Dear László,

Thank you for reviewing our manuscript, providing constructive comments as an expert both in thermal modelling and in the study area. We incorporated most of the suggestions, which significantly improved the models and the whole manuscript. Most importantly, the revised thermal conductivities we applied provide more realistic input for the models. We also tested the effect of selected input parameters on the model and provided an estimate on the uncertainties, including both a quantitative (resulting from the inversion) and qualitative (discussion on the effect of model assumptions and fixed input parameters) assessment. The temperature predictions have slightly changed in the revised models, together with the estimated amount of lithosphere extension, due to the revised input parameters we applied. Please find our detailed point-by-point responses to the comments below.

Kind regards,

Eszter and co-authors

REVIEWER#2 László Lenkey

Dear Eszter and coauthors,

The manuscript about modeling transient thermal processes in the lithosphere in the NW part of Hungary presents a method to assess deep lithosphere temperatures. The transient conductive heat transport equation is solved, and the calculated temperatures are fitted to observed temperature data to constrain the subcrustal stretching factor. The transient model considers the two most relevant processes, which were active during the evolution of the area: lithospheric stretching and sedimentation. The modeled lithosphere temperatures are used to deduce rheological inferences and estimate the depth of origin of mantle xenoliths found in the region. It is a valuable manuscript, but I suggest modifications and clarifications before publication.

The past and present temperatures are calculated by solving the transient conductive heat transport equation (Eq. 2). The calculated temperature depends on the initial conditions, the thermal parameters and the vertical velocity vz. You fix these quantities except the vertical velocities related to stretching, thus the results are valid for this specific model. Other choice of the quantities probably would result different stretching factors and different lithosphere temperatures. In the following I will discuss the effects of thermal conductivity of sediments and the sedimentation rate.

The thermal conductivity (TC) of sediments in the model ranges from 1.2 W/mK to 2 W/mK (Table 1). These values are lower than the ones measured on clastic sedimentary rocks from Hungary (ranging from 1.5 W/mK to 5 W/mK in Dövényi and Horváth, 1988; Dövényi et al., 1983, shales: 2.3 ± 0.56 W/mK, sandstones: 3.75 ± 0.71 W/mK summarized in Mihályka et al. 2024). Based on the measured TC values Dövényi and Horváth (1988) established TC-depth trends for shales and sandstones, which result in higher TC than used in the study. The TC of *carbonates is also lower than the measured ones. For conductivity of carbonates in Hungary see Dövényi et al. (1983). (limestones: 2.7 W/mK, dolomites: 4.4 W/mK).*

We thank the reviewer for pointing out this mismatch. We revised the calculation of thermal conductivities in the model, and the resulting ranges in sediments are now higher, but still lower than the average values reported by Mihályha et al. (2023), although the matrix thermal conductivity values by Dövényi and Horváth, 1988 were used for the individual lithotypes. This can be explained by the composition of the sediments, where the ratio of sales compared to sandstones in the deep compacted sediments is high. We also revised the thermal conductivities of carbonates based on Dövényi et al. (1983). For more details and discussion, we refer to the revised ms.

Indeed, the selection of TCs, together with the revision of the initial crustal and lithospheric thickness significantly influenced the modelled temperatures, resulting also in a revised posterior subcrustal stretching pattern and magnitude. We emphasise in the manuscript that the resulting solution is valid for this specific case of input parameters and test the effect of variations in several input parameters. For more details, please see the revised ms.

As the model temperatures are fitted to the observed values, we would expect lower heat flow using the model TC's compared to the observed heat flow. You provided the model results and the thermal parameters in an asset for reviewers, and I calculated the model heat flow in the depth interval 1000-1200 m (Fig R1). The modeled heat flow is uniform in the area: 70 ± 3 mW/m2. Except the Zala basin and part of the Danube basin, where the observed values are 90 mW/m2 and 85 mW/m2, respectively, the modeled heat flow is close the to the observed one (disregarding also the Transdanubian range, where groundwater flow occurs). Better fit to the heat flow could be achieved by varying the TC, heat production and subcrustal stretching factor, but it was not the purpose of the study as you mentioned in the manuscript.

This is a valuable suggestion to further vary the TC and heat production to achieve a better fit with observed heat flow, which we will consider for further modelling studies that concentrate on the shallow crustal temperature field.

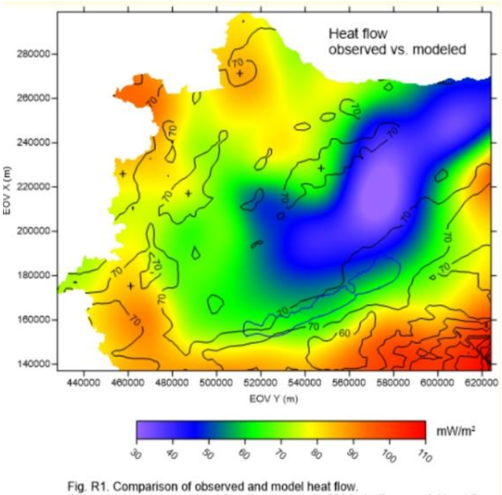

Fig. R1. Comparison of observed and model heat flow.
Colored map: observed heat flow (Lenkey et al., 2021), isolines model heat flow.

In Eq. 2 constant sedimentation rate is applied. Over the center of the basins, where sedimentation took place in Quaternary, the constant sedimentation rate is a good approximation. In the peripheral parts of the basins erosion has been taken place since Pliocene due to basin inversion and uplift. (See e.g. the seismic sections published in Szafián et al. (1999), a paper you refer.) Erosion increases the subsurface temperature thus, in the peripheral parts less lithospheric stretching is required to obtain fit to the observed temperatures.

We thank the reviewer for this suggestion, we added a discussion on the effect of assuming a constant sedimentation rate and neglecting the direct effect of erosion, as well as the incorporation of the effect of basin inversion. Please see also the responses to reviewer #1 and the revised manuscript.

As it is demonstrated varying the TC of sediments and sedimentation/erosion rate would change the modeled T and heat flow. The question arises: how much is the uncertainty of the derived stretching factors and the calculated deep lithosphere temperature?

Please make an estimate of the uncertainty of the stretching factor and the lithosphere temperature.

We performed a sensitivity analysis of initial crustal and lithosphere thickness as well as prior subcrustal stretching values (Appendix A). We also added a section “Model uncertainties and limitations” to the discussion. The standard deviation of beta values reported in https://data.mendeley.com/drafts/vp7jdp79y4 (the dataset will be available with the publication of the paper.) provides a qualitative estimate of uncertainty in relationship of observed temperatures and subcrustal lithosphere model effects. Please note that the LAB uncertainty cannot be assessed by the method and would add to the standard deviation of beta values. For more details, we refer to the revised ms.

My questions and notes related to the text are the following.

Lines 107-108 The sediment bulk thermal conductivities were finally obtained using the geometric mean of the bulk matrix conductivities and the thermal conductivity of the pore fluid.

How much was the porosity?

In the case of shale and sand, we used the porosity-depth trends for the Pannonian Basin by Szalay (1982) to derive compaction coefficients and estimate the porosity. For conglomerate and marl, typical values reported by Hantschel and Kauerauf (2009) were used. We also added this description to the revised ms.

Line 148 outflow temperatures were marked by uncertainties of ±5 °C,

Do you mean outflow temperature as temperature at the well head? Well head T is unreliable, the error can be much more than ±5 C.

We increased the uncertainty of outflow temperatures to ±10 ºC.

Line 184 What kind of numerical method did you use to integrate Eq. 2?

The last term in the equation is a partial derivation.

For the transient numerical modelling of the temperature evolution of equation (2), a 3D explicit 3-step Runge-Kutta finite difference approach was used, with a finite volume approximation and adaptive timestepping. We also added this to the revised ms.

Line 211 Eq.3 is mistyped. It is correctly: (Zcrust init- Zbasement)/ZMoho present.

Corrected.

Line 259 temperatures up to 170 ºC, meaning a geothermal gradient of ~45 ºC/km

gradT=(170-12)/4=39.5 C/km

Corrected.

Lines 262-263 Negative anomalies can be attributed to outcropping/near-surface basement rocks (mostly carbonates) having significantly higher thermal conductivities

Near Sopron and Rechnitz the lower temperature is partly caused by lower lithospheric stretching relative to the basin areas.

We extended the ms. with the effect of lower stretching compared to basins.

Lines 264-265 The conductive assumption is although not fully valid for parts of the Transdanubian range built up by fractured and karstified carbonate rocks.

A larger area than the Transdanubian rage is affected by groundwater flow and convective heat transport, because groundwater flow also occurs in the carbonate rocks covered by sediments.

We thank the reviewer for this suggestion that we incorporated in the model. We further limited the use of temperature observations in the vicinity of the Transdanubian Range based on the shallow temperature maps of Lenkey et al., 2021 to include measurements from areas that are potentially influenced by fluid flow, resulting in the reduction of temperature observations to 319. We also added to the text that fluid flow in buried carbonates can also occur, influencing the thermal field. For more details, we refer to the revised ms.

Line 270, Fig. 6. The grey color code to visualize the difference between model and observed temperatures is not suitable to quantify the difference.

Corrected.

Lines 322-324 Towards the Transdanubian Range (Balaton Highland), predicted model temperatures are slightly higher in the deeper part of the model compared to the NW part

(Sopron Mts.). This might be explained by the shift in the timing of active rifting, that migrated from NW towards SE (e.g. Balázs et al., 2016).

The rifting time was fixed in the model, so the temperature difference has a different reason, e.g. different subcrustal stretching factors.

We revised the text and excluded this paragraph.

Line 329 we compared the overall misfit between modelled and observed temperatures

How did you calculate the difference between the modeled and observed temperatures as they belong to different depths?

Only one observation per grid cell was supported in the models, so observations were restricted to 200 m deep intervals, and measurements with lower uncertainties were considered. We restricted the calculation of misfits also to the model resolution. We added the description of one observation per grid cell to the text in the methodology section. Please see the revised ms.

Lines 349-351 It must be noted that the predicted subcrustal stretching might not be entirely correct due to changes in the timing of stretching throughout the study area but provide a realistic picture for the degree of lithosphere attenuation.

It is not only the timing of stretching, which influences the stretching factors, but all parameters used in Eq. 2.

This is an important point; we also discussed the influence of other parameters in the revised ms.

Lines 366-368 These differences in shallow temperature predictions can partly be explained by the different calibration datasets used by Lenkey et al. (2017) and (Lenkey et al., 2021), excluding temperature measurements from (recent) geothermal wells documented in the OGRE database.

OGRe (2020) is a very useful database to get quick-look temperature data. However, no information is given about the conditions of the measurement. E.g. it is not known if the BHT value is corrected or not. In the Geothermal Database of Hungary (Dövényi, 1994, Lenkey et al., 2021) the observed data are corrected if possible, and every temperature data is quality checked, and depending on the type and conditions of the measurement they are ranked into quality categories.

We revised this sentence in the ms. and we are aware that the quality of the two datasets is not comparable. We also revised the uncertainty of outflow temperatures mostly reported in OGRE to account for larger uncertainties, as described in the previous comments.

Lines 398-399 give references to Porkoláb et al.

Reference updated