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Solid Earth Discussions

Interactive comment on "Stress rotation – The impact and interaction of rock stiffness and faults" *by* Karsten Reiter

Anonymous Referee #1

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Stress rotation - The impact and interaction of rock stiffness and faults

By Karsten Reiter

The paper addresses stress rotation based on geomechanical numerical models. The models consist of different elastic units that are oblique to the direction of contraction. These units have variable mechanical properties and are separated by slipping surfaces. The geometry and boundary conditions are inspired by the geology of the German Central Uplands. A series of models are run based on a 3D finite element method. Results are presented to discuss the roles of density contrast, a variation of Poisson's ratio, a contrast of Young's modulus and friction of the discontinuities.

The paper is of interest in the context of regional studies in central Europe, for applied

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studies dealing with local or regional stresses, and more generally for better understanding stress field at the regional scale in inhomogeneous areas. The results presented in the paper are interesting. However, I found that, while the literature review sections are lengthy, the methodology and the result sections are a bit sparse and need further clarification/explanation. I also found the paper difficult to follow and both the writing and the organisation of the paper need to be improved before publication. I recommend the publication after a major revision. Specific and technical comments are detailed below.

Specific comments:

Introduction and Section 2. The author decided to provide a short introduction followed by a section of literature review (section 2). I am not sure that this separation is appropriate for this paper. Section 2 is a bit lengthy, difficult to read and has a significant amount of information that I think is not needed in the frame of this manuscript. I think that deleting unnecessary information and merging contents of section 2 with the introduction and with section 4 will improve the manuscript. See below some suggestions for shortening the text.

L.54-61: I will delete this because it is detailed after when introducing the three orders.

L.62-69. These sentences could be significantly reduced. For example: “There are several features in the continental crust that can modify stress pattern on a local or regional scale. These features can be classified depending on their spatial coverage (Heidbach et al., 2007, 2010, 2018; Zoback et al., 1989; Zoback, 1992). According to this classification, stress sources refer to as first, second and third-order extend over distances >500 Km, between 100–500km and <100km. These distances are larger, approximatively the same, and smaller than the thickness of the lithosphere, respectively.”

I don’t think that it is necessary to introduce what is a stress. A reference to one textbook existing on the topic should be enough. Therefore, from my point of view,

section 2.2 can be entirely removed. Stress parameters such as Sh, SH and SV can be introduced when they are first encountered in the manuscript.

I don't think that section 2.3 is relevant. I think that referencing the world stress map in the geological setting is enough.

L.124-135. This paragraph is difficult to read and could be simplified as follow: "This study focuses on stress rotations that occur horizontally, i.e. in the map view. A vertical uniform stress field is assumed, which is consistent with previous studies (Heidbach et al., 2018; Zoback et al., 1989; Zoback, 1992). Vertical stress rotations observed within deep wells (Schoenball and Davatzes, 2017; Zakharova and Goldberg, 2014), due to evaporites (e.g. Cornet and Röckel, 2012; Röckel and Lempp, 2003; Roth and Fleckenstein, 2001), or man-made activities in the underground (e.g. Martínez-Garzón et al., 2013; 135 Müller et al., 2018; Ziegler et al., 2017) are not considered for simplification. On a map view, several potential sources of stress can superpose on top of each other and the resulting stress at a certain point comprises the sum of all stress sources from plate wide to very local stress sources. Differences between the resulting stress orientation and the regional stress source can be described by the angle γ (Sonder, 1990), which can be substantial and can last in a change of the stress regime (Jaeger et al., 2007; Sonder, 1990; Zoback, 1992). ". But I am not sure what is the meaning of "can last in a change of the stress regime".

L.152-158: "Mechanical strength describes the material behaviour under the influence of stress and strain." I am not sure about this definition. From my understanding, rock strength refers to the capacity of the rock to fail but not to the elasticity.

L.167-170: "Small differences between the horizontal stresses increases the effect of faults on the local stress pattern, whereas large stress differences lead to more homogeneous stress pattern" This is not clear. This depends on the orientation or the fault relative to the stress and this depends on the difference between the max and min principal stresses S1 and S3, which are not always Sh and SH.

Section 3. Alike section 2, this section is difficult to read.

L.175-180. “These data. . . Anatolia” I think that these sentences could be removed.

L.195-200: “Among other things. . . 2006”. This is not clear. You could replace by “In particular, these previous studies investigated the impact of. . ...

Section 4. I have several questions concerning the methods and assumptions. Some of these questions are partly addressed in the discussion, but I think the author should provide further justifications and clarifications. This does not necessarily imply running additional models, but the author should clarify, explain and justify the limitations of the models.

The dip of the contacts between the units (vertical) should be indicated in the methodology. How is it compared to the dip of the structures in Germany? How does the dip used in the models impact the results?

I found the term “basic material” not very clear, maybe use “reference material”.

Maybe the author can provide some illustrations of the actual model and mesh. The materials are elastic, but what about its strength (capacity to fail, see previous comment L.152-158)? Is it possible that the materials reach failure in some parts of the models due to the boundary conditions and stress concentrations? How this could modify the results? More generally, there is no indication of the stress magnitude within the model, except for the boundary condition.

I am afraid I do not fully understand the boundary conditions. What is the pre-stressed basic model, initial stress? Where is the virtual well? For which model does the boundary condition is calibrated? I imagine that different boundary conditions will be needed to fit the stress profile presented in Fig.4 depending on the rock properties. Is the boundary condition similar for all models? What is the impact of the boundary condition on the results? I agree that SHmax is more difficult to calibrate, however, it seems that the chosen value is significantly different than the one provided in the Brudy et al.

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(1997). In particular, there is no change in the stress regime in the case of Brudy et al. (1997). I think it is important to understand the impact of this change in the stress regime in the models and discuss it, as it is poorly constrained.

The results concern the stress orientation at a depth of 1000 m below the surface, where there is a strike-slip fault regime according to the chosen boundary condition. How do the results change with depth and as a function of the stress regime? Why the results only concern the depth orientation at 1000 m? Also, do the rotations only occur in map view or is there also stress rotation in cross-section. In other terms, is the plan of observation presented comprise the principal stress?

The author tests separately different parameters: the density, the PR and the YM. The ranges of parameters tested seem correct. Models are designed to test each parameter individually. I think that this is a relevant method for a generic study. I am wondering however what is the geological meaning of this. In nature, these parameters can be interdependent. For example, a rock with a low density may have a low YM as well. Also, do the materials and discontinuities have constant properties with depth? How does this potentially impact the results of the models? I recommend the author to discuss further these points.

Section 5.

In the methodology, it is stated that the model is orientated relative to the North. Therefore, why no presenting the results with actual stress orientations rather than talking about clockwise and anti-clockwise rotation. Maybe this will help a little bit the reading.

I found the results difficult to compare between the models. Maybe a cross-plot or a histogram comparing the various models could help.

I found that the results section lack of explanations of the behaviour of the model. For examples, what causes the rotation in the case of the density models? Why the models with the faults have little rotations. Is it because the faults are not critically

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stressed because they are not optimally orientated? More generally, I encourage the author to provide rationals for the observed behaviour.

Section 6.

It seems that the author made a significant effort in reviewing previous studies on stress rotations. I will suggest providing a table summarizing this. This will help the reader and be an added value for the manuscript.

Concerning stress rotation and faults. Do we expect the stress rotations to be time dependant and change between when the fault is locked and when the fault slip? Concerning the results from the upper panel in Fig. 10. There is a significant difference between the behaviour in the shallow part of the model and the deeper part. Is this related to the boundary condition and the fact that the faults are critical stress in the strike-slip regime and locked in the normal faulting regime?

I think that section 6.8 should be presented in the result section and not in the discussion. “The comparison will concern only the results of the models investigating the Young’s modulus, as this material parameter have the strongest impact” but the model integrate densities and Poisson ratio according to table 2? Also, to help the reader, maybe the author could cross-plot the stress rotations from the model with the stress rotations from Fig. 1.

General organisation. Generally, the necessary pieces of information are provided in the manuscript, but I found that the paper lack clarity and organisation. The investigated geometry is interesting. I think however that the results depend on the chosen geometry, especially the strike and dip of the discontinuities/units and are therefore limited in scope. From my point of view, this work is both a generic study and a simplified study case. Accordingly, I recommend the author to re-organise their manuscript into a more classic scheme. For example (1) an introduction that merges the content of sections 1 and 2 after removing all unnecessary materials, with a review of stress rotation, a review of the key controls and a summary of the objectives (a generic study that

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aims to identify the key parameters and a case study in central Europe where there is good coverage of the stress field and a good knowledge of the regional geology to test the parameters). (2) Methodology. (3) Geological setting of the study case. (4) Result section divided into (i) generic models and (ii) a more realistic model. (4) Discussions centred on comparing the results with previous works.

Text. I think that the manuscript suffers from numerous English mistakes and unclear sentences. This sometimes obfuscates the message and I think that the manuscript, in general, will benefit from thoroughly polishing the text before publication. Several suggestions are provided below, but this is by no means an exhaustive list.

Technical comments:

L.31: “It was suggested, that” remove coma after suggested.

L.35: “sediments, and were” remove “and”.

L:37-40: These sentences are not very clear. I am not sure to understand what “the assumed stress pattern (stress rotations)” refers to.

L.39: “can only partly explained” replace by “ can only be partly explained”.

L.43: “These 2-D models was” replace by “These 2-D models were”.

L.43: “stress pattern” replace by “stress patterns”.

L:43 “, applying” replace “ by applying” and remove coma?

L.44-46: Maybe this could be simplified. For example: However, these 2D models cannot account for topography, crustal thickness and depth variability in stiffness and can overestimate horizontal stresses (Ghosh et al., 2006). Furthermore, none of these previous studies compared the impact of the influencing factors separately.

L.47-48: Not clear. In this paper, we use a series of generic models to identify which properties can cause substantial stress rotations away from a material transition or a

discontinuity.

L.49: “orientations” replace by orientation.

L.49: “north-south orientation” N-S orientation.

L.51: Orientations are usually given with three digits. N030°.

L.50-51: “The basement structures there are striking about 30âÛę , which is perpendicular to the observed SHmax orientation” actually N030° is not perpendicular to N150°, there is a 20° misfit.

L.57: “The second major driver are” replace by “The second major driver is”.

L.57-58: “Plate boundary forces where identified and derive deviatoric stresses” this sentence is not clear.

L.62 : ”The most of these features” replace by “Most of these features”.

L.62-135: see some corrections in the Specific comments section.

L.135: “both is not a subject of that study” replace by “both are not the subject of this study”.

L.168: “between the horizontal stresses increases” remove s at increases.

L.169: “ is investigated” replace by “has been investigated”

L.191-192: “The explanation of that crustal structure are a cold, dense and slowly subsiding lithospheric root beneath the Alps (Müller and Zürich, 1984).” replace by “This crustal structure can be explained by. . .”

L. 193: “an subject” replace by “the subject”

L.195: “which factors contributes” remove s at contributes.

L.207: “topography has major effects” replace by “topography have major effects”

L.232: “grade varies considerably” remove s at varies.

L.243: “Model dimension” maybe replace by “Model geometry”.

L.247: “oriented 30âŰę counter-clockwise from east-west” why not just say oriented N030°.

L.248: “three unit” replace by ‘three units”.

L.257-260: “The finite. . .. 1986).” I think that the contents of these sentences are unnecessary. Maybe replace by “ The stress orientations in the models are investigated using the finite element method (FEM)”.

L.274: “Figure 3 visualize” replace by “Figure 3 visualizes”.

L.277: “Young’s modules” replace by “Young’s modulus”.

L.279-280: replace “where” by whereas” and “mantel’ by “mantle”.

L.314: “result in” replace by “results in a slightly counter-clockwise”.

L.341: “degreases” replace by “decreases”.

L.343: “exhibits” and “displays” remove s.

L.345: In terms of mechanical properties, the opposite of “stiff” is usually “compliant” (elasticity), whereas “weak” is the opposite of “strong” (strength).

L.368: “Fore sure it is really unlikely that” replace by “It is unlikely that”.

L.376: “in a depth of 1000 m depth” replace by “at a depth of 1000 m”.

L.388: “ are may be” remove are.

L.390: remove coma after suggest.

L.392: this sentence is not clear.

L.395: “the relative rotation are” replace by “the relative rotations are”.

L.401-402: “ The importance of stiffness differences is an result of other models too..” This sentence is not clear. “Similar impacts of stiffness contrast have been described in previous works. . .”

L.415-417: These sentences are unclear.

L.424: “this generic models” replace by “these generic models”.

L.462: There is 6.8.1 but no 6.8.2?

L.430: “indicates” replace by “indicate”

L.431: The work by Petit and Mattauer, (1995) concern mesoscale faults and I am not sure about this 2 km distance indicated here.

L.431: “is to” replace be “can be”

L.466: “parameter have the” replace by “parameter has the”

L.477: ”should deflected” replace by “should be deflected”

I hope this will help to improve the manuscript.

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