Introduction to level-set inversion

Jeremie Giraud, Mark Lindsay, Mark Jessell

My main sponsor

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[1] for more info about project:
https://cordis.europa.eu/project/id/101032994

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Overview

- Motivations
- Theoretical back
- Synthetic example
- Field application: Yerrida basin (WA)

Motivation and Objectives

Geol.

Geological modelling
Uses surface or shallow measurements only
→ (almost) Blind to what's not visible at surface

Geophysical (gravity) inversion
Gravity sensitive to the whole universe
→ Can image what geology does not see

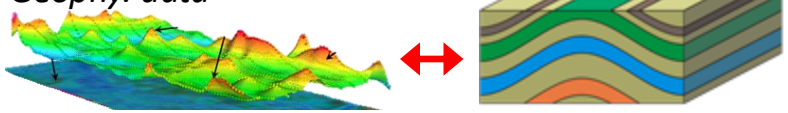
Geophy

Petrophysics + structural link: Populate structural model: petro and structural prior information

Petro

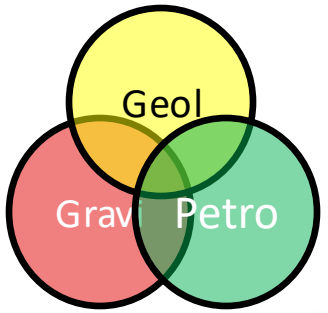
Deform geological bodies using geophysical inversion

Geophy. data

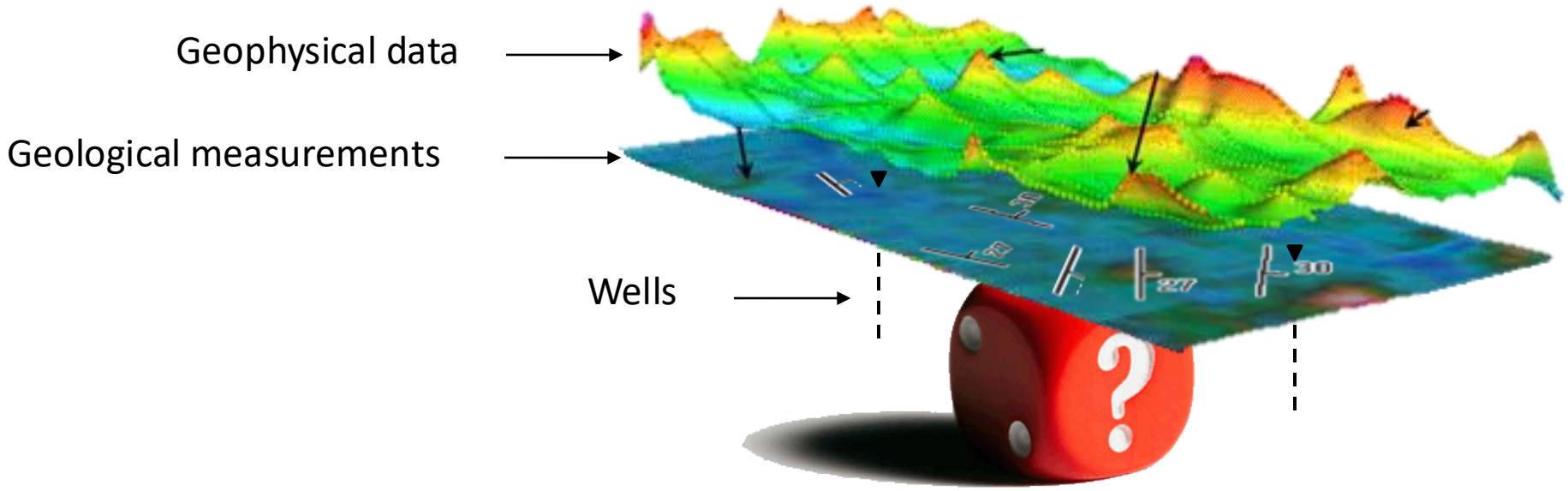


Geol. model

- Cooperative workflow using standalone engines
- Can be deterministic or probabilistic



Motivation and Objectives



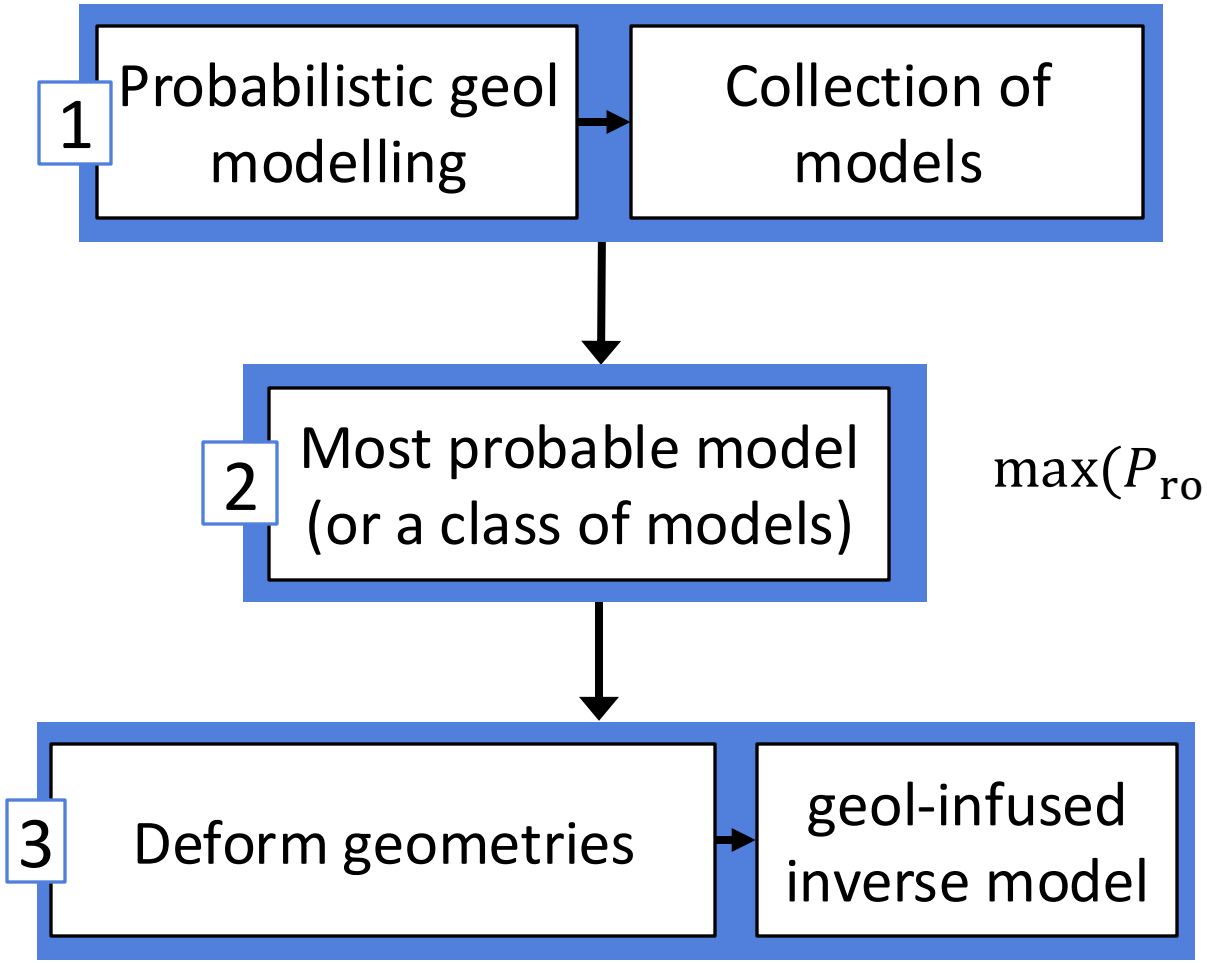
Cooperative modelling with geological modelling within geophysical inversion

Workflow

Standalone geological modelling

Extraction of geological info.

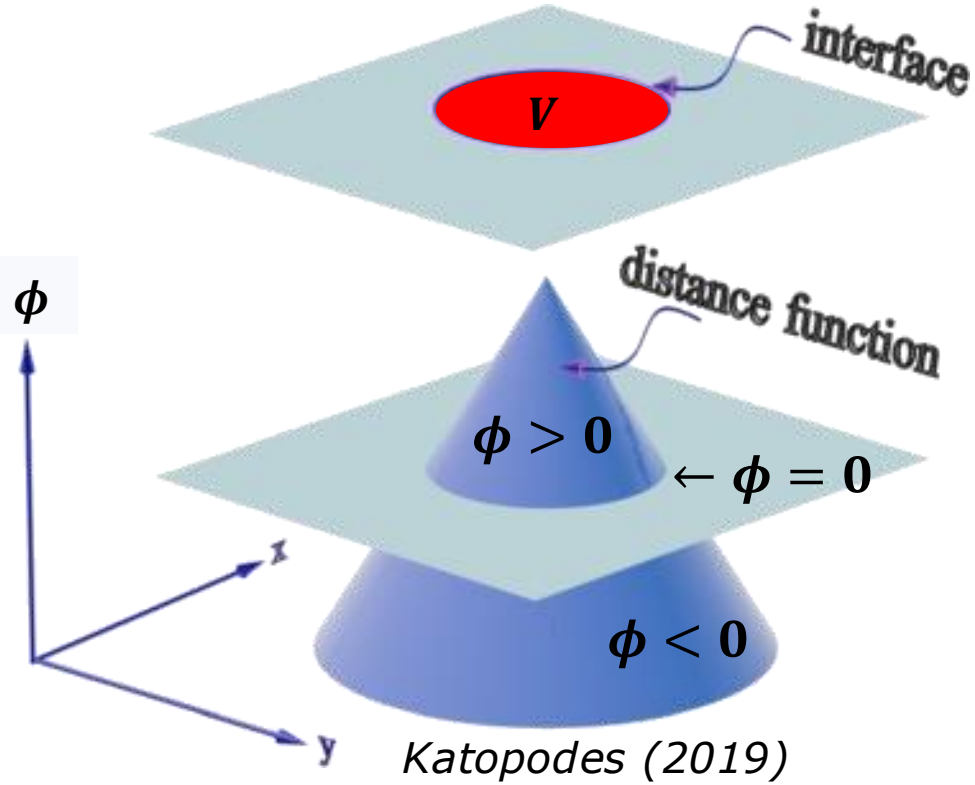
Standalone gravity inversion



Geometrical inversion

1. Definition of interfaces (signed distance)

Signed distance $\phi_k \begin{cases} > 0 \; inside \; unit \; k, \\ = 0 \; at \; the \; interface, \\ < 0 \; outside \; unit \; k, \end{cases}$



Katopodes (2019)

Geometrical inversion

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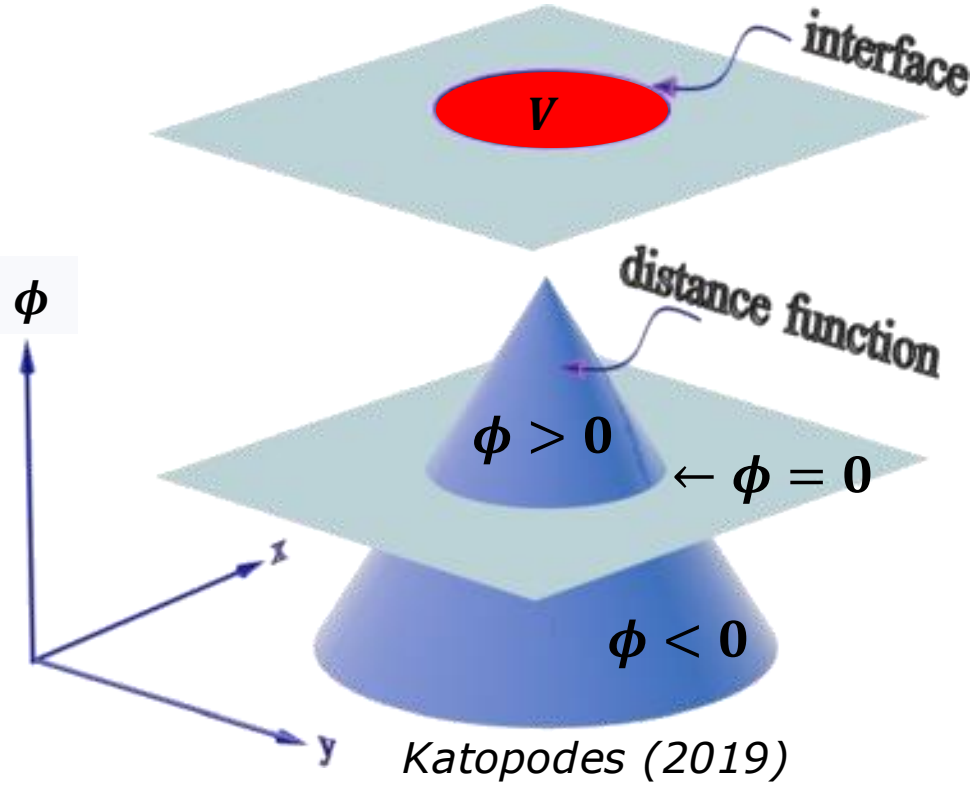
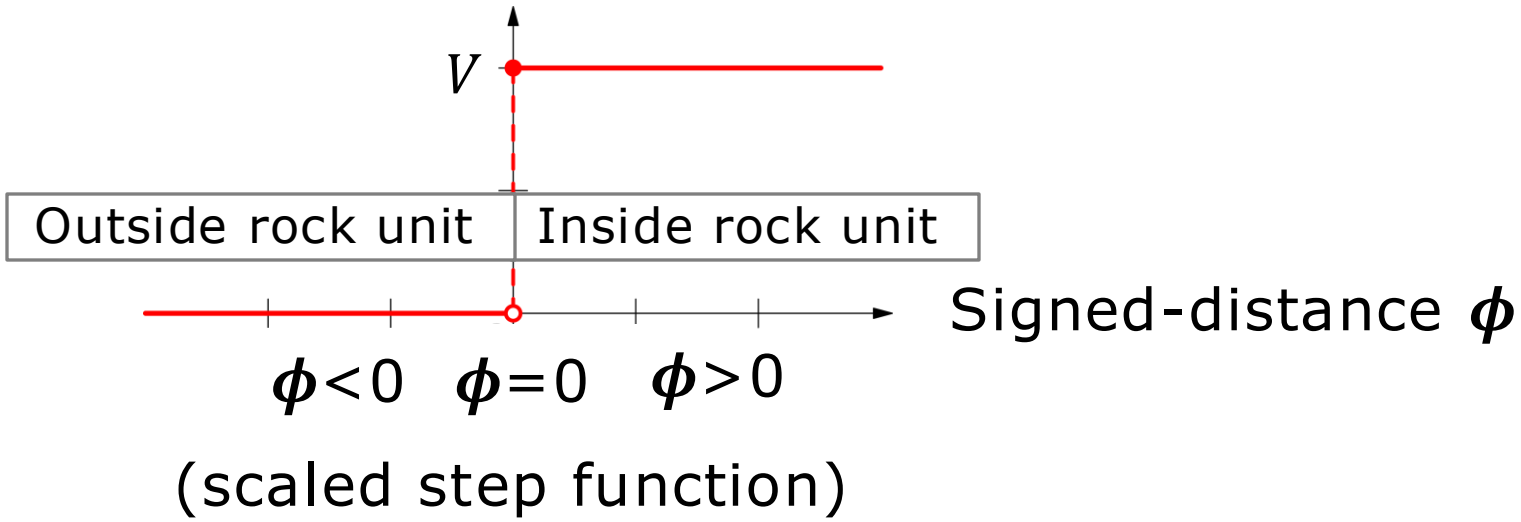


Katopodes (2019)

2. Calculate density model with values V

$$\boldsymbol{m}(\boldsymbol{\phi}_1, \ldots, \boldsymbol{\phi}_N) = \sum_{k=1}^{N} \left[V_k H(\boldsymbol{\phi_k}) \prod_{\substack{j=1 \\ j \neq k}}^{N} \left(1 - H(\boldsymbol{\phi_j})\right) \right]$$

Density contrast



(scaled step function)

Signed distance $\boldsymbol{\phi_k}$ $\begin{cases} > 0 \; inside \; unit \; k, \\ = 0 \; at \; the \; interface, \\ < 0 \; outside \; unit \; k, \end{cases}$

$$\boldsymbol{m}(\boldsymbol{\phi}_1, \dots, \boldsymbol{\phi}_N) = \sum_{k=1}^{N} \left[V_k H(\boldsymbol{\phi_k}) \prod_{\substack{j=1 \\ j \neq k}}^{N} \left(1 - H(\boldsymbol{\phi_j})\right) \right]$$

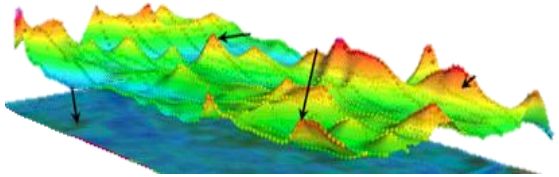
1. Definition of interfaces

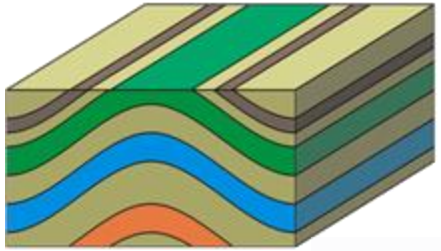
2. Calculate density model with values V_k

3. Link geophysical data to signed-distance

4. Calculate sensitivity of geophy data to interface location

$$\boldsymbol{J^{\phi_k}} = ??$$





geophy. data $\boldsymbol{d}$

$$\boldsymbol{J^m} = \frac{\partial \boldsymbol{d}}{\partial \boldsymbol{m}} = \frac{\partial \boldsymbol{d}}{\partial \boldsymbol{\phi_k}} \frac{\partial \boldsymbol{\phi_k}}{\partial \boldsymbol{m}} = \boldsymbol{J^{\phi_k}} \frac{\partial \boldsymbol{\phi_k}}{\partial \boldsymbol{m}},$$

inverted property model $\boldsymbol{m}$

$$\rightarrow \boldsymbol{J^{\phi_k}} = \frac{\partial \boldsymbol{d}}{\partial \boldsymbol{\phi_k}} = \boldsymbol{J^m} \frac{\partial \boldsymbol{m}}{\partial \boldsymbol{\phi_k}}$$

Multiple-body geometrical inversion

Signed distance $\boldsymbol{\phi_k}$ $\begin{cases} > 0 \; inside \; unit \; k, \\ = 0 \; at \; the \; interface, \\ < 0 \; outside \; unit \; k, \end{cases}$

$$\boldsymbol{m}(\boldsymbol{\phi}_1, \dots, \boldsymbol{\phi}_N) = \sum_{k=1}^{N} \left[V_k H(\boldsymbol{\phi_k}) \prod_{\substack{j=1 \\ j \neq k}}^{N} \left(1 - H(\boldsymbol{\phi_j})\right) \right]$$

$$\boldsymbol{J^{\phi_k}} = \frac{\partial \boldsymbol{d}}{\partial \boldsymbol{\phi_k}} = \boldsymbol{J^m} \frac{\partial \boldsymbol{m}}{\partial \boldsymbol{\phi_k}}$$

1. Definition of interfaces

2. Calculate density model with values V_k

3. Link geophysical data to signed-distance

4. Calculate sensitivity of geophy data to interface location

$$\frac{\partial m_j}{\partial (\phi_k)_j} = V_k \frac{\partial H\left((\phi_k)_j\right)}{\partial (\phi_k)_j} \prod_{\substack{s=1 \\ s \neq j}}^{N} \left[1 - H\left((\phi_s)_j\right)\right] - \sum_{t=1}^{N} \left[V_t H\left((\phi_t)_j\right) \prod_{\substack{u=1 \\ u \neq t \\ u \neq k}}^{N} \left[1 - H\left((\phi_u)_j\right)\right] \frac{\partial H\left((\phi_k)_j\right)}{\partial (\phi_k)_j} \right]$$

5. Local inverse problem to optimize interface perturbation

$$\boldsymbol{\Psi(\delta\phi, r)} = \left\| \boldsymbol{J^{\phi} \delta \phi^T} - \boldsymbol{r} \right\|_2^2 + \left\| \boldsymbol{\alpha W_s} \circ \boldsymbol{\delta \phi} \right\|_2^2 + \sum_{k=1}^{N} \left\| \boldsymbol{\beta_k W_p} \circ (\boldsymbol{\delta \phi_k} - \boldsymbol{v_k}) \right\|_2^2$$

6. Solve inverse problem

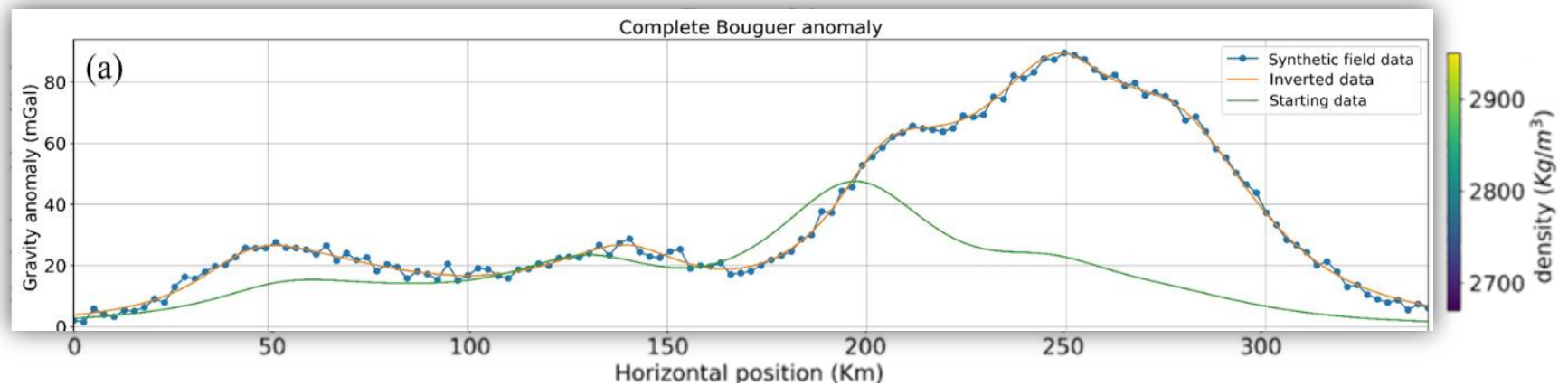
$$\begin{bmatrix} J^{\phi_1}, J^{\phi_2}, \dots, J^{\phi_N} \\ \alpha W_s \\ \beta_1 W_p \\ \beta_2 W_p \\ \vdots \\ \beta_N W_p \end{bmatrix} \begin{bmatrix} \delta\phi_1 \\ \delta\phi_2 \\ \vdots \\ \delta\phi_N \end{bmatrix} = \begin{bmatrix} r \\ 0 \\ \beta_1 v_1 \\ \beta_2 v_2 \\ \vdots \\ \beta_N v_N \end{bmatrix}, \text{(LSQR)}$$

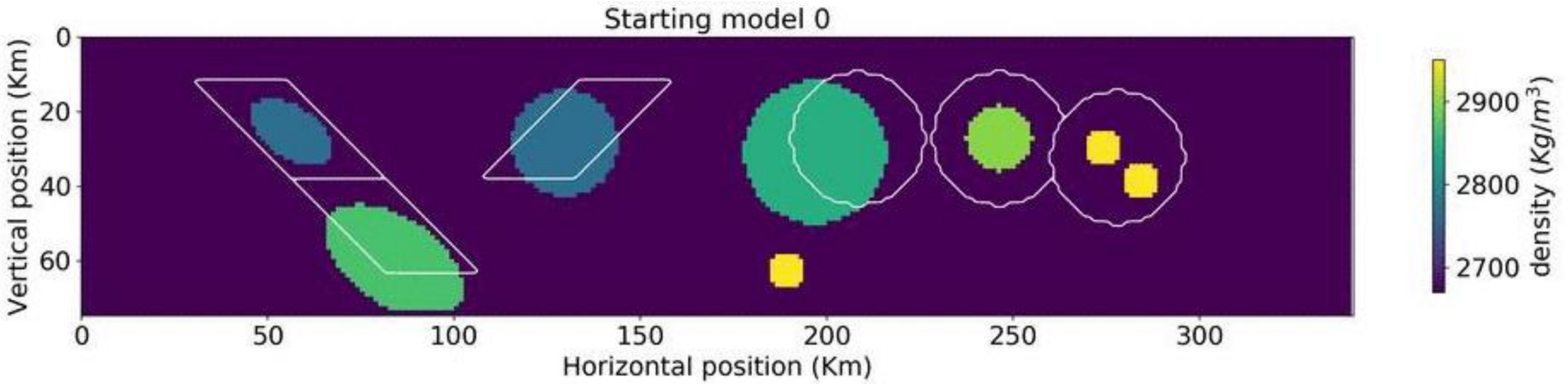
7. Increment signed-distances

$$\boldsymbol{\phi}^l = \boldsymbol{\phi}^{l-1} + \delta\boldsymbol{\phi}$$

- Ensure topology is OK
- Try new geol model?
- Or update again?

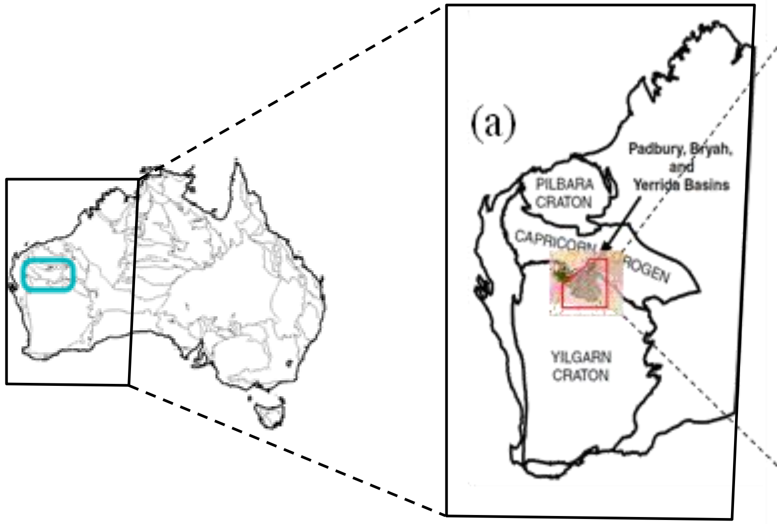
Synthetic case – test

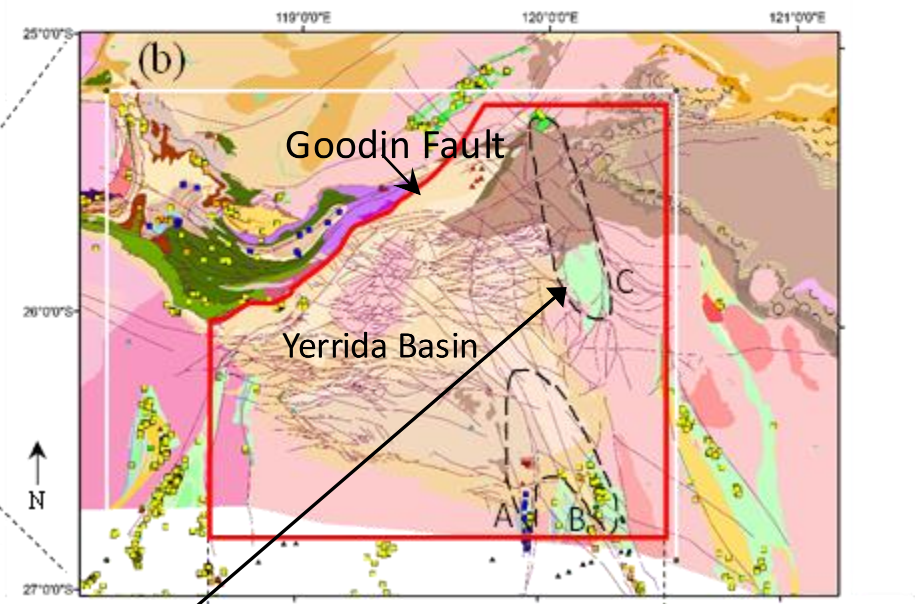


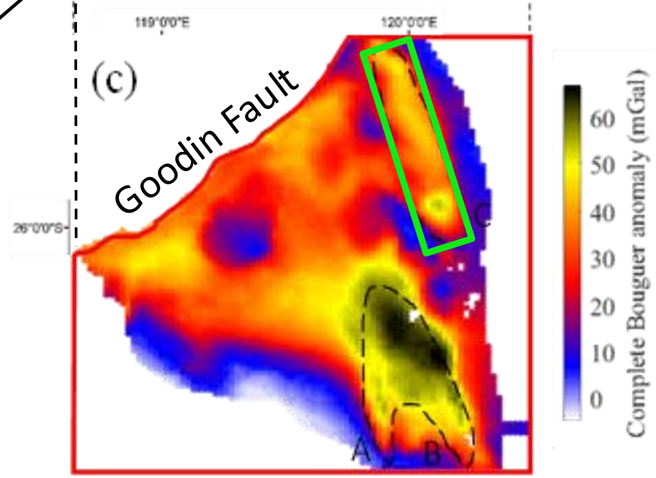


Giraud et al. 2021

Field application: Yerrida Basin







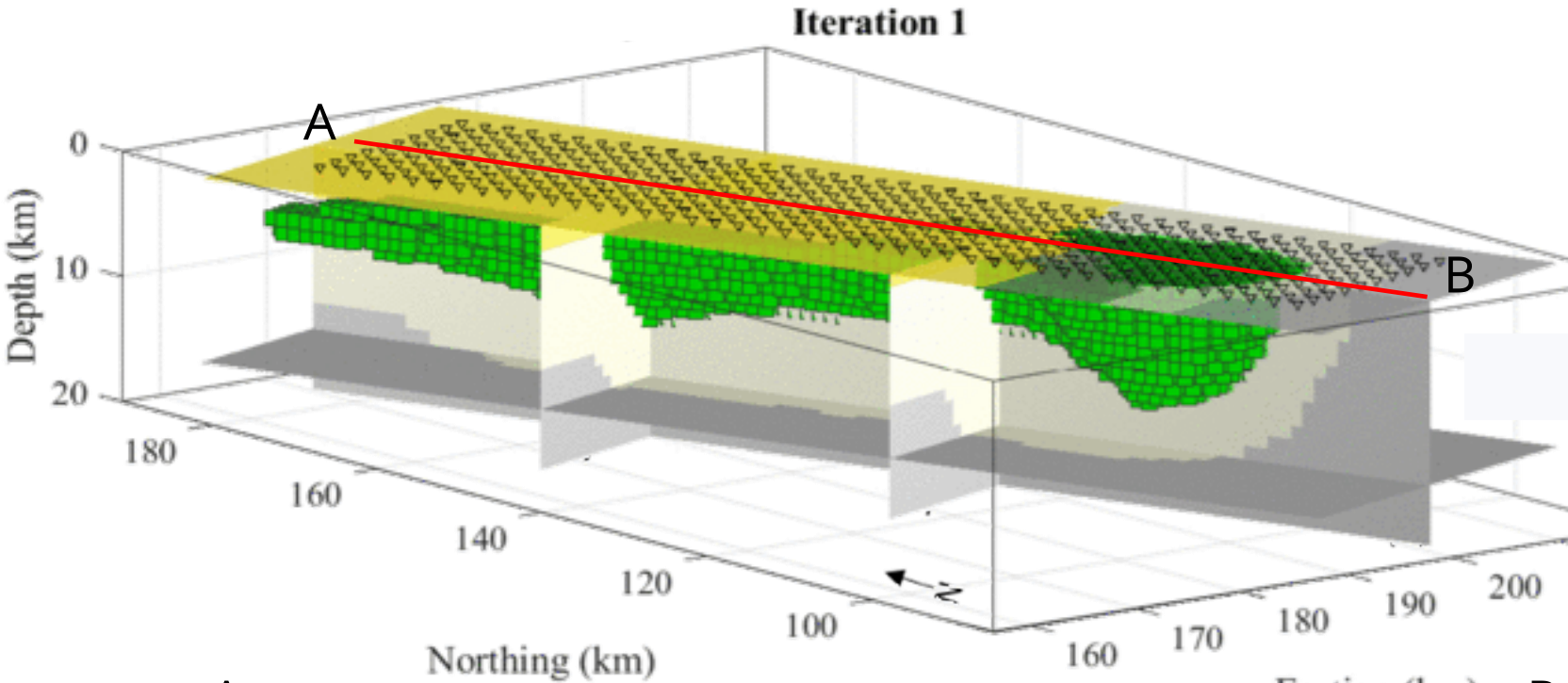
<u>Target</u>
- Dipping mafic Greenstone

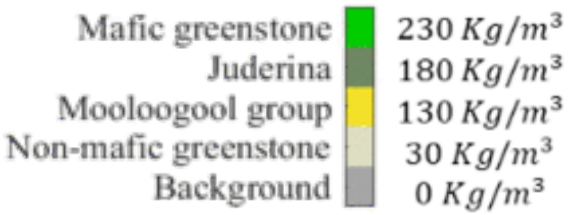
<u>Data</u>
- Geological measurements
- Gravity data
- Petrophysical info (samples)

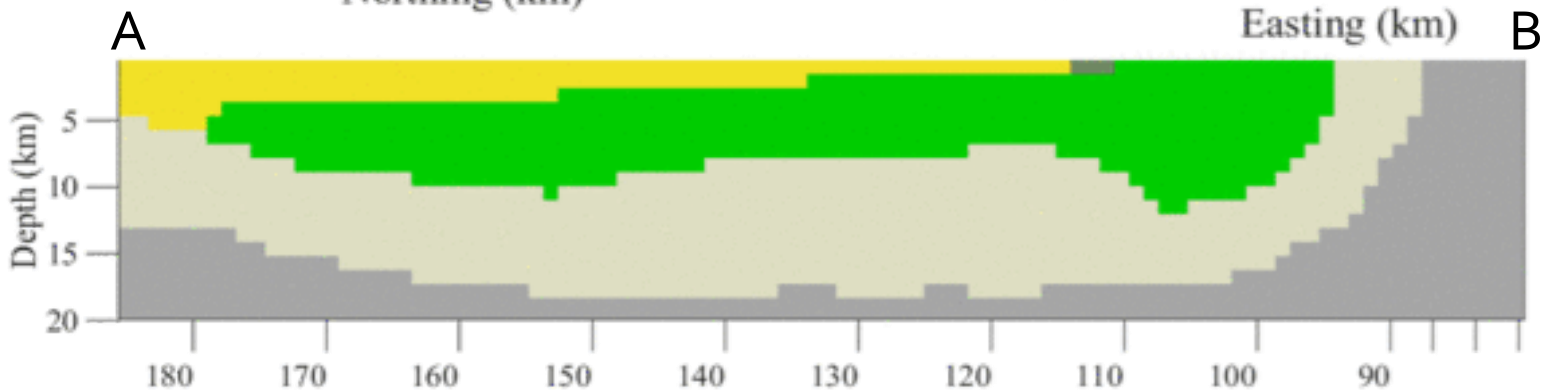
Modified from Lindsay et al. 2020, Pirajno et al. 1998, Giraud et al. 2020, 2021

Field application: Yerrida basin

- → Greenstone possibly broken into several pieces
- → In line with other recent studies (Lindsay et al., 2020, Giraud et al. 2020)
- → Geological data probably poorly informed about deep structures

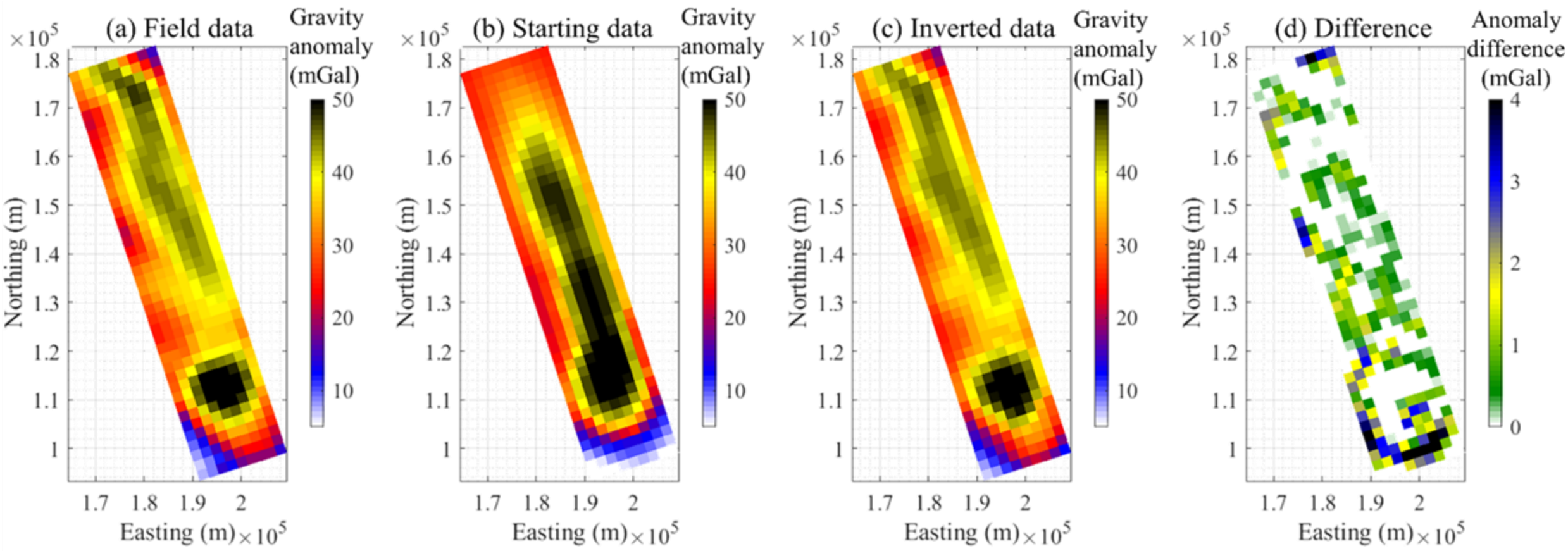






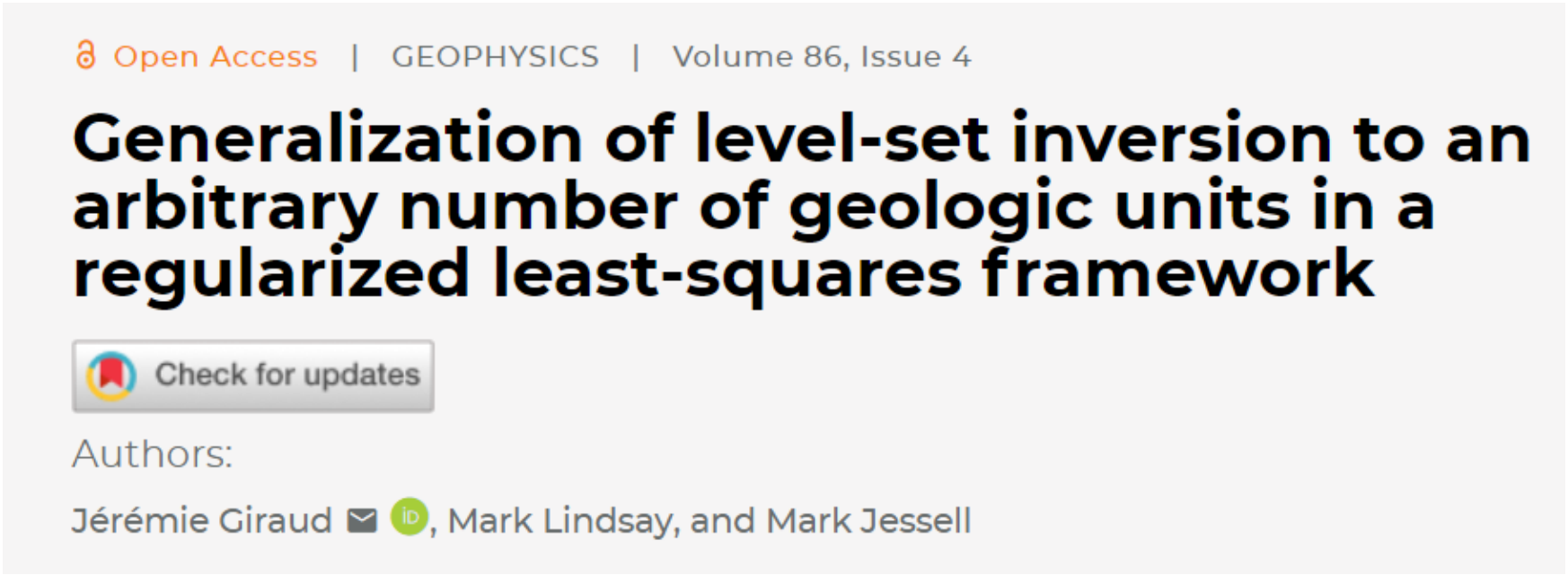
Giraud et al. 2021; Lindsay et al. 2021; Giraud et al. 2020

Field application: Yerrida basin



Giraud et al. 2021

For more info



(works even from a distance!)

Jérémie Giraud, Mark Lindsay, Mark Jessell; Generalization of level-set inversion to an arbitrary number of geologic units in a regularized least-squares framework. Geophysics, **2021**; 86 (4): R623–R637. doi: https://doi.org/10.1190/geo2020-0263.1

Questions?

Proposed approach

Geol.

Geological modelling
Very good with direct observations
→ Modelling concepts valid everywhere

Geophysical (gravity) inversion
Indirect measurement of subsurface
→ Sensitivity to full study area, can image unseen geological features

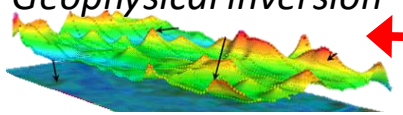
Geophy

Petro

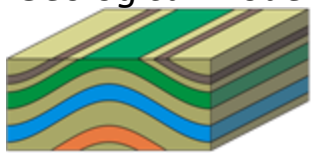
Populate structural model

Deform geological units using geophysical inversion[1]

Geophysical inversion



Geological modelling



…. but is the resulting model geological???

1. Giraud et al 2021 multiple level set inversions in Yerrida Basin

Proposed approach

Geol.

Geological modelling
Very good with direct observations
→ Modelling concepts valid everywhere

Geophysical (gravity) inversion
Indirect measurement of subsurface
→ Sensitivity to full study area, can image unseen geological features

Geophy

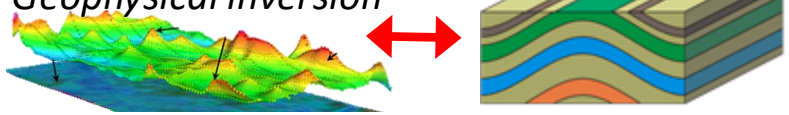
Petro

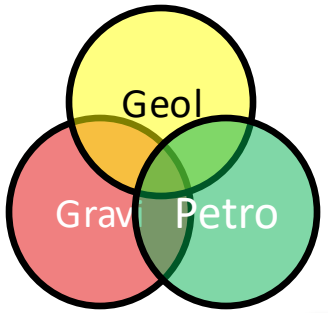
Populate structural model

Deform geological units using geophysical inversion <u>with geol. modelling component</u>

Geological modelling

Geophysical inversion



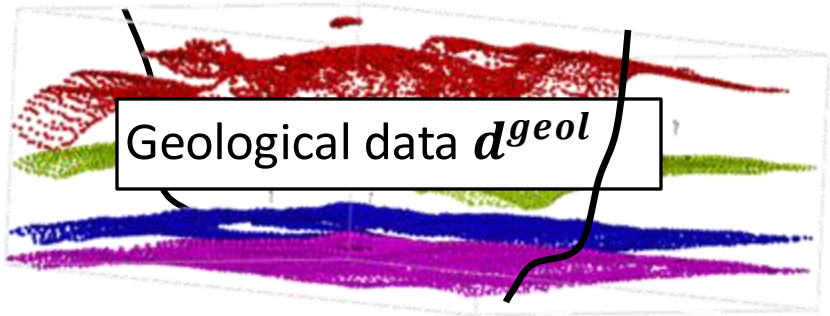


Implicit modelling: geology

Implicit geological modelling in a nutshell

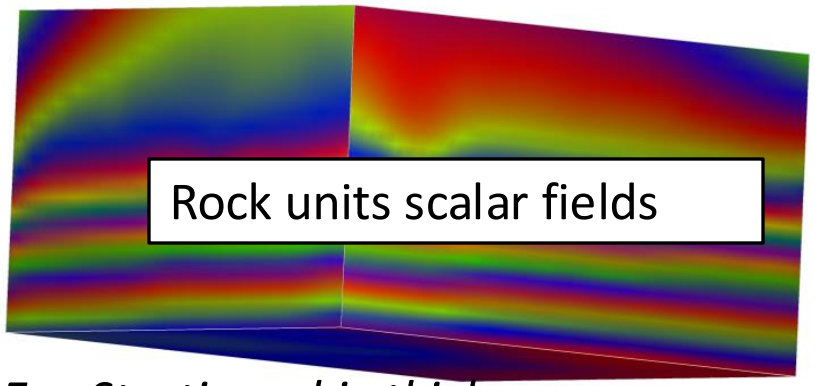
Implicit modelling: geology

Implicit geological modelling in a nutshell



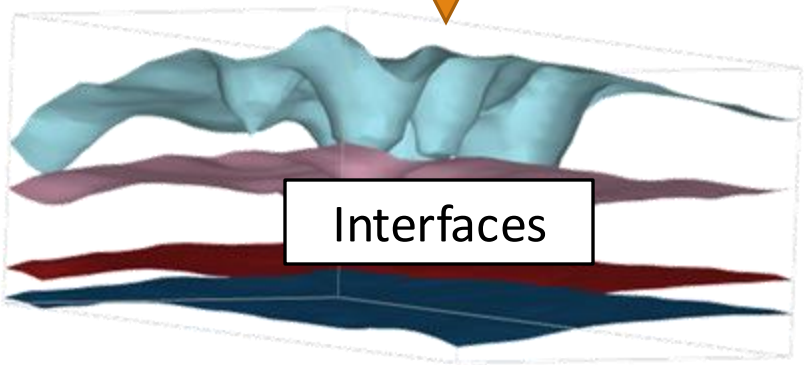
Ex.: Seismic horizons, borehole data, etc.

Implicit modelling[1]
→ Age relationships
→ Structural rules

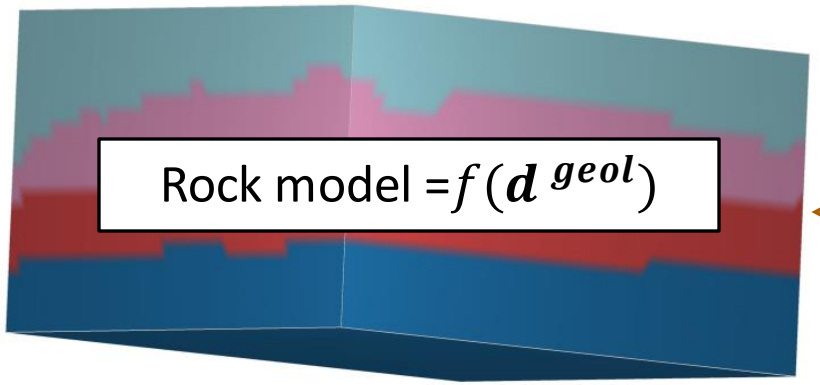


Ex.: Stratigraphic thickness

Identification of iso-values



Create and Populate mesh



Ex.: Rock model with density values

[1] Grose et al. 2021 Loop: Structural Implicit modelling

Geophysical problem formulation

Solve for update of distance $\delta\boldsymbol{\phi}$ with geol. modelling component

Signed dist.

Geophy. data

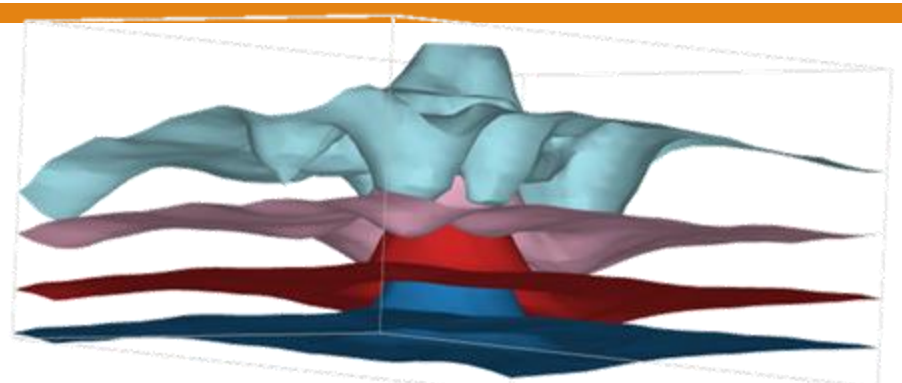
Geol. data

$$\Psi\left(\boldsymbol{\phi}, \boldsymbol{d}^{geophy}, \boldsymbol{d}^{geol}\right) = \underbrace{\left\|\boldsymbol{d}_{obs.}^{geophy} - \boldsymbol{d}_{calc.}^{geophy}\right\|_2^2}_{\text{Geophy. data misfit}} + \underbrace{\left\|\boldsymbol{W}^{-1}\left(\boldsymbol{\phi} - \boldsymbol{\phi}^{geol}\left(\boldsymbol{d}_{obs.}^{geol}, \boldsymbol{d}_{calc.}^{geol}\right)\right)\right\|_2^2}_{\text{Regularisation}}$$

Signed distances of geol. model

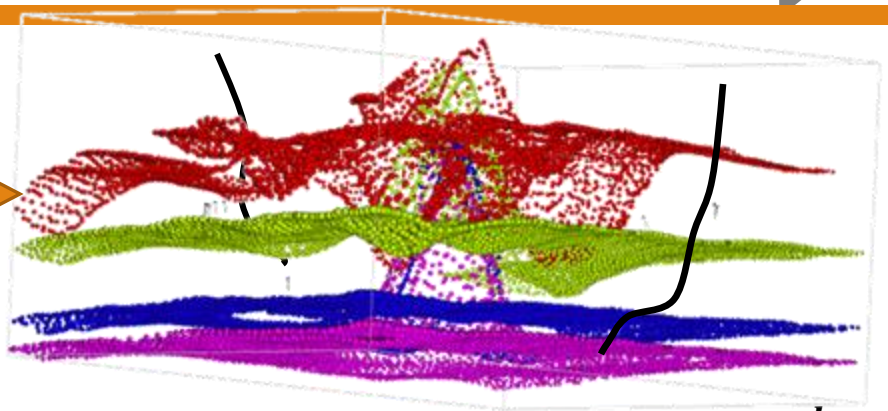
$d_{calc.}^{geol}$: geol data recovered from model proposed by geophysics

From geophysics to geology



Geophysical model $\boldsymbol{\phi}_*^n$ → interfaces

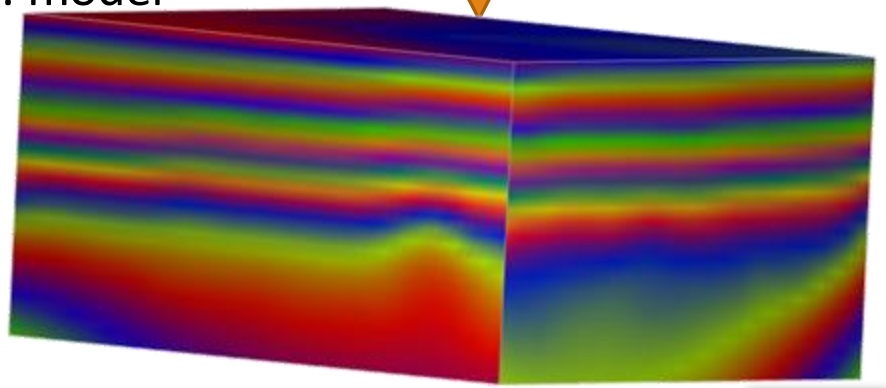
Identification of contact locations and orientation data



+ seismic horizons, borehole data, etc. in $\boldsymbol{d}^{geol}$

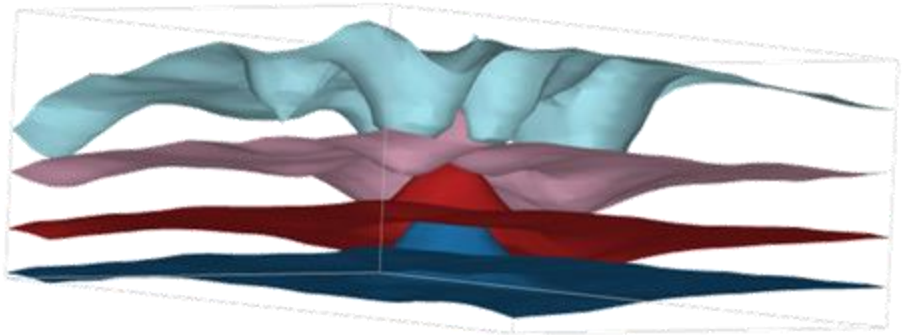
Implicit modelling [1]
→ Age relationships
→ Structural rules

Implicit geol. model



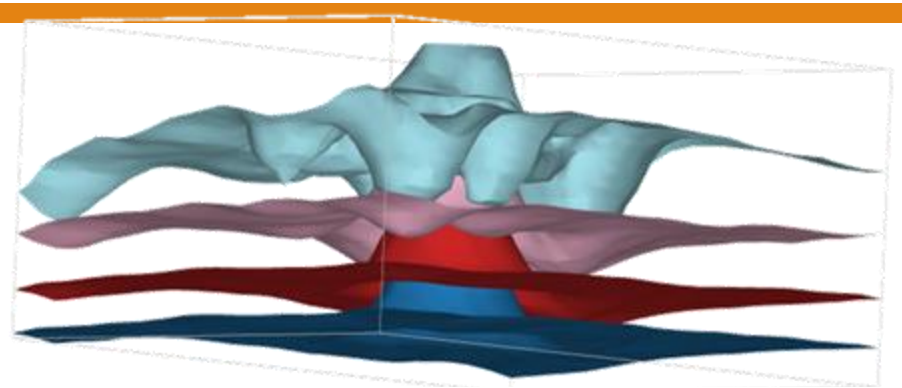
Identification of iso-values

Modified model ('geological' version)
→ $\boldsymbol{\phi}^{geol}\left(\boldsymbol{\phi}_*^n, \boldsymbol{d}^{geol}\right)$



[1] Grose et al. 2021 LoopStructural Implicit modelling

From geophysics to geology



Geophysical model $\boldsymbol{\phi}_*^n$ → interfaces

Identification of contact locations and orientation data

+ seismic horizons, borehole data, etc. as geological data

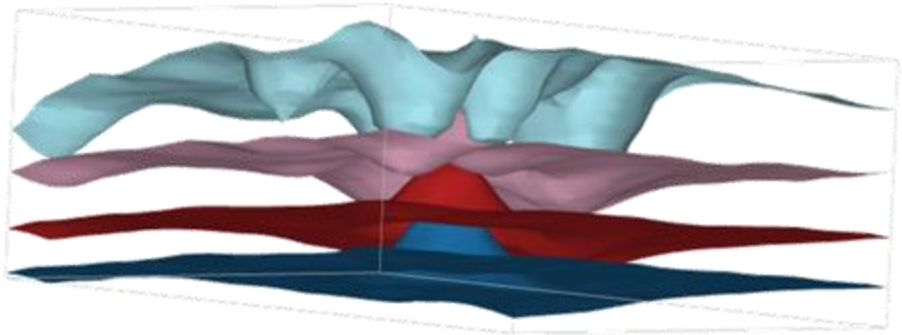
$$\boldsymbol{\phi}^{geol}\left(\boldsymbol{\phi}_*^n, \boldsymbol{d}^{geol}\right) \rightarrow \text{Calculate } \left\| \boldsymbol{W}^{-1}\left(\boldsymbol{\phi} - \boldsymbol{\phi}^{geol}\left(\boldsymbol{d}_{obs.}^{geol}, \boldsymbol{d}_{calc.}^{geol}\right)\right)\right\|_2^2$$

Modified model ('geological' version)
→ $\boldsymbol{\phi}^{geol}\left(\boldsymbol{\phi}_*^n, \boldsymbol{d}^{geol}\right)$

→ Structural rules

Implicit geological model

Identification of iso-values



In a nutshell: cost function

Iterative solver: at iteration *n…*

Optimize implicit field $\boldsymbol{\phi}$, to reduce geophysical data misft

Account for geological data $\boldsymbol{d}_{obs.}^{geol}$[1]

Geophysical data term

Geological model term

$$\min \; \boldsymbol{W}_d^{-1} \left\| \boldsymbol{d}_{obs.}^{geophy} - \boldsymbol{d}_{calc.}^{geophy} \right\|_2^2 + \left\| \boldsymbol{W}_p^{-1} \left(\boldsymbol{\phi}^n - \boldsymbol{\Phi}_{geol}^n \left(\boldsymbol{d}_{obs.}^{geol}, \boldsymbol{\phi}^{n-1} \right) \right) \right\|_2^2$$

Observations

Model response

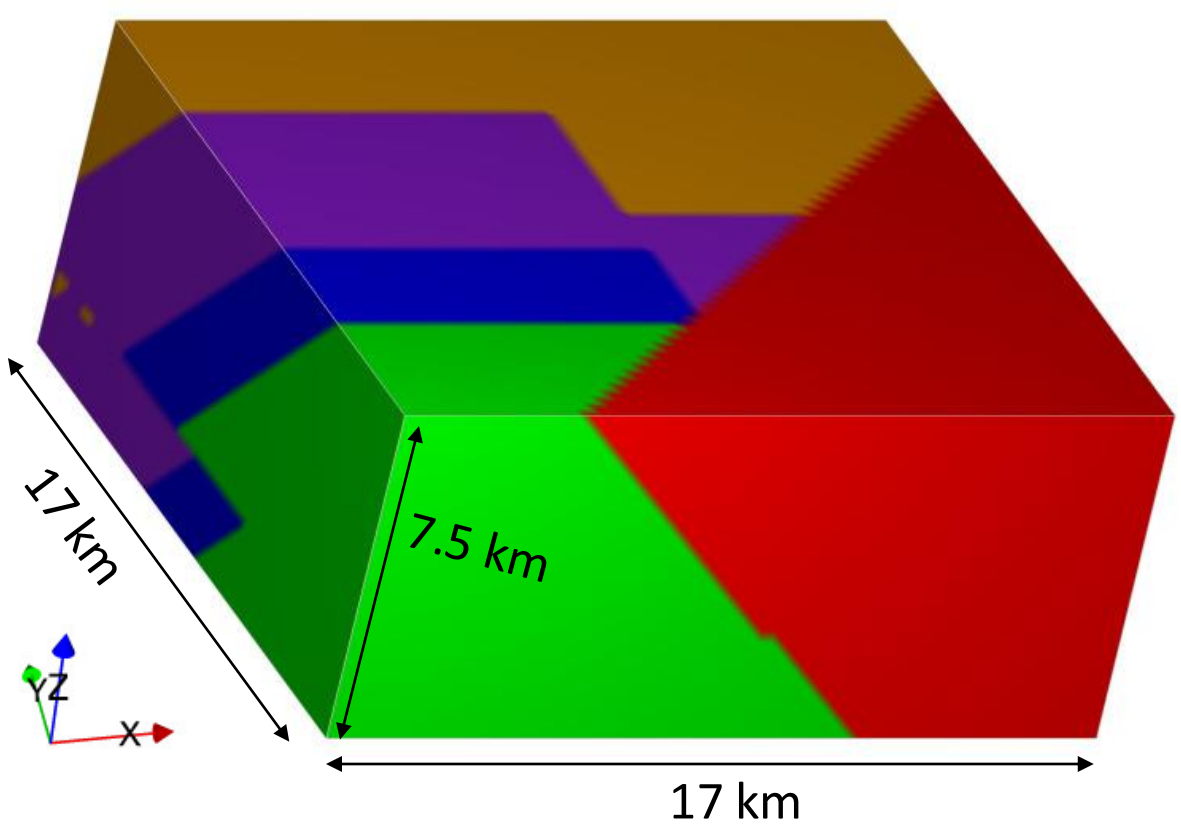
Inverted. model

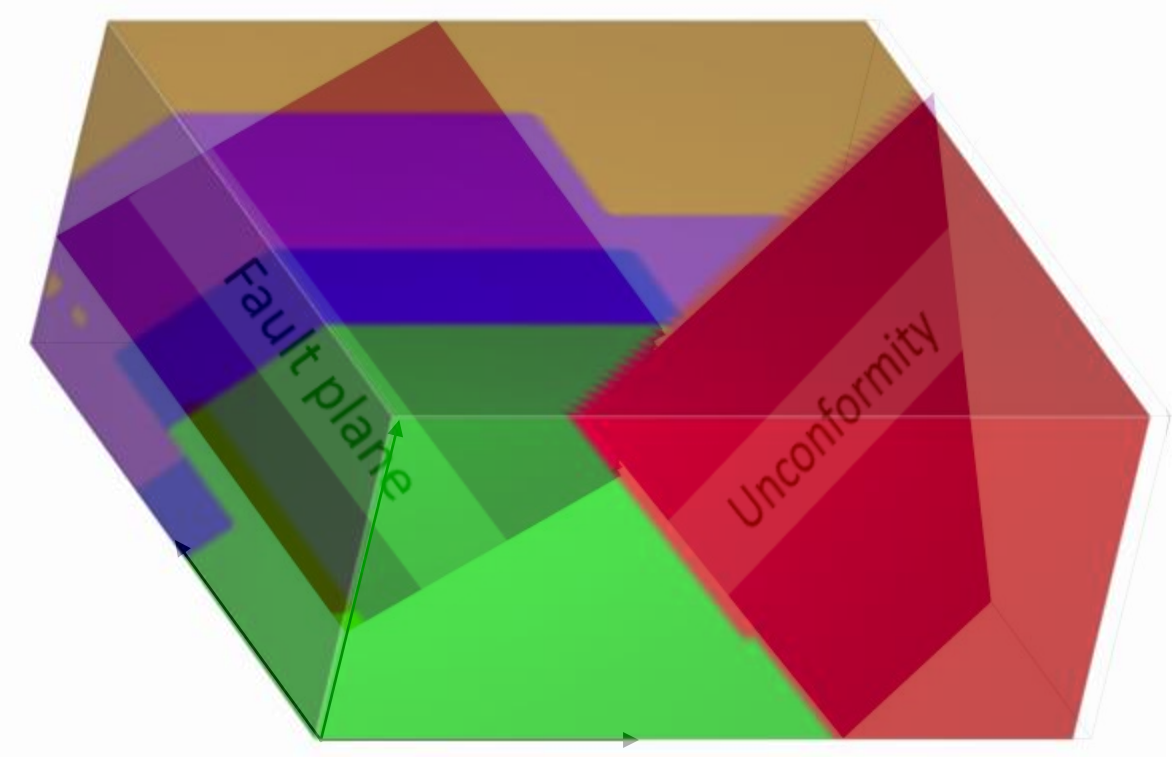
Geological projection (≈prior model)

[1]Giraud et al. 2022, 2023.

Synthetic test

Reference model

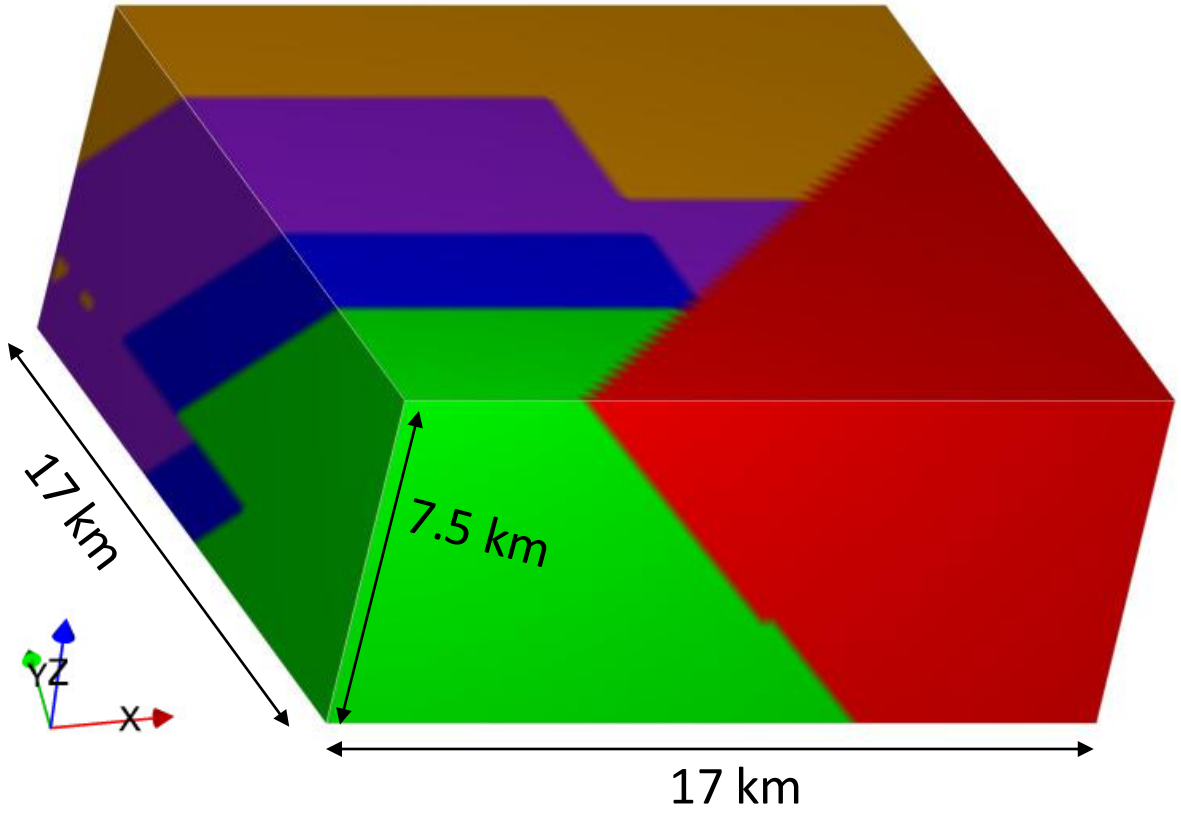




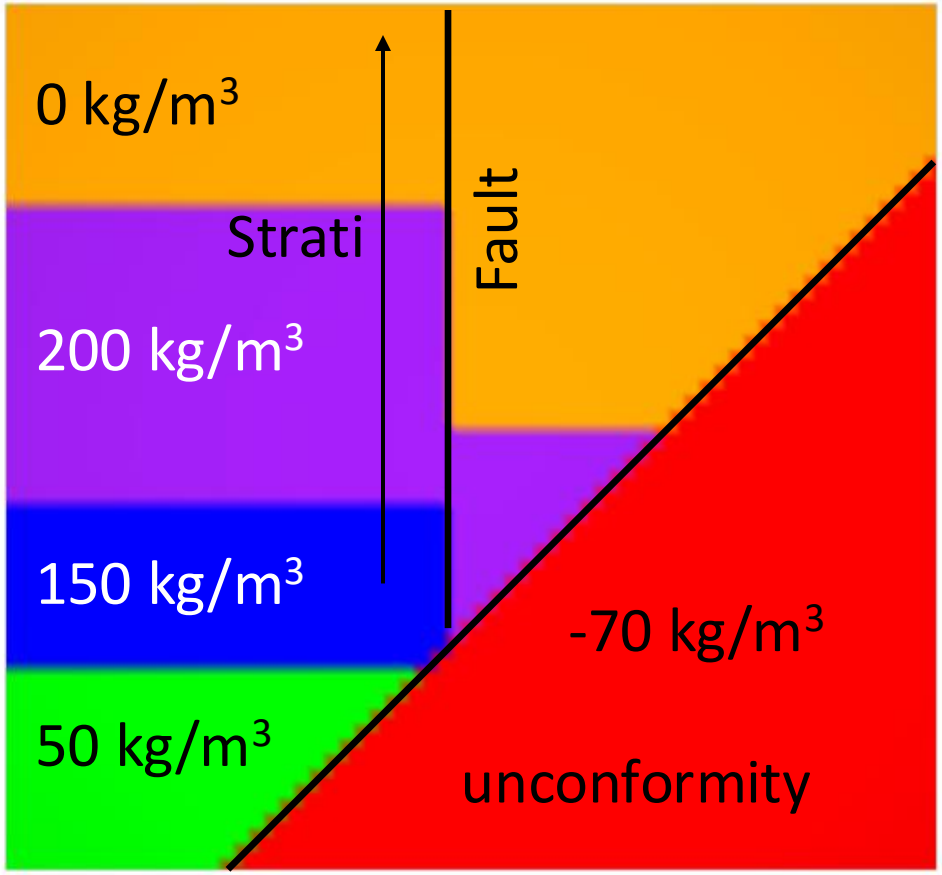
(generated using LoopStructural)

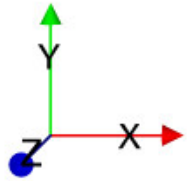
Synthetic test

Reference model



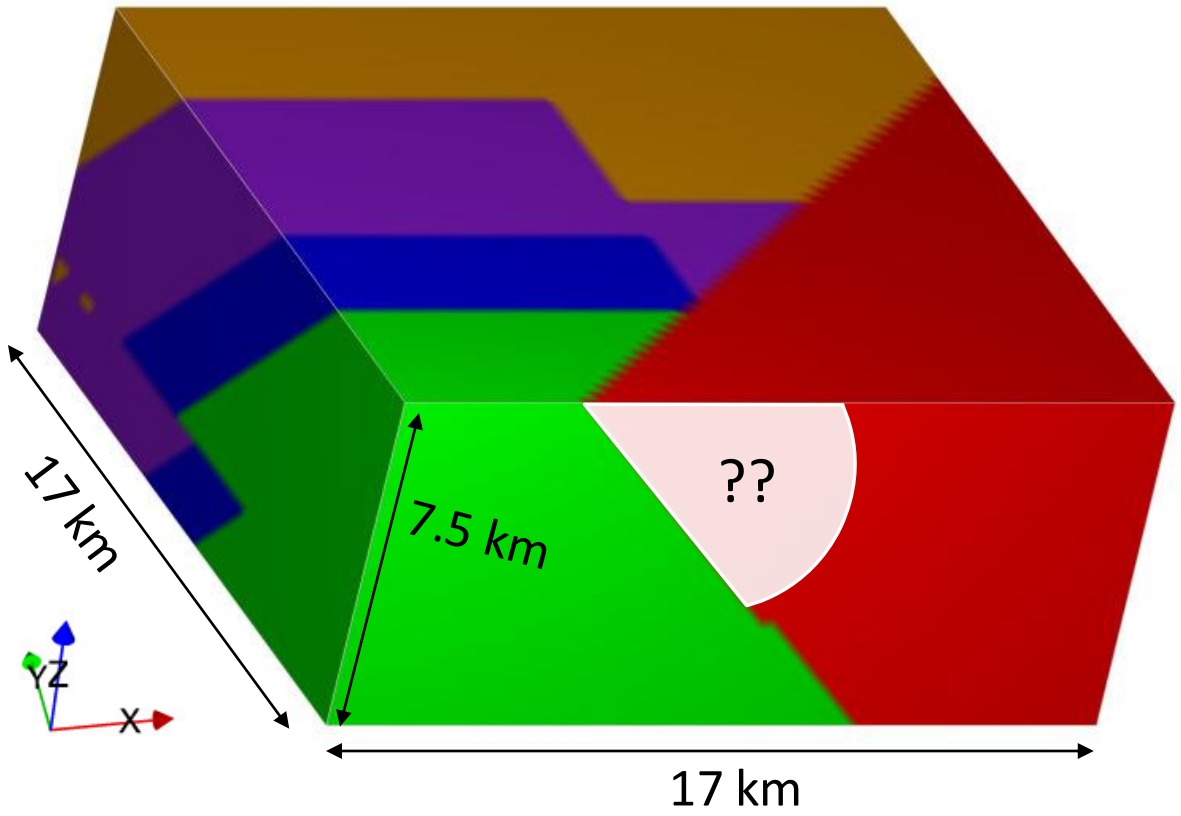
Top view



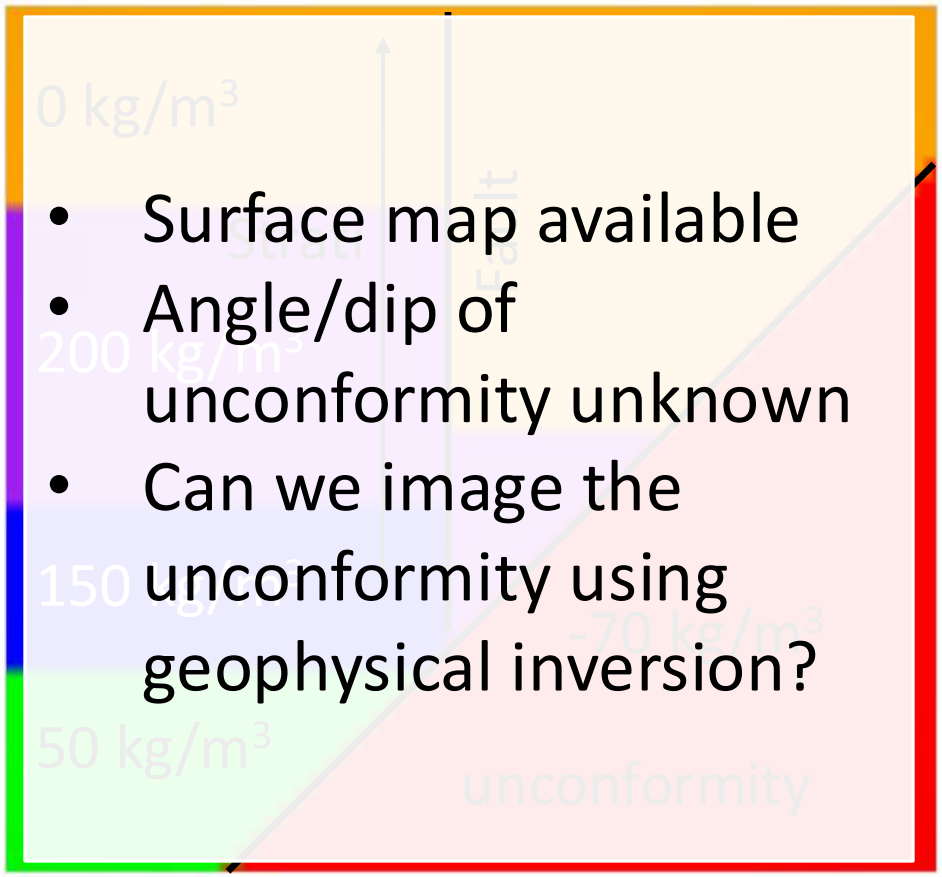


Synthetic test

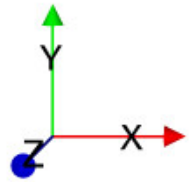
Reference model



Top view

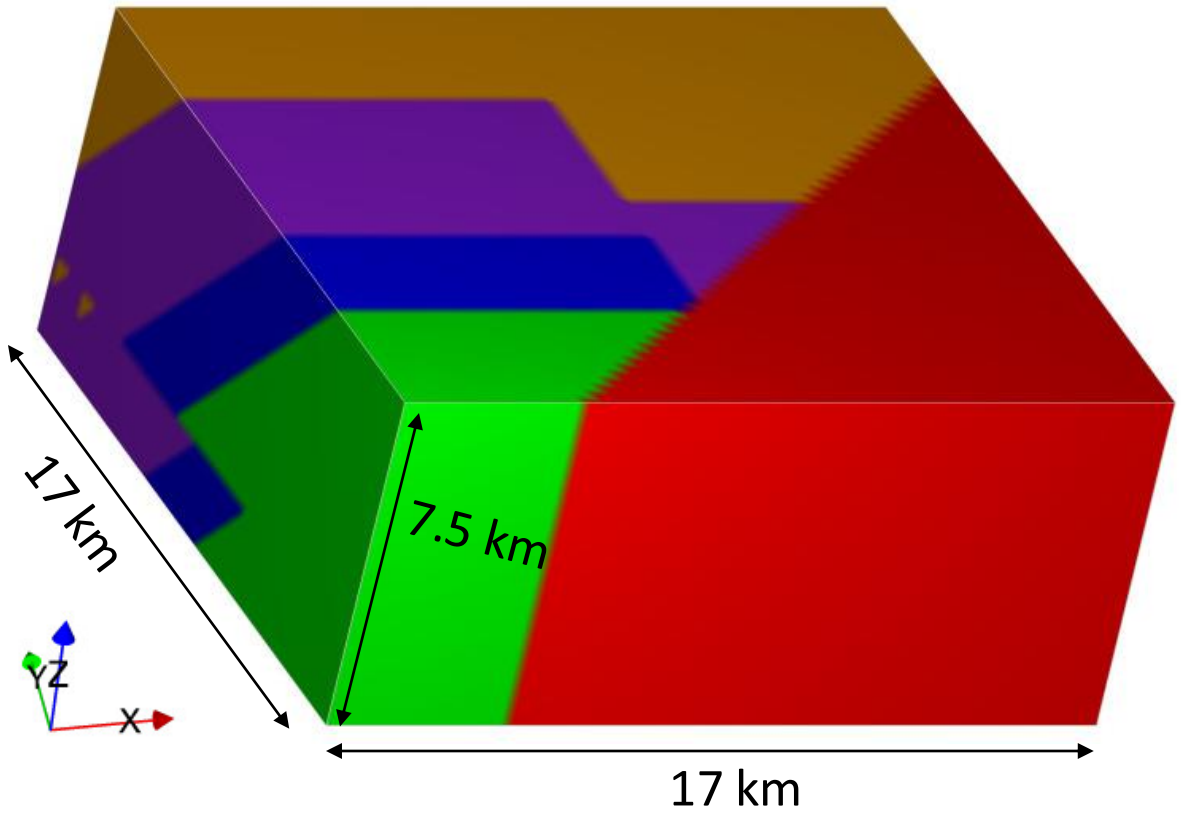


- Surface map available
- Angle/dip of unconformity unknown
- Can we image the unconformity using geophysical inversion?



Synthetic test

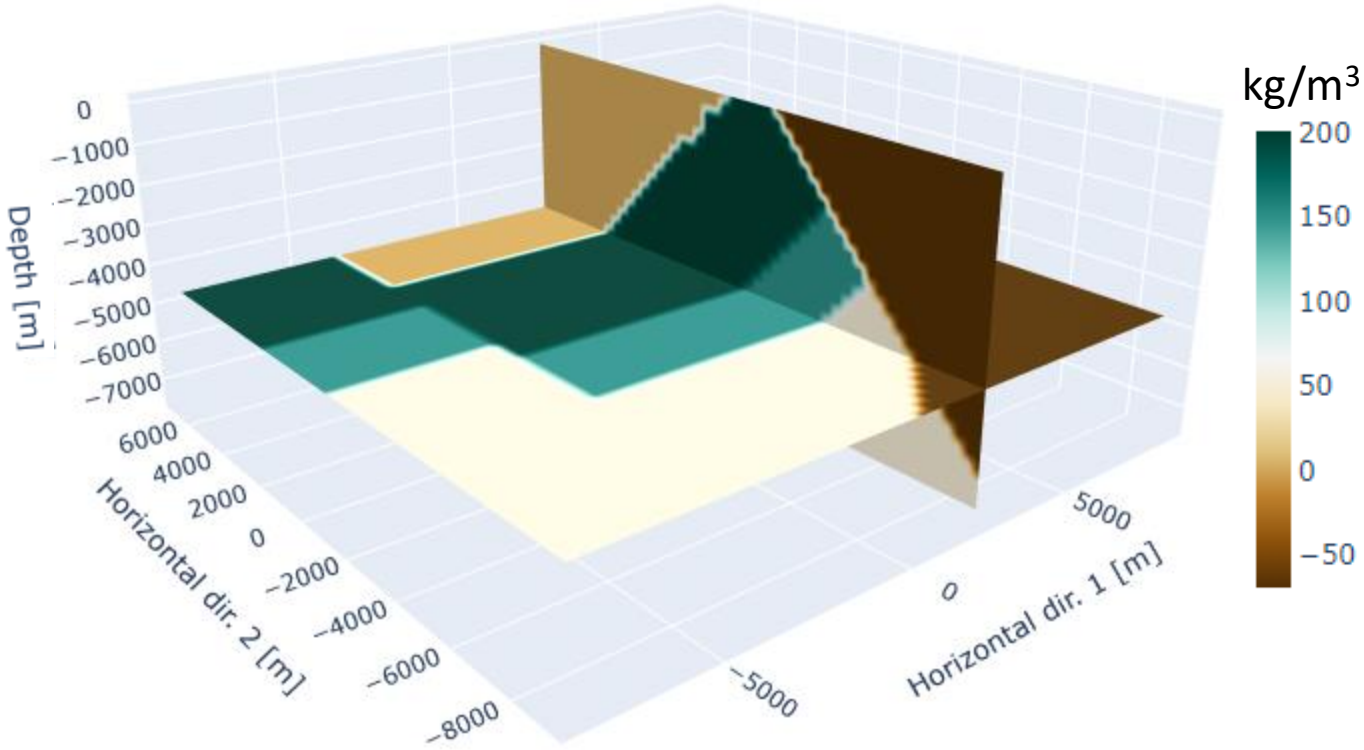
Starting model

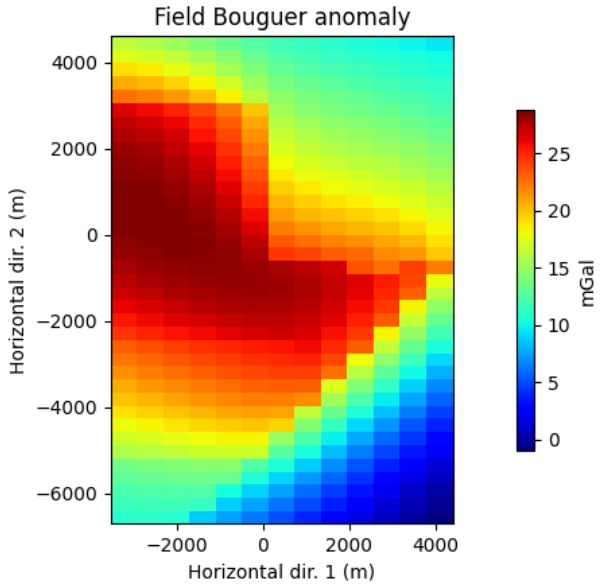


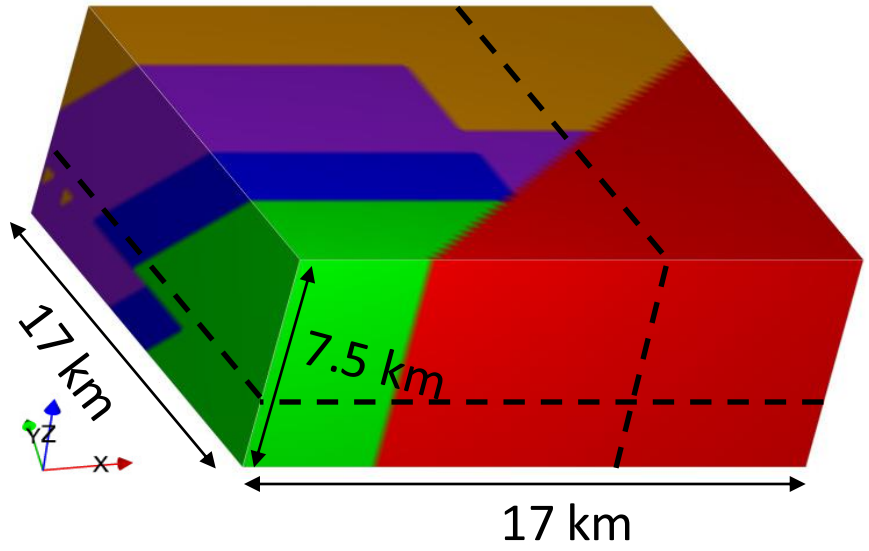
- Vertical contact (for the sake of testing) assuming no knowledge of contact angle
- Constraints only on unconformity
- Starting with large misfit

Synthetic test

Reference model

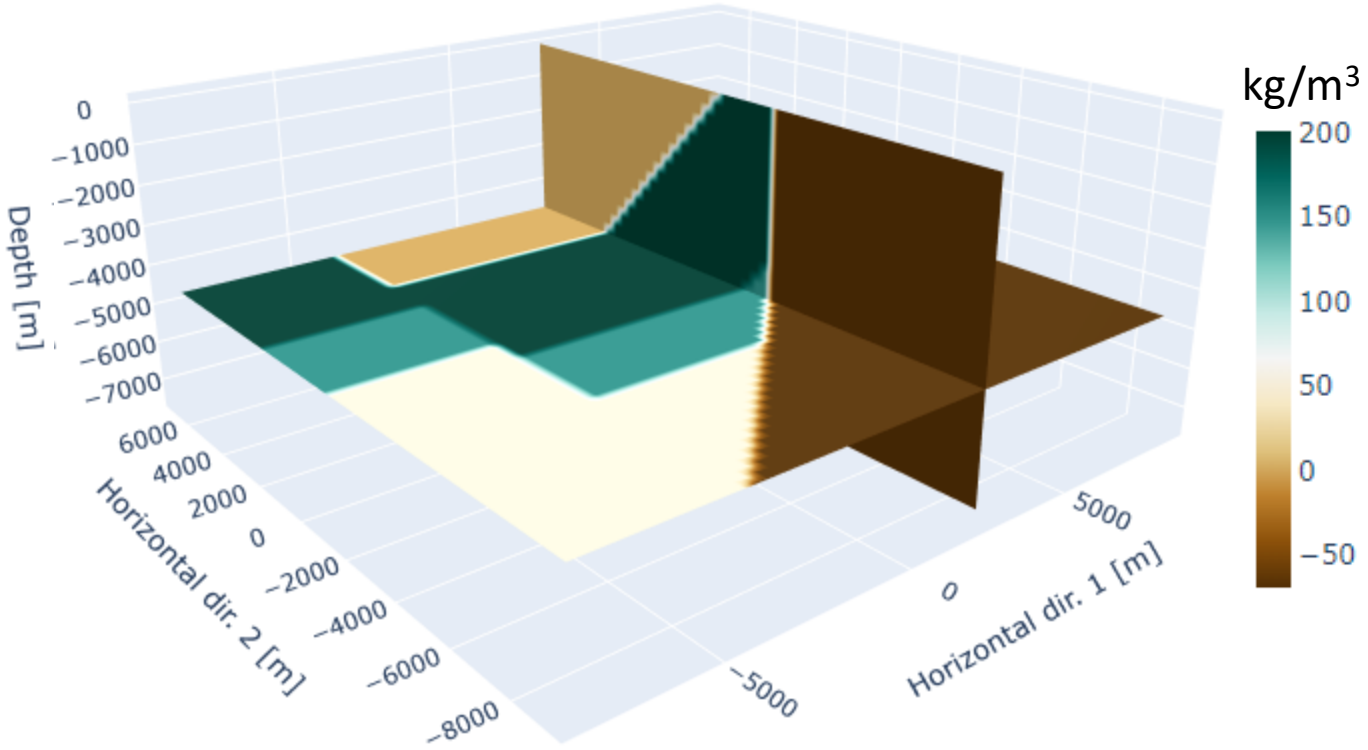


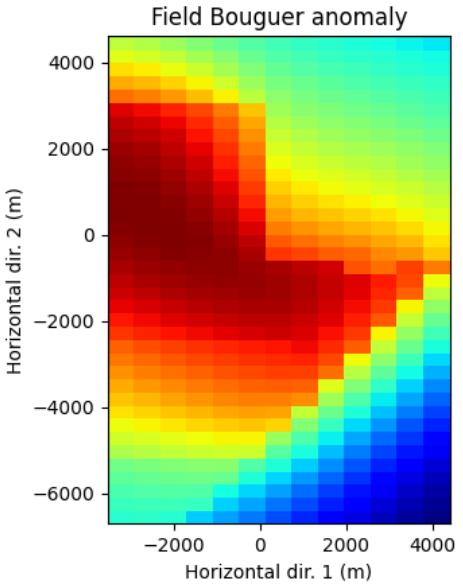


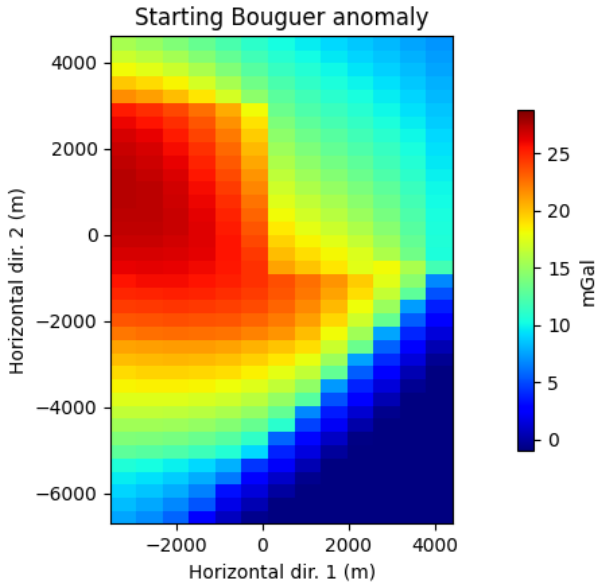


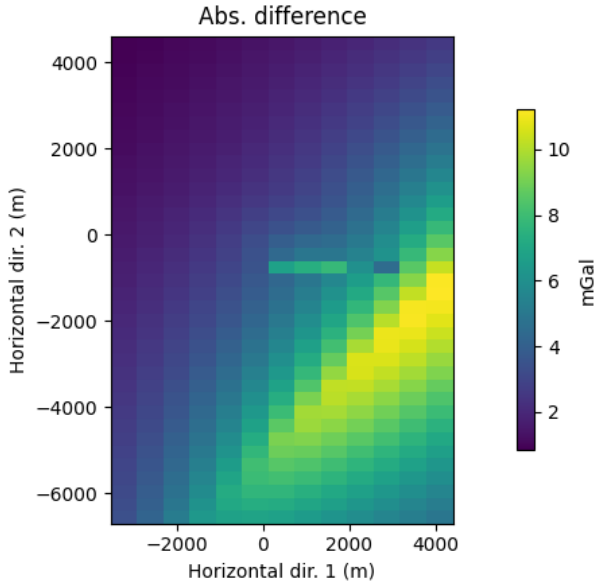
Synthetic test 2

Starting model





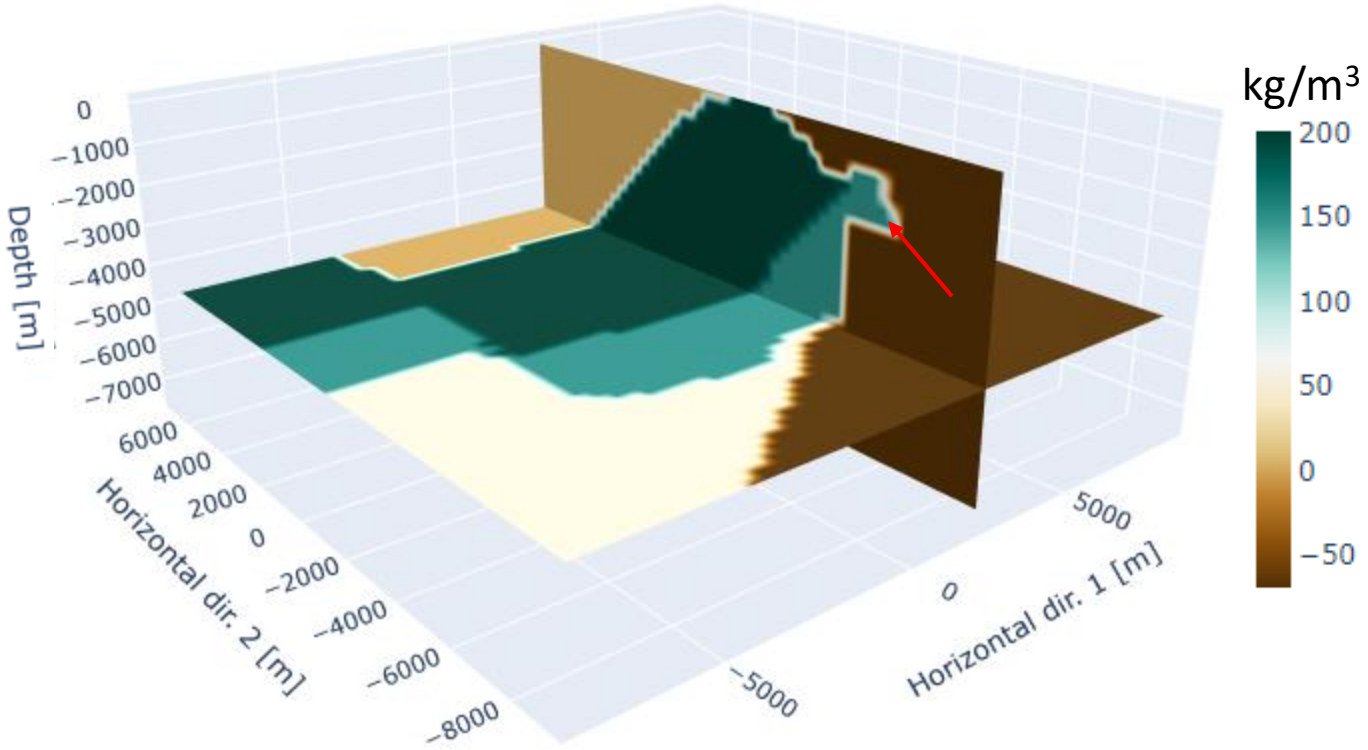




- High data misfit
- Visually very different from ref. model

Synthetic test 2

No geological constraints or correction



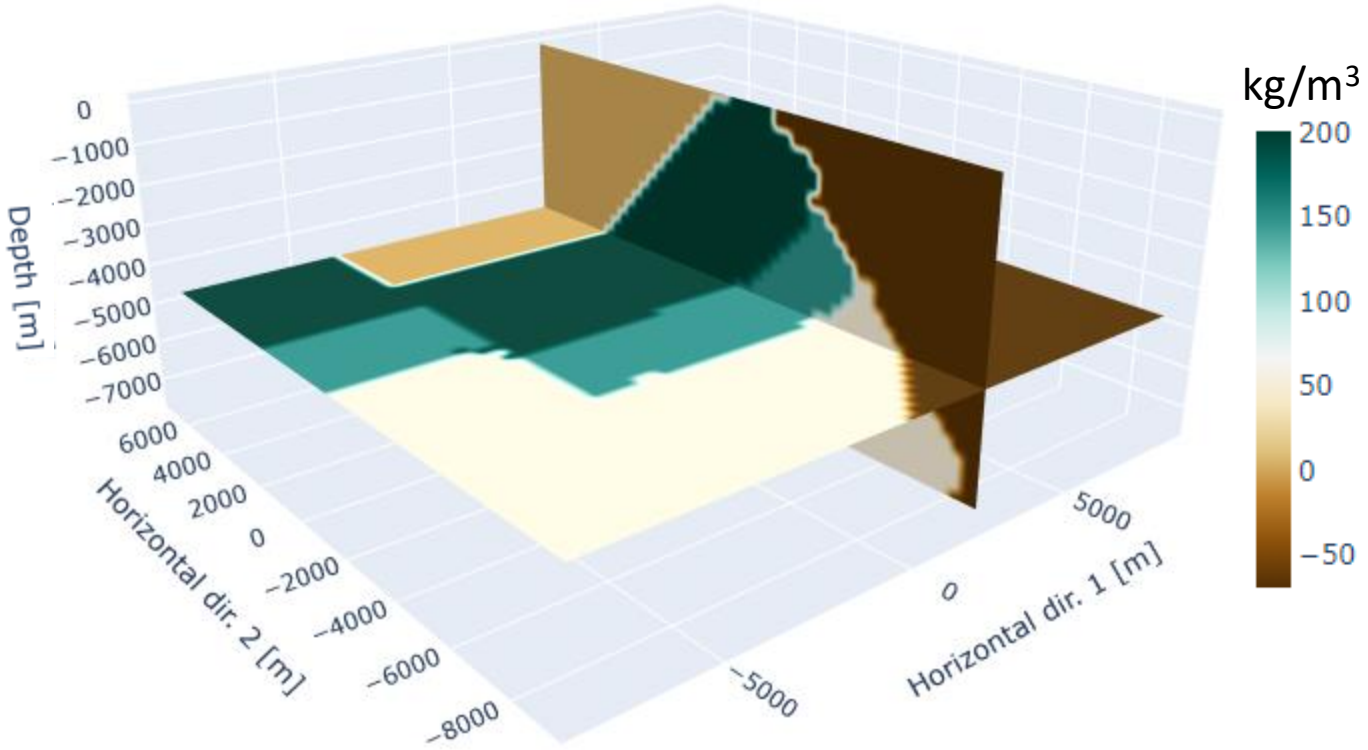
- Low geophysical data misfit
- Geologically inconsistent

$$\Psi(\delta\boldsymbol{\phi}, \boldsymbol{r}) = \left\|\boldsymbol{J}^{\phi}\delta\boldsymbol{\phi} - \boldsymbol{r}\right\|_2^2 + \lambda_s\left\|\boldsymbol{W}(\delta\boldsymbol{\phi} - \delta\boldsymbol{\phi}^{prior})\right\|_2^2$$

$$\boldsymbol{\phi}^n = \boldsymbol{\phi}^{n-1} + \delta\boldsymbol{\phi}$$

Synthetic test 2

Geological constraints term

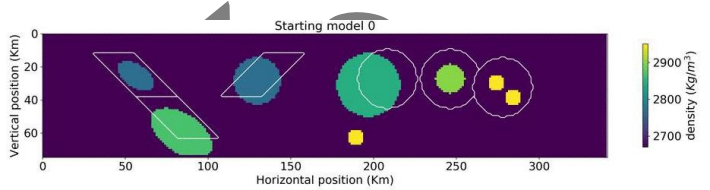


- Low geophysical data misfit
- 'Better' geologically

$$\Psi(\delta\boldsymbol{\phi}, \boldsymbol{r}) = \left\|\boldsymbol{J}^{\phi}\delta\boldsymbol{\phi} - \boldsymbol{r}\right\|_2^2 + \lambda_s\left\|\boldsymbol{W}(\delta\boldsymbol{\phi} - \delta\boldsymbol{\phi}^{geol}(\boldsymbol{\phi}_*^{n-1}))\right\|_2^2$$

$$\boldsymbol{\phi}^n = \boldsymbol{\phi}^{n-1} + \delta\boldsymbol{\phi};$$

Conclusion and discussion



Geol

Geological modelling
Uses surface or shallow measurements only
→ (almost) Blind to what's not directly visible

Geophysical (gravity) inversion
Gravity sensitive to the whole universe
→ Can image what surface geology does not see

Gravi

Flexible
- Geological constraints optional
- Different ways to add geological info
- Constraints can be applied only to some areas or some units

Deform geological bodies with inversion using geological modelling

Gravity but obvious to extend to mag

Can use with
- 1D (borehole)
- 2D constraints (seismic)
- 3D subvolume

Next (Field application)
- Modelling in Pyrenees and Southern France
- Mineral exploration case in Northern Europe

Next (Methodology)
- Exploration of model space, random generation of units not sampled by geology

Field application: Pyrenees

In a nutshell: cost function

Iterative solver: at iteration *n…*

Optimize implicit field $\boldsymbol{\phi}$, to reduce geophysical data misft

Account for geological data $\boldsymbol{d}_{obs.}^{geol}$[1]

Geophysical data term

Geological model term

$$\min \; \boldsymbol{W}_d^{-1} \left\| \boldsymbol{d}_{obs.}^{geophy} - \boldsymbol{d}_{calc.}^{geophy} \right\|_2^2 + \left\| \boldsymbol{W}_p^{-1} \left(\boldsymbol{\phi}^n - \boldsymbol{\phi}_{geol}^n \left(\boldsymbol{d}_{obs.}^{geol}, \boldsymbol{\phi}^{n-1} \right) \right) \right\|_2^2$$

Observations

Model response

Inverted. model

Geological projection (≈prior model)

[1]Giraud et al. 2022, 2023.

Context

Use of pre-existing regional geological model (PhD thesis of H. Wehr: Wehr 2017[1], Wehr et al. 2018[2])

Comprehensive compilation of data

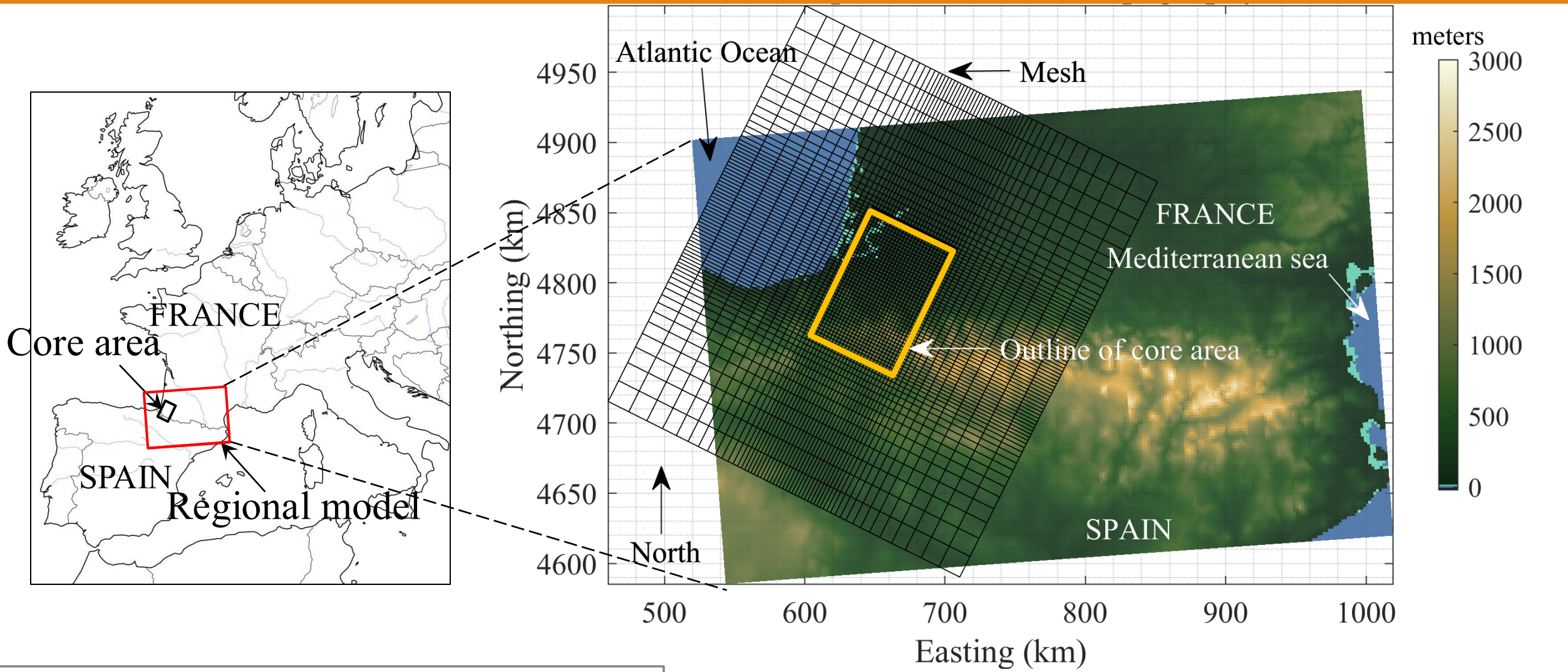
- Seismic
- Geological maps
- Boreholes
- Gravity
- Previous interpretations

Q1: Can we improve gravity data misfit?

Q2: Are there other plausible scenarios?

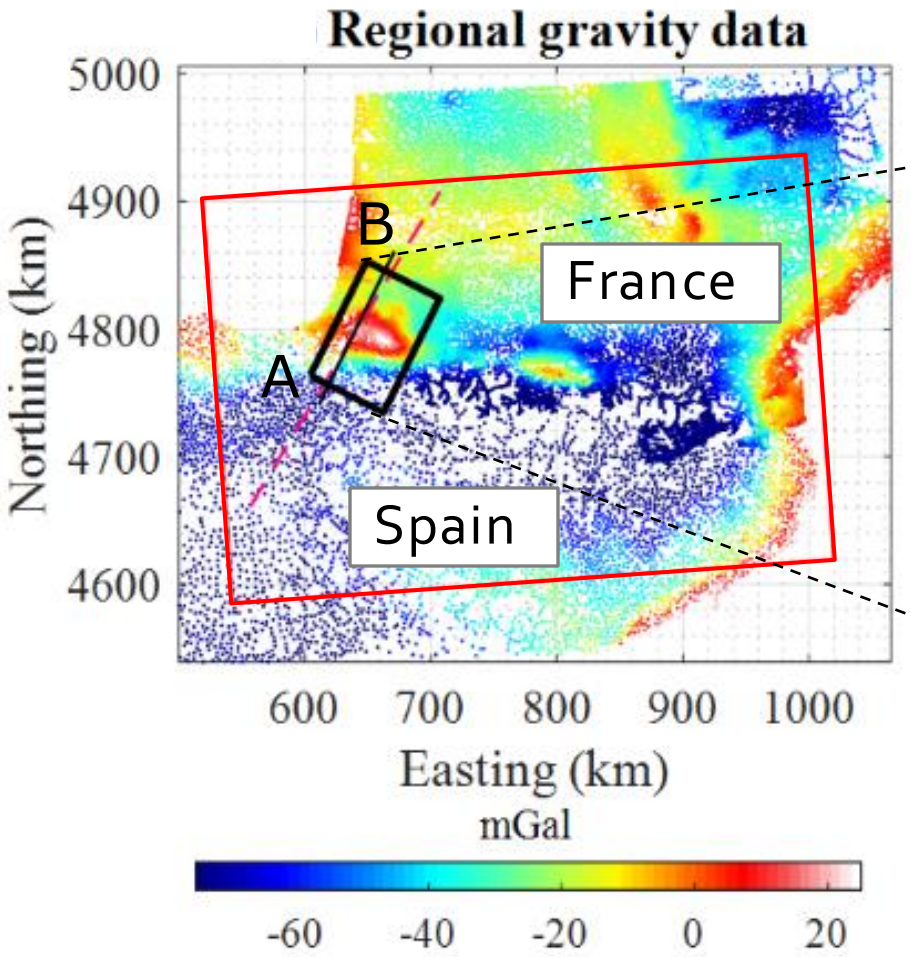
[1] Wehr, 2017, PhD thesis [2] Wehr et al. 2018, Tectonophysics

Context

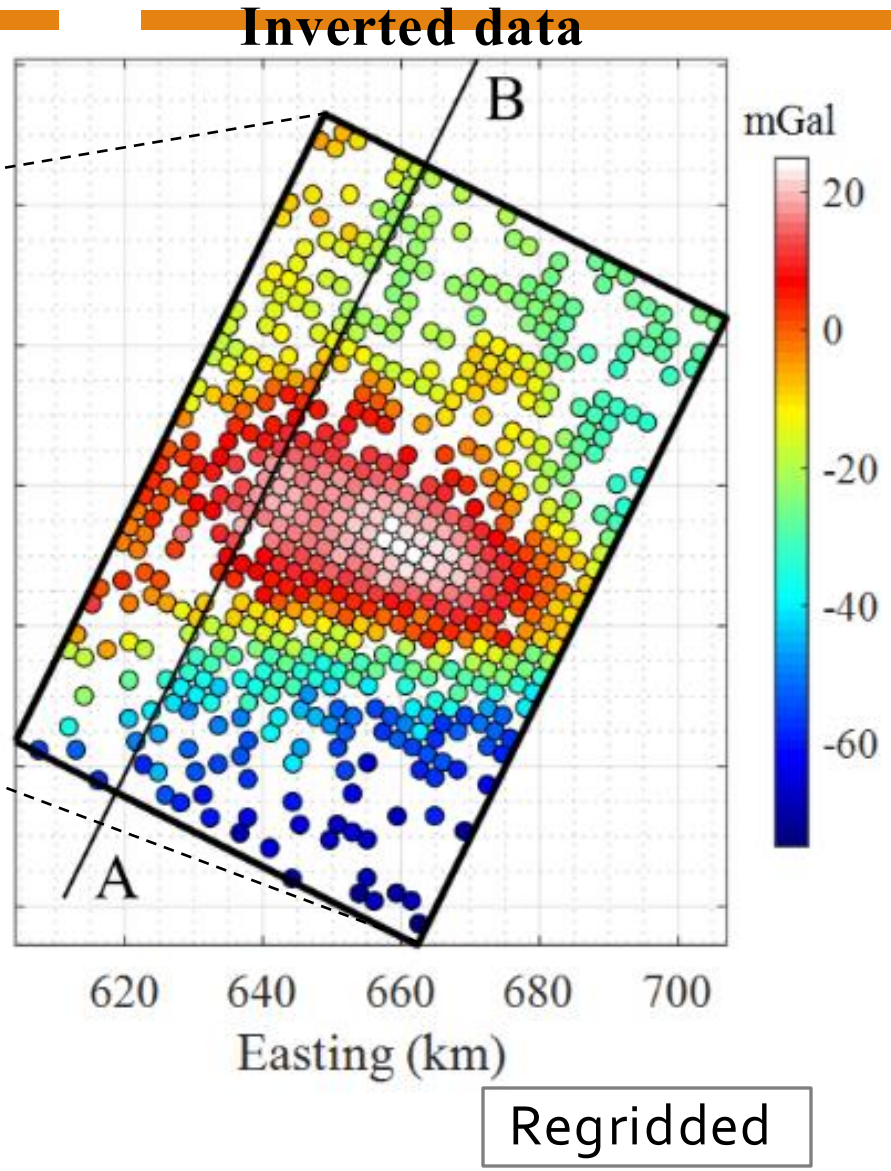


Area of interest: complex, H2 potential

Context – Gravity data



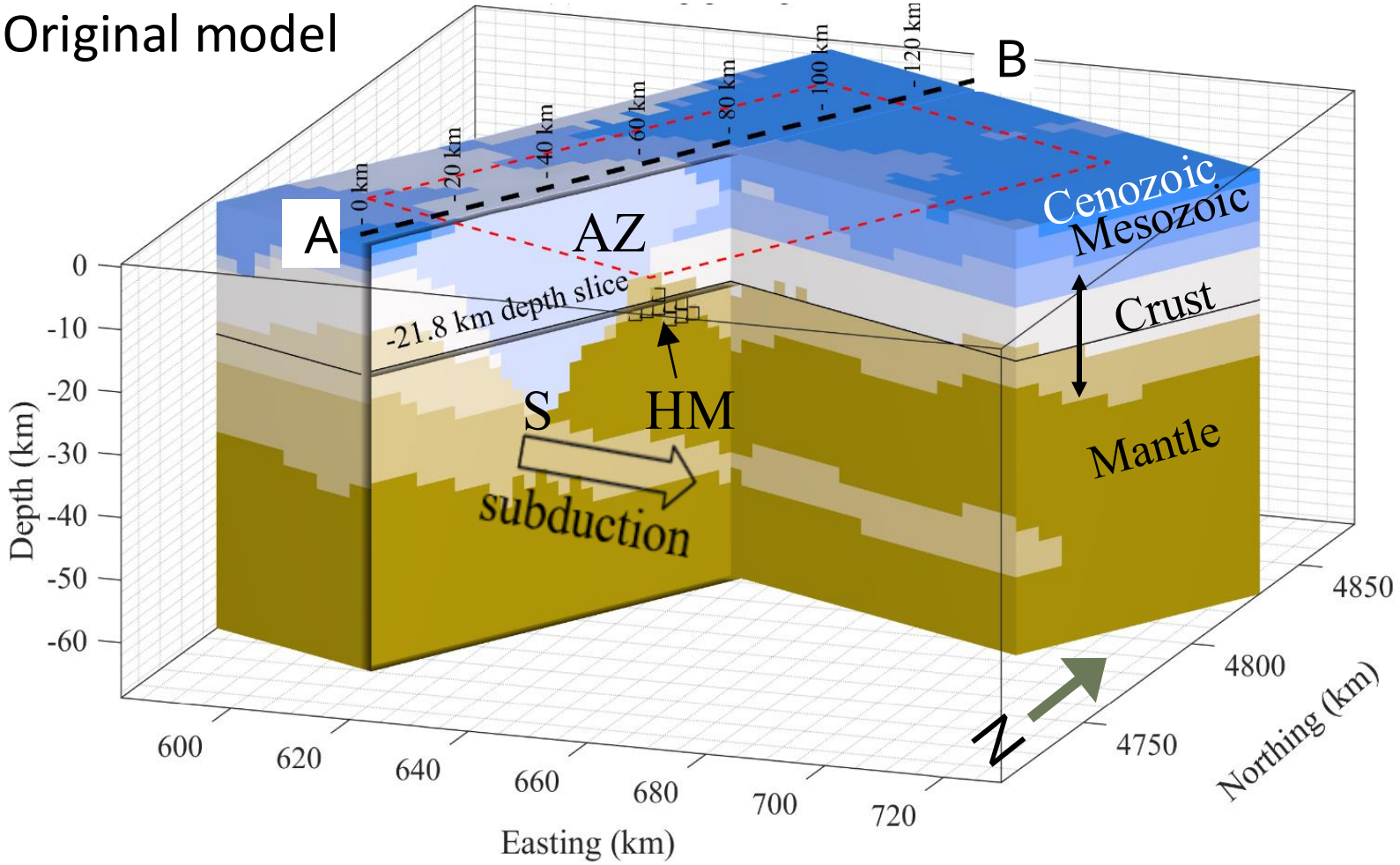
Complete Bouguer anomaly



Regridded

Geological model

Original model



S: Singularity
(beginning of subduction)

HM: Hydrated mantle.

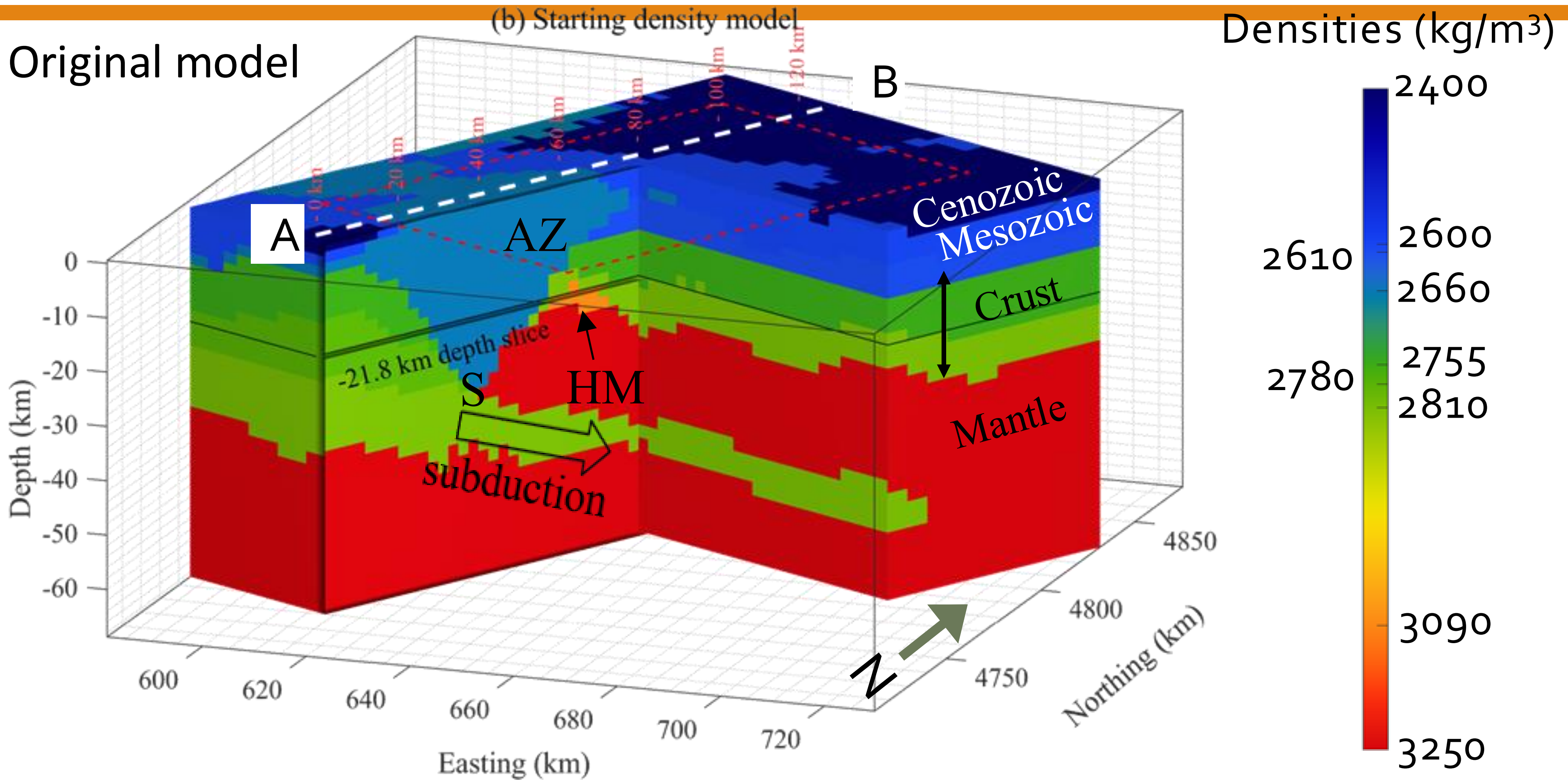
AZ: Axial Zone

Subduction

Geological modelling and data: Wehr et al. 2018, Wehr 2017. Model: courtesy of BRGM

Geological model

Original model



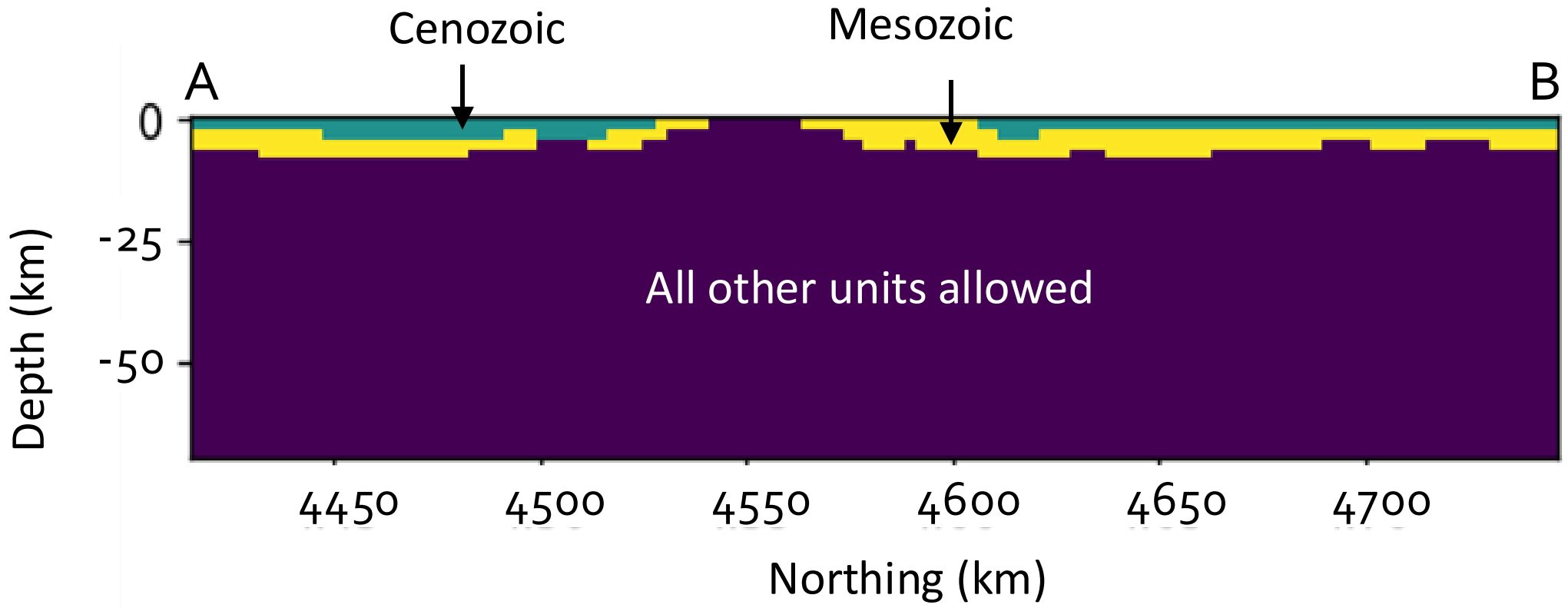
S: Singularity, beginning of subduction. HM: Hydrated mantle. AZ: Axial Zone

Geological modelling and data: Wehr et al. 2018, Wehr 2017. Model: courtesy of BRGM

Geological data

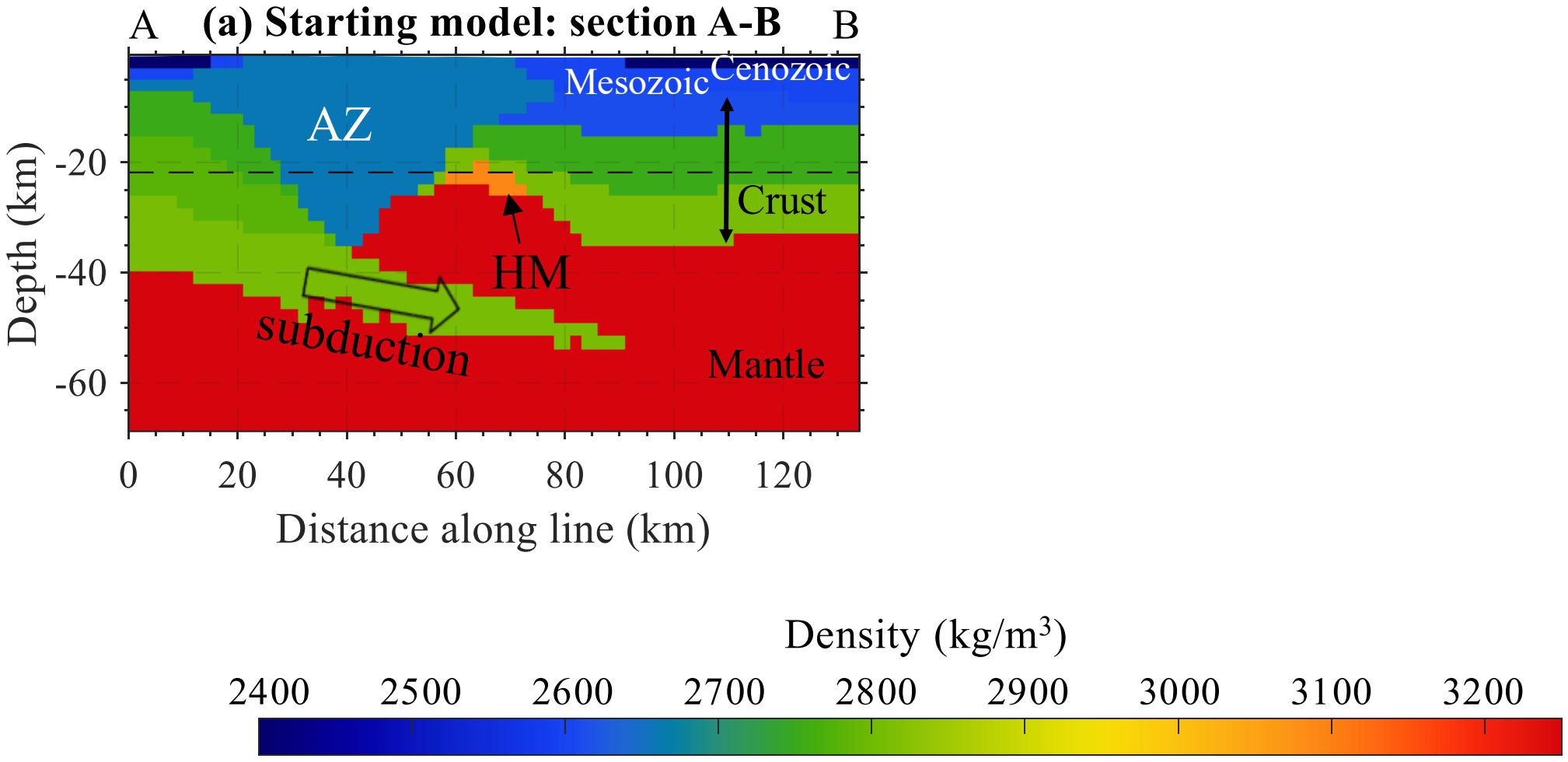
Contact and orientation data: <u>mesozoic + cenozoic only</u> in $\boldsymbol{d}_{obs.}^{geol}$

Other units: deep and uncertain → free to evolve



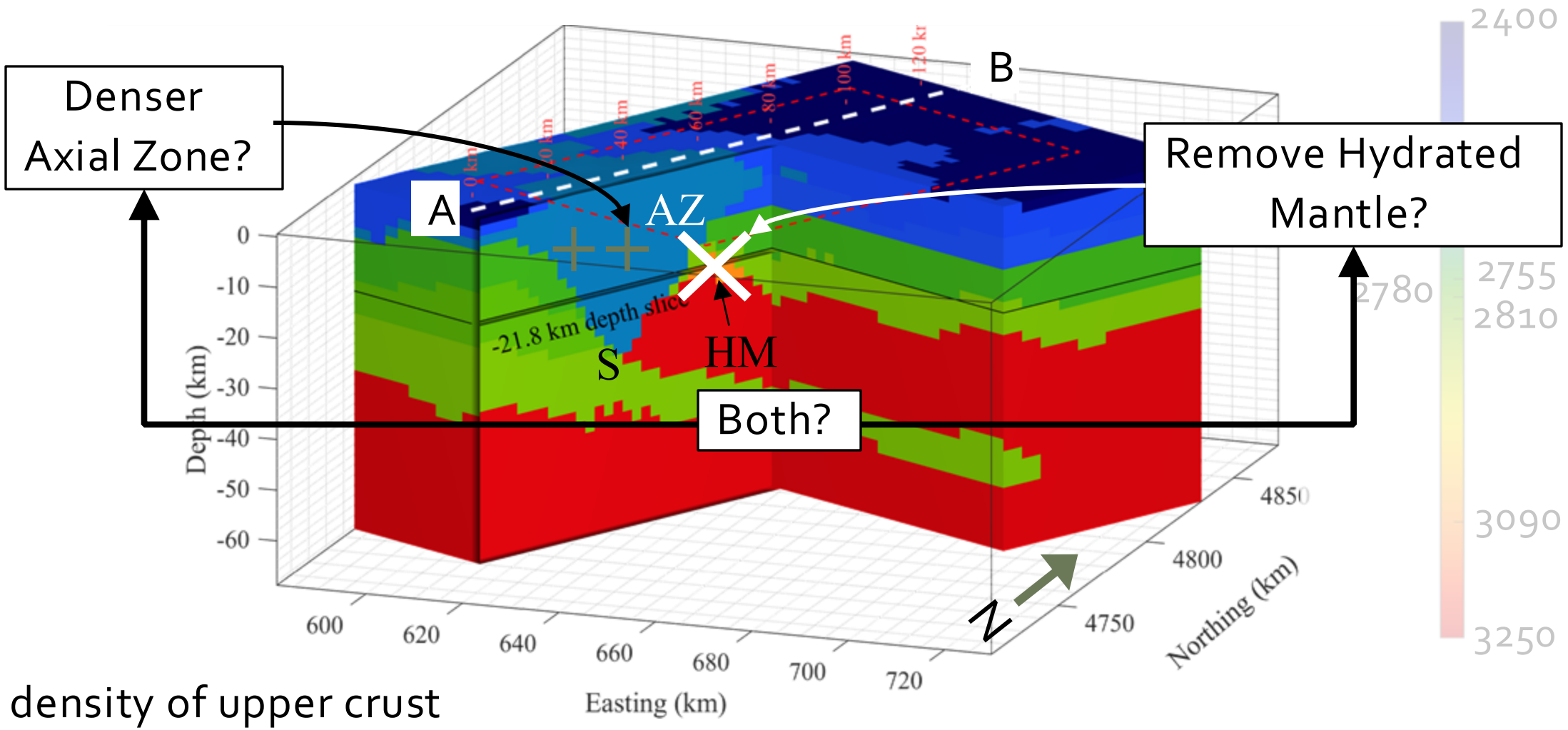
Starting from original model: A-B

Original scenario



Geological scenario generation

→ Reconcile geologically sensible scenarios with geophysical data

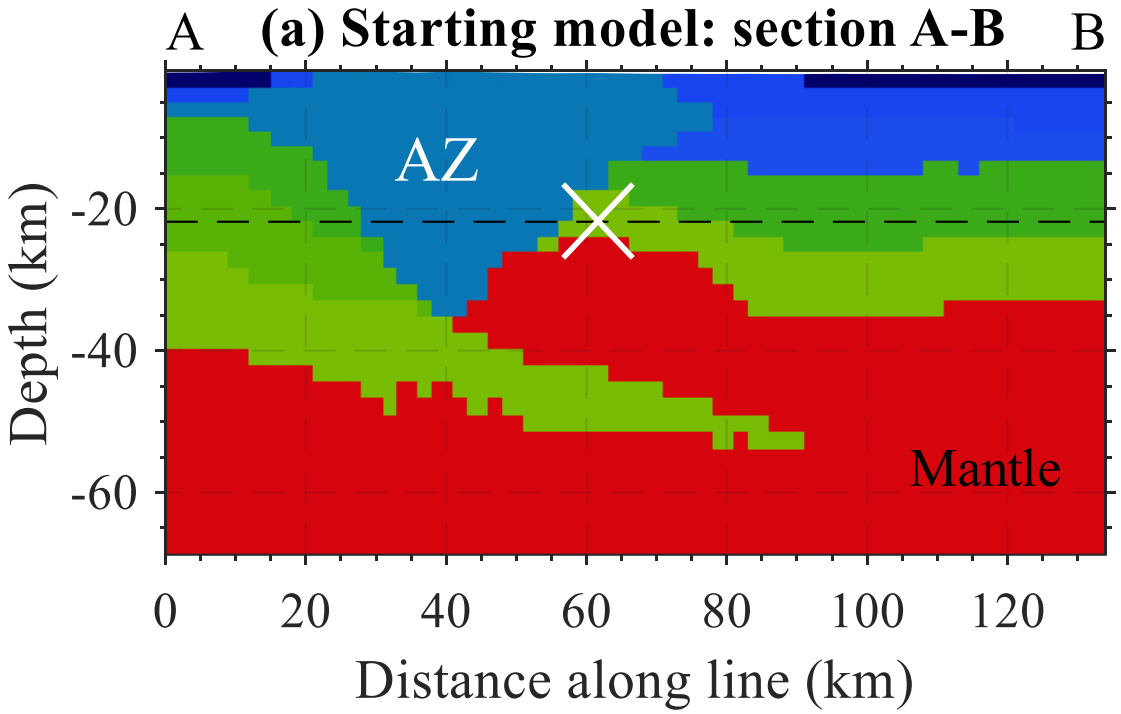


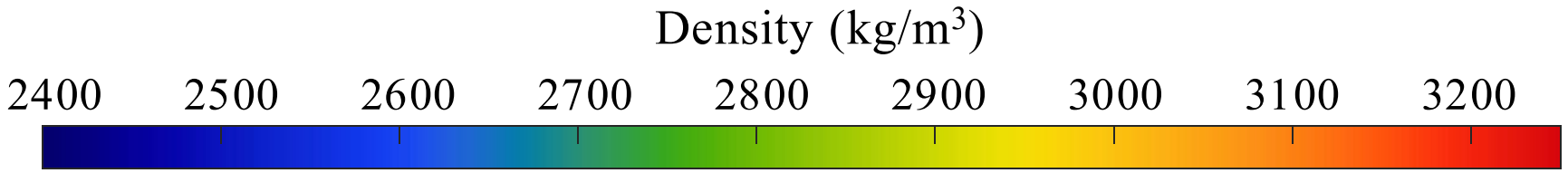
- AZ: density of upper crust
- HM: density of lower curst

Geological modelling and data: Wehr et al. 2018, Wehr 2017. Model courtesy of BRGM

Death of hydrated mantle

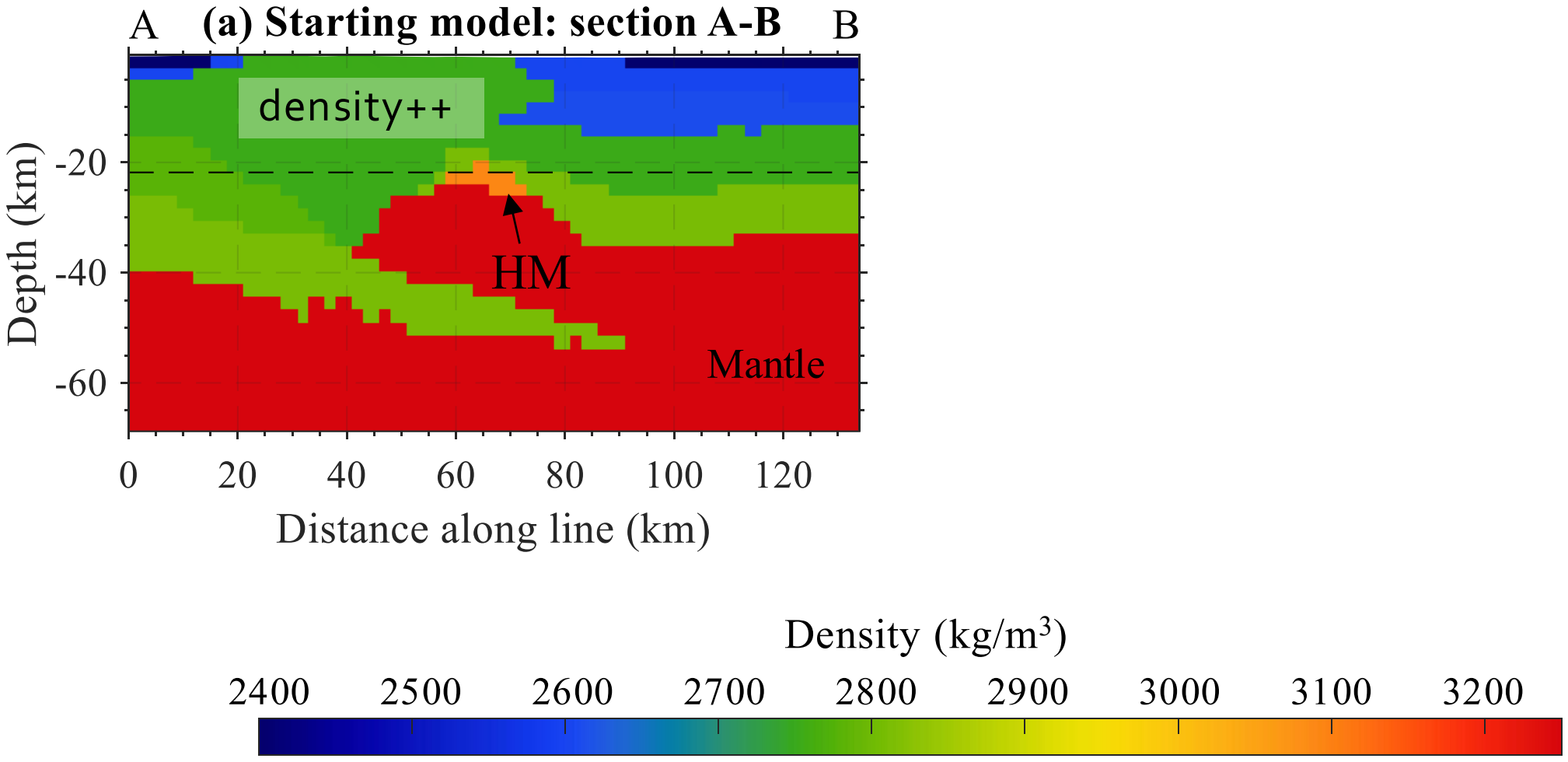
Removing HM





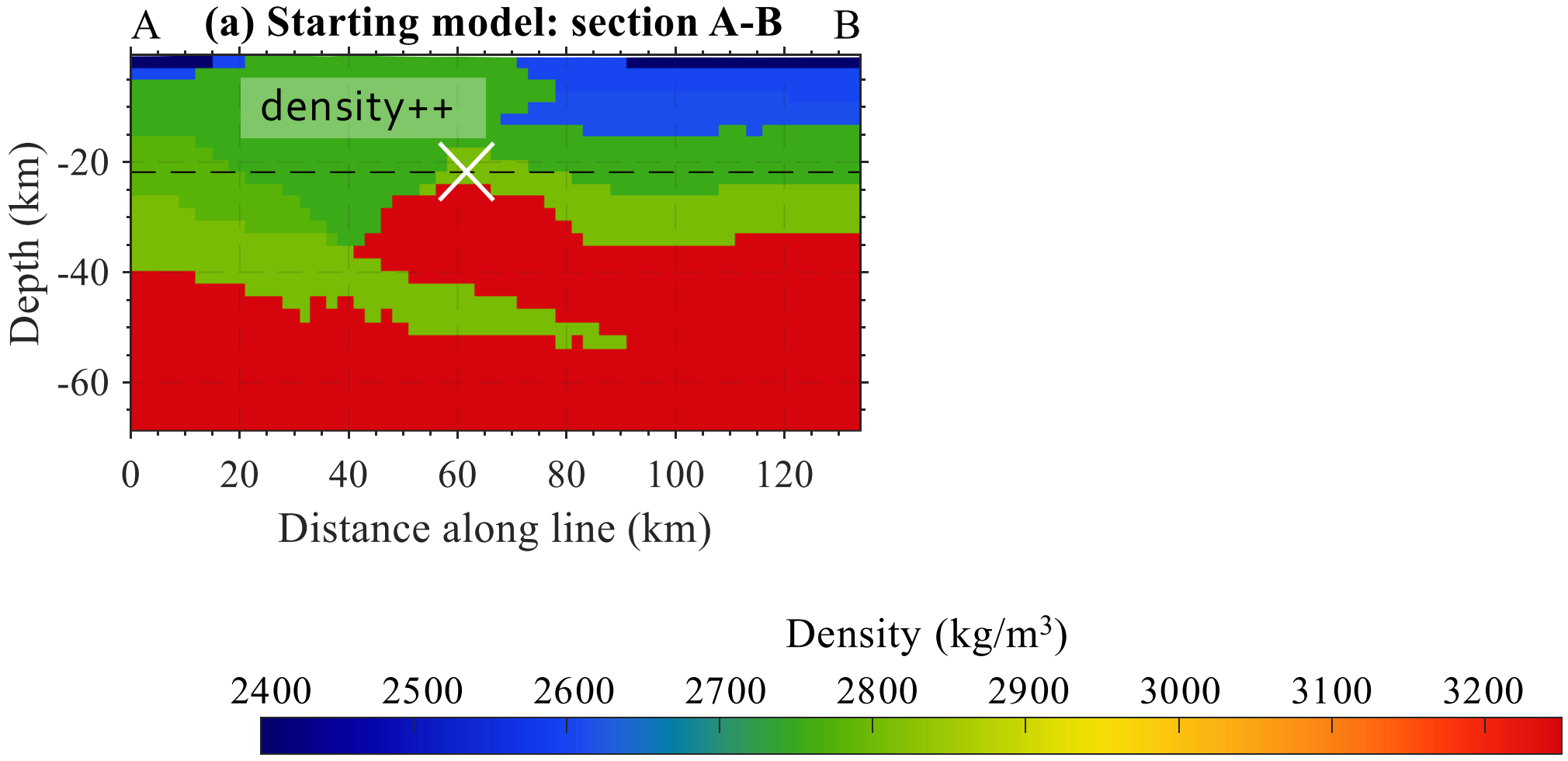
Denser axial zone

Denser AZ

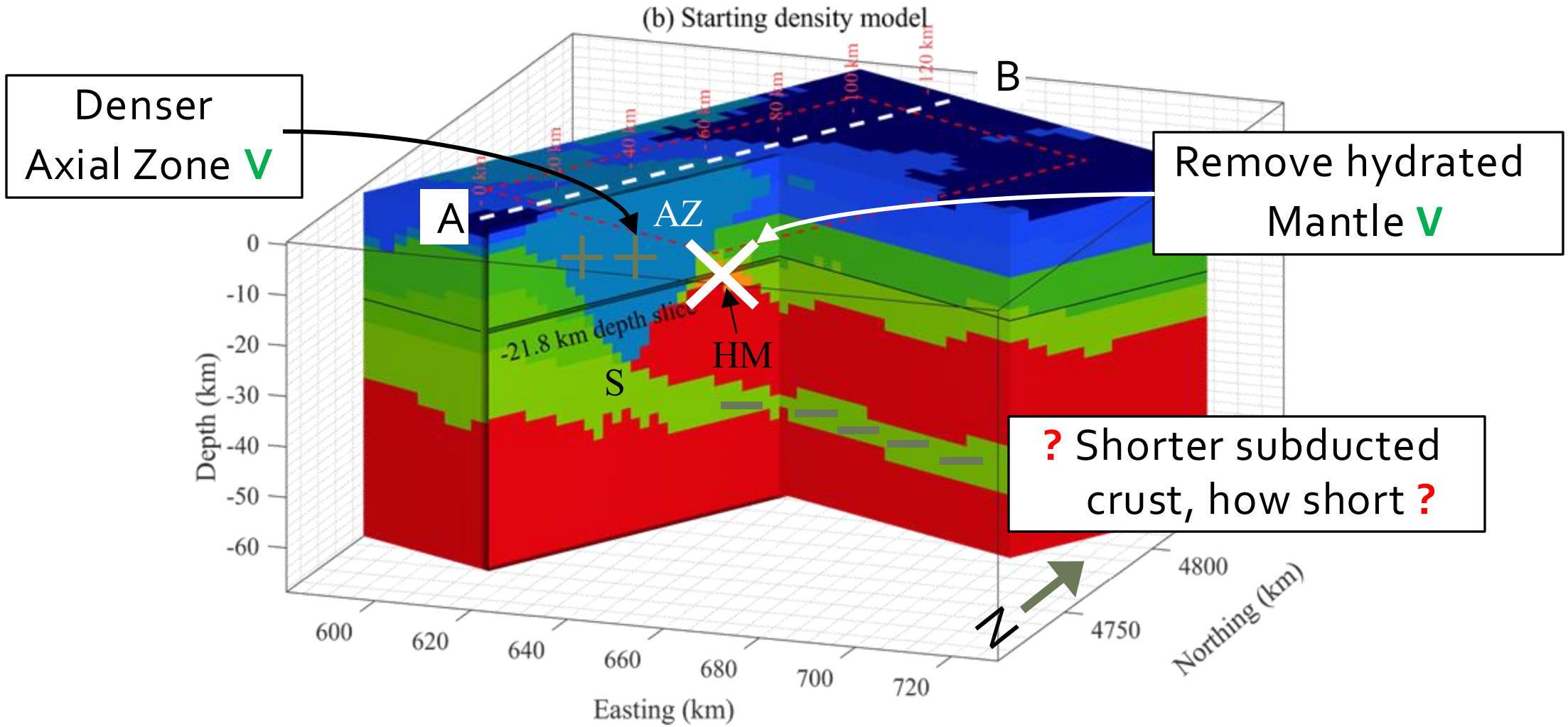


Denser axial zone + death of hydrated mantle

Removing HM, with denser AZ



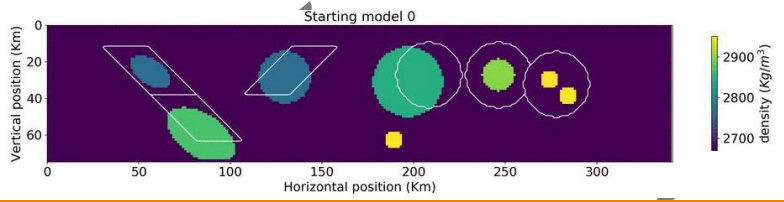
Geological questions



S: Singularity, beginning of subduction. HM: Hydrated mantle. AZ: Axial Zone

Geological modelling and data: Wehr et al. 2018, Wehr 2017. Model: courtesy of BRGM

Conclusion and discussion



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Gravity sensitive to the whole universe
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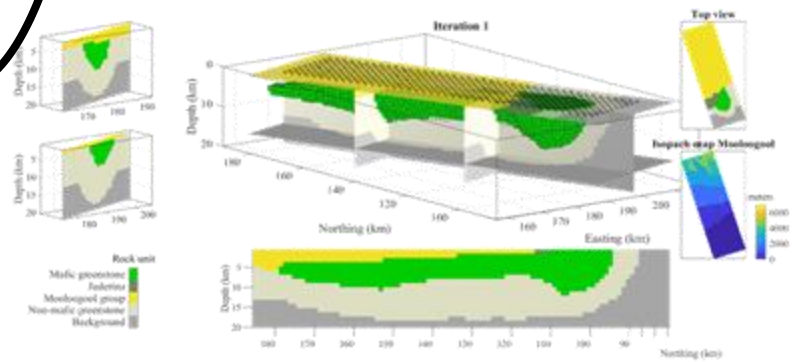
Gravi

Easy to extend to mag



Feed back to geology

Many models
+ other disciplines
(e.g., seismic, EM…)

Deform geological bodies using inversion

Intra-unit variation → semi-discrete inv.

Conclusion and discussion

Geol

Geological modelling
Uses surface or shallow measurements only
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Gravity sensitive to the whole universe
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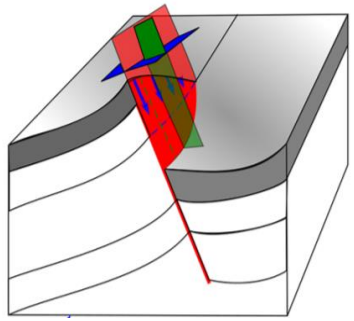
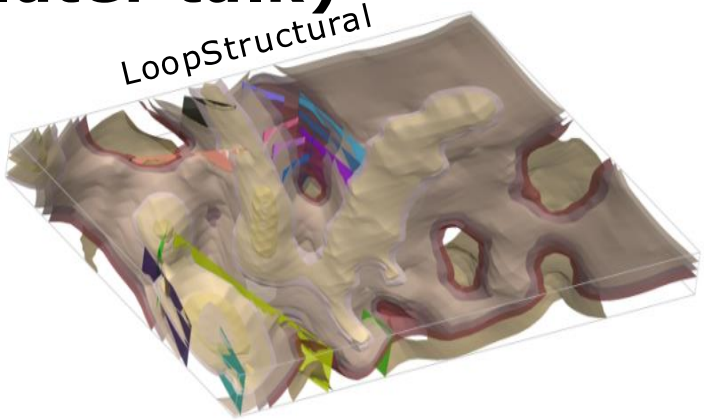
Gravi

→ Move to probabilistic world **(and trans-d: OK, see later talk)**
→ Make it more geol. Driven **(coupling with LoopStructural: OK, see later talk)**

Seismic imaging
Sparse, 'precise' (accurate?) information
→ Use 2D or small 3D seismic to constrain level-set inversion



Grose et al. 2021



Constraining 3D geometric gravity inversion with 2D reflection seismic profile using a generalized level-set approach: application to Eastern Yilgarn craton

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References

Lindsay, M., S. Occhipinti, C. Laflamme, A. Aitken, and L. Ramos, 2020, Mapping undercover: integrated geoscientific interpretation and 3D modelling of a Proterozoic basin: Solid Earth Discussions.

Grose, L., Ailleres, L., Laurent, G., and Jessell, M.: LoopStructural 1.0: time-aware geological modelling, Geosci. Model Dev., 14, 3915–3937, https://doi.org/10.5194/gmd-14-3915-2021, 2021.

Jessell, Mark, Guo, Jiateng, Li, Yunqiang, Lindsay, Mark, Scalzo, Richard, Giraud, Jérémie, Pirot, Guillaume, Cripps, Ed, Ogarko, Vitaliy, Submitted, Into the Noddyverse: A massive data store of 3D geological models for Machine Learning & inversion applications [under. rev.]

Rashidifard, M., Giraud, J., Lindsay, M., Jessell, M., and Ogarko, V.: Constraining 3D geometric gravity inversion with 2D reflection seismic profile using a generalized level-set approach: application to Eastern Yilgarn craton, Solid Earth Discuss. [preprint], https://doi.org/10.5194/se-2021-65, in review, 2021

Jérémie Giraud, Mark Lindsay, Mark Jessell; Generalization of level-set inversion to an arbitrary number of geologic units in a regularized least-squares framework. Geophysics 2021; 86 (4): R623–R637. doi: https://doi.org/10.1190/geo2020-0263.1

Lindsay, M. D., Occhipinti, S., Laflamme, C., Aitken, A., and Ramos, L.: Mapping undercover: integrated geoscientific interpretation and 3D modelling of a Proterozoic basin, Solid Earth, 11, 1053–1077, https://doi.org/10.5194/se-11-1053-2020, 2020

Giraud, J., Lindsay, M., Jessell, M., and Ogarko, V.: Towards plausible lithological classification from geophysical inversion: honouring geological principles in subsurface imaging, Solid Earth, 11, 419–436, https://doi.org/10.5194/se-11-419-2020, 2020

Pirajno, F., S. A. Occhipinti, and C. P. Swager (1998), Geology and tectonic evolution of the Palaeoproterozoic Bryah , Padbury and Yerrida Basins (formerly Glengarry Basin), Western Australia : implications for the history of the south-central Capricorn Orogen, Precambrian Research, 90.

Katopodes, N. D.: Level Set Method, in Free-Surface Flow, pp. 804–828, Elsevier., 2019.

Questions?