Introduction to unconstrained inversion and petrophysical constraints using Tomofast-x

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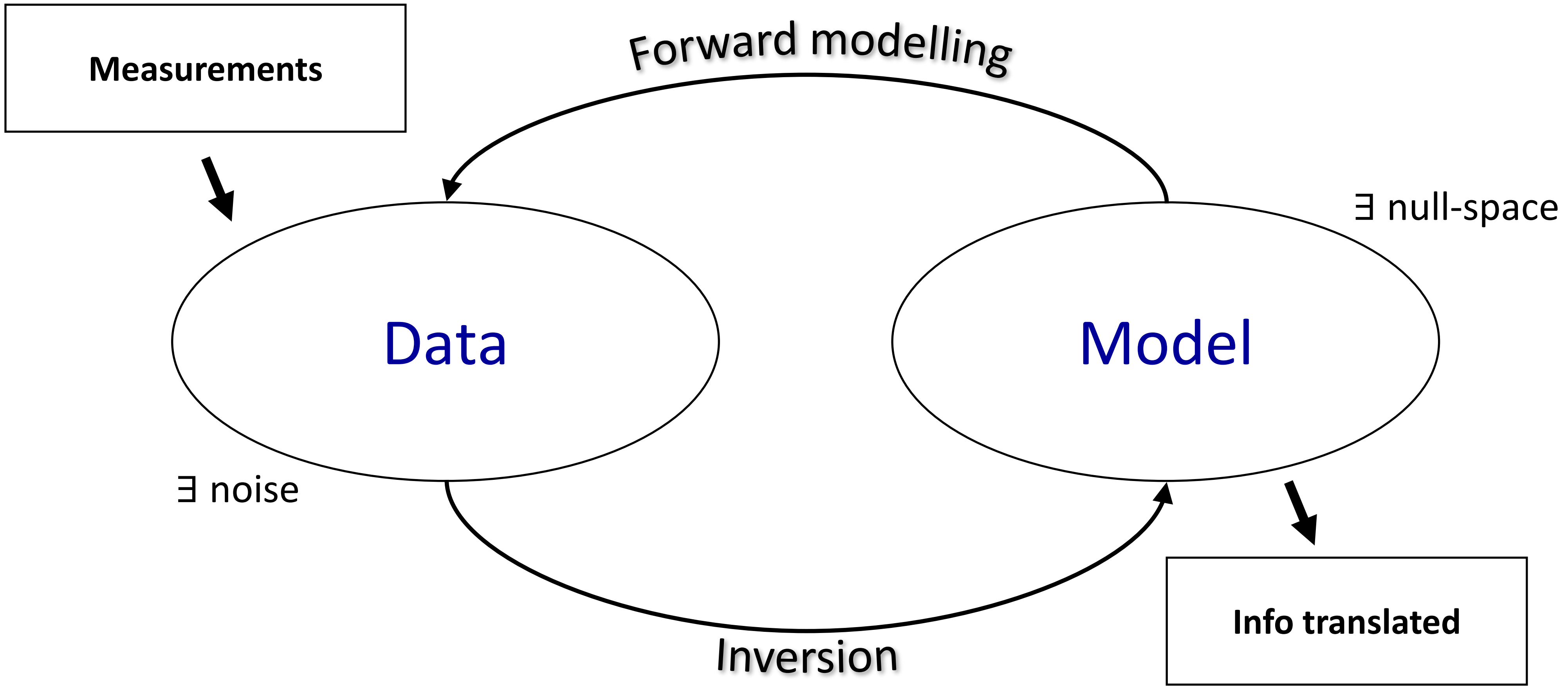
Jeremie Giraud, Roland Martin, Mark Jessell

THE UNIVERSITY OF WESTERN AUSTRALIA

ExploreGeo
Geophysical Consultants To Explorers

Inversion in a nutshell



Non-unique, can be tricky

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https://doi.org/10.5194/gmd-17-2325-2024

Geoscientific Model Development
Open Access

Tomofast-x 2.0: an open-source parallel code for inversion of potential field data with topography using wavelet compression

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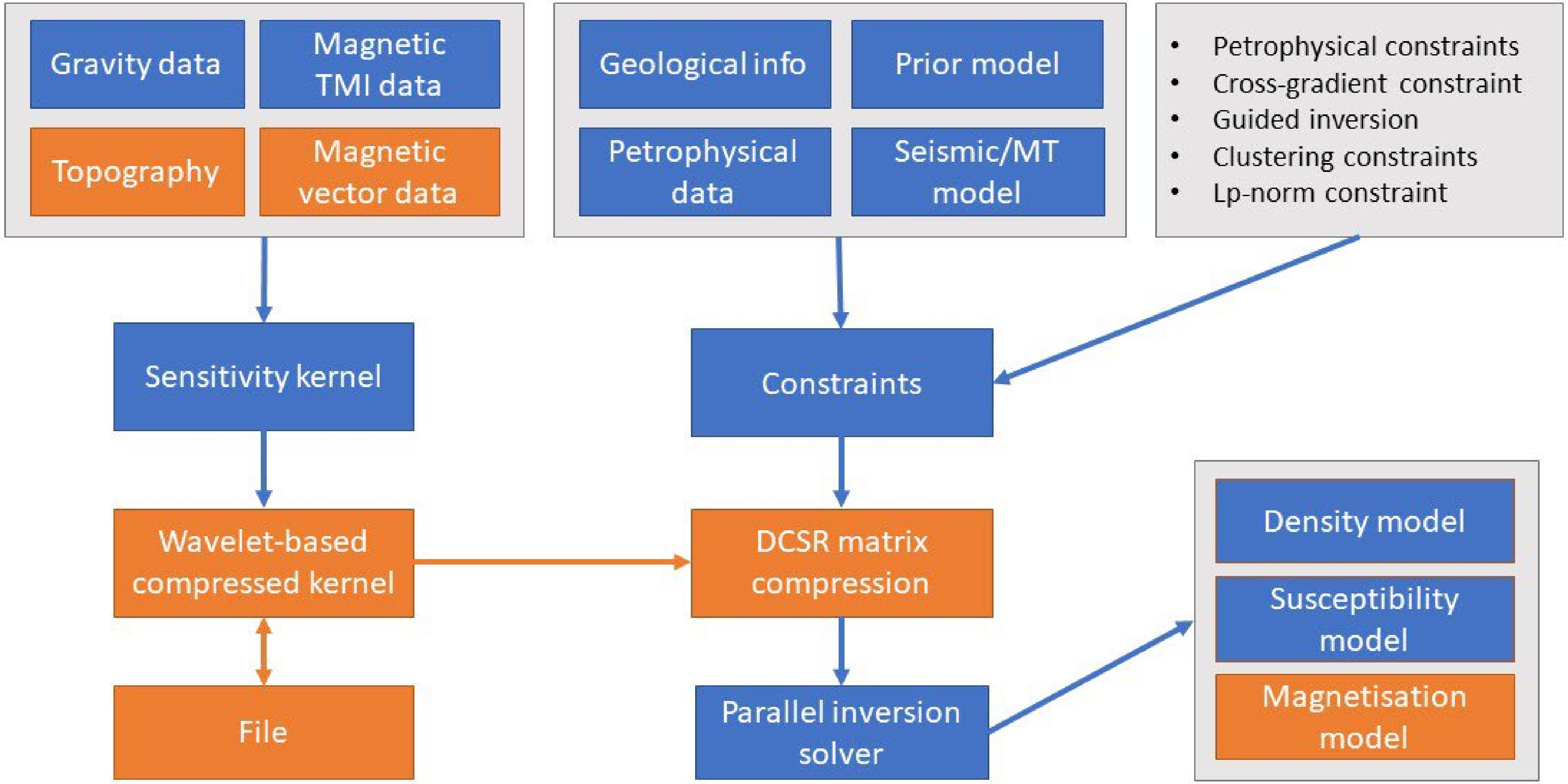
https://github.com/TOMOFAST/Tomofast-x

Tomofast-x 2.0 inversion workflow



Formulation

$$
\begin{aligned}
&\theta(\boldsymbol{d},\boldsymbol{m}) \\
&= \alpha_d \left\| \boldsymbol{W}_d \left(\boldsymbol{d} - \boldsymbol{g}(\boldsymbol{m}) \right) \right\|_{l_2}^2 && \longleftarrow \text{Data} \\
&+ \alpha_m \left\| \boldsymbol{W}_m \left(\boldsymbol{m} - \boldsymbol{m}_{pr} \right) \right\|_{\mathbf{L_p}}^2 && \longleftarrow \text{Prior model} \\
&+ \alpha_g \left\| \boldsymbol{W}_g \nabla \boldsymbol{m} \right\|_{\mathbf{L_2}}^2 && \longleftarrow \text{Smoothness} \\
&+ \alpha_x \left\| \boldsymbol{W}_x \left(\nabla \boldsymbol{m}_1 \times \nabla \boldsymbol{m}_2 \right) \right\|_{\mathbf{L_2}}^2 && \longleftarrow \text{Cross-gradient} \\
&+ \alpha_{pe} \left\| \boldsymbol{W}_{pe} \mathrm{P}(\boldsymbol{m}) \right\|_{\mathbf{L_2}}^2 && \longleftarrow \text{Petrophysics (clustering)} \\
&+ \alpha_a \left\| \boldsymbol{W}_a \left(\boldsymbol{m} - \boldsymbol{v} + \boldsymbol{u} \right) \right\|_{\mathbf{L_2}}^2 && \longleftarrow \text{Petrophysics (ADMM)}
\end{aligned}
$$

Each term = Parameter file section

Formulation

$$\theta(\boldsymbol{d},\boldsymbol{m})$$
$$= \alpha_d \left\| \boldsymbol{W_d}(\boldsymbol{d} - \boldsymbol{g}(\boldsymbol{m})) \right\|_{\boldsymbol{l_2}}^2 \quad \longleftarrow \text{Data}$$
$$+ \alpha_m \left\| \boldsymbol{W_m}(\boldsymbol{m} - \boldsymbol{m_{pr}}) \right\|_{\mathbf{L_p}}^2 \quad \longleftarrow \text{Prior model}$$

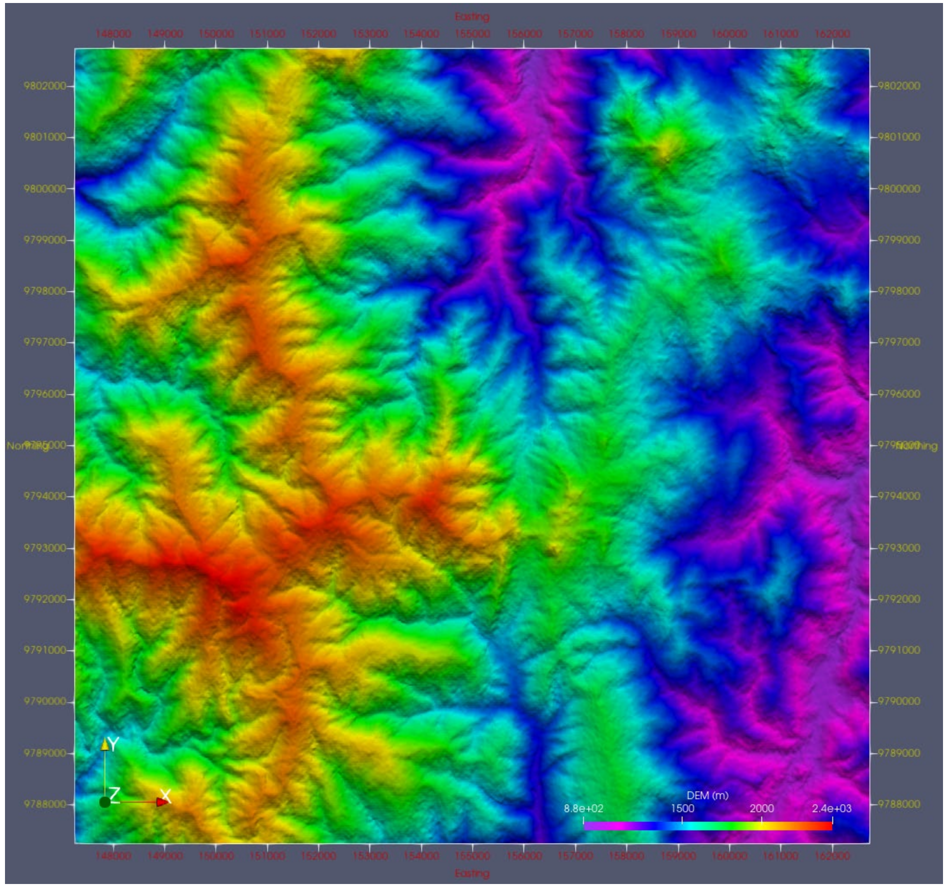
```
===========================================================================
DATA parameters
===========================================================================
forward.data.grav.nData                 = 256
forward.data.grav.dataGridFile          = data/gravmag/mansf_slice/data_grid.txt
forward.data.grav.dataValuesFile        = output/mansf_slice/grav_calc_read_data.txt

===========================================================================
MODEL DAMPING (m - m_prior)
===========================================================================
inversion.modelDamping.grav.weight      = 1.d-11
inversion.modelDamping.normPower        = 2.0d0
```

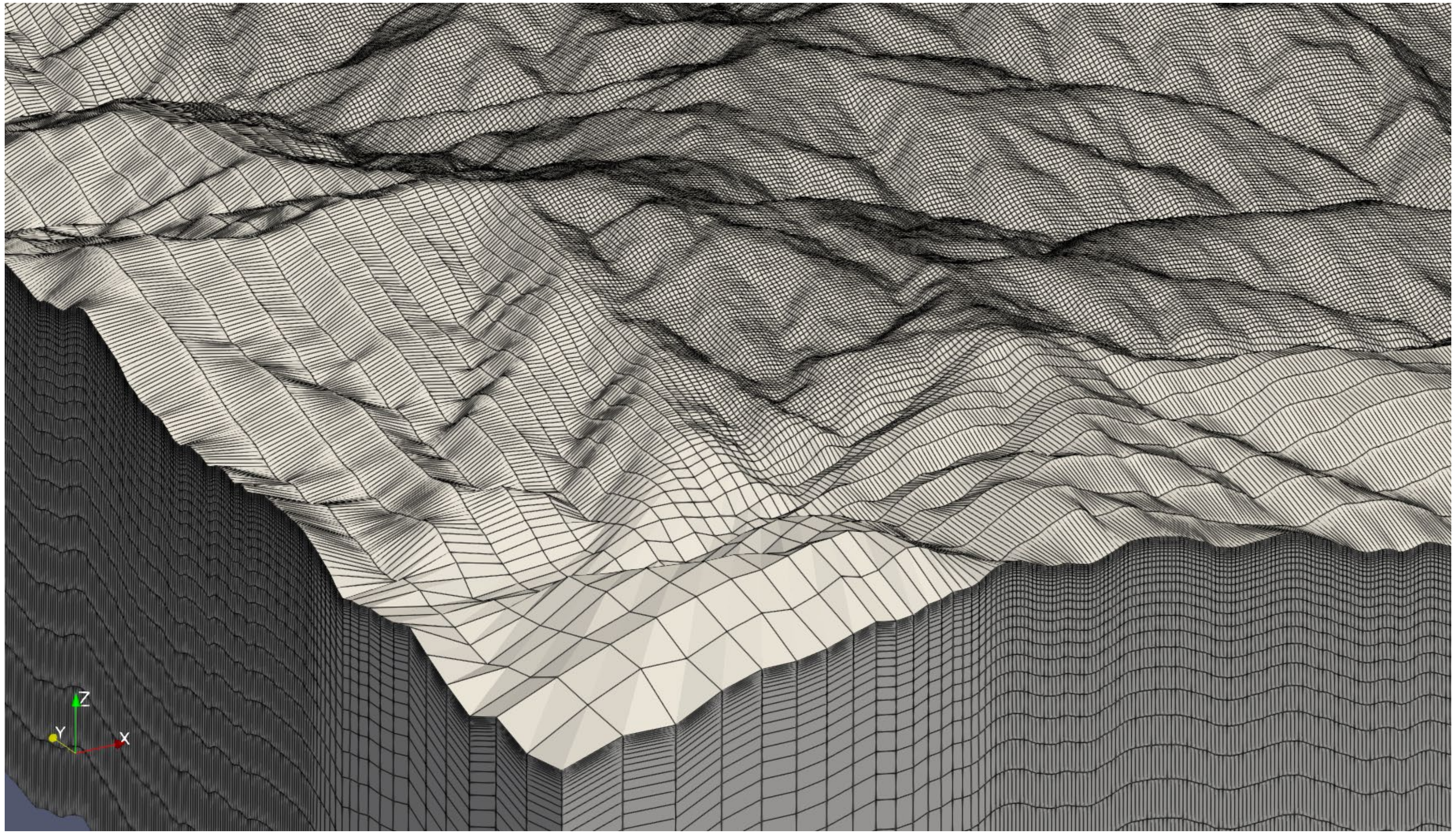
ustering)

DMM)

Each term = Parameter file section

Topography



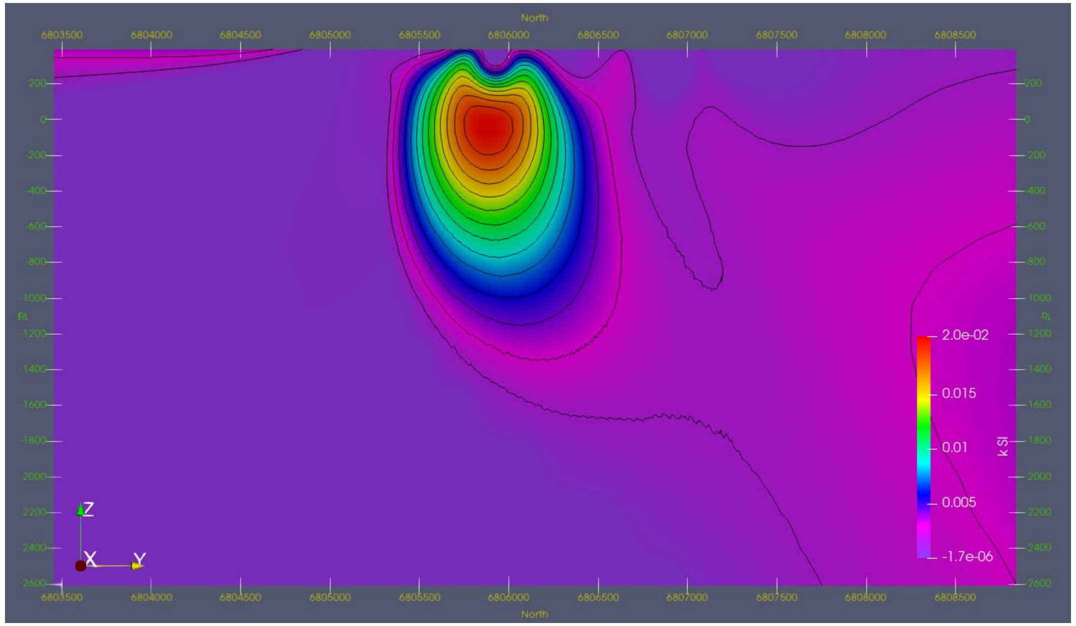


Wavelet compression

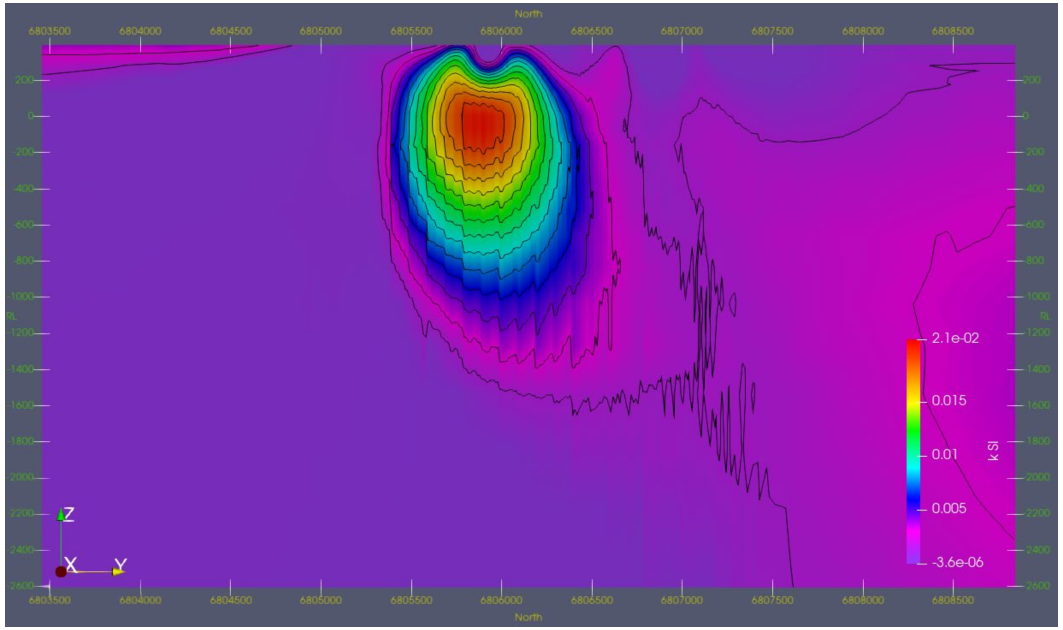
- Can be used to reduce the size of the problem by up to **three orders of magnitude** without seriously impacting on the solution.
- Speeds up the inversion by **an order of magnitude**.
- Compressed kernel can be later reused (e.g. imported in Python code).

Magnetic field data example

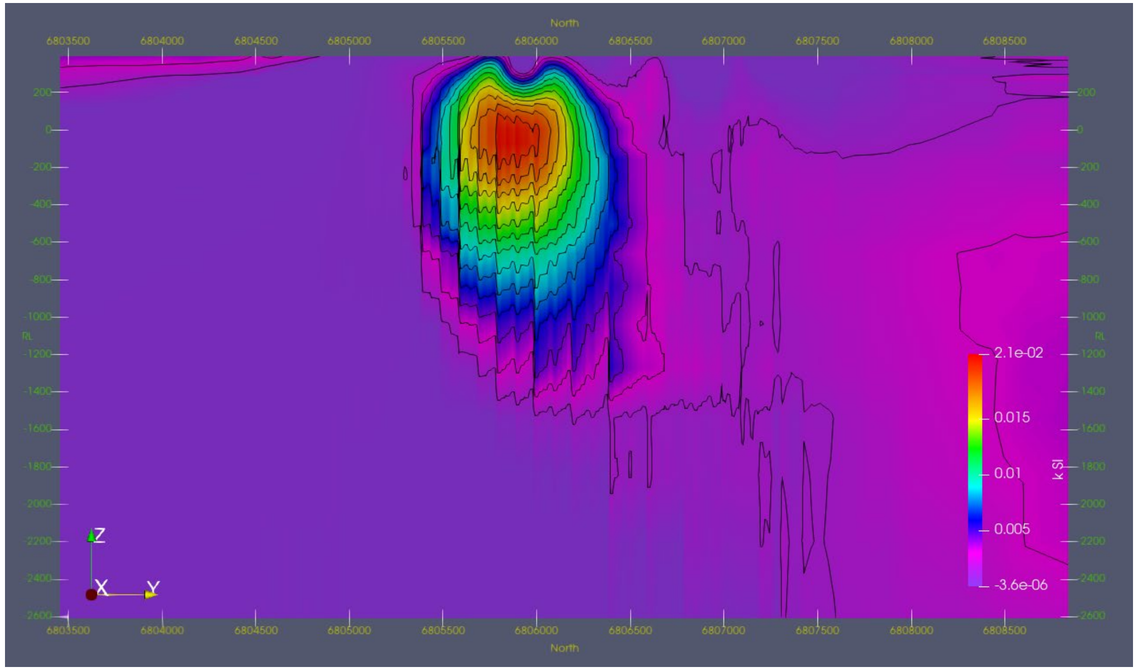
Model size = 242 x 218 x 27 cells
Number of data = 35,200



Compression = 5%

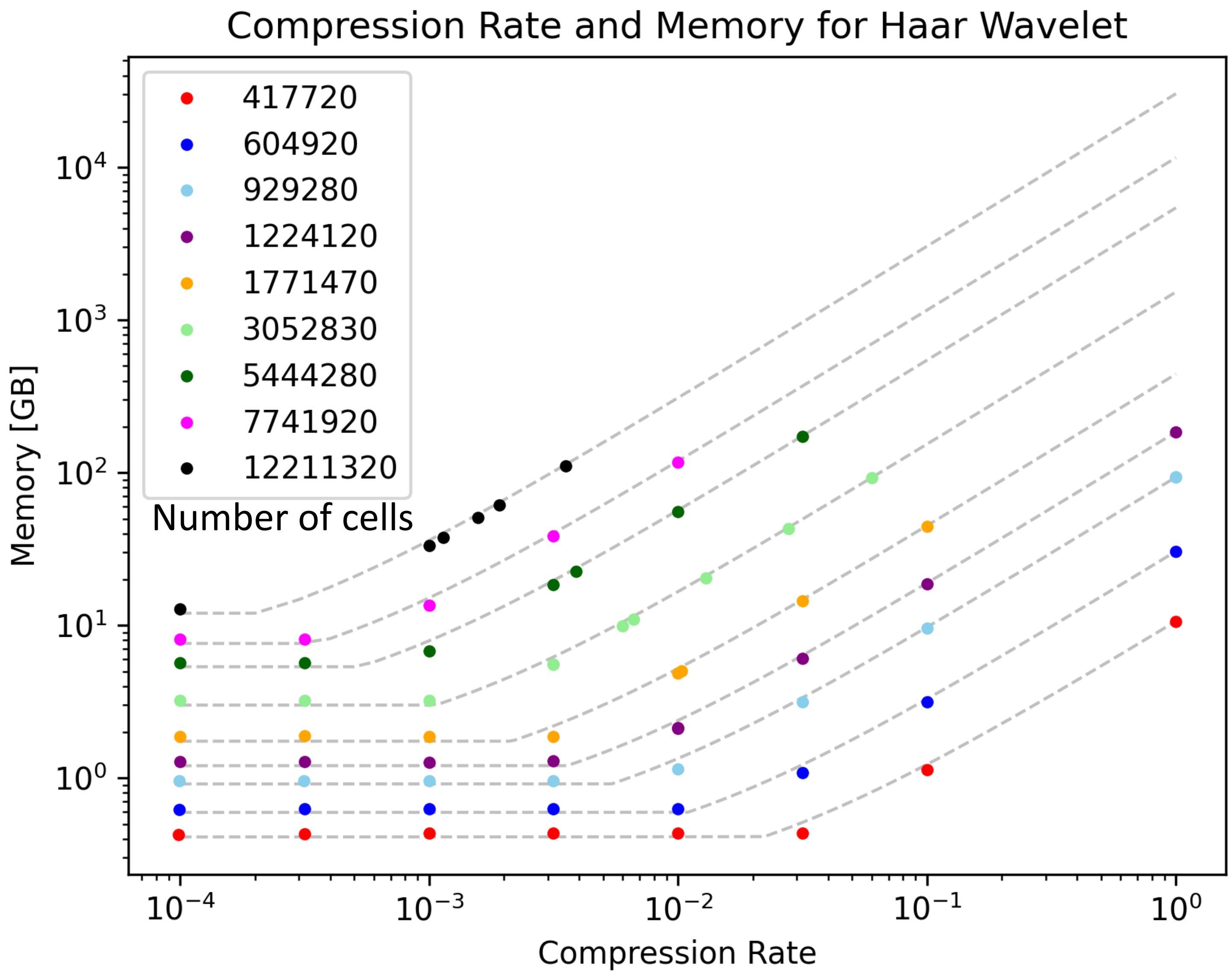


Compression = 1%



Compression = 0.5%

Memory usage for different compression rates



- Accurate memory prediction.
- Can reduce memory by 3 orders of magnitude.

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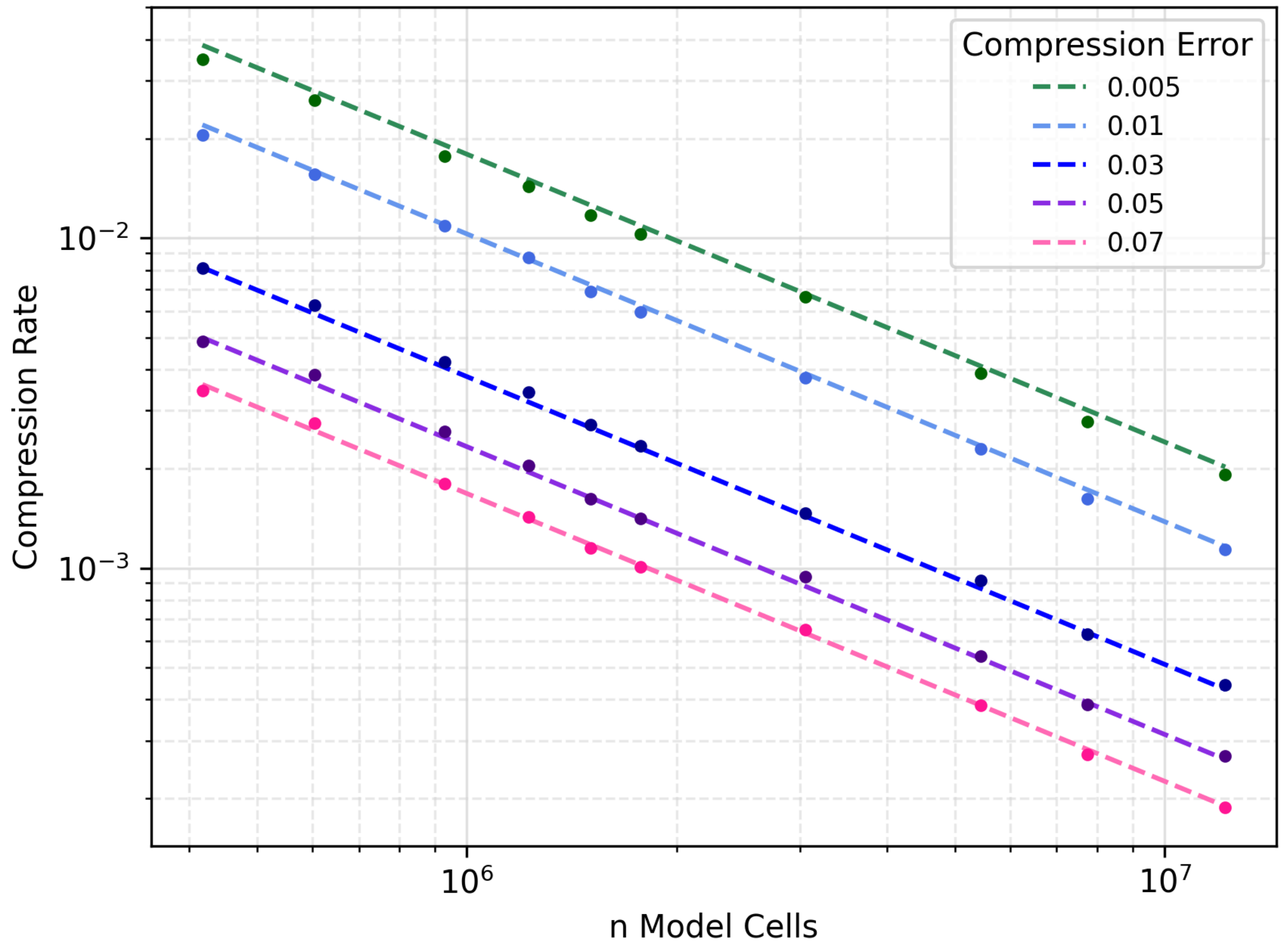
Compression rate for different compression errors



Compression error $= \frac{\|S_{true} - S_{comp}\|}{\|S_{true}\|}$,
where S is sensitivity matrix.

- Power laws scaling for a fixed compression error.
- Can predict optimal compression rate for any model size.

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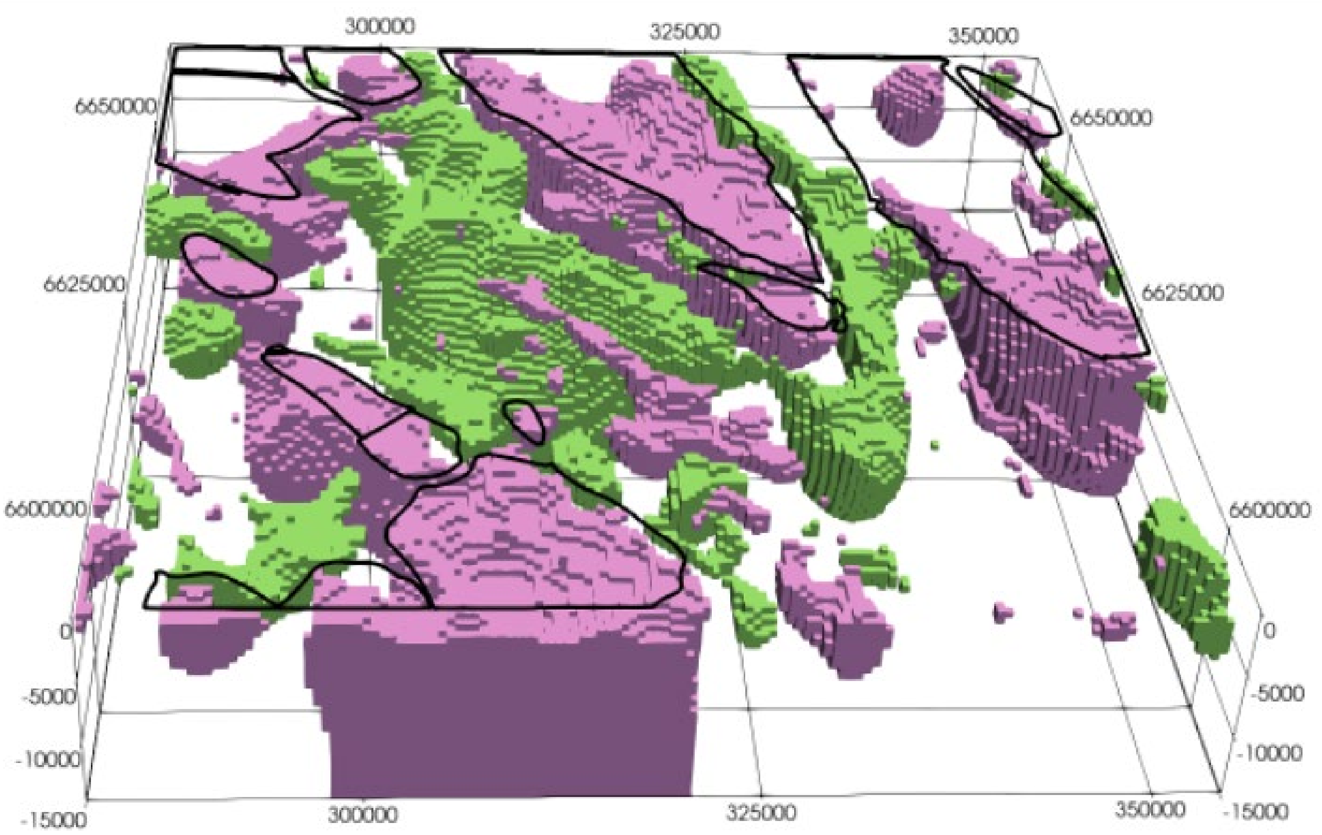
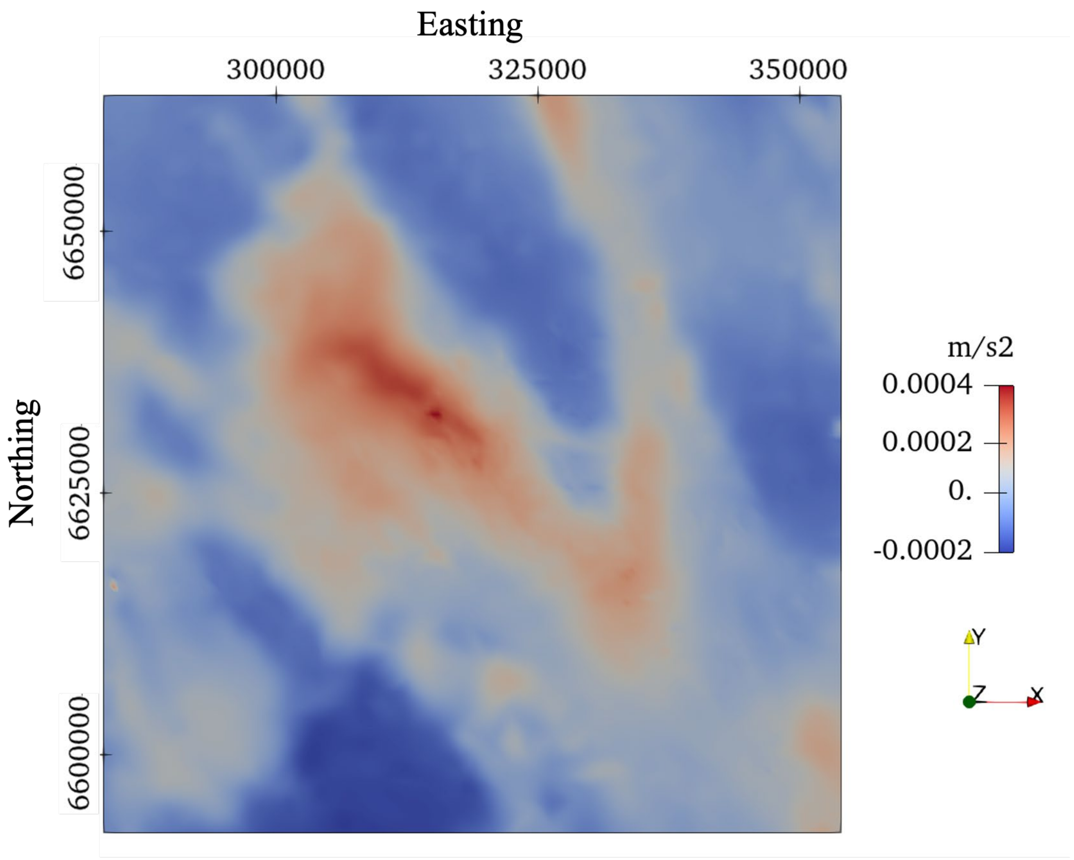
Inverted density model example





In black is the different Yilgarn Craton granites from the 1:2.5M State interpreted bedrock geology.
Pink = density anom. < -100 kg/m3 = granite
Green = density anom. > +80 kg/m3 = greenstones

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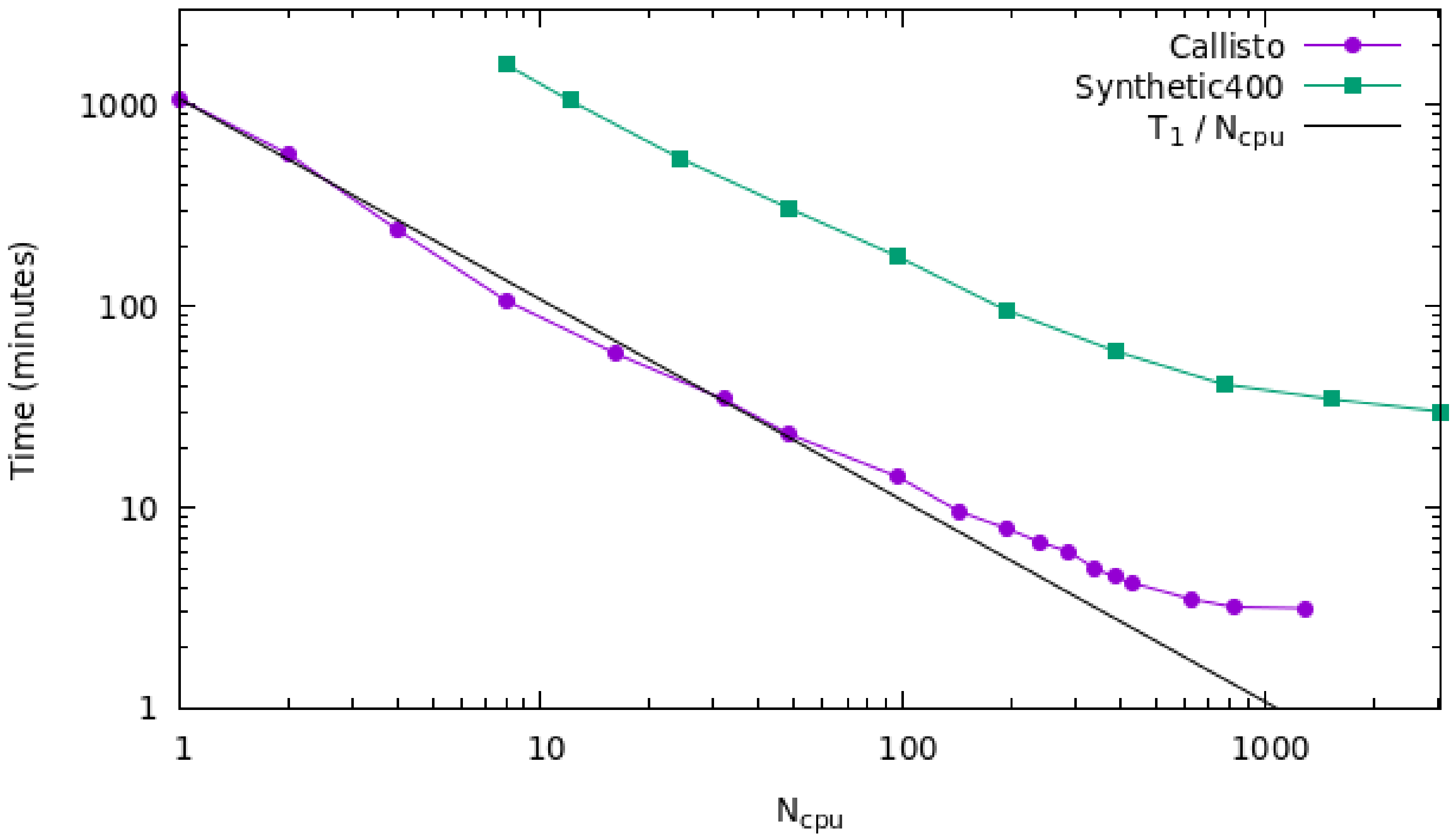
Parallel tests using supercomputer Gadi (NCI)

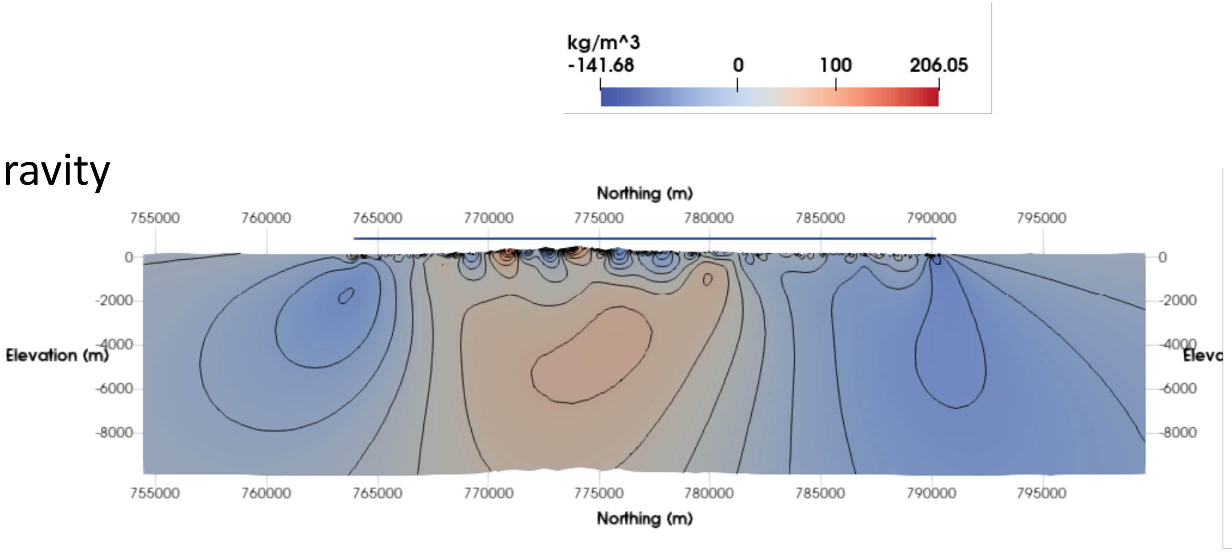


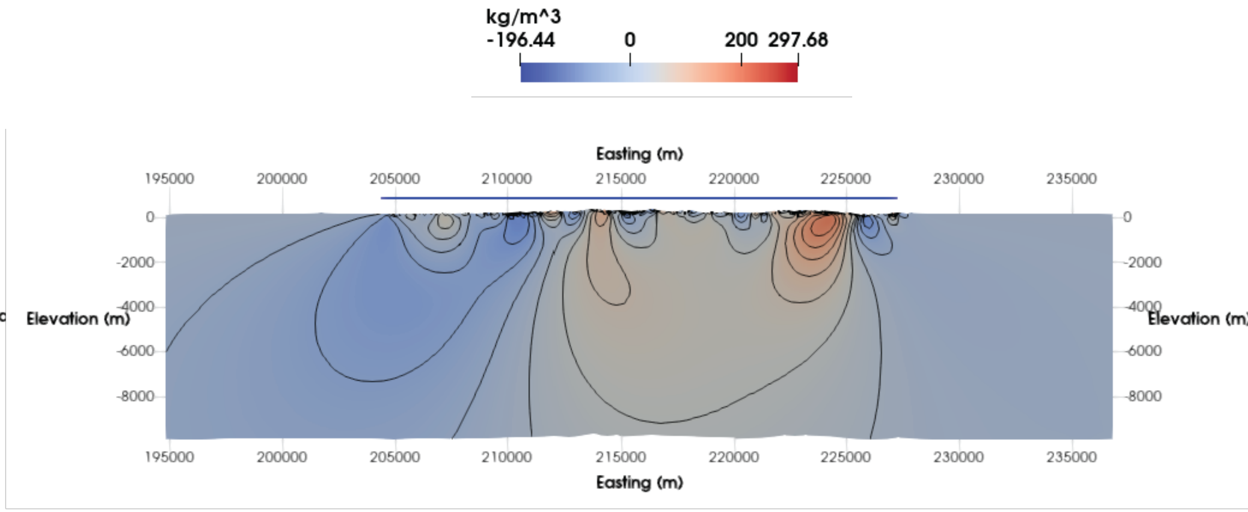
- Efficient parallelisation.
- Can save time by 2 orders of magnitude.

Name	ΔEast	ΔNorth	Depth	Releif	Nz	Ny	Nz	Ndata
Synthetic400	10000 (+5904)	10000 (+5904)	3290	1457.6	400 (+40)	400 (+40)	28	158006
Callisto	2500 (+3402)	2200 (+3402)	3290	24.6	200 (+42)	176 (+42)	27	35200

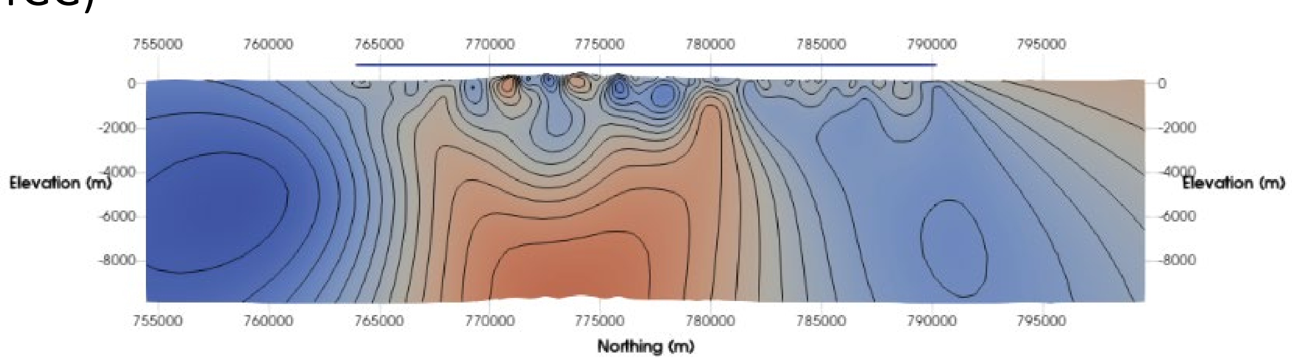
Gravity vs Full tensor gravity gradiometry

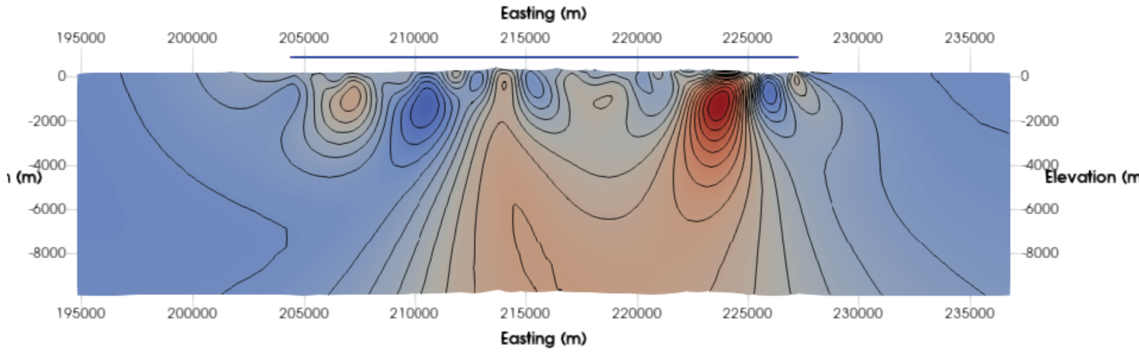
Gravity





Gradiometry
(FTGG)





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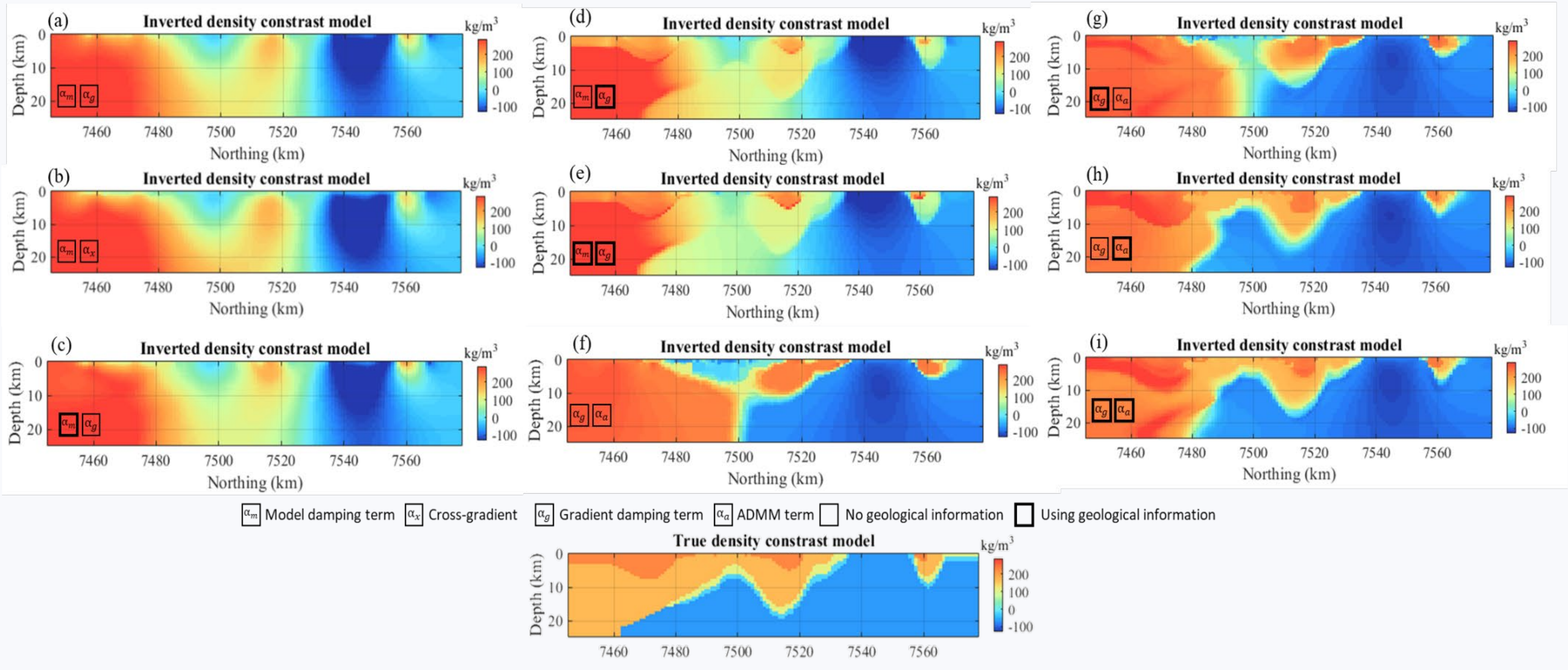
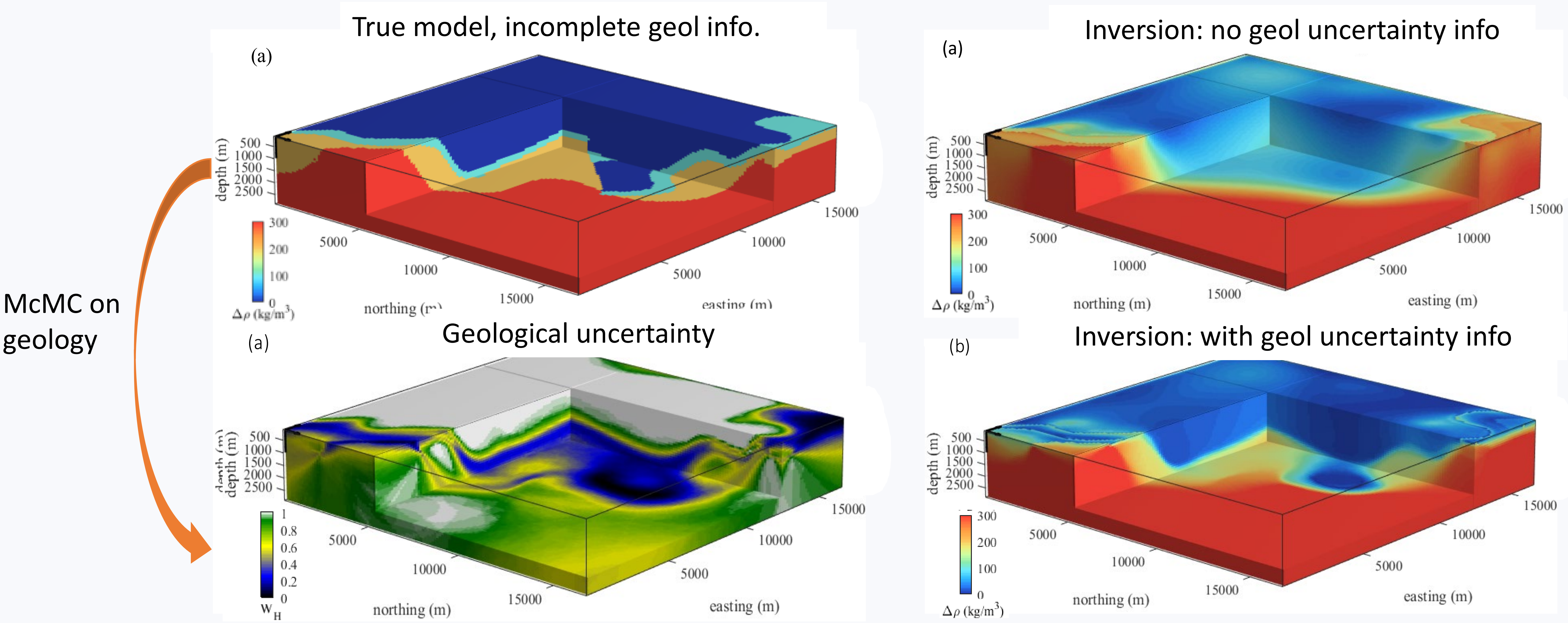
Different types of constraints



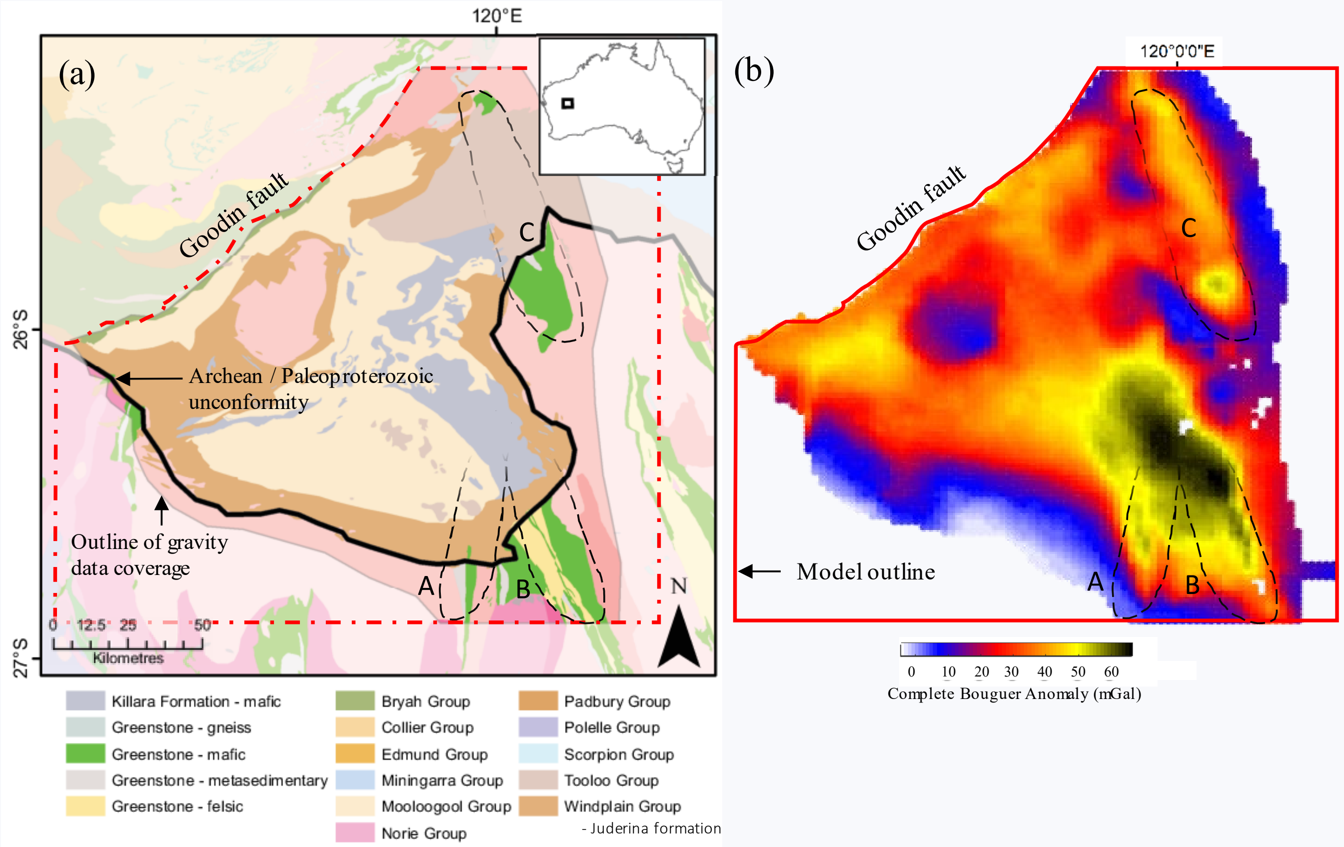
J. Giraud et al, Geosci. Model Dev., 14, 6681, 2021

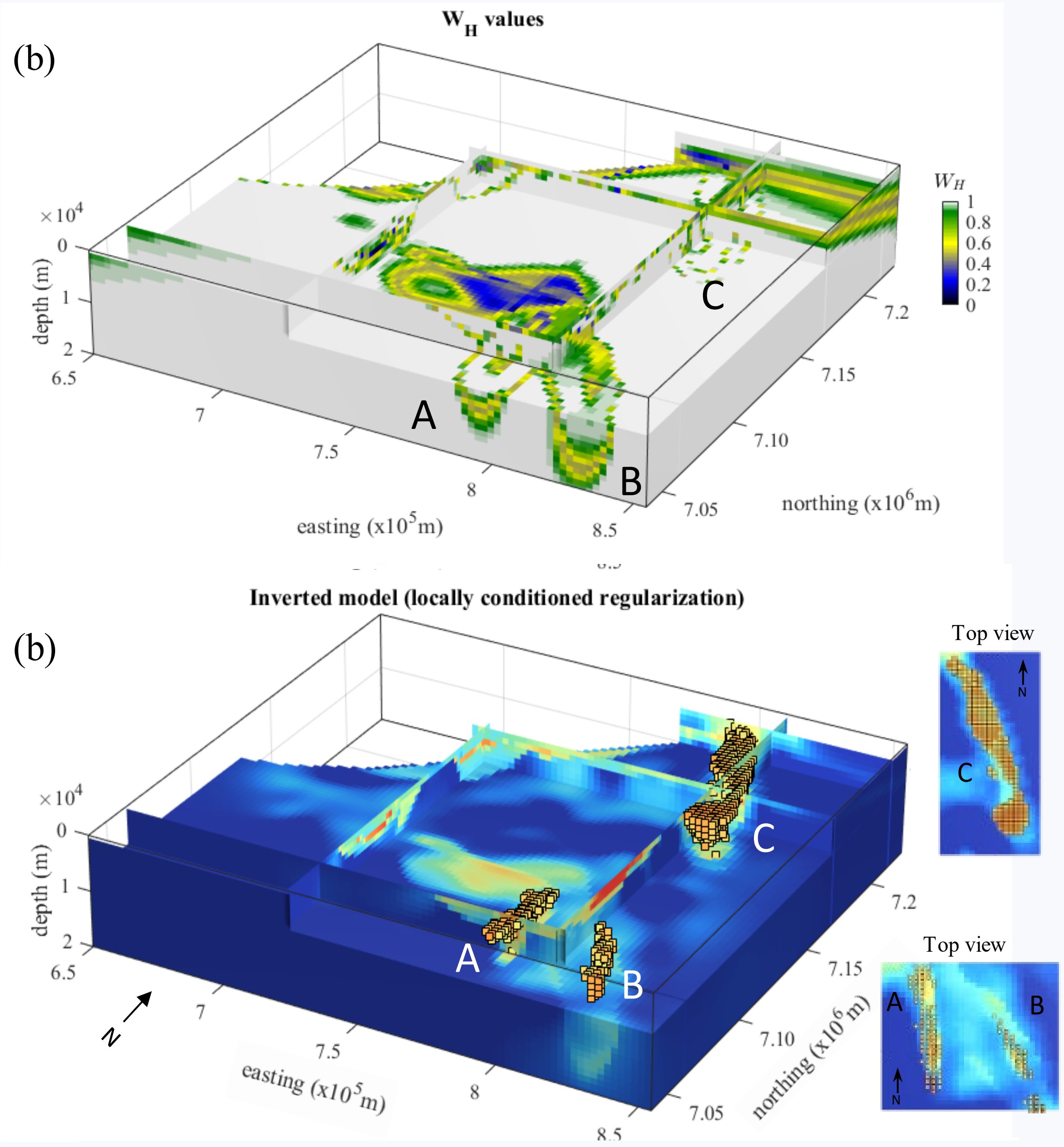
Local gradient regularization



J. Giraud et al, Solid Earth, 10, 193–210, 2019

Local gradient regularization





J. Giraud et al, Solid Earth, 10, 193–210, 2019

Cross gradient constraints

JOURNAL ARTICLE

Three-dimensional gravity anomaly data inversion in the Pyrenees using compressional seismic velocity model as structural similarity constraints

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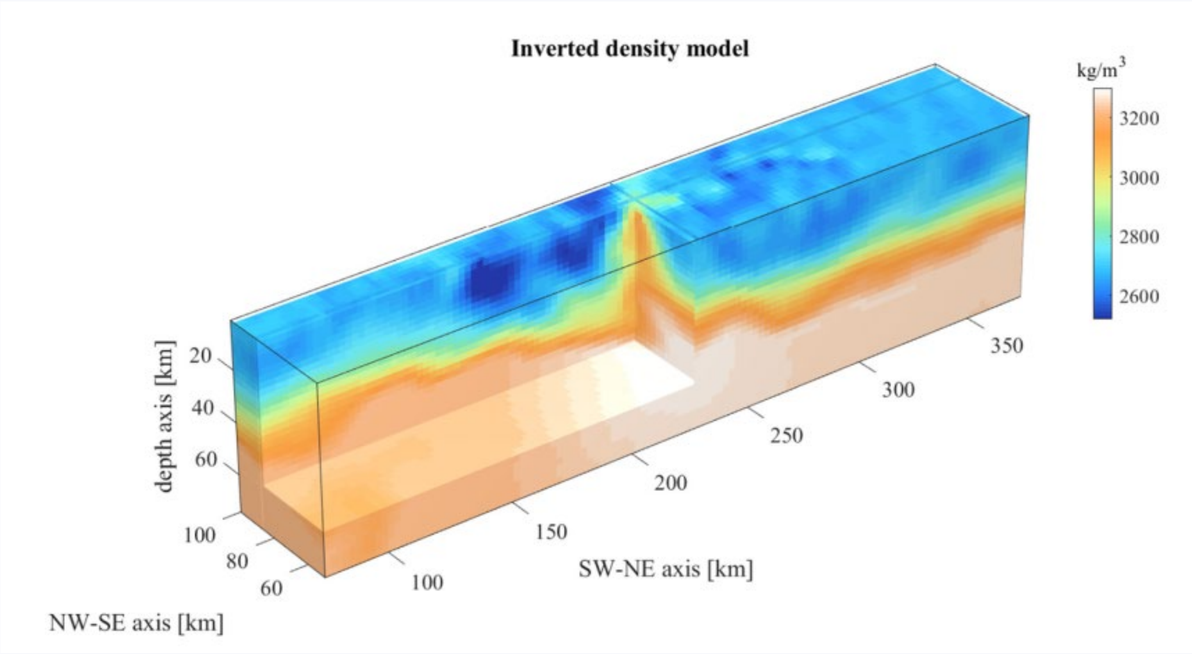
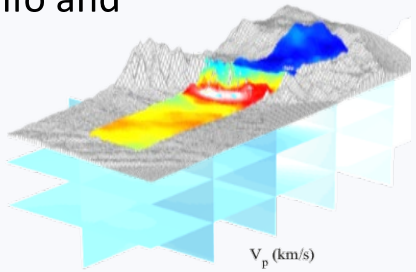
Roland Martin ✉, Jérémie Giraud, Vitaliy Ogarko, Sébastien Chevrot, Stephen Beller, Pascal Gégout, Mark Jessell

Geophysical Journal International, Volume 225, Issue 2, May 2021, Pages 1063–1085,
https://doi.org/10.1093/gji/ggaa414
Published: 01 September 2020 **Article history ▾**

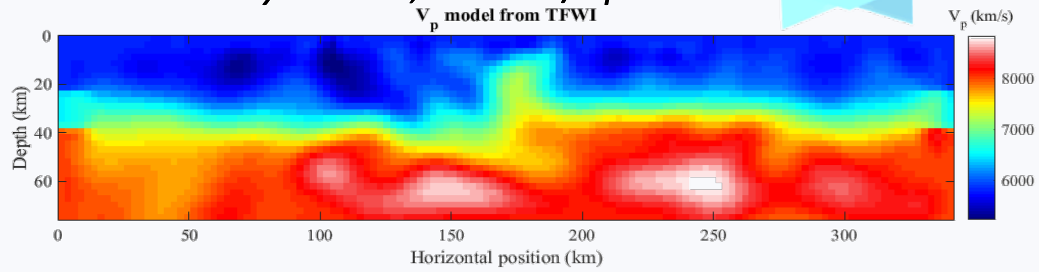


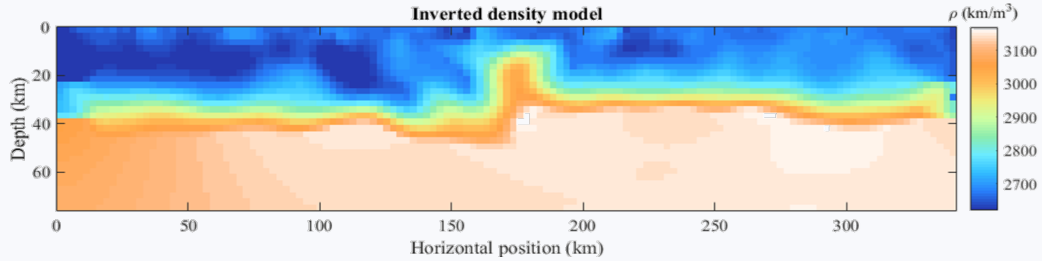
Cross-gradient with Vp

- → Exploit structural and petrophysical info and horizontal resolution of seismic
- → Reconcile different geophysics



Western Pyrenees, France/Spain





Martin et al. 2020

Petrophysical constraints (ADMM)

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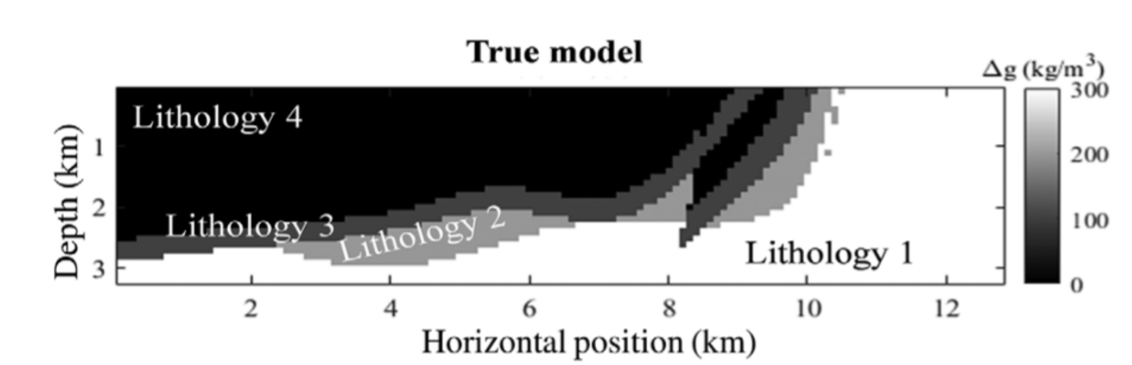
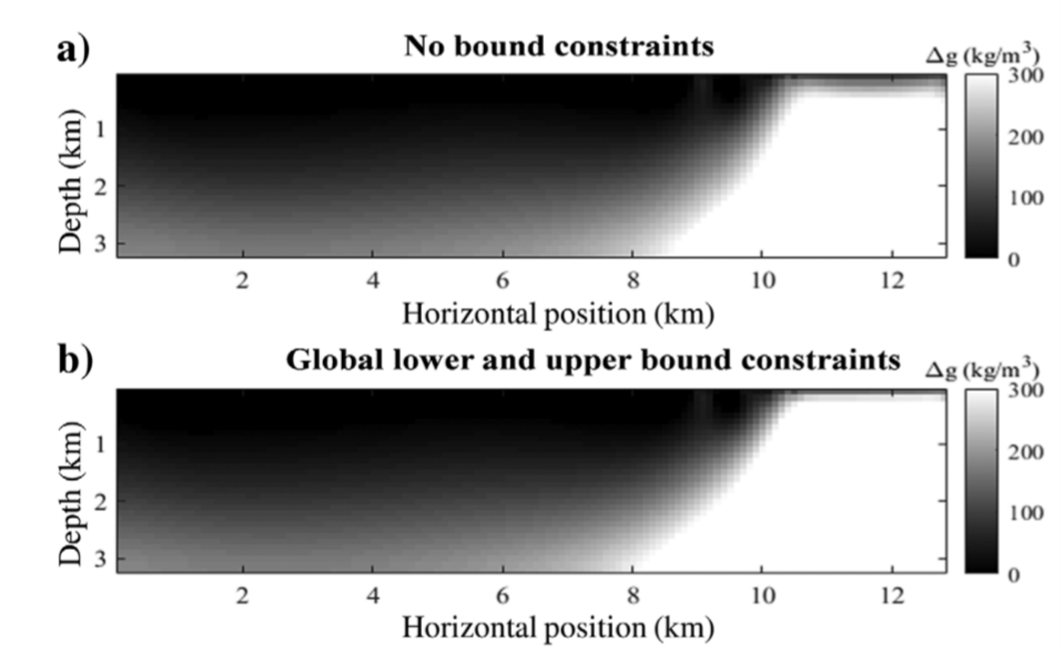
Disjoint interval bound constraints using the alternating direction method of multipliers for geologically constrained inversion: Application to gravity data

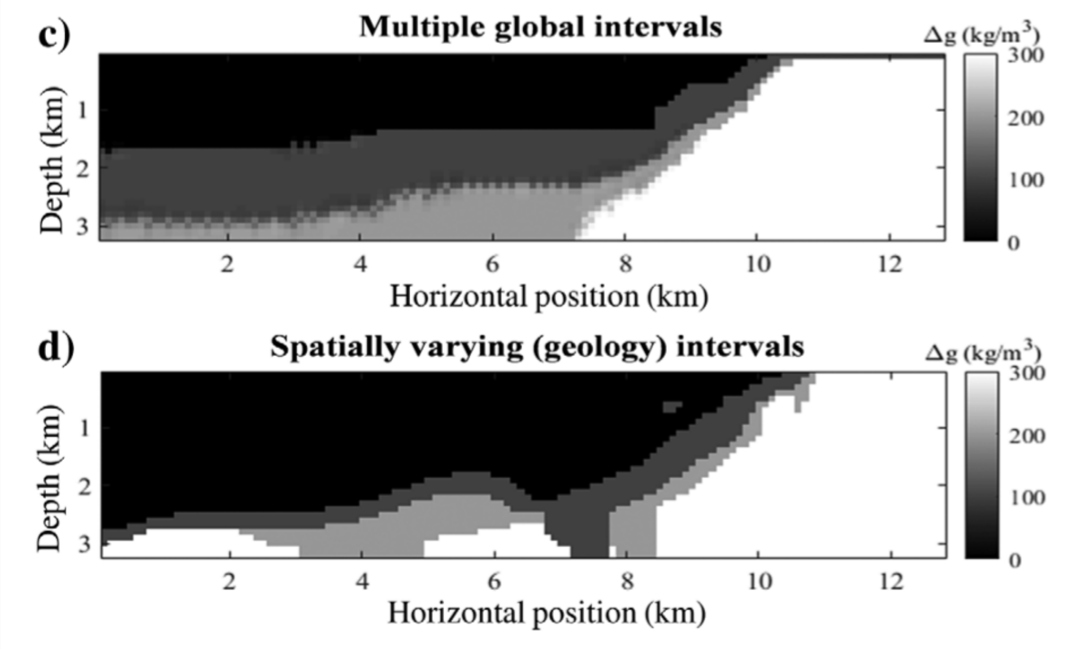
Check for updates

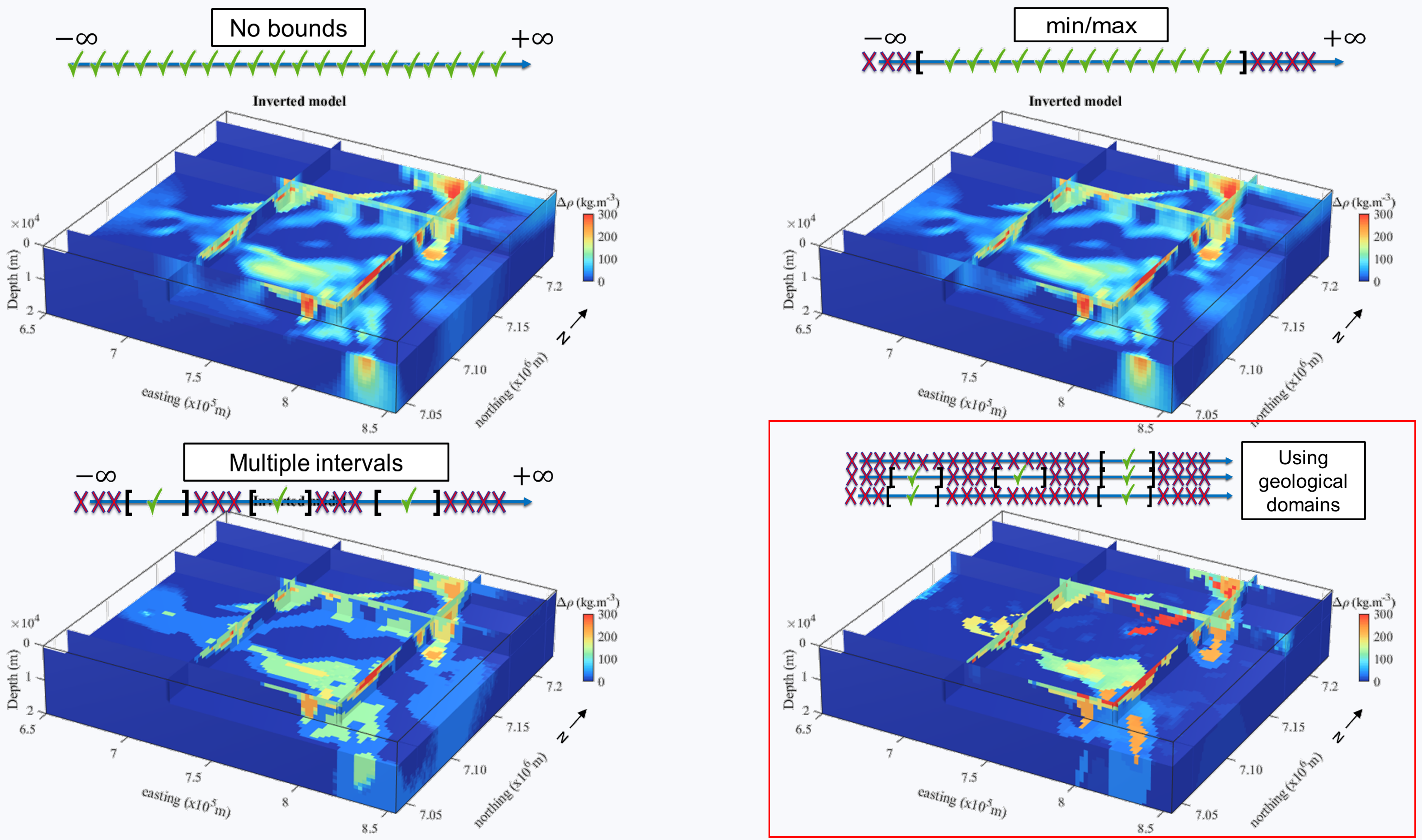
Authors:
Vitaliy Ogarko, Jérémie Giraud, Roland Martin, and Mark Jessell

https://doi.org/10.1190/geo2019-0633.1



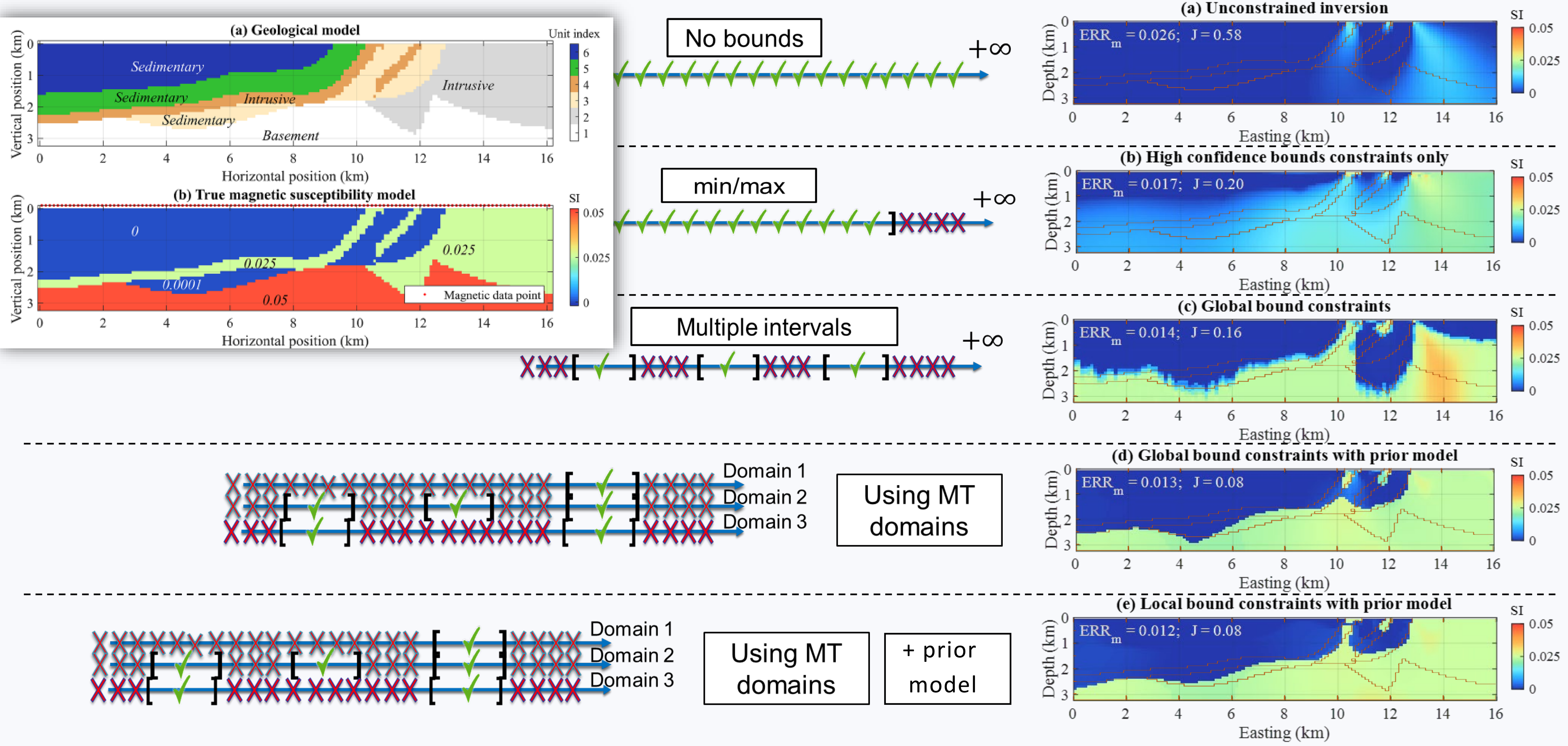






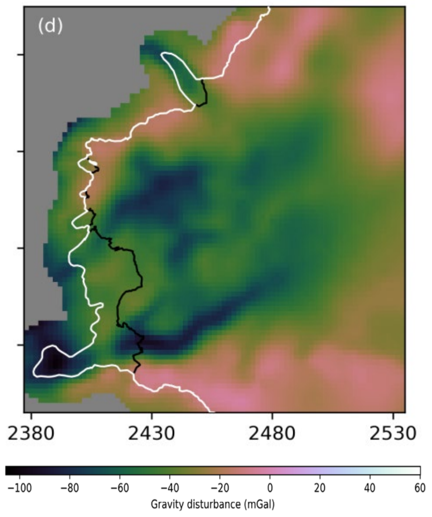
No bounds
−∞
+∞
Inverted model
min/max
−∞
+∞
Inverted model
Multiple intervals
−∞
+∞
Using geological domains
Δρ (kg.m⁻³)
300
200
100
0
×10⁴
Depth (m)
0
1
2
6.5
7
7.5
8
8.5
easting (x10⁵m)
7.05
7.10
7.15
7.2
northing (x10⁶m)
N

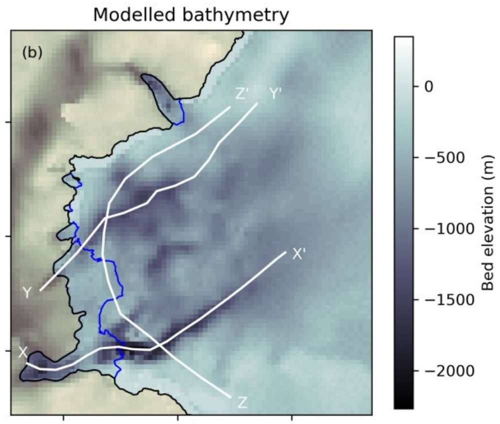
Using MT to constrain magnetic inversion

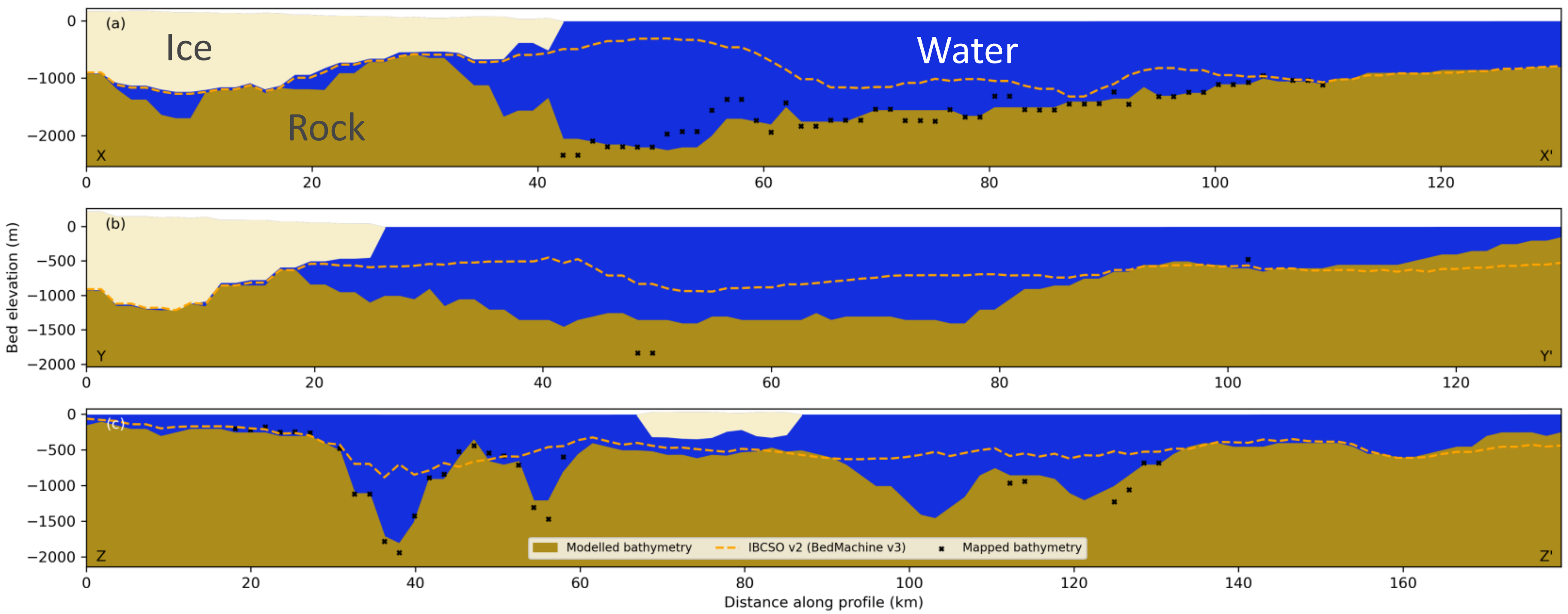


Giraud et al, Solid Earth, 14, 43–68, 2023

Gravity-derived Antarctic bathymetry using the Tomofast-x open-source code: a case study of Vincennes Bay (in review)







L. Bird et al https://doi.org/10.5194/egusphere-2025-211

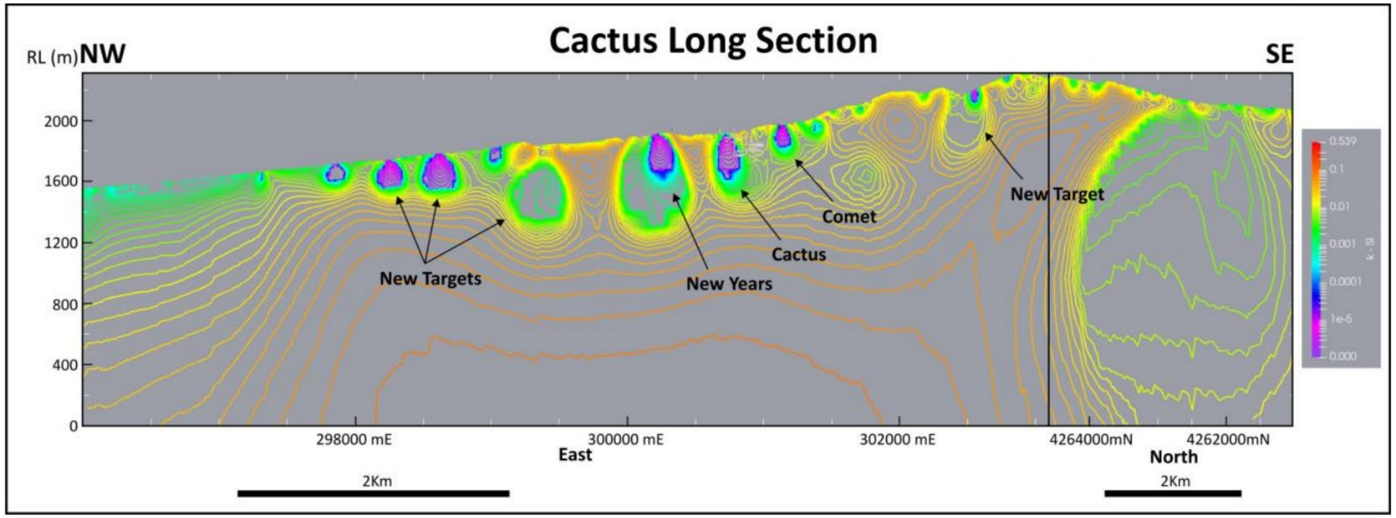
Commercial applications of Tomofast-x

Images provided by ExploreGeo
https://www.exploregeo.com.au/

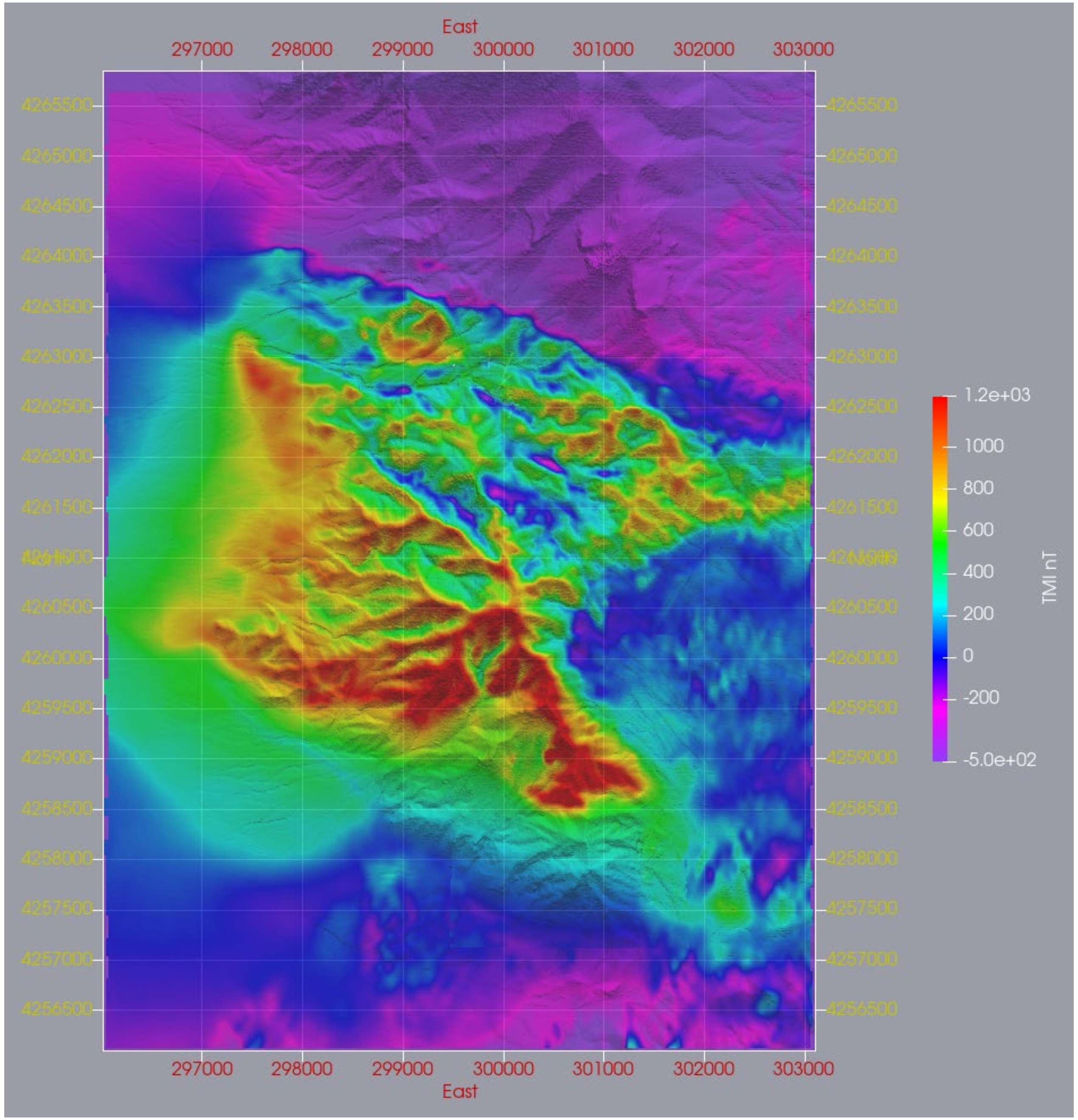
Example 1: Searching for magnetite destruction in strong topography

Published in Australian Stock Exchange (ASX):

New Modelling Highlights Multiple Untested Copper-Gold Targets at Frisco, Utah, USA
22 February 2024
Alderan Resources Limited

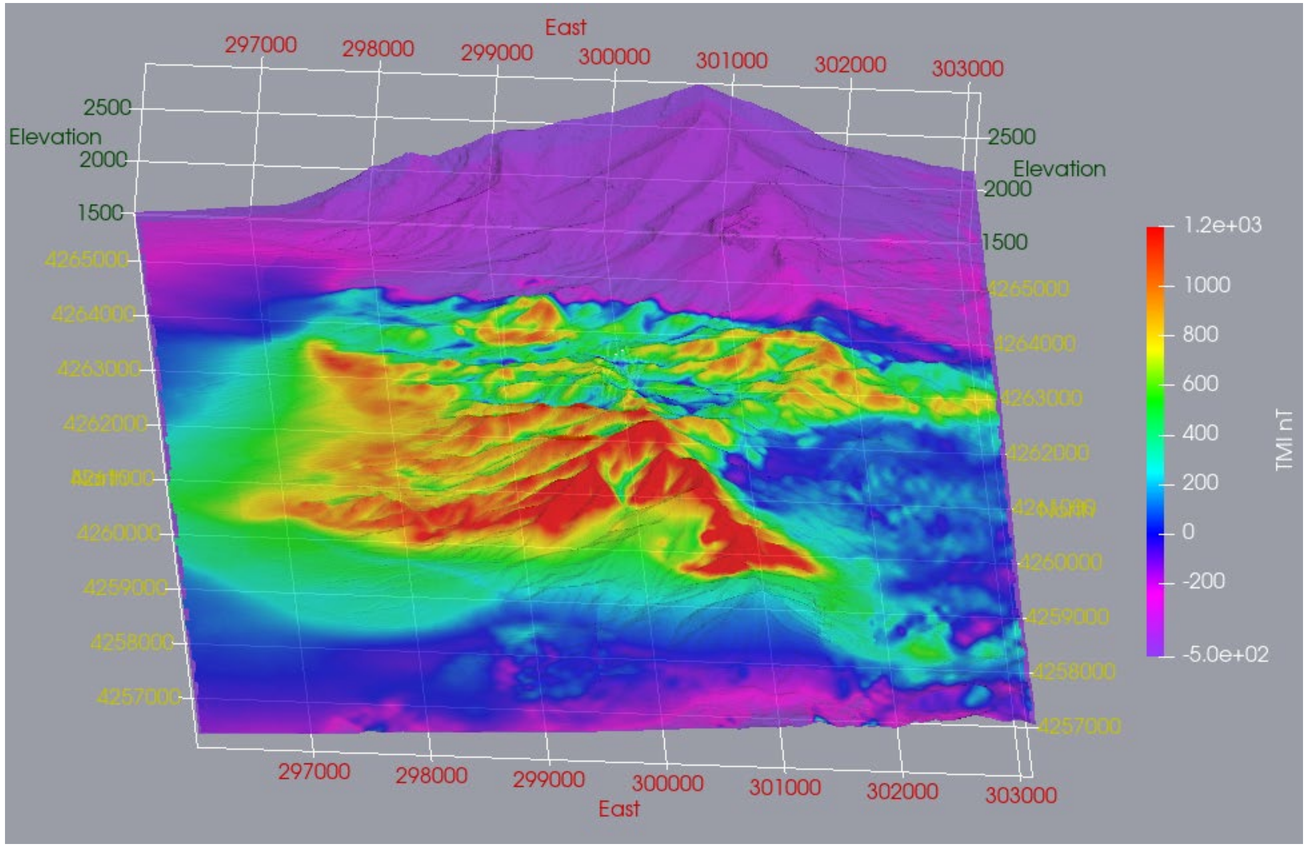


TMI draped on shaded DEM: strong correlation



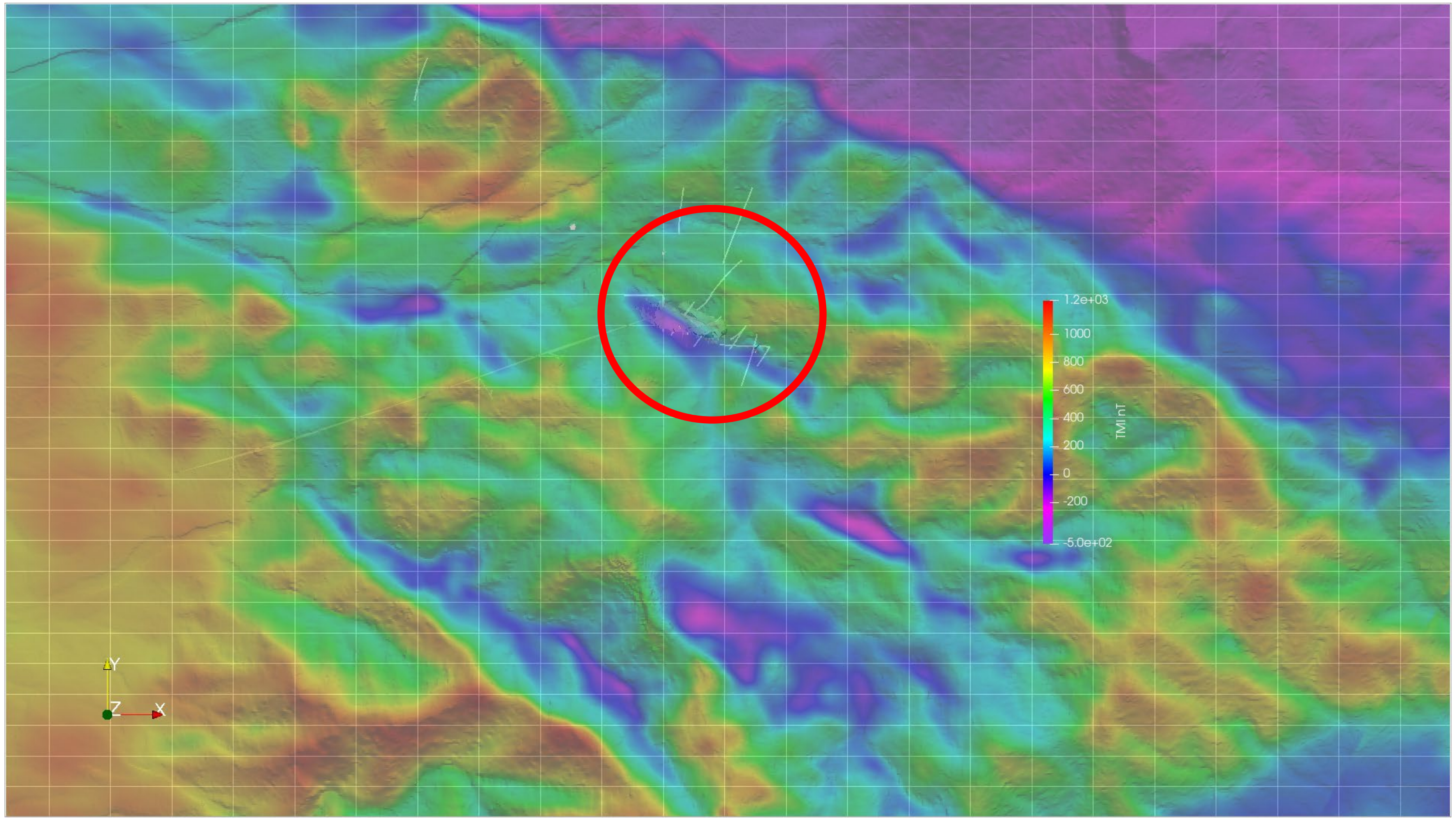
Based on a spatial relationship between gold and copper mineralisation and local lows within the TMI image the client believed there was a good association between mineralisation and low magnetic responses and was gearing up to go and drill all the lows.

TMI draped on DEM from an angle to highlight correlation



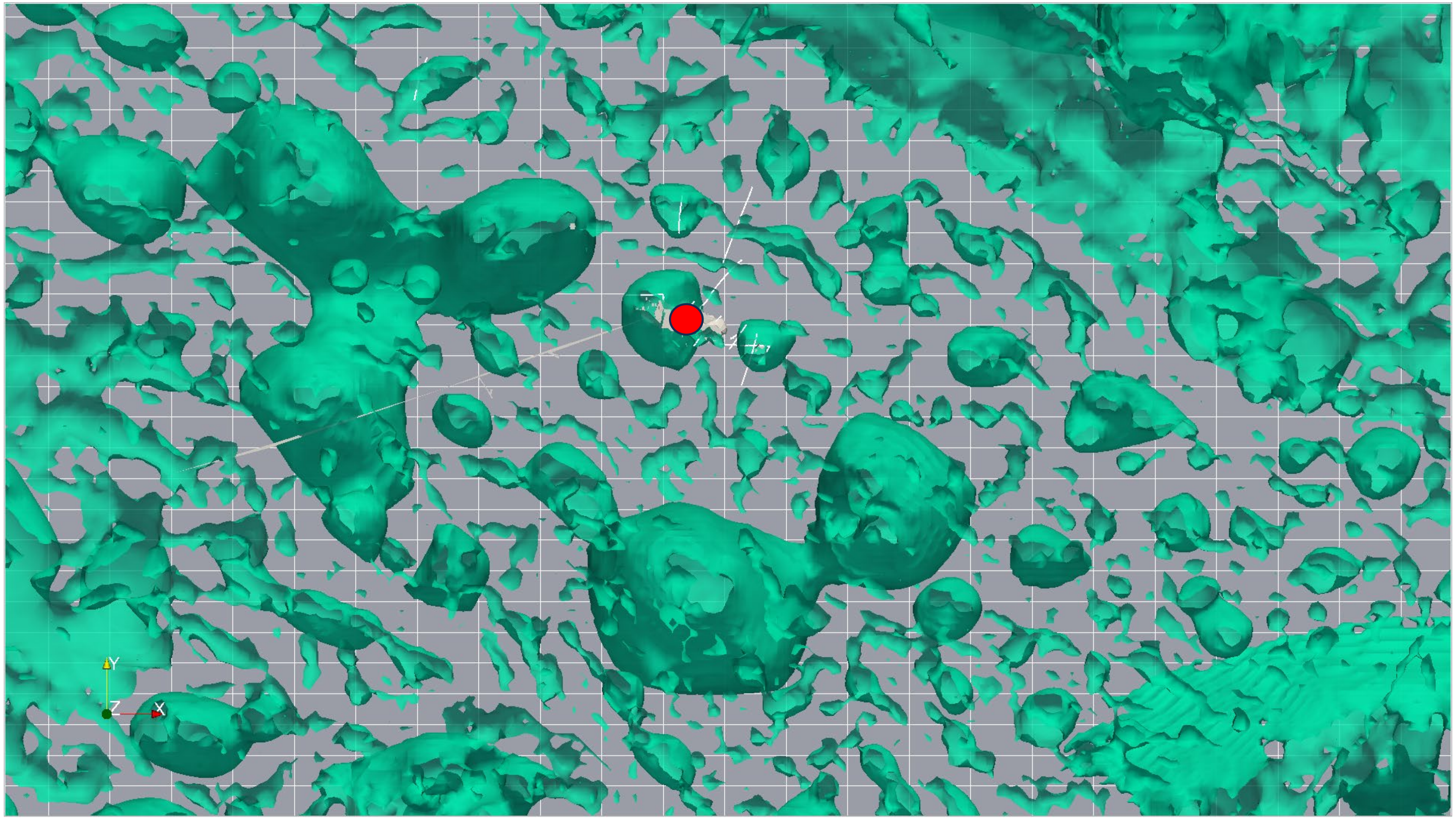
Looking at the magnetic data it is clear that there is a strong association between magnetic response and topography.

TMI draped on DEM with historical workings and drilling - is mag low from magnetite destruction or topo or both?

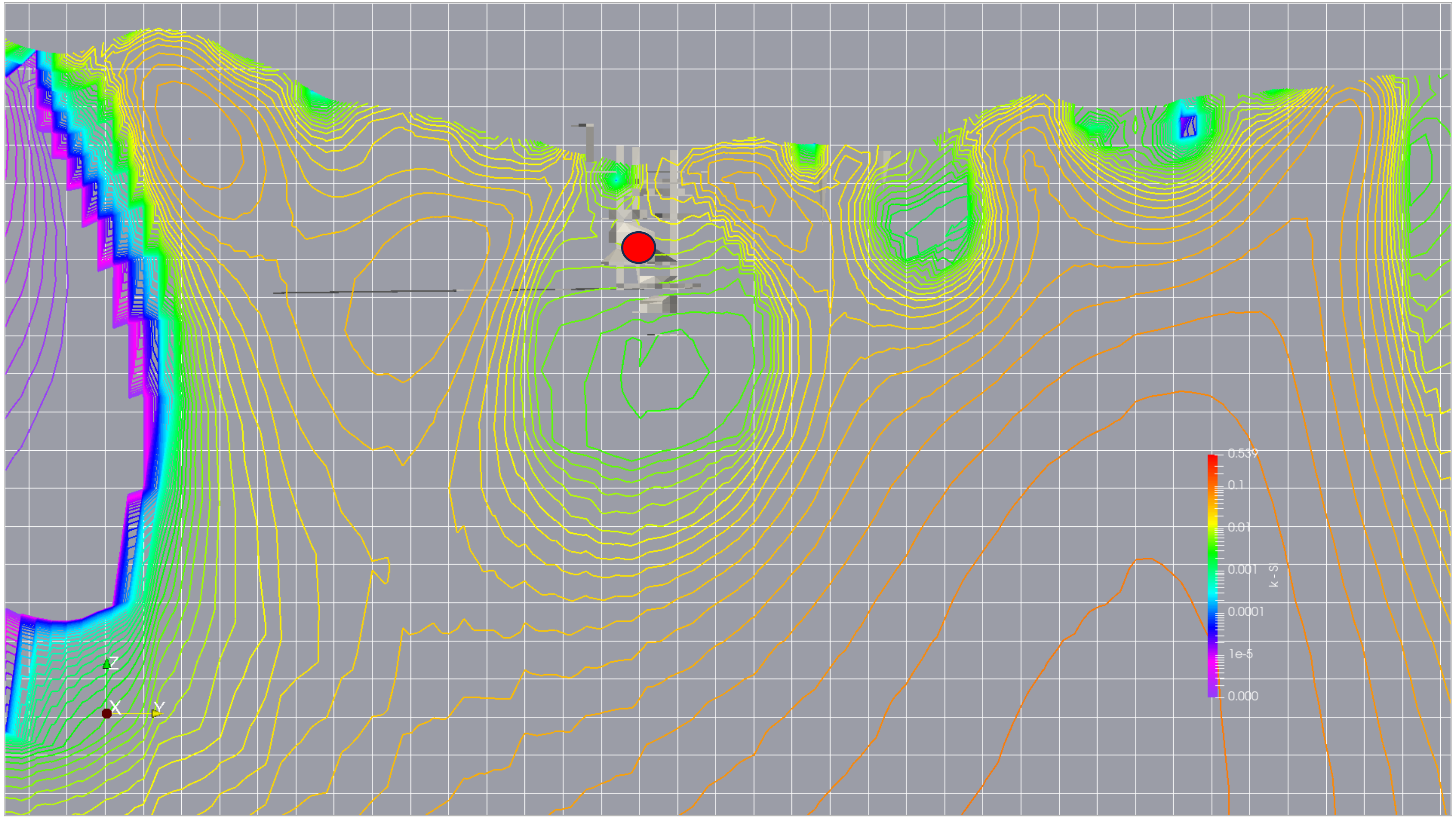


It is clear that there is a close relationship between the old mine (and known mineralisation from drilling) and a mag low but there is also a topo low here. Is the mag low due to magnetite destruction associated with gold and copper mineralisation or is the mag low a function of topography or both?

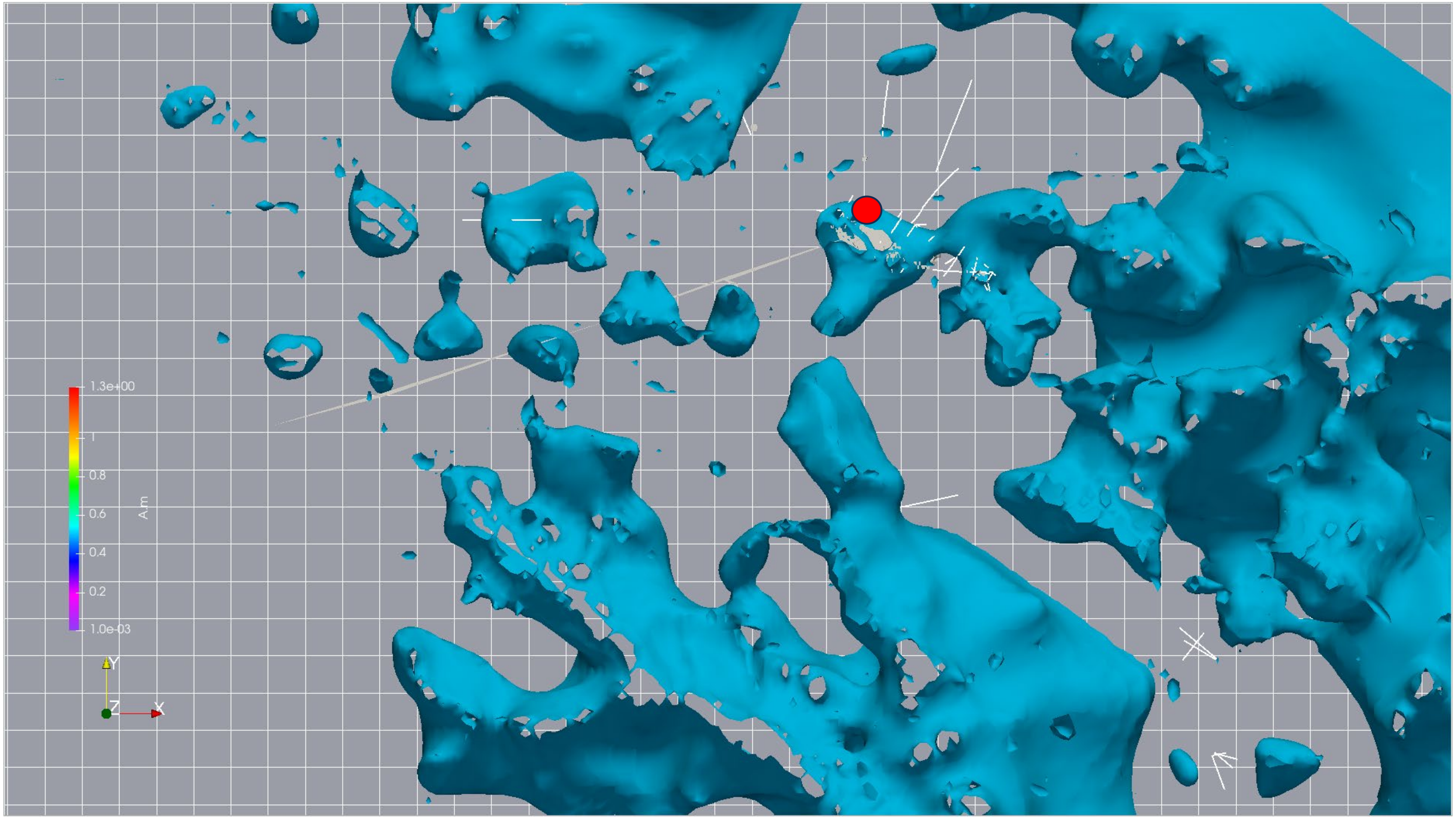
Isosurface of 0.04 mag sus from TMI inversion with workings and drilling



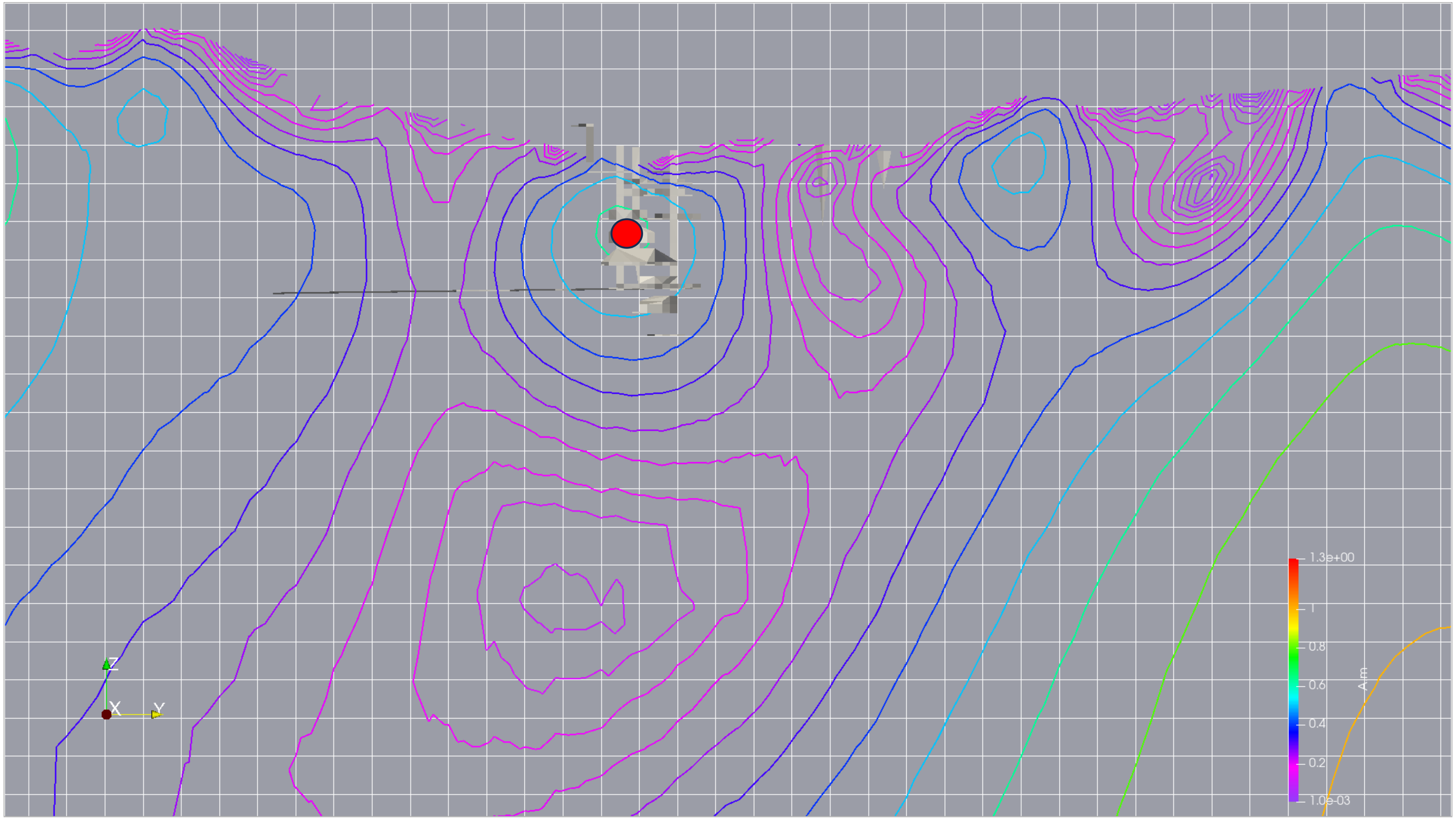
NS section TMI inversion showing workings



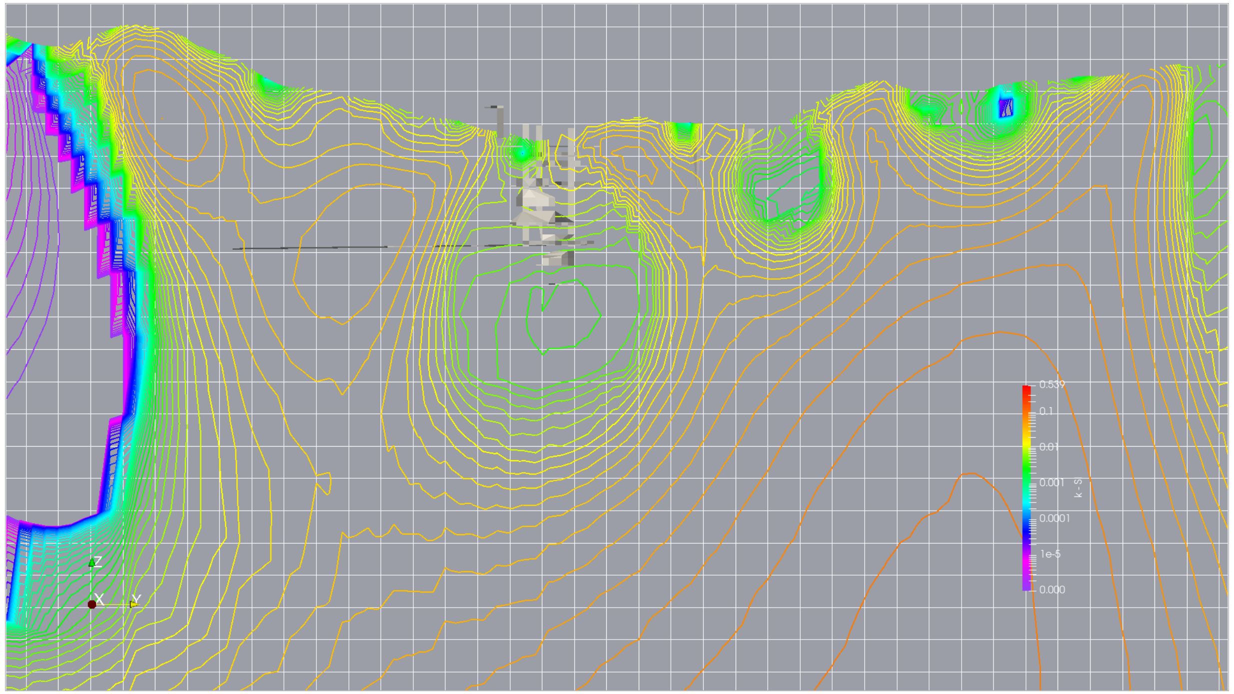
Isosurface of 0.5A/m from Magnetisation Vector Inversion with workings and drilling showing impact of remanence



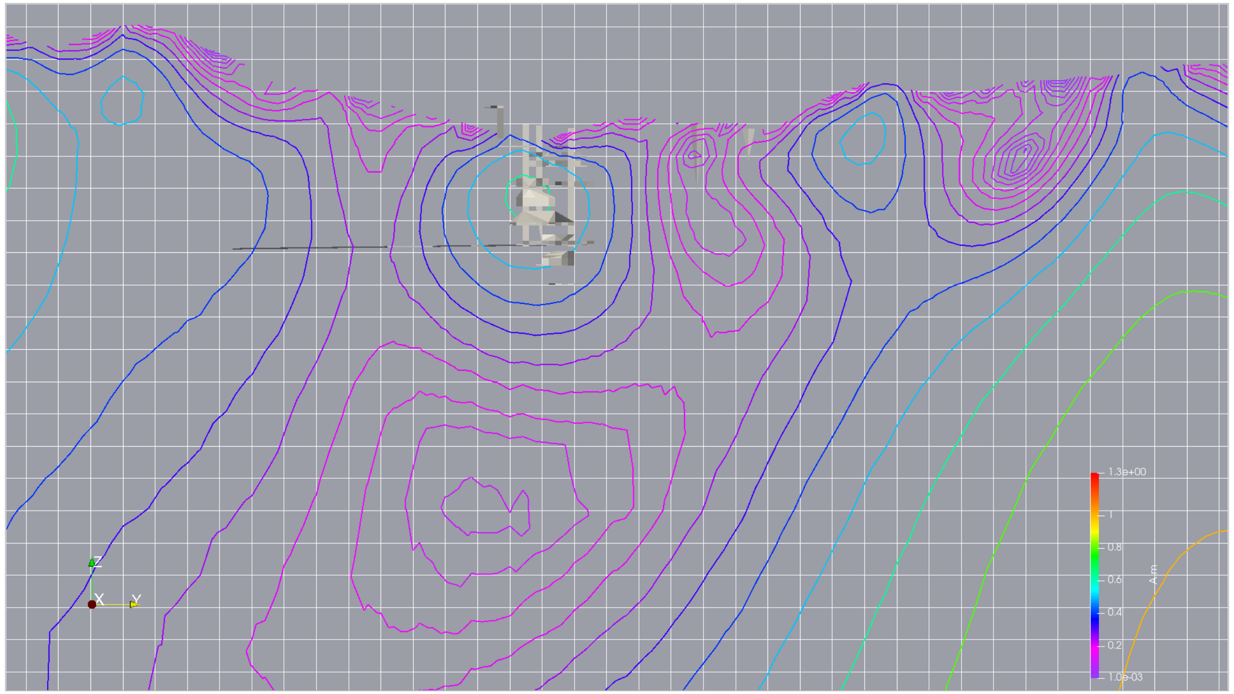
NS section Magnetisation Vector Inversion showing workings



TMI vs Magnetisation Vector Inversion



TMI shows a mag low coincident with mineralisation



MVI inversion shows a weak high

Example 1: Conclusions

- Tomofast-x inversion of the TMI shows a mag low coincident with mineralisation.
- However, the MVI inversion shows a weak high.
- Hence remanence is having an impact here and we need to be careful in assuming that the mineralisation is magnetite destructive - it may be introducing secondary magnetite which is fine grained and thus able to hold its magnetic direction.
- If the inversions are correct, then the mag low at the old Cactus mine is due to remanence and so not all mag lows are targets. If remanence is a general feature of gold mineralisation here, then we should be looking at susceptibility inversion lows which are also weak magnetisation inversion highs.
- A better petrophysical dataset is needed to understand what is happening here.