Subsurface space warping driven by gravity data

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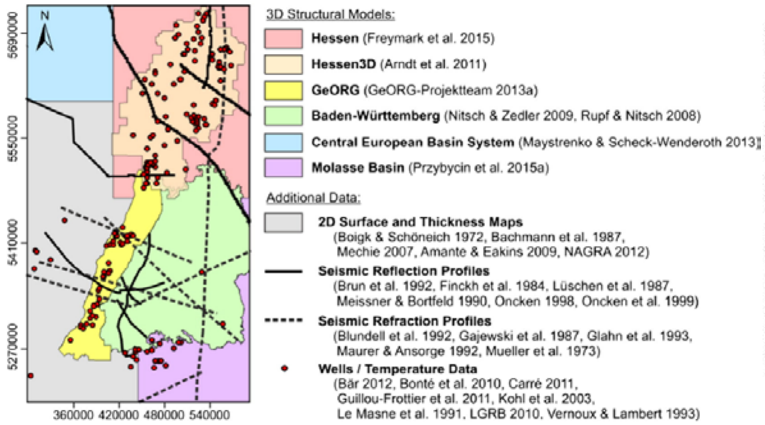
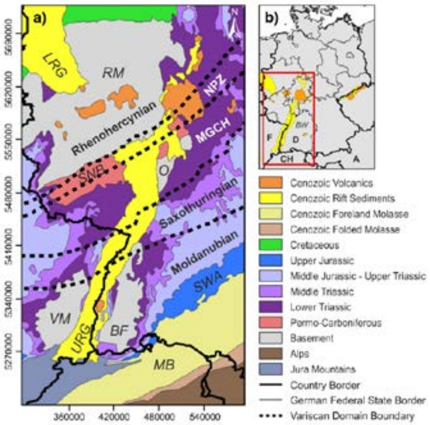
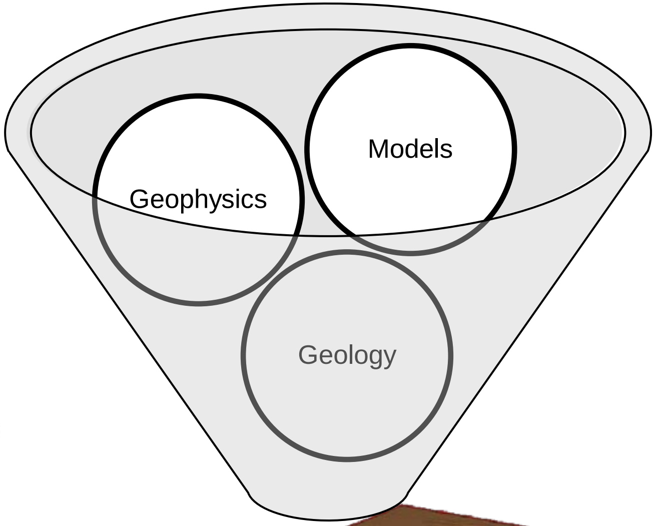
3-D subsurface modelling

Models

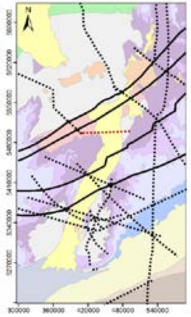


Geology

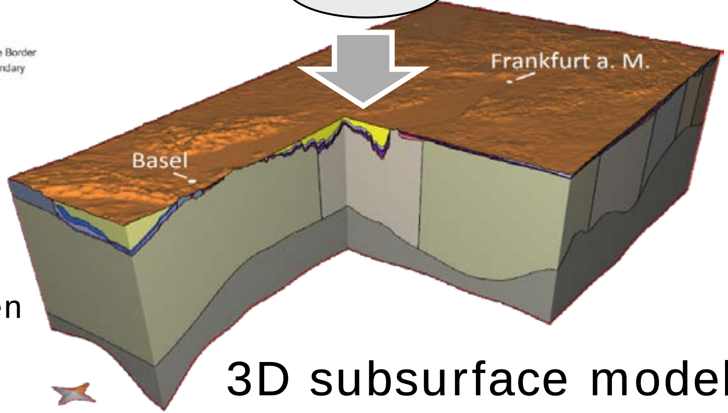




Geophysical data



Example:
Upper Rhine Graben
Freymark (2019)

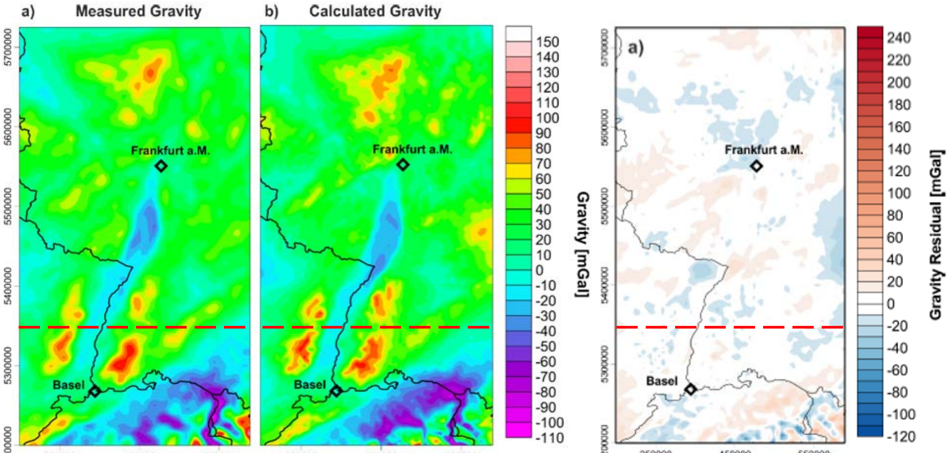


3D subsurface model

Freymark, J. K. (2019). Implications of the 3D structural and density configuration for the thermal and hydraulic fields of the Upper Rhine Graben (Doctoral dissertation, Universitätsbibliothek der RWTH Aachen).
https://publications.rwth-aachen.de/record/766731

Key: 3-D gravity modelling

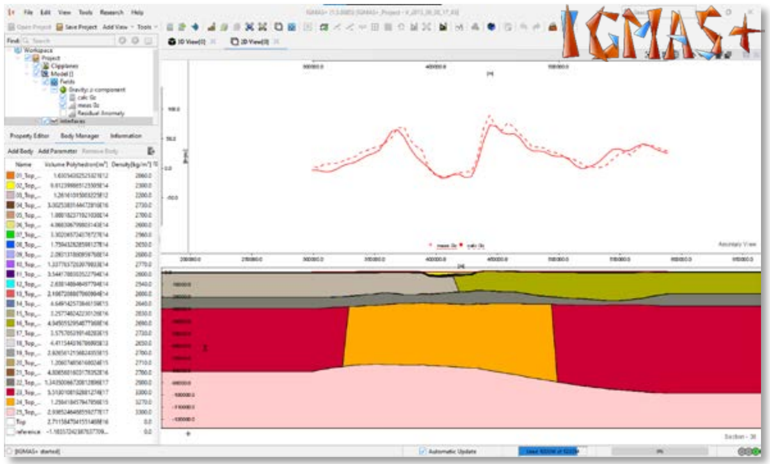
- Modelling requires **integration** of various structural geological and geophysical data
- (Interactive) 3-D gravity modelling: **key concept** to assess the inconsistencies
- Even gravity-constrained 3-D models contain **uncertainties**
- Manual geometry modifications: **time consuming**, **not reproducible**
- A **geometry optimization concept** is needed



Observed gravity (Free Air EGM2008)

Calculated gravity (Final 3D model)

Final 3D model



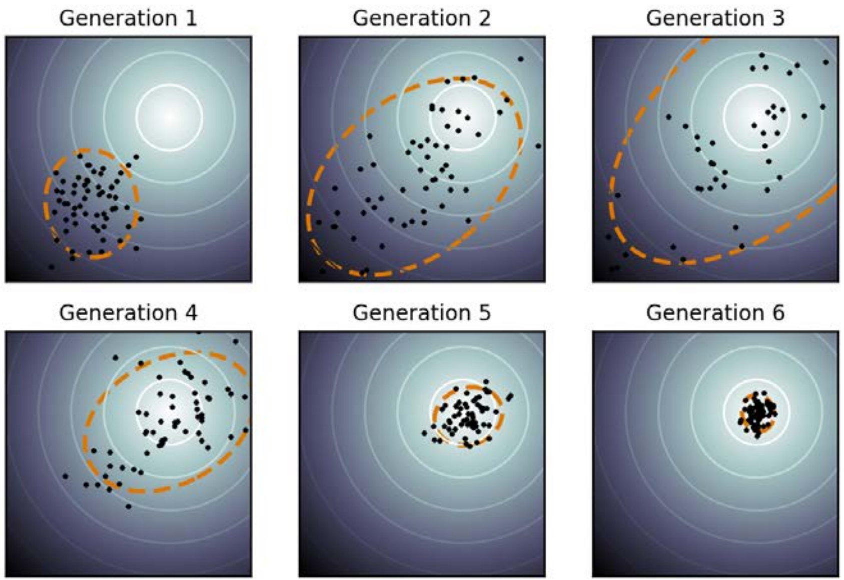
Vertical cross-section

Interactive geometry optimisation concept

- Concept details:
  - Alvers, M. R., Götze, H.-J., Anikiev, D., & Plonka, C. (2023). Inversion of potential fields by interactive optimization of 3D subsurface models using spring-based space warping and evolution strategy. GEOPHYSICS, 88 (3): G79-G93 https://doi.org/10.1190/geo2022-0222.1
  - Also: Alvers et al. (2013, 2014, 2015)

- Brief overview of the concept:
  - Model geometry optimisation is a highly **non-linear problem**
  - **Covariance-Matrix-Adaptation Evolution Strategy** (CMA-ES): high-dimensional space, fast convergence and overcomes local minima (e.g,. Hansen, 2016)
  - **Space warping** is used to preserve model topology

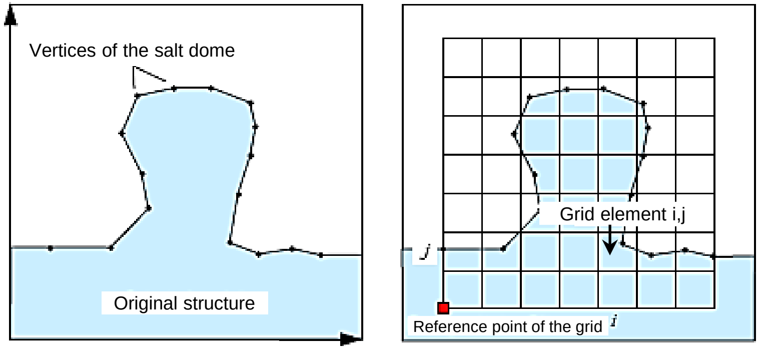
- Applications:
  - Imaging salt structures in the **North German Basin**
  - Revision of the mantle anomaly in **Upper Rhine Graben**

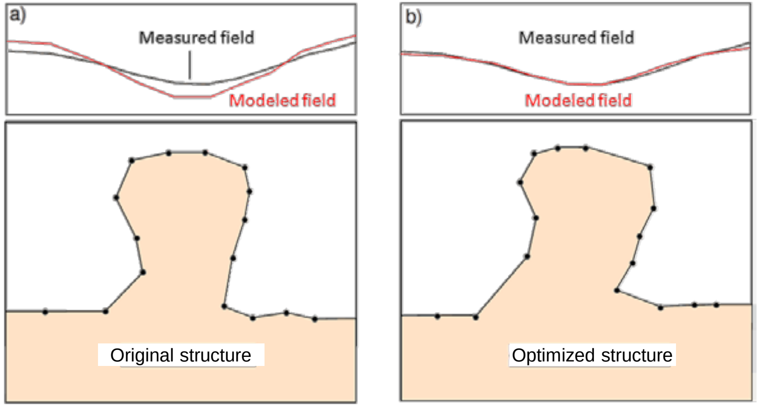


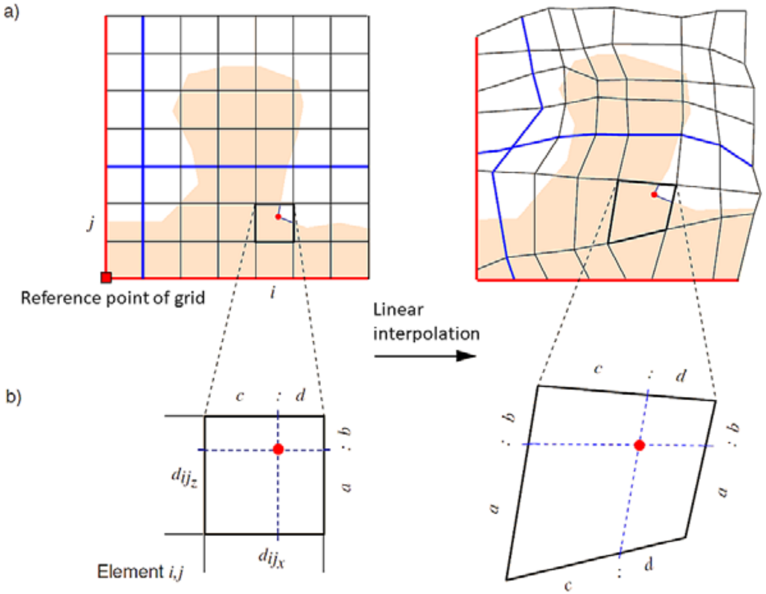
https://en.wikipedia.org/wiki/CMA-ES

Hansen, N. (2016). The CMA evolution strategy: A tutorial. arXiv preprint. DOI: 10.48550/arXiv.1604.00772.

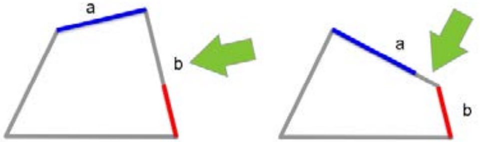
Space warping



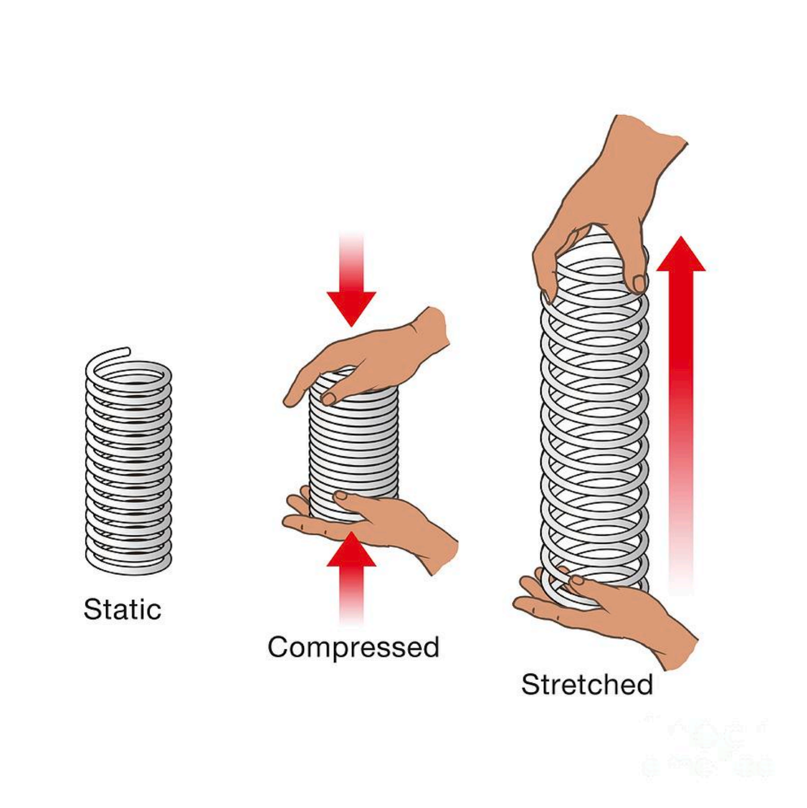


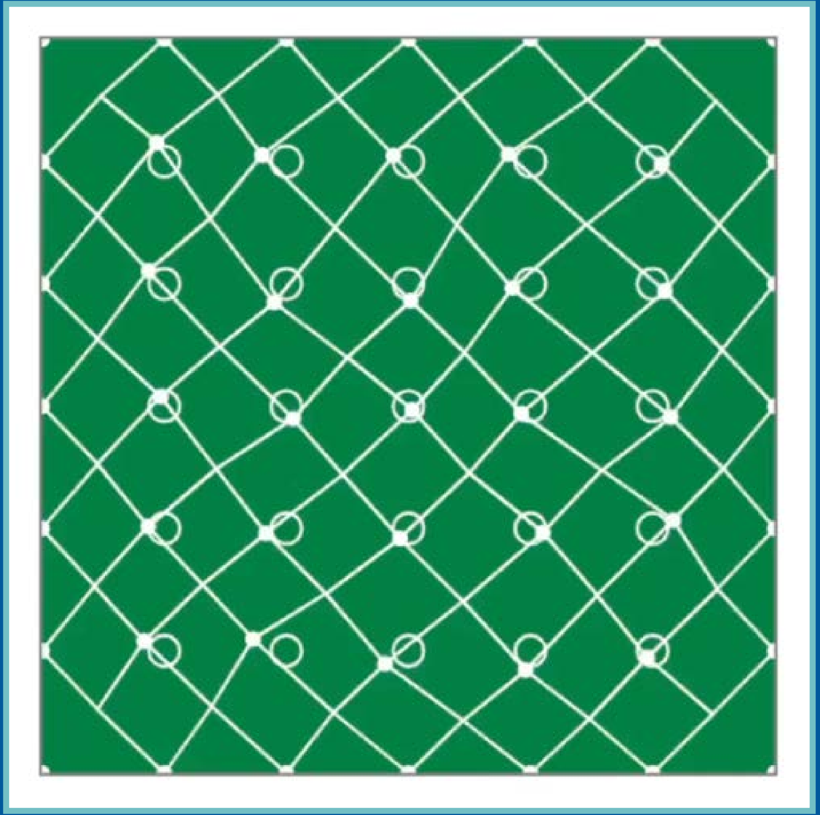


- We preserve topology by optimizing **grid legs**
- However: grid legs are **not independent**



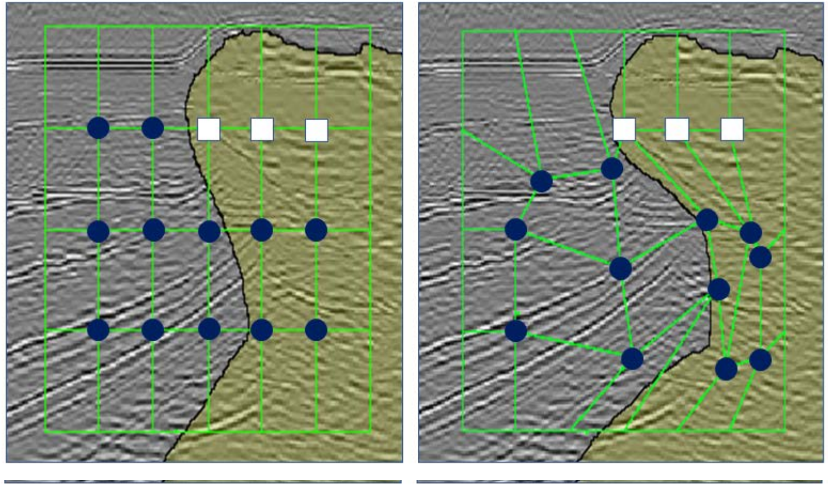
It’s spring time!

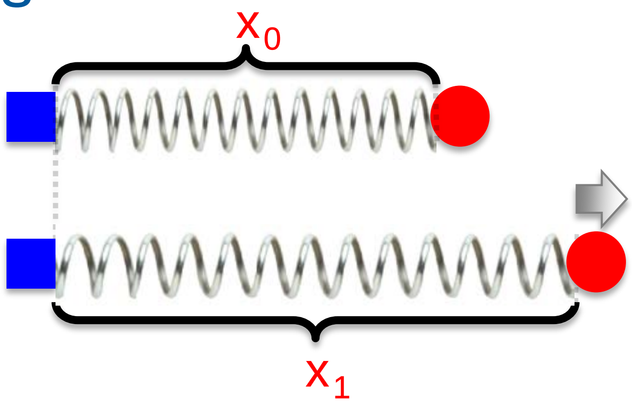




Visualization: courtesy of Dr. Günter Schmidt
http://home.mnet-online.de/mdeg/guenter/spring_demo2.html

Elegant solution: elastic springs



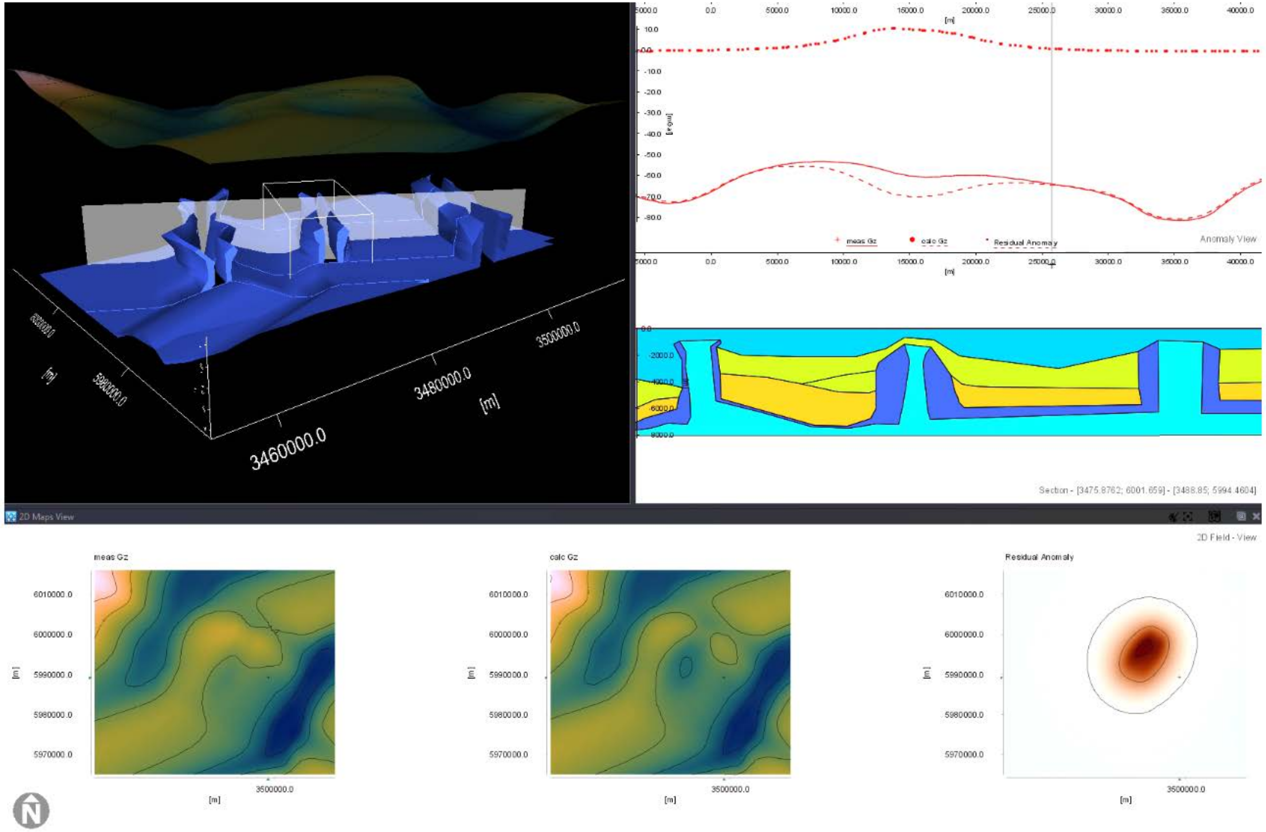


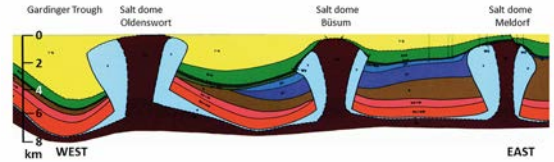
Hooke's law: $F = k\Delta x = k(x_1 - x_0)$

k - spring constant or stiffness

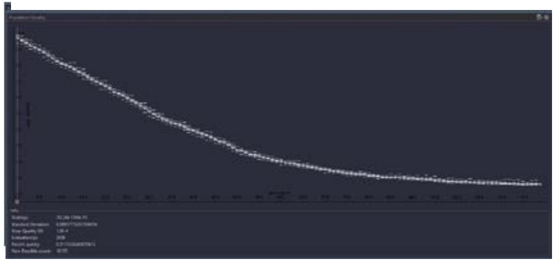
- Replace rigid connections of the space grid nodes with elastic springs
- Mutation step changes the spring constants **k**
- Equilibrium + Hooke's law gives a linear system of equations to update the node positions
- "Magic trick": the rest lengths of each spring set to be twice bigger as deformed

Application 1: North German Basin





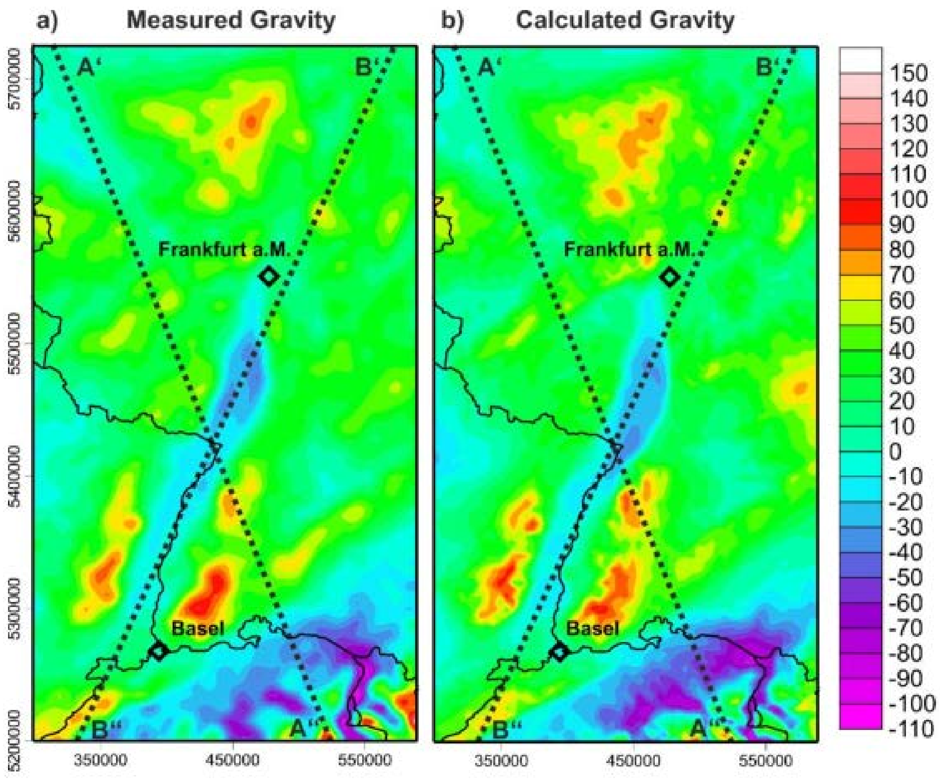
From Geotectonic Atlas of Northern Germany (Baldschuhn, 2001)

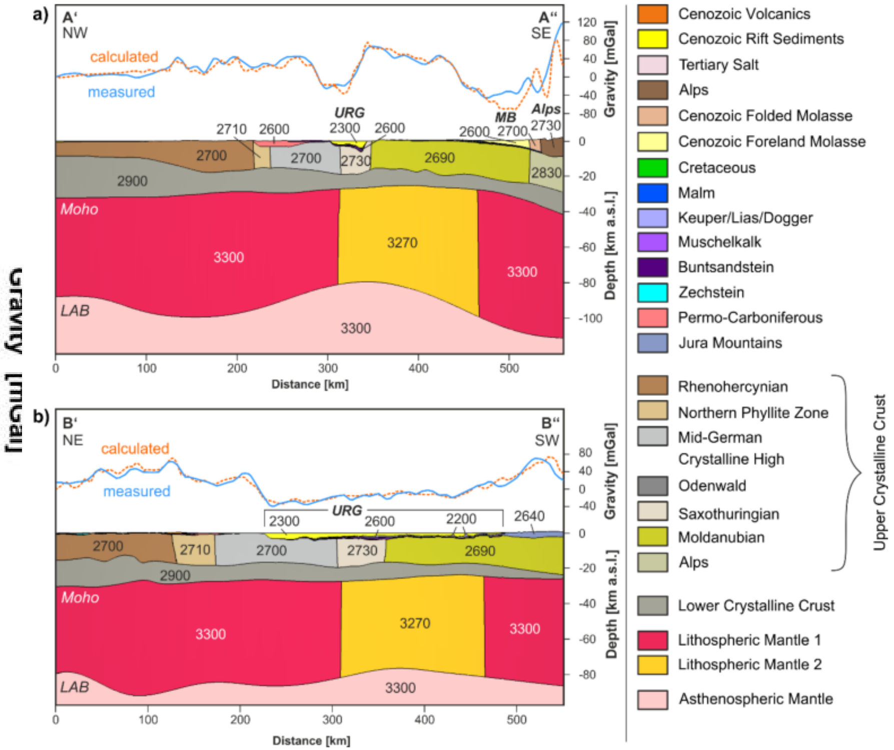


Quality function value history

https://igmas.git-pages.gfz-potsdam.de/igmas-pages/post/alvers-goetze-et-al-2023

Application 2: Upper Rhine Graben





FreeAir gravity anomaly EGM2008 (Pavlis et al. 2012)

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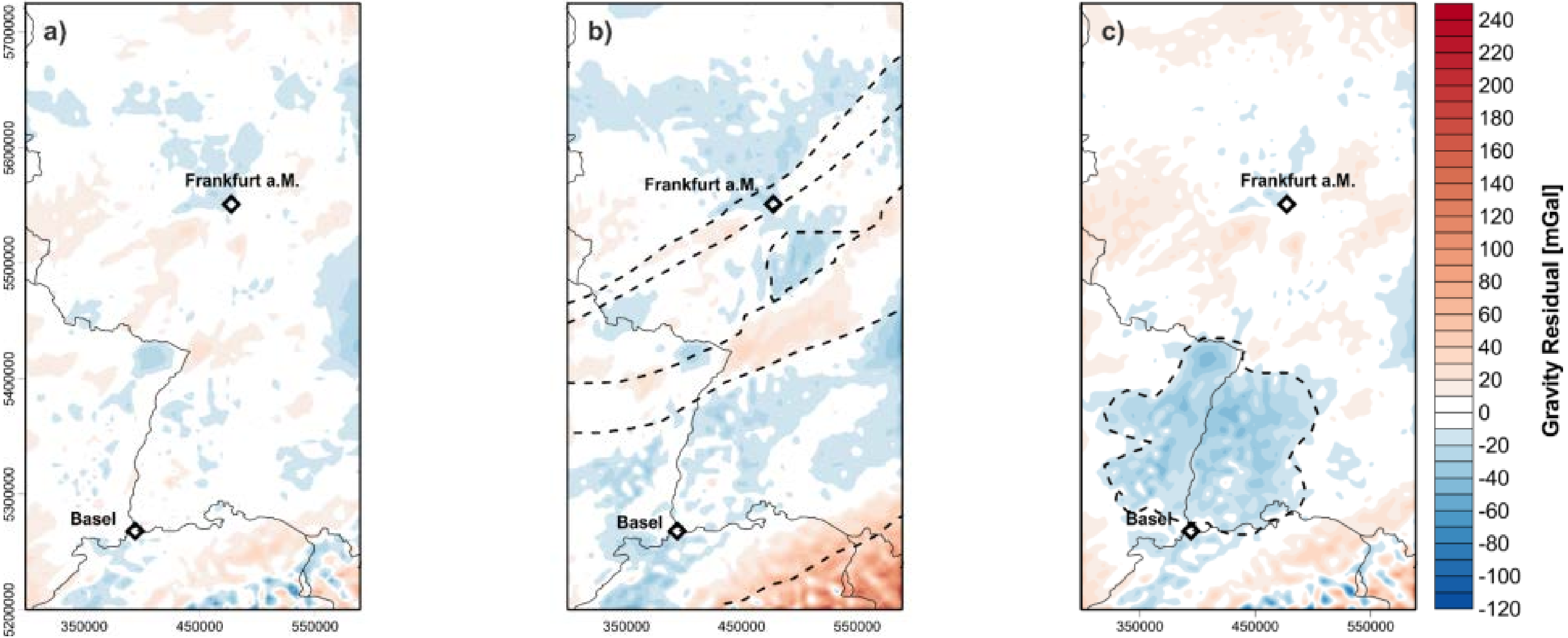
Application 2: Upper Rhine Graben

Gravity residuals for three model variants



Model with low-density mantle anomaly

Model with homogeneous upper crystalline crust

Model without low-density mantle anomaly

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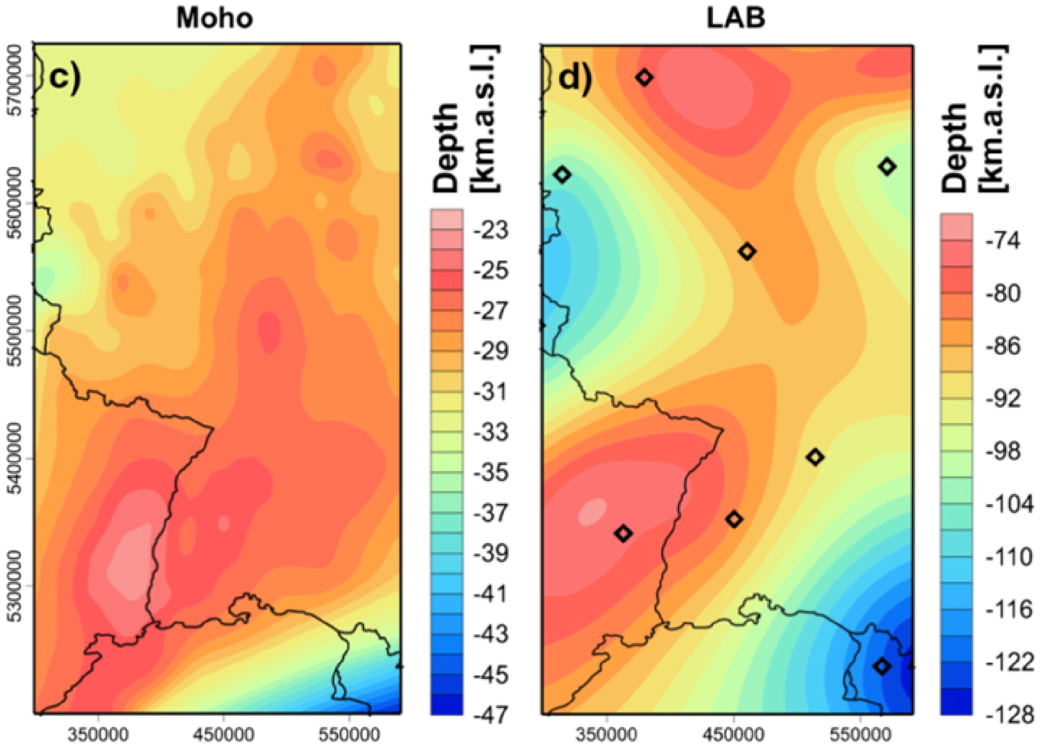
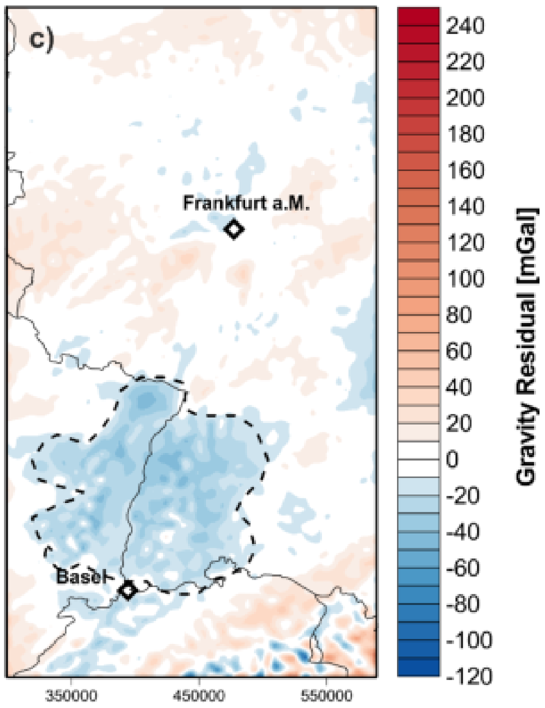
Application 2: Upper Rhine Graben



Deep structural configuration in the URG model



Model without low-density mantle anomaly

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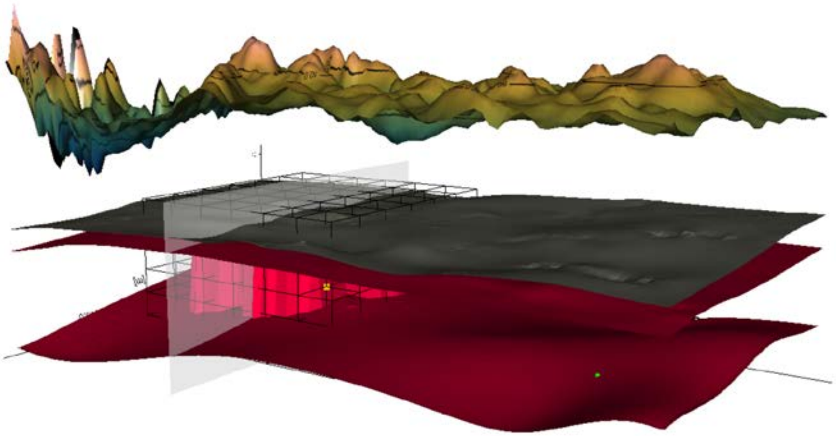
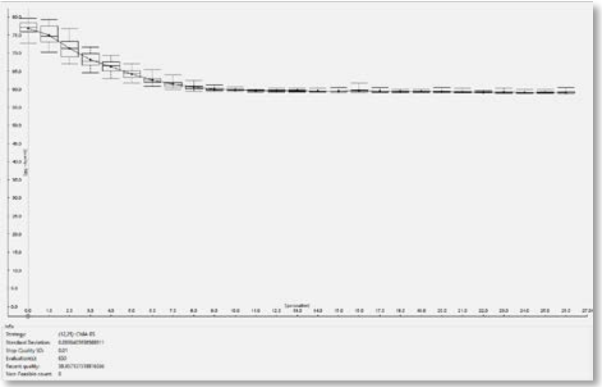
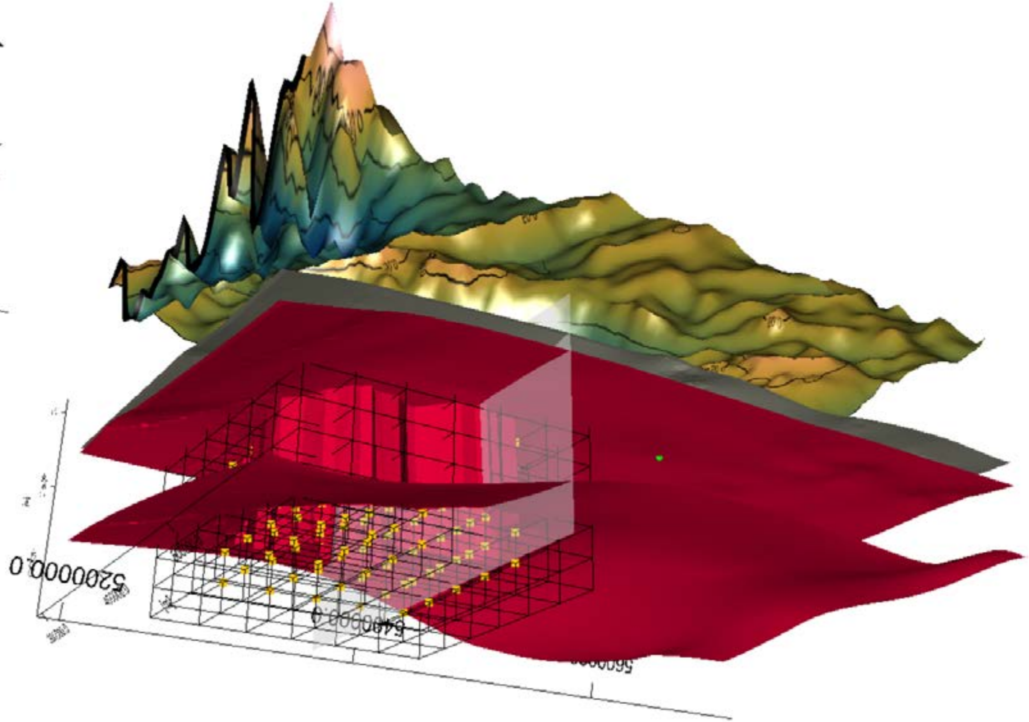
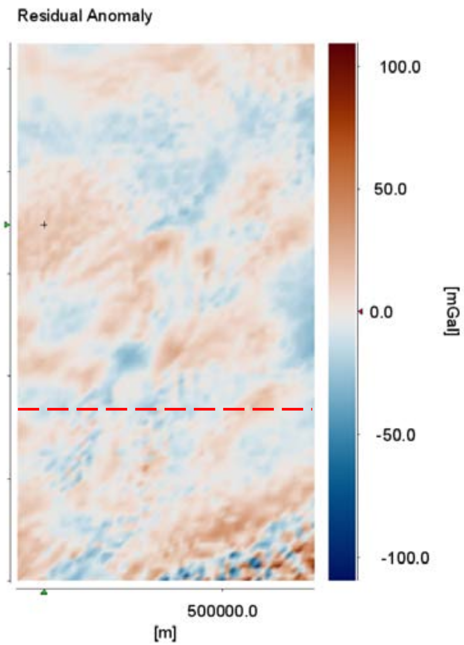


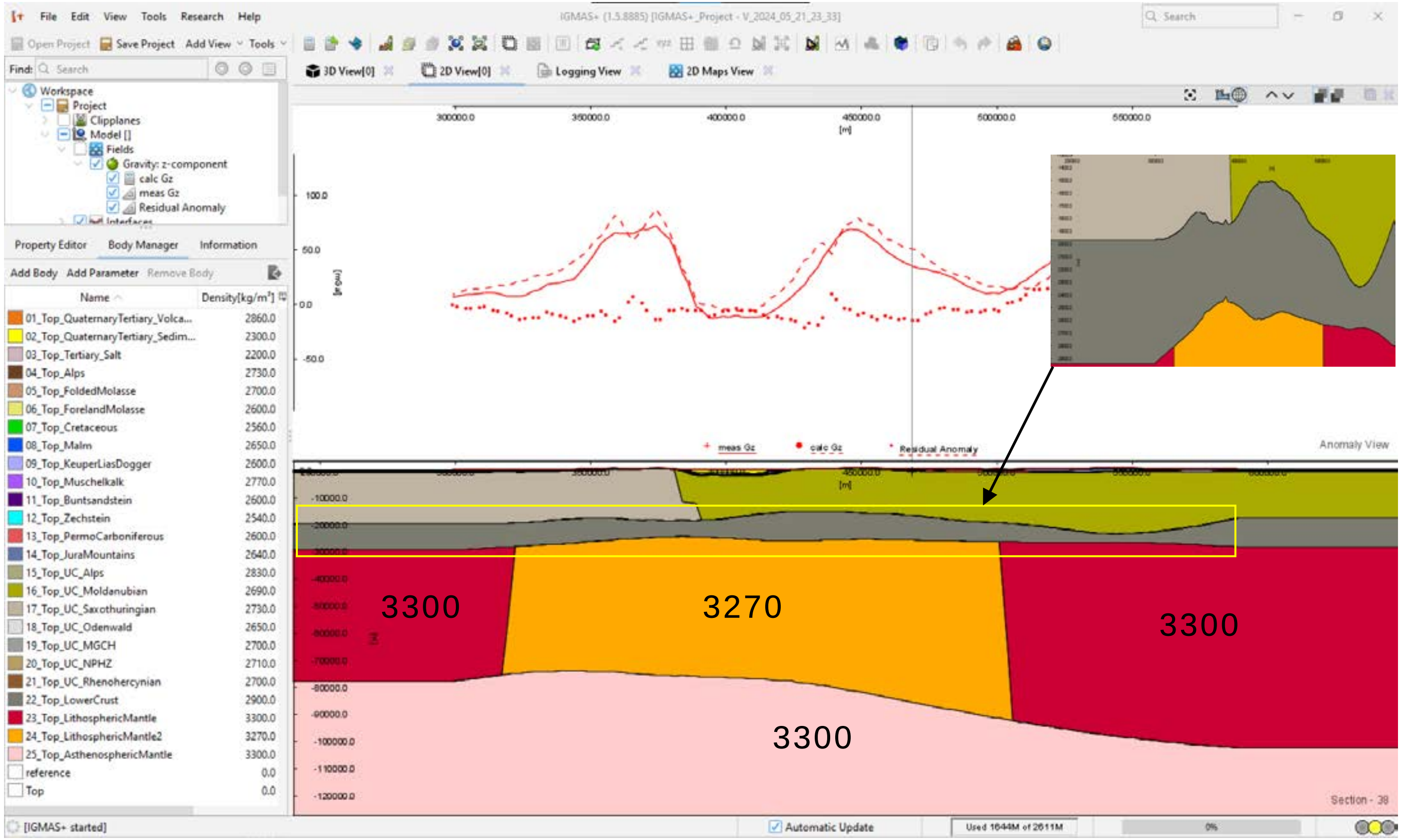




Application 2: Upper Rhine Graben

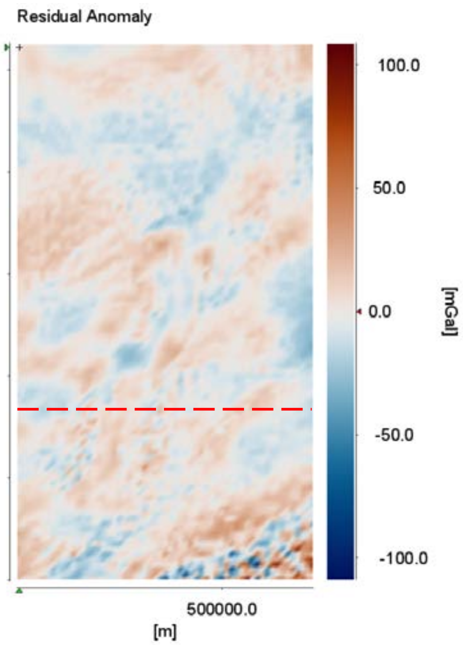
Model with low-density mantle anomaly

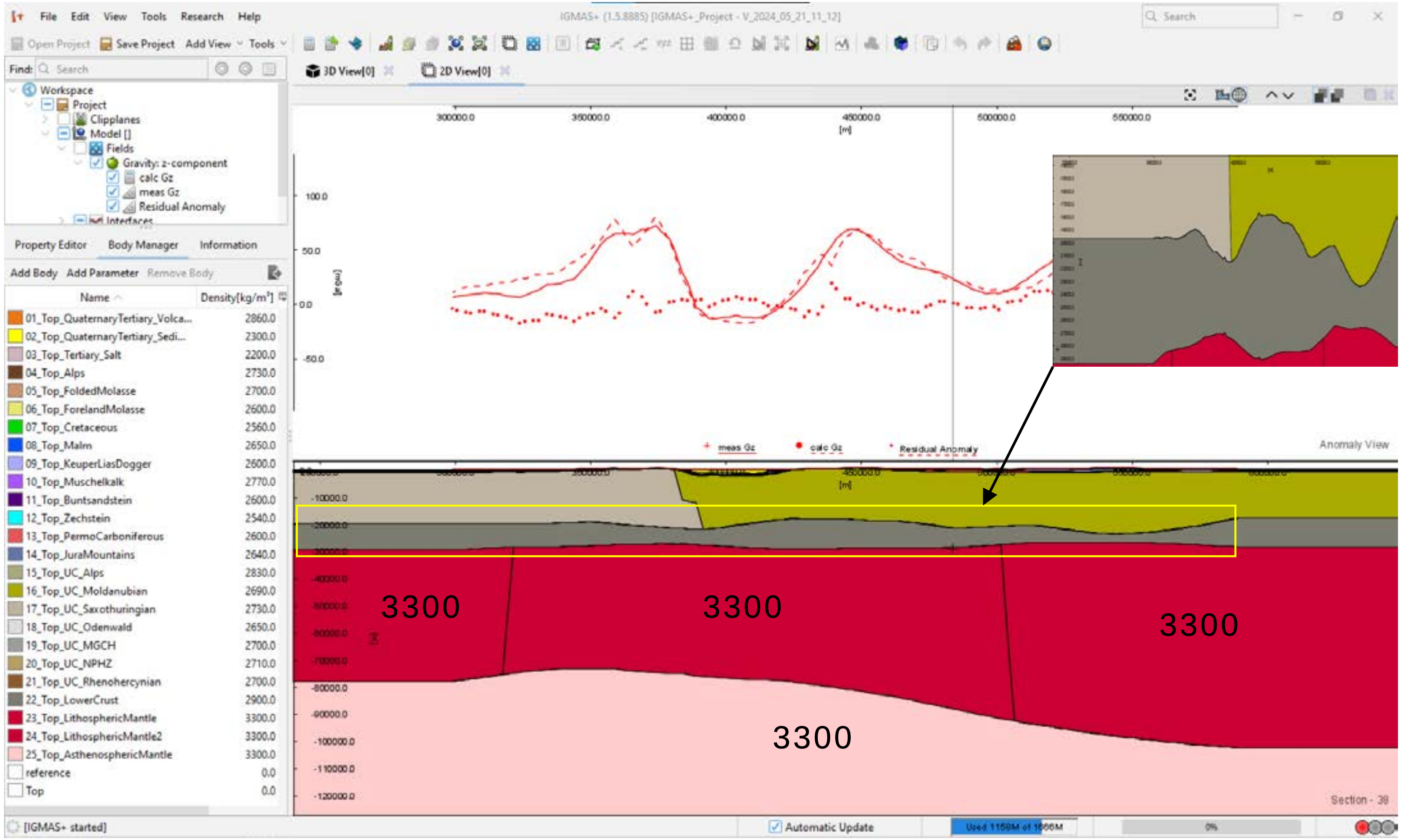




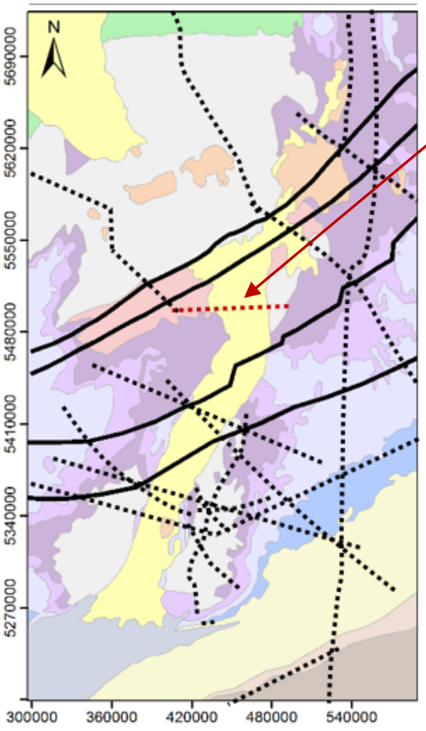
Application 2: Upper Rhine Graben

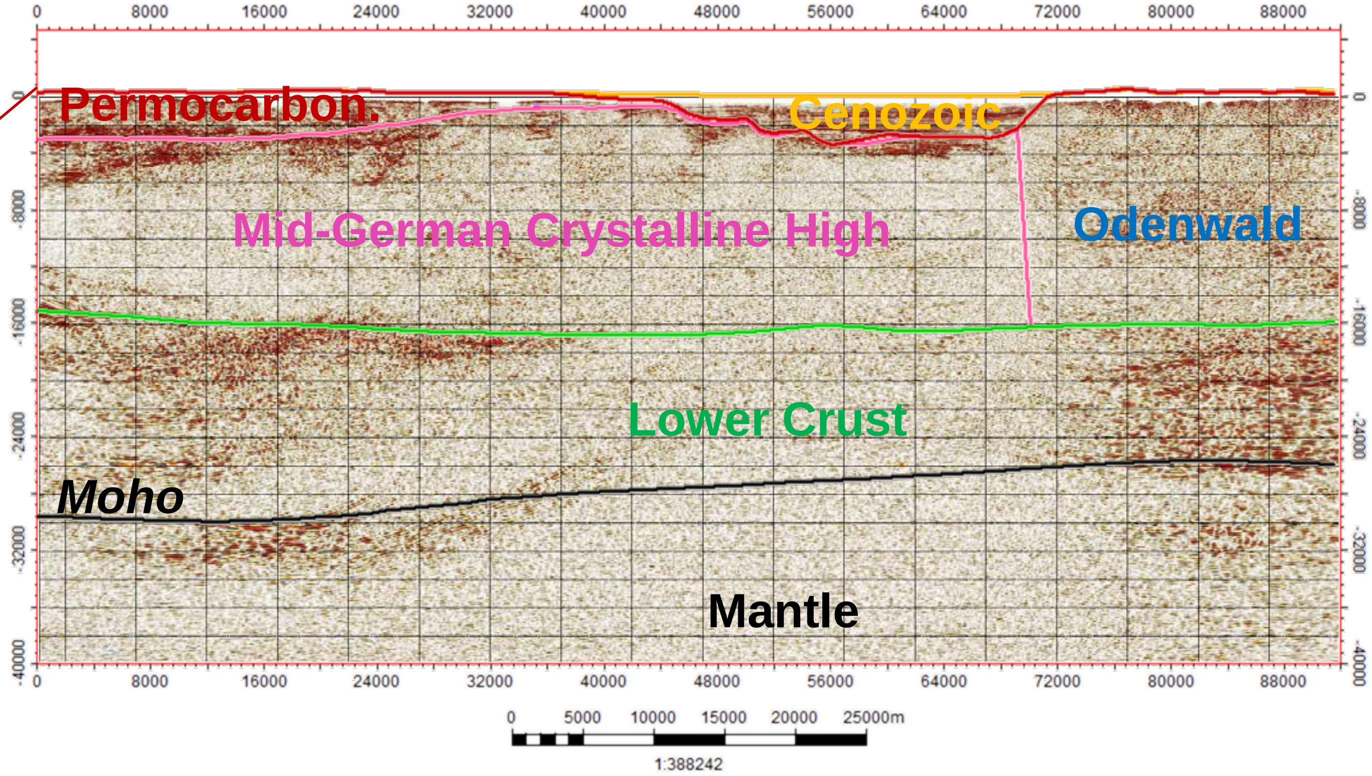
Model without low-density mantle anomaly but with optimized geometry





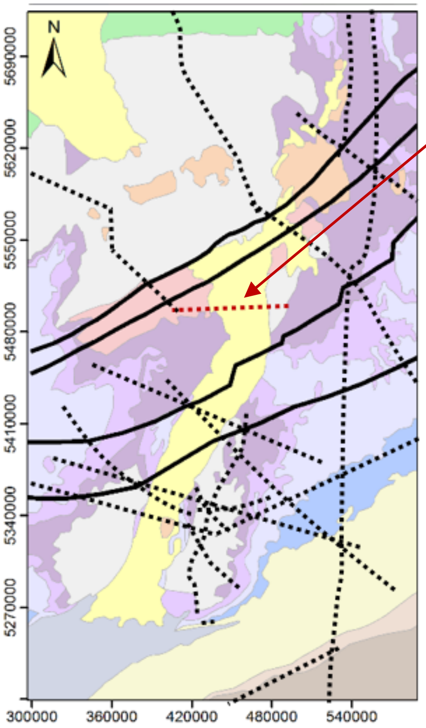
Application 2: Upper Rhine Graben

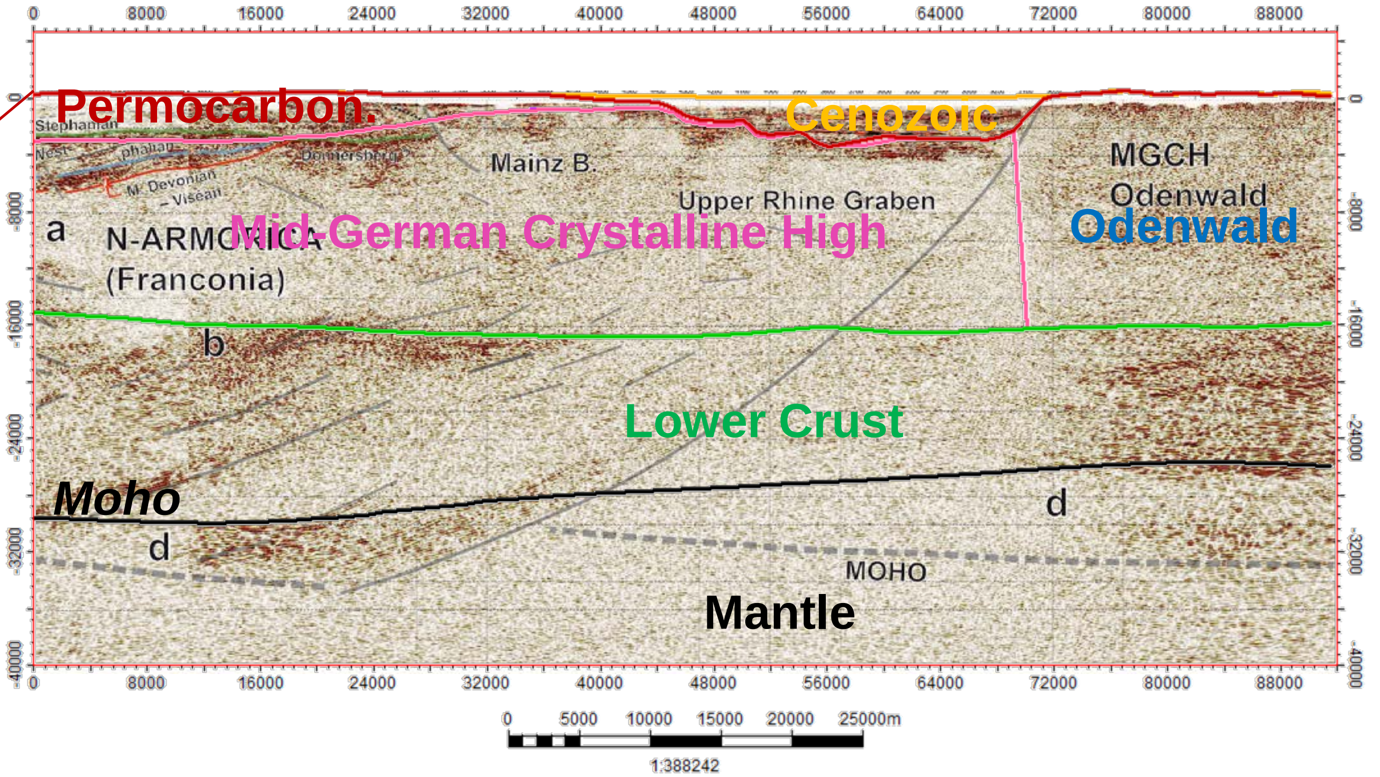




Re-processed, depth-converted and re-interpreted DEKORP 9N (following Schwarz and Henk, 2005) by M.Stiller and J.Freymark

Application 2: Upper Rhine Graben





Re-processed, depth-converted and re-interpreted DEKORP 9N by Bär et al (in prep.)
See also: Homuth, B., Bär, K., Weinert, S., Stiller, M. (2021): Reprocessing of the Hessian DEKORP seismic profiles. 81. Jahrestagung der Deutschen Geophysikalischen Gesellschaft, Abstract-Nr.: A-122.

Summary

- Motivation and concept of geometry optimization
- CMA-ES: appropriate non-linear algorithm for subsurface geometry optimization
- Subsurface space warping with the key element – elastic springs
- Applications: from salt dome reconstruction to mantle anomaly study
- Interactivity of the optimization process

References and acknowledgements

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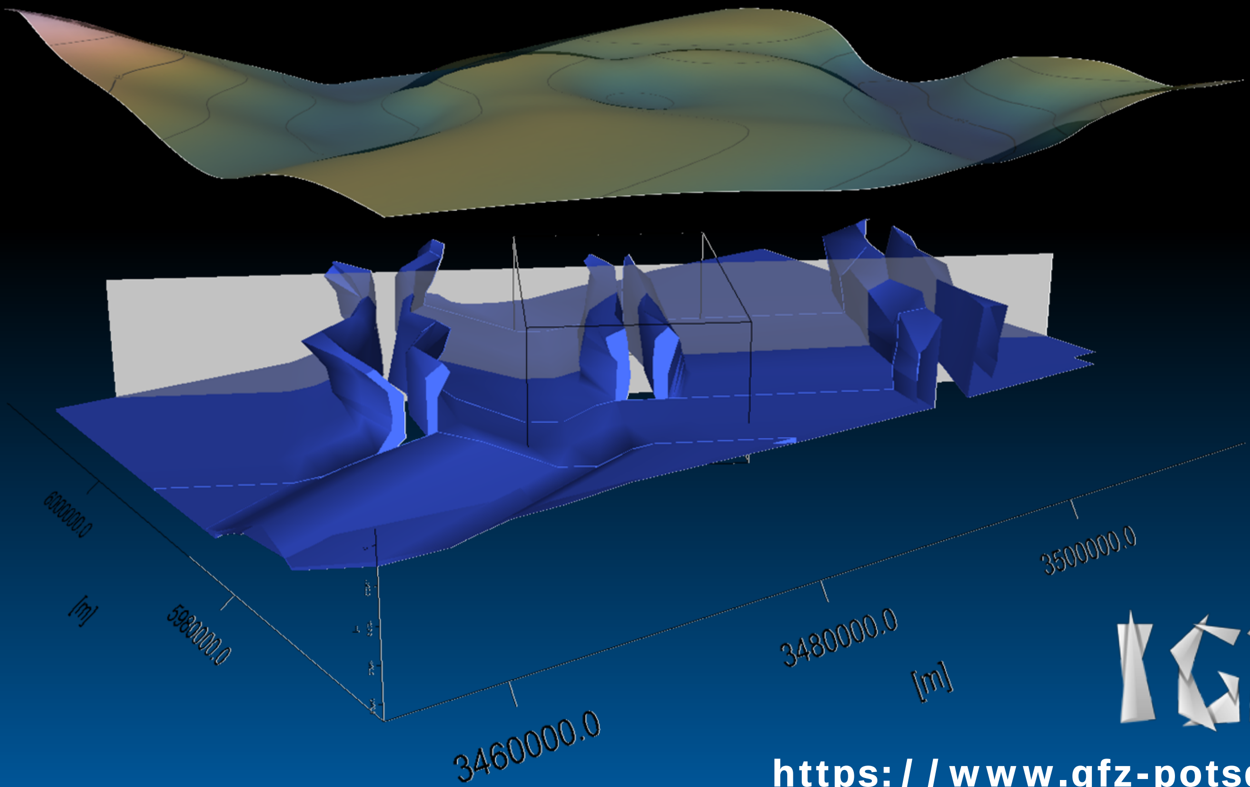
Thank you!



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