Response to Reviewer 2 for: "Large-scale englacial folding and deep-ice stratigraphy within the West Antarctic Ice Sheet" (MS No: tc-2019-245)

We are grateful to both reviewers for their constructive and helpful reviews of our manuscript. Below we respond (non-highlighted text) to the comments of reviewer 2 (highlighted in grey).

Anonymous Referee #2

This paper presents an extensive data set of airborne radar across the tributaries of the Institute Ice Stream. The high-quality data makes it possible to track folds in the lower part of the ice column and investigate the nature of a particular reflector band with a directional dependency of reflection strength, indicating crystal anisotropy in the lower layers of ice. Different ice rheology due to anisotropy and the redistribution of this ice in the folding process is identified as playing a role for the organization of inflow to the ice stream. This is an interesting data set, with most profiles published in the supplements, and highlights the importance of considering ice rheology and anisotropy when trying to understand large scale ice flow.

Technically the manuscript is sound and well written. But I would like to raise some points which could be improved in the final version.

We thank reviewer 2 for their review and helpful suggestions to improve the manuscript. We very much appreciate the recognition that our data is "high-quality", "interesting" and "highlights the importance of considering ice rheology and anisotropy when trying to understand large scale ice flow". We are also delighted that they find that "Technically the manuscript is sound and well written".

Technically the manuscript is sound and well written. But I would like to raise some points which could be improved in the final version. ***My main concern is how the anisotropy of the ice crystal fabric is discussed.*** *It is known from ice core data, seismic studies and also from numerical modelling that anisotropic ice is to be expected in ice sheets, and that this is linked to the dynamic setting and the deformation the ice has been subject to, as well as the influence of impurities in the ice. This is briefly mentioned here. However, there are different types of anisotropy, which are again linked to certain deformation regimes. To me it is not clear from this manuscript what kind of change in crystal fabrics is causing the reflection package described. The directional dependency of the reflector strength would indicate that it is a girdle type, typical for extensional flow, as a single maximum distribution (typical for shear) is symmetric to the vertical and therefore would not be different in profiles at different angles. I think it would be essential to discuss the different types of anisotropy and how they are linked to dynamics, to be able to interpret the influence on ice stream flow of the anisotropic ice package.*

As it stands now I would not agree that the data support the strong conclusion that is has been shown how anisotropy in the lower layers "modulates ice stream position, structure and dynamics). I do not disagree in general, I just think the authors have to be more convincing in their line of arguments. In summary I think there is need for a better interpretation of the links between anisotropy, ice dynamic setting, and folding structures.

We are very grateful to reviewer 2 for highlighting this issue with the manuscript. It drove us to re-investigate relevant literature, and to think carefully about which physical properties likely underpin the radar reflections we observe. We therefore suggest that we amend section 4.1 (lines 116-131) to the following, which we think much improves our explanations for the deep-ice layers, including the reasons for the anisotropy of R1:

"There are several possible explanations for the reflectivity of R1 and R2 including: (i) constructive interference from a series of multiple thin layers (Harrison, 1973; Siegert et al., 1999); (ii) preferred ice-crystal orientation fabrics (e.g. Matsuoka et al., 2004; Eisen et al., 2007); and (iii) an abrupt spike in the conductivity of the ice column associated with the deposition of volcanic ash (Paren and Robin, 1975; Corr and Vaughan, 2008). These explanations are not mutually exclusive however, and it may be that more than one may act in combination. However, because we observe that the strength of the returned energy from R1 is highly anisotropic, with higher reflectivity in the along-flow orientation (Figures 2, 3, 4, 6 and Supplementary Figures 1-4), we conclude R1 is most likely caused by ice-sheet permittivity rather than conductivity (Fujita et al., 1999; Wang et al., 2018). The depth of R1 rules out ice-density fluctuations, so we therefore attribute the reflection band to crystal orientation fabric. Radar reflection anisotropy associated with crystal orientation fabric has been verified by ice core evidence from Antarctica and Greenland (Eisen et al. 2007, Drews et al. 2012; Li et al. 2018). Deep-ice anisotropic scattering has been observed in convergent ice flow zones, like our study area, in East Antarctica (Matsuoka et al., 2003; Matsuoka et al., 2004). In those studies, anisotropic englacial reflections were attributed to stacked layers of single pole and vertical girdle fabrics observed in the Dome F ice core. Such a model is consistent with our radar observations and ice core observations elsewhere in West Antarctica. A single maximum crystal orientation fabric distribution (i.e. with a fabric characterised by strong vertical c-axes), typical for simple shear would not result in anisotropic scattering, as layer reflectivity would be the same in different survey orientation. A vertical girdle fabric on the other hand is consistent with anisotropic layer reflectivity, as crystals would have an oriented preferred fabric that would likely induce a backscatter response. Evidence for down-ice column evolution of crystal fabric (i.e. from isotropic to anisotropic, and then back to isotropic at depth) is observed in ice cores from West Antarctica (e.g. Gow and Williamson, 1976; Gow and Meese, 2007; Fitzpatrick et al., 2014), with anisotropic crystal fabrics typically associated with ice of last glacial age. However, as stated above, an anistropic crystal fabric (i.e. with a strong single vertical maxima) would not result in an anistropic radar response, so these gradual down-core changes cannot be the explanation for R1. In the Byrd core however, there is evidence for sharply alternating crystal fabrics (i.e. narrow cone to distributed cone and back again) associated with cloudy bands (1-60 mm thick) of glacial-age ice that incorporate tephra (Gow and Williamson, 1976; Horgan et al., 2011). Abrupt alternations in crystal fabric such as these are akin to those proposed as the cause of anisotropic radar scattering in East Antarctica (Fujita et al. 2003; Matsuoka et al., 2003; Matsuoka et al., 2004). Assuming that the cloudy bands in the Byrd core represent the same stratigraphy as R1, then this is a plausible explanation for the radar reflection anisotropy of this layer. The anisotropy cannot be due to directional roughness of layer reflectivity, as the anisotropy is unique to specific layers (Figures 6a and Supplementary Figures 1-4). R2 is also a prominent and strong reflection (Figures 2, 3, and 4), but unlike R1 it is not characterized by anisotropic reflectivity (Figure 6). We consider R2 to represent a layer with a discretely high conductivity, similar to the bulk of internal layers in Antarctica (Siegert, 1999). The anomalously high reflectivity of R2 may represent a pronounced acidity spike, or multiple spikes, in the stratigraphy."

Additional references for section 4.1:

Fujita, S., Matsuoka, K., Maeno, H., and Furukawa, T. (2003). Scattering of VHF radio waves from within an ice sheet containing the vertical-girdle-type ice fabric and anisotropic reflection boundaries. Annals of Glaciology, 37, 305-316.

Gow, A.J. and Meese D. (2007). Physical properties, crystalline textures and c-axis fabrics of the Siple Dome (Antarctica) ice core. Journal of Glaciology, 53, 573-584.

Matsuoka, K., T. Furukawa, S. Fujita, H. Maeno, S. Uratsuka, R. Naruse, and O. Watanabe, (2003). Crystal orientation fabrics within the Antarctic ice sheet revealed by a multipolarization plane and dual-frequency radar survey, J. Geophys. Res.,108(B10), 2499, doi:10.1029/2003JB002425.

We suggest that changes made to the conclusions section in response to comments from reviewer 1 have already addressed the issues raised by reviewer 2 regarding "*how anisotropy in the lower layers "modulates ice stream position, structure and dynamics)*".

We anticipate that the proposed changes to section 4.1 will have knock-on impacts to later sections of the paper (e.g. section 4.4 and conclusions section). We will address these issues accordingly if invited by the Editor to prepare a revised version of the manuscript.

Some smaller points: Lines 27-30: Folds can be generated in an anisotropic material by lateral compression, there is no need for a rheology contrast between two layers. Buckle folding, when a hard layer is embedded in a softer matrix, produces different kinds of folds (parallel folds), and the rheology contrast needed for this is much bigger than the range expected in natural ice. The paragraph reads as if the contrast in rheology is the origin of folding.
We propose to replace the wording "rheological properties" with "physical properties" here, so that lines 27-30 will read: "Like a structural geology problem, such folds can only be explained by the deformation of ice with contrasting physical properties near the base of the ice sheet. Evidence of variability in physical properties is consistent with ice-penetrating radar observations of a widespread englacial layer characterized by a strongly anisotropic ice crystal fabric, as postulated for ice folds in Greenland (Bons et al., 2016)."

Lines 103-104: to interpret the fold here as a natural boundary for the stream is a bit circular. The folding is linked to dynamics, so the fold where the dynamic setting is right (shear margin).
We do not interpret the fold as a natural boundary for the ice stream here. In lines 103-104 we observe the spatial relationship between the fold and the ice plain at the grounding zone of Institute Ice Stream. In fact, in the lower trunk of the Institute, the fold with the hand-shaped reflector is located in the middle of the ice stream trunk, it is not located at the ice stream shear margin (see Figure 5). What we do suggest in lines 103-104 is that given the spatial relationship, the fold *may* influence the location and form of the ice plain in the ice stream grounding zone, which may in turn feedback to the ice stream via buttressing effects. Perhaps the spatial relationship is a coincidence, but we thought it was worth drawing attention to.

Line 109, Comment on the supplementary figures: It is great to be able to see all the data, but would be really helpful would be a way to quantify the difference between the two profile directions in the relevant depth range and then plot this color-coded on a map.
We can attempt to do this. A figure of this nature was something that we had considered before submission but decided not to do on technical grounds. Defining the "relevant depth range" in an objective way will likely be problematic, and there are some locations where aircraft elevation was not consistent (see supplement) so there will be some missing data points.

Lines 112-113: Maybe this is the place to describe what kind of anisotropy you would expect and why.
As lines 112-113 are part of the results section, we will instead insert our description of the expected anisotropy etc. in section 4.1 of the discussion section, as proposed in response to the general comments of reviewer 2.

Line 150: Do you mean a band of ice, that is in the lower part the ice should be isotropic again? Or is it a thick basal layer?
We mean a band of ice (i.e. 'layer' R1). The lack of directionality in the reflection strength of layer R2 suggest that the ice below R1 is isotropic. R1 is the only layer ('band') that displays evidence for anisotropy in the RES data. We therefore propose to reword this sentence to read "Further, given the radar anisotropy observed, the most likely explanation for the folds is that they are caused by a combination of convergent ice flow and the distinct physical (i.e. varying crystal orientation fabric),

and subsequent rheological, properties of the band of ice associated with R1." We suggest removing the references to NEEM community members (2013) and Bon et al., (2016) here, as they are referenced in section 4.4.

Line 155: As mentioned above, how can you conclude that the fold is influencing the location of the shear margin? In the shear margin there is in general a compressive stress across flow, so it would be the other way around.
We accept that this is likely, but in response suggest that a feedback mechanism could operate where formation of an englacial fold containing a core with a distinct rheology could reinforce the position of the shear margin. We therefore propose to reword lines 154-157 to: "This spatial correspondence between the fold and shear margin is remarkable and may suggest that the folding of the deep ice modulates the position of the shear margin and controls trunk flow. The fold may therefore play an important role in the ice dynamics of the IIS-MIS catchment."

Line 165: I don't think that it would be possible to form fractures at the base of an ice sheet. The publication which is cited is about a mountain glacier, only a few hundreds of meters thick. This must be some other form of ductile entrainment of bottom material.
We propose removing the reference to Woodward and others, 2003, and inserting Winter and others, 2019 https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019GL084012 instead. This paper describes RES evidence for the incorporation of sediment at the base of the West Antarctic Ice Sheet rather than at the base of a mountain/valley glacier.