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Interactive comment on "Crystallographic analysis of temperate ice on Rhonegletscher, Swiss Alps" *by* Sebastian Hellmann et al.

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Review of "Crystallographic analysis ice on Rhonegletscher, Swiss Alps" by Hellman et al.

General

This paper provides a detailed description and analysis of the crystallographic fabric of ice taken from a core from the surface to bedrock in the central part of the ablation zone of a temperate valley glacier. It finds that multimaxima fabrics of the type commonly found in most valley glaciers, usually just from near-surface samples, occur at all depths within the glacier, with some systematic changes with depth in orientation of the clusters that constitute the fabric. This is a new finding and deserves to be pub-

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lished on this basis alone. The paper then, importantly, relates the fabric to the stress field derived from numerical modeling and finds a direct relationship between the orientation of the fabric and orientation of the modeled principal stresses. This leads to a possible explanation of these four maxima fabrics. I question parts of the interpretation and don't believe these fabrics are yet fully explained, as discussed in the specific comments below, keyed to lines in the text. I have also corrected a few typographical errors and made some suggestions for language usage.

Specific points keyed to line numbers in the text

Line 9-10. The language here doesn't clearly describe the observed relations, since there are four azimuths and colatitudes that define the fabric and three principal stress directions. It is the centroid of the fabric and the maximum principal stress direction that nearly coincide in orientation.

Line 31. The stress and kinematic conditions in valley glaciers are more complex than just combinations of simple and pure shear.

Line 94. Although the details of the numerical model need not be given here, the basic form of the flow law should be given, since the value of the flow law parameter A is defined. The value of the power law exponent, n, in the flow law should also be noted.

Line 117. It is not clear what is meant by fractures here, since there are no actual fractures in this core. This needs clarification. What are the physical manifestation of the 'fractures?" They must be defined by some combination and bubble or grain size distribution.

Line 135. Surely this is mm2 not μm2

Line 151. Here is some information about the fractures. Presumably these patterns are in the form of linear traces in thin section. Following Hambrey I like the term 'fracture traces' for these likely healed fractures.

Line 157. You use the term centroid here for the maximum eigenvector on these plots, and state that these are equivalent in the caption to Table 1. Yet in Figure 7 the two are represented and plotted as separate entities. The usage needs to be consistent. In this case how is centroid defined?

Line 173-174. It should be noted that Kamb, Hooke and others have discussed the issue of accounting for complex and branching shapes of large grains when making c-axis plots.

Fig. 6. The caption could be shortened by stating that the annotation is as in Fig. 5

Line 192. The c-axis fabric has orthorhombic (and perhaps close to axial) symmetry, but is this also true of the stresses? What about the other two principal stresses. Are they consistent with plane strain or plane stress, as appears to be assumed in Fig. 9? Are the principal stresses and strain rates in this section of the glacier near the surface parallel to the flow direction (σ1), vertical (σ 3) and horizontal (σ 2), with the lateral strain rate close to zero, as one would expect for a valley of constant width. One would expect the maximum principal stress to become inclined deeper into the ice as shear stress parallel to the base increases, which the modeled stress shows a tendency to do.

Line 200-204. This is a possible explanation, but I prefer the misorientation of the sample as the explanation, which as you state, fits very nicely when a 60o azimuthal 'correction' is made. A preserved fabric from earlier in the flow path is less likely at high temperatures when rapid recrystallization is expected.

Lines 210-213. With this explanation you would expect σ1 to be vertical to explain the fabric at 79m depth and not as given by the numerical model. Although the vertical normal stress increases with depth, it is the deviatoric stress that controls deformation, not absolute stress values, and this likely does not change greatly with depth. I think the main thing that changes with depth is not the vertical effective compression (σ1 – σmean) but the increasing addition of base parallel shear stress, that in general terms increases linearly with depth.

Line 217. There is almost certainly some dependence of fabric on strain, which may not be great with fast recrystallization.

Line 213-214. In simple shear the directions of principal stress are only aligned with those of principal strain for infinitesimal strains. The divergence grows as strain increases.

Line 238 I don't believe Cuffey and Paterson really explain why there should be four maxima when the stress deviates from unconfined compression. This is more of an observation than an explanation.

Lines 244-245. This is unclear. A change in direction of glacier flow could be associated with either an increase or decrease in strain rate and thus decrease or increase in recrystallized grain size. Why just a decrease?

Line 251 and Table 2. Table 2 does not really give the grain size distribution, only average numbers of grains and average and maximum size in each sample. It would be useful to know the number of grains in each size category. Also interesting to know if there is any difference between the large and small grains in COF.

Line 255-266. I'm not sure how much information is given by the air bubbles, except they do provide excellent evidence of active recrystallization by grain boundary migration. Bubbles are found both within grains and along grain boundaries both in temperate ice and in cold ice experiencing dynamic recrystallization, although the recrystallization mechanism may differ.

Line 269. Hooke and Hudleston were concerned with polar, not temperate ice. The study was made on the Barnes Ice Cap.

Line 276. Whether the multimaxima fabrics are a result of unrepresentative sampling is still arguable in some circumstances, although the case you have here for these being true multimaxima fabrics is a strong one.

Line 290-291. I think more data is needed to support this conclusion. The cores taken by TIson and Hubbard were in a different regime within the glacier – accumulation zone where perhaps there is longitudinal extension rather than compression, and close to the lateral margin of the glacier rather than in the center. This must lead to a more complex stress regime.

Line 298-299. The combination of compression plus simple shear as applied in these experiments makes sense for much of your core, but not for the highest one where the shear component is minimal, nor for the lowest one, where the $\sigma 1$ direction lies well outside the small-circle girdle of maxima. Some other explanation must hold in these places.

Line 300-301. I'm not sure if I'm properly interpreting what you are saying here, but the planes of maximum shearing stress in Duval's combined compression-simple shear experiments are not vertical and horizontal in his experiments, but inclined by an amount that depends on the relative amounts of normal compression and simple shear.

Line 312-316. Both Llorens et al. and Qi et a. are dealing only with simple shear, not with combined compression plus simple shear as in the torsion plus compression experiments. The conditions in the Rhone glacier I imagine change from horizontal compression with minimal base-parallel shear near the surface to horizontal compression combined with increasing base-parallel shear near the base of the glacier. As theory shows, shear stress increases approximately linearly with depth, while longitudinal stress stays approximately constant.

Fig. 9. The stress state shown in Fig. 9 is almost that of simple shear (no base-parallel longitudinal compression) with the shear plane (taken as the glacier bed) horizontal and $\sigma 1$ inclined at 45o to the shear plane. If it is simple shear, there will be no horizontal compression and thus no shortening in the glacier flow direction, which is incompatible with your data. If horizontal glacier flow-parallel compression is added $\sigma 1$ will move closer to horizontal than it would be for simple shear alone. This looks like being the case for much of the glacier from the stresses shown in Fig. 7. I would expect the

inclination of $\sigma 1$ to be near zero at the surface and something less than 45o close to bedrock, the amount depending on the amount of horizontal compression. Although not a smooth change, the $\sigma 1$ directions in Fig. 7 are consistent with this.

The plot in Fig. 9 does not correspond to any of the plots in Fig. 7, all of which have $\sigma 1$ at a shallower inclination than 45o and thus have associated planes of maximum shearing stress that are neither vertical or horizontal, unlike the situation in Fig. 9. The one closest to horizontal thus cannot be considered a plane of simple shear. The 'shear plane' must always be the presumably sub-horizontal glacier bed.

Line 340. I disagree with the statement here (see comments for lines 210-213). Although the absolute value of the vertical normal stress increases with depth, the deviatoric vertical normal stress changes much less. It is the increase in base-parallel shear stress combined with the horizontal compressive stress (σxx if you like) that causes $\sigma 1$ to rotate from near horizontal at the surface to inclined at some angle of less than 45o at the base.

Line 342. The second part (ii) of the explanation for multimaxima fabrics given here makes no sense by itself. All states of stress that are non isotropic involve shear stresses. If the multimaxima fabric depended solely on the state of stress – that is with instantaneous adjustment of the c-axis fabric as the stress field changes – then there should be a constant relationship between the positions of the maxima and the principal stress directions. This clearly is not the case as the relationship in the deepest sample shows. There is, however, as you note, a consistent relationship between the fabric and the $\sigma 1$ direction through most of the glacier and in all cases, with small deviations, the centroid of the COF fabric and the $\sigma 1$ direction lie in the vertical plane that contains the flow direction. This is a key relationship that I believe you have only partly explained.

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Please also note the supplement to this comment:
https://tc.copernicus.org/preprints/tc-2020-133/tc-2020-133-RC1-supplement.pdf

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