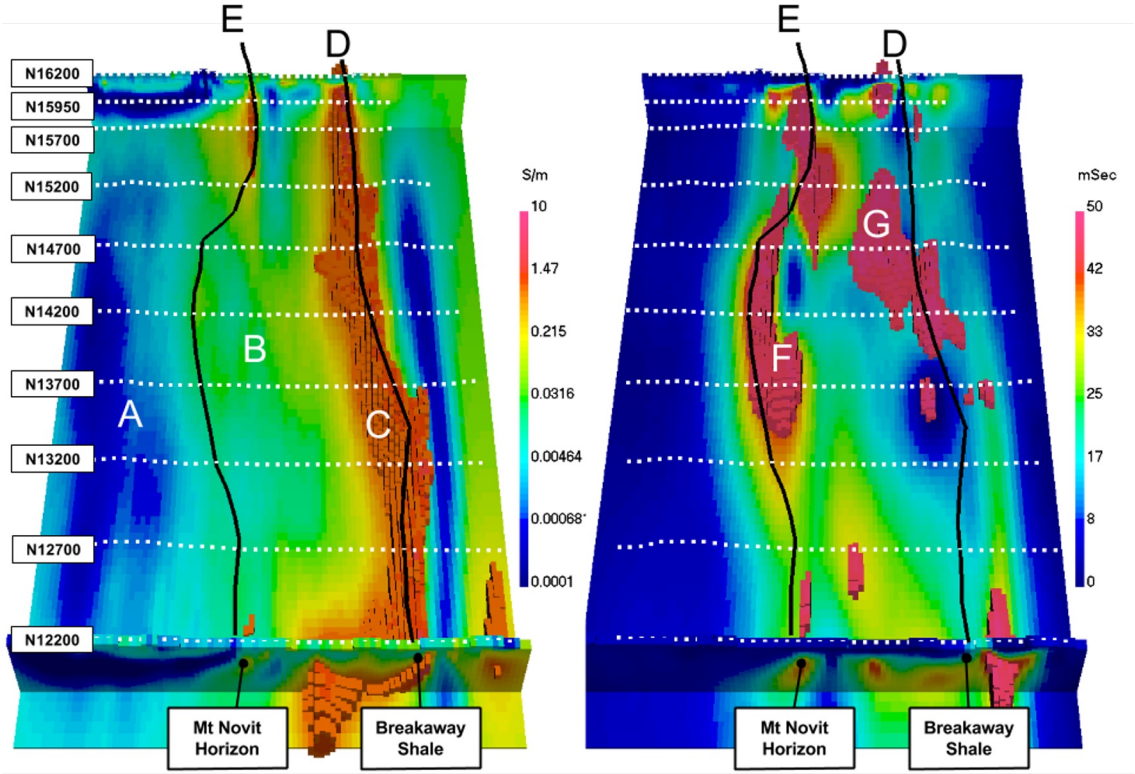
Eastern Creek Volcanics
Eastern Creek Volcanics - Quartzite



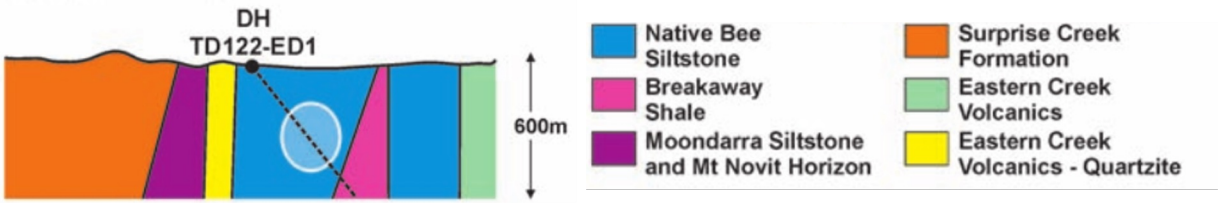
A: Surprise creek
(low σ, low η)

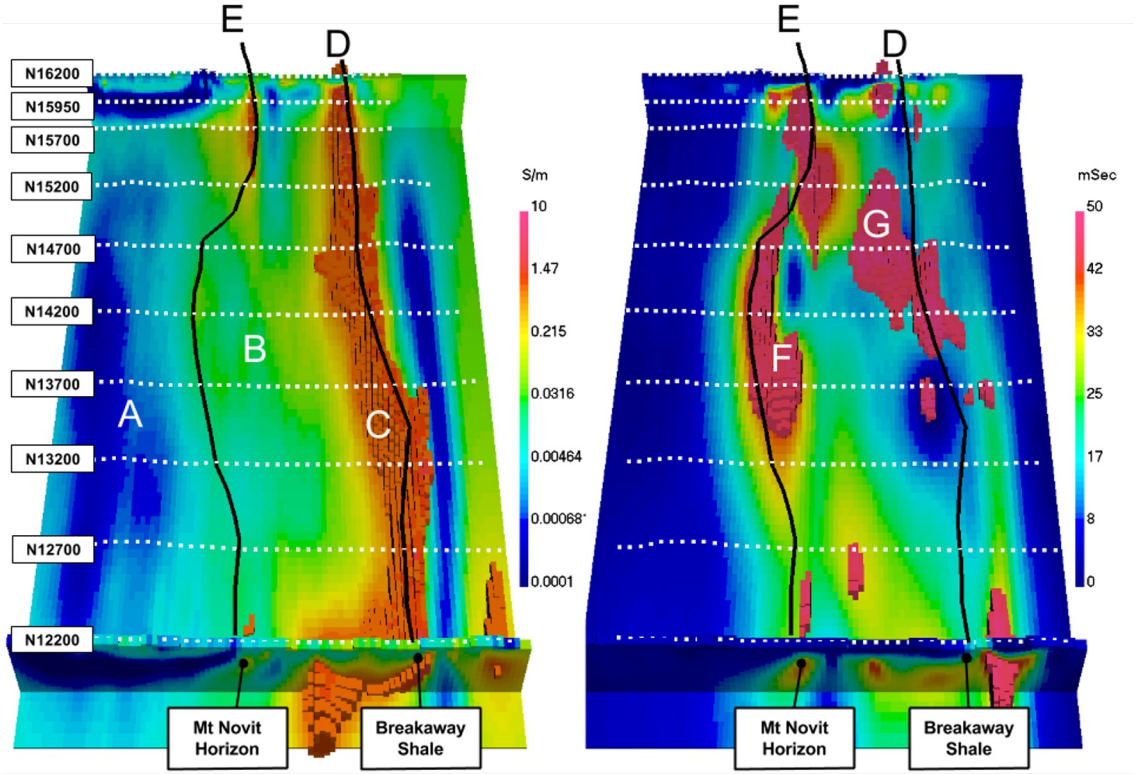
B: Moondarra, Native Bee siltstones
(moderate σ, low η)

C and D: Breakaway shales
(high σ, low η)

E and F: Mt. Novit horizon
(high σ, high η)

Interpretation





A: Surprise creek
(low σ, low η)

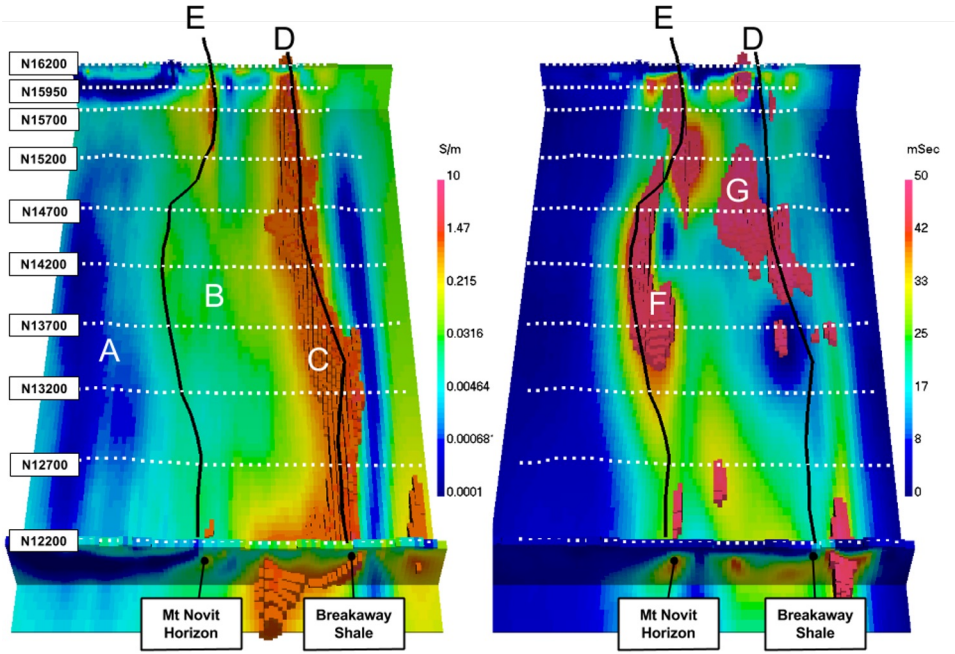
B: Moondarra, Native Bee siltstones
(moderate σ, low η)

C and D: Breakaway shales
(high σ, low η)

E and F: Mt. Novit horizon
(high σ, high η)

G: Possible mineralization
(high σ, high η)

Mt. Isa: Synthesis



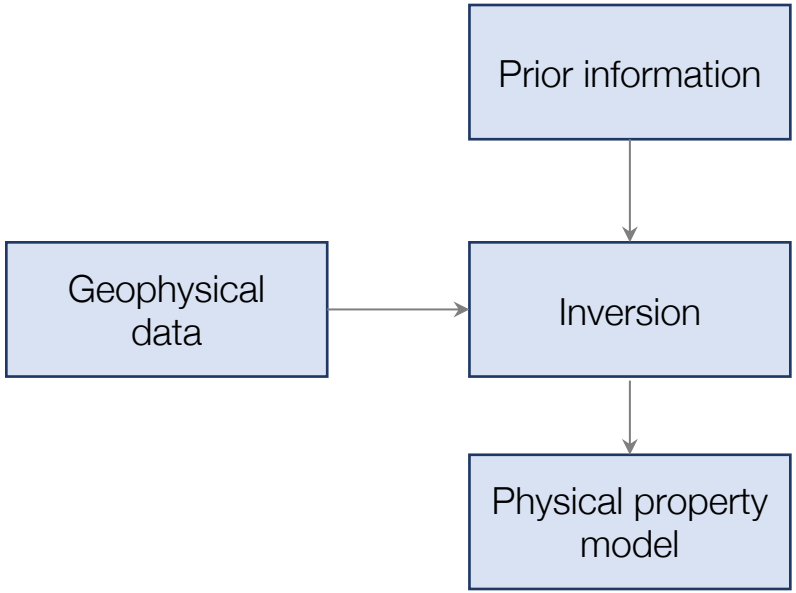
Chargeability delineates region of interest from background

Mt. Novit horizon is chargeable

Chargeability delineates Breakaway shale (high σ, low η) from mineralization (high σ, high η)

Summary

- Inversions are a tool for estimating physical property models from geophysical data
- Iterative process, requires assessing, updating assumptions and parameter choices
- Constrain with prior knowledge, additional data



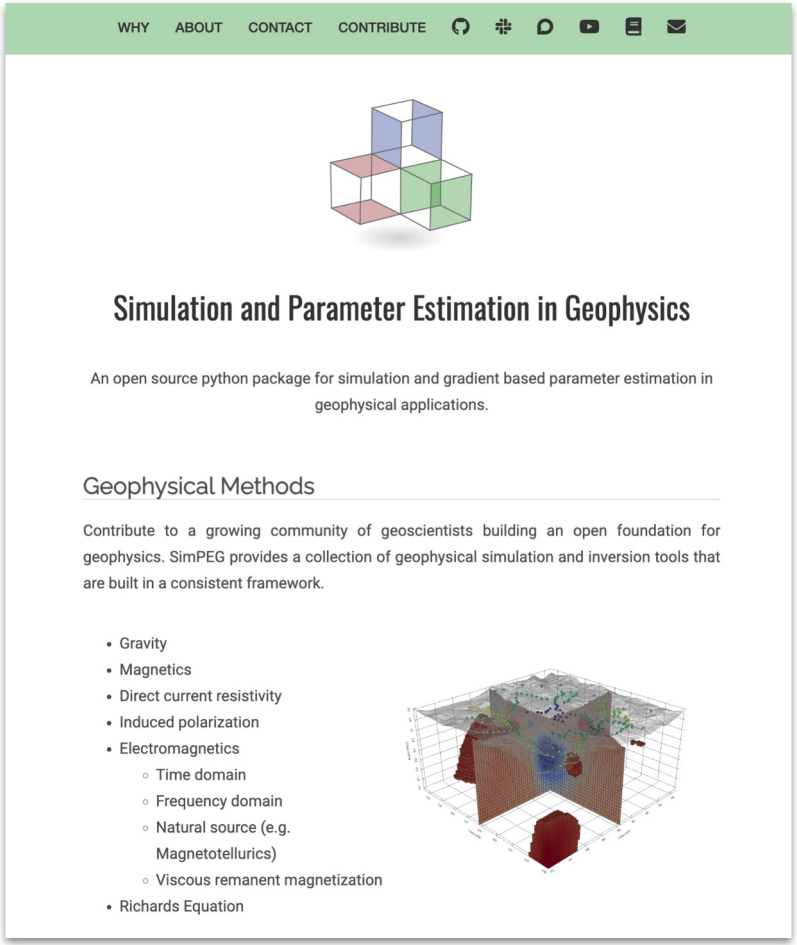
role of open-source tools

Inversions require ability to:

- simulate equations
- design model norm, data misfit
- perform optimization
- experiment with new ideas!

simpeg

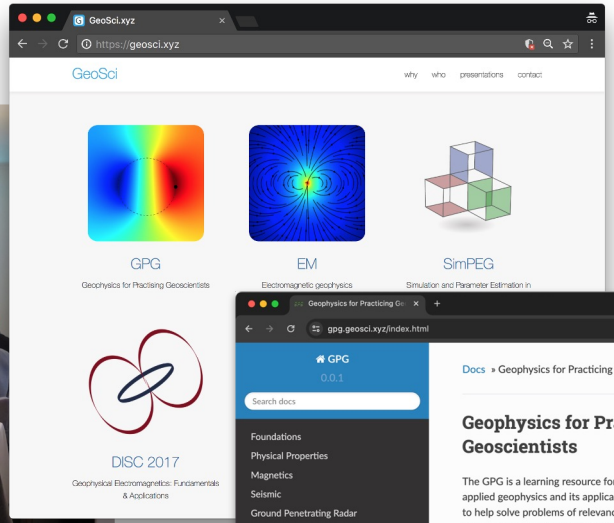
- open source project for simulation and inversion of geophysical data
- collaborative, community driven

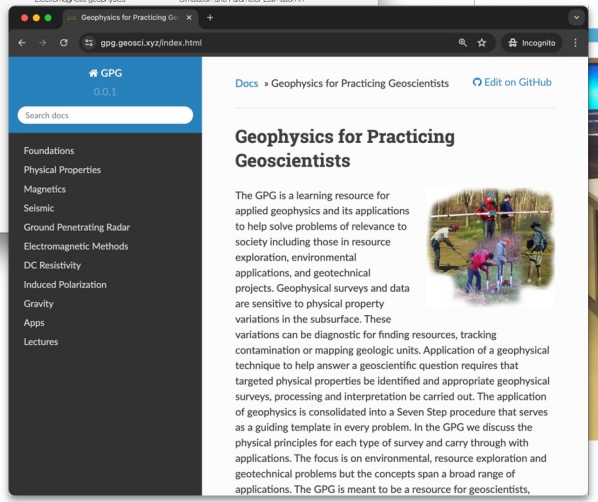


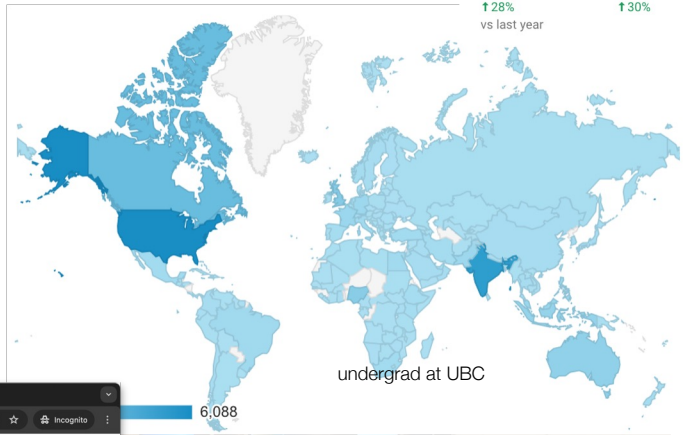
https://simpeg.xyz

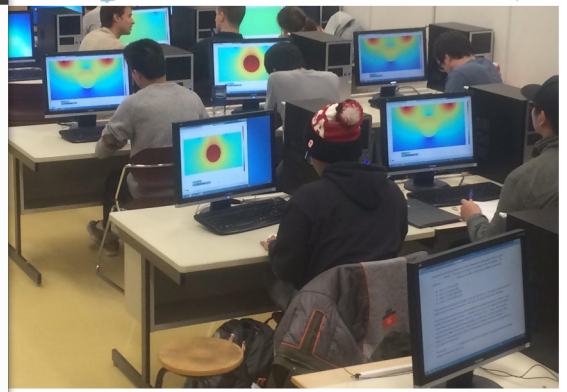
GeoSci.xyz open educational resources

https://geosci.xyz









electromagnetics course:
26 locations worldwide

Thank you!

geosci.xyz

simpeg.xyz

lheagy@eoas.ubc.ca

PDAC

S-IMEW

Student-Industry Mineral Exploration Workshop