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Interactive comment on "High stresses stored in fault zones: example of the Nojima fault (Japan)" *by* Anne-Marie Boullier et al.

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We thank the reviewers for their thoughfull reviews and comments. These allowed us to refine our results, to go further in the interpretations, and to improve the quality of our paper.

In his comment (RC1), Frans Aben pointed out that several mechanisms are currently under discussion for inducing dynamic pulverization, and asked us to contribute to that discussion. Let us first resume our main observations. Compressive microstructures (alignments of tiny fluid inclusions in quartz, kink-bands in biotite) correspond to a compression perpendicular to the Nojima fault, and to less than 5% shortening. High stresses or strain-rate plastic deformation of quartz is synchronous with the compressive microstructures. Extensive microstructures are E-W orientated laumontite-sealed mode I veins corresponding to an N-S extension and to an average of 10 to 20% extension as measured using the width of laumontite veins. There is almost no shear deformation observed in that sample except the type 1 breccia-like veins which are trans-tensional E-W orientated features. On the basis of crosscutting relationships, we propose that the compressive microstructures appear before the extensive ones. All these deformations are interpreted as dynamically induced 51.3m away from the Nojima fault. Moreover, it is suggested that they have formed during a single seismic event on the Nojima fault. We are aware that this is a very strong assumption. Do these observations provide information on the loading mechanism at the origin of the dynamic damage? Several processes have been recently proposed in the literature for explaining shallow damage zone pulverization (see review in Aben et al., 2017): dynamic compressive loading, dynamic tensile loading, fluid-assisted decompression, wrinkle-like pulses and super-shear, as listed in F. Aben's comment. Experiments reproducing compressive loading using Split-Hopkinson bars has produced microstructures qualitatively similar to those observed in the described sample. Thus, as suggested in our paper, compressive loading is a good candidate in our case. Experiments reproducing tensile loading are more difficult to realize (see review in Zhang and Zhao, 2013) and require specific sample shapes. These experiments reproduce simple fractures rather than pulverization (Zhang and Zhao, 2013). No microstructural analyses are available for comparing with the microstructures in the Nojima sample. Nevertheless, we have to keep in mind that dynamic tensile strength is lower than dynamic compressive strength (Zhang and Zhao, 2013). The fluid-assisted decompression model corresponds to hydro-fracturing due to a sudden drop of fluid pressure in the rock. If this mechanism may be efficient in high permeability sedimentary rocks present in the subsurface, it appears highly improbable in the case of the Nojima granodiorite, which has a very low permeability (10-8 to 10-9 darcy under 50MPa confining pressure, Lockner et al., 2009). Considering the model of wrinkle-like pulses related to a bimaterial interface (Shi and Ben-Zion, 2006), it is not appropriate in the present case because both footwall and hanging-wall of the Nojima fault are constituted by the same granodiorite and the profile of physical properties of rocks across the fault is symmetrical (Lockner et al., 2009). Moreover, this model does not apply at great depth (> 3 km, Ben-Zion and Shi, 2005) where dynamic damage has been demonstrated to occur in the Nojima sample on the basis of laumontite in the veins and microfractures. The last model is the super-shear, i.e., a rupture front propagating faster than the S-wave velocity (Bouchon et al., 2001) and the formation of a Mach-cone (Rosakis et al., 2007). If supershear is mostly observed during high magnitude earthquakes along simple large faults (Bouchon and Vallée, 2003), it may also occur along smaller linear segments (see review in Rosakis et al., 2007). It triggers damage laterally and also in depth (Bouchon and Karabulut, 2008). Thus, supershear could be invoked for inducing the dynamic damage at 51.3 m from the Nojima fault and at 3.7 - 11.1 km depth. Depending on the location of the rupture source and the direction and velocity of rupture propagation, the walls of the fault may be either tensile or compressive whatever the far-field tectonic stress configuration. It has to be pointed out also that the peak dynamic stress is much higher than the static stress and may trigger fracturing and damage at a large distance to the fault (Brodsky and Prejean, 2005). Thus, all these considerations may explain the occurrence of E-W orientated mode I cracks in the studied sample, an orientation which is not consistent with the far-field tectonic setting of the fault (left-lateral wrench fault with N-S compression, Famin et al., 2014). To conclude, we argue that microstructures we observed in the unique sample studied in this paper are due to dynamic damage. However, suggesting a unique mechanism for explaining this dynamic damage would be over-interpretating our data. We believe that additional studies are necessary including microstructural observations of orientated samples across the Nojima fault, including samples outside and inside the damage zone. We will add a section in our paper reproducing this discussion.

Another comment made by F. Aben concerns the term “residual stress” and its deviatoric nature. This point overlaps one comment made by the second anonymous referee, and will be answered later in detail by O. Robach who have made and interpreted the X-ray Laue microdiffraction. But let us clarify some points. The residual stress is a term used in material sciences and may be defined as the stresses remaining in a solid when all the applied stresses have been removed. Thus the total stress is the sum of the applied stress plus the residual stress. They may also be called internal stresses. Thus, residual stresses are investigated in solids or structures in order to evaluate their reaction to specific loading conditions. Similarly, behaviour of rocks submitted to quasi-static or dynamic loading will depend on their loading history and residual stresses. In the present case as in the other examples in the literature (Chen et al., 2011, 2015; Kunz et al., 2009), the elastic strain tensor is determined by X-ray Laue micro-diffraction (our Fig. S6) from the deformation of the crystal lattice (b/a, c/a, α, β, γ) compared to an undeformed lattice. This give us the deviatoric elastic strain (εxx + εyy + εzz = 0). The residual stress tensor is calculated by applying the Hooke's law on the elastic strain tensor. The von Mises or equivalent stress is in turn calculated from the residual stress tensor (our formula 3). We will clarify that point in our paper. We will also take into account the comments made by the second referee pointing out that the calculated von Mises stress is not purely deviatoric due to the anisotropy of the quartz lattice. The final F. Aben's remark ("the sentence at lines 6-9 page 13 on the confining pressure at depth causing the residual stress becomes redundant, since this is the lithostatic and not the deviatoric component by definition") suggests that there is misunderstanding of our point. Actually, this point also needs to be clarified. We ask the question: "How such large residual stresses may be preserved in such a small volume for such a long time?" As pointed out later in the paper (page 12, lines 13-15), we guess that dislocation density is high in the studied quartz crystals because of the high stress and strain-rate deformation conditions. More importantly, dislocations are probably entangled and mostly immobile due to the low temperature (<300°C) inhibiting reorganization of dislocations and stress release. Therefore, the low temperature rather than the confining pressure allows the conservation of the residual stress in the sample. We will correct our paper consistently.

The other comments have been taken into account and corrections have been

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Discussion paper

consequently made in our paper. Again, we thank F. Aben for his comments.

Please also note the supplement to this comment:
https://www.solid-earth-discuss.net/se-2017-130/se-2017-130-SC1-supplement.pdf

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