Responses to comments on egusphere-2023-1388

Title: The role of continental lithospheric thermal structure in the evolution of orogenic systems: Application to the Himalayan-Tibetan collision zone

Referee #1 Lin Chen:

In this manuscript, the authors used 2D thermomechanical models to investigate the role of plate thermal state in the continental collision. Through systematic parameter testing, they found that a cold pro-plate favors continuous subduction, whereas a hot pro-plate prefers slab break-off. On this basis, they attributed the along-strike variations, including subducting angle and crustal faulting style, in the India-Asia collision zone to the inherited lateral inhomogeneity of the Indian plate's thermal state. This is an interesting study, which brings us some novel insights (thermal state of the subducting plate) about the factors controlling on the deformation style of continental collision zone. I think this paper is suitable for Solid Earth after some revision.

My main comments are as follows:

1. *The authors systematically tested variations in temperature at moho and heat production in the crust, but I think the two types of parameters are not independent. Given that the temperature structure of the continental plate is defined by the steady-state heat conduction equation (i.e., Eqs. 11-13), the moho temperature is determined by the heat production distribution and surface heat flow. Thus, it is more reasonable to treat heat flow and crustal heat production as two independent parameters. Similar treatment can be found in Beaumont et al. (2004, JGR), Chen et al. (2019, Tectonophysics).*

R1: Thanks for pointing this out. According to Eqs. (11) - (13), the moho temperature and radioactive heat production are not independent. However, as we focus on the influence of each of these two parameters, when we test crustal radioactive heat production, we fix the corresponding moho temperature. More Specifically, the procedure to define a continental geothermal structure is as follows: (1) Choosing the surface temperature (T_T), moho temperature (T_B), and radioactive heat production (H), calculating the surface heat flow q_T on the basis of Eq. (12); (2) Based on the above known quantities and Eq. (11), we then get the temperature at an arbitrary depth in the crust. Thus, when we take parameter H as a variation, the moho temperature is fixed, and the crustal temperature gradient then increases with increasing H (see Figure 1 below). We've added a detailed description to the paper (lines 117-120):

"According to these equations, T_{moho} and H_r are not independent parameters, we thus fixed T_{moho} when investigating the influence of H_r. Specially, we first choose a surface temperature (T_T), moho temperature (T_B), and radioactive heat production (H), then calculate the surface heat flow (qT) based on Eq. (12). After that, we substitute the above T_T, q_T, and H into Eq. (11) to get the continental crustal temperature structure."

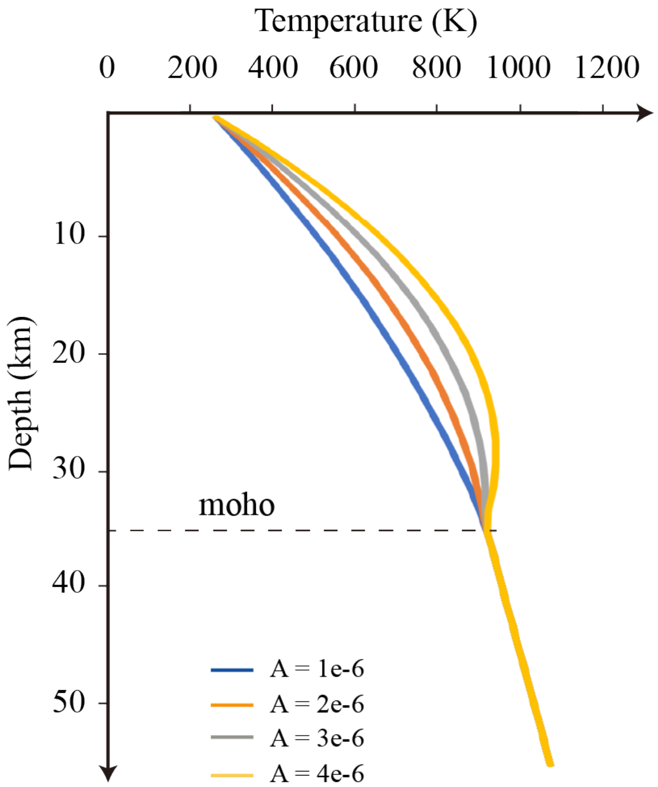


Figure 1. Continental temperature profile with different crustal radioactive heat productions and a fixed moho temperature of 600 ˚C.

Besides, we agree with the reviewer that surface heat flow is also an important parameter that is worth further study. We may test it in the future.

2: There are a number of factors controlling whether a slab breaks off or not. The thermal state of subducting continental plate was probably not mentioned in the previous studies. I suggest the authors to add some discussions about the factors controlling slab break off, comparing with previous studies, including Duretz et al. (2011) and others.

R2: Thanks for the suggestion. We've added a part discussing the factors controlling slab break-off and comparing them with previous studies in Section 4.1, lines 205-222:

"As to mode II, models with hot procontinental T_{moho} (≥ 500˚C) always evolve into continental subduction following a slab break-off. In these models, when the retrocontinental T_{moho} is determined, (1) as the procontinental T_{moho} decreases, the procontinental lithosphere becomes cold, which results in a rheologically strong lithosphere that can be subjected to greater deformation; the slab thus breaks off much latter (Fig. 5e). This is consistent with many of the previous numerical studies (van de Zedde and Wortel, 2001; van Hunen and Allen, 2011; Duretz et al., 2011). However, it appears that Duretz and Gerya (2013) proposed an apparent opposite tendency. It may come from the fact that these models do not use a layered crust. In consequence, a strong crust is more likely to result in strong crust-mantle coupling and a deeper slab break-off under slower convergence, while a weak crust leads to crust-mantle decoupling that may evolve into delamination. (2) The depth of slab break-off in our models is between 30 ~ 60 km, which has also been indicated by Davies and von Blanckenburg (1995), Li et al. (2002), Duretz et al. (2011), and Duretz and Gerya (2012). (3) After slab break-off, the buoyant continental lithosphere experiences a rebound accompanied by strong surface uplift within a short duration (Fig. 3c), which coincides with Duretz and Gerya (2013) and Magni et al. (2017). Slab break-off is often considered an early process of continental collision, and numerous numerical simulations have been conducted to investigate it. Comparing their results with our models, we suggest that slab break-off is closely related to the rheological strength of the lithospheres. Therefore, the parameters that have prominent impacts on it, such as oceanic plate age, convergence velocity, continental crustal structure, layered crustal rheological strength, the strength of the interface between the subducting and overriding plates, etc. (Gerya et al., 2004; Burov, 2011; Duretz et al., 2011; Magni et al., 2017; Koptev et al., 2022), may significantly influence the evolutionary path of slab break-off. "

3: The language needs improving. I sensed a lot of writing or grammar issues, some of which are marked in the annotated pdf file, but they only represent a fraction of the language problems, not all.

R3: Thanks for the suggestions, we've modified the paper accordingly. All the modifications are shown in the revised manuscript attached here.

1) Lines 6-8, "Continental collision is a crucial process in plate tectonics, whereas our understanding regarding the tectonic complexities at such convergent plate boundary remains largely unclear in terms of the evolution and the controlling parameters of its lateral heterogeneity." Rephrase this statement using short sentences.

R3-1: Thanks for the suggestions, we've modified the sentence (lines 7-9):

"Continental collision is a crucial process in plate tectonics. However, in terms of the evolution and the controlling parameters of its lateral heterogeneity, our understanding of the tectonic complexities at such a convergent plate boundary remains largely unclear."

2) Line 13, modify "relative".

R3-2: We've modified it to "relatively", line 14.

3) Line 14, delete "In contrast".

R3-3: We've deleted "In contrast" here, line 15.

4) Line 14, what is Hr?

R3-4: We've changed it into "Radioactive heat production", line 15.

5) Line 16, "geoscience" -> "geological"?

R3-5: We've modified it to "geological", line 18.

6) Line 19, add "most".

R3-6: We've added "most" here, line 21.

7) Line 22, "Continental collision following the closure of the ocean is…". Since the second half of this statement is specific, I suggest to specify which continent collided and which ocean closed."

R3-7: We've modified it, line 23:

"The collision between the Indian and Asian continents following the closure of the Neo-Tethys Ocean."

8) Line 25, delete "geoscience".

R3-8: We've modified it, line 27.

9) Line 27, "slding" -> "underthrusting"?

R3-9: We've modified it, line 29.

10) Line 28, "vary laterally from west to east", Be specific. How do them vary from west to east?

R3-10: We've modified it, line 28-29:

"Specifically, the horizontal underthrusting distance of the Indian lithosphere decreases and the subducting angle increases laterally from west to east."

11) Line 34, "manifested", change a word.

R3-11: We've modified it to "suggested", line 36.

12) Line 57, delete "Otherwise".

R3-12: We've modified it, line 59.

13) Line 61, "varies" -> "influences".

R3-13: We've modified it, line 63.

14) Line 63-64, "our model results are applied to draw some parallels with the Indian-Asian collision zone.", rephrase this statement.

R3-14: We've modified it, lines 65-66:

"the results of our models are used to draw comparisons with some first-order characters of the Indian-Asian collision zone."

15) Line 63, No mention of Table S1 before Table S2.

R3-15: We've modified it, line 65.

16) Line 71, delete "and we quoted directly from these publications".

R3-16: We've modified it, line 72.

17) Line 81, "friction" -> "frictional".

R3-17: We've modified it, line 82.

18) Line 107, "consists" -> "consisting".

R3-18: We've modified it, line 109.

19) Line 111, what about the resolution in the horizontal direction?

R3-19: The resolutions in horizontal and vertical direction are the same, we've modified it, lines 113-114:

… from 2 km × 2 km to 8 km × 8 km

20) Line 116, "plate" -> "half-space".

R3-20: We've modified it, line 121.

21) Line 134, "crustal Hr", *this parameter seems confusing. What does it really mean? Upper crust heat production, lower crust heat production, or the whole crust heat production?*

R3-21: We've modified it, we define continental upper crust heat production as H_{r_uc}, while lower crust heat production as H_{r_lc}, lines 141-142.

22) Line 134, “mimic” -> “capture”.

R3-22: We’ve modified it, line 142.

23) Line 138, “it takes the Model m2”, a conjunction is missing here.

R3-23: We’ve modified it, line 146, “and it takes the Model m2…”

24) Line 141, “at shallow”?

R3-24: We’ve modified it, line 149, “at surface”.

25) Line 142, “under” -> “due to”?

R3-25: We’ve modified it, line 150.

26) Line 143, “fully” -> “full”.

R3-26: We’ve modified it, line 151.

27) Line 147, “shallow”?

R3-27: We’ve modified it to “scraped off”, line 155.

28) Line 149, “initiated to”?

R3-28: We’ve modified it to “began”, line 157.

29) Line 150, “broke the neighboring retrolithopheric”, it is not clear.

R3-29: We’ve modified it, line 158.

30) Line 169, “relative” -> “relatively”

R3-30: We’ve modified it, line 175.

31) Lines 182-183, “(b) upper and (c) lower crustal radioactive heat production (Table S2)”, I suggest to use different symbols to denote the upper and lower crustal heat production. It is not a good idea to use Hr to stand for everything.

R3-31: We’ve modified it, we define continental upper crust heat production as H_{r_uc}, while lower crust heat production as H_{r_lc} (lines 141-142), Figures 4b, 4c, line 187-188.

32) Line 226, “on” -> “for”.

R3-32: We’ve modified it, line 249.

33) Line 226, “heterogeneous” -> “heterogeneity”?

R3-33: We’ve modified it, line 249.

34) Line 232, “extend” -> “end”?

R3-34: We’ve modified it, line 255.

35) Line 270, “relative” -> “relatively”.

R3-35: We’ve modified it, line 294.

36) Line 276, “inhomogeneous” -> “variation”.

R3-36: We’ve modified it, line 300.

37) Line 351, “feformation” -> “formation”.

R3-37: We’ve modified it, line 397.

Referee #2 Alexander Koptev:

The paper by M. Liu et al. is devoted to thermo-mechanical modelling aimed at studying the process of continental collision in the context of the various thermal structures of the continental lithosphere on both pro- and retro-sides of the orogen.

The scientific basis of this work is sound, as most of the main conclusions are well supported not only by modelling results but also by comparisons with observations in the Hymalayan-Tibetan orogen. The authors clearly show the strong similarity between the modelled compositional and deformational field and the geological and geophysical data in the Hindu Kush and eastern Tibet – this is the strength of the manuscript, which is also suffciently well written, structured, and illustrated.

2. *My only main point is that the current title of the manuscript ("The role of lithospheric thermal structure in the development of lateral heterogeneous of the continental collision system") is somewhat misleading, as one might expect full 3D modelling rather than 2D exploration of the end members with such a claim. I would also recommend emphasizing that only the continental segments were explored from the perspective of systemic variations in thermal properties. The example of natural application could also be mentioned. So something like "The role of continental lithospheric thermal structure in the evolution of orogenic systems: Application to the Himalayan-Tibetan collision zone" would be a better title in my opinion*

R1: Thanks for the suggestion. We've modified the title of our manuscript to "The role of continental lithospheric thermal structure in the evolution of orogenic systems: Application to the Himalayan-Tibetan collision zone". Lines 1-3.

2: I also fully agree with the previous comment that Moho temperature and radiogenic heat production are not independent parameters – assuming a steady-state geotherm with fixed boundary temperatures at the surface and LAB and fixed thicknesses of the crust and lithosphere, increasing/decreasing the Hr of the upper and/or lower crust should increase/decrease Moho temperature. I urge the authors to address this issue in the revised version of the manuscript and to better illustrate initial temperature distributions for the different scenarios examined in the study.

R2: Thanks for pointing this out. According to Eqs. (11) - (13), the moho temperature and radioactive heat production are not independent. In this paper, as we focus on the influences of each of the two parameters, when we tested crustal radioactive heat production, we fixed the moho temperature. Specifically, the procedures to define a continental geothermal structure are as follows: (1) Choosing a surface temperature (T_T), moho temperature (T_B), and radioactive heat production (H). According to Eq. (12), we can calculate the surface heat flow q_T; (2) Based on the above-known quantities and Eq. (11), we can get the temperature at an arbitrary depth in the crust. Thus, when we take parameter H as a variation, the moho temperature is fixed, and the crustal temperature gradient then increases with increasing H (see Figure 1 below). We've added a detailed description to lines 117-120:

"According to these equations, T_{moho} and H_r are not independent parameters, we thus fixed T_{moho} when investigating the influence of H_r. Specially, we first choose a surface (T_T), moho temperature (T_B), and radioactive heat production (H), then calculate the surface heat flow (q_T) based on Eq. (12). After that, we substitute the above T_T, q_T, and H into Eq. (11) to get the continental crustal temperature structure."

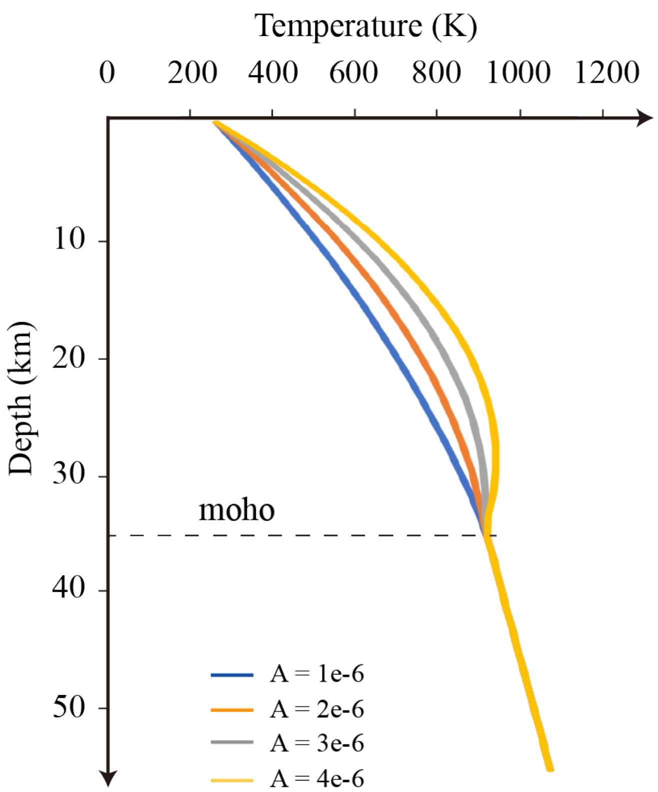


Figure 1. Continental temperature profile with different crustal radioactive heat productions and a fixed moho temperature of 600°C.

3: As for the effects of other parameters, such as the age of the oceanic plate and initial plate convergence (e.g., Duretz et al., Tectonophysics, 2011) or the strength of the interface between the subducting and overriding plates (e.g., Koptev et al., Terra Nova, 2022), on the dynamics of slab break-off and the shape of the orogen, I do not think additional experiments are necessary – a proper discussion with references to previous studies would suffice.

R3: Thanks for the suggestion. We've added a discussion on the dynamics of slab break-off, lines 205-222:

"As to mode II, models with hot procontinental T_{moho} (≥ 500˚C) always evolve into continental subduction following a slab break-off. In these models, when the retrocontinental T_{moho} is defined, (1) as the procontinental T_{moho} decreases, the procontinental lithosphere becomes cold, which results in a rheologically strong lithosphere that can be subjected to greater deformation; slab thus breaks off much latter (Fig. 5e). This is consistent with many of the previous numerical studies (van de Zedde and Wortel, 2001; van Hunen and Allen, 2011; Duretz et al., 2011). However, it appears that Duretz and Gerya (2013) proposed an apparent opposite tendency with slab break-off when the crust is strong, and vice versa. It may come from the fact that these models do not use a layered crust, which may lead to strong crust-mantle coupling and a deeper slab break-off under slower convergence. (2) The depth of slab break-off in our models is between 30 ~ 60 km, which is in the range indicated by Davies and von Blanckenburg (1995), Li et al. (2002), Duretz et al. (2011), and Duretz and Gerya (2012). In these cases, when the retrocontinental T_{moho} is defined, the time for the slab break-off increases as the procontinental T_{moho} decreases (Fig. 5e). (3) After slab break-off, the buoyant continental lithosphere experiences a rebound accompanied by strong surface uplift within a short duration, which coincides with Duretz and Gerya (2013) and Magni et al. (2017). Slab break-off is often considered an early process of continental collision, and numerous numerical simulations have been conducted to investigate it. Comparing their results with our models, we suggest that slab break-off is closely related to the rheological strength of the lithospheres. Therefore, the parameters that have prominent impacts on it, such as oceanic plate age, convergence velocity, continental crustal structure, layered crustal rheological strength, the strength of the interface between the subducting and overriding plates, etc. (Gerya, 2004; Burov, 2011; Duretz et al., 2011;

Magni et al., 2017; Koptev et al., 2022), may significantly influence the evolutionary path of slab break-off."

4: Please note in particular the paper of Duretz & Gerya (Tectonophysics, 2013), which explored the variable strength distribution in continental crust (which is inextricably linked to its thermal structure – see, e.g., the review by Burov, Marine and Petroleum Geology, 2011). It appears that this earlier study showed the apparent opposite tendency with slab break-off when the crust is strong, while weak crustal rheology has been shown to prevent detachment of the oceanic plate.

R4: Thanks for raising this point. In comparison with our models, Duretz and Gerya (2013) did not use a layered crust. Therefore, a stronger crust can give rise to stronger crust-mantle coupling, which may result in whole continental lithospheric subduction. At the same time, with a slower total convergence velocity (1.25 cm/yr until 500 km of convergence is accommodated), it has enough time for the subducting plate to be heated by the mantle to evolve into slab break-off. On the contrary, a weak crust can lead to crust-mantle decoupling, which may evolve into delamination. That's why Duretz and Gerya (2013) showed the opposite tendency compared with us. We've added an illustration in Section 4.1, lines 209-213:

"However, it appears that Duretz and Gerya (2013) proposed an apparent opposite tendency. It may come from the fact that these models do not use a layered crust. In consequence, a strong crust is more likely to result in strong crust-mantle coupling and a deeper slab break-off under slower convergence, while a weak crust leads to crust-mantle decoupling that may evolve into delamination."

5: Minor points:

1) *Line 14. Avoid abbreviations in the abstract.*

R: Thanks for the suggestion. We've modified these abbreviations, T_{moho} -> moho temperature, H_r -> Radioactive heat production. Lines 12-15.

2) *Lines 28-31. See also the role of the geometry of the subducting plate, which may be curved in 3D (Nettesheim et al., Solid Earth, 2018; Koptev et al., Tectonics, 2019).*

R: Thanks for the suggestion. We've modified this part, lines 30-31:

"Despite various mechanisms have been invoked, including geometry of the subducting plate (Nettesheim et al., 2018; Koptev et al., 2019), inhomogeneous inherit lithospheric structure, …"

3) *Line 86. Density depends not only on temperature but also on pressure (with a compressibility coefficient on the order of ~10 MPa).*

R: Thanks. As we use an imcompressible medium, we apply a simplified density function. The density in Eq. (1) only depends on temperature and satisfies Eq. (5): $\rho = \rho_0 (1 - \alpha (T - T_0))$; see illustrations in lines 74, 86, 87.

4) *Line 103. "user-defined viscosity cutoffs" should be provided in table S1 for each rock type.*

R: Thanks for the suggestion. We've added the viscosity cutoffs to table S1 and lines 14 in Supplementary Information, and also see line 104 in the revised manuscript.

5) *Lines 105-112. Please include key information (thickness and rheological type) for the weak zone. The thickness of the weak zone (80 km) given in Table S1 is confusing– it seems to be only a few km on Figure 1.*

R: Thanks for the reminder. The width of the weak zone is 10 km, and its rheological type is gabbro (Table S1). We've added the description (lines 107-108) and modified Table S1:

"A weak zone with a width of 10 km (gabbro, Wilks and Carter, 1990) abuts the oceanic plate to facilitate subduction."

6) *Lines 115-116. What is the thermal age of the oceanic plate?*

R: Thanks for the reminder. The oceanic plate is ~ 90 Ma. We've added it to line 110.

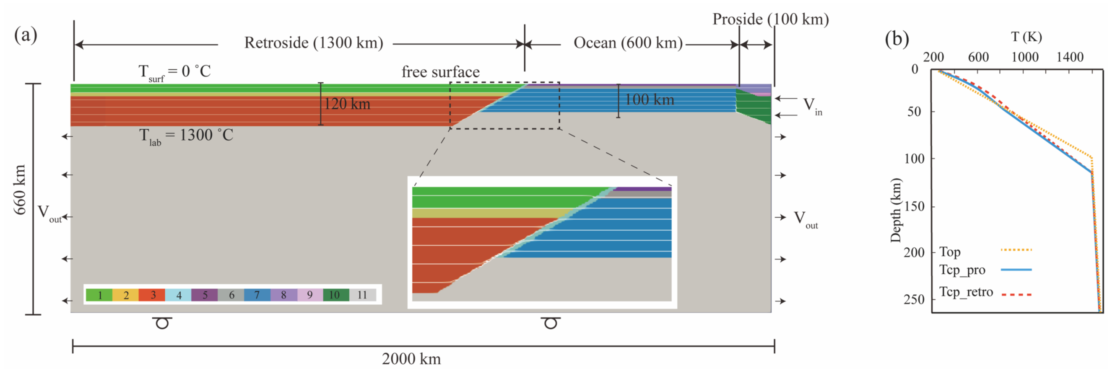
7) *Lines 116-117. Lower adiabatic gradient in the sublithospheric mantle (0.3 C/km) is suggested by e.g. Turcotte & Schubert, Cambridge University Press, 2002 and Sleep, Gcubed, 2003.*

R: Thanks for pointing this out. The higher adiabatic gradient of 0.5 ˚C/km used in our paper refers to Huangfu et al. (2019), Chen et al. (2020), and Cui et al. (2022) (line 123). We've noticed that adiabatic gradient in mantle was set to different values, such as 0.25 ˚C/km in Tetreault and Buiter (2012), 0.3 ˚C/km in Turcotte and Schubert

(2002), and 0.5 ˚C/km in Huangfu et al. (2019), the influences of varying adiabatic gradient in the mantle on the evolution of collision system may be another parameter that we shall investigate in the future.

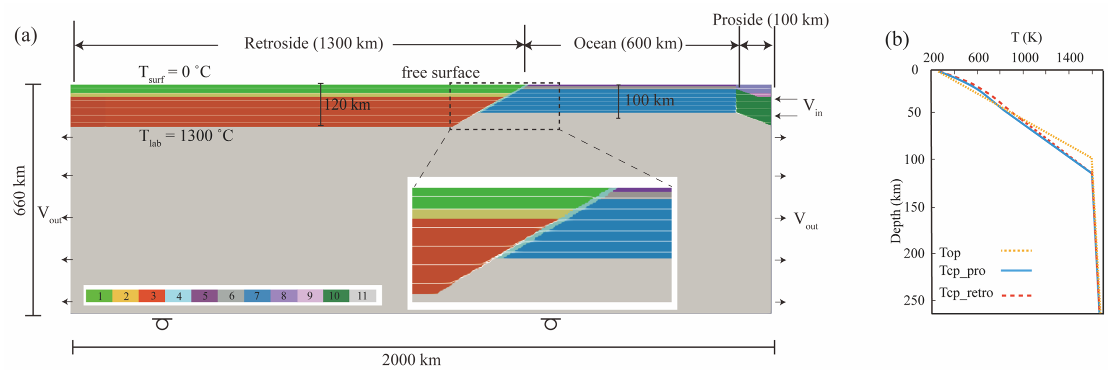
8) *Figure 1. Zoom in on the crustal segments at the transitions between oceanic segment and pro- and retro-continents. As it stands now, in the printed version, the oceanic sediments and the weak zone are barely visible.*

R: Thanks for pointing this out. We've modified Figure 1 with a zoomed-in subplot locates in the bottom right corner of Figure 1a, see line 133.



9) *Figure 1. Add the original distributions of the temperatures investigated in the study (see the main comment).*

R: Thanks for the suggestion. We've added the original distributions of the temperatures to Figure 1b, see lines 133, 138, 139.



10) *Lines 134-136. Please indicate that you have treated the thermal structures of overriding and subducting continents separately.*

R: Thanks for the suggestion. We've modified it, lines 141, 142:

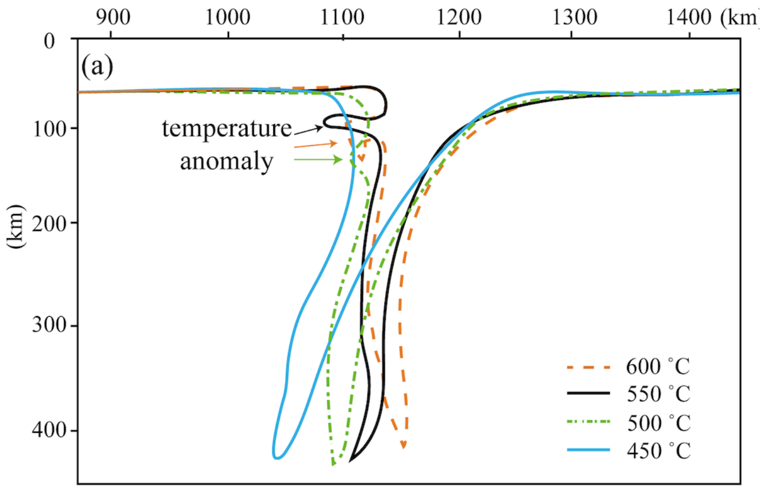
"We conducted 48 numerical experiments by varying the moho temperature, upper crustal H_{r_uc} and lower crustal H_{r_lc} of the retrocontinent and procontinent, respectively, …"

11) Lines 155-156. "3. Sensitivity. 3.2. Continental subduction…" – I think this is a typo that should be removed.

R: Thanks for the reminder. We've removed it, line 162.

12) Figure 5a, left panel. Add a vertical and horizontal scale and indicate what the corresponding lines show (a specific isotherm or a boundary in the compositional field?).

R: Thanks for the suggestion. We've modified it, geometries of the subducting plates in different models (Fig. 5a) are outlined by 800˚C isotherms, lines 229, 230.



13) Line 255. "lithospheric thermal structural difference". Please specify here and throughout the text that you mean a variation in the thermal structure of the continental parts of the system, while the thermal age of the oceanic segment remains constant.

R: Thanks for the suggestion. We've modified the paper, lines 121, 122, 179, 240, 278, 289, 297.

14) Table S1. Density (ro) – do you mean the reference density (ro0 from equation 5)?

R: Thanks. Density here in Table S1 is not the reference density (ρ_0, line 88) in Eq. (5), it refers to the initial density in Eq. (1), and changes with the evolution of model's temperature (ρ in Eq. (5), line 87).

15) Table S1. Sediments – do you mean oceanic sediments, since there is no sediment cover on the continents, correct?

R: Yes, it means the oceanic sediment, we’ve modified it in Table S1.