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Comment

Interactive comment on "Numerical models of trench migration in continental collision zones" *by* V. Magni et al.

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Author comments – reply to the review of C. Conrad

This paper uses a series of well-designed numerical models to determine how and why trenches migrate in continental collision zones. The authors discover that slabs tend to steepen after continental collision, and that this steepening generates a flow patterns in the mantle that drive trench advance. In fact, trench advance has been observed in continental collision zones, so the models presented in this paper present a good mechanism to explain this observation. Because the paper is well written and describes a simple process that may explain a fundamental observation of earth subduction, I think this paper should be published.

I also feel, however, that this paper could be improved both in terms of its presentation but also by improving the comparison between the model predictions and observations of trench migration at continental collision zones. I describe my suggestions below. Although I suggest several and significant revisions, I am recommending publication after "minor revision" because the paper is already in a nearly publishable form. I do feel, however, that the authors should consider my suggestions below, because I think addressing them would improve the impact of their paper.

1. It is a little unclear to me what "trench migration" actually means when applied to collisional subduction. For oceanic subduction, the location of the trench is obvious – it is the point where the subducting plate begins to become covered by the overriding plate. However, for continental subduction, this location is covered over by compressional tectonics of the continental crust. It is perhaps possible to estimate the location of where the trench would be without this continental crust, but this requires seismological observations – and these are only available for the present day, not past times, which makes estimating migration rates difficult. Is there a volcanological expression of trench migration? If so, can it be de-convolved with changes in slab dip? (which ultimately drive the trench migration, as demonstrated in this paper). Is there some other geological expression of trench migration for continental collision? I recommend that the authors add some discussion about how trench migration is measured in continental environments. Additionally, I think the authors should be more specific about how they determine the specific location of the trench in their models.

1 - REPLY: We thank the reviewer for his comment; this was indeed confusing in the text. We added this part in the Introduction (p.431 after line 13): "Once the continental collision occurs, the position of the trench becomes a deformed belt that marks a suture between the two plates. The mechanisms that drive the motion of this suture zone during the evolution of collision are still poorly understood. The combination of geological observations, such as structural and volcanological data, with interpretation of tomographic images may provide insights to infer the tectonic evolution of the collisional

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system. Evidences of the migration of the subduction zone towards the overriding plate trench advancing have been recognized in continental collision zones as India-Eurasia and Arabia-Eurasia (e.g., Replumaz et al., 2010; Hatzfeld and Molnar, 2010)."

And this to the Method (p.434, line 16): "In our models we refer at the trench position as the location of the shallow weak zone. In oceanic subduction, this refers to the area where the subducting slab begins to descend beneath the overriding plate. Whereas, in continental collision systems, this is a rather wide deformation zone between the pro- and the retro-wedge (Willet et al., 1993; Beaumont et al., 1996).

Furthermore a better explanation of how we determine the specific location of the trench in our models is given in the reply at point 3.

2. One of the significant results of this paper is that the authors use their models to predict that trenches should tend to advance in continental collision zones. They then provide, in the discussion, a summary of trench migration observations for various collisional zones, many of which are advancing. However, the authors motivate the paper by explaining the modeling efforts that have been used to investigate the dynamics of trench migration and continental collision in previous studies. I think it would make for a stronger paper if the authors motivated their study instead by the observation that many/most of the continental collision zones feature trench advance. This is distinctly different from oceanic subduction, in which most trenches are observed to be in retreat (both in laboratory models and for natural subduction, although the latter depends on the choice of reference frame). In general, I think it is better to motivate a study by pointing out the basic observation that the study seeks to explain – and it seems to me that this could easily be done in this case by moving some of the material from the discussion into the introduction.

2 - REPLY: We agree with this good suggestion, and revised the introduction by including after line 13 p. 431: "In natural cases, evidences of trench advancing have been recognized in continental collision zones as India-Eurasia and Arabia-Eurasia (e.g. Re-

plumaz et al., 2010; Hatzfeld and Molnar, 2010).” (before in the Discussion: p.441, lines 1-3) And the whole paragraph of the Discussion at p.441 lines 12-20

3. The low-viscosity zone between the plates is constructed using tracers. Movement of these tracers defines the location and shape of this weak zone. Also, the weak zone “moves with the velocity of the overriding plate” (p. 434 line 18). It is a little unclear to me how this is accomplished: Are the tracers pinned to the edge of the overriding plate? In that case how do they move to change the shape of the plate boundary? Or, are the tracers allowed to move freely? In that case, then what prevents the tracers from migrating away from the plate boundary and generating a low-viscosity region elsewhere? This is particularly a question for the wedge above the slab, which I would expect to have vigorous flow that would move tracers into the underlying mantle.

3 - REPLY: This was indeed unclear in the submitted text. We have rewritten the part that describes the technique we use to move the trench p434 lines 18-22: In our models the weak zone moves horizontally with the velocity of the overriding plate: at each timestep the horizontal velocity of a point within the overriding plate and close (about 30 km) to the trench is taken from the global model velocity field. This velocity is used to calculate the new position of the trench. The shallow weak zone between the plates has a fixed shape, whereas the shape of the weak mantle wedge changes to follow the variations of the dip of the slab during the model evolution. The position of a set of a hundred tracers within the slab at a depth interval of 50-150 km is used to re-shape the mantle wedge according to the slab dip.

4. The model is 2D (as are many subduction models). Thus, the mantle flow patterns that lead to trench advance are 2D patterns. However, in 3D, the slab steepening process that drives these mantle flow patterns could instead be accommodated by flow around the lateral edges of the slab, which (I think) would lead to lateral variations in trench migration following collision (much as it does for trench migration in oceanic subduction systems with a finite lateral extent). I think the authors should discuss the effects of their 2D assumption on the dynamics of the system, and discuss the changes

they would expect in 3D. Do these changes match with any of the geological constraints on lateral variations in trench migration rate?

4 - REPLY: We agree that the mantle flow is highly influenced by the 2D setup, however we performed some preliminary models in 3D and we obtained the same advancing behavior. The lateral variation in trench migration is not as evident as in oceanic subduction systems. We think this is due to the facts that: 1. there is a significant difference in the strength profile between continental and oceanic lithosphere (that makes the continent more difficult to deform); 2. once the buoyant continent enter the subduction zone the entire system slows down and after few million years subduction stops. This behavior clearly differs from the oceanic system where subduction keeps going for longtime. Hence, the forces (slab pull + mantle flow) that in the oceanic system cause the lateral variations in trench migration, in the continental system are not acting for enough time to play the same role. In 3D, the toroidal flow around slab edges might reduce the local trench migration due to slab steepening effects (which redistributes mantle material), but also reinforces trench migration by allowing extra pathways for mantle material to flow from below ocean to continent or vice versa. The lateral variation in trench migration will largely be influenced by the ability of the overriding plate to deform accordingly. This is not explicitly covered in this manuscript, and we therefore suggest this would be beyond the scope of this paper. We cannot answer the last question, as our 3D models are only preliminary. We took into account the reviewer's suggestion adding in the Discussion session (p. 440 after line 11): "The mantle flow patterns that lead to the advance of the suture in our models are two-dimensional. To test the effect of the toroidal flow around the slab edges we run some preliminary 3-D models of continental subduction and we found the same advancing behaviour."

5. The mechanism for trench advance is described on page 439, lines 16-20. However, I think this mechanism could be explained a little more clearly. In particular, the authors state that steepening of the slab "triggers return flow around the slab" (line 18). The term "around the slab" seems to imply "around the edges of the slab" (at least to me)

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– which is a 3D process that cannot be treated here (see above comment). Instead, I think the authors mean "one convection cell below the slab and a second one above the slab" – this seems to be what is shown in Fig. 9. But if there are two convection cells moving in an opposite sense, why does the trench migrate? The cell beneath the slab would tend to cause advance by pushing the entire system toward the right in the diagrams, but the one above the slab would tend to cause retreat by pushing the entire system toward the left. Is the cell beneath the slab more vigorous, so that it "wins", and causes advance? I think that the specifics of the trench advance mechanism should be explained more clearly and in more detail. Additionally, since this is a key aspect of the paper, I think a brief explanation of the mechanism should be included in the abstract.

5 - REPLY: This was indeed unclear in the submitted text. The two small-scale cells- above and below the slab- are evident during the stretching and the following break-off of the slab; the cell below the slab is more vigorous then the one above, representing an additional engine for trench/suture advancing. Furthermore, at this stage, the advancing is also favored by the exhumation (or 'eduction') of subducted continental material (p. 440 lines 12-19). Whereas, at the beginning of continental subduction, the trigger of trench advancing is the steepening of the slab and the formation of a return flow below the slab. We changed the sentence p.439 lines 18-20 with this: "This, in turn, triggers a return flow below the slab creating a small-scale cell that drives the upper plate towards the overriding plate and results in an advancing trench (Fig. 9)." We added this in p. 440 line 6: "...a small-scale flow circuit. In particular, one vigorous convection cell forms below the slab and a weaker one above the slab (Fig. 9c)." We added this sentence in the abstract (p430 line16) "...during stretching and break-off of the slab. These processes are responsible for the advance of the suture by triggering small-scale convection cells in the mantle that, in turn, drag the plates."

6. The authors describe a process in which subduction of an oceanic plate generates a slab of limited length in the mantle prior to continental collision. Does the trench migration behavior that is observed depend on the length of the already-subducted

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slab in the mantle? For example, if there were only a very short slab in the mantle prior to continental collision, then presumably the observed trench advance following collision would not occur because it is driven by descent of the already-subducted slab. At the other extreme, if a very long slab were already subducted, then it might become anchored in the lower mantle, and steepening of the slab would become more difficult – its continued descent into the lower mantle would then perhaps draw the trench toward the anchoring point (which would also cause trench advance but for a different reason). I think it would help to mention that the dynamics may depend on how much slab material is already in the mantle, and also to discuss how the results may be different if a longer or shorter mantle slab were present.

6 - REPLY: We do not expect that the length of the oceanic slab significantly change the behavior of the trench migration. However, this might have an effect on the amount of trench migration, since the dip of the slab once the continent arrives at the trench might be different. We run some models with a longer oceanic slab and the dynamic of the system was similar. We did not try with a shorter oceanic slab. This is not a realistic scenario, since the initiation of subduction with a short slab (as commonly used in subduction models) is not often appropriate for the real Earth. We took into account the reviewer's suggestion adding in the Discussion session (p. 440 after line 11 and after the sentences added for the reply of point 4): "Furthermore, in our models we do not change the length of the oceanic slab, whereas in natural cases continental collision might occur after a long-lived oceanic subduction. However, we expect that the dynamics of the system would not change with a longer oceanic slab. Though, this might have an effect on the amount of trench migration, since the dip of the slab once the continent arrives at the trench might be different."

7. The models predict trench advance following continental collision – this is something that can be compared against observations (as is done in this paper). However, it seems to me that the models make other predictions that could be tested against observations. For example, slabs beneath continental collision zones should be steeper

than other slabs, and they should be more often detached from the surface plates (because slab steepening and detachment are two processes described here as natural events that follow continental collision and that cause trench advance). Is there any evidence from mantle tomography that slabs beneath continental collision zones are typically steeper or more detached? (besides Ontong Java, as mentioned) Such evidence would tend to support the conclusions of this paper. Also, the models predict two episodes of trench advance – one associated with steepening of the slab and another associated with the detachment. Are these episodes observed in the geological record of trench motion in continental collision zones?

7 - REPLY: Following the reviewer's suggestion we added in the Discussion (p441, line 1): "Tomographic images beneath continental collisions show that slabs are steep and often detached (e.g., India, Replumaz et al 2004; Northern Apennines, Lucente et al., 1999; Faccenna et al., 2001; Piromallo and Morelli, 2003; Carpathians, Wortel and Spakman, 2001; Alps, Piromallo and Faccenna, 2004; Spakman et al., 2004)."

It is unlikely to be able to distinguish between the subsequent phases of trench advancing associated to the steepening of the slab and the one associated with the detachment, since trench migration is deduced from the geological record or tomography, and both lack the needed temporal resolution to resolve this.

8. I think that a few of the figures could be made smaller and clearer. In particular, Figures 2 and 4 show 3 panels for each of 6 different times, making 8 panels total. This makes the individual panels rather small, and the details of the flow patterns even smaller. I think it would be clearer if the middle column (temperature) was eliminated since it basically shows redundant information with the left column (viscosity). Also, I think the right column could be eliminated if the regions of continental crust were drawn in blue (or some unused color) over top of the viscosity in the left column. This would reduce the number of panels to 6, and they could be much larger. I also wonder if the trench position and trench velocity panels of Figs. 3 and 5 could be combined onto Figs 2 and 4 (similar to what is done for Fig. 6). Alternatively, it seems to me

that the information in Figures 3 and 5 is redundant to the information in Figures 7 and 8, and thus could be simply eliminated. Finally, I think Figure 7 could be made clearer if the oceanic and continental cases were always given the same colors (e.g., blue shades for oceans and green shades for continents) – this would highlight the differences between the oceanic and continental cases more clearly.

8 - REPLY As suggested by the reviewer, we eliminated the column with the temperature plots (Fig. 2 and 4) and we merged column 1 and 3 in a single column. Also, we merged Fig.2-3 and Fig. 4-5. We changed the colours and line styles in Fig. 7 and 8 as suggested.

– equation (6) – I think that the symbol for the density contrast is incorrect in this equation (it should be del rho_c).

Following the reviewer's suggestion, we changed rho_0 with rho_c

– Page 434, lines 13-24 – it seems to me that these paragraphs should be part of section 2.2 (Model Setup), rather than section 2.1 (governing equations).

Following the reviewer's suggestion, we moved this paragraph in section 2.2

– The sense of trench motion (advancing or retreating) should be clearly defined somewhere, as readers can become confused about which direction is retreat and which is advance. I think that Figure 1 would be a good place to define retreat and advance.

Following the reviewer's suggestion, we added in Figure 1 two arrows at the trench to explain the direction of trench retreating and advancing.

– Page 435, line 20 – the authors mention that the model uses a no-slip condition on the bottom boundary, which may seem counter-intuitive to some. The authors should justify this (the high viscosity lower mantle acts as a rigid boundary).

We took in to account the reviewer's suggestion writing in the revised version of the text: "Velocity boundary conditions are free-slip on all but the bottom boundary, where a no-slip condition is applied to model the effect of the high viscosity lower mantle acting as a rigid boundary.” (p.435, line 20)

– Page 437, line 3 – I think that {mu} should be {nmu}

As suggested by the reviewer, we changed the symbol with μ

– Page 441, line 18 – The authors describe how Ontong Java may be an example of behavior similar to continental collision. Is there evidence for trench advance here?

The only evidence available (to our knowledge) is based on the geodynamic reconstructions of (Hall, 2002), and we added this reference to the text.

– Figure 1 caption. The “continental plateau” is highlighted in yellow. I think that the yellow region is actually “continental lithosphere” or “cratonic lithosphere”. A “plateau” is usually a crustal feature, not a lithospheric one as is drawn here.

As suggested by the reviewer, we changed “continental plateau” with “continental lithosphere” in Figure 1

– Figure 3 shows different symbols/colors for the different phases of system development (1-4). I think that the colors of these symbols should match those that are used to designate these states in Fig. 2. Also, the stages should be labeled somewhere, so that the reader doesn’t have to dig through the text to figure out how these stages are defined. It is also difficult to distinguish the blue and purple colors in Fig. 2 – more distinct color choices for subduction phases 3 and 4 would help.

We corrected/changed the colors in Fig.2-3-4-5 as suggested. We added a description of the different phases in the figures.

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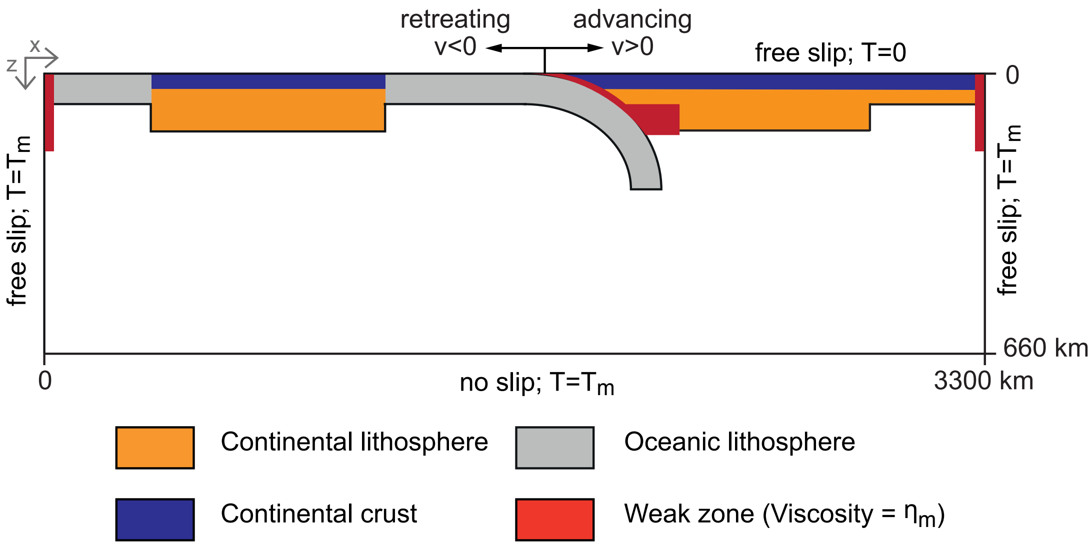

Fig. 1. 1 - After review

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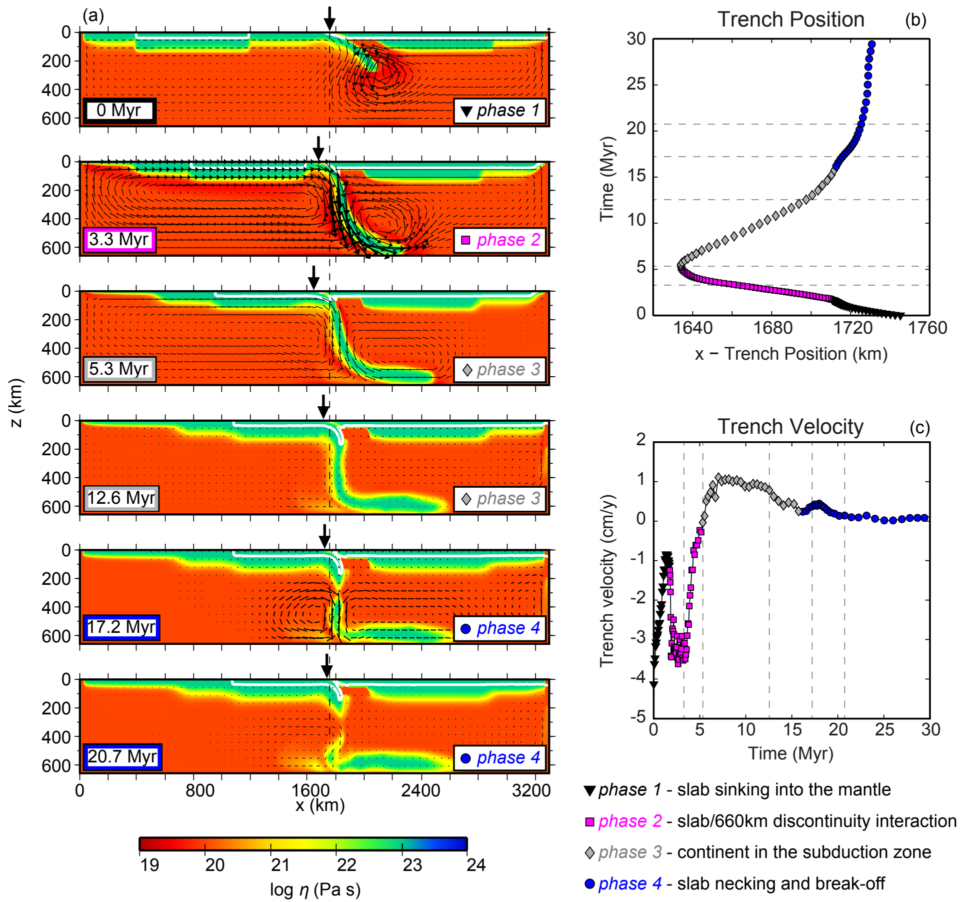

Fig. 2. 2 and 3 - After review

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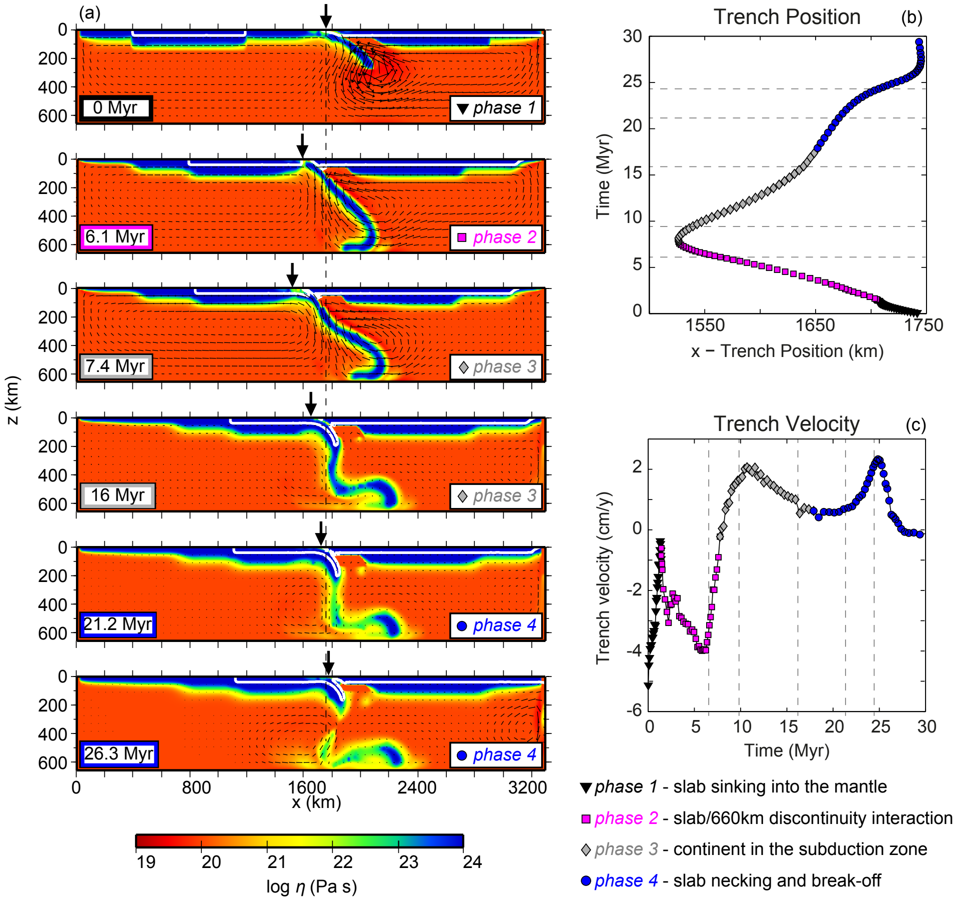

Fig. 3. 4 and 5 - After review

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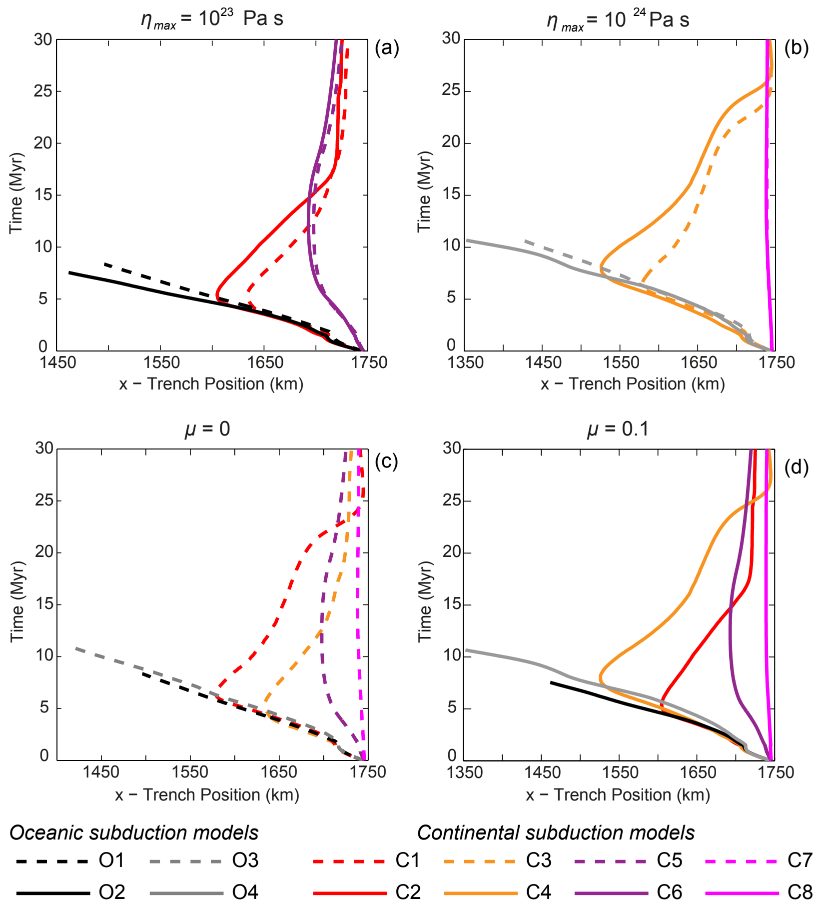

Fig. 4. 7 - After review

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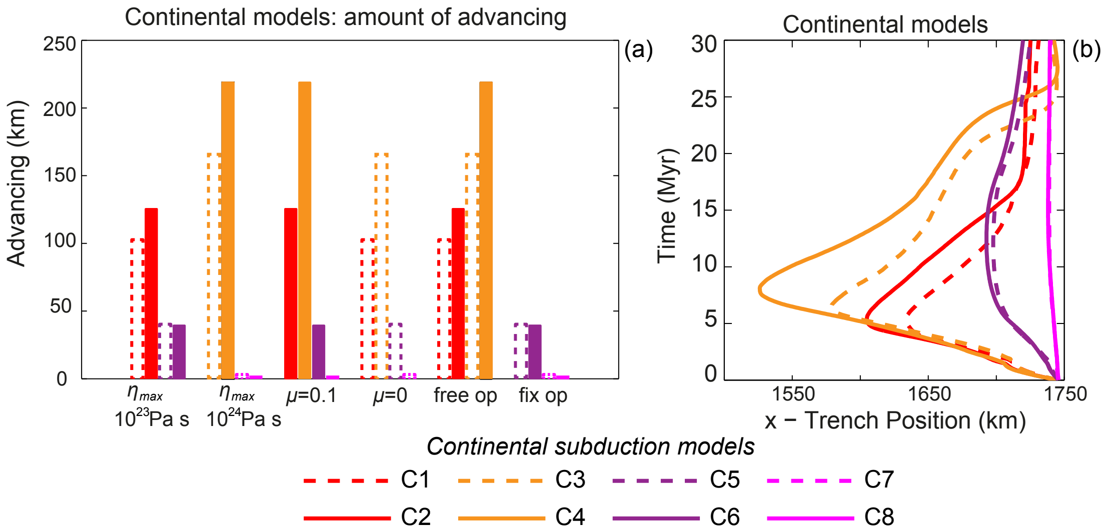

Fig. 5. 8 - After review

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