Surface geometry inversion of geophysical electromagnetic data

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Outline

- Motivation
- Surface geometry inversion
- Marine CSEM examples
- TEM examples
- Conclusions

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- **Motivation**
- Surface geometry inversion
- Marine CSEM examples
- TEM examples
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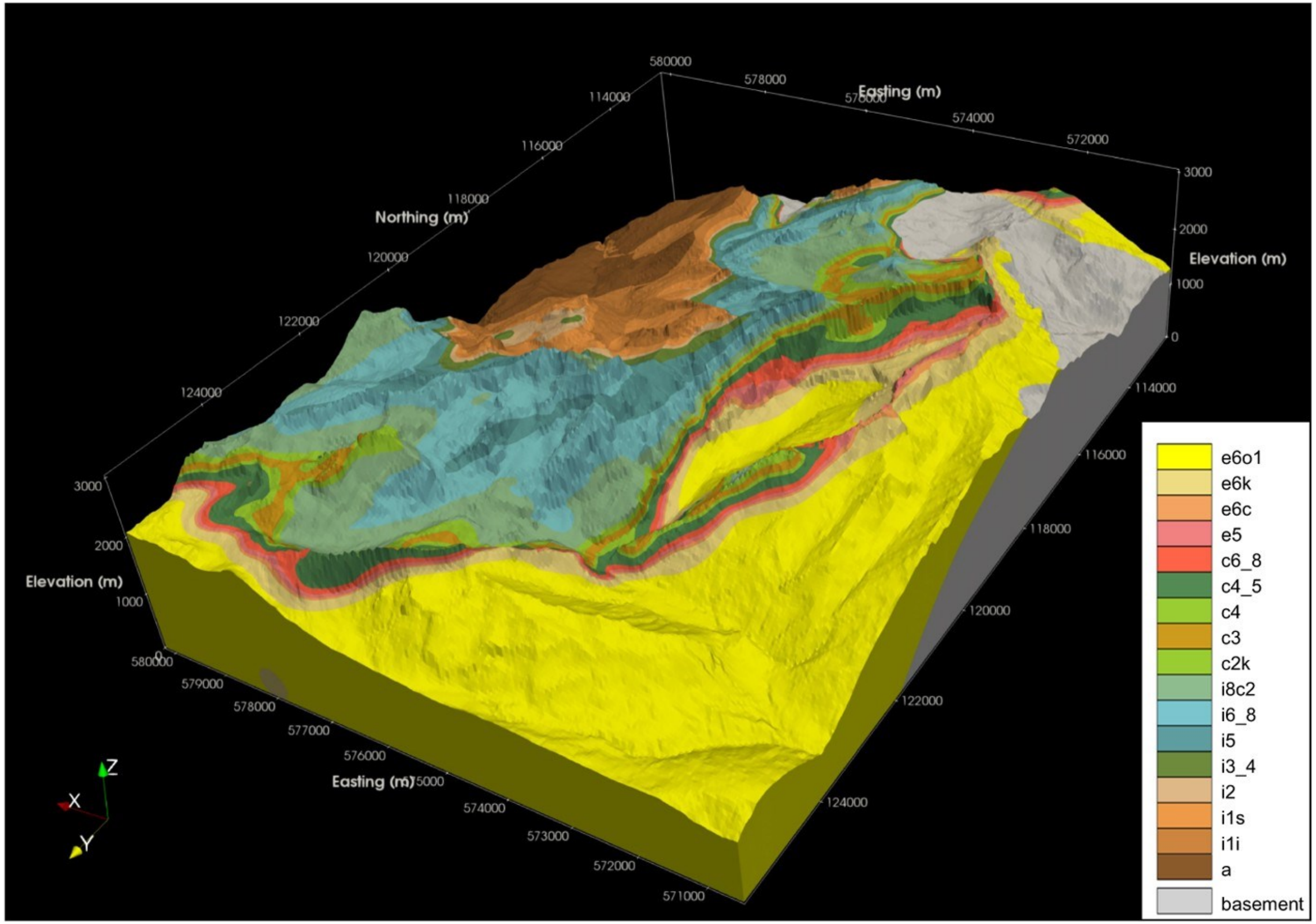
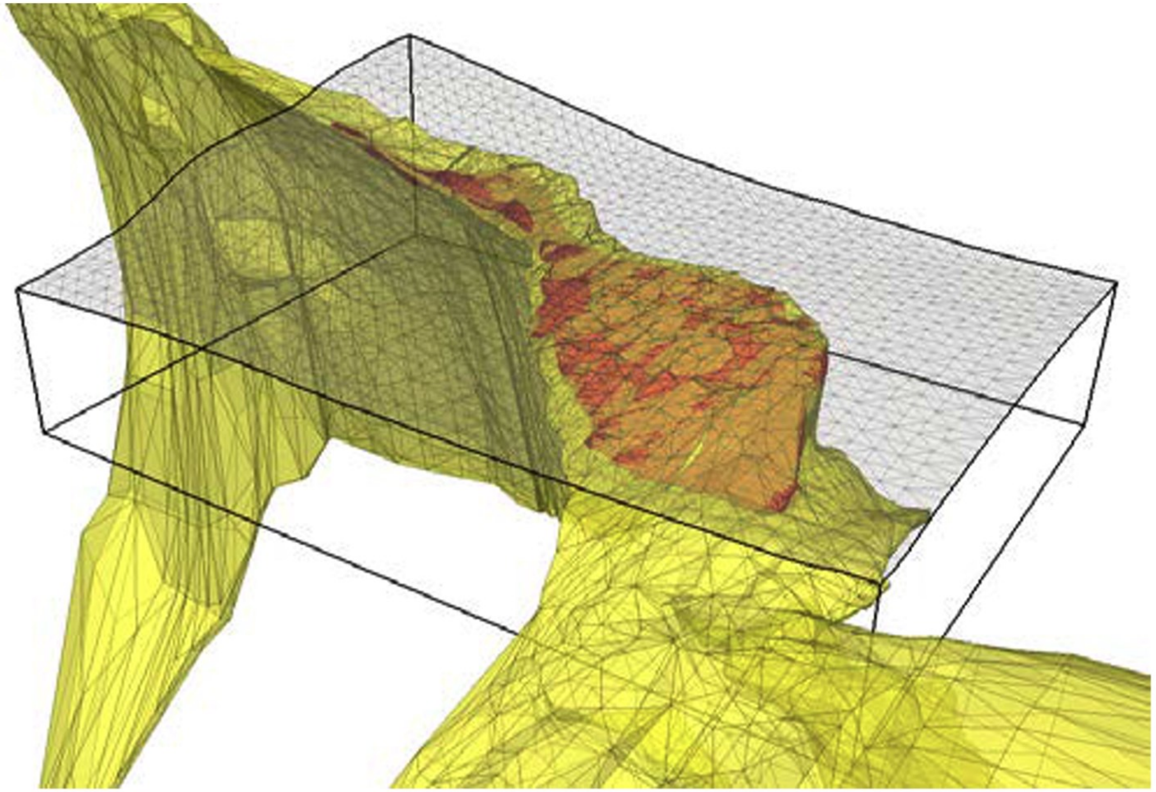
Geological models

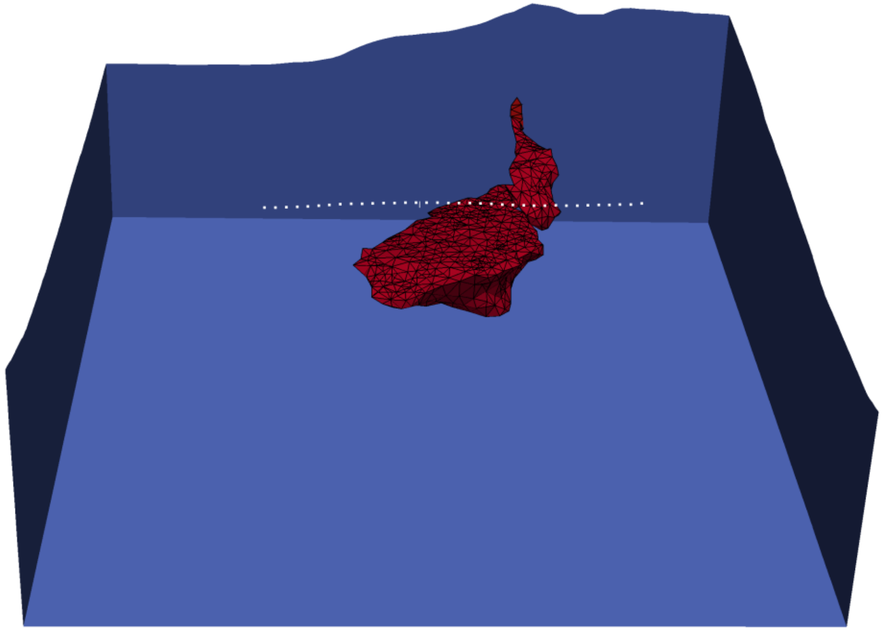


(Thornton et. al., Scientific Data, 2018)

Geological models



Ovoid massive sulfide ore deposit (Lelièvre et. al., TLE, 2012)



Jahandari & Farquharson (Geophysics, 2014)

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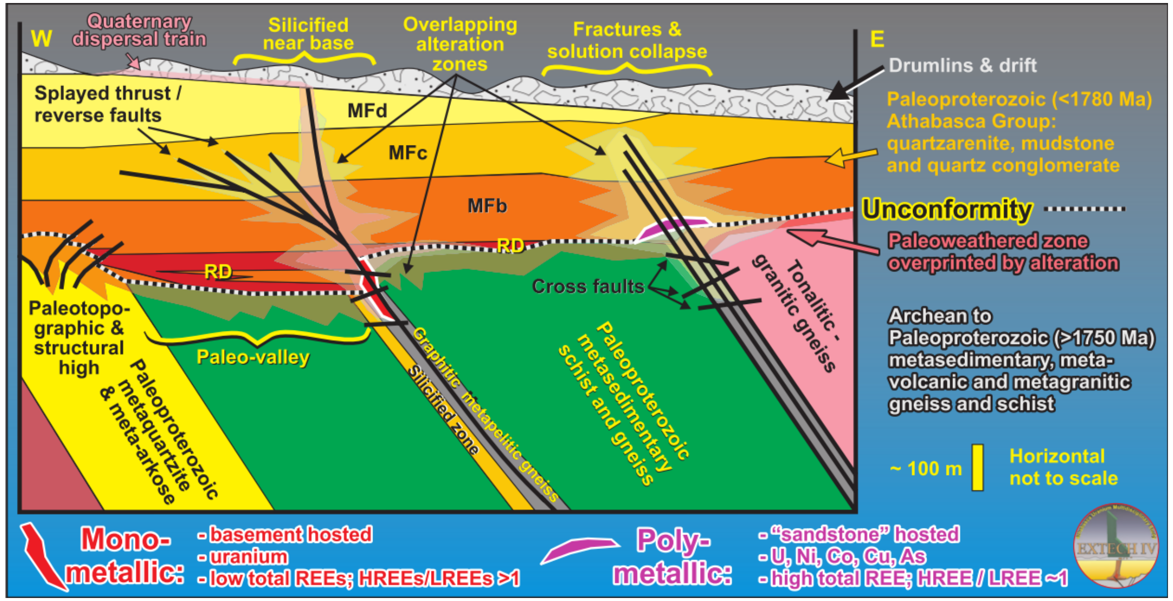
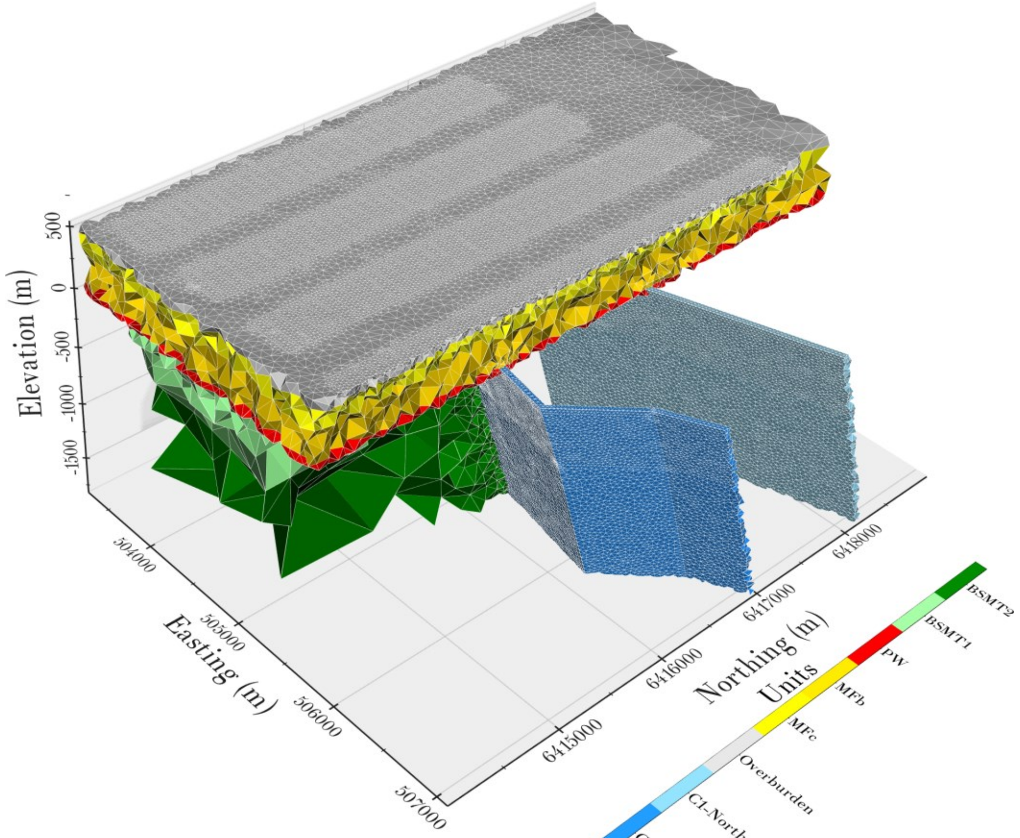
Geological models



(Jefferson et. al., 2007)



Lu et al. (Geophysics, 2021)

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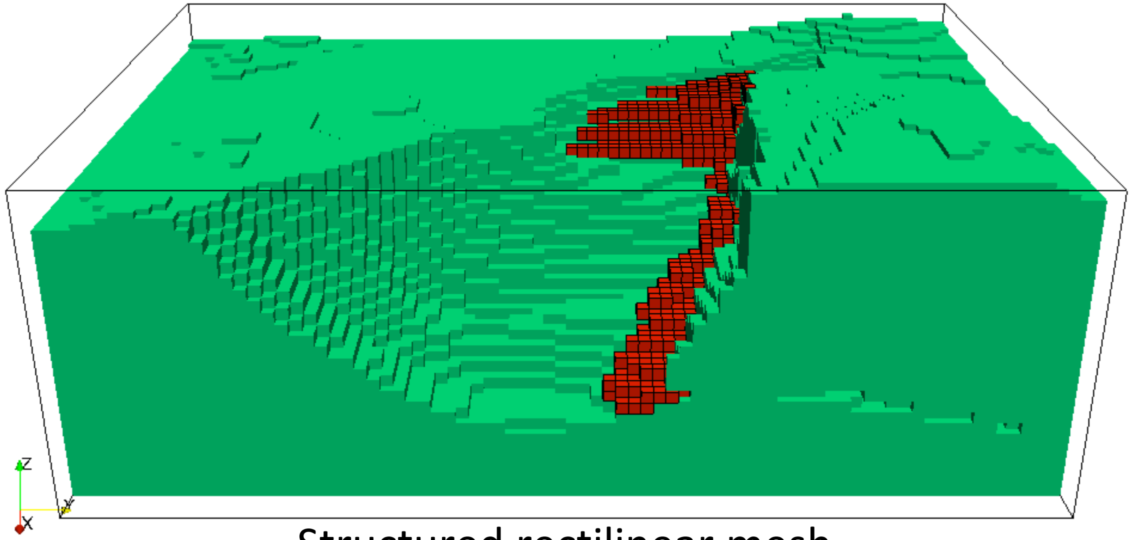
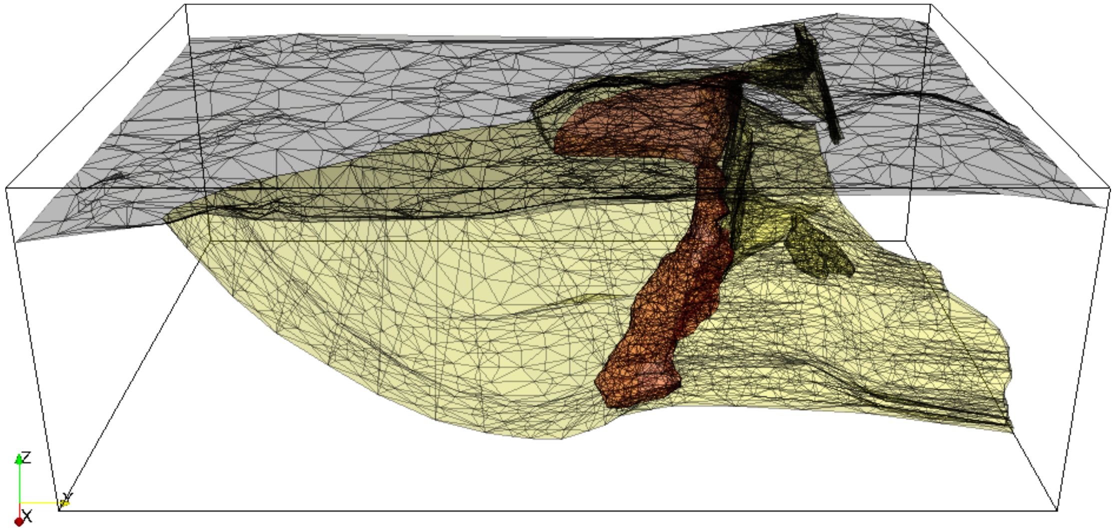
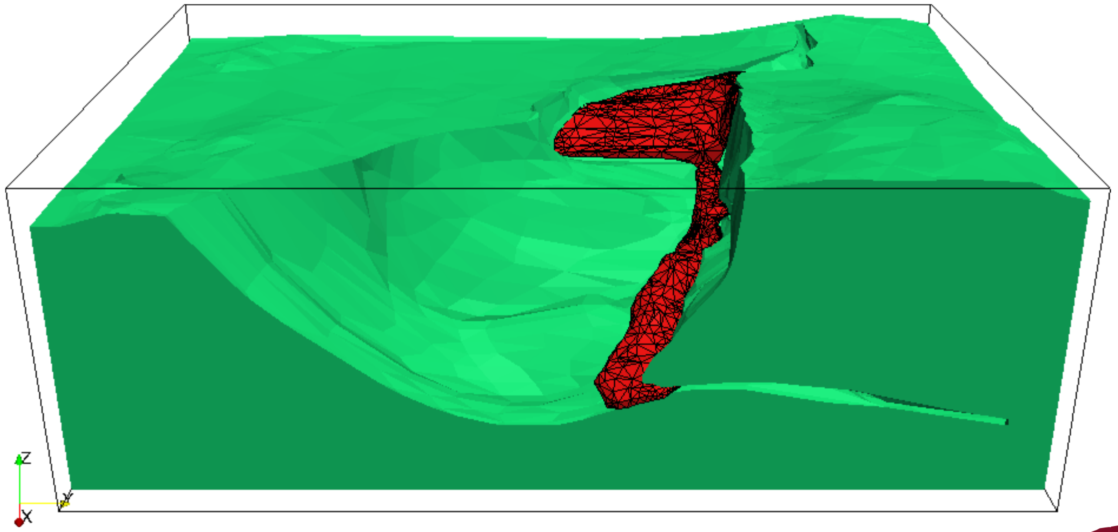
Geophysical modelling



Structured rectilinear mesh



Geological wireframe model



Unstructured tetrahedral mesh

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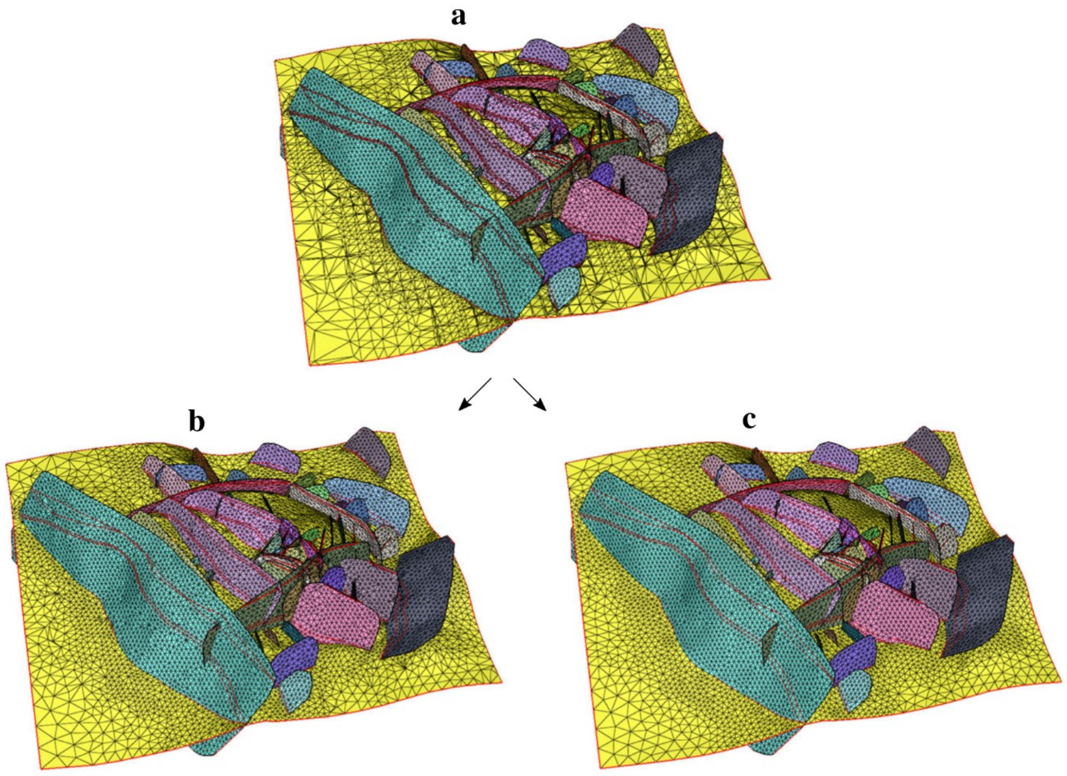
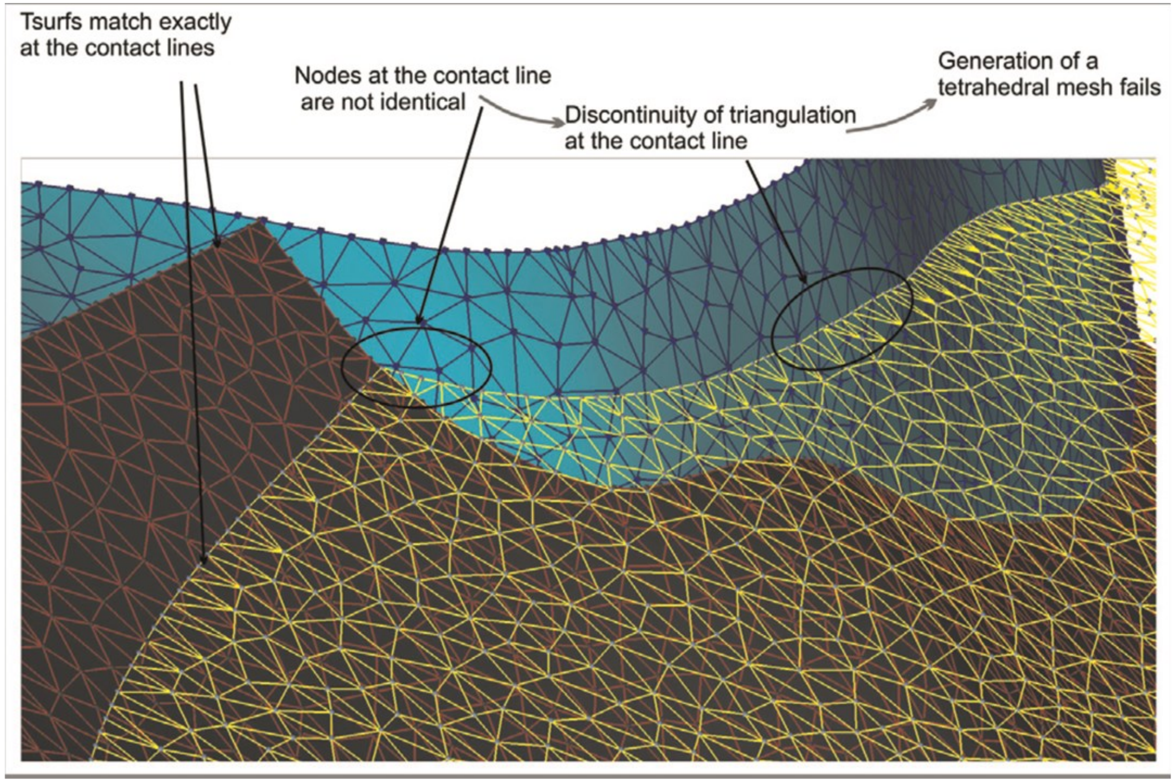
Geophysical modelling

Quality mesh from geological models



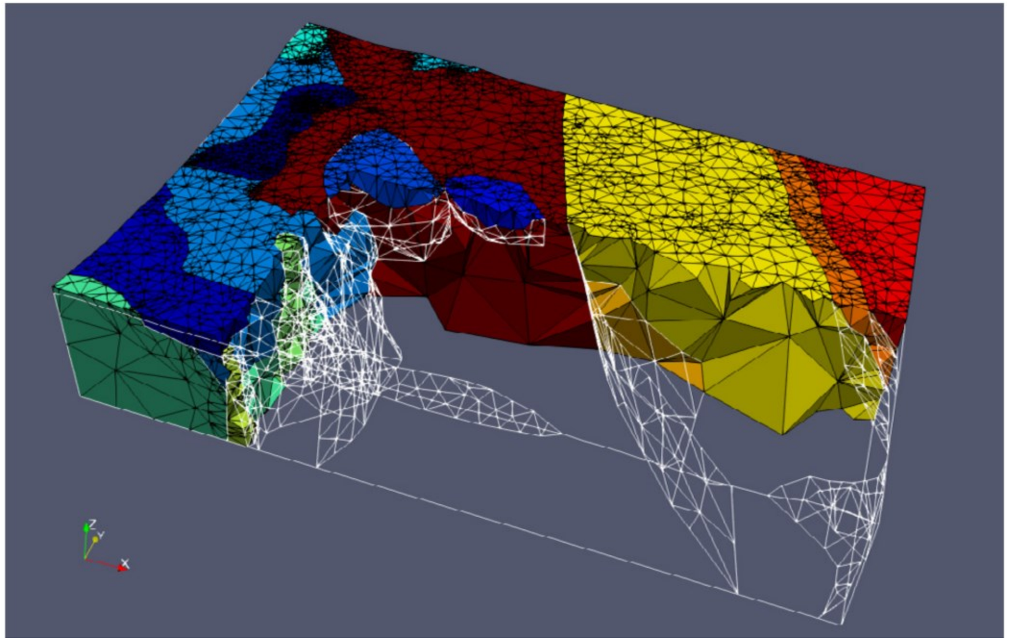
Surface mesh generation (Irakarama1 M.,2022)

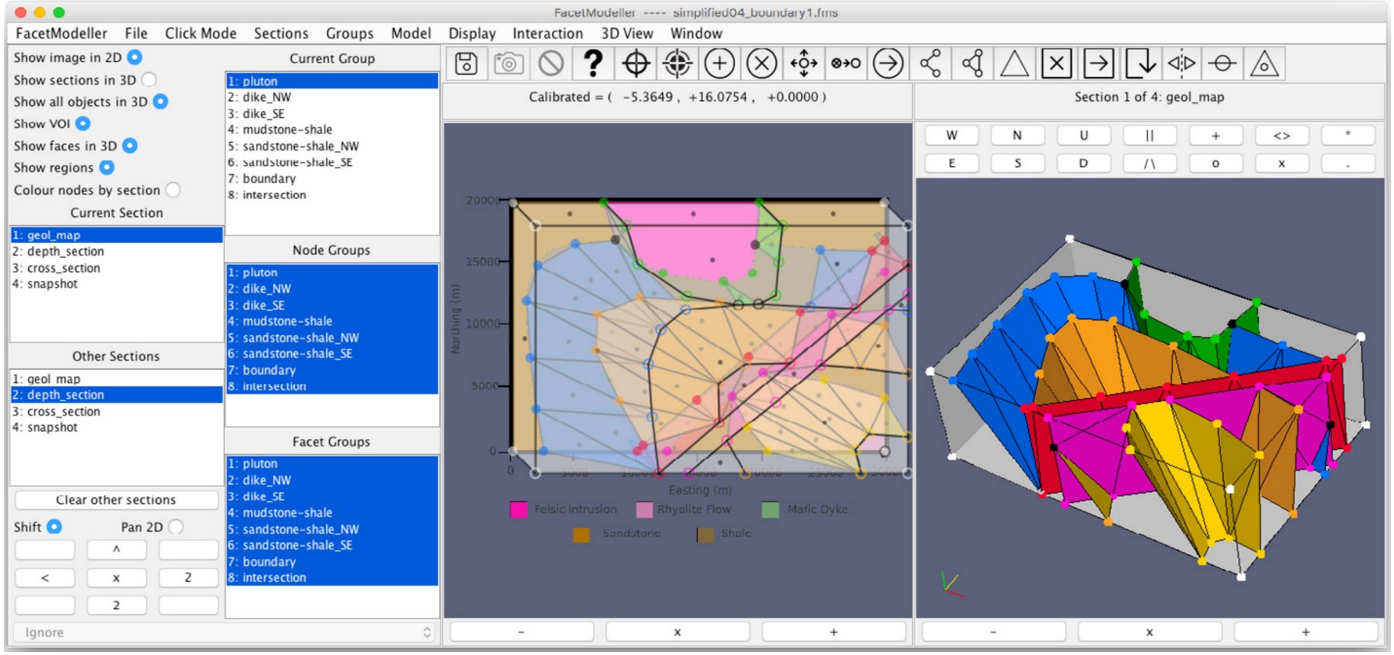


Geologic boundaries generated with Gocad (Zehner et. al., 2015)

Geophysical model building

Quality mesh from geological models



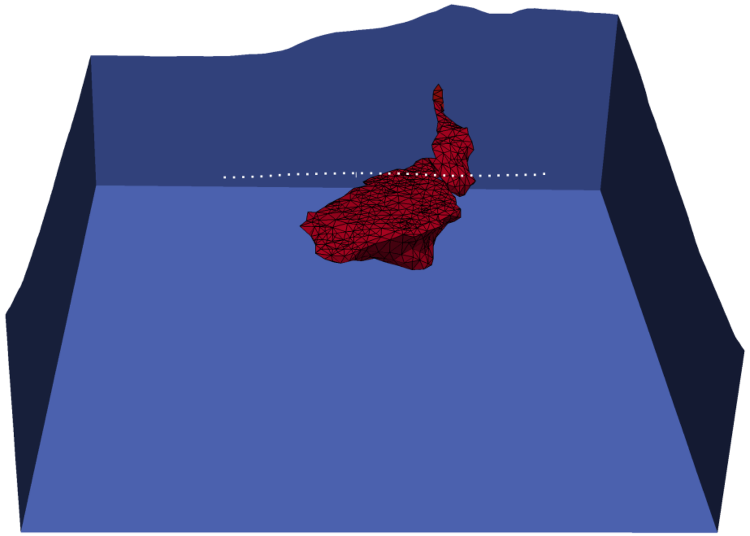


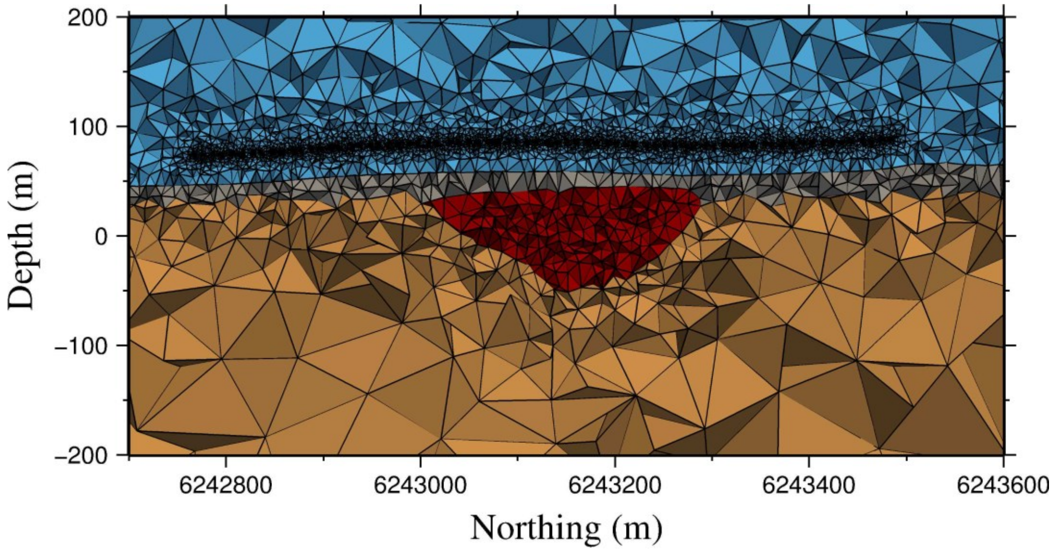
FacetModeller (https://github.com/pglelievre/facetmodeller)

Lelièvre et al. (SoftwareX, 2018)

Geophysical modelling

- Numerical methods
  - Finite element
  - Finite volume
  - Mimetic finite difference
  - Mesh free
- Geophysical data types
  - Gravity & magnetic
  - CSEM, TEM, MT, DC/IP
  - Seismic travel time





Jahandari & Farquharson (Geophysics, 2014)

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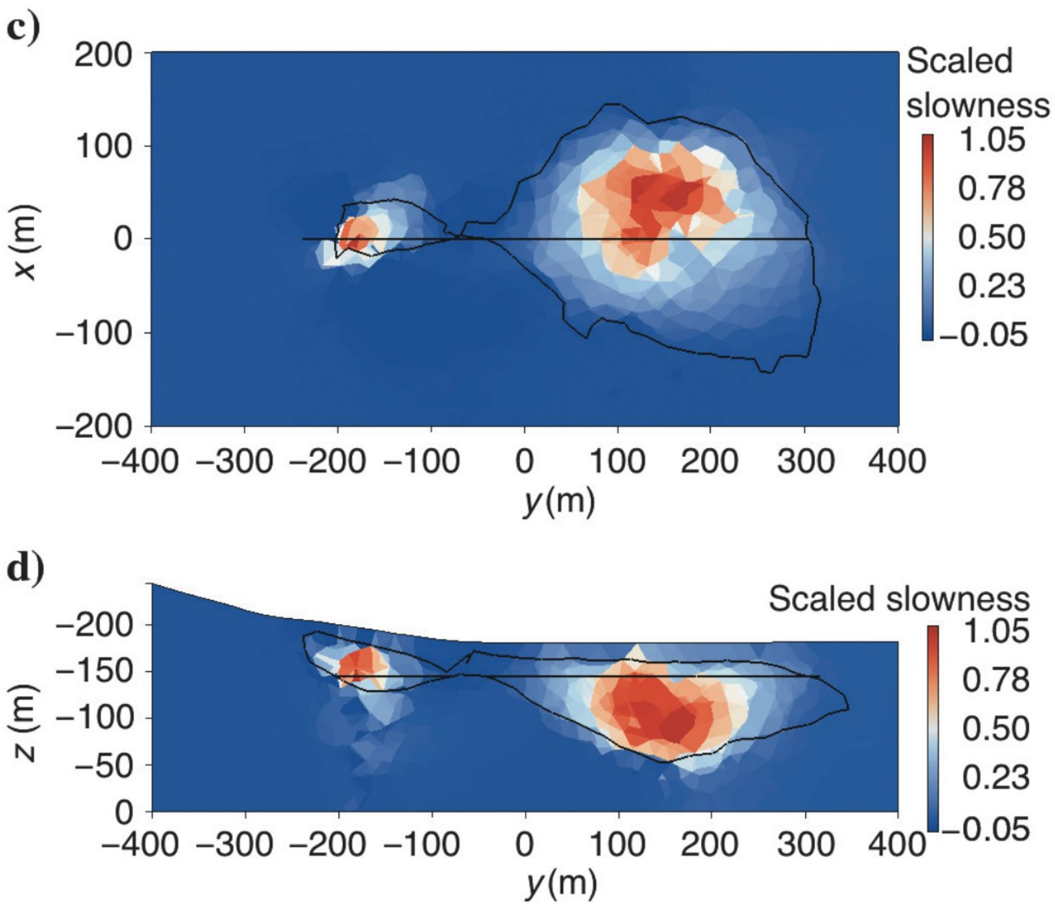
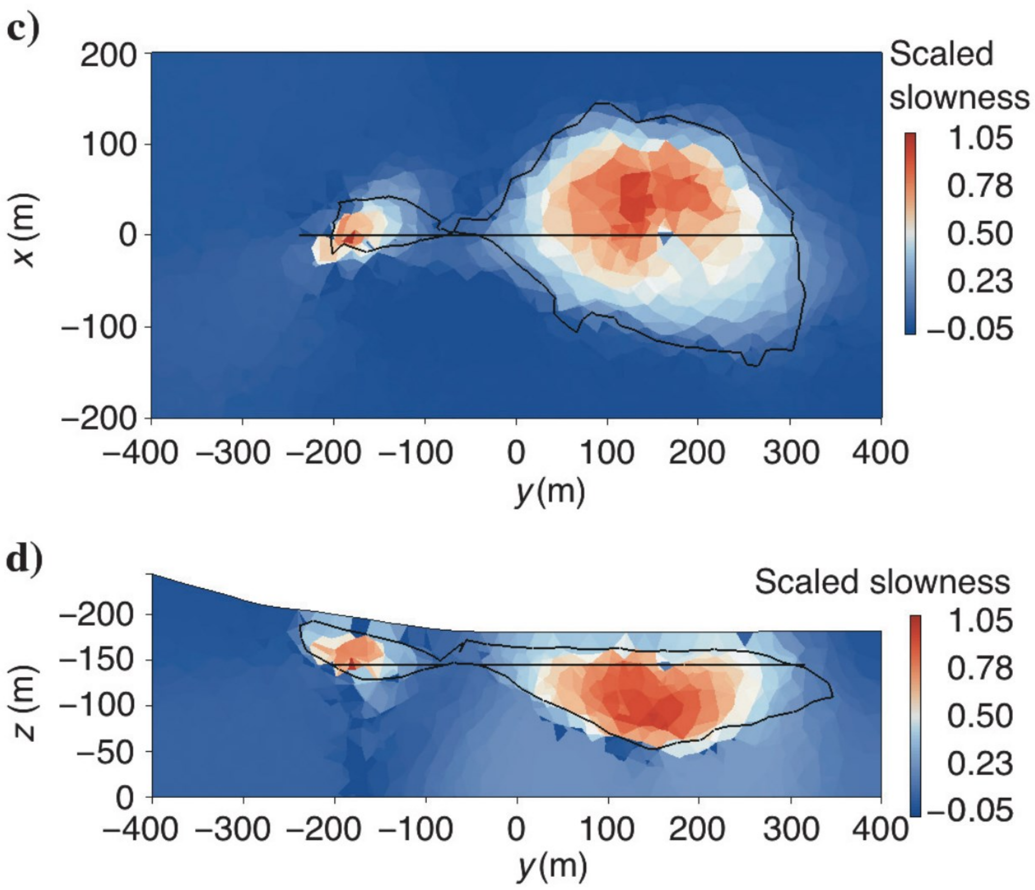
Occam-style, minimum-structure inversion



Seismic travel time inversion



Gravity + seismic joint inversion

(Lelièvre et. al. GJI, 2012)

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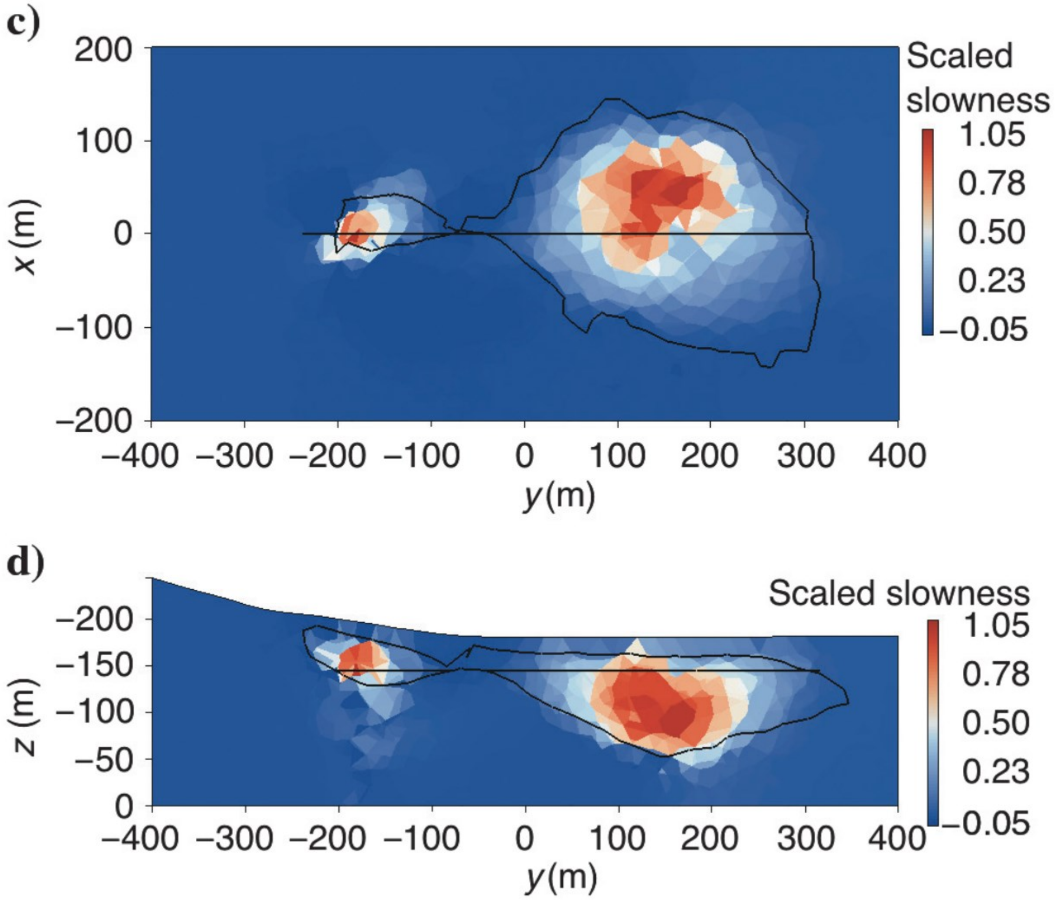
Occam-style, minimum-structure inversion



Seismic travel time inversion

(Lelièvre et. al. GJI, 2012)

Minimum-structure inversion objective function:

$$\phi(\boldsymbol{m}) = \phi_d(\boldsymbol{m}) + \beta\phi_m(\boldsymbol{m}),$$

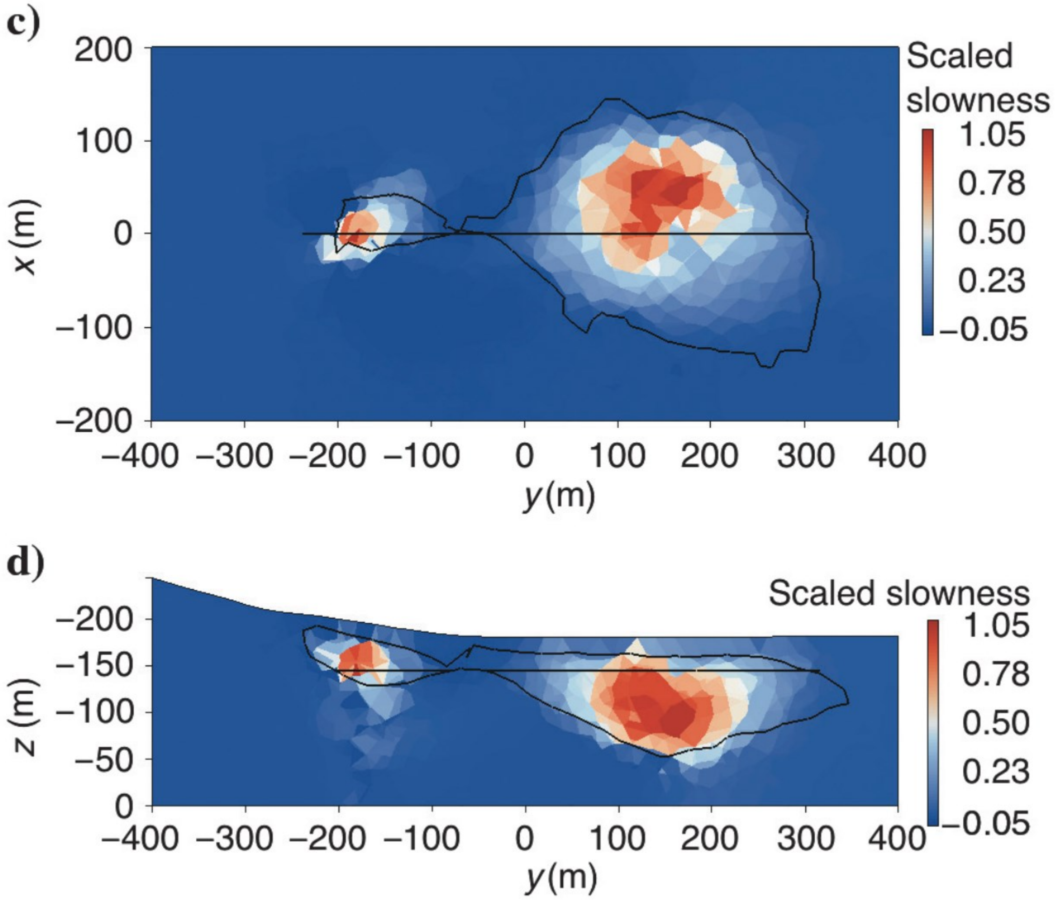
- Data misfit:

$$\phi_d(\boldsymbol{m}) = \| \boldsymbol{W}_d \, [\boldsymbol{d}^{obs} - \boldsymbol{d}(\boldsymbol{m})] \|^2,$$

- Model structure (smoothness):

$$\phi_m(\boldsymbol{m}) = \sum_k \| \boldsymbol{W}_k(\boldsymbol{m} - \boldsymbol{m}^{ref}) \|^2.$$

Occam-style, minimum-structure inversion



Seismic travel time inversion

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(Lelièvre et. al. GJI, 2012)

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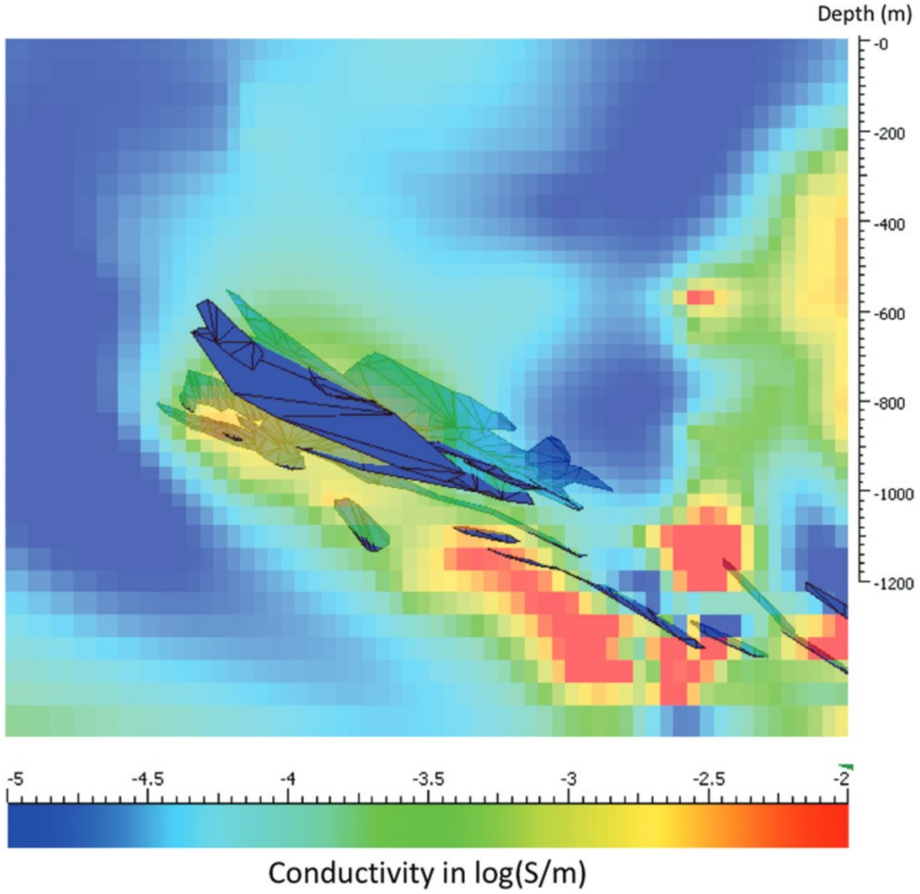
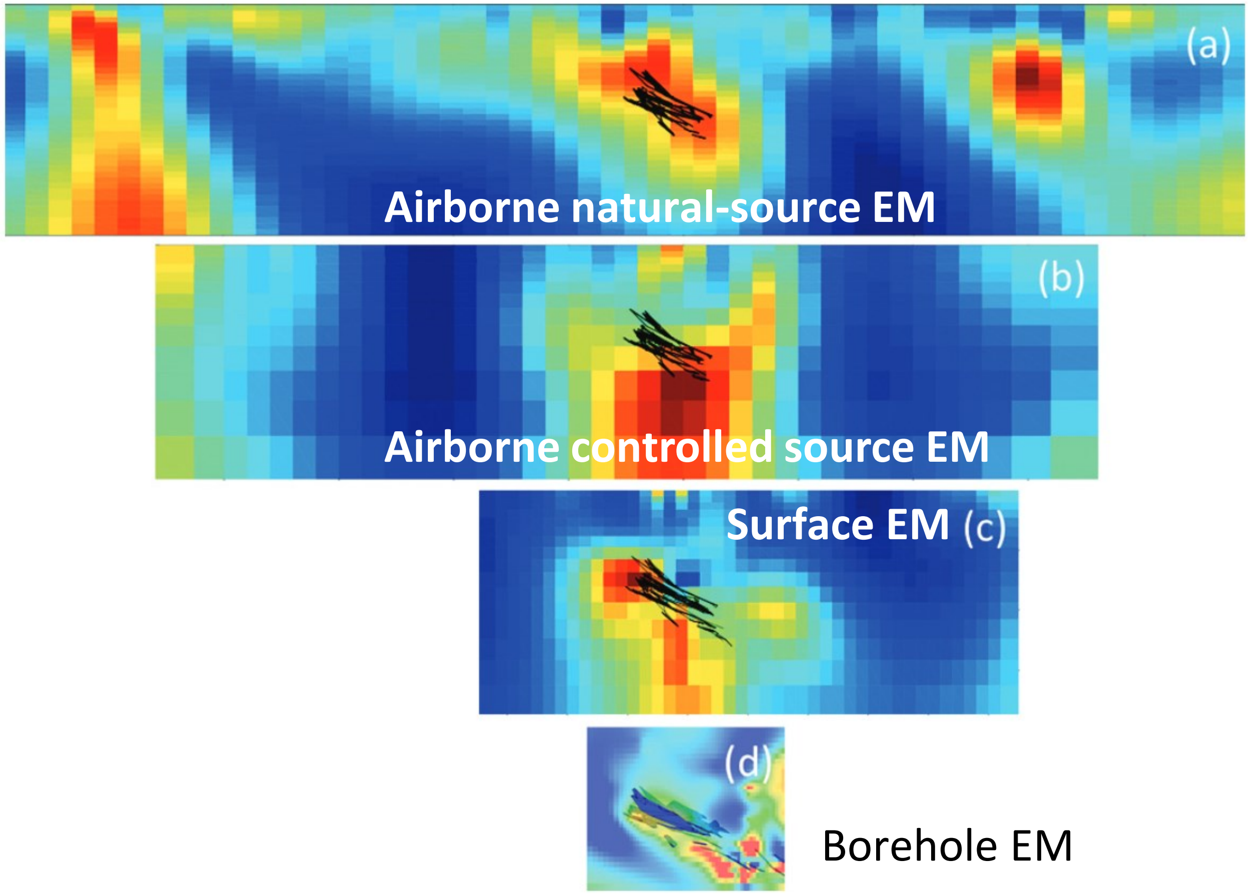
Occam-style, minimum-structure inversion



PULSE-EM surface-borehole TEM data inversion of the Lalor deposit

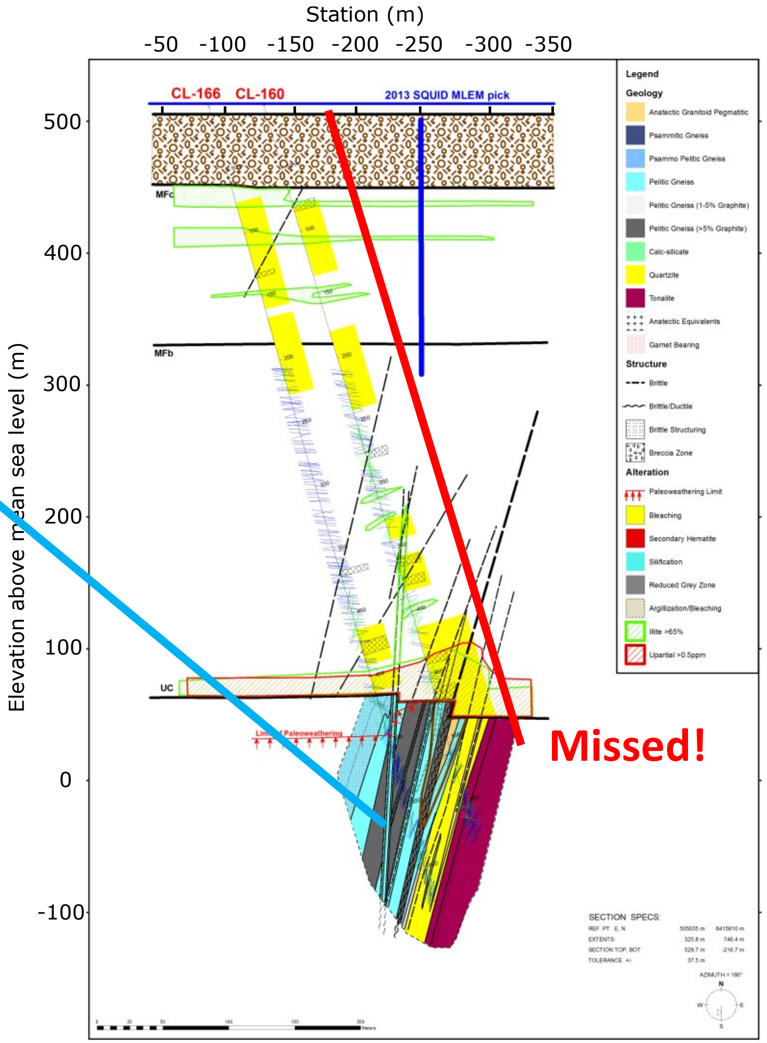


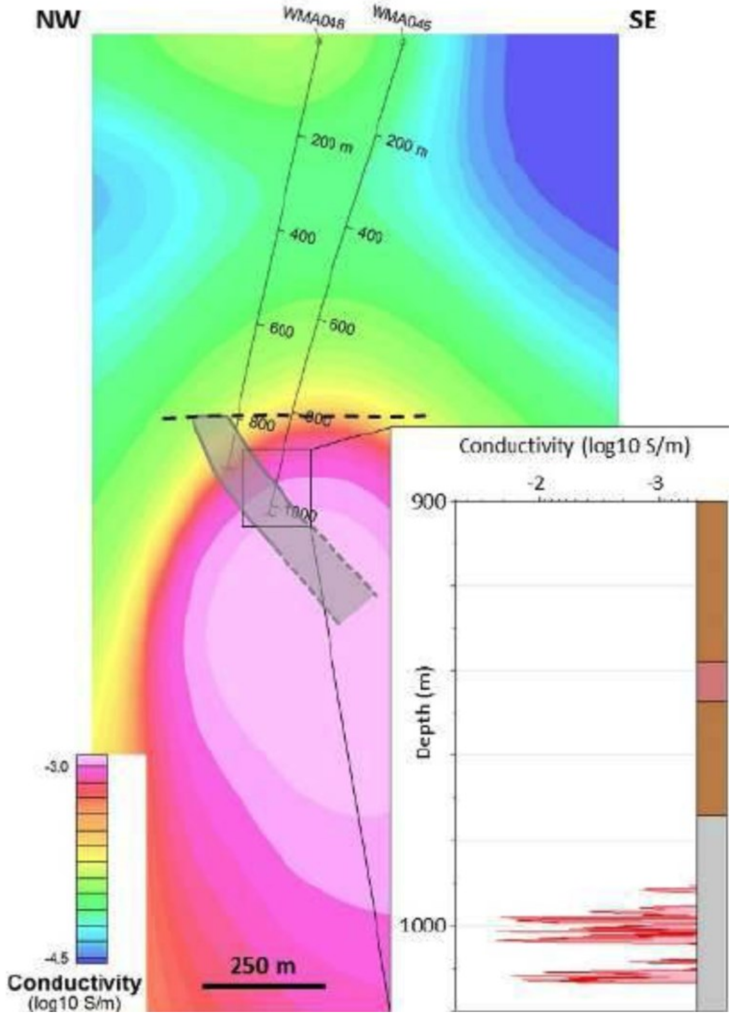
Vertical sections of conductivity models from different EM surveys

Yang et al. (Canadian Journal of Earth Sciences, 2018)

Occam-style, minimum-structure inversion

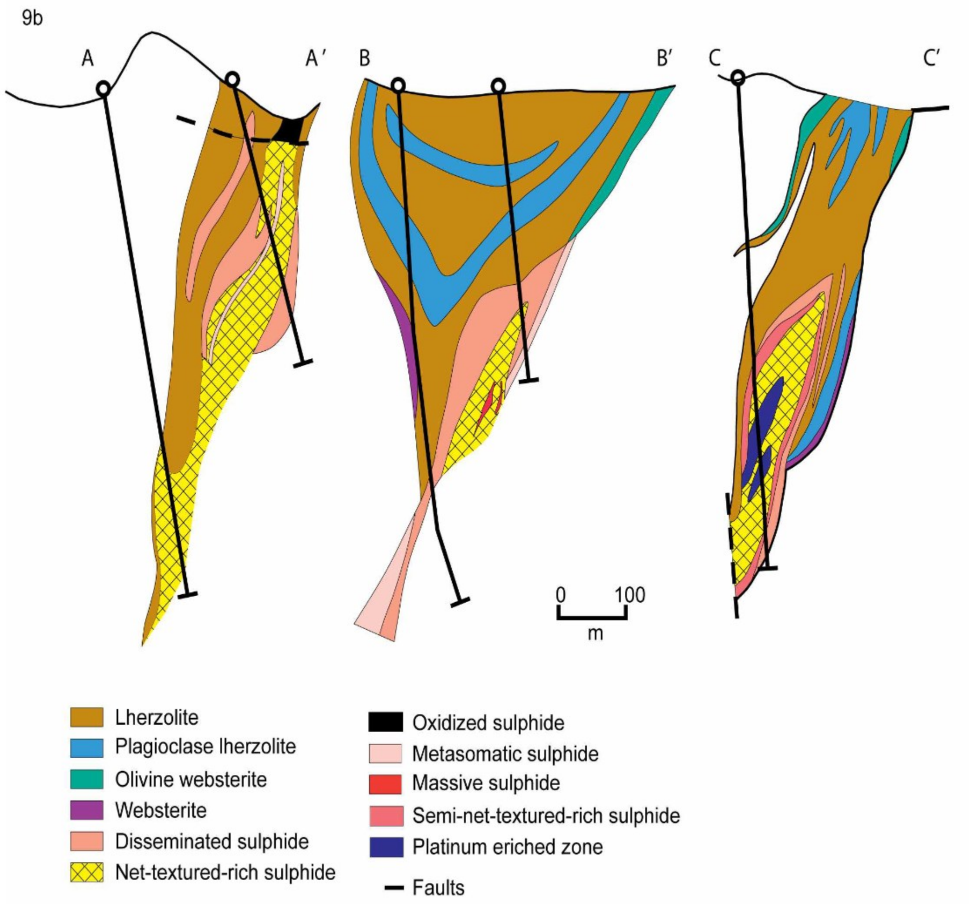
- Constructed models are smooth
- Lack of boundary information for the anomaly
- Problematic for steeply dipping thin structures



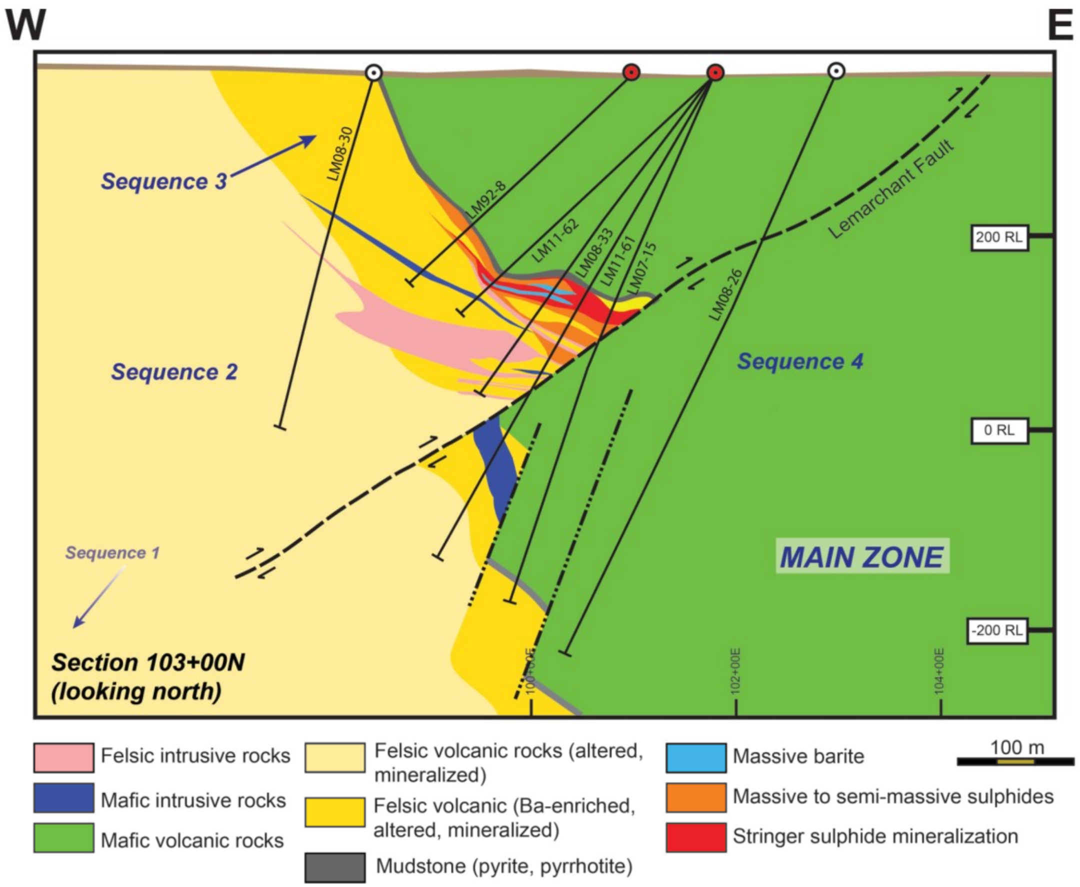


Keller (SEG, 2019)

Thin, steeply dipping ore bodies



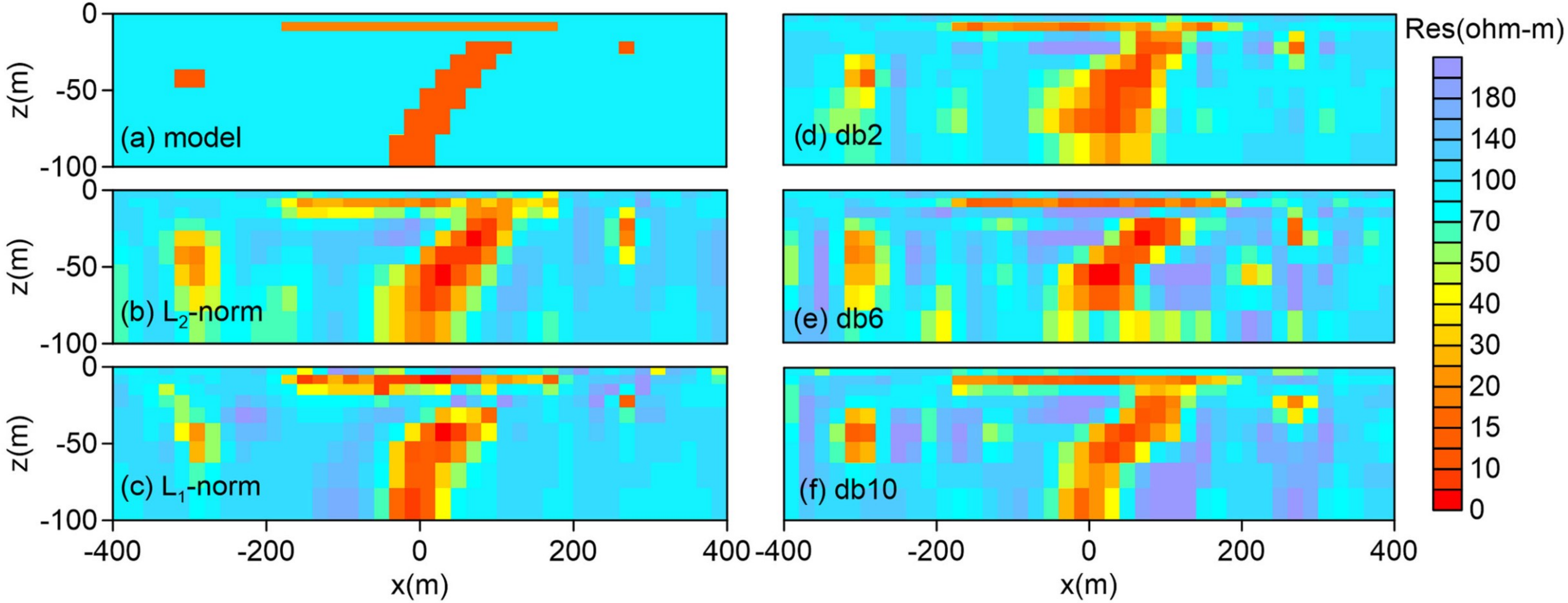
Jinchuan nickel sulphide deposit (Lightfoot, proceedings of Exploration 07)



Lemarchant Zn–Pb–Cu–Ag–Au-rich volcanogenic massive sulphide deposit, Newfoundland, Canada (Lajoie et al., 2018)

Inversion techniques to get sharper boundary

L1-norms and wavelet-based methods



Liu et. al. (GJI, 2015)

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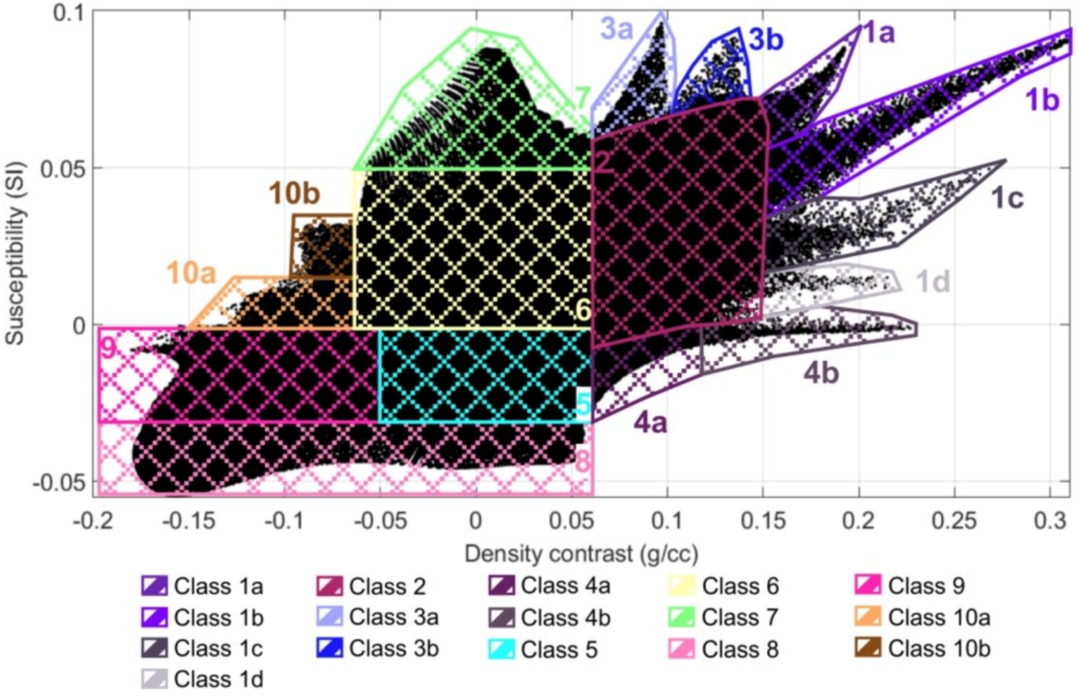
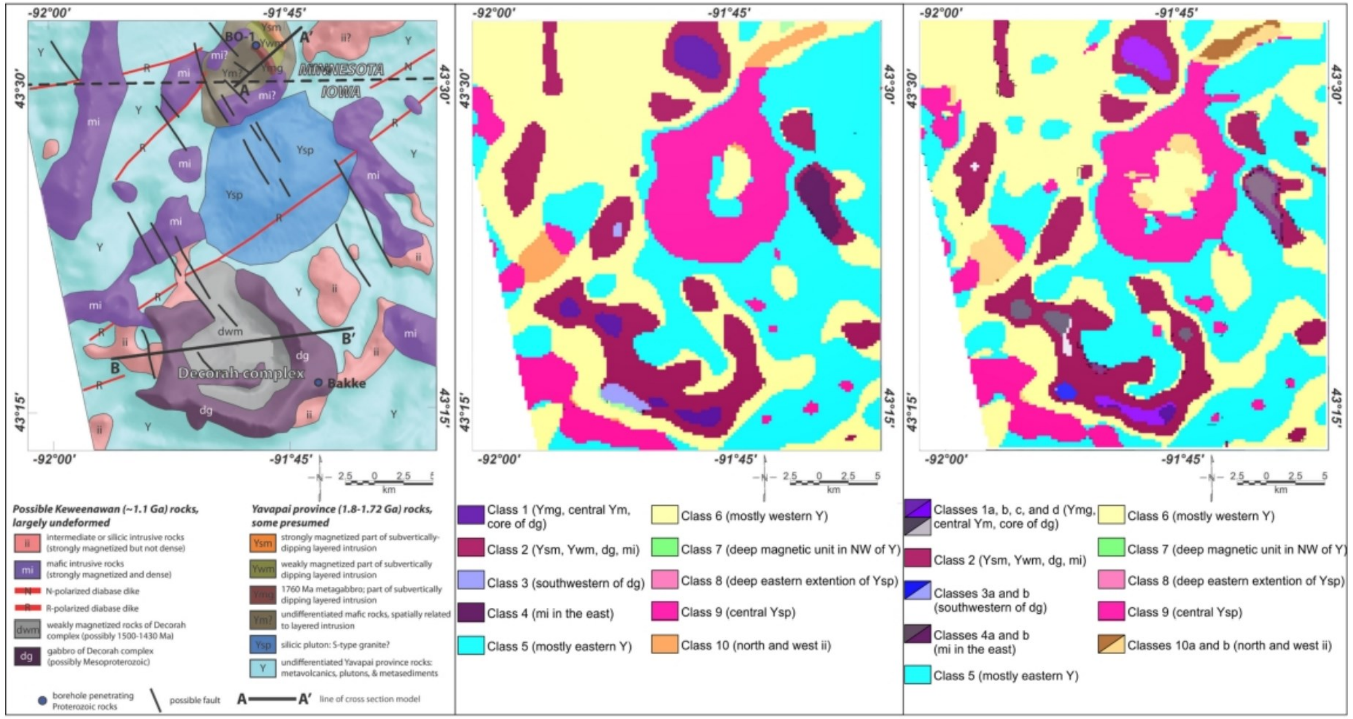
Inversion techniques to get sharper boundary

Clustering

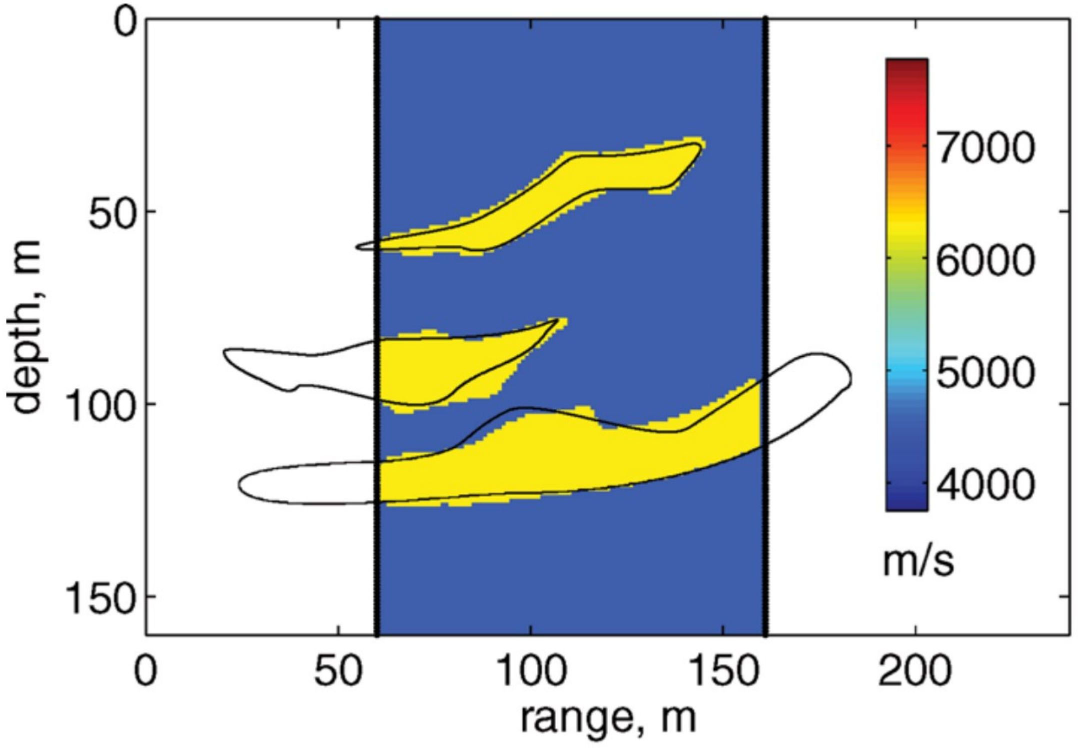




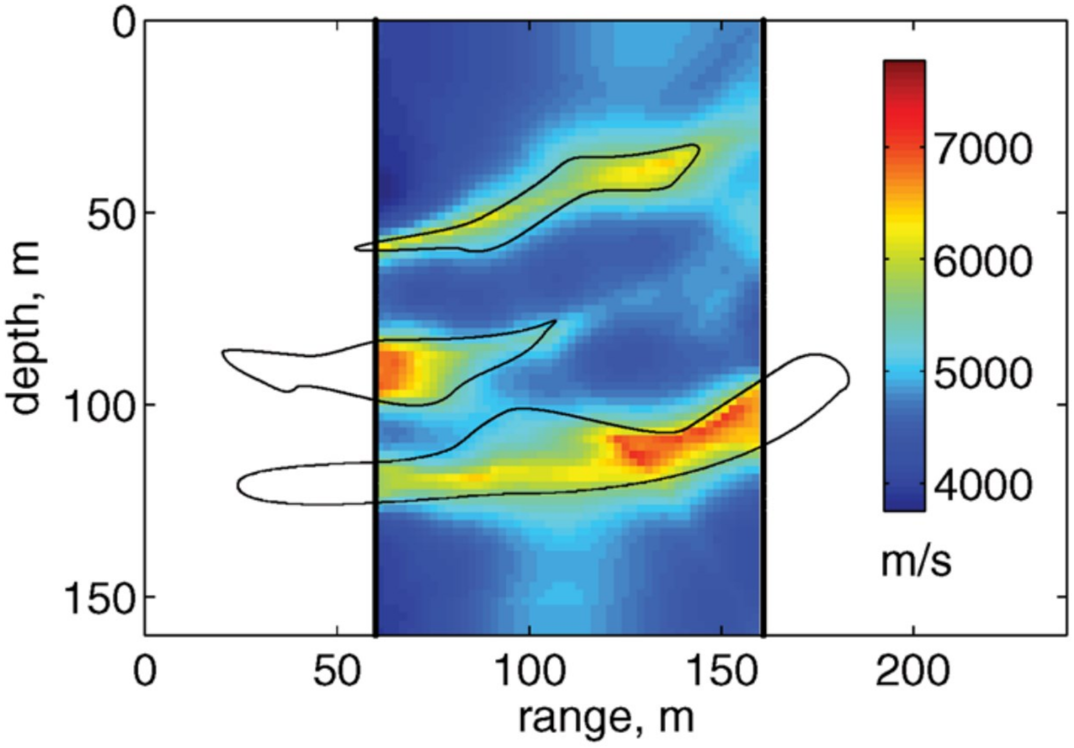
Sun et. al. (Interpretation, 2020)

Inversion techniques to get sharper boundary

- Level-set inversion



Level-set inversion



Minimum-structure inversion

(Zheglova et. al., GJI, 2013)

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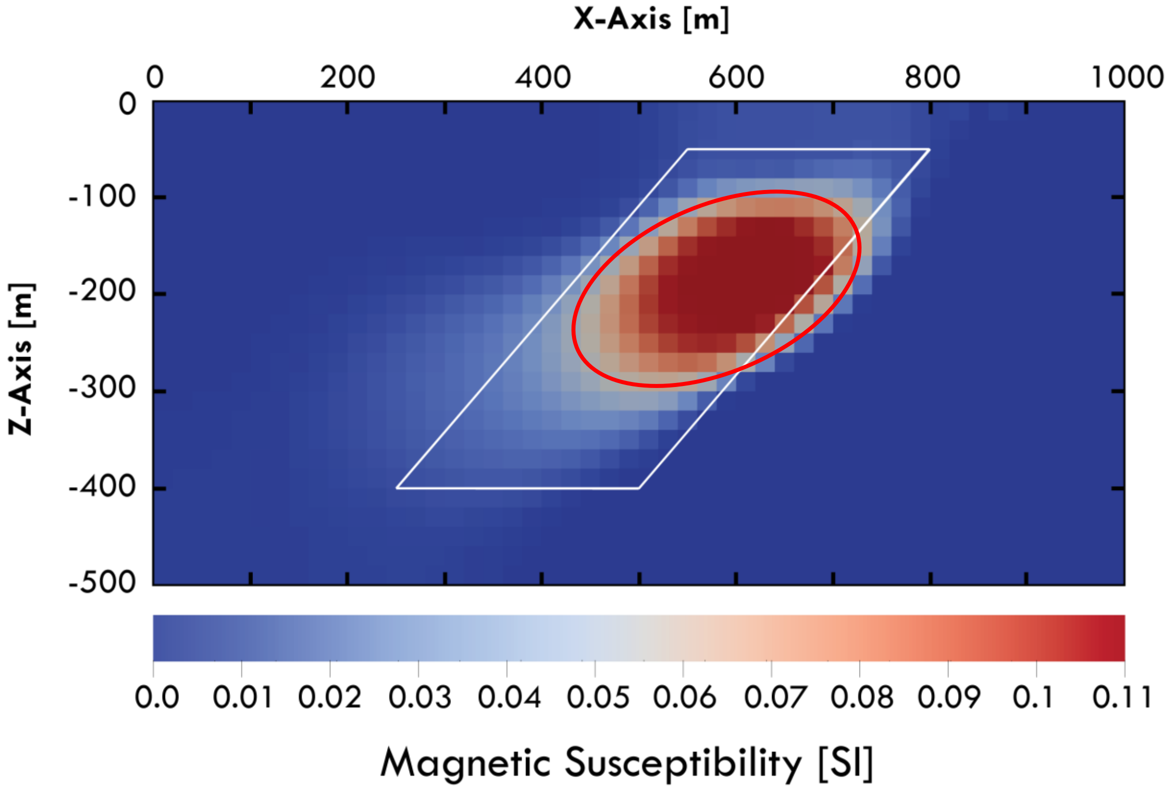
Surface geometry inversion (SGI)

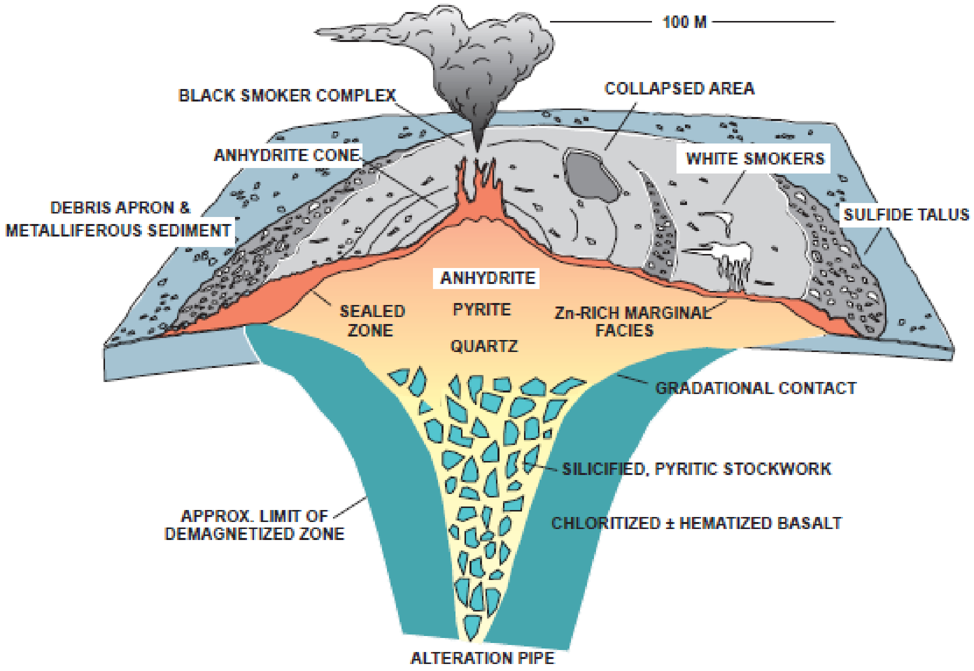
- ➢ Conventional inversion: physical properties inside a cell
- ➢ Boundaries: large physical property gradient



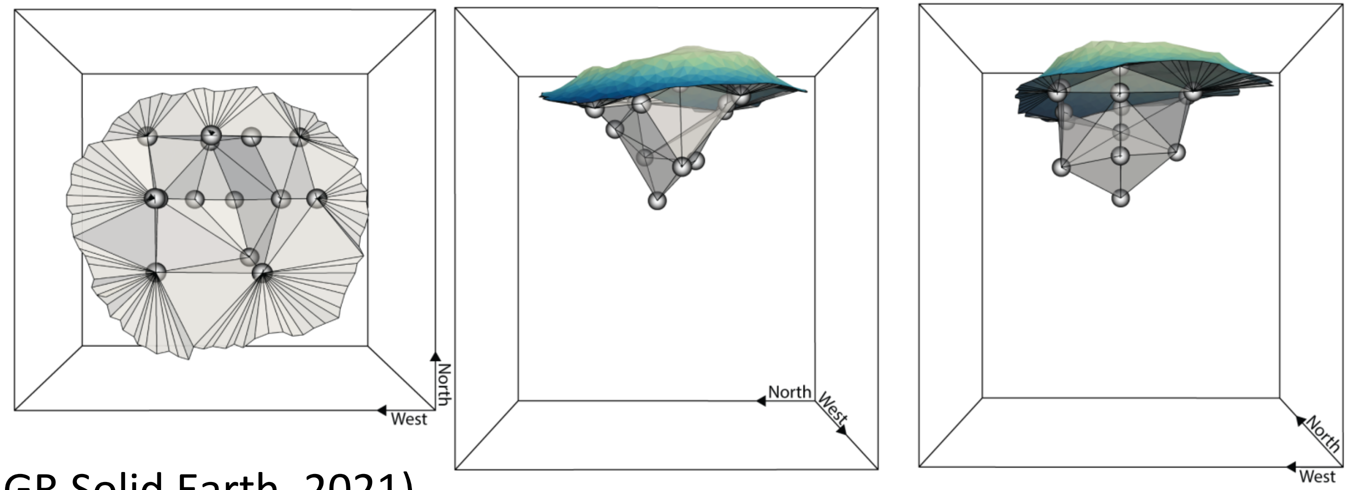
Galley et. al. (Geophysics, 2020)

Surface geometry inversion

- ➢ Conventional inversion: physical properties inside a cell
- ➢ Boundaries: large physical property gradient
- ➢ Surface geometry inversion: nodal coordinates
- ➢ Requires prior information of local geology
  - Anomaly type/shape
  - Typical physical property values
  - Late-stage interpretation



Hannington et al (1995)



Galley et al. (JGR Solid Earth, 2021)

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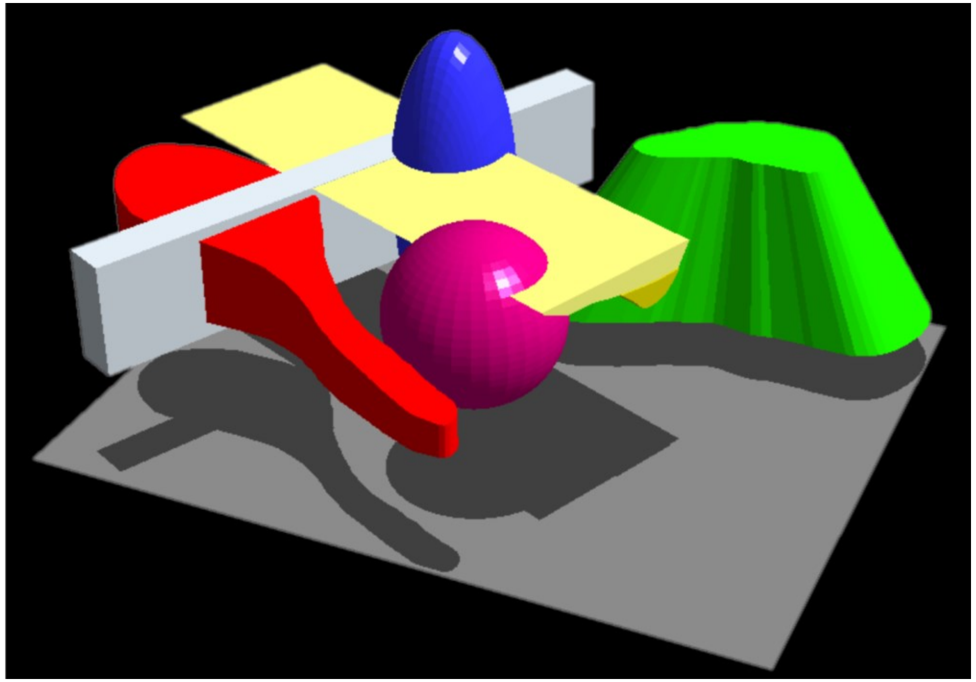
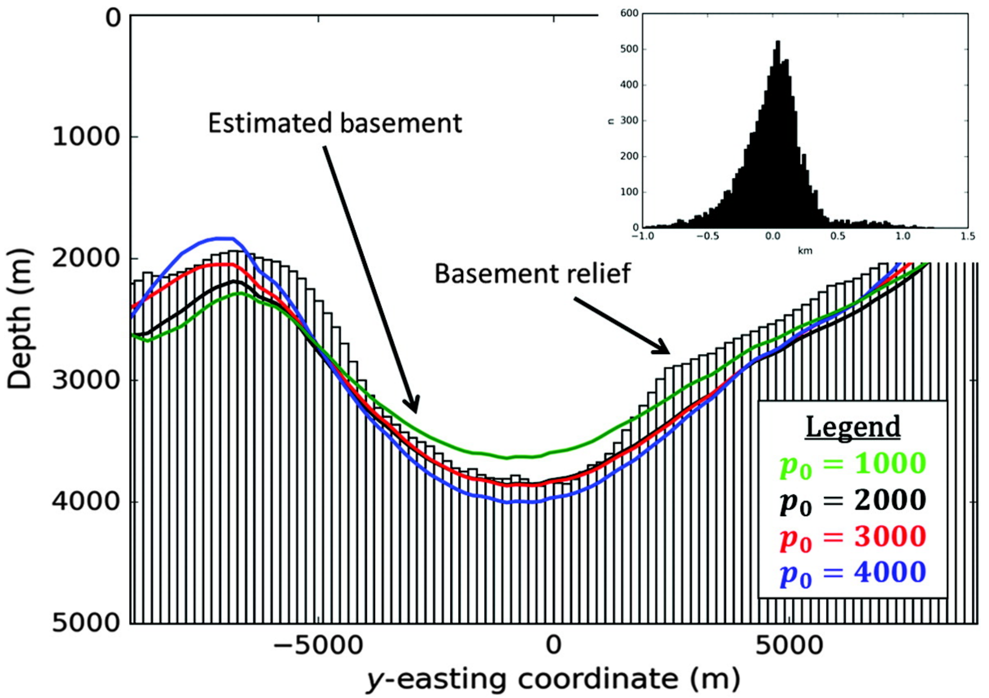
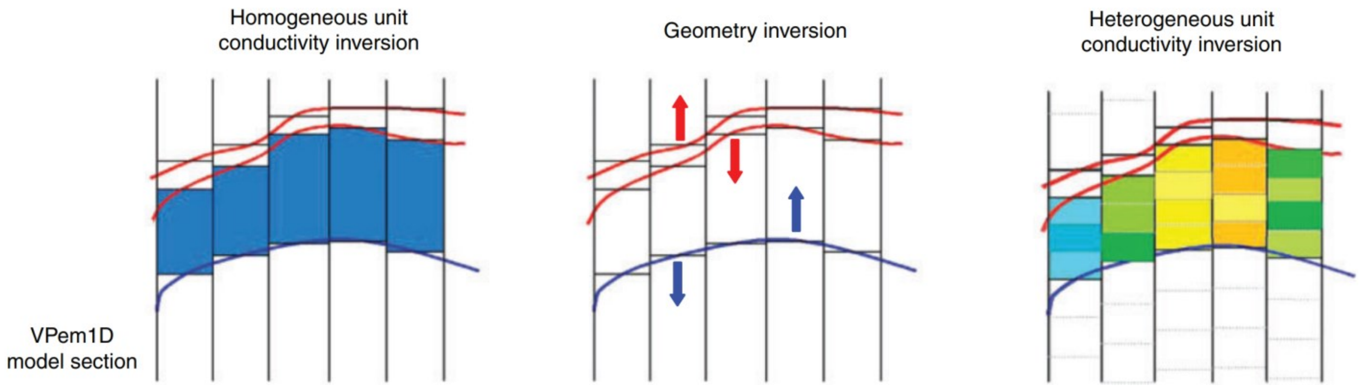
SGI: parametric inversion



Discrete body inversion
(Oldenburg & Pratt, 2007)



Hidalgo-Gato & Barbosa (Geophysics, 2019)



VPem inversion (Fullagar et al, 2015)

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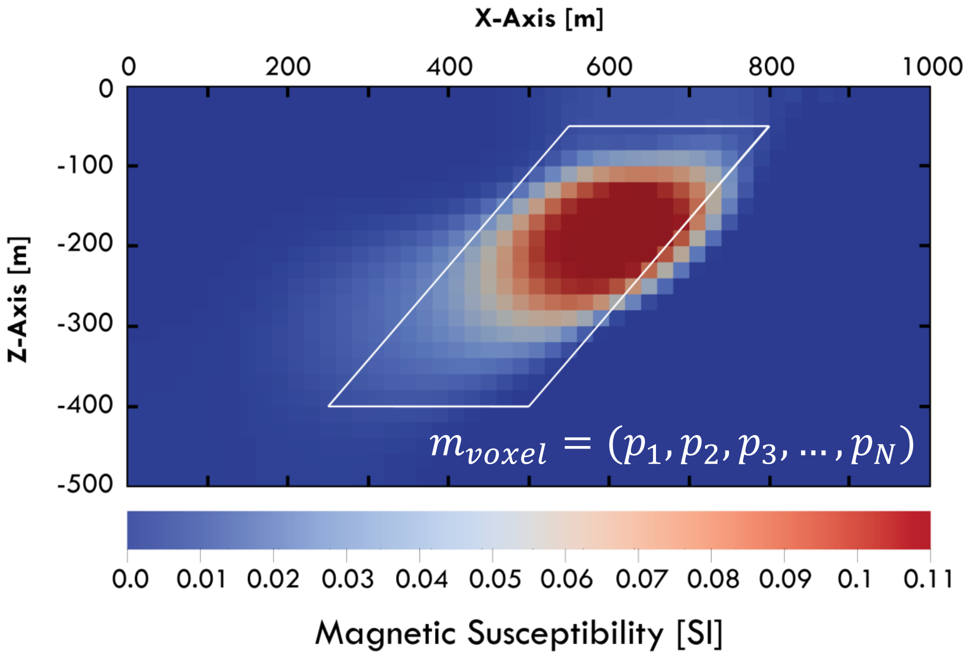
Outline

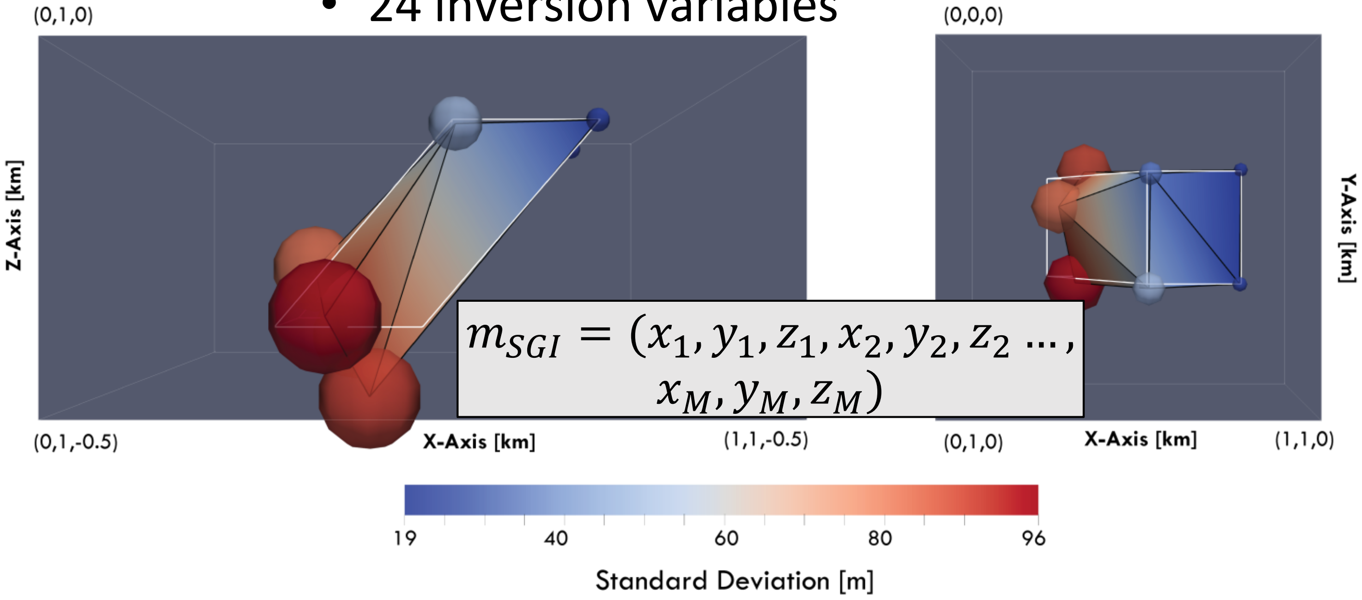
- ➢Motivation
- ➢**Surface geometry inversion**
- ➢Marine CSEM examples
- ➢TEM examples
- ➢Conclusions

Surface geometry inversion

- Minimum-structure magnetic inversion
  - Solves for the scalar effective Mag. Susc. in each cell.
  - 62500 inversion variables



- Surface Geometry Inversion
  - Solves for the geometry of a wireframe model
  - Physical properties can be fixed or inverted
  - 24 inversion variables



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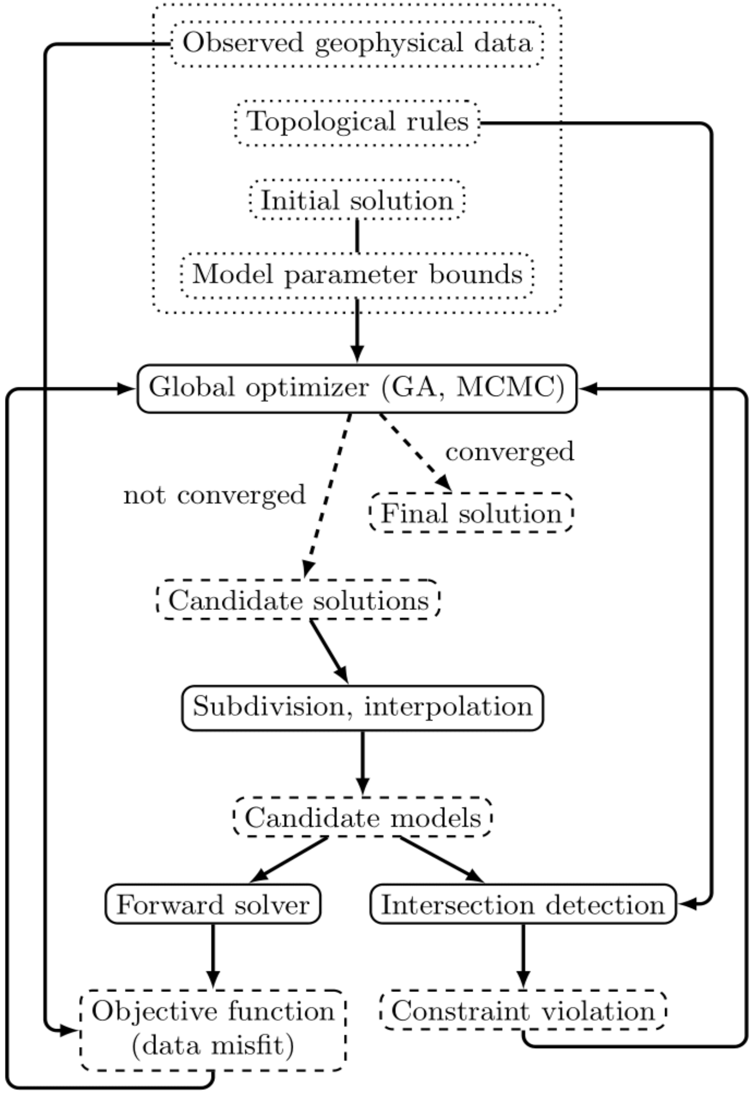
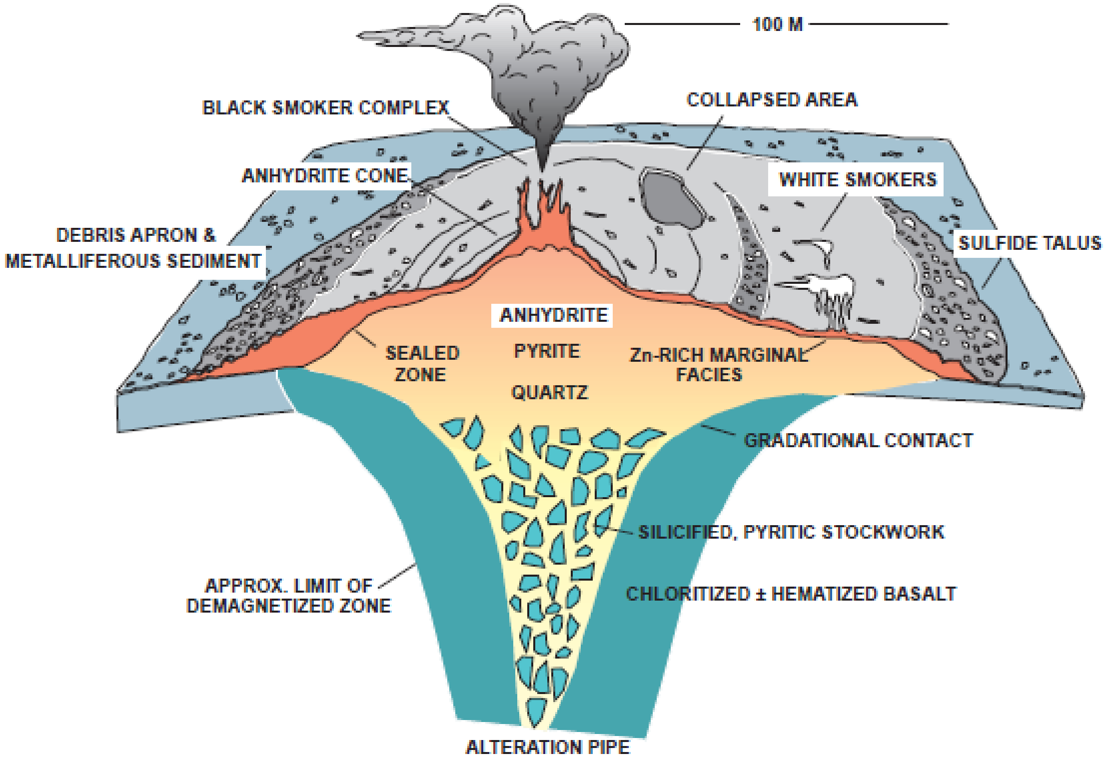
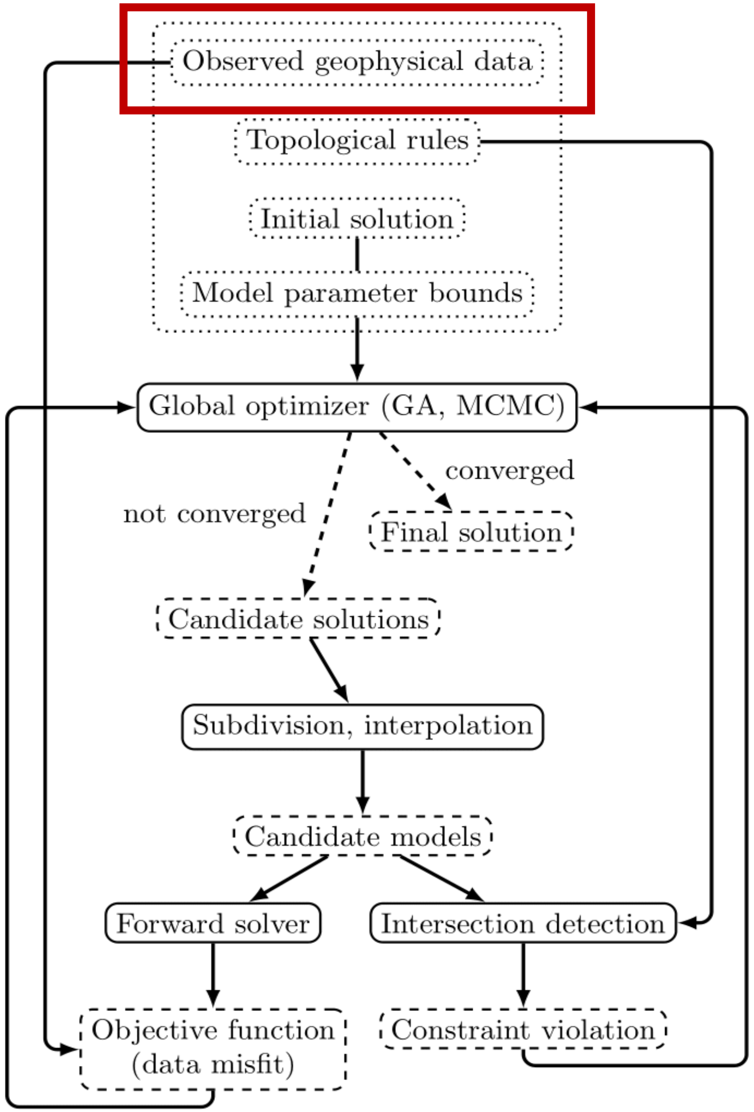
Surface geometry inversion

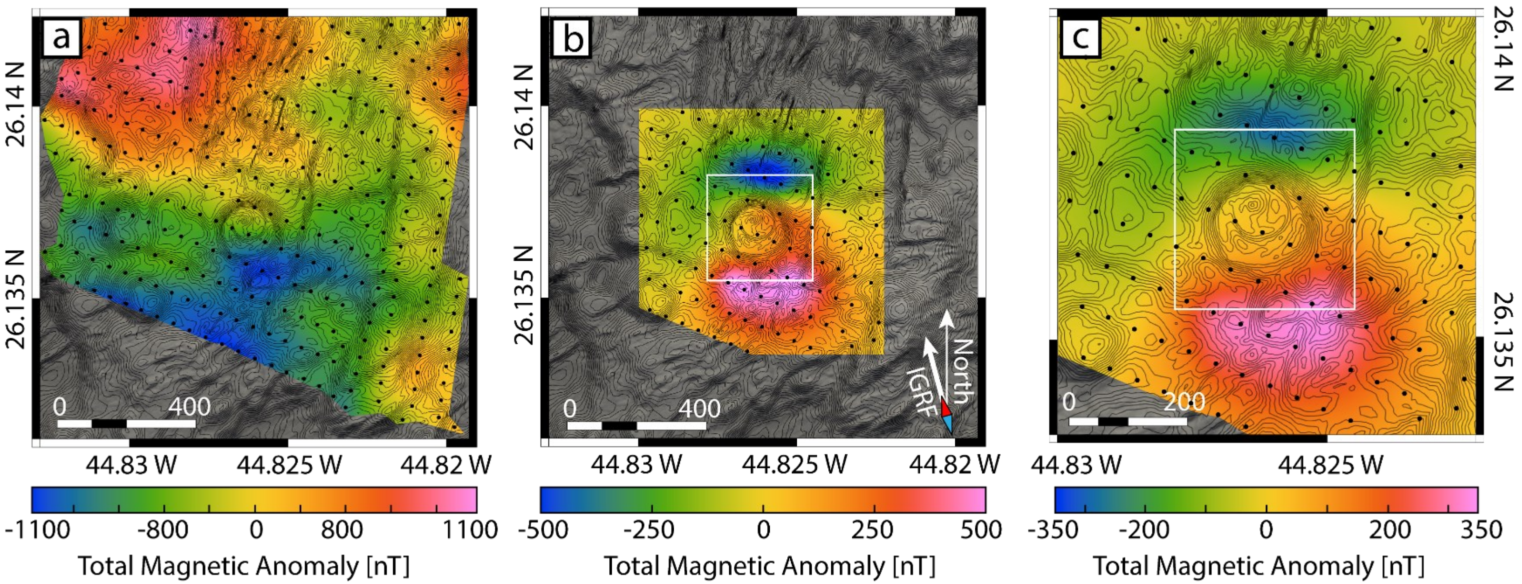




Hannington et al (1995)

Surface geometry inversion





Observed geophysical data

Galley et al. (JGR Solid Earth, 2021)

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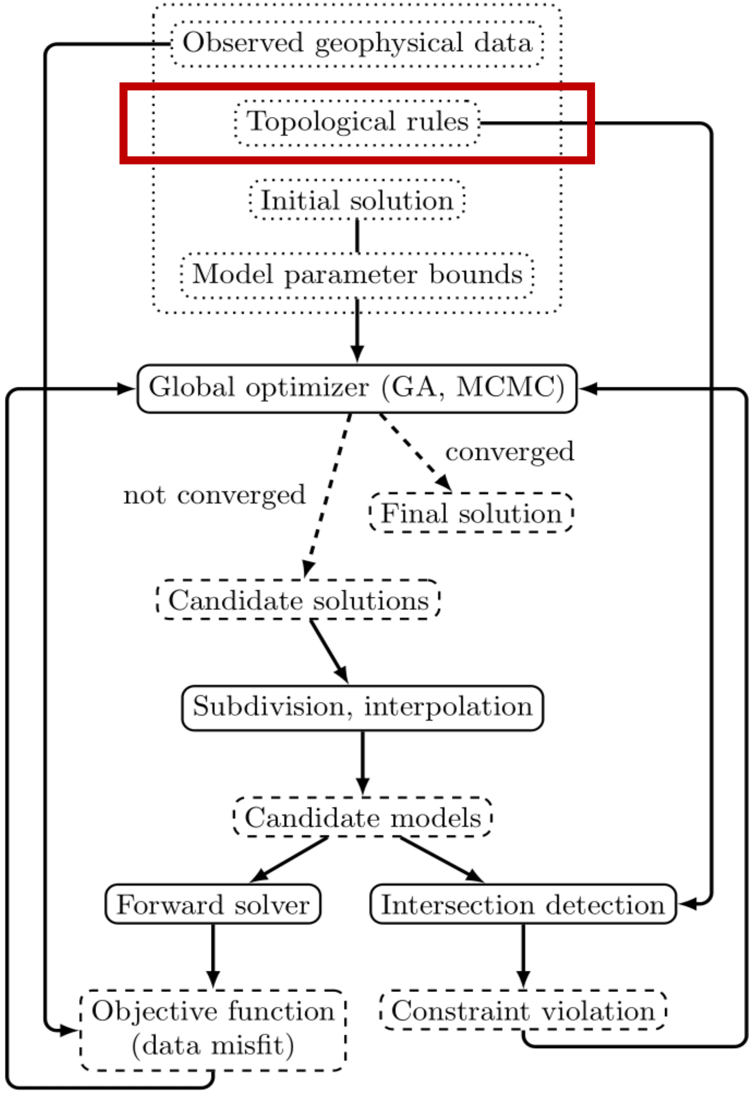
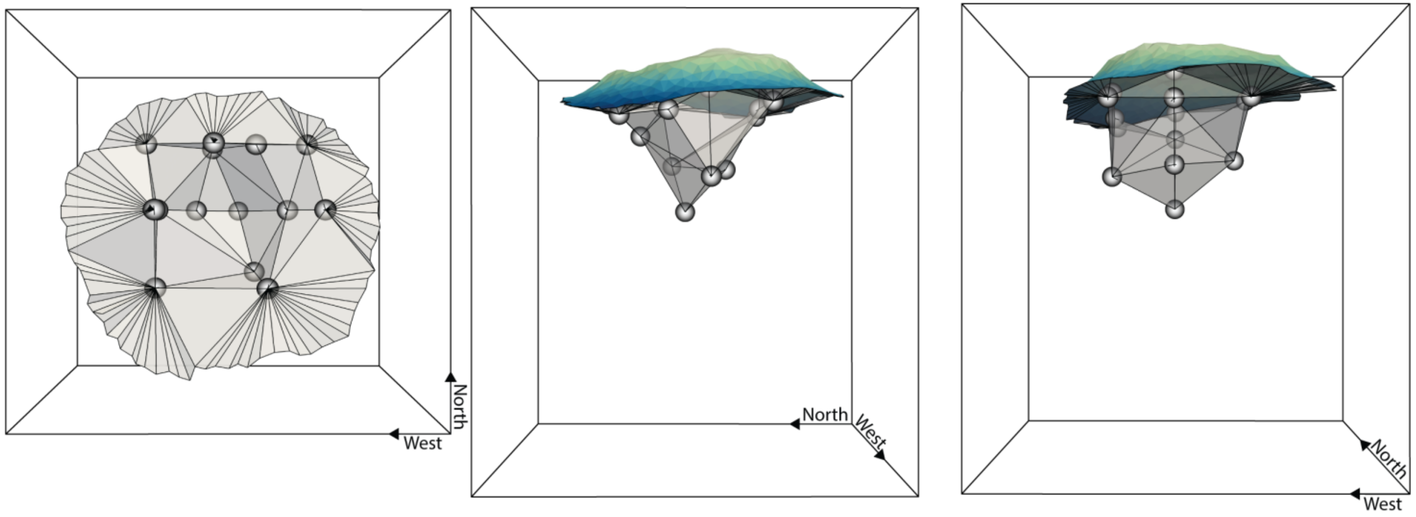
Surface geometry inversion

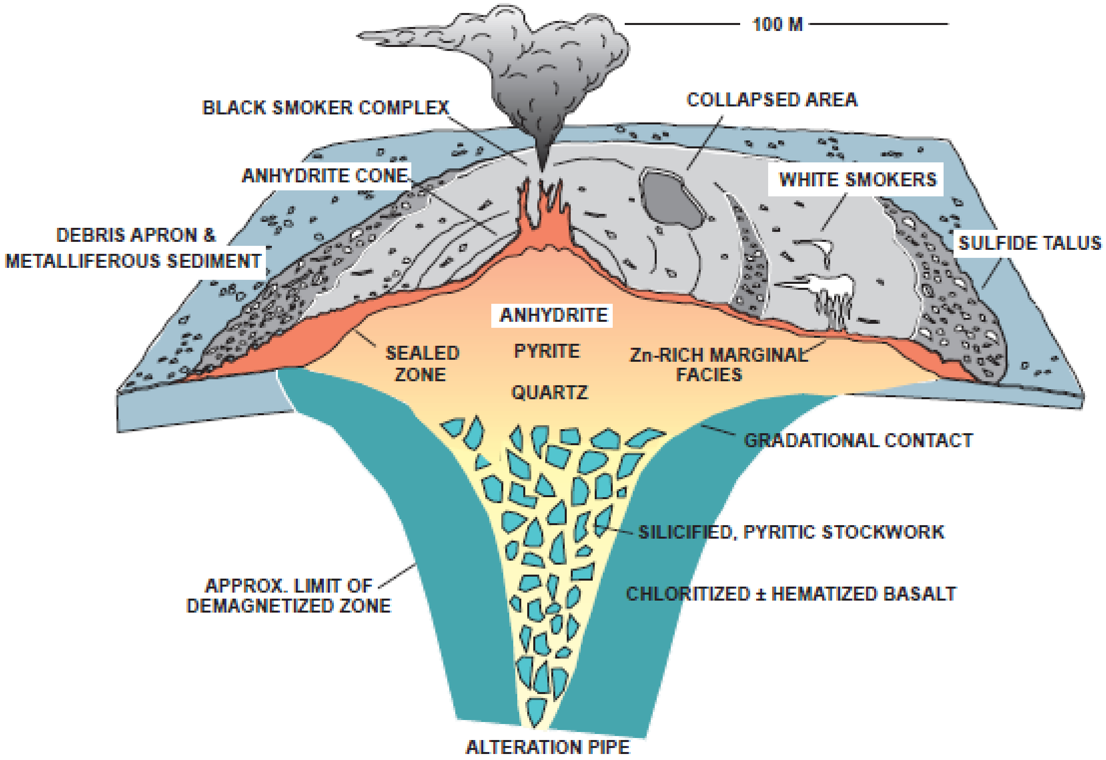




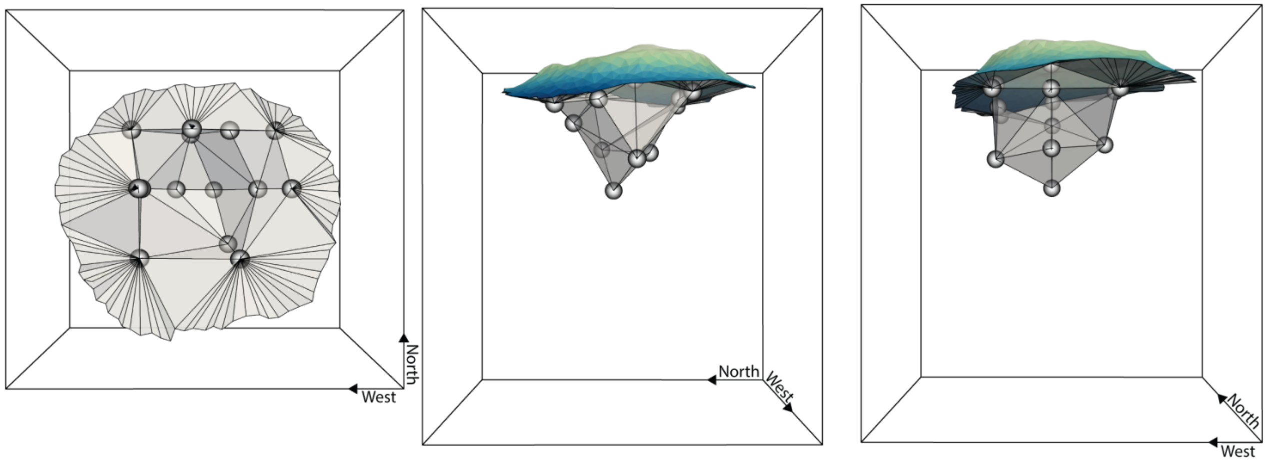
Topological rules

Galley et al. (JGR Solid Earth, 2021)

Block parameterization: blocky models



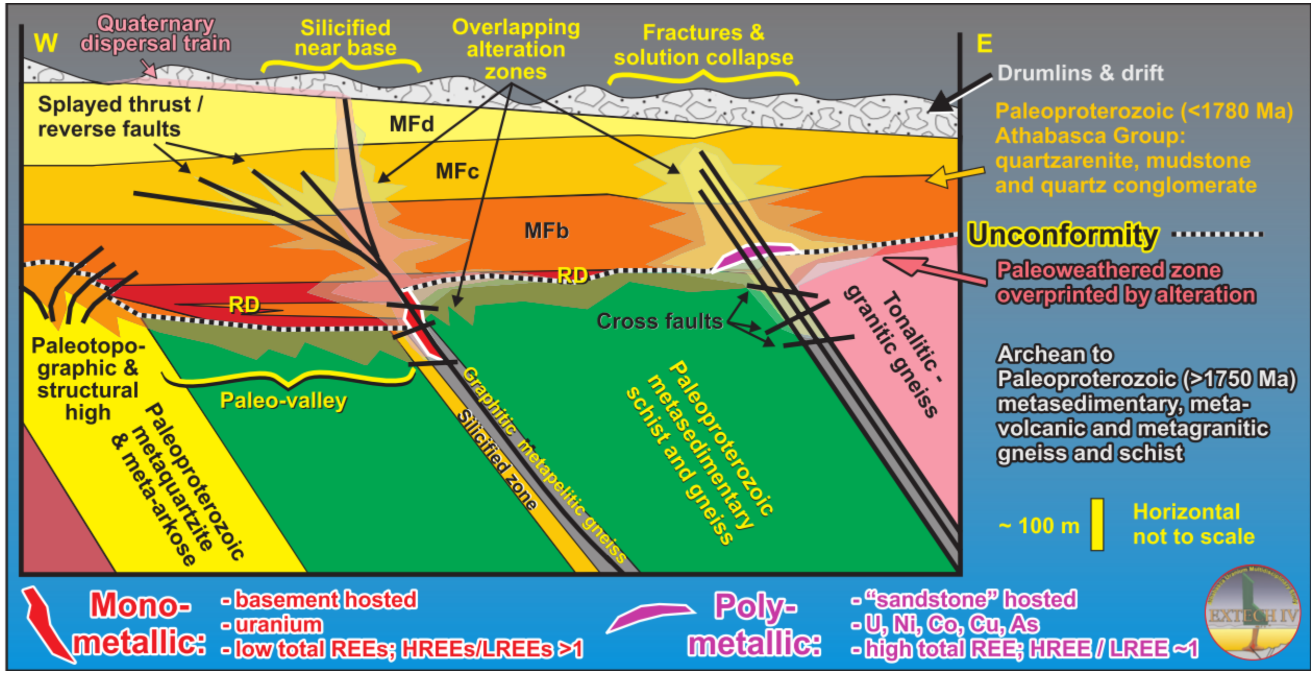
Hannington et al (1995)

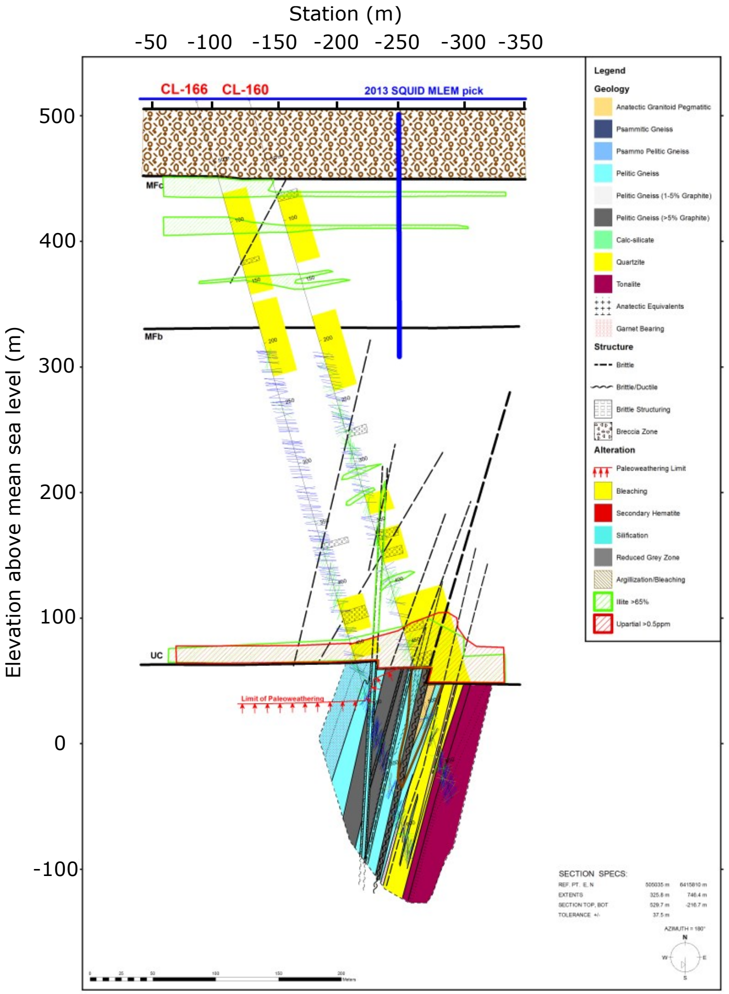


- Connect a small number of nodes into facets
- The facets comprise the wireframe representing the anomaly boundary
- The connections are fixed during the inversion

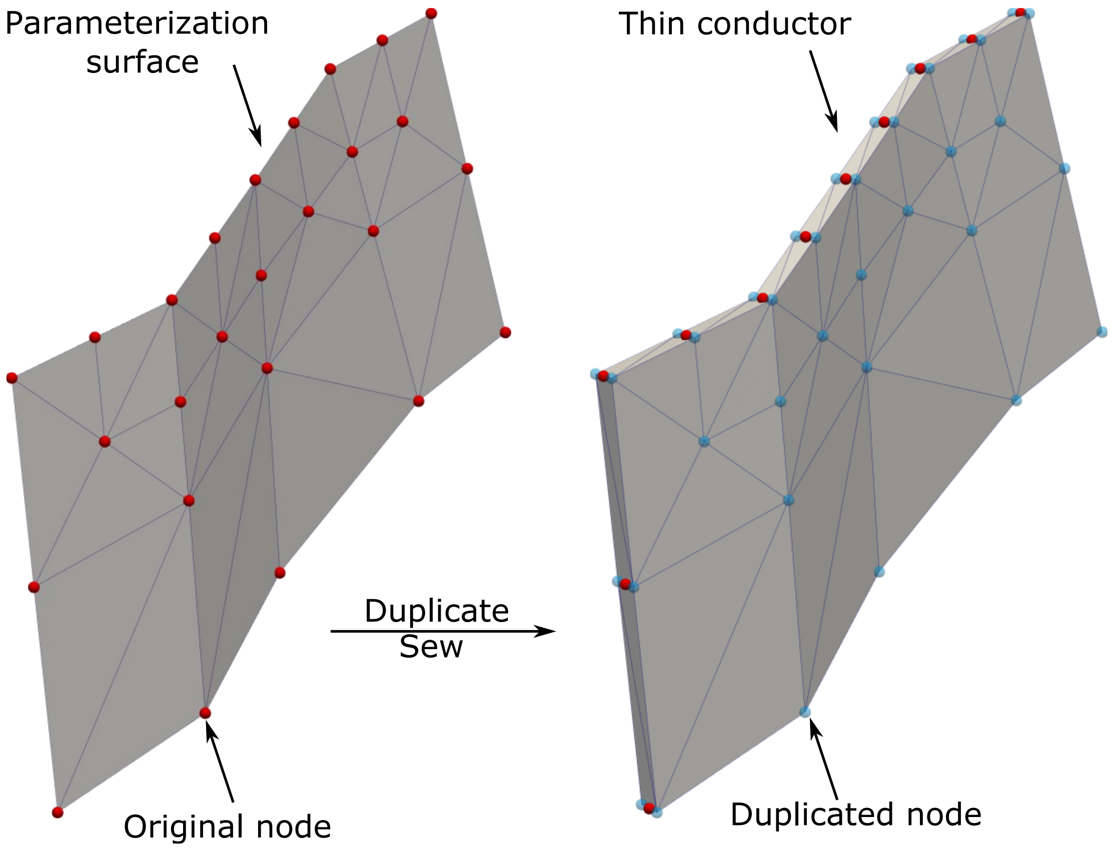
Galley et al. (JGR Solid Earth, 2021)

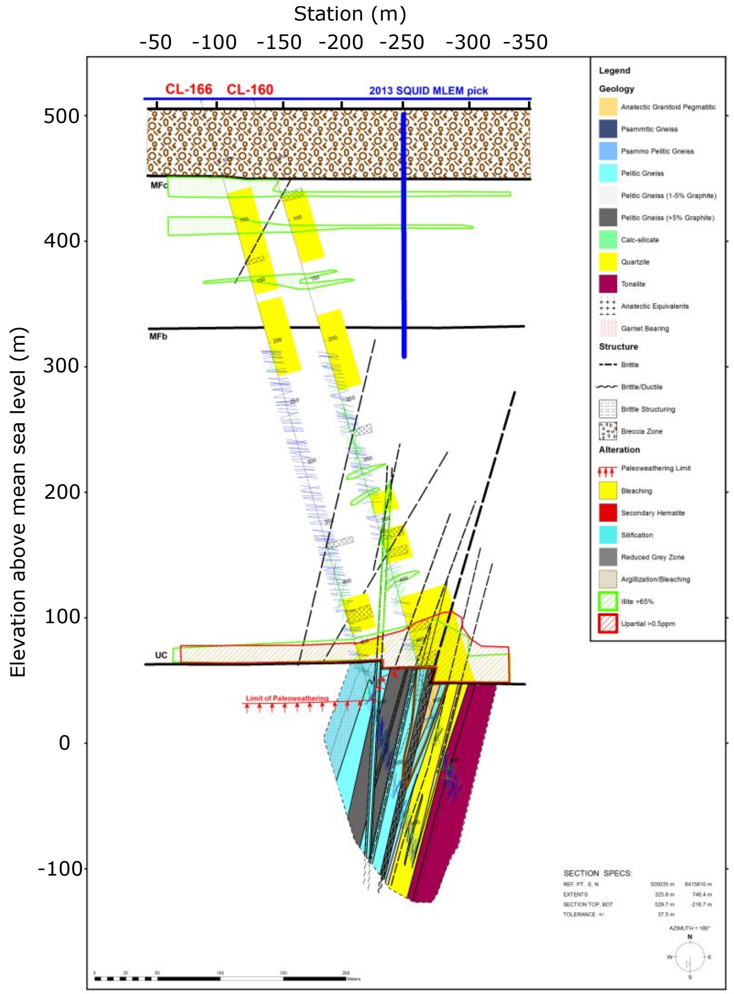
Surface parameterization: thin, plate-like models





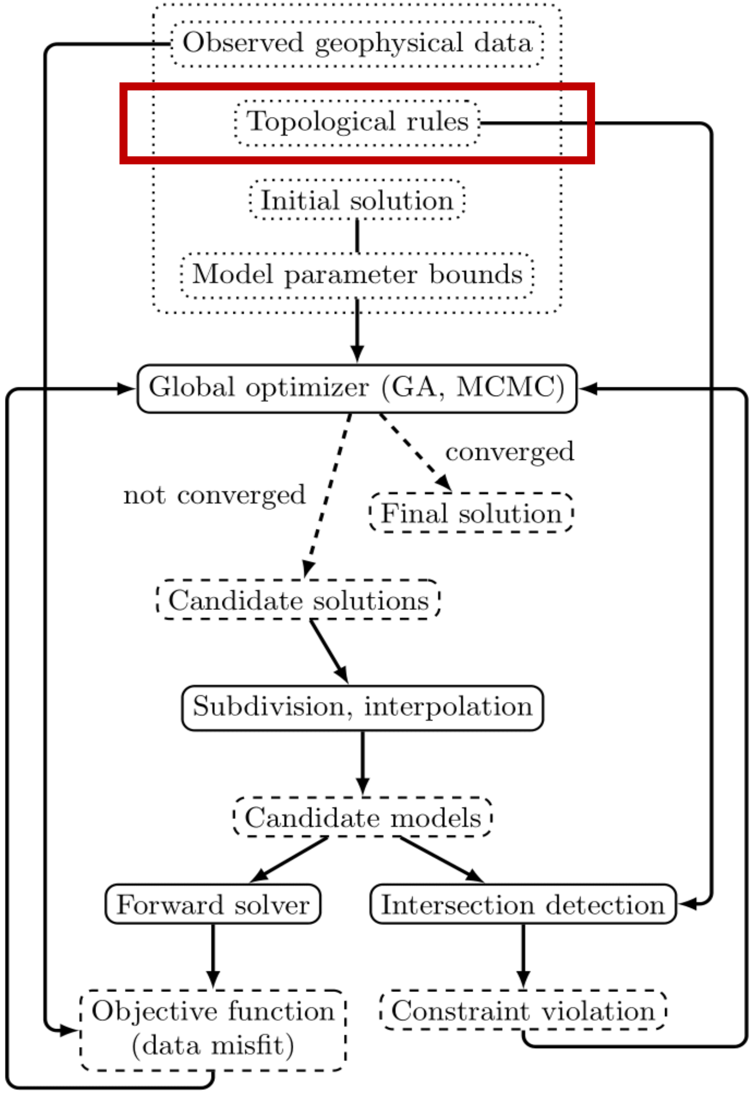
Surface parameterization: thin, plate-like models

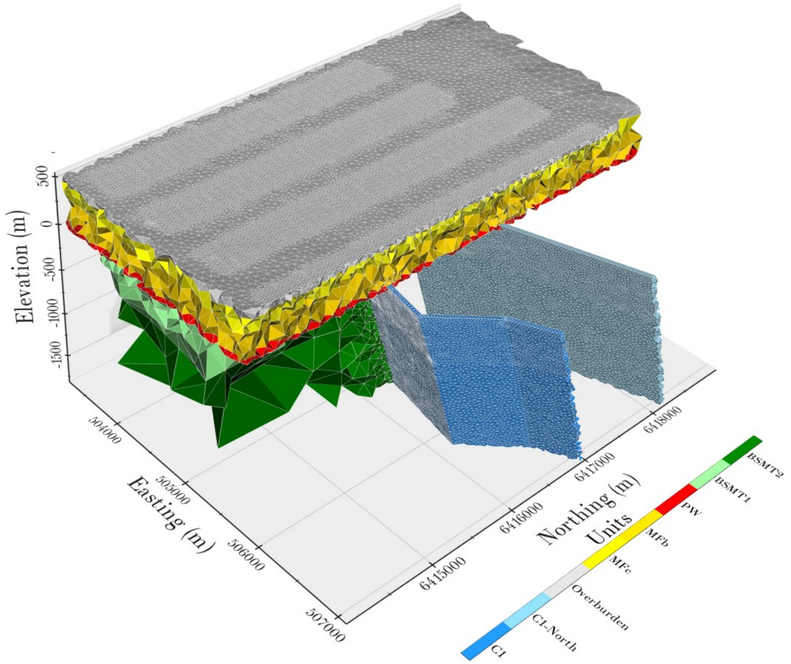




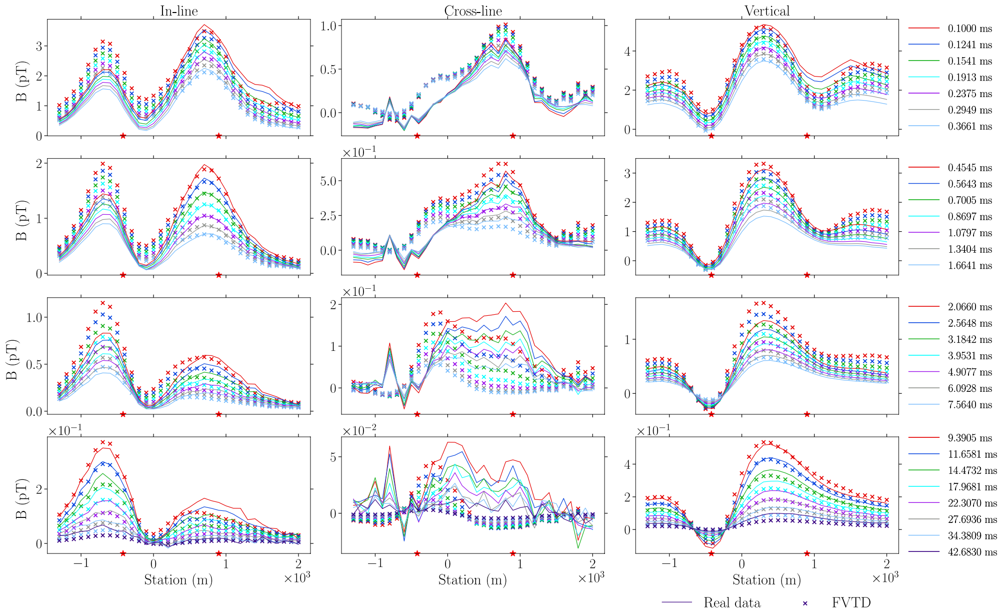
Surface parameterization of thin conductor

Model estimation





Lu et al. (Geophysics, 2021)



Trial-and-error modelling

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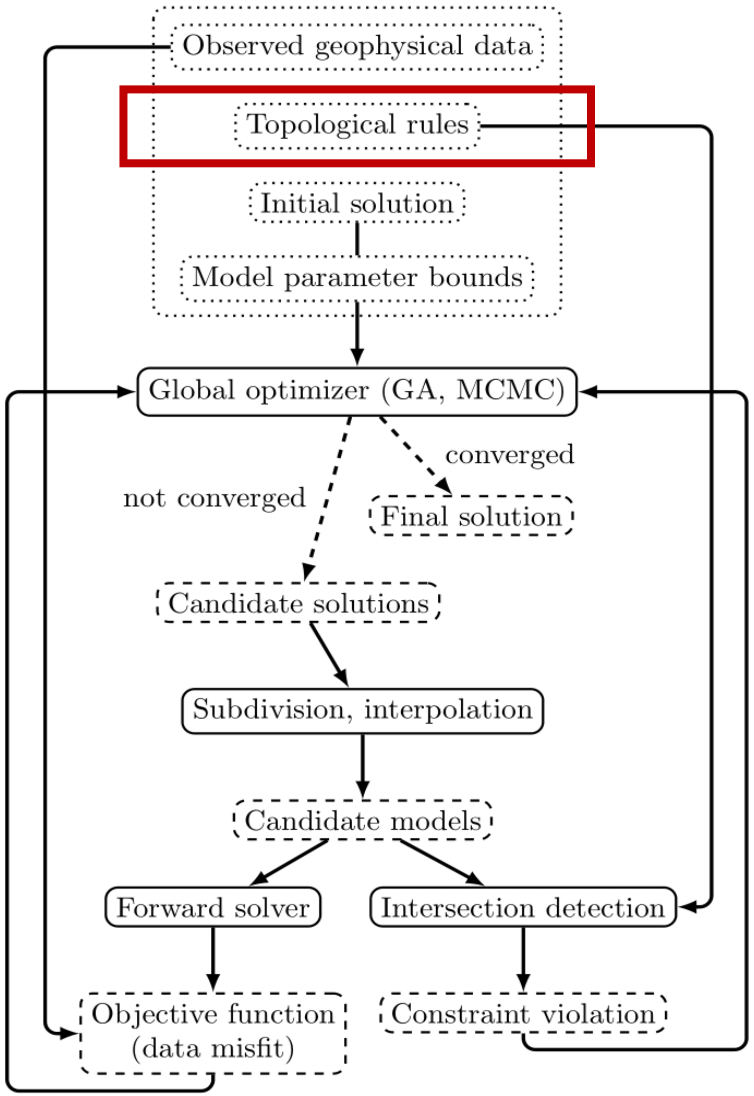
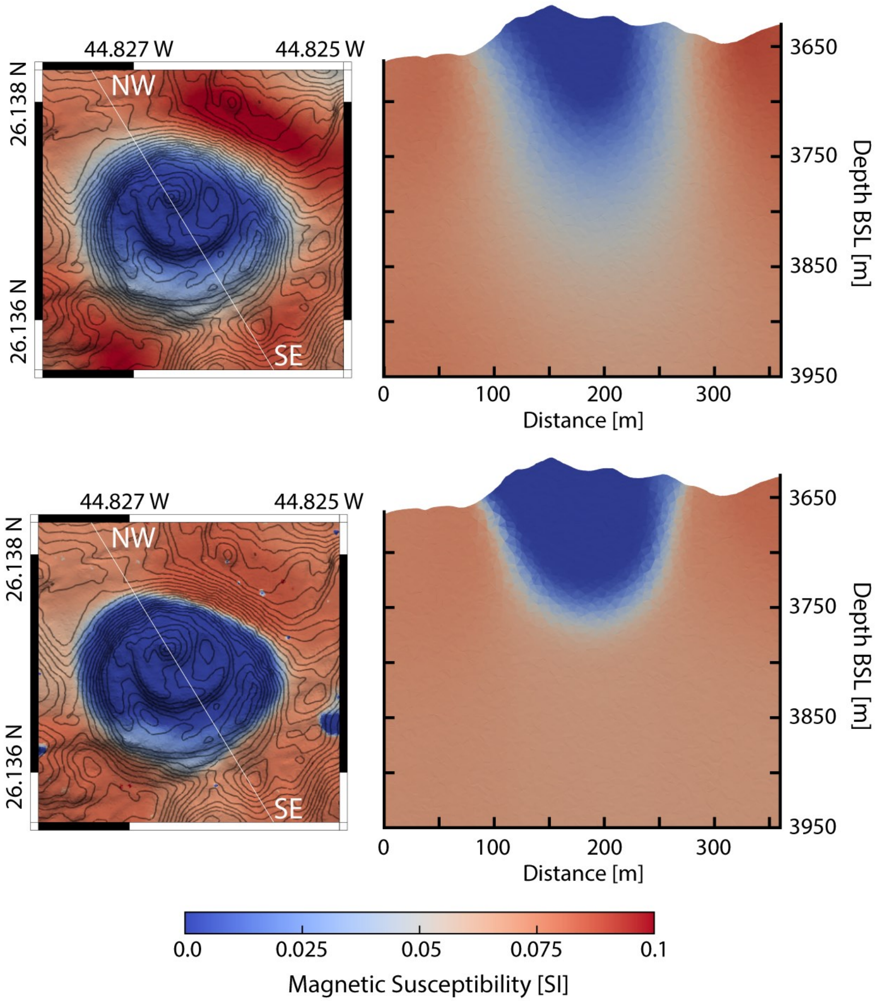
Model estimation





Constructed models from voxel inversion

Galley et al. (JGR Solid Earth, 2021)

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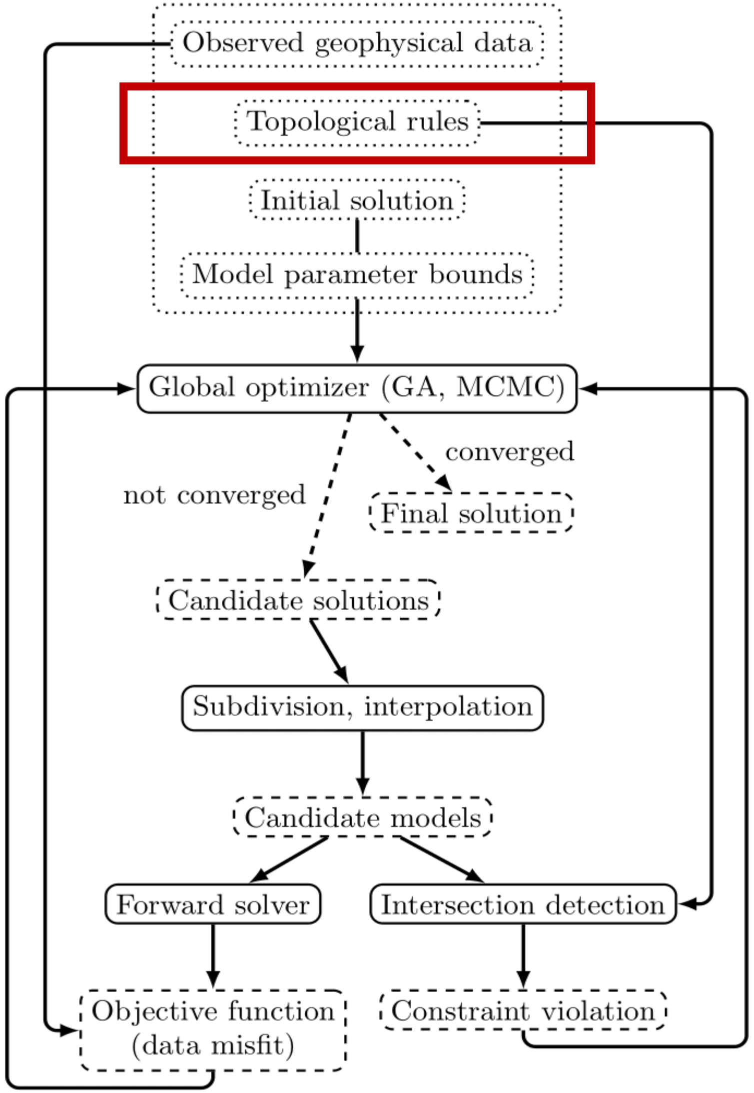
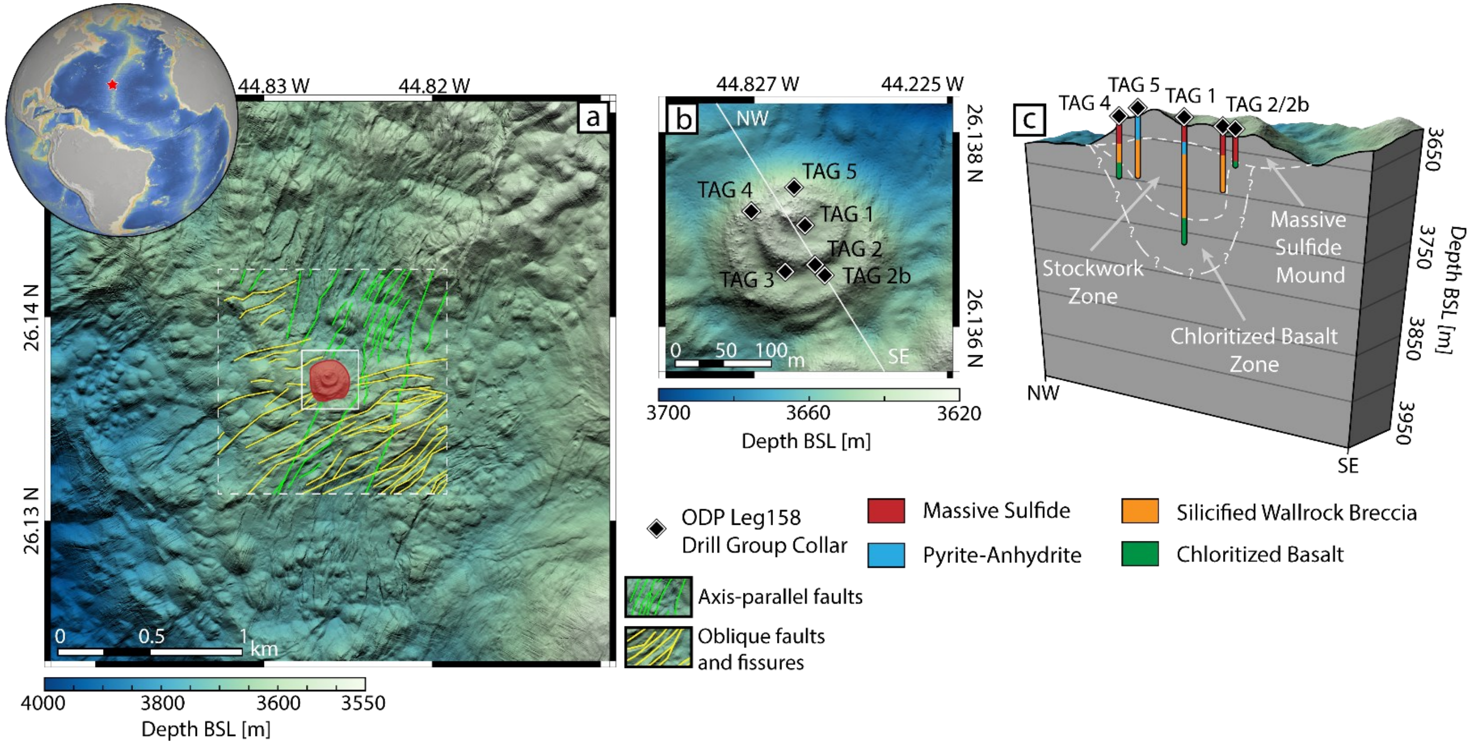
Model estimation





Drilling data

Galley et al. (JGR Solid Earth, 2021)

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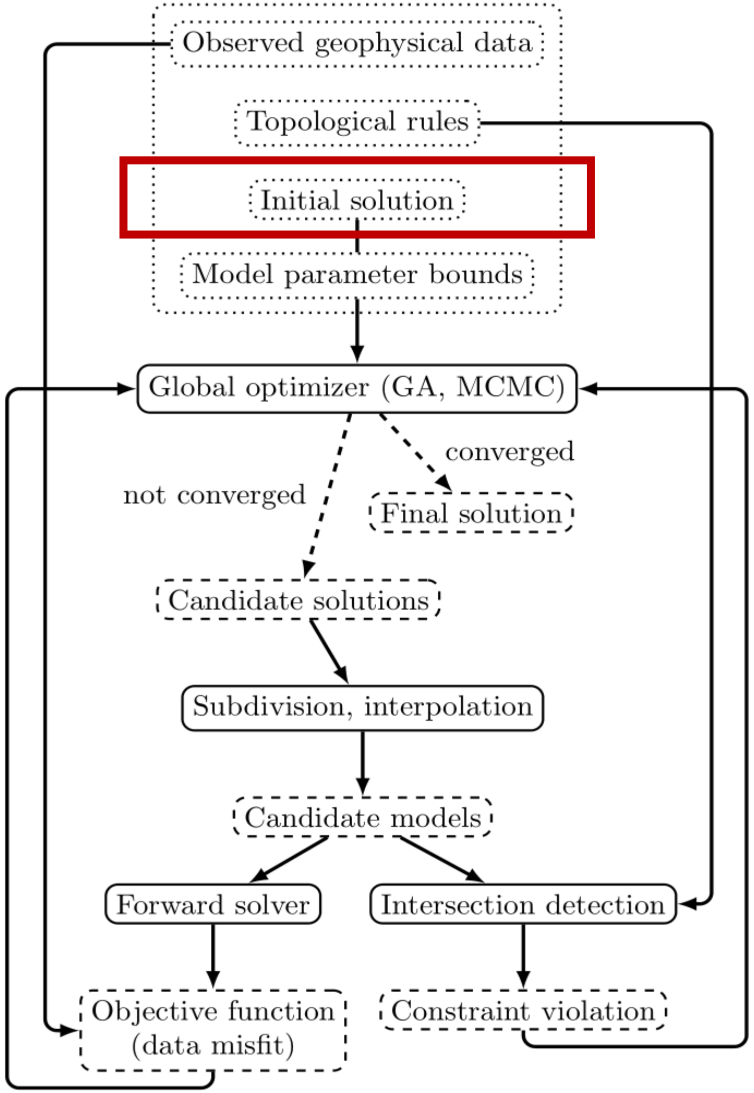
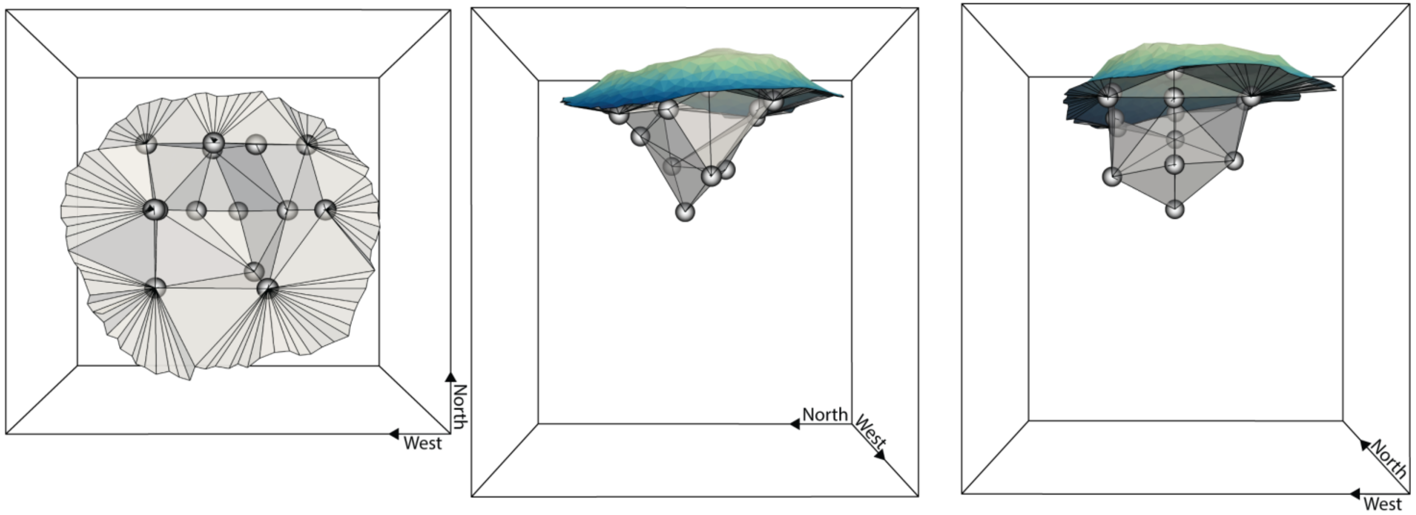
Initial solution

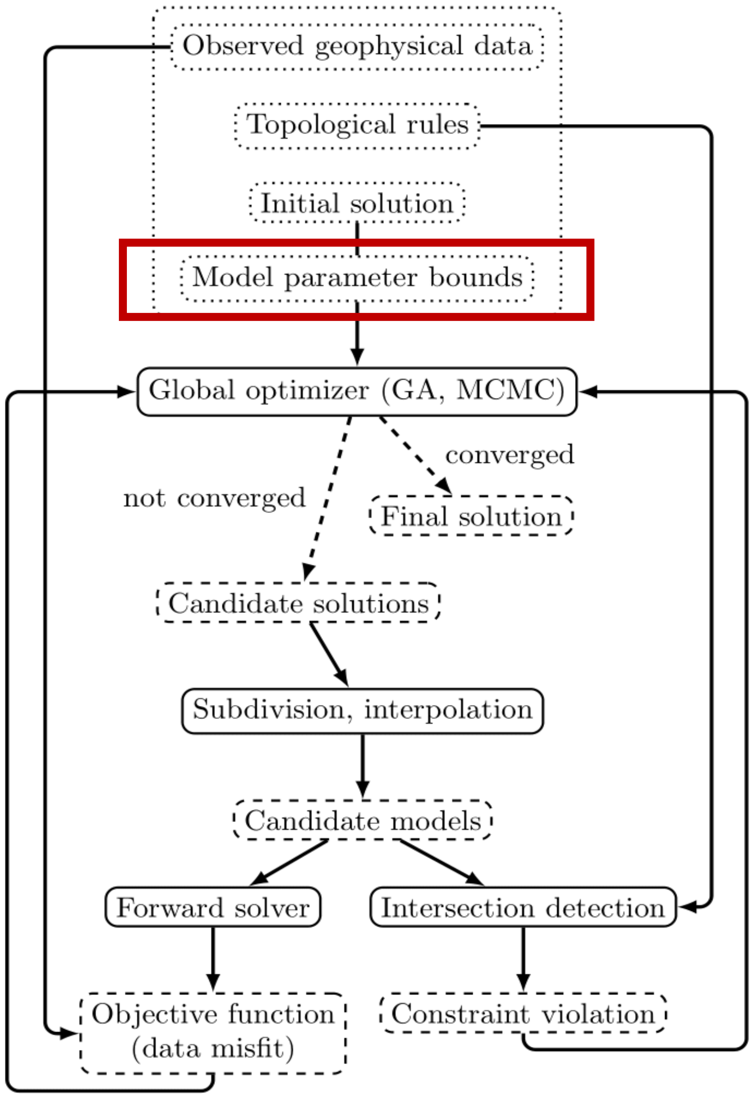


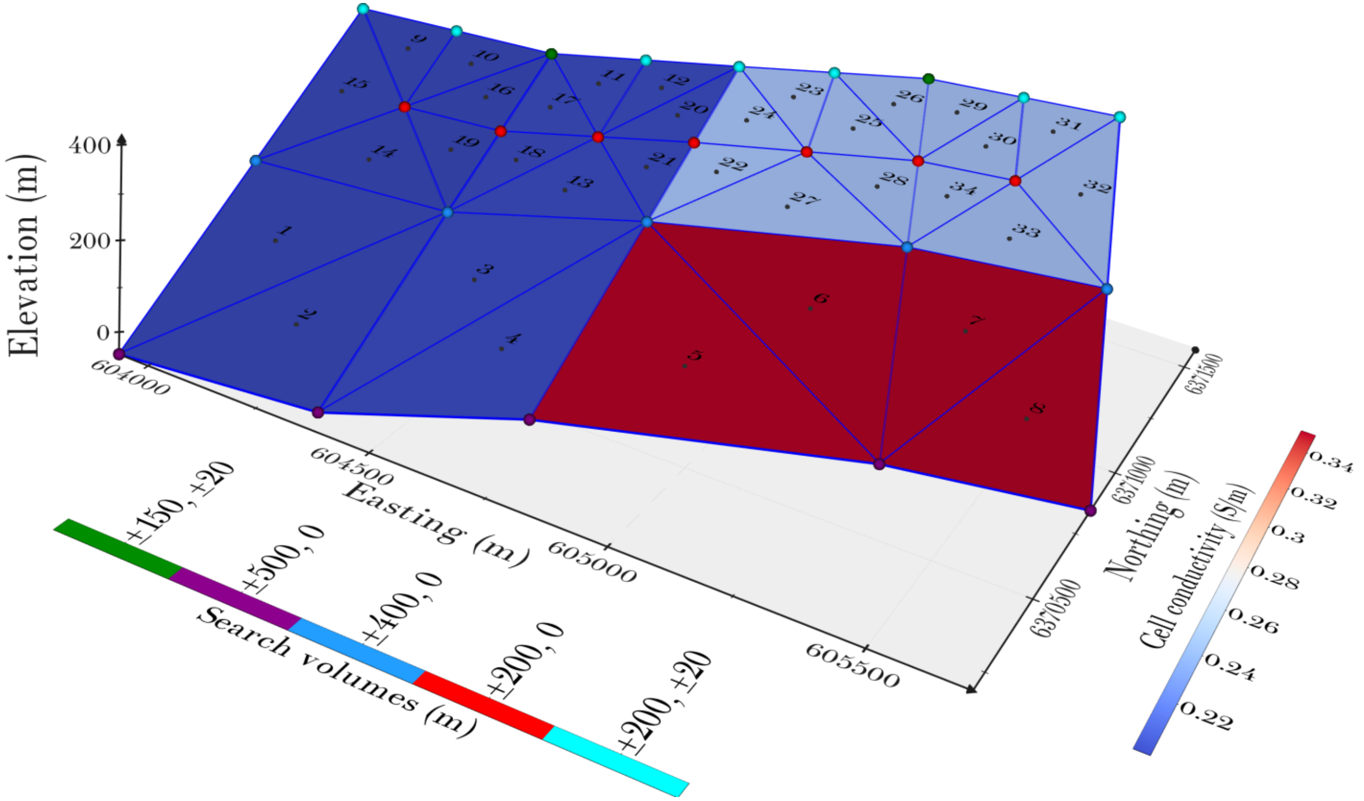


Topological rules

Galley et al. (JGR Solid Earth, 2021)

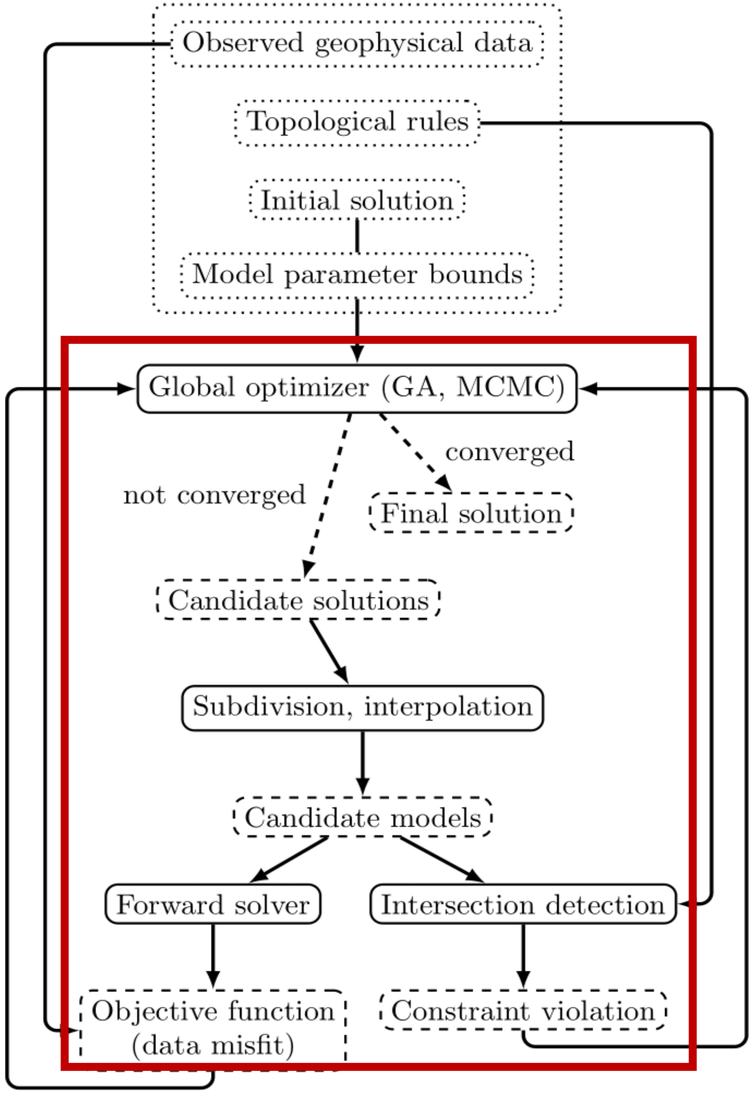
Model parameter bounds (search volumes)





Different nodes have different bounds (search volumes)

Surface geometry inversion



Surface geometry inversion objective function:

$$\phi(\boldsymbol{m}) = \phi_d(\boldsymbol{m}) ~~+ \beta\phi_m(\boldsymbol{m})~~,$$

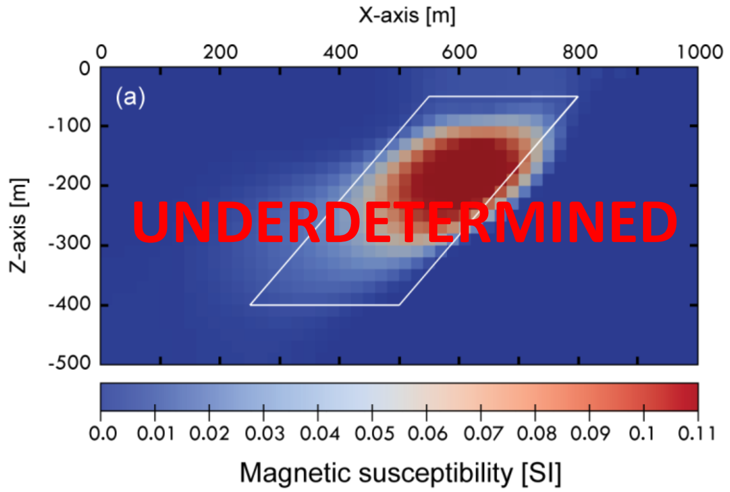
- Data misfit:

$$\phi_d(\boldsymbol{m}) = \| \boldsymbol{W}_d \, [\boldsymbol{d}^{obs} - \boldsymbol{d}(\boldsymbol{m})] \|^2,$$

- ~~Model structure (smoothness):~~

$$~~\phi_m(\boldsymbol{m}) = \sum_k \| \boldsymbol{W}_k(\boldsymbol{m} - \boldsymbol{m}^{ref}) \|^2.~~$$

Global optimization with genetic algorithm (GA)

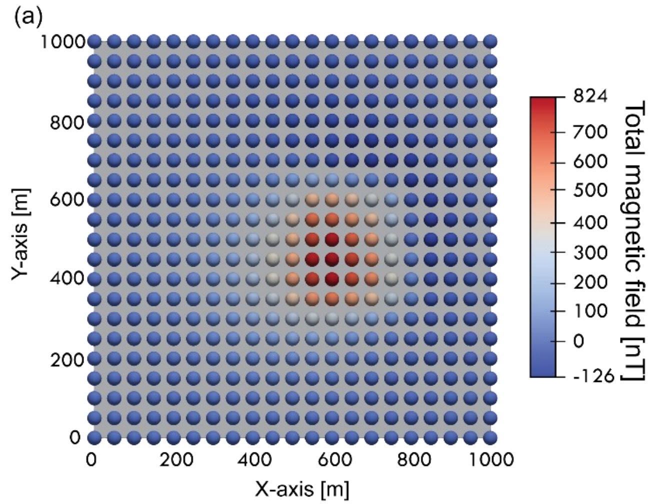


$$\mathbf{m} = (\chi_1, \chi_2, ..., \chi_M)$$

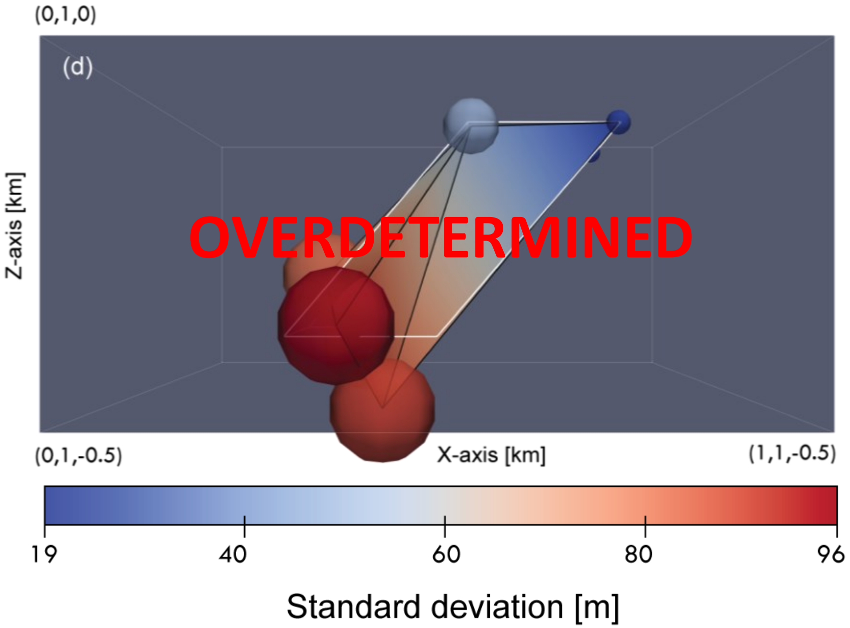
50x50x25 cells

→ 62,500 cells

Requires Regularization



400 data points



$$\mathbf{m} = (x_1, y_1, z_1, x_2, y_2, z_2, ..., x_M, y_M, z_M)$$

8 vertices

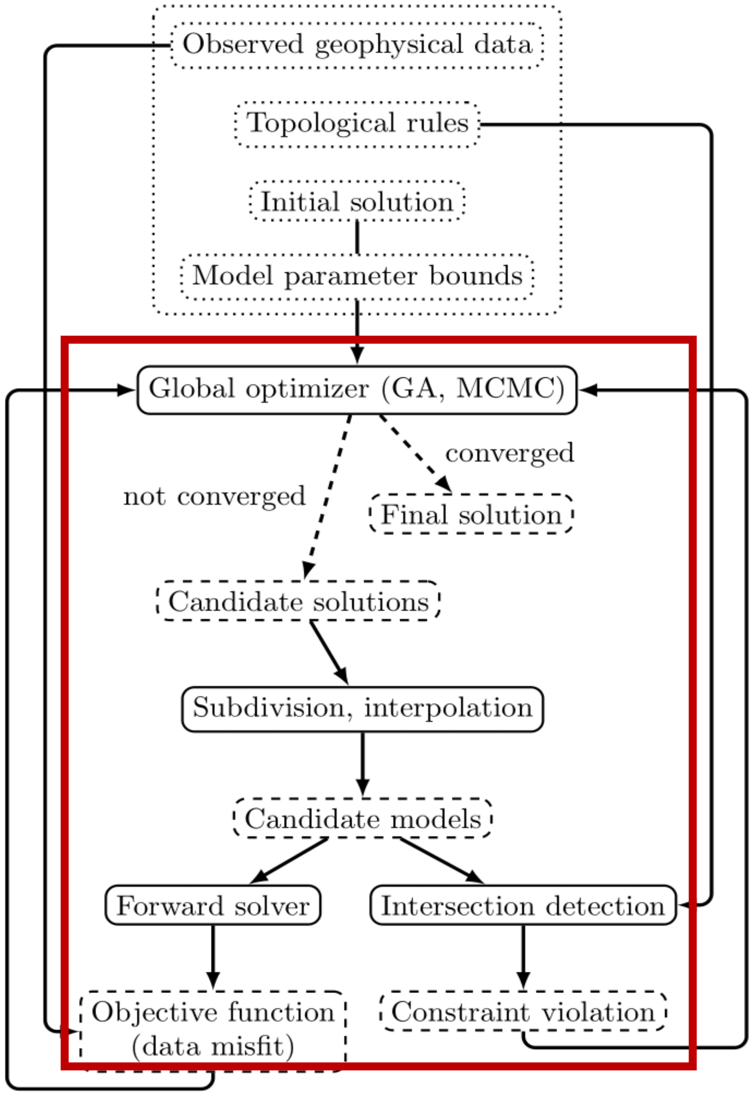
→ 24 model parameters

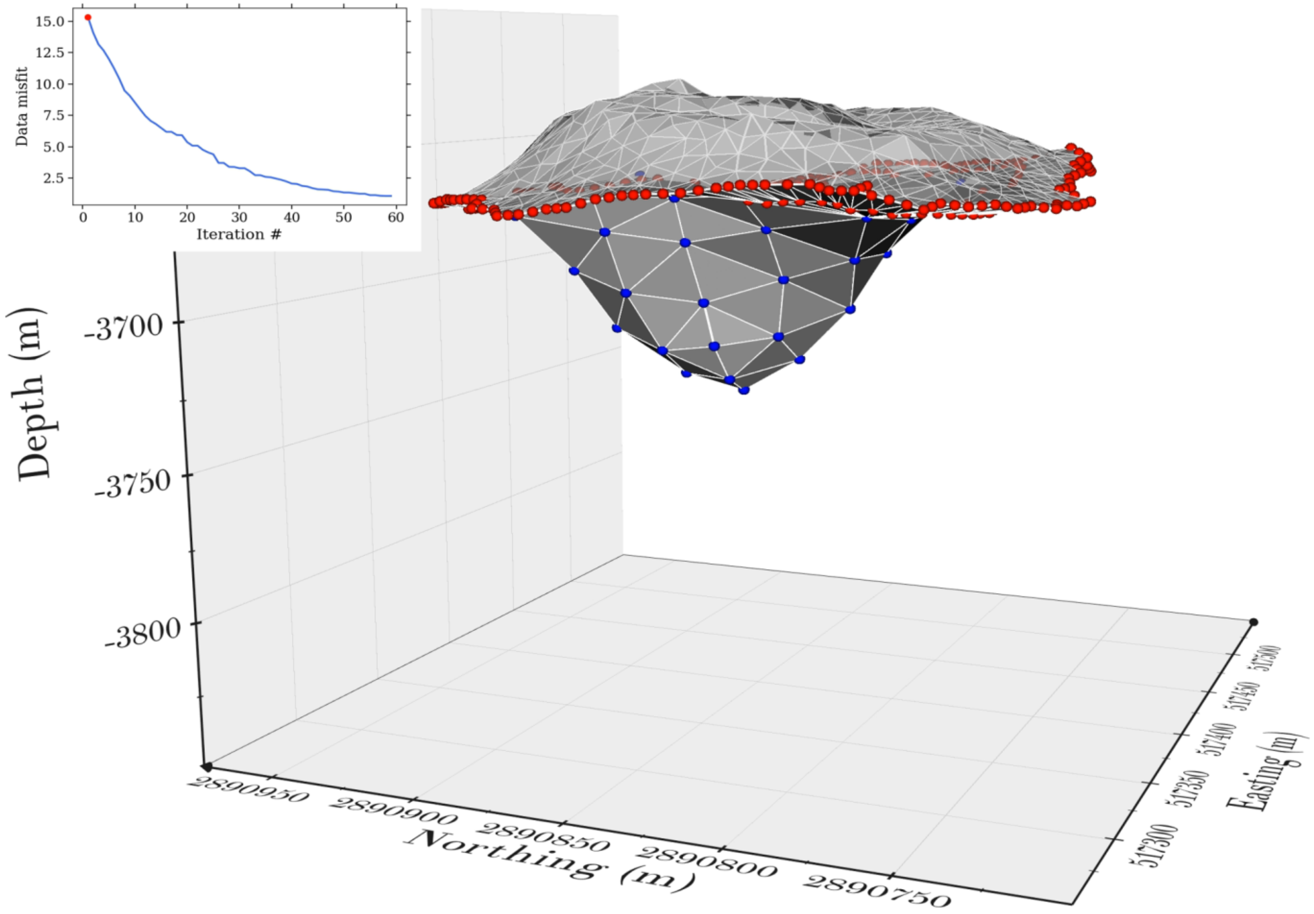
Only the Data Misfit is Necessary

-> no extra regularization calculations

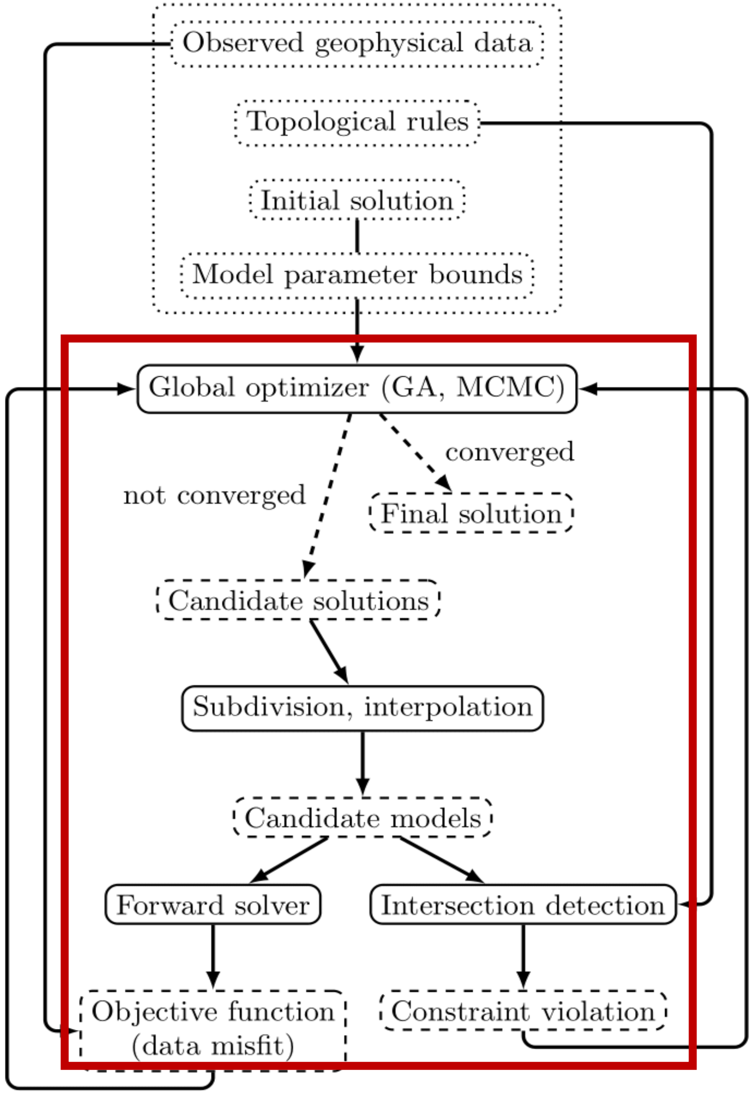
-> no solving for trade-off parameters

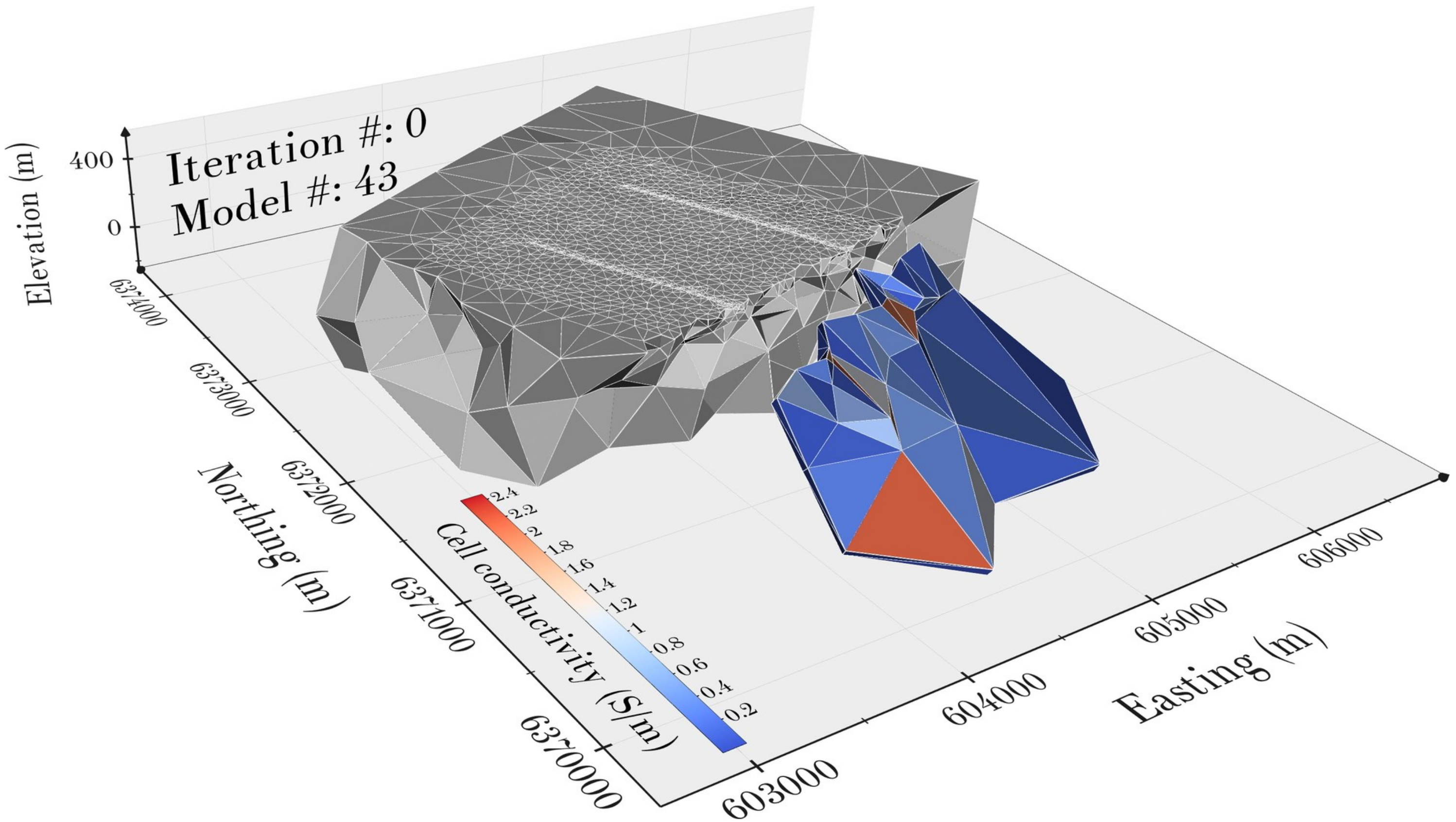
Surface geometry inversion



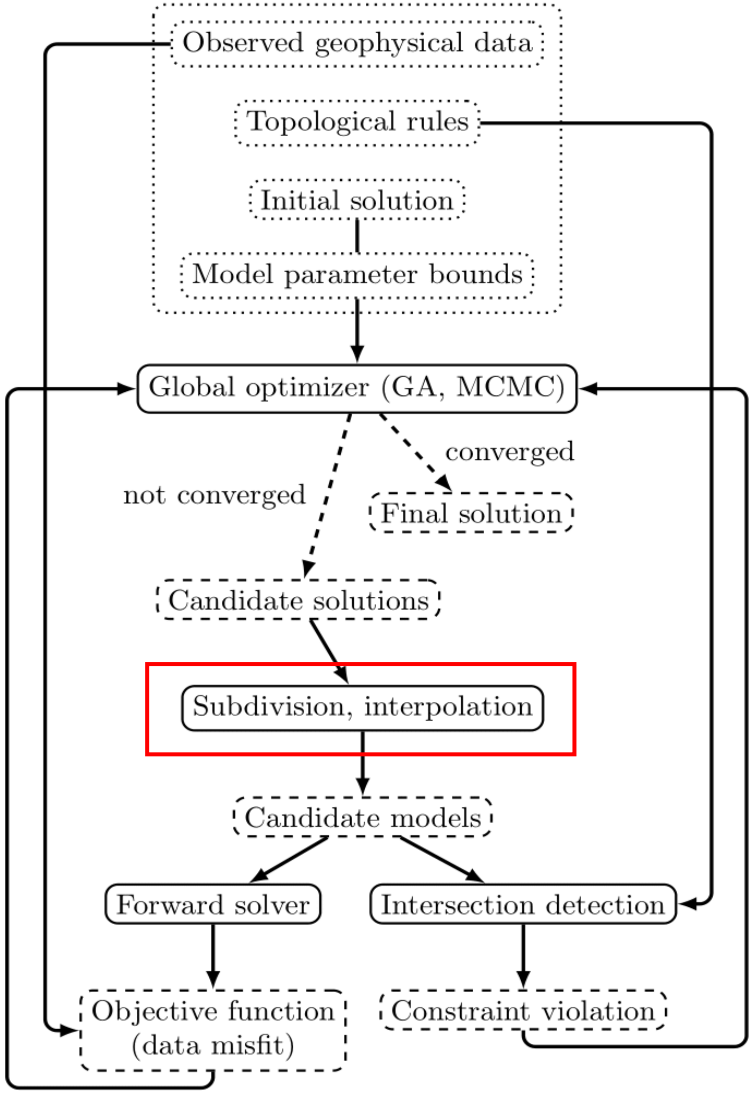


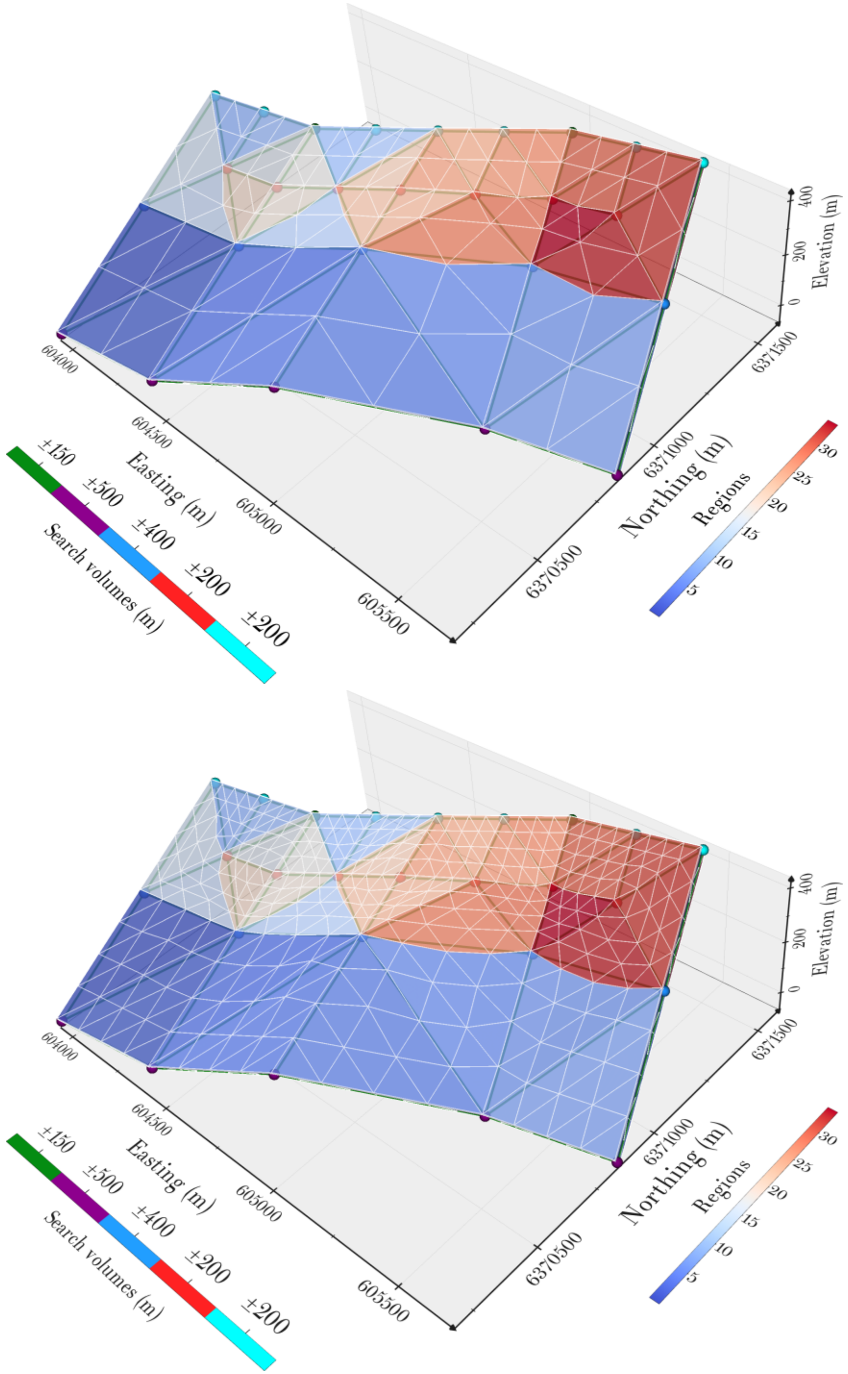
Surface geometry inversion



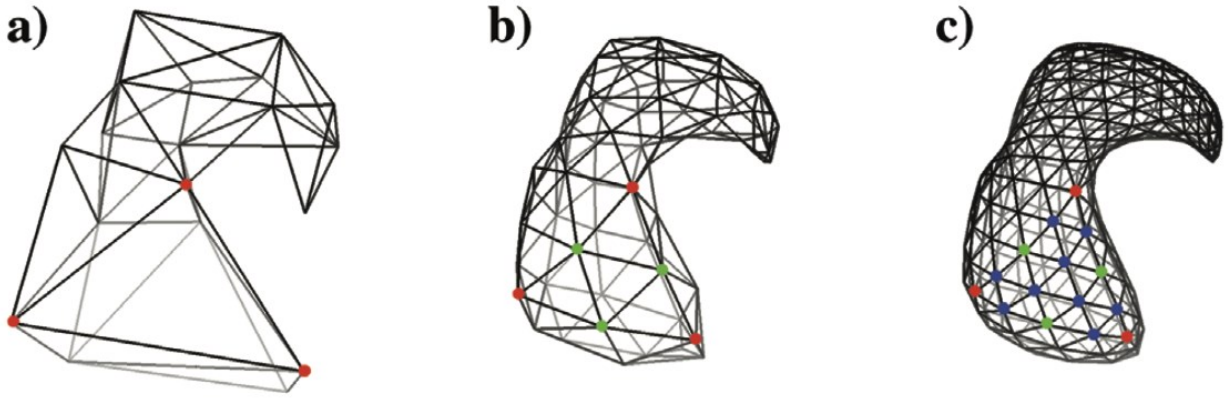


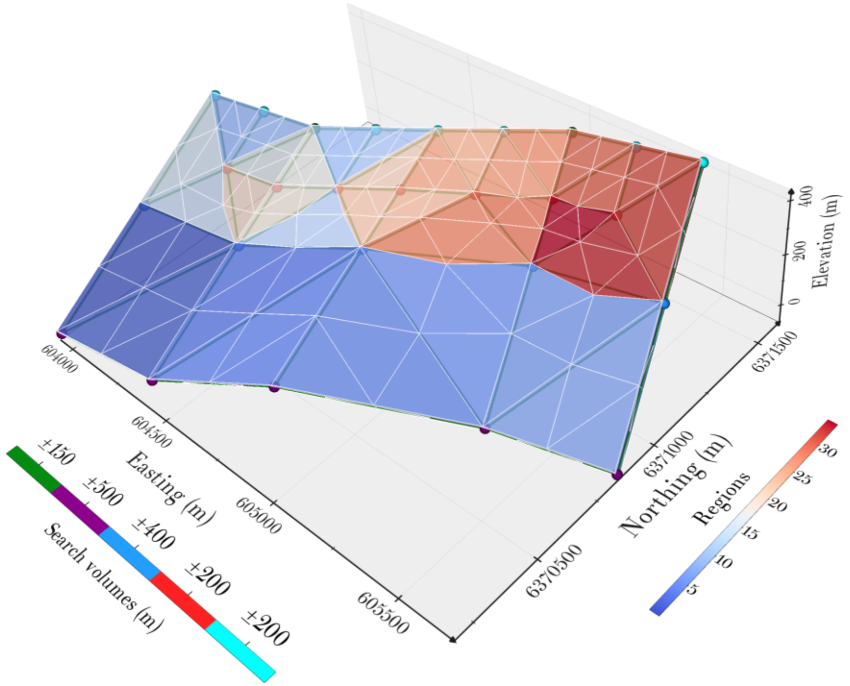
Model subdivision

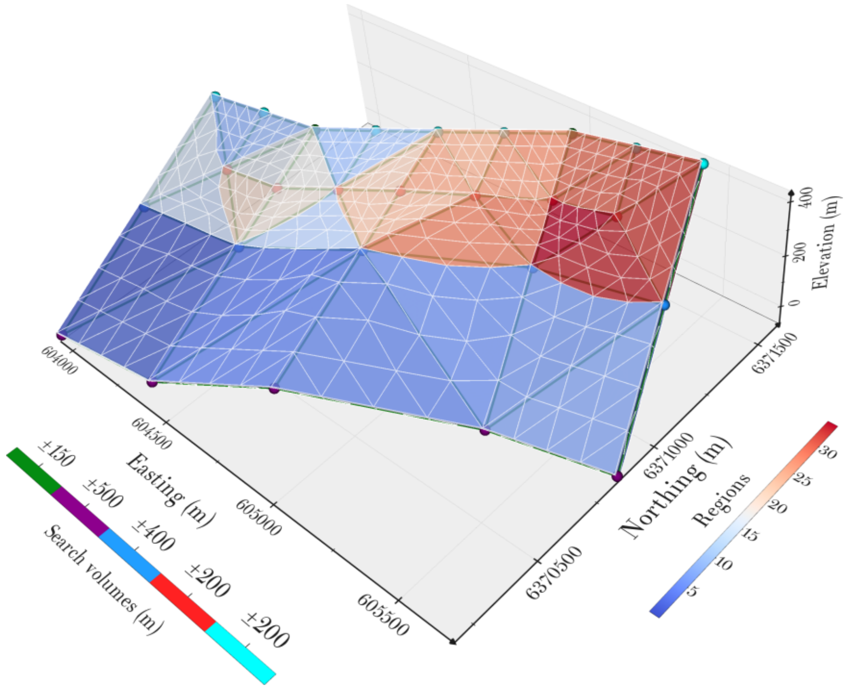




Model subdivision

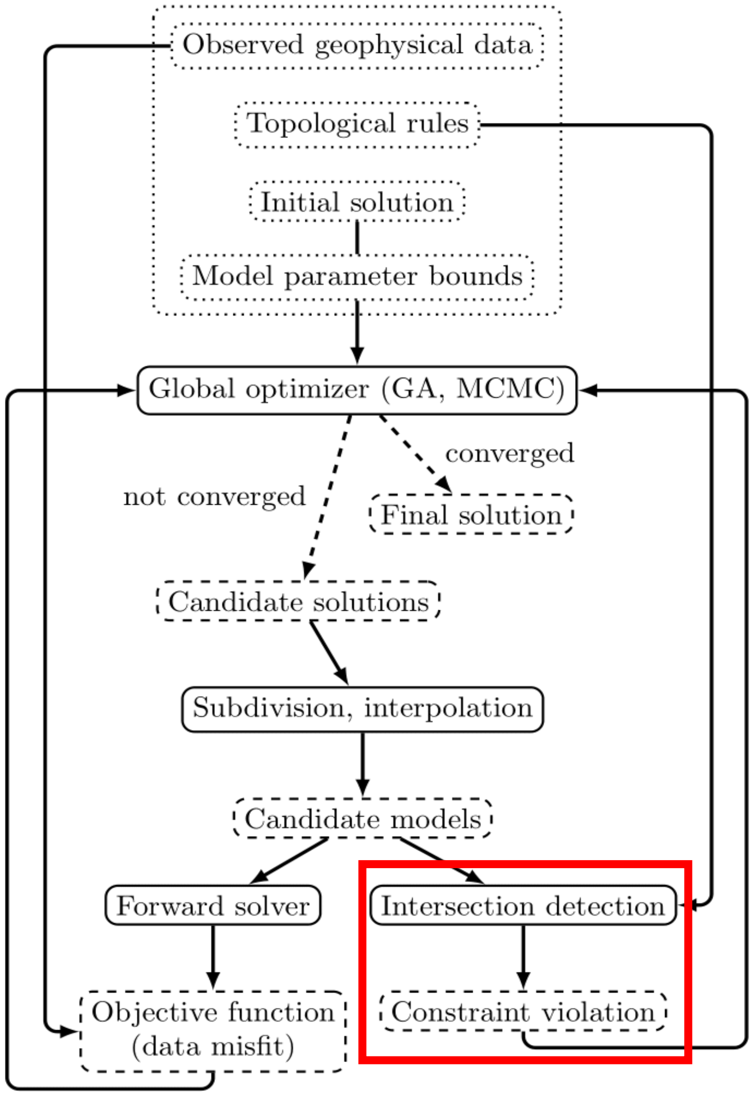


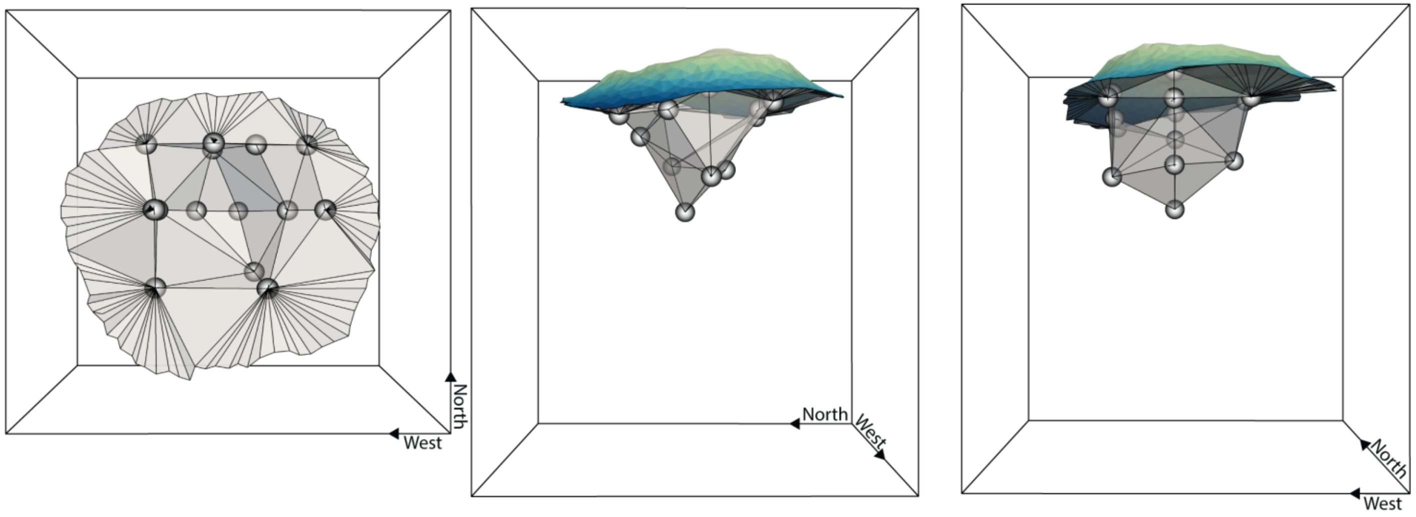


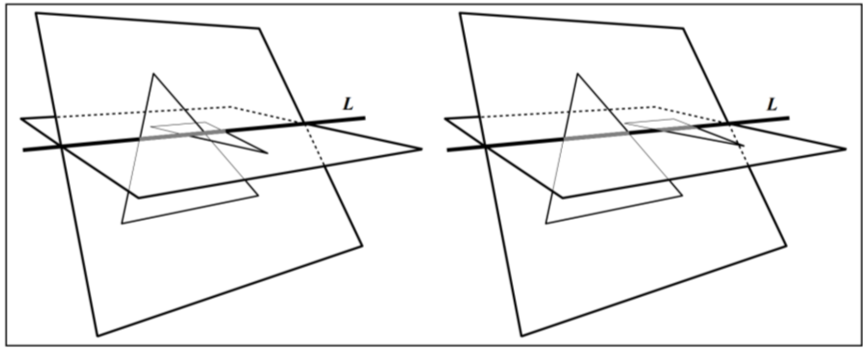


- ➢ Small # of nodes to reduce the # of inversion parameters
- ➢ Models can be subdivided up to two times
- ➢ 3D interpolation is performed to smooth the model

Triangle-triangle intersection detection

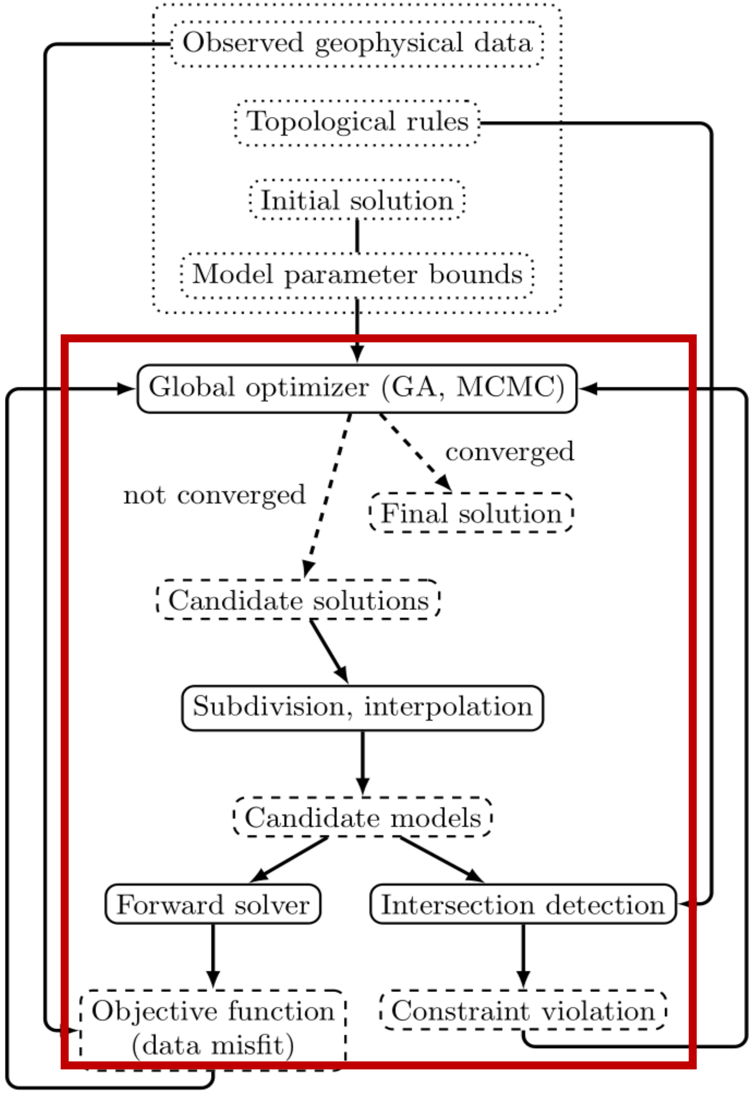


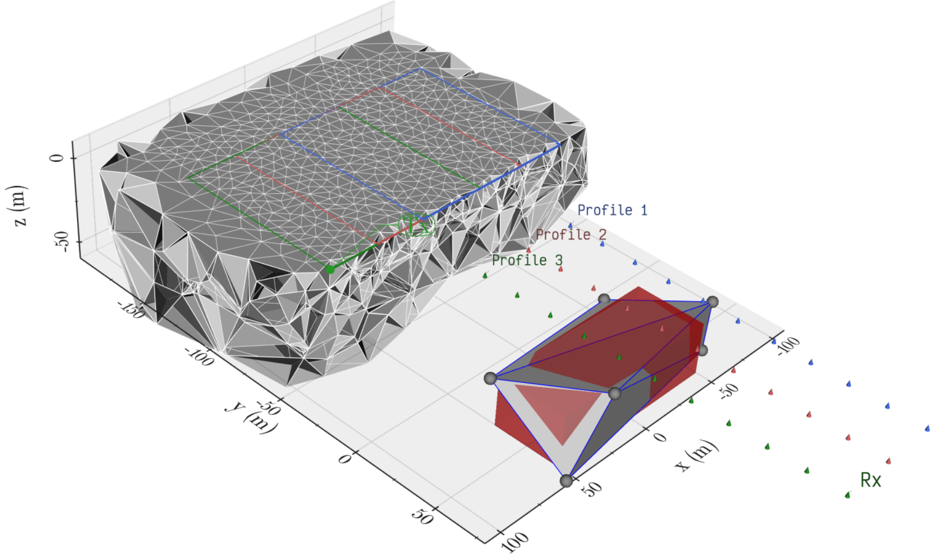




Moller, 1997

Surface geometry inversion for EM data





- To calculate the predicted data, the entire model needs to be discretized
- Automatic mesh generation for a given model (TetGen)
- Finite-element solver
- MPI + OpenMP parallelization

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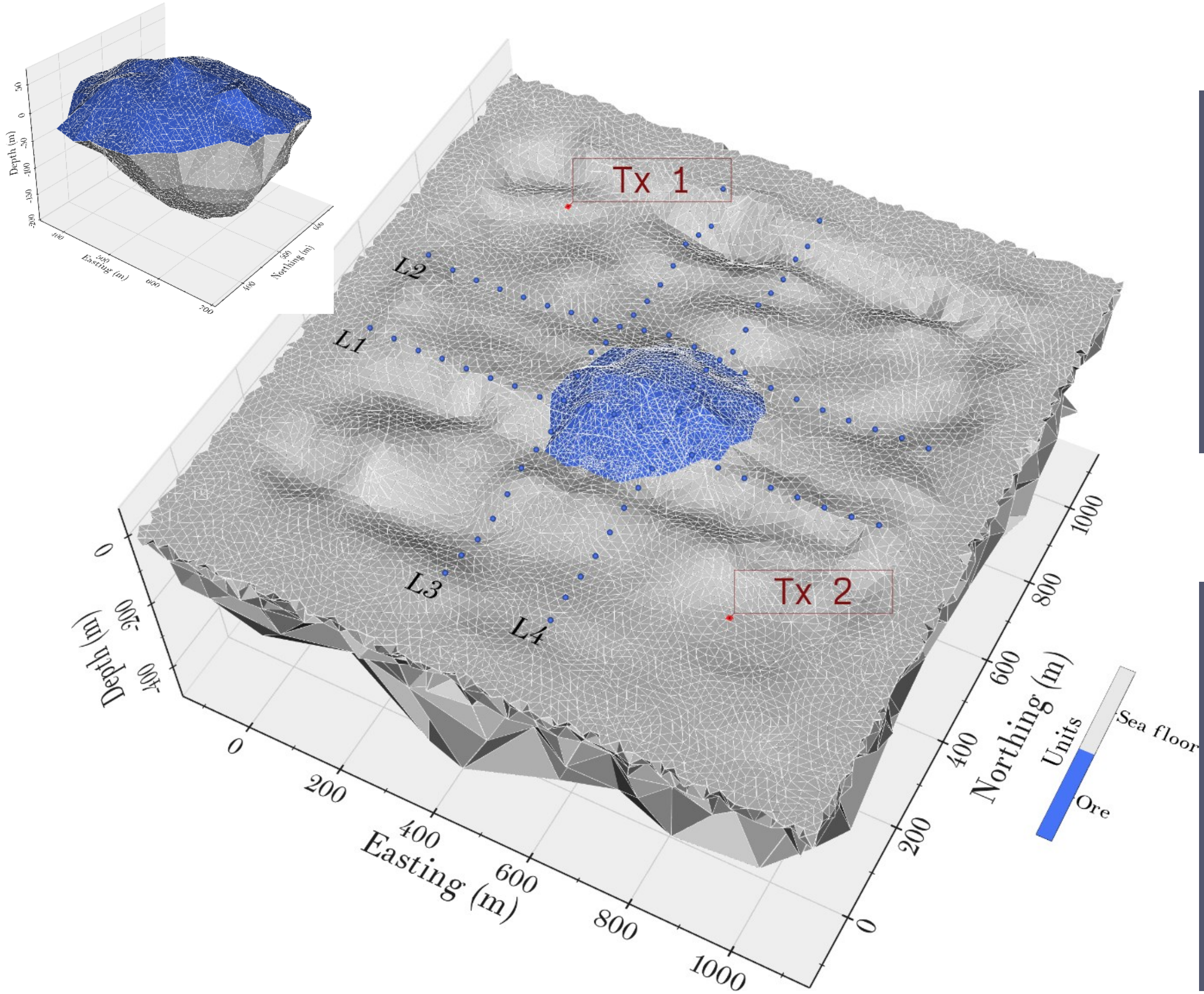
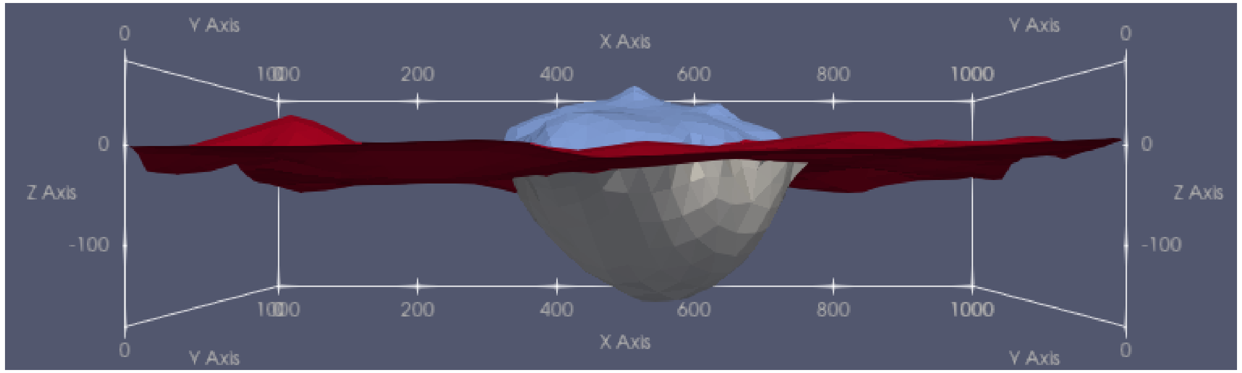
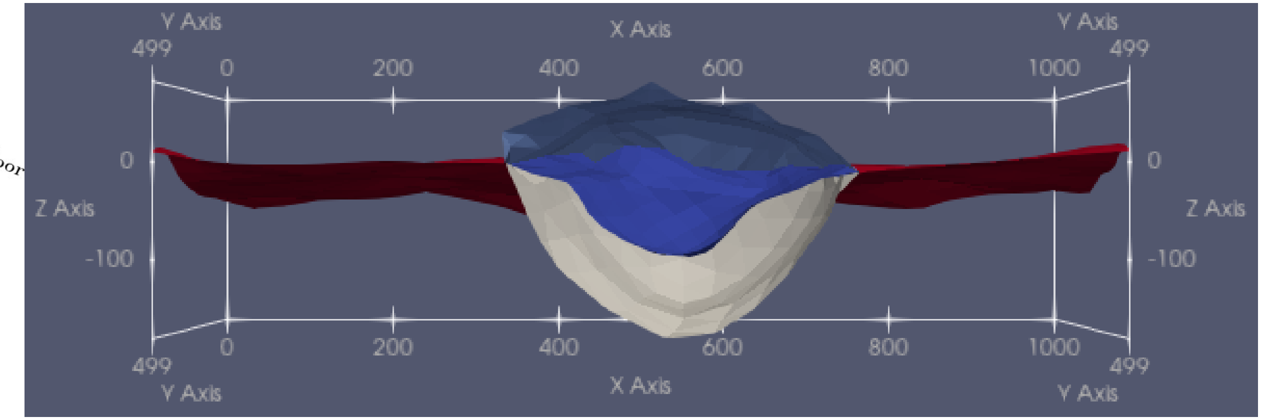
Outline

- Motivation
- Surface geometry inversion
- **Marine CSEM examples**
- TEM examples
- Conclusions

Marine CSEM example

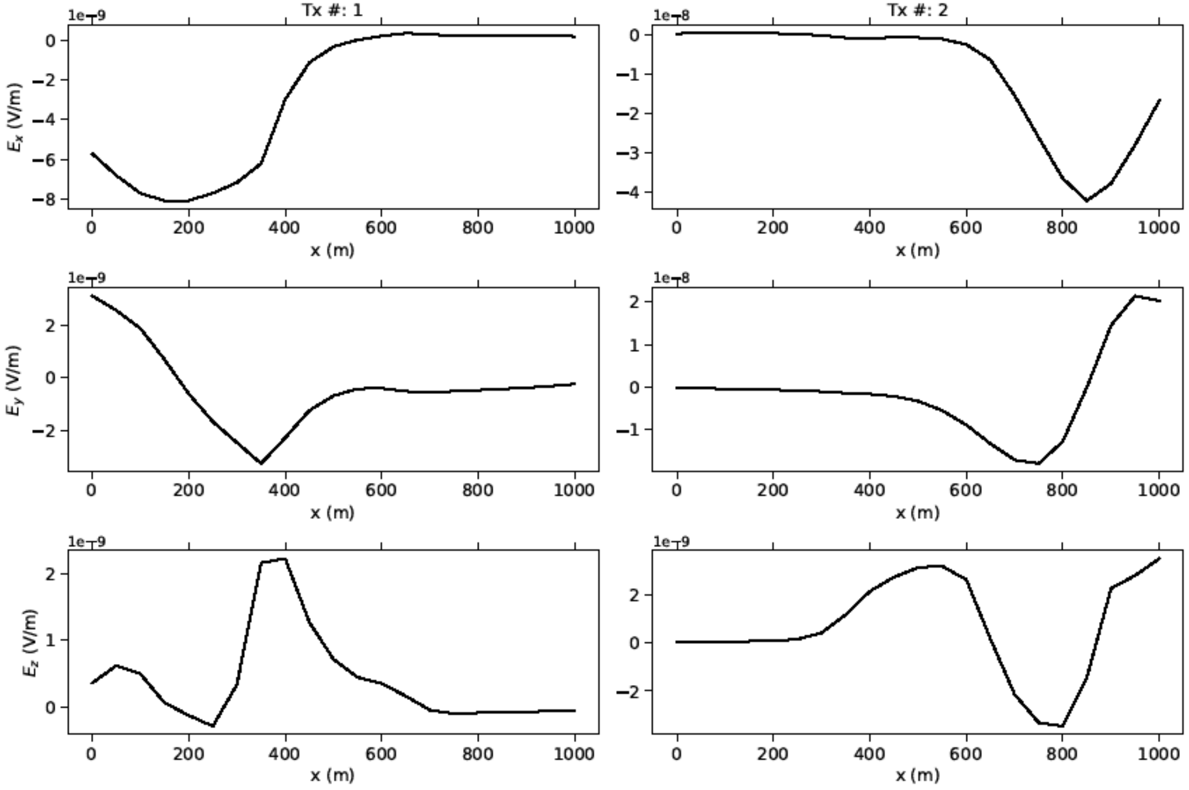




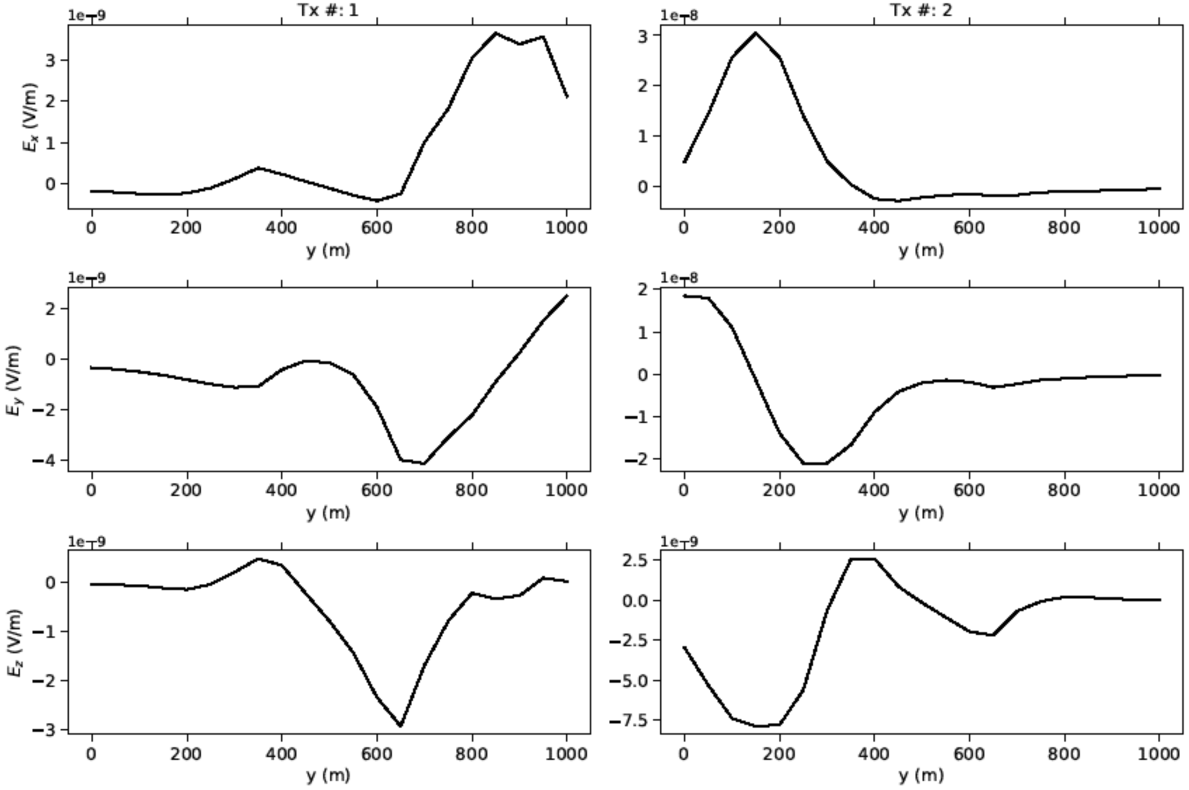


Tetrahedral meshes for the SMS deposits

Marine CSEM example: synthetic data

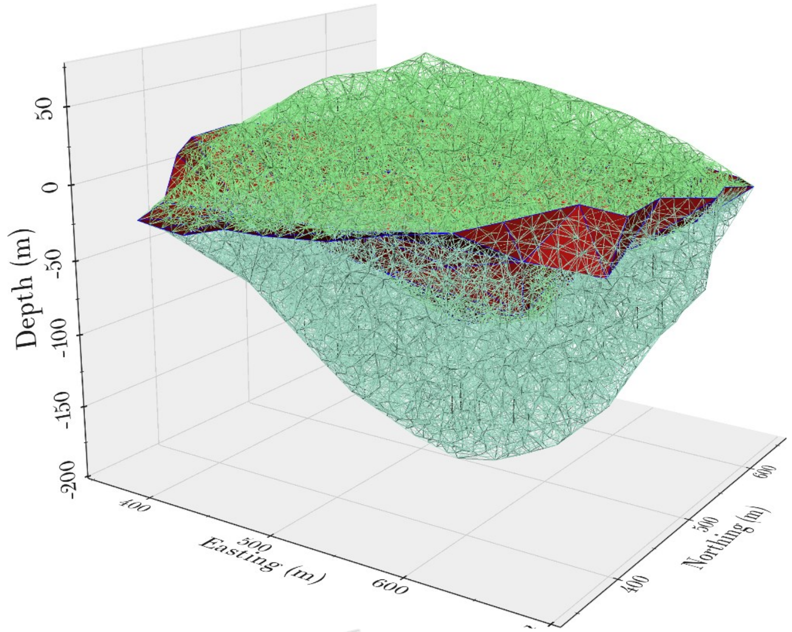


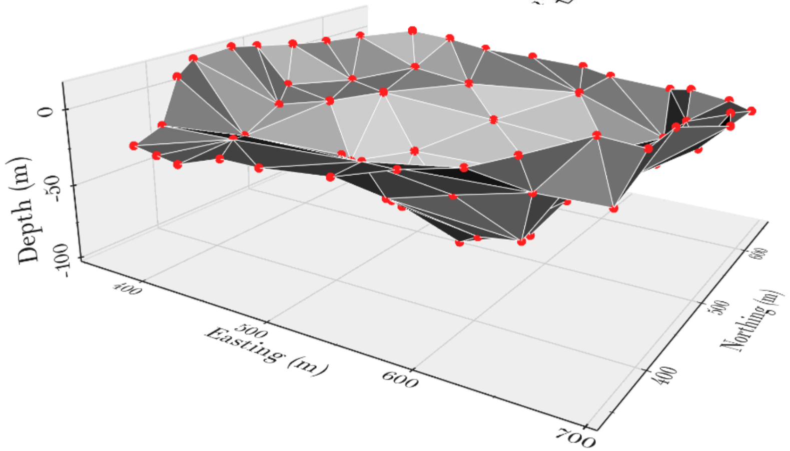
Electric field responses of profile L1



Electric field responses of profile L4

Marine CSEM example: model setup





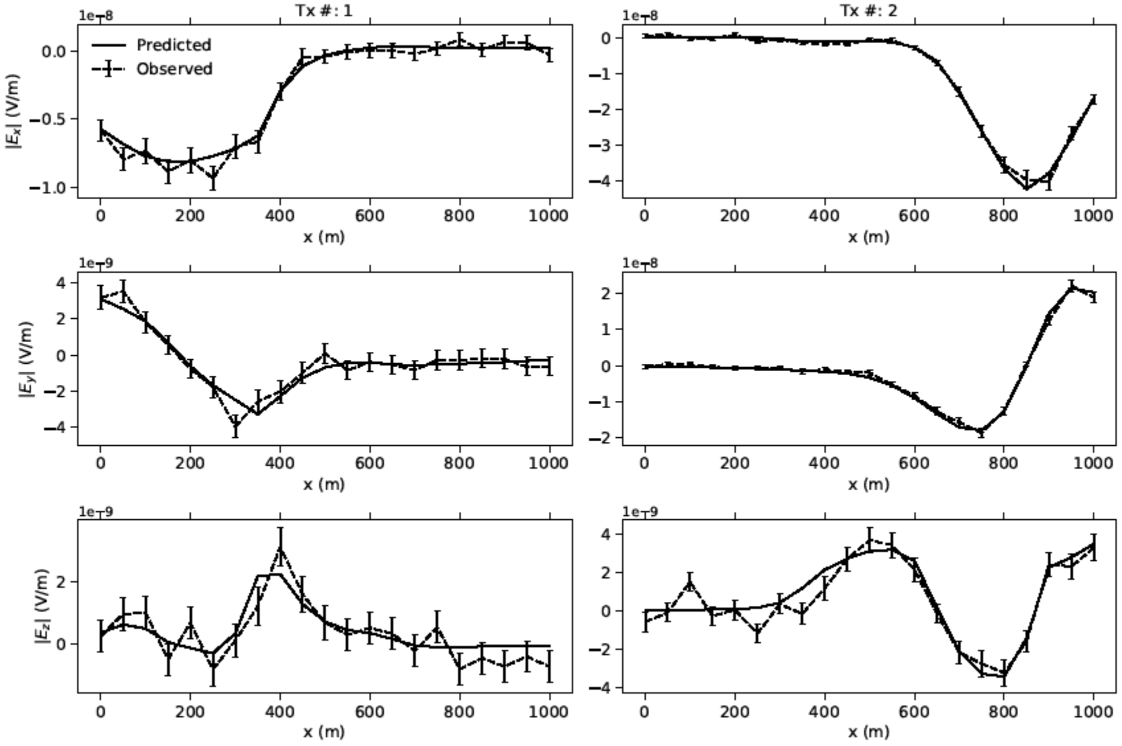
Conductivities:

- Ore body: 10 S/m
- Sea water: 0.33 S/m
- Seafloor: 0.1 S/m
- True conductivity is used for inversion

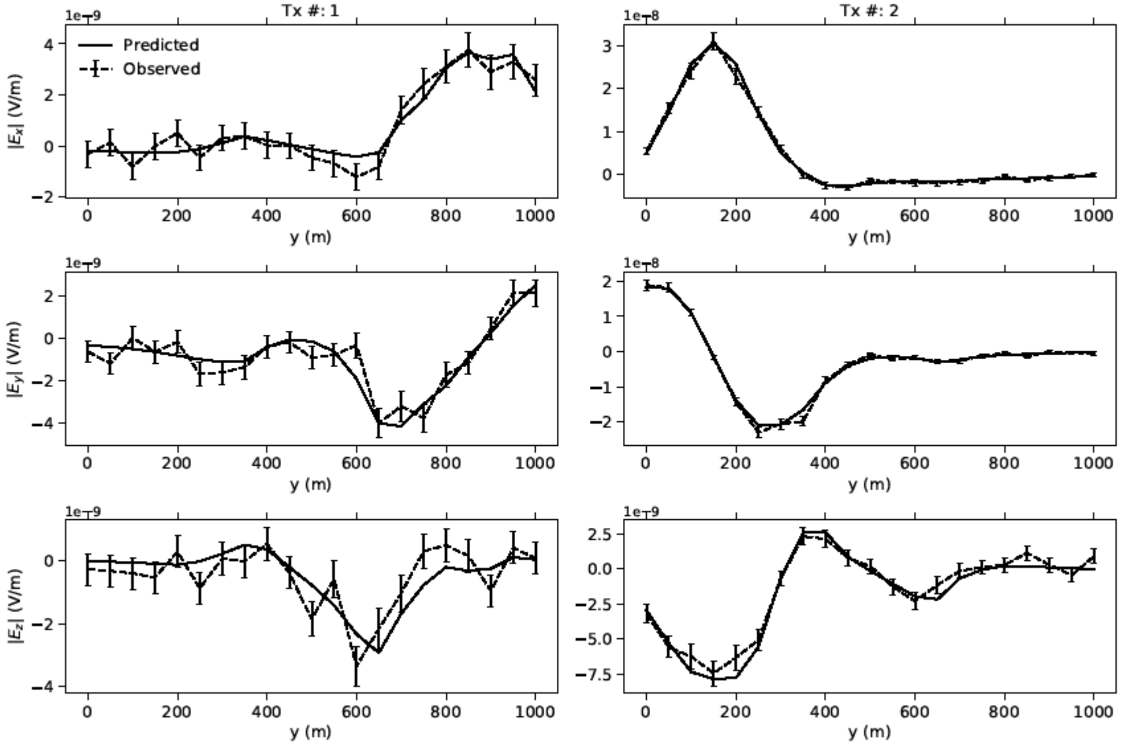
Inversion parameters:

- 38 nodes in the surface model
- Each node is allowed to move vertically
- Moving range is (-100, 5) m
- 5% Gaussian noise
- GA population: 239

Marine CSEM example: data fitting

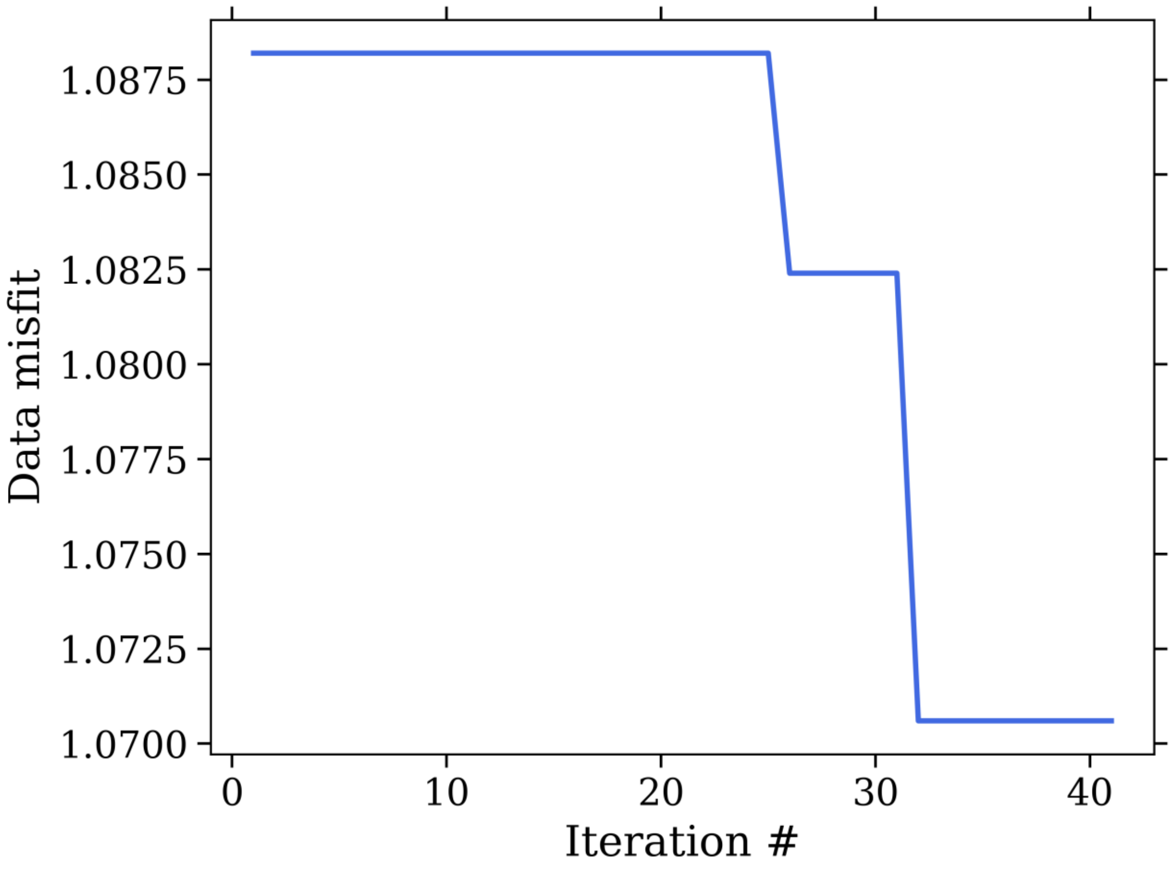


Electric field responses of profile L1



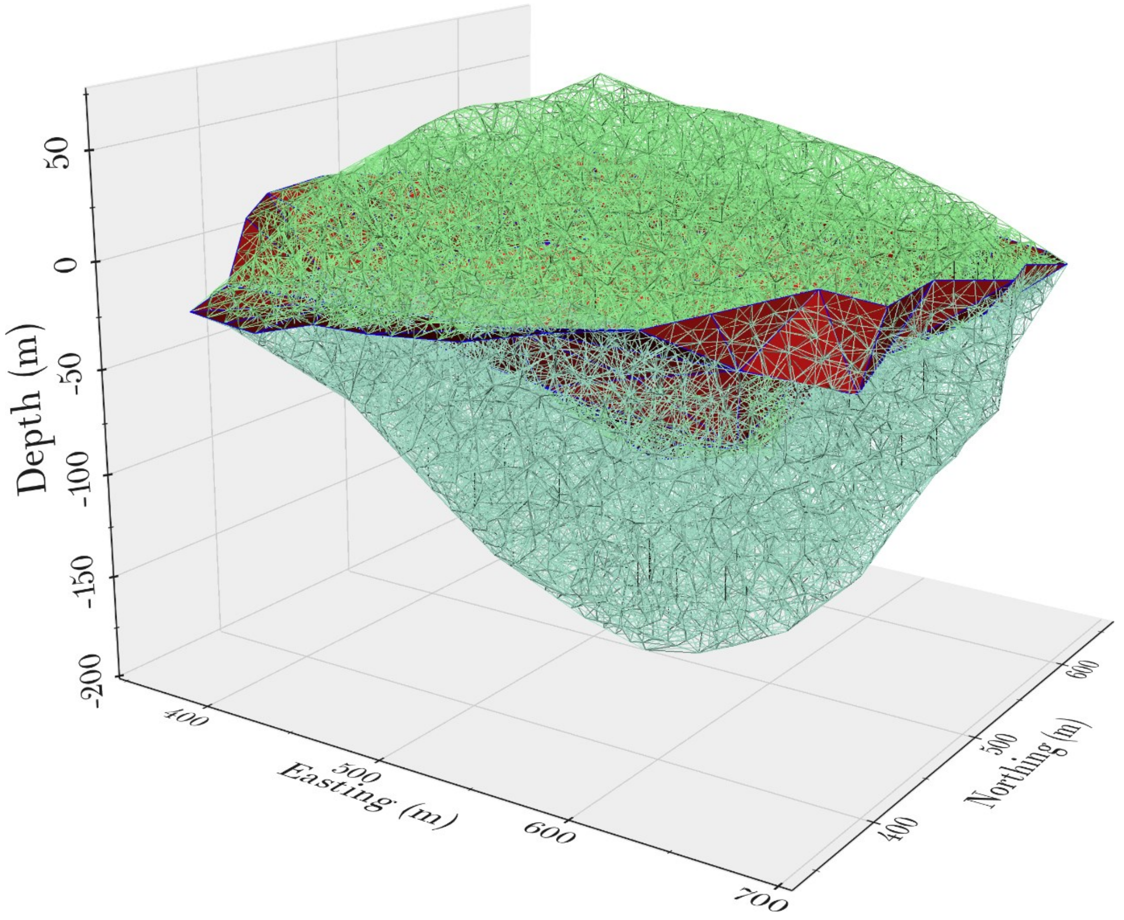
Electric field responses of profile L4

Marine CSEM example: convergence

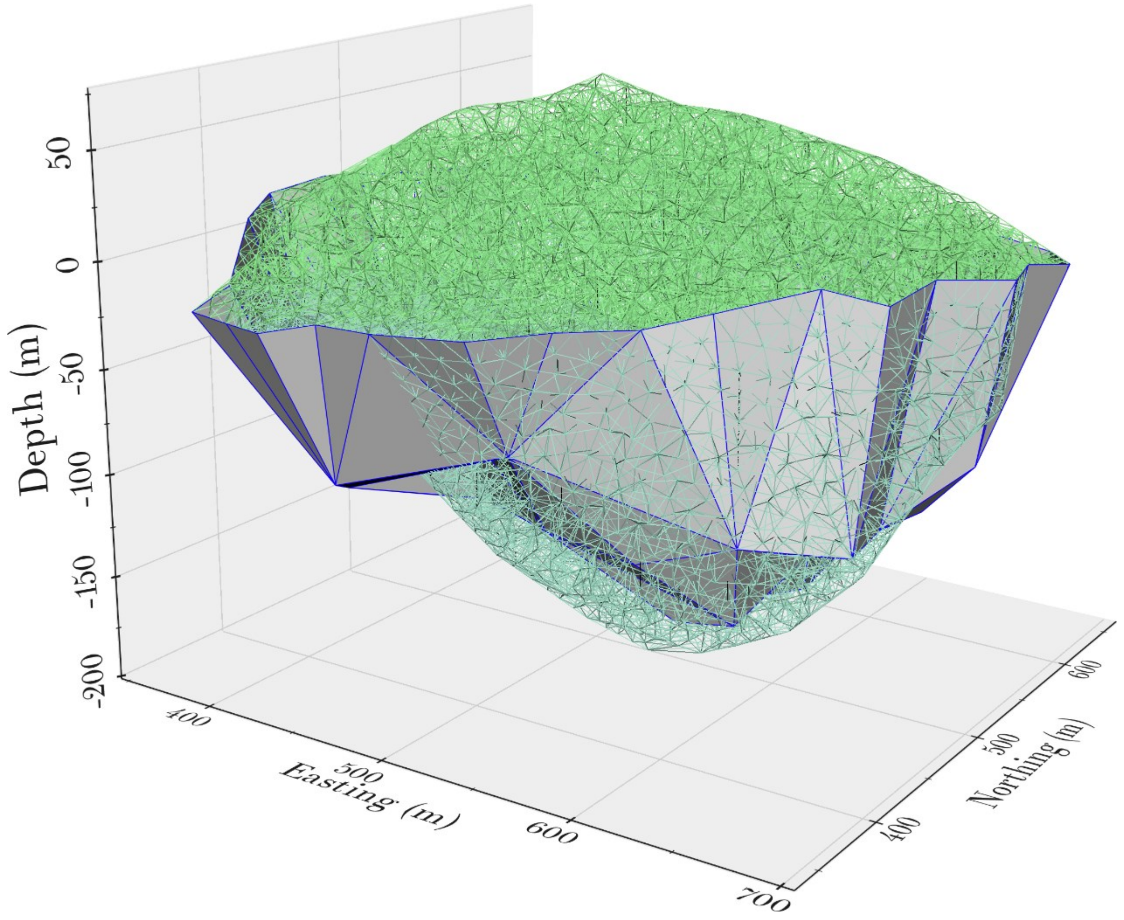


- # parameters: 38 (38 nodes each moving in one direction)
- GA population size: 239
- 240 CPU cores: Intel® Xeon® Gold 6248 Processor @ 2.5 GHz
- 1 CPU for each model (1 MPI process with 1 OMP thread)
- Computation time: 43 minutes
- Maximum RAM consumption: 656 GB

Marine CSEM example: constructed model



Input (red) and true model (green wireframe)

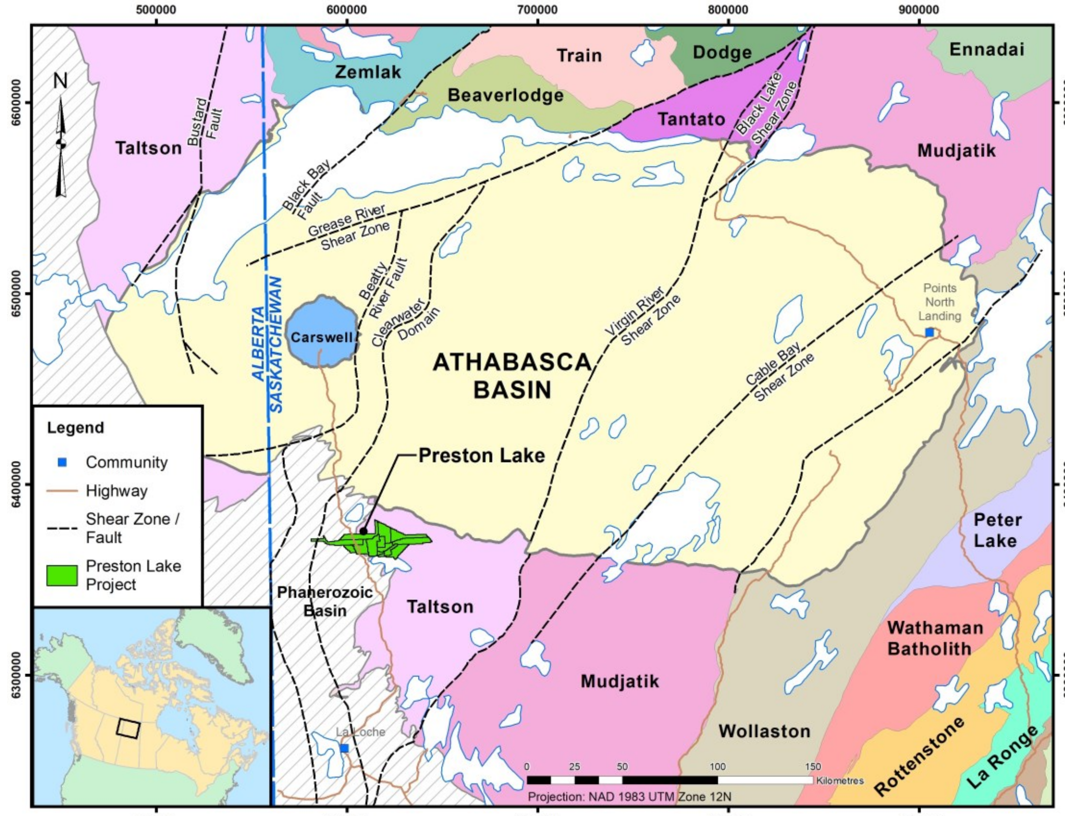


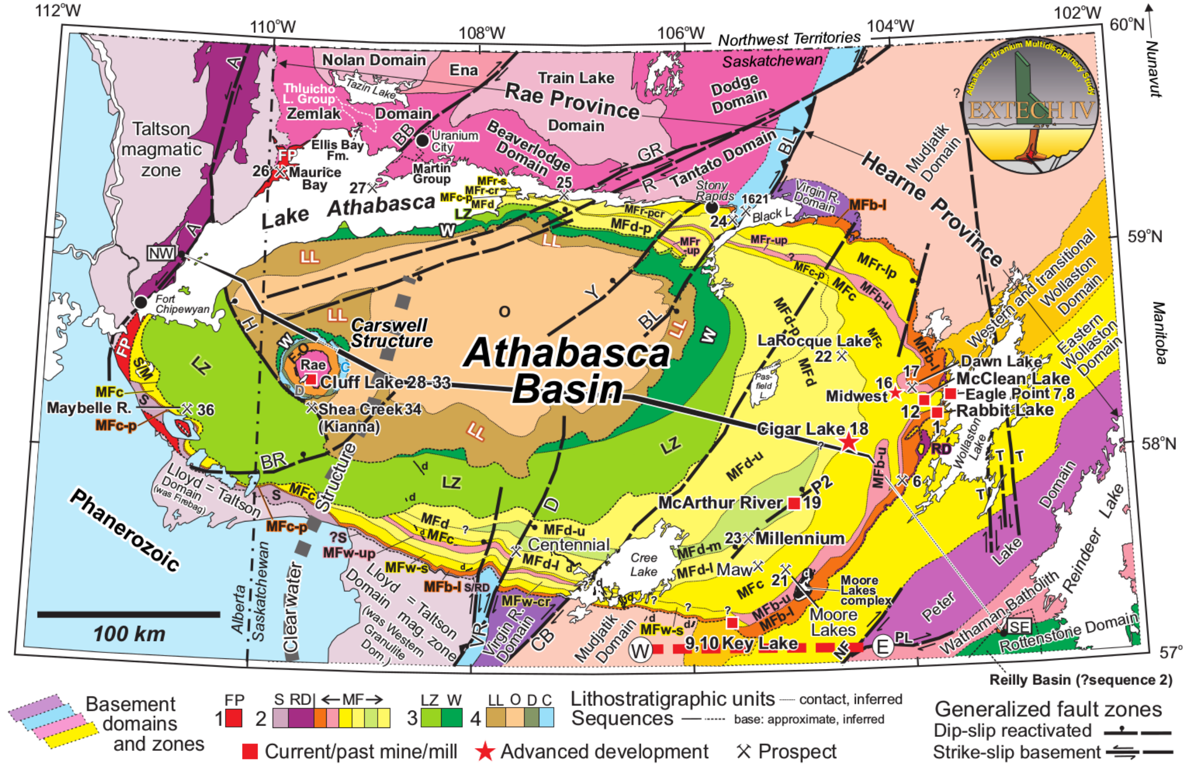
Constructed (gray) and true model (green wireframe)

Outline

- Motivation
- Surface geometry inversion
- Marine CSEM examples
- **TEM examples**
- Conclusions

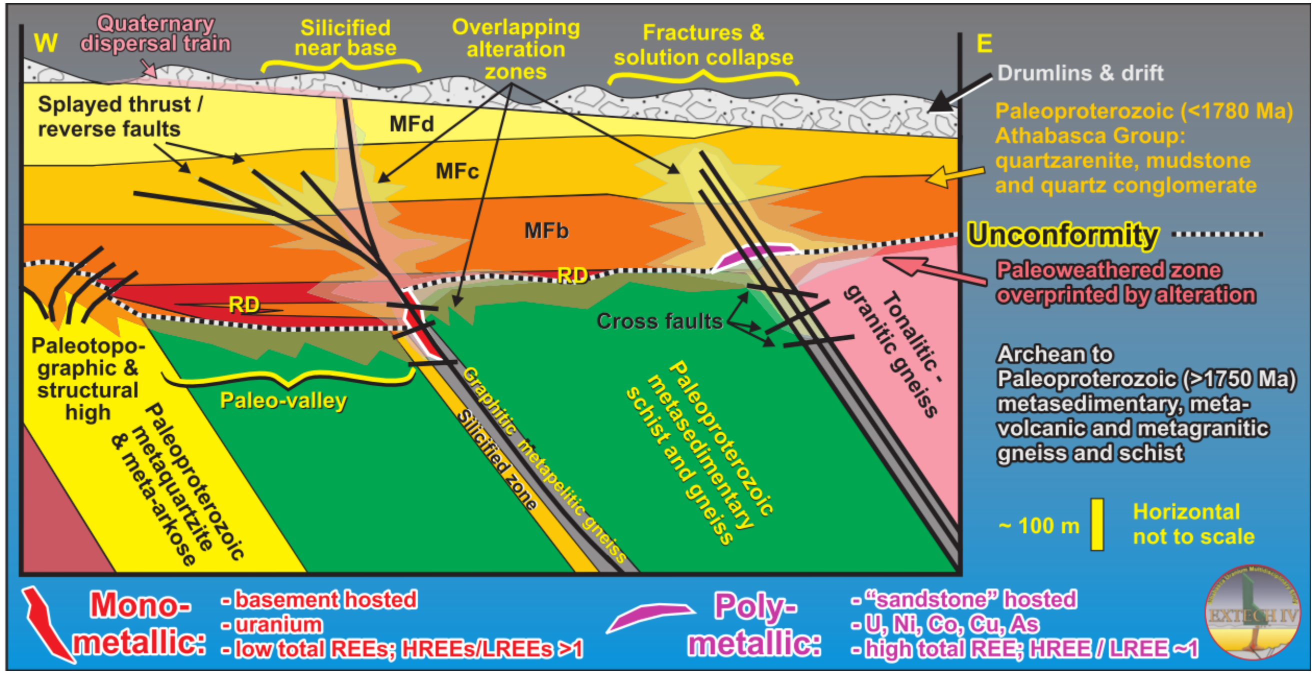
Real-data example: uranium exploration

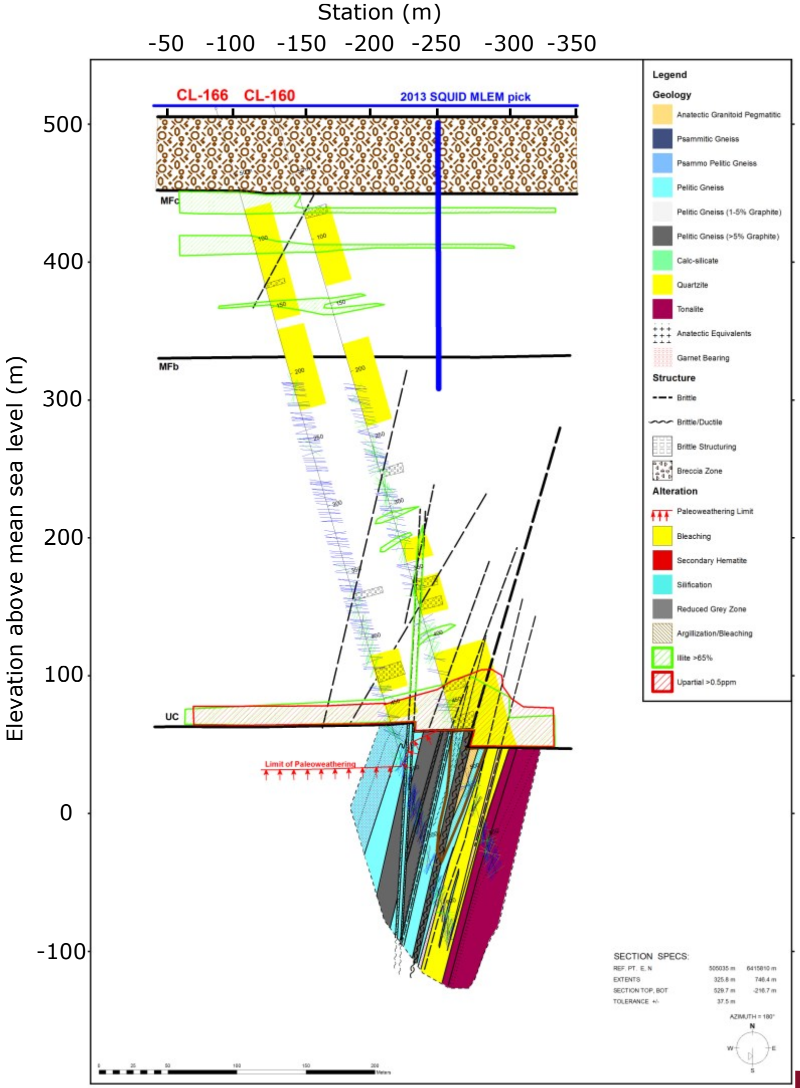




(Jefferson et. al., 2007)

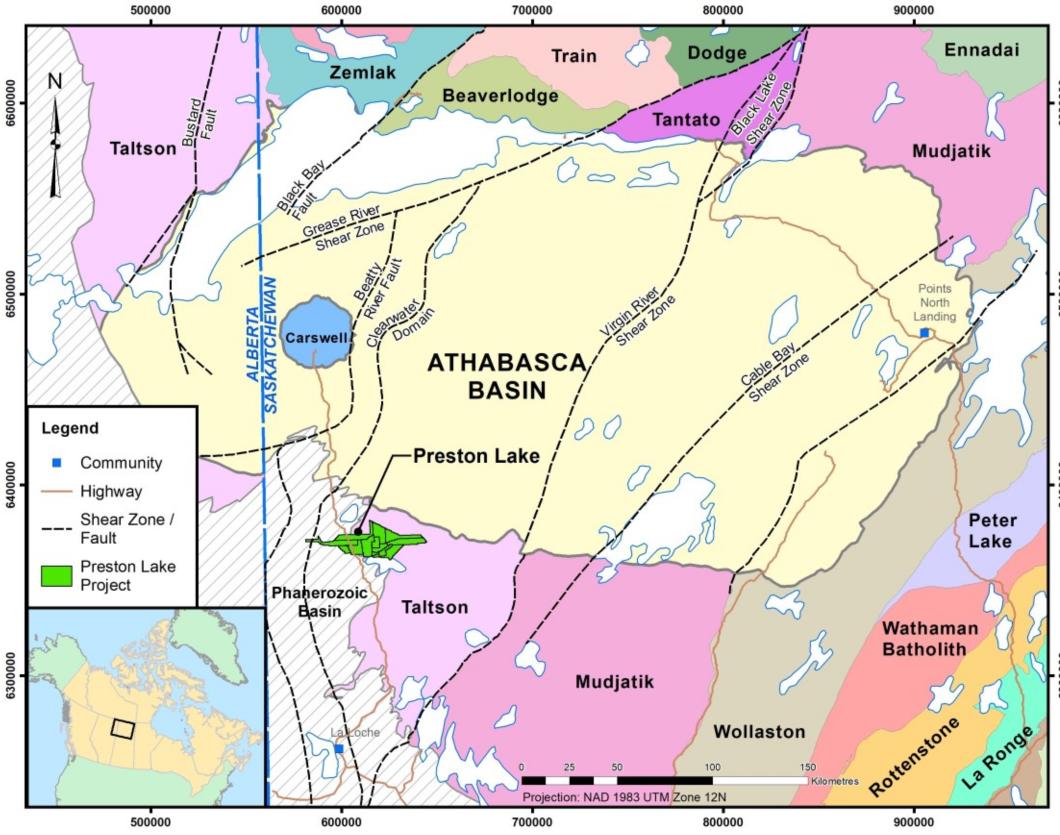
TEM example: uranium exploration



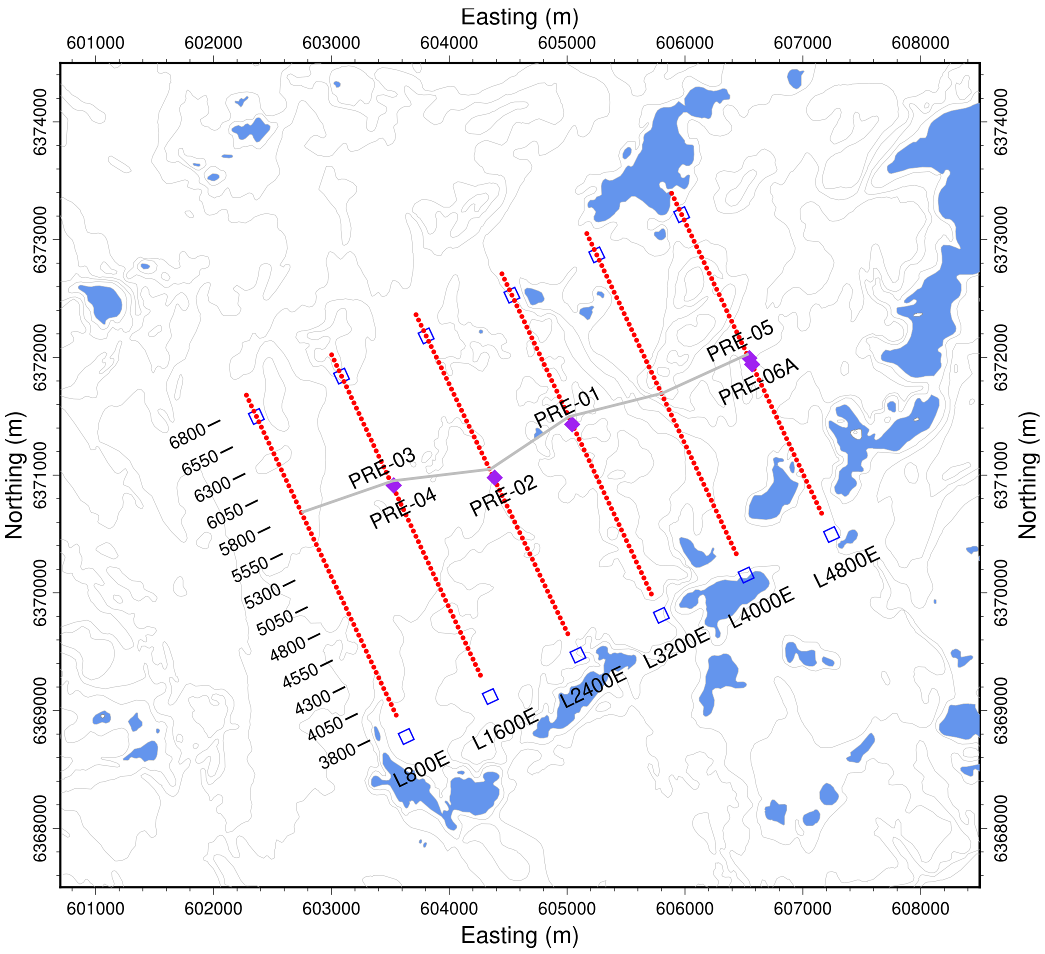


(Jefferson et. al., 2007)

Preston Lake project

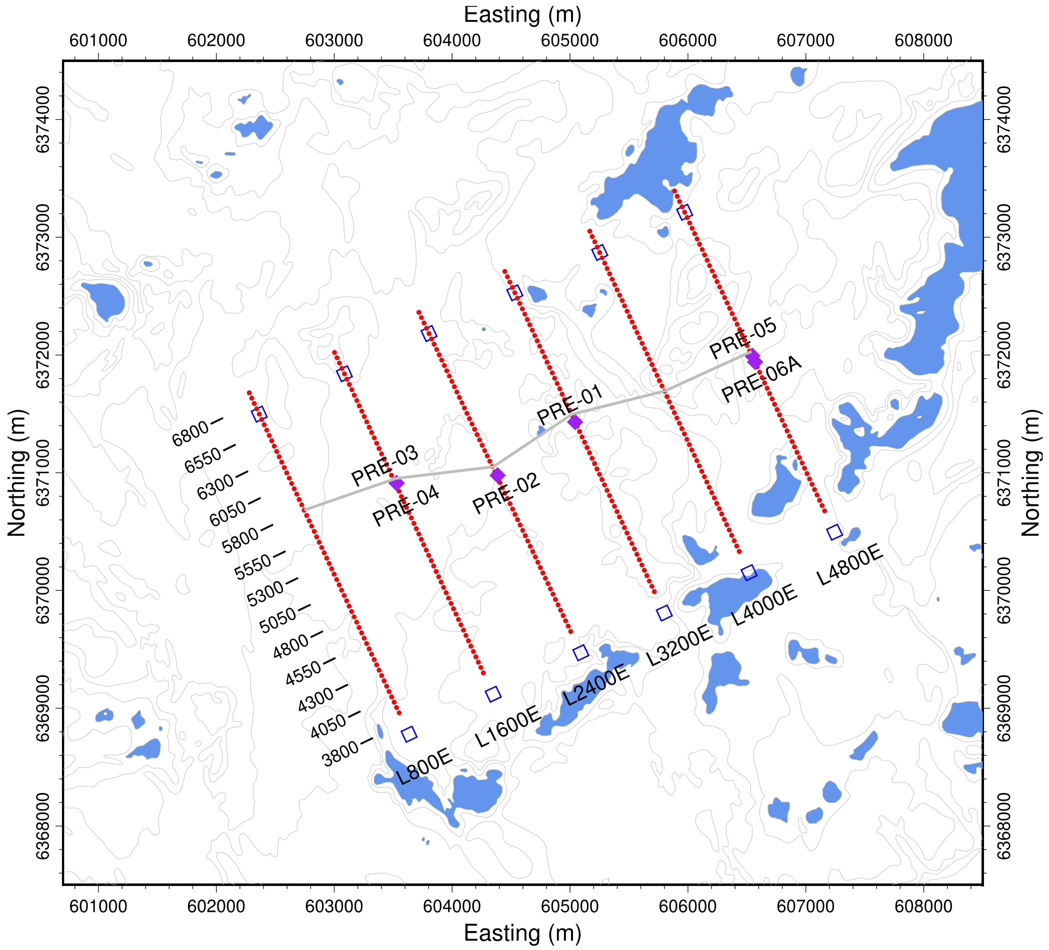


Project area



North Grid

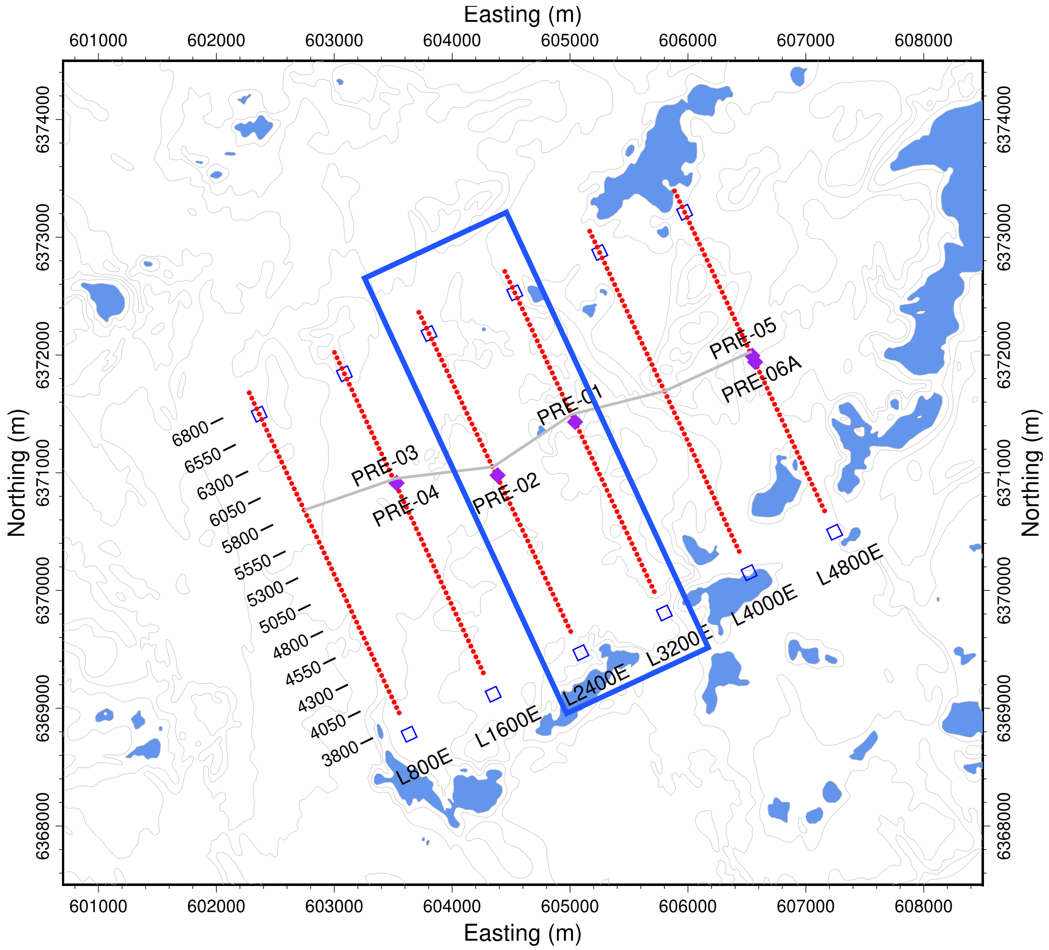
Preston Lake project: survey configuration



North Grid

- 100 by 100 m loop source
- Station spacing: 50 m
- Rx located 200 m to the grid north of the center of Tx
- Abitibi Geophysics ARMIT MK2 dB/dt & B sensor
- 61 stations: 3 km each profile
- 20 channels from 0.1042 ms to 6.0928 ms

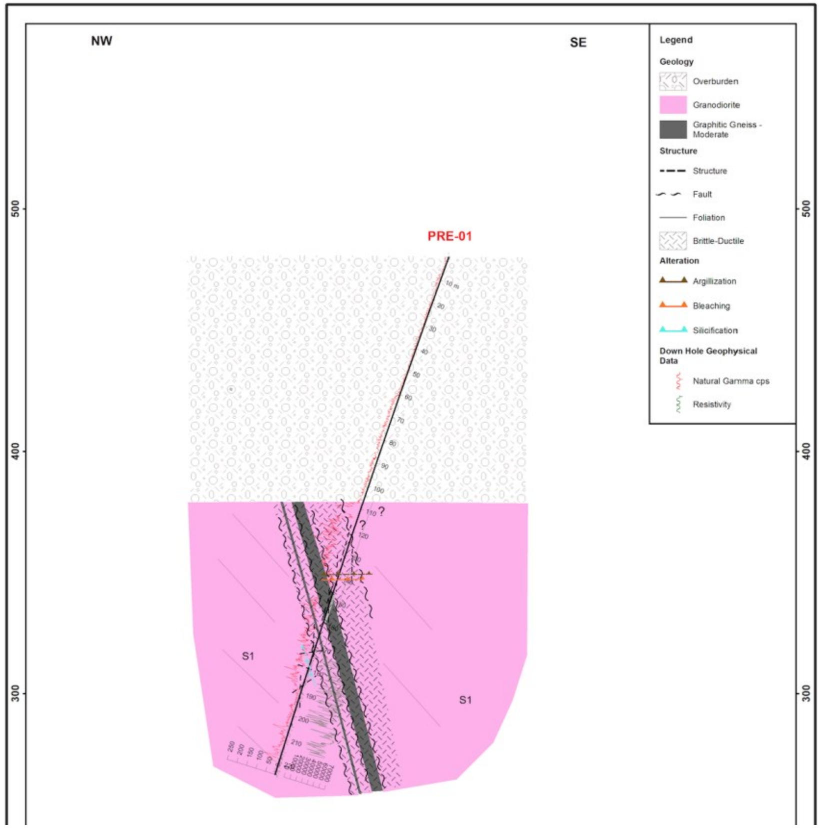
Preston Lake project: survey configuration

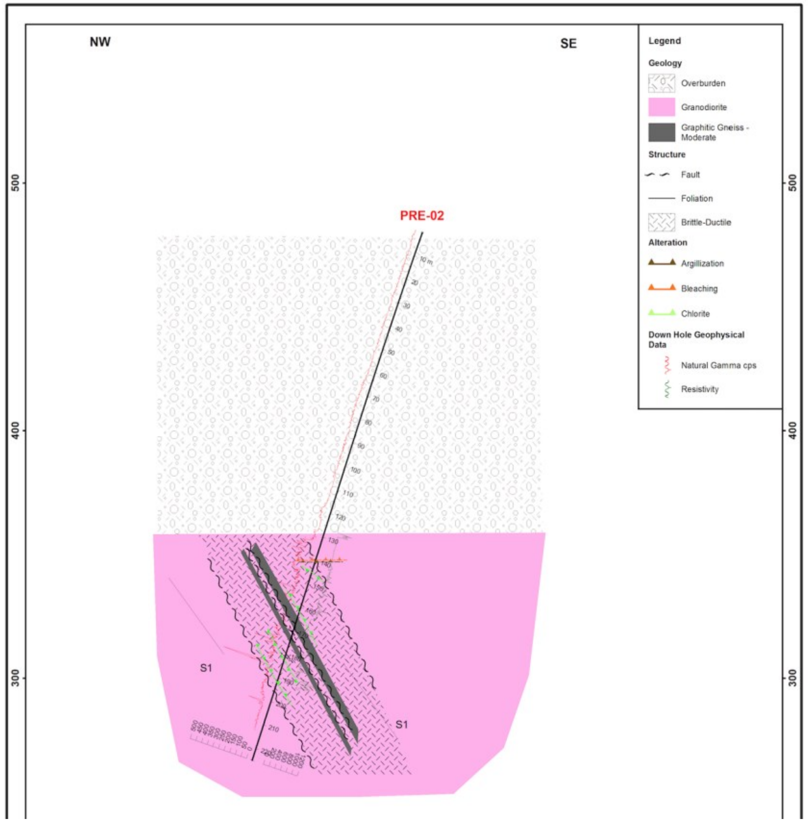


North Grid

- Only invert data from L2400E & L3200E
- Drill hole PRE-01 & PRE-02 intersected graphite

Preston Lake project: survey configuration





Basement: crystalline metamorphic basement rocks of the Taltson domain

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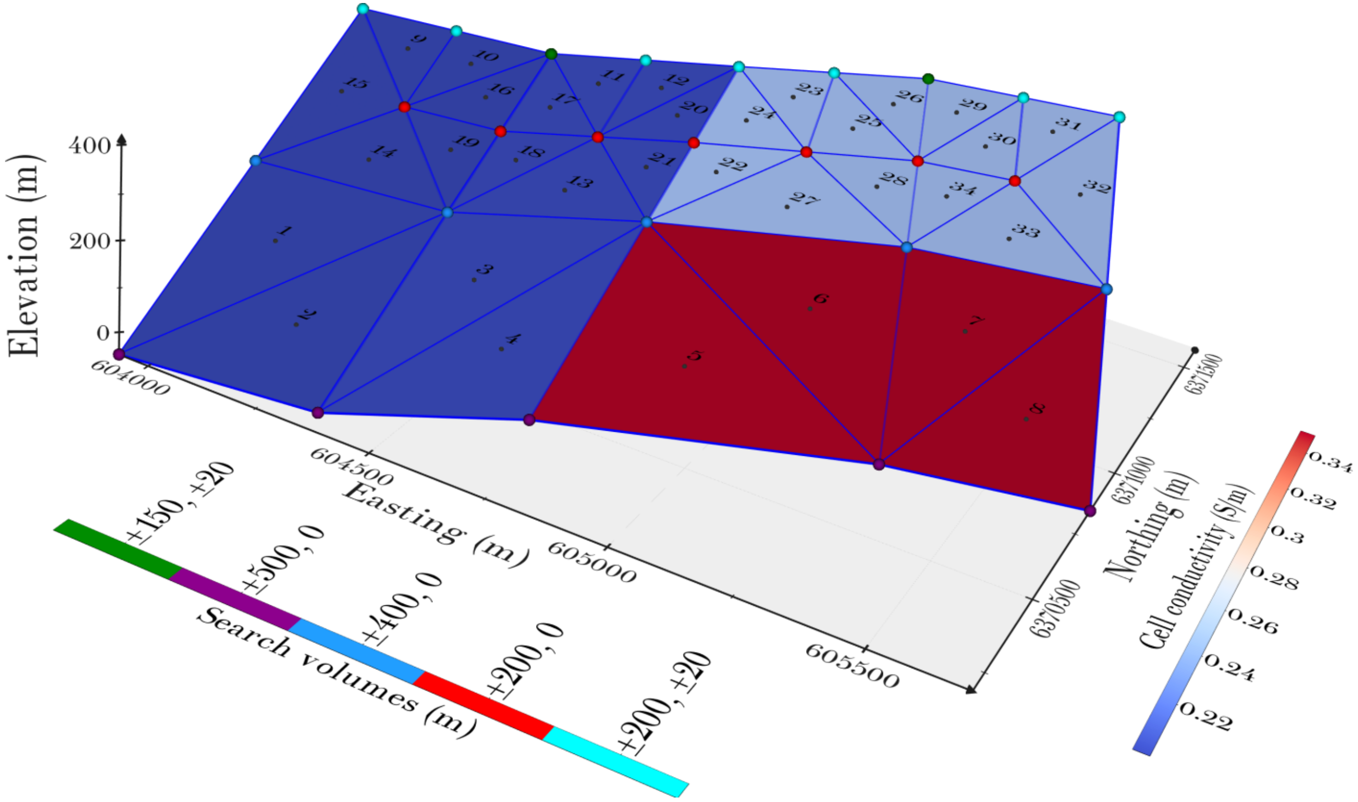
SGI of Preston Lake data: model setup



Initial model

- Background conductivity model obtained from trial-and-error modelling
- # parameters: 69 (26 nodes moving along strike, 9 nodes moving vertically, and 34 regions)
- GA population size: 599
- Data uncertainties: max(std, 2% data)
- 15 nodes with 600 Intel® Xeon® Gold 6248 Processor @ 2.5 GHz
- 1 CPU for each model (1 MPI process with 1 OMP thread)

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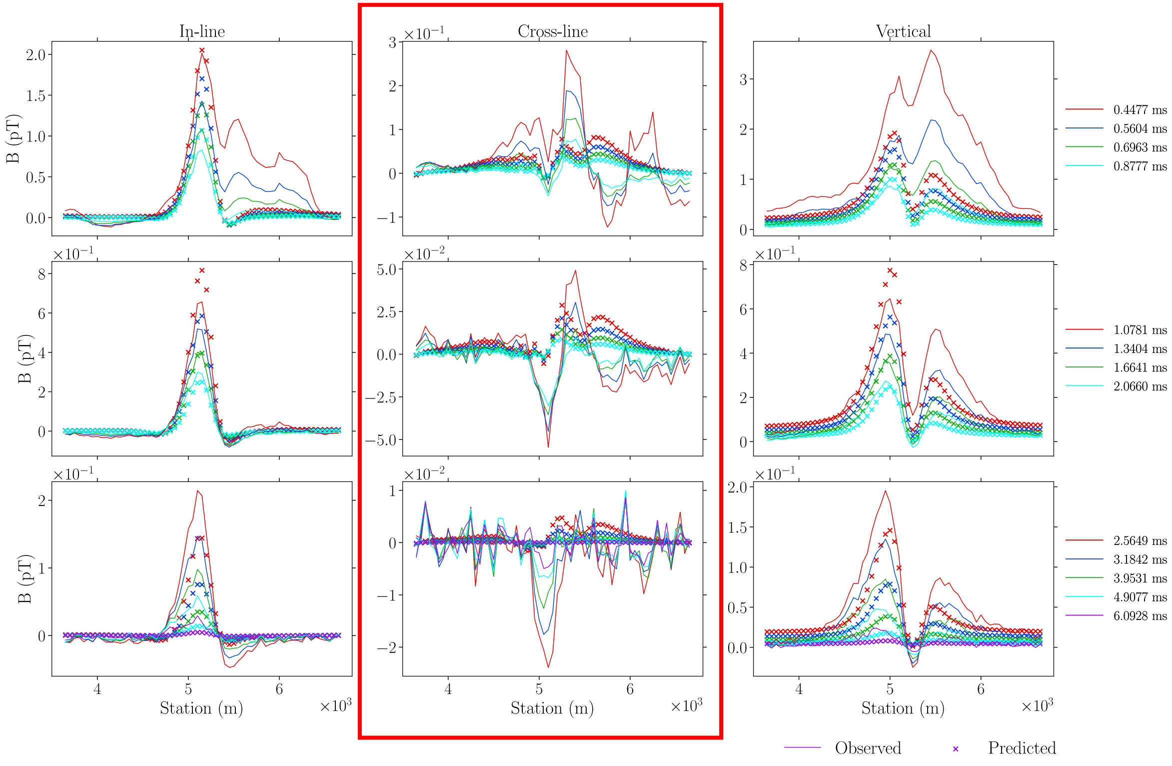
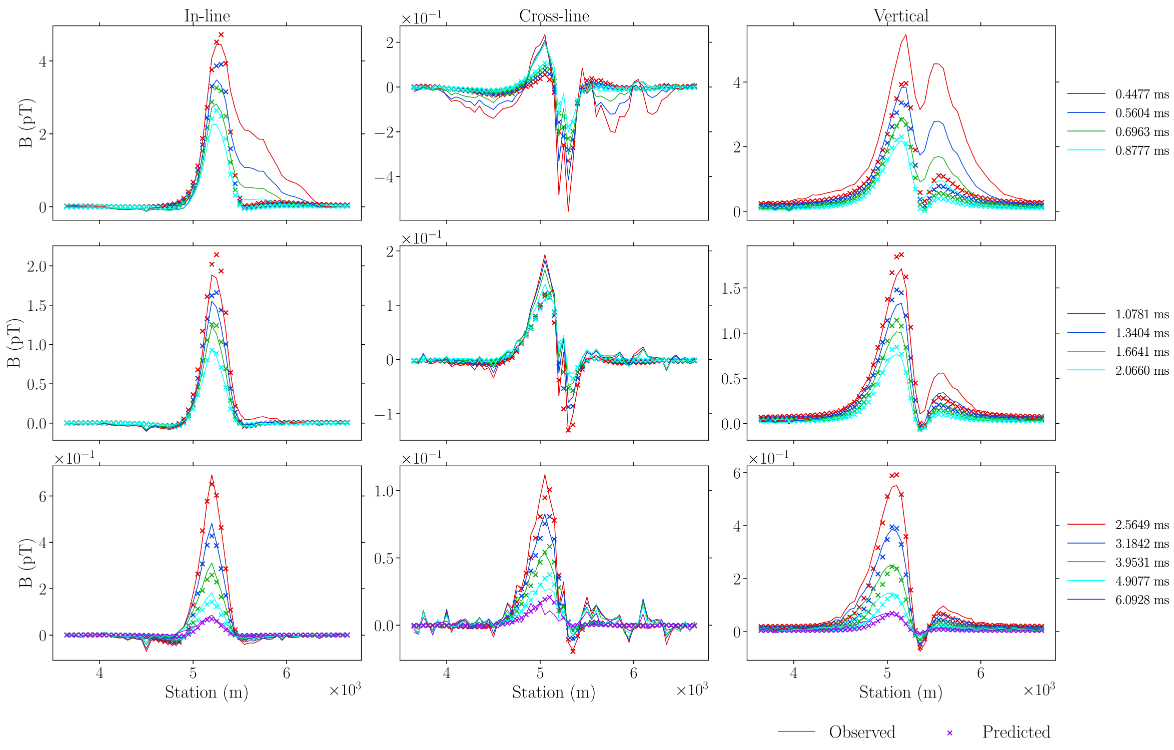
Data fitting

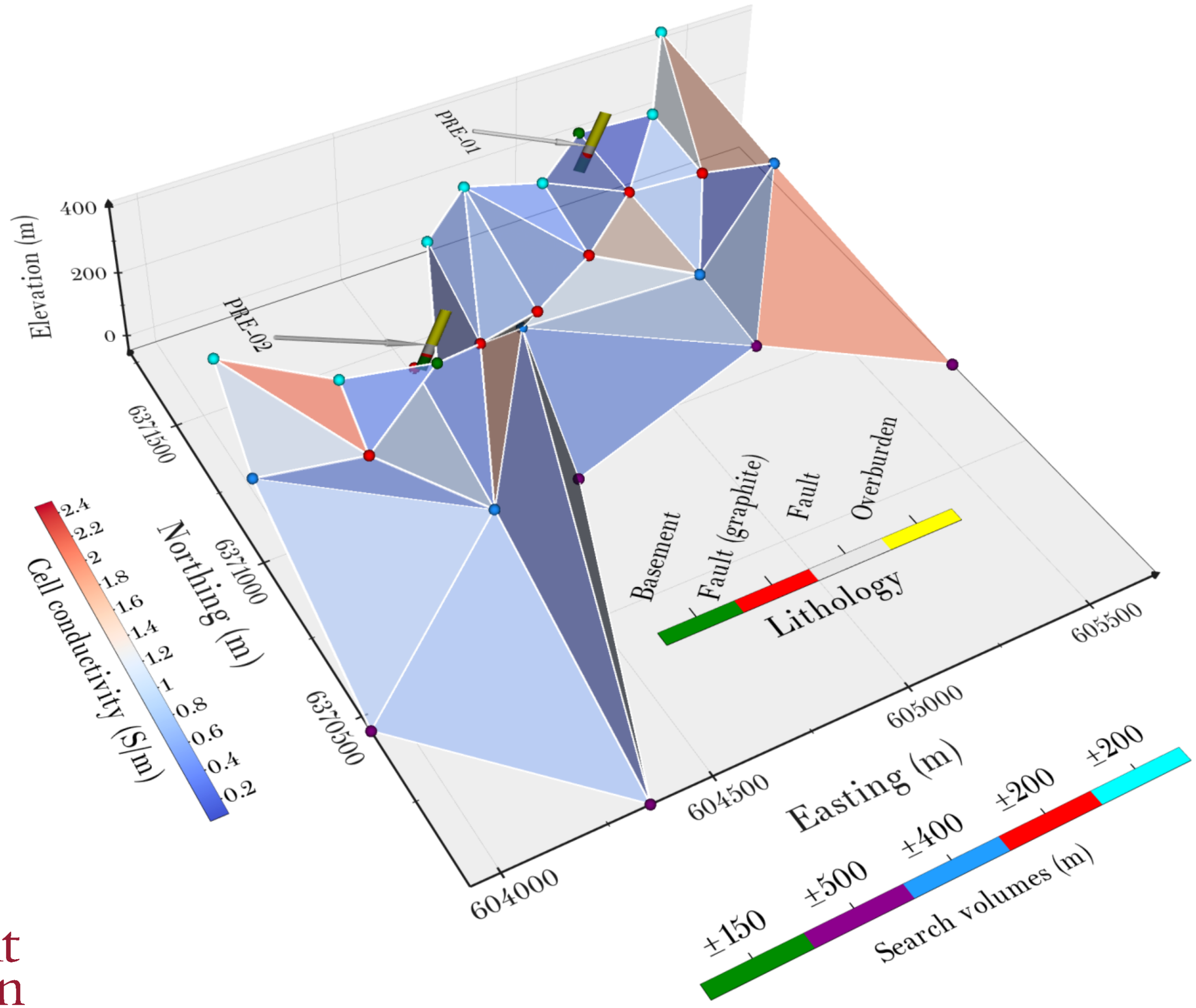


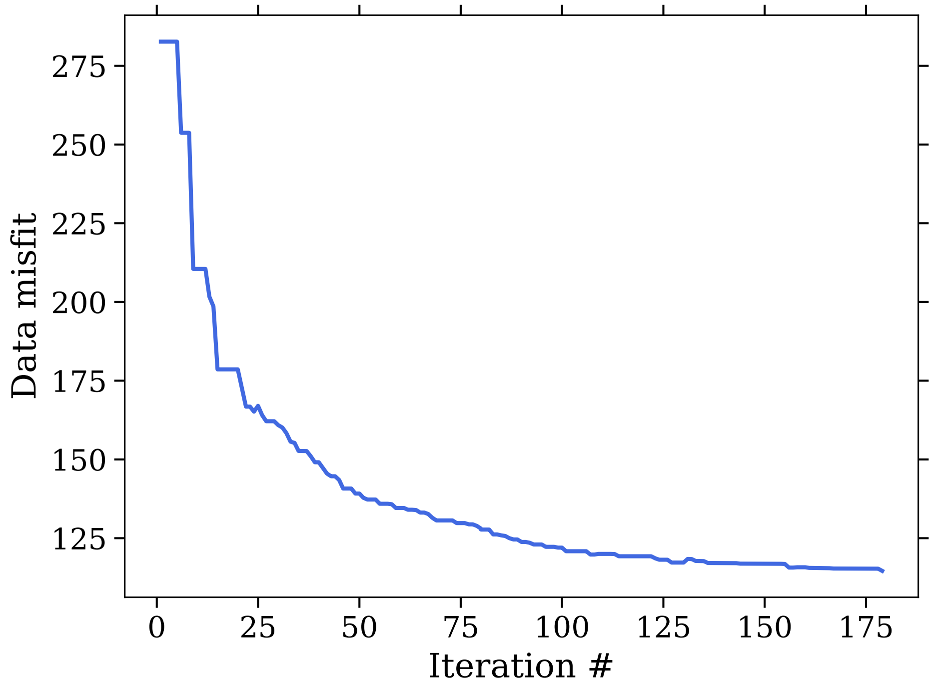
Data fitting of L2400E



Data fitting of L3200E

Constructed model and convergence





Each iteration takes about 1 hour to finish

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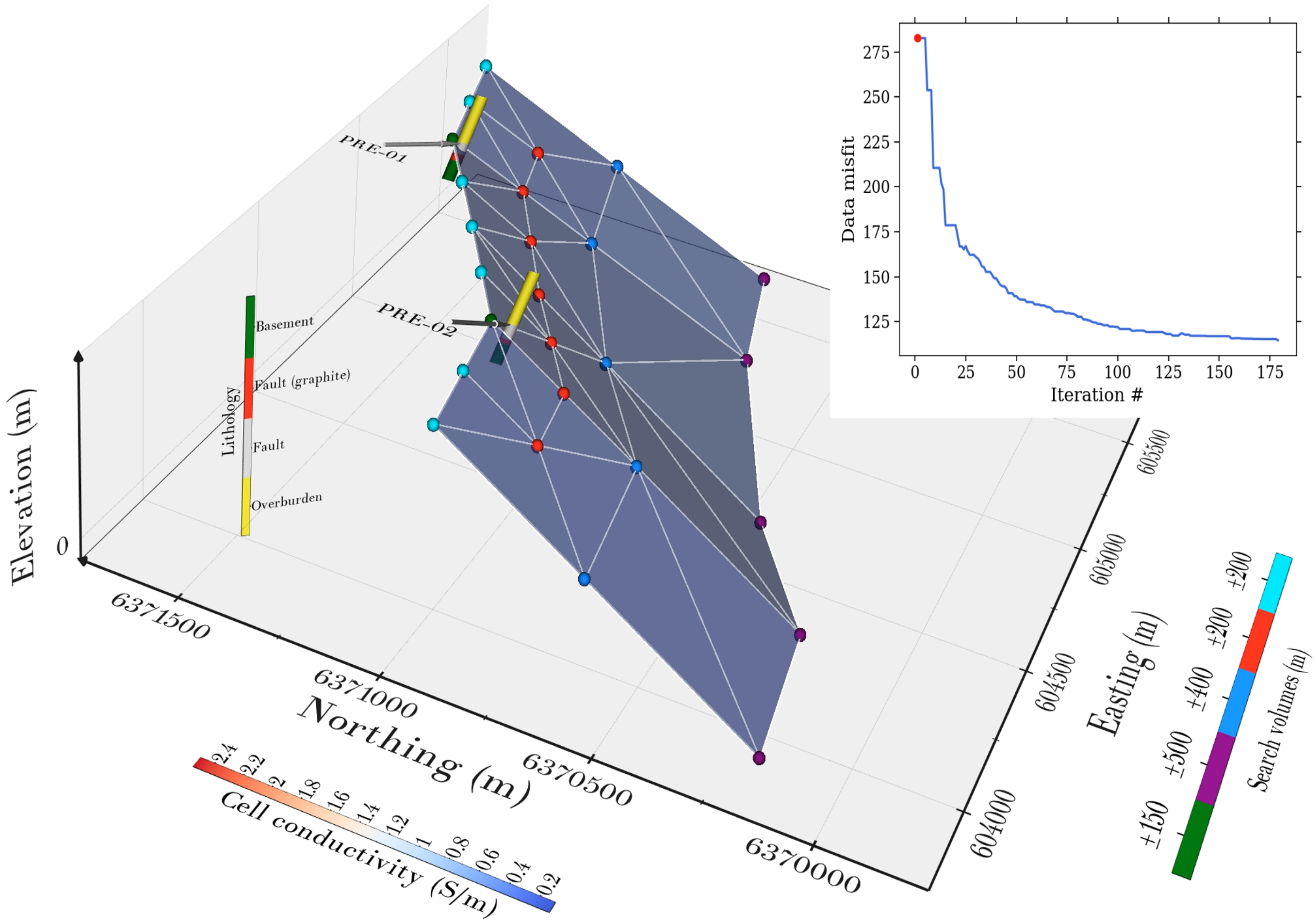
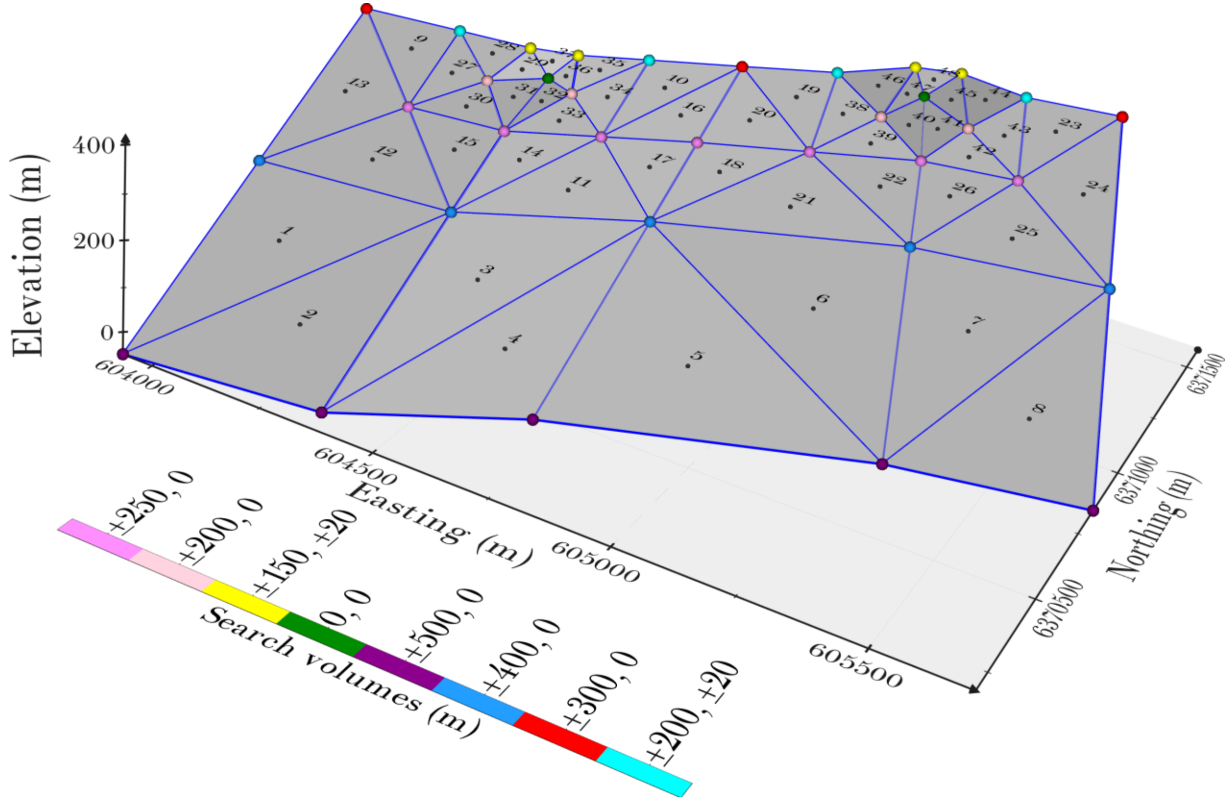
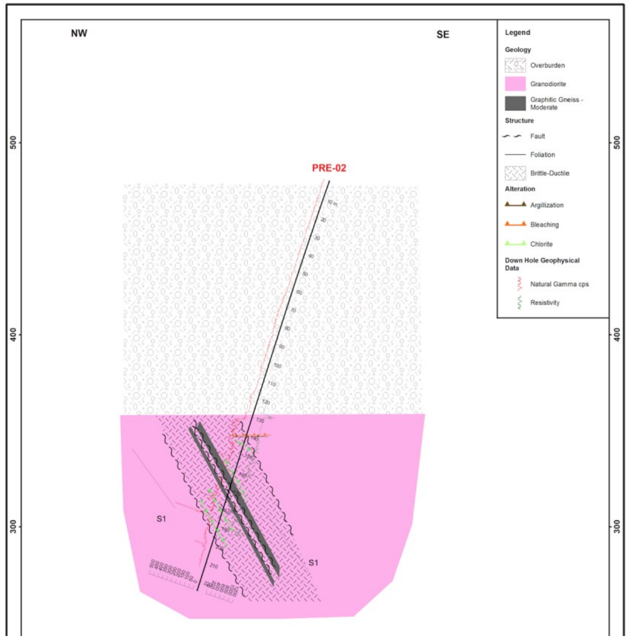
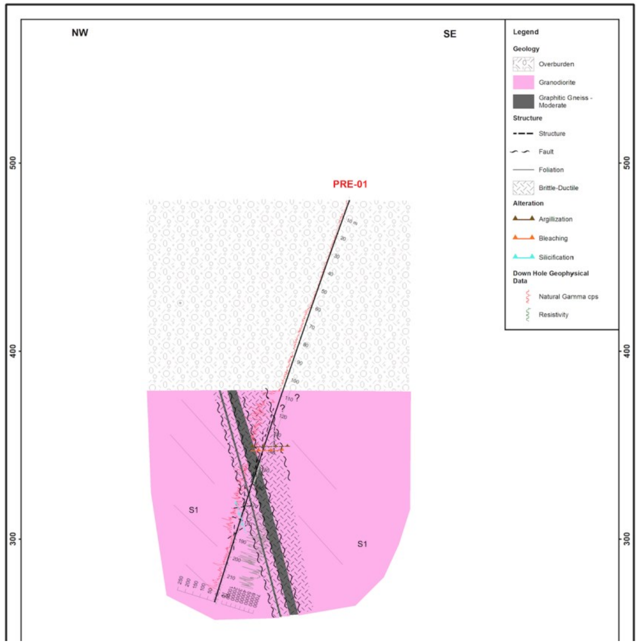

PRE-01
PRE-02
Basement
Fault (graphite)
Fault
Overburden
Lithology
Elevation (m)
0
6371500
6371000
6370500
6370000
Northing (m)
604000
604500
605000
605500
Easting (m)
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
Cell conductivity (S/m)
±200
±200
±400
±500
±150
Search volumes (m)
Data misfit
275
250
225
200
175
150
125
0
25
50
75
100
125
150
175
Iteration #

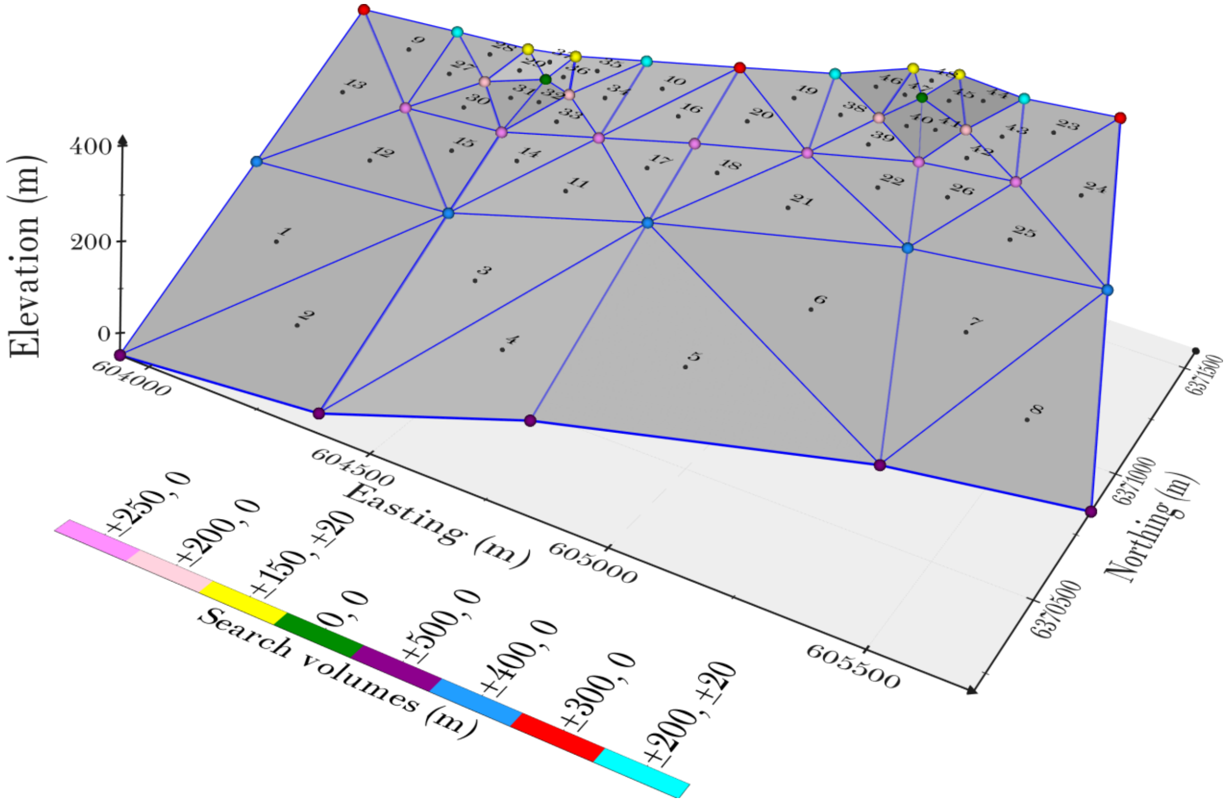
Constrained inversion







Constrained inversion



- # parameters: 88 (32 nodes moving along strike, 8 nodes moving vertically, and 48 regions)
- GA population size: 599
- Data uncertainties: max(std, 2% data)
- 15 nodes with 600 CPU: Intel® Xeon® Gold 6248 Processor @ 2.5 GHz
- 1 CPU for each model (1 MPI process with 1 OMP thread)

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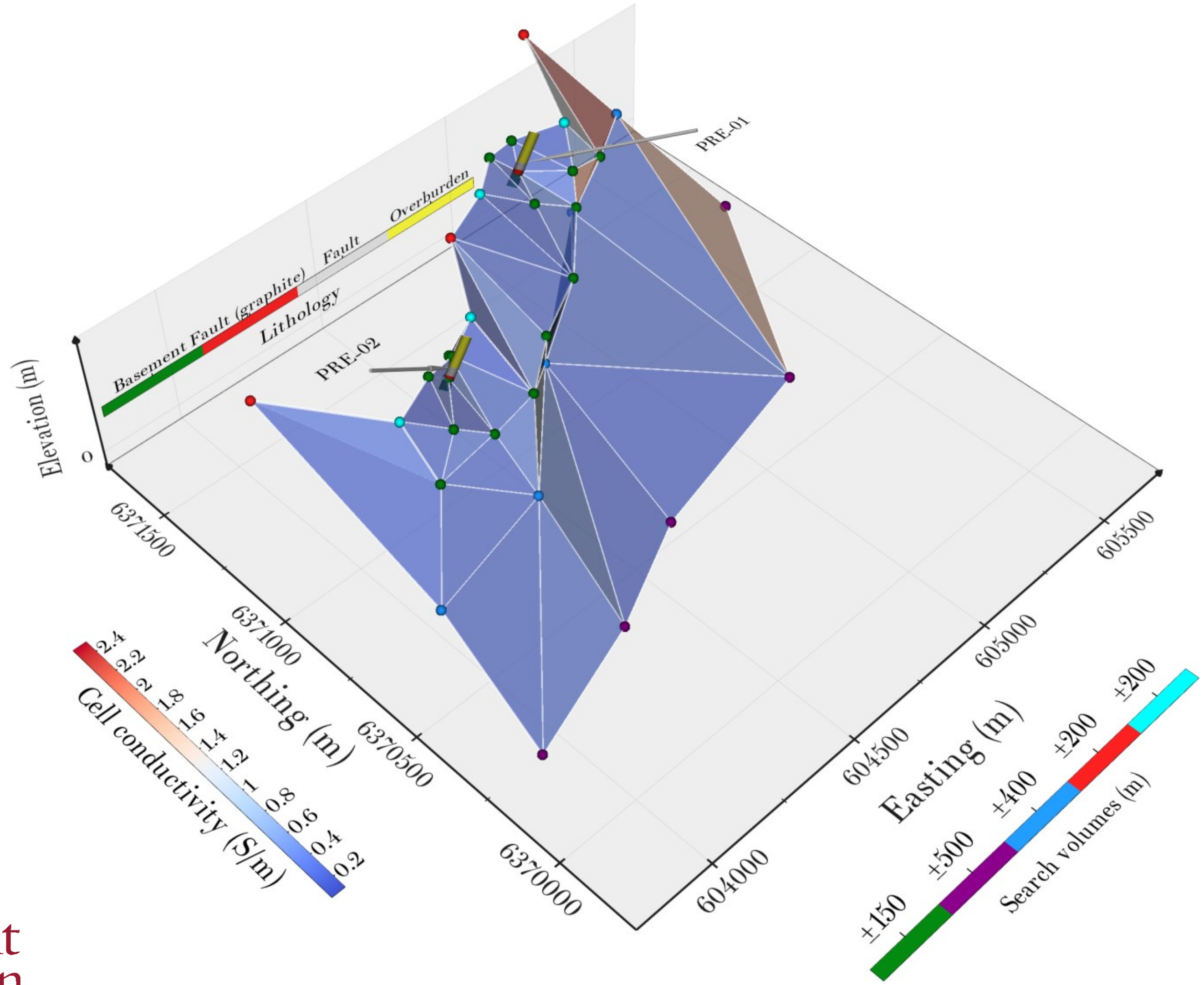
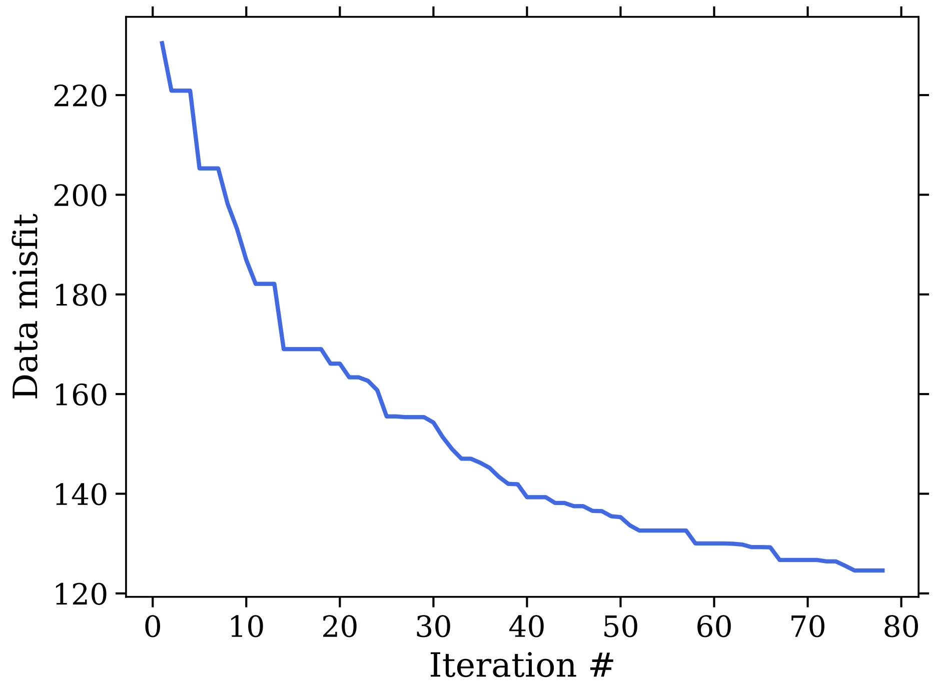
Constructed model and convergence





Each iteration takes about 1 hour to finish

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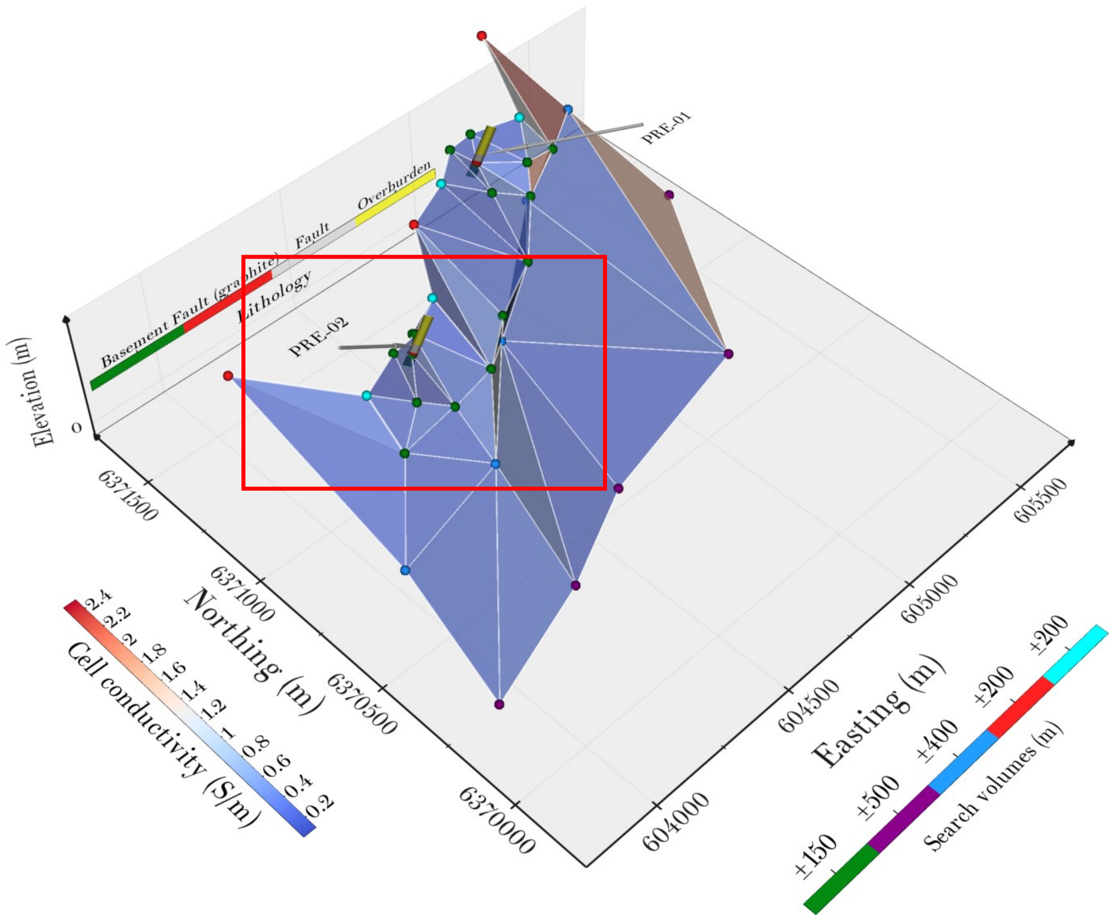
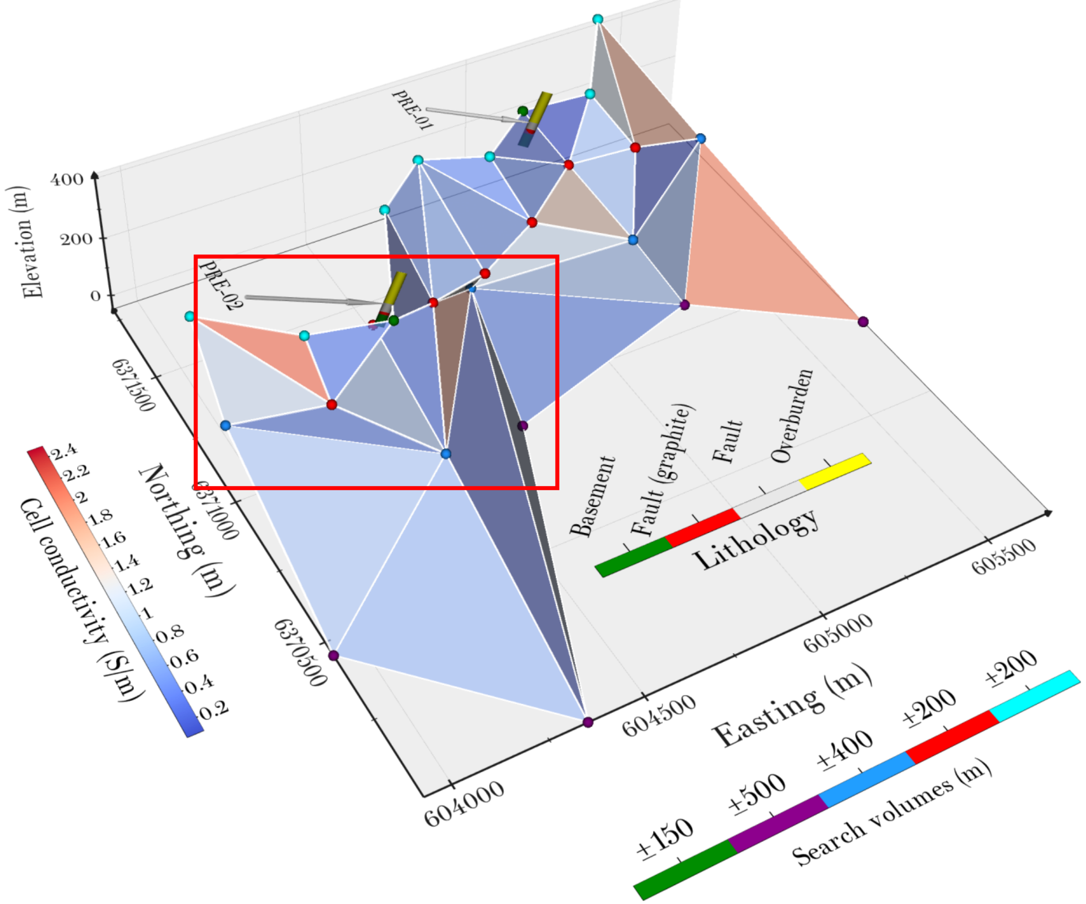
Constrained VS unconstrained



Constrained



Unconstrained

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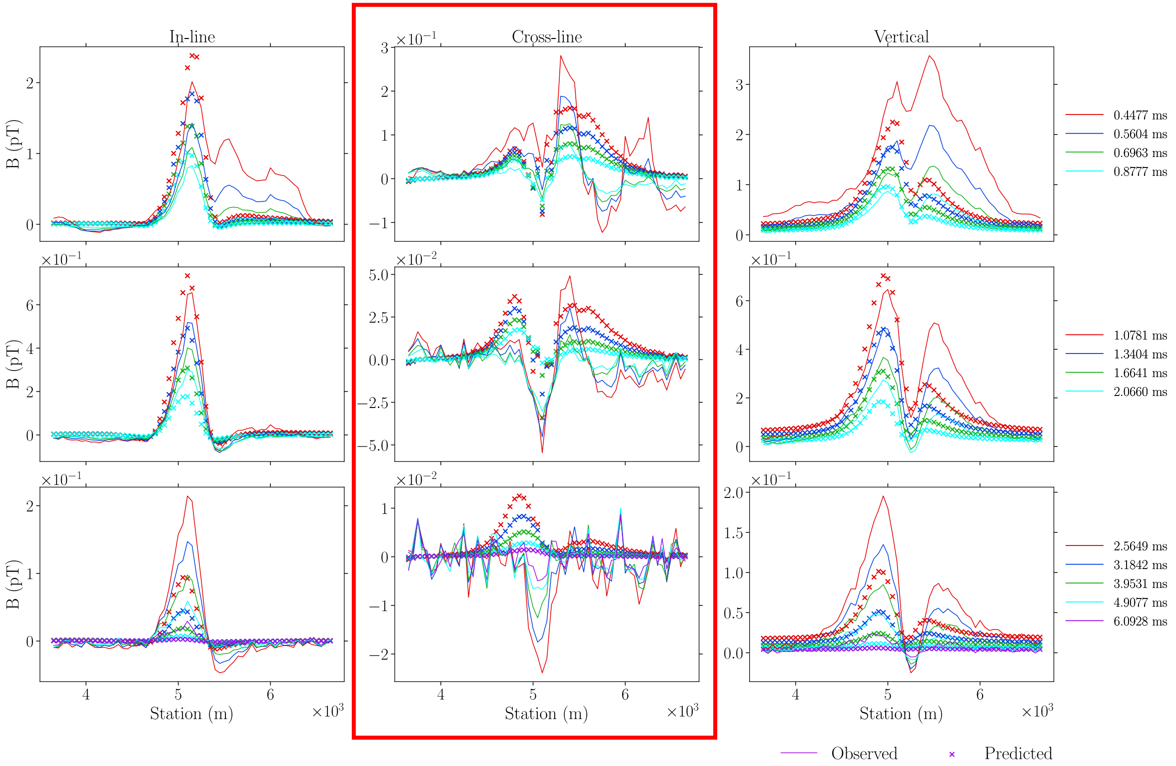
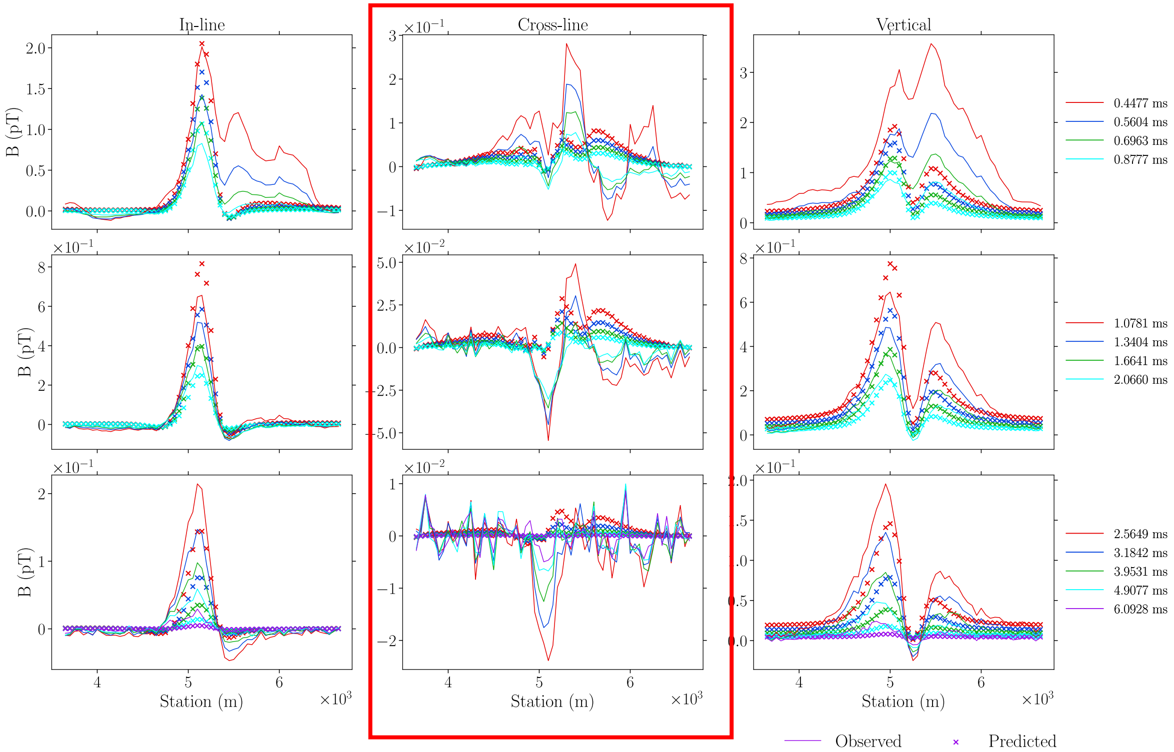
Constrained VS unconstrained (L2400E)



Constrained



Unconstrained

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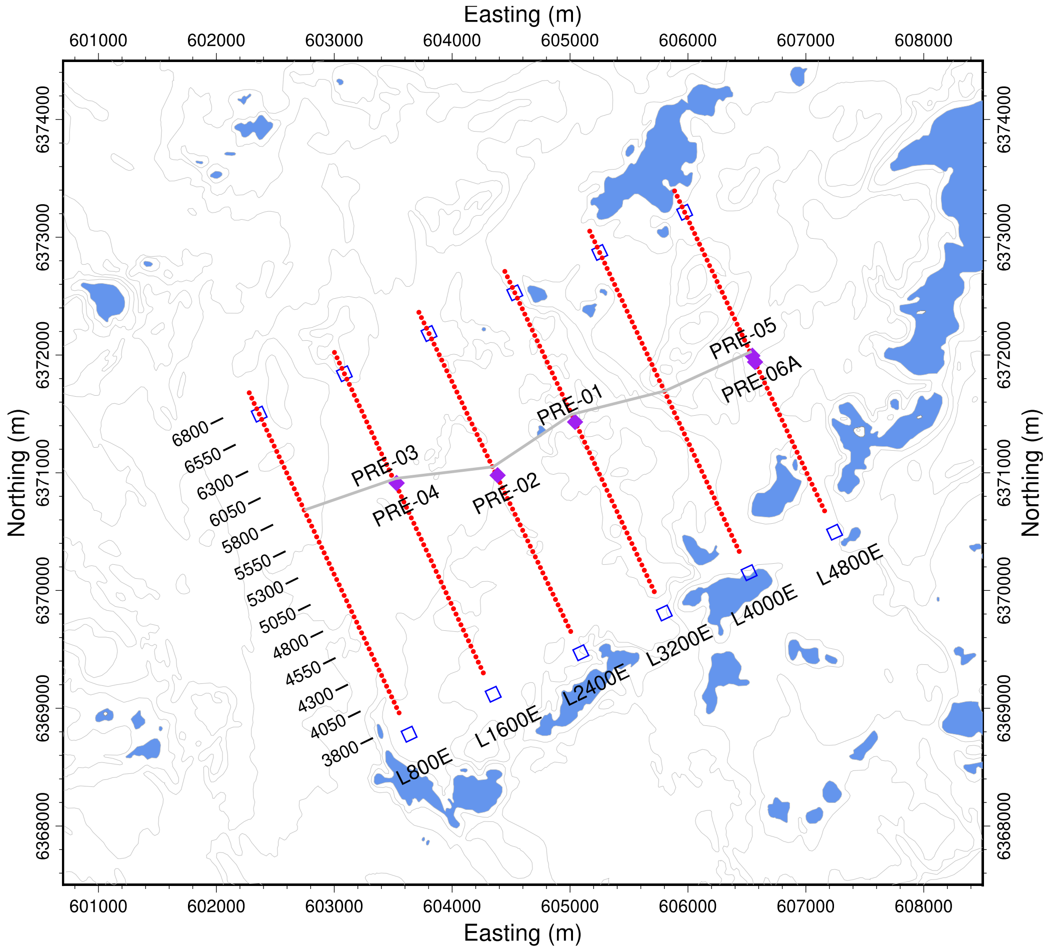
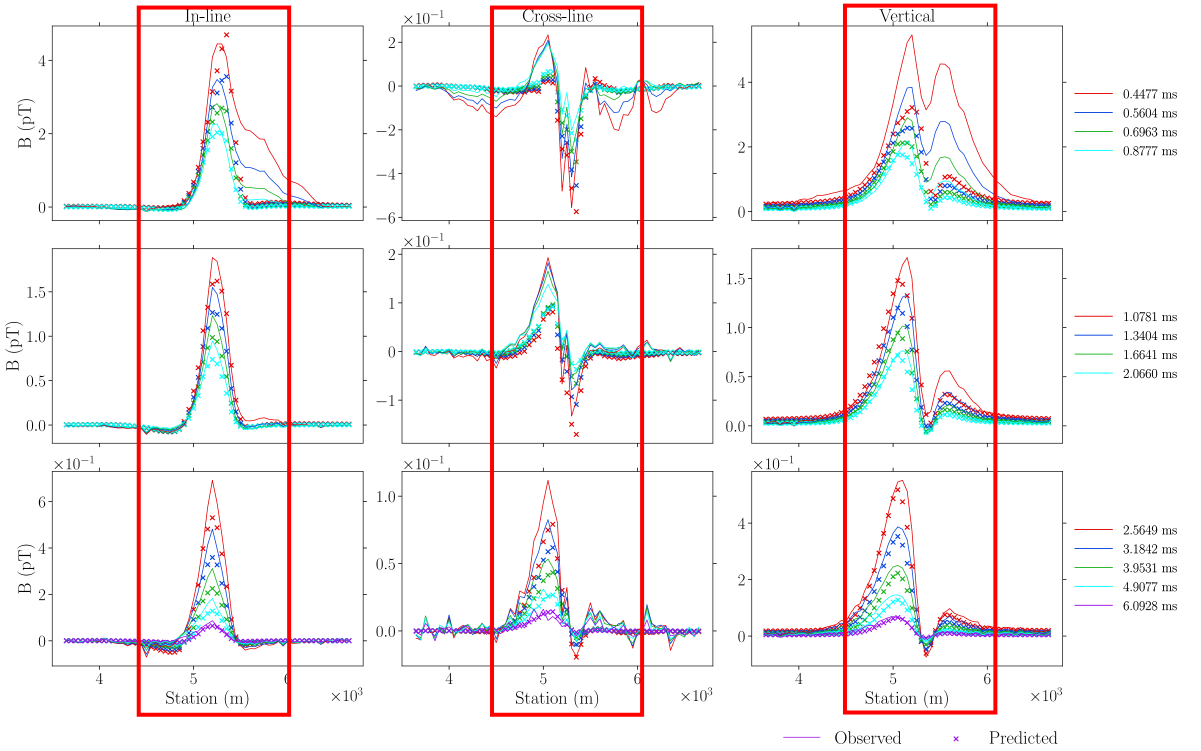
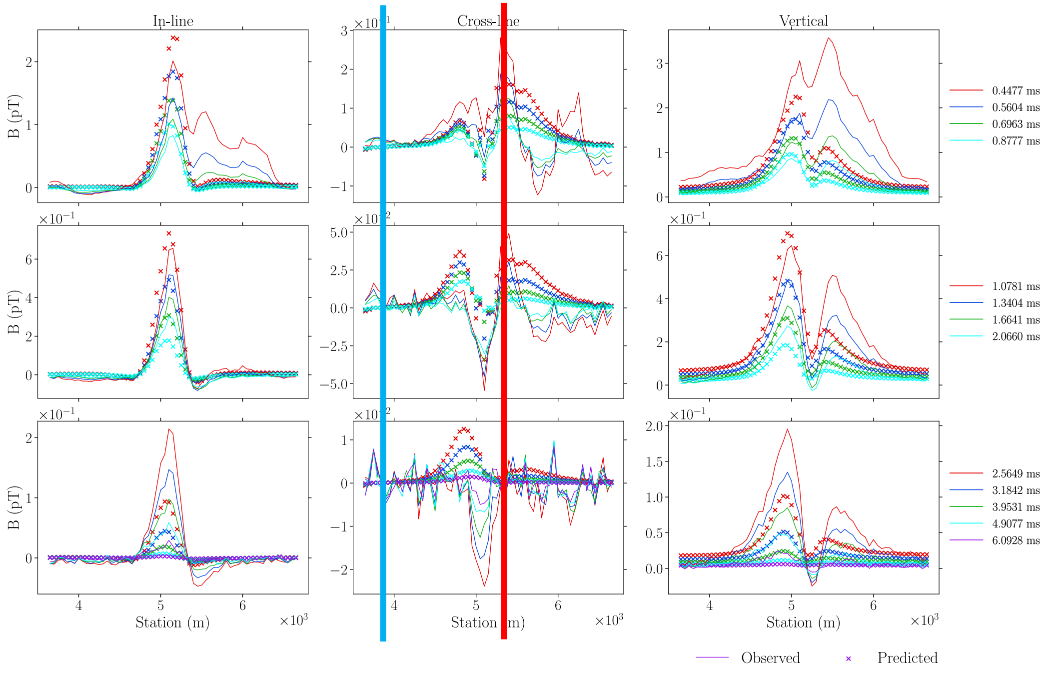
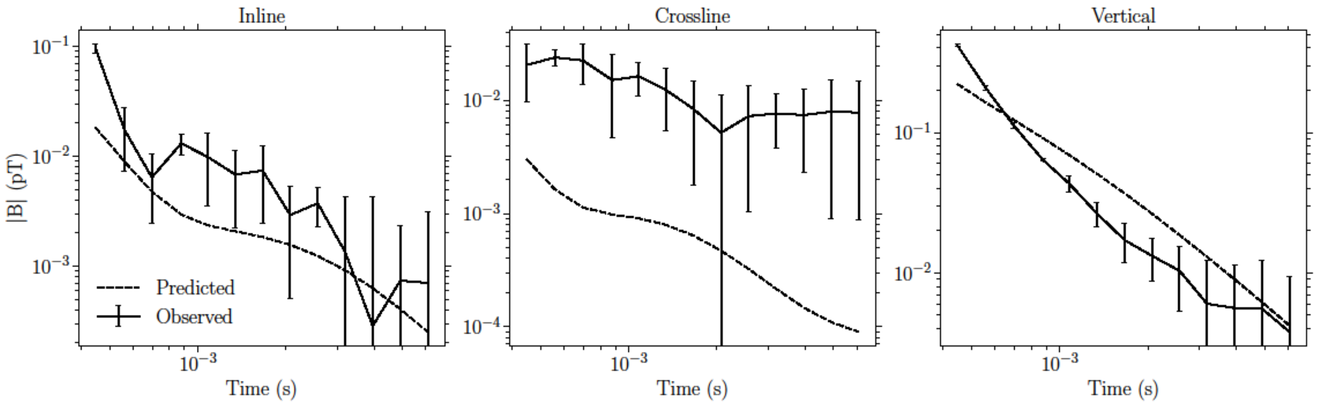
Decimated data inversion



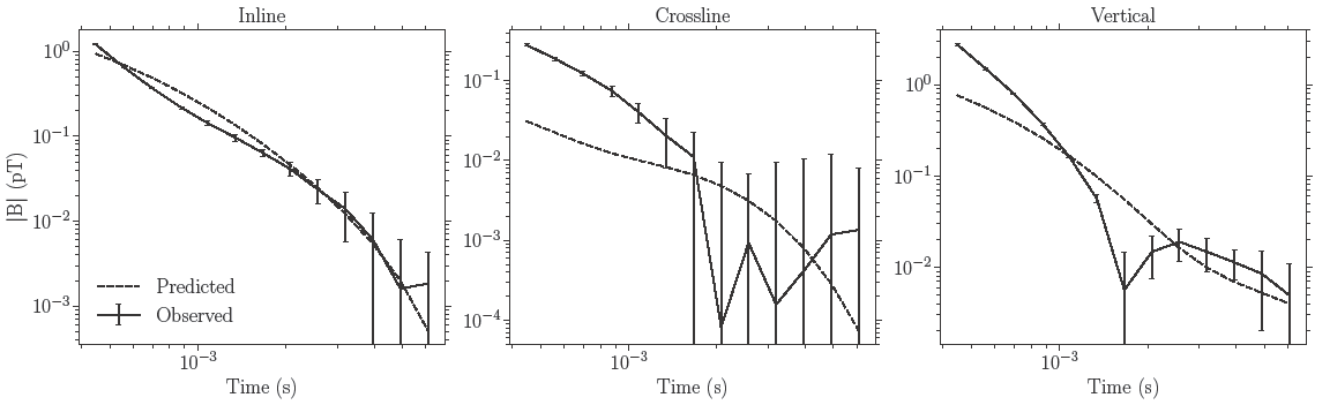


Decimated data inversion





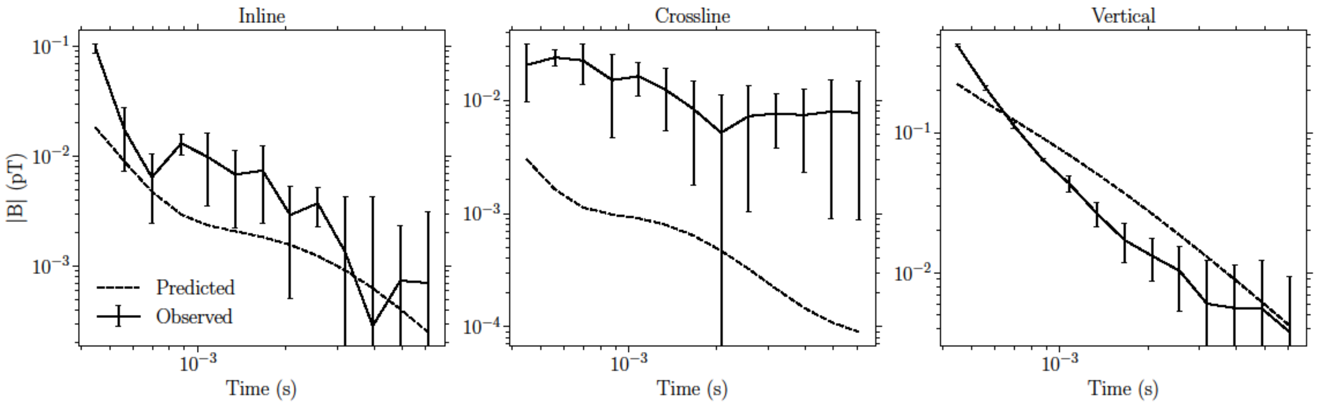
Station 3900S



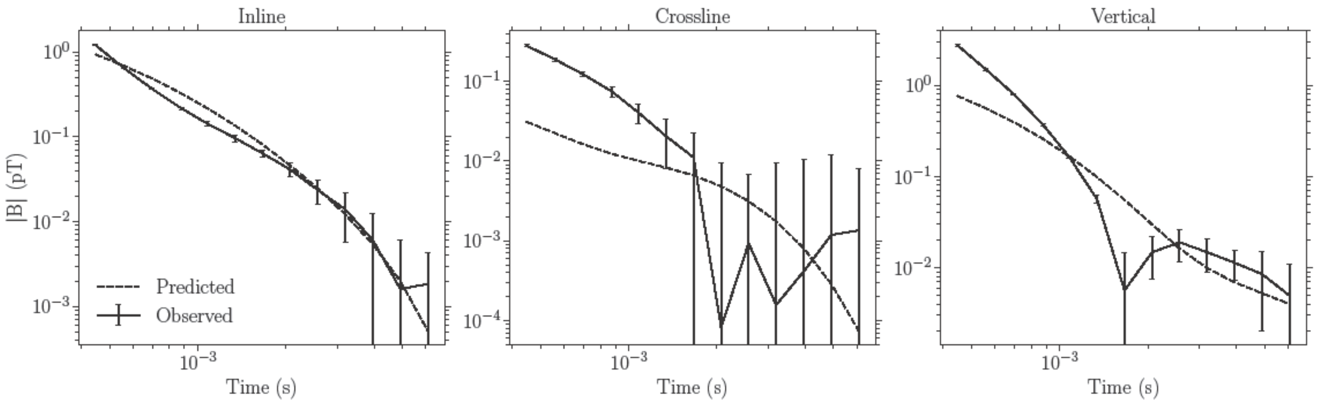
Station 5450S

Uncertainty calculation

- Uncertainty calculation:
  - Std from 3 measurements
  - Max(std, 2% of data)
  - No noise floor used



Station 3900S

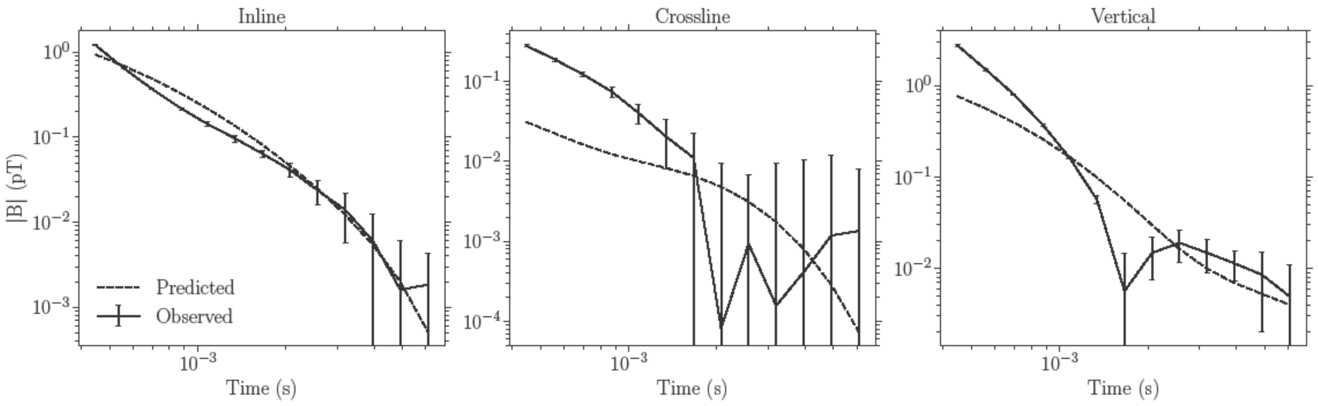


Station 5450S

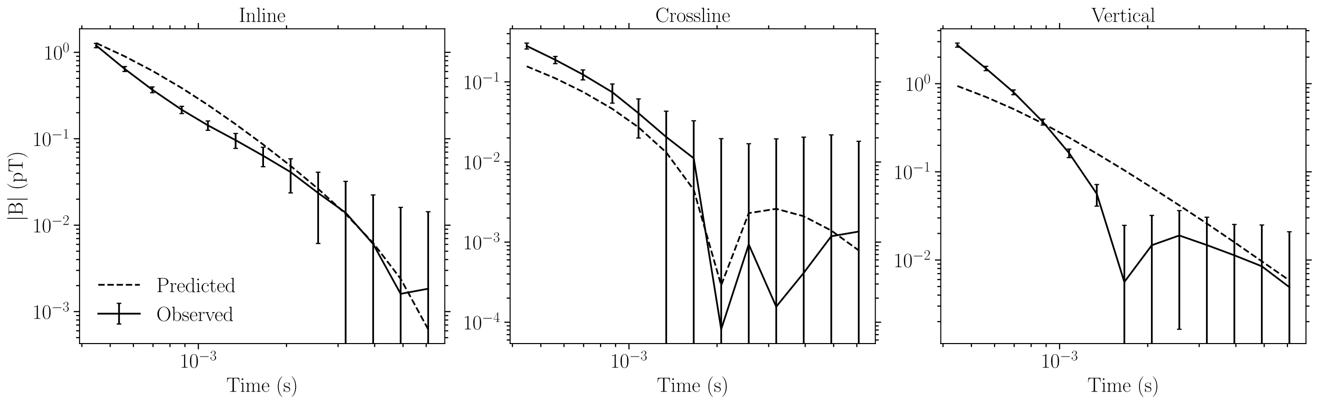
Updated uncertainty calculation

- Uncertainty calculation:
  - Std from 3 measurements
  - Max(std, 2% of data)
  - No noise floor used

- Updated uncertainty calculation
  - Std from 3 measurements
  - Max(std, 5% of data)
  - Noise floor: 0.001 pT

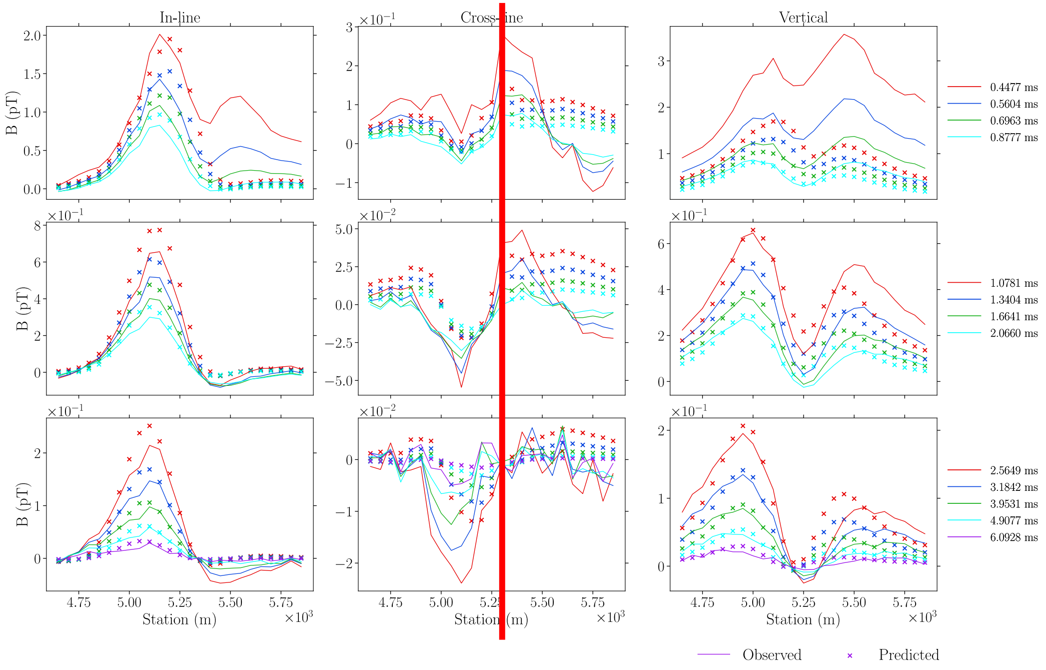


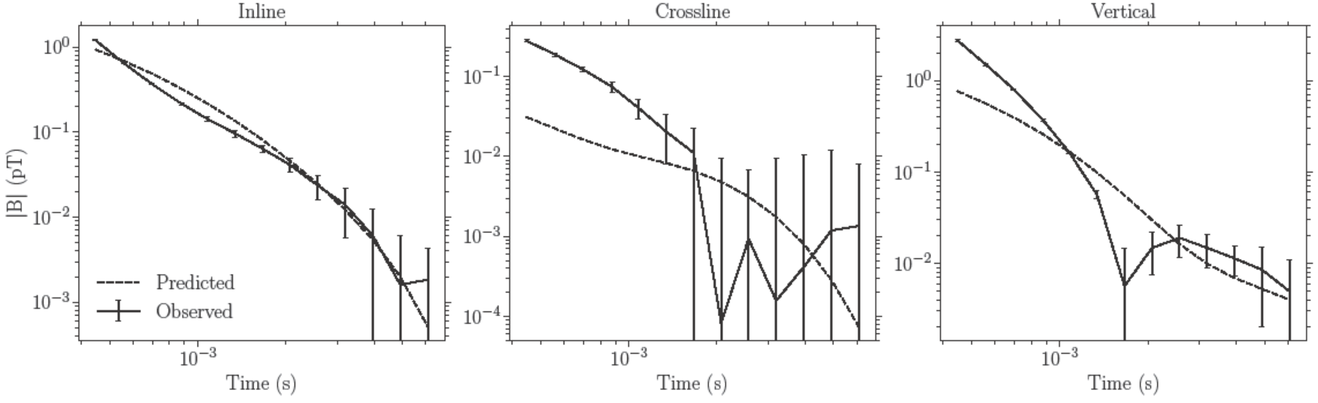
Original Station 5450S



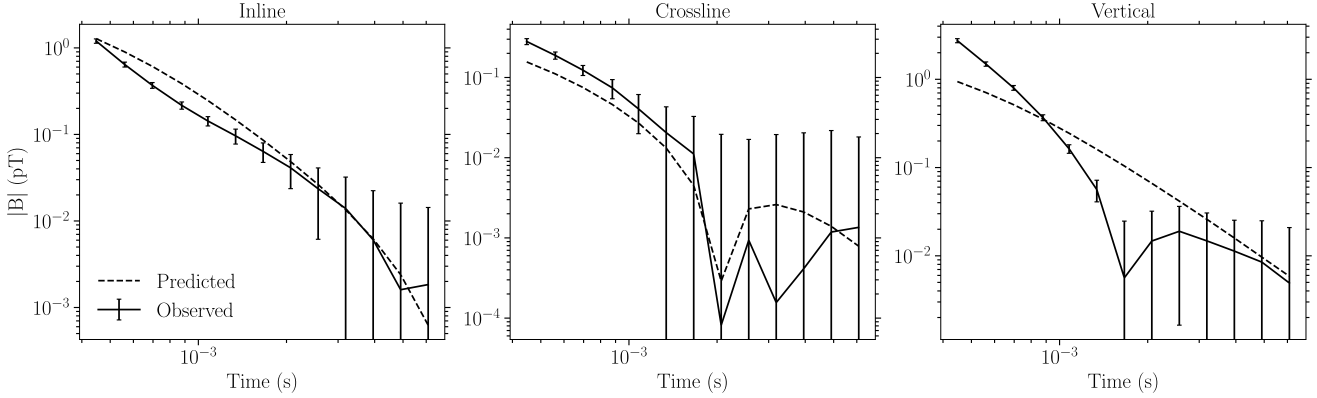
Decimated Station (5450S)

Decimated data inversion



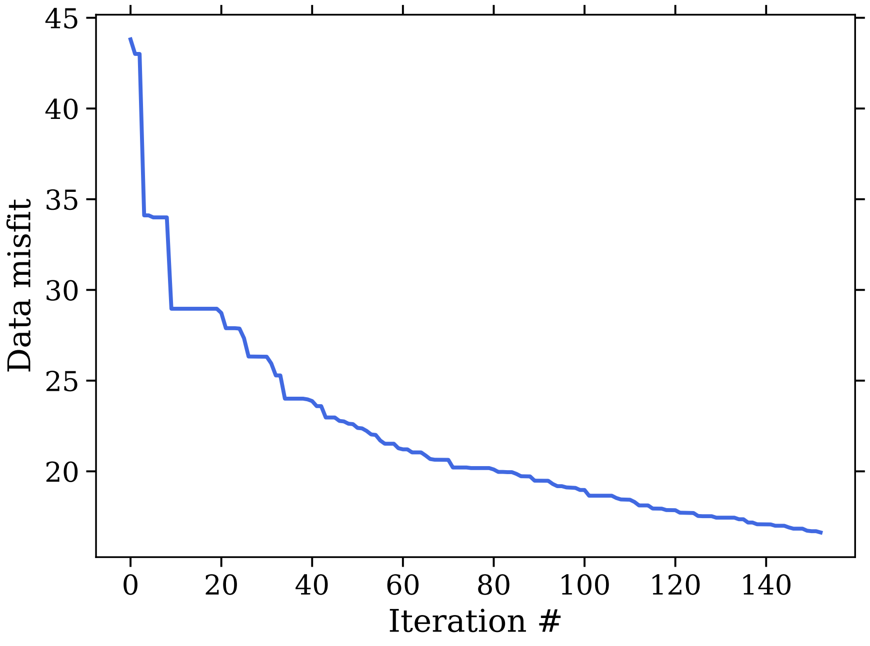


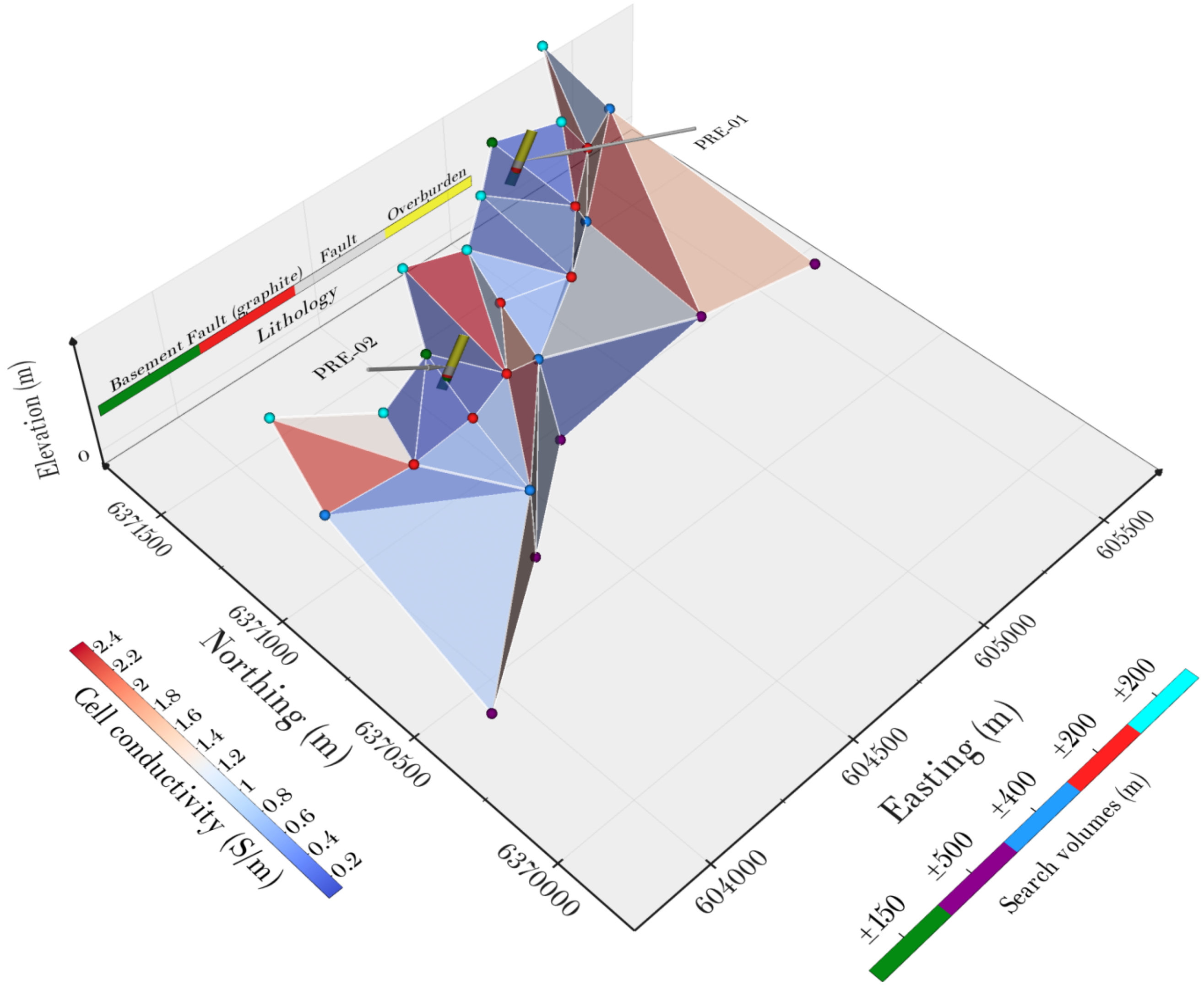
Original Station 5450S



Decimated Station (5450S)

Decimated data inversion





Each iteration takes about 40 minutes to finish

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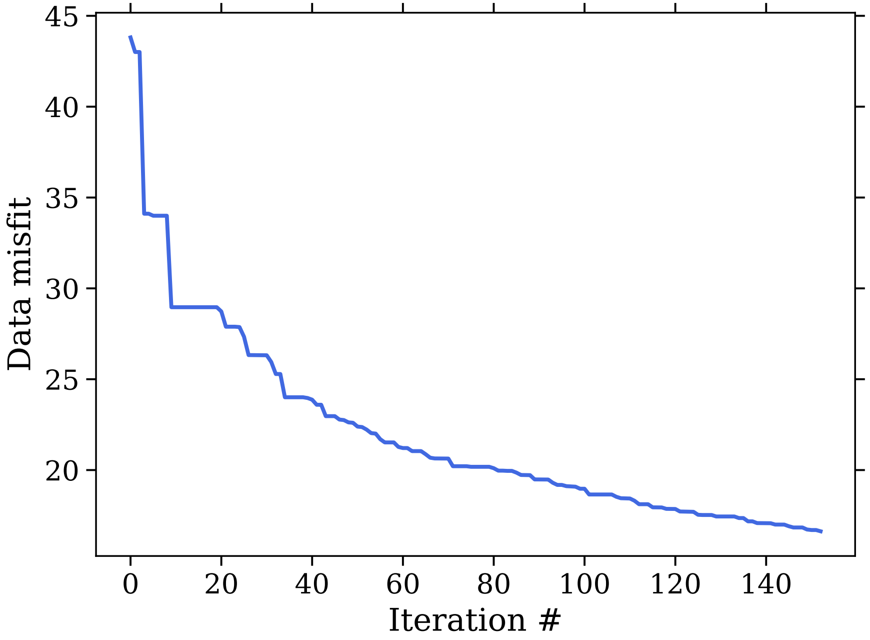
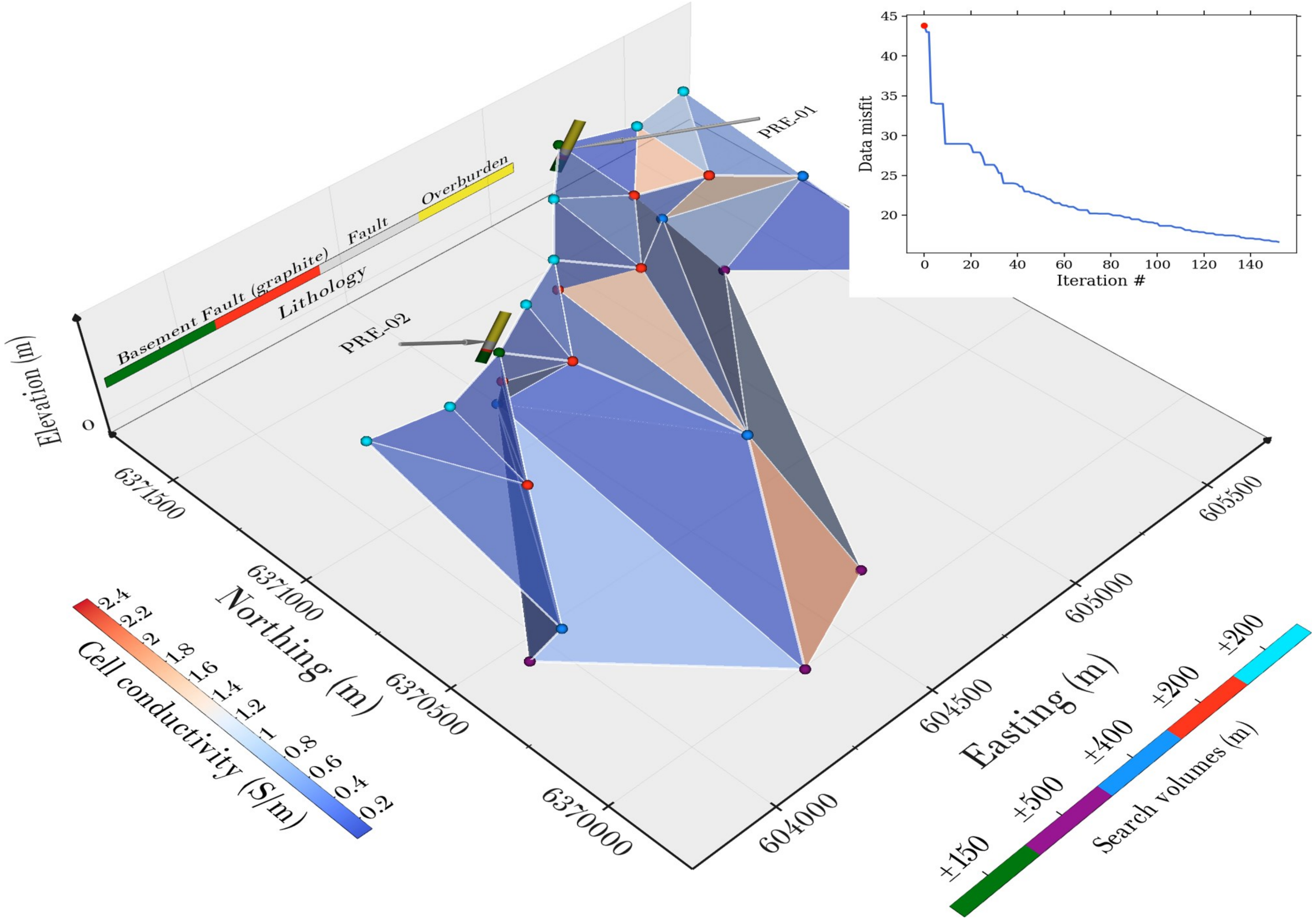
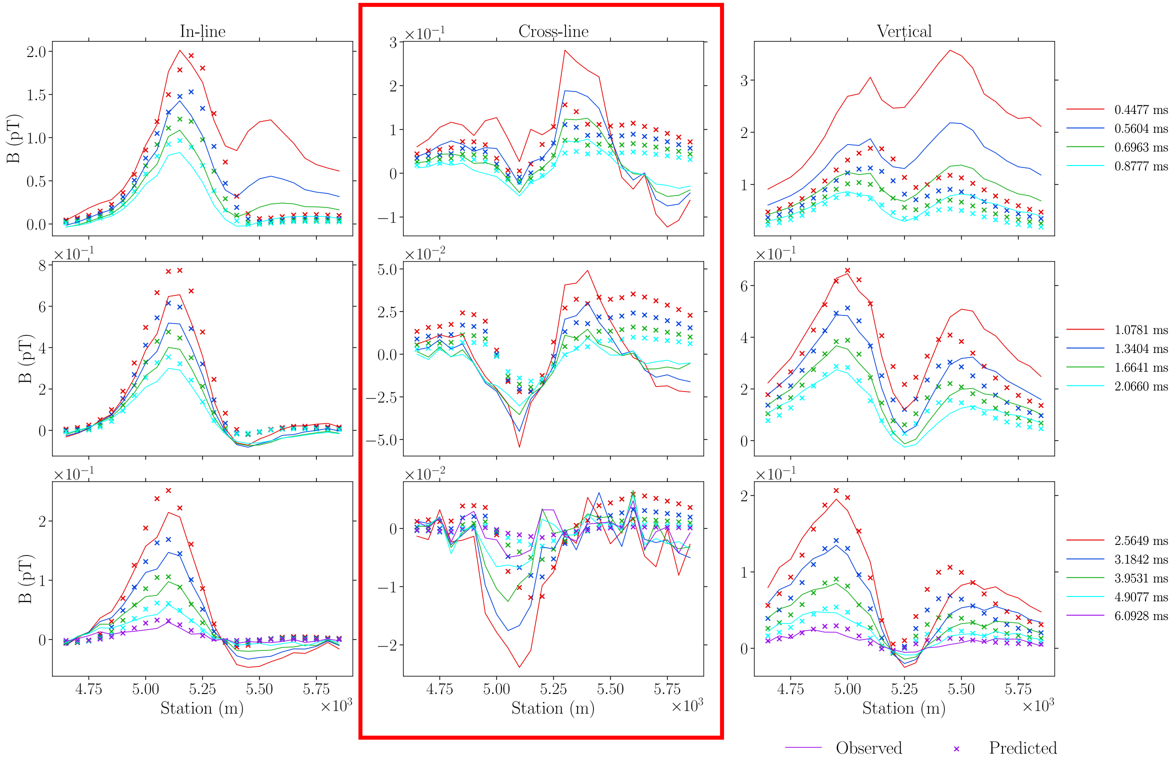
Decimated data inversion



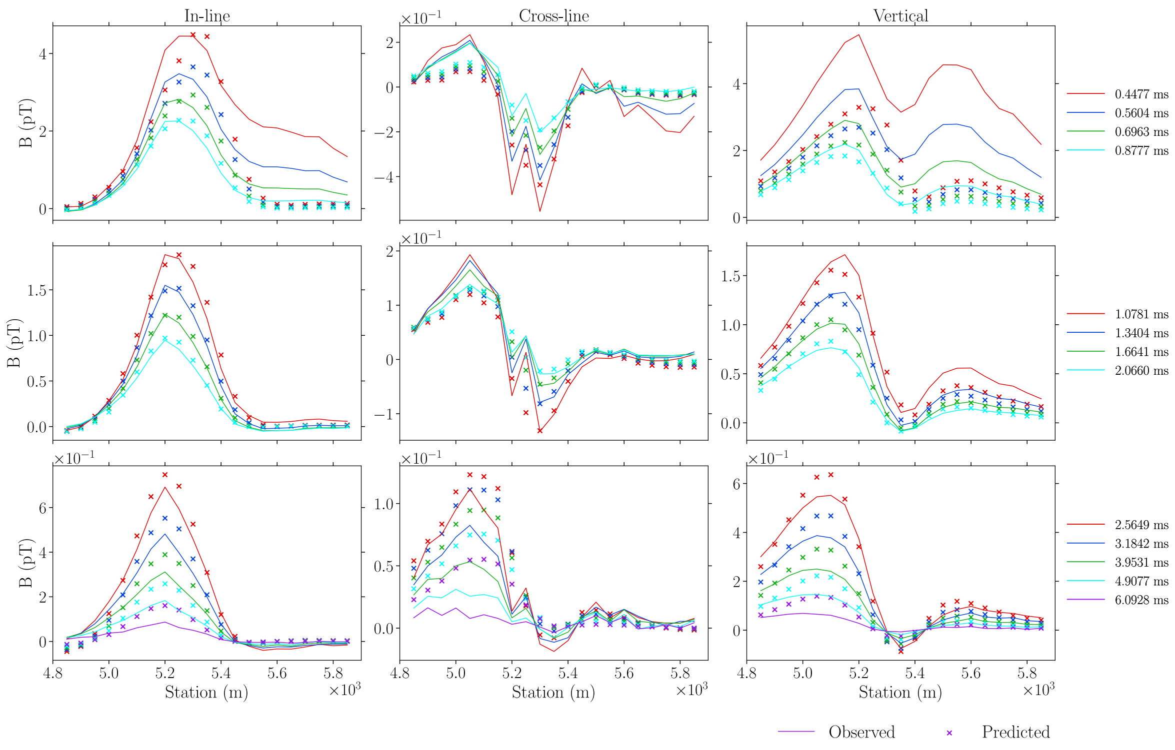


Each iteration takes about 40 minutes to finish

Data fitting



Data fitting of L2400E



Data fitting of L3200E

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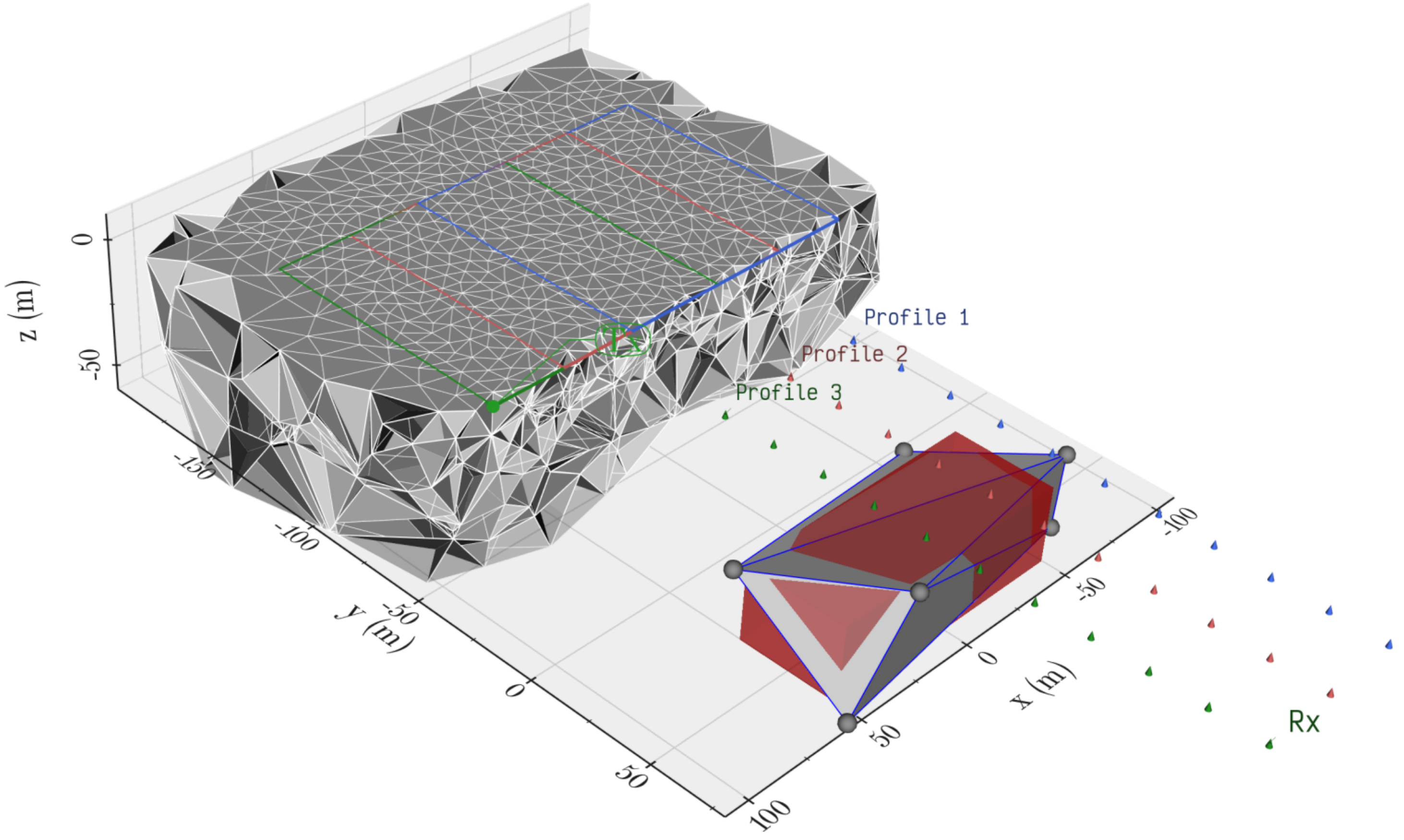
Uncertainty quantification: MCMC sampling



True model (red); Recovered model (gray)

- Block in half-space
- Moving loop survey
- Three profiles
- Background: 0.01 S/m
- Block: 2 S/m
- Parameterization: 8 nodes
- # parameters: 24
- Population size: 239
- Search volume: +/-30 m, +/-15 m, +/- 15 m in x-, y-, and z-direction

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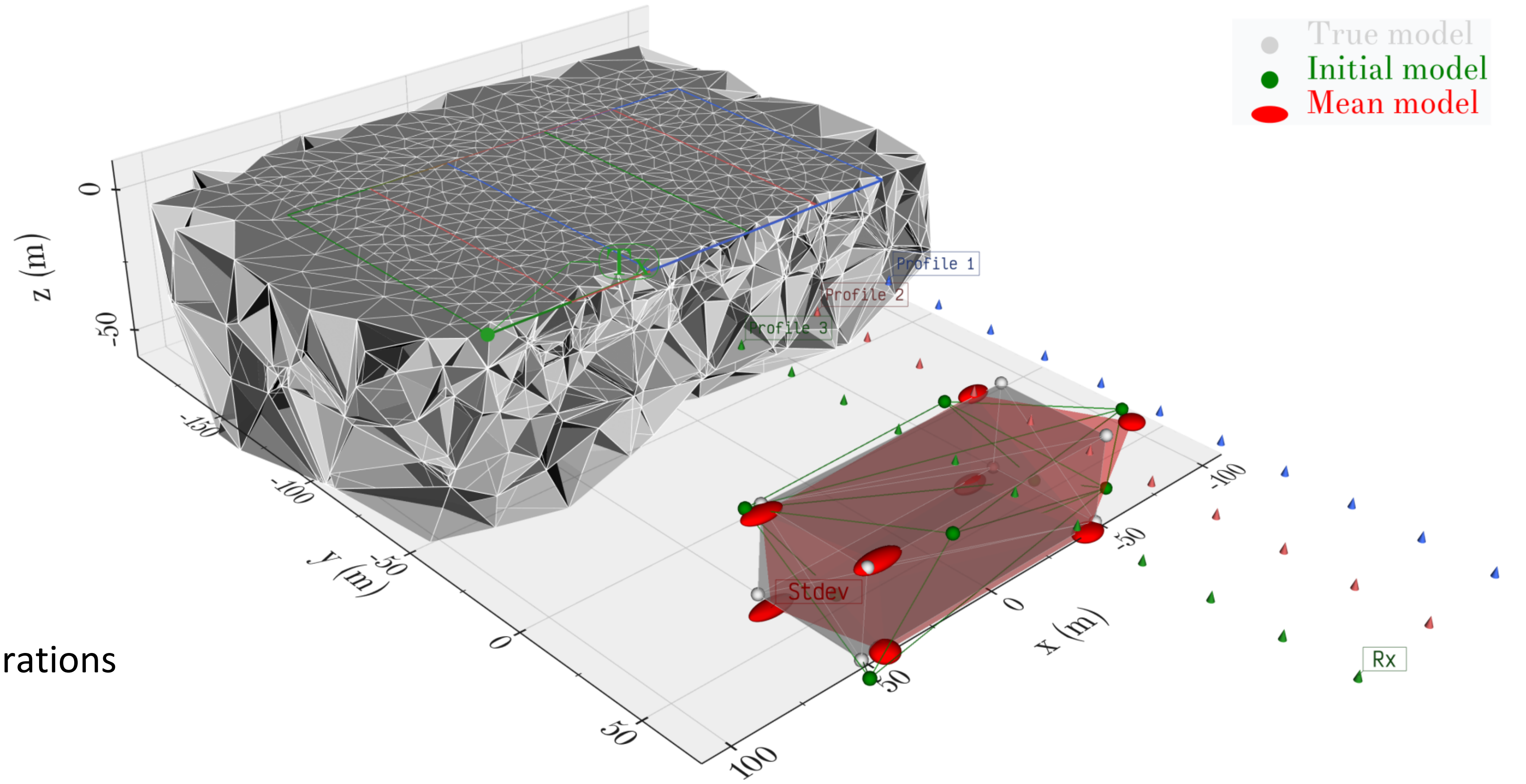
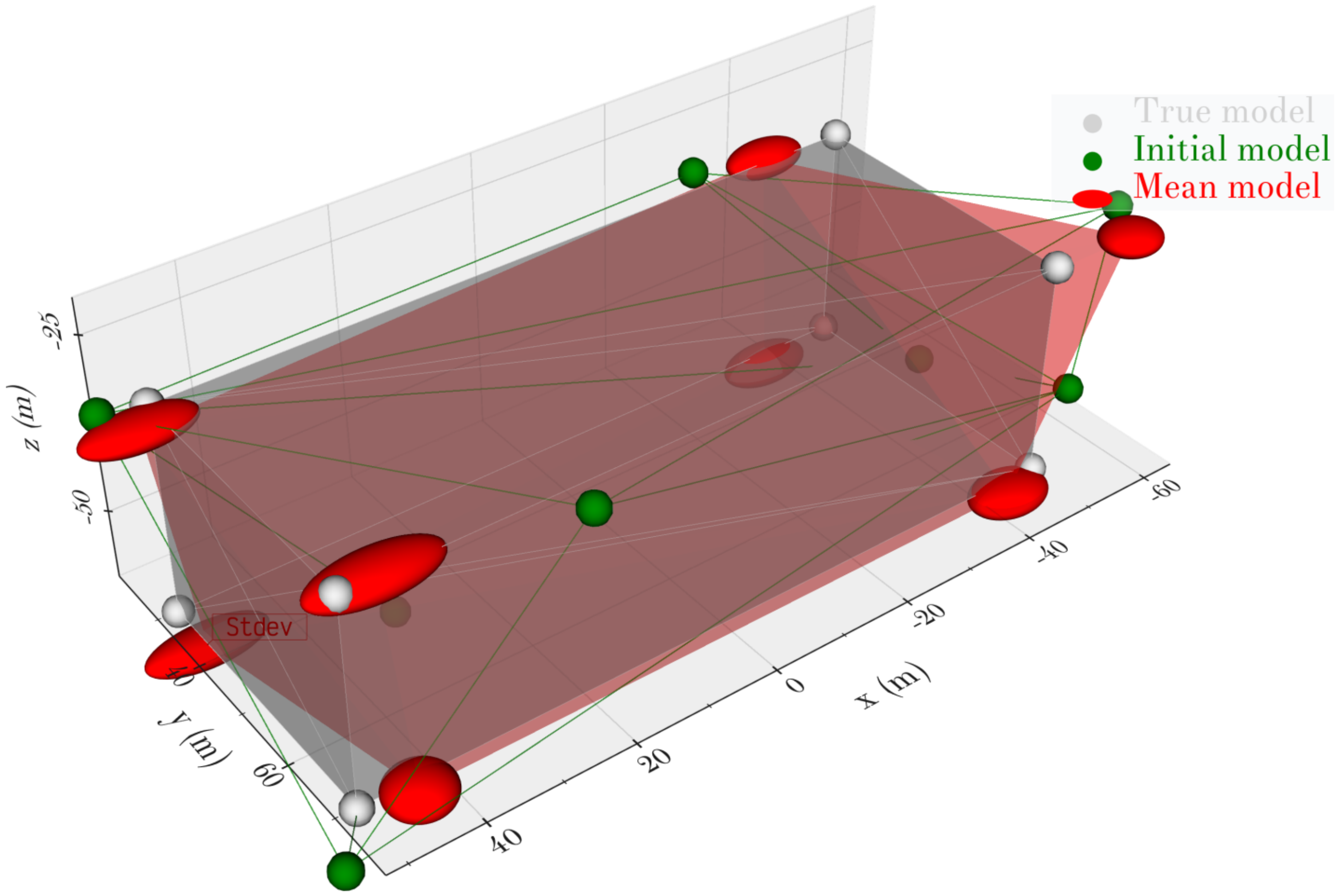
Uncertainty quantification: MCMC sampling



78,000 iterations

Mean model (red) is much closer to the true model (gray)

Uncertainty quantification: MCMC sampling



- Mean model is closer to the true model
- Uncertainty (standard deviation) is the largest in the x-direction
- In general, bottom nodes have larger uncertainty
- Uncertainty is also related to the initial model
- Uncertainty is the smallest in the z-direction

Outline

- Motivation
- Surface geometry inversion
- Marine CSEM examples
- TEM examples
- **Conclusions**

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Conclusions

- We have implemented a SGI algorithm for EM data
- The SGI algorithm works with both blocky and thin, plate-like anomalies
- The SGI algorithm has been tested using both synthetic and real-data examples
- Data uncertainties can significantly affect the inversion results
- Cross-line component of a MLTEM survey is also important
- MCMC sampling can be used for model uncertainty quantification

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