Dear Jochem,

Thank you for your comments regarding our manuscript. Please see our replies below. The comments included in the continuous text of the manuscript, and not mentioned below, were accepted, and are already implemented into the new version of the manuscript. If you would have some additional comments to our answers or any helpful feedback, please feel free to submit more questions.

With Best Regards,

Authors

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1. Nevertheless, for a better understanding of the workflow, I tried to reproduce the process of generating a few data points in this data compilation containing my own data (Haus Aden, 940 m bottom , Kück, 1988). I must admit, however, that I could not really reproduce the values that are ultimately shown in Table 2, lines 23 to 26 of this publication.

Please be aware that the values in Table 2 (from the manuscript) are mean values from all the tests carried out at a specific location. To see all the measurements from each of the test locations please refer to the data set of all stress magnitudes (https://fordatis.fraunhofer.de/handle/fordatis/272).

2. For one, the depth is given as 998 m but actually it was the 940 m level (Hauptquerschlag der 940 m Sohle).

From the mining reports the NHN (or then the NN) level is 938 m, whereas the actual depth below the surface was 998 m. We select the latter to compute stress gradients etc. and for further analysis of stress data. To avoid misunderstanding and clarify the difference in numbers we will explicitly mention this in the manuscript text.

3. Could it be the stress relocation effect of the cavity of the gallery was not considered, because it seems always the highest stress values were chosen no matter at which distance to the gallery wall these were measured?

Yes, this is correct. We have not assessed the individual data records (measurements) if they are potentially influenced by excavations or other man-made effects. This should be, however, the task for further studies. The key goal of this study was to make all available data public without any interpretation in the first place. We will add this information more prominent in the manuscript and state more clearly that individual data records may be influenced by mining activities and, thus, may not represent the undisturbed in situ stress state.

4. In line 23 (vertical borehole B2V) I can recognize the average Shmin of 14.2 MPa and the SHmax of 25.4 MPa, where always the maximum occurring value given in the Diplomarbeit is 23-26 MPa was used.

We assume that you refer to Table 2 from our manuscript and as stated before the values given there are mean values from a given test location. For the specific location that you refer to we have six stress measurements, where the values of Shmin from these tests were 9, 11.5, 17, 18, 15.5, and 14 MPa (with an average Shmin of 14.2 MPa and a SD of 3.4 MPa), whereas the computed values of SHmax are 17, 18.5, 29.3, 30.5, 30, 27 MPa (with an average SHmax of 25.4 MPa and SD of 6.0 MPa). However, we have decided to recompute the SHmax values based on the Shmin, mean Pr, and assumption of no pore pressure rather than taking values from the report. As a result, values from the hydrofracturing report presented in Table 1 (see attachment) and values in our manuscript differ slightly. In the end, we find the recomputed SHmax values from the hydrofracturing report (Table 1; see attachment) as questionable as the SHmax magnitude in some cases seems to be lower than the Shmin magnitude. However, if you have more insights here, we would be very happy to discuss this issue in more in-depth. We will extend the text accordingly to make the reader aware why there are differences in numbers.

5. In line 25 (vertical borehole B4V) the SHmax = 21.3 MPa, but in the Diplomarbeit the highest SHmax value is 14 MPa only. Long story short: I assume that the values given in the publication were correctly determined by a procedure that I simply cannot resolve.

In the well B4V, the same principle as before (i.e., in the well B2V) was applied. The values of SHmax were recomputed from the three stress measurements, within this test location, based on the Shmin magnitude, mean Pr, and assumption of no pore pressure rather than taking values from the report (see Table 2 in the attachment) and resulted in 22, 22, and 19.8 MPa (with an average of 21.3 MPa and SD of 1.3 MPa). Again, some of the predicted values of SHmax in the report seem to be below Shmin, which we consider as questionable. However, if you have more insights here, we would be very happy to discuss this issue in more in-depth.

Here also some discrepancy between results presented in Kück (1988), where results from 4 hydrofracturing tests were presented and the report from MeSy GmbH from 1994, where only 3 tests were presented, was observed.

<u>Reply to comments from the manuscript:</u>

6. Iserlohn is not visible on the map

The figure we are referencing is Figure 1c, Iserlohn is on this figure (see on the right side of the figure).

7. Shouldn't the plot 'd' be left of 'b' chronologically and in the same sense as in plot 'a'

We created this figure, so it goes chronologically with what is mentioned in the text of the manuscript. Thus, we think that this is appropriate and would like to leave the figure as it is.

8. Some discontinuities appear in black but in the caption the darkest color seems to be violet, maybe choose another color like red.

We would like to abstain from using colors like red and green which could mean ‘bad’ and ‘good’, as the uncertainty of the input parameters for computation of slip and dilation is high and we would not like to ‘scare’ the audience. The values presented in our paper should be treated more in a relative sense and proper probabilistic assessment of fault reactivation potential, including wide uncertainty of all input parameters, in the area should be carried out in the future using our data set. Also, the color scheme we selected is more readable for people with disabilities. Thus, we would like to leave the figure as it is.

Dear Paola Montone,

Thank you for your insightful comments regarding our manuscript. Please see our replies below.

With Best Regards,

Authors

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Reviewer: Figure 1: to clarify the spatial location of data for a wider international audience, Germany has to be included in a wider map (e.g., Europe).

Authors: We agree with the comment and implement a map of Europe into Figure 1b.

Reviewer: Figure 1b: it could be helpful for the readers to have information on the kinematics of faults and about their age and relevance. I would suggest also adding a first order tectonic scheme.

Authors: Thank you for the comment. We add an indication of fault kinematics and their age to the text in the chapter “Geological Setting”. We have also described the relevance of these structures in the area in the text in the same chapter. How these structures influence the present-day stress state of the area remains unknown, however results from the Natrap-1 well (presented in the manuscript) could prove that these structures perturb the regional stress state. We also add a sentence about first-order tectonic scheme of the region and add the NE-SW striking faults, as well as major natural regions of Germany (Westphalian Lowlands, Rhenish Massif, and Lower Rhine Plain) to Figures 1, 7, 9, and 10.

Reviewer: Figure 1a: Morawietz et alii is reported as 2021, please check the year.

Authors: This reference is reported as Morawietz et al., 2020 across the manuscript.

Reviewer: Figure 1c refers to a section that is not shown in Figure 1 a) or b). Please, also add some information about the lithology of the geological formation.

Authors: We improve that by adding a seismic line location to the Figure 1b. We are not sure to what exactly the second part of this comment refers to. We indicate stratigraphic units in the cross section in Figure 1c and describe the lithology in chapter “Geological Setting”. We hope that this amount of information will help the reader to familiarize him/herself with the geology of the region.

Reviewer: Line 75 to line 85: for a better comprehension this paragraph should benefit from an additional figure.

Authors: We tried to reduce the number of figures in the paper and believe that having a geological cross section in Figure 1c as well as fault maps in Figures 5,7, 9, and 10 is enough for the reader to comprehend that part of the text. Thus, we decided not add additional figure to the manuscript.

Reviewer: Line 108 and 109: I didn't find within figure 1b the places and names the authors reported along the text, as well as the toponyms described in the test location description. For those unfamiliar with the region, it is difficult to follow the text and almost useless to report so many names if they are not represented in the figure. Surely most readers do not know the studied region.

Authors: Thank you for this comment. We agree with the comment and add the names mentioned in the text to all figures of the manuscripts.

Reviewer: Line 206 and 207: This sentence has already been written on lines 191 and 192.

Authors: We amend the sentences to omit the repetition.

Reviewer: Line 231: Please provide more information about Muskat pressure plot.

Authors: We add reference to this sentence.

Reviewer: Caption Figure 6: not very clear the sentence "is shaded in light grey" (there is no shaded areas in the figure)

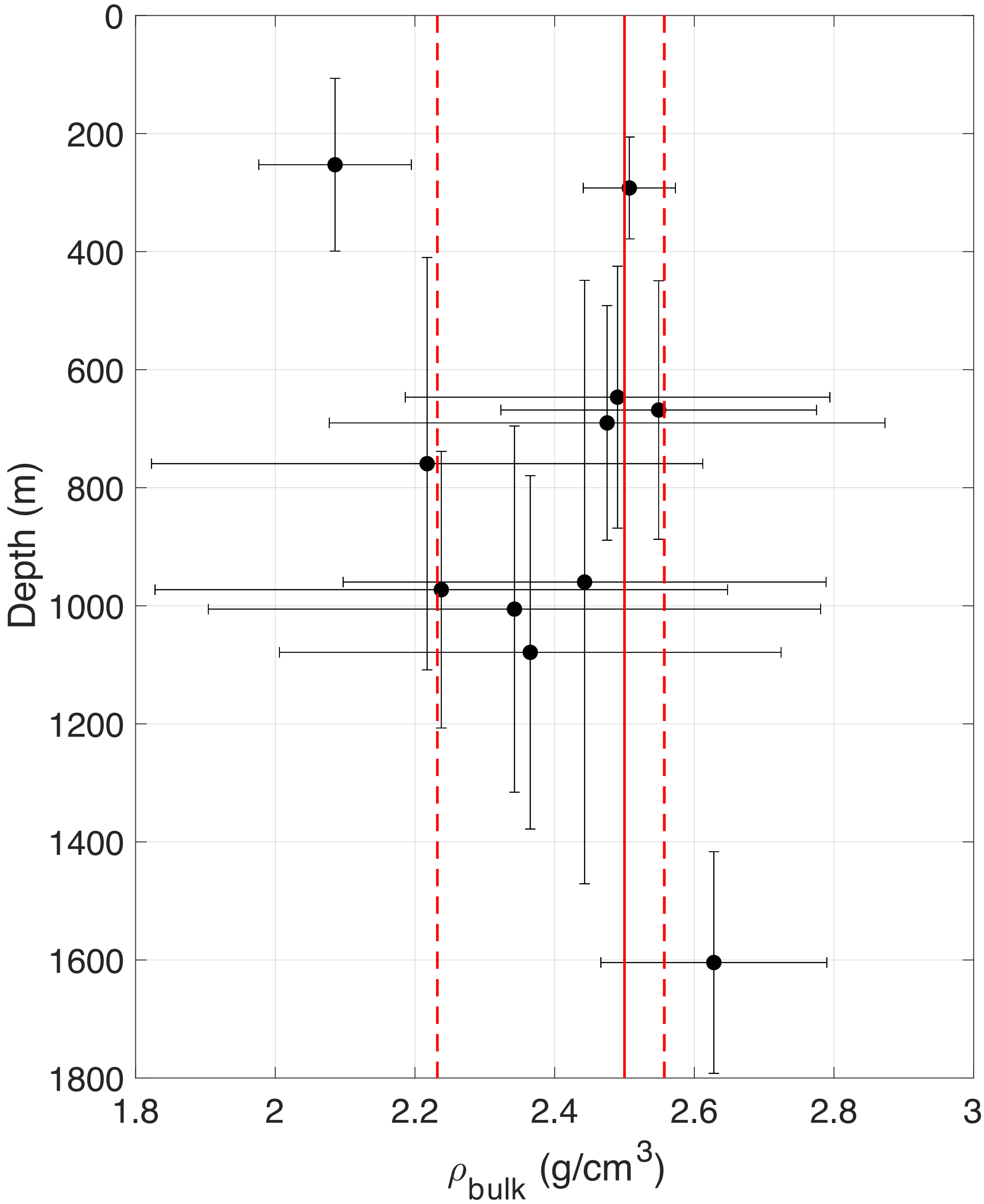
Authors: To improve readability, we change the shaded area to an ellipse outlined with red colour.

Reviewer: Line 320: please provide the location of Natrap 1 well

Authors: Natrap-1 well is presented in Figure 1c. We decide to include the names of cities where wells (discussed in the manuscript) were located; for the Natrap-1 well it will be the city of Hoetmar (and Natrap-1 well is therefore indicated as a green bubble). We update Figure 1b and 7 and include the mentioned location.

Reviewer: The authors use a standard density of 2.5 g/cm3 in their calculations. I am wondering if this value is not too low for this kind of rocks. Please give more explanations for this choice.

Authors: The bulk density value of 2.5 g/cm3 was based on the results from laboratory studies on the Ruhr Sandstone rock samples. We included in the manuscript references to two laboratory studies, which confirm these bulk density values (i.e., Brenne, 2016; Duda and Renner, 2012). Assuming, however, that coal seams (of much lower bulk density, i.e., approx. 1.5 g/cm3), as well as shales (of slightly higher bulk density i.e., approx. 2.7 g/cm3) are common in the Carboniferous layers of the greater Ruhr area, the mean bulk density of the area will fall around the value of 2.5 g/cm3. As a result, we consider this value to be a good first-order approximation for the region. For more local studies, of course, more detail bulk density profiles (or local geological models) should be considered. To prove our assumption on bulk density, we attach below the bulk density values registered from geophysical borehole logging campaigns in 11 wells across the greater Ruhr region penetrating in the Carboniferous rock mass. In the Figure below, with red solid line we indicate the assumption made in our study (i.e., bulk density of 2.5 g/cm3) and with dashed lines we present standard deviation limits based on data from the 11 considered wells. Although, we cannot statistically prove the correctness of our assumption, based on the gathered data, bulk density of 2.5 g/cm3 is still a reasonable assumption for the region at depths considered.



Reviewer: I am wondering what is the dipping of the induced fractures. Are all verticals?

Authors: To see the dip angle of induced fractures please see column "frac_DIP" from the database: https://fordatis.fraunhofer.de/handle/fordatis/272. But to answer the question, not all induced fractures were vertical.

Reviewer: The average Shmax orientation is affected by a large error (+-43°): although the statement starting at line 382 is formally correct it must be emphasized the large standard deviation. It may be argued that with such a large uncertainty it is difficult to find something in strong disagreement. In essence, I'm asking the authors to reshape the statement considering the existing important uncertainty.

Authors: We agree with the comment and make changes to the text in the "conclusions" chapter accordingly.

Reviewer: Lines 385 and afterwards. I would suggest authors to reshape the conclusion about the "most critically stressed structures" in a smoother way due to the large uncertainties on the results of this study.

Authors: We agree with the comment and make changes to the text in "conclusions" as well as "discussion" chapters. We also include a comment where we emphasize that to fully understand the uncertainty on the slip and dilation tendencies of the major faults in the region, more probabilistic assessment (such as the ones presented in Walsh and Zoback, 2016 or Healy and Hicks, 2022) are needed and should be investigated in future studies.

Dear Daniel,

thank you for your questions. We are coming back with answers.

In the end, the present-day in situ stress state of the greater Ruhr region is far from simple. Due to more than 700 years of coal mining activities across the region (i.e., rock withdrawal and pore pressure reduction due to pumping out of the water from the mines, as well as recent mine flooding operations), it is expected that the in situ stress state "situation" has changed significantly. The hydrofracturing tests we have analysed, although being located around 40 meters away from the mine infrastructure, can be still considered to be located within the mine's local sphere of influence. Thus, we expect that the derived stress magnitude values besides general measurement errors have also systematic errors (assuming that the undisturbed stress components are being measured). These uncertainties as well as the ones resulting from fault geometry assumptions and pore pressure values (see below) need a sound assessment to derive uncertainties and mean values of the slip tendency. The value that we present is only from a single set of parameters and should be interpreted with caution and we will make this clearer in the paper to avoid conclusions by the reader that are not robust.

Regarding the pore pressure the hydrofracturing tests recorded very low or zero values. These negligible pore pressures could be explained by i) impermeable rock mass (mentioned in the manuscript and exemplified with low permeability values registered during in situ testing) and ii) long-term mine water drainage (ongoing until this day) which led to significantly low pore pressure values within the mine and in its close vicinity. Additionally, fluid withdrawal in the Ruhr region could lead to a significant poro-elastic stress changes induced by the reservoir compaction (Segall & Fitzgerald, 1998; https://doi.org/10.1016/S0040-1951(97)00311-9). It has been also observed in the Ruhr region that the mine flooding operations produce a significant amount of microseismicity, potentially proving the criticality of the geological structures in the area and a significant amount of stress changes created by the mining activities (see: https://doi.org/10.23689/fidgeo-4002 and https://doi.org/10.23689/fidgeo-5401). We have, anyway, used the stress measurements from mines to construct total stress gradients of the area. Figure 6 presents a normalized stress polygon based on the assumption of no pore pressure with values of stress registered in coal mines and coal bed methane wells.

For the computation of the slip and dilation tendencies, we assumed that the pore pressure is present in the area at 1.2 km depth. This is due to the fact the pore pressure reduction by dewatering activities is a local phenomenon and areas located away from coal mines (or dewatering stations) are expected to remain unaffected. In the end, the pore pressure field of the greater Ruhr region remains relatively unknown. From the recent mine flooding operations in the area, it is known that in some coal mines the water level is located at depths between 0.6 to 1.2 km (see Fig. 1). Such water table reduction would mean a decrease in pore pressure values between approx. 6 and 12 MPa and showcase that local pore pressure differences will be significant in the region. Such pore pressure changes will drastically change (i.e., decrease) the slip tendencies of major faults in the region. We could agree that the assumption of the abnormally high pore pressure, we did in the manuscript, could be seen as a bit of an exaggeration. The abnormally high pore pressure values were assumed from the recent study by Kruszewski et al., 2021 (https://doi.org/10.1007/s00603-021-02636-3), where they established that elevated pore pressure gradients could be observed in the Ruhr region (based on a high density of water samples in the coal mines and recorded drilling fluid densities from the exploration drilling campaigns in the region). For simplicity, we agree on amending the pore pressure values in the computation of slip and dilation tendencies to a hydrostatic pressure of cold water starting from the surface (i.e., with a pore fluid density of 1000 kg/m3 the pore pressure at 1.2 km depth will amount to approx. 11.8 MPa). In this way, as you pointed out, the slip tendencies will stay below 0.75 (please see Fig. 2 for a new map of slip tendency).

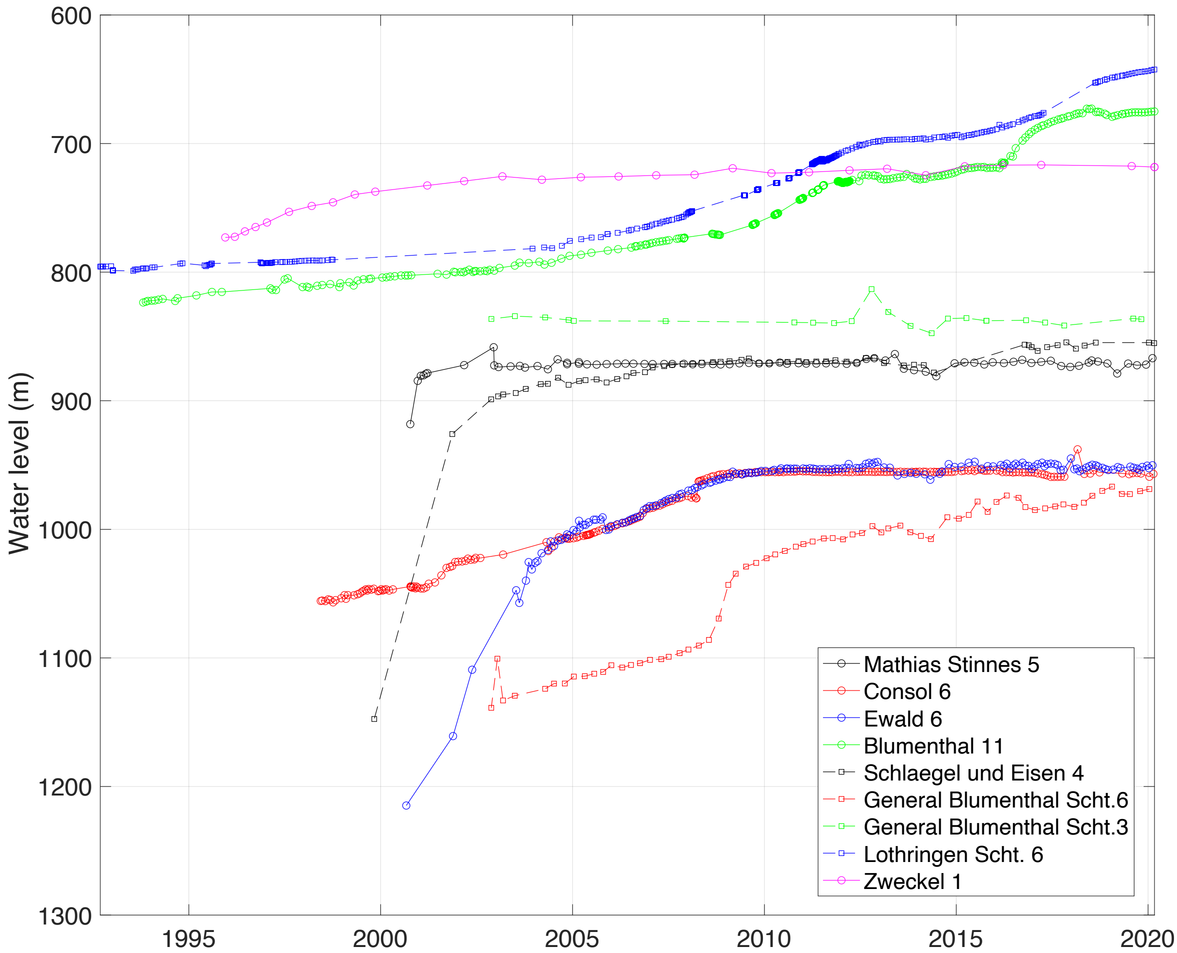


Fig. 1. *Water levels in different monitoring stations throughout the Ruhr region registered until 2020. The open-source data was accessed from geodaten.rag.de.*

The main scope of our study was, however, to present in situ stress magnitude and orientation data compilation. The slip and dilation tendencies presented in the manuscript were just one of the possible applications of this data set. The effects of pore pressure influence should be, however, investigated in follow-up studies using our database as a reference. Additionally, we would recommend performing in situ measurements in areas not affected by the coal mines (e.g., south of the Ruhr region) to compare with the ones performed in coal mines. I hope that cleared out your doubts and please do not hesitate to reply to this reply.

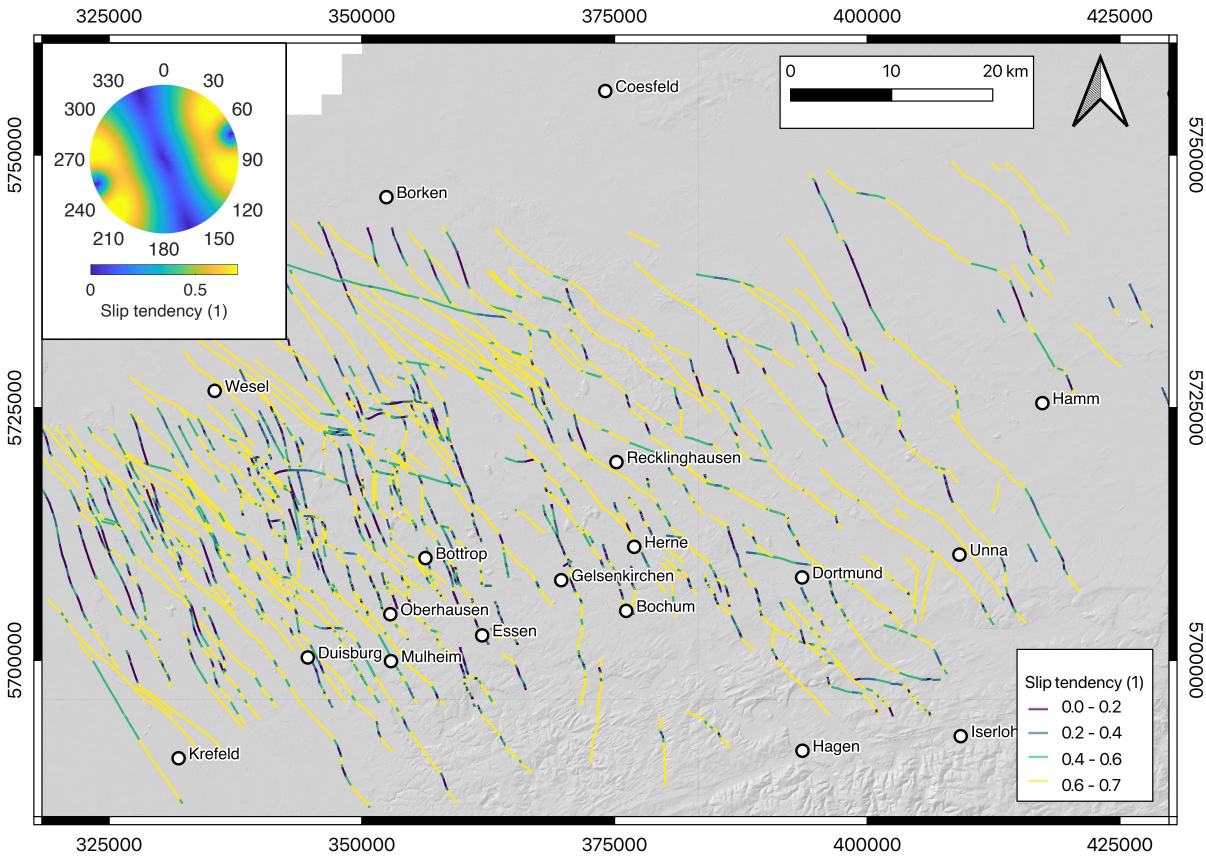


Fig. 2. *Slip tendency of geological discontinuities within the Ruhr region (GD NRW, 2017) at depth of 1200 m computed based on the stress tensor constrained from this study with P_p of 11.8 MPa, S_{hmin} of 17.4 MPa, S_{Hmax} of 33.7 MPa, S_v of 29.3 MPa, and average S_{Hmax} orientation of 161◦. Stereographic projection of slip tendency based on the constructed stress tensor is presented in the top left corner.*

Dear Joschka,

Thank you very much for your comments. They really helped us to improve the quality of our manuscript and posed some new and interesting questions regarding the importance of regional tectonics. What we would like to emphasize, that the main scope of our study is to provide a high-quality in situ stress magnitude and orientation dataset (and its detailed description) and to present ways of how this dataset can be used for future studies. We encourage, however, to use our dataset to motivate future studies related to topics regional geology or tectonics. Please see below our answers to your comments in detail.

With Best Wishes,

Authors

Comment: "In this context, what are 1900 m of depth below surface (your studied formation) compared to dozens of km horizontal movements that occured at the nearby Osning Fault?"

Author reply: We are not perfectly sure what the question is. Did you mean, how the Osning fault, being the limit of the Variscan Deformation Front, influenced our hydrofracturing test results? Such speculations would go far beyond what our data is able to provide. We encourage, however, future studies to use our dataset in combinations with modelling techniques to investigate such influence. However, from other studies that we about to publish we conclude that at a distance of 500 – 1000 m from an active fault the impact of the stress magnitudes is rather small compared to the uncertainties of the stress magnitude data.

Locally the stress orientation can be influenced by fault zones. However, in more homogenous sections, were no faults crosscut the rock mass, the stress orientations measured during hydrofracturing tests will reflect the actual far field stress. This could be seen e.g., in the "Heldburger Gangschar", which shows numerous dikes from Tertiary (Miocene) which crosscut all older structures and faults without any stress rotations.

Comment: "What does it mean when your data agrees with the regional stress regime (Shmax = +/-160 degrees)? What is the cause for this orientation? Did this stress orientation change over time? What are the major tectonic features in the surrounding?"

Authors reply: The mean orientation of S_{Hmax}, based on our and previous studies from the region, amounts to a value of 161 +/- 43°. This means that there is a high variability of the S_{Hmax} orientation in the region. The data that was used to compute this value is based on the present-day stress indicators (i.e., hydrofracturing tests and borehole breakouts) and, therefore, it represents the orientation of the currently acting SHmax. The main cause of the present-day stress orientation of the greater Ruhr region can be perhaps to best explained as a combination of the ridge push from the central and northern segments of the Mid-Atlantic ridge, the northwards directed push of Africa with respect to Europe. The (paleo)stress state has change over time (and in different geological periods) where the area, except of the Variscan orogeny and its deformation front, was affected by the tectonic movements of the

Late Triassic, Late Cretaceous transpression, and the Tertiary extensional movements (Drozdzewski, 1993). For more detailed information on the regional tectonics please see Drozdzewski, 1993 and Drozdzewski et al., 2009; we add both these references to our manuscript. We add the main tectonic features to the chapter "Geological Setting".

Comments: What I am missing in your analysis / discussion is the regional tectonic context.

Authors reply: We accept this comment and additional information and references to the "Geological Setting" chapter as well as briefly discuss the regional tectonic context of our data in the "Discussion" chapter.

Comment: Last but not least, the Alpine Orogeny definitely contributes to the present-day stress field in your study area, however the Alps and their far-field tectonic effects (i.e., basin inversion in Northern Germany and platform tilting in the south) are not mentioned in the text.

Authors reply: We agree with the comment and include the Alpine Orogeny to the text of the manuscript.

We would like to also thank for the extensive list of additional literature. We decided, however, not to include these, as we believe that they are not directly relevant to the focus of our paper.

References:

1. Drozdzewski, G. (1993). The Ruhr coal basin (Germany): structural evolution of an autochthonous foreland basin. International Journal of Coal Geology, 23(1-4), 231-250.
2. Drozdzewski, G. H., Hoth, P., Juch, D., Littke, R., Vieth, A., & Wrede, V. (2009). The pre-Permian of NW-Germany structure and coalification map. Zeitschrift der deutschen Gesellschaft für Geowissenschaften, 159-172.