Thermo-mechanical characterization of the European lithosphere for geothermal exploration

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1: Rationale

A volumetric resource assessment of geothermal energy or any other form of geothermal exploration requires knowledge on the subsurface temperature distribution.[1] As part of the EU FP7-funded Integrated Methods for Advanced Geothermal Exploration (IMAGE) project, we combine large-scale geophysical models with regional-to-local scale geothermal data to develop an improved thermo-mechanical model of the European lithosphere.

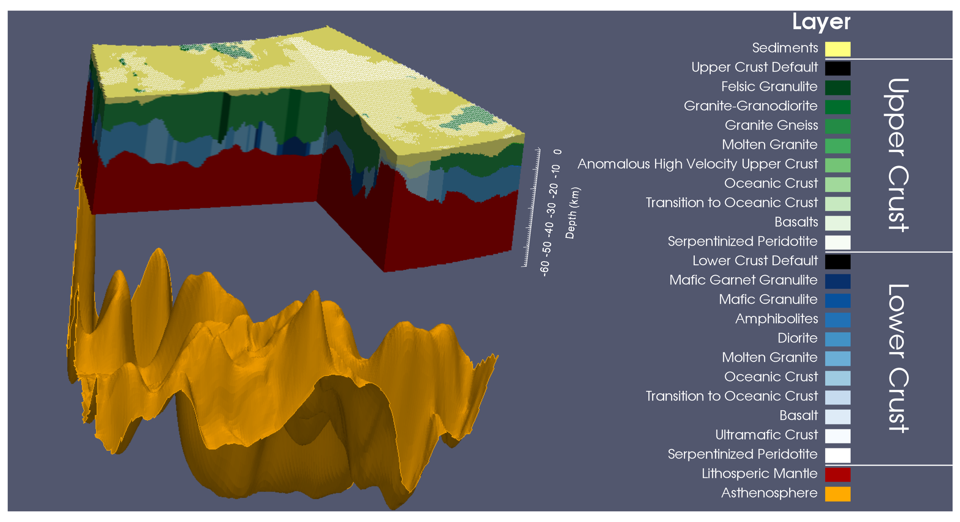
Aims:

- More realistic a priori **thermal properties**
- **Consistency** between model boundary conditions and temperature data
- Analyzing temperature **sensitivity** to parameter variations
- Quantifying **uncertainties** and identifying **non-conductive heat transfer**

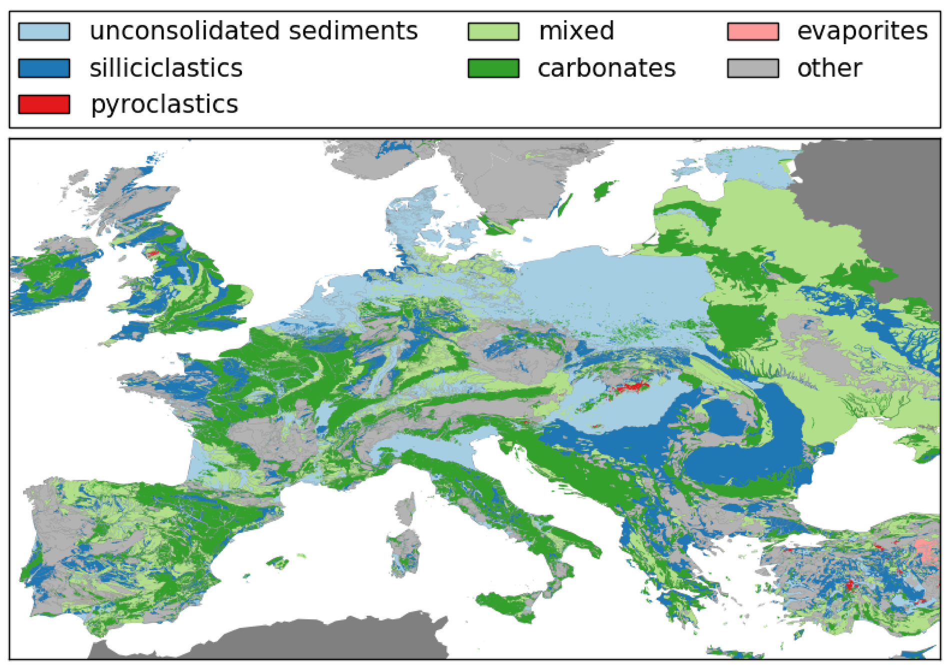
3: Thermal Model and Properties

As a starting point for our prior model we use an existing crustal geometry with different lithotypes for the upper and lower crust[2] (fig. 1a). The sedimentary cover is differentiated into lithotypes based on the surface geology[3] (fig. 1b): e.g. unconsolidated, consolidated, siliciclastics, carbonates). Each sedimentary lithotype consists of a lithology or a mixture of lithologies. Thermal properties are assigned accordingly. The model has a horizontal resolution of ~20 km and a vertical resolution of 250 m. Heat transfer is limited to vertical conduction only, with the annual mean temperature at the surface and the temperature at the lithosphere-asthenosphere boundary (LAB fig. 1c) - assumed to be 1200 °C - as upper and lower boundary conditions. The thermal conductivity is iteratively updated for temperature and pressure effects (fig. 1d: sediments,[4] upper and lower crust,[5] lithospheric mantle[6,7]).

2: Model Input



(a)



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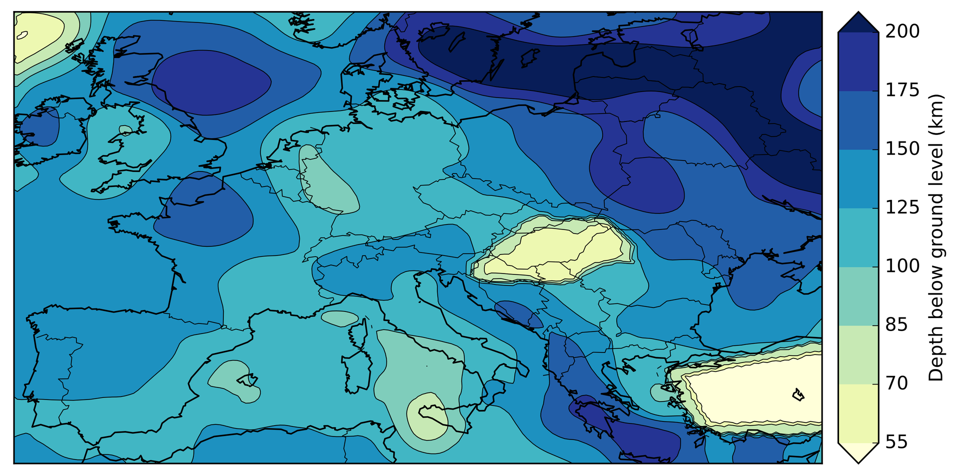

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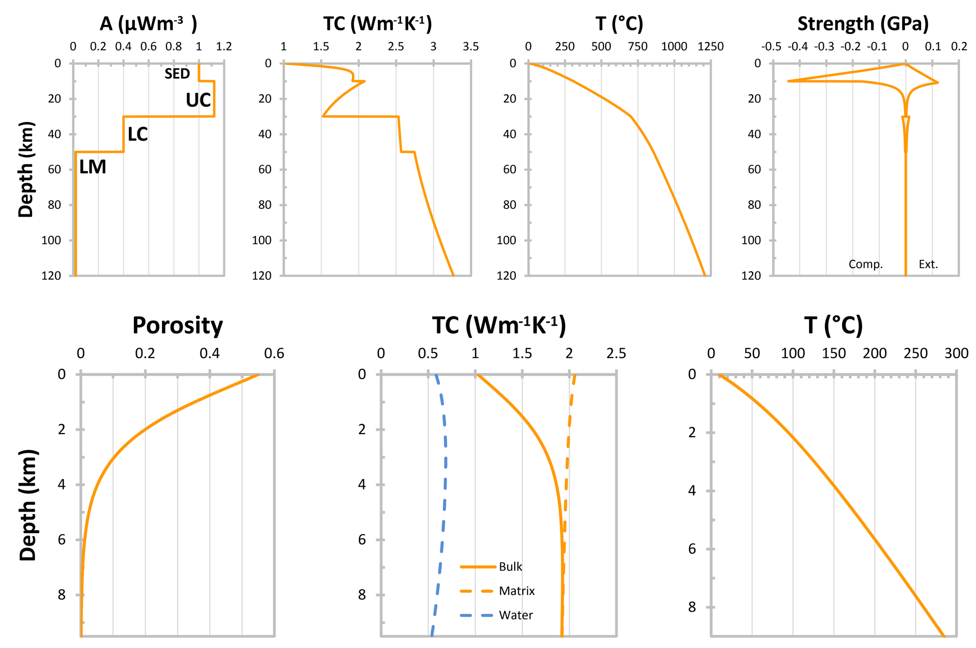
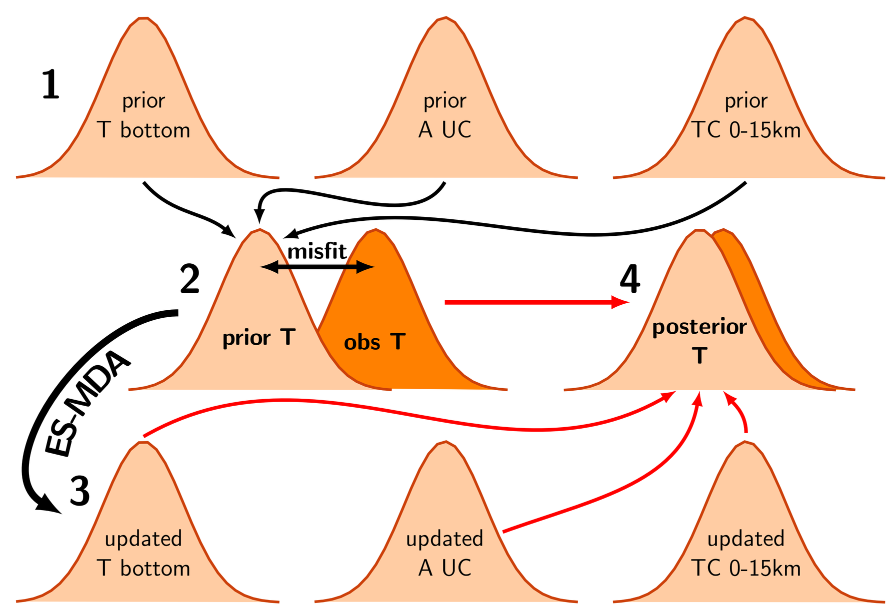


(d)

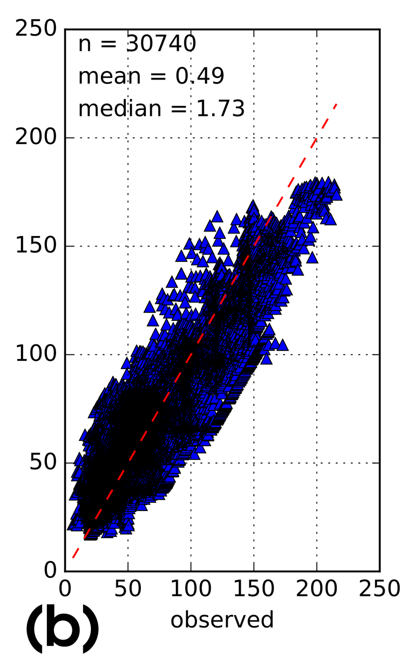
Fig. 1: **(a)** Geometry and composition used for the model. Sediments, upper crust, and lower crust are differentiated into lithological and rheological domains.[2] **(b)** Sedimentary domains are defined on the base of generalized surface geology models.[3] **(c)** Thickness of the thermal lithosphere[2] that is used as the depth of the lower thermal boundary condition.

Fig. 1 continued: **(d)** **(Top)** Example 4-layer lithosphere profile with thermal properties: **A** radiogenic heat production, **TC** (bulk) thermal conductivity, temperature, and computed strength under conditions of compression (-) and extension (+). SED = sediments, UC = upper crust, LC = lower crust, LM = lithospheric mantle. **(Bottom)** Porosity reduction of typical siltstone following Athy's law of compaction. The bulk thermal conductivity of sediments varies with depth due to: (1) Porosity changes effecting the geometrical average of the thermal conductivity of the rock matrix and the fluid phase (water). (2) The temperature dependence of the thermal conductivity of the rock matrix and water.[8]

4: Model Calibration



(a)



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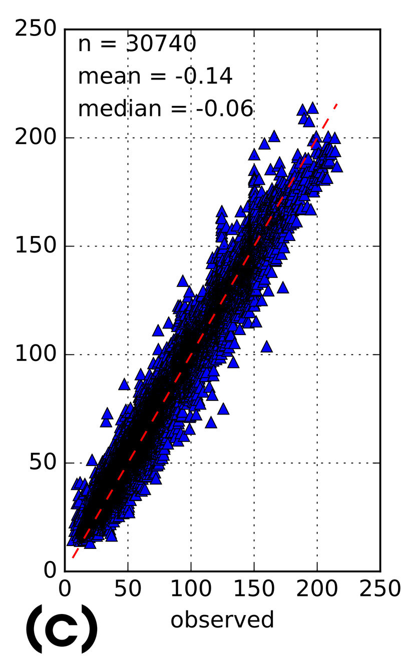
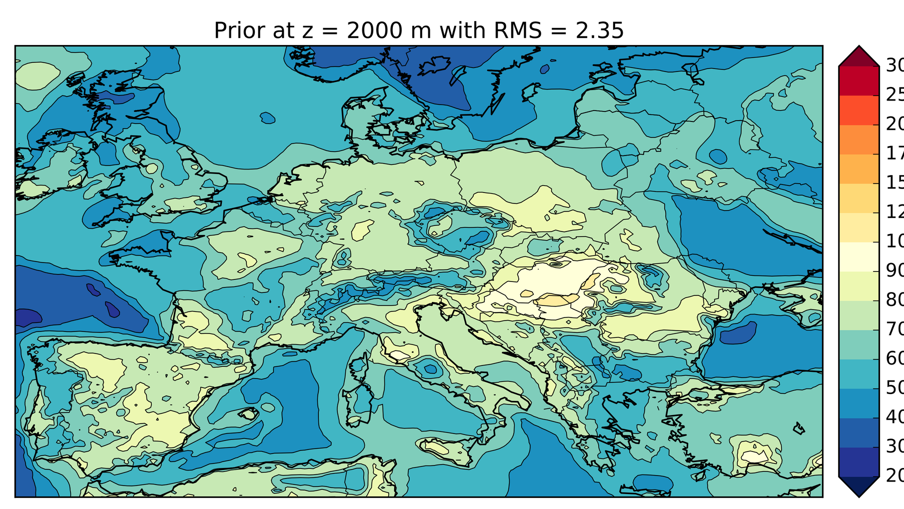


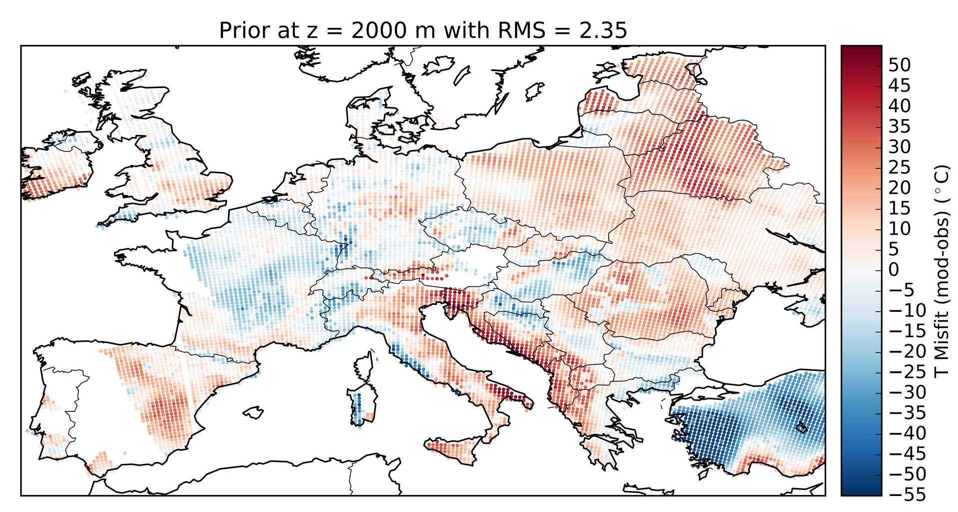
(c)

Fig. 2: **(a)** Schematic workflow of model calibration using Ensemble Smoother with Multiple Data Assimilation (ES-MDA).[9] **(b)** Temperature data (x-axis) plotted against prior model temperatures (y-axis) **(c)** Temperature data plotted against posterior model temperatures.

5: Results



(a)



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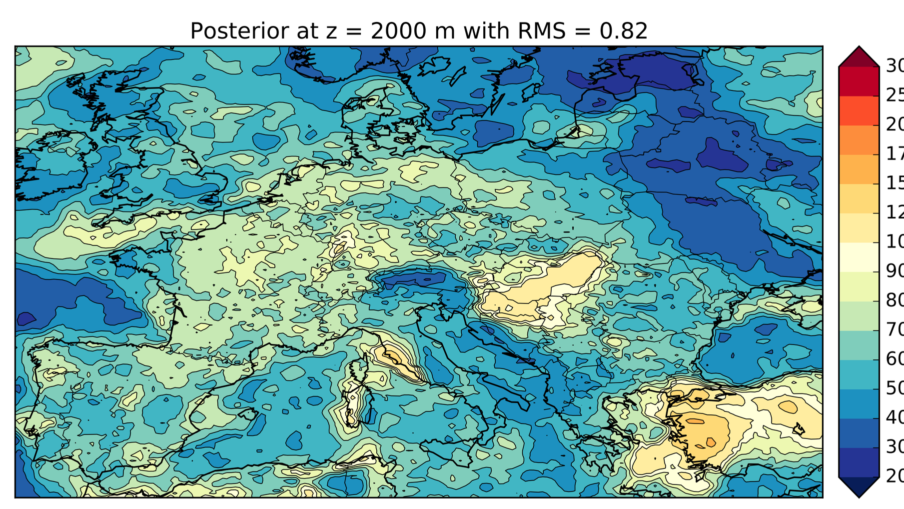

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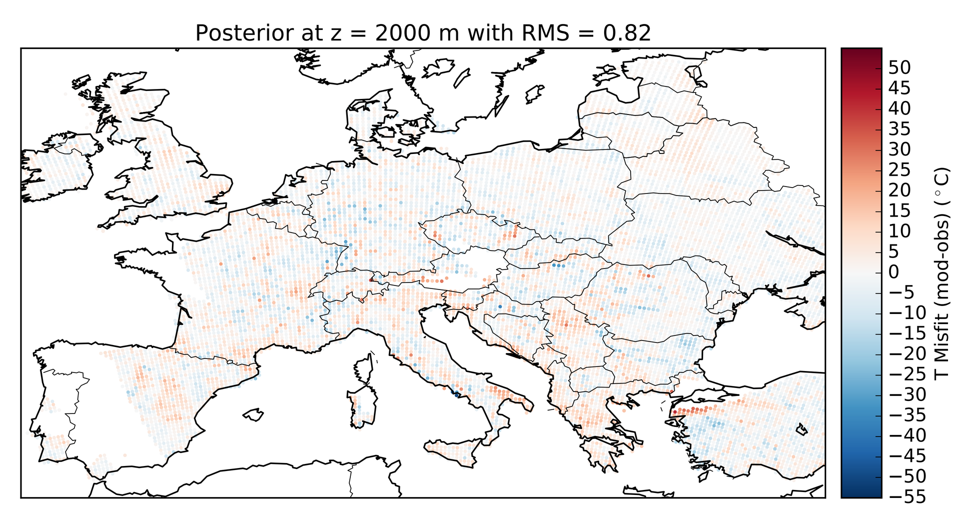
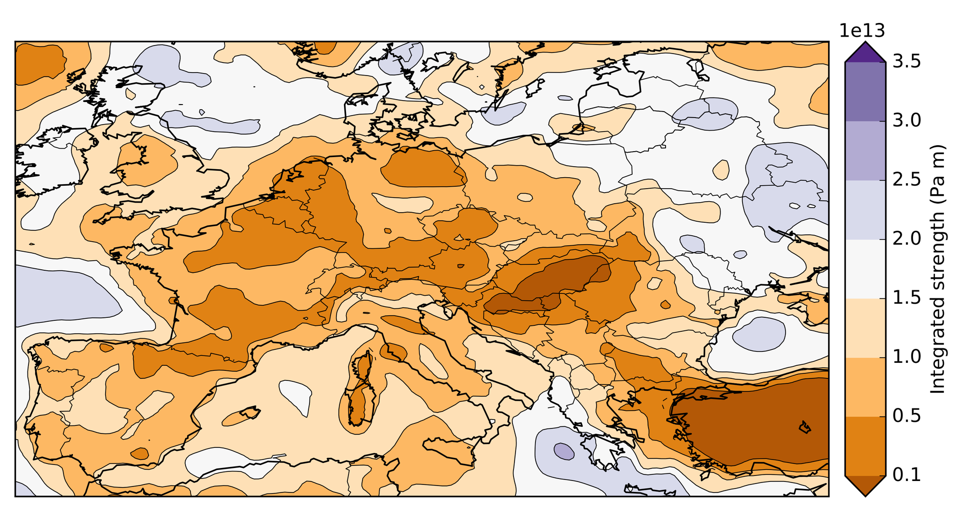


(d)



(e)

Fig. 3: **(a)** Temperatures at 2 km of the prior temperature model. **(b)** Temperatures at 2 km of the posterior temperature model after calibration. **(c)** and **(d)** Model misfits plotted for the prior and posterior model showing large misfits before calibration and reduced misfits after calibration. We use stochastic variation of thermal properties to obtain an improved fit with these temperature observations. Posterior thermal properties are therefore not necessary representing reality and should be considered *equivalent* to the combined effect of heat transfer processes and lithological differences. **(e)** Integrated strength of the lithosphere estimated under transpressional (strike-slip) conditions based on temperatures of the posterior mean model based on a fixed strain rate of 10^{-15} s^{-1}.

6: Conclusion

- The conductive thermal field within the European lithosphere is regionally and locally disturbed by active tectonic processes, volcanism, buoyancy-driven thermal convection, and advective groundwater flow.
- Temperature observations are a product of the above described processes and of lithosphere structure and composition that determine the thermal properties.
- With our approach, we stochastically vary thermal properties in order to obtain a fit with these temperature observations. Posterior thermal properties are therefore not necessary representing reality and should be considered *equivalent* to the combined effect of heat transfer processes and lithological differences.
- The thermal state of the lithosphere, rheology, and stress regime control the integrated strength of the lithosphere and determine the style of deformation. We have updated strength estimates for Europe, in particular affecting the upper part of the lithosphere.

References and acknowledgments

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