Dear Piotr,

Please find our responses to reviewer comments and the revised paper and figures of our manuscript “Extension and Inversion of Salt-Bearing Rift Systems”, for inclusion in the special volume “Inversion tectonics – 30 years later” in Solid Earth.

Let me first address the reviewers’ comments.

Comments by Antonio Teixell:

This manuscript uses analog models to investigate the tectonic inversion of salt-bearing extensional grabens. While models of tectonic inversion exist in the literature, some of them including polymer (=salt) layers, the ms. by Dooley and Hudec has the novelty of incorporating a subsalt deformable section, which aims to provide analogues for the compressional structure of pre-salt basements, often a poorly resolved problem in compressed rift systems. In comparison to other published models of compressional systems with multiple “salt” décollement levels (e.g. Couzens et al. 2003 –a paper that should be referenced), Dooley and Hudec’s models incorporate early episodes of extensional deformation, which feature synkinematic sedimentation to produce salt migration and diapiric structures (later submitted to compression). No surprise that in the models there is a marked decoupling between the subsalt and suprasalt units, which puts a warning on the subsurface interpretation of little exhumed, natural inverted rift systems, as the High Atlas of Morocco that is taken as a reference field case. After the early cartoons by Letouzey et al. in 1995, for moderately inverted salt-bearing rifts with no seismic information very often we are tempted to keep in place the parent normal faults (even if reactivated) that we infer as early triggers of observed salt diapirs. The analog models by Dooley and Hudec are welcome in that they remind us that as shortening increases, the connection between the diapirs and the parent faults is likely to be lost. This is likely to be the case in the High Atlas (although with the available data so far it is hard to tell), but also must happen in other basement-involved, salt-detached thrust systems as the northern Pyrenees, where we argued for largely decoupled and displaced salt walls in contrast to autochthonous diapir models (e.g. Labaume and Teixell, Tectonophysics, accepted). The inversion models by Dooley and Hudec provide inspiring images for such natural examples, if the model sand is accepted as a valid analog for crystalline or (non-horizontal) slate basements. Further challenges to the application to natural cases may come, as the authors explicitly recognize, from the tricky simulation of fault-inversion by faulted sand, which most commonly fails to reproduce fault weakening and reactivation. The ms. reads well and is appropriately illustrated, and deserves publication in Solid Earth with minor revision.

When analyzing the cross-sectional views of model 1, I had some trouble understanding the inversion features of the subsalt pile, as in Fig. 9 the inverted graben is not so evident (I mean, I did not get an appreciation of how subsalt faults were inverted). Not until I saw Fig. 10 that I got a clear idea (Fig. 14 also helped). The authors may want to consider presenting the uncompressed profiles before actually showing the compressed ones, which in fact represent one step further of an evolution. I also wondered what would happen if there was no salt fringe out of the modeled rift, as actually happens in many natural cases. Fringes cause the post-salt extension to be more diffuse that the first- phase graben system. What happens in basement in this case? On the other hand, Fig. 12 is a very nice polymer (=salt) volume illustration, which shows similarities to those obtained from natural salt cases after 3D seismic data. Note that minibasins are not always flanked by outward-vergent thrusts as written in line 367 (Fig. 9), which is interesting. Another interesting result is that after shortening, fault footwalls remain broadly inflated (beyond local diapirs). If applicable to nature, this suggests that, coun- terintuitively, some minibasins may be actually underlain by highest subsalt relief. The application of the model results for the High Atlas cases is preliminary; certainly more analogies can be explored by further work. A natural continuation of the models pre- sented could be including intervening horsts without salt between salt-bearing grabens. I believe that this happens in parts of the High Atlas, such as the Mouguer massif – would that impede major decoupling and translation? The Azag minibasin as drawn looks indeed tilted in a post-depositional stage (although the analog models do not get that much rotation), but note that cases like that are lagged by the absence of subsur- face data: there is little control about the stratal geometry at depth and one tends to complete sections in a conservative way. Again, analog models may help in showing the viability of geometric interpretations that may be adopted.

Our reply to Antonio:

Many thanks for the positive review of our inversion paper. You had some specific and general comments that I will address below.

"In comparison to other published models of compressional systems with multiple “salt” décollement levels (e.g. Couzens et al. 2003 –a paper that should be referenced), Dooley and Hudec’s models incorporate early episodes of extensional deformation, which feature synkinematic sedimentation to produce salt migration and diapiric structures (later submitted to compression)."

In reality in these models the lower decollement is simply that, a decollement to ensure that shortening is transferred across the rift system. In models where by the thin lower decollement was not present across the entire system the result was a shortcut fault transferring minor shortening up to the outer edges of the suprasalt sequence (Model 3). But I agree that Couzens et al. should be referenced, along with selected other papers with multiple detachment levels, for completeness.

"The inversion models by Dooley and Hudec provide inspiring images for such natural examples, if the model sand is accepted as a valid analog for crystalline or (non- horizontal) slate basements. Further challenges to the application to natural cases may come, as the authors explicitly recognize, from the tricky simulation of fault-inversion by faulted sand, which most commonly fails to reproduce fault weakening and reactivation."

Yes, I tried to temper the arguments in this manuscript as our model materials (sands) in the subsalt section may not reflect the "strength" of basement rocks in these orogens. However, we believe that, and as noted by you, that these models provide examples of possible basement deformation scenarios in areas where there is generally little or no basement exposure nor seismic data to aid interpretation.

"The authors may want to consider presenting the uncompressed profiles before actually showing the compressed ones, which in fact represent one step further of an evolution. I also wondered what would happen if there was no salt fringe out of the modeled rift, as actually happens in many natural cases. Fringes cause the post-salt extension to be more diffuse that the first- phase graben system. What happens in basement in this case?"

I pondered using a different order of presenting the 3 models when initially writing the manuscript. But I found the text flowed better when Model 1 could be described fully before delving into the details of the deformation (both pre- and post-inversion) with the use of Models 2 and 3 in a more discussion-like section. Your point on the salt fringe is well taken. Yes, this is likely to results in highly variable deformation styles across the inverted rift system – a mixture of coupled and decoupled geometries further adding to the complexity. We have done some work on this but more needs to be done, which could be applied to other areas in the High Atlas as you mention toward the end of your comments. A sentence or two will be added on this topic in the revised manuscript. One thing we noted is that without a significant salt fringe it was difficult to produce diapirs on the flanks of the segmented graben systems.

"Note that minibasins are not always flanked by outward-vergent thrusts as written in line 367 (Fig. 9), which is interesting. Another interesting result is that after shortening, fault footwalls remain broadly inflated (beyond local diapirs). If applicable to nature, this suggests that, counterintuitively, some minibasins may be actually underlain by highest subsalt relief."

For the most part minibasins are flanked by outward-vergent thrusts but you correct there are a few locations along the main rift system that are not. The text will be revised accordingly. Yes, the highest subsalt structural topography lies below the minibasins which is fascinating. I think the height-change maps showing the relief development during inversion quite spectacularly illustrate this with the minibasin system being ele- vated by this subsalt inversion, and with quite a low degree of rotation of the minibasin strata – more on that below.

"The Azag minibasin as drawn looks indeed tilted in a post-depositional stage (although the analog models do not get that much rotation), but note that cases like that are lagged by the absence of subsurface data: there is little control about the stratal ge- ometry at depth and one tends to complete sections in a conservative way. Again, analog models may help in showing the viability of geometric interpretations that may be adopted."

Yes, the models give possible answers to subsurface geometries and the processes that went into making them the way they are. But, they are just that, models. But there are sections from Model 1 that do illustrate significant rotation and Figure 16 will be altered to include an example of this. The original talk I gave on this model series had such a model example and you reminded me of that. Thanks!

Comments by Oriol Ferrer:

Using an experimental approach based on physical models, this manuscript analyses the role of syn-rift evaporites during extension and subsequent inversion of salt-bearing segmented rift basins. Different authors have addressed this type of studies using rigid basement blocs to simulate the basement with the consequent mechanical limitations that this methodology entails. The present manuscript has partly solved this limitation in an original way: a hybrid system that combines a rubber sheet (classically used to constraint the location of extensional faults during stretching) with polymer slabs (also used in physical modelling as “seeds” to constraint fault nucleation). This hybrid experimental setup allows to achieve a significant degree of inversion of pre-salt grabens (an inherent issue of the models that use rigid blocks). In addition, the en-echelon distribution of the different slabs allows to simulate a segmented rift system. Another interesting point addressed in the manuscript is how syn-rift salt controls the structural style during extension and consequently, how the inherited salt structures at the end of the extension constraints deformation during inversion.

The manuscript reads well and the quality of figures is excellent, they perfectly illustrate the text. The scaling of the experimental program is correct and the analog materials are the classical ones used in physical modelling of salt tectonics. The experimental re- sults are compared with natural examples from the Moroccan High Atlas but they would be perfectly applicable to other fold-and-thrust belts involving inverted salt-bearing rift basins such as the Pyrenees. I am sure this manuscript will be useful to the under- standing of inverted salt-bearing rift basins. For this reason, I recommend its publi- cation in Solid Earth journal after few minor revisions (please, see below general and specific comments, suggestions and questions).

Best regards,

Oriol Ferrer

General comments:

A point that I consider should be implemented in section “2.1. Model Design and Scaling” is as far as syntectonic sedimentation is concerned. What is the sedimentation rate? Did you keep the pre-extensional regional fixed? How much did you raise it every new synkinematic layer of sand? These are points that the reader should know. These points are addressed in the experimental results section, but they should be moved at section 2.1.

Include a figure like figure 2 of Roma et al. (2018b) could help to understand the procedure applied during model run. This is just a suggestion.

As far as setup is concerned, I don’t understand why did you modify the extension of the basal detachment layer in models 1 and 2/3 respectively. Why not to use the same for the 3 experiments? Can this modification influence the final results in any way?

The section 3 (Experimental results) is clearly described and well ordered. However, I disagree about the harpoon structure described in lines 28-287 (also in line 419, sec- tion 4.3. “Shortening in the subsalt section”). According to McClay (1995), the inversion of the wedge shaped synextensional strata produces typical “harpoon” or “arrowhead” geometries, the shape of which depends upon the geometry of the underlying extensional faults. In these lines of the manuscript, this geometry is wrongly applied to the inverted preextensional unit. Please, modify it.

Regarding this section, could the marginal grabens be related to edge effects of your experimental setup?

As it has been pointed out in the manuscript, the contractional reactivation of graben- bounding faults during inversion can be favored by the polymer infiltration into the granular material (sand). This infiltration occurs either at the interphases between polymer and pre- / supra-polymer sand during the setup of the experiments, and throughout the experiment when new surfaces (faults) developed. This process occurs when the sand- polymer interphase is preserved for a long time, so can we interpret that the longer the contact, the wider the area affected by polymer infiltration? If this is the case, the con- tractional reactivation of the sand-polymer interphase in the fault will be more effective because it will "lubricate" in a more efficient way. Is this observation true? Other prompt questions regarding this topic are: What is the infiltration rate? There is any control of this process during the construction/run of the experiments? What are the main factors that control it? I perfectly understand that these questions are out of the scope of the manuscript, but as a modeler and after to notice similar processes, I consider that this topic should be discussed in the manuscript.

Considering that model 2 was sliced at the end of the extensional stage, and model 1 is similar but with 25 cm of inversion, it would be interesting to include a section discussing the contractional reactivation of primary welds and what is the role that they play during inversion. Are they reactivated as thrust welds? What occurs with their surface? There is any increasing/decreasing on their surface during inversion? Have you noticed the opening of the primary welds during inversion in your 3D voxels? The paper by Roma et al. (2018b) includes some discussion about this topic that could be compared with the models included in the present manuscript.

Due to the few published works in analog modeling addressing the role of synrift evaporites during extension and subsequent inversion, I consider that some additional references such Soto et al. (2007); Ferrer et al. (2014); Roma et al. (2018b) should be included in the manuscript.
Ferrer et al. (2014). The role of salt layer in the hangingwall deformation of kinked- planar extensional faults: Isights from 3D analogue models and comparison with the Parentis Basin. Tectonophysics, 636, 338-350.
Roma et al. (2018b). Weld kinematics of syn-rift salt during basement-involved exten- sion and subsequent inversion: Results from analog models. Geologica Acta, 16 (4), 391-410.
Soto et al. (2007). Geometry of half-grabens containing a mid-level viscous décolle- ment. Basin Research, 19, 437-450.

Specific comments:

Line 50 "Calloway" should be "Callaway" Line 74 at the end of the line, modify "halo kinetic" for "halokinetic" Lines 109-110 Check the sentence Line 113 indicate the thick- ness of the basal polymer Line 114 indicate the dimensions of the slabs Line 157 indicate the % of sand and ceramic microspheres that you used, and if this % is in weight or volume Line 508 modify "teh" for "the" at the end of the line

Figure 2 is difficult to understand. Is the rubber sheet transparent?

Figure 4 Why did you use green polymer? I did not found the explanation in the manuscript.

The word “stage” is used indistinctly in capital or lowercase to refer to the different evolutionary stages of the models. Please, use uniform criteria.

There are some references that do not match those of the reference list. Among those I have detected: Bonini et al. (2011); Moragas et al. (2016); and Martín-Martín et al. (2016). Please, check which one is correct and unify. Similarly, there are missing references in the reference list: Adam et al., 2005 (line 180); Sibson, 1995 (line 430) and Anderson, 1951 (line 431).

Our reply to Oriol:

Oriol,
Many thanks for your thorough and positive review of our inversion paper. I will reply to your comments below, pasting in your text in order to answer specific comments if needed.
General comments:
1. Agree, will add more specific information on sedimentation rates etc. in the modeling methodology section. In general the height-change maps generated from the DIC system guided me here during all stages of the model runtimes. Base-level was raised just enough to clear any rising diapirs resulting in sequences that markedly thinned across the rift flanks.

2. This would be more difficult to do for a 3D system that is being modeled here. I think the figures as they stand give the readers a walk through of the model evolution and final geometries.

3. Ah! Yes. These experiments were not run in the order they are presented in! Models 2 and 3 were run before Model 1, and it became obvious that the thin basal decollement (3-4 mm of silicone polymer) needed to cover the entire base of the rig to facilitate inversion of the entire subsalt and supra salt sequence. The only difference this made to the pre-inversion geometries was pushing the marginal graben systems further towards the periphery of the model. These marginal graben are quite minor and the main focus is aimed at the main segmented rift system.

4. Yes, the "harpoon" reference is poor and will be removed. "Inverted subsalt graben" will be used or something to that effect.

5. Marginal graben – see point 3 above. It’s minor and not our focus.

6. This is a very interesting and modeling-focused point. In general the infiltration "depth" I believe is governed by the grain size of the sediments, and thus by the mixture of sands/censopheres used in these strata. You have likely seen the same phenomena, and I keep some of this material in my labs to show visitors that sand can fold if it has been "infiltrated" by polymer, but still fail in a brittle fashionunder higher strain rates! I really can’t answer all your questions in this section. I’m sure you have seen that welds between sub- and suprasalt sand layers appear to be very clean, unlike may between sand and a rigid, non-porous baseboard. But you commonly see a slight change in color of the strata just above and below the weld for about 2-3 mm, again depending on grain size. I will try to add in a sentence or two to clarify this, but for now it’s a known unknown, but the best explanation I have for efficient reactivation of these subsalt graben.

7. This is a great observation and something I will discuss. If you compare Model 1 (Figures 9 and 15b) with Model 2 (Figure 10) the primary welds are in different locations - much more toward the minibasin centers in inverted models, but at the flanks of the minibasins in non-inverted models. Yes, these have likely been "sheared off" during inversion as the entire minibasin is pushed upwards above the rising hanging walls of the segmented graben systems. And the length or extent of the welds becomes greater – e.g. see Section 33 in Figure 9. I'll add in Roma et al. *2018b) and discuss in the relevant section. Thanks.

8. Yes, additional references will be added as per your suggestion. Makes it more complete.

Specific comments:

Will fix those and add reference to volumetric percentages of sand and ceonspheres where appropriate.
Figure 2 – the stretching rubber sheet is black and is visible through the basal thin polymer layer. But I have it as green in Figure 2a. I'll adjust this and fix the caption to clarify.
Figure 4 – I though I did mention it. I'll check. This is to track where our model salt in the central graben flows to during extension and loading.
I will standardize on "Stage" to make it consistent.

Thanks for catching the references.
Again, many thanks for the comments and suggestions/discussions.

Paper revisions:

Again, many thanks to both Antonio and Oriol for their positive and comprehensive reviews of the paper. All of their comments have been addressed above and with revisions to main text and to some of the Figures. For example, the modeling setup figure was altered so the stretching rubber sheet seen in the overhead photo of Figure 2b matches the color of its representation in Figure 2a. In Figure 16 I added a detail of one cross section through Model 1 showing a tectonically tilted minibasin with a hypothetical erosion level line. I also did some general tightening of the text where I saw fit.

Also included in the revised text are clarifications to model setup and procedures such as the addition of synkinematic sediments. Additionally text has been added in the discussion addressing Antonio's comments on "connectivity" of salt in such basins. Indeed, there is plenty of work that needs to be done to address this and compare and contrast inverted salt-bearing basins with and without a salt fringe that, as noted, aids mobility. Oriol's comments on the "polymer-sand rind" seen in the models was a very modeling-specific query but I have added a short sentence in that section addressing this. In fact it led to a long discussion between Oriol and I and he sent images of similar "polymer-sand rinds" in his modeling work. In addition, his comments on the welds was great, as the position of primary welds between Model 1 and Model 2 are very different, due to primary welds formed in extension being shear off during inversion, shifting the locations of the welds. This has been addressed in the revised version of the paper. Most of these revisions were added in the Discussion section rather than in the Conclusions to keep the final words the reader sees as being a summary of the model findings rather than a litany of problems with the models themselves.

I hope that the revised manuscript proves acceptable for publication in the special volume "Inversion tectonics – 30 years later".

Sincerely,

Tim Dooley
30th April 2020

Extension and Inversion of Salt-Bearing Rift Systems

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Abstract:

We used physical models to investigate the structural evolution of segmented extensional rifts containing syn-rift evaporites and their subsequent inversion. An early stage of extension generated structural topography consisting of a series of en-échelon graben. Our salt analog filled these graben and the surroundings before continued extension and, finally, inversion.

During post-salt extension, deformation in the subsalt section remained focused on the graben-bounding fault systems whereas deformation in suprasalt sediments was mostly detached, forming a sigmoidal extensional minibasin system across the original segmented graben array. Little brittle deformation was observed in the post-salt section. Sedimentary loading from the minibasins drove salt up onto the footwalls of the subsalt faults, forming diapirs and salt-ridge networks on the intra-rift high blocks. Salt remobilization and expulsion from beneath the extensional minibasins was enhanced along and up the major relay/transfer zones that separated the original sub-salt grabens, forming major diapirs in these locations.

Inversion of this salt-bearing rift system produced strongly decoupled shortening belts in basement and suprasalt sequences. Suprasalt deformation geometries and orientations are strongly controlled by the salt diapir and ridge network produced during extension and subsequent downbuilding. Thrusts are typically localized at minibasin margins where the overburden was thinnest and salt had risen diapirically on the horst blocks. In the subsalt section, shortening strongly inverted sub-salt grabens, which uplifted the suprasalt minibasins. New popup structures also formed in the subsalt section. Primary welds formed as suprasalt minibasins touched down onto inverted graben. Model geometries compare favorably to natural examples such as those in the Moroccan High Atlas.

1. Introduction

As noted by Bonini et al. (2011), in their review paper, "basin inversion" is a commonly used term to signify shortening of formerly extensional basins (cf. Buchanan and McClay, 1991; Buchanan and Buchanan, 1995; Ziegler, 1987). Localization of shortening by extensional rifts, and their subsequent inversion, is not surprising as these are long-lived crustal weak zones. Inversion of graben and entire rift systems has been a significant focus of study since the early 1980s owing to its importance related to: (1) the role of pre-existing faults in focusing and accommodating shortening of the upper, shallow crust; (2) the role of pre-inversion high-angle faults as potential seismogenic sources and hazards, and; (3) their economic importance related to focused fluid flow and associated ore deposit generation was well as influencing hydrocarbon maturation, migration pathways, and trapping in inverted petroleum-bearing sedimentary basins (see Bonini et al., 2011 for further details and references). Deposition of evaporites in these systems, either as syn-rift deposits or immediately after rifting, can add complexity to the system in many ways. For example salt may have significant variation in thickness across the rift resulting in varying degrees of coupling between the basement and suprasalt sediments during subsequent extension and inversion (e.g. Withjack and Calloway, 2000). Salt may also be expelled from beneath depotroughs, during extension and/or loading to form diapir networks that may later focus shortening as plate motions evolve (e.g. Dooley et al., 2005). These diapir networks may be surrounded by patchy weld systems adding further complications to the system (cf. Rowan and Krzywiec, 2014).

Examples of basement-involved inverted salt-bearing rifts include the the Mid-Polish Trough (e.g. Krzywiec, 2012; Rowan and Krzywiec, 2014), the southern North Sea (e.g. Stewart, 2007; Stewart and Coward, 1995; Davison et al., 2000; Jackson and Stewart, 2017) and the High Atlas of Morocco (e.g. Saura et al., 2014; Domenech et al., 2016; Martín-Martín et al., 2016; Moragas et al., 2017; Teixell et al., 2017; Verges et al., 2017; Figure 1). The central High Atlas range is a doubly-vergent fold-thrust belt that formed by inversion of a Triassic-Jurassic rift basin during the Alpine orogeny (e.g. Teixell et al., 2003; Saura et al., 2014; Moragas et al., 2017). Within the central part of the range outcrop is dominated by Lower-Middle Jurassic deposits that form brand synclines or flat-topped plateaux, and separated by NE-SW oriented anticlines or thrust faults (Figure 1; Moragas et al., 2017). These ridges have had a variety of explanations for their origin such as transpressional deformation or the emplacement of Jurassic intrusions (see detailed discussion in Moragas et al., 2017, for more details). A few studies of individual structures proposed a diapiric origin for these ridges (e.g. Michard et al., 2011). However, more recent studies have interpreted the entire Central High Atlas as a complex salt-bearing rift basin with associated diapirism and minibasin formation, that was inverted in the Alpine orogeny. For example, Saura et al. (2014) documented more than ten elongated extensional minibasins that were originally separated by, now welded, salt walls. Thick evaporitic successions were deposited within the developing rift in the late Triassic (Verges et al., 2017). Extension continued into the Early Jurassic with coeval diapirism and minibasin formation, followed by a long post-rift stage where halokinetic processes continued to evolve (Moragas et al., 2017; Martín-Martín et al., 2016). Inversion began in the late Cretaceous (Domenech et al., 2016), squeezing a complex diapir and minibasin province. Such a diapir and minibasin province is likely to exhibit extreme variations in overburden strength, and thus behavior, during shortening. It is this salt-tectonic scenario that formed the inspiration for our experimental study.

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Many experimental studies of contractional tectonics utilize silicone polymer as a detachment, sometimes with spatially variable and multiple detachment levels, usually of uniform thickness, in thrust belt studies (e.g. Couzens-Schultz et al., 2003; and see the review by Graveleau et al., 2012). Some previous physical modeling studies of basement-involved extension and inversion of salt-bearing rifts include those of Dooley et al. (2005) with application to the North Sea, and Moragas et al. (2017) in their focused study on syn- and post-rift diapirism and inversion in the Moroccan High Atlas. Bonini et al. (2011) modeled detached extension and subsequent shortening of these graben, Soto et al. (2007) modeled the effects of high-level ductile detachments above a variety of listric fault geometries, and Roma et al. (2017, 2018a, b) as well as Ferrer et al. (2014, 2016) modeled extension and inversion above rigid planar and ramp-flat extensional master faults with high-level and variable-thickness salt layers. However, all the basement-involved inversion studies to date relied on non-deformable basement blocks to

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generate extension and subsequent inversion. An exception to this are the clay models of Durcanin (2009), but these models could not be sectioned and thus sections shown in this study are “hypothetical”. A new series of experiments was designed to produce segmented rift systems in deformable model materials, fill them with syn-rift evaporites and subject them to further extension, loading and, finally, inversion. Our goals with these models was to test: (1) where and why do diapirs form in a segmented extensional rift system?; (2) how much coupling is there between basement and cover separated by a relatively thick salt body during extension and contraction?; (3) what styles of shortening structures form in the suprasalt section during inversion and what controls their location and style?, and; (4) what are the styles of shortening in the subsalt section and can we get significant reactivation of extensional structures during inversion?

2. Modeling Methodology

2.1 Model Design and Scaling

Our goal with these models was to generate a series of en-échelon graben across a rift system in a similar fashion to models presented in Dooley et al. (2005). They achieved this by using non-deformable wooden blocks with a series of steps, whereas we wished to generate segmented rifts using deformable materials that could be serially sectioned at the end of the model run. Previous models of segmented rifts systems used offset rubber sheets to do this (e.g. McClay et al., 2002; Amilibia et al., 2005). However, these suffered from internal artifacts as the rubber is stretched to generate extension in the overburden it also constricts orthogonal to the extension direction, resulting in accommodation or transfer zones that are structural lows rather than highs in these locations (e.g. see Sections 2 and 5 of Figure 8 in Amilibia et al., 2005). In order to mitigate these effects we used a hybrid system comprising a single basal stretching sheet, a thin basal silicone detachment and a series of polymer slabs to generate a segmented rift system in the overburden (Figure 2). The stretching rubber sheet generated extension, whilst the basal polymer layer acted as an efficient detachment (during extension and contraction). In contrast, the polymer slabs served to focus extension at these sites, in much the same way that precursor diapirs focus strain in contractional models (e.g. Dooley et al., 2009, 2015; Callot et al., 2007, 2012). Dooley and Schreurs (2012) employed a variety of polymer "crustal weak zones" to focus extension in pull-apart basins and to concentrate and perturb deformation above basement strike-slip zones. Le Calvez and Vendeville (2002), Zwaan et al. (2016) and Zwaan and Schreurs (2017) also used polymer "ridges" to focus or "seed" extensional structures in their models, and Marques et al. (2007) used wedge shaped polymer layers to investigate transform faulting associated with ridge push. Dual motors generated the symmetric extension and contraction in these models (Figure 2).

Models are dynamically scaled such that 1 cm in the model approximates to 1 km in nature (see, for example, Brun et al. 1994 and McClay 1990 for detailed discussions on scaling). Models were conducted with combined horizontal velocities of 1.4 x 10^{-4} cm/s that yields a strain rate of 1.8 x 10^{-6} s^{-1}. This rate models an extensional fault system with a moderate displacement rate (e.g. Withjack & Callaway 2000; Dooley et al., 2005). More importantly, post-salt extension was pulsed in order to allow the model salt analog to react to the imposed strain and the differential loads induced by spatially-variable thickness of the synkinematic sediments added after each increment of extension. Models consist of 3 or 4 main evolutionary stages (Table 1): (1) pre-salt extension followed by addition of model salt into the main structural topography addition of a regional salt fringe and thin roof: (2) post-salt extension delivered in a series of pulses, as described above; (3) post-salt loading and downbuilding stage, allowing diapirs that formed in Stage 2 to continue to rise vertically, and; (4) inversion, where the moving endways are detached from the baseplates, the baseplates are clamped in place, and motion is reversed. We focus primarily on the results of one experiment (Model 1, Table 1) in the descriptive sections and use some of the results from two other experiments (Models 2 and 3, Table 1) to discuss salt tectonics styles and salt migration pathways in non-inverted and weakly inverted rifts in the discussion section. The only difference between Model 1 and Models 2 and 3 is that the thin basal detachment layer extended across the entire model base in Model 1, whereas it was limited to just covering the rubber sheet in Models 2 and 3 (see Figure 2).

2.2 Modeling Materials

As with other physical modeling studies of salt tectonics, we simulated rock salt using ductile silicone and its siliciclastic overburden using brittle, dry, granular material. The silicone was a near-Newtonian viscous polydimethylsiloxane. This polymer has a density of 950 to 980 kg m^{-3} and a dynamic shear viscosity of 2.5×10^4 Pa s at a strain rate of 3×10^{-1} s^{-1} (Weijermars, 1986; Weijermars et al., 1993). In some of our models the salt analog was dyed with minute quantities of powdered pigments in order to track salt flow paths in the completed model. The layered brittle overburden comprised different colored mixtures of silica sand (bulk density of ~1,700 kg m^{-3}; grain size of 300-600 µm; internal friction coefficient, µ, = 0.55–0.65; McClay, 1990;

Krantz, 1991; Schellart, 2000), and hollow ceramic microspheres ("glass beads") having a bulk density of 650 kg m^{-3}, average grain size 90-150 µm, and typical $\mu = 0.45$ (e.g. Rossi and Storti, 2003; Dooley et al., 2009).

The hollows spheres serve to lower bulk grain size, as well as allowing us to modify the density of the brittle overburden. Most physical models of salt tectonics have a layered brittle overburden of pure quartz sand, which creates density ratios that are much higher than those of nature. Exaggerated density ratios erroneously magnify overburden foundering, rise of active diapirs, and expulsion and extrusion of salt (Dooley et al., 2007, 2009). In our models, the pre-rift overburden sediments had a density ratio of equal to that of our model salt by our varying the sand-bead ratio in the brittle section. In this case the ratio of sands to censopsheres in the mixture was equal. This was done to minimize any density- or buoyancy-driven rise of the basal slabs that are also made of the same materials as our salt analog. In Stages 2 and 3 of the model runtime the density of the sedimentary load was increased to 1.1-1.2 times that of our model salt, by increasing the proportion of sands in the mixture to 65%. This was done to encourage salt remobilization from beneath the extensional minibasins in Stage 2 and to keep salt structures (diapirs) growing in Stage 3. Synkinematic strata were added to the model after each 1 cm increment of extension in Stage 2, with aggradation rate governed by any rising diapirs. Similarly, during Stage 3, the height data discussed below governed the regional aggradation rate, to just crest rising diapir networks.

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2.3. Data Capture, Visualization, and Interrogation

Computer-controlled cameras photographed the obliquely lit upper surface of the models at set time intervals. A digital image correlation (DIC) system, consisting of a high-resolution stereo charge-coupled device (CCD) system and associated software, tracked the surface-strain history, subsidence, and uplift values, as well as displacement vectors of the top surface of the model. The speckled nature of the sand and cenosphere mixtures used in our models are ideal for this type of monitoring system (see Reber et al., 2020, for further details). Adding synkinematic layers means data is incremental for individual layers during Stages 2 and 3 of Model 1. For more details on DIC monitoring techniques, see Adam et al. (2005). After completion models were impregnated with a gelatin mixture, left to partially dry for 12 hours and then sliced into closely spaced slabs. Coregistered digital photographs of these closely spaced serial sections (≤3.5 mm apart) yielded a 3D voxel of the completed model. Dip sections are the sliced and photographed cross sections, whereas crosslines, arbitrary lines and depth slices are virtual sections constructed from the voxel model. As a result, the crossline, arbitrary line and depth slice images are interpolated and thus not as sharp as those derived directly from photographed dip sections. In addition the 3D salt volume can be extracted from this voxel by coloring the salt in each section with a known pixel value (e.g. white for a value of 255).

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3. Experimental Results

3.1 Stage 1: Pre-Salt Extension

Stage 1 comprised 3 cm of uniform extension in order to generate structural topography that was infilled by our salt analog (Table 1). The basal weak slab array shown in Figure 2, was there to ensure a segmented rift system formed. Height-change data (ΔZ; Figure 3a) generated from our stereo-DIC system reveals the main rift system in Model 1 comprising en-échelon graben that step to the right across the underlying basal slab array (Figure 2). Three main depotroughs are seen along the segmented rift system, separated by zones of higher intra-rift topography, accommodation zones (Figure 3). Strain data illustrate the focused extension along the fault network across the rift system (Figure 3b). On many faults maximum extensional strains, and maximum width of faults, are recorded along their centers, although some deviate from this trend (Figure 3b). Weaker extensional systems form at the margins of the model, far from the central rift system (Figure 3). The accommodation zones are clearly seen in the strain data, and consisted of interlocking arrays of mostly soft linked extension faults with some rotation seen at fault tips (Figure 3b). Between the southern and central and between the central and northern subbasins, clear fault-tip rotation is seen with breaching of the major relay systems separating the subbasins (Figure 3b).

After Stage 1 extension, our salt analog was placed into the three subbasins and allowed to settle (Figure 4a). Once this had settled and filled the structural relief a 12-mm-thick regional layer of our salt analog was emplaced across the model as a series of tiles (Figure 4b), and allowed to degas prior to Stage 2.

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3.2 Stage 2: Post-Salt Extension

Our salt analog in Model 1 was buried under a thin (4 mm) sedimentary roof before undergoing a further 6 cm of extension during Stage 2 (Table 1). Figure 5 shows height-change data and strain from Model 1 after applying total of 4 cm of post-salt extension. Synkinematic sediments were added after each 1 cm of basement extension and the values shown in Figure 6 are incremental for that phase of extension, i.e. 3-4 cm post-salt extension. During this period the main depotrough comprised a sigmoidal extensional minibasin located above the original offset graben system (Figure 5a). A series of curvilinear fabrics define relatively minor surface faulting (Figure 5a). Strains seen on the upper surface were much more diffuse and spread across the rift system than those seen in the pre-salt extension, Stage 1 (Figure 3). The strain fields formed curvilinear systems of extension that, for the most part, defined minor graben above reactive diapirs, and appear to be diagnostic of detached suprasalt extension (cf. Dooley et al., 2005; Figure 5b). Maximum extensional strains were seen adjacent to the sigmoidal depocenter, as expected, delineating the margins of the main depotrough, and in locations that were accommodation zones during the pre-salt extension phase as the cover collapsed into the developing trough (Figures 3 and 5). Minor shortening strains are seen within the extensional minibasin/depotrough due to inner-arc contraction as it subsided into, and expelled, the salt (Figure 5b). The marginal graben at the ends of the model continued to subside during Stage 2 (Figure 5).

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3.3 Stage 3: Post-Extension Loading

Model 1 underwent 9 cm total extension prior to moving on to a downbuilding or post-extension loading phase in Stage 3. Stage 3 lasted for 5 days and synkinematic sediments were added daily, keeping apace and gently covering any positive topography that developed whilst continuing to load negative topography.

Height change maps of the model surface of Layers 1 and 4 are shown in Figure 6. Clearly illustrated in Figure 6a are the rising diapir networks as salt was expelled from beneath the composite minibasin in the model center. Comparing Figure 6a to the strain map in Figure 5b one can immediately see that the diapir networks closely conform to the strain patterns seen during Stage 2, evolving from reactive to passive features in Stage 3. Diapirs labelled 1-3 are all located on the footwalls of the main extensional minibasin, and, more importantly, in locations that lie above, and along, what were the original accommodation zones between the original subbasins (see Figures 3, 5 and 6). More linear salt walls are seen rising adjacent to the marginal graben systems and the extensional minibasins is flanked by upwellings along most of its length (Figure 3). Figure 6b illustrates the height change map after 4 days into Stage 3. Activity waned in these systems over time except for the more active and emergent diapirs (1 & 2 in Figure 6b). Smaller amounts of salt rise are seen flanking the central region of subsidence.

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3.4 Stage 4: Inversion

In Stage 4 Model 1 was covered with a thin roof sequence and subjected to 25 cm of lateral shortening (Table 1). Height-change maps reveal the evolution of the model during inversion (Figure 7). As expected from previous studies (e.g. Dooley et al., 2009, 2015; Callot et al., 2007, 2012; Duffy et al., 2018), initial shortening resulted in rejuvenation of the two main diapirs formed during Stages 2 and 3 (1 and 2 on Figure 7a). This was followed by uplift of the composite minibasin system and the formation of a series of linear and curvilinear uplifts (Figure 7b). These uplift patterns are very similar to the ridge networks seen during Stage 3 (compare Figures 6a with 7b). With continued shortening the minibasin system continued to rise and salt

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The final overhead view of Model 1 is shown in Figure 8. In this we see the central uplifted minibasin system forming an oblique plateau across the model, and flanked by the linear and curvilinear faulted ridge network. Flow directions of the salt sheets emanating from Diapirs 1 and 2 are indicated by red arrows (Figure 8). Major fault scarps were partially degraded exposing older strata, and some scarps abut, or override scarps with opposite sense of dip (Figure 8). On the right side of the model two fault scarps abut in the south and then coalesce forming a very narrow fault zone (Figure 8). These geometries and relationships are revealed by a series of four sections through Model 1 (Figure 9). The four sections illustrate the decoupled nature of deformation between sub- and suprasalt strata (Figure 9). The main feature is the structurally elevated extensional minibasin system that trended obliquely across the model (Figures 8 and 9). For much of the strike length this feature is flatted topped, and bounded on either side by detached suprasalt thrusts or secondary thrust welds as Diapirs 1 and 2 were squeezed shut (Figures 8 and sections 33 and 55 in Figure 9). Structural elevation of this minibasin system was partly aided by the inversion of subsalt graben that form inversion anticlines in the subsalt strata (Figure 9; see the next section for further discussion). Primary welds denote where the minibasins have touched down on the inverted subsalt strata. Also of interest in the suprasalt

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strata are emergent sheets and isolated salt bodies sourced from the squeezed and welded diapirs (e.g. section 33 and 55 in Figure 9), salt-cored thrusts and related secondary welding of portions of these as salt was ejected and hangingwall touched down onto footwall (e.g. Sections 33, 86 and 106, Figure 9). Other structures in the suprasalt section include highly overthrust popdowns, and narrow upright fault zones as hangingwalls collided during shortening (Section 86, Figure 9). A curious structured is observed in many sections, termed an "S" structure due to its shape (see Sections 55 and 86 in Figure 9). We will discuss the origins of this structure in the discussion section. In the subsalt strata structures are very different, consisting of inverted and heavily deformed graben systems in both the center and margins of the model as well as new popup structures (Figure 9).

4. Discussion

In this section we focus on: the formation and location of diapirs during extension and post-extension loading; shortening styles and location in the suprasalt section during inversion; shortening styles and locations in the subsalt section, and; comparison of model results to examples from the High Atlas in Morocco.

4.1 Diapir Formation and Location During Extension

In Model 1 the main diapirs (diapirs 1 and 2, Figure 6), and associated salt wall or ridge networks formed in the footwall of the main extensional systems that flanked the composite extensional minibasin. More specifically the most active diapirs formed in locations spatially associated with the interlocking accommodation zones that originally separated the subbasins (Figures 3, 5 and 6). These locations are similar to those documented in Dooley et al. (2005), although the transfer zones in those models were vertical and rigid. Model 2 was run with almost identical parameters as Model 1, but was not inverted, preserving the diapir geometries and locations (Table 1 and Figure 10). Figure 10a shows the height-change map that evolved during Stage 1 of this model (see Table 1), consisting of an en-échelon series of three graben that run obliquely across the model, similar to that seen in Model 1 (see Figure 3a). The only difference Model 2 showed was the presence of marginal graben that formed closer to the main rift system than that seen in Model 1. This was attributed to the narrower basal silicone detachment used in Model 2 (Figure 2 and Table 1). Likewise, the continued evolution of Model 2 through Stages 2 and 3 was very similar to that seen in Model 1 (compare Figures 10b, c with Figures 5a and 6a). The diapir network geometries and most active diapirs in Model 2 were also very similar to those seen in Model 1.

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A section from Model 2 illustrates the extensional minibasins formed above the main graben and diapirs located in the footwalls of these graben (Figure 10d). As we saw in the strain maps for Model 1 there was only minor discrete extension in the suprasalt strata and these are cored by reactive diapirs (Figure 10d). The main diapir in this section is located in the footwall of the main graben system, and just along strike from the accommodation zone that separated the southern and central subbasins (Figure 10a, d). Salt expelled from beneath the subsiding minibasin flowed up onto the footwall and helped feed this growing salt diapir. We believe that salt was also preferentially expelled up and along the accommodation zones that separated the original subbasins and into these growing diapirs, as these accommodation zones have more gentle relief compared to the steep faults that bounded the minibasins, thus offering a more efficient conduit for salt flow.

In order to corroborate this concept of preferred flow up and along transfer or accommodation zones, images from a third model, Model 3, are shown in Figure 11. Model 3 was subjected to the same amount of extension as Model 1, but a very limited amount of inversion (Table 1). In addition, the lack of a basal detachment across the entirety of the model base meant that shortening in the subsalt section was limited to shortcut thrusts close to the margins of the deformation rig that transferred shortening up to the weaker suprasalt section, with minimal shortening seen in subsalt strata in the central portion of the rift system (Figure 11a-e; Table 1). The lack of deformation in the subsalt strata means that primary welds seen in the sections in Figure 11c-e, occurred during extension rather than during shortening. Depth slices from Model 3 illustrate the composite, stepped, minibasin that formed above the en-échelon rift system (Figure 11a-b). The yellow marker salt that initially occupied the central graben of the rift (Figure 11f) is seen to be expelled up and out of this graben system into the footwall, where it helped inflate reactive diapirs that initially formed along these locations (Figure 11a-c; see reactive diapir on the right side Figure 10d for a non-inverted example). Model 3 also had substantial diapirs that flanked the rift in similar positions to those of Models 1 and 2, and yellow marker salt is seen to flow along and up the, now faulted, lower-relief accommodation or transfer zones and into these diapirs (Figure 11d-e). Thus, salt flow during extension and post-extensional loading in Model 3 was multidirectional, being driven by differential loading out and up onto the intra-rift horst blocks both up the main subsalt faults and along lower-relief pathways such as the transfer zones that separated the subbasins in this rift system. Flow up and along these conduits was eventually curtailed or stopped by primary welding (Figure 11c-e).

4.2 Shortening in the Suprasalt Section

Figure 12 shows the salt volume that was extracted from the serial sections and exported as a point cloud. This image beautifully illustrates the structural style in the shallow section. The central part of the model is dominated by the inverted extensional minibasin system that forms an oblique structural low. Primary thrust welds are denoted by gaps in the data, as the subsalt graben were inverted, welded against the base of the suprasalt strata, and structurally elevated the minibasin system (Figure 12). Note that the position of the primary welds in Model 1 (Figures 9 and 12) differs to those seen in our non-shortened or mildy-shortened Models 2 and 3 (Figures 10 and 11). In Models 2 and 3 the primary welds are located at the minibasin margins where the it welded down onto, or adjacent to, the crest of the footwall block (Figures 10 and 11). In Model 1 primary welds are located more toward the center of the minibasin and are related to the inversion of the subsalt graben system. Any welds that formed at the minibasin margins during Stage 2 extension and Stage 3 downbuilding in Model 1 were sheared off during inversion in a similar fashion to that documented by Roma et al. (2018b). The minibasin system is typically flanked by outward-vergent salt-cored thrusts, secondary thrust welds and remnant high-level salt bodies or sheets (diapirs 1 and 2, Figure 12). Thrust vergence reverses toward the margins of the model, and structures vary from salt-cored thrusts to box-like thrusted folds (Figure 12).

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Shortening in the suprasalt section is primarily controlled by the diapir and ridge network that formed during extension and post-extensional loading. This is clearly illustrated in Figure 13, which shows a height-change map, depth slice and dip section from Model 1. The diapir-ridge networks, labelled a-e on Figure 13, localized shortening structures because these are where the overburden was thinnest and thus weakest, and the diapir networks helped to focus deformation. Deformation in the shallow section is clearly detached from the subsalt structures, except where the minibasin system welded onto inverted subsalt graben (Figures 9, 12 and 13c). Height-change maps from the inversion phase also illustrate this reactivation of the pre-inversion diapir-ridge network (compare Figure 7 and 13). Minibasin subsidence patterns in Model 1 were primarily symmetric during extension and post-extensional loading, as evidenced by height-change maps (Figures 5 and 6), and by the stratal geometries seen in cross sections (Figure 9). During inversion the main minibasin system was structurally uplifted by the inverting subsalt graben (Figures 7), with little or no internal deformation except at the minibasin margins where suprasalt thrusts developed (Figures 9 & 13c). Only minor tilting caused by shortening of the main minibasin system is seen in the northern part of the model (section 106, Figure 9). Smaller minibasins developed above the marginal graben systems exhibit more severe tilting as they were carried up in the hangingwalls of major suprasalt thrusts (sections 33 and 55, Figure 9).

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As mentioned in Section 3.4, there is a curious structure observed in suprasalt strata in some sections through Model 1 that is termed an “S” structure due to its shape (sections 55 and 86, Figure 9). This structure is found in a deformed salt-cored box fold in the southern part of the model (Figures 9 and 12). A series of sections through this structure give a pseudo-temporal evolution of this structure (Figure 14). The structure started as a faulted box fold, localized along a salt wall (e in Figure 13), that initially formed during extension and post-extension loading. One of the hinges began to fail on one side of this box fold and eventually limb failure occurred, forming a small weld as the core began to narrow (Figure 14a-b). Eventually salt in the core was expelled and the limbs welded, leading to the “S” geometry (Figure 14c).

4.3 Shortening in the Subsalt Section

We noted briefly in Section 3.4 that deformation in the subsalt strata is very distinct from that seen in suprasalt strata (Figure 9). In subsalt strata the most obvious structures are the popup structures in cross-section views, and none of these are linked to structures in the shallow section (Figure 9). However the most interesting structures are found along the central portions of the model where the pre-salt graben have been strongly deformed and inverted (Figure 9). Some of these structures form the highest subsalt relief seen in Model 1 (e.g. section 33, Figure 9). Height-change maps from Stage 4 of Model 1 clearly illustrate that the main minibasin system was preferentially uplifted as an intact block during shortening (Figure 7). This uplift was thus a result of preferential inversion of the subsalt graben system. This is borne out in cross-section views through Model 1 that clearly show uplift of the main minibasin system as a coherent block forming an almost flat plateau along the length of the center of Model 1 (Figures 7, 8 and 9). Figure 15 shows detailed views of a non-inverted graben from Model 2 and an inverted graben from Model 1. In Model 2 the non-inverted section the structure consists of a mildly asymmetric graben with a smaller keystone graben formed against the more dominant right-side boundary fault (Figure 15a). Figure 15b shows a portion of Section 33 from Model 1 (Figure 9). In it we see a highly inverted basement graben system with a keystone graben system on the right margin as in Model 1 (Figure 15a-b). Inversion of this graben was asymmetric with greater uplift of the left side forming an inversion anticline that structurally elevated the suprasalt minibasin (Figure 15b). Based on the geometry of the non-inverted model the right side of the graben also saw significant inversion before being overthrust by a new subsalt thrust (Figure 15b). More minor new thrusts are seen to the left of the graben system. Only a minor amount of structurally-induced tilting is seen in the suprasalt sequence (2.5°, Figure 15b), attributed to the primary weld being slightly off the mid-point of the minibasin. Detached outward-vergent thrusts are located at the minibasin margins (Figure 15b).

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As noted by Amilibia et al. (2005), amongst others, inversion of normal faults in laboratory models using sand is quite limited, sometimes being seen at shallow fault tips but bypass or shortcut faults are far more common. Fault reactivation in nature can occur under stress levels lower than that required to initiate new faults (e.g. Sibson, 1995), due to preexisting faults having a lower cohesive strength and friction coefficient than that of intact rock (Anderson, 1951). The lack of significant reactivation in sandbox models can be explained by the relative lack of difference between the strengths of faulted and unfaulted sands, favoring the formation of new shortcut faults in more favorable orientations (see Amilibia et al., 2005, and Bonini et al., 2011, for more details). Significant reactivation of graben-bounding faults in our models (see Sections 33 and 106 in Figure 9; Figure 15b) are attributed to two factors. The first is the presence of the weak basal slabs that initially focused extension. Figure 15a shows remnant ‘horns’ of the polymer on either side of the graben, and during shortening these would help to focus initial shortening onto the graben system in the central part of the model, much like the way that precursor diapirs focus shortening in purely contractional experiments (e.g. Callot et al., 2007;

Dooley et al., 2009, 2015; Duffy et al., 2018). The second, and likely more important, reason is interstitial infiltration of polymer into a narrow zone of the brittle section forming a hybrid rheology along the pre-existing faults. This results in a slight change in color of the granular materials at the sand-silicone interface, which is just visible in Figure 15. Prior to inversion the base and sides of the graben were in contact with silicone, resulting in interstitial infiltration (Figure 15a). The upper portions of the graben-bounding faults were also in contact with silicone again allowing for interstitial infiltration (Figure 15a). During shortening this interstitial infiltration acted as a "lubricant" allowing reactivation and inversion of these faults (Figure 15b). This phenomena of interstitial infiltration has been observed in other laboratories that model salt tectonics with the same materials (O. Ferrer, *pers comm*, 2020), and is likely strongly dependent on the grain size of the strata adjacent to the salt analog. Faults in the granular materials used in physical models are generally dilatant which would enhance this infiltration phenomena.

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4.4 Comparison to Examples from the Moroccan High Atlas

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Saura et al. (2014) documented that inversion-related deformation in the central High Atlas of Morocco is mainly focused on minibasin margins with little internal deformation of these minibasins, with diapirs that originally separated these extensional minibasins soaking up much of the deformation, as is seen in our Model 1 (Figure 9). One such example is the Amezraï minibasin (Figure 16a; Saura et al., 2014; Moragas et al., 2017; see location on Figure 1). As in our Model 1, the Amezraï minibasin formed above a basement graben system and was flanked by complex diapirs located in the footwall of this graben system (Figure 16a-b). After inversion these flanks are the sites of significant upturn of flanking strata, thrusts welds and remnant pedestals, similar to structures found in Model 1 (Figure 16a-b). Similar geometries have just been described from the Maestrat Basin in Spain (Verges et al., 2020). The Azag minibasin lies further to the ENE along the central High Atlas (Figures 1 and 16c; Teixell et al., 2017). Again, this minibasin formed above a basement graben or half-graben system before being it was caught up in Alpine shortening resulting in the welding of adjacent diapirs (thrust or secondary welds; Figure 16c; Teixell et al., 2017), as seen in Model 1. The Azag minibasin also displays significant tilting in the E-W cross section of Figure 16c. Minibasins can tilt during subsidence either before or after welding (Rowan and Weimer, 1998; see Jackson et al., 2019, for more details), but the stratigraphic architecture of the Azag minibasin consists primarily of bowl- and tabular-shaped units indicating relatively symmetric subsidence during minibasin growth. Significant tilting of minibasins caused by shortening is seen in some locations in our Model 1 (Figure 16d), and thus, by analogy, the tilting and welding seen in the Azag minibasin is attributed to Alpine shortening and basement uplift.

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One notable difference between our model results (Figures 9 and 16b) and the example sections shown in Figure 16a, c is the amount of deformation seen in the basement or subsalt strata (Figures 9 and 16b). Basement geometries shown in Saura et al. (2014) and Teixell et al. (2017) are inferred due to lack of exposure. The geometry of the basement graben system beneath the Amezraï minibasin shown in Saura et al. (2014) was actually modified by Moragas et al. (2017) based on the results of their physical modeling study. In these natural examples the basement is shown as flat-topped as sub-salt shortening was taken up by simple fault reactivation and vertical uplift of hangingwall blocks (Figure 16a, c). If our physical models are indicative of the deformation intensity one would expect to see in the subsalt basement, then these more pervasive damage zones could have significant implications for fluid flow and for structural topography at the base of salt. However, our model basement consisted of essentially cohesionless materials, and likely does not accurately represent the strength of basement rocks in the High Atlas or crystalline basement in general. An alternative explanation is that the amount of shortening in Model 1 was simply far more than that experienced in the Central High Atlas. More work is required on this topic. Another topic that requires more study is the geometry of the salt isopach across a basin. In our Model 1 the decoupling between basement and suprasalt strata during both extension and inversion was enhanced by the presence of a salt fringe that covered our entire rift basin. In nature this is unlikely to be the case and many natural examples of syn-rift-salt-bearing basins illustrate the absence of salt across intra-basin horst blocks (e.g. the Scotian margin, Kendell, 2012), or where the salt has variable depositional thickness and influences the degree of coupling between basement and suprasalt strata (e.g. Coleman et al., 2017). The degree of coupling between basement and suprasalt cover is not only dependent on thickness variations of the evaporite sequence but also the composition, or mobility, of the evaporites (e.g. Jackson et al., 2019).

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5. Concluding Remarks

Our physical models successfully generated segmented rift systems in a deformable basement that were subsequently infilled with a salt analog and subjected to further extension and finally inversion. During extension and subsequent downbuilding diapir and ridge networks formed that exerted a strong control on deformation styles and patterns during subsequent inversion. Diapir networks formed primarily in the footwalls of the basement fault system, similar to that described by Dooley et al. (2005) and Moragas et al. (2017). Diapiric growth was encouraged by salt expulsion from beneath the subsiding extensional minibasin systems that formed above the original basement graben, with major diapirs forming consistently in the locations of major relay systems or interlocking transfer zones that originally separated the en-échelon basement graben. These more gently dipping structures facilitated more efficient salt expulsion driving diapiric growth at these locations. Extensional deformation in suprasalt strata was strongly decoupled.

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Inversion of these salt-bearing rifts produced strongly decoupled shortening belts in basement and suprasalt sequences. In the suprasalt section deformation geometries and locations were primarily controlled by the salt diapir network produced doing extension and subsequent downbuilding with thrusts formed minibasin margins where the overburden was thinnest and weakest. Extensional minibasins display little or no internal deformation as deformation was soaked up by diapirs and by these marginal thrusts, in a similar fashion to observations from the Central High Atlas of Morocco and other inverted basins. Complex structures form where salt-cored box folds weld shut by hinge and limb failure. In the subsalt section the structural style is very different consisting of strongly inverted and pervasively deformed graben systems along with the formation of new popup structures. Inversion of these graben uplifted and welded the composite extensional minibasin system forming an almost flat-topped plateau across the center of the model. Significant reactivation of graben-bounding faults during inversion was aided by interstitial infiltration of our salt analog that helped “lubricate” the precursor faults.

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6. Acknowledgements

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7. References

Adam, J., Urai, J., Wieneke, B., Oncken, O., Pfeiffer, K., and Kukowski, N.: 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(2), 283–301. http://doi.org/10.1016/j.jsg.2004.08.008, 2005.

Amilibia, A., McClay, K. R., Sabat, F., Muñoz, J. A., and Roca, E.: Analogue modelling of inverted oblique rift systems. Geologica Acta, 3(3), 251–271, 2005.

Anderson, E.M.: The dynamics of faulting and dyke for- mation with applications to Britain. Olivier and Boyd (eds.). Edinburgh, 203pp., 1951.

Bonini, M., Sani, F., and Antonielli, B.: Basin inversion and contractional reactivation of inherited normal faults: A review based on previous and new experimental models. Tectonophysics, 522-523(C), 55–88. http://doi.org/10.1016/j.tecto.2011.11.014, 2011.

Deleted: 2012

Brun, J., Sokoutis, D. and Van Den Driessche, J.: Analogue modelling of detachment fault systems and core complexes. Geology, 22, 319 – 322, 1994.

Buchanan, J.G., and Buchanan, P.G. (Eds.).: Basin Inversion, Geological Society Special Publication, 88. 596 pp, 1995.

Buchanan, P.G., and McClay, K.R.: Sandbox experiments of inverted listric and planar fault systems. In: Cobbold, P.R. (Ed.), Experimental and Numerical Modelling of Continental Deformation: Tectonophysics, 188, pp. 97–115, 1991.

Callot, J. P., Jahani, S., and Letouzey, J.: The role of pre-existing diapirs in fold and thrust belt development. Thrust Belts and Foreland Basins, 309–325, 2007.

Callot, J. P., Trocme, V., Letouzey, J., Albouy, E., Jahani, S., and Sherkati, S.: Pre-existing salt structures and the folding of the Zagros Mountains. Geological Society London Special Publications, 363(1), 545–561. http://doi.org/10.1144/SP363.27, 2012.

Coleman, A. J., Jackson, C. A. L., & Duffy, O. B.: Balancing sub- and supra-salt strain in salt-influenced rifts: Implications for extension estimates. Journal of Structural Geology, 102, 208–225. http://doi.org/10.1016/j.jsg.2017.08.006, 2017.

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Couzens-Schultz, B. A., Vendeville, B. C., and Wiltschko, D. V.: Duplex style and triangle zone formation: insights from physical modeling. Journal of Structural Geology, 25(10), 1623–1644. http://doi.org/10.1016/S0191-8141(03)00004-X, 2003.

Formatted: Font: Not Italic

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Davison, I., Alsop, I., Birch, P., Elders, C., and Evans, N.: Geometry and late-stage structural evolution of Central Graben salt diapirs, North Sea. Marine and Petroleum Geology, 17, 499-522, 2000.

Dooley, T., McClay, K., Hempton, M., and Smit, D. (2005). Salt tectonics above complex basement extensional fault systems: results from analogue modelling. In: Doré , A. G. & Vining, B. A. (eds) Petroleum Geology: North-West Europe and Global Perspectives—Proceedings of the 6th Petroleum Geology Conference, Geological Society, London, Petroleum Geology Conference Series, 6, 1631-1648, 2005.

Dooley, T. P., Jackson, M. P. A., and Hudec, M. R.: Initiation and growth of salt-based thrust belts on passive margins: results from physical models. Basin Research, 19(1), 165–177. http://doi.org/10.1111/j.1365-2117.2007.00317.x, 2007.

Dooley, T. P., Jackson, M. P. A., and Hudec, M. R.: Inflation and deflation of deeply buried salt stocks during lateral shortening. Journal of Structural Geology, 31(6), 582–600. http://doi.org/10.1016/j.jsg.2009.03.013, 2009.

Dooley, T. P., and Schreurs, G.: Analogue modelling of intraplate strike-slip tectonics: A review and new experimental results. Tectonophysics, 574-575, 1–71, 2012.

Dooley, T. P., Jackson, M. P. A., and Hudec, M. R.: Breakout of squeezed stocks: dispersal of roof fragments, source of extrusive salt and interaction with regional thrust faults. Basin Research, 27(1), 3–25. http://doi.org/10.1111/bre.12056, 2015.

Duffy, O. B., Dooley, T. P., Hudec, M. R., Jackson, M. P. A., Fernandez, N., Jackson, C. A.-L., and Soto, J. I.: Structural evolution of salt-influenced fold-and-thrust belts_ A synthesis and new insights from basins containing isolated salt diapirs. Journal of Structural Geology, 114, 206–221. http://doi.org/10.1016/j.jsg.2018.06.024, 2018.

Domènech, M., Teixell, A., & Stockli, D. F.: Magnitude of rift-related burial and orogenic contraction in the Marrakech High Atlas revealed by zircon (U-Th)/He thermochronology and thermal modeling. Tectonics, 35(11), 2609–2635. http://doi.org/10.1002/2016TC004283, 2016.

Formatted: Font: Not Italic

Formatted: Font: Not Italic

Durcanin, M. A.: Influence of synrift salt on rift-basin development: Application to the Orpheus Basin, off- shore Canada: M.S. thesis, The State University of New Jersey, 2009.

Ferrer, O., Roca, E., Vendeville, B. C.: The role of salt layers in the hangingwall deformation of kinked-planar extensional faults: Insights from 3D analogue models and comparison with the Parentis Basin. Tectonophysics, 636, 338-350, 2014.

Ferrer, O., McClay, K.R., and Sellier, N. C.: Influence of fault geometries and mechanical anisotropies on the growth and inversion of hangingwall synclinal basins: Insights from sandbox models and natural examples, in C. Child, R. E. Holdsworth, C. A. L. Jackson, T. Manzocchi, J. J. Walsh, and G. Yieldings, eds., The geometry and growth of normal faults: Geological Society of London, Special Publications, 439, doi: 10.1144/ SP439.8., 2016.

Graveleau, F., Malavieille, J., and Dominguez, S.: Experimental modelling of orogenic wedges: A review. Tectonophysics, 538-540(C), 1–66. http://doi.org/10.1016/j.tecto.2012.01.027 , 2012.

Jackson, C. A.-L., & Stewart, S. A.: Composition, Tectonics, and Hydrocarbon Significance of Zechstein Supergroup Salt on the United Kingdom and Norwegian Continental Shelves: A Review. Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins: Tectonics and Hydrocarbon Potential (pp. 175–201). Elsevier Inc. http://doi.org/10.1016/B978-0-12-809417-4.00009-4, 2017.

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Jackson, C. A. L., Duffy, O. B., Fernandez, N., Dooley, T. P., Hudec, M. R., Jackson, M. P. A., and Burg, G.: The stratigraphic record of minibasin subsidence, Precaspian Basin, Kazakhstan. Basin Research, 61(1), 570–25. http://doi.org/10.1111/bre.12393, 2019.

Jackson, C. A. L., Elliott, G. M., Royce Rogers, E., Gawthorpe, R. L., & Aas, T. E. (2019). Salt thickness and composition influence rift structural style, northern North Sea, offshore Norway. Basin Research, 31(3), 514–538. http://doi.org/10.1111/bre.12332, 2019.

Kendell, K. L.: Variations in salt expulsion style within the Sable Canopy Complex, central Scotian margin 1This article is one of a series of papers published in this CJES Special Issue on the theme of Mesozoic–Cenozoic geology of the Scotian Basin. *Canadian Journal of Earth Sciences*, *49*(12), 1504–1522. http://doi.org/10.1139/e2012-069, 2012.

Krantz, R.: Measurements of friction coefficients and cohesion for faulting and fault reactivation in laboratory models using sand and sand mixtures. Tectonophysics, 188, 203-207, 1991.

Krzywiec, P., Mesozoic and Cenozoic evolution of salt structures within the Polish Basin — An overview, Geological Society, London, Special Publications, 363, 381–394, doi: 10.1144/SP363.17, 2012.

Le Calvez, J. H., and Vendeville, B. C.: Experimental designs to model along-strike fault interaction. Journal of the Virtual Explorer, 7, 1–19, 2002.

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Marques, F., Cobbold, P., and Lourenço, N.: Physical models of rifting and transform faulting, due to ridge push in a wedge-shaped oceanic lithosphere. Tectonophysics, 443, 37–52, 2007.

Martin-Martin, J. D., Vergés, J., Saura, E., Moragas, M., Messager, G., and Baqués, V.: Diapiric growth within an Early Jurassic rift basin: The Tazoult salt wall (central High Atlas, Morocco), 36(1), 2–32. http://doi.org/10.1002/2016TC004300, 2016.

Michard, A., Ibouh, H., and Charriere, A.: Syncline-topped anticlinal ridges from the high Atlas: a Moroccan conundrum, and inspiring structures from the Syrian arc, Israel. Terra Nova 23, 314-323, 2011.

McClay, K. R.: Extensional fault systems in sedimentary basins. A review of analogue model studies. Marine and Petroleum Geology, 7, 206–233, 1990.

McClay, K. R., Dooley, T., Whitehouse, P., and Mills, M.: 4-D evolution of rift systems: Insights from scaled physical models. AAPG Bulletin, 86(6), 935–960, 2002.

Moragas, M., Vergés, J., Nalpas, T., Saura, E., Martín-Martín, J.-D., Messager, G., and Hunt, D. W.: The impact of syn- and post-extension prograding sedimentation on the development of salt-related rift basins and their inversion: Clues from analogue modelling. Marine and Petroleum Geology, 88, 985–1003. http://doi.org/10.1016/j.marpetgeo.2017.10.001, 2017.

Deleted: 7

Reber, J. E., Cooke, M. L., and Dooley, T. P.: What model material to use? A Review on rock analogs for structural geology and tectonics. Earth-Science Reviews, 202, 103107. http://doi.org/10.1016/j.earscirev.2020.103107, 2020.

Roma, M., Vidal-Royo, O., McClay, K., Ferrer, O., and Muñoz, J.-A.: Tectonic inversion of salt-detached ramp-syncline basins as illustrated by analog modeling and kinematic restoration. Interpretation, 6(1), T127–T144. http://doi.org/10.1190/INT-2017-0073.1, 2017.

Roma, M., Ferrer, O., Roca, E., Pla, O., Escosa, F. O., and Butillé, M.: Formation and inversion of salt-detached ramp-syncline basins. Results from analog modeling and application to the Columbrets Basin (Western Mediterranean). Tectonophysics, 745, 214–228. http://doi.org/10.1016/j.tecto.2018.08.012, 2018a.

Roma, M., Ferrer, O., McClay, K. R., Munoz, J. A., Roca, E., Graticos, O., and Cabello, P.: Weld kinematics of syn-rift salt during basement-involved extension and subsequent inversion: Results from analog models. Geologica Acta, 16(4), 391–410. http://doi.org/10.1344/GeologicaActa2018.16.4.4, 2018b.

Rossi, D., and Storti, F.: New artificial granular materials for analogue laboratory experiments: aluminium and siliceous microspheres. Journal of Structural Geology, 25, 1893–1899, 2003.

Rowan, M., and Weimer, P.: Salt-sediment interaction, northern Green Canyon and Ewing Bank (offshore Louisiana), northern Gulf of Mexico. AAPG Bulletin, 82(5), 1055–1082, 1998.

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Deleted: ¶

Rowan, M. G. and Krzywiec, P.: The Szamotuły salt diapir and Mid-Polish Trough: Decoupling during both Triassic-Jurassic rifting and Alpine inversion. Interpretation, 2(4), SM1–SM18. http://doi.org/10.1190/INT-2014-0028.1, 2014.

Saura, E., Vergés, J., Martin-Martin, J. D., Messager, G., Moragas, M., and Razin, P.: Syn- to post-rift diapirism and minibasins of the Central High Atlas (Morocco): the changing face of a mountain belt. Journal of the Geological Society, 171(1), 97–105. http://doi.org/10.1144/jgs2013-079, 2014.

Schellart, W. P. (2000). Shear test results for cohesion and friction coefficients for different granular materials: scaling implications for their usage in analogue modelling. Tectonophysics, 324, 1–16, 2000.

Sibson, R.H.: Selective fault reactivation during basin inversion: potential for fluid redistribution through fault-valve action. In: Buchanan, J.G., Buchanan, P.G. (Eds.), Basin inversion, Geological Society of London Special Publication 88, pp. 3–19. 1995.

Stewart, S.: Salt tectonics in the North Sea Basin: a structural style template for seismic interpreters. In: Ries, A. C., Butler, R. W. H. & Graham, R. H. (eds). Deformation of the ContinentalCrust: The Legacy of Mike Coward. Geological Society, London, Special Publications, 272, 361-396, 2007.

Stewart, S., and Coward, M.: Synthesis of salt tectonics in the southern North Sea, UK. Marine and Petroleum Geology, 12, 457-475, 1995.

Teixell, A., Arboleya, M., Julivert, M., and Charroud, M.: Tectonic shortening and topography in the central High Atlas (Morocco). Tectonics, 22(5), 1051, http://doi.org/10.1029/2002TC001460, 2003.

Teixell, A., Barnolas, A., Rosales, I., and Arboleya, M.-L.: Structural and facies architecture of a diapir-related carbonate minibasin (lower and middle Jurassic, High Atlas, Morocco). Marine and Petroleum Geology, 81, 334–360. http://doi.org/10.1016/j.marpetgeo.2017.01.003, 2017.

Verges, J., Moragas, M., Martín-Martín, J.D., Saura, E., Razin, P., Grelaud, C., Malaval, M., Joussiaume, R., Messager, G., Sharp, I., and Hunt, D.W.: Salt tectonics in the Atlas mountains of Morocco. In: Soto, J.I., Tari, G., Flinch, J. (Eds.), Permo-triassic Salt Provinces of Europe, North Africa and the Atlantic Margins. Tectonics and hydrocarbon potential. 563-576, Elsevier, 2017.

Vergés, J., Poprawski, Y., Almar, Y., Drzewiecki, P. A., Moragas, M., Bover-Arnal, T., Macchiavelli, C., Wright, W., Messager, G., Embry, J-C. and Hunt, D.: Tectono-Sedimentary Evolution of Jurassic-Cretaceous diapiric structures: Miravete anticline, Maestrat Basin, Spain. *Basin Research*, 1–55. http://doi.org/10.1111/bre.12447, 2020.

Weijermars, R.: Polydimethylsiloxane flow defined for experiments in fluid dynamics. Applied Physics Letters, 48(2), 109–111. http://doi.org/10.1063/1.97008, 1986.

Deleted:

Weijermars, R., Jackson, M. P. A., and Vendeville, B. C.: Rheological and tectonic modeling of salt provinces. Tectonophysics, 217, 143–174, 1993.

Withjack, M., and Callaway, S.: Active Normal Faulting Beneath a Salt Layer: An Experimental Study of Deformation Patterns in the Cover Sequence. AAPG Bulletin, 84, 627-651, 2000.

Ziegler, P.A. (Ed.).: Compressional intra-plate deformations in the Alpine Foreland: Tectonophysics, 137. 420 pp, 1987.

Zwaan, F., Schreurs, G, Naliboff, J., and S. J. H. Buiter, S. J. H.: Insights into the effects of oblique extension on continental rift interaction from 3D analogue and numerical models: Tectonophysics, 693 Part B, 239–260, doi: 10 .1016/j.tecto.2016.02.036, 2016.

Zwaan, F., and Schreurs, G. (2017). How oblique extension and structural inheritance influence rift segment interaction: Insights from 4D analog models. Interpretation, 5(1), SD119–SD138. http://doi.org/10.1190/INT-2016-0063.1, 2017.

Figure Captions

Figure 1. Summary geological map of the central High Atlas of Morocco. Jurassic intrusive massifs containing upper Triassic shale, basalt and evaporite inliers have been interpreted as former diapiric ridge that separated extensional minibasins formed during Permian to Early Jurassic punctuated rifting. AmMB, Amezraï minibasin. AzMB, Azag minibasin. Map redrawn and modified from Teixell et al., 2017.

Figure 2. Summary of experimental setup used in models shown in this study. (a) Cross section view of the pre-rift setup. Models consist of a stretching rubber sheet overlain by a thin basal detachment and polymer 'slabs' covered by a layered sandpack. (b) Overhead view of deformation rig prior to emplacement of the layered pre-rift overburden. See text for further details.

Figure 3. (a) Height-change map of Model 1 after pre-salt extension. Three en-échelon graben in model center are separated by accommodation zones with relays. Marginal graben formed at the model periphery. (b) Strain map of Model 1 during pre-salt extension. Accommodation zones consist of interlocking extensional faults. Note that some relays are breached. See text for further details.

Figure 4. Emplacement of syn-rift salt in Model 1. (a) Pre-salt graben are infilled with our salt analog. Colored silicone was emplaced in the central graben system in order to track flow in the final cross-section views. (b) A regional salt fringe is then emplaced across the entire model.

Figure 5. (a) Height-change map during post-salt extension in Model 1. Post-salt extension was now 4 cm. Note the composite minibasin extending across the model center, above the original graben system. (b) Strain map of the same increment of post-salt extension. Note the diffuse strains in the suprasalt cover. Most extensional strains mark outer-arc extension above reactive diapirs. Note the minor shortening strains within the minibasin due to inner-arc contraction within the subsiding minibasin.

Figure 6. Height-change maps of Model 1 after 16 (a) and 48 (b) hours of post-extension loading. In (a) we see the major diapir networks, formed during extension, continuing to rise as salt is expelled from beneath adjacent minibasins. After 48h loading (b) activity is now focused on two major diapirs. See main text for more details.

Figure 7. Height-change maps (a-d) reveal the evolution of Model 1 during inversion. Initial shortening and uplift was focused on the diapirs formed during extension and loading (a), followed by uplift of the composite minibasin above the model center and rejuvenation of the diapir and ridge networks (b-d).

Figure 8. Overhead view of Model 1 after 25 cm shortening. Diapirs 1 and 2 are clearly visible in this view as emergent salt sheets. Section lines are those shown in Figure 9. See text for further details.

Figure 9. Representative sections through Model 1. Locations are shown on Figure 8. Inset shows the model stratigraphy.

Figure 10. Details from Model 2 (see Table 1). (a) Height-change map that evolved during Stage 1 of Model 2. (b) Height-change map of Model 2 during post-salt extension. (c) Height-change map of Model 2 during post-extension loading. (d) Cross section from Model 2 illustrating extensional minibasins and diapirs of varying heights formed in the footwalls of the subsalt graben. See text for further details.

Figure 11. Details of Model 3. (a-b) Depth slices through Model 3. (c-e) Arbitrary lines through a portion of Model 3. (f) Original location of yellow marker 'salt' in the central graben of Model 3. See text for further details.

Figure 12. 3D reconstruction of the salt volume from Model 1. See main text for details.

Figure 13. (a) Height-change map from Stage 3 of Model 1 illustrating the diapir and ridge networks that formed during extension rising during post-extension loading. (b-c) Depth slice and dip section through Model 1 illustrating the five (a-e) main diapir networks.

Figure 14. Detailed views (a-c) of sections through Model 1 illustrating the evolution of an "S" structure.

Figure 15. (a) Detailed view of a non-inverted subsalt graben from Model 2. Note the asymmetric geometry and the formation of a keystone structure. (b) Detailed view of an inverted subsalt graben from Model 1. Inversion of this graben uplifted and welded the overlying extensional minibasin.

Figure 16. (a) Cross section through the Amezraï minibasin, Moroccan High Atlas. Note the uptilted minibasin margins, lack of internal deformation within the minibasin and the complex flanking diapirs and thrust welds. Redrawn from Moragas et al. (2017). (b) Detailed views of minibasin margins and associated secondary thrust welds from Model 1. (c) E-W cross section through the Azag minibasin. Note the thrust welds and tilted nature of the minibasin. Redrawn from Teixell et al. (2017). (d) Detail of a section from Model 1 illustrating a tilted minibasin, primary weld on top of an inverted subsalt graben, and secondary thrust welds on either side of the minibasin.

Table 1. Model names and values for extension and inversion for experiments described in the main text. *denotes basal detachment was limited to the central region of the model.