Review of "Inversion of transfer zones in salt-bearing extensional systems: insights from analogue modeling"

Authors: Elizabeth P. Wilson, Pablo Granado, Pablo Santolaria, Oriol Ferrer, and Josep Anton Muñoz

Dear editor and reviewers,

Thank you for taking the time and effort to review our manuscript. We sincerely appreciate your valuable comments, suggestions, and questions, which all help to improve the quality of the work. Our replies to each of Dr. Zwaan's comments and questions as well as the two reviewers are listed as bullet points beneath each original point.

We hope that our responses fully answer the questions and comments asked by the editor and the reviewers. We look forward to including our manuscript in his special issue on analogue modelling of basin inversion.

Frank Zwaan (editorial committee)

Some things to pay careful attention to:

Editor: Reviewer 2 points out that the research question is not very clear. I agree with that assessment: some topics are mentioned, but the reader needs to interpret a lot and it can be much more to the point.

> ***Authors:*** *The Introduction have been reorganized and text has been added to address these concerns and make the focus of the manuscript clearer.*

Editor: Linked to the previous comment: it is then not that clear why the parameters used in the set-ups are chosen as these are rather specific. It could for instance be useful to first (shortly) introduce the field examples in order to motivate the general study design, and/or weave these choices in the methods section as well (when mentioning a parameter in the set-up, you can explain where it comes from). This would be especially useful when introducing the different model phases.

> ***Authors****: We have introduced the main field example that has inspired the modelling program (South-Central Pyrenees) to justify the set-up design and explain the main differences with former studies such as Dooley and Hudec (2020) as well as the different model phases (two rift events and subsequent inversion).*

Editor: Scaling details seem to be missing, there is no explanation as to how the scaling values are obtained (formulas). Please add these somewhere in the manuscript.

> ***Authors****: Text has been added to the Table 2 caption.*

Editor: Specific details I noted:

Editor, Fig. 2: please indicate what is sand in the model. Now only the silicone is indicated, so it is not directly obvious what the cover is.

> ***Authors:*** *This has been updated.*

Velocities are given in cm/s, consider using cm/h for easy reading

> ***Authors:*** *The velocity has been converted to cm/h.*

Editor: Line 161-162: it is not 100% clear how this erosion works: what is the exact elevation benchmark for the scraping?

> ***Authors:*** *On line 164 it states that the regional sedimentation elevation was raised 1 mm for each new layer. The use of the scraper ensured that the elevation and distribution of each sand layer filled and covered the model at the correct elevation.*

Editor: Line 170: how exactly is the salt removed? i.e. is any salt that "sticks out" cut away? Perhaps add a sentence to specify

> ***Authors:*** *A sentence has been added to explain that any extruded salt that flowed onto the model surface was periodically removed by carefully cutting it away.*

Editor: Fig. 3: the normal faults in (c) and (d) are not that obvious. Consider making the lines a bit thicker to make them stand out a bit more.

> ***Authors:*** *This has been updated.*

Editor: Fig. 4: perhaps a little map-view inset could help to make the relations between the sections directly clear (without having to go to Fig. 5. Same for other figures.

> ***Authors:*** *Inset maps have been added to all 3 figures.*

Editor: Fig. 9 & 12: the thrusts are shown in red, but are poorly visible (to me, I have slight red-green colorblindness). Please consider another color.

> ***Authors:*** *I have attempted to choose a replacement color (similar to other colors used by Crameri, 2018, 2020) that will hopefully be more visible for readers that experience color blindness. Thank you for voicing this concern.*

Editor: Fig. 15: these plots seem incomplete? not each structure seen in the previous figures is provided? This figure also seems to present results, and as such would fit better in the results section. Perhaps it can be incorporated in Figs. 7 and 10?

Authors: *The plots have been added to their respective top view figures. Text has been added to the figure captions (Figs. 7 and 10), and text has been added to the results section for each model (paragraph 5, section 3.2; paragraph 6 section 3.3).*

Editor: Figure captions in general: please make sure that all abbreviations used in the figures are listed in their caption. This is not the case in various figure captions.

Authors: *Thank you. This has been corrected in all figures.*

Editor: In general, I would suggest avoiding abbreviations in the text, unless really necessary, as to promote readibilty (e.g. spell out minibasin instead of mb1).

Authors: *This has been updated in the text.*

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Elena Konstantinovskaya (Referee)

Reviewer: The submitted manuscript aims to demonstrate the variation of structural styles in salt-bearing segmented rift systems that underwent subsequent shortening and syn-shortening sedimentation. The sand-polymer-based analog experiments involved three models, in which two salt-bearing half-graben basins segmented by an intervening transfer zone experienced rifting (Model 1), rifting and inversion of the rift system (Model 2), and rifting and inversion with syn-contractional sedimentation (Model 3). The obtained results of analog modeling are compared to the geological structures of the Northern Lusitanian Basin, offshore Portugal and Isàbena area, South-Central Pyrenees, Spain.

Experimental setup and procedure are well described. Preparing and conducting experiments likely required a substantial amount of work. The manuscript represents a thorough analysis of experimental results and provides a new insight into the salt decoupled extensional and inversion systems.

Authors: *We appreciate these positive words.*

It would be helpful if the following comments and questions might be clarified:

Reviewer: Lines 110-115: why Mylar sheet remains not deformable under the simulation settings of extension and subsequent shortening?

Authors: *During extension, the mylar plastic is attached to the moving wall. After the extension and before the onset of shortening, the mylar is detached from the moving wall and fixed to the basal plate in order to detach the sand by moving the backstop wall over the mylar sheet.*

Under the applied strain rate and forces, the strength of the mylar plastic sheet is great enough to keep it from being deformed. This is well documented in many previous published works. It is true that the mylar undergoes tension during the extension phase, but it does not undergo any significant changes in length. So, we can presume a small amount of elastic strain takes place but nothing significant to affect the modelling results.

Yet, to avoid misunderstandings, the "non-deformable (under modelling conditions)" statement has been removed and a much more detail description of the experimental procedure regarding the mylar sheet is provided in the second paragraph of section 2.2.

Reviewer: Lines 110-115: The basal friction at the top of the steel plate and Mylar sheet is different. Did it influence the model deformation?

Authors: *It is not different since "We added a thin silicon layer (0.2 cm) underneath the sand pack completely covering both the steel plate, the rubber sheet and the mylar sheet" as currently stated in the main text and already explained in the figure caption of fig. 2 in the former version of the manuscript.*

Reviewer: Lines 120-130: Is there any difference in mechanical properties of the basement and upper sand packs? In sand material itself or in a way it was packed? See comment for lines 485-490.

Authors: *The mechanical properties and the sand material of the basement and upper sand packs are the same. The term 'basement' in our paper does not reflect any changes in rheological properties between the sand packages. Please see response to comment for lines 485-490.*

Reviewer: Lines 125-130: what procedure was applied to ensure that the triangular polymer prisms would not be deformed during the model buildup and burial of the prisms by 9 cm-thick sand pack simulating the basement?

Authors: *Procedure is now clarified in line 155.*

Reviewer: Lines 130-135, 140-145, 170-175: The applied combined velocity during extension phases was set equal to 2.78 x 10-4 cm/s (phase 1) and 1.67 x 10-4 cm/s (Phase 3) and to 1.67 x 10-4 cm/s during the shortening (Phase 5). Please explain what does "combined velocity" mean. Deformation of the polymer is sensitive to applied strain rate. How the velocity of extension and shortening was chosen? Was there any sensitivity study performed to determine the range of applicable strain rate?

Authors: *"Combined velocity" has been defined in the fourth paragraph of section 2.2.*

Yes, a series of tests were conducted to determine the possible velocities. No cover deformation was found at rates of extension below 2.22 x 10-4 cm·s-1. We then tested velocities to determine which velocities worked best with our set up to create the types of structures that we are investigating. (This is now stated in the fourth paragraph of section 2.2)

Reviewer: What was sedimentation rate of sand layers during syn-contractional deformation?

Authors: *The syn-contractional sedimentation rate was 2 mm of sand every 6 hours. This is now stated in the final paragraph of section 2.2.*

Reviewer: Line 170: Please clarify here which wall was pushed - the one at the side of the Mylar sheet or of the metal plate. It seems to be the right wall with attached Mylar sheet that was used for shortening (Figs 8 and 11).

Authors: *Yes, the wall used to push is the wall above the mylar sheet, as shown in Figure 2 and now clarified in the final paragraph of section 2.2.*

Reviewer: Line 180-185: what steps were undertaken to facilitate the models' slicing at intervals of 3 mm (!!) at the end of each experiment? Salt model polymer flows fast….

> ***Authors:*** *We have a workflow at the Geomodels lab using a specialized slicing machine that allows for rapid slicing and photography of the models. It is true that polymer flows quickly but the process was developed with this in mind to minimize the flow of polymer out of the model. We find there is no need to emphasize such specific part of the methodology here.*

Reviewer: Line 200-205. Why MF1 attains more slip than MF2 in Model 1? The master listric faults MF2 and MF1 in Fig. 4a and 4c have different geometry, in particular degree of curvature and dip angle. Could these differences be related to the shape of triangle shape of salt model seeds in the basement? The seed SS2 after the extension generally preserves its triangle shape (Fig. 4a), while SS1 has migrated resulting in a weld between the basement sand layers and basal sheet (Fig. 4c).

& Lines 240-250: "Half-graben 1 propagated along strike across the whole model width (Fig. 4 a-c). This is probably related to the presence of the underlying velocity discontinuity (V.D. in Fig. 2) that favors extension localization, lateral slip transfer along the strike of the polymer seed, and the formation of the largest depocenter of Model 1. Conversely, extension along MF2 produces a more diffuse structural pattern, with one largest depocenter right of the master fault".

Why MF2 and associated graben did not localize and propagate laterally to the same extent as MF1 and associated depocenter? Could it be that the behaviour of the V.D. between the rubber sheet and the Mylar sheet (MF2 system) was different from the V.D. between the steel plate and the rubber sheet due to the variation in the strength contrast between the basement materials: steel plate - rubber sheet - Mylar sheet? This suggestion is likely confirmed on lines 494-496.

> ***Authors:*** *In this section (section 3.1), as results, a purely geometrical description of the models is provided. Reviewer's accurate comments belong to the discussion, where we included, in former version of the manuscript, a discussion about this topic (see section 4.1, as stated in the last line of the comments). Still, in the current version and following reviewer's comments, few ideas regarding the different geometry of the master faults have been added.*

Reviewer: Line 273: It is not mentioned here whether Model 2 was subjected to extension before the shortening. How steady are the results of extension obtained in Model 1 (Fig. 4)? Could it be expected that the results of Model 1 were repeated in Model 2 during the extension, and the shortening has started from the same or similar point as shown in Fig. 4?

> ***Authors:*** *Yes, although this is stated in the model set-up and procedure we have included a "reminder" at the beginning of section 3.2.*

Reviewer: Line 313. Replace SS2 by SS1 as Fig. 7c represents the section across the SS1 salt seed.

Authors: *Yes, this has been corrected. Thank you.*

Reviewer: Line 310-315: If the results of extension in Model 2 repeated the results of Model 1, one could expect that the geometry of thrust fault systems in MF1 and MF2 during the shortening phase (Fig. 7a and 7c) would be controlled by the shape of listric faults MF1 and MF2 at the end of extension, which, in turn, might have been controlled by the behavior (degree of migration) of the model salt triangle seeds SS1 and SS2.

& Models 2-3: Could the lower degree of shortening along MF1 be resulted from the greater distance between MF1 and movable backstop at the right, if compared to the shorter distance between the backstop and MF2? In both cases, most of the shortening is accommodated along MF2 that is located closer to the movable backstop, and the shortening structures progressed laterally across the model, accommodating most of the contractional deformation. As a result, shortening was more distributed in the section across MF1, and it contributed to reactivation of MF1 to lower degree.

Authors: *We appreciate reviewer's comments. It is an interesting discussion that we have integrated in the second paragraph of section 4.2.*

Reviewer: Lines 485-490: "In our models, the syn-rift basin geometry and related sediment distribution are strongly controlled by the position of the underlying pre-salt basement faults, the amount and rate of slip attained by those faults, the original distribution and thickness of model salt, as well as the thickness and mechanical properties of the pre-kinematic sand pack".

However, in the model setup, nothing is said about the difference of mechanical properties of the basement and upper (pre-kinematic) sand packs (lines 120-130).

Authors: *Yes, this is a mistake. We meant the mechanical properties of the analogue model materials. This is an erratum and has been changed in the manuscript to state the 'analogue modelling materials (i.e., the sand and polymer)' in the first paragraph of section 4.1.*

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Anonymous Referee #2

General comments

Reviewer: The manuscript presents results on a series of three analogue models of inversion basin tectonics including a viscous décollement layer (salt) and weak zones in the basement that simulate subsidenence at half-grabens in the basement that later also localize the thrust faults. The results of the study are clearly illustrated, and the manuscript is well written. The study is however very similar to another already published study of Dooley and Hudec (2020), who employed the same technique, and their map-view patterns and cross-sections and doubly-vergent thrusts are also similar, except the shape of the weak seeds in the basement layer that act as nuclei for developing normal and thrust faults.

The introduction mentions a wealth of literature, analog modeling studies on the inversion tectonics of salt basins, but I miss the definition of the clear objectives of the study. What are the unresolved scientific issues (e.g. fault and layer thickness patterns?) associated with inverted basins, especially those with segmented half-grabens? For example, how might the individual segments interact in terms of laterally migrating salt in the source layer? What are typical deformation patterns in the cover sequence in the segmented half-graben basins that might control on fault development and extrusion of salt in later stages (e.g. inversion)? This is difficult to imagine, becuase the Figure 1 only shows a single segment of the half-graben array. Are there any map examples that may have resulted in the inversion of the segmented half-graben basins? I am sure that some lessons about such systems can be derived also from the study of Dooley and Hudec (2020) - however there is no mention of this in the Introduction nor in the Discussion. How are your sets of experiments similar/different with respect to the latter study?

> ***Authors:*** *Additional text has been added in the second paragraph of the Introduction to summarize the modelling program of Dooley and Hudec (2020) and to differentiate our work from theirs. As stated in the text, there has been very little focus on the influence and role of extensional transfer zones in subsequent inversion of salt-bearing rift systems. Past research has focused on the inversion of the individual basins themselves, with little more than a passing remark on the contraction of the transfer zone. Even the Dooley and Hudec (2020) paper dedicates very little space to the description of inversion and contractional deformation through the transfer zones.*

If you consider the Aras and San Juan basins (discussion), as equivalent transects inside a larger inverted basin with segmented half-graben, what can we learn from the similarity of the structures in these two transects with the vertical profiles accross your models? Is this comparison even possible given the large translation of the cover sequence above the basement?

Authors: *It is only by using models in conjuncture with cross sectional restorations that will provide insights into the structural history of fold and thrust belts. The Las Aras and San Juan basins are interpreted to be incorporated into the same thrust sheet, and, therefore, to be translated in approximately the same position relative to one another. The thrust sheet has been translated away from its original position, relative to the basement, so the model results cannot be used as a present-day comparison to the Pyrenean example but can provide insights into the kinematics of inversion and controls on the resultant contractional geometries.*

Response to comments in the annotated pdf -

Reviewer: Figure 1, I wonder if this general figure is appropriate for the objective posed in the Introduction (line 75 - geometry and distribution of several depocentres). I suggest trying to draw a figure that would explain the possible mass transfer and cover interaction between two adjacent and laterally offset half-grabens.

Authors: *We only show a single half-graben in Figure 1 to highlight the fact that there has been little focus on the interaction of segmented basins in salt-bearing half-grabens; the example itself comes from a study that focused on the structural style of half-grabens related to relative amounts of decoupling of the sub- and supra-salt extensional systems (Richardson et al., 2005). Additional text has been added to the first paragraph of the Introduction to better explain the purpose and reason for the figure choice. While your comment is valid, the focus on mass transfer of syn-rift sediments is not a key focus of the paper as sediment accumulates via aggradation and not progradation.*
*This introductory figure was selected to familiarize the reader with a previous breakthrough in the role of a thick evaporite layer in a decoupled extensional system so that it can be compared to our results which focus on the interaction of decoupled and offset half grabens***.**

Reviewer, introduction: For the Introduction paragraphs: What are unresolved questions regarding the natural salt bearing basins associated with their inversion stage and their potentially laterally segmented rift like original geometry? What are the examples from natural basins worldwide?

Authors: *The third Introduction paragraph has been modified to clarify better the unresolved questions regarding the influence of extensional transfer zones in the inversion of salt-bearing extensional systems. Additional text has also been added to the first two paragraphs to highlight the lack of previous works that focus on extensional transfer zones. As these zones are not typically the focus of studies, there are not many natural examples besides the studies sited in the first paragraph of the Introduction. We have also explained the main natural examples that have inspired our modelling program.*

Reviewer, Lines 61-62: ...in salt-bearing rift systems (Dooley and Hudec, 2020). Dooley and Hudec, 2020; specifically, carried out a very similar work to yours, their results should be outlined in the Introduction and reflected in the discussion, comparing with your models?

__Authors:__ Yes, while their models had a more regional scale by modelling a series of three segmented graben and does not explicitly discuss the influence of the transfer zones on contractional deformation, it is worth noting their results in the introduction. We have explained the main differences between our set-up and the one by Dooley and Hudec (2020) both in the Introduction and section 2.2

Reviewer, Lines 61-62: I suggest to explain more specifically on how the placement of the seeds (weak points) changes the style of the basement deformation as it is critical for your approach, too.

__Authors:__ This is explained in greater detail in the following section (paragraph three of section 2.2). The shape of the seeds was chosen to constrain the basement fault geometry.

Reviewer, Line 91: This viscosity number is wrong. It should be 1.6x10^4 ... (not -4). Correct in the scaling table and elsewhere in the text.

__Authors:__ Modified as suggested

Reviewer, Table 2: wrong numbers for viscosity (see previous comment)

__Authors:__ Modified as suggested

Reviewer, Line 116: is this correct word form? just "transfer" ?

__Authors:__ Transference is the correct word

Reviewer, Line 119: domain with respect to

__Authors:__ Modified as suggested

Reviewer, Line 119: in

__Authors:__ Modified as suggested

Reviewer, Figure 2: the basal salt in the multilayer is missing in the schematic profile

__Authors:__ The basal salt is included, however, the thickness of the basal salt has been increased in Fig. 2 for better visibility

Reviewer, Figure 2, caption: Explain in the caption and the text the purpose of the seeds.

__Authors:__ As previously commented, the purpose of the seeds is explained in lines 122-124

Reviewer, Figure 2, caption: 7 cm in

Authors: *Modified as suggested*

Reviewer, Line 159: some word missing in sentence

Authors: *This refers to the regional elevation of sedimentation. It has been modified*

Reviewer, Line 176: p

Authors: *Modified as suggested*

Reviewer, Line 159: Or just "Profiles"? Can you explain the virtual inlines?

Authors: *Virtual inlines make a reference to cross lines and inlines as used when working with 3D seismic volumes. We use the term 'virtual' to indicate that the inlines result from software interpolation of the photographed cross sections taken of the model to create the voxel and resultant 3D segy file used for the three-dimensional interpretation of the results. To clarify the origin of the "virtual inlines", in the current paper we state "Virtual inlines extracted from voxels (Fig. 4 d to f) show...)"*

Reviewer, Lines 517-518: I do not understand, what dogma? Can you explain?

Authors: *The structural dogma defined by White et al. (1986) states that the cross-sectional geometry of the sedimentary fill in the hanging wall of a listric fault is directly related to the shape of the normal fault, assuming extensional deformation by simple shear. The text has been updated to better clarify this.*

Reviewer, Line 707: completely

Authors: *Modified as suggested*