R1

Young and coauthors present a study of a well exposed core of a shear zone. The main hypothesis of the manuscript is that preexisting lithological heterogeneities on a small scale guides the rupture geometry of earthquakes. The manuscript is well written and well structured and proper observations are made and appropriate methods to underpin the interpretations are used. The systematic approach and methods used for the quantification of the geometry are novel in this field of study. The topic is definitely very suitable regarding the scope of the Solid Earth journal. Before publication, I would like to request revisions on the raised concerns regarding the timing of deformation and associated geometries as well as the careful remake of some figures.

Thank you for the constructive and comprehensive comments. Please see our responses and associated changes below.

General comments

The topic of where seismic rupture takes place is of high importance, and the idea that pseudotachylyte can often be found at rheological boundaries is valid, and has been observed before, also as bounding boudins (Toy et al 2011). In my opinion, this is not the best field site to establish this relationship, as the ductile deformation following pseudotachylyte emplacement is significant and alters the original geometries. The ultramylonite bands wrap around the pinch and swell structures and boudins, and therefore the pseudotachylyte generation predates these features. However, the authors argue that the stress concentrations necessary to form the pseudotachylyte, are generated by the pinch and swell geometries (line 540).

The pseudotachylytes we document include a variety from very fresh / barely deformed (Fig 6) to fully recrystallized / nearly indistinguishable from other ultramylonites in the shear zone (Table 1). The pseudotachylytes/black ultramylonites follow wavy lithologic boundaries, which is consistent with previous studies in other areas. The strain in the identified pseudotachylytes is low enough to preserve 10s-100s micron-scale structures, so we maintain that the outcrop-scale geometries are probably not affected on the ~10 m scale, where our interpretations of the geometries become significant. We have added more detailed documentation of the pseudotachylyte cross-cutting wall rock foliation (which is locally parallel and locally crosscut at a low angle along the lithologic interfaces).

We also added two paragraphs in Section 5.2 “Distribution of Preserved Earthquakes” discussing the geologic history of the site – the wavy lithologic bands and foliation began their development at higher (amphibolite facies) conditions, and pseudotachylyte formed during shear zone exhumation through lower amphibolite-upper greenschist conditions. We can therefore say with confidence that an assemblage of wavy foliations and lithologic layering represent the initial conditions at the onset of seismic activity, and this style of fabric continued to develop during the period of intermittent earthquakes and creep. In section 5.2 we now specifically mention that earthquakes may have nucleated locally and/or propagated into the transitional zone – either way, the precise location of earthquake slip is influenced by local stress conditions which are heterogeneous due to the wavy geometries.

Maybe it is possible to explain the observed geometries and distribution of pst like this:

Pseudotachylylte is generated along a lithological boundary. Pst are weaker than the host rock(s) during subsequent ductile shear, effectively lubricating the boundary and facilitate the formation of pinch and swell structures.

We agree the pseudotachylyte is weaker than surrounding rock when it forms - but according to available theory and modeling of boudinage, this should lead to effective decoupling that reduces tractions along the interfaces and suppresses boudinage / amplitude growth in pinch-swell structures. We have expanded the discussion on this point especially since it may be counter-intuitive. This is discussed in section 5.2.1: Interface cohesion, which examines evidence for interface coupling and discusses how this would affect the potential for interfaces to act as rupture guides, and comes up as well in 5.2.3: Interface geometry, which explains why this effective decoupling would reduce the rate of amplitude growth in pinch-swell geometries (relying on models in the literature). This is the phenomenon that we use to explain the longer-scale differences between pseudotachylyte-bearing and barren lithologic interfaces.

Furthermore, the thickness of the former pseudotachylytes is quite astonishing, considering a formation by a local stress variation. Also, pseudotachylytes generated by local stress variations are more likely to crosscut the mylonitic fabric, and this should be still visible even after further ductile overprint (Toy et al 2011, Hawemann et al 2019, Campbell et al 2020).

The thicker pseudotachylyte horizons contain interlayered mylonite and pegmatite horizons. Our submitted manuscript did not include the detailed observations of multiple horizons forming the thick accumulated layers of pseudotachylyte, which the reviewer rightly points out are too thick to be single event frictional melt layers. We have now included traces of those layers visible on the orthophoto on the map, and added explicit identification of this when presenting the possibility multiple ruptures/rupture bifurcation along a given pseudotachylyte-bearing interface in section 3.5.

We observe mostly pseudotachylytes parallel to local fabrics or cutting at a very low angle. We have improved documentation of this (Figs 3, 6, Sec 5.2) in the revised manuscript. Our observations, like those in the examples suggested by the reviewer, suggest that pre-existing structures played the major role in the orientation of the earthquake rupture surfaces. Therefore, it is not possible to determine the orientation of the stress tensor associated with seismic faulting. In strongly anisotropic rocks, without detailed quantification of *in situ* strengths and stress magnitudes during faulting, it is not possible to determine stress orientations.

Also, the analysis of the interfaces of pst-bearing and non-bearing contacts is hard to validate, as present-day geometries are not the geometries at the time of emplacement of the pseudotachylytes.

This point was addressed above.

I would therefore recommend either a thorough and robust explanation of the timing of the structures or a significant reinterpretation of the observed geometries before publication.

We have modified the discussion (Section 5.2) to centralize the explanation that the wavy foliation and layers developed prior to the seismic history of the Pofadder Shear Zone, and make the point that in heterogeneous layered rocks, viscous flow leads to strength and velocity anisotropies that would tend to always produce pinch-swell structures/boudinage. The post-seismic flow continued to enhance the wavy geometry everywhere, but more slowly on the pseudotachylyte-bearing interfaces.

Therefore, our interpretation is that the ruptures propagated along wavy surfaces. As no straight foliation or rupture planes were observed in this study or revealed in previous detailed maps covering a larger area (Melosh et al., 2014; 2016; 2018), there is no basis for suggesting that they existed in the shear zone.

Minor comments.

The introduction has to be extended towards the literature existing on the topics handled by the manuscript.

We have added the references supplied by both reviewers, and added more recent references throughout the text.

It is also surprising to never see new pseudotachylyte form next to a previous generation of pseudotachylyte, as they also should offer a high competence contrast.

Addressed above – thick layers contain thin wallrock selvedges showing they are multi-event composite layers.

Please also note the annotated pdf with comments!

Regarding annotated comments:

- We have modified the abstract text (abstract)
- We have modified the abstract and introduction text, expanding the literature presented in it (Introduction)
- The list of pseudotachylyte criteria is not ranked (section 3.4)
- We have expanded the text on multiple adjacent slip surfaces (addressed above) including a discussion of the possibility of adjacent surfaces being discrete or simply bifurcations (section 3.5)
- See Melosh 2018 for an in depth examination of folding in this field area (Section 3.5)
- We have removed the decimal points (Section 3.5)
- We have corrected the text related to the Spray 2008 reference following Reviewer comments (Section 5.2)

The descriptions and interpretations in this manuscript are very well and carefully executed. But they have to be supported by higher quality figures. Here are some comments on how to improve the figures, some pictures may have to be redrawn or retaken.

Thank you for this detailed list of suggestions to improve figure quality. We have attempted to address your concerns (please see responses below). While a complete response would require re-processing of the data, we have opted to make those improvements we can with the existing data and combed through the text to better characterize the scope of our sampling.

Figure 2:

The legend for the stereonet is bigger and placed more prominently than the stereonet itself. Change 000 to “N”. Try to place the scalebar more intuitively, for example just use a 1 m scale on the map itself.

Fixed

The map itself has a bit unpleasant colours. The background drone image is not advantageous as a background here, as it does not add any information. Maybe try to give some transparency to the geology-layer, also makes the colours more digestible. The contacts are all jagged lines, sadly. A lot of orientation data is presented, but does not add all too much, as this information is nicely shown in the stereoplot already. Maybe you could trace some foliations, would offer a more intuitive way to look at it. Also, some layers are offset by the late fractures, these should therefore be included into the map.

We have changed the field map presented in the text (Fig 2) to a simpler lithologic map so it is easier to read, and softened the saturation of the map colors to reduce the aesthetic contrast while keeping the same colour range to support colour blind-friendliness. We have increased the spatial resolution displayed in the thick black ultramylonite layers contacts to better portray the composite structure of some of these layers. The additional data (foliation and lineation measurements shown on the stereonets in figure 2) are now shown on a separate supplementary file. The high resolution basemap (orthotiff projected from a 3D model constructed by structure-from-motion using drone imagery) is now included as a supplementary file as well. We hope this facilitates presenting the most important data to all readers of the paper while also providing the necessary detail for readers who want it.

We have not included foliation traces, as the supplementary with complete foliation measurements would make this redundant and the reviewer’s request was related to questions about crosscutting relationships which are now addressed elsewhere.

There are no mappable offsets on fractures in this map area. We did not omit any structures from the map.

As the map is really a crucial part of this manuscript and is presented as “highly detailed”, it would be great to see it being improved and more carefully prepared.

We have revised the text to better represent the mapping resolution - all layers down to about 1 cm thickness were included on the map, but due to the spatial resolution variability of the structure-from-motion model, the position precision of contacts is only locally ~ 1 cm but in some areas probably several cm.

Figure 3: “All photos oriented with dominant foliation (NW) across the photo.” That still leaves two possible orientations. Otherwise the photos are okay, even though the various tools for scale fill up a significant part of the image for no good reason – something to consider in the next field season.

We have noted that the dominant foliation extends NW-SE in the figure caption.

Figure 4: What is the orientation of these images?

Caption now includes orientation.

Really low contrast in SEM Images, very dull, out of focus polarization microscope images.

Figure 6 a: out of focus and the PPL image shows some ghost topography- looks like the Analyzer was not retracted completely. Remove the dashed line along the mylonite-ultramylonite boundary. A white number 8 got lost in the upper part of a).

We have replaced the photos in figure 6 and revised the annotations..

Figure 6a:

I think it is a very good idea to make this list and show the observations in the samples and I don’t doubt a pst origin for these ultramylonites. However, the quality of the images and their scale often make it impossible to really support your interpretation of the microstructure.

We have replaced the photos with newer, sharper images. The changes requested below are discussed in the context of the new figure design.

(2) Flow banding is not easy to argue for here, I think, as it is parallel to the foliation.

Flow banding in pseudotachylytes is most commonly parallel to the vein margins, whether within the source fault vein as shown in Figure 6, or into off-fault injections (e.g. Sibson, 1975; Lin, 1994; Swanson, 2006). As the pseudotachylyte vein margins are not always parallel to the foliation (the pseudotachylyte veins are straighter and the foliation is wavy, parallel locally to mylonite layering) the parallel laminations within the black ultramylonite also demonstrate the cross cutting relationships.

(7) It is not very obvious that this is a polycrystalline clast. It looks to me like a feldspar with inclusions.

A new example is found in figure 6a.

(3) To me the boundary looks parallel to the host rock foliation.

A new example is found in figure 6b.

(5) I cannot see that on this scale.

We have removed mention of this microstructural element in the figure to avoid confusion.

Remove the dashed lines in e and b.

Done.