3D lithospheric-scale temperature modeling: application for the Hungarian part of the Pannonian Basin

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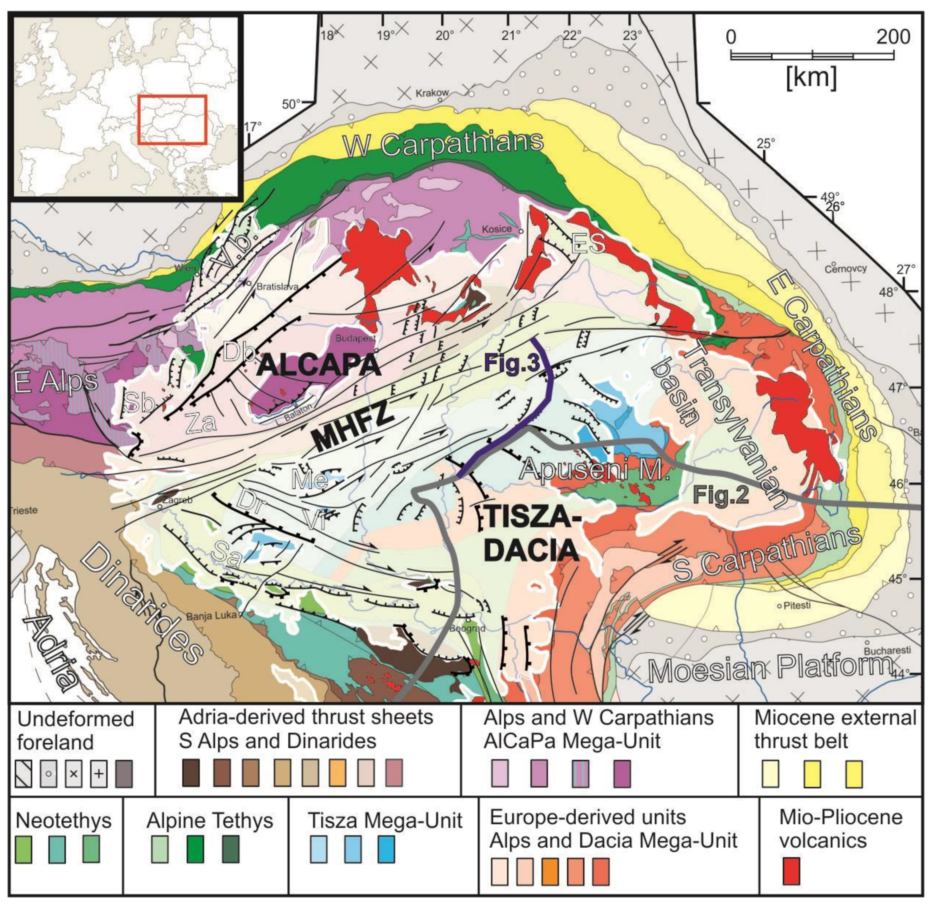
Tectonic setting



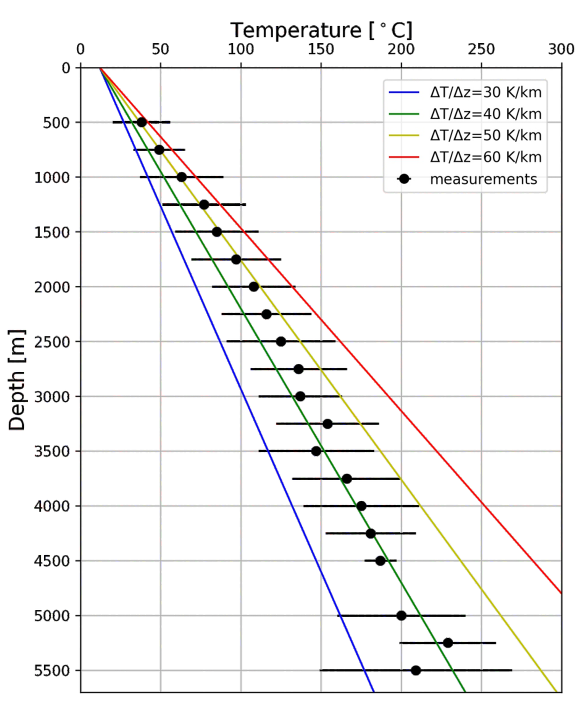
The Neogene formation of the Pannonian Basin by extension was preceded by Cretaceous-Paleogene contraction and nappe stacking in the Circum-Pannonian region. The former orogenic area now constitutes the basement of the Pannonian Basin and consists of two major structural units: the AlCaPa and the Dacia-Tisza mega-units.

The juxtaposition of the major basement units was followed by distributed extension (syn-rift phase), which resulted in the high thermal attenuation of the lithosphere and formation of a basin system consisting of numerous sub-basins. Extension in the Pannonian Basin migrated in space and time, from 20 Ma until 9 Ma with the peak in the Middle Miocene (16-12 Ma).

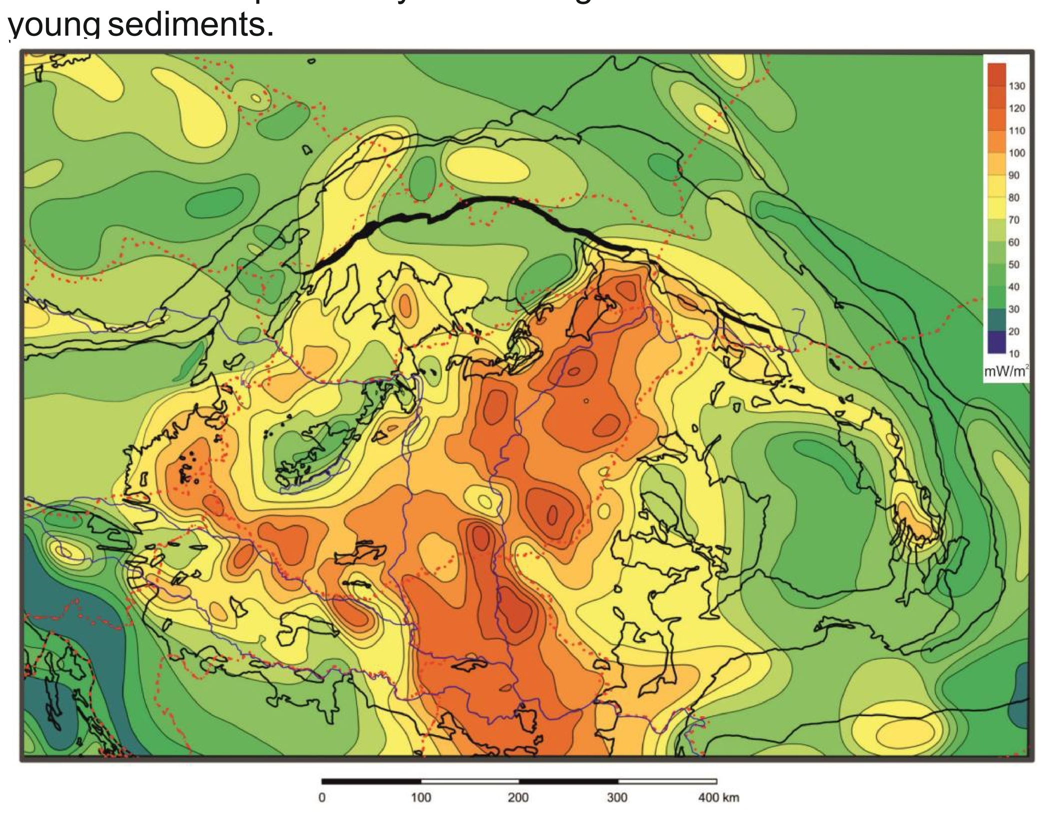
Post-rift sedimentation took place in a completely restricted lake environment (Lake Pannon). The thick siliciclastic deposits (up to 7 km beneath the Great Hungarian Plain) essentially determine the present hydraulic and thermal characteristics of the Pannonian Basin.

Tectonic map of the Pannonian basin after **[1]**. Vb = Vienna Basin, Dr = Dráva sub-basin, Sa = Sava sub-basin, Za = Zala sub-basin, Me = Mecsek hill, Db = Danube basin, ES = East Slovakian basin, MHFZ = Mid-Hungarian Fault Zone.

Geothermal conditions



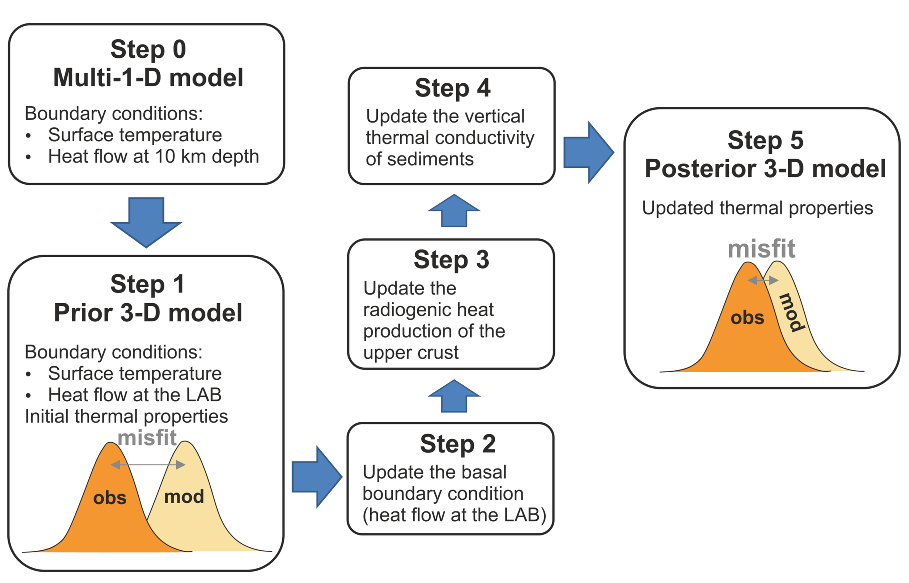
Hungary is one of the most suitable areas for geothermal development in Europe due to the elevated geothermal gradient (40-50 K/km) and high heat flow (with a mean value of 100 mW/m^2) **[2]**. The hottest areas can be attributed to the Great Hungarian Plain. On the other hand, lower heat flow in the Makó trough and Békés sub-basin can be explained by the cooling effect of the ca. 7-8 km thick young sediments.



Neogene and Quaternary clastic basin infill and Mesozoic carbonates represent the main target zones for geothermal utilization, but fractured crystalline basement rocks are also considered as high potential targets for deep geothermal development.

Temperature-depth profile of Hungary modified after **[3]** and **surface heat flow map of the Pannonian Basin and its surroundings** corrected for the cooling effect of fast sedimentation (**[2]**) modified in the Eastern Alps after (**[4]**).

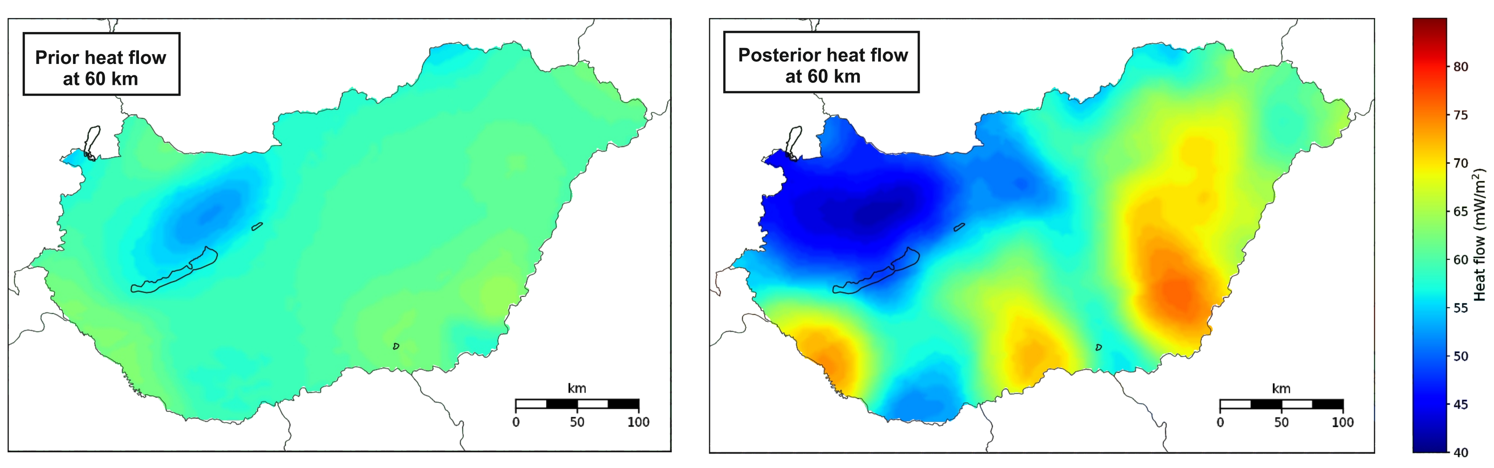
Methodology



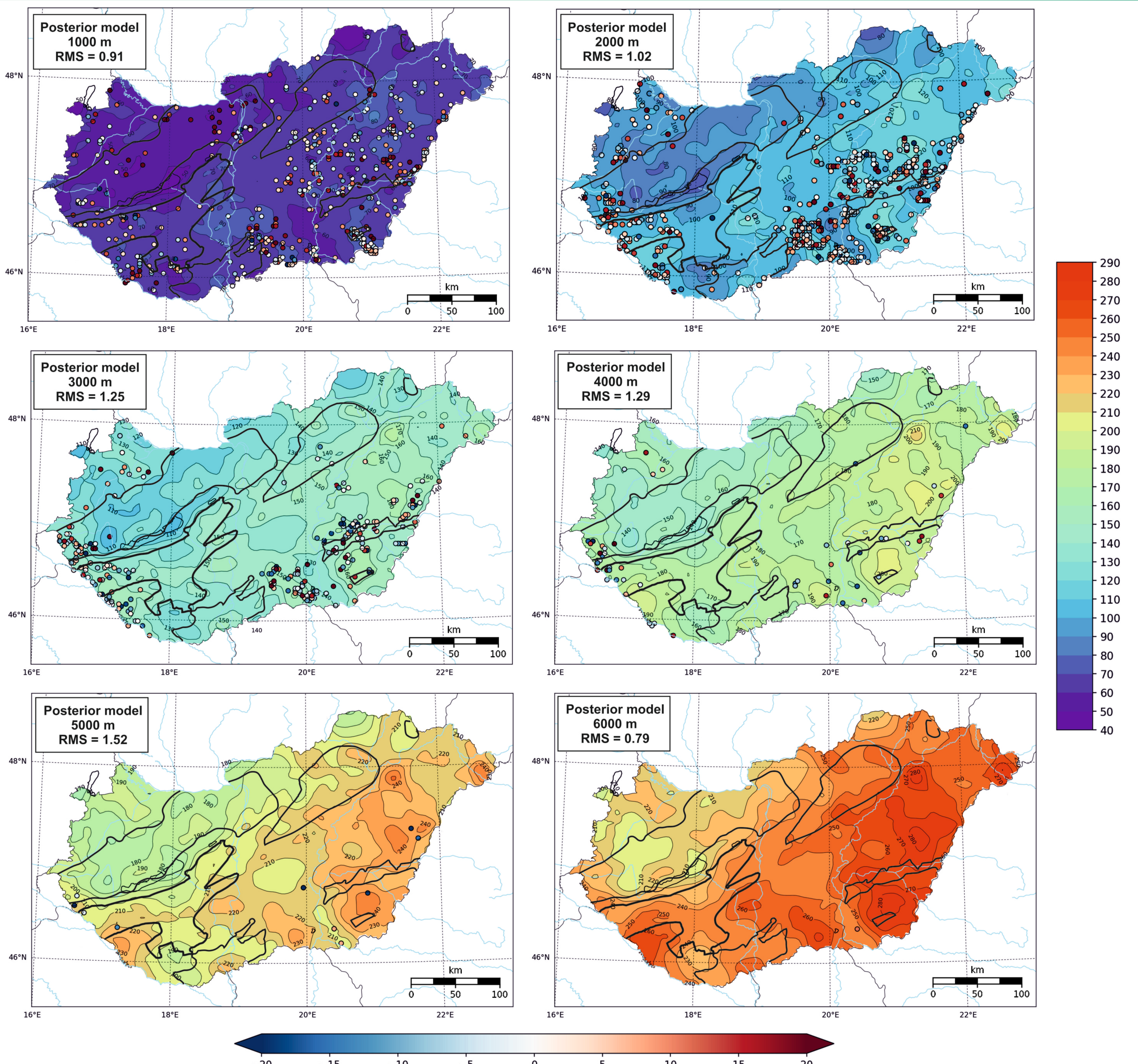
We first construct an *a-priori* physics-based forward model extending from the surface until the lithosphere-astenosphere boundary (LAB) following the methodology of **[5]**. The model is built up in a layered structure, where the thermal properties can be updated through the ensemble smoother with multiple data assimilation technique **[6]**. Calculations are made in steady-state, assuming conduction as the main heat transfer mechanism.

Prior heat flow in at 60 km is relatively smooth compared to the posterior model. It is important to note that the lateral variations in posterior heat flow may not be entirely realistic, but these values provide the best fit with measured temperatures through steady-state conductive modeling.

Layers	Thermal conductivity [W/m*K]	Radiogenic heat production [μW/m^3]	Boundary conditions	Calibration data
6 sedimentary layers obtained from **[7]**, following the sand/shale ratios after **[3]**	Variable: Bulk values per lithotype (mixed lithologies) dependent on compaction **[3]**	Constant: different bulk values depending on lithotype **[8]**	**Top:** constant temperature (12 °C) **Bottom:** heat flow (calculated by the multi-1D model from the constant value of 70 mW/m^2 at 10 km depth)	Temperature measurements from the Geothermal Database of Hungary **[3]** supplemented by heat flow observations sampled to well locations converted to equivalent temperature (about **5000** controlling points)
Upper crust	Pressure- and temperature-dependent **[9]**	Constant: 1.4		
Lower crust	Pressure- and temperature-dependent **[9]**	Constant: 0.4 **[12]**		
Lithospheric mantle	Lattice thermal conductivity **[10]** and radiative thermal conductivity **[11]**	Constant: 0.02 **[12]**		

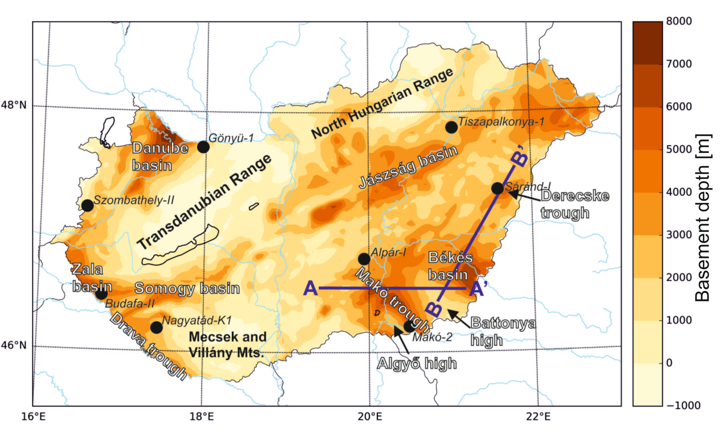


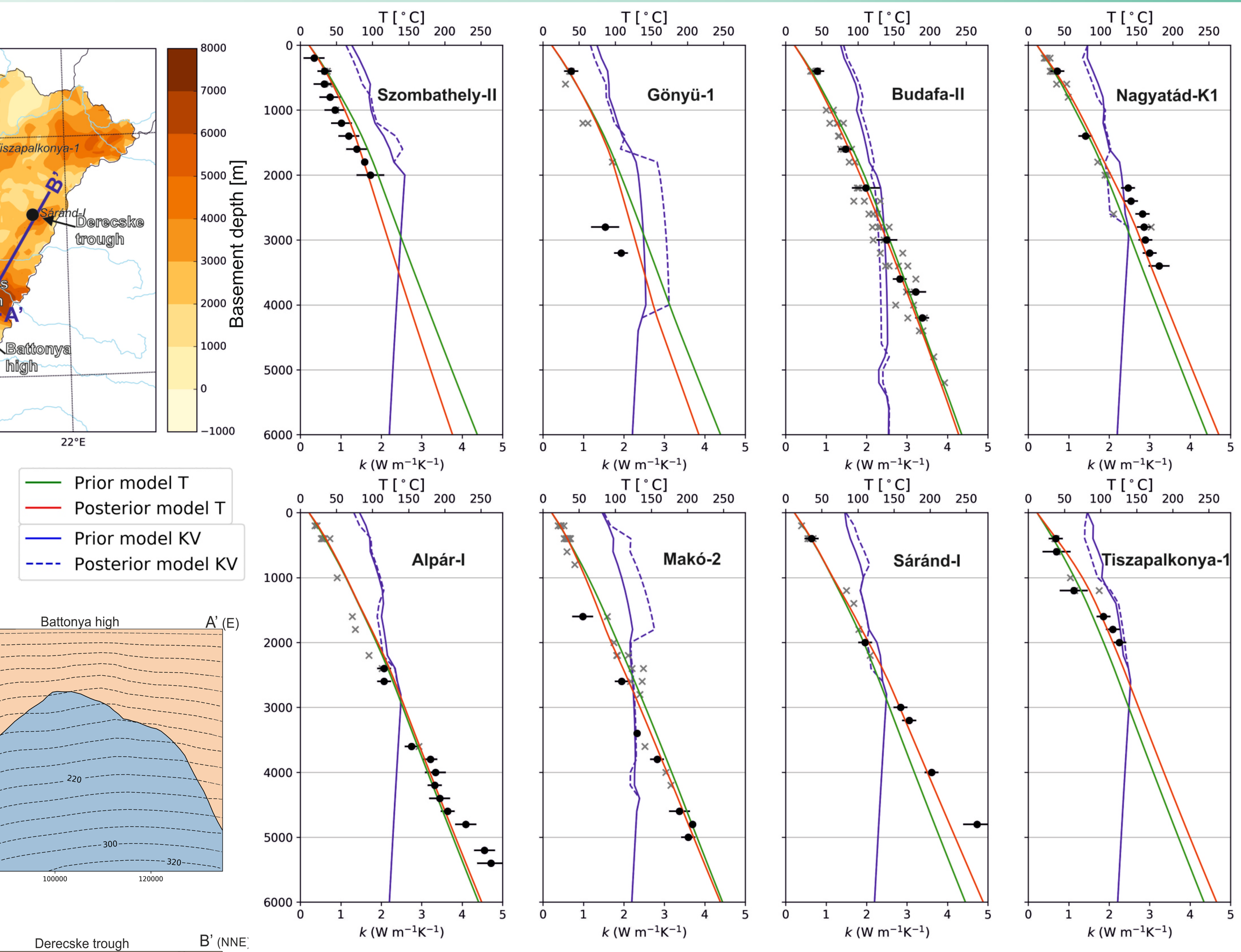
Results I.

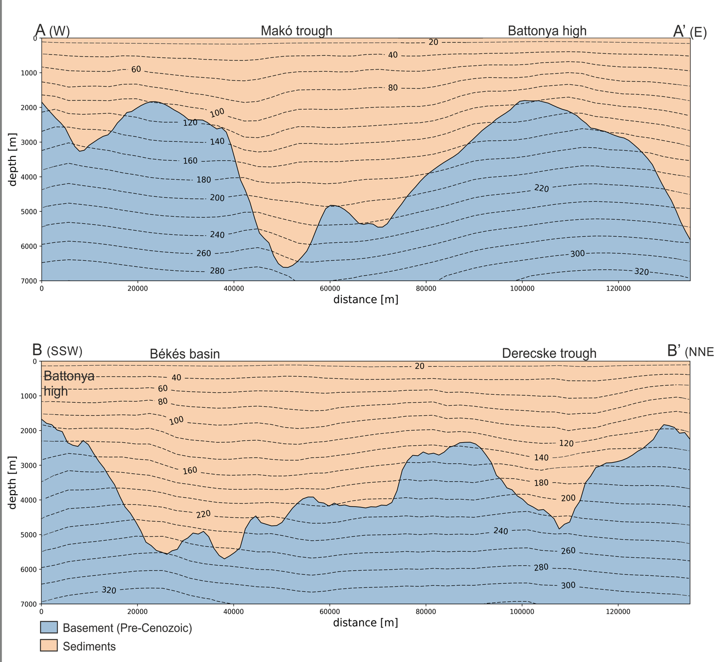


Temperature depth slices of the posterior model are presented between 1 to 6 km superimposed by the misfit of the modelled and observed temperatures in ±200 m interval (circles). The black contour indicates the location of the Mesozoic karstic reservoirs and their recharge areas in Hungary. Modeled temperature shows a pattern similar to the surface heat flow: in general, the model predicts lower temperatures in the northwestern, and higher temperatures in the southern, eastern and southeastern part of Hungary. Some areas exhibit very high (about 200 °C) temperatures at approximately 3500 m depth, forming one of the hottest regions in Europe.

Results II.







Temperature-depth and thermal conductivity-depth profiles of the models are presented at different well locations. The **cross section** represents subsurface temperature contours transferred from the posterior model. (For locations, see the **pre-Cenozoic basement depth map**.

- Temperature-depth profiles clearly support the added value of the data assimilation: our posterior model shows considerably better fit with measured records than the prior model
- Despite the higher misfit of modeled-observed temperatures where groundwater flows disturb the conductive regime, temperature measurements affected by fluid convection can be approximated by increasing the thermal conductivity of the corresponding layers (e.g. Gyonyu-1)
- Results suggest that the hottest areas below 3 km are linked to the basement highs surrounded by deep sub-basins of the Great Hungarian Plain
- Our model reveals potential target areas for deep geothermal development and can serve as an input for geothermal resource assessment. Additionally, further improvement may be reached by having a better constraint on the depth of the basement and the geometry and thermal properties of the sedimentary layers

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Acknowledgements

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