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Interactive comment on "Microstructure and texture evolution in polycrystalline ice during hot torsion. Impact of intragranular strain and recrystallization processes" *by* Baptiste Journaux et al.

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We thanks the reviewer for the in depth comments we received. Here is a detailed response for all addressed comments, along with an attached revised version of the Manuscript and Supplementary.

Specific comment 1: A deeper discussion of grain-size sensitive deformation mechanisms may be appropriate. For example, the different nature of the distribution of GND's near grain boundaries is an interesting and important observation. One inter-

pretation of this observation is that there is a heterogenous distribution in the magnitude and orientation of stress near grain boundaries. In other words, the presence of grain boundaries may enhance deformation, which would lead to a grain-size sensitive rheological behaviour such as described by Goldsby and Kohlstedt (2001). A grain-size sensitive rheological behaviour may operate at the higher strain conditions where weakening (increasing strain rate with time) is observed. Although it is possible that the weakening is entirely due to the alignment of grains with favourable orientation to operate easy slip at larger shear strain (i.e. geometric softening).

Response : In the conditions prevailing in the experiments presented in this article, that are, plurimilimetric grains, rather low stresses, and temperatures very close to Tm, the grain-size sensitive regime is not concerned. This assumption is corroborated by previous experiments under axial compression using similar microstructures and pressure and temperature conditions, which do not show any grain size dependence (Schulson and Duval, 2009, Montagnat et al., 2015) Indeed, the GSS regime prevails in areas of very small, micron-sized grains, and under conditions where strain accommodation mechanisms such as dynamic recrystallization are inefficient (because diffusion at the characteristic length scales of the system is too slow, see for instance the recent work of Bourcier et al. 2013 on halite). Grain boundary sliding has been observed in ice with large grains at faster strain-rates of about 10-5 s-1 (Weiss and Schulson 2000), but it occurred just prior to cracking and was accompanied by a large amount of decohesion that we do not observe in the present experiments. The analysis of the microstructure clearly indicates that in the torsion experiments presented here, dynamic recrystallization mechanisms (especially grain boundary migration) are very efficient, since we are close to Tm. Efficient dynamic recrystallization relaxes the local stress and strain heterogeneities, which are caused by the viscoplastic anisotropy of the ice crystals and, as expected are stronger in the vicinity of boundaries between differently oriented grains, well before grain boundary sliding occurs. The development of strong heterogeneity in the strain and stress field controlling the onset of the dynamic recrystallization observed in the present experiments is a direct consequence of deformation mostly produced by highly anisotropic dislocation motions within the crystals. The early onset of and widespread occurrence of dynamic recrystallization in our samples is an evidence of deformation mainly accommodated by dislocation motions. Indeed, the development of strong heterogeneity in the strain and stress field, which controls the dynamic recrystallization, is a direct consequence of deformation mostly produced by highly anisotropic dislocation motions within the crystals. Grain boundary sliding, if associated with effective accommodation of local strain incompatibility by diffusion creep or even by dislocation glide, should produce a much more homogeneous microstructure than the one we observed. In the present experiments, the strain distribution within the grains is heterogeneous, as a consequence of stress and strain heterogeneities, in particular when neighboring grains have contrasted behaviors due to different crystallographic orientations. On the other hand, there is no clear evidence for stress concentrations at triple junctions or at irregularities of the grain boundaries, which are expected in the case of grain boundary sliding. In summary, although grain boundary migration is certainly important as a strain accommodation process, all observations points to deformation mainly accommodated by intragranular dislocation motions, which is grain-size independent. Grain boundary migration is certainly affected by the gradient in dislocation density characterized in the present work. This gradient result probably in a characteristic length scale for formation of nucleii, as discussed in the article. However, this length scale is independent of the size of the deformed grains. Thus, we consider that a lengthy discussion of the grain-size sensitive regime is out of the scope of this article. Concerning the mechanical data, as pointed by the reviewer and shown in a large number of previous experiments studying tertiary creep (e.g., Bouchez and Duval, 1982; Jacka and Jun 1994), the texture-related weakening may easily explain the onset of tertiary creep, during which a constant grain size is observed owing to the balance between nucleation and grain growth by boundary migration.

References: [1] E. M. Schulson and P. Duval. Creep and Fracture of Ice. Cambridge University Press, 2009.

[1] Montagnat, M., T. Chauve, F. Barou, A. Tommasi, B. Beausir, and C. Fressengeas. 2015. “Analysis of Dynamic Recrystallization of Ice from EBSD Orientation Mapping.” Frontiers in Earth Sciences. http://www.gm.univ-montp2.fr/PERSO/tommasi/publications.html.

[2] Bourcier, M., M. Bornert, A. Dimanov, E. Héripré, and J. L. Raphanel. 2013. “Multiscale Experimental Investigation of Crystal Plasticity and Grain Boundary Sliding in Synthetic Halite Using Digital Image Correlation.” Journal of Geophysical Research: Solid Earth 118 (2): 511–26. https://doi.org/10.1002/jgrb.50065.

[3] Weiss, J., and E. M. Schulson. 2000. “Grain-Boundary Sliding and Crack Nucleation in Ice.” Philosophical Magazine A 80 (2): 279–300. https://doi.org/10.1080/01418610008212053

[4] Bouchez, J. l., and Paul Duval. 1982. “The Fabric of Polycrystalline Ice Deformed in Simple Shear: Experiments in Torsion, Natural Deformation and Geometrical Interpretation.” Textures and Microstructures, 5: 171–90. https://doi.org/10.1155/TSM.5.171.

[5] T. H. Jacka and L. Jun. The steady-state crystal size of deforming ice. Ann. Glaciol., 20:13–18, 1994.

Specific comment 2: A stress exponent of 3 is used to estimate the stress at the outside radius of the samples. Although probably appropriate for this study, it would be better to have a stronger justification for this selection. For example, if a grain-size sensitive mechanism is operation at higher strain (smaller grain size) conditions, a lower value of stress exponent may be more appropriate. Additionally, values of n of 4 have been observed in ice deforming by dislocation creep (e.g., Durham et al., 1983). A stronger justification for using n=3 would place more confidence in your calculated values of stress and make future comparison of this work more straightforward.

Response : The value of 3 for the stress exponent was chosen considering that most of our experiments are close to the secondary creep conditions. From previous work (a good review can be found in Shulson and Duval 2009), it was shown that during secondary creep (in fact at the minimum creep rate), the stress exponent for coarse-grained polycrystalline ice is close to 3. These studies also show that during tertiary creep this exponent increase, reaching a value close to 4. These early data is corroborated by recent work of Treverrow et al. (2012) presenting results from compression and shear tests, which observed stress exponents between 2.9 and 3.1 for the secondary creep, and of 3.5 for tertiary creep. Reference to this study has been added in the new version of the paper to justify the choice of the value of 3.

Modified text (P.4 L.28) "Since most of the present experiments recorded secondary creep conditions (Fig. 1), stress exponent of n = 3 was chosen based on results from Duval et al. (1983) and more recent work from Treverrow et al. (2012) that observed stress exponents between 2.9 and 3.1 during the secondary creep regime, and of 3.5 for tertiary creep in compression and shear tests.

References: [1] Schulson, Erland M., and Paul Duval. 2009. Creep and Fracture of Ice. 1 edition. Cambridge, UKâĂŕ; New York: Cambridge University Press.

[2] Treverrow, A., et al., Journal of Glaciology 58, no. 208 (ed 2012): 301–14. https://doi.org/10.3189/2012JoG11J149.

Specific comment 3: A discussion of some more of the recent work on the controls of ice CPO at low strain conditions would help strengthen some of the arguments in this manuscript. For example, Qi et al. (2017, JGR), discussed the importance of stress on controlling the nature of CPO in ice, and noted the importance of grain boundary migration at low stress and lattice rotation at high stress. Although those experiments were carried out at different conditions and using a different deformation geometry, they may provide some insight into the various conditions at which the texture with the M2 maxima are important.

Response : In the revised version of the manuscript, we include a comparison with both the work of Qi et al. (2017) and the more recent study of Qi et al. (2019). This com-

parison is interesting, since their experimental conditions are very different from the present ones: grain sizes are smaller, strain rates are faster, and stresses are higher. The confinement pressure (10 MPa in Qi et al. 2017) might also have some impact on the recrystallization mechanisms and texture evolution. Qi et al. 2017 presents results for axial compression. Studies in a similar highly anisotropic material, olivine, clearly indicate that the effect of recrystallization on the texture evolution is much more marked in simple shear (cf. review in Signorelli & Tommasi 2015). Thus we also compare our data to the very recent Qi et al. (2019) study, which presents data obtained in direct simple shear, which can be more easily compared to the present study, although some shortening normal to the shear plane (transpression) usually takes place in this configuration, as recognized by Qi et al. (2019). As stated in the revised version of the ms. the results of the three studies share many common points.

References : [1] Signorelli, Javier, and Andréa Tommasi. 2015. "Modeling the Effect of Subgrain Rotation Recrystallization on the Evolution of Olivine Crystal Preferred Orientations in Simple Shear." Earth and Planetary Science Letters 430 (November): 356–66. https://doi.org/10.1016/j.epsl.2015.08.018.

Specific comment 4: Sample TGI0.012 was deformed to very low strain and its data are missing from Figure 1. How certain are you that this small amount of plastic strain was imposed on the sample? The grain size of TSGI0.012 appears smaller than the unstrained sample, which suggests at least some plastic deformation occurred. Was a correction made for the compliance of the rig? Was there any evidence of elastic strain?

Response : About the elastic compliance of the rig, previous work on ice single crystals had shown that the strain measurement of the torsion apparatus used here is accurate even at very low strain (Montagnat et al. 2006, Chevy et al. 2010). Although small, this sample (TGI0.012) was affected by viscoplastic strain, not only by elastic deformation. Indeed, given the value of the shear modulus for ice, the elastic deformation is really small. At the maximum shear stress of 0.6MPa, the shear modulus of 3.5 GPa leads to γelastic of about 2.10-4. In addition, although subtle, the change in the texture relatively to the undeformed sample suggests that it experimented a small amount of viscoplastic strain.

As for the variation in grain size, different samples were used for each test, and owing to the sample growth procedure, a slight difference in initial grain size can occur. The difference between the grain size of the "undeformed" microstructure shown in the paper for illustration, and the one of the TGI0.012 is in the range of usual variation due to the preparation procedure. In any case, the very small strain that affected this sample did not trigger significant changes in the microstructure and in the texture. By consequence, this sample does not play a major role on the conclusions of the present study. It gives nevertheless a control on the very first stages of the deformation.

References: [1] M. Montagnat, J. Weiss, J. Chevy, P. Duval, H. Brunjail, P. Bastie, and J. Gil Sevillano. The heteroge- neous nature of slip in ice single crystals deformed under torsion. Philosophical Magazine, 86(27):4259– 4270, 2006. [2] J. Chevy, C. Fressengeas, M. Lebyodkin, V. Taupin, P. Bastie, and P. Duval. Characterizing short-range vs. long-range spatial correlations in dislocation distributions. Acta Materialia, 58(5):1837 – 1849, 2010.

Technical Corrections We thank the Reviewer for the detailed correction of the manuscript. The updated version of the manuscript has been corrected accordingly, a response to a specific comment is given hereafter otherwise.

p2 ligne 3 : “compression and extension are the dominant deformation mecha- nisms” – this is a bit awkward as most people discussion deformation mechanisms as related to flow behaviour, e.g., dislocation creep, diffusion creep, etc. It may be more clear to replace “deformation mechanisms” with “deformation geometries”. R : done

Line 6: remove “s” from “orientations” R : done

Line 10: remove “olivine” R : done

Line 23: replace “in return” with “consequentially” R : done

Line 27: add “rate” after “strain” ? R : done

Lines 28 – Page 3, line 2 – The statements made in this paragraph are a bit debatable. I am not sure if ice is a great analogue for mantle rocks. Hundreds (if not thousands) of high temperature experiments have been carried out to study the flow behaviour and microstructural characteristics of mantle rocks. Ice is significantly more anisotropic, in a viscous sense, than olivine and other mantle material.

Response : CPOs obtained under simple shear for ice and some minerals such as olivine or quartz are similar: in all cases the main slip system rotates into parallelism with the macroscopic strain much faster than the reorientation of the finite strain ellipsoid and the CPO reaches a stable position and intensity at rather low shear strains (2-5). By consequence, similar explanations (related to recrystallization) were proposed (see for instance Wenk et al. 1997, 1999 and Signoreli and Tommasi 2015). In terms of viscoplastic anisotropy, both ice and olivine do not possess enough available slip systems for accommodating a general deformation - in particular shortening or extension parallel to the [100], [010], and [001] axes in olivine and parallel to [0001] in ice (see for instance Castelnau et al. 2008). Comparing the intensity of anisotropy of the two materials is not straightforward. Ice has a higher symmetry (hexagonal): slip is only easy in the basal plane, but it shows with no anisotropy within this plane. Olivine is orthorhombic: it has more slip planes, but only two slip directions in these planes. In conclusion, both are extremely anisotropic materials. This leads to strain compatibility problems and stress concentrations in the polycrystal, which, at high homologous temperature, are resolved by recrystallization.

References: [1] H. R. Wenk, G. Canova, Y. Bréchet, and L. Flandin. A deformation-based model for recrystallization of anisotropic materials. Acta. Mater., 45(8):3283–3296, 1997. [1] H. R. Wenk and C. Tomé. Modeling dynamic recrystallization of olivine aggregates deformed in simple shear. J. Geophys. Res., 104(B11):25,513–

25,527, 1999. [3] Signorelli, J. and Tommasi, A.: Modeling the effect of subgrain rotation recrystallization on the evolution of olivine crystal preferred orientations in simple shear, Earth and Planetary Science Letters, 430, 356–366, https://doi.org/10.1016/j.epsl.2015.08.018, 2015 [4] O. Castelnau, D. K. Blackman, R. A. Lebensohn, and P. Ponte-Castaneda. Micromechanical modeling of the viscoplastic behavior of olivine. Journal of Geophysical Research, 113:B09202, 2008.

Page 3: line 10: remove “has” R : done Line 28: add “either” before “not” R : done Line 29: remove space after “mechanisms” R : done Page 4 Line 6: replace “packing evenly” with “evenly packing” R : done Line 17: replace “control visually” with “allow for observation of” R : done Page 5 Line 18: replace “does” with “do” R : done Line 31: replace “identify” with “identified” R : done Page 6 Line 20: replace “reminded” with “noted” R : done

Page 7 Line 1: here you say the noise was too large to distinguish any primary creep hardening in TGI0.012 R : See response to Line 5-6

Line1: add space after at end of sentence R : done Line 5-6: Can you say for certain the TGI0.012 stayed in the primary creep regime? The strain was very small and the data for that experiment is not presented in Figure 1 Response : This is an assumption, the text in the updated version of the manuscript has been modified to reflect the reviewer comment.

Line 21: add “essentially” before “random” R : done Line26-27: Did TGI0.012 really achieve the strain indicated? How did you account for compliance and elastic deformation of the sample? Response : Considering the value of the shear modulus for ice, elastic deformation is really small and cannot be measured by our sensor. Taking the max shear stress of 0.6MPa, the shear modulus of 3.5 GPa leads to gamma_el of about 2.10-4.

Page 8 Figure 1: missing data for TGI0.012 R : Data for TGI0.012 is too short in timescale to be practical to show in figure 1.

Figure 1 caption: replace “experiments” with “experiments”, or change this sentence unless you add data for TGI0.012 to the figure. Replace “The blank part of the curve corresponds to” with “the blank parts of some of the curves correspond to”. Remove “represented”. R : done

Page 9 Line 10: add “(by gamma = 0.2) R : done

Page 10 Figure 3: This is a nice plot but the large gap between gamma 1 and 2 suggests that maybe it is worthwhile mapping an axial section of TGI1.96? This would allow you to calculate the J-index at all strains by mapping form the center (almost unstrained) to the outside (almost gamma=2) of the sample. R : One axial section was measured with EBSD, but due to the coarse grain size, it was impossible to fractionate the section in different segments with ’supposed’ constant finite shear strains and still have a high enough number of measurements to obtain representative estimates of the CPO intensity. We could not therefore use radial sections to estimate the CPO evolution with increasing strain.

Line 1: replace “develops” with “develop” R : done Line 9: remove sentence about spatial resolution, that is already in the methods section R : done Page 12 Figure 5: what is represented by the pole figures? c-axes? R : Text has been added to the caption : Pole figures representing c-axis orientations are reported at the top right. Line 2: add “dislocations” after “those” R : done Line 9: add “investigated” after “strain” R : done Page 13 Line 3: replace “identify” with “identified” R : done Line 5: replace “kinds” with “types” R : done Line 16: remove “ t “R : done Page 17 Line 15: replace “these study” with “those studies” R : done Page 19 Line 7: Replace “advices” with “advice” R : done

Please also note the supplement to this comment:
https://www.the-cryosphere-discuss.net/tc-2018-213/tc-2018-213-AC1-supplement.zip

Interactive comment on The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-213, 2018.