Review of “**The analysis of slip tendency of major tectonic faults in Germany**” by Luisa Röckel, Steffen Ahlers, Birgit Müller, Karsten Reiter, Oliver Heidbach, Andreas Henk, Tobias Hergert, Frank Schilling.

Review by David A. Ferrill

GENERAL

The manuscript provides new slip tendency analyses to constrain the potential for fault activity in Germany, which is important for assessing seismic hazard as well as other fault related processes such as energy extraction and subsurface disposal or storage activities. This is a very interesting manuscript – the material should be of interest to a broad readership, and make a very nice contribution to Solid Earth.

My greatest concern with the article is that, for the article to stand alone and be easily understood, it needs to illustrate the regional stress field and provide representative slip tendency plots. Lacking this information, the slip tendency fault maps are difficult to understand and the related description is rather abstract.

A second concern is related to the justification for the assumption of a vertical fault set. This vertical-fault assumption needs to be (i) justified by providing the geological basis for assuming the faults are vertical, or (ii) explained with appropriate caveats provided regarding impacts of an incorrect assumption on slip tendency results for the stress fields of Germany.

Below are several specific comments and suggestions that could help improve the manuscript. Additional editorial comments are marked in an annotated pdf that will also be provided with this review.

We appreciate the very constructive comments and suggestions of the reviewer David Ferrill and tried to improve the manuscript according to his suggestions. E.g., we included the information on the stress field based on observations and we added the suggested slip tendency plots for different depth levels based on the model data from Ahlers (2021). We would also like to thank the reviewer for the comments in the attached document. See also below the answers to the specific comments.

SPECIFIC COMMENTS

Description and illustration of stress states and slip tendency plots for study area (Section 2.1, 3D Stress State):

What are the stress regimes in Germany? This section should summarize the stress state of the study area in terms of stress regimes (e.g., normal faulting, strike-slip faulting, thrust faulting), maximum horizontal stress directions, and variation as a function of depth. In present form, the paper relies on Ahlers et al. (2021), and discusses the stress analysis methodology of Ahlers et al. (2021) but not the result of that analysis which is a primary input for the slip tendency analysis in this paper.

Thank you for the suggestion. In subsection 2.2 “Stress State” we integrated a brief section (lines 72 - 80) highlighting the stress regimes and orientations in different areas of Germany. We also added subfigure 1 (b) that displays the available stress data (orientation, regime and location of stress magnitude data) in Germany from the World Stress Map (Heidbach et al. 2018) and the magnitude data base by Morawietz & Reiter (2020).

Furthermore, we added the major results from Ahlers et al. (2021) relevant to our analysis (lines 95 - 107). This includes a description of the stress regimes and orientations in 1 km depth and 8 km depth (mostly strike-slip regime and normal faulting regime respectively) as well as the new subfigures 1 (c) and (d) that visualize these results.

The manuscript would be greatly improved by illustrating the stress states by providing a map with representative slip tendency plots for subregions. Specifically, I recommend a map similar to figure 7 in Morris et al. (2021). Such a map would convey not only stress orientations, but also stress regime (cf. figure 1 in Morris and Ferrill, 2009, The importance of the intermediate principal effective stress (σ'_2) to fault slip patterns. Journal of Structural Geology 31, 950-959). Because of the variation in regime as a function of depth indicated by figure 11 of Ahlers et al. (2021, Solid Earth), it may be necessary to provide maps with representative slip tendency plots at two depths.

We added the new subfigures 1 (c) and (d) that also include the mentioned slip tendency stereo plots in depths of 1 km and 8 km. We chose the subregions according to variations in the orientation of the maximum horizontal stress and within different crustal units (shown in the new subfigure 1(a) to discriminate between such regions.

Assumption of “Vertical fault set” (Section 2.2):

Is there a technical basis for the “vertical” assumption, or is this just a matter of convenience? This assumption has major impact on slip tendency, and results are highly sensitive to stress regime. Please provide (i) a geological basis for assuming the faults are vertical rather than some other dip angle, and/or (ii) a rationale for making the assumption, with acknowledgement that -- if wrong -- this assumption can introduce large error in slip tendency calculation. Vertical faults may be ideally oriented for slip in a strike-slip stress regime, whereas vertical faults are never ideally oriented for slip in normal faulting or thrust (reverse) faulting Andersonian stress regimes. Therefore, the vertical-fault assumption will tend to skew slip tendencies lower values for stress regimes other than strike-slip regime.

GEOTIS is a huge database but information on the fault dip or type is only available for a subset. Since GEOTIS offers an exceptionally detailed and comprehensive fault data set, we still wanted to use this set despite the incomplete data to consider the more diverse strike pattern and spatial coverage the set offers. The use of a uniform dip allows the consideration of the entire data set and furthermore highlights the effect of the fault strike more clearly.

Following your suggestion, we included a statement in the description of the Vertical fault set (lines 141 - 144), highlighting the influence of the chosen uniform fault dip on the reliability of the results.

Results Section 3.1 – Vertical fault set:

Manuscript states that "Results near surface are visualized" (Line 115): What depth, and why near surface? Earthquakes tend to nucleate at significant depth rather than near the surface.

As noted earlier, if not correct, the vertical fault assumption is problematic and may artificially skew slip tendencies lower for stress regimes other than strike-slip regime where vertical faults are ideally oriented for slip. It would be good to acknowledge this in this results section

The visualization of results near the surface was due to a technical issue that has since been resolved. The map now shows the top view to be consistent with the figures displaying the Andersonian and Semi-Realistic fault set. However, we added subfigure 12(a), a cross section through the Vertical fault set in 8 km depth, where the majority of earthquakes have been localized alongside said seismic events.

We added a new paragraph to section 4.3 Influence of fault dip (lines 326 - 329), pointing to the source of error through the implementation of the faults as vertical in the respective stress regimes.

Subscripting for slip tendency symbols:

In all figures and throughout article, need to be consistent with subscripting of Ts, Tsnorm, Tseff, and Tsnormeff for consistency with text.

We replaced all figures referring to one of the above-mentioned slip tendency types with updated figures with consistent subscripts.

Referencing:

Although cited in the text, Morris et al. (1996) is missing from the reference list:

- Morris, A.P., Ferrill, D.A., Henderson, D.B., 1996. Slip tendency analysis and fault reactivation. Geology 24, 275–278.

Recommend citing the following paper in the Introduction (Line 41) as a very careful example of regional slip tendency analysis of 3D faults:

- Morris A.P., Hennings, P.H., Horne E.A., Smye, K.M., 2021. Stability of basement-rooted faults in the Delaware Basin of Texas and New Mexico, USA. Journal of Structural Geology 149, 104360.

We thank the reviewer for notifying us about the missing reference. We have added it to the list of references and have added the suggested reference to the list of previous works.

References:

Ahlers, S., Henk, A., Hergert, T., Reiter, K., Müller, B., Röckel, L., Heidbach, O., Morawietz, S., Scheck-Wenderoth, M., and Anikiev, D.: The Crustal stress state of Germany - Results of a

3D geomechnical model, TUdatalib [data set], https://doi.org/10.48328/tudatalib-437, 2021b.

Heidbach, O., Rajabi, M., Cui, X., Fuchs, K., Müller, B., Reinecker, J., Reiter, K., Tingay, M., Wenzel, F., Xie, F., Ziegler, M. O., Zoback, M.-L., and Zoback, M.: The World Stress Map database release 2016: Crustal stress pattern across scales, Tectonophysics, 744, 484–498, https://doi.org/10.1016/j.tecto.2018.07.007, 2018.

Morawietz, S. and Reiter, K.: Stress Magnitude Database Germany v1.0, GFZ Data Services [data set], https://doi.org/10.5880/wsm.2020.004, 2020.

Review of “The analysis of slip tendency of major tectonic faults in Germany” by Röckel et al.

Stephen Hicks, Imperial College London

(1) Overview of the manuscript

Roìckel et al. provide a detailed analysis of slip tendency for mapped faults in Germany using a variety of subsurface datasets. Although local slip tendency studies exist for Germany (e.g., Northeast German Basin - *Moeck et al., 2009, J. Struct. Geol.*; Roer Valley Rift - *Worum et al., 2004, J. Geophys. Res.*), this manuscript presents the first national-scale attempt to my knowledge. The computed slip tendency values are based on regional stress tensor information from an already-published 3D numerical geomechanical model (*Ahlers et al., 2021*). The main findings from this study are that (1) roughly northwest-southeast striking faults have a higher slip tendency in the regional stress field, and (2) there is a reported good spatial correlation between higher slip tendency and seismicity. I congratulate the authors for writing a manuscript with well-grounded objectives and sound, well-described methods. It is refreshing to see these vital fault analyses considered over a large regional scale. The manuscript is detailed, easy to follow, and well-written. Although the methods, data and results appear sound, I have two moderate-to-minor level comments on the comparison with seismicity and the presentation of the regional tectonic context, as detailed below.

I look forward to seeing this excellent work appearing in print soon!

We would like to thank the reviewer Stephen Hicks for his very helpful and constructive remarks. We tried to implement the suggested changes where possible. E.g., we added the suggested figure detailing the stress field in Germany as well as a comparison between the slip tendency of the more comprehensive Vertical fault set with seismic events and included some fault plane solutions in the discussion of the seismicity. Please see below our answers to the specific comments.

(2) General comments

(2-a) Regional tectonic context and past studies on slip tendency

Although the Introduction reads very well, I feel that it could be improved by including a better description regional tectonic/geological context, especially for a reader who is not familiar with the geology of Germany (like me). Specifically, what are the broad spatial patterns in the regional stress of Germany? What are the main fault structures? What is known about seismicity in Germany and the types of faults that get reactivated? How much of the seismicity in Germany is induced, and what might be the role of high pore fluid pressures in some of these cases? In particular, I feel the article could benefit from having a new figure that comes before all existing figures to present a regional map that highlights and labels specific regions of interest mentioned in the Introduction and throughout the paper (e.g., Roer Graben, Upper Rhine Graben). This map should also show how the stress regime varies across Germany (e.g., by showing indicative SHmax orientations and stress regimes).

We agree that the article would benefit from a more comprehensive description of the study area and added a brief description of the geological setting in the new subsection 2.1 “Study area” immediately following the introduction. We also added a brief description of seismic activity (both natural and induced) (lines 81 – 86). The stress state in Germany is briefly described (lines 72 – 80) in the subsection 2.2 "Stress State" and furthermore visualized in the new subfigure 1(b). This figure includes stress orientation data from the World Stress Map (Heidbach et al. 2018) using its color-code as well as the location of freely available stress magnitude data from the stress magnitude data base by Morawietz & Reiter (2020). The map should therefore provide an overview over the stress orientations in Germany. Major fault structures are shown alongside this subfigure. The crustal framework of Germany, on which the model by Ahlers et al. (2021) is based, has been displayed in the new subfigure 1 (a).

Whilst localised slip tendency studies in Germany have been cited (e.g., *Moeck et al., 2009*; *Worum et al., 2004*), it would be helpful to compare the results of these studies with the new slip tendency data from this manuscript.

In the discussion we added the subsection "4.7 Comparison with earlier studies" (lines 439 - 452) comparing the slip tendencies provided in Worum et al. (2004) and Peters (2007) with the results from our manuscript. We chose the scenarios from Worum et al. (2004) that matched our setting the closest, however, their results indicate lower slip tendencies in the strike-slip regime than in the normal faulting regime.

(2-b) Comparison with seismicity

I am not yet entirely convinced by the comparison between slip tendency and seismicity, which is described in Section 4.5 and illustrated in Figure 11, one of the main conclusions of this study. This concern arises for several reasons, which I describe below, and I try to provide some hopefully helpful suggestions to improve confidence in this conclusion.

(2-b-i) The seismicity catalogue used

Slip tendency is compared with earthquakes based on the *GruÌnthal und WahlstroÌm* (2012) seismicity catalogue. This catalogue runs until 2006, and locations of the more historical earthquakes are likely to be inaccurate, so I wonder whether this dataset could at least be supplemented with additional earthquakes since 2006 using modern operational catalogues (e.g., EMSC; GFZ-GEOFON; BGR)? Widening the earthquake dataset may help produce more confident correlations with slip tendency. Perhaps if one of these instrumental catalogues were considered on their own, then a lower magnitude threshold could be used, e.g., M_w 2.5-3.0?

We extended the catalogue in time and could add all events with Mw>3.5 for the period 2007-2021 using the GEOFON data (Quinteros et al. 2021). We also cross-checked this additional data set with the compilation from the European-Mediterranean Seismological Centre (EMSC), the one from the International Seismological Centre (ISC) and the data from the BGR.

We fully agree that the location of the historical events has probably large uncertainties, but at least the long time series covered by this catalogue gives us a better picture about the recurrence interval of the events in a low strain region with low to moderate seismicity. We also think that the choice of Mw ≥ 3.5 is reasonable to capture events that occurred on larger faults. Using empirical relations, events with lower magnitude have a rupture length of less than one kilometre which is a scale that is certainly not reflected by the fault compilations that we use here.

We also tested to use an event catalogue of modern times, i.e. beyond mid 70's, but this shows the same scatter. This is probably due to a larger number of small events that occur on small faults that are not mapped. One problem that this compilation has is of course the magnitude of completeness. In some areas of Germany networks have been installed or refined in the past two decades with a significantly lower magnitude threshold. Thus, the distribution of events using a catalogue with smaller magnitudes suffers from other problems.

Given these explanations we think that our choice to use Mw ≥ 3.5 is surely not a perfect solution and has the location issue, but on the other hand, the problems using other compilation we consider for our study are larger.

(2-b-ii) Comparing small earthquakes and large faults

Given that the best correlation between seismicity and slip tendency is reported for the Andersonian fault dataset, I am curious about the rationale behind selecting a minimum fault length of 250 km for this dataset? Earthquakes down to M_w 3.5 are considered in this analysis, but earthquakes this small would typically rupture a fault length down to tens of metres (e.g., by extrapolating earthquake scaling relations of (*Wells & Coppersmith, 1994*) rather than hundreds of kilometres. Earthquakes in Germany do not typically exceed Mw~5. So I wonder whether some of the small earthquakes may occur on more minor faults than currently considered and that may have an orientation not represented by the larger-scale faults. I realise that it is challenging to map every minor fault. Still, I would like to see how the reported slip tendency - seismicity correlation holds up if a more diverse fault dataset encompassing smaller-length faults (e.g., tens of km) is considered instead?

We agree with the reviewer that the integration of a more diverse fault set in the comparison with seismicity would be interesting and thus provide the additional figure 12 (a) and corresponding discussion to subsection 4.5 (lines 353 – 363) with the Vertical fault set that is more comprehensive than the other two fault sets both in terms of spatial coverage and strike directions. However, we want to highlight that the dip of the fault can have significant influence on the slip tendencies and that an interpretation of these slip tendencies together with the seismicity may by strongly biased by the uniform fault dips. We have furthermore adjusted to colour scheme of Fig. 12 to better highlight the regional differences in slip tendency.

To further address this issue, we extended the text and include the discussion of small scale faults (lines 364 - 370). We think that at that stage any further, quantitative comparison is not possible. Either we would have to map small scale faults that have a comparable rupture length that would fit to our majority of catalogue events that have magnitudes below 4.5 (which means a few kilometers rupture length only). Or, alternatively, we could use instead only large events with $M_w > 6$ that have according to empirical relations rupture length of > 10 km (Wells and Coppersmith, 1994). These would fit better to our fault resolution, but in a low strain area these magnitudes do not occur very often and even the largest recorded event in Germany from year 1911 with M_w 5.8 in the Albstadt shear zone would not be usable, but only the historical events where the epicenter estimation based on intensity reports is highly uncertain.

(2-b-iii) Associating earthquakes with faults

As mentioned above, the premise of the reported correlation relies on the implicit assumption that earthquakes are associated with either one of the fault structures considered or a minor fault whose orientation is represented by larger structures. I, therefore, wonder whether any focal mechanism data exists for Germany, from either operational catalogues or existing published studies, that can be used to state whether one of the nodal planes is parallel to the implicitly identified causative fault? I realise that focal mechanism data may be reasonably sparse for an aseismic region like Germany. Yet a quick look at the GFZ-GEOFON catalogue yields a handful of moment tensors for the study area, which could still at least be briefly presented and discussed. But perhaps there are more detailed focal mechanism datasets from local studies across Germany?

We used the dataset of the GFZ-GEOFON catalogue and plotted focal mechanisms together with the Andersonian fault set and its slip tendency (Fig. 12 (d)) and briefly discussed areas where the fault plane solutions fit the slip tendency results better (Upper Rhine Graben area) and areas where the nodal planes do not match the faults with higher slip tendencies in this area (lines 396 - 407). While the Vertical fault set offers a greater spatial coverage of faults as well as more diverse strike patterns, the overall slip tendency values of this fault set are so low that we preferred the comparison with the Andersonian fault set. However, the comparison further highlights that future studies featuring more detailed fault sets with more complex 3D geometries might be beneficial.

(2-b-iv) Presentation of the seismicity – slip tendency correlation

By visually looking at Figure 11, I am not entirely convinced that a spatial correlation exists, so it would be good to quantify the correlation numerically. One idea to consider is to discretise the study area into a grid. Then assign each grid point where a fault and associated slip tendency value exists to its average and/or maximum value and a seismicity parameter (e.g., log of total seismic moment, number of earthquakes, a binary choice of earthquake occurrence within *x* km radius). This approach would then allow a scatter plot of points to be shown with an associated correlation coefficient value.

Given the aforementioned problems of earthquake catalogues in low strain area versus coarse and for sure incomplete mappig of faults that cause the observed seismicity (plus the location problem of the large events as these were taken from intensity reports only) we do not think that such an estimate would tell us a lot. Furthermore, the largest problem is the unknown dip of most of the fault that changes the slip tendency values a lot.

(3) Specific, minor comments

(3a) In Figure 2, I find it hard to work out the dip direction of the fault. Could a solid line be possibly added to the fault surface to show the reader where the top of the fault is?

We added solid lines at the top of the faults to the respective figures, and hope they are now easier to understand.

(3b) For Figure 3, the locations of these vertical sections should ideally be shown on a map somewhere – either a previous map or a sub-panel of this figure. Also, the horizontal and vertical scales could benefit from fully labelled axes with a greater frequency of labels and ticks.

We added indicators of the locations of Fig. 4(a) and (b) in the newly added subfigure 1(b) and increased the ticks on the scales.

(3c) Figure 8 – even though it is implicitly shown in the axis orientation sketch, the caption should also clarify that the map in (a) is from an oblique/perspective viewpoint.

We added a clarification concerning the oblique view to the caption.

(4) Technical comments

(4a) Line 161 – possibly a word or punctuation missing between “fault set” and “additional histograms”. Maybe a “, with” is needed here?

We addressed the issue of a missing semicolon and added it at the respective location.

References:

Ahlers, S., Henk, A., Hergert, T., Reiter, K., Müller, B., Röckel, L., Heidbach, O., Morawietz, S., Scheck-Wenderoth, M., and Anikiev, D.: The Crustal stress state of Germany - Results of a 3D geomechnical model, TUdatalib [data set], https://doi.org/10.48328/tudatalib-437, 2021b.

Heidbach, O., Rajabi, M., Cui, X., Fuchs, K., Müller, B., Reinecker, J., Reiter, K., Tingay, M., Wenzel, F., Xie, F., Ziegler, M. O., Zoback, M.-L., and Zoback, M.: The World Stress Map database release 2016: Crustal stress pattern across scales, Tectonophysics, 744, 484–498, https://doi.org/10.1016/j.tecto.2018.07.007, 2018.

Morawietz, S. and Reiter, K.: Stress Magnitude Database Germany v1.0, GFZ Data Services [data set], https://doi.org/10.5880/wsm.2020.004, 2020.

Peters, G.: Active tectonics in the Upper Rhine Graben: Integration of paleoseismology, geomorphology and geomechanical modeling, Zugl.: Amsterdam, Vrije Univ., Diss, 2007, Logos-Verl., Berlin, 270 pp., 2007.

Quinteros, J., Strollo, A., Evans, P. L., Hanka, W., Heinloo, A., Hemmleb, S., Hillmann, L., Jaeckel, K.-H., Kind, R., Saul, J., Zieke, T., and Tilmann, F.: The GEOFON Program in 2020, Seismological Research Letters, 92, 1610–1622, https://doi.org/10.1785/0220200415, 2021.

Worum, G., van Wees, J.-D., Bada, G., van Balen, R. T., Cloetingh, S., and Pagnier, H.: Slip tendency analysis as a tool to constrain fault reactivation: A numerical approach applied to three-dimensional fault models in the Roer Valley rift system (southeast Netherlands), Journal of Geophysical Research: Solid Earth, 109, 233, https://doi.org/10.1029/2003JB002586, 2004.

Relevant changes to the manuscript

- A minor change to the last sentence of the abstract
- Addition of subsection 2.1 “Study area” to add a description of the geological context and seismicity in the study area
- A new paragraph in subsection 2.2 “Stress State” describing the broad stress pattern observed in the study area
- Addition of Fig. 1, visualizing the geological framework in the study area (a), as well as the stress field as derived from databases (b) and the geomechanical-numerical model (c) and (d), this study is based on. Subfigures (c) and (d) also include fault reactivation stereo plots.
- A caveat to the description of the Vertical fault set about the influence of vertical fault dip on the resulting reactivation potential
- Addition of a short discussion of the stress field in subsection “4.1 Influence of fault strike on slip tendency”
- A caveat to the discussion of the fault dip (subsection 4.3) about the Vertical fault set and the influence of vertical fault dip on the resulting reactivation potential
- New paragraphs added to subsection 4.5 “Comparison between slip tendency and seismicity” with a comparison between the slip tendencies of the Vertical fault set and seismic events and a discussion about small scale faults
- An updated paragraph in subsection 4.5 “Comparison between slip tendency and seismicity” about the comparison between the Andersonian fault set and seismicity
- An additional paragraph in subsection 4.5 “Comparison between slip tendency and seismicity” discussion fault plane solutions in the study area in comparison to the Andersonian fault set.
- Update of Fig. 12 to include the Vertical fault set (Fig. 12 (a)) and a map showing fault plane solutions (Fig. 12 (d))
- Addition of subsection “4.7 Comparison with earlier studies” where the results of this study are compared with the findings of Worum et al. (2004) and Peters (2007)
- A minor change to section “5 Main outcome & recommendations”
- Update to all figures to include subscripts and to accommodate further suggestions by the reviewers
- Update of supplement figures to include subscripts