



Review Report

Schmid et al., Brittle-ductile Coupling and Block Rotation During Rifting Revealed Through Digital Volume Correlation Analysis of a Crustal-scale Analogue Experiment, TEKTONIKA, 2024.

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1st Round of Revisions

Decision Letter

[Sent 15th February, 2023]

Dear Authors,

Thank you very much for your submission of the manuscript “High resolution DVC analysis of lower crustal flow in analogue models of rift interaction revealing brittle-viscous coupling processes”. We have now received 2 reviews of your manuscript which are attached to this email. Both reviewers have found the manuscript well written and organized and nicely illustrated. However, they indicate a few fundamental issues with the work that will need to be carefully addressed before this manuscript can be accepted for publication. Based on these reviews, along with our own assessment, we are recommending that the paper undergo revisions and another round of review after such revisions.

Our decision is to: Resubmit for Review

We believe the results of your DVC analysis using state-of-art 3D analogue modelling of rift process will be an excellent contribution to the scientific community. However, given the reviewers’ suggestions and own considerations, the manuscript needs significant revision before it can be accepted for publication in Tektonika.

We look forward to receiving a copy of your revised manuscript by 30th April 2023. The reviewers have used our compulsory review form to provide their comments. We ask that when submitting revisions, you use this review form to answer all reviewers’ comments, point-by-point. We ask you to submit both a copy of your revised manuscript, with changes clearly marked, and a clean version, during your resubmission. 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.

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

Yours sincerely,

Leonardo M. Pichel, PhD, Associate Editor - Tektonika

Janine Kavanagh, PhD, Executive Editor - Tektonika

Comments by Reviewer 1

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.

This manuscript revisits a single model from the 2018 Zwaan et al. paper, *Effects of sedimentation on rift segment evolution and rift interaction in orthogonal and oblique extensional settings: Insights from analogue models analysed with 4D X-ray computed tomography and digital volume correlation techniques*.

I enjoyed reading this manuscript and reviewing it. It must be my first ever review where there was virtually no need for suggestions to change grammar or syntax, as the language used is clear and grammatically neat, with well-constructed sentences. Also, the figures are of good quality, even though some details are often too small to discern.

However, to my regrets, I think there are major shortcomings in this paper, related to:

- the lack of a clear research question.
- the authors claim an improved data analysis, but the improvements are nowhere clearly stated.
- the results shown in figures seem only a gradual (spatial/temporal resolution) improvement compared to the figures in Zwaan et al. 2018
- the authors study coupling between brittle and viscous deformation in rifting, but use a measure that I think is not well suited to answer relevant questions
- there is no discussion to relevant literature (the literature from the introduction is not returning in the discussion)
- the authors spend much effort in interpreting displacements, while a major feature (dominant positive out-of-plane motions), may be non-reproducible and related to an error in the setup.

It remains thus unclear what we can learn from this work. I realize that my overall verdict may come across as harsh, but I think the authors should consider rewriting and redesign this study considerably. I will do some detailed recommendations in section B that may hopefully be helpful in that respect.

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:

Rewriting: Overall rewriting is needed to come up with an explicit research question, and a discussion of its relevance.

Reinterpretation: The authors should come up with a measure of coupling that is meaningful. The measure of coupling that the authors use is not useful as an indicator for interaction between the brittle and viscous layers, as I will try to argue in section B. The authors made no effort in the introduction to show why the study of coupling is relevant, defined no research question, and did not compare to relevant literature.

More figures: A better measure that shows the interaction between brittle and viscously deforming regions may require new figures, and perhaps new models.

I will detail my comments in section B.

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:

The text is redundant when it comes to discussing displacement magnitudes.

Figures are generally well designed, but even at large magnification contain vectors and text that are not readable.

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:

The research may not be reproduceable, as displacement fields are asymmetric, without a clear reason for this asymmetry, as the experiment itself is highly symmetric. The authors acknowledge that there may be model flaws, leading to asymmetric displacements, but have not set up new experiments to test this. It thus remains unclear what the scientific community can learn from this paper. I will provide more details for this judgement in section B.

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 authors revisit the deformation in one of the models of Zwaan et al. 2018, and focus on displacement in the viscous domain, that was already visible in that paper, but was not discussed in depth.
- The authors improve the quality of DVC-derived displacements for analogue models of tectonic deformation, in a temporal and spatial sense (even when the authors do not explicitly discuss what entails those improvements).

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

- A better justification for the relevance of this study
- Adding a research question
- A better justification (and redesign) for the measure of coupling, and the theoretical implications of this measure, such that a meaningful discussion of the results is possible
- A need for reproducing the model results by redoing the model
- An actual estimation of the rotation of the horst block from the data

- A discussion of relevant related research
- An explicit discussion of methodological improvements.
- Mention of essential model parameters, related assumptions, and justification
- Better description of the boundary conditions, especially for the bottom of the model, and a check that boundary conditions have been correctly applied.
- A better description/figures of the general concept behind DVC.

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]

The *Title* describes the main topic of the manuscript **succinctly** — [YES]

The *Title* includes **appropriate key terms** — [YES]

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

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

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

The *Abstract* describes the **main results sufficiently and adequately** — [YES]

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

The *Abstract* clearly states the **conclusions of the study** — [YES]

The *Abstract* is **clear and well structured** — [YES]

Comments:

The *Abstract* includes a **clear aim and rationale**: The authors write: *[..] we [..] investigate coupling processes between upper brittle and lower ductile crustal deformation during rift segment linkage*. This seems a good aim, however the abstract does not mention what coupling entails, nor how they are going to study this coupling.

The *Abstract* includes a **well-balanced description of the methods**. The authors write: *using an improved 3D Digital Volume Correlation workflow*. However, the abstract does not mention

what the improvement constitutes.

The *Abstract* clearly describes the **importance/impact of the study**. The authors do not indicate major open questions in rifting related to viscous lower crustal deformation and how their study helps answering these questions, nor mention the importance of their study subject for understanding higher level processes.

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.*

- 1 The *Introduction* provides **sufficient background and context** for the study — [NO]
- 2 The *Introduction* describes the **aim/hypothesis/rationale** clearly, providing **sufficient context** — [NO]
- 3 The *objective/hypothesis/rationale* **flows logically from the background** information — [NO]
- 4 The *Introduction* describes the study's **objective and approach** (last paragraph) — [NO]
- 5 The *Introduction* contains **relevant, suitable citations** — [NO]
- 6 The *Introduction* is **organized effectively** — [YES]

Comments:

1

The first paragraph focuses on the evolution of linkage structures in rifting. The second paragraph provides a single tectonic example of such structures (Victoria microplate), but there is no mention of open questions regarding such microplates, or its relevance to understanding of rifting in extensional settings.

2 and 3

There is no explicit aim or hypothesis. Implicitly the authors mention the role of ductile deformation for rift pass structures “*Lithospheric-scale modelling studies often include a lower part of the crust that deforms in a ductile fashion (e.g., Brune et al., 2017; Glerum et al., 2020; Neuharth et al., 2022) but pay little attention to its role in the creation of rift pass structures.*”, but the aim remains implicit. Hence I also conclude:

4

Because of the lack of a clear and explicitly stated goal and hypothesis, there is also no good relation to the coupling measures the authors use, nor a good relation to the design of their models. There is no mention of processes that may lead to viscous flow affecting the formation and kinematics of rift pass structures, i.e., because a theoretical framework is absent, the approach cannot be judged against the goals.

5

While several citations are provided, the way these citations are discussed does not provide a good overview of the current body of knowledge. When it comes to model studies, there should be given more discussion of rifting models in general, also ones that do not rift pass structures in specific, as viscous flow in general rifting models will be comparable for parts of the domain of the model in this study. When discussing previous studies the authors rely mostly on negative claims, such as: “*Crustal-scale modelling studies that include the ductile lower crust in the shape of a viscous layer [...] often lack a complete analysis of viscous deformation and to this date, only little effort has been made to obtain a detailed and quantitative description of deformation within the ductile lower crust simulated in such models.*” This is not very helpful, as there have been studies that incorporated viscous deformation in the lower crust (and mantle, which the authors do not discuss at all), these deserve a positive discussion of their findings in terms of the role of viscous deformation in rifting.

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.*

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

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

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

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

Comments:

1 and 2

DVC

Regarding the improved DVC analysis, no details are provided what entails the improvements.

Secondly, tests should be performed to show that the changes indeed lead to an improvement. The only mention regarding improvements is: “*Compared to Zwaan et al. (2018a), our vector resolution is improved by a factor of 4.*” However, there is always a trade-off between accuracy and spatial resolution in correlation methods. This study should thus show this trade-off and explicitly show how their workflow leads to a better trade-off compared to previous methods.

Coupling measure

Regarding the investigation of coupling, the authors write: “*Here, we define brittle-viscous coupling as the degree of similarity of individual displacement components (D_x , D_y and D_z) of the brittle and viscous domain, with a high degree of similarity indicating a strong coupling and a low degree of similarity indicating a weak coupling.*”

Because a hypothesis is lacking, we cannot check whether this definition of coupling is useful in any way. The authors also do not make any attempt in arguing that this definition of coupling will provide useful information about interaction between brittle and viscous domains in rifting or creating rift pass structures (or that coupling itself is relevant at all). Their definition of coupling implies that because vertical is opposite in direction brittle and ductile domains, there is no coupling, but still the upward motion can only be understood as a response to local extension in the upper crust. So, there is interaction (a word used by the authors in this context, lines 21, 124, 155, 263), but no coupling? Does this make sense? Also, is the fact that displacements are similar a sign of interaction between brittle and viscous deformation, what about interactions that cancel out? I invite the authors to rethink how to prove and quantify interaction between brittle and viscously deforming crust.

Model setup

Regarding the setup of the model, the authors reuse existing models and their data. They do not argue why this model, that has been designed for a different research question, is useful in answering their (implicit) research question. Since the question seems to be to study the interaction of viscous and brittle layers in the creation of rift pass structures, I wonder whether a single model is sufficient, as there are significant uncertainties in the geometry and rheology of the lower crust, which should be investigated for a meaningful study. What about interaction with the mantle lithosphere (e.g. Brun 1999, Narrow rifts versus wide rifts: inferences for the mechanics of rifting from laboratory experiments or many numerical models that include the full lithosphere)?

Boundary conditions

Also, the boundary condition at the bottom of the model is not discussed. What kind of boundary condition should the foam/Plexiglas layer represent, and why does this make sense in the process of extension of the lithosphere? Cumulative displacements at the bottom of the model are near zero. What are the implications? Should this represent the deformation of the (brittle) lithospheric mantle? How does this relate to approaches taken in analogue or numerical rifting models that do incorporate a lithospheric mantle?

In the supplementary material more information is provided on the material properties and scaling, but no reference to this document is made from the main text regarding the properties of the lower crust.

Reproducibility

The authors mention “*A possible explanation for this might be that the model was not perfectly horizontal positioned during CT scans and favoured gravitationally-driven out-of-plane flow near rift segment A.*” To me this implies that the experiment should be reperformed to check possible misalignments, as the asymmetric out-of-plane flow is very dominant in the results.

3 and 4

There is a mention in the Data availability statement to Schmid et al, in prep. No details on this dataset seem available.

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.*

- 1 The *Results* findings are **supported by data** — [NO]
- 2 The *Results* findings are presented **clearly and succinctly** — [NO]
- 3 The text in the *Result* section **cites tables and figures appropriately** — [YES]
- 4 The *Results* directly **relate to the study objectives** — [YES]
- 5 The *Results* present **data for all the approaches** described in the *Methods* section — [YES]
- 6 The *Results* **text belongs to the Results section**, not to *Introduction*, *Methods*, or *Discussion*. — [YES]
- 7 The *Results* section is **organised effectively** — [YES]

Comments:

1 **Rotations:** Seen the introduction, I suspect that what the authors refer to as “a counter clockwise rotation of the central rift-pass block “ (Lines 397 and 412) implies a rigid body rotation. However, one can not discriminate from *dy* alone whether a horizontal motion that looks like a rotation is due to a (semi) rigid body rotation (without strain) or more a simple shear (which also leads to rotations). To really discriminate between simple shear and rotation, one should compute finite strains. Currently, none of the figures shows a justification that (semi) rigid body rotation takes place.

2 **Discussion of dx,dy,dz fields:** I find sections 3.2.1-3.2.3 verbose. Especially the mention of maximum values is not very informative and slows down the reading speed considerably. These sections could be reduced in length.

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.*

- 1 The *Discussion* is **focused on the objectives** of the study — [NO]
- 2 The *Discussion* **addresses all major results** of this study, which are shown in *Results* — [YES]
- 3 The *Discussion* section makes **comparisons with other studies** that are relevant and informative — [NO]
- 4 The *Discussion* section properly identifies all **speculative statements** — [YES]
- 5 The *Discussion* section presents the **implications of the study** persuasively — [NO]
- 6 The *Discussion* section **highlights novel contributions** appropriately — [NO]
- 7 The *Discussion* section **addresses the limitations** of the study appropriately — [NO]
- 8 The *Discussion* section is **organised effectively** — [YES]
- 9 The *Conclusions* are **consistent** with and **summarise** the rest of the manuscript — [YES]
- 10 The *Conclusions* are **supported by the data** in *Results* and **follow logically** from the *Discussion* — [NO]
- 11 The *Conclusions* are **clear and concise** — [NO]

Comments:

1 There are no clear objectives, so the authors cannot check to what degree they were able to answer their hypothesis/research question.

2 In the discussion there is almost no discussion of other relevant literature, apart from a few papers that have been authored by the (co-)authors.

3 Since the model is taken 1) from another paper with different aims than the current, 2) a single model is used to support implications, 3) the measure for brittle-ductile interaction is not convincing, it cannot be judged whether results and conclusions are relevant and reproducible.

Furthermore: Lines 711-720: This discussion is very unsatisfying. The authors use the word “initiate” but forget to come up with any plausible force that may generate flow.

4 Since virtually no other literature is cited, we cannot know what the novel contributions are. Furthermore, the approach seems also like a step back compared to the Zwaan et al., 2018a paper, since the current paper only shows displacements, while the Zwaan et al. paper also shows strains, which are much more indicative for deformation than displacements. The relation and innovation compared to Schmid et al. 2022 is also unclear.

5 The limitations of the model design/coupling measure are not discussed at all.

6 The conclusions do not relate back to an overall aim. It is unclear how general these conclusions are, and whether they depend on model choices that have not been studied in detail.

The introduction spends quite some text to the rotation of the rift pass block, but in section 4.2 the authors state “*It is unclear whether flow in the viscous domain exerts a drag force on the rift-pass block in the brittle domain or vice versa.*” So, what has gone wrong? Since the main ingredients of this paper are rift pass structures and brittle-ductile interaction, it is surprising that this question can still not be answered. Or did I perhaps miss something?

7 The conclusions are quite lengthy compared to the information content.

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.*

1 Tables and Figures are **ordered logically** and **numbered sequentially** — [YES]

2 Tables and Figures have **captions that explain** all their major features — [YES]

3 Tables and Figures have **captions that complement** the information in the main text — [YES]

4 *Tables and Figures* present data that **relate** to the study objective — [YES]

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

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

7 *Figures* are **accessible** (elements are clearly labelled, accessible colour palettes, colour contrasts, font size legible, etc....) — [NO]

Please, check our [\[Figure guidelines\]](#)

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

9 *Figures* with **maps** have **sufficient location information** (in the map or caption) — [not applicable]

10 *Cross-sections* have clear labels for **scale and coordinates** at ends and within-section kinks — [YES]

11 All georeferenced elements are provided in common format (.shp, .geotiff, .kml) [in an open-access repository] — [not applicable]

12 *Citations* throughout are relevant, suitable, and comprehensive — [YES]

Comments:

1 I think the depiction of the basic workings of DVC are incorrect. We see two depictions of the model, at two subsequent time steps. Overlain is the discretization of the volume in voxels. The voxels are in an Eulerian frame, so these are space-fixed. We see at both time steps the same voxel being highlighted in red, i.e, these represent the same location in space. At the left, we see two individual voxels at time steps t and $t+1$, and the displacement vector suggests a movement in space. However, the red voxels at the right, being at the same location, represent a zero-displacement. This is inconsistent with a displacement. Thus, I would think that two different voxels have to be colored at the right, to make it consistent with displacement (see Adam et al. 2013, figure 2).

2 Only less than half of the figures have a title.

3 Many figures contain fonts or arrows that are at the limit of readability, even at large magnification. Colour palettes are overall decent.

4 For figure 5, the outward and inward arrows in the color bar only apply to panels a-c, and are not applicable (misleading even) to panels d-f. Same for the upward and downward arrows in figure 6. These only apply to panels a-c.

5 It is unclear at what depth the horizontal slices have been taken, and whether the brittle-ductile interface is at a fixed depth (Eulerian), or deforms along with the model (Lagrangian).

6 While only a minor issue, the 3rd axis is missing in figures 4-8. This should be depicted as arrow head or tail.

Comments by Reviewer 2

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.

This contribution is presenting detailed analysis on x-ray CT data of a rift system experiment. The authors re-analyse data collected for an earlier publication via an improved Digital Volume Correlation methodology. The paper focuses on two aspects; 1) the improved data analysis and 2) the interpretation of the re-analysed data.

The paper is well written and logically organized. The figures are clear and helpful to the understanding of the paper. I believe that this paper is worthy of publication after the points mentioned below are addressed. I would like to recommend moderate revisions.

Note, I will use the free form boxes below for comments. This is overall a very well-done paper and the general yes/no questions will not help terribly much for the improvement.

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:

[Free form box]

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:

[Free form box]

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

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...

Reanalysing data with improved methodology is a worthwhile endeavour and is unfortunately not done enough. This contribution in taking laboratory data (that is very hard to obtain and a speciality of the lab in Bern) and is able to show deformation patterns in individual areas of the model in great detail.

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

My main point, where I feel this paper could be improved, is related to the dual focus. While the authors are multiple times highlighting that the method used in this contribution is superior to the method used in the original data publication (Zwaan et al. 2018) the reader does not get a chance to see this. I would recommend either to lessen the focus in the current paper on the improved methodology or adding some actual comparison to the original publication. The second focus of the paper is on the analysis of the data. While the figures are very detailed and well described the reader does not learn how this can be applied to the natural system or what could be learned from the experiments that is not already known. Maybe I'm a bit ignorant on this point as I do not have a background in extensional tectonics but I feel that strengthening these parts of the paper would be helpful to reach a broad audience.

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:

1. I am not convinced that using an abbreviation in the title is a good idea. I would recommend spelling it out even though it will make the title long.
2. The abstract is very technical and definitely geared towards an audience that is very familiar with rifting. Is there a way to make it a bit more accessible? An example I found hard to follow is: L20:...concomitant rift segment linkage....
3. L35: not sure secluded is the right word choice here.

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:

L71-75: There is no need for this section as you talk about it again in lines 92-...

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:

1. L203: What is a I70f reconstruction?

2. L233: How does the change in voxel size in two dimensions affect the resolution. Your new voxels are now smaller than the actual resolution. Is this cause for concern?

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:

1. It is confusing to call the rift segments A and B and the cross-section locations A-A' and B-B'. Later in the manuscript you are introducing different terms for the cross-sections. Maybe just use them exclusively?
2. L332: This sentence is hard to follow with the left and right motion references.
3. L366-368: I have a hard time seeing this in the figure.
4. L472: Change ductile to viscous.
5. L571: decreases?

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:

1. Part of the current discussion reads like results. Especially when comparing the individual cross-sections. I would recommend moving these paragraphs into the results section.
2. The discussion is currently lacking a section on how the improved analysis is improving the interpretation of natural rift systems. With other words, why was it necessary to re-analyse the data? What can you now learn from the model that you could not do before?
3. I understand that this is probably discussed in the original paper of Zwaan 2018 but a short discussion on the limitations would be helpful. Especially as it seems that the

seeds that trigger the deformation have a discernible impact on the flow of the viscous layer.

4. Add to the conclusion what we have learned from all this and how it can be used.

5. L688: ...following paragraph.

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:

1. The figures are really nice!
2. **Figures 4, 5 and 6** have a mix-up with the numbering. Currently all the panels in a row or column have the same letter instead of roman numbers like in the text.
3. What is the height of the horizontal cross-sections?
4. The vectors are very hard to see on the scale of a printed page.
5. **Figure 7** caption: L534-537 should be moved into the main text.
6. **Figure 8** caption: L600-602 should be moved into the main text.

Authors' Reply to Reviewer 1

A1.2) Author(s) Responses:

We would like to thank the (anonymous) reviewer for their thorough and thought-out comments and improvement suggestions. The revised manuscript presents now a properly revised version of the original manuscript, where we come to meet most of the suggested improvements. We clarified the scientific goal of this study by emphasizing that (scarcely) existing volumetric data of analogue modelling studies provide an excellence fundament for revisiting and quantifying deformation in such models. However, we must emphasize that this work does not represent a modelling study. As such, we do not intend to investigate a specific parameter space (as for example rift configurations as in Zwaan et al., 2018) but rather use one model to demonstrate the benefit of revisiting existing XRCT data. To this end, we use an existing XRCT data set from Zwaan et al., (2018) to present our new DVC workflow that includes improved CT data preprocessing, refined DVC displacement analysis and postprocessing for visualizing and quantifying deformation. The newly included comparison of the recent DVC analysis by Zwaan et al., (2018) and this study shows that vector resolution can be refined without losing correlation accuracy. Our new DVC analysis captures up to 20% higher displacement values which lead to better defined shear zones and localized strain patterns. This displacement sensitivity analysis is now included in the Appendix and described in the method section.

The method section now clearly states specific improvements of our DVC analysis compared to the one used in Zwaan et al., (2018) and we discuss previous studies that used DVC with respect to their accuracy/vector resolution in the discussion section.

While the original manuscript solely focused on displacement components, we use displacements in the revised manuscript as a foundation to describe deformation by means of strains and present differential deformation styles within the brittle and viscous model domains. The revised manuscript includes the analysis of rigid-body rotation (obtained from polar decomposition of the deformation gradient tensor) to characterize and quantify rigid-block rotation of the rift-pass block and its effect on viscous flow in the underlying model layer. Further, we discuss these results in the context of existing conceptual models for block rotation (about a vertical axis) and suggest (based on strain results) that such block-rotation best fits with the “edge-driven” model, where lateral confinement of the rift-pass block (i.e., the rift segments) exert a resistance on the block and initiate rotation. This mechanism further implies that regional viscous flow in the lower crust is disturbed locally by rigid-body rotation.

Based on strain analysis, we use shear strains as a measure for mechanical brittle-viscous coupling. According to suggestions, we now include a proper definition of our mechanical brittle-viscous coupling and introduce the appropriate literature in the introduction of the revised manuscript. Our results show that mechanical brittle-viscous coupling spatially varies and we further discuss coupling in the context of the edge-driven model and show that a horizontal transitional between the two model domains occurs where shear is enhanced. In the case of

the edge-driven model, such a transitional layer has also been suggested in existing literature.

Our thorough revision also includes revised, and new figures that properly guide the reader throughout the manuscript. Comments regarding the readability of figures have been taken into account and all figures are consistently annotated with labels, titles and readable font size.

A2.2) Author’s responses:

We acknowledge that the original manuscript lacked a clear scientific aim and technical improvements compared to the DVC analysis in Zwaan et al., (2018) were not evident. In this context, we revised large parts of the results section that previously were solely based on displacement components. The revised manuscript clearly states the relevance of this study and demonstrates benefits of revisiting existing data using an improved DVC workflow. By including finite strain, this study presents advances compared to previous DVC studies as we quantify deformation in the brittle (i.e., rigid-body rotation) and viscous (i.e., viscous flow) model domains and discuss both features in the context of relevant literature.

We also included a proper definition of mechanical brittle-viscous coupling that allows us to discuss our findings in the context of relevant literature. All parameters regarding the model scaling and mechanical properties of the used model materials are listed in the Appendix.

B1.2) Author’s responses

We have revised the Abstract and it includes now a clear aim of this study. We present a new DVC workflow that includes CT data preprocessing, better vector resolution (without losing accuracy), and postprocessing of DVC data to investigate finite strains and rigid-body rotation.

Also, the revised Abstract includes now clear statements what our improved DVC workflow (compared to Zwaan et al., (2018) entails. We now emphasize the importance of our study clearly as it shows that (scarcely) existing volumetric data sets of analogue modelling studies should be revisited as imaging techniques improve.

We clarified our definition of coupling by using the expression “mechanical brittle-viscous coupling” that is properly introduced in the introduction including appropriate literature. Since this work focuses on the application of an improved DVC workflow, we state that we document differential deformation styles in the brittle and viscous model domain but leave out a proper description of mechanical brittle-viscous coupling and leave that part for the introduction.

B2.2) Author’s responses

1

We have revised the introduction and show that the role of the lower ductile crust in such settings is not fully understood and debatable. As mentioned above, the main goal of this study is to re-use a single model from Zwaan et al., (2018) to present our new DVC workflow. However, the selected model shows specific deformation features (i.e., rift-pass block rotation and viscous flow) that allow to discuss the analyzed model in the context of microplate rotation. In that sense, our study is not a modelling study but highlights the importance of revisiting existing CT data. Nevertheless, our model investigation has relevance regarding the topic of block-rotation and lower crustal flow and agrees with previous (modelling) studies that investigated microplate rotation about a vertical axis (e.g., Glerum et al., 2020).

2 and 3

We introduce the topic of block rotation by mentioning previous work regarding this topic. To this end, we explain two existing models (i.e., the floating block model and the edge-driven model) that have been suggested for microplate rotation of oceanic crust but has also been proposed as a viable mechanism for microplate rotation in continental settings. In most (numerical) studies that address this topic, the implementation of a lower ductile crust seems to be rather a necessity and the focus of such studies mainly remain on near-surface deformation. From this information, we consider it reasonable to conclude that more focus should be laid on the role and style of lower crustal deformation.

4

The revised introduction includes a paragraph dedicated to conceptual models of block rotation (see above) and its driving mechanism. In this context we also introduce our definition of coupling as existing literature proposes enhanced shear between upper brittle and lower ductile crust when a rigid block rotates above a viscous substratum (e.g., Thatcher, 1995). Based on the suggestion of Thatcher (1995) we define mechanical brittle-viscous coupling using shear strain that depicts horizontal planes of enhanced shear at the brittle-viscous interface.

5

There is indeed a large body of literature related to rifting, but we would like to refrain from citing a large number of publications addressing general rifting concepts. We focus in this manuscript on the evolution of a rift-pass structure in the brittle upper crust and its influence on the flow pattern in the lower ductile crust, and therefore we restrict our discussion of previous literature to papers discussing similar settings/models.

B3.2) Author's responses

DVC

The method section now includes paragraphs that are dedicated to vector resolution/accuracy, uncertainty and resulting sensitivity of capturing displacements. To this end, we added a figure in the Appendix that shows how displacements were previously (i.e., Zwaan et al. 2018) underestimated. The higher sensitivity for capturing smaller differences in displacements eventually results in better defined shear zones. Further, we state that overlapping (up to 75%) interrogation volumes increase the vector resolution without increasing the uncertainty/noise (e.g., Wieneke, 2015).

Coupling measure

The revised manuscript defines coupling as the mechanical brittle-viscous coupling between deformation styles in the upper brittle and lower viscous model layers. We further investigate such coupling processes at a horizontal layer (i.e., the brittle-viscous interface). According to literature, the edge-driven mechanism should initiate block rotation of the rift-pass block in the brittle domain and exert a drag force on the viscous lower crust. In such a setting, a horizontal transitional layer with enhanced shear has been proposed at the transition from brittle to ductile deformation. Our results show that such a zone develops below the rift-pass block and further, depicts spatial variations in the degree of coupling between deformation of the upper brittle and lower viscous model layer within that horizontal layer. Moreover, the horizontal zone of enhanced shear implies that upper brittle and lower ductile crust behave in different manners which results in differential deformation styles.

Model setup

The revised manuscript now clearly states that the aim of this study is to show how revisiting existing data can lead to new insights (by using a refined DVC workflow). In that sense, we chose that specific model as it provides a setup that is complex enough to show and discuss various aspects of deformation that, to our understanding, have not been presented in rift settings before. Further, we selected this model since it allows for the comparison with the previous DVC analysis in Zwaan et al., (2018). We do not claim to present an analogue modelling study (which indeed would require more experiments) but nevertheless, discuss our findings in the context of existing literature.

Boundary conditions

The original study by Zwaan et al., (2018) used a basal plexiglass/foam setup since it allows to accommodate oblique extension directions. We explicitly state now that this chosen setup may represent a brittle-ductile crust with enhanced radiogenic heat production on top of a viscously deforming weak mantle and support this setting with suggested literature (e.g., Bürgmann and Dresen, 2008; Mareschal and Jaupart, 2013; Zwaan et al., 2019).

Reproducibility

Incremental displacements (see Appendix) of the horizontal dy component show, that the negative motion increases over time and is in the same order as positive flow values at the end of the model run. We assume that this imbalance indicates that, at the final model stage, horizontal flow is not in an equilibrium state as it represents a dynamic process.

B4.2) Author's responses

Rotations

We have now performed a thorough strain analysis using the finite Green-Lagrangian strain tensor which is suited for large deformation as seen at the final model state. The usage of the deformation gradient F further allowed us to decompose finite deformation into stretch and pure rigid-body rotation in 3D. From the rigid-body rotation matrix we calculate the three Euler angles that describe rotations about each model axes in degrees. This procedure reveals that the rift-pass block indeed rotates as a rigid block without internal deformation. Further, we investigate such rigid-body rotation about a vertical axis slice-wise in each horizontal data slice over time (see description in the methods section). The findings are in agreement with the rotation of the rift-pass block, that can be obtained from top view images. This implies, that the rift-pass block rotation is fairly constant over the entire brittle layer depth and no energy dissipation (i.e., horizontal shearing within the rift-pass block) occurs. We think that our new results convincingly show that the rift-pass block rotation indeed is due to rigid-body rotation.

Discussion od dx, dy, dz fields

The revised manuscript presents only finite displacement at the end of the experiment. The admittedly lengthy description of incremental displacement components is entirely removed from the main text and we provide figures regarding all three incremental displacement components in the Appendix.

B5.2) Author's responses

1 Based on the improved DVC workflow, we present new data that demonstrates which has an improved

2 The revised discussion implements our new findings and discusses them within the context of the appropriate literature regarding 1) previous modelling studies that have used DVC, 2) work that investigates rigid-block rotation and potential driving mechanisms, and 3) work that addresses the importance of the ductile lower crust that (in our case among other work) suggests that deformation in the brittle upper crust is detached from deformation in the lower ductile crust, which is shown by a horizontal transitional layer where enhanced shear occurs.

3 We now put our findings in the context of existing literature. These results match well with the proposed edge-driven mechanism that initiates block rotation about a vertical axis by lateral shear and eventually exerts a drag force on the underlying viscous substratum, where regional flow is locally disturbed.

4 We compare our DVC workflow with previous studies that use DVC to quantify deformation in analogue models. In this light, we discuss vector resolution and accuracy and show that our DVC workflow poses an improvement with respect to previous studies. Moreover, we present deformation in horizontal slices which have not been done before. Postprocessing outside of the commercial DaVis software further allows us to intensively investigate deformation by

means of rigid-body rotation which presents a novel approach.

5

The paper focuses on the methodology and the potential of DVC analysis, using a single experiment as an example. We state in the revised manuscript, that crustal-scale models do not consider the lithosphere-scale, but that the influence of the lithospheric mantle on the flow is limited during the earliest stages of rifting (and that's what we're looking at)

6 Our conclusions now summarize findings regarding 1) DVC improvements and 2) differential deformation styles in the brittle upper and viscous lower model domain. Although we do not claim to present a modelling study here, our findings regarding the mechanism of rigid-block rotation are in agreement with numerical studies about microplate rotation and allow us to make preliminary statements regarding such mechanisms that drive rift-pass block rotation in continental settings. However, we agree that a thorough modelling study would be necessary to address this topic properly.

7 Conclusions have been shortened and appropriately summarize our findings.

B6.2) Author's responses

1 Thank you for pointing this out. As correctly stated, the two voxels colored should be at different positions for different time steps. We have changed that in the pertinent figure.

2 All figures have now titles.

3 All revised and new figures are presented in a consistent way and font sizes were adjusted for readability.

4 Where necessary, color bars now contain different motion indicators for model transects and horizontal slices. This is also annotated in the figure captions.

5 We have adjusted the methodology figure such that positions of the horizontal slices are now clearly visible. As now stated in the text, the crustal-scale model from Zwaan et al., (2018) does not accommodate for isostatic contribution from the mantle and hence, the viscous layer thins as the model width increases over time. Consequently, the brittle-viscous interface sinks over time. However, in the revised manuscript we look at the final deformation state (using the Lagrange-Green finite strain tensor) which allows us to precisely determine the position of the brittle-viscous interface at that time.

6 We have adjusted all figures in such a way that the third axis is now clearly indicated by either an arrow head (point) or an arrow tail (cross).

Authors' Reply to Reviewer 2

A1.2) Author(s) Responses:

We would like the reviewer for helpful comments and improvement suggestions. The revised manuscript entails some major changes with respect to the original manuscript, which we outline in the following:

- We clearly state the improvements of our DVC workflow compared to previous DVC workflows (i.e., the one used in Zwaan et al., 2018) and highlight the necessity to revisit (scarcely) existing XRCT data for conducting quantitative analyses for example by using DVC.
- We directly compare our DVC workflow with that in Zwaan et al., (2018) and quantitatively show that our workflow captures up 20% higher displacement values. As a result, shear zones (such a faults) are more localized and spatially better defined.
- Our revised manuscript includes deformation analysis by using finite strain (i.e., Green-Lagrange finite strain) and we quantify rigid-body rotation of the rift-pass block using polar decomposition of the deformation gradient tensor.
- Mechanical brittle-viscous coupling is properly defined and our definition is supported by relevant literature. Therefore, we present such coupling according to the literature and show that the degree of coupling may not only vary over time but shows spatial variations.
- Based on our DVC analysis, we observe differential deformation styles in the brittle upper (i.e., rigid-body rotation) and viscous lower (i.e., diffuse viscous flow) model domains.
- We conclude, that rotation of the rift-pass block is driven by the edge-driven mechanism and eventually exerts a drag force on the viscous substratum where flow is disturbed. These findings are discussed within the context of relevant literature.
- We include a discussion about previous modelling studies that used DVC and discuss their contributions in the context of vector resolution and accuracy.
- Our findings are supported by revised and also newly designed figures that help guiding the reader throughout the text.

A2.2) Author's responses:

The revised manuscript includes a displacement sensitivity analysis that compares DVC data

sets from Zwaan et al., (2018) and this study. In that sense, we demonstrate how our improved DVC workflow captures up to 20% higher displacement values previously have been underestimated. We clearly describe that our DVC workflow entails an improved CT data postprocessing, a higher vector resolution without losing accuracy (or increasing the noise level), and data postprocessing to calculate finite strains and rigid body rotation. Moreover, in an additional data publication, MATLAB scripts and DVC datasets are available as subsequent .txt files to recreate volumetric data sets and calculate strains.

We demonstrate our workflow based on the selected model from Zwaan et al., (2018) and reveal new insights into mechanisms that drive rift-pass block rotation about a vertical axis. These results are discussed within the context of relevant literature and imply, that near-surface deformation measurements in nature allow insights into the deformation behavior of a lower ductile crust.

B1.2) Author's responses

1. We have revised the title of this study and no abbreviation occurs in the title.
2. The revised abstract now properly summarizes the work of this study and includes a clear scientific aim, properly explained methods and the main findings of this study as well as implications for nature.
3. We have removed this sentence from the revised Abstract.

B2.2) Author's responses

1. We have revised this part.

B3.2) Author's responses

1. I70f is the Siemens name for an iterative reconstruction kernel that is optimized for bone tissue. We found that this kernel best enhances grain patterns in CT scanned analogue models and provides the best reconstruction algorithm for subsequent DVC analysis. This information is now given in the text of the method section of the revised manuscript.
2. DVC requires isotropic/cubic voxels. The CT volume reconstruction from CT slices, however, yields anisotropic voxels. Within the CT plane, pixel resolution depends on the chose CT scan window size (here 37 cm) applied on the fixed matrix resolution of 512 by 512 pixels. In our case, this results in a pixel resolution of 0.72 mm/px. Perpendicular to the CT plane, however, each slice has a thickness of 0.6 mm with a 0.3 mm overlap. We use a nearest neighbor interpolation that refines pixel resolution

within the CT plane from 0.72 mm/px to a resolution of 0.6 mm/px without creating artificial intensity patterns. This approach has recently been used by Poppe et al., (2019) from which we adapted it to obtain cubic voxels with a resolution of 0.6 mm per voxel..

B4.2) Author's responses

1. We agree that this caused confusion in the original manuscript. We therefore label the two rift segments “left” and “right rift segment” in the revised manuscript.
2. This sentence has been removed in the revised manuscript.
3. This sentence has been removed from the revised manuscript. Incremental displacement data is now in the Appendix. We have adjusted figure sizes as well as font sizes in all revised and new figures for readability.
4. This has been removed in the revised manuscript.
5. This sentence has been removed in the revised manuscript.

B5.2) Author's responses

1. We have revised the discussion and it now includes three sections. 1) discussion of previous analogue modelling studies using DVC with respect to their vector resolution and accuracy. 2) discussion of or findings from rigid-block rotation in the context of conceptual models of driving mechanisms. 3) discussion of mechanical brittle-viscous coupling in the frame of relevant literature.
2. In the original manuscript, we discussed brittle viscous coupling and the evolution of the rift-pass structure solely based on displacement components. The revised manuscript presents novel results that quantitatively describe initiation of block rotation (due to enhanced resistance along two confining rift segments; edge-driven model) and how such rotation in the brittle layer exerts a drag force on the underlying viscous substratum where viscous flow is locally disturbed. These two substantially different deformation mechanisms cause enhanced shearing within a horizontal layer in between which we use as a proxy for spatially varying degrees of coupling. Our study shows that mechanical brittle-viscous coupling may not just change over time (as existing literature suggests as strain rates may change over time) but can also

vary spatially. To our understanding, this is a new aspect that contributes to the understanding of rift-pass structures.

3. The main limitation of this (and most likely all crustal-scale) model is that it does not accommodate for isostatic contribution from the mantle. However, early stages of rifting may solely affect crustal levels of the lithosphere (as expressed by narrow, localized graben structures) and the contribution from the mantle lithosphere (as well as asthenospheric flow) are negligible at such early deformation stages. We state this limitation now in the revised manuscript.
4. We have revised the conclusions and now clearly and concisely state the major findings from this study and its implications for nature (as well as for potential future DVC studies).
5. This part has been removed and rewritten.

B6.2) Author's responses

1. Thank you!
2. This is on purpose. The numerous panels in these figures (now in the appendix) would have led to labels down to the letter x. To this end, we use a “chessboard” numbering where either rows or columns are labelled with letters from the alphabet and the other is labelled with roman numbers. In the original figures, the font size was too small to find roman letters. We have adjusted these figures and font sizes accordingly.
3. Horizontal cross sections are squares with length and width being 300 mm (i.e., symmetric from -150 mm to 150 mm). We have adjusted this in all revised and new figures.
4. Vectors should now be better visible. In the main figures, horizontal slices were created in MATLAB using larger vectors than in the previous submission. Images from model transects were created in DaVis to keep CT data as background. There, settings for vector sizes are limited but we increased the resolution such that, at least at higher zoom levels, vectors are visible.

5. We have revised the coupling section and made a new figure that guides the reader through the text. Previous Figure 7 has been removed.

6. We have revised the coupling section and made a new figure that guides the reader through the text. Previous Figure 8 has been removed.

2nd Round of Revisions

Decision Letter

[sent 17th November, 2023]

Dear Dr. Schmid and co-authors,

Thank you very much for the resubmission of the revision of the manuscript “High resolution DVC analysis of lower crustal flow in analogue models of rift interaction revealing brittle-viscous coupling processes” for consideration by Tektonika.

After considering the results from a further round of reviews and our own readings of the paper, we conclude that the manuscript has been significantly improved during revision, with several of the major concerns raised during review now resolved. However, there are some lingering comments raised by Reviewer 1 that will enhance your paper. In particular, these include clarifying the aim of the study in the text, being more explicit about the novelty of this work compared to Zwaan et al. (2018a) and some more information on key parameters like the rotation angle measurements and the Lagrange-Green tensor.

We agree that the points raised by the reviewer are important and will strengthen your work to make this an excellent contribution. However, we consider these to be minor corrections and so recommend a revised manuscript is submitted by 5th January 2024.

We ask that when submitting revisions you respond to each point raised and that you submit both a copy of your revised manuscript, with the new changes clearly marked, and a clean version, during your resubmission.

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.

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

Yours sincerely,

Leonardo M. Pichel, PhD, Associate Editor – Tektonika

Janine Kavanagh, PhD, Executive Editor - Tektonika

Comments by Reviewer 1

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.

The manuscript has improved since the first submission, there are a number of issues that are still not satisfactorily discussed or explained in the current stage. However, I believe that all of these issues can be solved after revisions.

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:

There are a number of components, such as aim of the study, the novelty of the DVC processing and its improvement with respect to Zwaan et al. (2018a), that need to be more explicitly explained.

Secondly, I have questions about the derivation of some quantities, such as rotation angle. Furthermore, I have doubts about the use of some other quantities, components of the Lagrange-Green strain tensor, for the assessment of coupling between brittle and viscous crust in the model.

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:

No reduction needed.

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:

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...

- Application of DVC on analogue models with viscous layers to monitor strain development.
- Use of analogue models to show how rotation of a rift pass block can be edge-driven or driven by viscous flow in the lower crust.

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

- The aim of the study is still not explicitly stated.
- The definition of coupling has improved, but it is still incompletely stated, and scattered over the manuscript.

- Clarity of writing on novelty of method.
- The authors do not provide a reference for their derivation of rotation. Since it does not resemble any rotation equation that I am familiar with, I cannot check the validity of the equation.
- The use of the Lagrange-Green tensor has limitations (w.r.t. the use in the manuscript) that the authors do not acknowledge (or do not realize).
- The interpretation of the rotation matrix R in the polar decomposition of the deformation gradient is incorrect, as R does not denote rigid body rotations (only).
- The main focus of the results is on cumulative displacement/strain, while incremental displacement/strain would better align with the discussion.
- There is an asymmetry in the results (y -direction) that is not explained and does not fit to the setup.
- There is no assessment of the noise in the results (relative to the Zwaan et al. 2018a paper).

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]

The *Title* describes the main topic of the manuscript **succinctly** — [YES]

The *Title* includes **appropriate key terms** — [YES]

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

The *Abstract* supports the rationale with **sufficient background information** — [YES]

The *Abstract* includes a **well-balanced description of the methods** — [YES]

The *Abstract* describes the **main results sufficiently and adequately** — [YES]

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

The *Abstract* clearly states the **conclusions of the study** — [YES]

The *Abstract* is **clear** and **well structured** — [YES]

Comments:

The *Abstract* includes a **clear aim** – [NO]

Regarding the aim: imaging the coupling between brittle and viscous model domains, the authors can be more explicit.

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

The authors are clear in the description of results from their analysis of the evolution of rift pass blocks, but do not stress the importance of their outcomes for the understanding of the evolution.

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]

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

The *Introduction* contains **relevant, suitable citations** — [YES]

The *Introduction* is **organized effectively** — [YES]

Comments:

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

The aim of this study is therefore to present the results [...]

I do not agree with the statement of the aim, in the sense of a research question. Namely, it is not testable. It is correct that the aim of a paper is to present results, but that is trivial. The true aim seems to me:

- Testing how the new DVC workflow is able to show more details on deformation styles in analogue models of upper and lower crustal layers.
- Study the degree of coupling between these layers during rift-pass evolution.

Please rewrite. Perhaps my suggestions can be used to formulate explicit aims.

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]

Necessary information about **data sources/acquisition/processing** is included — [YES]

Data used are accessible via either supplementary files or links in the data availability statement — [YES]

The *Dataset and/or Methods* are **organized effectively** — [YES]

Comments:

Choice of methods

Instead of specifying the technical details of the model, I would like to suggest the authors first state briefly what kind of processes they want to model, and why the chosen setup is valid for that purpose. For example, it is not clear what kind of boundary condition the foam and plexiglass bars represent. This has to be explicitly stated.

Novelty of processing

It remains unclear what exactly are the improved processing steps in the DVC method compared to Zwaan et al. (2018a). It thus remains unclear what is the novelty here. What I could make from the manuscript is that the authors use a higher spatial resolution than in Zwaan

et al. (2018a) (but without any methodological differences). This seems a rather minimal progress in DVC compared to Zwaan et al. (2018a). Furthermore, the authors apply a strain and rotation analysis that Zwaan et al. (2018a) did not perform. I would like to ask the authors to explicitly list the improvements, otherwise these improvements do not stand out against all descriptions of processing steps.

Overlapping interrogation windows

The authors use overlapping interrogation windows, which is fine. However, it should be mentioned that the displacement solutions for subsequent vectors are strongly correlated because the underlying data overlaps to a large degree.

Trade-off spatial resolution and noise

The authors write:

Using a final overlap of 75%, we obtain displacement vectors every second voxel resulting in a spatial vector resolution of 1.2 mm without decreasing the accuracy (Wieneke, 2015).

This is a sentence I do not fully understand, I which I suspect is also wrong. Generally, when taking the same method for DVC (and it seems that the same method is taken as in Zwaan et al. 2018a), increasing the spatial resolution always means increasing the noise. If that is not the case, the authors should be explicit what methods Wieneke (2015) provides to increase resolution while not increasing noise levels.

From Figure A4: the solution presented in this study seems to be noisier than the one from Zwaan et al. (2018a). Checking the level of displacements in areas far away from the rifts in the brittle domain (where one does not expect localized deformation), it seems that the newly processed data (figure A4) has more random noise than the old solution from Zwaan et al. (2018a).

How have uncertainties been determined (line 3140)? And these are uncertainties for what? For each of the displacement components? How can it be that the uncertainties are the same for both studies, when the Zwaan et al. sub-volumes contain $2*2*2 = 8$ times more voxels? Please comment.

Since the word noise is mentioned a few times in the introduction and method, it is strange that there is no assessment of the noise (or even discussion) of the results (compared to Zwaan et al. (2018a)).

Spatial resolution

If there is a 75% overlap between subsequent sub-volumes, the centers between sub-volumes have a distance of 25% of the volume width, correct? When each side of the sub-volume is 9.6 mm, I would think that subsequent sub-volume centers have a distance to each other of $9.6 \text{ mm} * 0.25 = 2.4 \text{ mm}$, instead of 1.2 mm as reported in the text. Did I misunderstand something, or is there an error in one of the numbers reported in the text?

Rotation angle

I do not recognize equation 4. Please provide a reference, and assumptions. For Euler angles it matters in what order rotations are applied, but the authors do not mention this order. I can thus not check whether the equation is valid. This is typical textbook material, so I'd like the authors to check their equation and provide an explicit reference.

Rigid body rotation

There is a misconception amongst the authors about the meaning of the rotation matrix R from the polar decomposition of the deformation gradient tensor F . R does not only contain rigid body rotations, but also rotation due to (simple) shear (as in shear zones). Only if stretch tensor V has non-zero values on the diagonal only, R is fully determined by rigid body rotations. If simple shear occurs (and V has non-zero off-diagonal values), shearing will contribute to rotation as well. In figure 5 it is clear that some rotations are affected by shearing. I am not aware of any method that can fully separate shear rotations and rigid body rotations. This should be acknowledged for in the description.

Coupling definition in section 2.4.3

In the introduction there is a start of something that builds to a definition of coupling, in lines 108-109 and 164-171. In lines 174-176 this becomes even more concrete:

Here, we investigate spatial variations of coupling between the brittle and viscous model domains as expressed by spatially varying shear strains at the brittle-viscous interface.

In section 2.4.3 there is again a mention of shear strains (E_{xz}), but no explicit connection how coupling is quantitatively connected to the level of shear strain. I suggest to make an explicit statement about what (normalized) values of E_{xz} are expected in brittle and viscous domains for settings of low and high coupling, respectively.

What also lacks in the definition of coupling is an explicit description of what is coupled, and I think the authors mean a geometrical coupling between brittle and viscous domains, i.e., a kinematic coupling. That would be wise to add, since one could also consider dynamic coupling,

i.e., the degree to which the brittle and viscous crust exert stresses on each other, but this is a type of coupling that we cannot assess with analogue models where we have no knowledge on stress levels. Thus, it is important to be explicit that the type of coupling considered here is in terms of kinematics.

Lagrange-Green strain

The Lagrange-Green strain is not a decomposition of the deformation gradient F , rather it is a quadratic function of F . This means that the off-diagonal components cannot be equated to shear strains (they only can for small strains), even though they are related to shear strain.

An alternative could be to compute the maximum possible shear strain (an invariant) based on the stretch tensor V (from the polar decomposition). Beware that the principal values from the Lagrange-Green strain tensor are not equal to principal strains, so one cannot use the same equations as one would use for infinitesimal strain tensors to compute the maximum shear strain. As far as I am aware, no symmetrical strain or stretch tensor has components that are equal to simple shear. For example, for large simple shear, the diagonal terms of the stretch tensor V are also affected (for very large shear strains, the diagonal terms become dominant, rather than the off-diagonals).

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** — [NO]

The *Results* findings are presented **clearly and succinctly** — [YES]

The text in the *Result* section **cites tables and figures appropriately** — [YES]

The *Results* directly **relate to the study objectives** — [YES]

The *Results* present **data for all the approaches** described in the *Methods* section — [YES]

The *Results* **text belongs to the Results section**, not to *Introduction*, *Methods*, or *Discussion*. — [YES]

The *Results* section is **organised effectively** — [YES]

Comments:

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

Apart from my objections to the claim on rigid body rotations and Lagrange Green strain off-diagonal components:

The use of E_{xy} is not fit as a general description of shearing in the horizontal plane. It is only representative for shear along x and/or y direction. If shear occurs along the diagonal, it will appear in E_{xx} and E_{yy} rather than in E_{xy} . The limitations of E_{xy} have to be acknowledged. Similar problems arise for E_{xz} , but since the system is layered in z direction, and with boundary conditions that force the system dominantly in x direction, I expect the problems to be smaller for E_{xz} than for E_{xy} .

Also, on the use of E_{xz} , in line 2432 the authors state:

Towards the model center (and the center of the rift-pass block), shear values decrease indicating an increase in mechanical coupling.

I am not convinced that the use of E_{xz} leads to valuable inference of coupling on all locations. Namely, in the center of the model D_x is near zero at all depths (figure 4). Thus, there is also no gradient to be expected of D_x along z, hence E_{xz} is very small. The absence of significant E_{xz} is thus noninformative. Figure 4f shows that E_{xy} is on the other hand relatively high in the center of the domain of the viscous layer, indicating a relatively high coupling (in the authors' definition).

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]

The *Discussion* **addresses all major results** of this study, which are shown in *Results* — [YES]

The *Discussion* section makes **comparisons with other studies** that are relevant and informative — [YES]

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

The *Discussion* section presents the **implications of the study** persuasively — [YES]

The *Discussion* section **highlights novel contributions** appropriately — [YES]

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

The *Discussion* section is **organised effectively** — [YES]

The *Conclusions* are **consistent** with and **summarise** the rest of the manuscript — [YES]

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

The *Conclusions* are **clear and concise** — [YES]

Comments:

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

Due to the setup, zero y-velocity boundary conditions, there is no regional flow in y direction that could lead to a floating block outcome. Hence, your preference for the edge-driven model is determined by your model setup. This has to be acknowledged.

We have adjusted this in the revised manuscript and acknowledge that the model setup (i.e., the boundary conditions) determines deformation according to the edge-driven model.

Out-of-plane flow asymmetry

The out-of-plane flow (D_y) in the viscous domain is not symmetrical (it is somehow dominantly positive). This may hint at a problem in the model setup. This, and its consequences have to be discussed.

Incremental vs. cumulative deformation

Figure 8 and the accompanying discussion focus on different phases. For being able to see what happens in different phases it is much more useful to inspect incremental rotation and shear than cumulative. For example, it may be that viscous flow drives the rotation in the rift pass block at a later stage of the model, however this is difficult to see from cumulative deformation.

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

Improved accuracy

line 1033: Why do the authors conclude that the results from Zwaan et al. 2018 are underestimating the displacements, rather than that the new results overestimate the displacements? This needs some more thoughts and explanation. Accuracy can only be tested against the actual value (definition of accuracy is the degree to which the estimated value conforms to true value). Please check if the estimated displacements can be tested against independent values. If there is no independent data, I think the authors can only state that the estimated displacements are higher compared to the Zwaan et al. paper, after which the authors can argue that is also better, supported by qualitative statements.

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

This relates to my earlier comments on the appropriateness of the Lagrange-Green strain components, the rotation equation.

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]

*Tables and Figures have **captions that explain** all their major features* — [YES]

*Tables and Figures have **captions that complement** the information in the main text* — [YES]

*Tables and Figures present data that **relate** to the study objective* — [YES]

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

*Tables and Figures have **succinct and informative titles*** — [YES]

*Figures are **accessible** (elements are clearly labelled, accessible colour palettes, colour contrasts, font size legible, etc....)* — [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]

Figures with maps have **sufficient location information** (in the map or caption) — [YES]

Cross-sections have clear labels for **scale and coordinates** at ends and within-section kinks — [YES]

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

Comments:

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

See my comment on incremental strain and rotation.

Comparison between figures 4f and 6b, showing D_y at the same moment in time (4 h) and in the same horizontal slice (H-H'), depict slightly different colors (even though the range is [-5,5] in both figures).

Authors' Reply to Reviewer 1

A1.2) Author(s) Responses:

We would like to thank the reviewer for the detailed and helpful review of the previous version of the manuscript. Bilateral discussions with the reviewer substantially improved our understanding of the advantages and disadvantages of the various strain tensors and helped to choose the finite stretch to describe deformation in the presented model appropriately. We are convinced that the revised manuscript properly addresses the concerns raised by the reviewer and that we have covered and improved all aspects listed by editors and reviewer. We provide detailed comments for each point in the form below.

A2.2) Author's responses:

We have revised the introduction (as well as the abstract) and clearly state now the aim of this work. Namely, to test a new DVC workflow that we developed (which includes XRCT data processing and actual DVC, postprocessing of DVC and appropriate use of strain quantities) by applying it on XRCT data of a crustal-scale two-layer model simulating the evolution of a rift-

pass structure previously presented in Zwaan et al. (2018). Further, we state that the use finite stretch allows us to investigate the evolution of such a rift-pass structure in the brittle model domain and its effect on viscous flow in the underlying substratum.

The definition of coupling is now presented in a specific subsection in the method section and we clearly state that we are investigating the kinematic coupling which is investigated by means of the maximum possible shear strain (derived from the stretch tensor V).

We improved the description of the applied DVC workflow and explicitly describe the steps that it contains in contrast to previous studies. Further, we have included a subsection to explain how we derived DVC uncertainties and compare and discuss our findings with the uncertainties presented in Zwaan et al. (2018).

We provide now the reference, from where we obtained the Euler angles to describe rotations in a 3D rotation tensor (i.e., Diebel, 2006; more than 1500 times cited, as of Today). The description of these Euler angles has improved and we list which Euler sequence we are using.

After helpful bilateral discussions with the reviewer, we acknowledge that the use of the Lagrange-Green strain tensor used in the previous version is not suited for our study. The use of finite stretch (giving rotations and stretches in the final state after rotation) in the revised version was chosen according to the arrangement with the reviewer.

We acknowledge in the revised manuscript, that the rotation matrix does not contain rotations only due to rigid-body rotation but may also contain a shear contribution. To this end, we checked the off-diagonal terms of the left stretch tensor V and compare their magnitude with the magnitude of the diagonal terms to estimate shear contribution (Appendix A4). Doing so, we are aware that the amount of shear contribution to rotations is not quantitatively captured. However, relatively low values of such ratio throughout most parts of the brittle model domain (except near the rift segments) may hint at a very low shear contribution to the rotation and the rotation of the rift-pass block about a vertical axis is approximately a rigid-body rotation. We therefore refer to the rotation of the rift-pass block as *quasi-rigid body rotation*.

We chose to mainly use cumulative displacement for better comparison with the study of Zwaan et al. (2018). However, we provide 1h-increments of displacement maps in the Appendix (Figs. A1-A3). For profiles of maximum possible shear, we also checked the profiles for incremental maximum possible shear as well as for rotations. These profiles show, that the evolution yields relatively constant increments of maximum possible shear as well as rotations which implies, that the cumulative data reasonably well represents what is observed in the time increments.

We are aware that an asymmetry (with respect to the out-of-plane flow component) exists in the original DVC data. In the revised manuscript, we mention this asymmetry and state that it is most likely due to the fact that the model was not positioned perfectly horizontal on the XRCT bed for scanning which favored gravitational flow in one direction. However, we are convinced that this does not alter our findings substantially which justifies our choice to correct this asymmetry by subtracting the mean flow (U_y component) within the entire model domain from the U_y displacement field.

We acknowledge the occurrence of noise in the revised manuscript and state that noise increases when using smaller sub-volumes (i.e., a higher vector resolution). In the revised workflow, we state that we employ convolution of the incremental DVC data set with a $3 \times 3 \times 3$ smoothing kernel to overcome this issue. Using a kernel with a physical size smaller than the final sub-volume size does act as a low-pass filter and therefore, does not alter the absolute values of displacements. However, we did not perform a quantitative assessment of noise.

B1.2) Author's responses

We have adjusted the Abstract in the revised manuscript and clearly state the aim of this study. Namely, to investigate and quantify the kinematic coupling between the brittle and viscous model domains. To do so, we analyze rotation about the vertical model axis (driven by the rift-segment configuration in the brittle domain) and its effect on deformation in the underlying viscous model layer. The rotation of the brittle model domain exerts a drag force on the viscous layer and, as a result, a shear horizon develops at the brittle-viscous interface. Also, we clearly state now the importance of the study. Our results suggest that displacement-, rotation- and strain measurements from the surface may help to estimate lower-crustal flow below rotating, rigid upper-crustal blocks. Consequently, substantial amounts of lower crustal material may flow out of the rift-axis perpendicular 2D plane causing overestimations of crustal extension in such rift transects.

B2.2) Author's responses

We have revised the introduction and clearly state the aims of this study. We state that the aim of this study is to test the new improved DVC workflow by revising an existing XRCT data set and apply the new DVC workflow. Thereby, we demonstrate that using finite stretch reveals new deformation phenomena in the analogue model which have previously not been described. Further, we show how upper crustal block rotation (about a vertical rotation axis) stimulates out-of-plane flow in the lower crust which has implications for 2D plane restoration and may cause overestimation of crustal extension in rift sections.

B3.2) Author's responses

Choice of methods

We have adjusted this section and rearranged the paragraphs. The revised manuscript now first states why this model setup was chosen and what the applied boundary conditions may represent in nature. We explicitly state why chose this setup and acknowledge that it is suited particularly for early rifting stages when deformation in the mantle is negligible.

Novelty of processing

The revised manuscript clearly lists the improvements of the revised DVC workflow and mentions all applied steps that have not been performed in Zwaan et al. (2018). Namely, we perform a preprocessing of the XRCT data to obtain cubic voxels, a necessity for DVC analyses, to guarantee proper displacement scaling. The effect of improperly scaled voxels is explicitly explained in a new subsection (2.4.), which describes and discusses DVC uncertainties. Further, the multi pass-DVC analysis uses overlapping sub-volumes which lead to an increased vector resolution (not spatial resolution due to correlated neighboring vectors).

Postprocessing of the incremental displacements contains outlier detection and replacement of spurious vectors as well as smoothing of incremental displacements using a 3 x 3 x 3 convolution kernel. Note, that using a kernel with a physical size (7.2 mm) smaller than the final sub-volume size (9.6 mm) minimizes lowpass filtering such that displacement peak values are not smoothed.

For obtaining cumulative displacements, we use an interpolation scheme (e.g., natural neighbor) to take material advection into account before summing up incremental displacements that are calculated on a fixed Eulerian grid.

Overlapping interrogation windows

The revised manuscript acknowledges that a higher vector resolution, due to overlapping sub-volumes, yields strongly correlated neighboring displacements and does not increase the spatial resolution.

Trade-off spatial resolution and noise

We acknowledge and state that increasing the vector resolution increases noise. The statement in the previous manuscript that previous statement that using overlapping sub-volumes reduces noise was unfortunately wrong and we apologize for that honest mistake. However, we now state that we apply spatial smoothing on incremental data as a postprocessing step to reduce noise.

Additionally, we implemented a subsection that describes how we obtained uncertainties for both studies. The results show that the final sub-volume size does not have an influence on the uncertainty; however, Figure 2 (new) illustrates the importance of XRCT preprocessing to obtain cubic voxels. For prismatic voxels, the anisotropy leads to massive differences in the actual values which must be corrected post-DVC.

Spatial resolution:

As correctly stated by the reviewer the vector resolution (using a final sub-volume size of 16 voxels) should be 2.4 mm instead of 1.2 mm. We have corrected this and apologize for that mistake.

Rotation angle

In the revised manuscript, we explain in detail how we obtained rotation angles using the left polar decomposition $F = V * R$. From the rotation tensor R , rotation angles are obtained using an Euler angle sequence [1 2 3] using the equations provided in Diebel (2006).

Rigid body rotation

After valuable exchange with the reviewer, we acknowledge in the revised manuscript that the rotation tensor R does not only contain rigid-body rotation but also rotation that is induced by shear. As a qualitative measure, we checked the values of the off-diagonal terms in the left stretch tensor V and compared their contribution to the values of the diagonal terms in V . We are aware that we cannot assess the amount of shear-induced rotation quantitatively, but our investigation shows that off-diagonal terms mainly occur near the rift segments. This is particularly important for the brittle model layer and shows that (apart from the rift segments) rotations in the rotation tensor indeed depict rigid-body rotation. Therefore, we believe that it is reasonable to refer to the rotation of the rift-pass block as a quasi-rigid body rotation where off-diagonal terms of V are negligible. We have stated this clearly in the revised manuscript.

Coupling definition in section 2.4.3.

We have revised our definition of coupling and clearly state now, that we refer to kinematic coupling which describes the coupling of deformation in the brittle and viscous model layers due to kinematics rather than forces, which are not accessible in analogue models. This definition is clearly stated in a dedicated subsection (2.5.2.), where we also mention definitions of coupling using forces/stresses in literature.

Lagrange-Green strain

In agreement with the reviewer, we discarded any use of the Lagrange-Green strain tensor and use finite stretch instead. Finite stretch results from the decomposition of the deformation gradient tensor and hence, does not square strain components. The left polar decomposition of F leads to the left stretch tensor V and the rotation tensor R , from which we calculate rotation about the vertical model axis. Moreover, the left stretch tensor V is used to calculate maximum possible shear γ_{\max} from the principal stretch values of V (i.e., $\gamma_{\max} = \lambda_1 - \lambda_3$).

B4.2) Author's responses

As stated above, we discussed bilaterally with the reviewer the use of appropriate strain tensors to quantify deformation. To this end, we discard any use of the Lagrange-Green strain tensor and its components and describe deformation using the finite stretch (i.e., rotations and maximum possible shear).

B5.2) Author's responses

Out-of-plane flow asymmetry

We are aware of the asymmetry in the original model and clearly state now, that the asymmetry has occurred because the model was not placed perfectly horizontal on the CT bed for XRCT scanning. However, we believe that this does not substantially affect the outcomes of this study. With this in mind, we accommodate for the asymmetry by subtracting the mean D_y component from the entire D_y displacement set and as such, the results are fairly symmetrical. This is clearly stated now in the revised manuscript.

Incremental vs. cumulative deformation

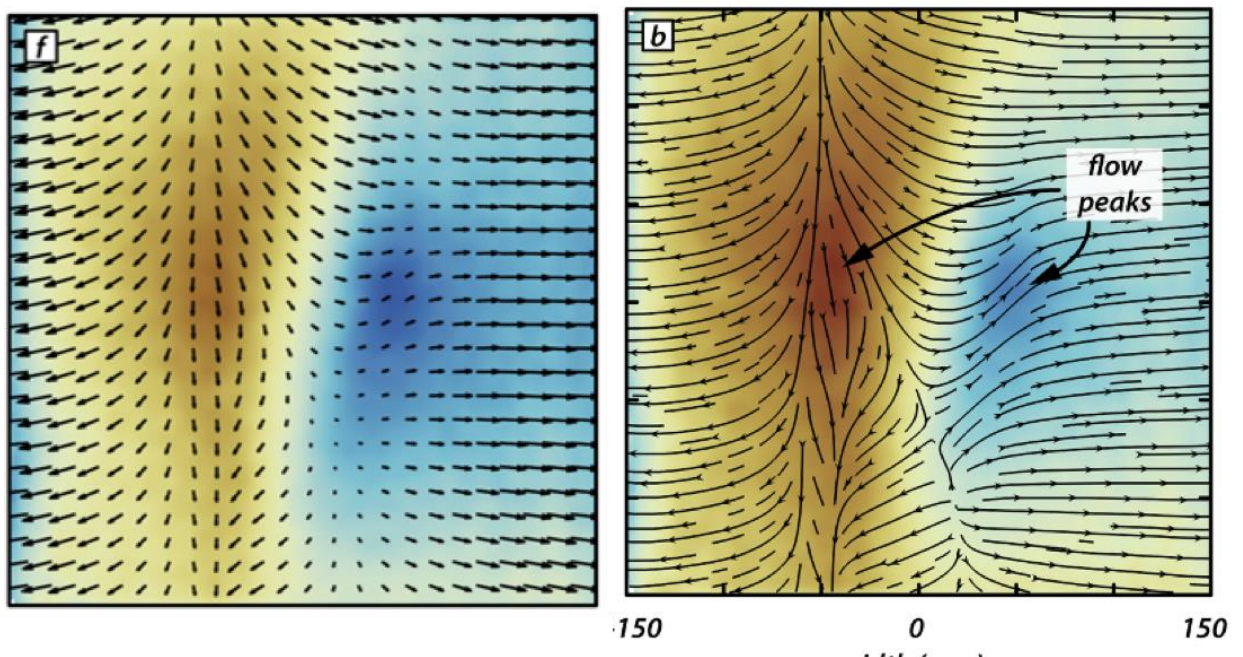
The focus of this section has changed and we do not directly compare rotation in the brittle model layer with flow in the viscous layer since this comparison seemed somewhat non-intuitive. However, we now provide depth profiles at three distinct locations in the model that document increasing shear in the viscous domain with increasing distance to the rotation axis of the rift-pass block. Similarly, to the previous plot, these profiles document a jump in the amount of shear at the transition from the brittle to viscous model layer. We also tested this for incremental shear (i.e., every 20 minutes) which show a fairly stable depth profile over time. Identically, we tested this for depth profiles for the vertical rotation component, which show identical evolution with a jump at the brittle-viscous interface (with higher, stable values in the brittle model domain). Therefore, we reason that the evolution is fairly stable over time which justifies to not show profiles of incremental displacement-, rotation-, or shear values.

Improved accuracy

We have adjusted the pertinent section and discuss the effect of cubic (this study) vs prismatic (Zwaan et al. (2018)) voxels in section (2.4.)

B6.2) Author's responses

We have adjusted this inconsistency. The revised data set shows now consistent color ranges as we adjusted the color bars for maximum values within the entire data set.



Vectors

We adjusted the vectors in all figures in such a way that we show less dense but larger vectors.

To avoid small vectors which are difficult to interpret, we normalized the vector lengths by the maximum value such that all vectors show unit length and are of the same size.

Color schemes

We have adjusted the pertinent figures. The used colormaps show now whiteish colors near the value zero, which is additionally enhanced by plotting the zero displacement/rotation zones using a white contour line. This has also been adjusted in the color bars. Additionally, confusing indicators for rotation direction or out-of-plane displacements have been adjusted and are clearer.

3rd Round of Revisions

Decision Letter

[sent 18th June, 2024]

Dear Authors,

Thank you very much for your submission of the revised manuscript “Brittle-ductile coupling during rifting as revealed through digital volume correlation analysis of a crustal-scale analogue experiment” submitted to Tektonika.

We believe overall the changes you have made have improved the manuscript. We received another review and, together with our own reviews, we have found there are some minor, but important, points that we would like you to address, as detailed in the attached review. The manuscript is nearly ready for formal acceptance, and we kindly ask the authors to address the reviewer’s suggestions, in particular on: i) further clarifications about the novelty of the method relative to previous publications, and ii) method descriptions and organization.

We look forward to receiving a copy of your revised manuscript by 31st July 2024. We ask that when submitting revisions, you use the review form to answer the reviewer’s comments, point-by-point. We ask you to submit both a copy of your revised manuscript with changes clearly marked and a clean version during your resubmission. 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.

Yours sincerely,

Leonardo M. Pichel, PhD, Associate Editor - Tektonika

Janine Kavanagh, PhD, Executive Editor - Tektonika

Comments by Reviewer 1

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.

The authors have made many good changes to the text and figures, improving the manuscript considerably. There have been a number of new sections added, and some of these raise new questions, see my main comments.

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:

I have made some major and minor comments that I think the authors should address before the submission is publishable. Some relate to comments made already to the previous version where I think the issues have not yet been solved.

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:

The text is relatively long and verbose. I have the impression that some reduction of text is

possible. I leave this up to the editor whether this is needed.

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

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...

- Application of DVC on analogue models with viscous layers to monitor strain development.
- Use of analogue models to show how rotation of a rift pass block can be edge-driven or driven by viscous flow in the lower crust.
- Evolution of rift-pass blocks and related lower crust deformation
- The section on kinematic coupling is clear, and is a great addition to the overall argumentation.

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

My main comments relate to the novelty of the revised approach. The way it is presented now, it is unclear what problem the authors aim to address (i.e. what are the weaknesses, points of improvement of existing methods?). Only after making this starting point explicit, it becomes clear for a reader what the authors add in terms of novelty and why this is valuable.

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]

The *Title* describes the main topic of the manuscript **succinctly** — [YES]

The *Title* includes **appropriate key terms** — [YES]

The *Abstract* includes a **clear aim and rationale** — [YES]

The *Abstract* supports the rationale with **sufficient background information** — [YES]

The *Abstract* includes a **well-balanced description of the methods** — [YES]

The *Abstract* describes the **main results sufficiently and adequately** — [YES]

The *Abstract* clearly describes the **importance/impact of the study** — [YES]

The *Abstract* clearly states the **conclusions of the study** — [YES]

The *Abstract* is **clear and well structured** — [YES]

Comments:

When discussing coupling, (line 78) I would advise to keep it strictly to kinematic coupling, and do not use the term “mechanical coupling”, since the dynamical component of coupling (e.g. stresses) has not been analyzed.

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]

The *Introduction* describes the **aim/hypothesis/rationale** clearly, providing **sufficient context** — [Yes]

The *Introduction* contains **relevant, suitable citations** — [YES]

The *Introduction* is **organized effectively** — [YES]

Comments:

The introduction introduces the context, problem, the aim and the approach in a proper manner.

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]

Necessary information about **data sources/acquisition/processing** is included — [YES]

Data used are accessible via either supplementary files or links in the data availability statement — [YES]

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

Comments:

Choice of methods

The current methods start right away with the description of model details (thickness over layers). I suggest that the authors start first with a few sentences of what the model aims to represent, i.e. what kind of tectonic setting, with what kind of assumptions on the relevant physics. Only in that way the reader can understand whether all model details make sense. Some of this information is currently given in the second sentence, however there it is already mixed with technical details.

While it is clear what the brittle and viscous layer represents, it is unclear what unit, or what boundary condition the foam-plexiglass base represents. Something similar applies to the rubber sidewalls: what kind of boundary condition (kinematic boundary condition?) do these represent, and it would help to add in the text in what direction these stretch.

Section 2.3

The first paragraph of section 2.3 reads as if it actually belongs to section 2.2, as no revised volume correlation seems to be introduced, rather the general working of DVC is discussed.

Novelty of revised approach

While the introduction has improved in this respect, section 2.3 still does not start off with a brief explanation what the novelty of the approach is. It would be very helpful if section 2.3 would start with

- Problem statement (weakness of existing, previous approach)
- General description of novel approach that aims to improve the existing methods

In this respect, the authors write:

Note that the overlap of sub-volumes increases vector resolution; however, it does not improve the spatial resolution as neighboring vectors are not independent.

So, it remains unclear why an overlap of interrogation areas is useful at all. I think it leads to a smoother result with less discontinuities compared to no overlap. But this is not yet mentioned as advantage.

Errors of DVC: aim

It would be good to start of section 2.4 with 1-2 sentences on what is the aim on the error analysis: I understand this includes testing the improvements of the new pre-processing and some parameter choices in the DVC approach. The readers will be greatly helped if this aim is stated upfront. Currently, only the caption of figure 3 states that 4 different cases are considered.

Errors of DVC, description of uncertainties

In section 2.4 the authors have added an analysis of uncertainties of DVC displacements, which I think is a very good idea. The reporting of the errors/uncertainties is however somewhat a mixed bag, with mention of “uncertainties”, “means” and “standard deviations”. Since the authors know the actual displacements, the error can be computed. I suggest mentioning both the mean of the error (denoting a bias) and the standard deviation of the error (denoting the spread around the mean) for each of the estimated parameters (u_x , u_y and u_z) in a consistent manner.

Errors of DVC: improvement due to pre-processing

The authors write: prismatic voxels overestimate the expected value by a factor of 2, yielding values of 10 mm (± 0.03 mm). This overestimation is a direct result of the anisotropic voxel size of 0.72 x 0.3 x 0.72 mm/px and was accounted for in Zwaan et al. (2018a) post-DVC analysis.

This makes me wonder, if the non-cubicness of the prismatic voxels can be accounted for in the post-DVC analysis (i.e. rescaling the u_y displacements) just as well? What is the actual improvement using the pre-processing step of nearest neighbor interpolation to get cubic voxels prior to DVC? The standard deviations of the errors seem not to be affected by any of the choices (prismatic vs. cubic and size interrogation area). Can we speak of an improvement at all in terms of errors of DVC?

Errors of DVC: idealized case

Assessing errors based on non-deformed sample provides an idealized case. Figure 2.21 of Thielicke, W. (2014). *The flapping flight of birds: Analysis and application*. Shows that deformation has a large influence on the estimated errors. This should be acknowledged.

Euler angle rotation axes

There seems to be a misconception about the meaning of the (1,2,3) Euler angle sequence. This sequence does not denote rotations about the x,y and z axes. Namely, after the first rotation (3) around angle ψ , the x and y axes have been rotated, forming now x'' and y'' . One can no longer speak for the next two rotations about rotation around the original x and y axes. The authors should stick to the notation of Diebel (2006). Since rotation 3 is the first, one can indeed speak about a rotation around z, but that is the exception.

Euler angle vector equation

Equation 6 is not equal to eq. 72 from Diebel. Mathematically equation 6 seems impossible, since R are [3x3] matrices, and can thus never be equal to a vector. Equation 6 should thus be revised such that it matches the original equation from Diebel.

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]

The *Results* findings are presented **clearly and succinctly** — [YES]

The text in the *Result* section **cites tables and figures appropriately** — [YES]

The *Results* directly **relate to the study objectives** — [YES]

The *Results* present **data for all the approaches** described in the *Methods* section — [YES]

The *Results* **text belongs to the Results section**, not to *Introduction*, *Methods*, or *Discussion*. — [YES]

The *Results* section is **organised effectively** — [YES]

Comments:

I have no major comments on the results.

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]

The *Discussion* **addresses all major results** of this study, which are shown in *Results* — [YES]

The *Discussion* section makes **comparisons with other studies** that are relevant and informative — [YES]

The *Discussion* section properly identifies all **speculative statements** — [YES]

The *Discussion* section presents the **implications of the study** persuasively — [YES]

The *Discussion* section **highlights novel contributions** appropriately — [YES]

The *Discussion* section **addresses the limitations** of the study appropriately — [YES]

The *Discussion* section is **organised effectively** — [YES]

The *Conclusions* are **consistent** with and **summarise** the rest of the manuscript — [YES]

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

The *Conclusions* are **clear and concise** — [YES]

Comments:

I have no major comments on the discussion and conclusions.

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]

Tables and Figures have **captions that explain** all their major features — [YES]

Tables and Figures have **captions that complement** the information in the main text — [YES]

Tables and Figures present data that **relate** to the study objective — [YES]

Tables and Figures present data that are **consistent** with and support the description of

results — [NO]

Tables and Figures have **succinct and informative titles** — [YES]

Figures are **accessible** (elements are clearly labelled, accessible colour palettes, colour contrasts, font size legible, etc....) — [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]

Figures with maps have **sufficient location information** (in the map or caption) — [YES]

Cross-sections have clear labels for **scale and coordinates** at ends and within-section kinks — [YES]

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

Comments:

The figures that have a blue-white-red colormap have no properly centered colormap, see my comment later on.

Authors' Reply to Reviewer 1

A1.2) Author(s) Responses:

We are very thankful for the thorough comments and suggestion of the reviewer. We are convinced that we have addressed the remaining concerns and changed manuscript and figures where needed. Regarding the length of the manuscript, we think that the current length is necessary to provide all the information for a comprehensive understanding of the work.

A2.2) Author's responses:

We have modified the text to highlight the issue we want to study first, followed by the details of the improved DVC analysis.

B1.2) Author's responses

We have checked again all occurrences and concisely use the term kinematic coupling instead of mechanical coupling.

B2.2) Author's responses

We have rewritten the text to better explain the tectonic context, before going into the details of the model set-up. The model represents a hot lithosphere with a thick crust. We have rewritten the start of the methods to better explain this (and moved any technical details of importance to the later in the methods).

B3.2) Author's responses

The foam represents a uniformly stretching ductile mantle. The rubber sidewalls are simply a technical means to contain the model materials, they have no real impact on the model results, although minor boundary effects can occur. Even so, our analysis is focused on the center of the model, where no boundary effects are present. We have added some details to the text.

We have adjusted the beginning of section 2.3. and reworked the (previously) first paragraph.

We have now reordered the methods in the following sections:

- 1) CT-data acquisition
- 2) Our revised DVC approach, in which we start off with the suggested limitations of the previous work and the general description of the new approach.

We have adjusted this sentence and clearly state in the revised manuscript that sub-volume overlap leads to smoother results.

We have added a few sentences at the beginning of subsection 2.4. to introduce the aim of the error analysis.

This has been revised and we use the terms “mean of error” as well as “1 standard deviation of error”. In addition, we provide the equation for how we obtained the mean of error as there are multiple definitions. As stated in subsection 2.4., we are interested in the error as the deviation of the expected value of displacement in each direction.

It seems indeed that the overestimation can be accounted for post-DVC (as was the case in Zwaan et al., 2018). In our opinion it is more consistent and logical to tackle this issue prior to the DVC analysis, especially if it is a known. Eventually it is a matter of preference. In terms of absolute errors, accounting for the overestimation pre-DVC may not present an improvement, however, it clearly shows, that the nearest neighbor interpolating scheme of the XRCT data set does not affect the result nor does it introduce artefacts.

Thank you for mentioning this. We have rephrased this sentence such that it acknowledges this.

Thank you for pointing this out. We were aware that the subsequent rotations do not occur about the original axes y and z but rather y' and z'' of the rotated coordinate systems but we did not properly explain that, since we are interested in rotations about the initial vertical z -axis. We use angle $\psi_{123}(R) = \text{atan2}(r_{12}, r_{11})$. To confirm the obtained angles, we compared the angle obtained from the full 3 by 3 rotation matrices to horizontal slices in the displacement data set where we calculated the rotation angle from 2 by 2 rotation matrices and obtained identical results. The revised manuscript contains now a better description of the Euler angles.

We have adjusted this part and use equation 72 from Diebel (2006) as it is.

Figures

We have changed the problematic colormap to a centered one with a clear white center.

B6.2) Author's responses

We have changed the problematic colormap to a centered one with a clear white center.

Acceptance Letter

[Sent 6th August 2024]

Dear Dr. Schmid and co-authors,

We have now reached a decision regarding your submission "Brittle-ductile coupling and block rotation during rifting revealed through digital volume correlation analysis of a crustal-scale analogue experiment".

The Associate Editor, Leonardo Muniz Pichel, and I are now satisfied that the comments raised by the reviewers and through the editorial process have now been fully addressed. You have carefully considered all of the points raised and your response gives a detailed account of the changes made, showing significant improvements through the review process. We are therefore happy to inform you that the paper has been now ACCEPTED to be published.

Your paper will now move to the Copyediting phase and our production team will be in touch with you to discuss this soon.

We look forward to publishing your manuscript and hope you will consider TEKTONIKA again in the future.

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

Yours sincerely,

Janine Kavanagh, PhD, Executive Editor – Tektonika

Leonardo Muniz Pichel, PhD, Associate Editor - Tektonika