Review Report

Habel et al., Upper-plate Shortening and Mountain-building in the Context of Mantle-driven Oceanic Subduction, TEKTONIKA, 2023.

Table of Contents

1st Round of Revisions

Decision Letter

Dear Dr. Replumaz and co-authors,

Thank you for submitting your manuscript "*Upper-plate shortening and Andean-type mountain-building in the context of mantle-driven oceanic subduction*" to Tektonika. We have now received 2 reviews of your manuscript. Based on these reviews, along with our own assessment, our decision is: Resubmit for review.

The first reviewer had some concerns regarding the thickness of the upper plate in your models and whether individual parameters such as slab shape could be isolated from other effects. The second reviewer had more substantial concerns about whether this work is applicable to the Andes (as well as other minor concerns). Tektonika are also working to ensure all figures are fully accessible to our readership, so we ask you to pay particular attention to the colour schemes of the following figures and modify them if possible to make them accessible to those with monochromacy:

- Figure 3 topography map,
- Figure 4 yellow box/line,
- Figure 5 line colours (perhaps different line types could help here)

We recommend this colour-blindness simulator to check accessibility of colour schemes:https://www.color-blindness.com/coblis-color-blindness-simulator/.

We ask that you carefully address each reviewer's concerns in your revised manuscript; in particular, we ask that you either add more justification for the Andes comparison or remove it as a focus of the manuscript. One reviewer has used our review form to provide their comments, and we ask that when submitting revisions you use this review form to answer their comments. The other reviewers comments should be responded to in a traditional response letter. We ask you to submit both a copy of your revised manuscript, with changes clearly marked, and a clean version, during your resubmission.

We hope that you will be able to address the reviewers' concerns and submit a revised manuscript within 2 months (please note that Tektonika does not impose a time limit on submitting revised manuscripts, this suggested timeline is provided as a guide only). If you require additional time for your resubmission, please don't hesitate to get in touch with the editorial team to discuss a revised timeline. Feel free to reach out at any stage if anything is unclear.

Thank you for giving us the opportunity to consider your work.

Yours sincerely,

Noah Phillips, PhD, Associate Editor - Tektonika

Janine Kavanagh, PhD, Executive Editor - Tektonika

Comments by Reviewer 1

The authors did a great job writing this paper. It is clear and well-written and the illustrations are easy to understand.

I have two comments/issues, that I wish the authors would address in a revised version of the paper:

1) The thickness of the continental plate. 53 km thickness means a very very thinned lithosphere. Of course, it is possible to thin the lithosphere to this amount, but this kind of thinning usually happens in restricted areas, as back-arc basins can only effectively form when smaller segments of oceanic trenches retreat fast (e.g. Magni et al., 2014, Magni 2020). Also, the effect of back-arc extension is supposedly included twice in some of the models: in the overall thickness of the upper plate, and the in the weaker areas within the upper plate. Understandably, the thinner upper plate has been probably chosen so that deformation in the upper plate is observable. The authors can reason, that the homogeneous, linear rheology of the lithosphere, and the slightly lower subduction rates (when compared to nature) require the thinner (and hence weaker) upper plate.

2) The authors multiple times highlight that the slab shape is really more of an effect of the force balance rather than the driving of deformation. This might be true, however, when looking at the models where there is some variation along the trench, we do observe that slab shape, convergence, and upper plate deformation are all tightly linked. Maybe if the force balance would be a bit more examined for models like SA05, we could see how the increased coupling between the upper and lower plate (maybe due to flatter slabs or slightly smaller initial distance, or small deviations in upper plate thickness) affects the convergence rate and therefore the upper plate deformation (which is visibly different across the weak zone in SA05 on some snapshots).

I recommend that if the authors address these comments, the article will be in good shape for publishing.

Á. Király

Comments by Reviewer 2

Please see the attached review form for the full review. Below I pasted the top section of this review. In summary, the models are really interesting and the paper is very well-written and clear. However, I think additional work is needed to either more robustly justify the Andean application or, if this is not feasible, take this out (i.e., turn this into a general subduction dynamics study).

~~~~~~~~~~

Overview: Habel and co-authors present 3-D analogue models of subduction that explore the effects of background upper mantle flow on subduction dynamics and upper plate stress regime in oceanic subduction settings. The main finding is that this imposed background mantle flow – which pushes the slab into the overriding plates – is needed to produce significant upper plate compression/shortening. These results are then applied to Andean orogenesis; the authors argue that background mantle flow is a key process for Andean shortening.

Assessment: I am only aware of one study (from the same group) that used analog models to investigate the impact of background flow on dynamic subduction evolution. The novelty of the experiments (and the relatively clear explanations of the results) is therefore a significant strength of the study. The paper is also well written with clear figures, illustrations, and organization. However, the applicability of these models to the Andes is, in my opinion, hard to justify. That's because one of the two plates is always "fixed" and the mantle flow in the successful model is directed towards the upper plate and extremely rapid (not clear to me how these aspects relate to the Andean situation). I think the authors need to either add more justification for this comparison (and probably additional models – e.g., lower flow velocity and/or both free plates) or remove it as a focus.

Section A: Overview of manuscript

A1) Overall evaluation, general comments & summary

A1.1) Reviewer's comments
~~~~~~~~~~

A1.1.1) General evaluation and publication suggestion – Required:

Please use this space to describe, in your own words, the core subject of the submission and your overall assessment of its suitability for publication.

Overview: Habel and co-authors present 3-D analogue models of subduction that explore the effects of background upper mantle flow on subduction dynamics and upper plate stress regime in oceanic subduction settings. The main finding is that this imposed background mantle flow – which pushes the slab into the overriding plates – is needed to produce significant upper plate compression/shortening. These results are then applied to Andean orogenesis; the authors argue that background mantle flow is a key process for Andean shortening.

Assessment: I am only aware of one study (from the same group) that used analogue models to investigate the impact of background flow on dynamic subduction evolution. The novelty of the experiments (and the relatively clear explanations of the results) is therefore a significant strength of the study. The paper is also well written with clear figures, illustrations, and organization. However, the applicability of these models to the Andes is, in my opinion, hard to justify. That's because one of the two plates is always "fixed" and the mantle flow in the successful model is directed towards the upper plate and extremely rapid (not clear how these aspects relate to the Andean situation). I think the authors need to either add more justification for this comparison (and probably additional models – e.g., lower flow velocity and/or both free plates) or remove it as a focus.

A1.1.2) What does the submission need to be publishable? (select as needed; comment for all cases)

- ☐ No changes required
- ☐ Rewriting
- ☒ Reorganising
- ☒ More data/figures
- ☐ Condensing
- ☒ Reinterpretation
- ☒ Other

Comments:

As mentioned, I think significant reorganization, and discussion, is needed to address the issues with the model-Andean comparison (more details later).

Independent of this, the presentation of the models could be improved. The model numbers do not increase as you progress through the text (e.g., SA03 first, then SA01), which is a bit confusing. Also, you go from a fixed upper plate model with no mantle flow (SA03) straight to a fixed subducting plate model with oceanic-directed flow (SA01). This is changing two important variables and so a bit hard to isolate the important processes. I would reorganize so that you are only changing one thing at a time.

A1.1.3) Can the submission be improved by reducing/adding any of the following? (select as needed; comment for all cases)

☒ Text

☐ Table

☒ Figures

☐ Supplementary material

Comments:

Additional text needed to justify the model setup, Andean comparison, and place the work into the context of previous studies (more later).

In general, the figures are clear and well done. You might consider splitting figures 4 and 5 into two separate figures each (e.g., one for all the uniform upper plate models; one for the tests with variable upper plate strengths including the corresponding uniform strength one), but also OK as is.

~~**A1.1.4) Please complete the following section if you recommend that the submission is NOT appropriate for publication (select as needed; comment if a box is selected)**~~

~~☐ Quality is poor~~

~~☒ Research is not reproducible~~

~~☐ Other~~

~~***Comments:***~~

A1.2) Author(s) Responses:

A2) Summary of main merits and main points of improvement

A2.1) Reviewer's comments

Please describe below in a few sentences (100 to 300 words) the main merits of the submission and suggestions for improvements.

The main merits I have found are...

- The study employs an original analogue modelling approach.
- To my knowledge, these are the first 3-D models that directly analyse how imposed mantle flow affects upper plate stress state.
- The paper is well written, and the figures are clear.

The main points of improvement I have found are...

- The main thing, in my opinion, is that the authors should justify how the model choices (very fast flow towards the upper plate; a fixed upper plate) are consistent with the Andes. If this is not possible, I think the study could be re-formulated as a general subduction dynamics paper.
- The models could be presented more logically. This refers mainly to the order that they are presented and how they are labelled.
- The study misses some important references about the aspects of subduction dynamics they examine. Notably about both upper plate stress state and fixed vs. free plates.

A2.2) Author's responses:

[Free form box]

Section B: Detailed evaluation of manuscript

B1) Title and abstract

B1.1) Reviewer's comments

*These statements are a **guide** to what good* Titles *and* Abstracts include. *Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

The *Title* describes the main topic of the manuscript **accurately** — [YES] / [**NO**]

The *Title* describes the main topic of the manuscript **succinctly** — [**YES**] / [NO]

The *Title* includes **appropriate key terms** — [**YES**] / [NO]

The *Abstract* includes a **clear aim and rationale** — [**YES**] / [NO]

The *Abstract* supports the rationale with **sufficient background information** — [**YES**] / [NO]

The *Abstract* includes a **well-balanced description of the methods** — [YES] / [**NO**]

The *Abstract* describes the **main results sufficiently and adequately** — [**YES**] / [NO]

The *Abstract* clearly describes the **importance/impact of the study** — [**YES**] / [NO]

The *Abstract* clearly states the **conclusions of the study** — [**YES**] / [NO]

The *Abstract* is **clear** and **well structured** — [**YES**] / [NO]

Comments:

I have queried the title because is mentions "Andean-type mountain building" and, as mentioned, I'm sceptical of this application for these models.

B1.2) Author's responses

[Free form box]

B2) Introduction

B2.1) Reviewer's comments

*These statements are a **guide** to what good* Introductions *include. Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

The *Introduction* provides **sufficient background and context** for the study — [YES] / [**NO**]

The *Introduction* describes the **aim/hypothesis/rationale** clearly, providing **sufficient context** — [**YES**] / [NO]

The *objective/hypothesis/rationale* **flows logically from the background** information — [**YES**] / [NO]

The *Introduction* describes the study's **objective and approach** (last paragraph) — [**YES**] / [NO]

The *Introduction* contains **relevant, suitable citations** — [**YES**] / [NO]

The *Introduction* is **organized effectively** — [YES] / [**NO**]

Comments:

I think the introduction is, overall, well written and helpful. The "nos" relate to two easily fixable points:

i) You are missing quite a few citations about upper plate stress state, convective cell dimensions/slab penetration, etc. I'll provide some of them in the line-by-line comments.

ii) The third (and last) paragraph is the least clear – it's too long and does not flow. I would break it up and try and make it more pointed with respect to what you want the reader to know about previous modelling.

B2.2) Author's responses

[Free form box]

B3) Data and methods

B3.1) Reviewer's comments

These statements are a ***guide*** *to what good* Method *sections include and good practices for* Dataset *accessibility. Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

The *Methods* are described **concisely and with enough detail** for reproducibility — [YES] / [**NO**]

Necessary information about **data sources/acquisition/processing** is included — [**YES**] / [NO]

Data used are accessible via either supplementary files or links in the data availability statement — [**YES**] / [NO]

The *Dataset and/or Methods* are **organized effectively** — [**YES**] / [NO]

Comments:

I recommend more info, or citations, about how the viscometer and density measurements are taken and how the laboratory values are scale up to real Earth values. This could go in a supplementary section. E.g., in "Scaling laws", it would be useful to have the equation for the time scale factor (and perhaps an equivalent of Table 1 with the "real Earth" values).

Also, what are the slab-mantle viscosity contrasts? This would be useful to compare to previous modelling studies.

B3.2) Author's responses

[Free form box]

B4) Results

B4.1) Reviewer's comments

These statements are a ***guide*** *to what good* Result sections *include. Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

The *Results* findings are **supported by data** — [**YES**] / [NO]

The *Results* findings are presented **clearly and succinctly** — [**YES**] / [NO]

The text in the *Result* section **cites tables and figures appropriately** — [**YES**] / [NO]

The *Results* directly **relate to the study objectives** — [**YES**] / [NO]

The *Results* present **data for all the approaches** described in the *Methods* section — [**YES**] / [NO]

The *Results* **text belongs to the Results section**, not to *Introduction*, *Methods*, or *Discussion.* — [**YES**] / [NO]

The *Results* section is **organised effectively** — [YES] / [**NO**]

Comments:

Here, my only suggestion is to re-organize to make the paper flow more naturally through the 5 models. This could be done by presenting the models in a different order and/or renaming the model runs.

B4.2) Author's responses

[Free form box]

B5) Discussion and conclusions

B5.1) Reviewer's comments

*These statements are a **guide** to what good* Discussions *and* Conclusions *include. Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

The *Discussion* is **focused on the objectives** of the study — [**YES**] / [NO]

The *Discussion* **addresses all major results** of this study, which are shown in *Results* — [**YES**] / [NO]

The *Discussion* section makes **comparisons with other studies** that are relevant and informative — [**YES**] / [NO]

The *Discussion* section properly identifies all **speculative statements** — [**YES**] / [NO]

The *Discussion* section presents the **implications of the study** persuasively — [YES] / [**NO**]

The *Discussion* section **highlights novel contributions** appropriately — [**YES**] / [NO]

The *Discussion* section **addresses the limitations** of the study appropriately — [YES] / [**NO**]

The *Discussion* section is **organised effectively** — [**YES**] / [NO]

The *Conclusions* are **consistent** with and **summarise** the rest of the manuscript — [**YES**] / [NO]

The *Conclusions* are **supported by the data** in *Results* and **follow logically** from the *Discussion* — [YES] / [**NO**]

The *Conclusions* are **clear and concise** — [**YES**] / [NO]

Comments:

The first discussion section (4.1) makes the case that imposed mantle flow is needed to produce upper plate shortening. Previous dynamic numerical modelling studies have shown that – in the case of a free overriding plate (probably more applicable to the Andes) – compression naturally occurs in the forearc region with extension further away (e.g., Capitanio et al., 2010, Tectonophys.; Schellart and Moresi, 2013, JGR; Holt et al., 2015, GJI). So, I think this discussion should be reformulated and this existing literature discussed. I think the authors should also consider previous studies that examine the effects of far-field mantle flow on subduction dynamics (e.g., Chertova et al., 2018, EPSL; Ficini et al., 2017, Sci. Reports) and fixed vs. free upper plates (Capitanio et al., 2010, Tectonophys; Holt et al., 2015 GJI).

The rest of the discussion deals with the applicability to the Andes. To make a successful comparison, more discussion about why the following is applicable to the Andes is needed:

- Why would we expect South America to behave (to first order) as a fixed upper plate with vigorous mantle flow pushing on the subduction zone from the west? In Section 4.2 and Figure 2, the fixed upper plate boundary condition is taken to mimic ridge push. I am confused by this, as it produces a resisting (not driving) force to trench retreat. See the above-mentioned studies for more detailed exploration of this. Also, the studies you cite earlier on in the paper (e.g., Husson et al., 2012) argue for mantle flow from the East (below the Atlantic). So, how does this preferred model (fixed OP, eastward flow) provide boundary conditions that are relevant to the Andes? Are there convection models that suggest vigorous eastward flow beneath the Nazca plate?
- Also, is the vigour of the imposed mantle flow velocities (greater than 4x the plate velocities) physical? This also warrants discussion.

B5.2) Author’s responses

[Free form box]

B6) Figures, tables and citations

B6.1) Reviewer's comments

*These statements are a **guide** to what good* Figures *and* Tables *include and how they are presented. Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

Tables and *Figures* are **ordered logically** and **numbered sequentially** — [**YES**] / [NO]

Tables and *Figures* have **captions that explain** all their major features — [**YES**] / [NO]

Tables and *Figures* have **captions that complement** the information in the main text — [**YES**] / [NO]

Tables and *Figures* present data that **relate** to the study objective — [**YES**] / [NO]

Tables and *Figures* present data that are **consistent** with and support the description of results — [**YES**] / [NO]

Tables and *Figures* have **succinct and informative titles** — [**YES**] / [NO]

Figures are **accessible** (elements are clearly labelled, accessible colour palettes, colour contrasts, font size legible, etc.…) — [**YES**] / [NO]
Please, check our [Figure guidelines]

Figures with **maps or cross-sections** contain all **elements to be understood** (north arrow orientation, scale, visible coordinates, sufficient coordinate grid intercepts) — [**YES**] / [NO]

Figures with **maps** have **sufficient location information** (in the map or caption) — [**YES**] / [NO]

Cross-sections have clear labels for **scale and coordinates** at ends and within-section kinks — [**YES**] / [NO]

All georeferenced elements are provided in common format (.shp, .geotiff, .kml) [in an open-access repository] — [**YES**] / [NO]

Citations throughout are relevant, suitable, and comprehensive — [**YES**] / [NO]

Comments:

-

B6.2) Author’s responses

[Free form box]

Section C: Additional comments

C1) Minor/line-numbered comments

C1.1) Reviewer’s comments

No line numbers in the manuscript makes it a bit tricky (something to add in the event of a re-submission) but I’ll try and identify by paragraph/section:

Introduction, last paragraph (pg. 3): Some Dvorkin et al. 1993 (Tectonophys) for one of the original toroidal flows references.

Introduction, last paragraph (pg. 3): “Kyrali” – spelling

Introduction, last paragraph (pg. 3): Influence of slab penetration on upper plate stress – see Holt et al (2015) for an earlier reference that demonstrates this. Also relevant for the effect of upper plate strength and mobility (fixed vs. free) on stress state.

Introduction, last paragraph (pg. 4): Sentence being “On the contrary…” – I found this sentence placement a bit strange. These are mainly numerical models – but placed in the analogue modelling section – and, to my understanding, the extension/shortening is due to slab folding on top of the lower model boundary. Is this relevant to your study?

Introduction, last paragraph (pg. 4): The statement about the Coltice study is too vague. Not sure what “dragged” and “Earth-like continents” are in this context.

Introduction, last paragraph (pg. 4): It is worth clearly stating how this study is different to Guillaume et al. (2021).

Methods, pg 6: What exactly does “quasi-Newtonian” mean here?

Scaling laws, pg 10, first sentences: I don’t follow this logic about the 10 cm/yr imposed mantle velocity. Even if the plate velocities were greater in the past, you are still imposing mantle flow > x4 the plate velocities – I think it is this relative value that matters.

Forces section, pg 10: Conrad and Hager (1999) is a good reference for viscous plate bending force and plate coupling shear force. I think the mantle force (pressure force) should be drawn as being perpendicular to the slab.

Forces section, pg 11: Which “published” experiments?

Figure 4: You draw the resisting forces due to fixing the plates pointing towards the trench. They should be in the opposite direction (i.e., a resisting rather than a driving force).

Measurements section, pg 12: “considering material as incompressible” – is it incompressible? Sorry, confused by this phrasing.

Measurements section, pg 13: “limits” -> “limitations”

Figure 5: I would add black lines for the vertical and horizontal axes. The x-axis font is larger than the y-axis font.

Results, pg 22: What is the viscosity contrast of the “weak silicone” relative to the regular/strong lithosphere?

Discussion, pg 24: I think the main limitations are actually: i) you fix the plates; ii) you impose a really high mantle flow velocity. Could you run tests without these restrictions?

Discussion, pg 29: “Chile” spelling.

Discussion, pg 29: I agree east-directed mantle flow case is most analogous to the Andean situation, but only if the subducting plate was free. Perhaps a good place to compare with either previous literature/models or new runs with free plates.

Discussion, pg 29: Again, I don’t think a fixed boundary condition is equivalent to ridge push.

Discussion, pg 31, first sentence/second paragraph: Sorry - given the rapid flow velocity and fixed boundary conditions - I don’t think the Andean boundary conditions are satisfied.

C1.2) Author’s responses

[Free form box]

C2) Other remarks

C2.1) Reviewer’s comments

[Free form box]

C2.2) Author’s responses

[Free form box]

Authors' Reply to Reviewer 1

Reviewer 1

The authors did a great job writing this paper. It is clear and well-written and the illustrations are easy to understand. I have two comments/issues, that I wish the authors would address in a revised version of the paper:

1) The thickness of the continental plate. 53 km thickness means a very very thinned lithosphere. Of course, it is possible to thin the lithosphere to this amount, but this kind of thinning usually happens in restricted areas, as back-arc basins can only effectively form when smaller segments of oceanic trenches retreat fast (e.g. Magni et al., 2014, Magni 2020). Also, the effect of back-arc extension is supposedly included twice in some of the models: in the overall thickness of the upper plate, and the thickness in the weaker areas within the upper plate. Understandably, the thinner upper plate has been probably chosen so that deformation in the upper plate is observable. The authors can reason, that the homogeneous, linear rheology of the lithosphere, and the slightly lower subduction rates (when compared to nature) require the thinner (and hence weaker) upper plate.

Indeed, despite the fast imposed mantle flow, once scaled to natural dimensions, the convergence rate in our models is relatively low (~2 $cm.yr^{-1}$ in model 5, Figure 5A) when compared to recent Andean conditions where it is ~8 $cm.yr^{-1}$. To be able to observe and quantify upper plate deformation, both horizontally and vertically, we decided to consider a "thin" upper plate more prone to deform because of the linear rheology of the plate. This relatively weak upper plate allows us to obtain almost similar rates for shortening rates in the models (~0.7 $cm.yr^{-1}$ in model 5) with respect to the long-term rate of Andean shortening (~1 $cm.yr^{-1}$, e.g. Brooks et al., 2011; Oncken et al, 2006). We now better explain why we used a thin overriding plate in the scaling laws section 2.2 (Lines 165-173) and when comparing our results with the Andes (section 4.2, lines 500-515).

2) The authors multiple times highlight that the slab shape is really more of an effect of the force balance rather than the driving of deformation. This might be true, however, when looking at the models where there is some variation along the trench, we do observe that slab shape, convergence, and upper plate deformation are all tightly linked. Maybe if the force balance would be a bit more examined for models like SA05, we could see how the increased coupling between the upper and lower plate (maybe due to flatter slabs or slightly smaller initial distance, or small deviations in upper plate thickness) affects the convergence rate and therefore the upper plate deformation (which is visibly different across the weak zone in SA05 on some snapshots).

In fact, for models 2, 4 and 5, although the slab dip varies during the experiment (Figure 5D), the deformation is constant through time (Figure 5B&C). As we discuss in the text, it suggests that shortening of the upper plate is primarily controlled by the imposed mantle flow and boundary conditions, rather than by the shape of the slab (Figure 6). Even though we do not discard the idea that flatter slabs favor a stronger coupling between the subducting and overriding plates as it has been proposed for the Andes (e.g. Capitanio et al., 2011; Molnar et Atwater, 1978; Martinod et al., 2010, 2020), in our experiments, the slab geometry is found to adjust (in cases variably) to mantle boundary conditions, rather than to be the primarily causal parameter leading to upper plate shortening.

Nevertheless, discussing in detail the force balance in our analogue experiments is less easy than in numerical experiments in which parameters such as the resistance along the slab interface can be directly extracted. Many hypotheses can be done, but cannot be constrained with analogue models. We insist on the fact that we cannot reproduce the conditions for flat slabs in our experiments, but in any case they do not appear to be necessary to generate shortening within our experimental upper plates (Lines 516-531).

I recommend that if the authors address these comments, the article will be in good shape for publishing.

We thank A. Kiraly for these various interesting comments and hope that our revisions appropriately answer these various points.

Authors' Reply to Reviewer 2

Reviewer 2

Section A: Overview of manuscript

A1) Overall evaluation, general comments & summary

A1.1) Reviewer's comments

A1.1.1) General evaluation and publication suggestion – Required:

Please use this space to describe, in your own words, the core subject of the submission and your overall assessment of its suitability for publication.

Overview: Habel and co-authors present 3-D analogue models of subduction that explore the effects of background upper mantle flow on subduction dynamics and upper plate stress regime in oceanic subduction settings. The main finding is that this imposed background mantle flow – which pushes the slab into the overriding plates – is needed to produce significant upper plate compression/shortening. These results are then applied to Andean orogenesis; the authors argue that background mantle flow is a key process for Andean shortening.

Assessment: I am only aware of one study (from the same group) that used analogue models to investigate the impact of background flow on dynamic subduction evolution. The novelty of the experiments (and the relatively clear explanations of the results) is therefore a significant strength of the study. The paper is also well written with clear figures, illustrations, and organization. However, the applicability of these models to the Andes is, in my opinion, hard to justify. That's because one of the two plates is always "fixed" and the mantle flow in the successful model is directed towards the upper plate and extremely rapid (not clear how these aspects relate to the Andean situation). I think the authors need to either add more justification for this comparison (and probably additional models – e.g., lower flow velocity and/or both free plates) or remove it as a focus.

A1.1.2) What does the submission need to be publishable? (select as needed; comment for all cases)

- ☐ No changes required
- ☐ Rewriting
- ☒ Reorganising
- ☒ More data/figures

☐ Condensing

☒ Reinterpretation

☒ Other

Comments:

As mentioned, I think significant reorganization, and discussion, is needed to address the issues with the model-Andean comparison (more details later).

Independent of this, the presentation of the models could be improved. The model numbers do not increase as you progress through the text (e.g., SA03 first, then SA01), which is a bit confusing. Also, you go from a fixed upper plate model with no mantle flow (SA03) straight to a fixed subducting plate model with oceanic-directed flow (SA01). This is changing two important variables and so a bit hard to isolate the important processes. I would reorganize so that you are only changing one thing at a time.

A1.1.3) Can the submission be improved by reducing/adding any of the following? (select as needed; comment for all cases)

☒ Text

☐ Table

☒ Figures

☐ Supplementary material

Comments:

Additional text needed to justify the model setup, Andean comparison, and place the work into the context of previous studies (more later).

In general, the figures are clear and well done. You might consider splitting figures 4 and 5 into two separate figures each (e.g., one for all the uniform upper plate models; one for the tests with variable upper plate strengths including the corresponding uniform strength one), but also OK as is.

~~**A1.1.4) Please complete the following section if you recommend that the submission is NOT appropriate for publication (select as needed; comment if a box is selected)**~~

~~☐ Quality is poor~~

~~☒ Research is not reproducible~~

☐ ~~Other~~

~~***Comments:***~~

A1.2) Author(s) Responses:

We improve the presentation of the models following the suggestions of Reviewer 2, we change the model numbers and names, reorganize the presentation so that only one parameter changes between each successive presented model and split figure 4 in 2.

To address the issues with the model-Andean comparison, we remove the comparison from the title of the papier and deeply rewrite the discussion.

A2) Summary of main merits and main points of improvement

A2.1) Reviewer's comments

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The main merits I have found are...

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The main points of improvement I have found are...

- The main thing, in my opinion, is that the authors should justify how the model choices (very fast flow towards the upper plate; a fixed upper plate) are consistent with the Andes. If this is not possible, I think the study could be re-formulated as a general subduction dynamics paper.
- The models could be presented more logically. This refers mainly to the order that they are presented and how they are labelled.
- The study misses some important references about the aspects of subduction dynamics they examine. Notably about both upper plate stress state and fixed vs. free plates.

A2.2) Author's responses:

We improve the presentation of the models following the suggestions of Reviewer 2, we change the model numbers and names, reorganize the presentation so that only one parameter changes between each successive presented model and split figure 4 in 2.

In the revised version, we add and discuss the references suggested by Reviewer 2, in particular models with free plates.

Section B: Detailed evaluation of manuscript

B1) Title and abstract

B1.1) Reviewer's comments

*These statements are a **guide** to what good* Titles *and* Abstracts include. *Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

The *Title* describes the main topic of the manuscript **accurately** — [YES] / [**NO**]

The *Title* describes the main topic of the manuscript **succinctly** — [**YES**] / [NO]

The *Title* includes **appropriate key terms** — [**YES**] / [NO]

The *Abstract* includes a **clear aim and rationale** — [**YES**] / [NO]

The *Abstract* supports the rationale with **sufficient background information** — [**YES**] / [NO]

The *Abstract* includes a **well-balanced description of the methods** — [YES] / [**NO**]

The *Abstract* describes the **main results sufficiently and adequately** — [**YES**] / [NO]

The *Abstract* clearly describes the **importance/impact of the study** — [**YES**] / [NO]

The *Abstract* clearly states the **conclusions of the study** — [**YES**] / [NO]

The *Abstract* is **clear** and **well structured** — [**YES**] / [NO]

Comments:

I have queried the title because is mentions "Andean-type mountain building" and, as mentioned, I'm sceptical of this application for these models.

B1.2) Author's responses

We change the title to "Upper-plate shortening and mountain-building in the context of mantle-driven oceanic subduction: insights from analogue modelling". We also modify the last sentence of the abstract, to be more precise for the comparison with the Andes, according to the comments of Reviewer 2.

B2) Introduction

B2.1) Reviewer's comments

These statements are a ***guide*** *to what good* Introductions *include. Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

The *Introduction* provides **sufficient background and context** for the study — [YES] / [**NO**]

The *Introduction* describes the **aim/hypothesis/rationale** clearly, providing **sufficient context** — [**YES**] / [NO]

The *objective/hypothesis/rationale* **flows logically from the background** information — [**YES**] / [NO]

The *Introduction* describes the study's **objective and approach** (last paragraph) — [**YES**] / [NO]

The *Introduction* contains **relevant, suitable citations** — [**YES**] / [NO]

The *Introduction* is **organized effectively** — [YES] / [**NO**]

Comments:

I think the introduction is, overall, well written and helpful. The "nos" relate to two easily fixable points:

iii) You are missing quite a few citations about upper plate stress state, convective cell dimensions/slab penetration, etc. I'll provide some of them in the line-by-line comments.

iv) The third (and last) paragraph is the least clear – it's too long and does not flow. I would break it up and try and make it more pointed with respect to what you want the reader to know about previous modelling.

B2.2) Author's responses

We add the citations suggested. We removed the sentences related to the work of Husson et al (2012) and Coltice et al (2019) to simplify the last paragraph.

B3) Data and methods

B3.1) Reviewer's comments

These statements are a ***guide*** *to what good* Method *sections include and good practices for* Dataset *accessibility. Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

The *Methods* are described **concisely and with enough detail** for reproducibility — [YES] / [**NO**]

Necessary information about **data sources/acquisition/processing** is included — [**YES**] / [NO]

Data used are accessible via either supplementary files or links in the data availability statement — [**YES**] / [NO]

The *Dataset and/or Methods* are **organized effectively** — [**YES**] / [NO]

Comments:

I recommend more info, or citations, about how the viscometer and density measurements are taken and how the laboratory values are scale up to real Earth values. This could go in a supplementary section. E.g., in "Scaling laws", it would be useful to have the equation for the time scale factor (and perhaps an equivalent of Table 1 with the "real Earth" values).

Also, what are the slab-mantle viscosity contrasts? This would be useful to compare to previous modelling studies.

B3.2) Author's responses

The viscosity of the weak lithosphere is ~16% of the strong lithosphere viscosity. We add this precision in the text.

B4) Results

B4.1) Reviewer's comments

*These statements are a **guide** to what good* Result sections *include. Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

The *Results* findings are **supported by data** — [**YES**] / [NO]

The *Results* findings are presented **clearly and succinctly** — [**YES**] / [NO]

The text in the *Result* section **cites tables and figures appropriately** — [**YES**] / [NO]

The *Results* directly **relate to the study objectives** — [**YES**] / [NO]

The *Results* present **data for all the approaches** described in the *Methods* section — [**YES**] / [NO]

The *Results* **text belongs to the Results section**, not to *Introduction*, *Methods*, or *Discussion.* — [**YES**] / [NO]

The *Results* section is **organised effectively** — [YES] / [**NO**]

Comments:

Here, my only suggestion is to re-organize to make the paper flow more naturally through the 5 models. This could be done by presenting the models in a different order and/or renaming the model runs.

B4.2) Author's responses

We improve the presentation of the models following the suggestions of Reviewer 2, we change the model numbers and names, reorganize the presentation so that only one parameter changes between models and split figure 4 in 2.

B5) Discussion and conclusions

B5.1) Reviewer's comments

*These statements are a **guide** to what good* Discussions *and* Conclusions *include. Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

The *Discussion* is **focused on the objectives** of the study — [**YES**] / [NO]

The *Discussion* **addresses all major results** of this study, which are shown in *Results* — [**YES**] / [NO]

The *Discussion* section makes **comparisons with other studies** that are relevant and informative — [**YES**] / [NO]

The *Discussion* section properly identifies all **speculative statements** — [**YES**] / [NO]

The *Discussion* section presents the **implications of the study** persuasively — [YES] / [**NO**]

The *Discussion* section **highlights novel contributions** appropriately — [**YES**] / [NO]

The *Discussion* section **addresses the limitations** of the study appropriately — [YES] / [**NO**]

The *Discussion* section is **organised effectively** — [**YES**] / [NO]

The *Conclusions* are **consistent** with and **summarise** the rest of the manuscript — [**YES**] / [NO]

The *Conclusions* are **supported by the data** in *Results* and **follow logically** from the *Discussion* — [YES] / [**NO**]

The *Conclusions* are **clear and concise** — [**YES**] / [NO]

Comments:

The first discussion section (4.1) makes the case that imposed mantle flow is needed to produce upper plate shortening. Previous dynamic numerical modelling studies have shown that – in the case of a free overriding plate (probably more applicable to the Andes) – compression naturally occurs in the forearc region with extension further away (e.g., Capitanio et al., 2010, Tectonophys.; Schellart and Moresi, 2013, JGR; Holt et al., 2015, GJI). So, I think this discussion should be reformulated and this existing literature discussed. I think the authors should also consider previous studies that examine the effects of far-field mantle flow on subduction dynamics (e.g., Chertova et al., 2018, EPSL; Ficini et al., 2017, Sci. Reports) and fixed vs. free upper plates (Capitanio et al., 2010, Tectonophys; Holt et al., 2015 GJI).

The rest of the discussion deals with the applicability to the Andes. To make a successful comparison, more discussion about why the following is applicable to the Andes is needed:

- Why would we expect South America to behave (to first order) as a fixed upper plate with vigorous mantle flow pushing on the subduction zone from the west? In Section 4.2 and Figure 2, the fixed upper plate boundary condition is taken to mimic ridge push. I am confused by this, as it produces a resisting (not driving) force to trench retreat. See the above-mentioned studies for more detailed exploration of this. Also, the studies you cite earlier on in the paper (e.g., Husson et al., 2012) argue for mantle flow from the East (below the Atlantic). So, how does this preferred model (fixed OP, eastward flow) provide boundary conditions that are relevant to the Andes? Are there convection models that suggest vigorous eastward flow beneath the Nazca plate?
- Also, is the vigour of the imposed mantle flow velocities (greater than 4x the plate velocities) physical? This also warrants discussion.

B5.2) Author's responses

We deeply rewrite the discussion according to Reviewer 2 comments.

We agree that the imposed mantle flow is not needed to produce upper plate shortening, and we change the text accordingly in the revised version.

In 2D, no compression occurs with a continental overriding plate (Holt et al., 2015), while in 3D, backarc shortening is favored for the center of wide slabs driven by poloidal mantle flow resulting from downdip slab motion (Schellart and Moresi, 2013), or by larger negative buoyancy force of an older and thicker subducted slab with more vigorous flow in the mantle wedge, increasing traction at the base of the overriding plate (Capitanio et al., 2011). These models, focusing on the subduction process more than on the deformation of the overriding plate, show that in nature the mantle flow associated with the South Atlantic convection cell is not sufficient to promote the Andean mountain-building, and that the Pacific convection cell below the Nazca plate is mandatory to drag the plates against each other. As an experimental setup with a double flow is too complex to make, we choose to fix the upper plate to the back wall, which exerts a resisting force that allows the South America plate relative drift toward the subducting plate (Figure 8). Indeed, in our models 2, 4 and 5 the mantle flow drives the oceanic plate against the upper plate, and the trench advances toward the upper plate, which favors its shortening and thickening (Figure 6). The back wall to which the overriding plate is fixed together with mantle flow dragging the oceanic plate generate the proper boundary conditions that lead to strong upper plate shortening, and best reproduce the Andean context (Figure 8).

We also agree that Model 3, with mantle flow driving the upper plate, which is fixed, against the subducting plate, cannot be compared easily to the Andes. Indeed, in this model, the trench retreats, favoring the lateral spreading of the upper plate and its shortening is very limited (Figure 5).

We now present in the introduction the effects of far-field mantle flow on subduction dynamics, and compare our imposed mantle flow to an "easterly"-directed horizontal mantle wind, favouring steepening of "West"-directed slab dip angles globally observed (Ficini et al., 2017).

B6) Figures, tables and citations

B6.1) Reviewer's comments

*These statements are a **guide** to what good* Figures *and* Tables *include and how they are presented. Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

Tables and *Figures* are **ordered logically** and **numbered sequentially** — [**YES**] / [NO]

Tables and *Figures* have **captions that explain** all their major features — [**YES**] / [NO]

Tables and *Figures* have **captions that complement** the information in the main text — [**YES**] / [NO]

Tables and *Figures* present data that **relate** to the study objective — [**YES**] / [NO]

Tables and *Figures* present data that are **consistent** with and support the description of results — [**YES**] / [NO]

Tables and *Figures* have **succinct and informative titles** — [**YES**] / [NO]

Figures are **accessible** (elements are clearly labelled, accessible colour palettes, colour contrasts, font size legible, etc.…) — [**YES**] / [NO]
Please, check our [Figure guidelines]

Figures with **maps or cross-sections** contain all **elements to be understood** (north arrow orientation, scale, visible coordinates, sufficient coordinate grid intercepts) — [**YES**] / [NO]

Figures with **maps** have **sufficient location information** (in the map or caption) — [**YES**] / [NO]

Cross-sections have clear labels for **scale and coordinates** at ends and within-section kinks — [**YES**] / [NO]

All georeferenced elements are provided in common format (.shp, .geotiff, .kml) [in an open-access repository] — [**YES**] / [NO]

Citations throughout are relevant, suitable, and comprehensive — [**YES**] / [NO]

B6.2) Author's responses

Following a suggestion of Reviewer 2, we split figure 4 in 2 for a more progressive presentation of the models. We also change the yellow box/line of Figure 4, and add different line types in

Figure 5.

the following figures and modify them if possible to make them accessible to those with monochromacy:

- Figure 3 topography map,

Section C: Additional comments

C1) Minor/line-numbered comments

C1.1) Reviewer’s comments

No line numbers in the manuscript makes it a bit tricky (something to add in the event of a re-submission) but I’ll try and identify by paragraph/section:

Introduction, last paragraph (pg. 3): Some Dvorkin et al. 1993 (Tectonophys) for one of the original toroidal flows references.

We add the reference.

Introduction, last paragraph (pg. 3): “Kyrali” – spelling

Corrected.

Introduction, last paragraph (pg. 3): Influence of slab penetration on upper plate stress – see Holt et al (2015) for an earlier reference that demonstrates this. Also relevant for the effect of upper plate strength and mobility (fixed vs. free) on stress state.

We add the reference.

Introduction, last paragraph (pg. 4): Sentence being “On the contrary…” – I found this sentence placement a bit strange. These are mainly numerical models – but placed in the analogue modelling section – and, to my understanding, the extension/shortening is due to slab folding on top of the lower model boundary. Is this relevant to your study?

We precise that the section is also dealing with numerical modelling. We also add that, indeed, the slab alternates periods of steepening/shallowing due to folding.

Introduction, last paragraph (pg. 4): The statement about the Coltice study is too vague. Not sure what "dragged" and "Earth-like continents" are in this context.

We remove this sentence and the previous one, to make this paragraph more fluid.

Introduction, last paragraph (pg. 4): It is worth clearly stating how this study is different to Guillaume et al. (2021).

We add: "We build upon the preliminary work by Guillaume et al. (2021), first analogue experiments with mantle flow but without overriding plate, …"

Methods, pg 6: What exactly does "quasi-Newtonian" mean here?

We remove the word "quasi-": "Given that strain rates in the models are much lower than that, silicone can be considered as a Newtonian material in our experimental conditions."

Scaling laws, pg 10, first sentences: I don't follow this logic about the 10 cm/yr imposed mantle velocity. Even if the plate velocities were greater in the past, you are still imposing mantle flow > x4 the plate velocities – I think it is this relative value that matters.

Forces section, pg 10: Conrad and Hager (1999) is a good reference for viscous plate bending force and plate coupling shear force. I think the mantle force (pressure force) should be drawn as being perpendicular to the slab.

Forces section, pg 11: Which "published" experiments?

The previous experiments with mantle flow, Guillaume et al (2021).

Figure 4: You draw the resisting forces due to fixing the plates pointing towards the trench. They should be in the opposite direction (i.e., a resisting rather than a driving force).

Measurements section, pg 12: "considering material as incompressible" – is it incompressible? Sorry, confused by this phrasing.

We change to "as material is incompressible".

Measurements section, pg 13: "limits" -> "limitations"

Changed.

Figure 5: I would add black lines for the vertical and horizontal axes. The x-axis font is larger than the y-axis font.

Results, pg 22: What is the viscosity contrast of the “weak silicone” relative to the regular/strong lithosphere?

The viscosity of the weak lithosphere is ~16% of the strong lithosphere viscosity. We add this precision in the text.

Discussion, pg 24: I think the main limitations are actually: i) you fix the plates; ii) you impose a really high mantle flow velocity. Could you run tests without these restrictions?

We deeply rewrite the discussion according to comment of Reviewer 2.

Discussion, pg 29: “Chile” spelling.

Changed.

Discussion, pg 29: I agree east-directed mantle flow case is most analogous to the Andean situation, but only if the subducting plate was free. Perhaps a good place to compare with either previous literature/models or new runs with free plates.

Discussion, pg 29: Again, I don’t think a fixed boundary condition is equivalent to ridge push.

Discussion, pg 31, first sentence/second paragraph: Sorry - given the rapid flow velocity and fixed boundary conditions - I don’t think the Andean boundary conditions are satisfied.

Acceptance Letter

Dear Dr. Replumaz and co authors

We have reached a decision regarding your submission to Tektonika, "Upper-plate shortening and Andean-type mountain-building in the context of mantle-driven oceanic subduction".

Our decision is to: Accept Submission

The Associate Editor, Noah Phillips, and I are happy that you have fully addressed the comments raised during the review process and thank you for addressing them so carefully in your revised copy and in your rebuttal letter. We have one additional small request, which is that the scaling equations that you have used in Table 1 are included as equation in the text itself (section 2.2). However, this point can be picked up during the copyediting process.

Congratulations, and thank you again for submitting your work to Tektonika!

Yours sincerely,

Janine Kavanagh, PhD, Executive Editor – Tektonika

Noah Phillips, PhD, Associate Editor - Tektonika