TEKTONIKA

Review Report

Gabriel et al., Impact of Material Strength on Releasing Bend Evolution, TEKTONIKA, 2025.

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1st Round of Revisions

Decision Letter

General comments:

The manuscript has been reviewed by two referees. The reviews are clear and insightful. While the reviewers' comments were generally favourable, areas of concern were found. The reviewers' concerns must be addressed before the manuscript can be accepted for publication in the journal.

The reviewers agree that the manuscript is well-written and presenting a neat study with state-of-art monitoring and analytical techniques. It shows kinematic sequences of strong and weak clay experiments throughout two characteristic stages of fault evolution clearly demonstrate that the strength of the material as a profound impact on fault geometries, pattern, growth mechanism and kinematic. These novel results have the potential to further improve the understanding of the mechanics of crustal strike-slip zones.

However, areas of concern are highlighted, regarding the clarification of experimental assumptions and statements in relation to material mechanics, scaling and DIC analysis, as well as limitations of methods and some result description. In addition, the improvements in the figures and organization, as well as a short comparison to other physical models of strike slip tectonics should be added with some discussion.

Consider together, these revisions sum up to moderate modifications, which will further improve the work. We encourage the authors to consider carefully the reviewers' comments and to return a revised version of the manuscript in a maximum two months.

Detail comments:

1. A definition of the term, kinematic efficiency, is needed.
2. It would be better for the authors to address the comparability of weak clay experiments and the layered hot crust rheology, as is assumed in the western United States.

3. The right-lateral secondary faults and the left-lateral cross faults may not conjugate faults. The cross faults are more like extensional faults that accommodate the divergence of the releasing plates, while the right-lateral faults are secondary structure of the PDZ.
4. Line 317: northerwesternmost?
5. Line 490: off of faults (off-faults)?
6. Line 609: (dashed lines on Figure 7d)?
7. Lines 615-616: extensional faults in pull-apart basins show components of slip on normal faults?
8. Line 696: ‘cold’ not ‘cool’ crust?
9. Line 703: add a period “.” After (e.g., Hatem et al., 2022)

Comments by Reviewer 1

For author and editor

Summary

The authors present a series of scaled analogue clay experiments of a strike-slip system with releasing bend geometry with strong and weak clay materials to study the impact of rock strength on the fault pattern, growth mechanism and kinematics of the PDZ and releasing bend. The models are dynamically scaled and monitored my 2D DIC strain monitoring and photogrammetry of surface evolution. The analysis demonstrates that in the weaker clay experiment, numerous secondary normal faults and left-lateral cross faults lead to significant reorganization of the primary slip pathway and increased off-fault deformation, and conversely, the stronger clay experiment results in fewer secondary faults, minimal cross faults, and a more stable primary slip pathway, with both experiments showing shallower fault dips and left-lateral slip due to lateral flow at depth. In the discussion, the fault patterns observed in the experiments have been compared with patterns of natural strike-slip fault examples.

General Comments

I very much enjoyed reading the manuscript, which is well written and presenting the modelling results in a comprehensive style with well-designed figures and diagrams. The new analogue modelling results of strike-slip zones with realising bends using strong and weak clay materials provide novel insights in the releasing bend fault geometries of strike-slip systems in strong and weak crustal rocks. The experiment time-series results of fault pattern, growth mechanism and kinematics utilise robust and well-designed analytical routines of 2D DIC strain analysis and structure-in-motion analysis. The fault evolution in the experiments is analysed in detail with incremental strain data being interpreted using shear strain and divergence for classification of fault types and a range of parameters like "kinematic efficiency". The realistic geometries and characteristic kinematic sequences of the strong and weak clay experiments throughout two characteristic stages of fault evolution clearly demonstrate that the strength of the material as a profound impact on fault geometries, pattern, growth mechanism and kinematic. These novel results have the potential to further improve our understanding of the mechanics of crustal strike-slip zones.

I have provided a range of comments for consideration by the authors to clarify some experimental assumptions and statements in relation to material mechanics, limitations of methods and some result descriptions to improve clarity of statements and readability for readers. Being a physical modeller myself, I also suggest some clarification of statements referring to analogue modelling characteristics like material mechanics, scaling and DIC analysis.

My recommendation for this manuscript is "Accept with minor revisions".

I provide an annotated manuscript with detailed comments for further consideration by authors. The main comments for revision by the authors are briefly summarised below.

Comments by Reviewer 2

Dear authors,

I have read through this manuscript and for the most part it was a pleasure to read. Attached you will find numerous comments on the manuscript that I'd like you to address before this can be consideed for publication. My main issues at the moent are:

1. The figures are too small and as I indicate on some of them they need to be broken apart so as to improve legibility – see comments.

2. More figures would be better. And introductory figure is warranted.

3. Some sections of text ccould use work, and some sections would be better moved to different sections of the manuscript – see comments.

4. It seems like a missed opportunity to not compare your results to other published examples of strike-slip analog models. This does not have to a major section but I feel it is warranted, as right now it reads as a study using analog modeling that is operating in its own vacuum. See comments.

Overall the manuscript requires major to moderate revisions, but primarily moderate. Again, see comments and suggestions.

Authors’ Reply to AE

We have revised the paper and responded to the helpful comments of the two reviewers and the Associate Editor. Our responses to the reviewer comments are in blue below.

Associate Editor

The manuscript has been reviewed by two referees. The reviews are clear and insightful. While the reviewers’ comments were generally favourable, areas of concern were found. The reviewers’ concerns must be addressed before the manuscript can be accepted for publication in the journal.

The reviewers agree that the manuscript is well-written and presenting a neat study with state-of-art monitoring and analytical techniques. It shows kinematic sequences of strong and weak clay experiments throughout two characteristic stages of fault evolution clearly demonstrate that the strength of the material as a profound impact on fault geometries, pattern, growth mechanism and kinematic. These novel results have the potential to further improve the understanding of the mechanics of crustal strike-slip zones.

However, areas of concern are highlighted, regarding the clarification of experimental assumptions and statements in relation to material mechanics, scaling and DIC analysis, as well as limitations of methods and some result description. In addition, the improvements in the figures and organization, as well as a short comparison to other physical models of strike slip tectonics should be added with some discussion.

Consider together, these revisions sum up to moderate modifications, which will further improve the work. We encourage the authors to consider carefully the reviewers’ comments and to return a revised version of the manuscript in a maximum two months.

Detail comments:

A definition of the term, kinematic efficiency, is needed.

We clarified the definition of kinematic efficiency presented in section 2.4 of the methods section.

It would be better for the authors to address the comparability of weak clay experiments and the layered hot crust rheology, as is assumed in the western United States.

We are not certain what is meant by this comment. We have a section comparing the results from the weak clay experiment to features seen in the Brawley Seismic Zone. We also discuss the comparability and scaling of our experiments in the methods section. We use the similarities seen in the Brawley Seismic Zone as validation of our results and validation that the results in our weak experiments are different than those in stronger clay and crust. We do not seek to model the Brawley Seismic Zone in this study.

The right-lateral secondary faults and the left-lateral cross faults may not conjugate faults. The cross faults are more like extensional faults that accommodate the divergence of the releasing plates, while the right-lateral faults are secondary structure of the PDZ.

We agree with this assessment and have clarified our wording throughout the paper to better reflect this view.

Line 317: northerwesternmost? Revised

Line 490: off of faults? We changed the phrasing of this sentence to make the meaning clearer.

Line 609: (dashed lines on Figure 7d)? Now 9d. Additional delimitators have been included in the caption to better clarify the purpose of the dashed lines.

Lines 615-616: extensional faults in pull-apart basins show components of slip on normal faults? Yes, this is correct, normal faults accommodate extension with dip slip.

Line 696: ‘cold’ not ‘cool’ crust? Replaced “cool” with “relatively cold.”

Line 703: add a period “.” After (e.g., Hatem et al., 2022) We added a period to the end of the sentence.

Authors’ Reply to Reviewer 1

Reviewer A:

I very much enjoyed reading the manuscript, which is well written and presenting the modelling results in a comprehensive style with well-designed figures and diagrams. The new analogue modelling results of strike-slip zones with realising bends using strong and weak clay materials provide novel insights in the releasing bend fault geometries of strike-slip systems in strong and weak crustal rocks. The experiment time-series results of fault pattern, growth mechanism and kinematics utilise robust and well-designed analytical routines of 2D DIC strain analysis and structure-in-motion analysis. The fault evolution in the experiments is analysed in detail with incremental strain data being interpreted using shear strain and divergence for classification of fault types and a range of parameters like “kinematic efficiency”. The realistic geometries and characteristic kinematic sequences of the strong and weak clay experiments throughout two characteristic stages of fault evolution clearly demonstrate that the strength of the material as a profound impact on fault geometries, pattern, growth mechanism and kinematic. These novel results have the potential to further improve our understanding of the mechanics of crustal strike-slip zones.

I have provided a range of comments for consideration by the authors to clarify some experimental assumptions and statements in relation to material mechanics, limitations of methods and some result descriptions to improve clarity of statements and readability for readers. Being a physical modeller myself, I also suggest some clarification of statements referring to analogue modelling characteristics like material mechanics, scaling and DIC analysis.

I provide an annotated manuscript with detailed comments for further consideration by authors. The main comments for revision by the authors are briefly summarised below.

66-68: “While viscosity and stiffness control the accumulation of stresses due to the applied strain, the strength of the material determines when and where new faults develop.” To explain the relationship of rheological terms (Viscosity, stiffness, strength, etc.) a figure or diagram showing generic stress-strain curves could be helpful for the reader. It also helps to clearly define the use of terms in the manuscript.

We opted not to add a diagram to the introduction because the distinction between constitutive properties and strength properties is not central to the paper. We did rewrite the sentence that mentioned viscosity, stiffness and strength to better explain why we are investigating the influence of material strength in this study.

84: “experiments with viscoelastic wet kaolin clay”

Can the authors further explain why wet clay can be utilised to simulate crustal scale faults in brittle rocks? If clay is described as a viscoelastic material, which deforms under stress in a combination of both viscous (fluid-like) and elastic (solid-like) responses, is it a good brittle rock analogue material? Even if viscoelastic materials fail under high stresses, they typically shear failure characteristics differ from brittle materials. Would it be better to describe the rheology of clay in tectonic simulations as a viscoelastic-frictional plastic material where the dominant frictional-plastic stress-strain behaviour fully resembles brittle rock deformation? Can the authors please provide further references?

Previous work has established that the wet kaolin deforms as a viscoelastic material prior to frictional failure. The very next section describes in more detail the material rheology. To prevent the reader from presuming that the clay does not have frictional failure before we have a chance to describe the material properties, we have modified the introduction to the methods section. Within the material properties subsection (2.1), we have clarified that the clay fails frictionally and cite papers that test and establish wet kaolin rheology.

89: “We utilize Digital Image Correlation techniques”

Reference? Adam et al. introduced the method for analogue tectonic modelling: Adam, J., Urai, J.L., Wieneke, B., Oncken, O., Pfeiffer, K., Kukowski, N., Lohrmann, J., Hoth, S., van der Zee, W., Schmatz, J., 2005. Shear localisation and strain distribution during tectonic faulting--new insights from granular-flow experiments and high-resolution optical image correlation techniques. Journal of Structural Geology 27, 283–301.

We moved the first mention of DIC to later in the paper and added the Adam et al. (2005) paper. This is a great paper that has transformed our discipline.

115-125: Material parameters in paragraph: It would be helpful for the reader to summarize material properties and scaling parameters in a table.

Good suggestion that was echoed by the other reviewer. We have added a table for the material properties.

Figure 1: Basal plate configuration

With the given basal plate geometry in the releasing bend a gap between the moving plates will form with a displacement discontinuity. The basal displacement discontinuity is characterised by the lack of basal displacement and will increasing in size over time. This is rather artificial. How is this being compared to natural cases?

You should show the basal plate geometries at start and end of the experiment (with gap) to discuss this briefly in the text. Why did you not consider a different experiment setup with basal rubber segment covering the releasing band as usually being done in literature?

The 2.5 cm depth of the claybox scales to a depth of about 1-4 km in the crust where we do not expect distributed deformation. In consideration of these shallow depths, it would not be appropriate to have distributed deformation with a basal rubber band. The localized extension and shear at the dislocation (also used in other releasing bend experiments) captures the upper crustal deformation from releasing bend faults that that in crust extend to much greater depths. The increasing size of the gap captures the localized extension and crustal thinning that occurs within all releasing bends and pull part basins (e.g., Mann, 2007). We have added text to explain this and refer to other releasing bend experiments that use basal dislocations. The referenced figure, now figure 2, shows the plate movement. We also clarified the text to emphasize that we are simulating shallow crustal deformation.

153-54: “we create a vertical discontinuity within the clay pack”

What is the rationale to introduce the vertical discontinuity across the releasing bend and the main PDZ? Would it not more representative to localize the entire fault trace in undeformed material?

This is a great question and helped us improve clarity in the writing. This study investigates how established releasing bends evolve within crust of different strength, and we do not here consider the initiation of the bend. We cut the entire length of the releasing bend fault, so our experiments capture the fault evolution after the releasing bend is established. In this way, the experiments start with an active through-going fault similar to established crustal releasing bends around the world today. We have added additional comments to the specified lines in our methods section and the beginning of our results section clarifying our aims in establishing a full precut fault through the bend and expanded the explanation of the spin-up period.

157-58: “To capture both horizontal displacements and vertical elevation …”

Did you consider to measure 3D surface displacement with a Stereo DIC setup?

3D DIC setups are wonderful tools but difficult to fund. The last time I got a quote for such a system (~2016) it was $50k (USD). To substantiate such costs within a proposal to NSF, the 3D DIC would need to be essential for the experiment analysis. These experiments, which were performed as an unfunded undergraduate thesis project for Alana Gabriel, yield sufficient information with 2D DIC and structure from motion.

261-63: “To assess the partitioning of divergence as either dip slip along faults of any orientation or distributed off-fault extension, we calculate the median of the divergence accommodated along faults”

This is very innovative but the map view images of the experiment surface utilised for 2D DIC analysis are only a 2D representation of more complex 3D surface deformation. This can be much more reliably analysed in 3D surface flow DIC with stereo cameras because you can observe “ true” dx,dy,dz displacement components identifying normal faults via subsidence.

With the 2D DIC, we are able to resolve horizontal components of displacement regions of convergence and divergence. This is sufficient to track the slip sense along active faults, which is all we need for this study.

You rightly utilise the incremental DIC data to analyse the fault localisation processes and kinematics. You could also quantify the total geological strain by summing up the incremental strains. Total strain maps would allow a direct comparison to geological strains in nature.

This paper investigates how activity on the faults shifts and evolves around releasing bends. Total cumulative strain maps don’t provide additional information on these shifts. For a different study that directly compares models and specific crustal releasing bends, cumulative strain maps would be more appropriate.

Figure 2: Why did you precut the releasing bend transfer segment when you want to study the fault localisation in the releasing bend? Would it not more realistic in comparison to natural examples only to precut (if at all) the main strike-slip segments?

Please see response to the comment regarding lines 153-154.

Is the colour scale quantitatively scaled? If yes, can you provide min max values, pls?

We added a saturation color bar to the strain map figures which are now figures 3 and 5

357: “Cross faults accommodate left-lateral shear.”

Are the cross faults comparable to oblique slip faults forming in relationship to the simple shear strain ellipsoid (R') or are structures in the releasing bend not easily classified in terms of simple shear zone secondary structures? I would describe the cross faults as antithetic riedel shears (R').

We intentionally do not use Riedel terminology for several reasons. The secondary faults in the releasing bend experiments formed as normal faults than accommodate some component of strike-slip. The orientation of the cross faults depends on the local extension direction, which is sensitive to nearby fault geometry. The Riedel nomenclature was developed for structures formed under homogeneous distributed simple shear, which is not the case here. Also, we find Riedel nomenclature leads people to conflate orientation with causal mechanisms without consideration for temporally and spatially heterogeneous stress fields. Much more insight is gained when we consider the evolving strain fields without the lens of Riedel interpretations. Our final reason for not using Riedel nomenclature is in the interest of clear communication for all. The Riedel terms are confusing to anyone who is not a seasoned expert. Referring to structures as P, X', X etc. impedes communication of our science because non experts must look up meanings of the jargony terms.

513-15: "In both experiments, the precut releasing segment accommodates greater divergence as the dip of the initially vertical fault shallows and accommodates greater normal slip."

This potentially is being influenced by the evolving gap in the basal plate creating a zero-velocity displacement discontinuity that has no comparison to nature. This could have been avoided with a continuous basal velocity condition where the gap is simulated by a stretching rubber sheet. This would require some further discussion.

Please see response above to comment regarding figure 1, now labeled figure 2. The localized extension appropriately simulates crustal thinning within releasing bends.

605ff: "The unexpected left-lateral slip along secondary faults may arise from variations in normal fault strike."

Could this be an artefact due to 2D projection of 3D slip vectors? The left-lateral slip component could be representing oblique slip normal faults at the basin margin accommodating subsidence towards the basin centre close to the moving edge of the releasing plate.

The 2D incremental displacement fields reveal oblique slip along the faults (see Figures 3 and 5). By analyzing the divergence along the vorticity fields, we are able to determine 3D slip sense along the faults. Indeed, the normal faults have left-lateral slip. We have improved the text to clarify that the secondary faults develop as normal faults with oblique slip.

Figure 5: Depth map at 60 mm displacement.

The topographic reconstructions seem to be under-utilised. Why do you not show the surface evolution for all experiment stages shown in Figures 2 & 3? Is this not relevant for understanding the basin evolution. Time-series maps of the actual subsidence centre would allow to assess the vertical throw of active normal faults identified with the divergence maps.

In this study, we use the topographic reconstruction to verify overall thinning of the claypack and shallowing of the precut fault surface over the course of the experiment. The experimental data reveal general trends in the fault evolution within stronger and weaker crust. Verifying occurrences of vertical throw could be interesting for a study that focuses on details of specific fault characteristics such as throw distribution, fault length or other specifics.

Authors' Reply to Reviewer 2

Reviewer B:

I have read through this manuscript and for the most part it was a pleasure to read.

Attached you will find numerous comments on the manuscript that I'd like you to address before this can be considered for publication. My main issues at the moment are:

1. The figures are too small and as I indicate on some of them they need to be broken apart so as to improve legibility – see comments.

We have rearranged and split the figures to better show the fault evolution following the reviewer's very helpful suggestions. The original figures 2a and 3a are now in their own figure labeled figure 3. The strain maps are larger and better annotated to highlight key features of the fault evolution.

2. More figures would be better. And introductory figure is warranted.

We have added two more panels to figure 2 to better show the experimental set up. We have added an additional figure in the introduction to highlight past releasing bend experiments.

2nd Round of Revisions

Decision Letter

Dear authors,

Thanks for submitting the revised manuscript. The manuscript has been reviewed by two structural geologists. Although the review comments are mostly positive, places need further improvement before the publication of this work. We encourage the authors to run an additional modelling experiment without precut. This will strengthen the argument for modelling results comparison with previous work. For the comparison of modelling results and natural deformation, the authors need to add more reasoning (or potentially additional modelling) on why it is comparable. It is better to put more words on the rheology of crustal strength of the areas where "Brawley Seismic Zone" and "Southern Gar Basin along the Karakoram fault" develop. Also, some figures need to be reorganized and redrawn.

Please see the attached review feedback for details.

Additional comments:

In lines 640-642 and other places where you use "conjugate fault" to describe the right-lateral and left-lateral faults, it might be incorrect. The "left-lateral faults" are actually confined by larger "right-lateral faults". The "left-lateral faults" are more likely secondary faults bounding the rotated blocks. Indeed, these types of faults are commonly observed in strike-slip fault systems (e.g. Kim et al., 2004, Fault damage zones).

With all the best,

Hongdan and Graeme

Comments by Reviewer 1

Recommendation: Accept with minor revisions

Summary

The authors exhibit two end-member analogue clay models simulating a releasing bend system. This set of experiments are designed to investigate the influence of rock strength on fault network evolution, and the kinematic accommodation and slip distribution on and off the primary displacement zone (PDZ) within releasing bend. To achieve this, the authors use a tabletop split-box apparatus filled with either strong or weak clay materials which achieved by different water content. During the running, 2D Digital Image Correlation (DIC) strain monitor surface evolution of fault networks in models. Then to assess the accommodation of fault slip in the releasing bend system, authors calculate the kinematic efficiency of the fault system. Results of the experiment shows that, stronger clay model develops less secondary faults, minimal cross faults, and a stable long-consist primary slip pathway. While, the weaker clay model develops numerous secondary normal faults and left-lateral cross faults, resulting in reorganization of the primary slip pathway and diffusion of off-fault deformation. Both models illustrate shallower fault dips and opposite strike-slip motion relative to the loading slip motion due to the lateral flow at depth. In discussion, authors declare the repeatability of their experiments, discuss the mechanical reason for fault slip changing, accommodation of divergence, and the development of opposite slip sense. Finally, they compared the fault patterns in the models with two natural strike-slip fault system.

General Comments

First, the manuscript is well-organized, with logically linked paragraphs and clear flow of sentences. Figures are well-laid out and closely correlate with the text. The arguments regarding the impact of material strength on analogue modeling provide new insights into understanding the strike-slip deformation in both strong and weak crustal rocks. In terms of results, the 2D DIC strain analysis and structure-in-motion analysis offer robust illustrations of the fault evolution network and kinematics for each model. Furthermore, I personally appreciate the authors' use of "kinematic efficiency" and "divergence accommodation along fault system" to quantify the details of fault evolution in each model. Through objective descriptions and analysis of the results, authors make a compelling case that the strength of the material is a primary factor influencing fault geometries and kinematics. When compared to natural cases, the experiments in this research demonstrate their relevance in enhancing our understanding of the mechanics of crustal strike-slip tectonics.

My recommendation for this manuscript is "Accept with minor revisions".

Below, I have provided detail comments and concerns for the authors' further consideration.

Detail Comments

Introduction

37-38: "Releasing bends arise when echelon faults segments connect such that strike-slip creates localized extension around the bend."

Reference? Although structural geologists and modelers are likely familiar with the mode of releasing bend. For other readers, it might be friendly to have a citation.

44-46: "Whether strain within releasing bends and step-overs is localized along a few faults or distributed among many faults depends on previous fault configuration, nature of loading, and material properties."

Please add one or two references for the cases you mentioned - "previous fault configuration", "nature of loading", and "material properties".

Results

343: "… and no new secondary faults initiated (Figure 3d&3)."

Is it "Figure 3d&3e"? Please check.

347-350: "In contrast, the two active secondary faults above the moving basal plate…. and exhibited spatially heterogeneous combinations of right-lateral shear, extension and left-lateral shear at different locations along the fault (Figure 3e)."

Where are the two secondary faults on Figure 3e? Could you point it out on figures?

467: "The dip slip along faults…"

"dip-slip"? Check if there are other misspelling.

Discussion

"Section 5.4 Crustal Comparisons and Implications"

The authors applied the results of models on "Brawley Seismic Zone" and "the Southern Gar Basin along the Karakoram fault", which is good. The results of their experiments are also robust. But for the two natural cases, temperature, crustal thickness and strength are all different. Although temperature and thickness control the crustal strength, those two parameters also likely have their own effects on the fault patterns. Previous scholars suggest that mechanical layer thickness can influences the timing of stages, fault patterns of normal fault system (Ackermann et al., 2001 - https://doi.org/10.1016/S0191-8141(01)00028-1). Similarly, in the releasing bend system, most secondary faults have dip-slip component.

Thus the authors want to emphasize the influence of strength on the two natural cases, my concern is, it might be useful to exam the influence of thickness and temperature in strong and weak clay models to declare their order of impact. So that when compared with the natural cases, authors can make a more comprehensive discussion about the impact of crustal strength on releasing bend system.

For the thickness, authors can add two supplement models: thinner layer in strong and weak clay models. Then compare them with the models in the main text. About the temperature, may be try to wet the clay with hot water or cooler water, but the scaling law might be unrealistic…

According to this concern, at the beginning of the authors' ABSTRACT, please also state that the crustal strength, temperature, thickness variation are all potential factors, but the strength variation may be the primary factor. Thus, the arguments will be more rigorous.

Figures

Figure 2:

Could the authors use an overhead photo (not subfigure d, too small) of the model and illustrate the length and width of their model? Also, if the authors like, they can put all the information in subfigure b and c to the overhead photo, and enlarge the figures.

Figure 4:

I like the authors' creation, but this figure really stretches my mind. Perhaps it is my own problem. Still, it is difficult for me to correlate the lines in this figure to the authors' model and see which fault is active or connects to primary pathway. If possible, please find another way to illustrate your thoughts.

Comments by Reviewer 2

Dear Hongdan

I went through manuscript describing releasing bend experiments and I enjoyed detailed work on analytical part. I have some comments regarding model preparation and comparison to natural cases, which should be addressed before the publication of this work.

Experimental setup:

- Please mentioned that only one plate of your model is moving and what would be changes in results if both plates move simultaneously.

- Also highlight that moving plate is not underplating the fixed plate. You might discuss how this would affect the results.

- Line 175: You mention four papers which use precut in their model, however none of them is describing a releasing bend model without the precut. It's a pity that you did not run a model without a precut, so we have direct comparison between these models.

- Line 179: Mentioned analogue models without pre-cut show different structural styles. Their depression is bounded two bounding faults while through going fault does not follow exactly the plate boundary. In these models, we see much more development on the side of the moving plate, while little deformation is observed from the precut to the side of the fixed plate. The reason why you used the precut is not clear to me and should be better advocated.

- Figure 3: We see plenty of fault traces on the figure that are not highlighted by strain map. Deformation is concentrated in pre-cut fault. We don't learn much from this. Annotate in figure caption that this is stronger model.

- Line 383: Yes, but due to movement only of one plate, we form more faults on the side of the moving plate. This should be mentioned in the paper.

- Line 498: You mentioned that with formation of secondary faults you, model is more efficient. That's does not support reasoning for creating the precut.

- Line 526: none of these models have a precut, they are not the same.

- Line 568: "under similar conditions" please describe how similar? It's done in the same lab, they should be the same. What has changed?

General comments and comparison to natural cases:

- Line 587: you used term "shallows" several times in the MS. I would prefer something like: „decreasing dip" - Figure 7: light grey area plot: We are in strike-slip model, things are moving inside and outside the section. Whatever comparison to area, is useless. I would delete it from the figure.

- Figure 10a: This figure has to be redrawn. Download DEM, go through publications that describe fault lineaments, plot all faults and make a nicer comparison to your results. This is just butchered copy and paste from Sanchez et al., 2010.

- Line 762: 1 would appreciate not simplified, but detailed representation. It looks like you are picking faults that are only similar to your model. You can highlight them, but all faults have to be mapped.

- Comparison to Southern Gar Basin is not well documented in this paper. You have to mention that releasing bends form along transpressional feature of Aylari range. Karakorum fault system is a very complex structure with apparently both transpressional and transtensional features I went through regional DEM, several publications and what is presented in this paper is not very well presented and compared to your model.

Authors’ Reply to AE

Editor comments:
Thanks for submitting the revised manuscript. The manuscript has been reviewed by two structural geologists. Although the review comments are mostly positive, places need further improvement before the publication of this work. We encourage the authors to run an additional modelling experiment without precut. This will strengthen the argument for modelling results comparison with previous work. For the comparison of modelling results and natural deformation, the authors need to add more reasoning (or potentially additional modelling) on why it is comparable. It is better to put more words on the rheology of crustal strength of the areas where “Brawley Seismic Zone” and “Southern Gar Basin along the Karakoram fault” develop. Also, some figures need to be reorganized and redrawn.

Dear Graeme and Hongdan,
We appreciate the helpful feedback during this round of reviews. To strengthen the paper, we have revised the manuscript and made the following changes.
- Polished the manuscript to correct spelling inconsistencies, figure citations and to reduce unclear wording
- Included more information to clarify boundary conditions and the impact of the claybox setup used in this study
- Clarified the intended purpose of the models in the text including the reasoning for precutting the releasing bend fault
- Improved the represented comparison of our models to the crustal examples
- Improved quality and clarity of the figures

Responses to comments are in blue below.

In lines 640-642 and other places where you use “conjugate fault” to describe the right-lateral and left-lateral faults, it might be incorrect. The “left-lateral faults” are actually confined by larger “right-lateral faults”. The “left-lateral faults” are more likely secondary faults bounding the rotated blocks. Indeed, these types of faults are commonly observed in strike-slip fault systems (e.g. Kim et al., 2004, Fault damage zones).

It is interesting that when conjugate fault sets are examined in detail, rarely are both the faults equally cross-cutting and usually one has greater slip than the other. What makes the fault sets conjugate is then the opposing slip and the angle of intersection, not the cross-cutting nature nor the equal distribution of slip. Throughout the paper we call the cross-faults ‘secondary faults’ consistent with Kim et al. (2014) and many other fault studies. Within the single paragraph where we use the term conjugate our aim is to draw attention to the overall pattern of primary and secondary faulting. We adjusted the wording when we first use the term conjugate faults to clarify our use of the term.

Authors' Reply to Reviewer 1

Summary

The authors exhibit two end-member analogue clay models simulating a releasing bend system. This set of experiments are designed to investigate the influence of rock strength on fault network evolution, and the kinematic accommodation and slip distribution on and off the primary displacement zone (PDZ) within releasing bend. To achieve this, the authors use a tabletop split-box apparatus filled with either strong or weak clay materials which achieved by different water content. During the running, 2D Digital Image Correlation (DIC) strain monitor surface evolution of fault networks in models. Then to assess the accommodation of fault slip in the releasing bend system, authors calculate the kinematic efficiency of the fault system. Results of the experiment shows that, stronger clay model develops less secondary faults, minimal cross faults, and a stable long-consist primary slip pathway. While, the weaker clay model develops numerous secondary normal faults and left-lateral cross faults, resulting in reorganization of the primary slip pathway and diffusion of off-fault deformation. Both models illustrate shallower fault dips and opposite strike-slip motion relative to the loading slip motion due to the lateral flow at depth. In discussion, authors declare the repeatability of their experiments, discuss the mechanical reason for fault slip changing, accommodation of divergence, and the development of opposite slip sense. Finally, they compared the fault patterns in the models with two natural strike-slip fault system.

General Comments

First, the manuscript is well-organized, with logically linked paragraphs and clear flow of sentences. Figures are well-laid out and closely correlate with the text. The arguments regarding the impact of material strength on analogue modeling provide new insights into understanding the strike-slip deformation in both strong and weak crustal rocks. In terms of results, the 2D DIC strain analysis and structure-in-motion analysis offer robust illustrations of the fault evolution network and kinematics for each model. Furthermore, I personally appreciate the authors' use of “kinematic efficiency” and “divergence accommodation along fault system” to quantify the details of fault evolution in each model. Through objective descriptions and analysis of the results, authors make a compelling case that the strength of the material is a primary factor influencing fault geometries and kinematics. When compared to natural cases, the experiments in this research demonstrate their relevance in enhancing our understanding of the mechanics of crustal strike-slip tectonics.

My recommendation for this manuscript is “Accept with minor revisions”.

Below, I have provided detail comments and concerns for the authors' further consideration.

Detail Comments

Introduction

37-38: “Releasing bends arise when echelon faults segments connect such that strike-slip creates localized extension around the bend.”

Reference? Although structural geologists and modelers are likely familiar with the mode of releasing bend. For other readers, it might be friendly to have a citation.

We have added a citation.

44-46: “Whether strain within releasing bends and step-overs is localized along a few faults or distributed among many faults depends on previous fault configuration, nature of loading, and material properties.”

Please add one or two references for the cases you mentioned - “previous fault configuration”, “nature of loading”, and “material properties”.

References are included after the quoted topic sentence.

Results

343: “… and no new secondary faults initiated (Figure 3d&3).”
Is it “Figure 3d&3e”? Please check.

We have corrected the numbering and lettering of our in-text references here/
We have corrected the labels here to “3d&e.” We have reviewed the manuscript and corrected other discrepancies.

347-350: “In contrast, the two active secondary faults above the moving basal plate…. and exhibited spatially heterogeneous combinations of right-lateral shear, extension and left-lateral shear at different locations along the fault (Figure 3e).”

Where are the two secondary faults on Figure 3e? Could you point it out on figures?

We have corrected the reference to indicate Figure 3d. This figure includes a label indicating the spatial differences in displacement.

467: “The dip slip along faults…”

“dip-slip”? Check if there are other misspelling.

We have polished the manuscript to ensure consistent usage of “dip-slip” or “strike-slip” when used as an adjective and “dip slip” or “strike slip” when used as a noun.

Discussion

“Section 5.4 Crustal Comparisons and Implications”

The authors applied the results of models on “Brawley Seismic Zone” and “the Southern Gar Basin along the Karakoram fault”, which is good. The results of their experiments are also robust. But for the two natural cases, temperature, crustal thickness and strength are all different. Although temperature and thickness control the crustal strength, those two parameters also likely have their own effects on the fault patterns. Previous scholars suggest that mechanical layer thickness can influences the timing of stages, fault patterns of normal fault system (Ackermann et al., 2001 - https://doi.org/10.1016/S0191-8141(01)00028-1). Similarly, in the releasing bend system, most secondary faults have dip-slip component. Thus the authors want to emphasize the influence of strength on the two natural cases, my concern is, it might be useful to exam the influence of thickness and temperature in strong and weak clay models to declare their order of impact. So that when compared with the natural cases, authors can make a more comprehensive discussion about the impact of crustal strength on releasing bend system. For the thickness, authors can add two supplement models: thinner layer in strong and weak clay models. Then compare them with the models in the main text. About the temperature, may be try to wet the clay with hot water or cooler water, but the scaling law might be unrealistic…

According to this concern, at the beginning of the authors’ ABSTRACT, please also state that the crustal strength, temperature, thickness variation are all potential factors, but the strength variation may be the primary factor. Thus, the arguments will be more rigorous.

Thickness, strength and temperature are not independent characteristics of the crust. Where heat flux is faster, the crust is also both thinner and weaker. Because of the interdependence of these variables, structural geologists often use one parameter as a proxy for others. For example, the effective thickness of flexed crustal plates considers both the plate thickness and stiffness of the crustal material. In this manuscript, the weaker and stronger experiments simulate the conditions of 1) high heat flow, thinner and weaker crust and 2) low heat flow, thicker and stronger crust. The independent effects of each of these parameters are beyond the scope of this paper.

Restraining bend and strike-slip experiments with different claypack thickness show similar fault evolution but the thicker experiments take greater displacement to develop faults (Hatem et al., 2015; Hatem et al. 2017; Chaipornkaew et al., 2022). Other differences such as the width of the zone of secondary faulting also change but these features are not the focus of this manuscript which focuses on the patterns and style of secondary faulting. Additionally, the clay does not have the same strength dependency on temperature as crustal rocks, so it is not appropriate to vary the temperature of the clay.

We have modified the text at the end of the introduction that establishes the goal for comparing the experimental results with the crustal examples. We also added more context to the start of section 5.4 on the comparison of experimental results to crustal fault patterns.

Figures

Figure 2:

Could the authors use an overhead photo (not subfigure d, too small) of the model and illustrate the length and width of their model? Also, if the authors like, they can put all the information in subfigure b and c to the overhead photo, and enlarge the figures.

Figures 2b and c are boundary conditions of the model from an overhead view. We have included model dimensions in the caption and a scale bare to figure 2b.

Figure 4:

I like the authors' creation, but this figure really stretches my mind. Perhaps it is my own problem. Still, it is difficult for me to correlate the lines in this figure to the authors' model and see which fault is active or connects to primary pathway. If possible, please find another way to illustrate your thoughts.

We added additional information to the caption to highlight the most important takeaways from this figure and to better highlight the interpretations that derive from the figure. We added additional text to the caption to specifically clarify the symbol (end caps) representing connections with the primary slip pathway. We added text to clarify the figure's representation for correlating active faults and plate displacement.

Authors' Reply to Reviewer 2

Reviewer #2:

Experimental setup:

- Please mentioned that only one plate of your model is moving and what would be changes in results if both plates move simultaneously.

The end of the first paragraph of section 2.2 "Experiment Setup" already describes that one plate is stationary and the overlying plate moves. We added text to explain that the stepper motor displacement is more reliable when the overlying, rather than underlying, plate is moved.

- Also highlight that moving plate is not underplating the fixed plate. You might discuss how this would affect the results.

Previous restraining bend experiments by Hatem et al., (2015) show that the fault development is similar whether the overlying or underlying plate is connected to the stepper motors. The difference is the asymmetry of the fault development as faults develop preferentially over the underlying plate. We have added new text describing the impact of switching plate stacking.

- Line 175: You mention four papers which use precut in their model, however none of them is describing a releasing bend model without the precut. It's a pity that you did not run a model without a precut, so we have direct comparison between these models.

The topic sentence of that paragraph describes that the goal of this study is to investigate the evolution of already established releasing bends. How releasing bends become established depends on pre-existing structures and history of tectonic loading (Schreurs and Dooley (2012) and references therein); such an investigation is beyond the scope of this study. By starting the two experiments with identical established releasing bends within different strength clay we isolate the impact of material strength on subsequent fault evolution. To clarify our goals, we have modified the wording here, at the start of the methods, beginning of the discussion, and added text in the introduction.

- Line 179: Mentioned analogue models without pre-cut show different structural styles. Their depression is bounded two bounding faults while through going fault does not follow exactly the plate boundary. In these models, we see much more development on the side of the moving plate, while little deformation is observed from the precut to the side of the fixed plate. The reason why you used the precut is not clear to me and should be better advocated.

See response to comment above about the aims of our student that warrant a precut fault surface. Because we start with a precut that is aligned over the basal discontinuity this precut fault surface serves as one boundary of the central graben in both experiments. The preferential development of graben over the moving plate owes to asymmetry created with the step in the basal boundary. We have added text in the results to describe this preference.

- Figure 3: We see plenty of fault traces on the figure that are not highlighted by strain map. Deformation is concentrated in pre-cut fault. We don't learn much from this. Annotate in figure caption that this is stronger model.

Fault traces that are without incremental strain are inactive during the stage shown - we point out inactive fault traces in Figure 3c. We modified the caption and figure to clarify that this is the stronger model and made similar changes to Figure 5.

- Line 383: Yes, but due to movement only of one plate, we form more faults on the side of the moving plate. This should be mentioned in the paper.

We added text to describe the role of plate stacking in creating the asymmetry of the fault pattern.

- Line 498: You mentioned that with formation of secondary faults you, model is more efficient. That's does not support reasoning for creating the precut.

Correct, we are not analyzing the initiation of releasing bends but pre-cut a fault to create an established releasing bend.

- Line 526: none of these models have a precut, they are not the same.

Our statement that the evolution of the fault zones within the experiments is generally similar remains valid. We have modified the wording to make clear that the experiments of this study start with a precut releasing bend and the cited experiments do not.

- Line 568: "under similar conditions" please describe how similar? It's done in the same lab, they should be the same. What has changed?

While the clay never has the exact same strength values for each experiment, the repeated experiments have strength values within uncertainty. The text has been reworded to improve clarity, and readers are referred to the supplement for more details on the repeated experiments.

General comments and comparison to natural cases:
- Line 587: you used term "shallows" several times in the MS. I would prefer something like: „decreasing dip"

It is interesting that while structural geologists often describe that fault dip steepens, we don’t often say that fault dip shallows. This construct can ‘sound’ odd, but it is just as valid as ‘steepens’. The first time that we describe fault dip shallowing in the main text, we introduce this as equivalent to decreasing fault dip for improved clarity.

- Figure 7: light grey area plot: We are in strike-slip model, things are moving inside and outside the section. Whatever comparison to area, is useless. I would delete it from the figure.

The cross sections (Figure 7c-e) are conceptual. The light grey area is to indicate the space that is created as a result of extension within the releasing bend. We have modified the figure labels and caption for clarification.

- Figure 10a: This figure has to be redrawn. Download DEM, go through publications that describe fault lineaments, plot all faults and make a nicer comparison to your results. This is just butchered copy and paste from Sanchez et al., 2010.

We have modified the figure to reduce annotations that are not relevant to this study. For the crustal map figures, we rely on the mapping done by Sanchez et al. (2010) and by geologists who contributed to the USGS Quaternary Fault and Fold Database. The DEM and fault vectors were available publicly for the Brawley Seismic Zone, but we could not locate the same data for the Southern Gar Basin. A new map of this structure is beyond the scope of this project.

- Line 762: 1 would appreciate not simplified, but detailed representation. It looks like you are picking faults that are only similar to your model. You can highlight them, but all faults have to be mapped.

Figure 10c includes only faults in the Quaternary Fault and Fold Database (QFDD) from the USGS. The focal mechanisms highlight subsurface faults within the diffuse Brawley seismic zone, but we did not perform any field work to confirm the surface location and prefer to use one consistent fault map that incorporates the work of the community of geologists who have mapped this region (QFFD). We have modified the figure to clarify.

- Comparison to Southern Gar Basin is not well documented in this paper. You have to mention that releasing bends form along transpressional feature of Aylari range. Karakorum fault system is a very complex structure with apparently both transpressional and transtensional features I went through regional DEM, several publications and what is presented in this paper is not very well presented and compared to your model.

Studies of the Karakoram fault history have investigated the Southern Gar basin as well as the nearby Ayilari Range, Zhada Basin, and Namru-Menci Basin. Some researchers suggest that the Karakoram fault originated along the current trace with few changes in kinematics, while others suggest the fault has propagated along it’s trace (Wang et al. 2011). Despite debate regarding the initiation timing and kinematic fault history, there is general agreement that the Southern Gar Basin has exhibited transtensional (dextral normal motion) since at least ~12 or 13 (Lacassin et al., 2004; Wang et al. 2011) with a similar geometry to that within the claybox experiments presented here.

All this to say, the Karakoram Fault (including the Southern Gar Basin) is certainly a complex system, as is the Brawley seismic zone with the southern San Andreas fault. The experiments of this study do not aim to reproduce the evolution of either of these regions but instead compare the pattern of faulting from the experiments with the mapped faults at these crustal examples that share geometry and kinematics with the experiments. Furthermore, we refrain from comparing the models with the larger Karakorum region (or the Southern San Andreas) because the experiments are not set up to do this. We have altered the wording in this section and added some additional information to acknowledge the regional complexity. We have also adjusted the ordering of ideas to be more consistent with recognized fault evolution chronology.

Lacassin, R., Valli, F., Arnaud, N., Leloup, P. H., Paquette, J. L., Haibing, L., ... & Zhiqin, X. (2004). Large-scale geometry,
offset and kinematic evolution of the Karakorum fault, Tibet. Earth and Planetary Science Letters, 219(3-4), 255-269.
Wang, S., Wang, E., Fang, X., & Lai, Q. (2011). U–Pb SHRIMP and 40Ar/39Ar ages constrain the deformation history of
the Karakoram fault zone (KFZ), SW Tibet. Tectonophysics, 509(3-4), 208-217.

3rd Round of Revisions

Decision Letter

Dear Authors,

thanks for the submitted revised materials. We generally agree with the changes based on the feedback two reviewers. However, we think the following two issues need to be addressed before heading for acceptance.

- Conjugate fault sets formed in the same stress field and they commonly have similar sizes. It is very confusing to use "conjugate fault" to describe the structures that have opposite shear sense but with different sizes. In Figure 8, the cross faults are bounded by secondary faults. They are Riedel shears of the secondary faults.
- The Southern Gar Basin forms as part of the Karakoram fault (KF) zone in the southwestern Tibet Plateau (Phillips et al., 2004; Chevalier, 2019). This area is part of the orogenic belt which is locally collapsing. The orogenic belt is thick and weak, which is evidenced by ductile (mylonite) rocks revealed along this fault zone. It is difficult to conclude that the strike-slip fault of KF is a strong fault.

References

Chevalier, M. L., 2019, Active Tectonics along the Karakorum Fault, Western Tibetan Plateau: A Review: Acta Geoscientica Sinica, v. 40, no. 1, p. 37–54, doi:10.3975/cagsb.2018.101601.

Phillips, R. J., R. R. Parrish, and M. P. Searle, 2004, Age constraints on ductile deformation and long-term slip rates along the Karakoram fault zone, Ladakh: Earth and Planetary Science Letters, v. 226, no. 3–4, p. 305–319, doi:10.1016/j.epsl.2004.07.037.

Authors' Reply to Round 3

Thanks for the submitted revised materials. We generally agree with the changes you have made based on the feedback from the two reviewers. However, we think the following two issues need to be addressed before heading for acceptance.

• Conjugate fault sets formed in the same stress field and they commonly have similar sizes. It is very confusing to use "conjugate fault" to describe the structures that have opposite shear sense but with different sizes. In Figure 8, the cross faults are bounded by secondary faults. They are Riedel shears of the secondary faults.

Not a conjugate set, they have a conjugate relationship which conveys orientations and change in slip sense.

The Riedel terminology would be inappropriate in this case as it was developed for structures under homogenous, distributed simple shear and the terminology is opaque to non-experts (and sometimes even to experts).

We have adjusted the wording to avoid calling the structures in our experiments conjugate "sets." We describe the faults as having a conjugate pattern. This phrase describes the overall pattern of faulting and draws attention to the characteristic opposing slip and angle of intersection consistent with conjugate faults. Our usage is consistent with the literature including Kelly and Anderson (1998). This particular paper refers to faults of different sizes as "conjugate" and finds conjugate fault systems to be unstable when the faults are active simultaneously. Thus, we should expect faults within conjugate systems to have inequal lengths.

• The Southern Gar Basin forms as part of the Karakoram fault (KF) zone in the southwestern Tibet Plateau (Phillips et al., 2004; Chevalier, 2019). This area is part of the orogenic belt which is locally collapsing. The orogenic belt is thick and weak, which is evidenced by ductile (mylonite) rocks revealed along this fault zone. It is difficult to conclude that the strike-slip fault of KF is a strong fault.

It is reasonable to infer the Southern Gar Basin is "relatively stronger" than the Brawley Seismic Zone without considering if it is inherently "strong" in an absolute sense. We have changed wording in this section of the paper to clarify the Southern Gar Basin is "relatively" stronger. Both crustal thickness and heat flow are contributors to crustal strength. The Brawley Seismic Zone is in an extensional region with thin crust and high heat flow. The Southern Gar Basin is in a region with localized extension; however, the Tibetan Plateau enjoys overall crustal shortening and thickening. A reasonable estimate for crustal thickness at the Southern Gar Basin is generally is between 60-75km (Zhang, 2011). The rift basin housing the Brawley Seismic Zone is known to be exceptionally thin crust of only ~5 km thick in some areas (Hauksson, Stock & Husker et al., 2022). Furthermore, Lachenbruch et al. (1985) has estimated the heat flow to be ~140 mWm-2. The Southern Gar Basin has a much lower heat flow estimated at 40-50 mW/m2 (Xia et al., 2023). We have adjusted the wording the text to emphasize our inference that the crust around the Southern Gar basin is stronger than the crust around the Brawley Seismic zone.

We do not claim that that the Karakoram fault is strong. Our study make no inferences about fault strength.

References

Egill Hauksson, Stock, J. M., & Husker, A. L. (2022). Seismicity in a weak crust: the transtensional tectonics of the Brawley Seismic Zone section of the Pacific–North America Plate Boundary in Southern California, USA. Geophysical Journal International, 231(1), 717–735. https://doi.org/10.1093/gji/ggac205

Kelly, P. G., Sanderson, D. J., & Peacock, D. C. P. (1998). Linkage and evolution of conjugate strike-slip fault zones in limestones of Somerset and Northumbria. Journal of Structural Geology, 20(11), 1477–1493. https://doi.org/10.1016/s0191-8141(98)00048-0

Lachenbruch, A. H., Sass, J. H., & Galanis, S. P. (1985). Heat flow in southernmost California and the origin of the Salton Trough. Journal of Geophysical Research, 90(B8), 6709–6709. https://doi.org/10.1029/jb090ib08p06709

Xia, B., Artemieva, I. M., H. Thybo, & Klemperer, S. L. (2023). Strong Variability in the Thermal Structure of Tibetan Lithosphere. Journal of Geophysical Research Solid Earth, 128(3). https://doi.org/10.1029/2022jb026213

Zhang, Z., Deng, Y., Teng, J., Wang, C., Gao, R., Chen, Y., & Fan, W. (2011). An overview of the crustal structure of the Tibetan plateau after 35 years of deep seismic soundings. Journal of Asian Earth Sciences, 40(4), 977–989. https://doi.org/10.1016/j.jseaes.2010.03.010

Acceptance Letter

Alana Gabriel, Hanna Elston, Michele Cooke, Christ Ramos Sanchez:

We have reached a decision regarding your submission to тектоniка, "Impact of material strength on releasing bend evolution".

Our decision is to: Accept Submission