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

Karsten Reiter

reiter@geo.tu-darmstadt.de

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I have to thank Referee #1 for having read and reviewed the manuscript carefully and in detail. She/He understood both, the indention of the paper and the modelling approach (generic models) very well. RC1 gives many detailed suggestions to shorten and clarify the manuscript, which are very helpful. RC1 proposes to reorganize the paper by integrating the section "Stress in the Earth’s Crust" into the introduction in a shortened form. That’s a reasonable suggestion.

In the following, I will give comments and answers to specific questions or suggestions. RC1’s questions are marked by quotes.

“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?”

All contacts are vertical in the used models. For the zone transitions in the German Variscites, NNW directed trusting combined with sinistral but also dextral shearing due to oblique convergence has been identified. The dip angle of that units is uncertain, but according to some authors probably only about 10°. Furthermore, changes of rock type and material properties with depths are uncertain. Only reflection seismic profiles (DEKORP) from the 1980’s and their interpretations are available. A variable dip angle like the suggested one has not been tested. I don’t want to speculate on potential results, but a resulting pattern will be different to the presented model results. However, it was not the goal to model that region appropriate. The focus was on the question to identify the impact of the chosen material properties, low friction discontinuities and their interaction as well.

“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,. . .)? 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.”

The visualization of the mesh would need a big figure, as the model even in the map view (x-y-direction) consists of about 11,000 Elements. The lateral resolution is 3km, as described in the manuscript. As only elastic material properties are used, failure is not possible. I tested the EEE and eee Model using two different Coulomb failure criteria. The models are run first with a cohesion (C) of 30 MPa and a friction angle (FA) of 40° and second with C= 10 MPa and a FA of 30°. For the EEE model with C=30 MPa and FA=40°, no failure (Yield criteria <1) will be reached. For the eee model using that criteria and for both models (EEE and eee) using C=10 MPa and FA=30° failure occurs. Conditions of failure or close to failure (Yield criteria $\sim$1 or >1) occurs only near the surface (a few km) and close to the material transition (~20-30 km). Around the material transition, (near) failure can be observed within the stiff units only. For the EEE model with C=10 MPa and FA=30°, failure is more spaciously distributed near the surface. In the case of failure, the SHmax (SH) orientation will be balanced, which means, that SH rotates back in the north-south orientation, like the boundary conditions. In general, failure compensates stress rotation in the same way like low friction contact surfaces (faults).

The stress magnitudes of the reference model are shown in figure 4. Magnitudes of the other models are similar on the same place, depending on the material properties and whether there is a significant material transition in the neighbouring unit or not. For models having a lower Young's modulus, Shmin (Sh) and SH are lower, and the opposite for the models with the larger Young's modulus. Usage of variable material properties within the model units lead to different stress magnitudes within these units. The adjustment of the boundary conditions would always depend on which point of comparison would be chosen. Overall, the boundary conditions are defined by displacement, based on the reference model.

"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?"

Before boundary conditions will be applied to the model, initial stress conditions are needed. These initial stress condition are a more complex issue. First of all, gravity acts instantaneous to a model, which would lead to significant settlement of the model. The initial stress condition avoids the settlement to a large extend. Furthermore, the observed ratio between SV (vertical stress)) and SH plus Sh are not a linear function with depth in contrast to simple isotropic or hydrostatic assumptions. The k-ratio

((SH+Sh)/2*SV) is much larger than one in the first hundred to thousand(s) of meters and becomes smaller than one in greater depth. This observation is supported by many data, but also by a semi-empirical function, provided by Sheorey(1994). His model is representative for an Earth without topography and tectonics. By settling the model without lateral shortening, but a large Poisson' ration under gravitational load, the derived stress state provides a quite good fit to Sheorey's profile as a function of depth and the Young's modulus. Therefore, the initial stress conditions provide a stress state with depth, which accounts broadly speaking for conditions without tectonic shortening. The models are pre-stressed in this way and underwent the tectonic component, or the difference between Sh and SH by the application of lateral boundary conditions. The subject of initial stress condition where kicked out, because reviewers usually are not interested in that subject and asks to skip that topic.

The boundary conditions are simple, the model is shortened in north-south direction by 400 m and extended by 60 m in east-west direction, as shown in Fig 2. of the manuscript. The virtual well is in the centre of the model. The boundary conditions are calibrated on the reference model (Fig 4.). These boundary conditions are applied to all the different model runs. The usage of a different Young's modulus leads to a change of the magnitudes of SH and Sh. A larger Young's modulus will lead in larger stress magnitudes and vice versa. However, as mentioned earlier, a fit of a virtual well (stress profile) from a heterogeneous to a homogeneous model depends on the selected area or unit. Therefore, homogeneous boundary conditions are chosen. Less shortening/extension along the boundaries would lead to a lower difference between SH and Sh.

"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. (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."

It depends on the chosen way to put a regression line on Brudy's SH data. There is a change of rock properties with depth at the KTB site, which is visible in the magnitude data. I wouldn't take too much effort to fit the model to the SH magnitudes. They are not measured; they are calculated based on several assumptions. The rocks in greater depths, like the KTB well becomes more and more ductile. That was one of the reasons, why they had to stop drilling. To me, a proportional increase of SH versus Sh over lager depth sections is questionable. From the modelling standpoint, it is hard to model such increasing differential stresses. Complex boundary conditions are needed combined with low Poisson's ratio's for greater depths.

A change of the stress regime from TF to SS and to NF in greater depth like visualized by the virtual well is assumed by several authors like for the Alberta basin. Similar changes of the stress regime are reported for many other regions. However, the change of the stress regime with depth is not a subject of that manuscript. The stress orientation is visualized for a depth of 1000 m below surface. This depth is not affected by general changes of the stress regime from one of the models to another one. More important, the stress magnitudes become smaller within the stiff units next to the soft units. This seems to be the major reason for the observed stress rotation (and observed reaching of failure, using a Coulomb criteria), not the change of the stress regime.

"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 orientation of SH changes with depth, which is shown in Fig 10. The visualization of SH orientation is always in a depth of -1000m, to make it comparable. The scope of that paper is to investigate the impact of the material properties and faults,

as mentioned in the introduction. Due to the simplification of the model, I don't want to interpret the stress changes with depth too much in detail. However, the stress rotation decreases with depth (Fig. 10). Next to the material transition, SH and Sh becomes smaller near the surface and larger near the bottom of the model, within the stiffer units. In other words, the units with a lower Young's modulus causes a reduction of the stress magnitudes (SH and Sh) within the neighbouring stiffer units near the surface and increasing stress magnitudes in greater depth. It is not an issue of regime change. Magnitudes of SV, SH and Sh are pretty close to the principal stress magnitudes.

"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."

Sure, the tested material properties are not independent in nature. However, there is no linear relation between density, Young's modulus nor the Poisson's ratio. As shown by Fig. 3, density and Young's modulus for sediments are quite variable. For example, a limestone can have a smaller density, but larger Young's modulus as a shale. However, there is no geological meaning of the material variation, as it is a generic study. Sure, these properties will change with depth (or temperature) This is not included in the model. But usage of linearly increasing rock properties will affect the model results only slightly. Important is the effect of the material transition. For linear increasing density, Young's modulus or Poisson's ratio, the resulting effect remains similar.

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

Gravitational load is one of the major sources of stress in the Earth crust. This body force effects the magnitude of SV. However, due to the mechanical effect, which is specified by the Poisson's ratio, a locally increased SV lead to a local increase of SH and Sh, which can affect the stress pattern locally too.

The models with the faults have SH rotation next to the faults, as the principal stresses are always parallel or perpendicular to a fault (contact) like next to a free surface. However, observed stress orientation, which are presented in the figures are always placed away from the faults (>12.5 km), as I am only interested in the far field effects, not the near field effects. This near field effects around faults would be a different subject. The orientation is not optimal, but the chosen properties (C=0, FA∼5°) are that low, that the units on each side are decoupled from each other for sure. In general, active faults do not have a large impact on the far field stress pattern at all, except close (∼<10 km) to the discontinuity. That distance again depends on the Young's modulus.

"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?"

In the case of homogenous material properties, the far field stress pattern is independent whether a fault is locked or not, as shown by the model series with variable friction properties. The stress rotation is not time depended for the models, it's a function of the variable material properties and the boundary conditions. The faults in the models did not have any cohesion, the friction coefficient is quite low (0,1) which is a friction angle of about 5-6°. The different orientation of SH in the shallow and deeper parts are not affected by the boundary conditions.

The complex pattern in the upper cross-section (eEe) of Fig. 10 is a product of the fact, that no fault (or a locked fault) is included at the material transition. The pattern is a product of the interaction of the different Young's modulus in the neighbouring units. This leads to a reduction of SH and Sh near the surface, next the material transition within the stiff units. This leads to the complex stress pattern. Active faults decouple that (|e|E|e|, Fig. 10). They balance the stress orientation (and the stress magnitudes to a certain point).

"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."

Yes, it is an option, to place section 6.8 in the result section. Yes, the models apply all estimated material properties from the Variscan units in Germany (Table 2). It could be an option, to plot an average orientation from Fig 1 in comparison next to fig 11, allowing a better comparison.

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