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Interactive comment on "Pseudotachylyte as field evidence for lower crustal earthquakes during the intracontinental Petermann Orogeny (Musgrave Block, Central Australia)" *by* Friedrich Hawemann et al.

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General comment on pseudotachylyte generation in lower crustal rocks in response to Torgeir Andersen's review of Hawemann et al. by Neil Mancktelow, Giorgio Pennacchioni and Friedrich Hawemann

Torgeir Andersen raised the fundamental point in his review about potential models for development of pseudotachylytes, and implicitly intermediate depth earthquakes, under conditions typical of the middle to lower crust. He noted that we favoured a brittle

fracture precursor to both shear zone and the pseudotachylyte development but that we did not discuss this in any detail. This is correct because the aim of the current manuscript was mainly to unequivocally establish the conditions of pseudotachylyte formation as part of a logical progression of papers where in the next submission the interaction between multiple events of fracturing, localized ductile shearing and pseudotachylyte development could be discussed with reference to the current work and without having to re-establish the conditions all over again. The crucial result of the current work is that the conditions of both shear zone and pseudotachylyte development were around 650°C and 1.2 GPa and that there is no evidence of water-rich fluid infiltration before, during or after individual periods of shear zone localization or pseudotachylyte generation. Torgeir took issue with our use of the word "cycles", but the important point is that there is repeated shearing and pseudotachylyte formation, as shown by overprinting relationships. According to John et al (2009), this is exactly what is not observed in the Krakenes gabbro, which corresponds to the photo uploaded by Torgeir. We will wait with the formal reply to Torgeir's review until we have the second review as well, so that we can update our manuscript to include both sets of comments. Most of the formal comments we can readily include and we thank Torgeir for the suggestions. However, here, in the interactive discussion section, is a good chance to discuss the general question of deep pseudotachylyte development, where we think the arguments have become a bit dogmatic and need some critical re-evaluation. Seismic frictional melting is generally accepted as a viable mechanism for pseudotachylyte generation. The perceived problem is that the differential stress required to cause brittle fracturing in deep and dry rocks, as established for the current study, is high and commonly considered to be "unrealistic". The compilation of Byerlee reaches to the range of ca. 1.2 GPa appropriate to our study and would indicate that the required differential stress (sigma1 – sigma3) should be approximately equal to the (effective) confining pressure, i.e. ca. 1.2 GPa. This "problem" of the large stresses necessary for fracture at such depths led to the proposal of two alternative mechanisms (1) dehydration embrittlement and (2) shear instabilities and "self-localizing thermal runaway".

In the case in question here, the first possibility is clearly not relevant, because the conditions are "dry" and remain "dry". So the discussion is restricted to either slip and frictional heating on a discrete fracture or crystal plastic shear localization and shear heating leading to thermal runaway. In both cases, the fundamental driving mechanism is the transfer of recoverable stored elastic energy in a larger body of surrounding rock via localized permanent deformation into heat at a rate that is faster than that at which the heat can diffuse away. The theoretical basis for self-localizing thermal runaway have been a series of numerical models from Kelemen and Hirth (2007), Braeck and Podladchikov (2007), John et al (2009), and Thielmann et al. (2015). All of these models are fundamentally 1-D, which means they assume the initial required perturbation and the shear zone that develops is planar and infinite in 2D. An important point in all these models is that they necessarily require an initial precursor perturbation in the rheology. In this sense they are not strictly "self-localizing" – the planar zone of localization is actually prescribed. It is accentuated during subsequent deformation but it is present from the beginning. In the case of John et al. (2009) this is justified by the statement that both the eclogite-facies shear zones and the pseudotachylytes "have higher degrees of hydration, caused by infiltration of external fluids, and up to three-orders-of-magnitude-smaller grain sizes than the almost dry wall rock". So this requires some planar precursor that has reduced grain size, increased permeability and allowed fluid infiltration. Our experience from other areas (Mancktelow and Pennacchioni 2005; Pennacchioni and Mancktelow 2007; Menegon and Pennacchioni 2009; Gonclaves et al. 2016) and from the Musgrave Block, is that this necessary initial precursor in originally relatively homogeneous and isotropic rock is itself a fracture – the question then is whether this fracture also developed under deep conditions, in which case we are back to the original argument about whether fractures can develop in deep dry rocks? The geometry of the shear zones also suggests some form of precursor fracture. If they developed under viscoelastic conditions from point irregularities a more conjugate pattern would be expected, with initial angles at 45° to the shortening direction (e.g. Grujic and Mancktelow 1998; Mancktelow 2002). The photo that Torgeir provided as

part of his review is somewhat misleading as it could be taken to imply, without further explanation, that the pseudotachylyte developed by thermal runaway from the shear zone. This clearly cannot be the case because the displacement across the ductile shear zone is too small. Alternatives would be (1) that the shear zone itself is localizing on the already existing pseudotachylyte or (2) that the pseudotachylyte localizes on the pre-existing shear zone. However, in the original John et al (2009) paper it is claimed that "both types (i.e. shear zones and pseudotachylytes) formed in a single, continuous and fast event". In this interpretation, the shear zones are cases that did not make the step to thermal runaway and the pseudotachylytes the cases that did – and supposedly consumed almost all the evidence for the shear zone of the initial stages. In Fig. 1(h and j) of that paper, this is implied by the final broadening of the zone of melting (which would indeed involve a "delocalization" and broadening in the final stage). This is then taken as an argument why the precursor ultramylonite of the shear zone is not preserved as clasts – the evidence is lost due to complete melting of the ultramylonite precursor. However, this is rather hard to believe. As can be seen in the natural example of Fig. 1b of John et al. (2009) (although too small to really see details), there are plenty of clasts within the pseudotachylyte all showing evidence for brittle fracture and not ultramylonitic shear. In the model of Thielmann et al (2015), there is instead real continued localization, so that the pseudotachylyte should be observed within a broader shear zone. Our experience from the Musgrave Block is that the clasts directly reflect the protolith in which the pseudotachylyte developed. If this protolith was little deformed, then the clasts appear to be generally brittle without mylonitization. If, as is sometimes the case (see uploaded image), the pseudotachylyte developed in a pre-existing shear zone, then the clasts are also directly comparable to the surrounding matrix and are not always totally consumed. Following the model of John et al. (2009), in this case it should be expected that the whole precursor shear zone should melt and a geometry as in the photo would not be expected. It should be noted in this photo that there is common small garnet in the background protomylonite, in the localized mylonite/ultramylonite, in the clast within the pseudotachylyte, and in the pseudotachylyte injection veins, so that all these structures developed under the regional lower crustal conditions (i.e. ca. 650°C, 1.2 GPa). So, in summary, we do not exclude that thermal runaway in viscoelastic shear zones may occur and could explain some natural examples. However, the observational evidence from the area of the current study strongly suggests that brittle fracture is a necessary precursor for both shear zone localization and pseudotachylyte formation – with the necessary implication that differential stresses were (at least transiently) sufficiently high for brittle fracture under dry high pressure conditions.

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Fig. 1.