Reviewer 2

We would like to thank Marco Bonini for his constructive comments and suggestions. They gave us the opportunity to better explain the rationale of our modeling study as well as to precise some modeling technical points. Our replies to the specific comments (in italics) are given point by point below:

The manuscript by Guillaume et al. presents the results of a series of analogue models addressing the role of simultaneous shortening and orthogonal extension under different rheological conditions, including the role of inherited crustal heterogeneities. The paper is concise and well written, and figure are well drafted. In addition, the aims are clearly stated, and the modeling results are analyzed through up-to-dated techniques (Particle Image velocimetry (PIV), and subsequent velocity and strain analysis). The extent of the conclusions is generally supported by the presented data, and the results may be attractive for an international readership. The manuscript is thus suitable for being published in Solid Earth (SE) after a minor/moderate revision. The issues that should be addressed during the revision are listed below and keyed to line number in the text.

General points

> *1) Conceptual simulation of indentation and lateral extrusion. In this experimental study, lateral extrusion is achieved by applying a shortening-orthogonal extension to the model. However, in this experimental procedure the system is not developing spontaneously, but its evolution is imposed by the boundary conditions (i.e., the shortening-orthogonal extension). In other models, lateral extrusion (associated with V-shaped strike-slip systems) simply resulted from a model set-up with lateral strength/thickness variations (Sokoutis et al 2000, Tectonophysics), and/or accomplished by weak lateral confinement (e.g., Ratschbacher et al., 1991, Tectonics). The authors agree on that and acknowledge the primary role exerted by a weak crust in favouring a lateral tectonic escape (Lines 403-404). On this basis, I think that some more discussion on the rationale of the modelling and its comparison with previous models would be necessary for a more in- depth comparison with the natural cases sketched in Figure 14.*

Reply: Indeed, in our series of models, crustal lateral extrusion is controlled by applying a shortening-orthogonal extension. We made this choice for two reasons. The first one was to be able to systematically vary and precisely control the relative rate of extension over shortening. The second reason was to be able to reproduce systems in which far-field forces may also produce orthogonal stretching participating in crustal deformation. We now make it more clear in the Introduction and Procedure section:

"While these studies provide some elements for understanding the coexistence of different tectonic regimes and associated structures, there is a lack for a systematic investigation of the role of the relative ratio between shortening and stretching rates, as horizontal extrusion may not always only result from orthogonal indentation, but may also be controlled by far-field forces leading to non-plane strain deformation."

"The layer(s) are then deformed by applying a constant velocity boundary condition at the edges of the model through pistons activated by step motors, which allows us to precisely control the stretching rate to shortening rate ratio."

We have also extended the comparison of our models to those in previous studies as suggested. We added a comparison of our models with those by Corti et al. (2006), Duarte et al. (2011), Rosas et al. (2012, 2015).

2) *Adopted terminology. The reasons of using the terms 'extrusion rate' (stretching velocity) and 'indentation rate' (shortening velocity) should be discussed in more detail. Indentation refers to a case where the colliding block is much shorter than the indented continent. However, I cannot identify this condition in the model setup of Figure 1. So why not use the terms shortening rate and extension rate? Please comment on this.*

Reply: In the initial set-up, the colliding block indeed appears as large as the indented continent. However, in most of the models (except BI01 and BI10), applied stretching makes the colliding block width progressively smaller than the continent. We acknowledge that the difference in size remains small, and to avoid confusion and keep things simple, we followed the suggestion of Reviewer 2 by replacing "indentation rate" by "shortening rate" and "extrusion rate" by "stretching rate" in the manuscript and figures.

3) *Rheology of analogue materials. The lower crust has been simulated using PDMS silicone putty (Lines 85-86). Consequently, this silicone has a lower density than the overlying Fontainebleau quartz sand that simulates the upper crust. As correctly stated by the authors, this implies an inappropriate density ratio between upper and lower crust in the models. Density contrast in the model should be equal- or at least similar - to nature. In other terms the viscous layer is too buoyant (or the sand too heavy). This may produce a strong vertical instability that may amplify the folding of the brittle-ductile interface during shortening or extension, and ultimately affect the modelling results at some extent. Please clarify the choice of the PDMS silicone (technical advantages?).*

Reply: The choice of using low-density PDMS silicone was made for practical reasons. Increasing the density of the PDMS silicone by adding iron powder to make it as dense or slightly denser than the sand (~1400-1500 kg/m^3) would have also modified its viscosity. It would have increased to values around 10^5 Pa.s (e.g., Fernandez-Garcia et al., 2019), which has implications on the scaling of the brittle-ductile models. Maintaining stretching/shortening rates equivalent to values in nature in the range ~1.5-6.5 mm/yr would have required imposing piston velocities as low as ~6 mm/h, which was too slow for the motors we used. We now explain better the technical reasons that led us to this choice:

"For the two-layered models, the density ratio between the brittle and ductile parts of the crust is high (1.45). Increasing the density of the viscous layer would have resulted in a strong increase of its viscosity, which would have required applying speeds too low for the capacities of the engines used."

We agree with reviewer 2 that such low density may favor vertical instabilities, which is now indicated in the manuscript. To further test its potential impact, we did the exercise of performing additional 2D numerical models of crustal shortening based on a modified example of the benchmarked code from Gerya (2019). We varied the initial configuration (including a seed or not) and the density of the viscous layer considering values similar to that in our analogue models (965 kg/m^3) or similar to that of the sand in our analogue models (1400 kg/m^3) (Fig. 1). For an amount of deformation in the range of our models (11% of shortening), we show that the effect of the low-density viscous layer on deformation location is almost null when a seed is present (Fig. 1A) while for models without any initial seed (horizontal layering), some differences appear, e.g., the width between conjugate thrust faults, or the localization of deformation along a single or multiple close thrust faults (Fig. 1B). However, the overall pattern of deformation remains similar. We therefore consider that the first-order results for the brittle-ductile models should not be very different with respect to models that would use a higher density viscous layer, especially for models with low or moderate amount of deformation and short duration.

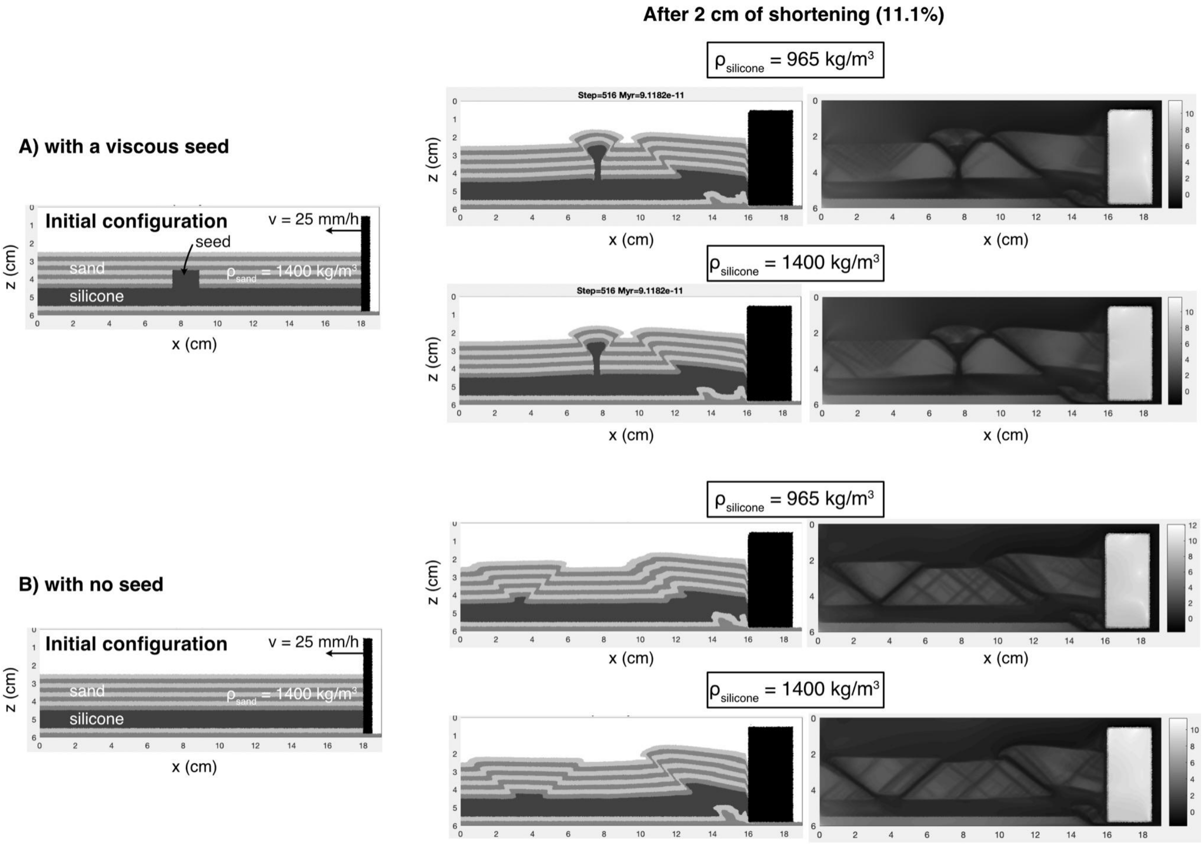

Fig. 1. Illustration of the influence of the density of a viscous layer in 2-D numerical models of crustal shortening, based on the Sandbox_shortening_ratio example of Gerya (2019). The initial configuration embeds layers of materials with properties equivalent to the sand and silicone used in the analogue models with A) a seed in the central part of the model and B) no seed. The model is shortened by moving toward the left a "rigid" mobile wall at a constant velocity of 25 mm/h. The

right panels show the geometry and strain location after 2 cm of shortening (11.1%) for models with a silicone layer with a density of 965 kg/m^3 or 1400 kg/m^3.

4) *Line 83. Was the cohesion of the sand measured in this study? If not, please provide a reference.*

Reply: We now refer to previous studies by Klinkmuller et al. (2016) and Schreuers et al. (2016) for the cohesion of the sand we used. We also refer to Rudolf et al. (2022) for the measurements of friction coefficients.

5) *Lines 126-130. Please report in Table 2 the Ramberg and Smoluchowsky-like numbers (Rm, Sm) for both model and nature.*

Reply: We now report R_m and R_s numbers in Table 2.

6) *Lines 147-149. Corti et al. (2006, Spec. Paper GSA) performed similar analogue models characterised by coeval shortening and orthogonal extension, which were applied to the Sicily Channel.*

Reply: We now refer to the models by Corti et al. (2006) in the Introduction, when presenting the distribution of deformation around the Sicily Channel. We also discuss how the models by Corti et al. (2006) compare to our models and those by Dhifaoui et al. (2021):

"Instead, models by Corti et al. (2006) that used a similar set up than \citet{dhifaoui21} with extension applied on one wall during compression but with a brittle crust, do not show V-shaped conjugate strike-slip faults. Interestingly, in these experiments, the authors used a low V_e/V_s value of 0.2. The absence of strike-slip faults is therefore consistent with our minimum value ($V_e/V_s>0.9$) for effective lateral crustal escape."

7) *Lines 180-182. The convexity observed in some models could result from a high friction of the side walls. Have you adopted any technical practices to minimize this effect?*

Reply: We did not adopt any particular method to decrease the friction on the side walls. On the other hand, having friction-free side walls would imply that the edges of the models correspond to perfectly lubricated strike-slip faults in nature, which would not necessarily be more suitable. The effect of high friction in the models on fault shape is visible for model BI10 for instance where it is limited to the first 2-3 cm from the W-E edges. Our fault mapping for thrust faults discarded these areas. The convexity we describe is generally in the center of the models where boundary effects should be limited and we therefore consider these features a result of the models and not simply related to edge effects.

8) *Lines 301-305. Have you considered the possibility that these anomalous faults departing from the edges of the graben could represent only boundary effects?*

Reply: We now indeed include boundary effects as a possible explanation for the orientation of these anomalous faults. See our reply to comment #3 by Reviewer 1.

9) *Lines 413-416. It is not clear why shortening-parallel thrusting should develop in this model. Has shortening-parallel thrusting been identified in any model of this series? Please clarify. Spontaneous shortening-parallel thrusting resulted in the above-mentioned model by Sokoutis et al (2000), which - differently from this experimental series - were isostatically compensated. This may represent a key difference with respect to the current series of models.*

Reply: We did not mean that shortening-parallel thrusting should necessarily develop in this model, but rather that model BI01 should be the most favorable model given that it shares common boundary conditions (i.e. a first phase of stretching and a second phase of orthogonal shortening) with previous models that showed basin inversion, or formation of thrust faults with a low angle with respect to the shortening direction. We modified this paragraph to clarify. We also now refer to the study by Sokoutis et al. (2000) to indicate that lateral variations in crustal thickness/strength and isostatic compensation could be important parameters in promoting basin inversion under these boundary conditions.

10) *Lines 422-423. Please give more details about the characteristics of fault reactivation. From the tectonic setting (basin-parallel shortening) I would expect some component of strike-slip movement. What is the dominant kinematics of reactivated normal faults?*

Reply: The reviewer is right. We now indicate that preexisting faults are reactivated in transtension.

11) *Figure 1. Please indicate the 'seeds' in the model setup.*

Reply: We now indicate in Fig. 1 the position of the seeds in the entire model and not only on the lateral visible section.

12) *Figure 12. What does the yellow layer at the base of the model configuration in the left panel represent? This model is referred to as purely brittle, but this yellow area is equivalent to the basal ductile silicone of the models shown in the middle and right panels. Please clarify this.*

Reply: The yellow layer was representing the ductile (silicone) layer. In the bottom figure of the left panel, it was representing the seed located in the center of the model. To make it less confusing we now indicate "seed" on the figure and we changed the colors to make them consistent with those of Fig. 1 (set-up). We also now indicate the meaning of the colors in the caption.

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