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Reply to the Comment by S. H. Faria and S. Kipfstuhl on "Deformation of grain boundaries in polar ice"

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Reply

Reply to the Comment by S. H. Faria and S. Kipfstuhl on "Deformation of grain boundaries in polar ice"

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We agree with many of the remarks made by Faria and Kipfstuhl in their comment on our paper concerning deformation of grain boundaries in polar ice. However, they do not invalidate the use of the deformation tensor we have proposed. We reply to each of their three points in turn.

Point I). Their comment is completely consistent with what we have written, as well as with the detailed discussion published in [1]. We agree that a microstructure is not uniquely determined by its corresponding texture tensor, as different microstructures can have the same tensor. *E.g.*, as suggested by [2], arrays of squares, equilateral triangles, or hexagons with $\alpha = 120°$, all have an isotropic texture tensor, as all these microstructures are indeed isotropic! It is actually the aim of such a texture tensor to capture statistical information, and not to focus on geometrical details. We note that the "special case" shown in fig. 1b is not relevant for material science, and our tensor was developed essentially to quantify the changes occurring in a disordered structure upon mechanical deformation.

Point II). Indeed, deformation of ice is induced by the motion of dislocations within the grains. However, this mechanism deforms the grain shapes, and so the grain boundaries. Consider first a basic example often used to illustrate the strongly anisotropic plastic deformation of ice along basal planes: a pile of playing cards. By pushing a border of the pile (shearing), the cards will slide over each other: the global shape of the pile is modified and reflects the deformation applied. In a polycrystalline ice sample, strain incompatibilities between neighbouring grains of different crystallographic orientations complicate the picture and lead indeed to strain heterogeneities within the grains. Our texture tensor is by nature unable to

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analyse strain at scales below the average grain size, and so to reveal these intracrystalline heterogeneities. However, it captures correctly, in the statistical sense, the plastic deformation at scales larger than the average grain size, as long as no recrystallization processes modify the microstructure and wipe out some of the deformation recorded by the grain shapes. This problem has been already detailed [3]. We have shown that the effect of recrystallization processes, such as normal grain growth, preclude obtaining the true value of the strain experienced by a layer. Nevertheless, comparisons between adjacent layers are still relevant. This leads us to conclude that most of the observed heterogeneities have a mechanical origin. Note also that these results have been confirmed by simulations with an explicit microstructure evolution model, and a related paper is currently in preparation (see [4]).

Point III). We have never seen in our ice thin sections a grain boundary so far from equilibrium as the one illustrated by the fig. 1c of [2]. The method used by these authors to obtain these images (sublimation during a few hours) should first be properly validated by a comparison to well-established ones, such as images of thin sections under cross-polarized light (the method applied in our work). A statistical tool (rather than descriptors of individual cell shapes, such as inertia ellipses [5], or partial descriptors, like linear intercept [6]) is useful precisely to get rid of irrelevant details and focus on the overall anisotropy of the pattern. This is discussed in detail in a paper in preparation and a PhD Thesis in preparation [7]. Irregular, far-from-equilibrium, grain boundaries can be found in ice when migration recrystallization occurs. In polar ice, migration recrystallization takes place at a temperature above $-10\,^{\circ}$C, that is for depths below 2900 m in the case of the Dome Concordia ice core. Concerning the calculation of [2], note that it is an order of magnitude calculation. It is certainly not a rigorous proof of the equality between the grain growth rate and the strain rate. As a matter of fact, it is in contradiction with our measurements: the increase of $|U_{zz}|$ with depth during the upper 1000 meters. If the strain rate and the grain growth rate had been equal, $|U_{zz}|$ would have remained constant with depth.

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