Reply to reviewer 1

Text for submission textbox:
We would like to thank reviewer 1 for the helpful comments and suggestions.

In order to provide an orderly reply, we have uploaded a PDF with an overview of all comments and our replies to these (see below).

1. Reply to Reviewer 1 – Ernst Willingshofer

1.1. General comments

General comments: The manuscript by Zwaan et al., "A systematic comparison of experimental set-ups for modelling 1 extensional tectonics" describes and compares analogue experiments that simulate extension of the crust or part of the crust, focusing on the type of forcing (foam based, rubber sheet, velocity discontinuity) at the base of the experiments.

The manuscript will be a very valuable contribution for the modelling community at large, because it gives a good overview on common practice of modelling crustal extension and it comes with a set of recommendations that are particularly useful for starting as well as experienced modellers. I thus consider the above quoted manuscript as a very useful paper and fully support its publication.

My comments as detailed below mainly concern the details provided on the initial strength of the layers. Other suggestions as outlined in the annotated manuscript are targeted towards gaining clarity.

Figure 3 provides an overview of experimental and corresponding natural strength profiles for the experiments that have been conducted. From the figure caption, I infer that these strength profiles are sort of estimates rather than calculated. I would much prefer seeing absolute values for brittle and ductile strength as these values can be compared by the community to what they calculate for their model. As such your models, would be a "frame of reference" to which others can easily compare their results to, find communalities as well as differences. It is not much of an effort to calculate brittle and ductile strengths for the initial conditions of the various experiments because the rheology data (your table 1 and table 3) are readily available.

- The strength profiles of Fig. 3 are indeed qualitative. We agree that providing quantitative strength values could help the applicability of the figure. The reason we nevertheless prefer to keep Fig. 3 qualitative is that the strength differences between brittle and viscous materials are such that viscous strengths cannot be visualized if kept to scale. Instead we exaggerated viscous strengths somewhat to allow showing them We show instead quantitative strength values in Fig. 12. We have added to the figure caption of Fig. 3 that the profiles are qualitative (and why) and refer to Fig. 12 for strength values.

This would also allow you approach the item of coupling-decoupling from the strength ratio of brittle to ductile layers (see papers by Davy and co-workers, 1995, JGR) point of view next to the BD ratio.

- Thank you for pointing out the very interesting publication by Davy et al. (1995). The authors use the brittle-to-viscous strength ratio to analyze brittle-viscous coupling in compressional experiments and show a relationship between strength ratios (strength contrasts) and type of faulting: distributed faulting for low strength contrasts and localized faulting for high strength contrasts. This is in general accordance with insights from rift models. For instance, Brun (1999), Moresi et al. (2007) and Buiter et al. (2008) show how low strength contrasts lead to (distributed) wide rifting and high contrasts to (localized) narrow rifting in two-layered brittle-viscous systems. We observe similar trends in our experiments. However, our experiments also show how the style of rifting in addition can be affected by the set-up of a model. We observe for instance how a low contrast/high brittle-viscous coupling system can lead to distribute rifting (as expected) when a foam/rubber base is involved, whereas the use of a plate/conveyer base may overprint the intrinsic style of rifting and lead to a localized flexural depression instead. This is in line with the concept that the mantle lithosphere can have an important control on rift style (e.g. Brun 1999 and Corti et al. 2003).
- We have added strength calculations to the Methods description, Table 2, the results and the discussion. In Discussion section 4.4 and 4.5 we address the effect the set-up can have on final model results.

Along these lines, I am not convinced about the geological meaning of the high velocity experiments in which, if correct, the strength of the ductile layer is about the same as the brittle layer. When converted to natural systems, I think this is not a realistic choice of brittle and ductile strength combinations. A young/hot/weak lithosphere as labelled in Fig. 3e would more likely be characterized by a strength profile where the integrated strength of the ductile crust is distinctly lower than the peak strength in the upper crust (see the papers on the crème brule versus jelly sandwich discussion or the paper by Burgmann and Dresen 2008, which you quote). Possibly this inconsistency solves itself ones you calculate the strength profiles for the experiments.

- Some of the higher extension velocity models indeed have non-realistic extension values. We have added an extra column to Table 2 (model parameters) to indicate the equivalent natural extension rate when assuming a lower crustal viscosity of 10^21 Pa*s. However, as the viscosity of the lower crust can vary, these values need to be taken as indicative. With a higher lower crust viscosity, equivalent natural extension rates would be lower. Another motivation for keeping the high velocity experiments is that we tried to simulate a range of rheological layerings and extension velocities to achieve different brittle-ductile coupling.

I hope that my comments are useful to the authors and look forward to seeing your response.

Ernst Willingshofer

Specific comments:

Meaning of VD: the often-used velocity discontinuity is not necessarily a pre-existing basement fault; it can be a substitute for any irregularity (geometric, compositional, rheologic etc) in the system.

- We agree that a VD can be induced by various irregularities. Still the defining characteristic is that it represents an abrupt change of velocity, thus a fault or shear zone, developing along such irregularities. We have modified the description of VD's in the methods section by adding a statement that VDs can be triggered in various ways.

Experiments (eg. P and C series) where the structures develop at the outside and propagate toward the inside are probably controlled by boundary effects. As such you should not assign much value to them.

- We agree that as far as model result interpretation goes, these are boundary effects and may not make much geological sense. Yet boundary effects are part of the model and as such they (may) influence the experimental result. Therefore, we prefer to describe the boundary effects, without indeed assigning much geological value to them. The fact that these are boundary effects, and why they occur is discussed in the Discussion section 4.3.

Make sure to refer to the correct figures; eg. when describing the experiments of section 3.3; you need to refer in many instances to fig. 3 instead of figure 1.

- Thanks for noticing, we have corrected these and other wrong figure references

Almost all top-view figures are quite dark in printed form. Maybe you can enhance the brightness to make the structures clearer.

- This has been modified in the new version

In context of wide-versus narrow rifting or localized versus distributed deformation the following papers might be useful:

- The discussion of wide versus narrow rifting is a fascinating one which still generates new insights. Our experiments are for initial extension (low values of total extension) and as such are not necessarily indicative of whether the final mode of rifting will also be wide or narrow (see also Figs. 10 and 11 in Tetreault and Buiter, 2018). We prefer therefore to not address the discussion of narrow and wide rifting. We have removed references on wide versus narrow rifting from the abstract and conclusions. We have included some of the references where appropriate.

Lithosphere-scale: Beniest A, Willingshofer E, Sokoutis D. and Sassi W (2018) Extending Continental Lithosphere With Lateral Strength Variations: Effects on Deformation Localization and Margin Geometries. Front. Earth Sci. 6:148. doi: 10.3389/feart.2018.00148

Cappelletti, A., Tsikalas, F., Nestola, Y., Cavozzi, C., Argnani, A., Meda, M., Salvi, F., 2013. Impact of lithospheric heterogeneities on continental rifting evolution: Constraints from analogue modelling on South Atlantic margins. Tectonophysics 608, 30– 50. doi:10.1016/j.tecto.2013.09.026

Nestola, Y., Storti, F., Cavozzi, C., 2015. Strain rate-dependent lithosphere rifting and necking architectures in analog experiments. J. Geophys. Res. Solid Earth 120, 584– 594. doi:10.1002/2014JB011623.

Crustal scale experiment with VD: Gabrielsen H.R., Sokoutis D., Willingshofer E. & C3

Faleide J.I., 2016. Fault linkage across weak layers during extension: Examples from analogue experiments and their consequence for fault analysis in the Barents Sea. Petroleum Geoscience, 2015-029, doi: 10.1144/petgeo2015-029.

1.2 Reply to supplement comments by reviewer 1

Please also note the supplement to this comment: https://www.solid-earth-discuss.net/se-2018-96/se-2018-96-RC1-supplement.pdf

Line 34 – "young or old regions, or wide or narrow extension"
Be more specific what you consider as young, old, wide or narrow.

- We have now rephrased to 'various tectonic settings or lithospheric conditions'. The different types of lithosphere are discussed in the main text.

Line 56-58 – "Analogue materials used to simulate brittle parts of the lithosphere include, among others, quartz or feldspar sand, silica flour, microbeads, and (kaolinite) clay" (+ references).
Perhaps it would be usefull here to add the overview paper on granular materials used for analogue modelling of Klinkmüller et al., 2016, Tectoniphysics.

- We added Klinkmüller et al. 2016.

Line 59-60 – "Pure silicone oils and silicone putties" (+ references)
Here you definitely need to quote Weijermars and Schmeling 1986, next to a more recent overview by Rudolf et al., 2015.

- We added the suggested references

Line 89 – "fracture"
Better call this structure "fault" because it accommodates displacement.

- We agree, it is modified

Line 150-151 – "the asthenospheric mantle is simulated with low viscosity materials, such as honey, glucose syrup or even pure water (+ references)
Here you could add "mixtures of polytungstate with glycerol", which we use a lot in Utrecht (see for example Willingshofer and Sokoutis, 2009, Geology or Luth et al., 2013, Tectonophysics, van Gelder et al., 2017, EPSL)

- We have added "mixtures of polytungstate with glycerol" along with a reference to Willingshofer et al. 2005, in which the material is nicely described.

Line 241 – "constant velocity gradient"
This is a bit strange wording: if there is a velocity gradient then the velocity can not be constant everywhere. Please clarify.

- There is a gradient, of which the slope is constant. We have rephrased it.

Line 261 (on section 2.2.2 heading "Localized deformation set-ups)
See also Gabrielsen et al, 2016, JPetGeoSci., which falls in this category.

- We added Gabrielsen as a reference for plate base set-ups here

Line 385 – "distinct features" you mean "structures"?

- Indeed, "structures" is better, we have modified it

Line 397-399 – "In Experiment F4, the brighter tones at the rift shoulders visualise local uplift: parts of the experiment that are uplifted present less of a barrier to the X-rays since these pass through less material, which shows up It is not clear to me why the brighter spots in the CD scan should represent uplift since you do not have isostacy in the models. Please explain.

- After careful consideration, we have decided to remove the reference to rift shoulder uplift. As already stated, colors in the CT data do not represent altitude (merely scan values). The bright colors are due to the fact that these parts stick out so the X-rays can cross with ease and register a lower value. But as pointed out, these brittle-only models should not develop any isostatic response. The coloration is thus solely due to the "sticking out" of the material. Therefore we cannot back up this statement here, and have also removed it when describing the brittle-viscous results (see comment on line 416) in order to avoid confusion.

Line 413 – "brittle sand" The sand that is used is per definition "brittle". There is no ductile sand. Beter rephrase like "brittle layer".

- It is modified.

Line 416 - "this experiment also develops rift shoulder uplift" I am wondering why this "uplift" is stronger at the right hand side of the rift?

- See previous comment on rift shoulder uplift.

Line 426-428 – "However, an additional phase of extension (30 min at 40 mm/h) helps to highlight these conjugate faults (Fig. 6a')" What does that mean? Is this a different experiment, or did you stretch the experiment shown in Fig. 6a even more to obtain 60 mm of extension? Please explain.

- We did indeed stretch the same model a bit further. We rephrased to 'In addition, remarkable conjugate faults develop within the reference experiment duration (300 min, 40 mm of extension), but are not well visible on our top view images since they do not create significant topography (Fig. 6a). However, an additional phase of extension in experiment R1 (30 min at 40 mm/h) helps to highlight these conjugate faults (Fig. 6a').' and modified the figure caption.

Line 460 - should be 2g??

- It should be 2h, it is corrected.

Line 467 – "brittle-viscous base plate experiments"
This sounds like as if the base plate itself is brittle-viscous. Please rephrase.

- It is rephrased to 'base plate experiments with brittle-viscous layering'.

Line 469 - "Rifting initiates at the short sidewalls"
It looks to me that these rifts are controlled by the setup (no side walls at the short margins?). As such the results must be treated with caution.

- Indeed, these are boundary effects due to higher friction along the short sidewall, which are discussed later on in Discussion section 4.3.

Line 473 - 2h?

- It should be 2i, it is corrected

Line 473 - how much rotation took place and around which axes?

- The rotation is ca. 3° around a vertical axis near the tip of the propagating rift, which is now added to the text. We also added some details to Fig. 8c,d and 9c where this is visible

Line 493 - passive downbending"
Please elaborate what you mean by "passive downbending". Why isn't the rift developing where the plates are separating?

- The sand layer is bending down as the underlying viscous layer is stretched. We slightly modified the text and point out that these processes are discussed further in Discussion section 4.4.

Line 504 - "not observe a difference between the symmetrical and asymmetrical set-ups"
this is probably related to the fact that the amount of extension you applied is quite low. The asymmetry will develop once more extension is applied.

- We do not observe a clear difference by means of our top view images, the main graben structure appears to be more or less symmetric. However, we do not have any (CT) sections for this experiment, and previous models have shown that there should be asymmetric structures. We simply cannot observe these details and can therefore not comment more on this. What we can say however, is that simply applying more extension would likely not help: after 4 cm of extension, we have no material left to deform in the rift domain (also mentioned in the discussion). Instead we would need to add sediments to have material that can deform. This is addressed in Discussion section 4.2.

Line 507-508 - develops two rifts that originate from the short sidewalls and propagate"
Again, these models seem to have been biased by boundary affects (structures that propagate from the outside in).

- See previous comment on these boundary effects. They are part of the experiment, but may indeed not be representative of a natural situation.

Line 624 – "see" (comment not included, to be deleted?)

- Not changed because we did not understand the comment and felt that the phrase is in order.

Line 638 – "stronger rigid relation"
Not sure to understand what you mean by that. Please rephrase.

- It is rephrased. We meant the friction between the model material and the short sidewalls. We added an explanation: the internal friction angle of sand is larger than the friction angle between the sand and the plastic or sheets (36.1 versus ca. 20˚). Therefore, we have more friction, more drag and thus more boundary effects.

Line 669 – 'down-bent' depression bordered by marginal grabens"
The result of this experiment is consistent with the high extension velocity experiment of Gabrielsen et al. 2016 (their fig. 5). However, I am not convinced that the strength profile of your high velocity experiment shown in Fig. 3, is representative for the strength ratio between brittle and viscous layers.

- We have included a reference to Gabrielsen et al. 2016, who indeed seem to observe a similar effect in their experiments. See also previous comments on Fig. 3.

Line 692 - "high extension velocities improve localization (experiment C11, Fig. 9f, g)"
Again, I do not think that this is a "realistic" model.

- We have now scaled all model velocities and added the values to Table 2. It is true that the high extension velocities are in some cases unrealistic. The extension velocity is indeed too high when assuming a lower crustal viscosity of 10^21 Pa*s (24 mm/y), but when assuming a viscosity of 10^22 Pa*s, it becomes more reasonable (2.4 mm/h). We also lose some deformation along the sidewalls due to boundary effects (the sand is moving slower than the silicone below), implying that the actual extension velocity may even be a bit lower. Therefore this model undergoes quite high but not impossible extension rates.

Line 705 – "asthenospheric-scale"
You mean "lithosphere-scale" experiments, I assume.

- We mean models involving both the lithosphere and asthenosphere, in contrast to possible models involving the whole lithosphere, but not the asthenosphere. It is rephrased, see also next comment.

Line 811-812 – "The conveyor base set-up would therefore be more appropriate for lithospheric-scale models."
Not sure to understand what you try to say here, because in lithosphere-scale models of extensional systems, box-in-box constructions or a movable wall is used for allowing gravity driven extension.

- What is meant is that a conveyor system may be appropriate to model deformation driven by a convection cell in the mantle/asthenosphere, as stated in the previous sentence. It is slightly rephrased (see also comment by reviewer 2)

I also would argue that a conveyor belt or base plate kinematic conditions at the bottom of crustal-scale models should not impact greatly on the result.

- We agree, when little extension is applied. However, when (in a symmetric system), 2 plates part, the underlying fixed table becomes exposed. This does not happen in the conveyor belt equivalent, in which the base is never stable (except for the VD). This is drawn in Appendix A1, panels (a) and (j). The more extension is applied, the more the model basal boundary conditions differ.

Line 819 – "next necessary step"
I would add to that, that a better understanding of feedback relations between rifting and magmatism is needed as well.

- We have added magmatism as a factor to include in the models

Line 1460 (Fig. 3 caption) – "Schematic experimental"
Why schematic?? You should calculate the strength profiles, since you have the data to do it.

- See previous comment on this topic.