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Interactive comment on "3D crustal stress state of Western Central Europe according to a data-calibrated geomechanical model – first results" *by* Steffen Ahlers et al.

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Answer to anonymous referee #2:

Ahlers et al. present a 3D geomechanical finite element model of Germany and surrounding that has been partly calibrated with observations. They compare calculated crustal stresses with available observations from the World Stress Map and other databases. Overall, the fit is acceptable and allows further analysis and model improvements. The model seems to be the first step toward a complex model for Germany that can be used for dedicated local and regional stress field modelling. This is of major importance, as Germany restarted the search for a nuclear waste disposal

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Discussion paper

facility, hence this model and any successors will be much appreciated and exceptionally helpful. The modelling approach is well established and has been used by some of the coauthors since many years. It is a combination of the stress models of (mainly) the Karlsruhe group with subsurface models of the GFZ group. The model development as presented in this manuscript was therefore, as I see it, a very easy task (mesh the subsurface structures with Hypermesh - "push" with calibrated values in Abaqus - done).As no time-dependent material is involved, even computation time was likely short, despite more than 1 million elements. Additionally, as observations were partly used as constraints (model boundaries designed after stress orientation, stress values), it is no surprise that the fit of the model to the few available observations is at a good level. The model is thus just a start - but at the same time something that has been missed, which is the most important point on the positive side for this manuscript. Frankly, I had problems to give my full support for this manuscript as (a) it is only a first and expected result and (b) the values (e.g. as grids in different depth slices in 2 km steps or so) are not even made available for the interested reader on GFZ websites or services like Pangaea.de. Furthermore, the presentation of the study and results can be partly improved, see my many suggestions below. A discussion of your results with previous models, independent if they are simple or not, should also be made. I would emphatically ask the authors to revise the manuscript along my suggestions and consider publishing results like a gridded 3D stress field over depth, so that the manuscript deserves the role as stand-alone paper.

We thank the anonymous referee #2 for reviewing our manuscript carefully and for his/her suggestions. The complete modeling results are now published and available under: https://doi.org/10.48328/tudatalib-437 In the following, we will address the specific comments in detail.

Specific comments Title: the title is an example for smart exaggeration, but should be changed. The model and manuscript are part of a German project. You even write in lines 163ff "This area was chosen ... to simplify the definition of boundary conditions later on and with regard to important crustal structures which may affect the recent stress field in Germany... Additionally, model boundaries are selected distal to the German border to avoid possible boundary effects in the area of main interest." So Germany is your goal, please use it in the title. Western Central Europe would also include Switzerland as whole, which is not completely part of your model. Also, avoid a phrase like "first results". There won't be a paper with "second results" and even "third results". How about "A data-calibrated geomechanical model for Germany - insights on the 3D crustal stress state".

Thank you for your suggestion, we changed the title to '3D crustal stress state of Germany according to a data-calibrated geomechanical model'.

Abstract: Please avoid citing references. You may use the term Western Central Europe here, but please emphasize that your area of interest is Germany, especially in light of the ongoing nuclear waste disposal location search. Add 2-3 more sentences on results, e.g. on the "salt problem".

We removed the references and avoid the term 'Western Central Europe' now. However, we did not add more sentences on the results. We think that a brief overview of our results is sufficient for this abstract. If we would address, for example the 'salt problem' in the abstract we would also need to address several other specific issues, which may influence our results. Instead, the salt topic, among others, is treated in the discussion section.

L31f: This sentence needs references, e.g. from the search in Switzerland, Sweden and Finland. Add a short introduction on the ongoing search in Germany and why a 3D stress state model of Germany is desired.

We have added some references, e.g. for Germany and Switzerland (line 30f) but no further details since the focus of this study is not on the search for a nuclear waste repository in Germany and we don't think that a more detailed description is necessary here.

L41, first 3D model for Germany: please add a few sentences with references to 3D geomechanical models for other parts of the world.

We have added some references to other 3D geomechanical models at the end of the introduction in line 45f.

Section 2.1: should be expanded and more references should be added, e.g., regarding the evolution of the area. Kley & Voigt (2008) will be of help here.

We have expanded Sect. 2.1. regarding the evolution from the cretaceous to recent times. (line 70-77).

L53/54: Please add reference for this crustal thickness statement (e.g. the works by Gregersen and colleagues or Mazur and colleagues).

We have added a reference to Mazur et at., 2015 (line 54).

L55, Tornquist-Teisseyre Zone and the Thor Suture: this needs more discussion, also in the setup of your model. Looking at Fig. 1b, the Trans European Suture Zone (TESZ) is shown only with the TTZ in Poland and the northern TESZ branch, the STZ in Denmark. In Fig. 1c you show the TESZ with TTZ in Poland (as above) but the more southerly located Thor Suture (southern branch) in Denmark. Nothing is said about the Tornquist Fan in between and the thickness variations here (see the works by Gregersen and colleagues, among others). Which line do you follow in Poland? Mazur et al. (2015, Tectonics, https://doi.org/10.1002/2015TC003934) placed it a bit further southwest than commonly done before.

This may be a misunderstanding since in the first version, we did not use the terms TTZ and STZ completely correct. In figure 1d (former 1c) we show the crustal units of Western Central Europe. To avoid further misunderstandings we have removed the term TTZ and use the term Tornquist Suture now (line 55 and figure 1d). The Tornquist Suture together with the Thor Suture in the northwest represents the border between the EEC and Avalonia, based on Kroner et al. (2010). In figure 1 c (former b) we show the younger tectonic framework based on Kley and Voigt (2008) which includes the TTZ and STZ. In our model only the Thor and Tornquist sutures are implemented as boundary between the crustal units of Baltica and the EEC as displayed in Fig. 5. The tectonic framework in figure 5 is only indirectly represented in the model by the varying thickness of the sedimentary unit (see Fig. 4).

Fig. 1a: Please add a scale of 200 km (representing the search radius you apply later). Change the word "Location" to something more feasible.

Since we are using a Mercator projection for the plot, it would not be correct to add a scale. However, we have added the dimensions of the model edges in the new figure 1b. This should be sufficient for orientation. We have changed ‘location’ to ‘location of measurement’.

Fig. 1b&c: Please update with a more appropriate representation of the whole TESZ. Which TESZ structure is included in the model, the one after Kley & Voigt or the one after Kroner et al.?

Please see our comments above. We have expanded Sect. 2.1 (line 70-77) and edited Fig 1c and d.

Fig. 1: Please increase font size of lat/long numbers.

You are right the font size was quite small. We have increased it.

Section 2.4: I miss a couple of sentences with presentation and discussion of the 3D models shown in Goes et al. (2000, GPC, https://doi.org/10.1016/S0921-8181(01)00057-1) and Warners-Ruckstuhl et al. (2013, GJI, https://doi.org/10.1093/gji/ggt219). These two as well as some in Table 1 should be picked up in the Discussion.

You are right, the publication of Warners-Ruckstuhl et al., 2013 has been missing in our table. We have added it. We did not add the publication of Goes et al, 2000 since there are no results shown regarding the crustal stress field in our model area and the stress model mentioned of Loohuis et al, 2001 (in preparation) seems not to have been published.

Section 3.1: You should add that you also neglect any remaining rebound effects due to the previous glaciation, see e.g., Brandes et al. (2015, Geology, https://doi.org/10.1130/G36710.1).

This is already mentioned, e.g. in the discussion (line 443ff).

L143ff: How is the stress orientation calculated here? Do you use stress2grid for some grid points along a line and then calculate a mean? Which search radius is applied? Or just one coordinate representative for the center point of a boundary? What error can result for the stress orientation?

The calculation is described in detail in Sect. 4.1. However, we have replaced 'observed' with 'mean' to avoid further misunderstandings and added a reference to the mean SHmax orientations displayed in the new subfigure (line 178).

Section 3.2: You state Germany is your area of interest, and the model has some extension in west-east direction giving you some buffer around Germany. However, in the north-south direction your area of interest is very close to Germany's borders, much closer than in east-west direction. Why? Can any geometry effects be exluded in that direction?

As mentioned in Sect. 3.2 (line 172ff) the model area was chosen with regard to (1) the orientation of SHmax (2) important crustal structures which may affect the recent stress field in Germany e.g. the Bohemian Massif, the Avalonia-EEC boundary and the European Cenozoic Rift System. and (3) additionally distal to the German border. Therefore, the focus was not the distance to the German border. If this had been the only criterion, the model area could have been chosen much smaller, like in the north. Geometry effects cannot be excluded but as shown in Fig. 11 they occur outside of Germany, also in the north.

Fig. 4: Avoid rainbow color scale! There are several scientific color scales nowadays available (http://www.fabiocrameri.ch/colourmaps.php). Add that most of the caption information belongs to the subfigures in the lower left. Country borders should also be found in the main subfigures, otherwise it is awkward for the reader to retrieve suitable information from the figure.

Thank you for your suggestion! We have changed the color bars and added country borders to the depth maps. As the subfigures are quite small, it is almost impossible to add all information to these figures. Instead, we have added an enlarged and labeled figure of the database of the top of crystalline basement as a supplement.

L205f: How reliable is the assumption of vertical boundaries here?

This is difficult to assess, but due to the very poor data situation, this seemed to be the most sensible choice. There are no arguments supporting other geometries.

Fig. 5: The ALCAPA section in the upper right appears to be much smaller in geographical extent than the one shown in Fig. 1c, where the whole southern part is covered with ALCAPA. Is the line in Fig. 1c misplaced? Did you change your model geometry?

You are right, the boundary of the ALCAPA unit was wrong. The displayed boundary was the alpine deformation front and not the boundary used in the model. We have corrected it with information of Brückl et al., (2010).

L254f: Although clearly without significance for the result, did you consider to make your model roughly some few 100 metres bigger & smaller in size (as you can roughly pre-calcuclate those extensions and shortenings) so that you get correct coordinates "today"?

As you mentioned, this will not matter for our model size. If this is required for smaller or higher resolution models, there is the possibility to rectify the model geometry afterwards so that the results can be captured at the correct 'today' coordinates.

Section 4.1., first paragraph: This description irritates the reader. You talk about two grids where you compare nearest grid points? Why don't you calculate the database values on the centre points of the elements in the FE model? Or calculate values from two sources on an identical grid?

We have used a grid of 0.5°, as we find this suitable for a model of our resolution. For comparison we have to interpolate the results on a plane first since the nodes of our mesh are located at different depths. In the end we use the nearest values to avoid additional uncertainties due to a second interpolation.

L264: Please add reference for this statement.

This is a definition made in stress2grid.

L265: Please add reference for the <25. Why not 15 or 22.5?

This is the maximum standard deviation of the WSM data used (WSM quality A to C) for the calculation of the mean SHmax orientation. To make it easier to understand, especially since we now mention the standard deviation of the derived grid too, we have now replaced the SD with the WSM quality (line 290f).

L267: Why 5 km?

Since the SHmax orientations do not show significant changes with depth we use a medium depth, where we did not expect any effects of the topography and which is well validated by our calibration data.

Fig. 6: I suggest to add two more subfigures. It would be interesting to have a subfigure depicting the number of stress data in each grid point of the WSM grid and one which shows the standard deviation of each grid point. It might help to compare if outliers in the histogram (d) or the map (b) fall together with those.

We think that the standard deviation and/or the numbers of data used for each grid is no information that creates significant added value and for which two further figures are not necessary. However, we mention the median of the standard deviation in the text now (line 297). Anyone interested in this specific information can easily calculate it from the WSM data using the stress2grid tool. All settings used are mentioned in the text (line 290ff).

Fig. 6d indicates that your model needs a stress orientation change of roughly 10 Have you tested that?

Yes, we have tested it, but we were not able to get a better result.

Figs. 7&8: Suggest to (i) split the quality color in (a) into two each for above and below 1 or 1.5 km, and (ii) color-code the histogram in (c) with the 6 colors so that one can distinguish, especially in Fig. 8c, the different quality and depth sources.

That is a good suggestion! We have color-coded the histograms depending on the quality, but we think that it is not useful to add three additional colors.

Fig. 9: Please make profile lines thicker. I also suggest to add the RSR over depth to this figure (or create separate figure). In view of this figure, I suggest to calculate the misfit (weighted sum of squared model minus observation difference divided by observation error) for each profile and quantity, and use them in the discussion. Can be even used in future studies with improved models.

Yes, the lines have been quite thin. We have increased the thickness of the lines and added the RSR over depth. We are not able to quantify our model error, so we cannot calculate such a misfit. However, you are right, stress model uncertainties are an interesting and important subject.

Fig. 10: Please use different color scale (not rainbow). Scale should be 0 to 3. I suggest to check earthquake catalogues if focal mechanisms are available for some of these depth slices and plot them too. There are some remarkable edge effects in the upper 4000 m, or shall it be a true thrust mechanism?

We have changed the colors and the scale. Yes, these are edge effects we mention it in the figure caption now (line 412f). In general, it is a good idea to consider focal mechanisms (FMS) as an additional data base for comparison with model results. However, we decided not to show FMS in comparison to our model results. Although FMS can represent the stress state of the crust, this is not always the case. It is because a focal mechanism is a kinematic information at first hand. If the fault is not optimally oriented in the contemporary stress fields or if there is slip partioning among several faults, slip on a single fault may not represent the stress state, e.g. in the San Andreas fault system there are pure strike-slip earthquakes on some faults whereas there are parallel fault strands where slip exhibits a strong thrust-component to accommodate the overall slight oblique relative motion between the Pacific and North America Plate. The same is true on the North Anatolian Fault in the Sea of Marmara where most earthquakes on the main fault are pure strike-slip events despite the extension going on, which is taken up by subsidiary faults. In addition, depth information on hypocenters is generally poorly constrained. Things are different when not single FMS are compared to the stress field but inversion of FSM is performed, since a presumption in the inversion is that all earthquakes occurred in the same homogenous stress field. However, due to low seismicity rates in most parts of Germany not many inversions have been done and moreover an inversion result is representative for the area in which the earthquakes have occurred which would allow comparison only for larger areas. Furthermore, the model shows that the regime changes with depth, so that the depth of the FMS plays a central role in a comparison. However, the focal depth is subject to large uncertainties, especially for the low magnitude earthquakes, so that the focal depth is often set at 10 km. The true depth position is often not known.

Discussion: Please compare your results also to previous models listed in Table 1, but also the values shown in Figures 4 & 10 of Warners-Ruckstuhl et al. (2013).

We already mention almost all models listed in Table 1 in Sect 5.1. We have not added a detailed discussion in comparison to the results of Warners-Ruckstuhl et al., 2013 since the results do not show a specific cause of stress perturbation regarding our model area.

L400: yet?

No, we are not planning to implement it.

L452ff: Here it would be good to have RSR over depth in Fig. 9.

Please see our comment above.

L488ff: Here it would be nice to refer to focal mechanisms in Fig. 10.

Please see our comment above.

Technical comments: L110: Move '(Fig. 1a)' after 'database' as otherwise the reader thinks your model is shown in Fig. 1a.

Thank you, we have changed it, as suggested.

L142: initial stress

Thank you, we have changed it, as suggested.

L259f: Sentence sounds awkward, suggest: 'A mean SHmax orientation is used on a regular 0.5 grid, as we do not use individual data records for this comparison.'

You are right, we have restructured the sentence.

L332: do not

Thank you, we have changed it, as suggested.

L437: comma after '(KTB)'

Thank you, we have changed it, as suggested.

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