Response to Peter Hudleston,

We thank Peter for his thoughtful review. We present our detailed responses (shown in black text) to the Reviewer's comments (shown in blue).

p. 1, line 2 I don't understand what is meant by "equivalent to an extrusion of 150%" There is no extrusion in these experiments (except by the limited bulging, but that is minor). This figure of 150% relates to the "equivalent strain" shown on Fig. 3, but this is also confusing to me. It requires a definition. For another possible measure of strain intensity, a simple shear strain of 2.6 - the maximum in these experiments - corresponds to a maximum stretch of 2.94 or an extension of 1.94.

Apologies- extrusion is not what we meant. The word should have been "extension". And the reviewer is correct, the extension is 1.94 not 1.5. The purpose of the statement in the abstract is to make the magnitude of the strain clearer to readers who are not so familiar with shear strain. We have changed this statement to "….up to shear strain (γ) = 2.6, equivalent to a maximum stretch of 2.94 (final line length is 2.94 times the original length)."

p. 4, line 16 It seems to me the statement here should be the other way round. That is, if gamma measured and gamma calculated are very close in value, it implies that epsilon axial is very small, and thus bulging is slight. If bulging is calculated first, how is it done?

We have some redundancy in our measurements here. For each sample, we were able to measure the thickness before deformation. For most we have measurements after deformation, although these lack precision. For all but three samples we have a good estimate of shortening perpendicular to the shear plane (see response to your comment later) from the cross sectional area of "bulge" formed by lateral extrusion. We have measurements of piston offset (perpendicular to cylinder axis) and axial piston displacement (LVDT measurements). Piston offsets and axial displacements are similar suggesting that simple shear dominates. Shortening strain perpendicular to the shear plane is small compared to simple shear values calculated from measured offsets, also suggesting that simple shear dominates. We restructured the first paragraph in Section 2.3 to clarify this.

p. 6, line 8-9 "There are almost no subgrain…."

Corrected!

p. 6, line 13-15. I would interpret flattening strain to mean shortening normal to the shear plane, not axial shortening, and that this would be determined by the difference between ho and h1 - although I see from Table 1 that the measurement of h1 is not precise. The "axial strain" as calculated here, as I understand it, would only be a true axial strain if the deformation were coaxial, which it is not.

This is a good point. Axial strain is not precise. We actually mean flattening strain. We have changed this to flattening strain in the text.

p. 9, line 11 "There is a range of grain ….."

Corrected!

p. 9, line 16-18 The stress drop following peak stress (Fig. 3) is rapid, yet the possible reasons for this given here - weakening due to grain size reduction and thus increase in the contribution of grain size sensitive deformation mechanisms, and geometric softening due to the development of CPO are both likely to be gradual. So why so rapid a drop?

This comment highlights something we had not thought about. The rate of stress drop appears very rapid because the strain scale goes to higher strains than we are used to looking at. If the figure is plotted on approximately the same scale as an axial experiment, it is clear that the stress drop rate in axial and shear experiments are comparable. Most of the weakening occurs in the first 10% to 15% of strain with the steepest stress-strain slope between peak stress and ~5% strain. The stress drop rate also corresponds approximately to the rate of strain-rate enhancement in constant load creep tests. The figure below plots the direct shear data at approximately the same strain scales as axial constant rate (Qi et al., 2017) and constant load (Budd et al., 2013) experiments. We know from up-strain, warm experiments that CPO development can correlate to the weakening that occurs over the first 10% of strain (Vaughan et al., 2017). Unpublished work shows that grain size distributions can also evolve in a way that correlates with mechanical weakening ((Vaughan, 2016)(and new -10 and -30°C up strain axial experiments we have just analysed in the last three weeks). CPO and grain size both correlate to “strength” and provide plausible explanations for weakening. We still do not understand this in detail. In the text we have clarified this by adding two sentences in Section 4.1: “Because the x-axis in Fig. 3 is scaled to large strains, the decrease in stress with strain after the peak stress seems more dramatic than in axial compression experiments. In fact, the evolution of stress with strain in our experiments is very comparable to that in axial compression tests (Qi et al., 2017) when data from both types of experiment are plotted at the same scale. Furthermore the pattern of decrease of stress with strain from peak stress matches the pattern of increase of strain rate with strain in constant load experiments in both axial compression and in shear (Budd et al 2013).

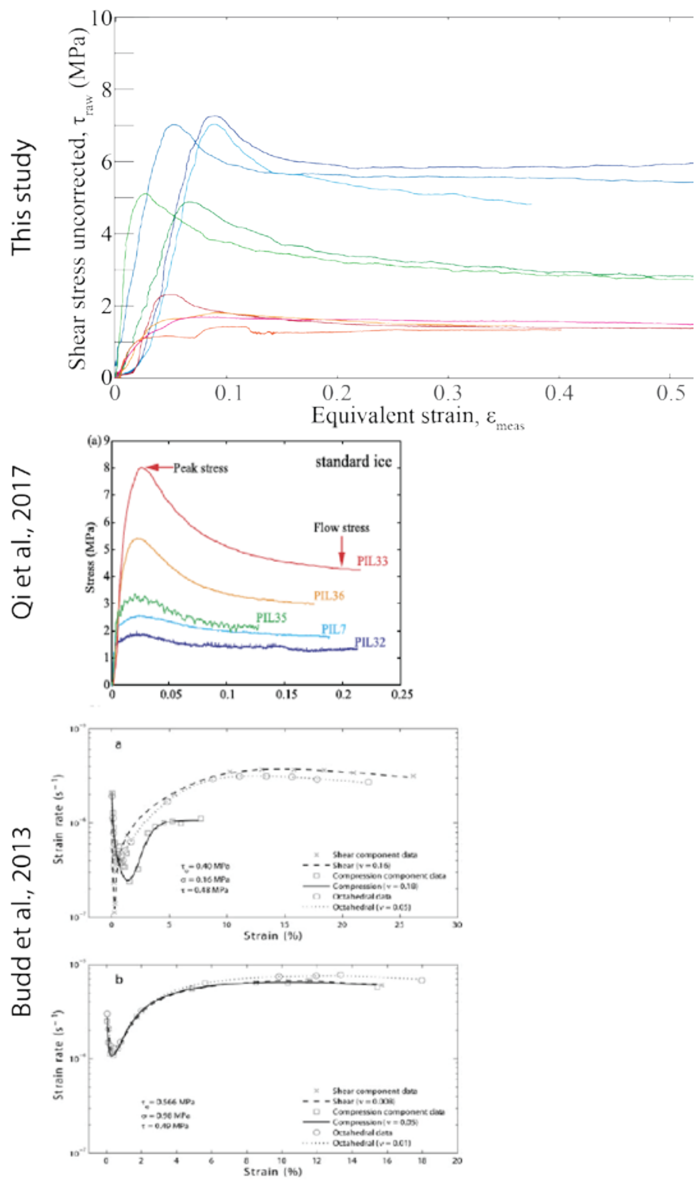

Figure 1. Plots of stress/strain rate vs. strain. All strains are equivalent to axial compressive strains.

p. 10, line 3-4 The flattening that occurs in the samples is not just accommodated by extension normal to the shear direction but also by extension parallel to the shear direction. So it's not clear why there should just be preferred elongation in the direction normal to the shear direction. Why not a broadening in all directions?

Li et al. (2000) provided this explanation for the elongation of the c-axis clusters. We agree with the reviewer that flattening also occurs by extension parallel to the shear direction, and it is not clear why the elongation is normal to the shear direction based on the explanation by Li et al. (2000). It should be noted that simple-shear simulations by Llorens et al. (2016 EPSL, 2017 Phil Trans) also show an elongated maximum, even though there is strictly no flattening involved.

To fully explain this phenomenon, further analyses of the CPO development in the numerical simulations is needed.

We added a sentence after the sentence in lines 3-4: “However, the explanation by Li et al. (2000) is not entirely satisfactory, as (i) flattening is in all directions perpendicular to the shear plane and (ii) the elongated maximum is also observed in numerical simple-shear simulations by Llorens et al. (2016, 2017), in which no flattening strain is allowed. In these simulations, elongation is most pronounced at low strain rate where recrystallisation has a stronger effect on the CPO than at high strain rates. First assessment of the numerical CPO development suggests that the elongation may result from the orientation-dependent rotation rate of c-axes towards the steady-state maxima.

Figs. 5-7. The fields of view shown may be deceptive, but the average grain size and number of grains counted are hard to reconcile with the images. In particular, why only 144 grains in the lowest strain sample at -5 and 3000+ grains for the highest strain sample at -30 for a grain size that is on average larger?

The images shown do not all include all of the area mapped at that step size. Our design of the figures was to present similar sized areas at the same scale to facilitate easy comparison of microstructures. For some of the maps (e.g. at -30°C) we have mapped much bigger areas than shown in the figure. If we show the whole area, the microstructural detail will be lost. Although the images are (in most cases) a sub-area of the full map, the grain size distributions and KAM are derived from the whole mapped area. We have added a sentence in Section 3.4 on page 8: “Note that except for two −5°C samples (PIL91 and PIL82), the analyses of grain size and KAM are based on larger areas than those presented in the figures.”

For the samples deformed at -5°C, large portions of the surfaces were not preserved, so we were not able to analyze large areas. This relates directly to using wooden pistons (used for the first three experiments); removing the sample from wooden pistons without damage was difficult. For the samples deformed at -30°C, we were very successful at preserving and polishing the surfaces, allowing us to map larger areas.

Figs. 5-7. In principle the plane of section here - the shear plane - is a plane of no strain, so one would expect to find little or no SPO. It would be interesting to see sections perpendicular to the shear plane and containing the shear direction, where one would expect to see a more pronounced SPO, and where it might be possible to get more information about the recrystallization mechanisms. Also, to the extent that there is SPO it should be in the shear direction, yet in the image for the highest strain at -30, the direction of max elongation appears to be at an angle to the shear direction. Is this just an illusion?

We are very grateful that the reviewer pointed out the issue with the highest strain sample (PIL135) in Figure 7. After re-examining the figure, we found that it was not aligned with the shear direction (the black arrow in the figure). We have now re-aligned the image. The grain shape is not as obvious in the sub-area chosen for our re-aligned image, and we now realize that we were making statements based only on the area shown in the figure, rather than the whole area mapped. Across the whole mapped area, there is little SPO.

Imaging profile plane sections was much more challenging than imaging the shear planes. At the time of drafting of the paper, we had some profile plane data and tried to include it. The resulting manuscript structure was confusing and detracted from the key focus on the CPO. We have subsequently developed the methods to get data from the profile planes (the "edges" of 5 mm thick ice plates) and we now have excellent profile plane data for the -20 and -30°C experiments and some data for the -5 °C experiments. The CPOs from profile plane maps are indistinguishable from the CPOs measured from the shear plane. There is potential for much more detailed analysis of the microstructures (misorientations, weighted mean Burgers vectors, CPOs based on grain size fractions, spatial arrangements of grains contributing to the two clusters, etc.) that is beyond the scope of this paper. A full presentation of methods and results will add significant length and we feel this will detract from the primary objective of presenting the CPO data in a succinct manner. We intend to publish more detailed work on the microstructures and this will include the new profile plane data.