

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

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(1) Overview of the manuscript

Röckel 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 *Gruñthal und Wahlstroim (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 $M_w > 3.5$ 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 $M_w \geq 3.5$ 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 $M_w \geq 3.5$ 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 $M_w \sim 5$. 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 be 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 mapping 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:

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