Point-by-point response to the reviews including a list of all relevant changes made in the article se-2021-95_Fazlikhani et al.

Reply letter to referee comment by Anonymous (RC1) on the article se-2021-95

We would like to thank Anonymous referee RC1 for constructive and generally positive comments helping further improvement of our manuscript quality. Following are comments made by anonymous referee (RC1) in italic and authors reply.

Comment 1: *Carboniferous-Permian boundary: Seismically the tectonic-stratigraphic contact between the Rotliegend and the subjacent ST sediments and metamorphics cannot be easily constrained in most of the seismic sections. This makes the exact definition of Rotliegend basin architectures very difficult, as they may be given by intra-BSF 1 (BSF is basaement seismic facies) reflections. Rotliegend thickness is very variable (0-2800 m) if drillhole data are used. I am not sure if this can be improved by different processing parameters, but this is certainly one of the weak points in the geological story.*

Reply to comment 1: Thank you for your comment. Thickness of Rotliegend units is highly variable in the study area, as it is also mentioned by anonymous referee. Beyond the study area and in SE Germany Naab Basin stores maximum of ca. 2800 m of Carboniferous-Rotliegend sedimentary rocks (Müller 1994). In the vicinity of FRANKEN seismic survey thickest Rotliegend units is penetrated by well Mürsbach 1 with 109 m (Table 1). A summary of penetrated Rotliegend units and their thickness changes in the study area is given in section 2.2, lines 110-131 and in the Table 1. We agree with anonymous referee that the boundary between Rotliegend sedimentary rocks and underlying low-grade metasedimentary rocks is not particularly reflective. In the section 3.3 line 227-237 we describe seismic reflection facies related to the Rotliegend units and mention that upper parts of the Rotliegend units are semi-continuous and medium amplitude reflections. To the depth it is not easy to distinguish the boundary between Rotliegend and low-grade metasedimentary units only based on the seismic reflection data. Hence, interpreted Rotliegend unit thickness would represent the minimum thickness, and as anonymous referee mentioned some of upper parts of interpreted low-grade metasedimentary rocks could also represent lower parts of the Rotliegend. However, it appears that there is a limited density difference between Rotliegend units with ca. 2500kg/m3 and Carboniferous units with 2520-2560 kg/m3 (e.g. Hofmann 2003) creating very limited velocity contrast between highly compacted Rotliegend units and low-grade metasedimentary rocks. This is basically main reason why the boundary between Rotliegend and low-grade metasedimentary rocks is not reflective. For instance, we referee anonymous referee to Fazlikhani et al 2017 (https://doi.org/10.1002/2017TC004514, 2017) where high density and therefore velocity contrast between sedimentary rocks and basement units create a very high amplitude reflection.

Comment 2: *Basement Seismic Facies (BSF) concept: The BSF 1-3 scheme looks logical at first, as it depicts a similar superposition everywhere - also in the published DEKORP seismic sections that are extensively discussed and form an important cornerstone of the paper. BSF 2, a packet of high-amplitude and continuous reflections is interpreted as reflecting a system of Variscan* *shear zones. This has been seen identically in the DEKORP publications (op. cit.), but note that some of these interpretations were in part dramatically disproven by the drilling data of the KTB further to the SE of the studied area. So, are these reflections necessarily images of shear zones? They may be, or may be not, and without ground-truthing by drillholes this is a difficult conclusion. More neutrally, BSF 2 reflections as zones of high seismic impedance contrast, that may relate zo a marked lithological change, grading downward into BSF 3, a seismic facies characteristic for higher grade metamorphics and plutonics of the Cadomian basement of the Mitteldeutsche Kristallinschwelle.*

Reply to comment 2: Unit boundaries show high amplitude reflections if important velocity change occurs, for example the Permian-Triassic boundary in the study area (Fig. 3E). In such cases unit boundaries show thin (<ca. 20 ms) high amplitude reflections, instead bundle of high amplitude reflections (BSF2) interpreted as shear zones in this study are 100-700 ms thick and dipping reflections shallowing generally westward. Shear zone interpretation along the FRANKEN survey is correlated against DEKORP90-3B/MVE and DEKORP85-4N, transecting the Münchberg nappe units and underlying shear zones. Surrounding Münchberg nappe units shear zones transporting nappe units are imaged as thick (>1000 ms) high amplitude reflection below the Münchberg nappe units (see Fig. 5) that are described at the surface a zone containing several thrust fault, low-grade metasedimentary rocks schist and phyllites.

As it is mentioned in lines 279-285, interpreted shear zones are not a distinct lithological unit but rather highly deformed parts of various rock units and therefore includes the upper parts of the Saxothuringian parautochthonos (highly sheared parts of inner shelf facies) and lower parts of allochthons involved in Variscan tectonics. Similar intrabasement, high amplitude and dipping reflections are interpreted as orogenic and postorogenic shear zones in the Norwegian Caledonides (Phillips et al., 2016; Fazlikhani et al., 2017; Wrona et al., 2020), offshore Brazil (Strugale et al., 2021; Vasconcelos et al., 2019), offshore New Zealand (Collanega et al., 2019), and in the South China Sea (Ye et al., 2020) and many other places.

Across the Franconian Fault System (FFS) towards the west, continuation of these high amplitude reflections are observed along the DEKORP90-3B/MVE profile (Fig. 5). At the intersections of DEKORP90-3B/MVE profile with FRANKEN1802, 1803 and 1804 profiles similar high amplitude reflections are observed and interpreted as Variscan shear zones. In our methodology we start from the well-studied DEKORP90-3B/MVE and DEKORP85-4N profiles where pre-Permian basement units are exposed and their seismic reflection characteristics are directly correlated with surface geology. At the next step we used DEKORP90-3B/MVE profile as a guided to interpreted pre-Permian units and structures along the FRANKEN survey. KTB borehole is tied to DEKORP85-4N and KTB-8502 2D sections and KTB 3D seismic cube (e.g. Hirschmann 1996 and references therein). Along mentioned seismic reflection data several high amplitude and dipping reflections are identified (SE1-4) and are interpreted as thrust zone. For instance, SE1 is interpreted as a ca. 450 m thick thrust zone (Altenparkstein Fault Zone) being part of the Franconian Fault System (de Wall et al., 1994). In addition to interpreted thrust zones, some sub-horizontal high amplitude reflections are also observed (B1-B2, G1-4) that are displaced by SE1-4 reflections. These sub-horizontal reflections are interpreted as Erbendorf high velocity body (e.g. Hirschmann 1996).

Based on the observations from the DEKORP profiles imaging Variscan basement units exposed east of Franconian Fault System, tectonostratigraphic superposition of Variscan nappe units and published studies from various locations, BSF2 reflections are interpreted as Variscan shear zone. Our interpretation is also in agreement with anonymous referee that BSF2 reflections are unit boundaries, as interpreted shear zones are (in the study area) boundary between higher grade metamorphic and plutonic of the Cadomian basement and low-grade metamorphosed inner and outer shelf facies.

Comment 3: The FRANKEN seismic survey itself: The ST basement here has much weaker BSF facies expression than in the DEKORP lines. I am not clear if this is driven by different choices of the seimic processing parameters, or it but could equally well reflect a NW-ward (e.g. FRANKEN 1801) and SW-ward (FRANKEN 1802, 1803) change in ST basement characteristics (e.g. loss of possible shear zone signature). Possible causes for this are discussed (lines 426 ff. of the ms), but it is the marked absence of other (e.g. drillhole) data and observations that makes any interpretation difficult.

Reply to comment 3: Agreed, without well control and only based on seismic reflections it is very difficult to comment on the rock types observed along the FRANKEN survey weaker appearance of ST basement along the FRANKEN seismic could be related to the acquisition and processing parameters. DEKORP profiles are aimed to images deeper (down to Moho) parts of the crust while FRANKEN seismic is targeting mainly the first 10 km of the crust. We agree with anonymous referee that additional well data would have been a great help in the interpretation of the deeper parts of the profiles. However, at present day, are available deep wells in the study area are integrated in our seismic interpretation practice and are presented in Table 1.

Comment 4: In summary, the paper appears to need some thorough revision before being acceptable for publication. There is also a multitude of typographic errors to be corrected (I have not started to do this and trust that copy editing can do the job), and the citations and reference list need a close look at (see e.g. the citations of SCHWAN, 1974, and SCWAN, 1974 for an obvious example) and improvement.

Reply to comment 4: Agreed, we have revised the manuscript according to the referee comments. Please see revised version of the manuscript.

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.

Reply letter to referee comment by Prof. Uwe Kroner (RC3) on the article se-2021-95

Dear Prof. Kroner,

Many thanks for your comments and suggestions which indeed helped in improving the quality of our manuscript. Please see below list of comments and authors reply. We would be happy to further discuss and clarify our replies if needed.

Comment 1: *The Geological setting needs a concise review regarding the loads of tectonometamorphic constraints published in the last years (see for this the recent publications of Hallas et al. 2021 and Schönig et al. 2020 and references therein).*

Reply to comment 1: Thank you for your suggestion and references. We have slightly revised the geological settings accordingly. However, since the focus of the manuscript is the presence of Variscan shear zones - not necessarily their possible initiation mechanism and timing – and their influence on the post Variscan structural configuration, we believe that more information regarding the Variscan orogeny itself might lengthen the manuscript. We plan to discuss implications of our findings in Variscan orogenic development in an another manuscript in greater details where we will give more comprehensive review regarding the loads of tectonometamorphic constraints.

Comment 2: *For example, the Fichtelgebirge constitutes the footwall of the Münchberg Massif but the hanging wall of Variscan high pressure nappes inside the Erzgebirge Fichtelgebirge Zone. By no means the lithologies of the Fichtelgebirge constitutes autochthonous units of the Saxothuringian Zone as sketched in figure 1.*

Reply to comment 2: Thank you, we have revised figure 1 accordingly.

Comment 3: *Saxothuringian Basement is not an appropriate term for the Basement Seismic Facies - BSF3. The Saxothuringian basement encompasses various nappes (BSF1), shear zones (BSF2) and the Cadomian basement plus early Paleozoic overstep sequences of the Autochthonous Domain (sensu Kroner et al. 2007). Therefore, BSF1-3 constitutes Saxothuringian Basement.*

Reply to comment 3: Thank you for your comment. We have updated our terminology in revised version.

Comment 4: *If you correlate BSF3 with lithologies of the Autochthonous Domain (why not) than a remarkable result of your study is the occurrence of BSF3 just SW of the Fichtelgebirge as evidenced in figure 8, i.e., the interpretation of the NW-SE seismic profile FRANKEN-1803. Please discuss the possible occurrence of the Autochthonous Domain SW of the Fichtelgbeirge.*

Reply to comment 4: This is a very interesting comment that surely has valuable implications for the assemblage of Variscan terrains during the orogenic event. In order to keep the focus of this manuscript first on presenting new seismic reflection dataset and then on the structural setting and controls west of exposed Variscan units (Bohemian Massif) we would like to preserve descriptions and discussions related to the Variscan tectonics in an another dedicated contribution summarizing recent published works and their significance in regard to presented Variscan structures and units in this manuscript. Please also see reply to comment 1.

Comment 5: *In your 3D sketches of Figure 11 you propose a generally W-directed tectonic transport which deviates at least 45° from the classical late Variscan (N)NW shortening (Wurm 1926, Stephan et al. 2016). Do you mean with this direction the initial W(SW) nappe stacking or the finite displacement the entire stack?*

Reply to comment 5: Shown general W-directed tectonic transport refers to the initial W-SW directed nappe stacking. We have added additional text in the figure 11 caption clarifying this issue.