Estimating the subsurface temperature of Hessen/Germany based on a GOCAD 3D structural model – a comparison of numerical and geostatistical approaches

Wolfram Rühaak, Kristian Bär, Ingo Sass

Institute of Applied Geosciences, Chair of Geothermal Science and Technology, TU Darmstadt, Germany

Introduction

Based on a 3D structural GOCAD model (Arndt et al. 2011) and an extended geothermal database (Bär et al. 2011) of the federal state Hessen/Germany the subsurface temperature distribution is computed. Since subsurface temperature data for great depth are typically sparse, two different approaches for estimating the spatial subsurface temperature distribution are tested.

Numerical Modeling

One classical approach for estimating the subsurface temperature distribution is the numerical computation of a 3D purely conductive steady state temperature distribution (Rühaak et al. 2010). The numerical model is based on measured thermal conductivity data for all relevant geological units and surface temperatures (Sass et al. 2011). The basal heat flow is estimated following the approach of Arndt et al. (2011). It is spatially varying from 65 mW m^{-2} to 95 mW m^{-2} according to the presumed Moho depth using data from Dèzes & Ziegler (2001).

The model is calibrated using continuous temperature-logs. Only conductive heat transfer is considered as not enough data for convective heat transport at great depths are available. The fit of the modeled logs is very good in the areas that are not convective influenced (logs 1-19, 22), within such areas the fit is poor (logs 20 - 21).

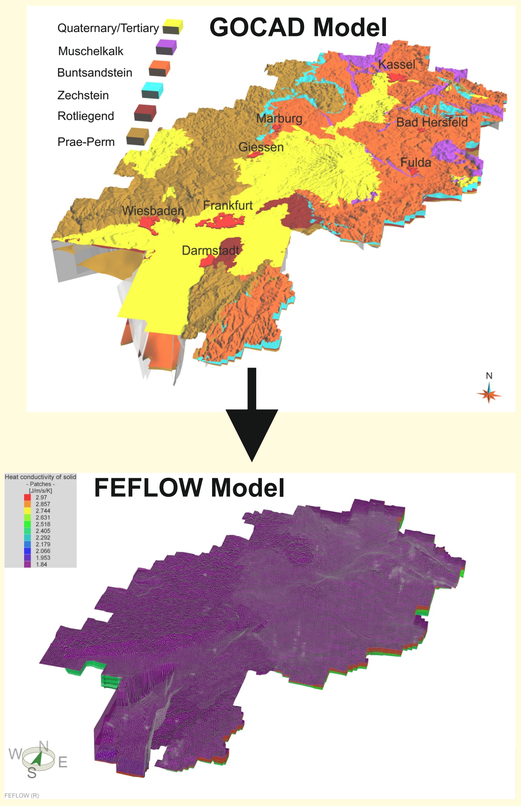


Fig. 1: The purly conductive FEFLOW heat-transport model for Hessen.

Table 1: The thermal model properties. λ always at 20 °C.

Nr	Unit	k [m^2]	Porosity (-)	λ_s[W m^{-1} K^{-1}]	$(\rho c)_s$ [J m^{-3} K^{-1}]
1	Quaternary/Tertiary	1.0×10^{-16}	0.016	1.84	2.0×10^{6}
2	Muschelkalk	7.6×10^{-17}	0.043	2.10	1.8×10^{6}
3	Buntsandstein	2.5×10^{-14}	0.135	2.97	1.8×10^{6}
4	Zechstein	7.2×10^{-16}	0.115	2.55	2.1×10^{6}
5	Rotliegend	7.2×10^{-15}	0.089	2.42	2.0×10^{6}
6	N' Crystalline Basement	1.8×10^{-16}	0.036	2.81	1.8×10^{6}
	S' Crystalline Basement	3.9×10^{-17}	0.002	2.40	2.1×10^{6}

3D Kriging of Temperature Measurements

The other approach to estimate the subsurface temperature distribution is by 3D ordinary Kriging. Here a modified approach is applied where the quality of the temperature measurements is taken into account (Rühaak 2006, Rühaak 2012). A difficult but important part is to derive good variograms for the horizontal and vertical direction. The variograms give necessary information about the spatial dependence of the data. The horizontal variogram is based on all data from the Odenwald and Sprendlinger Horst (ODW), Hanau Seligenstädter Senke (HSS), Hessen North-East (NE) and Schiefergebirge (RH). Data from the Mainzer Becken (MZ) and the Oberrheingraben (ORG) are not used for this variogram as they are strongly convective disturbed. The vertical variogram is based on data from all regions but only high quality measurements from continuous logs are used.

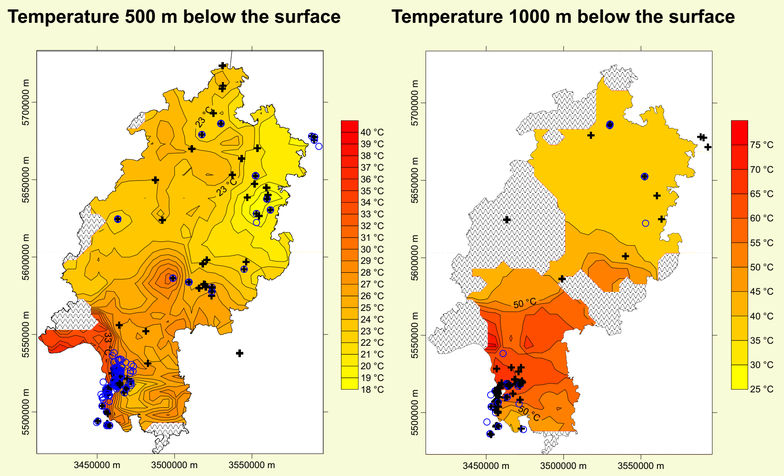


Fig. 2: Result of the 3D Kriging interpolation: the temperature in 500 m and 1000 m below the surface, respectively. Black crosses mark available data in a vertical distance of no more than 300 m above the depicted slice, while the blue circles depict available data with a distance of no more than 300 m below the slice. The Kriging is applied with a search distance of horizontal 60 km and vertical 300 m, together with a octant search (max 12 values, max 5 empty octants).

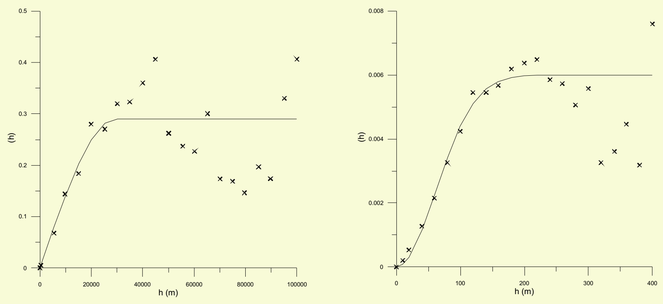
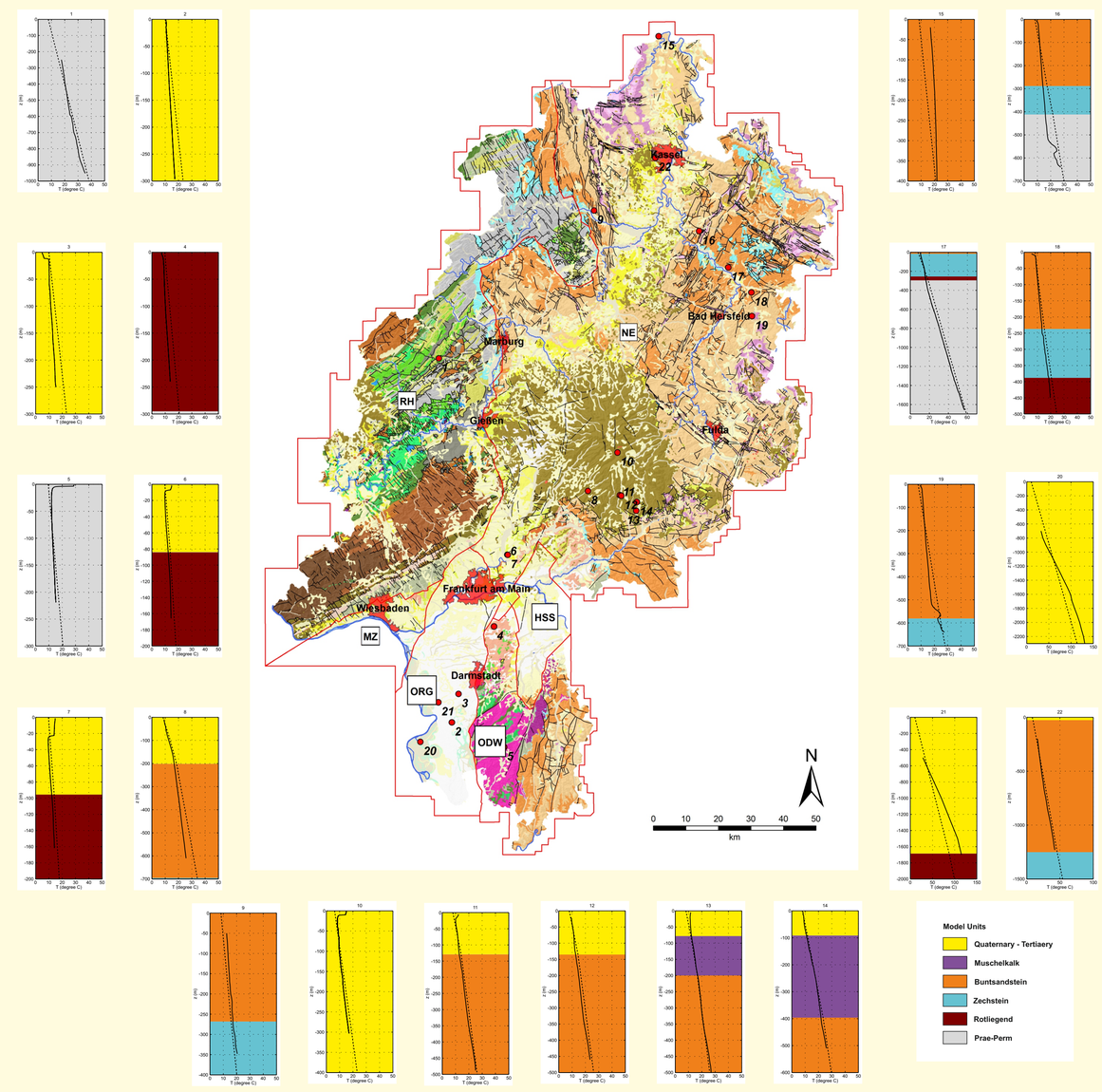


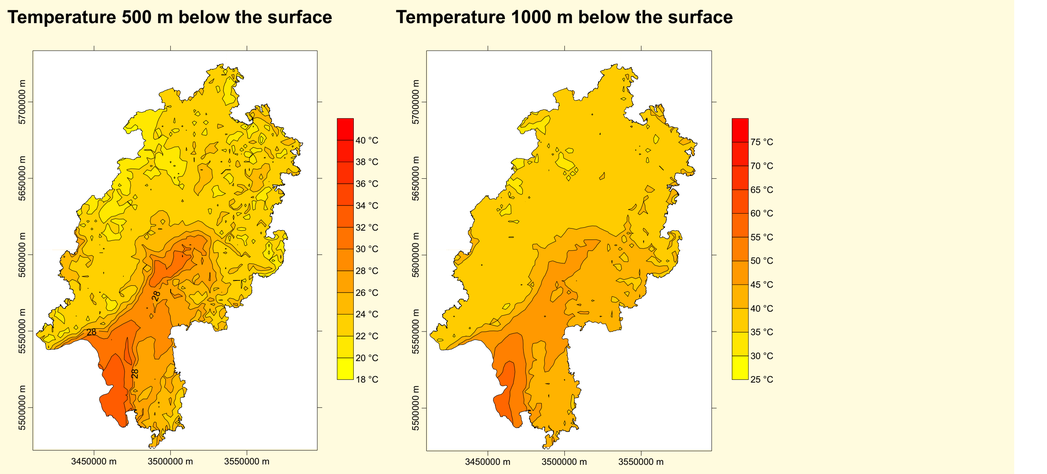
Fig. 3: The variograms used for the Kriging: Left the one used for the horizontal direction (Spherical: sill = 0.29, range = 29,500 m); Right the one used for the vertical direction (Gaussian: sill = 0.006, range = 150 m).

Table 2: The different quality classes for the temperature measurements.

Code	Measurement Description (based on work of the database maintainer, LIAG Hannover)	Estimated Error (K)	n
1	undisturbed logs	0.01	1360
2	disturbed temperature logs	2.4	200
11	BHT with at least 3 temperature measurements taken at different times in the same depth; corrected with a cylinder-source ansatz	0.5	58
21	Production test (DST)	0.5	
12	BHT with at least 2 temperature measurements taken at different times in the same depth; corrected using the Horner-plot method	0.7	85
13	BHT with at least 2 temperature measurements taken at different times in the same depth; corrected with an explosion line-source ansatz	0.7	
14	BHT with one temperature measurement, known radius and time since circulation (TSC)	1.6	46
15	BHT with one temperature measurement, known TSC	1.6	
16	BHT with one temperature measurement, known radius	3	280
17	BHT with one temperature measurement, unknown radius and unknown TSC	3	

Comparison: measured (straight line) versus modeled purely conductive logs (dashed line)





Discussion and Outlook

Differences in the predicted subsurface temperature distribution are mainly related to convective processes, which are reflected by the interpolation result, but not by the numerical model. Therefore, a comparison of the two results is a good way to obtain information about flow processes in such great depth. This way an improved understanding of the heat transport processes within this mid enthalpy geothermal reservoir (1000 m – 6000 m) is possible.

The computation of a fully coupled flow and heat transport model would be ideal. However, due to the small number of data any such result lacks of reliability.

To obtain the theoretical variograms necessary for the Kriging is a difficult task. Especially the quality of the horizontal semi-variogram is poor. However, it is sufficient for obtaining a reasonable spatial temperature distribution. Especially the inclusion of a weighting algorithm (Rühaak 2012) helps to improve the Kriging result as artefacts due to low quality measurement only have a small impact - where high quality data are available.

The combination of both approaches might result in a temperature model with a good fit to the given temperature measurements as well as a good extrapolation of subsurface temperatures in depths where no data is available. Such a model increases the quality of geothermal potential predictions compared to purely numerical or geostatistical approaches.

In this study the paleoclimate signal was not taken into account, which is relevant especially for depths up to approximately 1000 m. Also heat production was neglected for the numerical model. Both aspects as well as the influence of fault zones as conduits for convective heat transport should be addressed in future work. Additionally the impact of a temperature dependent thermal conductivity should be studied in future.

References

Arndt, D., Bär, K., Fritsche, J.-G., Kracht, M., Sass, I., & Hoppe, A. (2011): 3D structural model of the Federal State of Hesse (Germany) for geo-potential evaluation. Z. Dt. Ges. Geowiss., 162(4), 353-369.

Bär, K., Arndt, D., Fritsche, J.-G., Götz, A. E., Kracht, M., Hoppe, A. & Sass, I. (2011): 3D-Modellierung der tiefengeothermischen Potenziale von Hessen – Eingangsdaten und Potenzialausweisung. Z. Dt. Ges. Geowiss., 162(4), 371-388.

Dézes, P., Ziegler, P. A. (2001): European Map of the Mohorovičić discontinuity, - In: Mt. St. Odile [Edts.]: 2nd EUCOR-URGENT Workshop (Upper Rhine Graben Evolution and Neotectonics), France.

Rühaak, W., (2006): A Java application for quality weighted 3-d interpolation. Computers & Geosciences 32,1.

Rühaak, W., Rath, V. & Clauser, C., (2010): Detecting thermal anomalies within the Molasse Basin, Southern Germany. Hydrogeology Journal 18, 8.

Rühaak, W (2012): 3-d interpolation of subsurface temperature data with known measurement error using Kriging (in preperation).

Sass, I., Hoppe, A., Arndt, D. & Bär, K. (2011): Forschungs- und Entwicklungsprojekt 3D Modell der geothermischen Tiefenpotenziale von Hessen. unveröffentlichter Abschlussbericht, 218 S. 105 Abb., 19 Tab., 30 Karten, 7 Anl., 1 CD-ROM, 1 DVD-ROM, Technische Universität Darmstadt.

TECHNISCHE UNIVERSITÄT DARMSTADT



Contact:
Wolfram Rühaak
Darmstadt University of Technology
Institute of Applied Geosciences
Chair of Geothermal Science and Technology
Schnittspahnstrasse 9 D-64287 Darmstadt Germany
E-mail: ruehaak@geo.tu-darmstadt.de