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Interactive comment on "Impact of upper mantle convection on lithosphere hyper-extension and subsequent convergence-induced subduction" *by* Lorenzo G. Candioti et al.

Anonymous Referee #2

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The study presented here uses 2D thermo-mechanical models to investigate formation of hyper-extended passive margins (extension), thermal relaxation, and subduction initiation during convergence. I find it an interesting study, with lots of complex aspects and I think considerable work was put into it. The manuscript has the potential to show some interesting results regarding subduction initiation and with respect to structural inheritance, however, I find the manuscript needs some further polish of the arguments in order to be publishable. Some parts are well written (i.e., Discussion) and the figures are high quality, but other parts need more work and clarification.

Most importantly, the key findings do not stand out after just one read of the paper.

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Discussion paper

Both the abstract and the conclusion are very long and very stuffy. Also, there is a weak correlation between arguments in introduction-results (investigation)-discussion. I therefore recommend the manuscript to be published in Solid Earth, after some major and minor comments below have been addressed.

Major points:

1. Clarity of the manuscript. The model is very complex and it has lots of details, but the authors haven't always explained the concepts clearly or properly. I have written down some specific examples that the authors can fix easily. However, they should try to verify that their findings are backed by arguments that are explained in a logical way.

The abstract should be shortened to include the top 3 most important results, and be revised for clarity and shorter sentences. For example, what do the authors want the paper be known/cited for?

In the introduction, the link between mantle convection and lithosphere deformation is quite abrupt (with a sentence about age of the Earth that is irrelevant to this study). The question 'why is convection important?' is not satisfactorily introduced or linked to coupled lithosphere-mantle deformation.

General suggestion: too many commas. Try to rephrase/split sentences with more than 2 commas or that are longer than 2 lines.

2. Results section. I think the reference model (M1) should be described separately (evolution between extension, relation, convergence). Then compare models M2-M6 with M1 to highlight the effect of various factors. Figures should be adapted accordingly. The reason for this are the following: - in current form, the comparison is all over the place and it is confusing. It is not very clear which simulations the main text is referring to sometimes. - the current arrangement of figures is random. It starts with 2, 5, 8, 4, 10 etc. Their placement should follow a logical order of arguments.

The comparison between M1-M6 should be done in terms of Ra. The k, viscosity cutoff,

flow laws, they essentially affect the Ra.

3. Thermal softening. A quick search in the manuscript finds 'thermal softening' only in the abstract, very late discussion and conclusion, yet it is suggested as a key process that controls subduction initiation. I'm pointing out that it is incompletely described and linked to the hypothesis of the study and results.

For example, Line 425: thermal softening is introduced only now. not clear why bring it up here?

Line 461: say that structural and thermal softening are important, but they were introduced late, without much context.

Moreover, the authors suggest in multiple places that it is the structural softening (inheritance) and convection (slab suction) that help initiation. The authors need to clarify what are the main findings, and arguments need to be revised. One finding that I think is important: the required driving force to initiate subduction is much smaller, when convection and structural inheritance are considered.

4. Modelled vs parameterised convection. In Line 126, 3 types of simulations are introduced: 1) model convection with a weak asthenosphere, 2) parametrised convection, by scaling the thermal conductivity to the Nusselt number 3) impact of different viscosity structures

First, the treatment of the mantle convection is not clear in the main text (Lines 124-130). What drives convection? How is the applied parametrised convection different? When is the onset of convection? Is convection only during the thermal relaxation stage? What controls the size of the convection cells? Also, explain how the Ra_avg is calculated.

In point 3) above which approach are you using: modelled/parameterized convection? While it is explained better in Appendix B, the differences between them are not clear in the main text. For example, 1) would be M1, while 2) is M, and 3) is M6?

5. Other questions.

The geodynamic cycle modelled: 1) 30 Myr extension at 2cm/yr 2) 70 Myr thermal relaxation 3) 20 Myr convergence at 3 cm/yr

What is the motivation behind these choices: 1) why thermal relaxation 2) why those time intervals 3) why those extension/convergence rates? Also, what are the boundary conditions during thermal relaxation?

Why the choice of those parameters to change?

Are the surface processes important? Have you run models without? Do they introduce further heterogeneities in the model that affect the outcome?

6. Subduction initiation. It seems like symmetric vs asymmetric spreading also controls to a large extent subduction initiation, whether it is single/double subduction. I feel very little discussion is about that, and more on structural and thermal softening.

Also, there are other previous efforts to model extension/compression to obtain structural inheritance and subduction initiation (i.e. Gulcher et al 2019). The authors discuss simpler treatments of subduction initiation in paragraph 280, but do not relate to newer efforts to avoid the use of artificial features. So, are these newer models better for studying subduction initiation?

Minor points:

Line 8-10: revise sentence

Line 10: only from the abstract it is not clear what the parameters were used, so saying that a viscosity of 5e20 Pa.s was used (as compared to what?) is not very meaningful. Rephrase

Line 20: multiple use of 'geodynamic' in the same sentence

Line 29-30: rephrase.

Line 31: while it is an interesting fact - the calculation of the age of the earth - is not very relevant to the manuscript.

Line 35: rephrase

Line 40: unlikely to be problematic

Line 41: delete likely

Line 55: authors relate to numerical aspects such as time step size, without mentioning why? The context was on physical aspects of convection.

Line 64-65: should be in the first paragraph of introduction

Line 68: Why only upper mantle? This is discussed late in discussion (section 4.4, paragraph 395)

Line 69: delete 'of applying'

Line 74: revise sentence - its meaning is not clear to someone who hasn't read the methods/results section.

Line 88: reference to the code how it was benchmarked? (Info in appendix A, but should be in the main text too)

Line 89: rephrase

Line 96: repeats with Line 92, also Duretz et al 2016/2016a?

Line 105: based on the sentence the crust should be: 3*5+4*5 = 35 km thick. But a sentence earlier it is 33km

Line 103: what is the mathematical expression for the perturbation? in case the model needs to be reproduced?

Line 111: more details on the rheology? Indicate appendix A for reference

Line 113: reference to "corresponding laboratory flow law estimates"?

Line 113-114: rephrase. i.e. The mantle lithosphere is rheologically stronger than the mantle asthenosphere due to the temperature gradient.

Line 120: what is the motivation for alternating between calcites and pelites for sedimentation algorithm?

Line 130 - give reference to Table 1.

Line 133: viscosity cutoff for M1 is not provided to understand the difference.

Line 134: realistic value? Are the other values not realistic?

Line 148: Figure 2

-> can define a variable F = 2xtau_II

Line 160: introduce the horizontal driving force per unit length, but what is it proxy for?

Line 168: you can't see to a depth of 660 km as indicated

Line 195: values

Line 197: what is the delta GPE showing? (Info given in appendix)

Line 224: reference to fig 9a, yet that figure is for extension stage.

Paragraph 220-225: confusing.

Line 228: what is mechanical heterogeneity? increases the strength of the weak layers

Line 233: breaks later than the continental. after gives the impression of location.

Line 234: what do you mean ' Mantle convection does not establish as early as rifting and crustal separation.'?

Lines 243, 245: use of realistic. close to the Ra estimated for the Earth.

Line 250: which modulates mantle velocities.

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Discussion paper

Line 250-254: why the discussion on time step size (a numerical feature) here?

Lines 255-257: which simulation results are the authors referring here?

Paragraph 258: reference figure 5e,j in this paragraph. Also, maybe plot density averages in passive margins/exhumed mantle separately?

Line 272: you jump from density differences to values of tectonic forces. An additional sentence needs to connect them (i.e. estimate the buoyancy force due to modelled density differences). How much is needed to initiate subduction? (a similar calculation is done in line 315)

Paragraph 280: this should come before the Cloos 1993 paragraph

Line 286: yes, but under convergence

Line 294-295: total convergence is double sided, while in M1 is single-sided (asymmetric). Not clear why subduction initiation is stable only in M1. Convection cell size important? how about thickness of lithosphere at the point? M2-M5 are quite symmetric and they all have Ra_avg $\sim$1e5, while M1 has Ra_avg$\sim$1e6. That should have an effect.

Line 312-315: - suction force induced by down-welling in the convection cell in M1. What is the similar force in the other simulations?

Line 330: not sure what the reference is for. The double-subduction term was not coined by those workers.

Line 332: sentence not clear. Which simulation are you referring? would say M2-5 are more or less symmetric double subduction

Line 343: onset of convergence - unclear when this happens?

Line 357-361: use of 'realistic'

Paragraph 395: this paragraph should be in the methods, as it motivates/explains your

model domain until 660 km. The sentence 'The convective patterns simulated in our study are in agreement with these observations.' is irrelevant because you don't model the lower mantle.

Paragraph 410: this should come earlier - I had questions about it earlier. on previous work on subduction initiation.

Line 418: most definitely will have an impact

Paragraph 430: and melting

Line 444-446: rephrase/simplify.

Figures and Tables: Table 1: thermal conductivity should be 'k' without the 'th' subscript. The authors can also provide the formula for the Ra number in the main text. How was the Ra_avg calculated?

Table 2: there should be a column 'Description' to describe the meaning of each parameter i.e. 'rho0' - reference density. Use k instead of k_th for thermal conductivity. What is dry/wet mantle? I assume wet mantle applies only to M6? Plastic and elastic parameters are also listed. Not very clear in the main text.

Figure 4: why plot the vertical velocity field separate from the horizontal? should plot arrow/streamlines field to see the convection cells.

Figure 10: should be merged with Figure 4. One column velocity, one column temperature.

Figure 5: What if you plot the profiles at the rift axis (within a distance) vs off-axis on either flanks of the rifts? Caption: g-j show enlarged areas.

Figure 6: legend: temp contours are red.

Figure 8: the line plots are not entirely clear. Maybe use a dotted line instead of dashed line? and same thickness.

Appendix A

Line 481: that's a strange notation of i,j indices (Einstein notation).

Eq A2: if written in Einstein notation, then vectors are written in terms of scalar components (a_i should not be bold). Same in Line 482 a=[0,g]. -> revise this appendix for completeness of sentences, and explanation of all parameters. For example, what is Ap, tauP etc. Gamma value? in eq A10

Appendix B

Paragraph 531: rephrase

Line 560: not clear

Appendix C

Line 595: gamma_T=1?

Line 601: g=10^4?

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