# THERMO-MECHANICAL MODELS OF THE EUROPEAN LITHOSPHERE FOR GEOTHERMAL EXPLORATION

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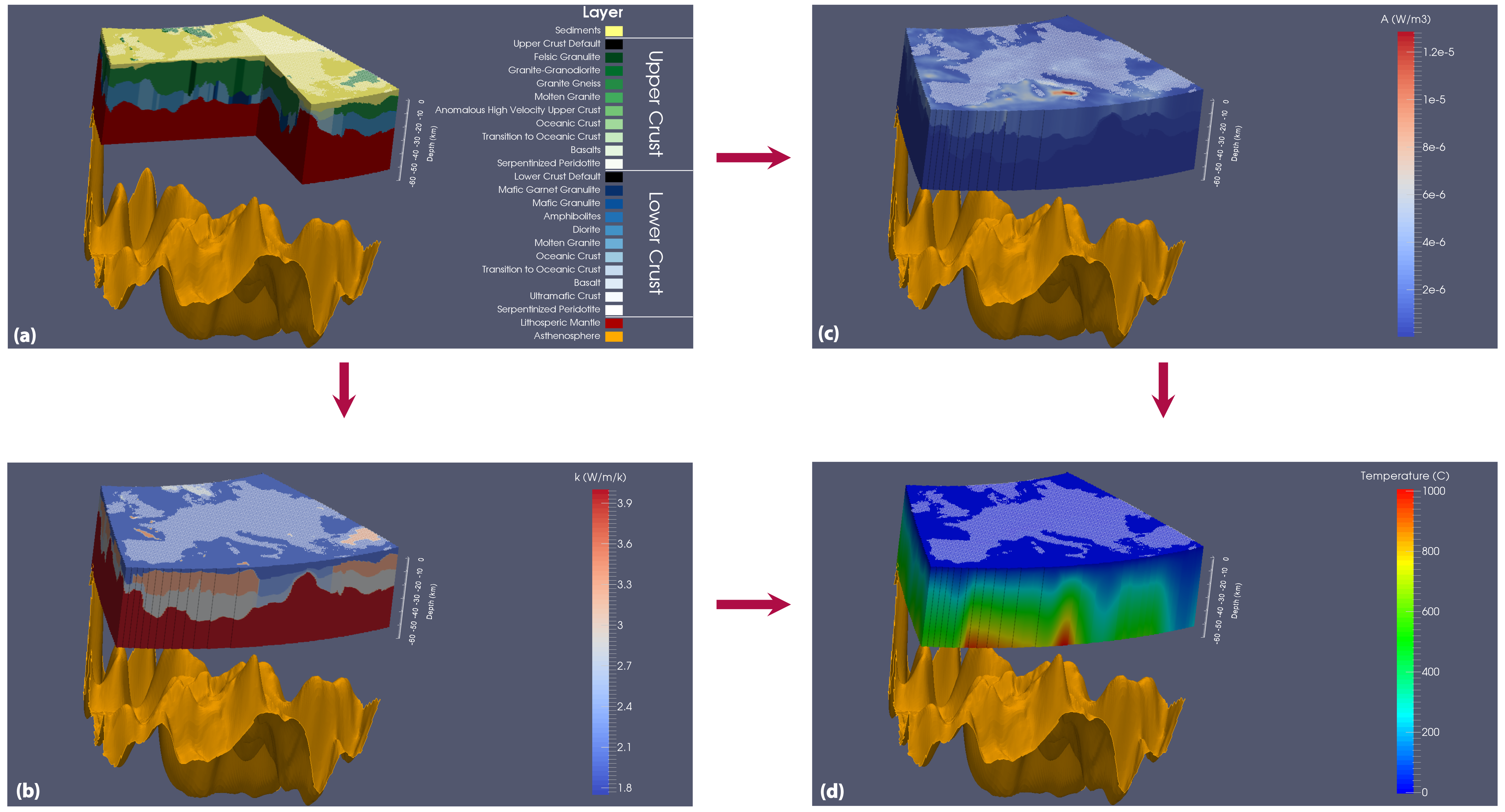


**Fig. 1:** **(a)** Geometry and composition. **(b)** Thermal conductivity. **(c)** Radiogenic heat production. **(d)** Thermal model.

## 1: Rationale

As part of the EU FP7-funded Integrated Methods for Advanced Geothermal Exploration (IMAGE) project we will develop an improved thermo-mechanical model of the European lithosphere.

For the assessment of the prospective resource base of enhanced geothermal systems in Europe we developed a temperature model for the upper 10 km of the crust [1]. The mode of heat transfer was limited to vertical conduction and the model consisted of two layers with a fixed thermal conductivity: a sediment and basement layer. The surface heat flow and Moho depth allowed us to constrain the radiogenic heat production in the upper crust (cf. [2]). Available temperature data were used directly to constrain the 3D temperature distribution up to a depth of 6 km. However, this approach created inconsistencies between the calculated and observed heat flow.

Aims:

- More realistic a priori **thermal properties**
- **Consistency** between model boundary conditions and temperature data
- Analyzing temperature **sensitivity** to parameter variations (cf. [3])
- Understanding **uncertainties** and effects of **non-conductive heat transfer**

## 2: Workflow

1. **Crustal geometry** (Fig. 1a)
2. Populating the model with **thermal properties** (Fig. 1b and 1c)
3. Define **boundary conditions**
4. Calculate the **a priori thermal model** (Fig. 1d, 3a and 3b)
5. **Model calibration** using data assimilation technique
6. Calculate the **strength model** (Fig. 4)

The full model will have a horizontal resolution of $\sim$20 km while the vertical resolution will be 250 m for the first 10 km and will decrease to 2.5 km at larger depths. As a starting point for our model we use an existing crustal geometry with different lithotypes for the upper and lower crust [4]. We are in the process of defining different sedimentary lithotypes for the sedimentary layer (e.g. unconsolidated, consolidated, salt).

The new thermal model together with compositional data will be used to estimate the strength distribution in the lithosphere [5]. The strength distribution could be used to obtain a more reliable estimation of the stress field which is important for optimizing the pressure applied to geothermal wells to enhance flow rates, while minimizing the risks of induced seismicity.

## 3: Thermal Properties and Preliminary Thermal Model

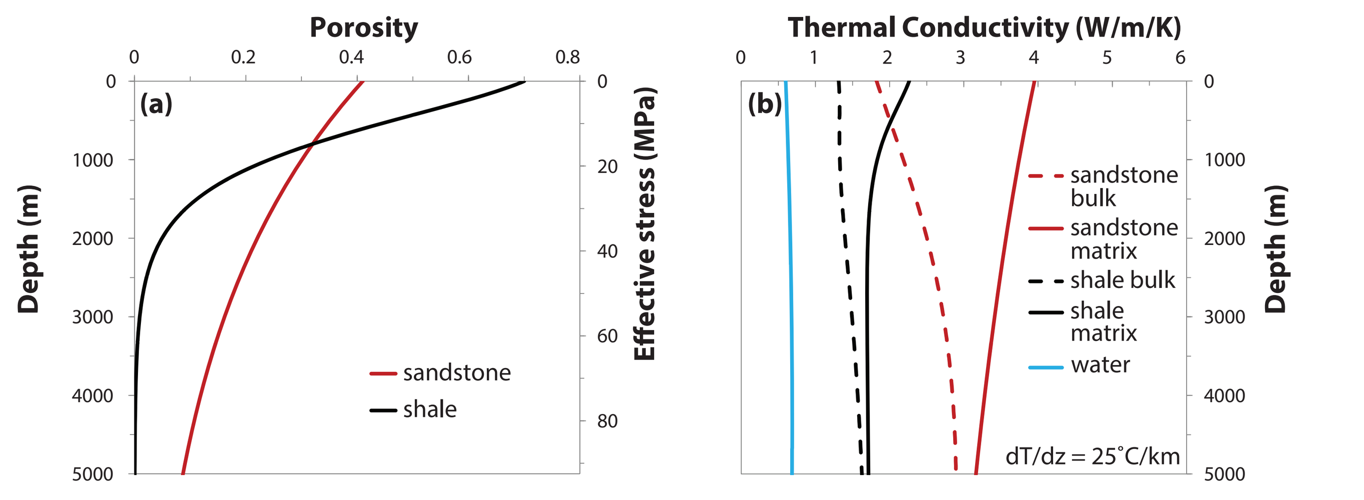


**Fig. 2:** **(a)** Porosity reduction of typical sandstone and shale following Athy's Law of Compaction. **(b)** The bulk thermal conductivity of sediments varies with depth due to: Porosity changes effecting the geometrical average of the thermal conductivity of the rock matrix and the fluid phase (water). The temperature dependence of the thermal conductivity of the rock matrix and water [6].

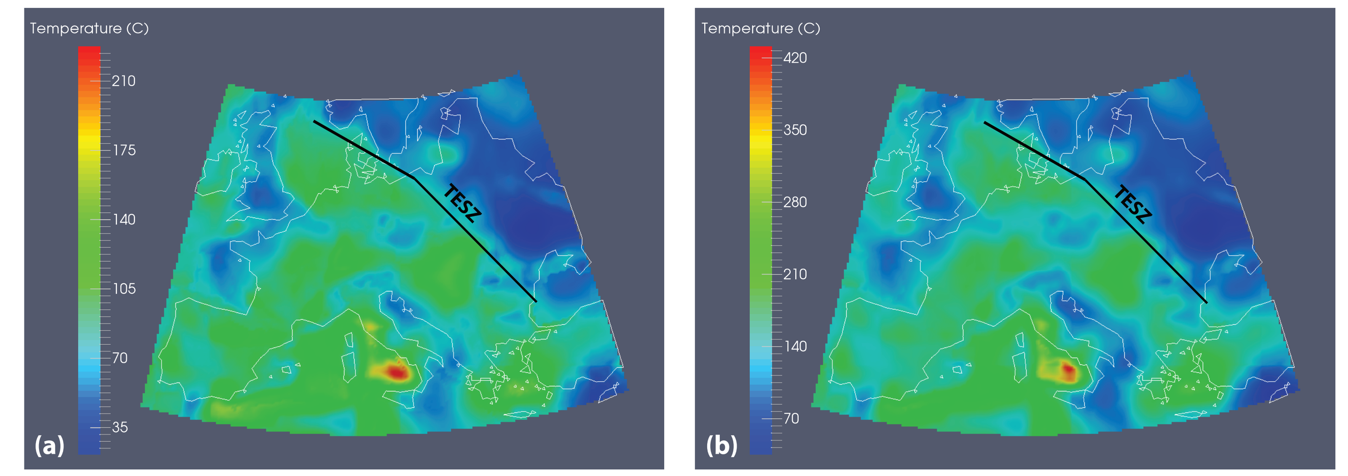


**Fig. 3:** **(a)** Temperature at 5km depth below ground level. **(b)** Temperature at 10km below ground level. The TESZ-line (black) indicates the Trans-European Suture Zone. The preliminary thermal model is based on vertical conduction only. Surface temperatures are used as boundary condition for the top, while for the bottom the extrapolated heat flow is used. For our future model we will change the bottom boundary condition to the depth of the Lithosphere-Asthenosphere boundary (1200°C isotherm).

## 4: Data Assimilation

Parts of the thermal model including the corresponding thermal properties will be calibrated using a probabilistic approach:

- Define uncertainty ranges for feed-in parameters:
  - Thermal conductivity and radiogenic heat generation
  - Depth of the Lithosphere-Asthenosphere boundary (1200 °C isotherm)
  - Temperature data (BHT and DST measurements, maps)
- Probability density functions of temperature and thermal properties
- Quantify uncertainty

Challenges for calibration:

- Quantity and uneven distribution of temperature data (measurements, maps)
- Handling of temperature maps (to be treated as points with high uncertainty?)

Currently the technique is being tested on a small synthetic case (100x100x35 cells). In the future we would like to apply this approach to areas of our model for which sufficient temperature data are available (e.g. the Netherlands [7]).

## 5: Preliminary Strength Model

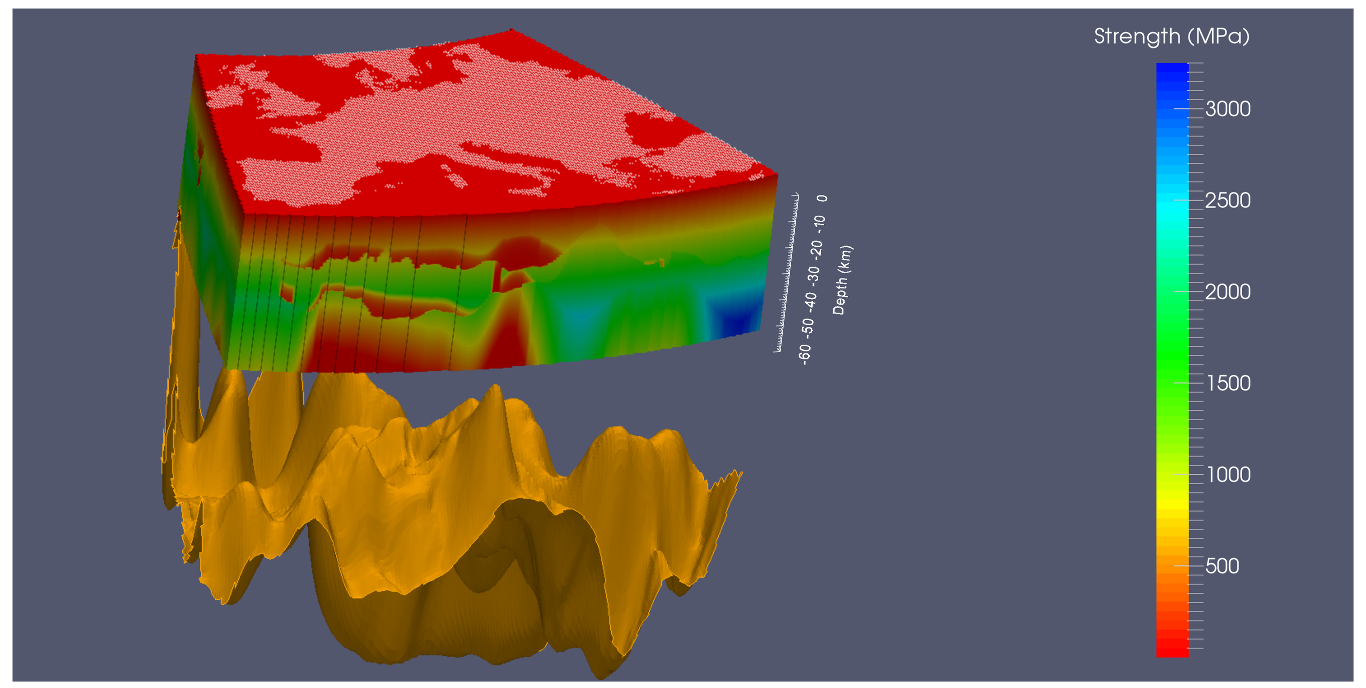


**Fig. 4:** Strength model.

The thermal model was used in combination with rheological laws to calculate the strength. Different rheologies were assigned according to the crustal lithotype:

- Upper crust: quartzite (dry) or granulite
- Lower crust: mafic granulite or diorite (wet) or diabase (dry)
- Lithospheric mantle: olivine (dry)

## 6: Outlook

- Incorporate **sedimentary lithotypes** and more realistic **thermal properties**
- **Calibration** of the a priori temperature model using data assimilation
- **Comparison** of the thermal model with other models [8]
- Improve **strength model**

## References and Acknowledgements

[1] J. Limberger, P. Calcagno, A. Manzella, E. Trumpy, T. Boxem, M. P. D. Pluymaekers, and J.-D. van Wees. Assessing the prospective resource base for enhanced geothermal systems in europe. *Geothermal Energy Science*, 2(1):55–71, 2014.

[2] H. N. Pollack and D. S. Chapman. On the regional variation of heat flow, geotherms, and lithospheric thickness. *Tectonophysics*, 38(3–4):279–296, 1977.

[3] M. Scheck-Wenderoth, M. Cacace, Y. P. Maystrenko, Y. Cherubini, V. Noack, B. O. Kaiser, J. Sippel, and L. Björn. Models of heat transport in the central european basin system: Effective mechanisms at different scales. *Marine and Petroleum Geology*, 55:315–331, 2014.

[4] M. Tesauro, M. K. Kaban, and S. A. P. L. Cloetingh. EuCRUST-07: A new reference model for the European crust. *Geophys. Res. Lett.*, 35(5):1–5, 2008.

[5] S. Cloetingh, Van Wees, J. D., P.A. Ziegler, L. Lenkey, F. Beekman, M. Tesauro, A. Förster, B. Norden, M. Kaban, N. Hardebol, D. Bonté, A. Genter, L. Guillou-Frottier, M. Ter Voorde, D. Sokoutis, E. Willingshofer, T. Cornu, and G. Worum. Lithosphere tectonics and thermo-mechanical properties: An integrated modelling approach for Enhanced Geothermal Systems exploration in Europe. *Earth-Sci. Rev.*, 102(3–4):159–206, 2010.

[6] T. Hantschel and A. I. Kauerauf. *Fundamentals of Basin and Petroleum Systems Modeling*. Springer Berlin Heidelberg, Germany, 2009. ISBN 978-3540723172.

[7] D. Bonté, Van Wees, J.-D., and J. M. Verweij. Subsurface temperature of the onshore Netherlands: new temperature dataset and modelling. *Geol. Mijnbouw-N. J. G.*, 91(4):491–515, 2012.

[8] M. Tesauro, M. K. Kaban, and S. A. P. L. Cloetingh. A new thermal and rheological model of the European lithosphere. *Tectonophysics*, 476(3–4):478–495, 2009.

The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement no. 608553 Project IMAGE (http://www.image-fp7.eu).

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