UPDATING THE THERMO-MECHANICAL STRUCTURE OF THE EUROPEAN LITHOSPHERE WITH SUBSURFACE TEMPERATURE DATA

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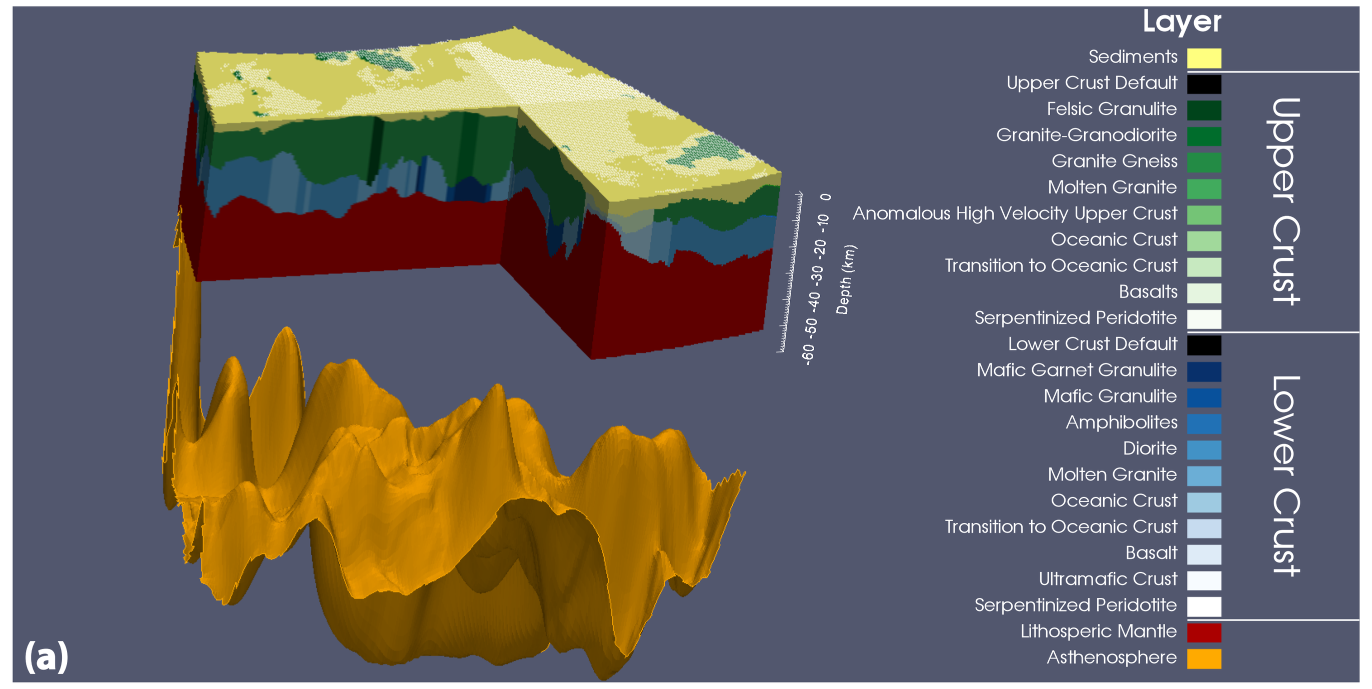

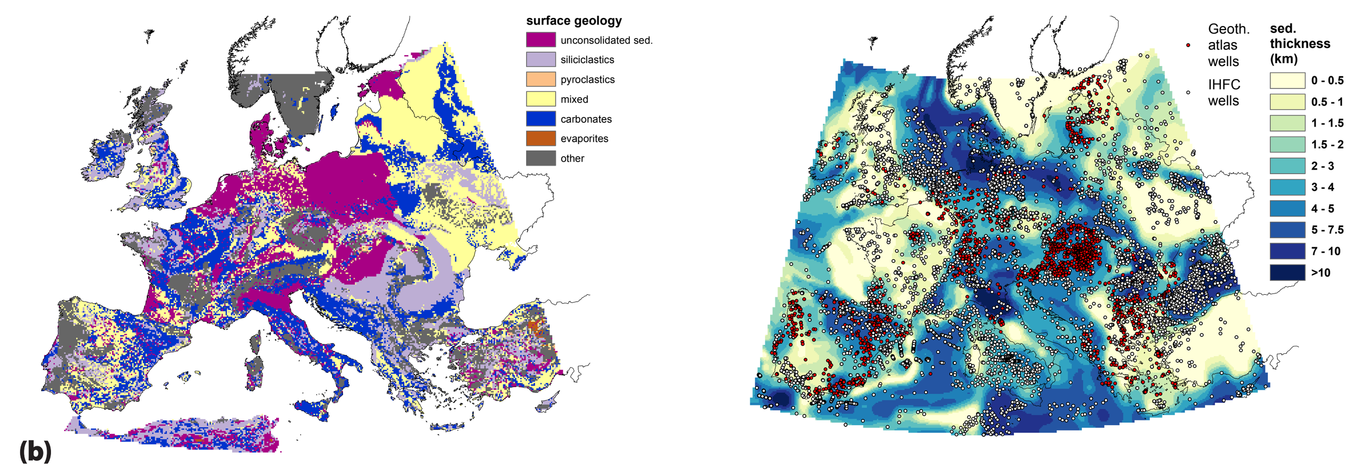

Fig. 1: (a) Geometry and composition. **(b)** Generalized surface geology. **(c)** Sediment thickness and locations of wells and heat flow measurements.

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 (cf. [2])
- Quantifying **uncertainties** and identifying **non-conductive heat transfer**

2: 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 [3] (fig. 1a). The sedimentary cover is differentiated into lithotypes based on the surface geology [4] (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 thermal conductivity is iteratively updated for temperature and pressure effects (fig. 2: sediments cf. [5], upper and lower crust cf. [6], lithospheric mantle cf. [7, 8]). 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) - assumed to be 1200 °C - as upper and lower boundary conditions, respectively.

2: Thermal Model and Properties (Continued)

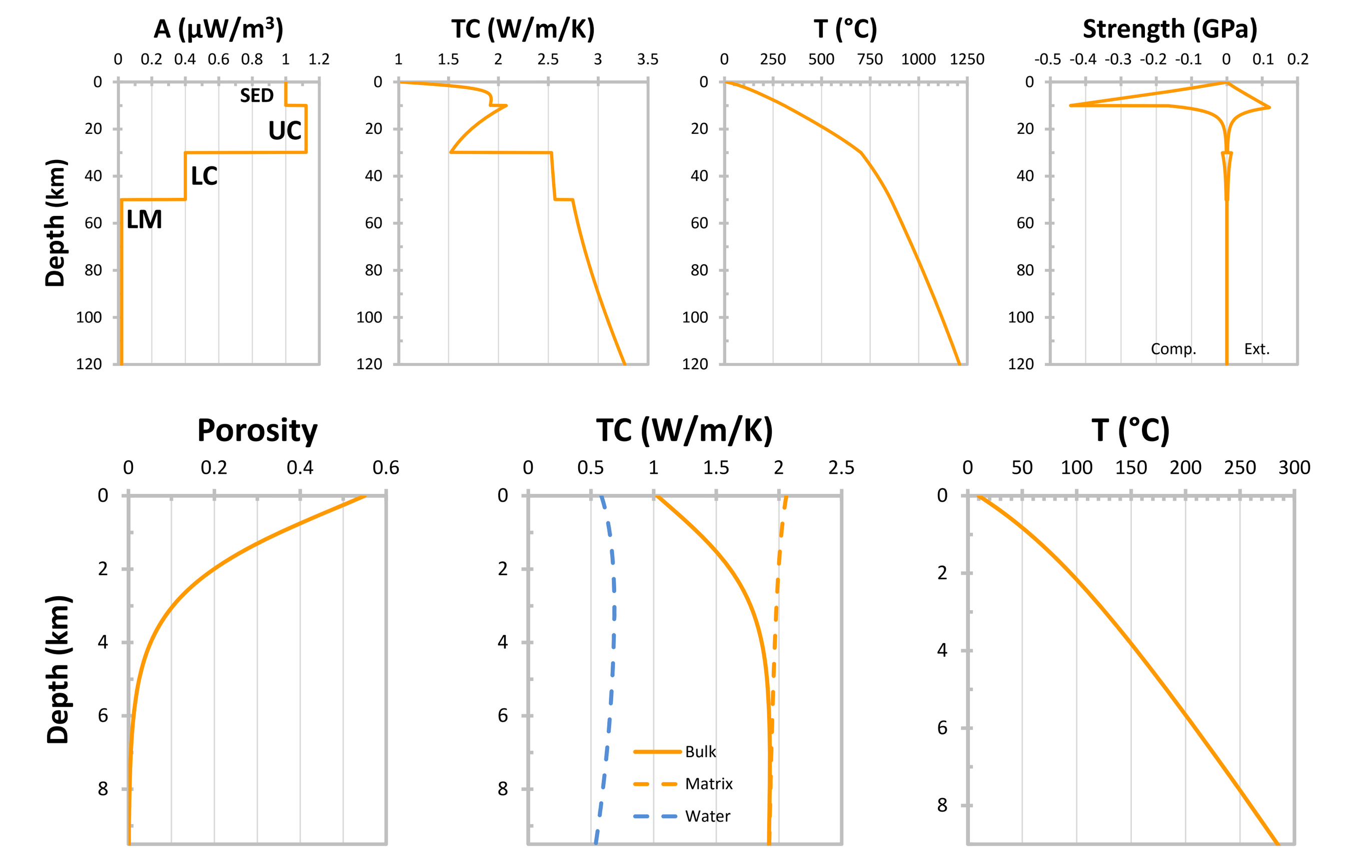

Fig. 2: (Top) Example 4-layer lithosphere profile with thermal properties: **A** radiogenic heat production, **TC** (bulk) thermal conductivity, **T** temperature, and computed strength under conditions of compression (-) and extension (+). (SED = sediments, UC = upper crust, LC = lower crust, LM = lithospheric 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 [9].

3: Model Calibration

The prior thermal model and the corresponding thermal properties are calibrated using an ensemble smoother with multiple data assimilation (ES-MDA) approach [10]. A compilation of available temperature data [1] have been converted into regular-spaced grids consisting of 28917 cells at depths between 1 - 6 km depth. For each grid cell, an uncertainty has been assigned based on the amount of wells (fig. 1c, 3a, 3b) [11, 12, 13] that are present within each grid cell and on the depth of the grid.

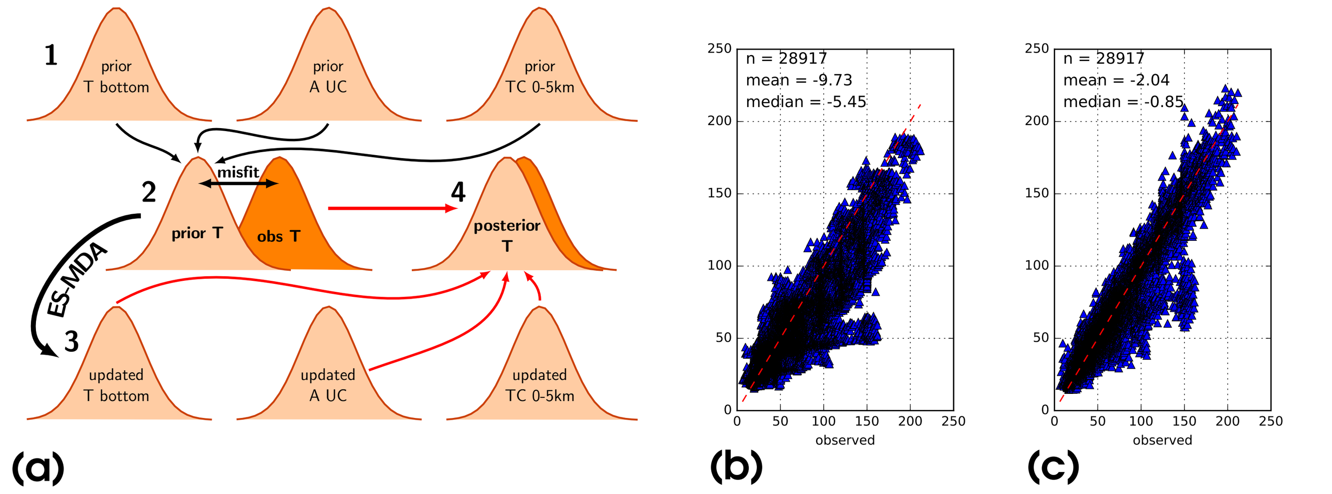

Fig. 3: (a) Schematic workflow of model calibration. **(b)** Temperature data (x-axis) plotted against the prior model temperatures (y-axis) **(c)** Temperature data plotted against the posterior model temperatures showing an improved fit.

Uncertainty ranges for feed-in parameters:

- Temperature data (± 3 °C for points at 1km depth with more than 5 wells to ± 17 °C for points at 6 km depth without wells)
- Temperature at the bottom of the model (1200 °C ± 200 °C)
- Radiogenic heat generation in the upper crust (± 100%), radiogenic heat generation in the top 20 km (± 10 - 25%), and thermal conductivity in the top 5 km (± 5 - 25%)

According to the uncertainty ranges, probability density functions (pdf) are assigned to the prior model parameters and to the observations. The model parameters are then stochastically varied to minimize the misfit between model and observations, given the prior pdf's and the model covariance. This results in updated model parameters and pdf's (fig. 3a).

4: Model Calibration Results

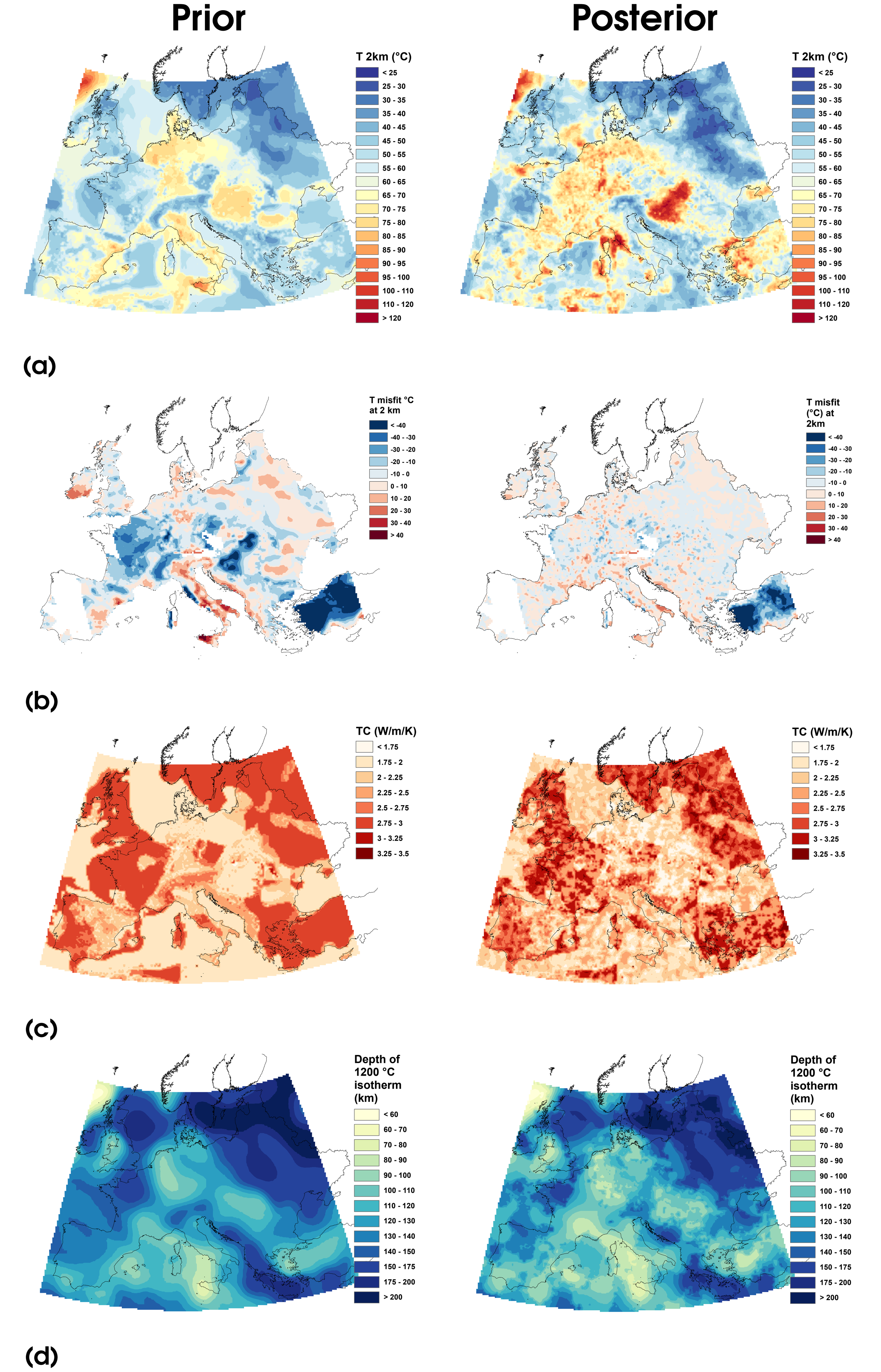

Fig. 4: (a) Computed temperatures at 2 km of the prior temperature model compared to posterior mean model. **(b)** Prior model temperature misfits at 2 km depth compared to posterior mean model temperature misfits. Blue colors indicate that the modeled temperatures are too low in comparison to the observations and red colors indicate that the modeled temperatures are too high. **(c)** Prior model bulk thermal conductivity at 2 km depth compared to posterior mean model. **(d)** Prior model depth of the lithosphere-asthenosphere boundary (LAB) compared LAB depth of posterior mean model.

4: Strength Model

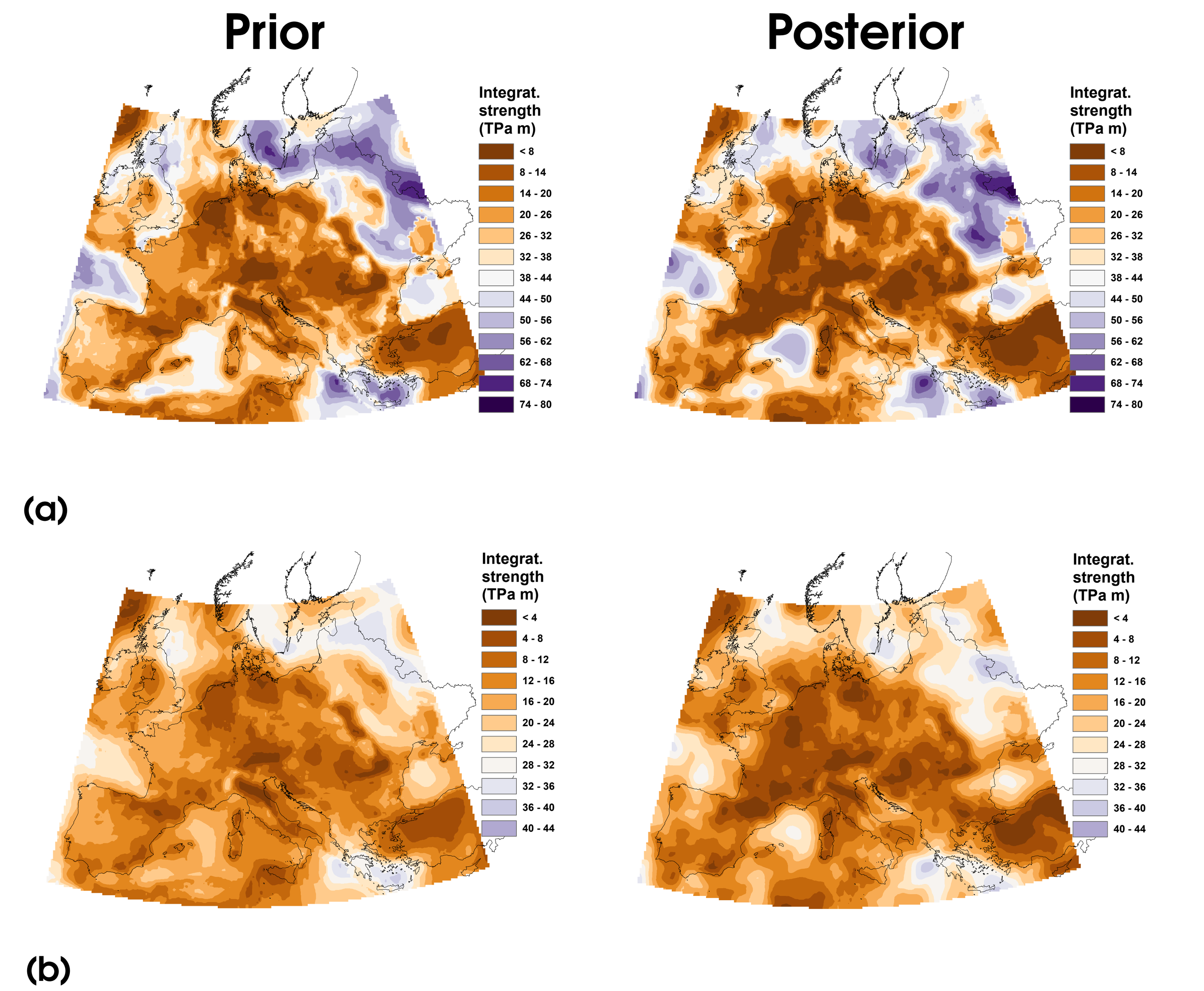

Fig. 5: (a) Integrated strength of the lithosphere estimated under conditions of compression based on the temperatures of the prior model (left) and posterior mean model (right). **(b)** Integrated strength of the lithosphere estimated under conditions of extension based on the temperatures of the prior model (left) and posterior mean model (right). All estimations based on a fixed strain rate of 10^{-15} s^{-1}.

The thermal model was used in combination with rheology to calculate the (integrated) strength (fig. 5). Different rheologies were assigned according to the crustal lithotype [14]:

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

References and Acknowledgements

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