RC2: 'Comment on egusphere-2024-852', Michele Cooke, 29 Apr 2024

The paper presents interesting strike-slip experiments where the direction of applied simple shear is orthogonal and oblique to zones of either increasing or decreasing strength. The results are novel and will be of interest to many readers – especially as many crustal strike-slip faults cross materials of different strength. The pattern of faulting depends on the spatial heterogeneity of material strength. The experiments and analysis of the experimental data are strong and the figures are effective but the text needs revision. The manuscript has many instances of awkward English grammar that can be rewritten for clarity. I highlighted many (but not all!) in the specific suggestions.

We appreciate the reviewer's positive feedback and welcome your suggestions. We have rewritten large sections of the manuscript for clarity taken into account the suggestions by Reviewer 2, and the English has been improved.

I also provide some general comments that can strengthen both the presentation of the experiments and the interpretations.

1. The zones of heterogeneous strength are referred to as 'vertical contrast' through much of the paper and 'horizontal contract' on line 296. I found this descriptor very confusing. Because 'contrast' as noun means the difference between two materials and the term 'vertical contrast' doesn't make sense to describe a zone of one material. Also, I thought that 'vertical contrast' meant that the strength was varying with depth. I suggest describing these features as vertical zones of different strength from the surround material.

We agree that the way the zones of contrasting strength are described in the manuscript may have led to confusion. We have now changed this description throughout the text, and also in the title, which is now: "Strike-slip faulting affecting vertical domains of contrasting brittle strength in the upper crust: Insights from analogue models".

The text describing the experimental results switches between past and present tense. I recommend past tense since you are describing particular experiments that have occurred at a specific time in the past. In the discussion, where you infer general fault behavior from the experiment results, you can switch to present tense because you may be talking about general fault behavior that is not linked to a specific experiment.

We now describe the results using past tense throughout.

2. The two materials were described as having different relative strength based on their internal friction angle (lines 140-141). This parameter informs the angle of fault development but not strength. The cohesion values, which you also have, provide better measure of material strength.

Granular materials deform according to the Mohr fracture criterion. In our opinion, the relative strength difference between the two brittle materials used in our models (quartz sand and microbeads) is a function of both the cohesion and the internal friction angle. The extrapolated cohesion values are low for both materials, with the sand having a value of c. 50 Pa and the microbeads of c. 25 Pa. On the other hand, the internal friction angle between the two materials (determined in ring-shear tests) is c. 36° for sand and c. 22° for the microbeads, an important difference with the microbeads being the weaker material.

3. The results often described the greater or lesser number of faults. How many faults? Is the difference statistically significant? Do the experiment only have few active faults at any one time but these reorganize so that new faults grow? Within the experiments with fewer faults, did the faults accommodate greater shear strain?

We agree that describing the number of faults at any particular stage using the incremental strain is not very meaningful, as the number also depends on the threshold and color scheme used. Instead, we now focus on the finite, cumulative strain figures, but are – at the same time – reluctant to contribute too much weight to the exact number of faults.

4. The greater number of faults that develop in the lower cohesion material makes a lot of sense because new faults will grow in this material at lower levels of stress – it is easier to grown new faults in weaker material. This point should be more clearly presented in the discussion. Right now, the discussion lines (287-290) refers to grain size and packing but the more relevant impact of grain size and packing is the difference in cohesion/strength. At least some of the citations on lines 289-290 refer to deformation within lithified rocks– this is not the same as the faults within a loose granular media. Note: Li et al., 2021 is missing from reference list.

We agree that the microbeads are mechanically weaker than the quartz sand, but not only because of difference in the cohesion, but also because of the difference in the internal friction angle.

We suspect that the differences in initial deformation behaviour between quartz sand and microbeads is due to differences in dilatant behaviour, related to differences in grain size, grain shape, grain size distribution. The microbeads are well-rounded and have a narrower grain size distribution promoting deformation over a wider zone (grains roll, more dilatancy needed), whereas the quartz sand consists of angular grains, and have a wider grain size distribution leading to faster strain localization (deformation along a narrow shear zone; grains slide, less dilatancy). We have modified the references.

5. The discussion missed the opportunity explain/postulate why the different fault patterns emerged within the experiments.
    a. The removal of the cardboard facilitated development of antithetic faults – Why? I suspect that the cardboard removal produces zones if increased dilation and lower strength that facilitate faulting, In fact, Bellahsen and Daniel (2005) used this technique to introduce normal faults in a sandpack (https://doi.org/10.1016/j.jsg.2004.12.003).

We have now added that the cardboard removal locally increases dilation (in the method section)

We have restructured the discussion in four sections, i.e. the first section (4.1) discusses models with a homogeneous brittle analogue material; section 4.2. now discusses the influence of vertical domains of contrasting brittle strength and the relative order of weak-strong-weak or strong-weak-strong domains on the fault kinematics; section 4.3. discusses the fault evolution of synthetic faults that crosscut the central domain, and section 4.4. compares our model results with a natural example from the Iberian Peninsula. We also have added new figures for each of these four sections. We also changed the order of Figures 4, 5 and 6 such that we first discuss the two models with N20°E domains, then the models with N-S domains, and finally the models with N20°W domains.

    b. Lines 328-329 gently speculates that the differences in fault orientation could be related to friction angle. Because the friction angle is well established to have direct impact on fault orientation, this relationship can be explored more rigorously. The two materials have ~10˚ difference in friction angle and the difference in fault orientation within the two materials is often 10˚˚. This is not a coincidence. The paper missed the opportunity to explore situations where the difference in fault angle is not 10˚ , Those situations could provide interesting insights into how the stress states might different near regions of heterogeneity.

The two analogue materials, microbeads and quartz sand have internal friction angles of 22° and 36° respectively, thus one would expect differences in fault orientations of about 7° (36-22/2). This difference is observed in our quartz sand and microbeads only models (Model A1 and Model A2), where the fault strikes between the synthetic faults differ by about 7-8°. The same difference we also find in the models with vertical domains of contrasting brittle strength (Series B, C and D models), if we consider the outer domains of the models (i.e. western and eastern domain). The synthetic fault strikes of these domains differs if they consist of microbeads or if they consist of quartz sand.

We have improved the discussion of the synthetic fault strike orientations (relating them to Mohr-Coulomb failure criterion, and the difference in internal friction angles). The same applies also for early-formed antithetic faults in Series B, C and D models; there we also find differences of about 5-7° between the initial strike of antithetic faults in quartz sand and the initial strike of antithetic faults in microbeads. However, we now also discuss those antithetic faults in our models, that are not in the "conjugate position" of the synthetic faults, generally form later and are confined between earlier formed and overlapping synthetic faults. These late antithetic faults form in a modified stress field (that differs from the bulk stress field) due to deformation between overlapping synthetic faults.

We also discuss how the fault strike of synthetic faults changes as they propagate from one analogue material in the other.

c. Related to point b, the discussion could summarize the strain state by showing a composite of all the rose diagrams. We can then see if the differences of fault orientation between beads and sand are systematic.

We have added rose diagrams to illustrate fault orientations at different increments, as well as for the finite fault pattern.

d. The discussion missed the opportunity to explain why the stronger material develops the first faults at lower applied strain than the weaker material. This is not an expected result at all and is a very interesting finding. I suspect it may have to do with the different dilatancy of the two materials.

We now address this point in the discussion and consider the difference in dilatant behaviour as a potential explanation.

e. Why do antithetic faults develop only on one side of the experiments B1 and B2. Why does the side switch when the central zone has weaker material or stronger material? This significant result has not been adequately explained. Is this pattern repeatable?

We appreciate the comment made by the reviewer as it brings up an interesting point of the model results. The development of faults on one side of the model is something we already noticed during the development of the article, but we do not have a clear explanation for it. One of the hypotheses we are considering is that the first fault to form is the one that will determine the rest of the fault pattern.

Concerning the change of fault direction in the section, we have created a new section in the discussion, where we discuss how faults are connected in the central section, and we have added an explanatory figure for it.

6. When citing papers that are just a few examples of papers that make the point, one should add 'e.g.' before the citation. Here are some places where you could add e.g.: Lines 41, 45, 46, two on 47, 156, 316, 329, 332 etc

We appreciate the reviewer's suggestions, and have added, e.g. before the citations.

Specific suggestions:

Line 37: I recommend reading two more papers on strike-slip development within laboratory experiments: Hatem et al. 2017 (https://doi.org/10.1016/j.jsg.2017.06.011) and Visage et al. 2023 (https://doi.org/10.1016/j.tecto.2023.229704)

Thanks for the suggestion; we have also cited these papers.

Line 50: awkward What is 'they'?

Line 57-58: Awkward. I think that you mean to say "… strike-slip faults may change their expression as they cross regions of different rheology and display different orientation or different number of active faults".

Regarding these two comments, we have made important changes in this section and modified the expressions originally used.

Line64: I suggest changing 'natural' to 'crustal'. To say that the experiments are compared to natural faults implies that the experiments are unnatural. In English this can mean that they are spiritual, magical or fabrications. The experiments are natural systems that develop within the laboratory.

We agree and have changed to "crustal scale example"

Line 70: This is a good place to explain the role of the plexiglass bars to distribute the basal shear. For example, you don't put the viscous layer directly on the basal plates because the viscous layer alone will not distribute shear all the way across the box.

We have improved the description and illustration of the model set-up. We now clearly mention the role of the viscous layer, i.e. to distribute the deformation in the overlying brittle layer over the entire width of the model.

We have improved and restructured section 2. Methods. We now have included "Deformation monitoring and quantification" in section (2.4), separate from the "Analogue model setup" (section 2.1). We believe that this improves the flow of the methods section. In addition, we have modified and improved the wording.

Line 80: Awkward wording

Line 91: Awkward wording (contrast)

We have changed the paragraph and improved the wordings.

Line 108: the resolution of the cameras is not so relevant as the resolution of your horizontal velocity data points. What does 'average resolution of 300 px' refer to?

As it was unclear, we have removed this from the manuscript.

Line 129: What is the displacement increment in 30 seconds?

This has been changed; this is now in section 2.4.

Lines 155 and 158. These are very standard equations so you might not need to be included (in my opinion).

We have kept the equations as such, as we believe it facilitates reading of the scaling text.

End of the section 2.2: The scaling section gives us a lot of values of scaling parameters but doesn't take the opportunity to explain the implications of these values. How much crustal time does 1 minute of the experiment represent? How much crustal length does 1 cm of the experiment represent? Do some of these values suggest that the experiment does not exactly scale to the crust?

These scaling factors are now indicated in the text.

Line 173: What is the difference of the displacement required to develop the first faults in the Quartz sand and the micro beads? Is this difference significant? The earlier development of faults in the stronger material is not intuitive and warrants explanation in the discussion.

See above, we address this the new and expanded version of the discussion.

Line 185-187: Figure caption for 3 and other figures should explain the rose diagrams. Is the length of the rose indicating number of faults or degree of strain accommodation? Why not make the sinistral and dextral faults different colors on the rose diagrams. Also, larger rose diagrams will be easier to see.

We have now explained the statistical analysis applied for the rose diagram, and have given sinistral and dextral faults different colors in the rose diagrams, corresponding to those colors used in the figures, i.e. sinistral = red; dextral = blue.

Line 210-211: Awkward. Located in the microbeads? What spacing?

Line 229: Awkward. "the same occurs"

Line 237 Awkward. Change to "In this series of models" and change 'behavior of both models' to 'affect the fault pattern that emerged within the two experiments"

Line 238 Awkward: There are no domain. Domains of what?

Line 239 Awkward: Change "both cut,," to "both cross…" Change "…when these faults…" to "…where these faults…"

Line 241: Unclear: What does it mean specifically that deformation is less localized within the band?

Line 242: Unclear: What does 'strike counterclockwise' mean? You might have a counter-clockwise change in strike from one position to another but one strike can't be counterclockwise. I see a sigmoidal shape that has one change from the western region to the central zone and a different change from the central region to the eastern region. But I see this in more in model C1 than model C2 so I'm not sure I understand what the text means.

Line 252: change to "models of series B…"

Line 260: Instead of 'takes longer' change to 'required greater applied displacement'. Because the time involved depends on the rate of loading. As far as I'm aware of these materials are not sensitive to loading rate so the deformation is more a factor of the amount of applied strain than the duration of the experiment. (same comment for line 282)

We appreciate the reviewer's suggestions. Referring to all the above comments, we have largely rewritten the description of the model results (line 169- line 270), and incorporated the comments mentioned above. We have also separated more clearly results from discussion.

Line 294: "they have different rupture criteria". Both materials grow new faults following Mohr-Coulomb failure and the rupture criteria is the same. It is not the case that one material fails in tension and the other shear.

We agree, and have modified the wording.

Line 298: awkward -> "heterogeneity of the models impacts the structure and …". By the way, I prefer to describe the experiments as 'experiments' rather than 'models' because it seems that many geoscientists (in the US) think of numerical models when we say 'models'.

We have opted to stick with "models", as it should be clear from early on in the manuscript, and from the title, that we performed analogue models.

Line 302: awkward -> 'compared to'

Modified

Line 306: These are parallelograms or trapezoids but not rectangles

We agree, and have changed the wording.

Line 306-307: The model is not compartmentalized, the faulting or the deformation is compartmentalized within the experiment.

We agree, and have modified the text.

Line 348-349: Explain why you think that the region of slates is similar to having a central region of the experiments with microbeads. What about the angle of the faulting?

In this case we have relied on the existing literature for the use of microbeads as a possible analogue to this type of deformed rocks (Panien et al., 2006). The exact similarity with the proposed natural example has not been taken into account. Its comparison with the natural example has been rather more general, and focused on the observation how the faults are distributed, what their patterns and kinematics are, and whether the initial change of orientation happens.