A stress field model for the Unterhaching geothermal plant: Challenges and solutions in local model calibration

GFZ Helmholtz Centre POTSDAM

Poster-EGU23-5935

Sophia Morawietz[1,6], Moritz Ziegler[1], Karsten Reiter[2], Oliver Heidbach[1,6], Inga Moeck[3,7], Ingmar Budach[4], Hartwig von Hartmann[3], and Jennifer Ziesch[5]

1 GFZ German Research Centre for Geosciences, Potsdam (smorawie@gfz-potsdam.de); 2 Institute of Applied Geosciences, Technical University of Darmstadt, Germany; 3 Leibniz Institute for Applied Geophysics (LIAG), Hannover, Germany; 4 Geothermie Neubrandenburg GmbH, Neubrandenburg, Germany; 5 State Authority for Mining, Energy and Geology, Hannover, Germany; 6 Institute of Applied Geosciences, Technical University of Berlin, Germany; 7 Faculty of Geosciences and Geography, Georg August University of Göttingen, Germany

Introduction

The relevance of stress

The stress field of Earth's upper crust is crucial for geodynamic processes and of key importance in planning and managing the utilization of the subsurface, such as geothermal energy extraction, stimulation of enhanced geothermal systems, or safety assessment of deep geological repositories. The contemporary 3-D stress state also provides the basis to assess the impact of induced stress changes which can lead to the reactivation of pre-existing faults, the generation of new fractures, or subsidence due to long-term depletion.

An omni-present challenge: The lack of data

However, information on the stress state of Earth's crust is sparse and often not available for the areas of interest. So far, the stress tensor orientations and stress regimes have been systematically compiled and provided by the World Stress Map (WSM) project in a public-domain database. Yet, the acquisition of stress tensor orientations is not necessarily accompanied by the determination of the stress magnitudes, which, however, are required when investigating questions related to stability and hazard mitigation strategies of georeservoirs. To estimate the 3-D stress state, geomechanical-numerical modelling is applied (Fig. 1). For the calibration of such models, stress magnitude data are essential. A major challenge is to bridge the scale gap between the widely scattered data that is required for model calibration and the high-resolution small-scale geological model in the target area.

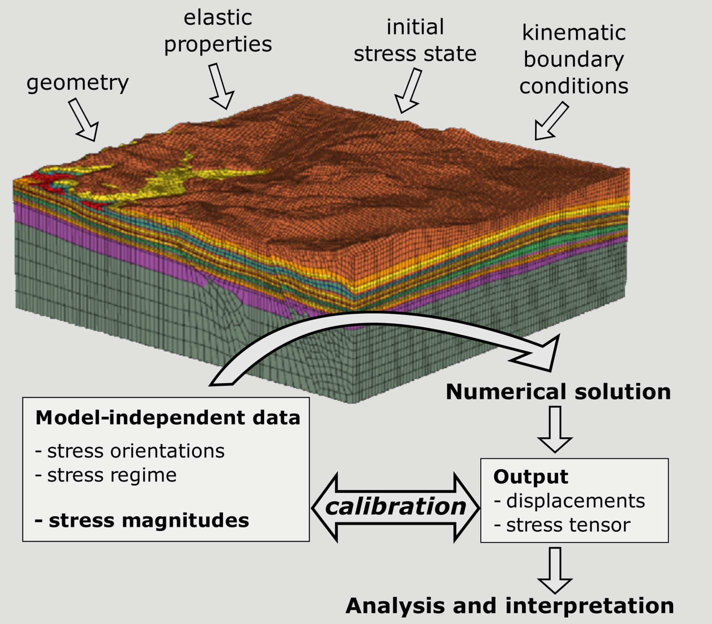


Fig. 1: Procedure and key components of geomechanical-numerical modeling.

Our method: A multistage model calibration

Ziegler et al. (2016) presented a multistage approach to resolve this challenge. For this, two successively calibrated models are created – one large-scale model with coarse resolution but available stress magnitude data for calibration (root model), and one local model with fine resolution, e.g., based on a 3-D seismic survey of the target area, but without any stress data (branch model). Synthetic data obtained through the large-scale root model is used to calibrate the small-scale branch model.

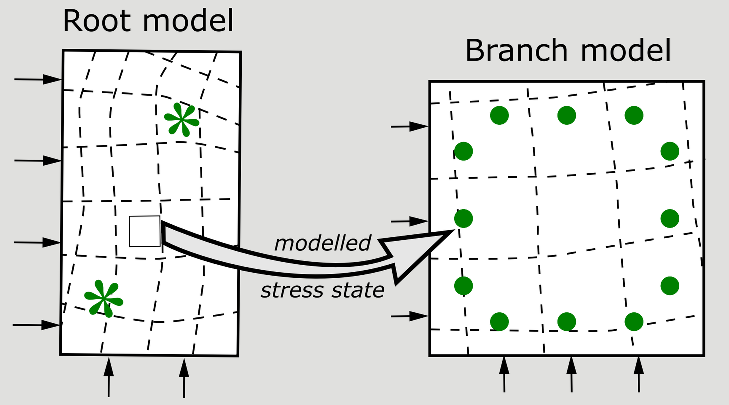


Fig. 2: Clarification of the terms root model and branch model. Stress measurement data is available only in the root model (green star symbols). For the calibration of the branch model, which covers a part of the root model area, synthetic stress data in form of the minimum and maximum horizontal stress magnitudes Shmin and SHmax, respectively, are used. These are extracted from the result of the root model calibration (green dots).

On this poster...

First, we validated the multistage approach by means of generic models to rigorously quantify the associated introduced uncertainties. For this purpose, we implemented a highly simplified model lithology with only vertical stratification and no lateral changes.

In a second step, we applied the multistage approach in a real-world setting and demonstrated the applicability on a local model of Unterhaching, south of Munich/Germany, where a geothermal district heating plant is located. Here, a local high-resolution model based on a 3-D seismic survey (Budach et al., 2018) has been successfully calibrated on a regional-scale stress model of the Bavarian Molasse Basin. The results of the local-scale model agree with the large-scale model. At the same time, stress change due to rock property variability, only resolved in the local-scale model, is shown.

Generic validation of the multistage calibration method

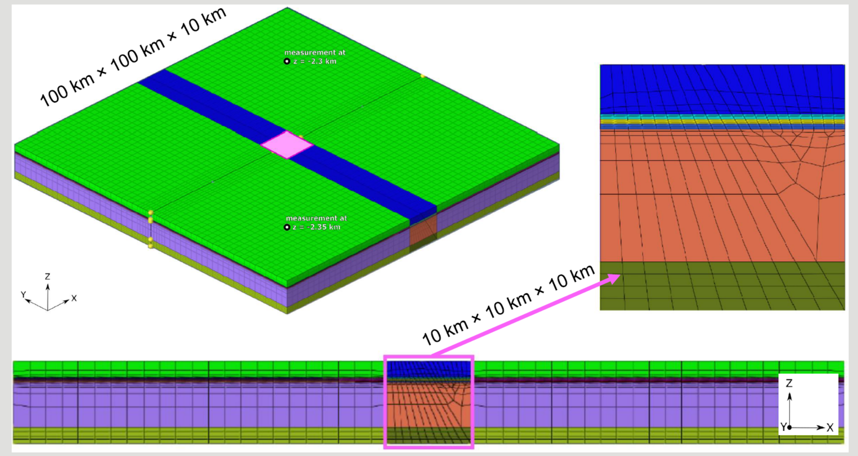


Fig. 3: Overview of the model geometry designed for the generic validation of the multistage calibration method. In lateral direction, the large-scale root model expands ten times the extension of the small-scale branch model. No active fault was included. The branch model includes three finely resolved lithologies, where the root model represents only one averaged layer (see Fig. 4 and 5).

color code	letter code	fine/coarse	E	ν	ρ
yellow	Y	both	15	0.29	2350
red	R	both	30	0.29	2460
dark green	D	both	45	0.24	2850
teal	T	coarse	25	0.27	2500
orange	O	fine	40	0.25	2600
blue	B	fine	15	0.29	2400
light green	L	fine	20	0.27	2500

Fig. 4 & Table 1: Profile view of the generic structure models see figure (left). Color and letter code representing the elastic properties of the lithological units see table (right). The schemes are not true to the model scale. Coarse lithology resolution: only one lithological unit between 2.0 km and 2.6 km depth. Fine lithology: three lithological units between 2.0 km and 2.6 km depth.

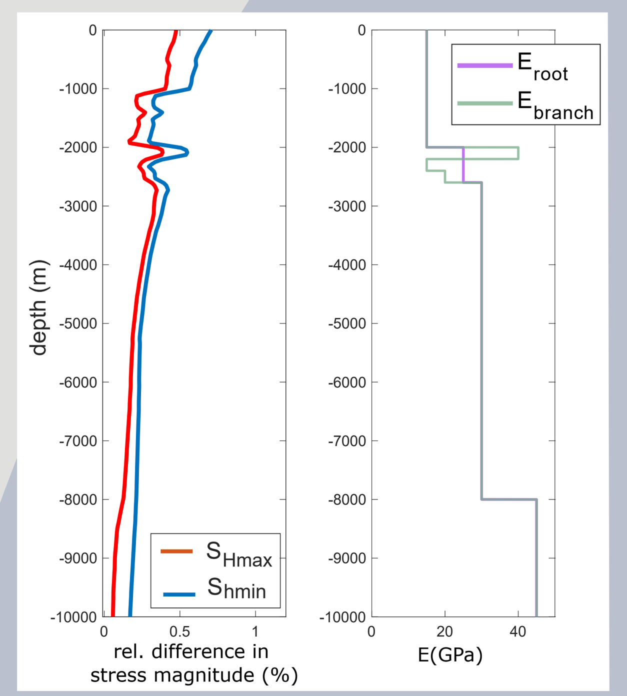


Fig. 5: Vertical profiles at the center of the model extension. Left: Relative differences between the reference model and the results of the multistage calibration (branch model) in the magnitudes of the principal horizontal stress components. Right: Different lithology representation in the root and the branch model in terms of Young's modulus E. The differences in the resulting stress mainly depend on the differences of the elastic parameters, namely Young's modulus, and the properties resolved only in the branch model. This is in line with our expectations given the relationship between stress, elasticity and deformation and the linear-elastic model assumption.

Deviation of stresses < 2% in the entire model space ⟹ **Validation successful ✓**

The case study around the Unterhaching geothermal plant

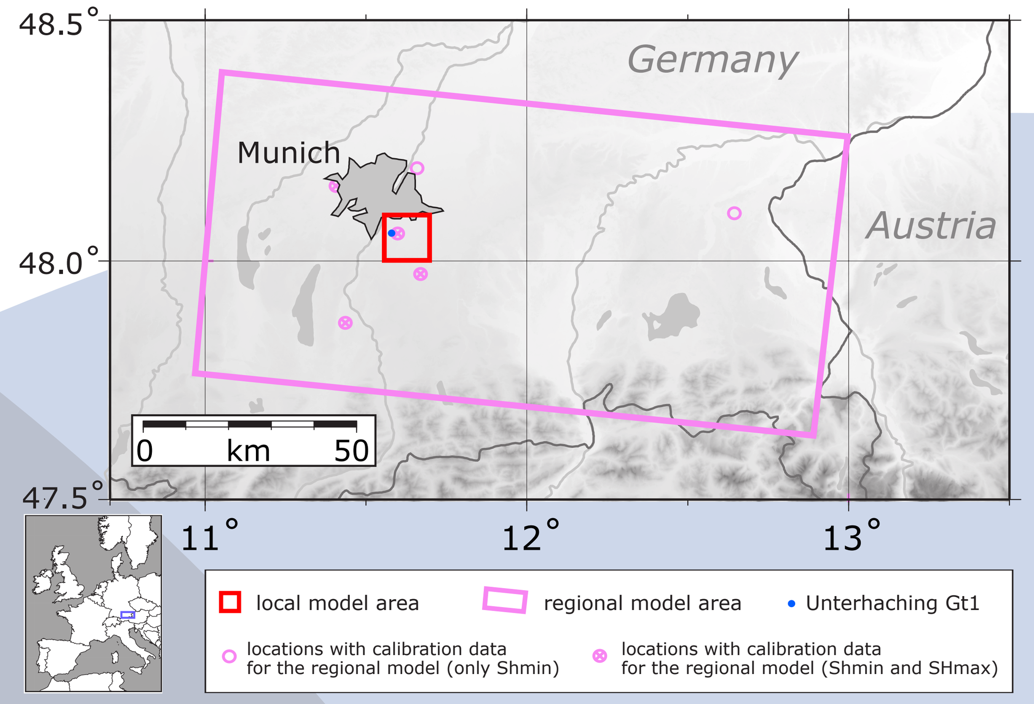


Fig. 6: Map of the eastern Bavarian Molasse Basin. Extension of the regional-scale stress model provided by Ziegler and Heidbach (2023) in pink. Extension of the local model around Unterhaching (this poster) in red.

How the multistage approach was applied in the case study

Regarding the lithological and therefore geomechanical structure, the regional root model and the local branch model have two lithologies in common, both in assigned geomechanical properties and, at least mostly, in depth position: the foreland Molasse and the basement. For calibration data extraction, only points were used for which the geomechanical assignment in the root and the branch model was the same.

Where the root model and the reference data come from

Basis for the branch model Unterhaching is the most probable scenario (referring to the highest Bayesian weight) from the study by Ziegler and Heidbach (2023). Their model is covering the region of the Bavarian Molasse Basin (Fig. 6). In the area around Unterhaching, three data points can be used as reference for the branch model result. These are included in Figure 8. However, the SHmax value has a lower reliability as it is not a measuring point, but was theoretically constrained through many assumptions using the frictional limit theory (Budach et al., 2018). The Shmin values were determined by leak-off tests (LOT), which means a higher but still not high reliability (Quality C out of range A–E after Morawietz et al., 2020).

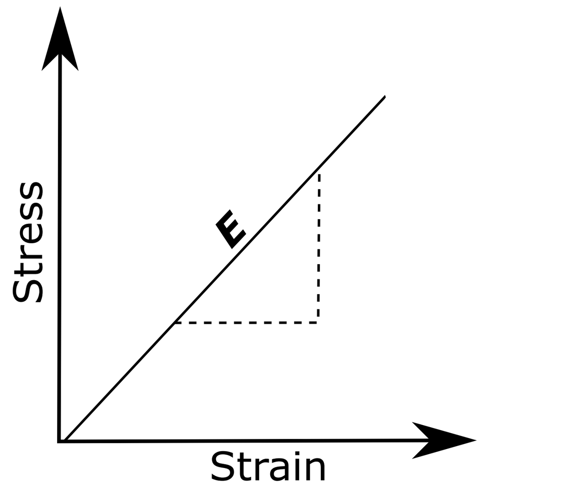


Fig. 9: Illustration of Hooke's Law. Our models assume a linear-elastic stress-strain relationship. Consequently, the slope of the stress-strain curve is the elastic modulus or Young's modulus E.

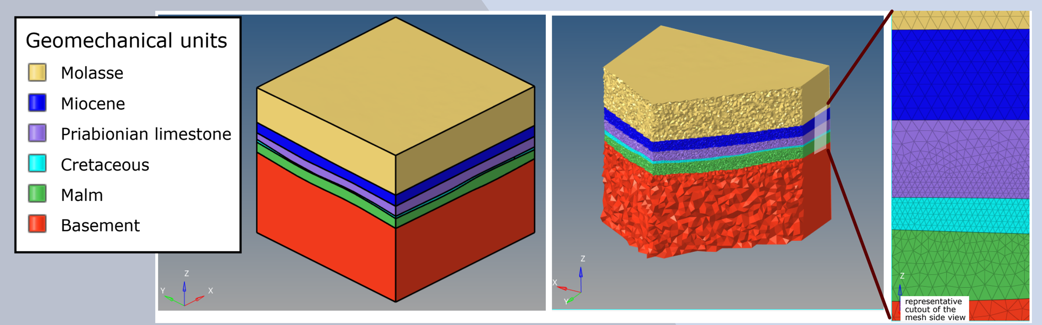


Fig. 7: Discretized Structural model of the local branch model around Unterhaching with its designated geomechanical units.

Unit	E (GPa)	ν	ρ (g/cm³)	approx. number of elements	dominant range of edge length (m)
Molasse	15	0.29	2250	1 240 000	100–200
Miocene	39	0.23	2758	2 720 000	~100
Priabionian limestone	42	0.27	2000	3 550 000	35–100
Cretaceous	22.5	0.25	2647	11 070 000	~40
Malm	45	0.23	2600	3 850 000	40–100
Basement	45	0.24	2850	300 000	100–500

Table 2: Lithological units in the models of the case study Bavarian Molasse/Unterhaching. Listed are the elastic properties and a quantification of the 3-D-element representation implemented in the branch model.

Exemplary view of the model result

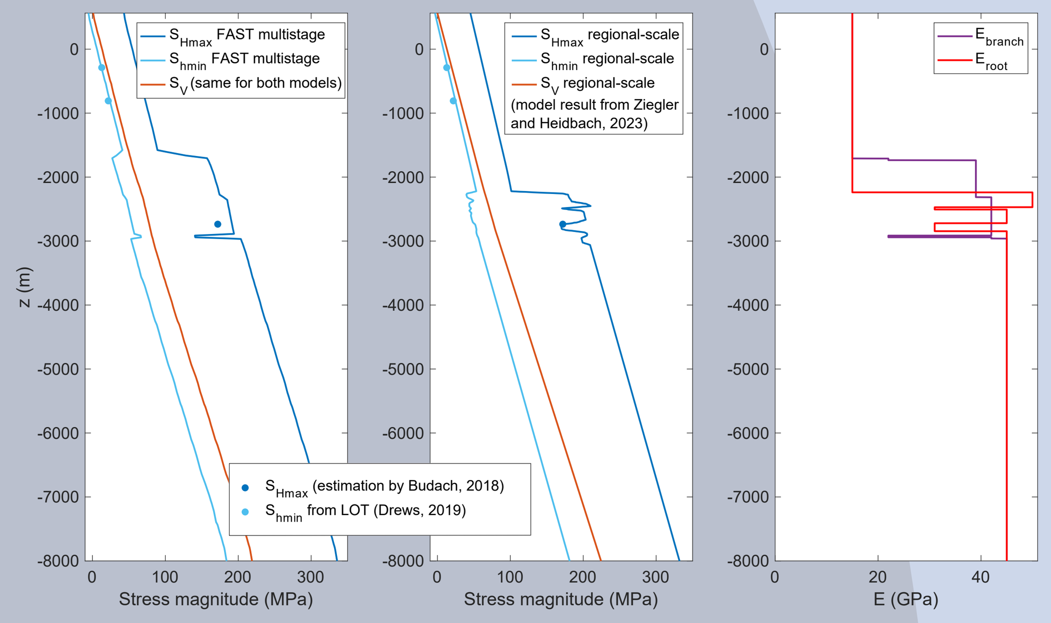


Fig. 8: Model results along a vertical profile at location of Unterhaching drilling site (well Gt1) of (left) the local model results based on FAST multistage calibration as well as data from Drews et al. (2019) and Budach et al. (2018) for comparison; (middle) regional model results as well as data from Drews et al. and Budach et al. for comparison; (right) E-moduli with depth used for the local models (branch) and the regional model (root).

How to read the results

In the regional model, the reference data points are very well fitted, especially the SHmax value. However, this is due to the fact that, first, the SHmax information is narrowly connected to calibration points for the regional model from Ziegler and Heidbach (2023), as they are based on the same unverifiable assumptions (Budach et al., 2018), and second, the Shmin points are in a depth range that is reflected with the same E-modulus in both models.

The very well fitted SHmax magnitude in the regional model (middle graph in Fig. 8) is in contrast to the SHmax magnitude in the branch model (left graph in Fig. 8). This highlights the value of the multistage approach in that it allows a stress state independent from the root model and the root model calibration points based only on the lithology. The lithology differs in the root and branch model in the according depths (right graph in Fig. 8). Furthermore, the apparently fine resolution in the range 2 km – 3 km depth is only apparently of augmented information content. In fact, it is inaccurate information that does not correspond to the actual lithology at the location.

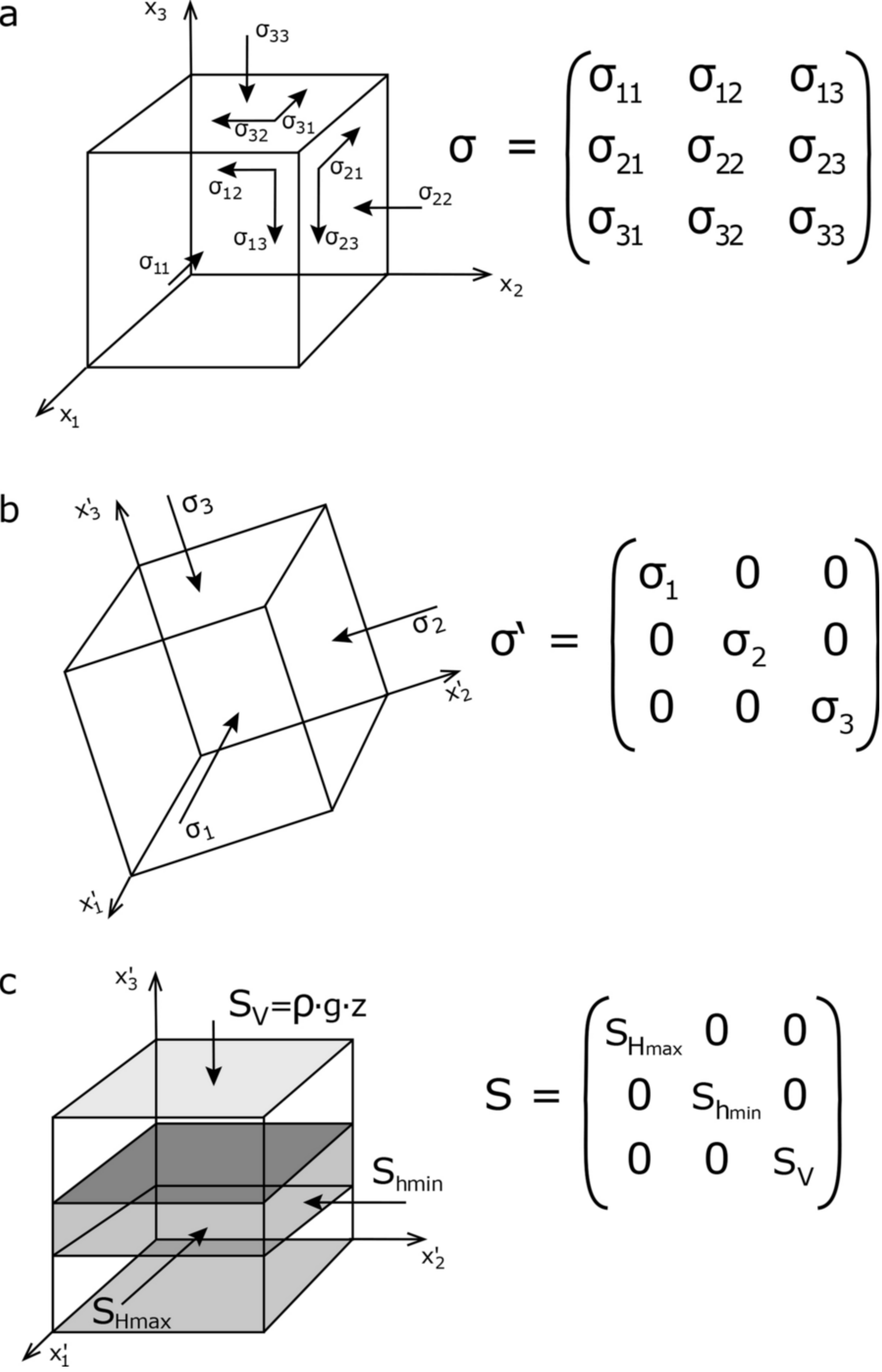
Conclusion

A local 3-D seismics-based model has a greater significance and should thus be used and trusted. The right graph in Figure 8 makes the different representation of the lithologies specifically clear: Young's modulus E, which is decisive for the model result due to the translation of displacements to stresses according to Hooke's law (Fig. 9), differs significantly in the depth range 1.5 km – 3 km. The distribution implemented in the branch model again corresponds much more to the actual local conditions in the subsurface than the curve from the regional root model.

The research was carried out within the framework of the project *SpannEnD II* (2022-2026), which is funded by the Federal Company for Radioactive Waste Disposal (BGE).

References

Budach, I., Moeck, I., Lüschen, E., and Wolfgramm, M. (2018). Temporal evolution of fault systems in the Upper Jurassic of the Central German Molasse Basin: case study Unterhaching. International Journal of Earth Sciences, 107:635–653
Drews, M. C., Seithel, R., Savvatis, A., Kohl, T., and Stollhofen, H. (2019). A normal-faulting stress regime in the Bavarian Foreland Molasse Basin? New evidence from detailed analysis of leak-off and formation integrity tests in the greater Munich area, SE-Germany. Tectonophysics, 755:1–9.
Morawietz, S., Heidbach, O., Reiter, K., Ziegler, M., Rajabi, M., Zimmermann, G., Müller, B.,and Tingay, M. (2020). An open-access stress magnitude database for Germany and adjacentregions. Geothermal Energy, 8(1):1–39
Ziegler, M. O. (2022). Rock properties and modelled stress state uncertainties: A study of variability and dependence. Rock Mechanics and Rock Engineering, 55(8):4549–4564
Ziegler, M. O. and Heidbach, O. (2020). The 3d stress state from geomechanical – numerical modelling and its uncertainties: a case study in the Bavarian Molasse Basin. Geothermal Energy, 8(1):1–21
Ziegler, M. O. and Heidbach, O. (2023). Bayesian quantification and reduction of uncertainties in 3d geomechanical-numerical models. Journal of Geophysical Research: Solid Earth, pagee2022JB024855
Ziegler, M. O., Heidbach, O., Reinecker, J., Przybycin, A. M., and Scheck-Wenderoth, M. (2016). A multi-stage 3-D stress field modelling approach exemplified in the Bavarian Molasse Basin. Solid Earth, 7(5):1365–1382
Ziegler, M. and Heidbach, O. (2021a). Manual of the Matlab Script FAST Calibration v2.0. World Stress Map Technical Report, GFZ German Research Centre for Geosciences, Potsdam



Explanation of the stress tensor. ***a*** *The nine components of the stress tensor describe the stress state at an arbitrary point and enable calculation of the stress vector on any surface through that point. To describe the stress tensor components, an infinitely small cube with unit surfaces is used.* ***b*** *Due to the conservation of momentum (no rotation), the stress tensor is symmetric, and thus a coordinate system exists where shear stresses vanish along the faces of the cube. In this principal axis system, the remaining three stresses are the principal stresses.* ***c*** *Assuming that the vertical stress in the Earth's crust* $S_V = \rho \cdot g \cdot z$ *(g is gravitational acceleration, ρ is the rock density, z is the depth below surface) is a principal stress,* S_{hmin} *and* S_{Hmax} *are also principal stresses. This so-called reduced stress tensor is fully determined by four components: the* S_{Hmax} *orientation and the magnitudes of* S_V*,* S_{Hmax}*, and* S_{hmin}*.*

From "An open-access stress magnitude database for Germany and adjacent regions" by Morawietz et al., 2020, Geotherm Energy 8, 25. Link to Figure: https://geothermal-energy-journal.springeropen.com/articles/10.1186/s40517-020-00178-5/figures/1