Solid Earth Discuss., author comment AC2
https://doi.org/10.5194/se-2021-95-AC2, 2021

Reply on RC2

Hamed Fazlikhani et al.

Author comment on "Variscan structures and their control on latest to post-Variscan basin architecture: insights from the westernmost Bohemian Massif and southeastern Germany" by Hamed Fazlikhani et al., Solid Earth Discuss.,
https://doi.org/10.5194/se-2021-95-AC2, 2021

Reply letter to referee comment by Prof. Jonas Kley (RC2) on the article se-2021-95

Dear Prof. Kley,

Thank you very much for your comments and suggestions which indeed helped in improving the quality of our manuscript. Please see below list of comments and authors reply. In-text comments and their replies are also listed below. We would be happy to further discuss and clarify our replies if needed.

Comment1: *It would be helpful to have a map of the boreholes that encountered Rotliegend with thicknesses and interpreted subbasins. The text with all this information is a bit cumbersome to read.*

Reply to comment 1: We have added thickness of penetrated Rotliegend rocks and color coded basement drilled wells, please see revised Figure 1.

Comment 2: *You should elaborate somewhat on the interpreted relationship of the Variscan shear zone(s) and younger faults. With the main shear zone being very gently dipping and undulating, it is not easy to understand how it determines the locations and orientations of relatively steep faults or what "away from the shear zone" means for such geometries.*

Reply to comment 2: Interpreted shear zone shows antiformal geometry to the east and gets flat to the west. We argue that the geometry of the shear zone developed prior to Permian-Mesozoic brittle faulting (line 457-472), creating a locally folded shear zone. Number of major interpreted Permian normal faults in the study area also decrease westward, suggesting that such pre-Permian configuration of shear zone might locally localize the strain dictating the location of Permian faults. However, it should be noted that not all of the Permian fault are developed around the antiformal parts of the shear zone, showing that the orientation of Permian regional stress field is also a key controlling factor in brittle fault development. As the Permian faults grow and linkup, only the ones that detach to the underlying shear zone grow larger while other abandon. Please see revised text and Fig. 11b.

In addition, at the surface, number, spacing and length of reverse faults decrease westward, while normal faults developed in the Mesozoic cover increase. We also observe that brittle Mesozoic fault are clustered around the folded portion of the shear zone. Combination of mentioned observations suggest that pre-Permian structural heterogeneities localize the strain and facilitate Permian brittle faulting. Later during the Cretaceous inversion event, major reverse faults - either newly initiated or reverse reactivated Permian normal faults - are also developing around the folded parts of the shear zone. However, it is not entirely clear if the location and magnitude of reverse faults is controlled by the shear zone geometry, by preexisting brittle Permian faults or a combination of both structures. Please see revised chapter 5.2, Fig. 11b and Fig. 12.

Comment 3: *You don´t make a very explicit argument as to why younger reverse faults tend to splay from more strongly inclined segments of the shear zones. I assume this is due to the shear zones approaching the orientation of an ideal newly formed thrust fault. If that is what you think, you could say so more clearly.*

Reply to comment 3: Based on our observations, also mentioned in "Reply to comment 2", we argue that major reverse faults (entirely or some segments of them) are most likely reverse reactivated Permian normal faults. Our interpretation is based on the overlapping location of folded portion of shear zone and major Permian normal faults and reverse faults and wedge shape Permian stratigraphy. We also add that Permian faults developed in wide range of vertical and lateral scales in response to regional stress field and only the ones detaching into the shear zone have the chance to grow larger. In addition, reverse faults show a multi-segmented and curved geometry at the surface suggesting some degree of preexisting brittle fault involvement in their development. Although the latter statement needs more and detailed observations and documentation, we believe that reverse fault are developed in response to the combination effects of Cretaceous regional stress field and favorable orientation and Permian normal faults for reactivation, as it is mentioned in comment 3. Please see revised version of the manuscript.

Comment 4: *An intriguing structural detail in your interpretations is that SW-dipping Rotliegend normal faults do not become reactivated as reverse faults but still somehow manage to localize the very probably Late Cretaceous NE-dipping reverse faults. The new faults almost invariably pass through the tips of the older normal faults located near the base Buntsandstein. Any idea how this can be explained mechanically? My first intuition would be to expect the basement shoulder bordering a Rotliegend basin to become chopped off and thrust over the basin fill. In that case, however, the new reverse fault would carry a bit of basin and the decapitated old normal fault in its hanging-wall. I don´t know whether it is possible to come up with a good explanation, but you might acknowledge this as an enigmatic feature.*

Reply to comment 4: We do agree with Prof. Kley that the development of reverse faults in the study area are very enigmatic. Several questions arise in this regard, including why W and SW dipping Permian normal faults are not reactivated, or why the amount and the scale of reverse fault decreases westward? First limitation in our study is related to observing and describing structural details that are very important but are sub-seismic scale. Here it is very difficult and would be speculative to interpret faults, fault segments or upper tip of a fault of smaller than some tens of meters long, which is very important to draw any conclusion regarding the fault kinematics. Hence, it is very difficult to tell if normal faults in the hangingwall of a reverse fault is actually displaced portion of Rotliegend normal fault. Further detail studies in fault interaction, 3D seismic dataset would be very helpful.

In additions, it is not possible to connect interpreted faults across 2D profiles, except for km-scale large faults that are also mapped at the surface. This is particularly challenging in the study area experiencing several deformation phases from upper Paleozoic (Variscan orogeny) to upper Cenozoic time interval. We agree that it is definitely possible to develop reverse faults cutting through an existing but oppositely dipping Permian fault, translating parts of the footwall block and upper parts of the normal fault, but difficult to prove with utilized dataset and outcrop limitation in northern Bavaria. We have clarified this issue in our revised version.

Comment 5: *In Figs. 6 to 9, the lowermost panels showing your profiles in depth domain and without vertical exaggeration exhibit some inconsistencies with respect to the detailed seismic interpretation (mostly thicknesses and thickness trends) and loss of structural detail that is not enforced by the scale of the illustrations. I have marked some of the inconsistencies in the pdf. It looks like you have done the interpretation again. I would recommend to transfer the more detailed interpretation in time domain to the depth domain profiles and adjust their geometries. I assume you have done so with the line drawings, anyway.*

Reply to comment 5: Thank you for your attention, we have revised depth sections in Figs. 6-9 as suggested.

In-text comments

Line 75: *I find it difficult to argue with stress directions in orogenic settings where large translations and strong rotations are involved. Plus, why does the change from SW- to NW-directed transport indicate a 45° change in stress (maximum horizontal, I guess)?*

Reply: Agreed. Since details of Variscan related deformation phases is beyond the scope of this work, we tried to very briefly summarize relevant parts of published works. However, we have revised the text.

Line 80: *That should be D4 (Rotliegend). D3 is the main folding phase in the Rhenohercynian realm.*

Reply: We have revised the text accordingly.

Line 171: *The Heustreu fault shows clear signs of inversion (outcrops on A 71 motorway)*

Reply: We have revised the text accordingly.

Line 236: *Reads strange. In reality that must be a hiatus surface or, more commonly, an angular unconformity. Its being imperfectly imaged doesn´t make it transitional.*

Reply: Agreed. Please see revised manuscript.

Line 344: *Unnecessary and equivocal (it´s only clockwise when you view your section from the SE, but there is no convention for that different from vertical-axis rotations which are always described as seen from above). It´s also uncommon to indicate an azimuth for rotation (except something like "E-NE-ward tilting of blocks").*

Reply: We have revised the text accordingly.

Line 454: *But isn´t it easier to reconcile with SW-directed transport?*

Reply: We are only observing shallowing direction of mapped shear zone on seismic reflection profiles. Only based on seismic reflection data we cannot define any kinematic indictor concluding in the main transport direction. In addition, considering a spoon-shape 3D geometry for the mapped shear zone, both W-SW and NW tectonic transport direction could produce similar geometry of shear zone. However, based on the kinematic indicators observed and described in the exposed parts of the Saxothuringian Zone, we tend to prefer the W-SW transport direction. Please see revised manuscript.

Line 457: *Please specify: That is NW-SE-directed shortening across the ST zone plus dextral strike-slip parallel to it?*

Reply: We have revised the text accordingly.

Line 462: *Those are the SW-NE profiles. Why do SW-NE-trending folds show up prominently here? But maybe I got the first sentence wrong.*

Reply: We have revised section 5.2 accordingly.

Line 474: *How can the shear zones only be reactivated on the hanging-wall side of the faults?*

Reply: We argue that when a normal fault is active, down-dip slide and rotation of hangingwall block will eventually reactivates the underlying shear zone, while the footwall side remains unaffected.

Line 498: *Any idea how that works in terms of mechanics? How does a steeper shear zone favour higher fault displacement?*

Reply: We describe the relationships between shear zone geometry and brittle fault development in revised manuscript and add a cartoon (Fig. 12) clarifying this relationship.

Line 504: *Doesn´t that revert your argument from l. 491 f.?*

Reply: We show that when shear zone is folded, brittle fault has larger offset. However, such relationship seems to not be persistent, and at some point when accumulative amount of fault offset is in the order of several kilometers, faults tend to breakthrough and displace the shear zone. We have tried to clarify this in revised manuscript.

Figure 2: *Why do positive amplitudes of the synthetic trace correlate with negative ones of the real trace?*

Reply: This might be related to the higher resolution of synthetic seismograms derived from high resolution sonic log recording small velocity variations.

Figure 11: *I don´t understand this. What does sub-parallel mean when you refer to an undulating, overall sub-horizontal surface? Or how can you stay away from it? The block diagram and seismic profiles suggest the shear zone is present everywhere at depth.*

Reply: Correct. We have revised the figure and description, clarifying this issue.

Please also note the supplement to this comment:
https://se.copernicus.org/preprints/se-2021-95/se-2021-95-AC2-supplement.pdf