Response to Referees' Comments

We are grateful for the referees in pointing out where more information should be provided and where clarification is needed. In the responses below, we include additional information to bolster claims made in the manuscript. We disagree with the referees on a number of points, as indicated.

These responses are provided in the order in which the referees' comments were made. These responses are provided in the order in which the referees' comments were made. The referee comments are italicized.

Referee No. 1

1) "The scientific conclusions provided in the paper are not new and far too weak for the expectations of a standard research paper in The Cryosphere".

We dispute this criticism, although accept that we may not have made the strongest case for our arguments. The method we describe is new, as we believe are the conclusions drawn from its application. We also disagree strongly with the notion that multimaxima fabrics are "not enigmatic." They are <u>not</u> well understood, and there are thus good reasons for focusing attention on them, as explained in point #13 below. The fact that the fabrics remain enigmatic was a prime reason for undertaking the study.

The main conclusions of the study are:

i. This is the first study that allows a-axes as well as c-axes to be measured in coarse-grained ice by application of EBSD, and does so in a setting that is clearly dominated by shear. The only other study that measured a-axes in coarse-grained ice we are aware of used the less accurate, and lower angular resolution etch-pit technique (Matsuda and Wakahama, 1978) and did not consider the fabric in relation to the kinematic setting in the ice body. [We should note that a-axes have also been measured in fine-grained Antarctic ice using both semi-automated Laue X-ray diffraction, (Weikusat et al., 2011), and EBSD (Obbard et al., 2006; Obbard and Baker, 2007; Weikusat et al., 2017). They have also been measured in sea ice using EBSD (Wongpan et al, 2018)]. We show that a-axes are preferentially aligned and thus, in this case, slip is not isotropic in the basal plane as is often assumed, although this assumption is shown not to hold true based on recent experimental work (Journaux et al., 2019; Qi et al., 2019). Theoretically, slip is isotropic when $n = 1$ or 3 in the flow law, but not when $n = 2$ or 4 (Kamb, 1961). To an extent yet to be explained, a-axis orientations may provide information on kinematics and rheology, and full crystallographic orientations, which can help better characterize deformation, recovery and recrystallization mechanisms (Prior et al., 2015), are therefore important.
ii. The study draws attention to the issue of interlocking grains of complex shape and the problem of individual grains being counted multiple times and thus contributing to false maxima in fabric diagrams. This problem is not new and was clearly recognized by early workers. However, little to no attention has been given to it in recent work.
iii. We provide data from separated parts of single samples and combined data from well separated samples in the same part of the glacier with fairly well-definied kinematics to

suggest that what might be taken in individual samples as fabrics with three or four c-axis maxima become a simpler fabric that is very similar to what is expected conceptually for deformation dominated by slip on the basal plane under simple shear combined with some shortening normal to the shear plane. This is a new interpretation.

iv. The fabric pattern (both c-axis and a-axis) is similar to what is found in experiments involving simple shear, in which sub-sampling produces fabrics that could be considered individually as multimaxima fabrics.

v. We bolster microfabric evidence given by others for dynamic recrystallization involving grain-boundary migration in coarse-grained ice in contributing to the development of the crystallographic fabric.

2) "The method described, although sounding interesting, is not compared to any other type of measurement, for instance, many sample analyses over a continuous part of a core, or of a block of ice in order to provide enough grains for a good statistics".

Comparing our method with others of handling large grain sizes is an omission in the manuscript that will be addressed. We did <u>not</u> claim to be the first to combine orientation data from multiple sections to overcome the problem of sampling when dealing with very large grain sizes (see Rigsby, 1951; Kamb, 1959; Gow and Williamson, 1976; Thwaites et al., 1984), nor in recognizing that individual grains may appear multiple times in a single thin section (or in separate thin sections from the same block or core segment of ice) and thus be responsible for enhancing maxima in pole diagrams (see Bader, 1951; Rigsby, 1951; Kamb, 1959; Jonsson, 1970). Our method provides a way of dealing with the specific technical challenges of using EBSD for coarse-grained ice. The time/ resource limitation for EBSD is time on the instrument and with fast EBSD speeds, the sample exchange becomes the limit. Making a composite means that we collect data equivalent to 10 to 20 full sample sections with only one exchange of samples: that means half a day of SEM time rather than 2 weeks of SEM time. As the above references document, the issues associated with sampling coarse-grained ice with interlocking texture were most clearly addressed in the early work on ice fabrics using the U-stage, by spacing successive thin sections between 5 and 15cm. In recent work where fabric has been analyzed using AITA or EBSD, however, the issue of the same grain possibly contributing multiple points to a fabric diagram does not appear to be addressed. For example, we could not find a description of how sampling was handled for coarse-grained ice (multiple samples from continuous core according to the referee) in Dahl-Jensen et al. (2013) (and associated supplemental data) and Montagnat et al. (2014), nor is it clear from these papers if efforts were made to consider the likelihood of multiple points contributing to the CPO from individual parent grains appearing several times in a thin section. Generally, in the more recent papers that use AITA, where multi-maxima CPOs are presented, the associated discussion is brief and simply makes note of the complex, large interlocking crystals (Dahl-Jensen et al., 2013; Fitzpatrick et al., 2014; Montagnat et al., 2014). There is no attention given to the problem of multiple sampling of single grains and thus the potential for false maxima or reasons given for the multi-maxima pattern. We note that representing data using all-pixel orientations does take into account the issue of parent grains with satellite island grains, but this is only if the sample is large enough to contain a sufficient number of grains to provide a truly representative fabric. If the sample does not contain a representative number of grains, as is often the case with coarse-grained ice, then using one-point-per-grain provides a more representative fabric (fig. R1).

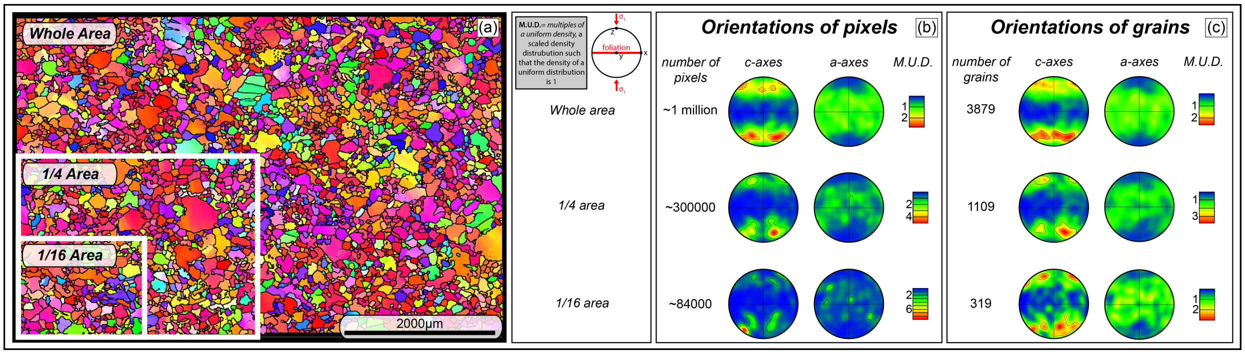

Figure R1: EBSD map and associated CPO plots for sample PIL36 deformed in uniaxial compression at -9.8**°C** from Qi et al. (2017), highlighting the difference in representing data as all-pixel orientations vs. one-point-per-grain orientations as a function of sample size. (a) EBSD map, with boxes representing subsampled areas. (c) CPO plots (c- and a-axes) of all pixel orientations from the entire sample area, ¼ the sample area and 1/16 the sample area. (d) CPO plots (c- and a-axes) of one-point-per-grain orientations from the entire sample area, ¼ the sample area and 1/16 the sample area.

The issue of statistics is not straightforward for coarse-grained ice with the existence of multiple maxima. Any way of attempting to eliminate the effects of multiple counting of individual grains that appear more than once in a thin section or in multiple sections intersecting a single crystal would be ad hoc. Doing statistical tests while ignoring this phenomenon is of little use. Kamb's (1959) method of contouring provides a way of establishing the statistical significance of maxima in a fabric, but this is only meaningful if multiple points from the same grain are excluded.

3) "are we sure not to measure several times the same large crystal coming from the depth of the block, since some crystals are more than 90mm large? Owing to the fact that exact shape and location of grains are lost, there is no way to verify such a situation, as is done in figure 2 for instance. The introduction pretends that the use of a-axes measurements could provide supplementary information to check the belonging of measured areas to one single crystal or several, but this procedure is not used neither described later."

First, it is important to note that even with the maximum size thin section (using any method of analysis), the exact shape and extent of individual grains remain unknown. Bader (1951) and Rigsby (1968) were the first to illustrate the likely complexity of individual grains crossing successive thin sections.

Figure 2 in the manuscript is provided precisely to give an illustration of the problem within a single 2D section as shown under cross-polarized light. For this figure, we removed grains we *believed* to be islands of the same parent grains based on the c-axis orientations. By examining the one thin section, or even successive thin sections depending the potential size and shape of individual grains, it is not possible to state with certainty that two grains with the same or very similar c-axis orientation are branches of the same grain. One would have to trace every measured grain through an undetermined number of successive thin sections in order to say with certainty which grains are repeated in individual thin sections. It is possible to confirm a common parent to island grains in a single thin section using both c-axes and a-axes. As stated in the introductions, we in fact show how this is done in figure 6 in the manuscript where three grains with the same c-axis orientation also have the same a-axis orientations, we did not just pretend to do it. We were able to use the a-axes as confirmation that tight clustering of points in composite samples that appear as maxima, likely come from the same grain, because the c- and a-axes are nearly identical, thus highlighting the probability of false maxima. We will clarify this in section 6.2 (l. 347-359) by stating that the c-axis clusters are coupled with corresponding a-axis clusters, which as for the whole sections, likely indicates repeated representations of the same grain.

4) "There is only a very weak discussion about the orientation error produced by this multi-slicing technique, although it could be quite strong, and add on at each slicing step."

Greater attention should have been given to this important point, which we do here in order to justify the conclusions we reached concerning the fabric diagrams. We consider the process in several stages. Each sample is first squared into a rectangular prism, with one side vertical and another parallel to foliation, using guides to ensure perpendicularity. Guides are then used for each of steps 1-4 (Fig. 5), cutting the sample progressively into slabs, rods, cubes and slices. The errors involved in each stage of this process are estimated to be less than 0.5°. The error involved in slight twisting between slices during assembly into a composite section is estimated to be no more than 1°. Combining data from two or three composite sections in a sample adds only possible errors of misalignment in mounting for EBSD measurement. This is estimated to be no more than 0.5°. The largest source of error is in combining data from the three samples (Fig. 8). The reference frame for this is the foliation plane (xy-plane with vertical, x, recorded on each block when removed from the glacier.) The error in combining data from the three samples is estimated to be no more than 1°. Adding these sources of error, we estimate the uncertainties in positioning points on the pole diagrams in Fig. 7 to be no more than 4° and in Fig. 8 to be no more than 5°. The overall effects of such errors are likely to modestly diffuse rather than strengthen the maxima shown, but they will not modify the basic pattern. We assert that the measurements we have made are sufficient to establish the main features of the fabric in Fig. 8.

5) "The too limited number of measured crystals is attributed solely to the measurement technique (AITA or EBSD) in using too small samples. This is not so true since it is possible to measure several contiguous samples from an ice core – see Dahl-Jensen et al. (2013) and Montagnat et al. (2014), for instance where analyses along contiguous samples from 1 m long cores were done."

We do <u>not</u> make such a claim about measurement techniques (see #2 above), although we did not discuss other ways in which authors have addressed the problem. This is something that needs to be added. Early workers had addressed the problem of sample size by making multiple sections from different parts of a sample or core, spacing thin sections between 5 and 15cm intervals, (Rigsby, 1951; Gow and Williamson, 1976; Thwaites et al., 1984) or from more than one sample (Kamb, 1959).

6) "One of the main conclusions is related to the observation, in some previous studies, of multi-maxima, and their attribution to a too limited number of crystals. This result is not so new and was intuited by most of the authors responsible for the mentioned studies. Experimental observations such as the ones from Qi et al. 2019 shown in the paper enabled to confirm this *intuition already since, with a larger number of grains, the multimaxima texture do not exist anymore."*

Our reanalysis of the Qi et al. (2019) dataset is a new and unique contribution. Using their data, we emphasize that if you sample a small subset (a statistically insufficient) number of grains, one can produce an apparent multi-maxima CPO from an otherwise well-defined simple shear CPO. This is not a point made by Qi et al. (2019), who were not concerned with multimaxima fabrics and who did not consider subsets of their data.

7) *"Although there is one dominating orientation in the combination of samples presented on figure 8 the multi-maxima remains, with 3 main orientations. So the result is not so obvious and can not lead to such a firm conclusion"*.

We admit that the pattern is not clear cut, but the strong split maximum lying in the plane perpendicular to the foliation and containing the vorticity axis is just what is expected for simple shear, as observed in in torsion experiments (See paper, lines 379-385), and accentuated by adding a component of compression normal to the shear plane (fig. R2). One of the two weak submaxima in the plane normal to foliation and parallel to the shear direction (fig. R2) is what is expected in simple shear, as in the experiments of Qi et al. (2019), which also show a hint of a submaximum offset in the opposite direction, a second sub-maximum (fig. R2) that is more apparent in our samples.

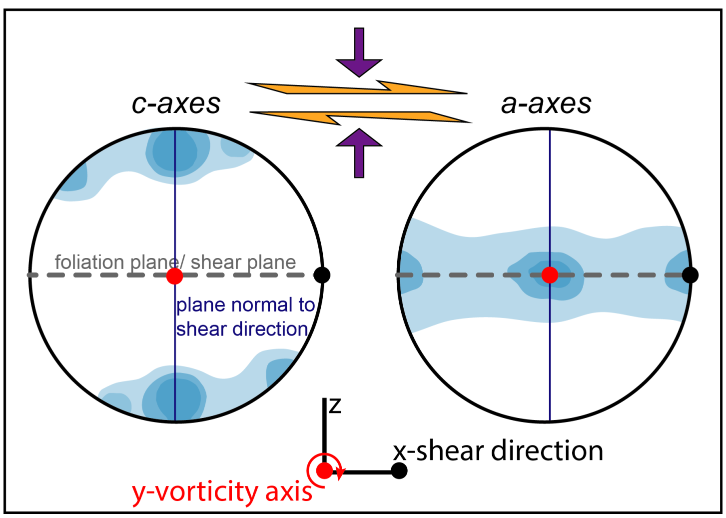

Figure R2: Schematic pole figures highlighting the relationship of the CPO to the foliation/shear plane (gray), the vorticity axis (red) and the plane normal to the shear direction (navy blue).

8) *"Moreover, to be more affirmative, one would have needed more results, on various samples which is not shown in this study."*

Yes, of course, more data on more samples is desirable, but the resources available to conduct this work were limited. We consider this a self-contained study that should prompt further research. We might stress the amount of work involved in extending such an enterprise. Each individual large sample takes hours of physical labor to collect, insulate and haul over rough terrain to a freezer at the research station. Then preparing the samples for transport in several stages to Otago in New Zealand, while ensuring that they stay well below freezing at all times, requires careful packing in large coolers, each of which can only contain 4 samples, and close monitoring during transit. Additionally, there are particular challenges of working with coarse-grained ice using EBSD. Each large section takes >1 hour to analyze at a coarse step size (50µm), additional time to analyze any areas of interest in finer detail, and another hour to do a sample exchange, run the sublimation cycle to clean frost off of the sample for imaging, bring the stage down to the correct temperature, and set up another analysis. *If* all goes smoothly, only 3-4 sections can be analyzed per day. Beyond this, there is the time taken to prepare the composite sections, steps which are laid out in l. 225-237 (fig. 5) and take ~5-6 hours for each sample, and an additional ~2 hours to prepare whole sections once the slabs of each sample are polished, allowed to sublimate overnight and photographed.

9*) "The other conclusion related to grain boundary migration dominating dynamic recrystallization processes in the studied conditions is not new at all, and simply confirm the observations by most authors working on dynamic recrystallization mechanisms in warm conditions see for instance De la Chapelle et al., 1998, but also the laboratory work by Jacka and co-authors, or the most recent work by Journaux et al. 2019."*

Yes, many studies attribute multimaxima fabrics to dynamic recrystallization dominated by grain boundary migration, citing the large interlocking nature of the grains that form at high temperatures (Rigsby, 1955; Gow and Williamson, 1976; Gow et al., 1997; Duval, 2000; Diprinzio et al., 2005; Gow and Meese, 2007; Montagnat et al., 2014). This is not of course new, nor did we claim it to be. However, we do provide additional textural observations in support of this assertion: individual grains lack significant internal distortion, and no visible shape preferred orientation. We could add evidence of grain boundary drag around bubbles (e.g. Fig. 6a), similar to pinning effects discussed by Evans et al. (2001).

10*) "Although the authors used the review paper by Faria and co-authors (2014), it is necessary to provide the references of the original works to whom the credit should be give. Otherwise the community will little by little lose track of these original work and the credit will only go to the one who wrote the review."*

We agree with this comment. The point is easily addressed.

11*) "About open cones CPO in polar bore holes, once again the citation of Faria et al. 2014 is inappropriate, since Faria and co-authors did not make any measurement along deep ice cores, and this is not true I think, that this type of CPO is not observed along polar ice cores."*

We also agree with the second part of this statement. There are certainly fabrics close to open cones (sometimes called small circle girdles) in the upper parts of polar ice cores (e.g. Ross ice shelf, Gow and Williamson, 1976; Byrd Station, Gow and Williamson, 1976; Camp Century; Herron and Langway, 1982; Cape Folger, Thwaites et al., 1984; Dye 3, Herron et al., 1985; Siple Dome, DiPrinzio et al., 2005; Siple Dome, Gow and Meese, 2007; NEEM, Montagnat et al., 2014). In most of these cases these fabrics are identified as such.

12) *"Also less clear than in experimental work, some CPO very close to open cones are observed in the bottom od the GRIP, GISP2, BYRD cores for instance."*

We agree with this, too. Our statement on this needs clarification. Sometimes CPOs at the base of ice sheets are identified as possible open cones/ small circle girdles or modifications of open cones/small circle girdles (e.g. Byrd Station, Gow and Williamson, 1976; Tison et al., 1994; GRIP, Thorsteinsson et al., 1997; GISP2, Gow et al., 1997; Siple Dome, DiPrinzio et al., 2005; Siple Dome, Gow and Meese, 2007), even though these types of fabrics typically show some clustering that is interpreted as a multimaxima CPO. It is important to note that the eigenvalue technique of fabric representation, often used with AITA analyses, does not distinguish between small circle girdles and multimaxima fabrics (Fitzpatrick et al., 2014).

13*) "Line 118: the multi-maxima CPO is not enigmatic and some hypotheses were given by different authors… See for instance De la Chapelle et al. 1998"*

We disagree strongly with the statement that multi-maxima CPO are not enigmatic. Indeed several hypotheses have been advanced to explain these fabrics, but there is no consensus on their significance. We address here at some length the reasons for our disagreement.

Multi-maxima crystallographic fabrics have been recognized since the 1950s, though there has been little focus on them in recent years, perhaps due to the large grain size and sampling difficulties. They have been documented in coarse-grained ice in many studies of valley glaciers (Rigsby, 1951; Meier et al., 1954; Kamb, 1959; Higashi, 1967; Jonsson, 1970; Fabre, 1973; Vallon et al., 1976; Tison and Hubbard, 2000; Hellmann et al., in review), in deep warm parts of polar ice sheets (Gow and Williamson, 1976; Matsuda and Wakahama, 1978; Russell-Head and Budd, 1979; Gow et al., 1997; Diprinzio et al., 2005; Gow and Meese, 2007; Montagnat, 2014; Fitzpatrick et al., 2017; Li et al., 2017), and at the margins of polar outlet glaciers (Kizaki, 1969). They have also been produced in experiment, in torsion tests (Steinemann. 1958) or torsion combined with compression (Duval, 1981; Russell-Head, 1985) and in compression alone combined with annealing (Maohan et al., 1985). Despite this attention, we believe these fabrics remain poorly understood,

This is why we believe this to be the case.

First, there is the question of whether or not the maxima are truly distinct. This is due to the possibility of there being many island grains of a single parent creating false maxima (Rigsby, 1951; Kamb, 1959) or there being an insufficient number grains to define the fabric (Kamb, 1959). Tests of significance do not account for repeated counts of island grains. The most likely confusion is between true multimaxima fabrics and small-circle girdle distributions (Kamb, 1972; Maohan et al., 1985; Thwaites et al., 1984). We note that per-pixel fabric diagrams produced whether by AITA or EBSD automatically bias towards large grains and can potentially produce spurious maxima (fig. R1). Plotting grains as one-point-per-grain for bulk CPO analyses can reduce this bias.

Second, and likely because there may be single grains with island satellites producing their own individual maxima, the number of maxima recorded is variable, from three to five or six (e.g. Rigsby, 1951, 1960; Kizaki, 1969; Jonsson, 1970), although four is the "ideal" number arranged in a rhomboid or diamond pattern (Rigsby, 1951, 1960); however the shape of the pattern is variable. The angles between the maxima and the "center of gravity" of the individual clusters vary between 25 and 45 degrees (Rigsby, 1951; Kamb 1954; Jonsson, 1970; Gow and Williamson, 1976; Russell-Head, 1985; Budd and Jacka, 1989).

Third is the relationship of the fabrics to the state of stress or strain. For fabrics that are most distinctly of four-maxima type, it is commonly assumed that the fabric is related to the state of stress and that the maxima reflect basal planes aligned in orientations of high shear stress (Duval, 1981), even though there are only two planes of maximum shear stress in a general (triaxial) state of stress. It has been suggested that these fabrics develop in ice that has undergone prolonged shear (Kamb, 1959, Higashi, 1967), and also that they may represent partial annealing in ice that may be under a low state of stress (Higachi, 1967; Budd and Jacka, 1989) or nearly stagnant conditions (Russell-Head and Budd, 1979). There is thus uncertainty about the stress level under which the fabrics develop and how much of the history of deformation experienced by the ice is reflected in the fabric. Many authors have noted that the center of the set of maxima lies near the pole to foliation (Rigsby, 1951; Meier et al., 1954; Kamb, 1959, Kizaki, 1969; Jonsson, 1970), which in marginal ice is the plane of high shear stress and also one of high shear strain. However, similar fabrics are found near the center of glaciers where shear parallel to foliation is a minimum, yet maxima are still centered around the foliation pole (Fig. R3; e.g. Kamb, 1972, Fig. 17b) or parallel to the direction of maximum compression (Hellmann et al., in review). If the fabric reflects the state of ambient stress, with no memory of stress or strain history, there should be a consistent relationship between the fabric elements and principal stress directions and there should be no distinction between fabrics developed under coaxial and non-coaxial kinematics. This does not appear to be the case because in simple shear the maximum principal compressive stress is at 45° to the shear plane and the maxima are arranged about the normal to the shear plane (as is found along the margins and at the base of valley glaciers), whereas in coaxial deformation, as would be expected in the near-surface central parts of valley glaciers, the maxima are symmetrically arranged about the maximum compression direction (fig. R3; Hellmann et al., in review) or the pole to foliation (fig R3; Kamb, 1972, Fig. 17b). Thus there is ambiguity about the relationship between the maxima and the orientation of principal stresses (as inferred from strain rates or from modeling) and the relationship between the maxima and orientation of the principal directions of cumulative strain, whether the strain history is one of coaxial or non-coaxial type.

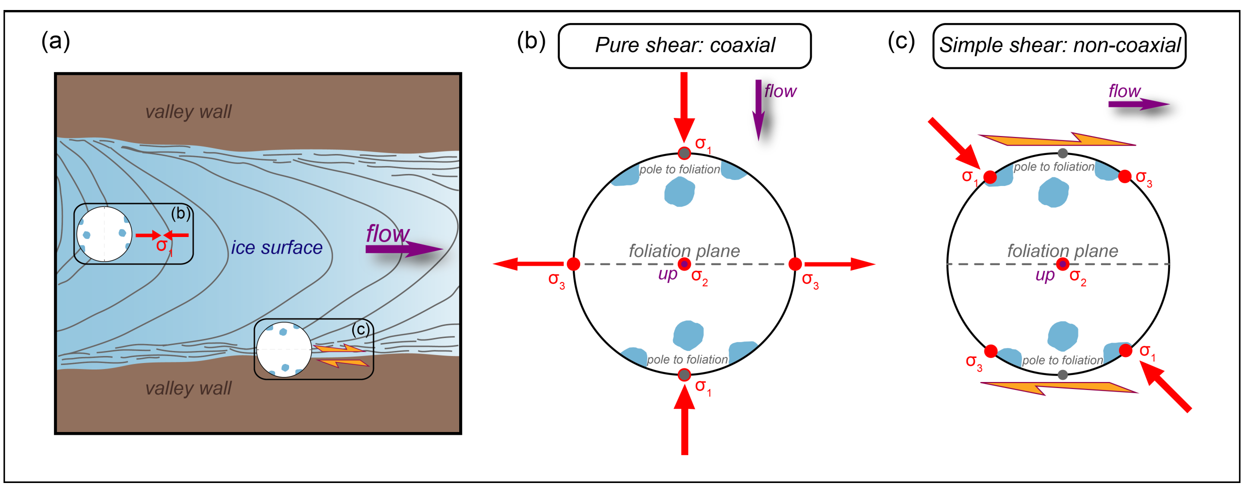

Figure R3: (a) Schematic relationship between classic four maxima fabric pattern and inferred state of stress in valley glaciers. (b) pure shear, found near the surface in the center of glaciers in the ablation zone where ice is in longitudinal compression, with σ_1 is horizontal and perpendicular to foliation, which is typically nearly vertical and transverse to glacier flow. (c) simple shear, with σ_1 inclined at 45° to the foliation, which is steep and parallel to the valley sides.

Fourth, in addition to these uncertainties, it has been suggested by (Matsuda and Wakahama, 1976) that the maxima represent crystals that are in a mechanical twin relationship with one another. Duval (1981) suggests the possibility of annealing twins rather than mechanical twins. The texture in thin section gives little indication of twinning, however. The possibility of twinning can only be investigated if both c- and a-axes are known.

14) *"Part 6.3: lines 430 to 326, the dynamic recrystallization processes are mentioned as a likely difference between the experimental and natural conditions, owing to the difference in strain rate. Although already in the experimental conditions is dynamic recrystallization very active, especially at this high temperature, and the driving force for GBM is even stronger since it is associated to the storage of dislocations at GB, the latter being expected to be stronger at high relative strain rate. At lower strain rate, we expect the dislocation storage to be slower relative to GB mobility."*

There are data to support our statement. Cross and Skemer (2019) using empirical data show that dynamic recrystallization is fastest under high temperature, low stress conditions, although also stating that this conclusion needs testing because it is counterintuitive. In any case, both grain boundary mobility (function of temperature) and driving force (function of the storage of dislocations as a result of stress) are important and the scaling between these two from experiment to natural conditions is not known.

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