Reviewer #1

Dear Jörg Lang,

We are grateful for your thorough and constructive comments. We appreciate your suggestions a lot. Thank you for helping us to improve our work.

Please find our replies to all your comments in the tables below.

Kind regards,

Jacob Hardt et al.

General comments

Reviewer	**Authors' response**
Define goals / research questions need to be better defined. At the beginning, several questions are posed and the authors get back to those questions in the discussion. However, there is a mismatch between the questions posed at the beginning and those answered in the discussion and there are actually two separate sets of questions. My suggestion is to better define the main questions and placing the "secondary" questions within short explanations provided with each main question.	Thank you for detecting the mismatch between the questions in the intro and in the discussion! We have corrected that. Also, we followed your idea to merge the different sets of questions as follows: *"1. What happens if salt structures are only partly covered by the ice and which role does the type of salt structure play?* *This requires an investigation of different shapes and sizes of the salt structures during loading- and unloading processes.* *2. What influence do the geometries of both ice margin and subsurface salt structure have on salt flow patterns?* *This requires us to investigate loading- and unloading-induced intrasalt flow patterns.* *3. Can these results help us to understand spatial patterns of present-day geomorphological features, such as surface cracks, above salt structures in northern Germany?"*
The issue of young salt tectonic activity in the study area should be explained in more detail. A challenge when studying ice-load induced salt movements is how to distinguish them from other (longer-term) movements.	Thank you! We rewrote the study area section significantly and also point to some of the sites where young salt activity was mentioned in the literature (Sperenberg, Rambow, Rüdersdorf). We also added this remark: *"In general, it is challenging to differentiate ice-sheet induced salt tectonic movements from other (longer-term) tectonic movements, as the salt structures are usually coupled to tectonic lineaments (see discussion in Hardt et al., 2021). Therefore, approaches that take into account both the geomorphology and the deeper subsurface are necessary."*
The description of the study area should provide a bit more information	We provided a bit more context on the evolution of salt structures in the study area.

on the phases of salt tectonic activity. Have those salt structures been rising during the latest Cenozoic prior to the Pleistocene glaciations? Does it matter?	There is some sparse information that few salt structures in the study area were reactivated due to GIA, which is now also mentioned in the text (Rüdersdorf, Sperenberg, Rambow; Ludwig & Stackebrandt 2010). However, these are not the structures that we modelled in this study. In general, I think this is an interesting aspect that we should keep in mind for future investigations. At this point, we can't say, if it matters whether structures were active during the latest Cenozoic in the study area, or not.
Ice-sheet load in the models is not dynamically scaled (e. g., Lines 130 / 185ff). I am aware that scaling is a huge challenge for any physical model. However, the displacements in the models are very high in relation to the total thickness of the model section (>10 mm vertical displacement vs 35 mm thick model section). Salt extrusion observed in one run seems another example of extreme deformation. However, if the models are to be compared to natural examples and numerical models (the numerical models may of course have over shortfalls), somewhat more context should be provided and the limitations should be pointed out more clearly. Maybe a comparison to other physical models of salt tectonics helps to provide more context. I think the discussion would benefit from some more consideration here.	To increase the transparency on the issue of scaling, we have added a new section to the discussion titled "remarks on the scaling of our models". We acknowledge that the displacements are high with respect to the natural prototypes. We hope that the limitations of our models and our main intentions of studying three-dimensional processes rather than absolute rates are being more clearly communicated in the revised version of the MS.

Detailed comments

Reviewer	**Authors' response**
Line 11: Throughout the manuscript, you are switching between "glacial loading" and "ice-sheet loading / ice loading". Please check and decide for one term – I think "ice-sheet loading" is the most appropriate and widely used term	Thanks, we now consistently use the term "ice-sheet loading".
Line 12: This sentence is a bit misleading and should be split up and modified. The presented model is not only based on the Scandinavian ice sheet, but on the overall geological situation (salt structures, ice margins, etc.) in northern Germany.	Agreed, we have modified the sentence according to your suggestion: *"We investigate the influence of ice-sheet loading and unloading on subsurface salt structures using physical models, based on the geological setting of northern Germany, which*

	was repeatedly glaciated by the Scandinavian Ice Sheet during the Pleistocene."
Line 18: "salt-source layer" is the more common term.	OK – changed.
Line 28: Throughout the manuscript, you are switching between "salt structure", "salt dome" and "salt diapir". Please check for consistency and if the terms are used according to their definitions.	The different terms were chosen intentionally to differentiate between the different salt structure types (domes and pillows) that we modeled. We double checked the manuscript for consistency and included a definition for both terms, in agreement with a comment from Reviewer 2.
Line 35: The surface cracks are only one feature your models can help explain. I recommend making a broader statement here.	Thank you, we expanded it: *"Our results lead to a better understanding of spatial patterns of the surface cracks that were mapped at the surface above salt structures and offer further room for interpretation of the influence of salt movements on the present-day landscape."*
Line 48: You should explicitly state here that future glaciations are considered a real issue for such long-term safety considerations.	Thank you, we added the aspect of future glaciations. *"With regard to radioactive wastes, the long-term stability needs to be predicted for up to 1 Ma, and future glaciations are a factor that has to be considered in this case (BGE, 2020; Fischer et al., 2015)."*
Lines 50-51: Please rephrase or extent to explain the impact.	Thank you, we have sharpened the wording: *"These salt tectonic processes can be triggered by large scale tectonic movements and changing sedimentary loads, which might be a result of changing climatic conditions including glaciations."*
Line 52ff: As glacio-isostatic adjustment and it's effects are important processes in the context of the study, this should be explained a bit better. Also, what are "hydrogeological adaptations"? Please elaborate.	OK, we have rephrased the passage and gave some more context. It now reads: *"The load of the large Pleistocene ice-sheets pushed down the Earth's crust. In reaction to the unloading (i.e., melting of the ice-sheets), glacial isostatic adjustment (Lambeck et al., 2014) and processes such as postglacial rebound (Spada, 2017) set in and are still ongoing. As an example of postglacial rebound, Fennoscandia is still moving upwards, whereas regions to the south of the Baltic Sea (such as the study area) are moving downwards (Bungum & Eldholm, 2022). In addition, the ice-sheet advances modified subsurface hydro-thermal systems, which are still in the process of adapting to present-day conditions (Amberg et al., 2022; Frick et al., 2022)."*

Lines 57-59: This is misleading and oversimplifying: The link between neotectonics and ice loading is not just based on the parallel orientation. This would be a very weak link…	Thank you! This misleading sentence was also mentioned by Reviewer #3. I rewrote it accordingly. It now simply reads: *"In northern Central Europe, postglacial seismic activity has been identified at several preexisting faults (Brandes et al., 2015; Müller et al., 2021)."*
Line 61: "the spatial distribution of" can be deleted.	OK – deleted it.
Lines 62 / 70: Again, there is a switch in terminology: Please use either "Zechstein salt" or "Permian salt". Permian may be more correct, as some salt structures in northern Germany may also include some Rotliegend salt. However, for your study area, Zechstein seems appropriate.	OK – we now consistently use "Zechstein salt".
Line 85ff: As those questions are central to the study, maybe use bullet points or number here to make them more striking. Also, there are only 3 questions here, while the discussion tries to answer 4 questions. It is a bit confusing that 3 questions are presented here and 4 similar, but slightly different questions in the next section. Maybe restructure this section, presenting higher-order questions (I think this is the second set) first, each question followed by a short explanation that may include the lower-order, more detailed questions (don't forget to modify the questions in the discussion accordingly!) Furthermore, all those questions (especially the first set of questions) should be put into a wider context, as your study is not just about checking some specific model configurations, but is a new approach to an understudied topic.	This goes together with your first general comment. As outlined before, we are now using a list to highlight the questions. Also, we have merged the two sets of questions (which we think works fine) and added some more context.
Line 94-96: This sentence should be placed at the beginning of the next section.	We thought this sentence would be a nice transition into the next chapter – but we're absolutely fine with its new place at the beginning of the next section.
Line 102: Maybe rephrase to "…varies in thickness between…", as the thickness is the important part here.	Thank you, we changed it to: *"The Mesozoic and Cenozoic overburden on the Zechstein salt varies in thickness in the region between more than 3000 m above deep-seated pillows, to only few hundred m above the highest salt domes (Stackebrandt and Beer, 2015) – some domes in northern Germany even pierce to the land surface (Künze et al., 2013; Sirocko et al., 2002; Stackebrandt, 2005)."*

Line 105: This is a huge leap from the very general features of the salt structures to the very specific surface cracks. I wonder if the surface expressions of salt structures and their association with younger morphological features should be explained in more detail.	This whole section (study area) was significantly rewritten and expanded. We also rearranged this passage to make the shift from the general features to the local landforms more straightforward. We wouldn't want to go into more detail on other morphological features here, as we want to keep the focus of the MS on the experiments and their discussion.
Line 110: I think we don't need a long description of the regional Quaternary geology here, but at least the term "W2" should be explained – please add just one sentence introducing the Weichselian ice advances into the area.	Agreed, we added two sentences on the Weichselian ice advances to the first paragraph of this chapter: *"During the Weichselian, the study area was transgressed by the W1 advance, which occurred in late Maritime Isotope Stage 3. The Weichselian W2 advance occurred in Maritime Isotope Stage 2 and corresponds to the Last Glacial Maximum. The W2 advance reached only into the northern parts of the study area (Fig. 1; Lüthgens et al., 2020)."*
Line 155: Fault or strain pattern?	"Fault" is intended. When looking at the slabs, we were mainly interested in the faults.
Line 156ff: The first part of this section provides a lot of background information on the regional geology. I wonder if this should be better placed in the "Study area" – section, while the model set-up should focus on the model	We fully understand your concern. We've decided to keep the "study area" section more general and to provide the geological details that influenced how we precisely designed the models in the "model design" section. We think this way the paper is a bit more accessible to readers who are not so much into the study area but are more interested in the model design and the results, as they don't get lost by jumping back and forth between the chapters. We would therefore advocate leaving the structure as it is.
Line 177: Please add: Was the model surface flattened? Were the sand layers compacted before loading?	Yes, the surface was flattened and no, the sand layers were not compacted before loading. Both statements were added to the respective section: *"All subsequent layers of sand were added across the entire model without compacting them, just cresting our rising pillows and diapirs. In this way the model surface was flattened after each load was applied."*
Line 121: "ice-sheet load" seems more appropriate (see earlier comment).	OK.
Line 256: "Between W2 and W2"? Please check! May be rephrase to avoid the regional terminology.	This was indeed misleading. We clarified this passage:

	"In model run 4, we used an even more undulating load margin as in run 3 for the first 24 h and then removed part of that load for the next 24 h, which is located between the W2 main ice marginal position and several recessional ice marginal positions (see Fig. 5 for illustration)."
Line 280: Why place the cross sections in the supplement only? I recommend adding them as a regular figure.	We discussed this a lot and initially decided to move them to the supplement, as the results are mainly based on the strain and Z maps and as there are a lot of figures already. However, we are happy to follow your recommendation and brought the cross sections back into the main text (new Fig. 8), adding explanations to the respective results sections.
Line 281: Discussion: Please see my earlier comments on the questions. If you decide to modify the questions / goals, some reorganization may be necessary here. However, I don't see any issues with the overall structuring of the discussion with the questions as section headings.	Thank you, we took care of that with respect to your other comments!
Line 288, 300: Is "connectivity" the appropriate term here? Please consider rephrasing.	Thank you! We believe that this is the appropriate term for the process we aim to describe.
Lines 290-291: The last sentence of the section starts the interesting part of the discussion. Please elaborate further.	We have merged this section with the next one and do elaborate on this point in the section "Can these models help us…", which we have also slightly expanded.
Line 293: My impression is that the focus of this section is rather the position of the (ice) load margin relative to the salt structure than the type / size of the salt structure. Please also check with the next section. Maybe the section should better be combined.	Thank you. We have merged this section with the previous one and believe it reads better now.
Lines 294-295: Please define "larger" and "smaller". Does this refer to the area, volume of salt or else?	Here we refer to the size of the structures in plan view. We made this clearer in the text: *"When comparing our different modeled structures in plan view, it is apparent that the bigger structures (in this case the pillows) showed significantly stronger reactions to the loading and unloading cycles than the smaller structures (in this case the domes), irrespective of roof thickness and strength."*
Lines 305-307: The resistance to salt flow caused by thinning salt layers is a well known phenomenon in salt tectonics. Some references seem appropriate here.	We slightly changed the wording and included appropriate references (Hudec and Jackson, 2007; Wagner & Jackson, 2011) *"Consequently, the NB domes were placed at a distance from the load margin in our models. These structures lacked connectivity as they*

	were not part of a salt corridor at depth and were only fed via the thinned source layer, which was additionally confined by the rim synclines adjacent to the diapirs, which increase the resistance of salt to flow (Hudec & Jackson, 2007; Wagner & Jackson, 2011).”
Line 349: This is not exactly what we wrote. Our point was rather that a relatively small obstacle may initiate the formation of glacitectonic thrusts. Furthermore, I am still skeptical about rising salt structures acting as (significant) obstacles to ice flow, as the ice sheets did transgress other, even higher topographic obstacles, e.g. some low mountain ranges near the maximum extends of the Middle Pleistocene ice sheets in northern Germany.	We regret the little misunderstanding and corrected the passage accordingly: *“Lang et al. (2014) concluded that salt rise alone would not be sufficient to create obstacles large enough to stop an inland ice sheet, but suggested that rising salt structures in the foreland of an advancing ice-sheet may favor the formation of glacitectonic thrusts.”* To your second point: we can only say that this definitely needs more research. It is true that ice sheets are capable of transgressing high obstacles. But as you also mentioned in your 2014 paper, there are some (few) examples of obstacles acting like a nunatak (e.g., Sperenberg dome). I can imagine that at the edge of the ablation zone the topographic highs don’t have to be too large to form an obstacle to the ice sheet - but this requires more dedicated investigations.
Line 361: I find your observation of the intense deformation in salt structures that are partly loaded very interesting. The reason we placed the ice-margin 1000 m away from the salt structure in the numerical models was exactly the strong deformation occurring if the ice margin was located exactly on top of the salt structure. This strong and rapid deformation commonly triggered the numerical models to crash. We never really addressed this issue in our papers. I fully agree that such a configuration should result in larger displacements.	Thank you, we appreciate your very interesting comment concerning your own model results. It is good to know that your models seemed to go in a similar direction when the structures were partly loaded! This is a promising aspect for future research!
Figure 5: in the central part of the figure, it looks like the orientation of the load is different in the cross section and in the map view. The map shows a left-right (west-east?) trending margin of the load. I would understand the cross-section to show a top-bottom (north-south) trending margin. Please clarify.	Thank you for pointing this out! You are right, the depiction of the weight and the metal plate in the second line in the center of the figure (“side view”) is misleading. This was mistakenly adopted from an earlier version of this figure, where the map views were rotated 90 degrees to the left. I removed the depiction of the weight from the side view as we believe, this little extra detail is not necessary for the comprehension. (see below)
Figures 6, 8, 9 and 11: I suggest naming the stages above each panel, so the reader does not	Done! We added the terms “loading” or “unloading” above each panel.

have to look up what “stage 2” actually represents.	
Supplement: I wonder why the supplement (one figure showing cross sections from the model) is not included as a regular figure? You don’t show any cross sections, so this might be a nice addition.	Solved with similar comment above. Sections are now a regular figure.

Revised Figures

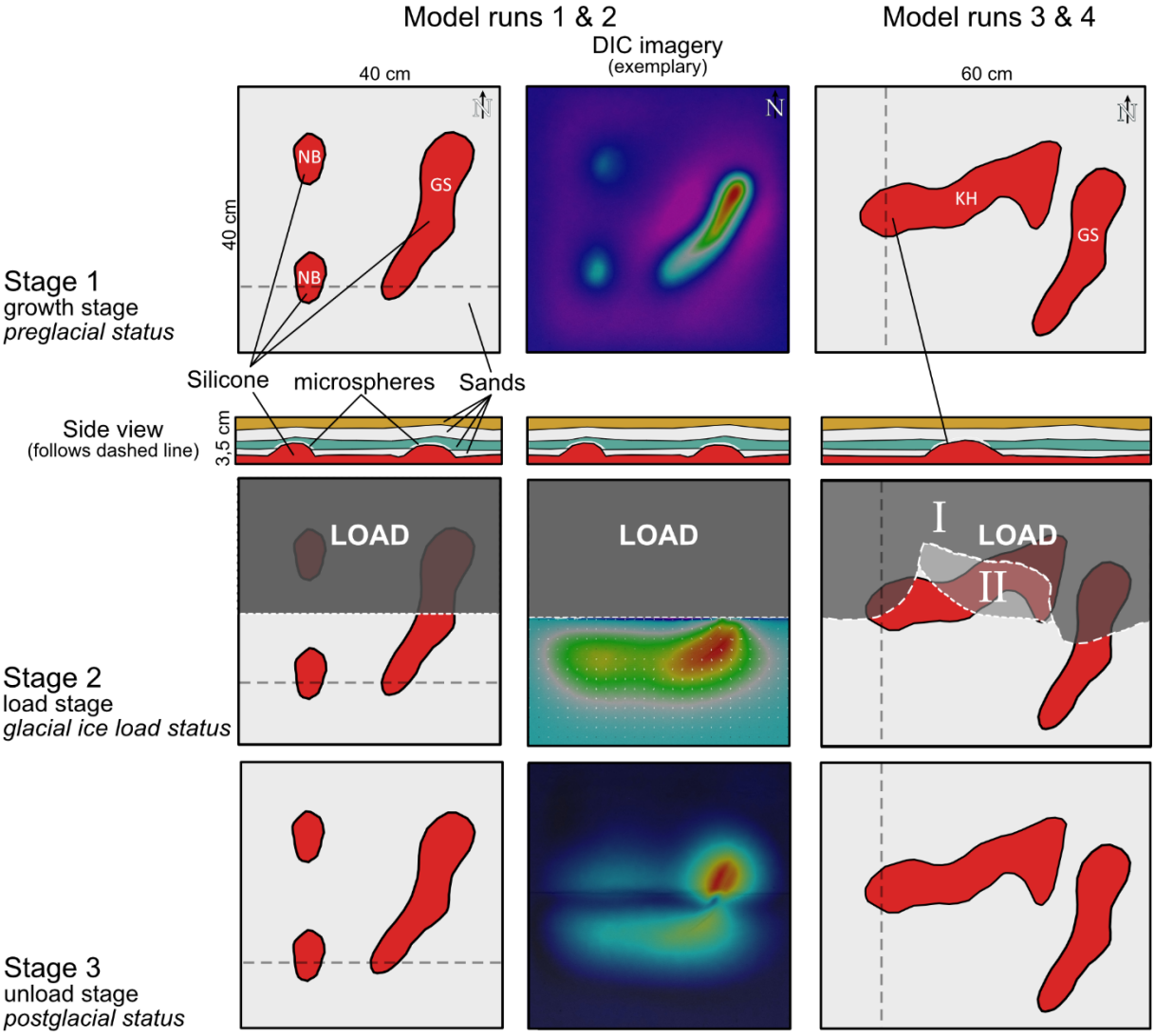

Figure 1: Sketch illustrating the general physical model setup and the three model stages. The left column depicts the setup of model runs 1 and 2; the middle column shows exemplary DIC imagery of these runs. The right column depicts the setup of model runs 3 and 4, where the two domes were replaced by the KH salt pillow, which was parallel to the load margin. The middle image of the right column shows the load margin: In model run 4, first the areas “I” and “II” were loaded for 24 h, then area “II” was unloaded and area “I” was kept under load for another 24 h. Light grey dashed line in left and right columns depicts orientation of sections (Fig. 13).

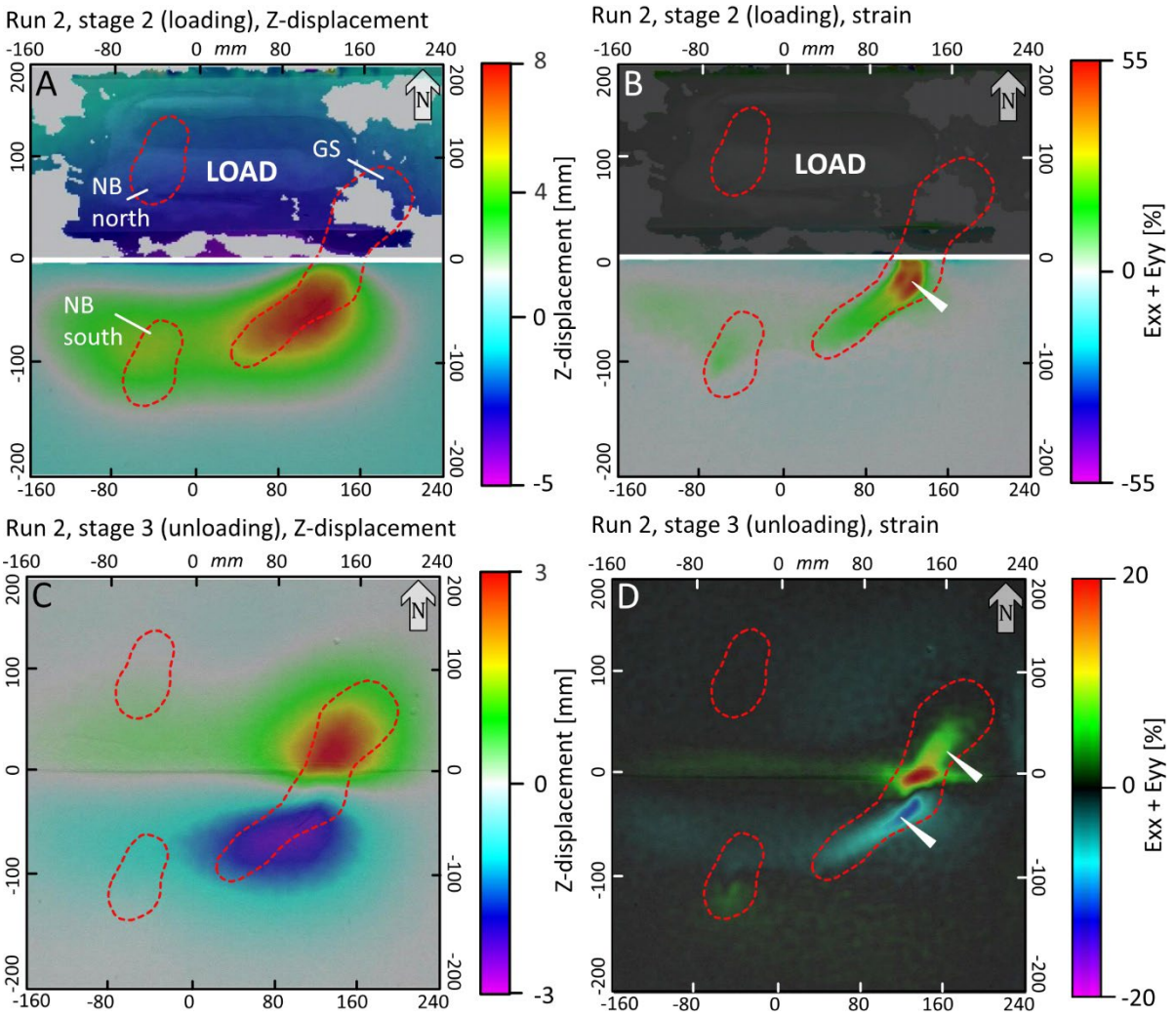

Figure 2: Summarizing DIC imagery of run 2. In stage 2, the load was applied to the north of the horizontal white line. A: Z-map showing total vertical displacement in mm of stage 2. The grey colors in the upper half of the figure are "no data" areas. B: Strain [%] map of the total strain of stage 2. C: Z-map showing total vertical displacement in mm of stage 3. D: Strain [%] map of the total strain of stage 3. Red dashed outlines depict approximate position of salt structures. White arrows indicate position of crestal graben structure.

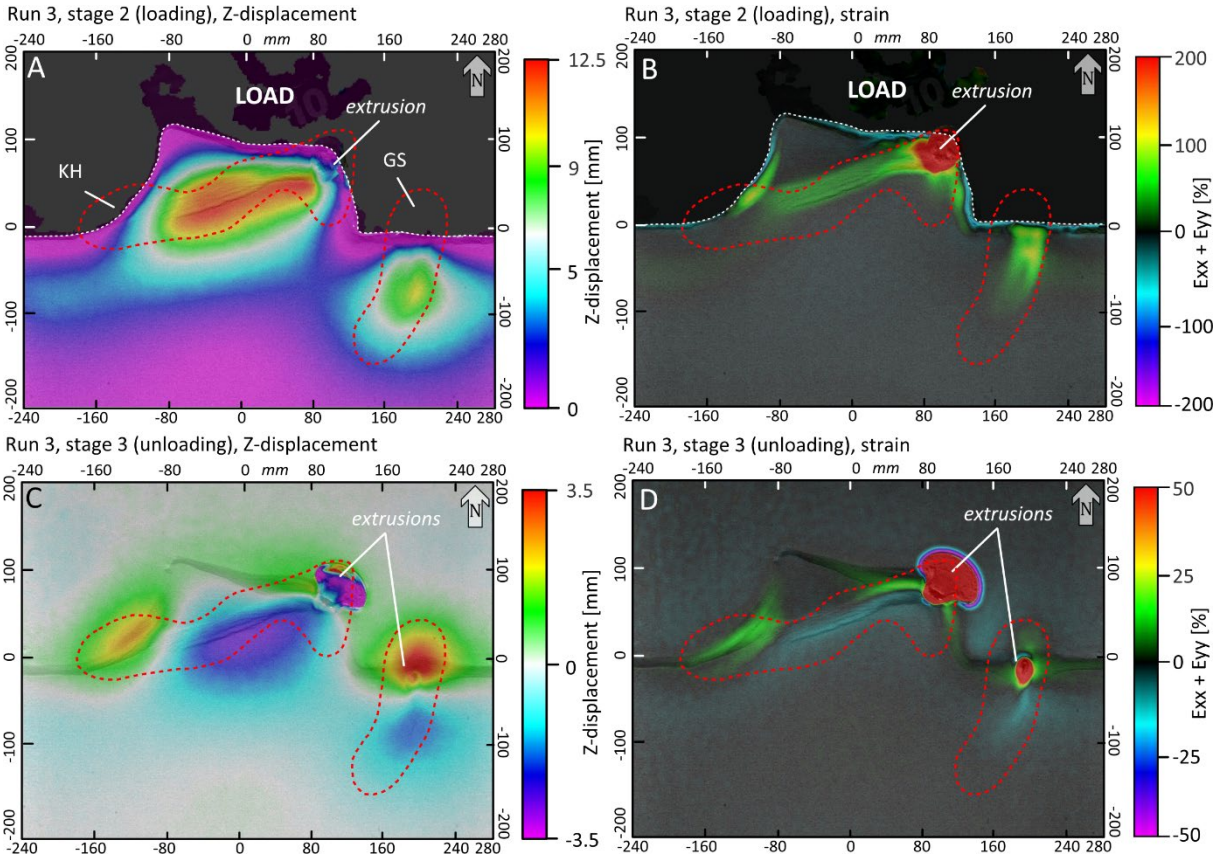

Figure 3: Summarizing DIC imagery of run 3. In stage 2, the load was applied to the north of the dotted white line. A: Z-map showing total vertical displacement in mm of stage 2. B: Strain [%] map of the total strain of stage 2. C: Z-map showing total vertical displacement in mm of stage 3. D: Strain [%] map of the total strain of stage 3. Red dashed outlines depict approximate position of salt structures.

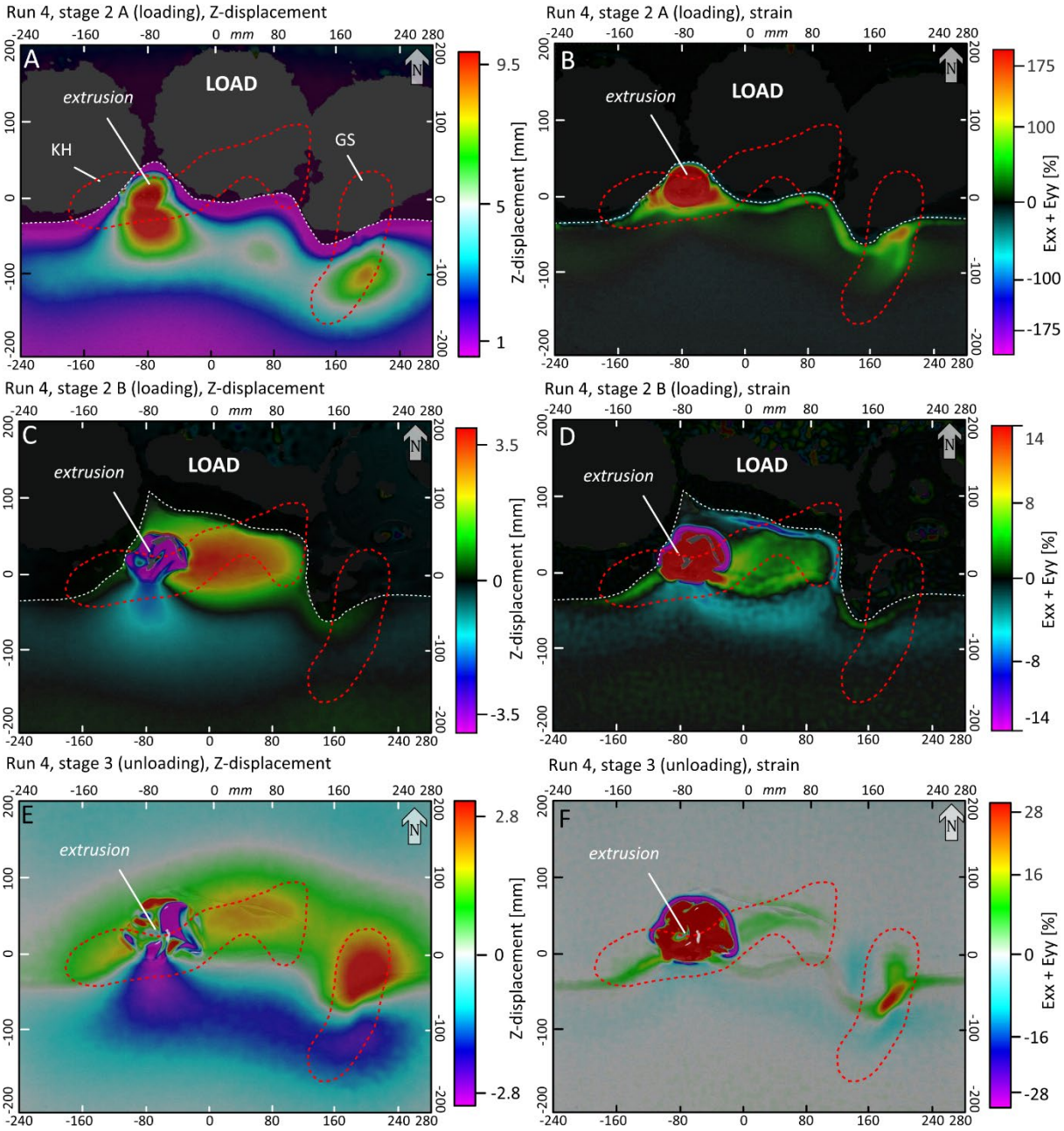

Figure 4: Summarizing DIC imagery of run 4. In stage 2 A and 2 B, the load was applied to the north of the dotted white line. A: Z-map showing total vertical displacement in mm of stage 2 A. B: Strain [%] map of the total strain of stage 2 A. C: Z-map showing total vertical displacement in mm of stage 2 B. D: Strain [%] map of the total strain of stage 2 B. E: Z-map showing total vertical displacement in mm of stage 3. F: Strain [%] map of the total strain of stage 3. Red dashed outlines depict approximate position of salt structures.

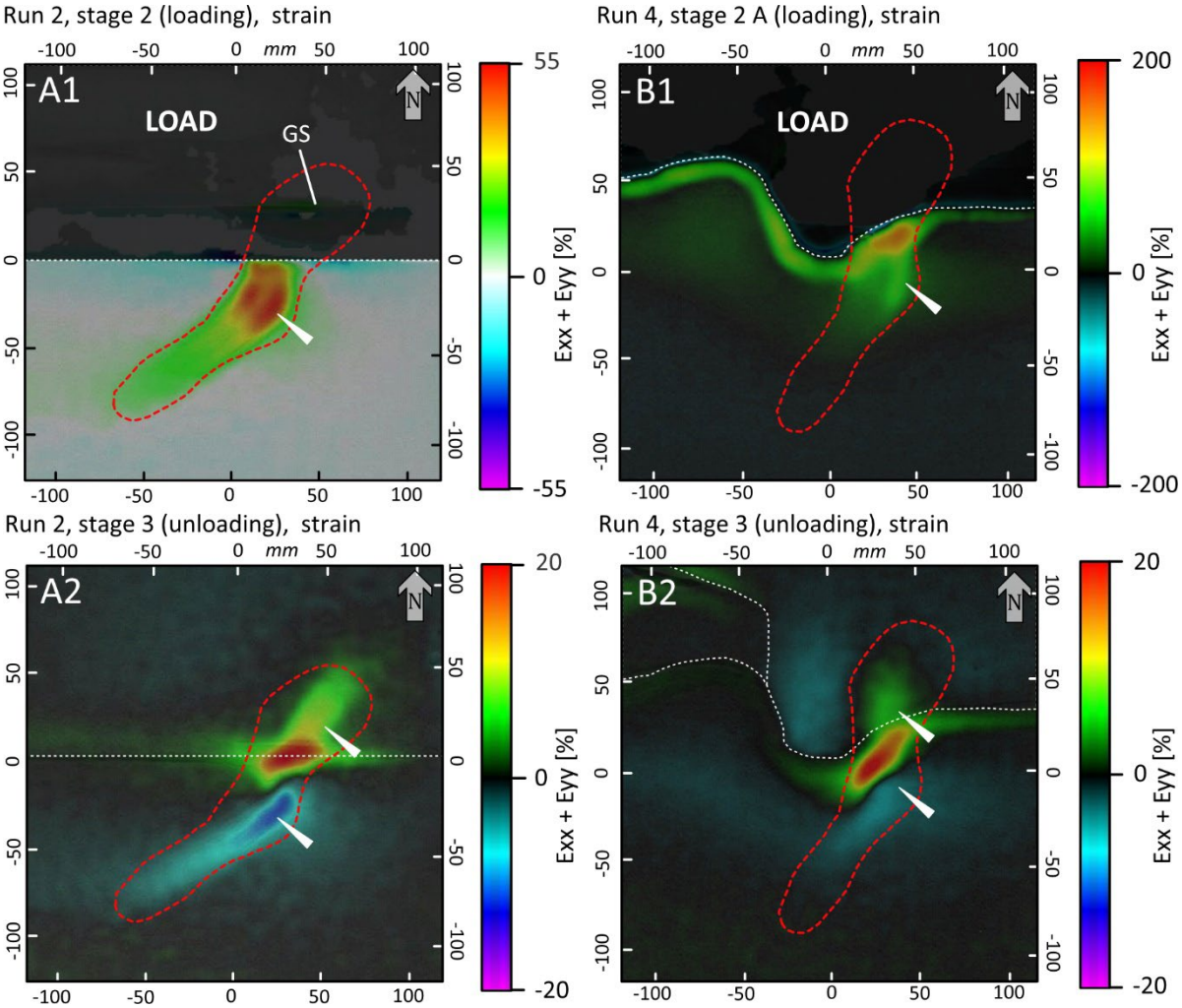

Figure 5: Comparison of strain patterns above GS pillow using different load geometries (white dashed line): Left column - straight load margin; right column: lobate load margin. Red dashed outlines depict approximate position of salt structures. White arrows indicate position of crestal graben structures.