

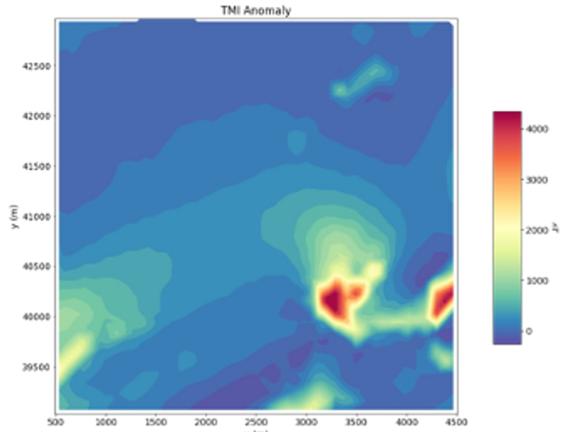
inversion, visualization, and open-source tools

Lindsey Heagy

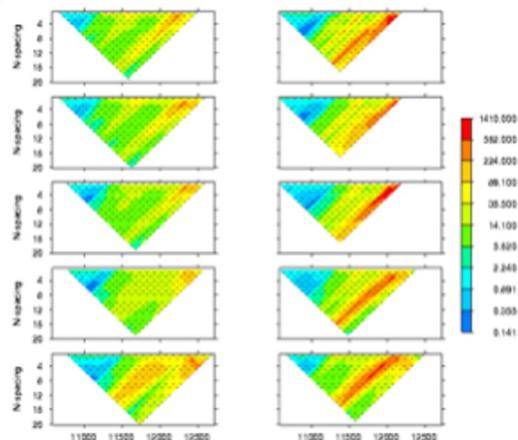
University of British Columbia – Geophysical Inversion Facility

geophysical data

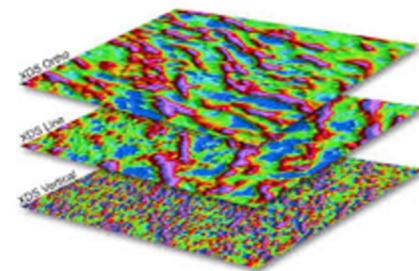
maps (mag, grav,)



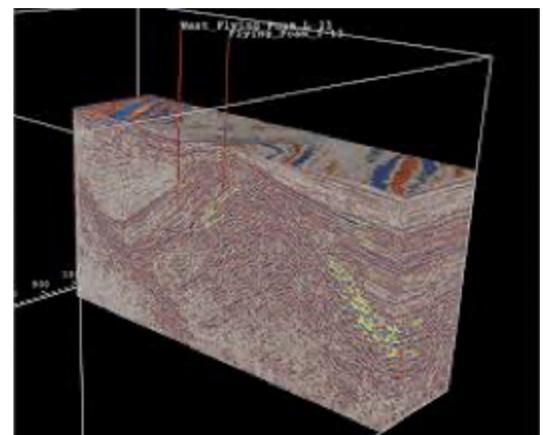
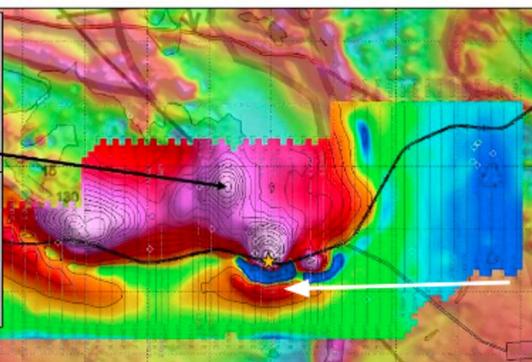
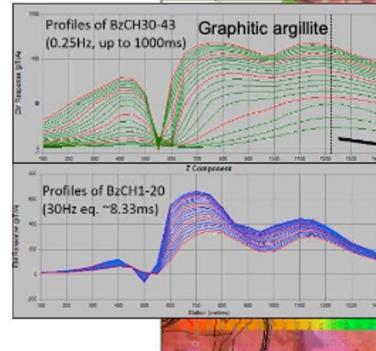
pseudosections (DC, IP)



multiple maps, volumes
(EM, seismic)

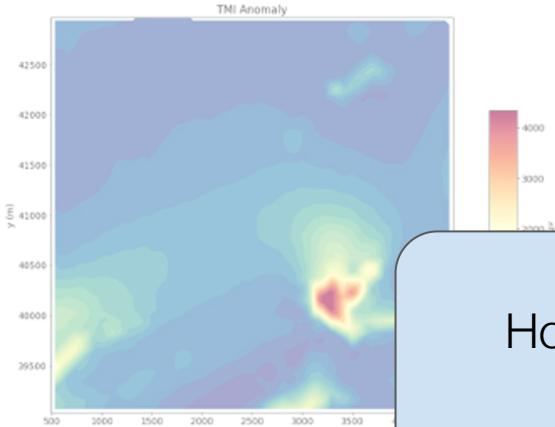


profiles,
timeseries
(EM)

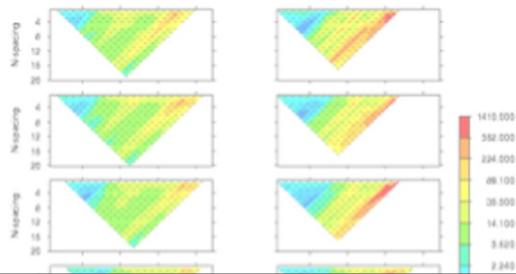


geophysical data

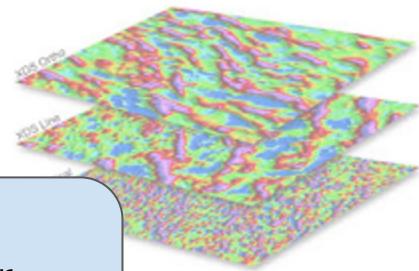
maps (mag, grav,)



pseudosections (DC, IP)

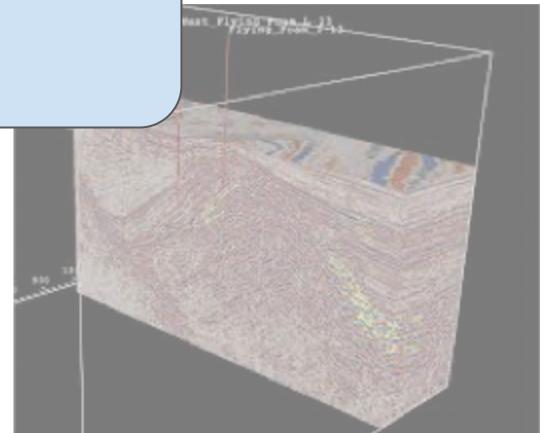
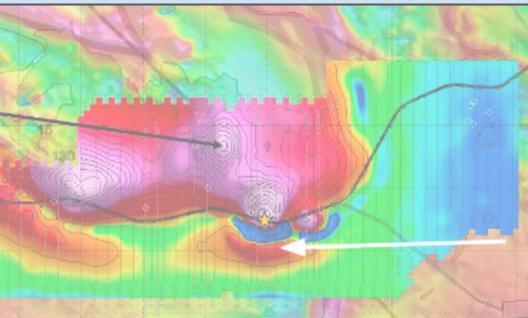
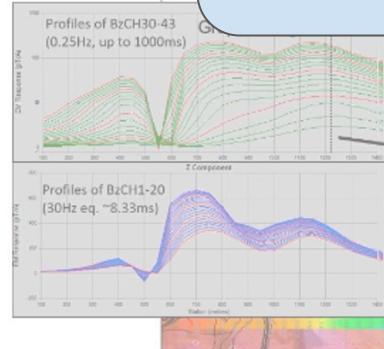


multiple maps, volumes
(EM, seismic)

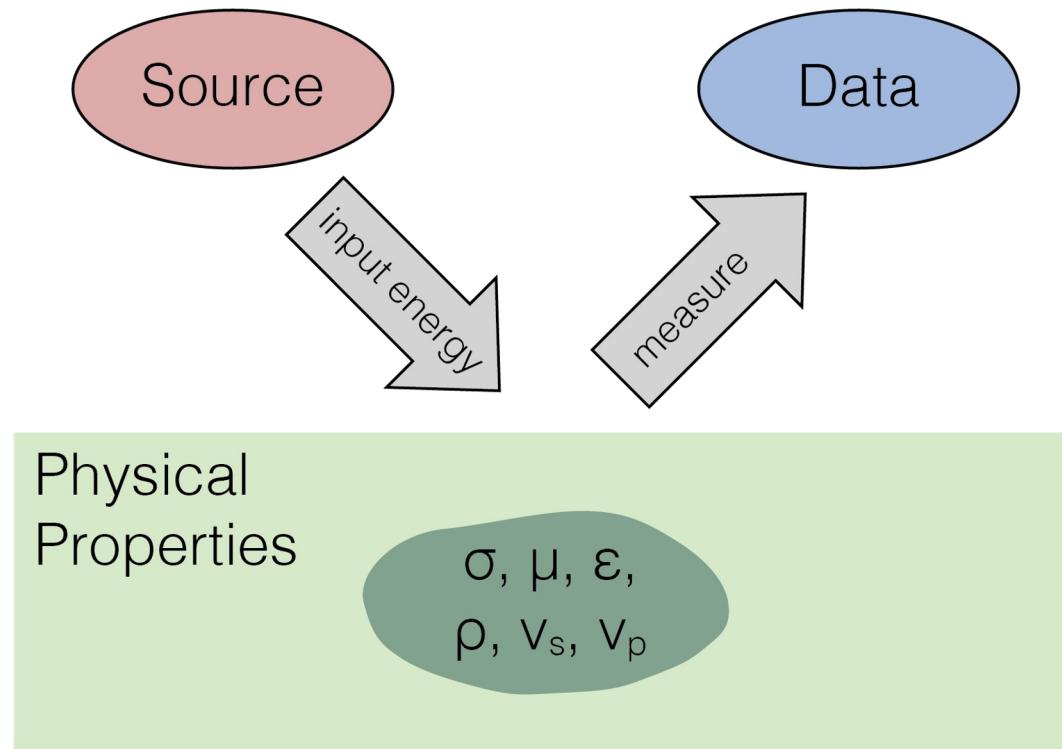


How do we use these data to answer our geologic questions?

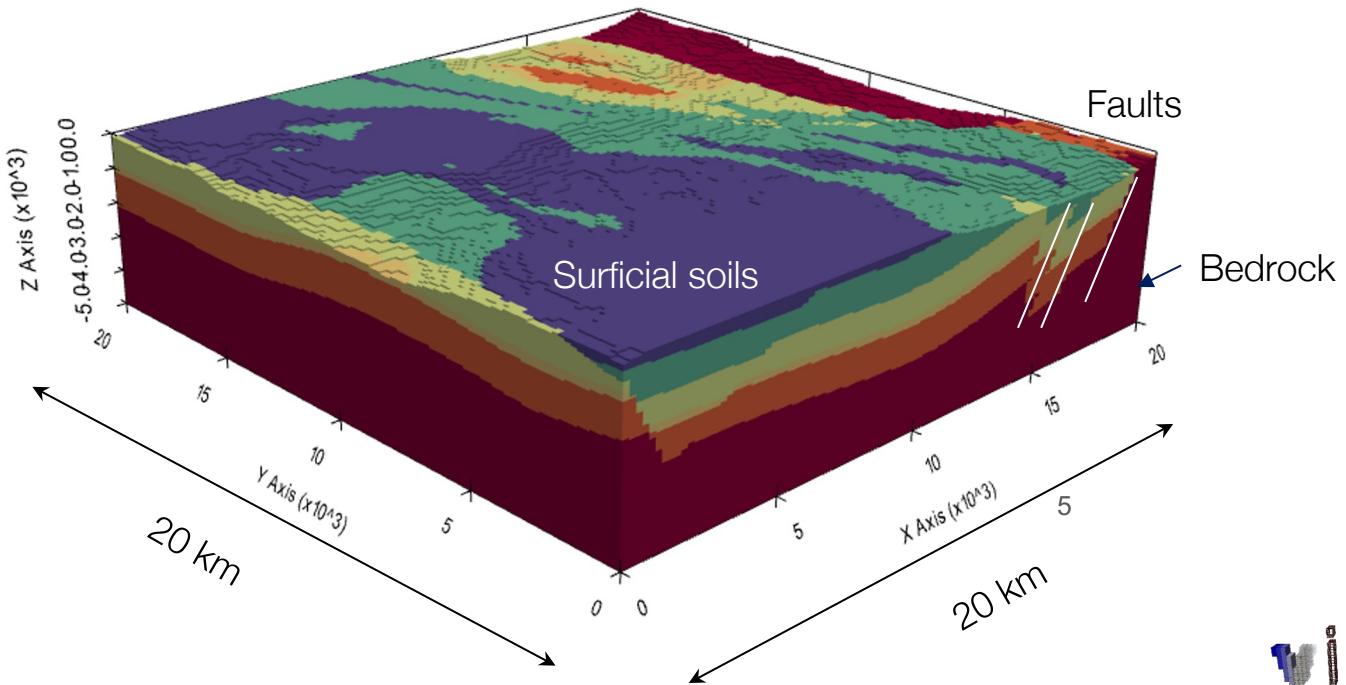
profiles,
timeseries
(EM)



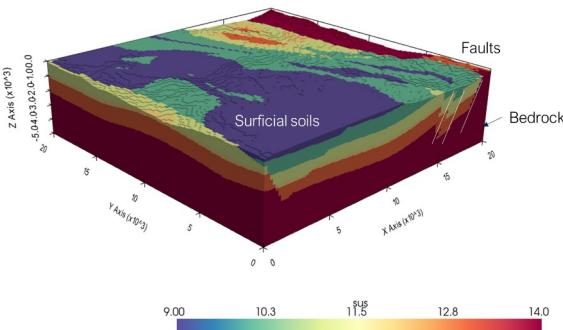
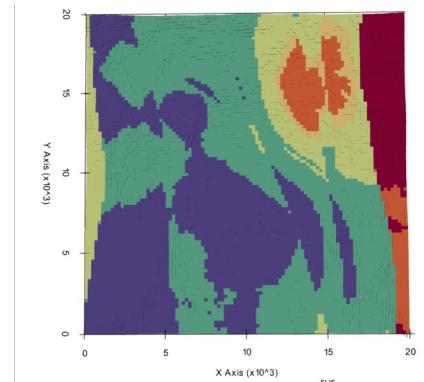
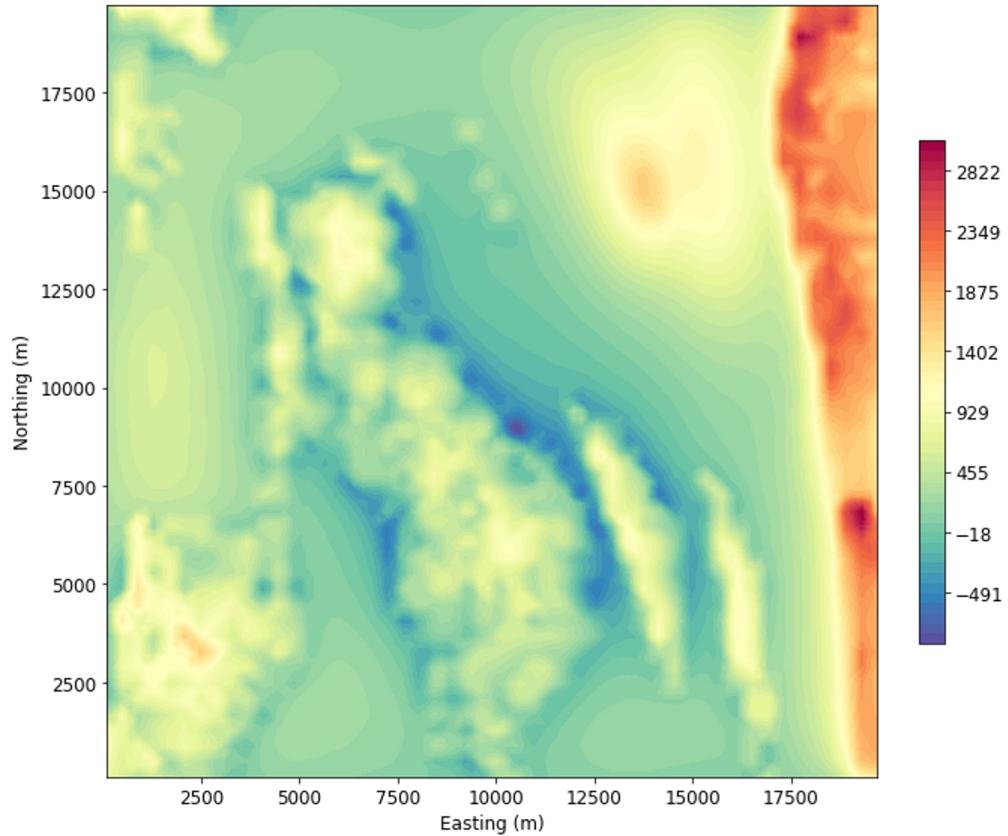
basic geophysical experiment



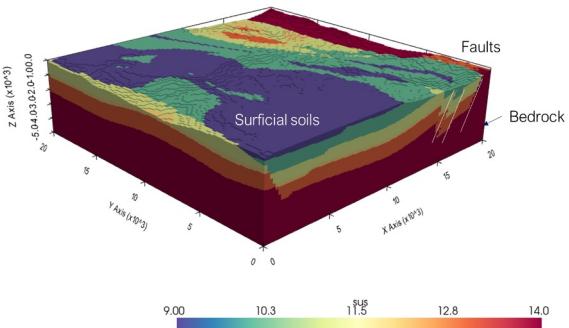
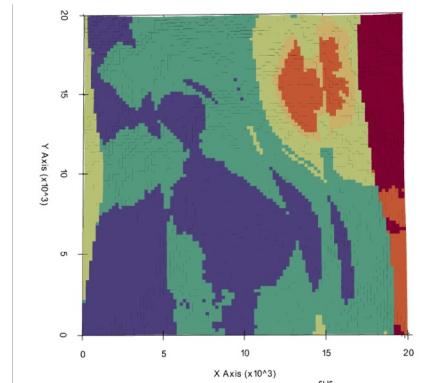
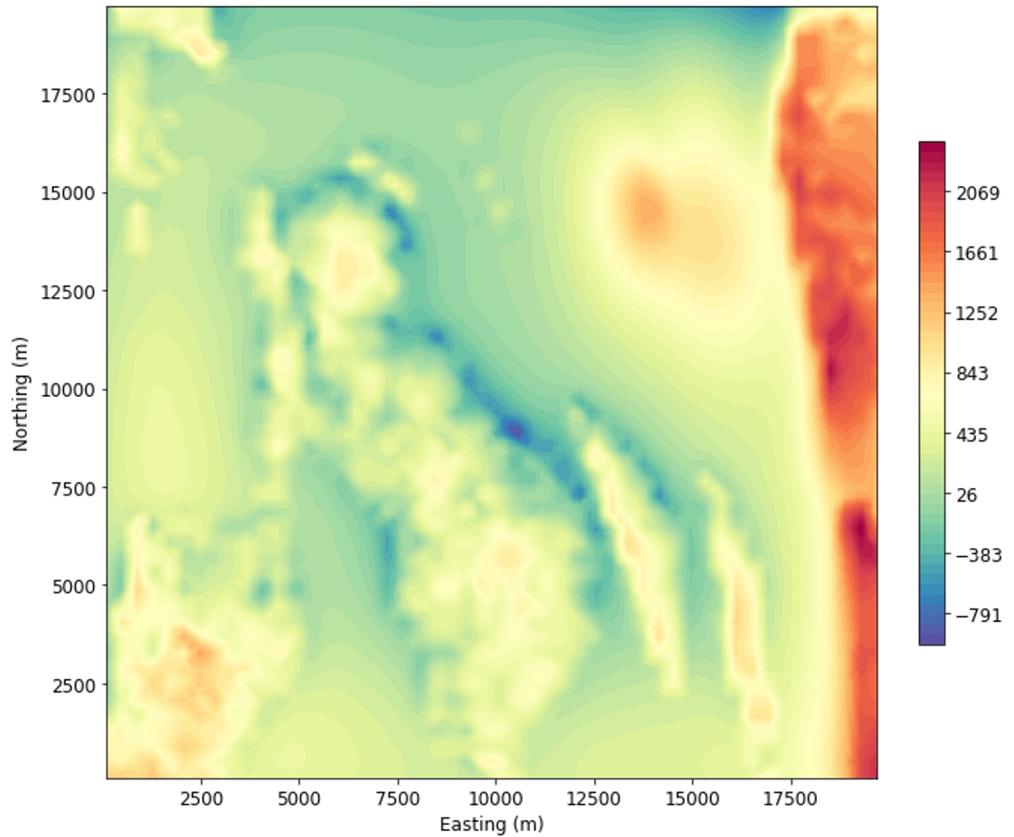
connecting geology and geophysics: why invert data?



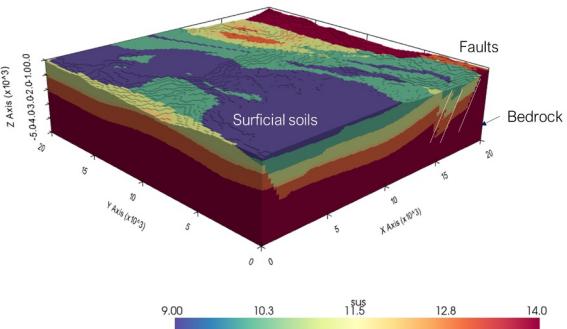
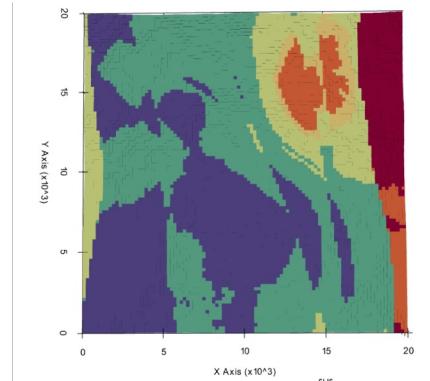
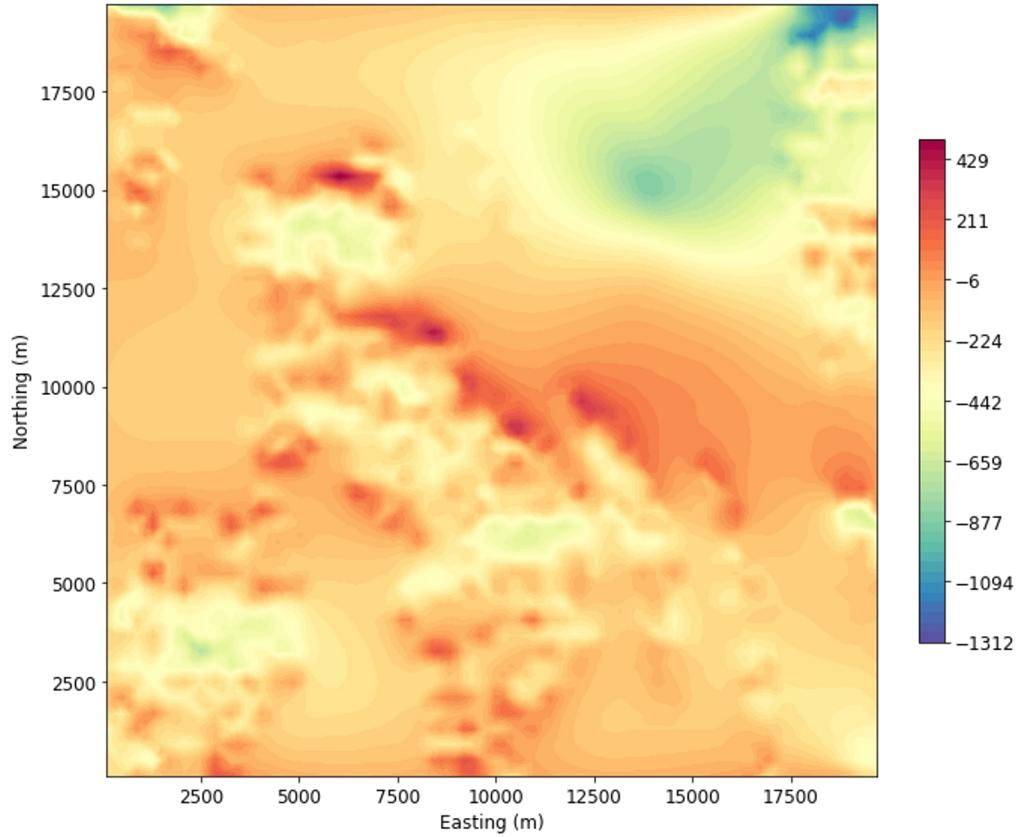
Measured magnetic data at I=90, D=0 (Magnetic pole)



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

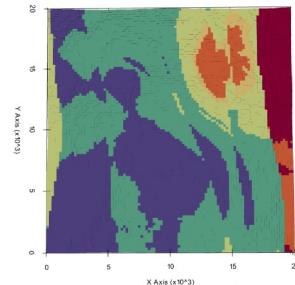


Measured magnetic data at $I=0$, $D=0$ (Equator)

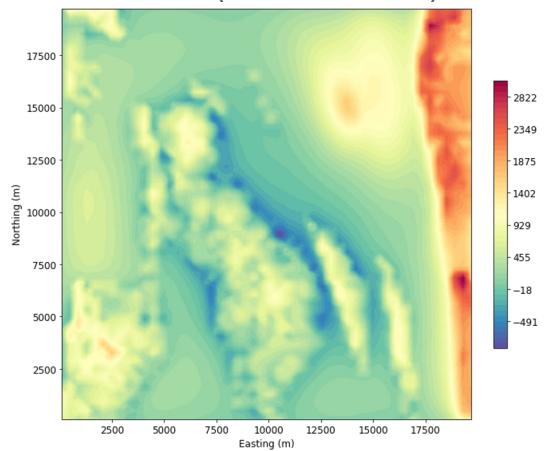


Why invert data?

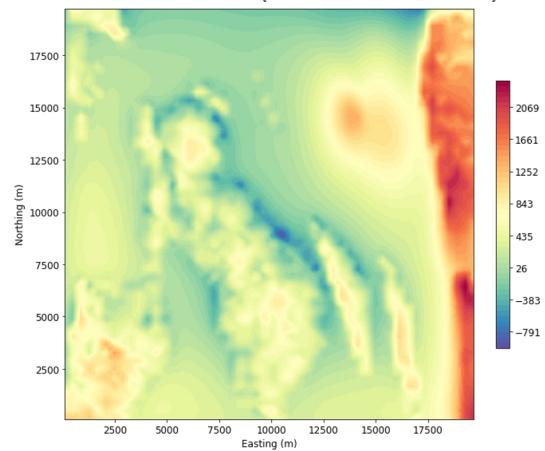
different source → different data (even for the same geology)



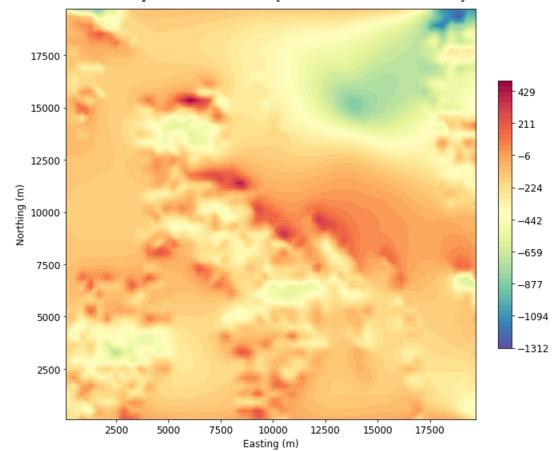
Pole ($l=90$, $D=0$)



California ($l=66$, $D=-6$)

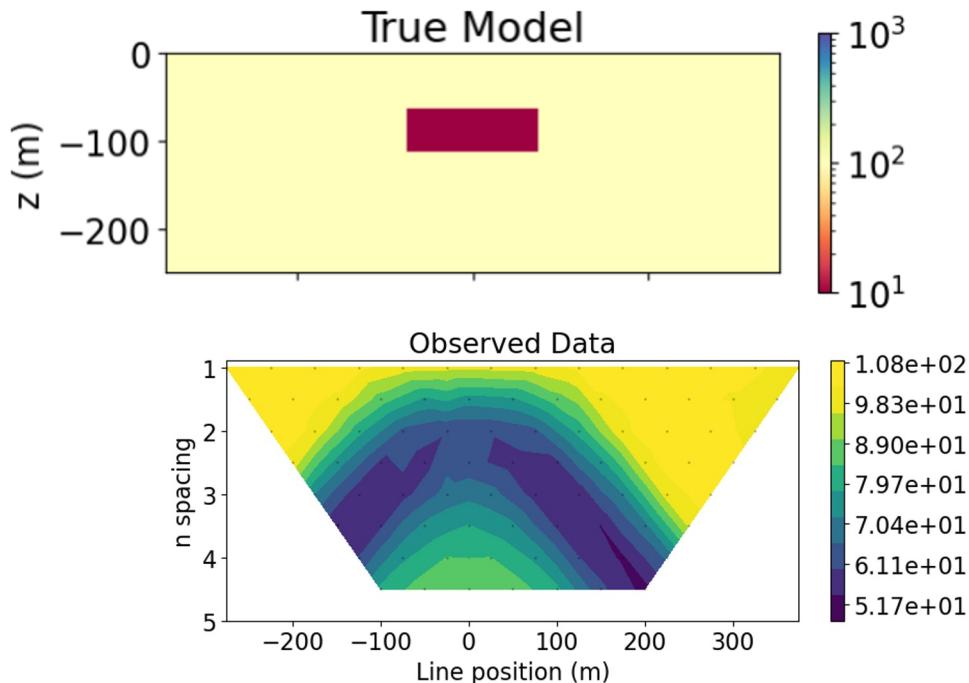


Equator ($l=0$, $D=0$)



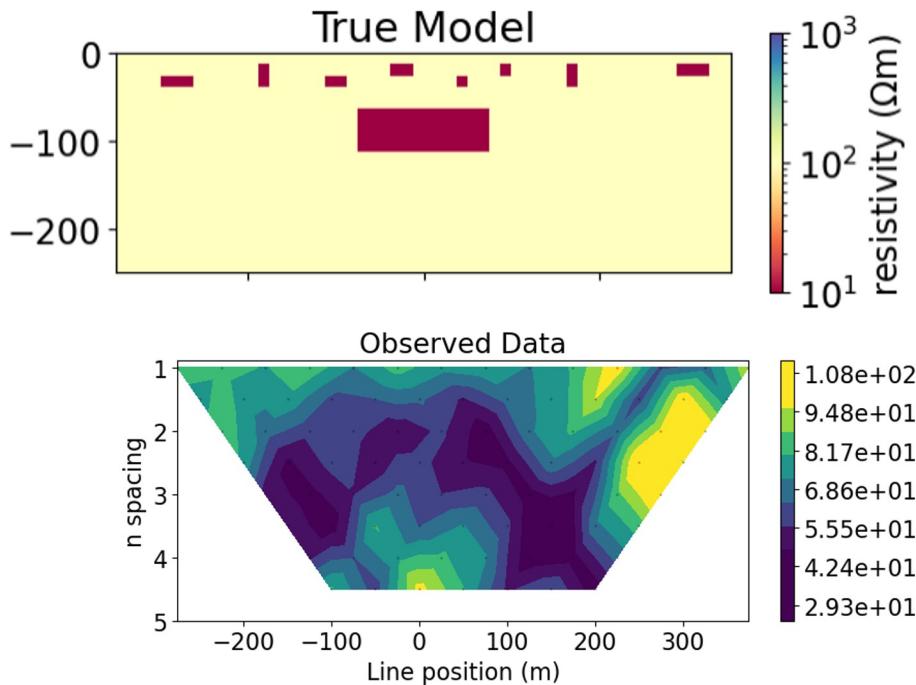
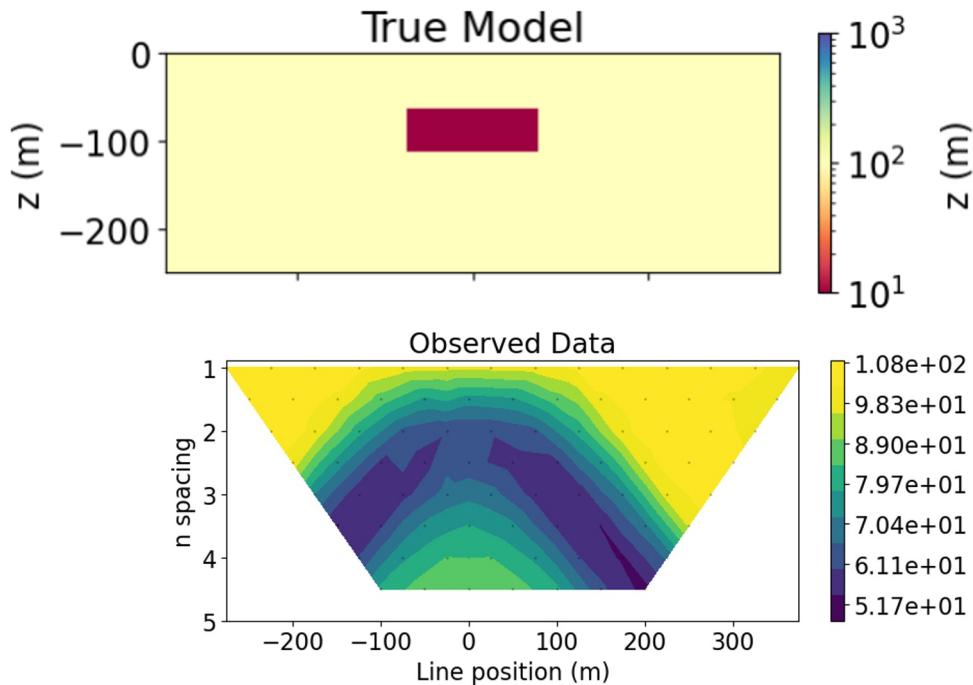
Why invert data?

data aren't always interpretable directly



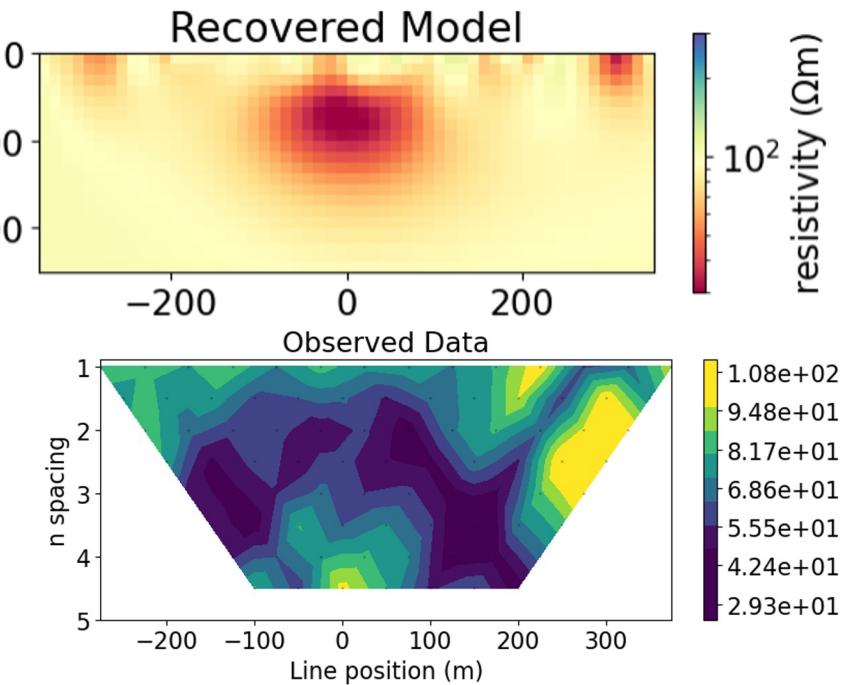
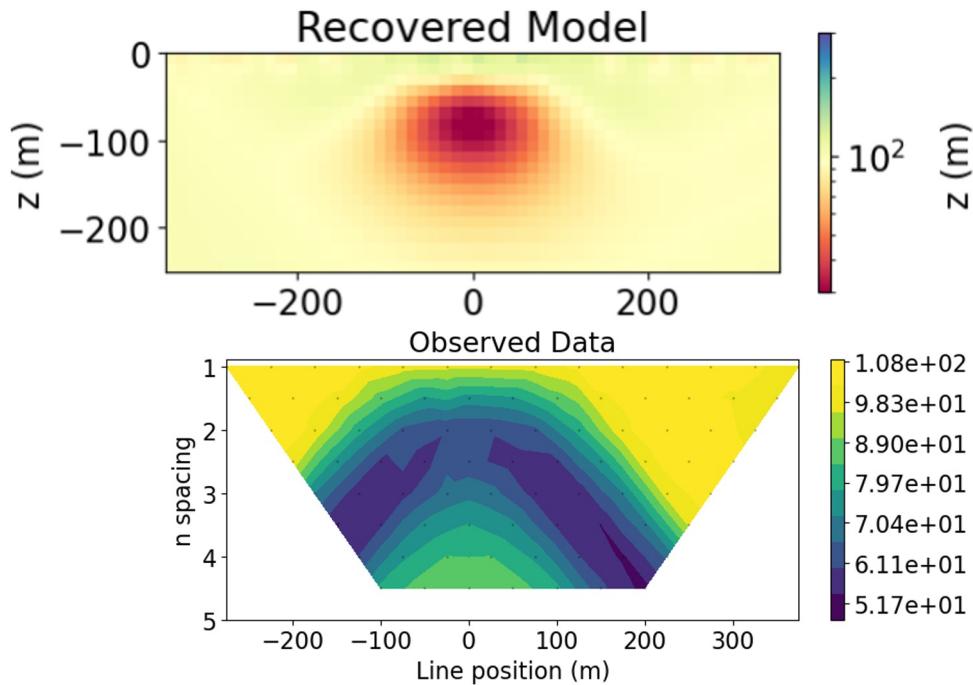
Why invert data?

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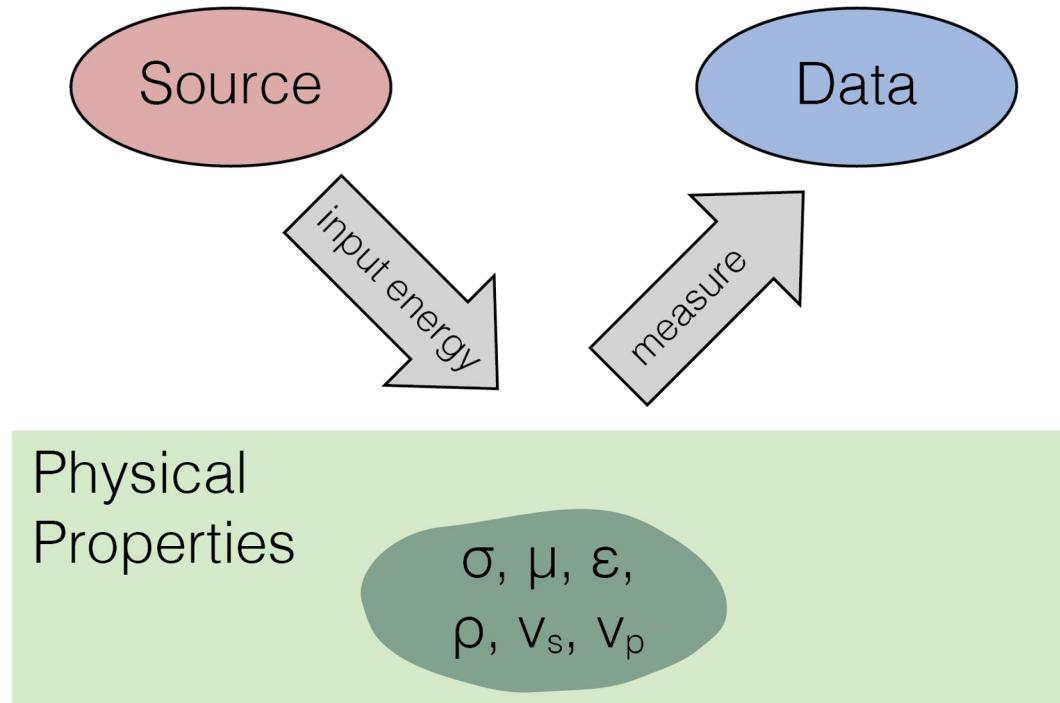


Why invert data?

data aren't always interpretable directly

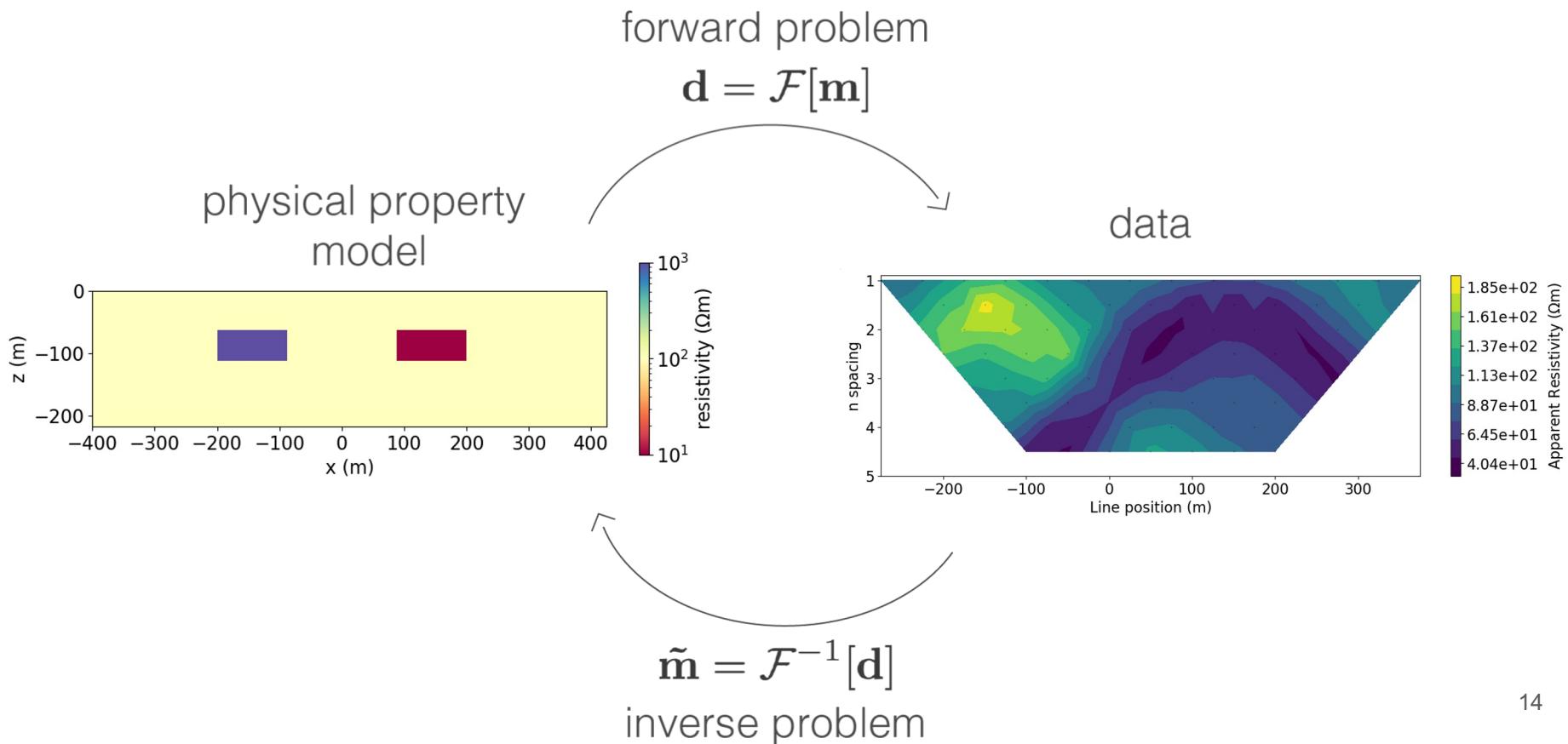


basic geophysical experiment



physical properties: connection point between geology and geophysics

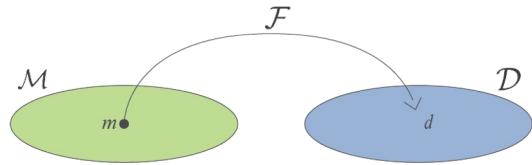
Forward and inverse problems



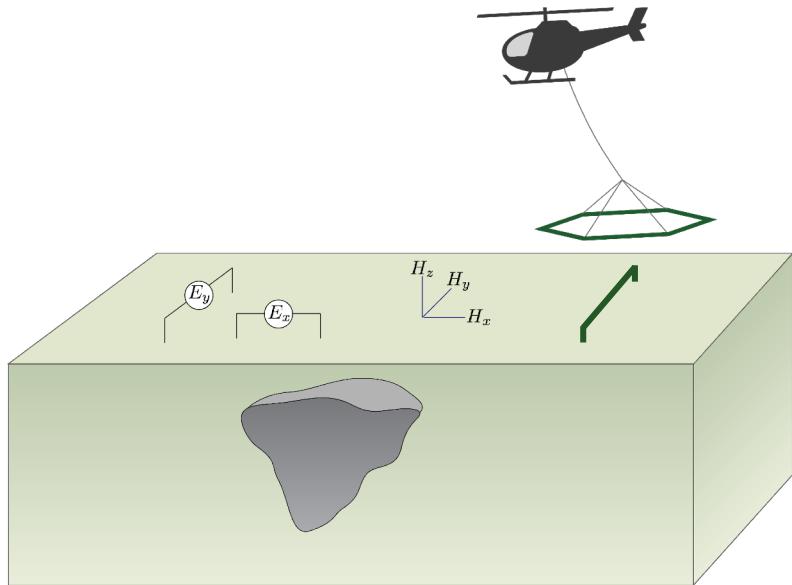
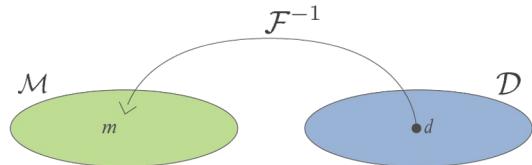
Statement of the inverse problem

Given

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



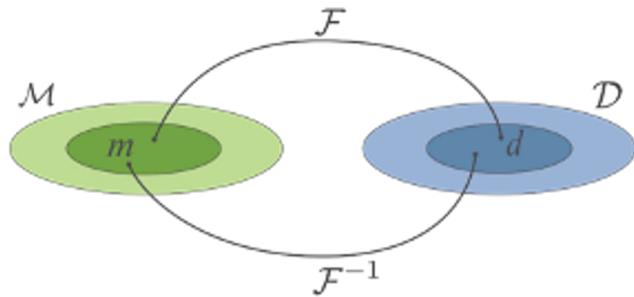
Find the Earth model that gave rise to the data



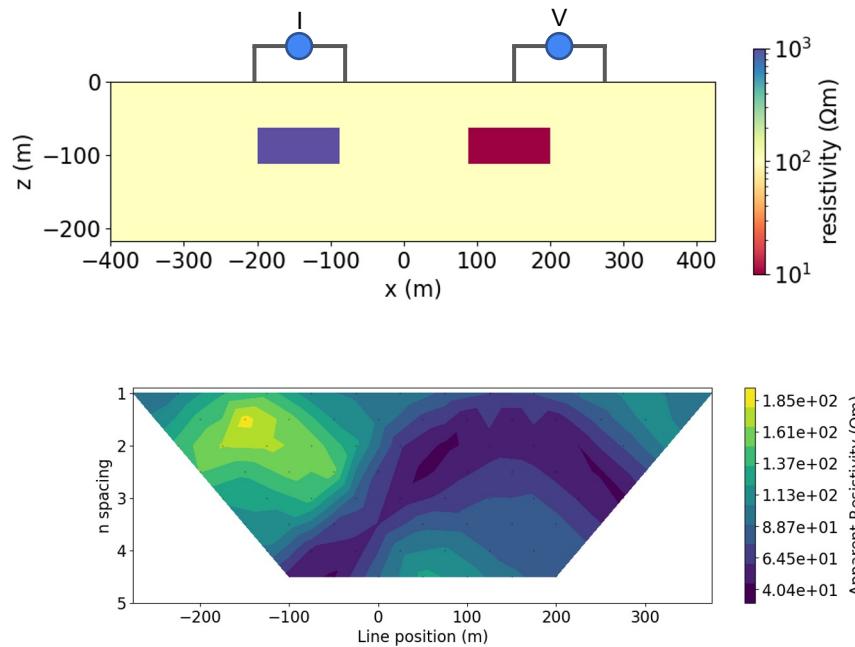
Inverse problems

The inverse problem is non-unique & ill-posed

Many models can fit the data



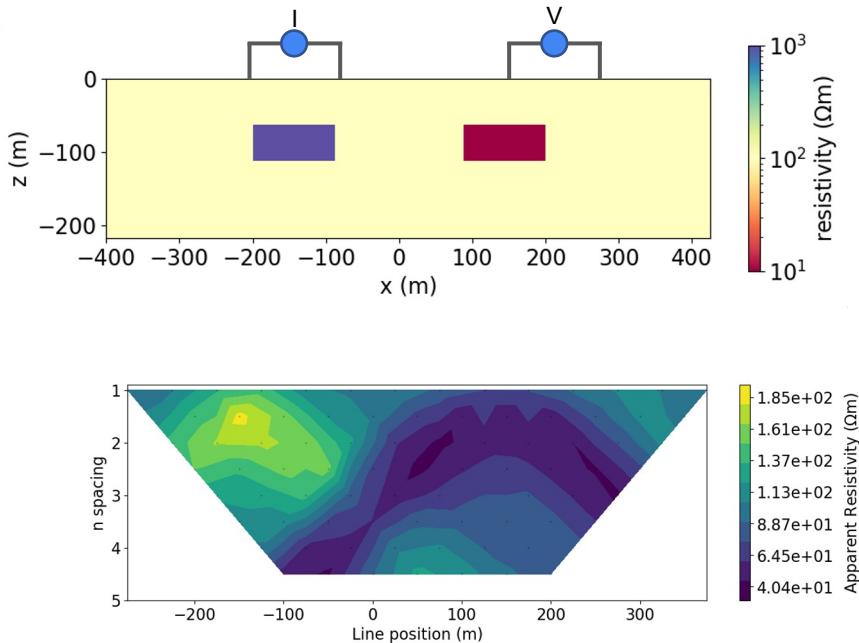
as an example of extreme non-uniqueness....



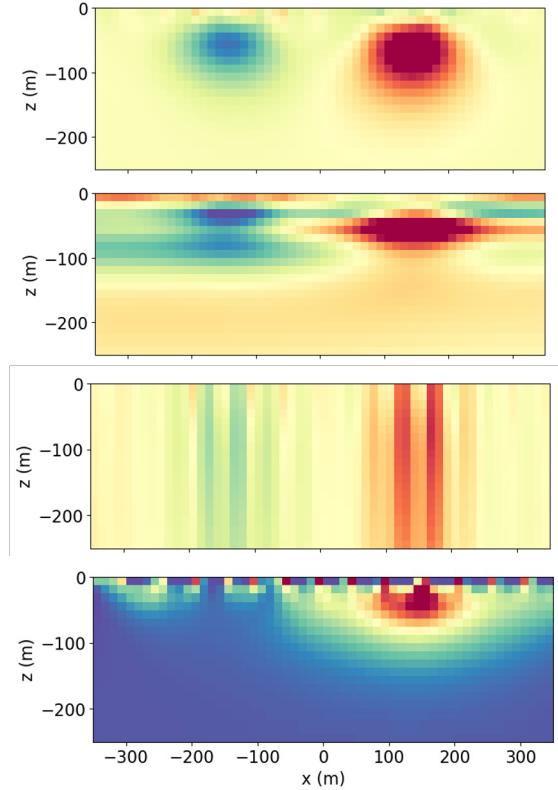
Inverse problems

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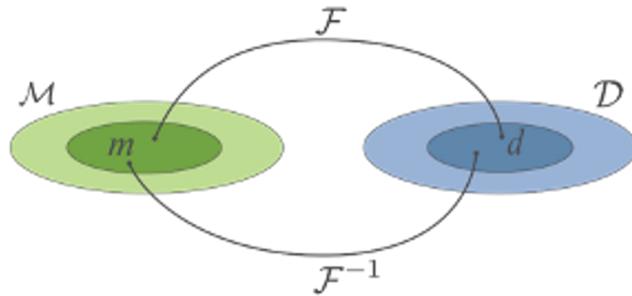
extreme non-uniqueness...
recovered models (all fit the data)



Inverse problems

The inverse problem is non-unique & ill-posed

Many models of the subsurface can fit the data

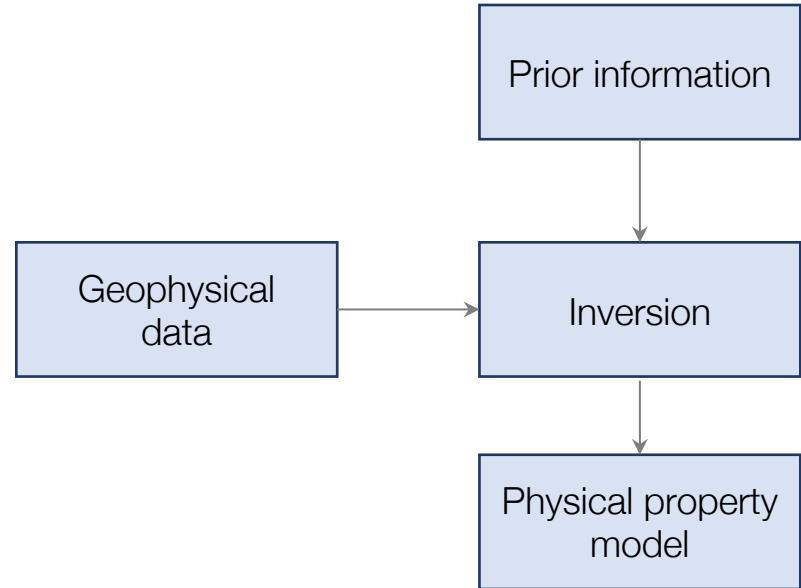


any approach to the inverse problem must address these issues

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

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

\mathbf{m}



find a model

that fits the data



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

and respects prior knowledge

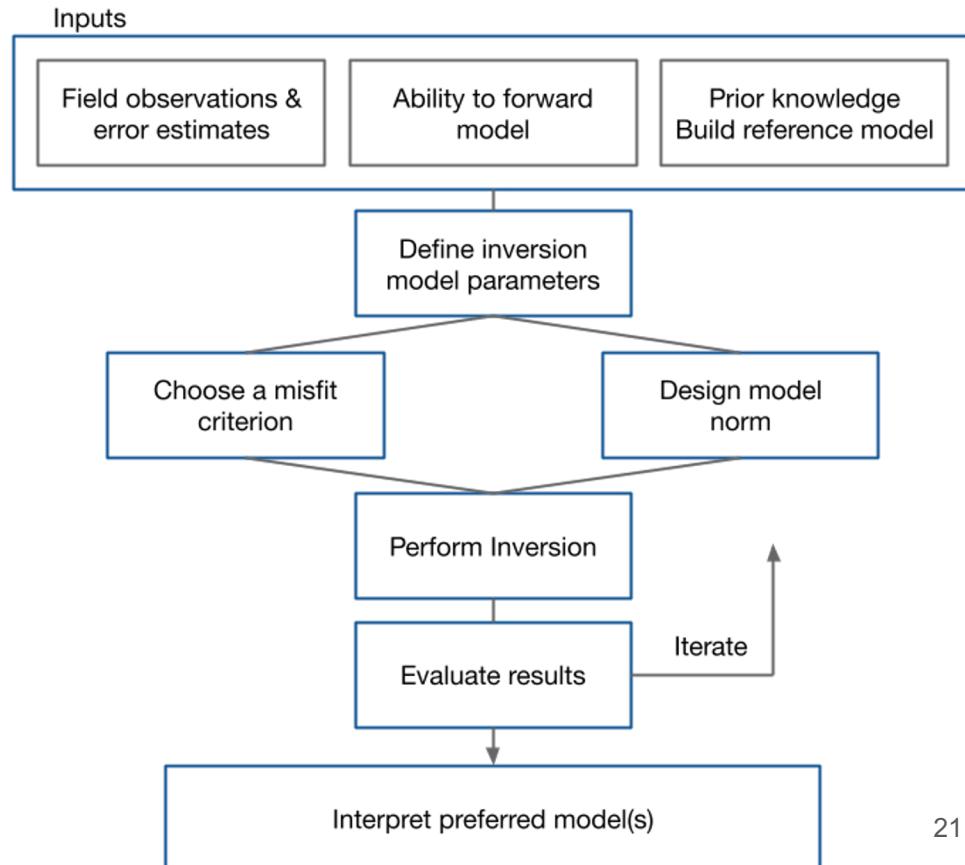
- drill logs
- geophysical logs (e.g. resistivity)
- spatial patterns
- other geophysical data
- ...

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

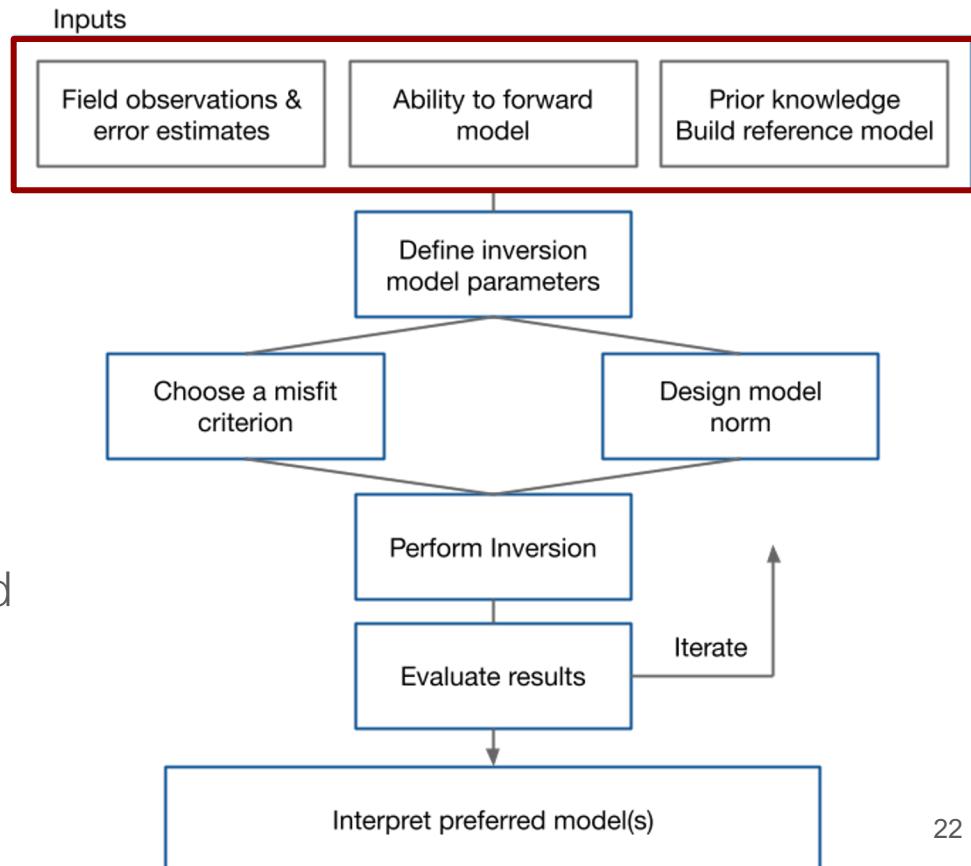
What processing has been done?

Ability for forward model

Assemble geologic, petrophysical information

Build a reference model

What is the question you want answered from the inversion?



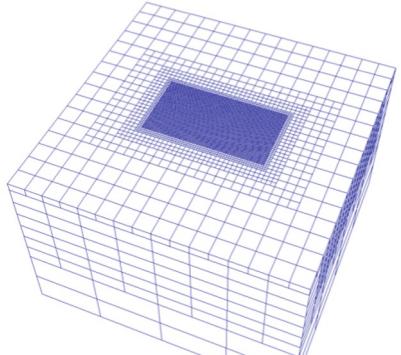
forward modelling

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

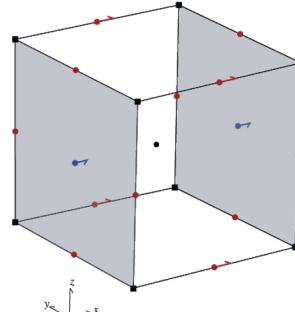


governing equation

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

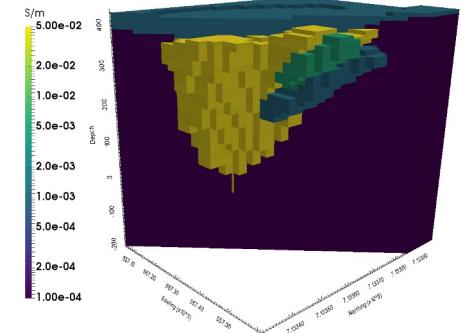
discretized equations

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

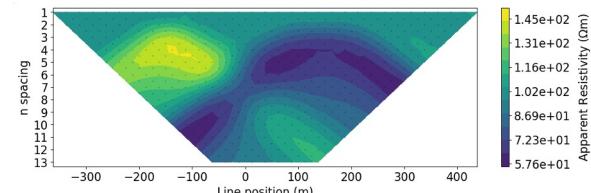


- Cell Center
- Node
- Edge
- Face

physical property model



simulated data



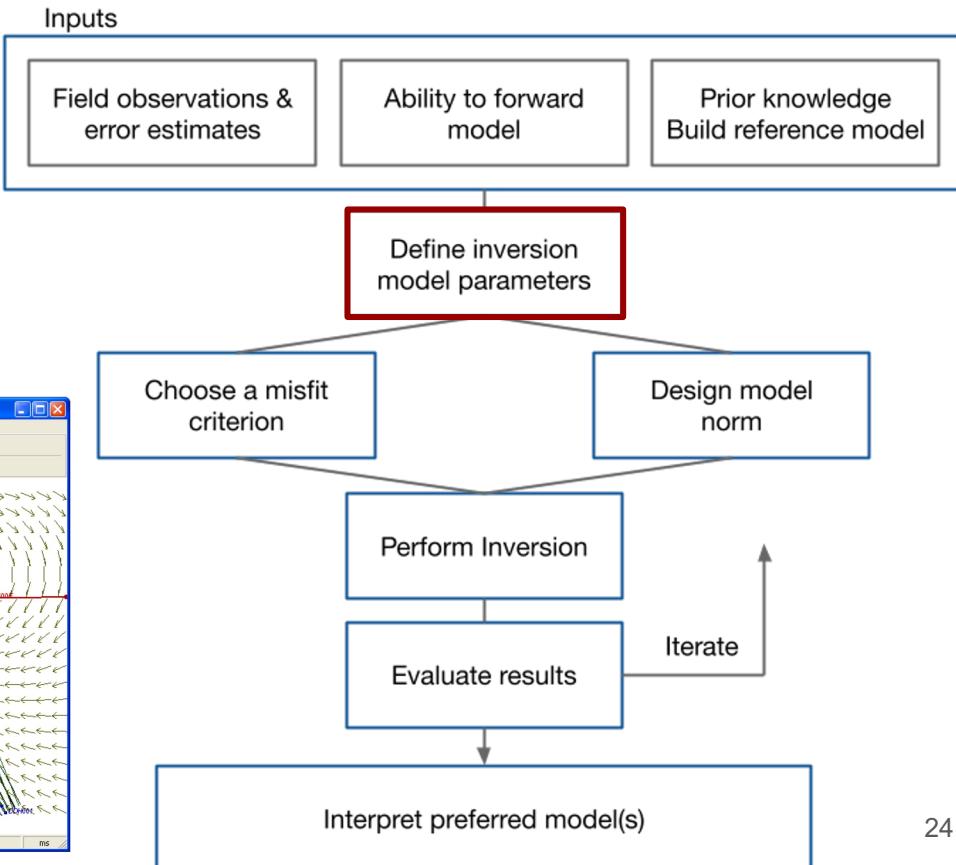
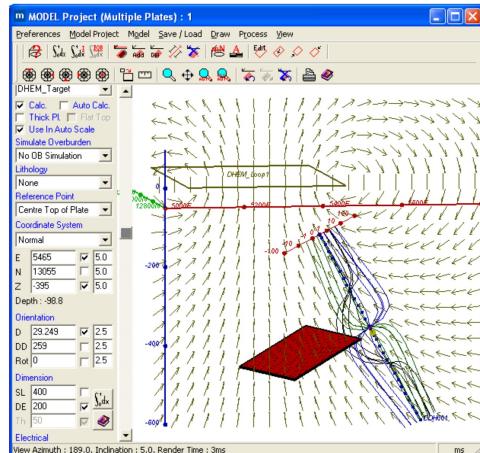
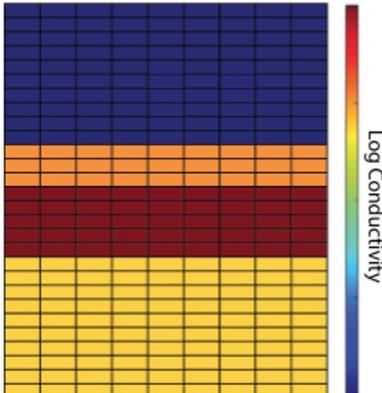
inversion model parameters

identify relevant physical properties

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

define parameters to invert for

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



fitting the data

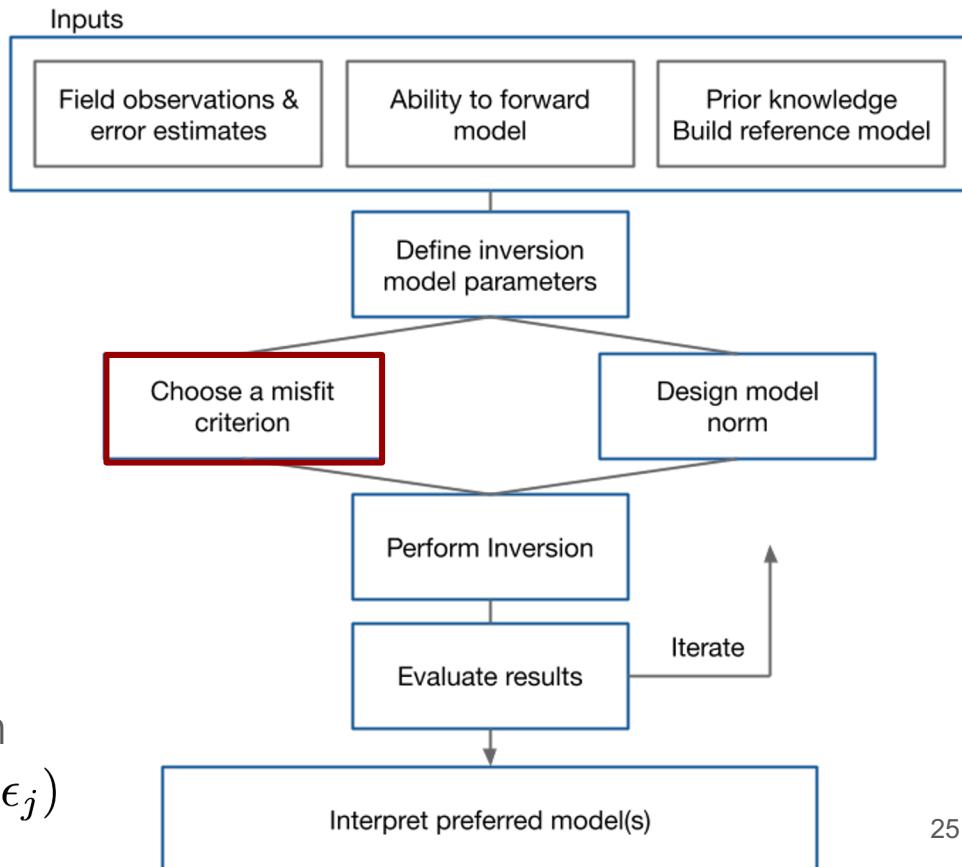
Observed data

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

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

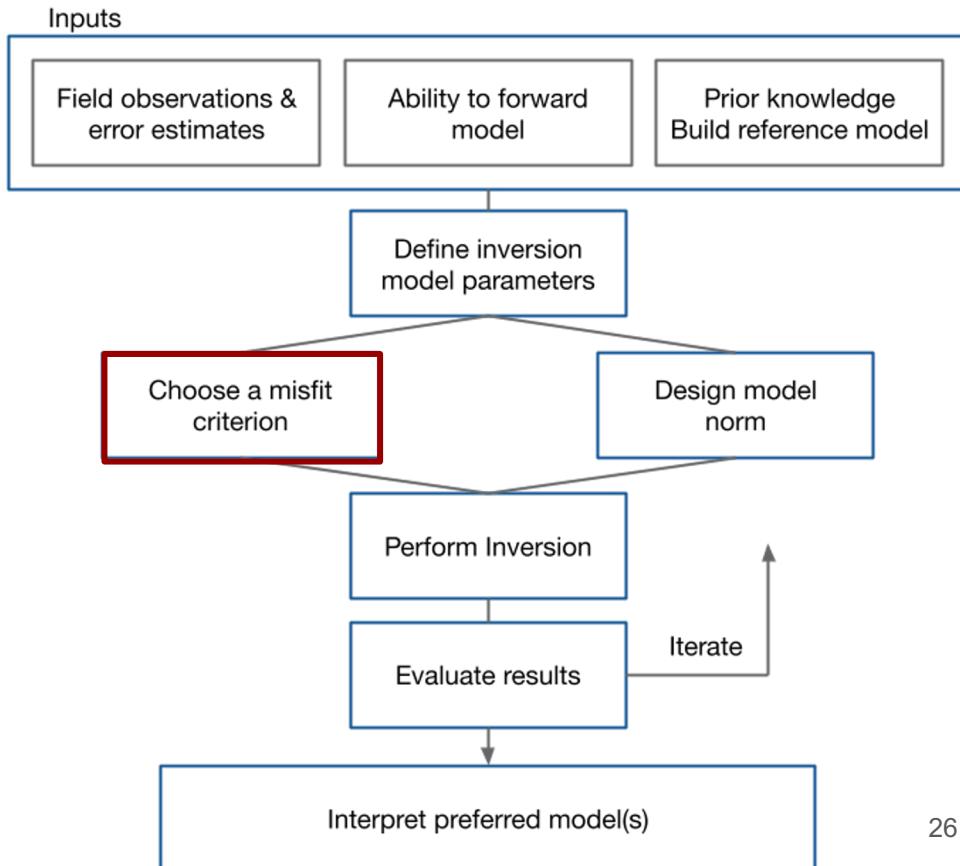
$$\phi_d = \sum_{j=1}^N \left(\frac{F_j(m) - d_j^{obs}}{\epsilon_j} \right)^2$$

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

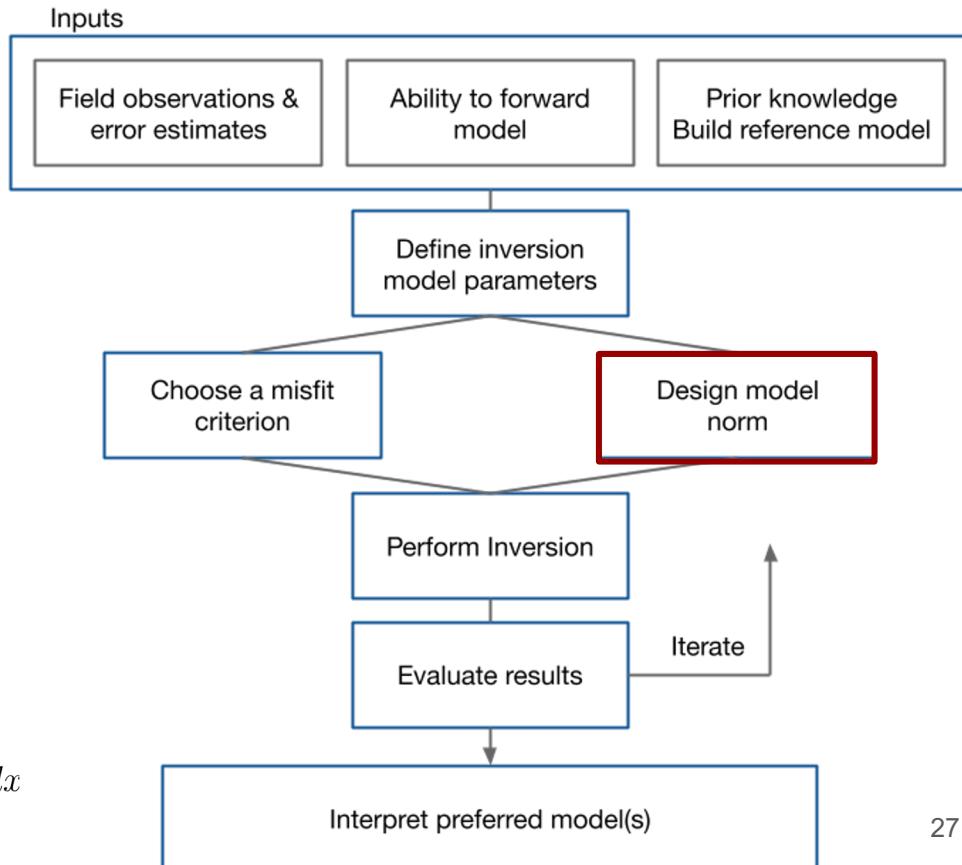
$$\phi_m = \int (m - m_{ref})^2 dx$$

- smooth model: penalize large changes spatially

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

- combination

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



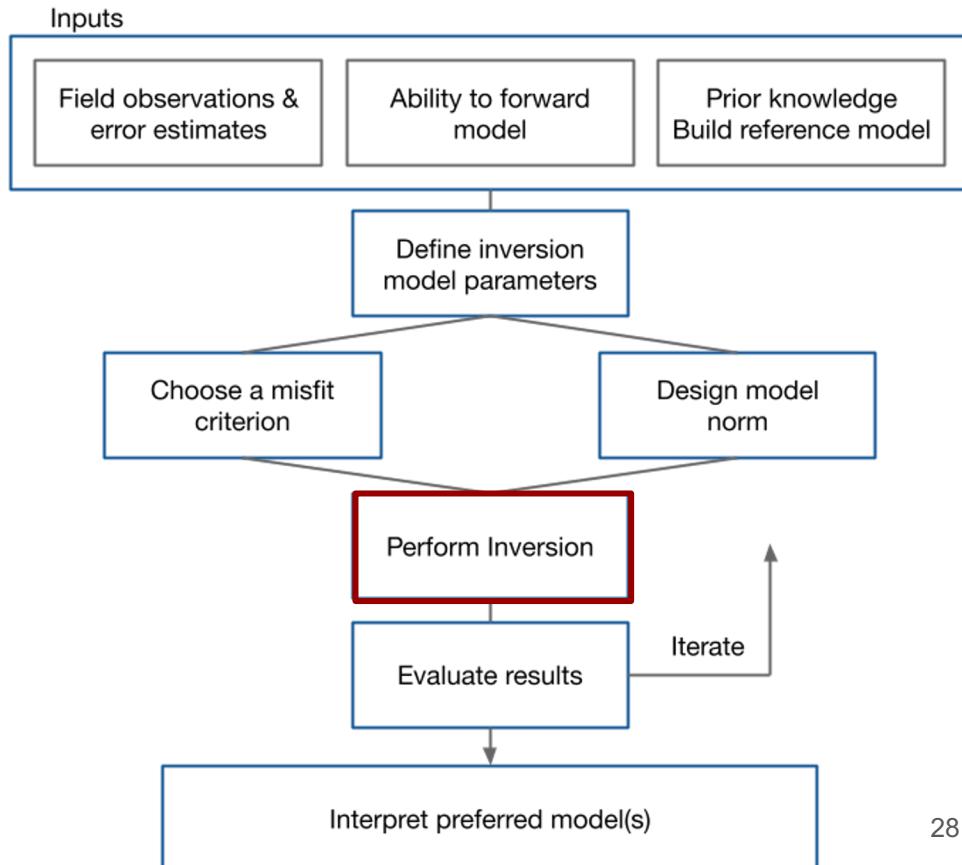
running the inversion

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

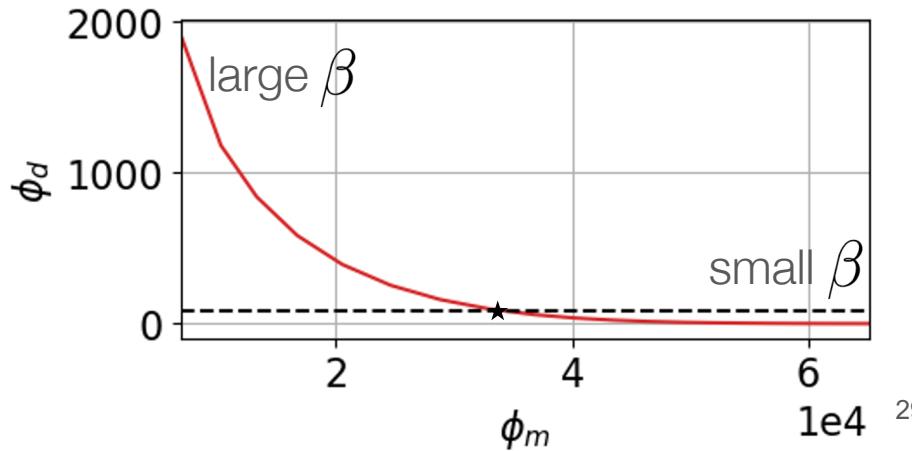
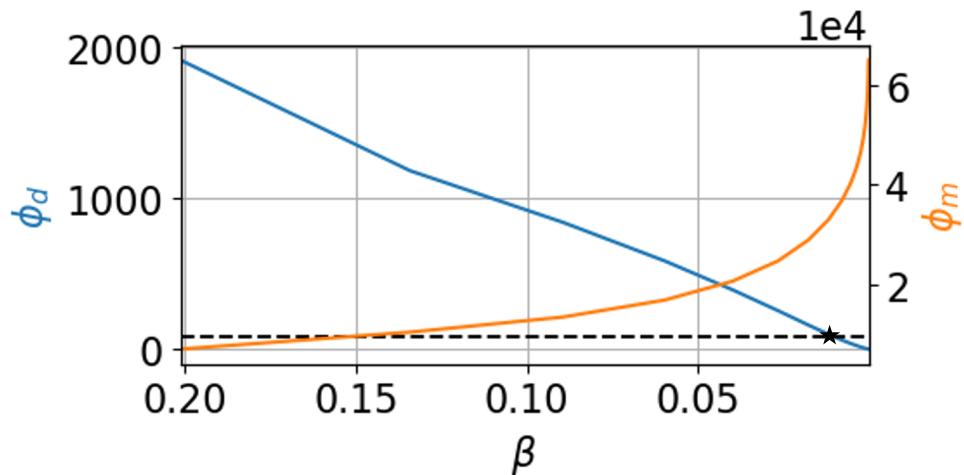
$$\beta \rightarrow 0 : \quad \phi \sim \phi_d$$

$$\beta \rightarrow \infty : \quad \phi \sim \phi_m$$

Visualize influence with Tikhonov Curve

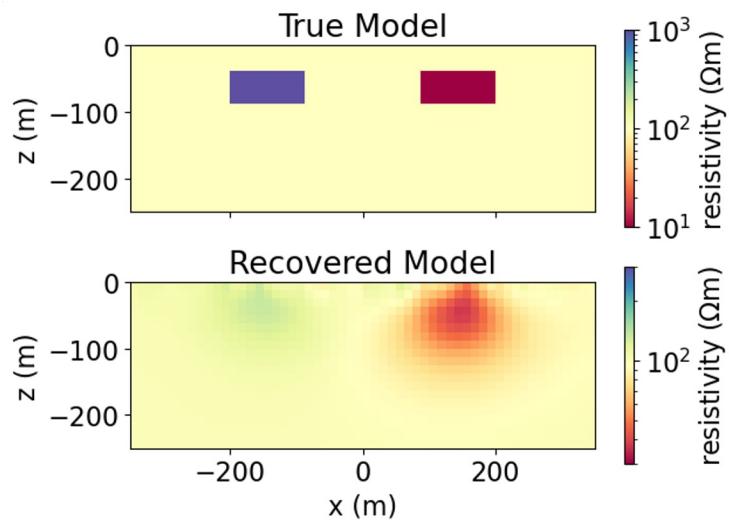
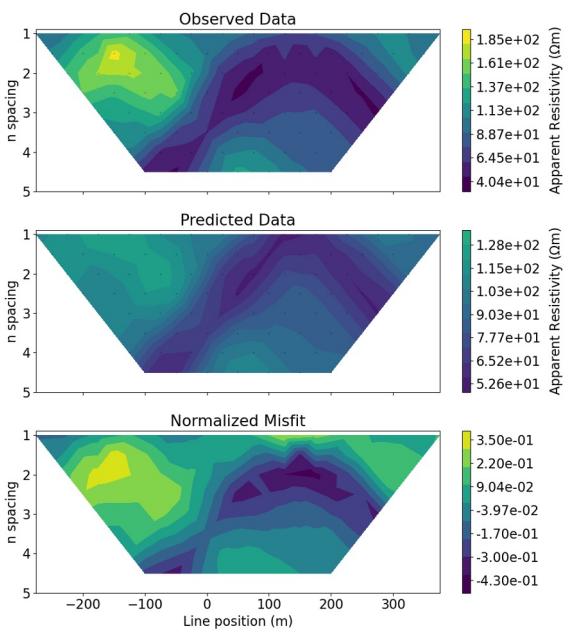
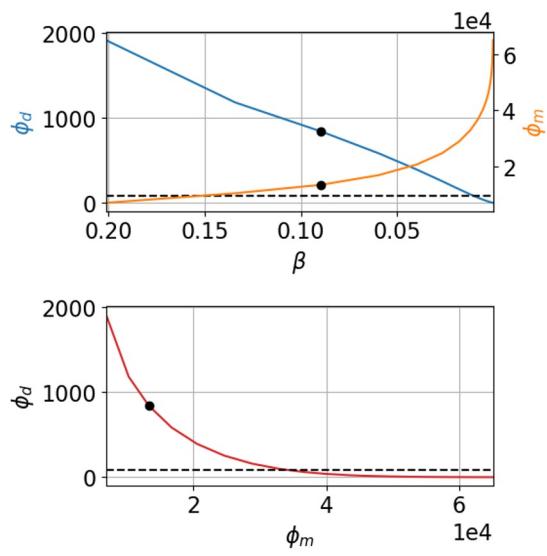
Desired misfit $\phi_d^* \simeq N$

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



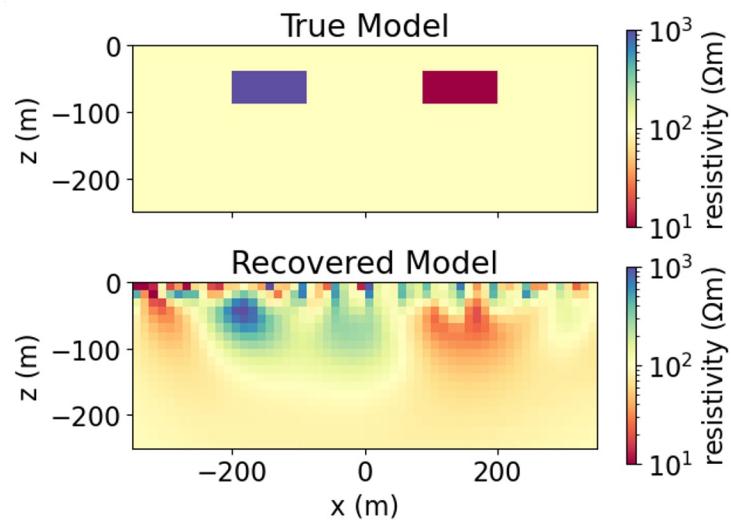
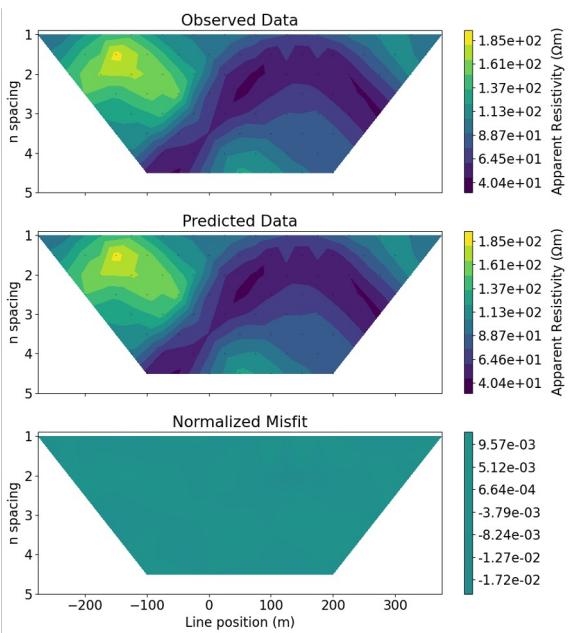
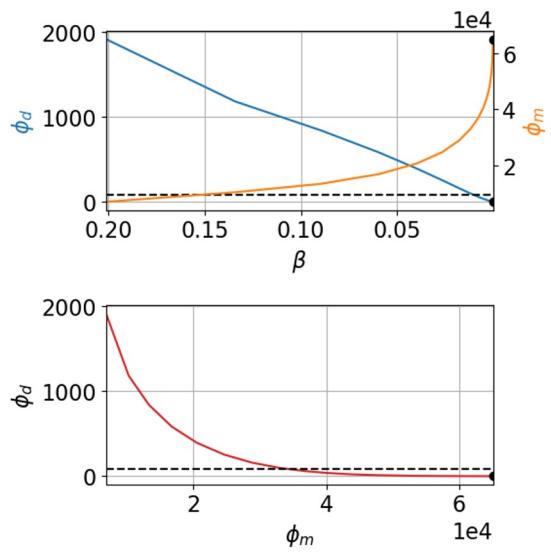
Role of β

Large β : under fit



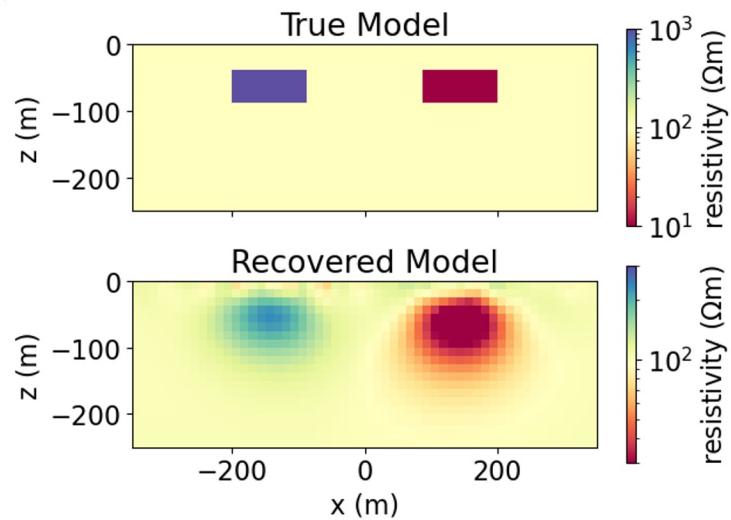
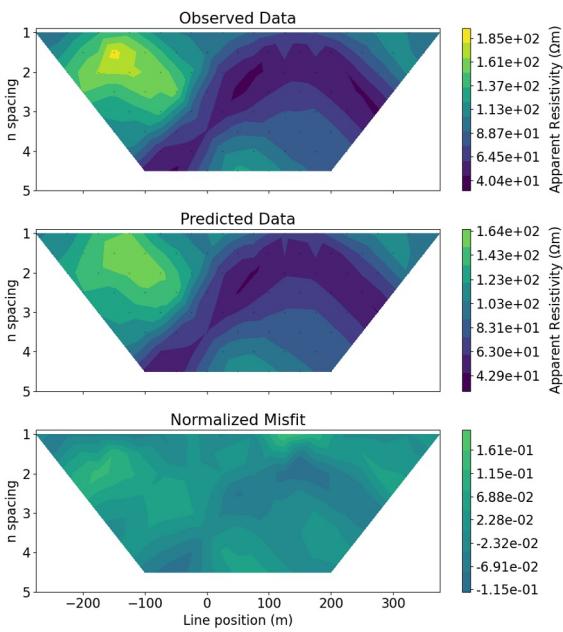
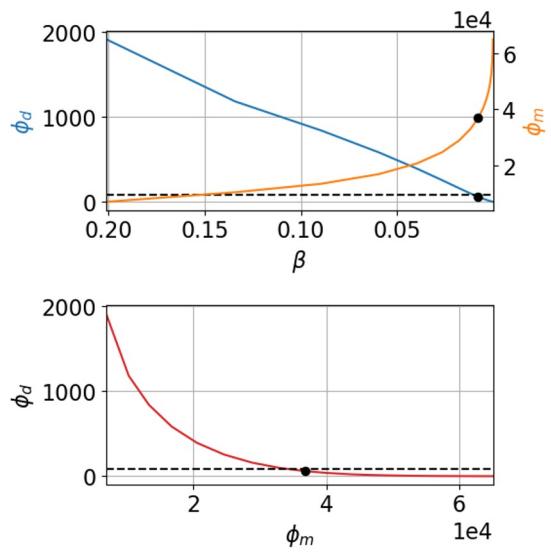
Role of β

Small β : over fit



Role of β

β : just right!

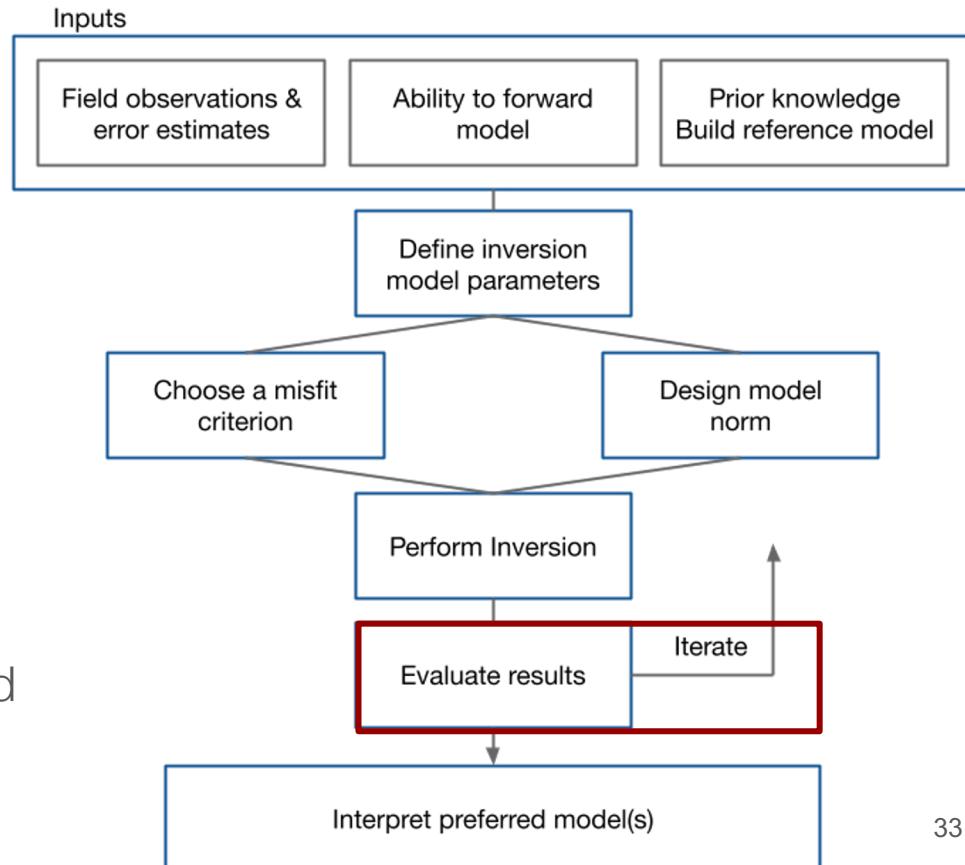


Flowchart for the inverse problem

How do we solve our problem?

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

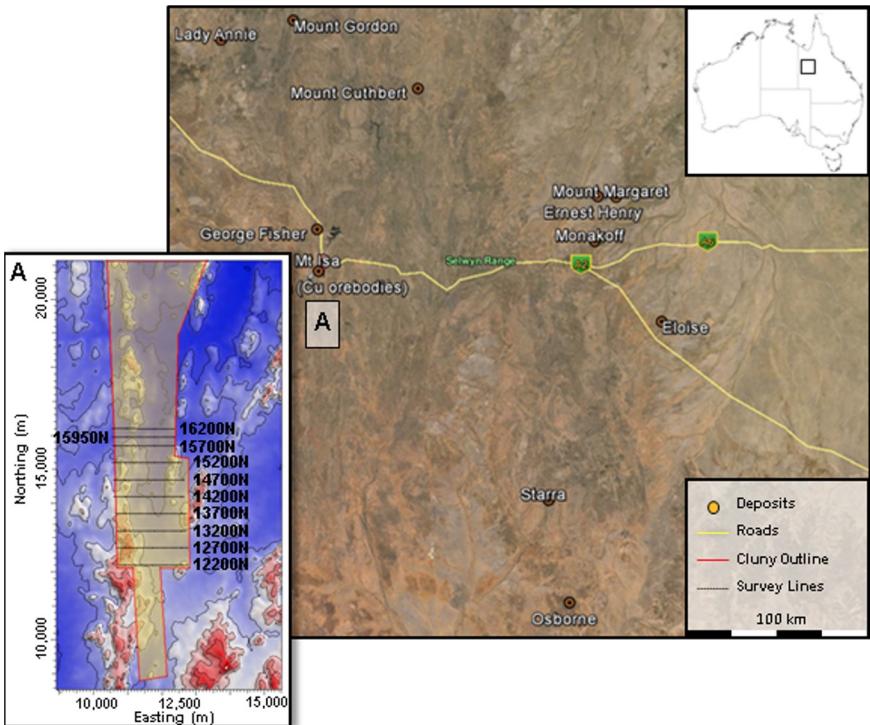
- often requires multiple inversions to obtain model for interpretation
- iteratively update design of model norm, noise estimates, ...
- use geologic knowledge, common features in multiple inversion to build confidence in results



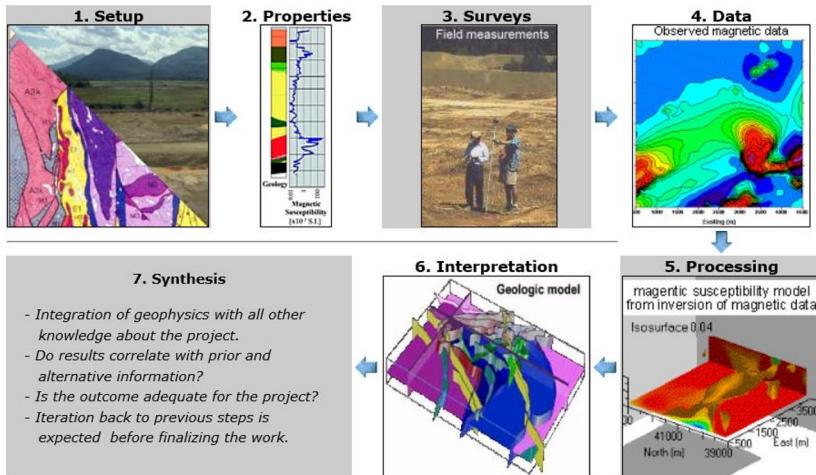


Case study: Mt. Isa

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



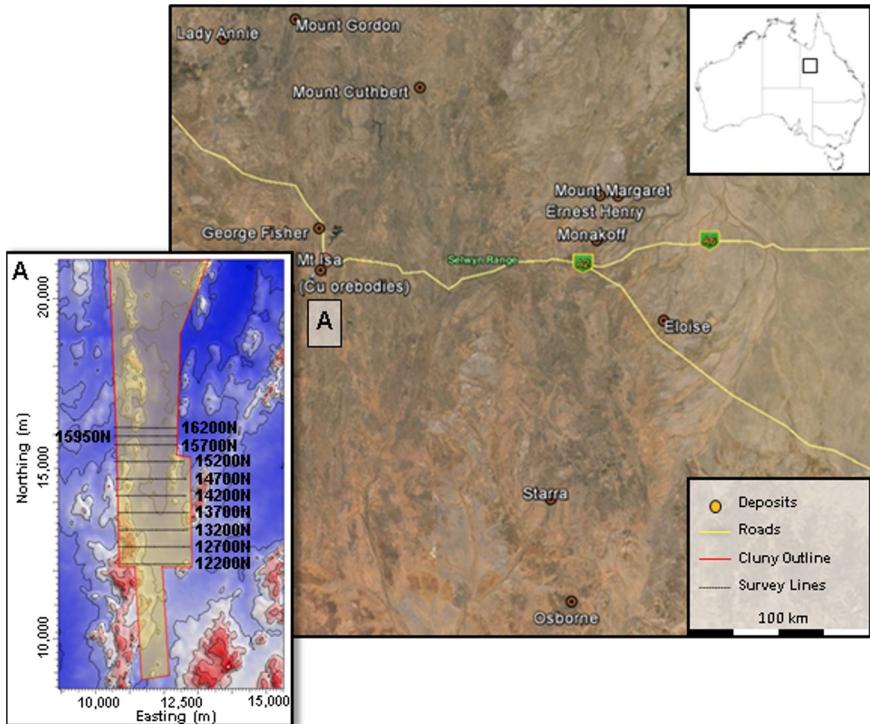
Seven step framework for geophysics



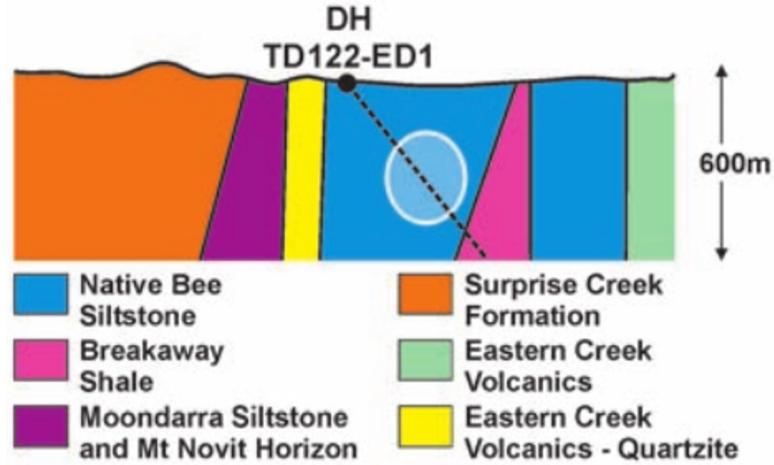
gpg.geosci.xyz

Setup

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



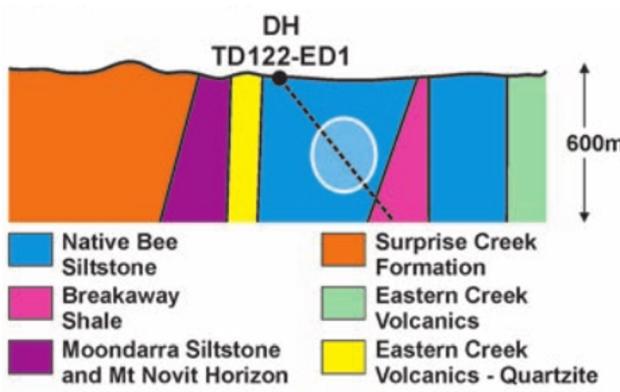
Geological model



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

Properties

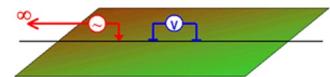
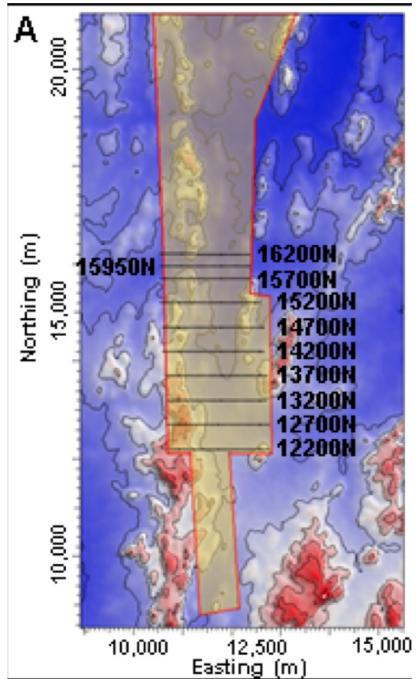
expect mineralized zones to be conductive
do you anticipate any challenges?



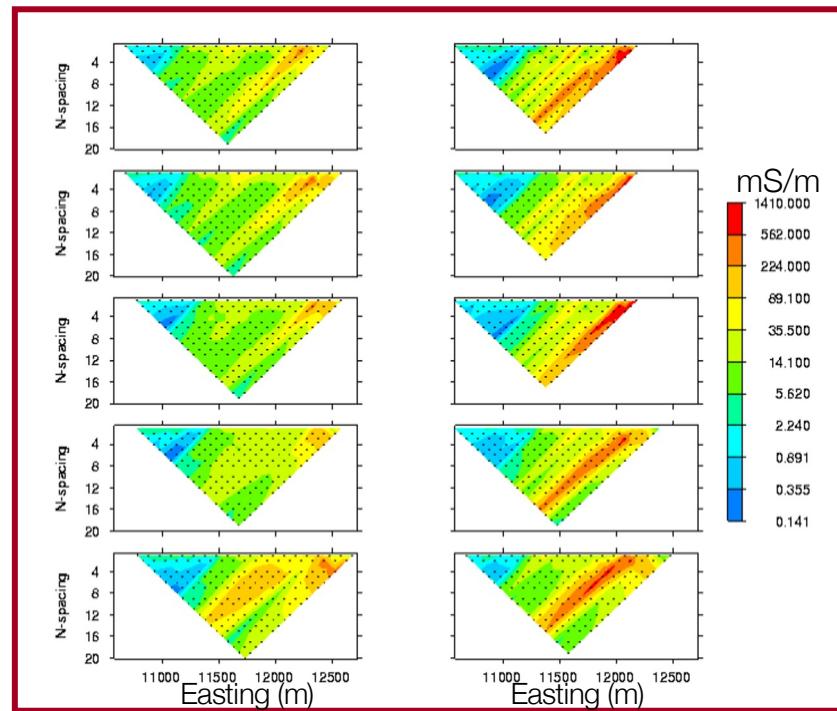
Rock Unit	Conductivity
Native Bee Siltstone	Moderate
Moondarra Siltstone	Moderate
Breakaway Shale	Very High
Mt Novit Horizon	High
Surprise Creek Formation	Low
Eastern Creek Volcanics	Low

Survey

8 survey lines, 2 configurations

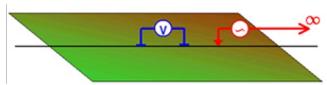
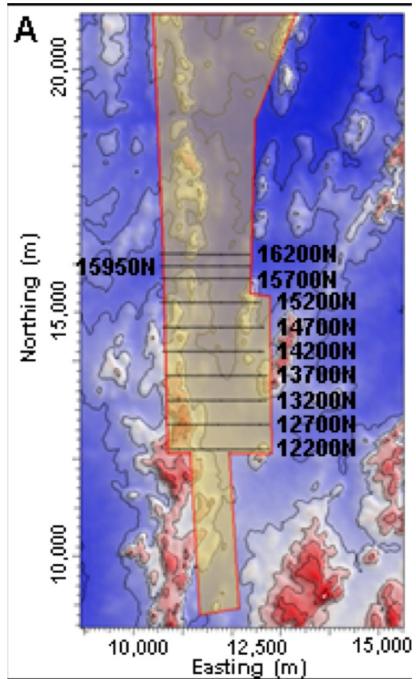


data set 1:
pole-dipole

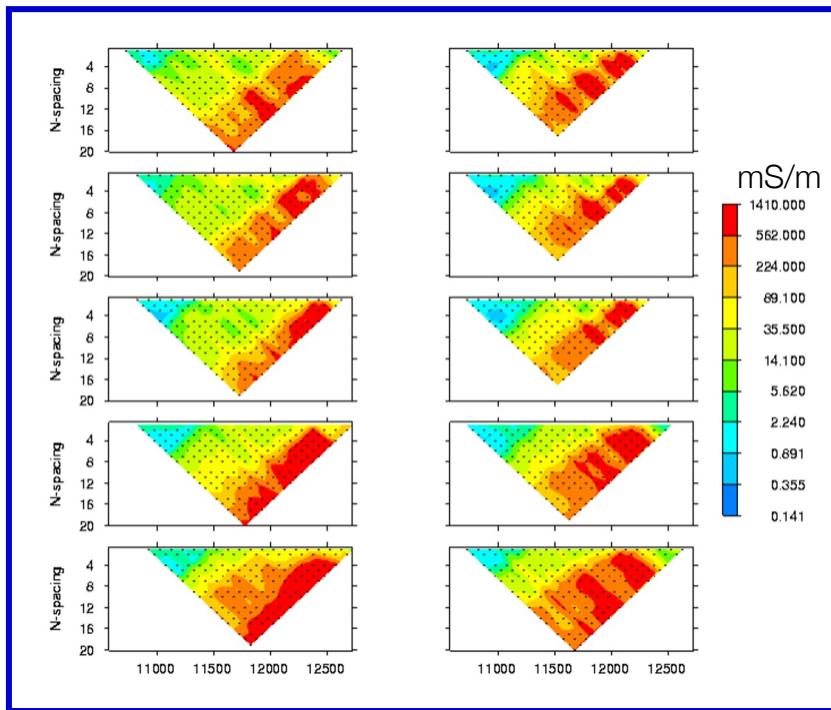


Survey

8 survey lines, 2 configurations

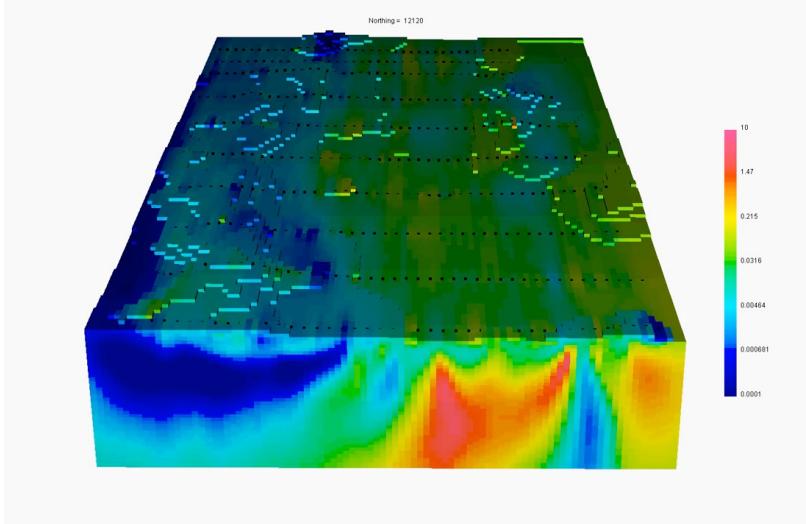
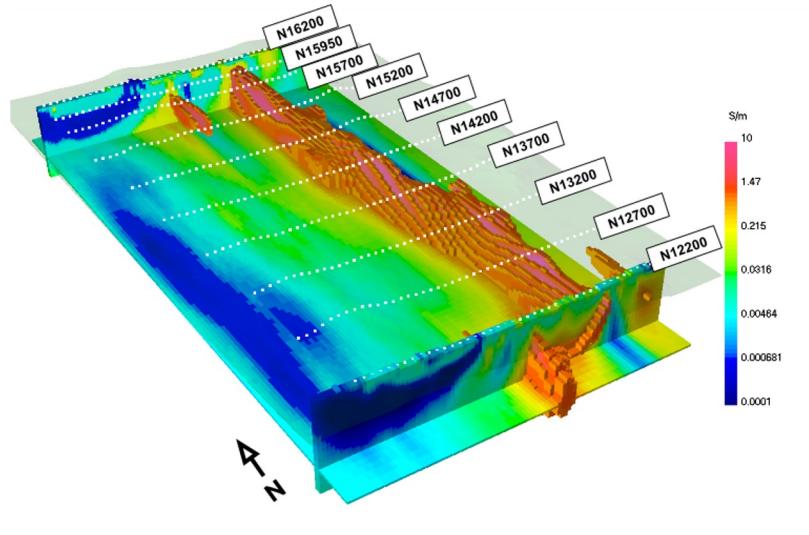


data set 2:
dipole-pole



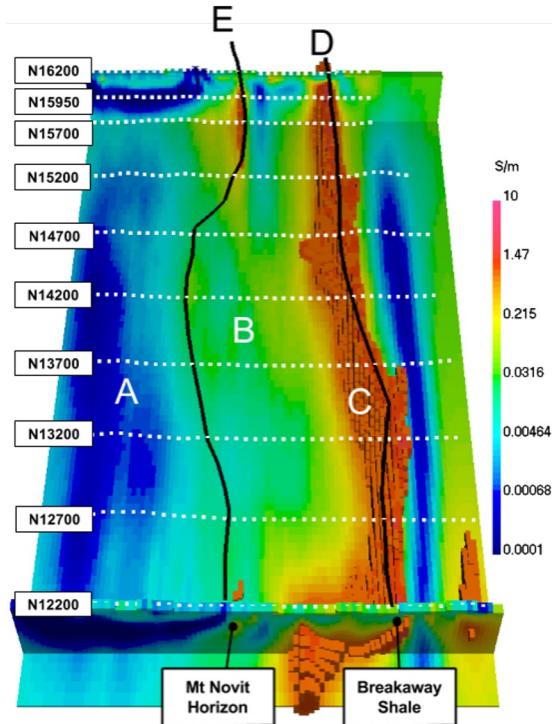
Processing and interpretation

invert to obtain resistivity model

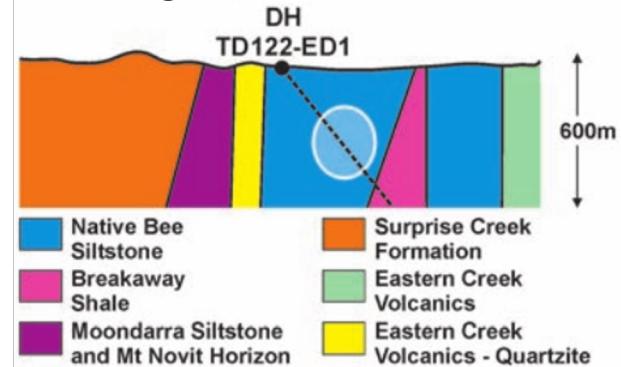


Synthesis

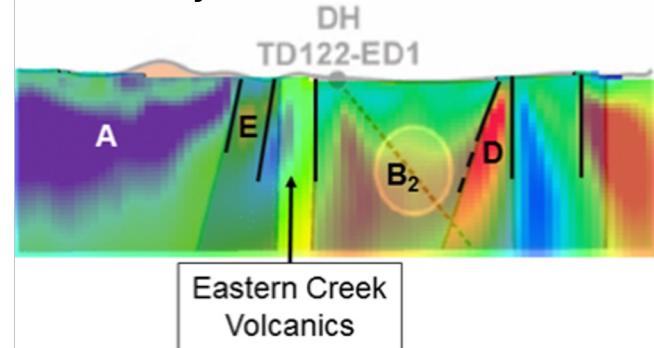
3D resistivity model



Geologic section



Resistivity section

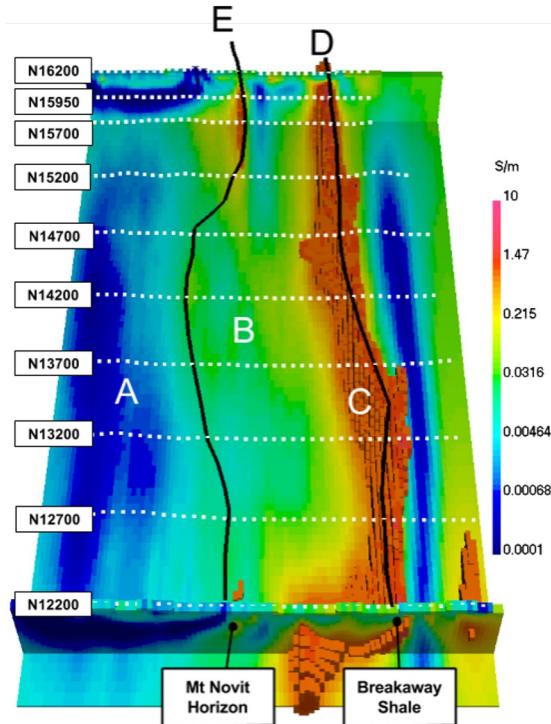


Synthesis

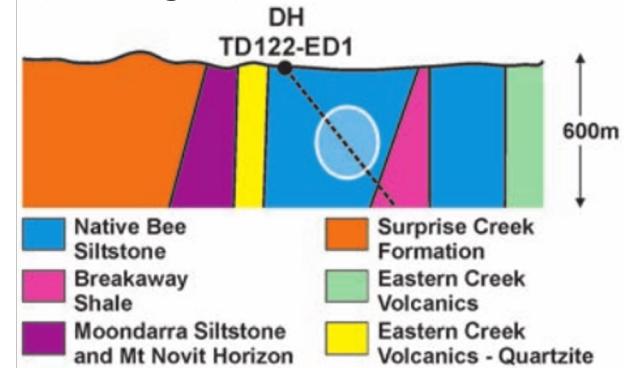
Identified a major conductor
→ black shale unit

Some indication of a
moderate conductor

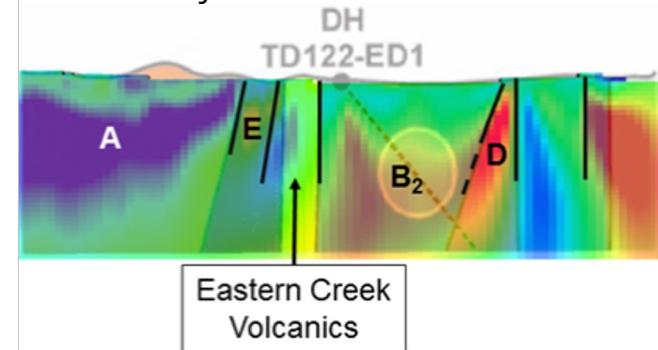
3D resistivity model



Geologic section



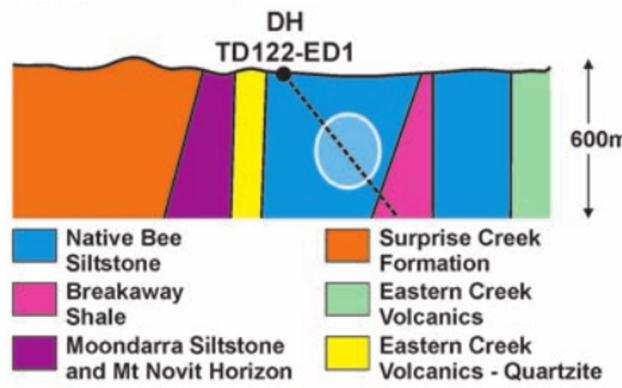
Resistivity section



Can IP help?

Additional physical property:
chargeability

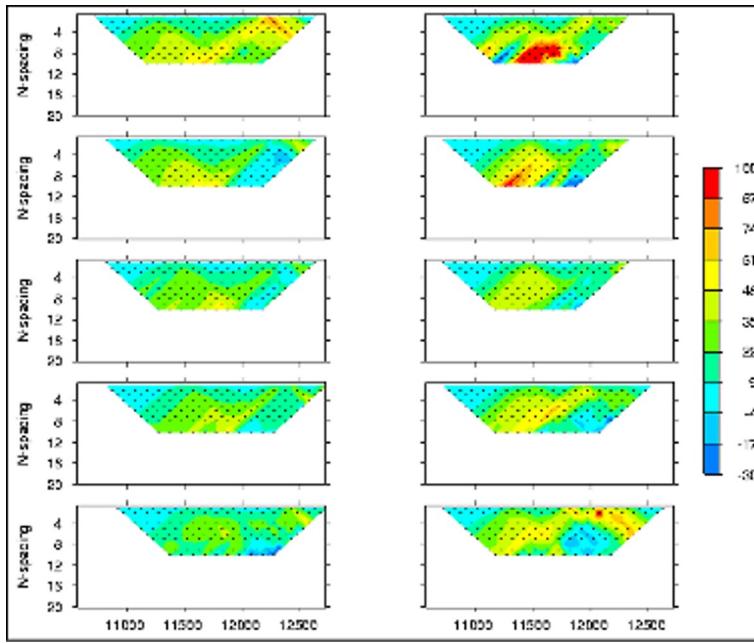
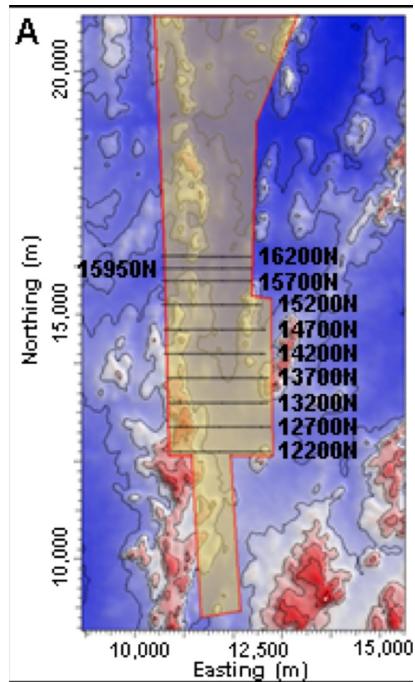
Do you expect mineralization
(disseminated sulfides) to be
chargeable?



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

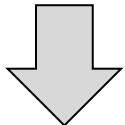
Survey and Data

IP data collected at same time as DC

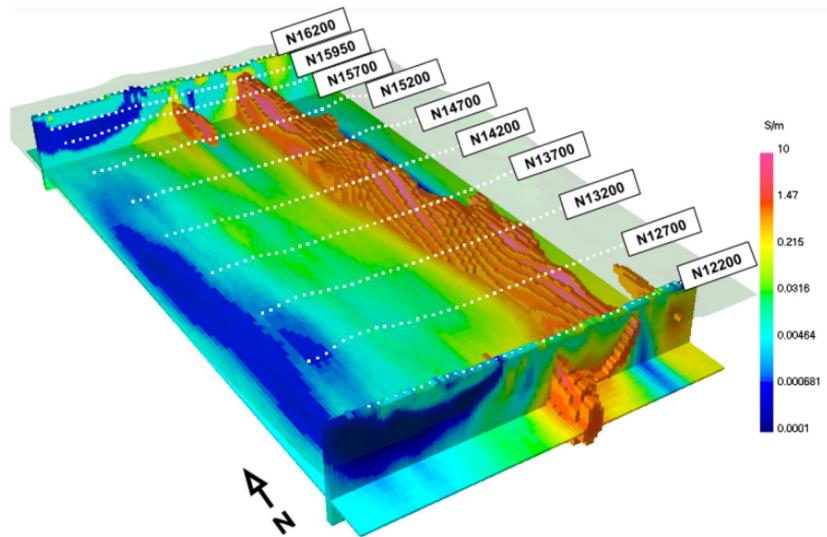


Processing: two step process

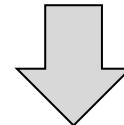
DC data



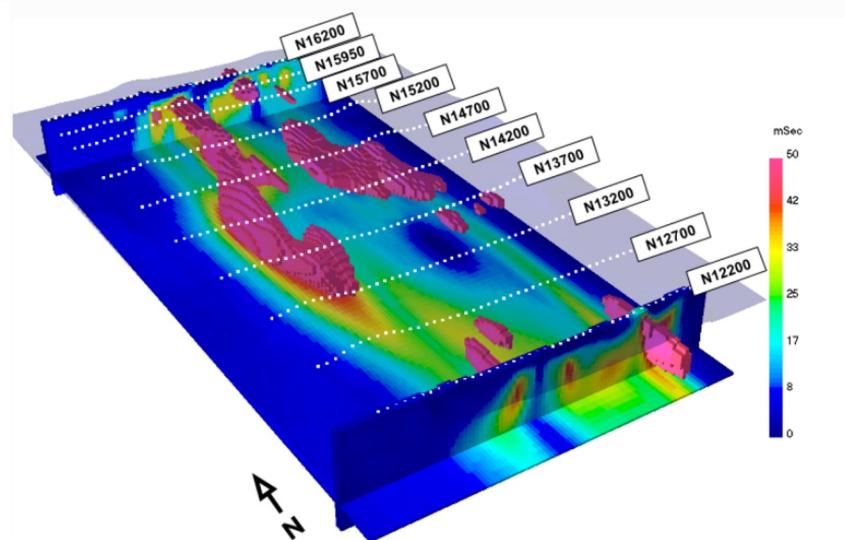
Resistivity model (ρ)



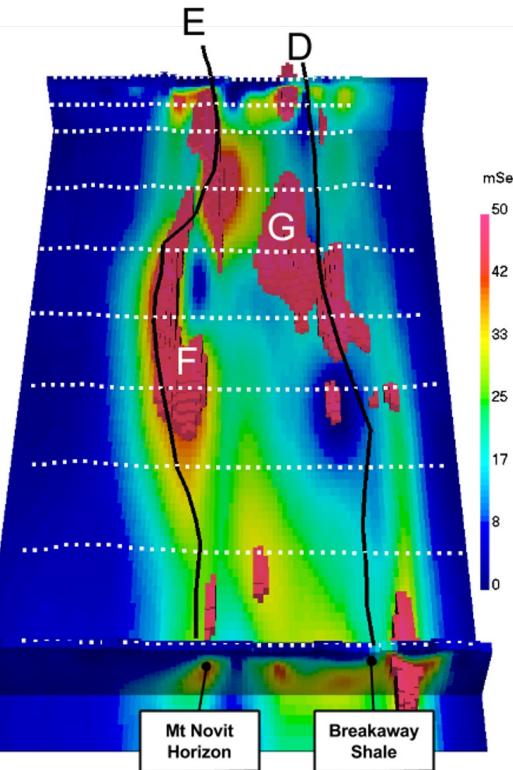
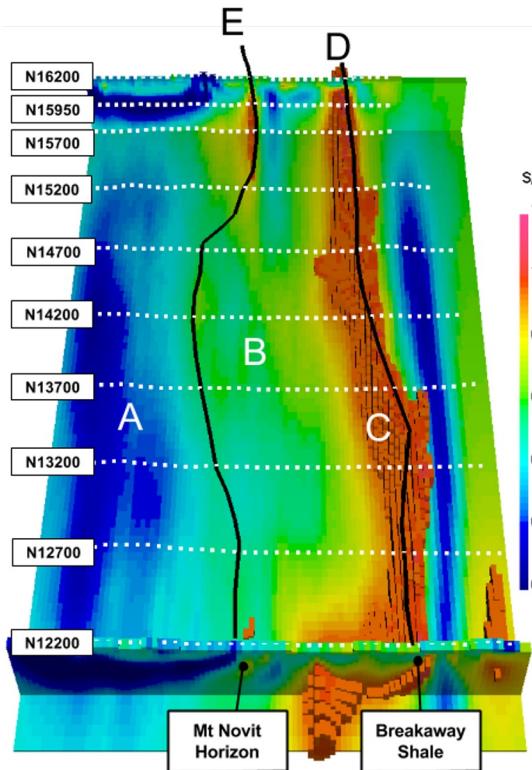
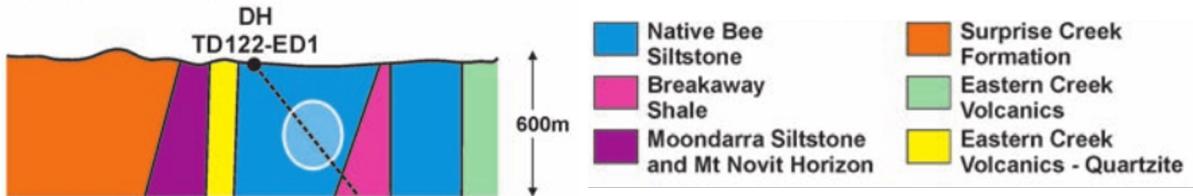
IP data



Chargeability model (η)

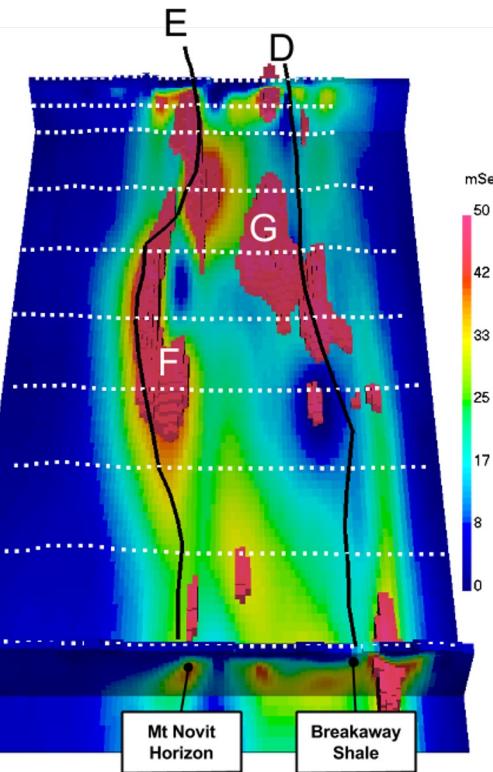
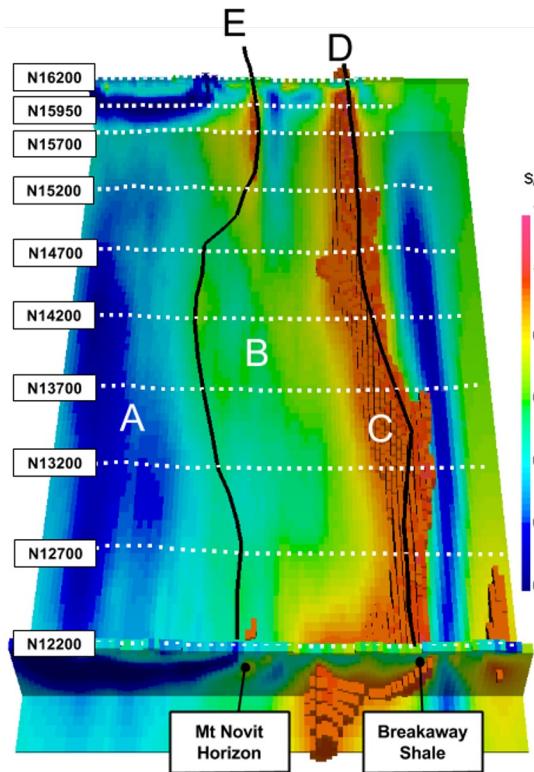
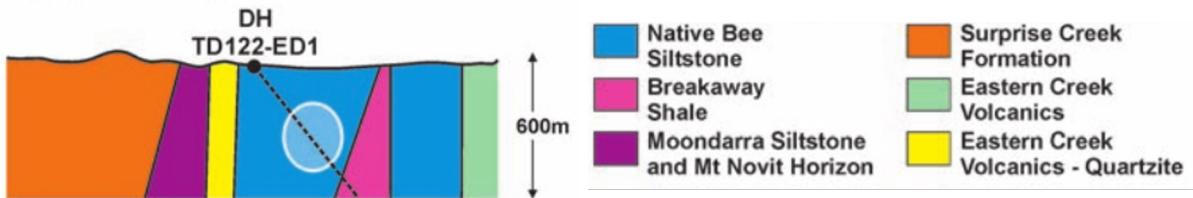


Interpretation



A: Surprise creek
(low σ , low η)

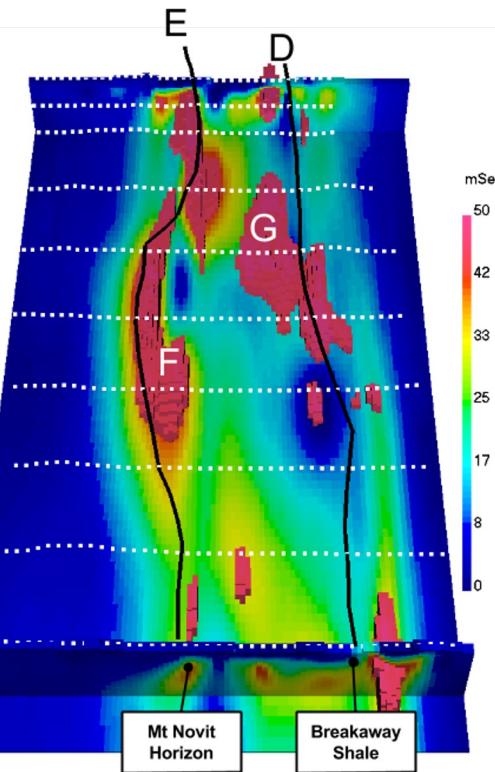
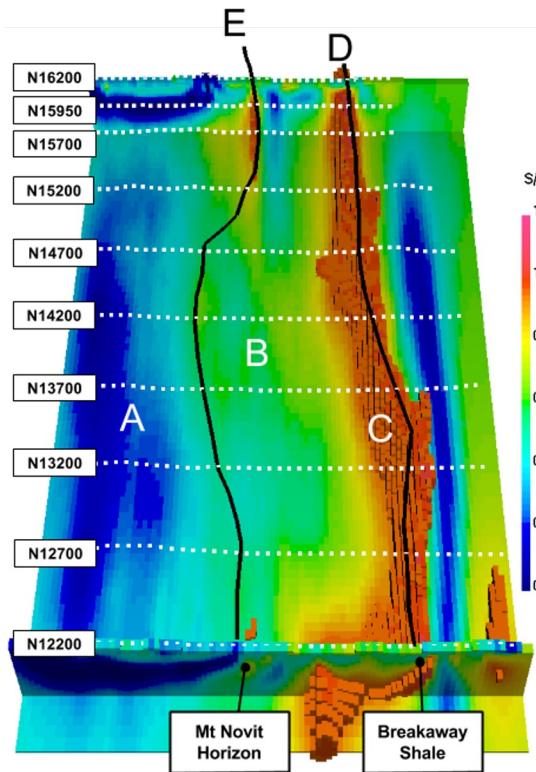
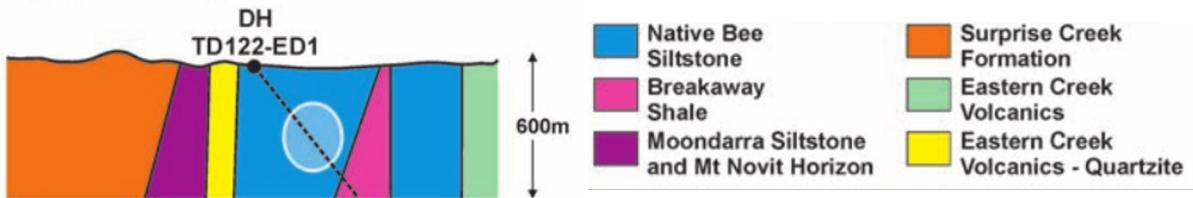
Interpretation



A: Surprise creek
(low σ , low η)

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

Interpretation

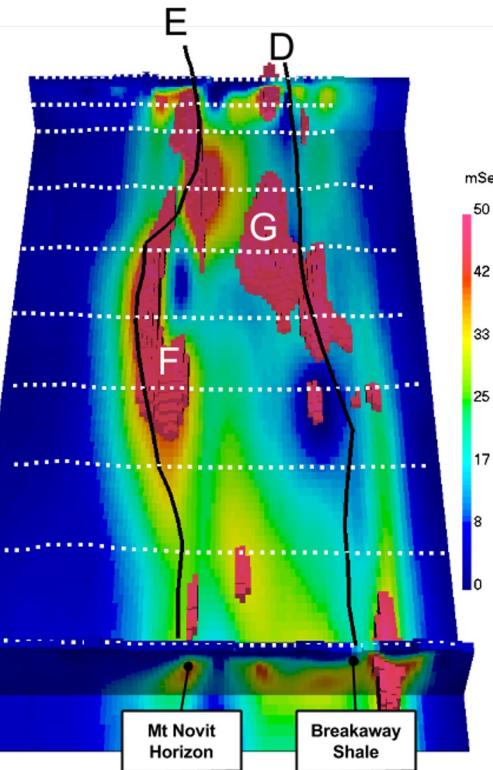
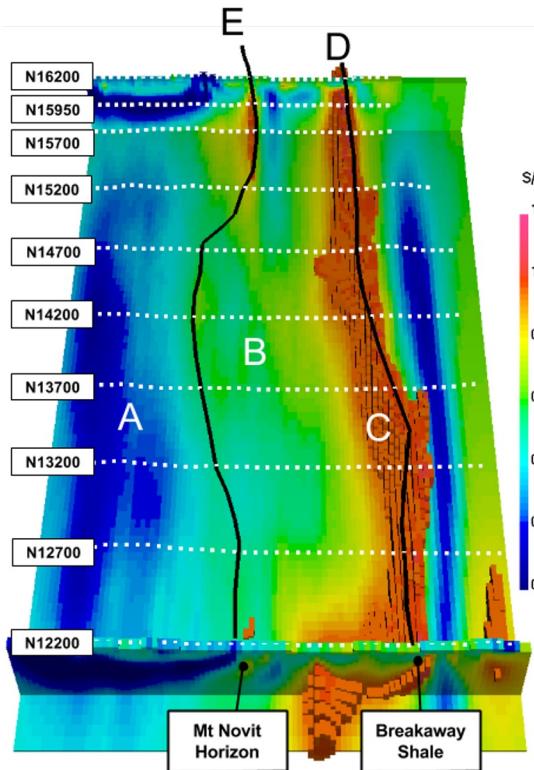
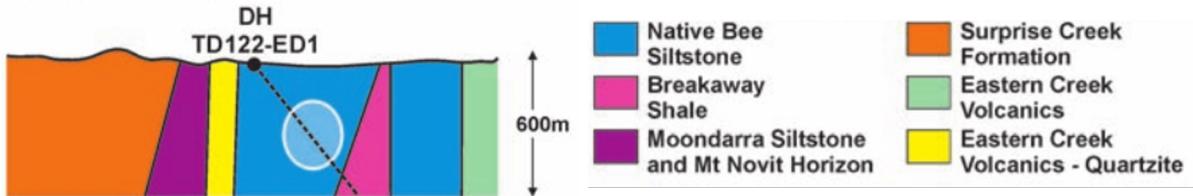


A: Surprise creek
(low σ , low η)

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

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

Interpretation



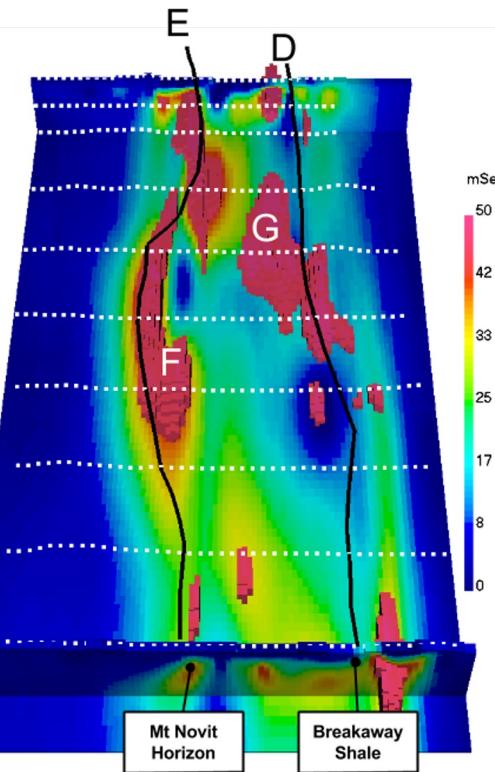
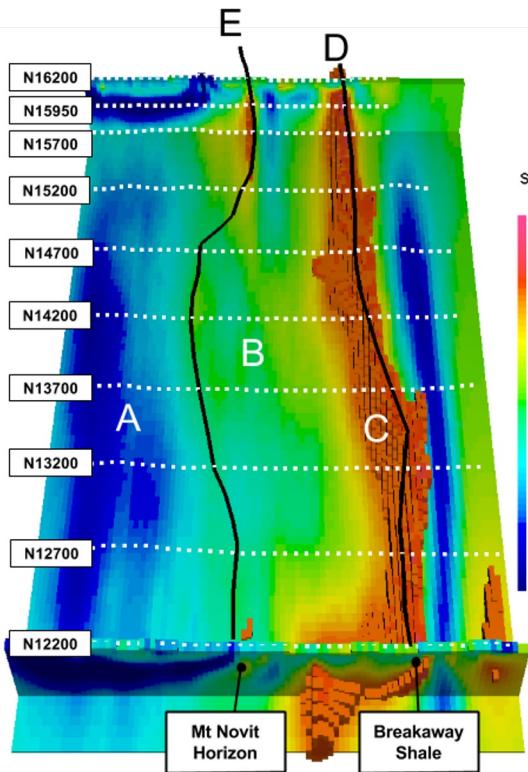
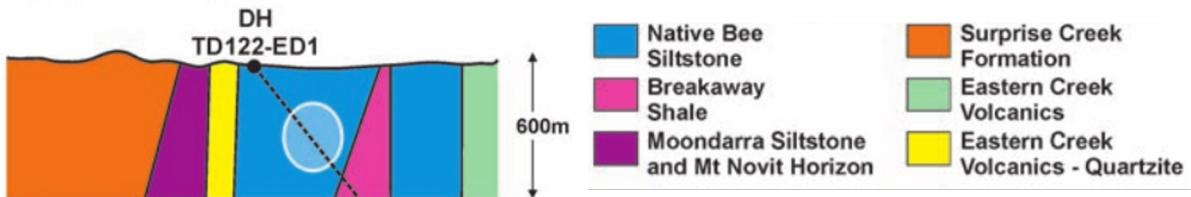
A: Surprise creek
(low σ , low η)

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)

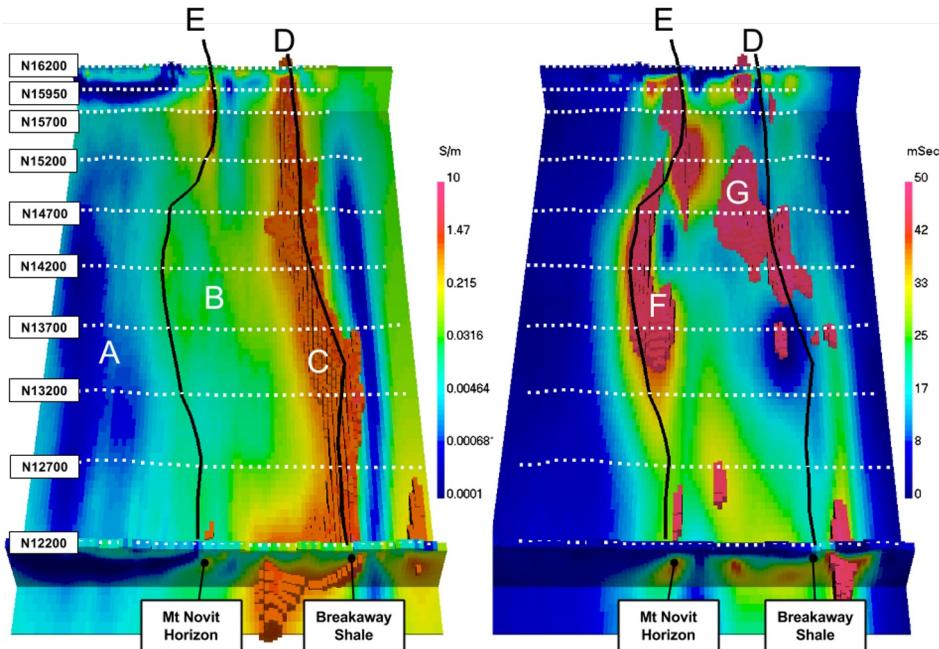
B: Moondarra, Native Bee siltstones
(moderate σ , low η)

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



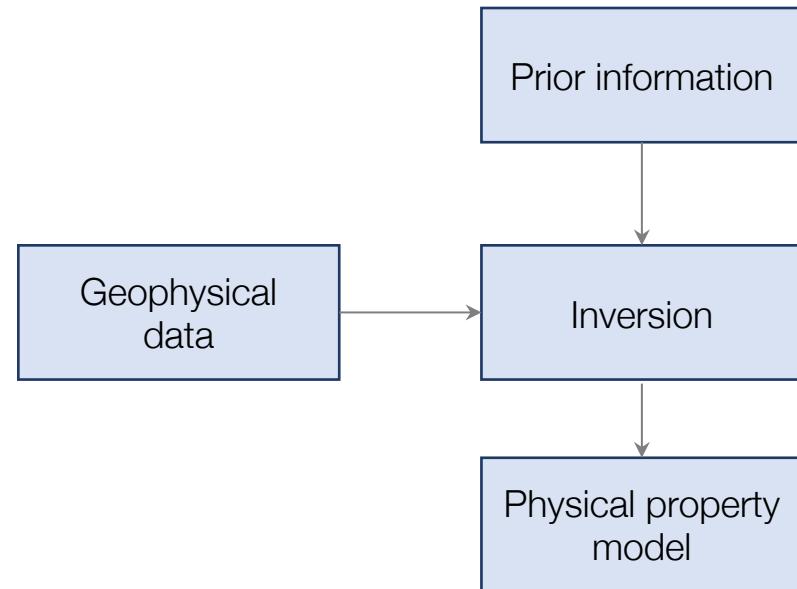
Chargeability delineates region of interest from background

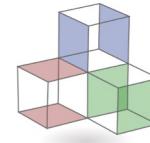
Mt. Novit horizon is chargeable

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





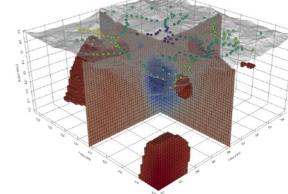
Simulation and Parameter Estimation in Geophysics

An open source python package for simulation and gradient based parameter estimation in geophysical applications.

Geophysical Methods

Contribute to a growing community of geoscientists building an open foundation for geophysics. SimPEG provides a collection of geophysical simulation and inversion tools that are built in a consistent framework.

- Gravity
- Magnetics
- Direct current resistivity
- Induced polarization
- Electromagnetic
 - Time domain
 - Frequency domain
 - Natural source (e.g. Magnetotellurics)
 - Viscous remanent magnetization
- Richards Equation



role of open-source tools

Inversions require ability to:

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



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

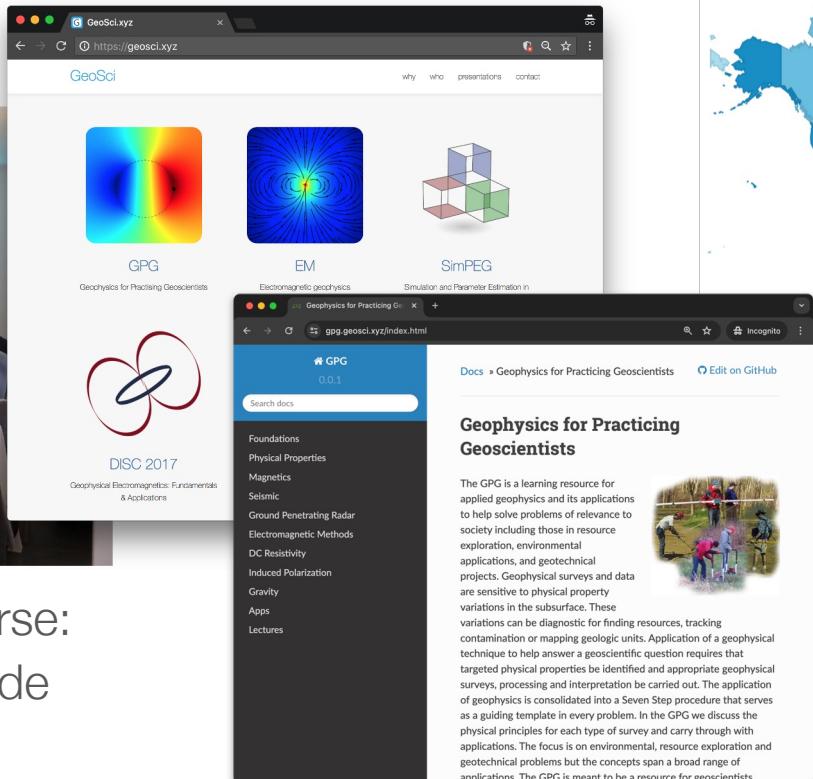
<https://simpeg.xyz>

GeoSci .xyz



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GeoSci

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Induced Polarization

Gravity

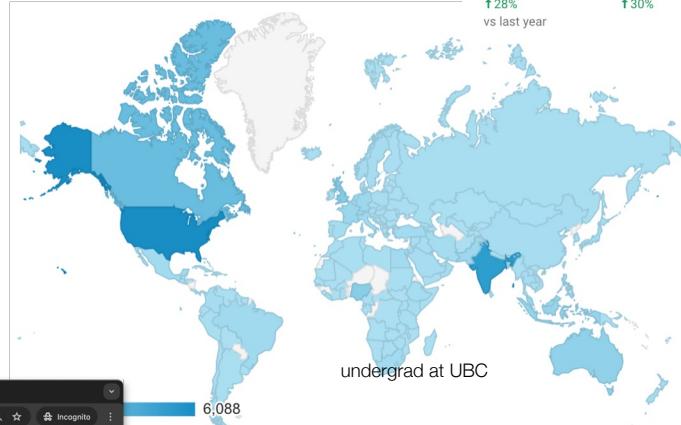
Apps

Lectures

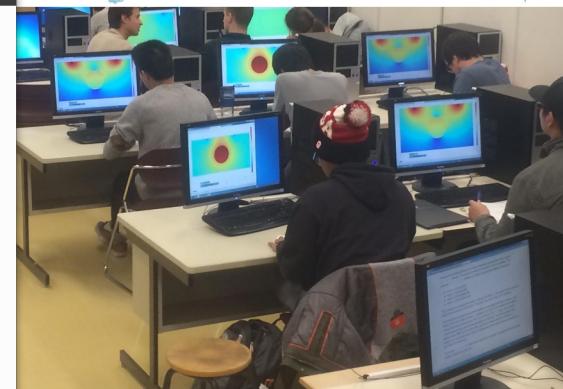
Docs » Geophysics for Practicing Geoscientists Edit on GitHub

Geophysics for Practicing Geoscientists

The GPG is a learning resource for applied geophysics and its applications to help solve problems of relevance to society including those in resource exploration, environmental applications, and geotechnical projects. Geophysical surveys and data are sensitive to physical property variations in the subsurface. These variations can be diagnostic for finding resources, tracking contamination or mapping geologic units. Application of a geophysical technique to help answer a geoscientific question requires that targeted physical properties be identified and appropriate geophysical surveys, processing, and interpretation be carried out. The application of geophysics is consolidated into a Seven Step procedure that serves as a guiding template in every problem. In the GPG we discuss the physical principles for each type of survey and carry through with applications. The focus is on environmental, resource exploration and geotechnical problems but the concepts span a broad range of applications. The GPG is meant to be a resource for geoscientists,



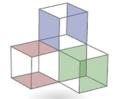
electromagnetics course:
26 locations worldwide



Thank you!



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lheagy@eoas.ubc.ca

