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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 Hellmann et al.

General comments This paper provides a careful analysis of the measured fabric in the central part of a Rhonegletscher, in the ablation area through ice cores (not quite to bedrock).

The authors did a really thorough and rigorous analysis of the fabric using multiple thin sections in 3 orientations. The most well analyzed core I have seen for a temperate glacier, I appreciated the thoroughness, as it was necessary because of the dominance by large grains and a grain size distribution that if far from normal. This paper in some form should be published because of the beautiful data set.



While the data analysis is done really well, the interpretation in terms of stress state is not as thorough and rigorous. Their qualitative interpretation of the stress state and its relation to fabric and recrystallization processes is confusing and in a few places incorrect. The paper would benefit from a summary of the key states of stress, key metamorphic processes, citing the original research (going beyond Cuffey and Paterson and the Faria reviews). As a reader, if I am to trust their interpretation of the fabric, I need to trust that they understand the underlying physics. At this point, the physics is description is still lacking. It is imperative that the interpretation of the fabric in terms of the stresses be written with the same care and rigor that that fabric was measured.

First, it would be helpful to clarify when deviatoric stress is being used versus total stress. Deviatoric stress control most of the deformation and pressure plays a minor, if any, role in deformation, therefore describe the deviatoric stress states rather than "absolute" stress and "overburden." For example, the authors suggest that there is less deformation in the surface layers because the "absolute" stress there is low, but this is not the case - the vertical compressive deviatoric stress is no necessarily smaller at the surface, it is typically about the same - it is only the pressure term in the total stress that is smaller at the surface and pressure does not drive fabric (only gradients in pressure or overburden can drive flow).

I would suggest that they re-write the description of the stress state in terms of more formal tensor components, and more specific (and correct) wording. And please be explicit about what is behavior linked to stress and what is behavior linked to strain rate (and discuss with respect to the statement that strain rate ultimately drives fabric development not stress).

In terms of writing, there are numerous run-on sentence, imprecise wording, and extensive use of passive voice, all of which slows down the reader. I provide examples of a few of these (but not all of them) below, I encourage the authors to edit carefully for these three writing issues.

Specific suggestions:

Line 1 Abstract - the first line of the abstract should offer some kind of bigger picture motivation, something to entice readers beyond those already rheology and fabric "geeks" - this is a neat paper with respect to the unique measurements and it would nice for the broader glaciology community to read it.

Line 20: delete "to that" - not necessary

Line 23: delete "do"

Line 24: Faria offered great reviews in his 2014 papers, but be careful citing those papers when there are better papers that are more directly or more originally related to the statement. Here by citing Faria, it implies that that paper was the first to discover that COF evolves in a glacier. Provide more direct/original citations please (or be explicit that you are citing Faria as a review article).

Line 30: delete "quickly" unless you want to provide the timescale that quickly is indicative of (words like quickly, clearly, mostly, etc don't add any information and can lead to confusion).

Line 53 - run-on sentence, breakup into two or three.

Lines 74-78 - lots of passive voice here, rewrite

Line 78 - I'm still a little confused how you knew the orientation, did the drill head not spin on the cable as it was lowered or raised?

Figure 2/3: I like the diagram in figure 3, but why not just calculate the bulk surface strain rate components from these measurements instead of the figure 3 plot.

Figure 2/3 - Did you measure the emergence velocity? I would expect emergence, and this will affect the stress state.

Line 89 - This paragraph seems to shift to modeling methods, from drilling methods.



While it mostly reads ok, perhaps make this a different section? Especially since the section is titled "field site and data acquisition" I also think one paragraph describing the model is a bit thin. If you are actually using the model to interpret your data, please describe it more rigorously and explain the weaknesses with the model output - how much do you trust the modeled principal strain rates and directions? Given that you just assumed a rate factor from another glacier and tuned the sliding to fit this glacier site? Did you conduct a sensitivity study to assess the impact of your parameter selection on the stress and strain rate output from the model? Given that the model inputs are approximate, I'm not entirely sure that the model provides any better qualitative assessment of the expected principal stresses and strain rates than a simpler flow band description explained with clear assumptions.

Line 91 - delete "simply"; say "steady state" model or something like that.

Line 97 - I realize that the model is not intended to be a perfect match, but tuning the model to only one surface velocity is limiting. But I think that's ok, if you are mostly going for the style of stresses and not the real magnitudes (but see my comment above about just using a simpler flow band description because models like this not tuned well can induce complexities that might be interpreted as real). Importantly, the stress distribution with depth at the site of the borehole is highly dependent on the sliding coefficient. When you use these results to interpret the data, please discuss this with respect to the limitations of the model (see my comment above about the vertical distribution of stresses). Oh - and what was used for accumulation/ablation rates? The vertical strain rate at the core site will depend on the ablation rate. Did you measure the vertical velocity at the surface?

Line 123 - delete "as discussed later" and "important" - they don't provide any useful information here.

Figure 5 - nice figure, I am interested in the other 2 eigenvectors - are they equal? Also, please provide some examples of the size distribution (histogram? or statistical distri-

bution curve? You have some statistics in table 2, at a minimum, provide the median. But I would suggest putting the size distribution for each depth in the supplementary information. Put a reference in Figure 2 caption to Table 2 and the supplementary information for the size distribution.

Line 166: "oriented in the direction of glacier flow - just be more specific with wording here. The c-axes points within xxdeg of the flow direction (155deg).

Line 180 - I think this section would be best started with an overview of the deviatoric stress state (if it isn't already in the background), as measured from the surface stakes and as inferred from the model, in terms of the stress tensors and principal directions.

Line 181 - This first sentence doesn't add anything and isn't necessary and is subjective. Just cut it.

Line 192 - see my note from line 180. It is difficult for me to separate the effect of the longitudinal compression alone - I'd rather see a description of the full deviatoric stress state as a function of depth and then look at what components are doing most of the work. Also, there are two horizontal stresses (sigma xx and sigma yy) better to describe these as longitudinal and transverse.

Line 198-202 - Misorientation is most likely, is there a need to go into complex (and incorrect) explanation about surface stress? See my comment above that the "absolute stress" doesn't affect the fabric, only the deviatoric stresses do. This is a really fundamental point, please interpret your fabric in terms of deviatoric stresses.

Line 211 - I'm not sure I understand this, overburden doesn't generate anything, only gradients in overburden (even better to use formal deviatoric stress terminology).

Line 228. I think the author is referring to recrysllization when they say "these processes" - please note that it is not true that they were "just attributed to temperature" - cummulative strain has always been known to be a key part of the process. Please cite earlier work - maybe back from the 70s or 80s on this rather than suggest that this



is new knowledge?

Line 233 Because normal and shear stresses are the two types of stresses, then the statement that a combination of normal and shear must have been involved to create the fabric is minimally useful. Please provide more specific description.

Line 239 what does it mean for a tensor to provide "hints" (that seems to me like an anthropomorphism)?

Line 239/240 Do you mean that this site is not 100% sliding? That's the only way to avoid borehole shearing. It seems like the model set up already defined a limited amount of sliding, there must be some non-zero component of tau xz. So that was an input to the model, not an output.

Line 241 A parabola is typically for an xˆ2 relationship, that is not the case for the curve resulting from Glen's flow law.

Line 243 - how long ago was "recently" can you provide estimates for the timescale of the last significant change in stress state and express that timescale as a percent strain the crystal experiences?

Line 244 - I think the authors mean "latter" not "later"

Line 244 - I'm not quite sure why a mean grain size reduction would necessarily occur after a change in flow direction, unless you are suggesting that the change in direction is triggering specific recrystallization (migration or rotation). I am also not sure I understand the citation to Faria here, as recrystallization has been described in many papers before. Perhaps you can be more specific about what Faria contributed that is specific to this analysis? And please more carefully cite the statements here (alternativly, if you write an overview of the stress state and metamorphism of the crystals in the beginning that describes and cites each process as background and properly cited, you can avoid having to add too many citations in this discussion section.

Line 256 I really like the images of the bubbles and the grain boundaries - it does show fast grain boundary migration and active interaction between bubbles and boundary movement. How do you know it was a "complete" recrystallization?

Line 258 The image of bubbly and bubble free ice brings up a question I have as to whether there are signs of refrozen water in these thin sections. Water filled crevasses refreeze with a different microstructure that is typically bubble-free or with patterns of bubbles and distinctly different crystals. Some of the small grain "fracture" noted in the paper also might be a post-depositional process. Perhaps it is ok to include these in your analyses, as the same crystal evolution processes are happening, but it might be useful to discuss the ice from snow compaction versus any refrozen water and how that might influence the fabric and grain size distribution (and bubble)

Line 265 - again, I believe you mean to use the word latter.

Line 265 - please define "fast" - fast compared to what? How fast is fast?

Line 273 - delete "as employed in our study?

Line 278 - again, Faria is not the first one to say that temperature is not the only driving process behind boundary migration recrystallization.

Line 280 - be careful using such a strong word as "only" - also, this is a long run-on sentence and would be better to be split up and explained in more specific wording.

Line 280-295 - These sentences don't actually explain how the diamond shape forms, just that it happens at high strain rates in certain orientation of stress. Rewrite this to explain the underlying physical process, if possible. If not possible to explain the physics, then explain this as being associated with specific conditions, with physics still to be determined.

Line 290-291 - The word "only" is too strong, this sentence seems to be a hypothesis you are trying to suggest that your data support (but I don't know what the "certain strain rate" is).



Line 293 - "the absolute strain rate... is expected to be" - please clarify which components of the strain rate tensor you are referring to, or if you mean the effective strain rate (tensor invariant). There is very little discussion of inherited fabric in this paper, How does inherited fabric affect the deeper layers (I don't agree that the surface is necessarily inherited because of any less strain rate at the surface - the only component of the strain rate tensor that is smaller at the surface is the simple shear parallel to the bed).

Line 310 - how do you judge "good agreement"?

Line 317 - "clearly" is not a helpful word - at this point, I am a bit bogged down in generalities and imprecise wording in the fabric and stress/strain relationship, that I am struggling to judge for myself what the source of the 4 maxima are.

Line 335 - I do believe twinning has been observed use EBSD (such as Obbard's work on the Fremont glacier and/or at Siple Dome), I can't remember which one she noted the a-axis alignment that would suggest twinning.

Line 340 - This statement isn't correct, at least the way I am understanding it (increasing overburden/pressure). Please describe the fabric in terms of deviatoric stress tensor as a function of depth, and, in addition, explain more clearly why 4 single maxima are created rather than a girdle, I think you tried to explain this, but it didn't come through very clearly.

Line 346 - yes, in terms of "comprehensive" analysis of the thin sections measurements - this paper is awesome. In terms of interpretation based on stress state, this paper needs work. There have been some other work on temperate glaciers (including some ongoing work on a glacier in Alaska I think - by Gerbi and others? I'm not sure the status of their publications).

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