

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

Dear Dr MacGregor,

We are grateful to you and both reviewers for their constructive and helpful reviews of our manuscript. Below we respond (non-highlighted text) to your comments (part1) and those of the reviewers (parts 2&3) (highlighted in grey). Our specific actions in each response are highlighted yellow. We also include a short section (part 4) detailing other significant changes we have made to the manuscript. All references to line numbers refer to the originally submitted manuscript, not the revised manuscript.

PART 1: Editor Decision: Publish subject to revisions (further review by editor and referees) (05 Feb 2020) by [Joseph MacGregor](#)

Comments to the Author:

Thanks for submitting your work to The Cryosphere, and my apologies for the delay in my decision. After review of your MS and the thoughtful referee comments, I consider it likely that the MS will be suitable for publication following revision. Both referees raise substantive issues with the attribution of the folding to rheology, so I encourage the authors to moderate the text carefully in this regard.

We have responded in detail to the comments of both reviewers in line below. **We have made the conclusions less assertive and have moderated the text carefully throughout** (e.g. typically referring now to ‘physical properties’ rather than specifically ‘rheology’). In response to a very helpful suggestion from reviewer 2 **we have now strengthened aspects of the manuscript** that discuss possible explanations for the crystal fabric and anisotropic radar response.

Separately, the supplementary figures are useful, but it is not clear to me – given a finite number of intersections – why the authors do not simply measure the peak reflectivity of the candidate anisotropic layer in both flight directions and then map that quantity. This is important because it is the best opportunity for quantitative assessment of the proposed origin of the layer presently available.

We are currently working on developing this quantitative assessment and deriving a figure from it. This task will likely not be completed in advance of the deadline to submit the corrections however (i.e. today, 4th May), so we thought it wise to submit the manuscript as is with the figure to follow if required. **The status of this issue is therefore pending, but we can undertake this work within a couple of days.** *This is the only first review item that currently (i.e. at 4th May 2020) remains outstanding.*

In the supplementary figure caption, an important caveat is raised given aircraft altitude, but I find that unconvincing for several reasons:

- A geometric spreading correction for the aircraft altitude difference could easily be done. The difference in Fresnel zone due to altitude difference should be minor, or at least it shouldn't be significant enough to affect the anisotropic behavior of the layer.*
- If the authors still find this altitude difference problematic, they could simply not include/interpret/show those flights where that altitude difference is considered significant.*

For SI figures where there was a difference in aircraft elevation at the flight crossover location, **we have retained the SI plots, but have annotated parts ‘a’ and ‘c’ of the figure as ‘OFFSET’**. We have also **added the phrase** “...figures with aircraft elevation offsets are clearly marked with ‘OFFSET’ in parts ‘a’ and ‘c’.” to the SI figure captions.

- The flights are not always oriented along/across the present-day ice-flow direction.

We have oriented all the radargrams in the SI figures, and throughout the manuscript, in common directions (i.e. ice flow is left to right for 'down-ice' tie lines, and into page for 'across-ice' flight lines).

The absolute difference of the IMAFI grid's "+" intersections to ice-flow direction should also be considered as a confounding factor.

We have acknowledged this issue at the end of the methods section, by inserting the following text:

"Though the survey grid design allows us to undertake a detailed analysis of the pseudo-3D englacial structure of the IIS, the grid layout and orientation of the 2D survey flights was not aligned exactly along and across ice flow. This oblique offset can have implications for the 2D imaging of 3D englacial structures (Bingham et al., 2015). In general, however, our survey grid is approximately aligned along and across flow throughout most of our area of interest. As a result, we refer from this point onwards to 'across-' and 'along-' flow flight lines, although we acknowledge that in many places the flight lines are slightly oblique to both along and across ice flow vectors."

PART 2: Response to Reviewer 1 for: "Large-scale englacial folding and deep-ice stratigraphy within the West Antarctic Ice Sheet" (MS No: tc-2019-245)

Anonymous Referee #1

General Comments:

This paper aims at explaining observations of englacial folding in the lower ice sheet column obtained from radio echo sounding. The deep-ice unit is analysed by mapping anticlines using a high-resolution grid of radio echo sounding data from 2010/11. Analysing the returned radar power at certain cross-overs allows to evaluate if englacial layers show signs of anisotropy. Evaluating different hypothesis explaining the formation of such complex near basal structures such as subglacial freeze-on, varying ice rheology and entrainment of basal material, the authors conclude that the deformation and folding of the near basal unit is related to convergent ice flow and layers of anisotropic ice. The paper shows a nice and extensive data set of radargrams and returned radar power at cross overs. However it is rather difficult to orient oneself between the different figures to really understand how the data is related to the ice flow. The different hypotheses are discussed but I feel that the evidence to choose one hypothesis over an other is lacking in parts. I'm not sure what the goal of the paper is - presenting the large-scale englacial folding or resolving how such a structure is obtained. I don't think the latter point is achieved.

We thank reviewer 1 for their review and helpful suggestions to improve the manuscript. We very much appreciate the description of our "nice and extensive dataset of radargrams". We believe that this dataset is unique for a modern SAR-processed radio-echo sounding survey in Antarctica. There are certainly few airborne RES surveys of an appropriate orientation and such closely spaced survey lines across the onset zone of a major Antarctic ice stream system like the Institute-Möller ice stream complex.

We would disagree with the comment that it is "...rather difficult to orient oneself between the different figures to really understand how the data is related to the ice flow...", as we have provided maps of ice flow in four of the six figures, whilst the location of figure 3d (figure 3 is one of the two figures that does not have its own ice flow map) is shown on figure 1c (formerly 1d), where ice flow contours are shown above a map of bed elevation. However, we were happy to adopt many of the later specific suggestions from reviewer 1 for our figures (i.e. labelling tie and across lines, adding the

location of radargrams in figure 2 to figure 1a, and having additional area boxes in figure 1). We hope that accepting these should also address reviewer 1's general comment.

Reviewer 1 states that they are *“not sure what the goal of the paper is - presenting the large-scale englacial folding or resolving how such a structure is obtained”*. The primary purpose of the manuscript is to report the discovery of the large-scale englacial folding AND the unusual deep ice stratigraphy (i.e. extensive thick high reflectivity layers at depth) across the study area. Secondary goals of the manuscript are to infer the physical properties of these folds and layers; to develop hypotheses for how the layers, and associated structures, might form; and to assess any potential glaciological impact. Whilst our *“nice and extensive dataset”* can be used to identify the englacial structures, and, in combination with ice velocity datasets, can be used to describe its spatial relationship with ice flow, we acknowledge that it does have its limitations. Whilst we can infer some physical properties (i.e. strong preferred crystal fabric) from the data, we lack direct measurements of physical properties (e.g. from ice cores corresponding to the airborne RES survey) to ‘calibrate’ the radar data, so we are unable, at present, to resolve *“how such a structure is obtained”*. However, from the available datasets, and with reference to glaciological theory, combined with existing observations elsewhere in Antarctica and Greenland, we have been able to develop initial explanations for *“resolving how such a structure is obtained”*. Full determination of the processes responsible for the englacial structures is beyond the current dataset and therefore this paper, however, and will need to await future direct investigations and observations (e.g. coring and geophysical measurements) designed specifically for addressing this question. We note that the current RES dataset was not designed, or acquired, to answer such a question; it was designed to test for the presence or absence of subglacial sediments beneath Institute Ice Stream. The discovery of the englacial structures and layers was therefore serendipitous. Given this context, we would argue that we have successfully reported the englacial layering and structures, inferred possible physical properties, proposed possible processes responsible for fold formation, and assessed the glaciological implications of the folding. That we have not fully resolved *“how such a structure is obtained”* is not, in our opinion, a major issue. We have undertaken the best assessment and interpretation of the evidence possible, given the data currently at our disposal.

Specific Comments:

- Line 4: this process might also involve freeze-on of basal water?

We acknowledge that local freeze-on of basal water is possible, but the widespread and extensive nature of the deep-ice facies we report is inconsistent with the freeze-on of basal water being an important process in its formation. The sentence in line 4 reports that we observe little evidence for basal water within our study area (e.g. there are few definite subglacial lakes) as detailed later in the manuscript. **We have therefore made no change here**. Additional discussion of this issue is outlined in our comments on lines 134-140 below.

- Line 18: the citation of Dow et al. 2018 is not entirely correct in this context - as the impact of freeze-on units on ice-sheet flow and dynamics has not been investigated by that paper as they use a subglacial hydrology model and not an ice-flow model.

We have simply removed the reference to this paper at this point in the manuscript (though we retain it elsewhere).

- Line 27-28: This sentence ‘Like a structural geology problem, ...’ is very assertive statement and I wonder why you are so sure about this. Does this come from the literature (but then references are missing) or does it come from your own findings (then say so)? Here in the introduction it seems to be at the wrong place.

We have inserted references to papers by MacGregor and others, JGR, 2015 <https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2014JF003215> and Hudleston, Journal of

Structural Geology, 2015 <https://www.sciencedirect.com/science/article/pii/S0191814115300365> here. Both these papers draw attention to similarities between ice sheet englacial structures and structural geology, and we hope that their inclusion will address reviewer 1's comment.

- Line 57: *You mention the ice thickness in this sentence but not how thick the lower-ice column is. It is mentioned in the abstract but here would be a good place too.*

The thickness of the lower ice column varies significantly (i.e. 100-1000 m). We have inserted the following to the end of the sentence "...up to ~1000 m thick".

- Line 59: *I think not only Figure 3 but also Figure 6 could be referred to.*

We agree. We have added the reference to figure 6 here.

- Line 60-61: *R2 is referred to as a band of prominent reflection that "sometimes diverges and bifurcates, becoming a series of 3-4 layers". Is it the band that diverges and bifurcates or rather the series of layers within? I suggest a clearer wording.*

We have reworded lines 59-61 to: "Beneath R1, within the low-reflectivity lower-ice column, a second highly reflective englacial reflection (R2) is observed. R2 sometimes diverges and bifurcates, becoming a series of 3-4 layers (Figure 2b)."

- Line 64: *I'm not sure if instead of Figure 2a you rather mean Figure 1d? It is not clear where exactly you refer to in Figure 2a - which tributary and which lateral boundary (I guess in the center - parallel to K'K and J'J)?*

We have referred to figure 1c (formerly 1d) instead of 2a.

- Line 67: *Can you give examples where the amplitudes of up to 40% are seen? Maybe highlight in one of the Figures so that it is clear to what you refer to.*

We have shifted the annotations of the englacial folds so that they mark the peak of the fold axis in the ice column. This now shows where the amplitudes of the folds account for ~40% of the ice column on figures 5c and 5d.

- Line 69: *For the statement that rather bed conformable undulations than folds are found along flow Figure 2b-c might not be the best example. Comparing the transects where the anticlines are marked (Figure 1d and 3a-b) it is obvious that the chosen along profile in 2 is not crossing many marked anticlines. Along flow one would expect not to see much of a fold that is oriented along flow (e.g. as shown in Figure 4 it is difficult to see the along flow pattern).*

The purpose of referring to 2b-c here is that these radargrams demonstrate that there are no folds or overturnings in radar data acquired in that orientation. They are presented as typical examples of the survey data and show that the deep reflective layers are very extensive (i.e. over distances of ~250 km or more) and bed conformable. If referring to figures 2b-c in line 69 remains an issue we can simply remove reference to 2b-c, as 3c demonstrates the same point just not over such a large spatial area. However, we would prefer to leave line 69 as is, and have therefore made no change. The evidence for bed conformable layering down flow is inconsistent with localised basal freeze-on being behind the formation of the deep ice units. Such a process could not explain this layer stratigraphy and structure.

- Line 93-94: *This surface flow stripe is not visible in any of the figures (neither main text nor supplement). It would be nice to see the mapped fold together with the flow stripe.*

The position of the surface flow stripe was mapped in the original figure 5a, but we have added an additional subplot (comparable to the size and area of the original 5a, now 5b) to figure 5 that shows RADARSAT surface imagery of the ice stream trunk with the flow stripe and areas of surface crevassing visible. This should provide the 'raw data' of the surface flow stripe requested by reviewer 1.

- Line 97: Could you highlight where the "significant shift in basal reflectivity" is seen? This would make it much clearer for the reader what you mean.

We have added dashed red lines to the radargrams in figure 5 to highlight where for those individual radargrams the bed is particularly bright (i.e. there is high basal reflectivity).

- Line 98: Same as above - highlight the onset zone of IIS so that it is very clear to what you are referring to.

We have amended the sentence to: "...that extends from the onset zone where ice is typically flowing at 50-125 m yr⁻¹, into the trunk...". This should provide clarity without overly cluttering figure 5.

-Lines 102-103: From the text/figures it is not clear to what exactly you are referring to. E.g.: - where is "grid-SW margin" to be found? - where is the ice plain? Mark/label it so that it is clear. I can guess but rather would like to be sure. Add these explanations to the overview Figure 1.

The ice plain is located just beyond the grid-north limit of the original figure 5a. We have expanded the area of figure 5a to include it. We have annotated the ice plain on the figure. From this annotation and the map, it should be clear where the grid-SW margin of the ice plain is.

- Line 113: I'm not sure that the observation of no high relief in basal topography is enough to say that anisotropy is not forming in soft layers due to enhanced stresses on the stoss-face of basal hills. One can imagine that if locally basal freeze-on exists, then the plume of accreted ice pushing into the ice column might act as an obstacle to the meteoric ice flow.

We have simply deleted the sentence at the end of the paragraph (lines 112-113) that dismisses this idea (i.e. the sentence "We do not observe any high relief basal topography in our study region, hence this specific explanation is unlikely to hold here." has been deleted).

- Lines 133-134: The usage of deep-ice units in this sentence is not clear as it seems to be used in two different contexts: 1) as the basal freeze-on units of accreted ice from the bed raising into the ice sheet as hypothesised by Bell et al, 2011; and 2) as the unit of ice between R1 and the bed. So I wonder what in this paper is understood by the "deep-ice units". It is defined as the ice between R1 and the bed. I don't think you expect the whole unit to be frozen on by basal water. With basal freeze-on one would expect the to have some local areas where "material" is rising into the ice sheet and advecting downstream - shaping the meteoric layers above.

We confirm that for our study area, the "deep-ice unit" is the body of ice between R1 and the bed. To limit confusion in lines 133-134, we have inserted "basal ice" instead of "deep-ice unit" when referring to the paper on basal ice features in East Antarctica by Bell et al. 2011. The sentence now reads: "The 'freeze-on' hypothesis for the formation of basal ice (Bell et al., 2011) cannot explain the deep-ice unit and incorporated layers (i.e. R1 to the ice sheet bed) for four reasons:.....".

- Lines 134-140: The arguments against basal freeze-on, of slow-flowing and thin ice likely frozen to the bed, as well as fast-flowing ice over a wet bed, do not entirely exclude the formation of basal freeze-on plumes. In order to exclude basal freeze-on the possibility of water needs to be excluded. Where is the evidence that there is no water at the base of the ice-sheet? Is it visible in the radar data? It would make sense to map the anticlines together with the main topographically-constrained subglacial drainage network to evaluate if basal freeze-on is possible. Further the ice velocity itself cannot exclude the formation/existence of substantial freeze-on units.

We suggest that including an additional figure showing the relationship of the mapped anticlines with the subglacial hydrological drainage network in the manuscript is unnecessary. Such a figure could not explain or dismiss the widespread existence of the strongly reflective deep ice layers R1 and R2 across the study area (see lines 52-55 of the manuscript), even in areas that are almost certainly underlain by cold based ice. Furthermore, GIS-derived subglacial hydrological models assume a fully warm-based

ice sheet, which is unrealistic. Maps of the subglacial hydrological pathways of the Institute Ice Stream have previously been published in Jeofry et al., Earth System Science Data, 2018a <https://doi.org/10.5194/essd-10-711-2018> (Figure 3); Jeofry et al., Nature Communications, 2018b <https://doi.org/10.1038/s41467-018-06679-z> (Supplementary Figure 1); and Le Brocq et al., Nature Geoscience, 2013 <https://doi.org/10.1038/ngeo1977> (Supplementary Figure S11). All show subglacial water routing obliquely through our focused study area, and obliquely to the mapped folds. In addition, there is relatively limited evidence for subglacial water in RES data across the catchment; there are very few subglacial lakes for example. In lines 139-146 of the original manuscript submission, we describe the limited evidence (in our, and others', RES data) for "significant ponding of subglacial water" in the study area. We have therefore taken no action in response to this suggestion from reviewer 1, except to insert references to the work of Jeofry et al., 2018a and 2018b in the sentence "(3) IIS has a well-defined and efficient topographically-constrained subglacial drainage network, without widespread stores of subglacial water to act as water sources (Wright and Siegert, 2012; Jeofry et al., 2018a, 2018b)".

With regards to the questions "Where is the evidence that there is no water at the base of the ice-sheet?" and "Is it visible in the radar data?" we refer the reviewer to lines 139-146 of the manuscript, where we describe the limited evidence (in our, and other, RES data) for "significant ponding of subglacial water" in the study area.

- Lines 147-149: I don't understand the argument that because R1 and R2 have a consistent stratigraphic position "the structures and extent of the deep-ice structures must be the result of the deformation and localized folding of meteoric ice". How is this meant - a stratigraphic position in the vertical ice column? They will always be on top of each other - unless one is melted away. E.g. basal freeze-on would lead to the same result just pushing up the entire ice column - with the vertical distance between the layers diminishing.

It is true that basal freeze-on would lead to the same result by pushing up the entire ice column, but it is physically unrealistic for this to have occurred over such a widespread area as we observe R1 and R2. The volumes of water required would be, quite simply, enormous and freeze-on rates would have to be consistent right across the study area. We might expect freeze-on locally (and we do not dispute the possibility of localised basal freeze-on), but not over the extensive area that we map the layers (see Lines 52-55 and Figure 1). In addition, freeze-on cannot be responsible for the formation of the basal ice layers over high subglacial mountain ranges, e.g. the Ellsworth Subglacial Highlands, where the ice is cold based and has likely been for millions of years. Therefore, the only physically realistic explanation for the consistent stratigraphic position of R1 and R2 in the ice column, over such a vast geographical area, is that they reflect layers that were initiated at the surface by meteoric deposition (i.e. of snow and/or volcanic ash), but that will have undergone physical modification (i.e. to crystal fabric orientation) in the ice column during burial and strain. We have referenced figure 1, in addition to figure 2, in line 147 however, to direct the reader to the extensive geographical distribution of the deep ice layers.

- Line 148: What exactly is your deep ice structure? In parts it sounds that it is all the ice below R1? Or do you mean the layer pattern at depth? Is there a difference between units and structure?

By deep ice we mean all the ice between R1 and the bed. Units are the layers of ice (like geological units), the deep ice structure refers to the geometry of the units (e.g. folds) in the deep ice.

- Lines 149-151: It is not clear to me how the anisotropy observed in a layer leads to the folding of the ice unit below. In the paper by Bons et al., 2016 it is not one anisotropic layer that leads to folding but a body of anisotropic ice.

In response to a comment from reviewer 2, we have amended lines 149-151 to: "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. crystal orientation fabric), and consequent rheological, properties of the band of ice associated with R1.” As is clear from figure 6 (and multiple other examples in the supplementary information) R1 is a broad band (described in line 58 as “up to 200 m” thick) that is rather different from the narrow reflections we typically think of as englacial layers observed in RES data. As such, R1 is more a body or package of ice than a single layer (and therefore potentially like Bons et al, 2016). Furthermore, we do not know the properties of most of the ice below R1 as, unlike in Greenland, as we do not have direct observations (e.g. from ice cores) to calibrate against. We can infer from the RES data that R1 is anisotropic, and that R2 is likely isotropic. However, we do not know the physical properties of the rest of the deep ice units as it is typically an echo-free zone below R1. It may be anisotropic, either in places or throughout, but we cannot determine that from the currently available data.

- Lines 169-171: Why would the spiraling flow of basal ice only happen at that specific location and why only on one side of the ice stream onset?

We **have deleted lines 169-171 and the reference** to Schoof and Clarke 2008.

- Lines 173-176: "strongly contrasting physical and rheological properties of glacial and interglacial ice" might not be the only explanation that basal units are "folded, sheared and overturned".

We accept that englacial layers in Greenland and Antarctica can be deformed by the freeze-on of basal ice (which we assume reviewer 1 is alluding to here), but based on the currently available literature for Greenland (which we cite in lines 175-176) the most widespread accepted explanation for such folding is the strong contrast in physical and rheological properties between glacial ('soft') and interglacial ('hard') ice. **We have therefore made no change to this sentence.**

- Line 203: I do not agree that you "demonstrated" that the deep-ice units have different physical properties than the ice above. You showed that one band does show in some places anisotropic behaviour.

We **have reworded this sentence** to: “We have demonstrated the presence of an extensive package of deep-ice units beneath the Institute and Moller ice streams. At least one layer in the deep ice has physical properties (i.e. ice crystal orientation fabric, rheology) significantly different to the upper ice column.”

- Line 204-206: I'm not happy with the statement in this sentence. The paper does not show that convergent flow heavily deforms deep-ice units, that this process leads to the formation of large-scale englacial folds and that these folds modulate ice-stream position structure and dynamics.

We **have reworded this sentence** to: “At the lateral boundary of the onset of enhanced ice flow of IIS, where ice flow is convergent, these deep-ice units have been heavily deformed. Deformation has led to the development of large-scale englacial folds that may modulate ice-stream position, structure and dynamics.”

- Conclusions: The conclusion seems to me in parts too assertive. In my view the study is not really conclusive how this structures are really formed. I agree not so much with the top part but agree with the bottom half. It is still not clear what exactly is meant by deep-ice unit.

We **have now addressed this issue with the changes made to lines 203, and lines 204-206 (see above).** Those statements are now less “assertive” than they were. We acknowledge that our study may not be conclusive as to how the structures formed, but that reflects the serendipitous nature of the discovery and the datasets currently available. More conclusive understanding will require additional work (i.e. new geophysical/ice core observations and/or numerical modelling) beyond this ‘discovery’ paper. As stated previously, the deep ice unit is all the ice between R1 and the bed. **We have made no additional changes to the conclusions section** in response to this comment by reviewer 1.

- *Figures 1: The figures in the paper are not very well related to each other. It is difficult to see where the transects are taken relative to ice velocity, bed topography surface slope and the mapped anticlines. I suggest that the boxed area of 1d is not only shown in 1a but everywhere in 1. Ideally 1d would show bedtopography upstream of the section in 1d. Help reader to orientate by defining the orientation of the grid used in the figure.*

We have added the boxed area shown in 1d (now 1c) to 1a & 1b. We have also expanded the extent of 1d (now 1c) up-ice. However, we are unclear what the reviewer means by “Help reader to orientate by defining the orientation of the grid used in the figure.”. The orientation of 1a-c should be clear from the inset figure in 1a. We would be happy to modify the figure in response to additional clarification on this, however.

- *Figure 2: Where is this line (2a) in Figure 1 - maybe useful to show the tie line 1 and the across line 1 (or other number) as to allow reader to orient oneself in the overview figure. An overview of the shown radar profiles would be nice (see in Figure 1).*

We have added the location of the radar data shown in 2b-c to figure 1a as well as showing it in 2a. We have inserted this sentence to the figure 1 caption “White line is survey tie line 9, shown in figure 2.”

- *Figure 3: What is the criteria for a fold - in 3b I can't see a fold in the radargram where the third "A" from left (from Y1 towards Y2) is. Further comparing the mapped "A" with Figure 1d it seems to me that sth. is wrong. In 1d "HSR" is the second from right and not the third as shown in radargram and the spacing between the folds is different than in overview Figure 1d.*

Folds were mapped where the englacial layers were folded and were not bed conformable. In the case of 3b, we were somewhat overenthusiastic in our labelling of the third A from the left, based on our down-ice mapping of a fold in parallel radar lines (i.e. we tracked it back (up-ice) to that location on the 3b radargram from down-ice radargrams). We have deleted the third “A” from the left.

With regards to the ‘HSR’, we made an error in the manual labelling of this feature in figure 3b. Further up-ice, where 3b is located, it does become harder to confidently identify the folds. However, through identification of the diagnostic form of a package of whirlwinds in the surrounding ice column, we were able to correctly identify the HSR at 36 km along the radargram (see Figure 3b). We have now moved the labelling of the HSR from the 3rd to the 1st fold from the right.

- *Figure 4: Numbering the radar lines would be helpful (eventhough one can deduce the numbering) especially in context with Figure 1 (if there is some numbering).*

We have added numbering and labelling of survey lines to Figure 4 and 1a.

- *Figure 5: Distance taken from where for Figures 5b and c? Why not just show the "length" of these two radargrams (as a distance is o.k.). Why is the "signature of englacial folding" (caption line 5) not mapped/marked? What is the criteria for mapping these folds?*

The distance is from the start of the radargram. This was an error, which we have now corrected, so that the radargrams x-axes are from 0-25 km. We have added additional arrows to highlight the two most obvious englacial folds apparent in figure 5. Mapping of the folds is based on obvious deviation of englacial layering from the bed profile, and identification of folding in up-ice radargrams.

- *Figure 6: in (b) why not mark in the white circle the along line in blue and across in red. In (c) and (d) it's not entirely clear if the colour of the vertical line represents the colour of the crossing transect. Maybe it makes more sense to mark in (c) in red where the across transect crosses and vice versa in (d). The caption explaining this is slightly confusing. For (c) and (d) it's not clear where -5 and 5 is e.g. is (c) going downstream from -5 to 5 or upstream? Are the across profiles (d) always oriented the same way? An orientation would help.*

Because of the scale of the figure we were concerned that two 10 km-long plots of the radargram locations would be lost, hence why we originally opted for the circle and cross to demonstrate location. We have updated the figure replacing the circle/cross with a white circle overlain by the location and extent of the radargrams that are shown in 6c and 6d, as suggested by the reviewer.

We have swapped the colours of the vertical lines in the radargrams. This makes sense.

The radargrams in c and d are oriented along the direction of the survey flight. Fortunately, in this case the survey flights were in directions that are logical for the display of the radargrams in this figure. Therefore, we have amended the figure caption to state that ice flow is left to right for 6c (i.e. radargram is from bottom to top of survey grid), and into the page for 6d (i.e. radargram is left to right across survey grid). We have oriented all the radargrams in the supplementary figure section to match these orientations.

- *Figures in Supplement: I'm not sure if the across profiles all (d)'s are always along the same orientation. Especially when looking at "HSR" in along tie10 it seems to me that it "jumps" from one across profile to the other. It would be nice to have the same geographical orientation for all along and across profiles at all times. As mentioned above it would be nice to know where the tie lines are.*

No, the across profiles were not always in the same orientation, as they were oriented in the direction of the survey flight, and different survey flights were flown in different directions. We have now oriented all the radargrams in the same way, i.e. ice flow from left-to-right for down flow TIE lines (radargram oriented grid south to grid north), and ice flow into page for across flow lines (radargram oriented grid west to grid east).

Tie and across lines have now been labelled on figure 1 and 4 of the manuscript (see response to comment by reviewer 1 on figure 4).

Technical corrections:

- *Caption 2: Line 2 - "ubiquity and widespread" is this not the same message?*

We have deleted "ubiquity"

- *Caption 2: Line 2 - band of ice-layers rather than "deep-ice layers"*

We have made this change.

- *Caption 2: Line 4 - "thin black line" of grounding line is not easy to differentiate from the "thin black lines" of the survey grid.*

Agreed, we have changed the grounding line to a white line, and the white radar line to a thick black line.

- *Caption 2: Line 5 - "bifurcation of R2 into 3-4 layers" happens also earlier around 50 km.*

Agreed. We had not spotted this. We have amended the caption accordingly.

- *Caption 2: Line 5 - in (c) mention tie line 9 as used in Figure 4 and supplementary figures.*

Agreed. We have inserted the following sentence to the caption of figure 6: "Radargrams in 2b and 2c are radar survey 'tieline' 9, which is also shown in Figure 4 and Supplementary Figure 1."

- *Caption 2: Line 6 - replace "show" with "shown".*

Agreed. We have amended the caption accordingly.

- *Caption 5: Line 4 - the transects are not "perpendicular" to the ice flow rather at an angle of 45 degrees oblique to ice flow.*

Agreed. We have amended the caption accordingly.

PART 3: Response to Reviewer 2 for: “Large-scale englacial folding and deep-ice stratigraphy within the West Antarctic Ice Sheet” (MS No: tc-2019-245)

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 have amended 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 (corresponding to power anisotropy for a specific radar layer) (e.g.

Matsuoka et al., 2004; Eisen et al., 2007); (iii) Birefringent propagation (corresponding to power oscillations as a function of ice depth) (Fujita et al., 2006); and (iv) 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 (ii) or (iii) (Fujita et al., 1999; Wang et al., 2018). The depth of R1 certainly rules out ice-density fluctuations. In general, it is difficult to separate-out (ii) and (iii). However, for the case of R1, we can assume that anisotropic scattering is the dominant cause of power anisotropy (the along and across flow profiles have similar long-wavelength behavior and the power anisotropy is localized for a set of radar layers). We therefore attribute R1 to a 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; Montagnat et al., 2014). 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 anisotropic crystal fabric (i.e. with a strong single vertical maxima) would not result in an anisotropic 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 that have been added to reference list:

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.

Fujita, S., Maeno, H., and Matsuoka, K.: Radio-wave depolarization and scattering within ice sheets: a matrix-based model to link radar and ice-core measurements and its application, *Journal of Glaciology*, 52, 407-424, <https://doi.org/10.3189/172756506781828548>, 2006.

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.

Montagnat, M., Azuma, N., Dahl-Jensen, D., Eichler, J., Fujita, S., Gillet-Chaulet, F., Kipfstuhl, S., Samyn, D., Svensson, A., and Weikusat, I.: Fabric along the NEEM ice core, Greenland, and its comparison with GRIP and NGRIP ice cores, *The Cryosphere*, 8, 1129–1138, <https://doi.org/10.5194/tc-8-1129-2014>, 2014.

We suggest that changes made to the conclusions section in response to comments from reviewer 1 (lines 203, lines 204-206) have already addressed the issues raised by reviewer 2 regarding “*how anisotropy in the lower layers “modulates ice stream position, structure and dynamics)”*”. **No further changes have therefore been made to this comment.**

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 have replaced the wording “rheological properties” with “physical properties” here, so that lines 27-30 now 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).” **References by MacGregor & Hudleston were inserted into lines 27-30 in response to a comment from reviewer 1.**

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 believe that it is worth drawing attention to. **No change made.**

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 are currently working on developing this quantitative assessment and deriving a figure from it. This task will likely not be completed in advance of the deadline to submit the corrections however (i.e. today, 4th May), so we thought it wise to submit the manuscript as is with the figure to follow if required. **The status of this issue is therefore pending, but we can undertake this work within a couple of days.** *This is the only first review item that currently (i.e. at 4th May 2020) remains outstanding.*

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. Please see our response to the 'general comments' of reviewer 2 above. Extensive changes have been made to section 4.1 that describe the likely nature of the anisotropy in response to general comments made by reviewer 2. **We therefore make no further change.**

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 have reworded 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 have removed the references** to NEEM community members (2013) and Bon et al., (2016) here. They are still 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 have therefore reworded 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 have removed the reference to Woodward and others, 2003, and have inserted 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.

PART 4: Additional significant changes made by the authors

1. We felt that it was important to clarify in the methods section which 'flavour' of PASIN radar data we were using. Therefore, **we have inserted the following sentences:** "The data used were from the chirp mode of the PASIN system (Jeofry et al., 2018a; Ashmore et al., 2020). We did not use PASIN pulse channel data in this study."
2. **We have updated section 4.4 to account for the publication of Ashmore et al. 2020**, which strengthens the dating of the deep ice units. The central part of this section now reads: "A new radiostratigraphy across West Antarctica (Ashmore et al., 2020) enables us to infer the likely age of the deep ice units in the IIS-MIS. The best 'direct' constraint on the age of the deep-ice package is from the dated radar englacial layer tied to the Byrd ice core (Siebert and Payne, 2004; Ashmore et al., 2020). Linking the radar stratigraphy of the IIS-MIS catchment to the radar transect of Siebert and Payne (2004) where our 2010-11 survey data intersects their profile (Ashmore et al., 2020), indicates that the transition between the upper undisrupted high reflectivity ice and the lower deep-ice unit (i.e. R1) can be dated to approximately 16 ka. There are some potential uncertainties associated with this correlation (e.g. resolution of the Byrd ice core, the resolution, geolocation and vertical and along track sampling of the SPRI-NSF-TUD RES data etc.). However,

assuming this correlation to be correct, the low-reflectivity zone between R1 and R2 is of last glacial age, with the potential for even older ice in places.”

3. We have removed Figure 1c, which mapped the extent of unit R2. Figure 1d is now 1c.

Dr Neil Ross
Newcastle University
4th May 2020



Large-scale englacial folding and deep-ice stratigraphy within the West Antarctic Ice Sheet

Neil Ross¹, Hugh Corr², and Martin Siegert³

¹School of Geography, Politics and Sociology, Newcastle University, UK

²British Antarctic Survey, High Cross, Cambridge, UK

³Grantham Institute and Department of Earth Science and Engineering, Imperial College London, UK

Correspondence: Neil Ross (neil.ross@newcastle.ac.uk)

Abstract. It has been hypothesized that complex englacial structures identified within the East Antarctic and Greenland ice sheets are generated by: (i) water freezing to the ice-sheet base, evolving under ice flow; (ii) deformation of ice of varying rheology; or (iii) entrainment of basal material. Using ice-penetrating radar, we identify a widespread complex of deep-ice facies in West Antarctica that exist in the absence of basal water. These deep-ice units are extensive, thick (>500 m), and incorporate multiple highly reflective englacial layers. At the lateral margin of an enhanced flow tributary of the Institute Ice Stream, these units are heavily deformed and folded by the action of lateral flow convergence. Radar reflectivity analysis demonstrates that the uppermost reflector of the deep-ice package is highly anisotropic, representative of ice with a strong preferred crystal fabric and, consequently, will have a different rheology to the ice above and below it. Deformation and folding of the deep-ice package is an englacial response to the combination of laterally-convergent ice flow and the physical properties of the ice column.

1 Introduction

Recent advances in radar technology have enhanced the quality and resolution of ice-penetrating radar data, revealing complex structures in the lower ice sheet column. Thick deep-ice units have been imaged above the Gamburtsev Mountains in East Antarctica (Bell et al., 2011; Wrona et al. 2018) whilst in Greenland units heavily deformed by ice flow have been discovered

15 (NEEM community members, 2013; Bell et al., 2014; Bons et al., 2016). These have been interpreted as the product of the accretion of basal water (Bell et al., 2011), deformation caused by varying rheology of the ice column (NEEM community members, 2013; Bons et al., 2016), or a combination of both (Bell et al., 2014; Wrona et al., 2018). Only a few studies (e.g. Wolovick et al., 2014, 2016; ~~Dow et al., 2018~~; Leysinger Vieli et al., 2018) have assessed the impact of such units on ice-sheet flow and dynamics, and there are only limited reports of the existence of thick deformed deep-ice units in West Antarctica
20 (Jacobel et al., 1993; Siegert et al, 2004). Englacial seismic boundaries in deep-ice across the West Antarctic Ice Sheet have been reported (Bentley, 1971; Horgan et al., 2011). Once interpreted as sediments within the ice (Bentley, 1971), it is now understood that these reflections represent a shift in the orientation of the ice crystal fabric (Gow and Williamson, 1976; Horgan et al., 2011; Robin and Millar, 1982). The spatial extent and significance of such fabrics in West Antarctica, and of deep ice units in general, have not been determined, however.



25 Here, we present ice-penetrating radar data revealing an extensive package of deep-ice facies locally characterized by a zone of large-scale folding at the lateral margin of a tributary of convergent enhanced (i.e. $>25 \text{ m a}^{-1}$) ice flow (Joughin et al., 1999; Bamber et al., 2000). Like a structural geology problem ([MacGregor et al., 2015](#); [Hudleston, 2015](#)), such folds can only be explained by the deformation of ice with contrasting ~~rheological~~-physical properties near the base of the ice sheet. Evidence of ~~rheological~~ 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 30 postulated for ice folds in Greenland (Bons et al., 2016).

2 Methods

Airborne 150 MHz ice-penetrating radar data were acquired over the Institute and Möller ice streams (IIS, MIS) of West Antarctica in 2010/11 (Ross et al., 2012; Jeofry et al., 2018a). Coverage extended from the ice stream grounding zone to the ice divide (Figure 1a). A high-resolution grid with an across ice flow line spacing of 7.5 km, and tie lines at 25 km spacing, 35 was acquired over the central parts of the ice stream catchments.

Data acquisition, processing and analysis of the radar data is described fully by Jeofry et al. (2018a) and is briefly summarized here. Range from the aircraft to the ice surface was determined using the aircraft radar altimeter or LiDAR measurements. Ice thickness was determined by multiplying the two-way travel-time between the picked ice surface and the picked reflection from the ice sheet bed by 0.168 m ns^{-1} and applying a 10 m correction for the firn layer (Jeofry et al., 2018a).

Bed elevation

40 was calculated by subtracting ice thickness from ice surface elevation. Internal ice sheet layering, and the determination of fold axis positions, were visualized and manually picked using geophysical software. 2D synthetic-aperture radar (SAR)-processed radargrams are displayed with a natural logarithm applied to enhance reflections at depth. [The data used were from the chirp mode of the PASIN system \(Jeofry et al., 2018a; Ashmore et al., 2020\). We did not use PASIN pulse channel data in this study.](#)

Analysis of the returned radar power of internal reflectors at flight line crossover points was implemented to evaluate possible anisotropy within the ice column. This was possible due to the stepped nature of the aerogeophysical survey (i.e. most of the

45 survey was flown in a series of blocks of constant aircraft elevation), implemented for acquisition of high-quality gravity data (Jordan et al., 2013), that meant that aircraft-to-ice surface range was consistent between flight lines at many crossover locations. At those cross-over points where the aircraft-to-surface range was the same in perpendicular survey lines, we stacked radar traces over 41 traces ($\sim 400 \text{ m}$ along track) and determined the returned integrated power down ice, between samples 200 and 1400 (two-way travel time of 54,545 ns) in the across- and along-ice flow directions.

[Though the survey grid design allows us to undertake a detailed analysis of the pseudo-3D englacial structure of the IIS, the grid layout and orientation of the 2D survey flights was not aligned exactly along and across ice flow. This](#)



oblique offset can have implications for the 2D imaging of 3D englacial structures (Bingham et al., 2015). In general, however, our survey grid is approximately aligned along and across flow throughout most of our area of interest. As a result, we refer from this point onwards to 'across-' and 'along-' flow flight lines, although we acknowledge that in many places the flight lines are slightly oblique to both along and across ice flow vectors.

503 Observations

3.1 Ice-sheet stratigraphy and physical properties

The radar data reveal an extensive deep-ice unit with a distinctive ice-sheet stratigraphy across an area $>250,000 \text{ km}^2$ (Figure 1). The unit extends from the Ellsworth Subglacial Highlands (Ross et al., 2014; Winter et al., 2015; [Goldberg et al., 2020](#)) to a region of thin cold-based ice between the MIS and Foundation Ice Stream (Bingham et al., 2015), and from the ice-stream trunk (Siegert et al., 2016) to near the Weddell-Ross ice divide (Figure 1a-c). The stratigraphy of the ice sheet column comprises a high-reflectivity upper unit, typically 750-1500 m in thickness, with thinly-stratified minimally-disrupted layering, typical of meteoric ice, overlying a low-reflectivity lower-ice column up to ~1000 m thick (Figure 2). The boundary between these two stratigraphic units is often sharp and associated with either a distinctive thick (up to 200 m) band of high-reflectivity (R1) or a marked reduction in returned radio-wave energy, depending on radar instrument orientation (Figures 3 and 6). Beneath R1, within the low-reflectivity lower-ice column, a second highly reflective englacial reflection (R2) is observed. R2 sometimes diverges and bifurcates, becoming a series of 3-4 layers (Figure 2b). ~~Beneath R1, within the low-reflectivity lower-ice~~

~~60 column, a second band of prominent reflections (R2) is observed. R2 sometimes diverges and bifurcates, becoming a series of 3-4 layers (Figure 2b).~~ Here, for simplicity, we refer to R2 as a single 'reflection package'. Between R1 and R2, a series of very thin and very low-reflectivity reflections can be imaged, but below R2 (i.e. between it and the bed) layering is typically absent except for occasional, localized, near-bed reflections (Figure 2c).

The deep ice unit is extensively folded (Figures 3 and 4) at the lateral boundary of an enhanced flow tributary (Figure ~~2a~~1c) ~~65~~ that feeds the IIS (Figures 1b-~~d~~c, 2a). The geometry and structure of the deep ice unit that includes R1 and R2 differs markedly in three dimensions in this area. Radar data orthogonal to ice flow (Figure 3a and 4) show substantially folded layering (with amplitudes of up to 40% of the ice column in places), with clear evidence of a series of bed-unconformable anticlines and synclines (Figure 3a, 3b, 4). Along ice flow, however, the same unit is characterized by more subdued reflections, with bedconformable undulations rather than folds (Figure 2b-c, 3c and 4). The deep-ice folds we observe are comparable in scale to

70 those within the onset zone and trunk of Petermann Glacier in Greenland, (Bons et al., 2016) rather than the higher-frequency, lower-amplitude buckling often associated with enhanced ice flow (Conway et al., 2002; Ng and Conway, 2004).



The structure of the upper part of the ice sheet is highly affected by the presence and folding of the deep ice unit below R1 and does show evidence for higher-frequency folding. The upper ice column is disrupted by ‘whirlwind’ or ‘tornado’ features

(Karlsson et al., 2009; Winter et al., 2015) caused by radar energy dispersion through focused SAR processing of sloping and buckled layers in airborne radar data (Holschuh et al., 2014) (Figure 3a and 3b). Whirlwinds have been identified as a signature of either structural disruption of the ice by enhanced flow, or slow ice flow over rugged basal topography. In our data, whirlwinds tend to be vertical to sub-vertical throughout the majority of the ice column but display a prominent deviation from vertical (i.e. they bend) at depth, specifically in the low reflectivity unit between R1 and R2 (Figure 3a and 3b). The whirlwinds approach and show greatest deviation towards R2, yet never cross this reflection boundary (Figure 3a and 3b). Due to their 3D geometry, whirlwinds are visible in data acquired perpendicular and sub-perpendicular to ice flow, but not in radar data acquired parallel to it (Figure 3) (Bingham et al., 2015).

3.1.1 Relationship between englacial folding and ice flow

A close spatial coincidence between the deep-ice folds and the onset of enhanced ($\sim 25 \text{ m a}^{-1}$) flow in the IIS catchment exists (Figure 1d). Five anticlines and synclines with a wavelength of 3-5 km are directly associated with the lateral boundary of an

enhanced flow tributary of IIS (Bamber et al., 2000). These folds have axes oriented precisely along flow and are mappable in more than twenty across-ice-flow flight lines over a distance of $\sim 150 \text{ km}$ (Figures 1d-1e and 4). Due to lateral ice-flow convergence, the amplitude and wavelength of the folds associated with the shear zone increase and decrease, respectively, down-ice flow until high ice velocities ($>150 \text{ m yr}^{-1}$) and associated strain rates, and bright basal reflections, make identification in the main trunk of the IIS difficult (Figure 1d and 5). The folds are highly non-bed-conformable, despite the bed topography being notably flat (Rose et al., 2015) or characterized by long wavelength topographic variation (Figures 3a and 3b).

3.2 Down-ice propagation and glaciological implications of the englacial folds

Though eventually the englacial radar reflection signature of the folds is significantly modified by highly convergent fast flow in the IIS trunk, mapping of the fold axes combined with surface observations from RADARSAT and MODIS (Figure 5) demonstrates an association between the most prominent fold (Figure 3d) and a well-defined surface flow stripe (Figure 5a) (Glasser and

Gudmundsson, 2012; Ely and Clark, 2016) that extends from the onset zone where ice is typically flowing at 50-125 m yr⁻¹, into the trunk, through the ice stream grounding zone, and onto the Ronne Ice Shelf (Figure 5b). Radar data oriented obliquely to the ice flow direction (Figure 5c and d) demonstrate that this fold, and the surface flow stripe, are associated with a significant shift in basal reflectivity (Siegert et al., 2016), suggesting that glaciological processes in the onset zone of



IIS, of which the fold is a product, are likely to play an important role, alongside in situ subglacial topography and geology, in determining the compartmentalization and nature of ice flow

100 within the IIS trunk (cf. Siegert et al., 2016; Jeofry et al., 2018b). The IIS trunk is divided into at least two flow compartments that relate to upstream tributary flow (Figures 5a and b), with crevasse patterns on the surface of the ice stream trunk either side of the flow stripe evidencing very different strain regimes (Figure 5a). We also observe that the surface feature above the englacial fold coincides with the grid-SW margin of the ice plain at the IIS grounding zone (Fricker and Padman, 2006). The fold may therefore play a role in buttressing the IIS, by influencing the position and form of the ice plain.

105 3.3 Returned power of englacial layers

R1 is often characterized by pronounced anisotropic reflections throughout the survey area. To demonstrate this anisotropy, we investigated the returned power of R1 in and around the broad enhanced flow tributary of the IIS (Figures 6b). At survey crossover points within a 127.5 km x 75 km zone, R1 often displays clear anisotropy, with much stronger (typically 10 dB or more) returned radar power in the along ice flow direction than in radar survey data across ice flow (Figures 6 and Supplementary

110 Figures 1-4). This anisotropy is similar in magnitude to that observed in East Antarctica as ice flows over large subglacial obstacles (Fujita et al., 1999; Siegert and Fujita, 2001; Wang et al. 2018); the explanation being that enhanced stresses on the stoss-face of basal hills lead to exaggerated strain in specific 'soft' layers (of glacial as opposed to interglacial age). ~~We do not observe any high relief basal topography in our study region, hence this specific explanation is unlikely to hold here.~~

4 Discussion

115 4.1 Physical explanations for englacial reflections

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 (corresponding to power anisotropy for a specific radar layer) (e.g. Matsuoka et al., 2004; Eisen et al., 2007); (iii) Birefringent propagation (corresponding to power oscillations as a function of ice depth) (Fujita et al., 2006); and (iv) 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 (ii) or (iii) (Fujita et al., 1999; Wang et al., 2018). The depth of R1 certainly rules out ice-density fluctuations. In general, it is difficult to separate-out (ii) and (iii). However, for the case of R1, we can assume that anisotropic scattering is the dominant cause of power anisotropy (the along and across flow profiles have similar long-wavelength behavior and the power anisotropy is localized for a set of radar layers). We therefore attribute R1 to a 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; Montagnat et al., 2014). 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 anisotropic crystal fabric (i.e. with a strong single vertical maxima) would not result in an anisotropic 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. 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

120 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 (Wang et al., 2018). As the depth of R1 rules out ice density fluctuations, we attribute the unit to comprise a strong ice crystal fabric,



noting also that significant variability in crystal fabric is observed in the lower parts of West Antarctic ice cores (e.g. Gow and Williamson, 125 1976; Fitzpatrick et al., 2014), and that radar reflection anisotropy has been verified by ice core evidence from Antarctica and Greenland (Eisen et al. 2007, Drews et al. 2012; Li et al. 2018). The anisotropic layers 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 130 (Siegert, 1999). The anomalously high reflectivity of R2 may represent a pronounced acidity spike, or multiple spikes, in the stratigraphy.

4.2 Formation of the deep ice unit

The ‘freeze-on’ hypothesis for the formation of ~~deep ice units~~basal ice (Bell et al., 2011) cannot explain the deep-ice unit and incorporated layers (i.e. R1 to the ice sheet bed) for four reasons: (1) unlike Greenland, West Antarctica lacks input of water from

135 surface ablation processes, so the water would need to be derived entirely from subglacial melt – across the majority of the area covered by R1 and R2 the ice is typically thin (i.e. <1.5 km), slow flowing (i.e. <25 ma⁻¹) and likely frozen to the bed; (2) in the central IIS catchment, where the bed is wet, the ice is relatively fast-flowing so the basal ice observed there could not have formed by freeze-on as it would advect down-flow before a significant thicknesses of ice could develop (without unrealistically high rates of freezing) (cf. Dow et al., 2018); (3) IIS has a well-defined and efficient topographically-constrained subglacial

140 drainage network, without widespread stores of subglacial water to act as water sources (Wright and Siegert, 2012; Jeofry et al., 2018a, 2018b); and (4) although during more extensive glacial conditions hypothesized subglacial lakes in the upper catchment of IIS-MIS associated with thicker ice and a low gradient ice sheet surface slope (cf. Livingstone et al., 2013) could provide subglacial water for basal ‘freeze on’, we observe the deep-ice unit in locations far removed from potential subglacial meltwater pathways (e.g. Winter et al., 2015; Bingham et al., 2015) (Figures 1 and 2). Proposed active subglacial lakes in the IIS-MIS catchment investigated

145 with ice-penetrating radar demonstrate little evidence for significant ponding of subglacial water (Siegert et al., 2014, 2016), with no apparent connection to the englacial folds in these locations.

Given the consistent stratigraphic position of R1 and R2 in all areas of the IIS-MIS they are found (e.g. Figures 1 and 2), regardless of bed conditions and flow speeds, we conclude that the structures and lateral extent of the deep-ice structures must be the result of the deformation and localized folding of meteoric ice. 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. Further, given the radar anisotropy observed, the most likely

150 explanation for the folds is that they emanate from a band of ice with distinct rheological properties in the lower third of the ice sheet column (NEEM community members, 2013; Bons et al. 2016).

4.3 Physical properties and rheology of the folds: modulation of ice flow

The most prominent fold observed is consistently associated with the boundary of enhanced ice flow and the ice stream trunk surface flow stripe (Figures ~~4d1c~~, 3a-b and 5). 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.

~~This spatial correspondence between the fold and shear margin is remarkable, 155 and points to the folding of the deep ice modulating the position of the shear margin and controlling trunk flow. It therefore plays an important role in the ice dynamics of the IIS-MIS catchment.~~ The simplest explanation is that the core of the fold contains higher viscosity material, be that ice and/or sediment, which is less conducive to deformation than adjacent ice. The high viscosity material resists ice flow, leading to (relatively) fast ice flow to one side and slower flow on the other, where up to four other folds are present. Evidence supporting the core of the primary fold being more resistant to flow exists in observations 160 of ice surface ‘bumps’ directly above the largest anticline in some across flow survey lines.

The core of the most prominent anticline contains a consistently bright ‘hand-shaped’ reflection at the bed, several hundred meters high and wide (Figures 3a, 3d, 4 and 5) that allows its unequivocal identification (Figure 5). This reflection is observed, below R2, in more than fifteen across-flow lines and in the survey lines cutting obliquely across the ice stream trunk (Figure

5). Along-flow, the feature is a set of bed-conformable reflectors (Figure 3c). Our interpretation of this reflection is that it 165 represents sediment drawn up into fractures in the base of the ice sheet during compressional fold formation (cf. ~~Woodward Winter~~ et al., ~~2003~~2019); such an inclusion of sediment would significantly alter the rheology of the core of the anticline. This may determine the position of the lateral margin of the tributary of enhanced ice flow, the different ‘compartments’ of ice stream trunk flow, and the position of the IIS ice plain.

~~One possible explanation for the fold and ‘hand-shaped’ reflector, involves spiraling flow of basal ice (Schoof and Clarke, 170 2008), which acts to corrugate ice across flow and leads to fluting at the ice bed. This explanation also involves a sharp rheological contrast between the ice above and the basal unit, which possesses a Reiner-Rivlin rheology.~~

4.4 The influence of climate history on ice sheet stratigraphy, structure and rheology

The radar reflections that characterize the IIS-MIS deep-ice unit have distinct signatures that are comparable to deep-ice reflections recorded beneath the central Greenland Ice Sheet where, because of strongly contrasting physical and rheological prop-



175 eries of glacial and interglacial ice, deep ice of Eemian age and older, is folded, sheared and overturned (NEEM community members, 2013; Bell et al., 2014; Bons et al., 2016; MacGregor et al., 2015). Similarly, it is possible that the varying reflection properties of the IIS-MIS deep-ice package are associated with boundaries or interfaces between ice accumulated during contrasting climatic periods (i.e. glacial/stadial and interglacial/interstadial periods). The last deglaciation in West Antarctica was characterized by a rapid increase in the rate of surface accumulation (WAIS Divide Project Members, 2013), and a 192-year

180 period of acid deposition associated with major volcanic activity (Gow and Williamson, 1976; McConnell et al., 2017). ~~The current lack of a reliable radiostratigraphy across West Antarctica prevents a confident assessment of the likely age of the deep ice units in the IIS-MIS. The only independent constraint on the age of the deep ice package is from radar englacial layer dating tied to the Byrd ice core (Siegert and Payne, 2004). Linking the radar stratigraphy of the IIS-MIS catchment to the radar transect of Siegert and Payne (2004) where our 2010-11 survey data intersects their profile, indicates that the transition between~~

185 ~~the upper undisrupted high reflectivity ice and the lower deep ice unit (i.e. R1) can be dated to approximately 16 ka. There are, however, uncertainties associated with this correlation (e.g. resolution of the Byrd ice core, the resolution, geolocation and vertical and along track sampling of the SPRI-NSF-TUD RES data etc.), so we emphasise the preliminary nature of this correlation at this stage. If the correlation were shown to be robust, however, then the low-reflectivity zone between R1 and R2 would be of last glacial age. A new radiostratigraphy across West Antarctica (Ashmore et al., 2020) enables us to infer the likely age of the deep ice units in the IIS-MIS. The best 'direct' constraint on the age of the deep ice package is from the dated radar englacial layer tied to the Byrd ice core (Siegert and Payne, 2004; Ashmore et al., 2020). Linking the radar stratigraphy of the IIS-MIS catchment to the radar transect of Siegert and Payne (2004) where our 2010-11 survey data intersects their profile (Ashmore et al., 2020), indicates that the transition between the upper undisrupted high reflectivity ice and the lower deep ice unit (i.e. R1) can be dated to approximately 16 ka. There are some potential uncertainties associated with this correlation (e.g. resolution of the Byrd ice core, the resolution, geolocation and vertical and along track sampling of the SPRI-NSF-TUD RES data etc.). However, assuming this correlation to be correct, the low-reflectivity zone between R1 and R2 is of last glacial age, with the potential for even older ice in places.~~ As glacial ice tends to be rheologically 'softer' than interglacial ice, enhanced flow often occurs in

190 such layers (Paterson 1991; Pettit et al., 2014; NEEM community members, 2013). The strongly preferred ice crystal fabric of R1 could be the product of differential shear associated with ice sheet physical properties produced by: (i) the abrupt change in WAIS accumulation (WAIS Divide Project Members, 2013); and/or (ii) the volcanic deposit known as 'Old Faithful' (Jacobel and Welch, 2005), both associated with the termination of the last glacial period in West Antarctica. R2 would then represent ice older, potentially significantly older, than the Last Glacial Maximum. The bifurcation of R2 into multiple layers (Figure 195 2b) may be of note here; multiple tephras dating to the last glacial cycle (i.e. at 22.3 ka, 32.4 ka and 44.8 ka) have recently been recorded in parts of West Antarctica (Iverson et al., 2017). Older widespread West Antarctic tephras from Marine Isotopic Stages 6 and 5 are also recognised in marine sediments from the continental shelf (Hillenbrand et al., 2008).



Englacial processes similar to those responsible for the formation of the deep-ice unit in the IIS-MIS catchment are likely to occur elsewhere in Antarctica. Radar data from the Siple Coast region record the presence of a major fold and upwarping of ice, for example (Siegert et al., 2004). The formation of this fold was originally ascribed to a Holocene-age ice flow reorganization,

200 but formation through deformation and folding of deep ice of varying rheological properties by convergent ice flow is a viable explanation prior to ice-flow direction change.

5 Conclusions

We have demonstrated the presence of an extensive package of deep-ice units beneath the Institute and Moller ice streams. At least one layer in the deep ice has physical properties (i.e. ice crystal orientation fabric, rheology) significantly different to the upper ice column.~~We have demonstrated the presence of an extensive package of deep-ice units beneath the Institute and Moller ice streams with physical properties (i.e. ice crystal fabric, rheology) significantly different to the upper ice column.~~ At the lateral boundary of the onset of enhanced ice flow of IIS, where ice flow is convergent, these deep-ice units have been heavily deformed. Deformation has led to the development of large-scale englacial folds that may modulate ice-stream position, structure and dynamics.~~At the lateral boundary of~~
205 ~~the onset of enhanced ice flow of the IIS, these deep-ice units have been heavily deformed by convergent ice flow, leading to the formation of large-scale englacial folds that modulate ice-stream position, structure and dynamics.~~ Due to the extensive spatial extent of the deep-ice unit, and its vertical and horizontal variability in crystal fabric and rheology, such units have important implications for assumptions underlying our understanding of ice sheet tributary and trunk flow. Our results confirm that ice flow across the bulk of West Antarctica, and potentially other ice masses, is more complex than is currently incorporated

210 within the set-up and application of many numerical ice-sheet simulations used to determine ice dynamics and predict global sea level. As future ice flow models with greater computational power and grid resolution incorporate the effects of rheology on ice dynamics, they must ensure that they reflect internal ice sheet stratigraphy and deformation structures such as those reported here.

Data availability. SEG-Y files of the 2D-focused SAR processed radar data are available from the UK Polar Data Centre [https://data.bas.](https://data.bas.ac.uk/metadata.php?id=GB/NERC/BAS/PDC/00937)
215 [ac.uk/metadata.php?id=GB/NERC/BAS/PDC/00937](https://data.bas.ac.uk/metadata.php?id=GB/NERC/BAS/PDC/00937). Ice thickness picks for the IMAFI survey are available from the UK Polar Airborne Geophysics Data Portal <https://legacy.bas.ac.uk/data/aerogeo/dataset/imafi/>.

Author contributions. NR and MJS wrote the paper. HC and NR processed the data. NR collected and analyzed the data. MJS was PI of the IMAFI project. All authors contributed to the final version of the manuscript.



Competing interests. The authors have no competing interests to declare.

220 *Acknowledgements.* We thank: Institute and Möller ice stream Antarctic Funding Initiative (IMAFI) science and field team (Fausto Ferraccioli, Tom Jordan, Rob Bingham, David Rippin, Anne Le Brocq, Carl Robinson, Ian Potten, Doug Cochrane, Mark Oosterlander); British Antarctic Survey logistics; John Woodward and Kate Winter for discussions regarding entrainment of basal sediments; Rob Larter for information regarding Antarctic tephra deposits dating to the last glacial cycle; Tom M Jordan for discussions on ice crystal fabric; TCD editor Joe MacGregor, Rob Bingham and four anonymous reviewers for helpful recommendations and comments on earlier versions of this manuscript.~~and Rob Bingham and two anonymous reviewers for helpful comments on earlier versions of this manuscript.~~ The IMAFI project was funded by UK NERC AFI Grant NE/G013071/1. Aspects of this work were 225 inspired/motivated by the Scientific Committee for Antarctic Research (SCAR) AntArchitecture community.

References

- Ashmore, D.W., Bingham, R.G., Ross, N., Siegert, M.J., Jordan, T.A., Mair, D.W.F.: Englacial Architecture and Age-Depth Constraints Across the West Antarctic Ice Sheet, *Geophysical Research Letters*, 47, e2019GL086663, <https://doi.org/10.1029/2019GL086663>, 2020
- Bamber, J. L., Vaughan, D. G., and Joughin, I.: Widespread Complex Flow in the Interior of the Antarctic Ice Sheet, *Science*, 287, 1248-1250, <https://doi.org/10.1126/science.287.5456.1248>, 2000.
- Bamber, J. L., Gomez-Dans, J. L., and Griggs, J. A.: Antarctic 1 km Digital Elevation Model (DEM) from Combined ERS-1 Radar and ICESat
230 Laser Satellite Altimetry: Boulder, Colorado USA, National Snow and Ice Data Center, <https://doi.org/10.5067/H0FQ1KL9NEKM>, 2009
- Bohlander, J., and Scambos, T.: Antarctic coastlines and grounding line derived from MODIS Mosaic of Antarctica (MOA): Boulder, Colorado USA, National Snow and Ice Data Center. 2007
- Bell, R. E., Ferraccioli, F., Creyts, T. T., Braaten, D., Corr, H., Das, I., Damaske, D., Frearson, N., Jordan, T., Rose, K., Studinger, M., and Wolovick, M.: Widespread persistent thickening of the East Antarctic Ice Sheet by freezing from the base, *Science*, 331, 1592-1595, 235 <https://doi.org/10.1126/science.1200109>, 2011.
- Bell, R. E., Tinto, K., Das, I., Wolovick, M., Chu, W., Creyts, T. T., Frearson, N., Abdi, A., and Paden, J. D.: Deformation, warming and softening of Greenland's ice by refreezing meltwater, *Nature Geoscience*, 7, 497-502, doi: 10.1038/ngeo2179, 2014.
- Bentley, C. R.: Seismic evidence for moraine within the basal Antarctic ice sheet, in Crary, A.P., ed., *Antarctic snow and ice studies II: American Geophysical Union, Washington, DC*, 89-129, <https://doi.org/10.1029/AR016p0089>, 1971.
- 240 Bingham, R. G., Rippin, D. M., Karlsson, N. B., Corr, H. F. J., Ferraccioli, F., Jordan, T. A., Le Brocq, A. M., Rose, K. C., Ross, N., and Siegert, M. J.: Ice-flow structure and ice dynamic changes in the Weddell Sea sector of West Antarctica from radar-imaged internal layering, *Journal of Geophysical Research Earth Surface*, 120, 655-670, <https://doi.org/10.1002/2014JF003291>, 2015.
- Bons, P. D., Jansen, D., Mundel, F., Bauer, C. C., Binder, T., Eisen, O., Jessell, M. W., Llorens, M-G., Steinbach, F., Steinhage, D., and Weikusat, I.: Converging flow and anisotropy cause large-scale folding in Greenland's ice sheet, *Nature Communications*, 7, 11427, 245 <https://doi.org/10.1038/ncomms11427>, 2016.
- Conway, H., Catania, G., Raymond, C. F., Gades, A. M., Scambos, T. A., and Engelhardt, H.: Switch of flow direction in an Antarctic ice stream, *Nature*, 419, 465-467, <https://doi.org/10.1038/nature01081>, 2002.



- Corr, H. F. J., and Vaughan, D. G.: A recent volcanic eruption beneath the West Antarctic ice sheet. *Nature Geoscience*, 1, 122-125, <https://doi.org/10.1038/ngeo106>, 2008.
- 250 Dow, C. F., Karlsson, N. B., and Werder, M. A., Limited Impact of Subglacial Supercooling Freeze-on for Greenland Ice Sheet Stratigraphy, *Geophysical Research Letters*, 45, 1481-1489, <https://doi.org/10.1002/2017GL076251>, 2018.
- Drews, R., Eisen, O., Steinhage, D., Weikusat, I., Kipfstuhl, S., and Wilhelms, F.: Potential mechanisms for anisotropy in ice-penetrating radar data, *Journal of Glaciology*, 58, 613-624, <https://doi.org/10.3189/2012JoG11J114>, 2012.
- Eisen, O., Hamann, I., Kipfstuhl, S., Steinhage, D., and Wilhelms, F.: Direct evidence for continuous radar reflector originating from changes
255 in crystal-orientation fabric, *The Cryosphere*, 1, 1-10, <https://doi.org/10.5194/tc-1-1-2007>, 2007.
- Ely, J. C., and Clark, C. D.: Flow-stripes and foliations of the Antarctic ice sheet. *Journal of Maps*, 12, 249-259, <https://doi.org/10.1080/17445647.2015.1010617>, 2016.
- Fitzpatrick, J. J., Voigt, D. E., Fegyveresi, J. M., Stevens, N. T., Spencer, M. K., Cole-Dai, J., Alley, R. B., Jardine, G. E., Cravens, E. D., Wilen, L., A., Fudge, T. J., and McConnell, J. R.: Physical properties of the WAIS divide ice core, *Journal of Glaciology*, 60, 1181-1198, 260 <https://doi.org/10.3189/2014JoG14J100>, 2014.
- Fricker, H. A. and Padman, L.: Ice shelf grounding zone structure from ICESat laser altimetry, *Geophysical Research Letters*, 33, L15502, <https://doi.org/10.1029/2006GL026907>, 2006.
- Fujita, S., Maeno, H., Uratsuka, S., Furukawa, T., Mae, S., Fujii, Y. and Watanabe, O.: Nature of radio-echo layering in the Antarctic ice sheet detected by a two-frequency experiment, *Journal of Geophysical Research*, 104 (B6), 13,013-13,024, 265 <https://doi.org/10.1029/1999JB900034>, 1999.
- 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.
- Fujita, S., Maeno, H., and Matsuoka, K.: Radio-wave depolarization and scattering within ice sheets: a matrix-based model to link radar and ice-core measurements and its application, *Journal of Glaciology*, 52, 407-424, <https://doi.org/10.3189/172756506781828548>, 2006.
- Glasser, N. F., and Gudmundsson, G. H.: Longitudinal surface structures (flowstripes) on Antarctic glaciers, *The Cryosphere*, 6, 383-391, <https://doi.org/10.5194/tc-6-383-2012>, 2012.
- Goldberg, M.L., Schroeder, D.M., Castelletti, D., Mantelli, E., Ross, N., and Siegert, M.J.: Automated detection and characterization of Antarctic basal units using radar sounding data: Demonstration in Institute Ice Stream, West Antarctica, *Annals of Glaciology*, 61, 2020 (in press).
- Gow, A. J., and Williamson, T.: Rheological implications of the internal structure and crystal fabrics of the West Antarctic Ice Sheet as revealed by deep core drilling at Byrd Station, *Geological Society of America Bulletin*, 12, 1665-1677, <https://doi.org/10.1130/0016-2707606>, 1976.
- 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.
- Harrison, C. H.: Radio echo sounding of horizontal layers in ice, *Journal of Glaciology*, 12, 383-397, <https://doi.org/10.3189/S0022143000031804>, 1973.



- Holschuh, N., Christianson, K., and Anandakrishnan, S.: Power loss in dipping internal reflectors, imaged using ice-penetrating radar, *Annals of Glaciology*, 55, 49-56, <https://doi.org/10.3189/2014AoG67A005>, 2014.
- 275 Horgan, H. J., Anandakrishnan, S., Alley, R. B., Burkett, P. G., and Peters, L. E.: Englacial seismic reflectivity: imaging crystal-orientation fabric in West Antarctica, *Journal of Glaciology*, 57, 639-650, <https://doi.org/10.3189/002214311797409686>, 2011.
- Iverson, N. A., Lieb-Lappen, R., Dunbar, N. W., Obbard, R., Kim, E., and Golden, E.: The first physical evidence of subglacial volcanism under the West Antarctic Ice Sheet, *Scientific Reports*, 7, 11457, <https://doi.org/10.1038/s41598-017-11515-3>, 2017
- Jacobel, R. W., Gades, A. M., Gottschling, D. L., Hodge, S. M., and Wright, D. L.: Interpretation of radar-detected internal layer folding in 280 West Antarctic ice streams, *Journal of Glaciology*, 39, 528-537, <https://doi.org/10.3189/S0022143000016427>, 1993.
- Jacobel, R. W., and Welch, B. C.: A time marker at 17.5 kyr BP detected throughout West Antarctica, *Annals of Glaciology*, 41, 47-51, <https://doi.org/10.3189/172756405781813348>, 2005.
- Jeofry, H. Ross, N., Corr, H. F. J., Li, J., Gogineni, P., and Siegert, M. J.: A new bed elevation model for the Weddell Sea sector of the West Antarctic Ice Sheet, *Earth System Science Data*, 10, 711-725, <https://doi.org/10.5194/essd-10-711-2018>, 2018a.
- 285 Jeofry, H., Ross, N., Le Brocq, A., Graham, A., Li, J., Gogineni, P., Morlighem, M., Jordan, T., Siegert, M. J.: Hard rock landforms generate 130 km ice shelf channels through water focusing in basal corrugations, *Nature Communications*, 9, 4576, <https://doi.org/10.1038/s41467018-06679-z>, 2018b.
- Karlsson, N. B., Rippin, D. M., Vaughan, D. G., and Corr, H. F. J.: The internal layering of Pine Island Glacier, West Antarctica, from airborne radar-sounding data, *Annals of Glaciology*, 50, 141-146, <https://doi.org/10.3189/S0260305500250660>, 2009.
- 290 Jordan, T. A., Ferraccioli, F., Ross, N., Corr, H. F. J., Leat, P. T., Bingham, R. G., Rippin, D. M., Le Brocq, A., Siegert, M. J.: Inland extent of the Weddell Sea Rift imaged by new aerogeophysical data, *Tectonophysics*, 585, 137-160, <https://doi.org/10.1016/j.tecto.2012.09.010>, 2013.
- Joughin, I., Gray, L., Bindschadler, R., Price, S., Morse, D., Hulbe, C., Mattar, K., and Werner, C.: Tributaries of West Antarctic Ice Streams Revealed by RADARSAT Interferometry, *Science*, 286, 283-286, <https://doi.org/10.1126/science.286.5438.283>, 1999.
- 295 Leysinger Vieli, G. J.-M. C., C. Martín, C., Hindmarsh, R. C. A., and Lüthi, M. P.: Freeze-on generates complex ice-sheet stratigraphy. *Nature Communications*, 9, 4669. <https://doi.org/10.1038/s41467-018-07083-3>, 2018.
- Li, J., Vélez González, J., Leuschen, C., Harish, A., Gogineni, P., Montagnat, M., Weikusat, I., Rodriguez-Morales, F., and Paden, J.: Multichannel and multi-polarization radar measurements around the NEEM site, *The Cryosphere*, 12, 2689-2705, <https://doi.org/10.5194/tc12-2689-2018>, 2018.
- 300 Livingstone, S. J., Clark, C. D., Woodward, J., and Kingslake, J.: Potential subglacial lake locations and meltwater drainage pathways beneath the Antarctic and Greenland ice sheets, *The Cryosphere*, 7, 1721-1740, <https://doi.org/10.5194/tc-7-1721-2013>, 2013.
- MacGregor, J. A., Fahnestock, M. A., Catania, G. A., Paden, J. D., Gogineni, S. P., Young, S. K., Rybarski, S. C., Mabrey, A. N., Wagman, B. M., and Morlighem, M.: Radiostratigraphy and age structure of the Greenland Ice Sheet, *Journal of Geophysical Research Earth Surface*, 120, 212-241, <https://doi.org/10.1002/2014JF003215>, 2015.
- 305 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.
- Matsuoka, K., Uratsuka, S., Fujita, S., and Nishio, F.: Ice-flow-induced scattering zone within the Antarctic ice sheet revealed by highfrequency airborne radar, *Journal of Glaciology*, 50, 382-388, <https://doi.org/10.3189/172756504781829891>, 2004.



McConnell, J. R., Burke, A., Dunbar, N. W., Köhler, P., Thomas, J. L., Arienzo, M. M., Chellman, N. J., Maselli, O. J., Sigl, M., Adkins, J. F., Baggenstos, D., Burkhart, J. F., Brook, E. J., Buizert, C., Cole-Dai, J., Fudge, T. J., Knorr, G., Graf, H.-F., Grieman, M. M., Iverson, N., McGwire, K. C., Mulvaney, R., Paris, G., Rhodes, R. H., Saltzman, E. S., Severinghaus, J. P., Steffensen, J. P., Taylor, K. C., and Winckler, 310 G.: Synchronous volcanic eruptions and abrupt climate change ~17.7 ka plausibly linked by stratospheric ozone depletion, *Proceedings of the National Academy of Science*, 114, 10035-10040, <https://doi.org/10.1073/pnas.1705595114>, 2017.

Montagnat, M., Azuma, N., Dahl-Jensen, D., Eichler, J., Fujita, S., Gillet-Chaulet, F., Kipfstuhl, S., Samyn, D., Svensson, A., and Weikusat, I.: Fabric along the NEEM ice core, Greenland, and its comparison with GRIP and NGRIP ice cores, *The Cryosphere*, 8, 1129–1138, <https://doi.org/10.5194/tc-8-1129-2014>, 2014.

NEEM community members: Eemian interglacial reconstructed from a Greenland folded ice core, *Nature*, 493, 489-494, <https://doi.org/10.1038/nature11789>, 2013.

Ng, F. and Conway, H.: Fast-flow signature in the stagnated Kamb Ice Stream, West Antarctica, *Geology*, 32, 481-484, 315 <https://doi.org/10.1130/G20317.1>, 2004.

Paren, J. G., and Robin, G. de Q., Internal Reflections in Polar Ice Sheets, *Journal of Glaciology*, 14, 251-259, <https://doi.org/10.3189/S0022143000021730>, 1975.

Paterson, W. S. B.: Why ice-age ice is sometimes "soft", *Cold Regions Science and Technology*, 20, 75-98, [https://doi.org/10.1016/0165232X\(91\)90058-O](https://doi.org/10.1016/0165232X(91)90058-O), 1991.

320 Pettit, E. C., Whorton, E. N., Waddington, E. D., and Sletten, R. S.: Influence of debris-rich basal ice on flow of a polar glacier, *Journal of Glaciology*, 60, 989-1006, <https://doi.org/10.3189/2014JoG13J161>, 2014.

Rignot, E., Mouginot, J., and Scheuchl, B.: MEaSUREs InSAR-Based Antarctica Ice Velocity Map, Version 2, Boulder, Colorado USA, NASA National Snow and Ice Data Center Distributed Active Archive Center, <https://doi.org/10.5067/D7GK8F5J8M8R>, 2017.

Robin, G. de Q., and Millar, D. H. M.: Flow of ice sheets in the vicinity of subglacial peaks: *Annals of Glaciology*, 3, 290-294, 325 <https://doi.org/10.3189/S0260305500002949>, 1982.

Rose, K. C., Ross, N., Jordan, T. A., Bingham, R. G., Corr, H. F. J., Ferraccioli, F., Le Brocq, A. M., Rippin, D. M., and Siegert, M. J.: Ancient pre-glacial erosion surfaces preserved beneath the West Antarctic Ice Sheet: *Earth Surface Dynamics*, 3, 139-152, <https://doi.org/10.5194/esurf-3-139-2015>, 2015

Ross, N., Bingham, R. G., Corr, H. F. J., Ferraccioli, F., Jordan, T. A., Le Brocq, A., Rippin, D. M., Young, D., Blankenship, D. D., and 330 Siegert, M. J.: Steep reverse bed slope at the grounding line of the Weddell Sea sector in West Antarctica, *Nature Geoscience*, 5, 393-396, <https://doi.org/10.1038/ngeo1468>, 2012.

Ross, N., Jordan, T. A., Bingham, R. G., Corr, H. F. J., Ferraccioli, F., Le Brocq, A., Rippin, D. M., Wright, A. P., Siegert, M. J.: The Ellsworth Subglacial Highlands: inception and retreat of the West Antarctic Ice Sheet: *Geological Society of America Bulletin*, 126, 3-15, <https://doi.org/10.1130/B30794.1>, 2014.

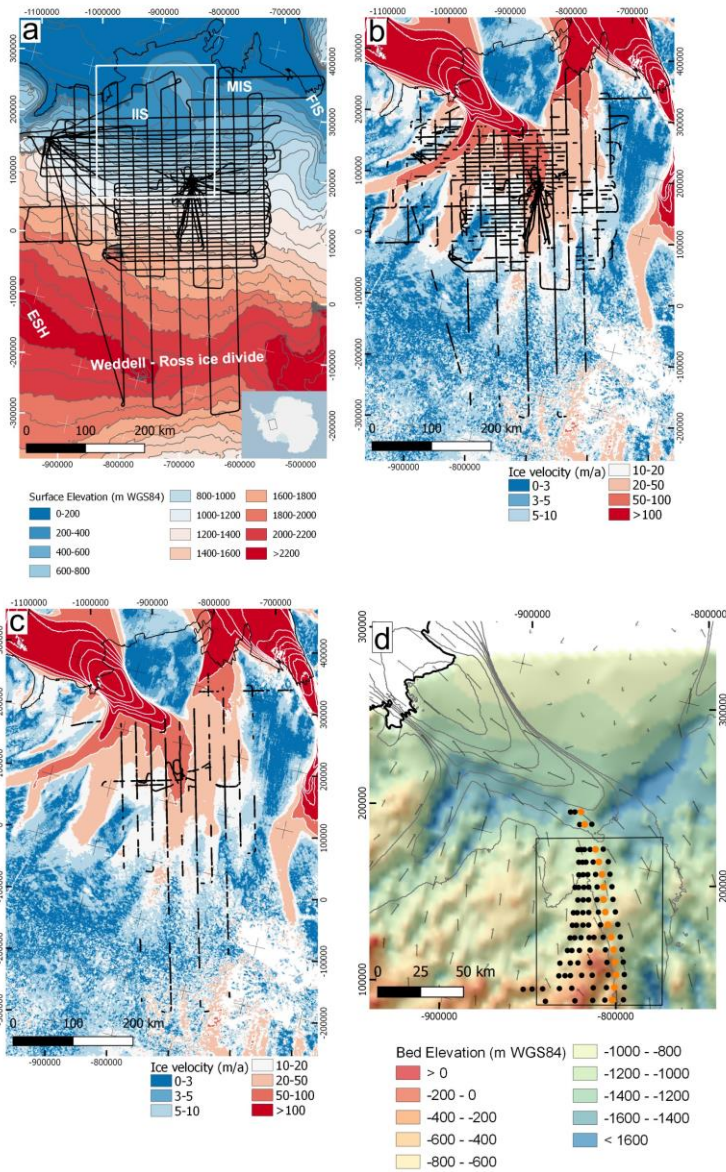
335 ~~Schoof, C. G. and Clarke, G. K. C.: A model for spiral flows in basal ice and the formation of subglacial flutes based on a Reiner-Rivlin rheology for glacial ice, *Journal of Geophysical Research*, 113, B05204, <https://doi.org/10.1029/2007JB004957>, 2008.~~

Siegert, M. J.: On the origin, nature and uses of Antarctic ice-sheet radio-echo layering: *Progress in Physical Geography*, 23, 159-179, <https://doi.org/10.1177/027030913339902300201>, 1999.

Siegert, M. J., Welch, B., Morse, D., Vieli, A., Blankenship, D. D., Joughin, I., King, E. C., Leysinger Vieli, G. J.-M. C., Payne, A. J.,



- 340 and Jacobel, R.: Ice flow direction change in interior West Antarctica, *Science*, 305, 1948-1951, <https://doi.org/10.1126/science.1101072>, 2004.
- Siegert, M. J., and Payne, A. J.: Past rates of accumulation in central West Antarctica, *Geophysical Research Letters*, 31, L12403, <https://doi.org/10.1029/2004GL020290>, 2004.
- Siegert, M. J., Ross, N., Corr, H. F. J., Smith, B., Jordan, T. A., Bingham, R. G., Ferraccioli, F., Rippin, D. M., Le Brocq, A.: Boundary
345 conditions of an active West Antarctic subglacial lake: implications for storage of water beneath the ice sheet, *The Cryosphere*, 8, 15-24, <https://doi.org/10.5194/tc-8-15-2014>, 2014.
- Siegert, M. J., Ross, N., Li, J., Schroeder, D. M., Rippin, D., Ashmore, D., Bingham, R., and Gogineni, P.: Subglacial controls on the flow of the Institute Ice Stream, West Antarctica, *Annals of Glaciology*, 57, 19-24, <https://doi.org/10.1017/aog.2016.17.312>, 2016
- Siegert, M. J. and Fujita, S.: Internal ice-sheet radar layer profiles and their relation to reflection mechanisms between Dome C and the Trans 350 Antarctic Mountains. *Journal of Glaciology*, 47, 205-212, <https://doi.org/10.3189/172756501781832205>, 2001.
- Wang, B., Sun, B., Ferrocchioli, F., Martin, C., Steinhage, D., Cui, X., Siegert, M. J.: Summit of the East Antarctic Ice Sheet underlain by extensive thick ice-crystal fabric layers formed by glacial-interglacial environmental change, in: Siegert, M. J., Jamieson, S. S. R., White, D. A., eds., *Exploration of Subsurface Antarctica: Uncovering Past Changes and Modern Processes*, Geological Society, London, Special Publication 461, 131-143, <https://doi.org/10.1144/SP461.1>, 2018.
- 355 WAIS Divide Project Members: Onset of deglacial warming in West Antarctica driven by local orbital forcing, *Nature*, 500, 440-444, <https://doi.org/10.1038/nature12376>, 2013.
- Winter, K., Woodward, J., Ross, N., Dunning, S. A., Bingham, R. G., and Corr, H. F. J., and Siegert, M. J.: Airborne radar evidence for tributary flow switching in the Institute Ice Stream, West Antarctica: implications for ice sheet configuration and dynamics, *Journal of Geophysical Research Earth Surface*, 120, 1611-1625, <https://doi.org/10.1002/2015JF003518>, 2015.
- Winter, K., Woodward, J., Ross, N., Dunning, S.A., Hein, A.S., Westoby, M.J., Culberg, R., Marrero, S.M., Schroeder, D.M., Sugden, D.E., and Siegert, M.J.: Radar-Detected Englacial Debris in the West Antarctic Ice Sheet, *Geophysical Research Letters*, 46, 10454-10462, <https://doi.org/10.1029/2019GL084012>, 2019
- 360 Wolovick, M. J., Creyts, T. T., Buck, W. R., and Bell, R. E.: Traveling slippery patches produce thickness-scale folds in ice sheets, *Geophysical Research Letters*, 41, 8895–8901, <https://doi.org/10.1002/2014GL062248>, 2014.
- Wolovick, M. J., and Creyts, T. T.: Overturned folds in ice sheets: Insights from a kinematic model of traveling sticky patches and comparisons with observations, *Journal of Geophysical Research Earth Surface*, 121, 1065–1083, <https://doi.org/10.1002/2015JF003698>, 2016.
- ~~Woodward, J., Murray, T., Clark, R. A., and Stuart, G. W.: Glacier surge mechanisms inferred from ground-penetrating radar: Kongsvegen, 365 Svalbard, *Journal of Glaciology*, 49, 473–480, <https://doi.org/10.3189/172756503781830458>, 2003.~~
- Wright, A., and Siegert, M.: A fourth inventory of Antarctic subglacial lakes, *Antarctic Science*, 24, 659-664, <https://doi.org/10.1017/S095410201200048X>, 2012.
- Wrona, T., Wolovick, M., Ferraccioli, F., Corr, H., Jordan, T. and Siegert, M. J.: Position and variability of complex structures in the central East Antarctic Ice Sheet, in: Siegert, M. J., Jamieson, S. S. R., White, D. A., eds., *Exploration of Subsurface Antarctica: Uncovering Past*
370 *Changes and Modern Processes*, Geological Society, London, Special Publication 461, 113-129, <https://doi.org/10.1144/SP461.12>, 2018.



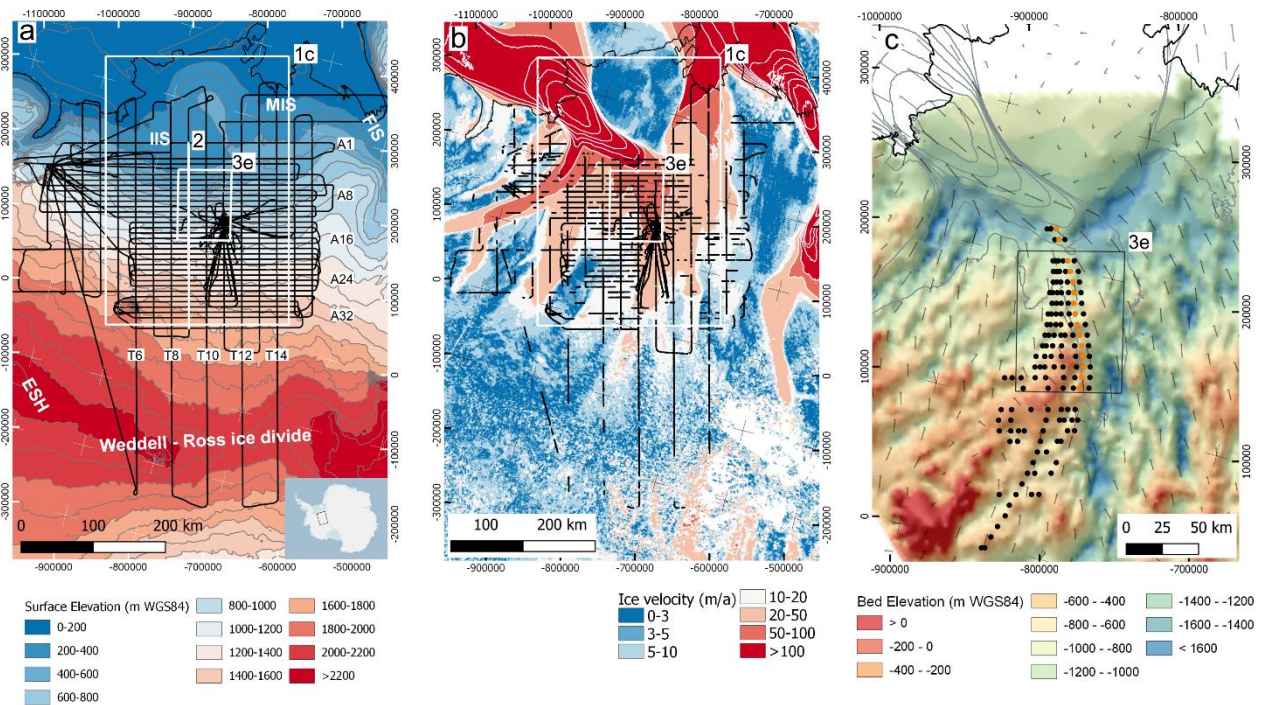


Figure 1. (a) Ice-penetrating radar survey flights over the catchments of the Institute and Möller ice streams (thick black lines), overlain on ice surface elevation (m WGS84) (Bamber et al., 2009). Thin black line in 1a-1c is MODIS grounding line (Bohlander and Scambos, 2007); Grey lines are ice surface elevation contours at 100 m intervals; Möller Ice Stream (MIS), Institute Ice Stream (IIS), Foundation Ice Stream (FIS), Weddell-Ross ice divide and Ellsworth Subglacial Highlands (ESH) are indicated. White boxes indicate extents of Figures 1c and 3e. White line is survey tie line 9, shown in figure 2. Inset shows Antarctic location of Figures 1a-b; (b) Observations of deep-ice unit R1 in radargrams across the study area (thick black lines), overlain on MEASURES ice velocity (Rignot et al., 2017). White lines are velocity contours at 50 m a⁻¹ intervals. Gaps in observations are where either data were not acquired or where the deep ice unit could not be identified in the radar data (e.g. because of signal attenuation etc.). White boxes indicate extents of Figures 1c and 3e; (c) Folded deep ice beneath IIS, relative to basal topography (Ross et al., 2012) and surface ice flow (Rignot et al. 2017). The location of fold axes peaks, identified in radargrams, are represented by black and orange circles, the latter colour denoting the position of the fold with the 'hand-shaped-reflection' (Figure 3d) at its core. Black box defines limits of Figure 3e. Thin grey lines are 50 m contours of MEASURES ice velocity (Rignot et al., 2017). Arrows show direction and magnitude of ice flow (Rignot et al., 2017). Figure 1. (a) Ice-penetrating radar survey flights over the catchments of the Institute and Möller ice streams (thick black lines), overlain on ice surface elevation (m WGS84) (Bamber et al., 2009). Thin black line in 1a-1d is MODIS grounding line (Bohlander and Scambos, 2007); Grey lines are ice surface elevation contours at 100 m intervals; White box is extent of Figure 1d; Möller Ice Stream (MIS), Institute Ice Stream (IIS), Foundation Ice Stream (FIS), Weddell-Ross ice divide and Ellsworth Subglacial Highlands (ESH) are indicated. Inset shows location of Figures 1a-c in Antarctica; (b & c) Observations of deep-ice units R1 (b) and R2 (c) in radargrams across the study area (thick black lines), overlain on MEASURES ice velocity (Rignot et al., 2017). White lines are velocity contours at 50 m a⁻¹ intervals. Gaps in observations are where either data were not acquired or where the deep ice unit could not be identified in the radar data (e.g. because of signal attenuation etc.); (d) Folded deep ice beneath



IIS, relative to basal topography (Ross et al., 2012) and surface ice flow (Rignot et al. 2017). The location of fold axes peaks, identified in radargrams, are represented by circles. The orange dot denotes the position of the fold with the ‘hand-shaped reflection’ (Figure 3d) at its core. Black box defines limits of Figure 3e. Thin grey lines are 50 m contours of 13 MEASURES ice velocity (Rignot et al., 2017). Arrows show direction and magnitude of ice flow.

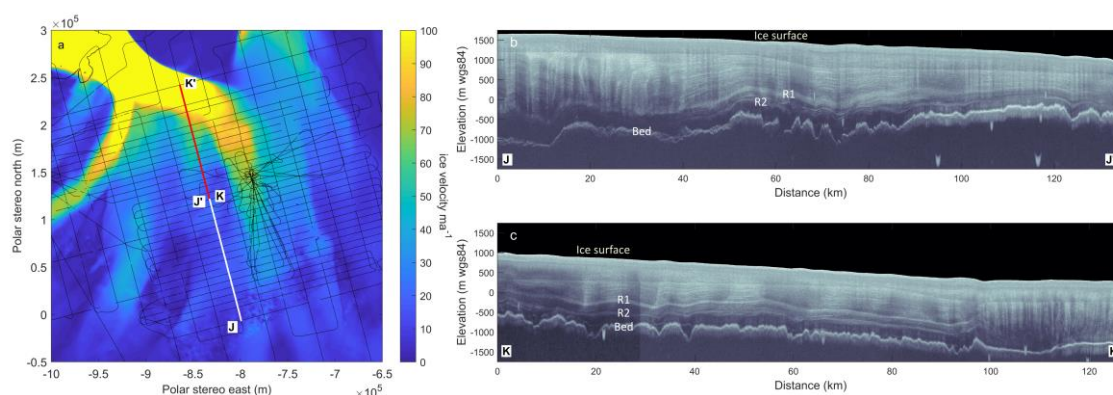


Figure 2. 260 km of radar data along tieline 9 demonstrating the typical stratigraphy of the ice column (high reflectivity meteoric ice, underlain by low reflectivity lower ice column with high reflectivity layers, and the brightness and widespread nature of the band of ice layers (R1 and R2) throughout the IIS and MIS catchments: (a) map of ice velocity (Mouginot et al., 2019) with IMAFI survey grid (thin black lines), grounding line (white line) and location of radar data in 2b (thick black line) and 2c (thick red line). Ice velocity colour scale is saturated at 100 m a⁻¹; (b) radargram of upper to mid IIS catchment (thick black line in 2a). Note bifurcation of R2 into 3-4 layers between 50-80 km; (c) continuation of radargram shown in b into the mid- to lower- IIS catchment (thick red line in 2a). Radargrams in 2b and 2c are radar survey ‘tieline’ 9, which is also shown in Figure 4 and Supplementary Figure 1. Isolated U-shaped ‘blobs’ are artefacts associated with SAR processing of the radar data. Figure 2. 260 km of radar data demonstrating the typical stratigraphy of the ice column (high reflectivity meteoric ice, underlain by low reflectivity lower ice column with high reflectivity layers, and the brightness, ubiquity and widespread nature of the deep ice layers (R1 and R2) throughout the IIS and MIS catchments: (a) map of ice velocity (Mouginot et al., 2019) with IMAFI survey grid (thin black lines), grounding line (thin black line) and location of radar data in 2b (white line) and 2c (red line). Ice velocity colour scale is saturated at 100 m a⁻¹; (b) radargram of upper to mid IIS catchment (white line in 2a). Note bifurcation of R2 into 3-4 layers between 60-80 km; (c) continuation of radargram shown in b into the mid- to lower- IIS catchment (red line in 2a). Isolated U-shaped ‘blobs’ are artefacts associated with SAR processing of data.

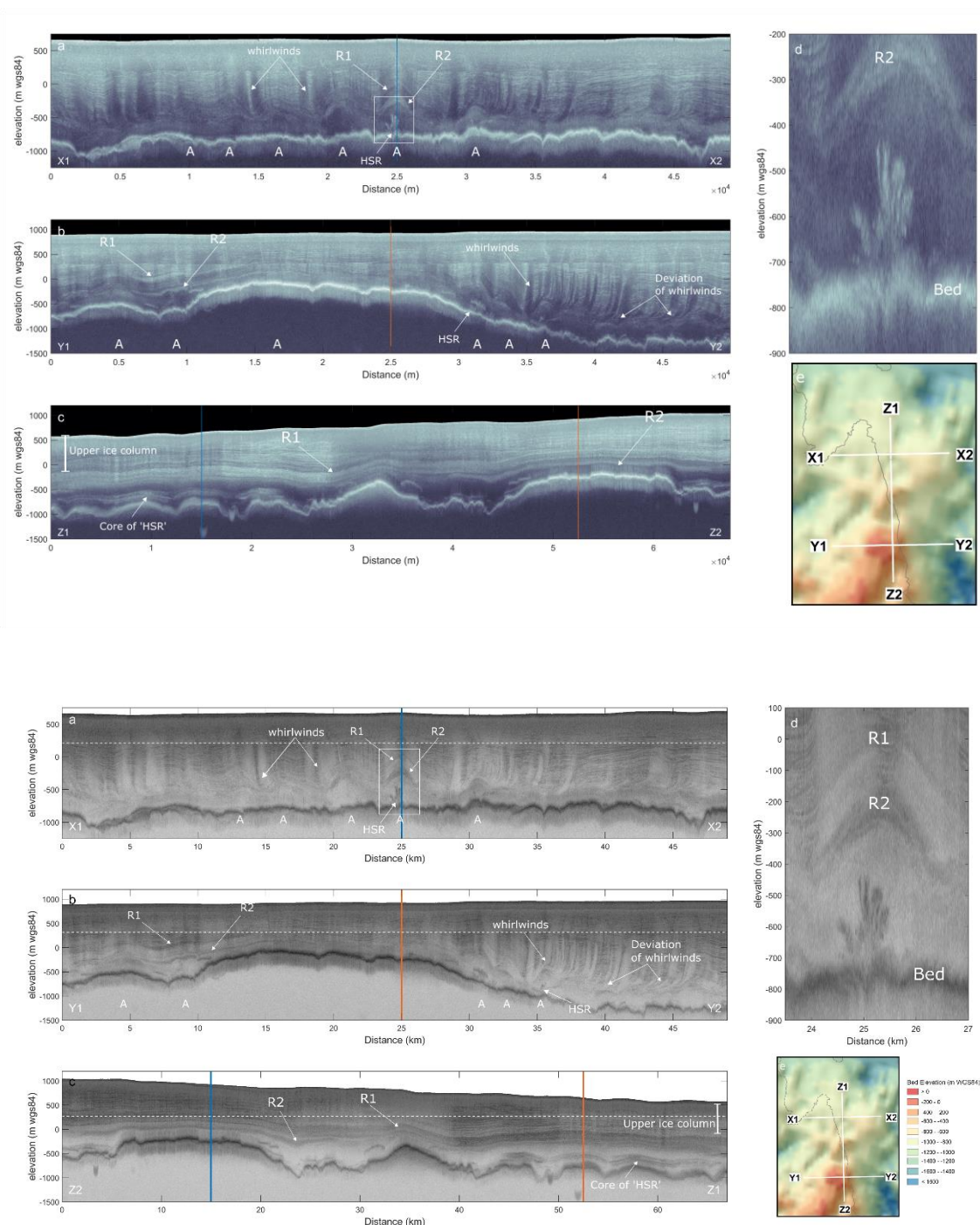


Figure 3. Ice-penetrating radargrams showing detailed englacial layering and folding: (a) Across-flow radargram (X1-X2), with englacial folds and hand-shaped reflection ('HSR'). View is down-ice. Intersection with along-flow radargram Z1-Z2 indicated by blue vertical line. Position of fold anticlines indicated ('A'). White box is location of Fig. 3d.; (b) Across-flow radargram (Y1-Y2), showing early development of englacial



folds and their positions ('A'). Intersection with along-flow radargram Z1-Z2 indicated by red vertical line. (c) Down ice-flow radargram (Z1-Z2) connecting 3a and 3b. Ice flow is approximately left to right. Deep-ice units R1 and R2 are annotated. Intersections with radargrams X1-X2 and Y1-Y2 are indicated by blue and red vertical lines, respectively; (d) zoom-in of hand-shaped reflection from Fig 3a; (e) map of subglacial topography (Ross et al. 2012) showing positions (white lines) of radar transects X1-X2, Y1-Y2 and Z1-Z2. Thin grey line is 50 ma^{-1} velocity contour (Rignot et al. 2018). Note that Fig. 3a has a different Y-axis scale to Figs. 3b and 3c. Figure 3. Ice-penetrating radargrams showing detailed englacial layering and folding: (a) down-ice, across-flow radargram (X1-X2), with englacial folds and hand-shaped reflection ('HSR'). Intersection with along-flow radargram Z1-Z2 indicated by blue vertical line. Position of fold anticlines indicated ('A'). White box is location of Fig. 3d.; (b) up-ice, across-flow radargram (Y1-Y2), showing early development of englacial folds and their positions ('A'). Intersection with along-flow radargram Z1-Z2 indicated by red vertical line. (c) Down ice-flow radargram (Z1-Z2) connecting 3a and 3b. Deep ice units R1 and R2 are annotated. Intersections with radargrams X1-X2 and Y1-Y2 are indicated by blue and red vertical lines, respectively; (d) zoom-in of hand-shaped reflection from Fig 3a; (e) map of subglacial topography (Ross et al. 2012) showing positions (white lines) of radar transects X1-X2, Y1-Y2 and Z1-Z2. Thin grey line is 50 ma^{-1} velocity contour (Rignot et al. 2018). Note that Fig. 3a has a different Y-axis scale to Figs. 3b and 3c.

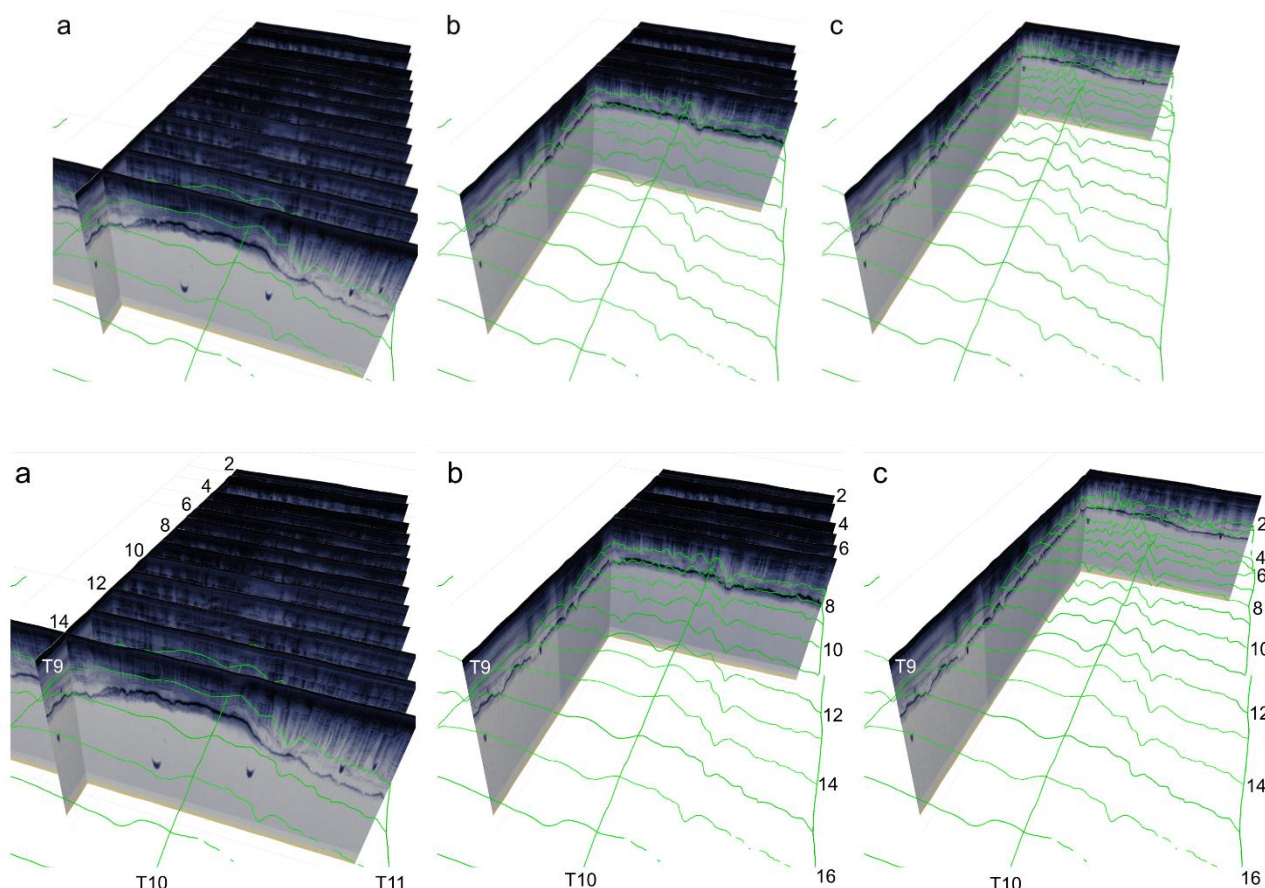
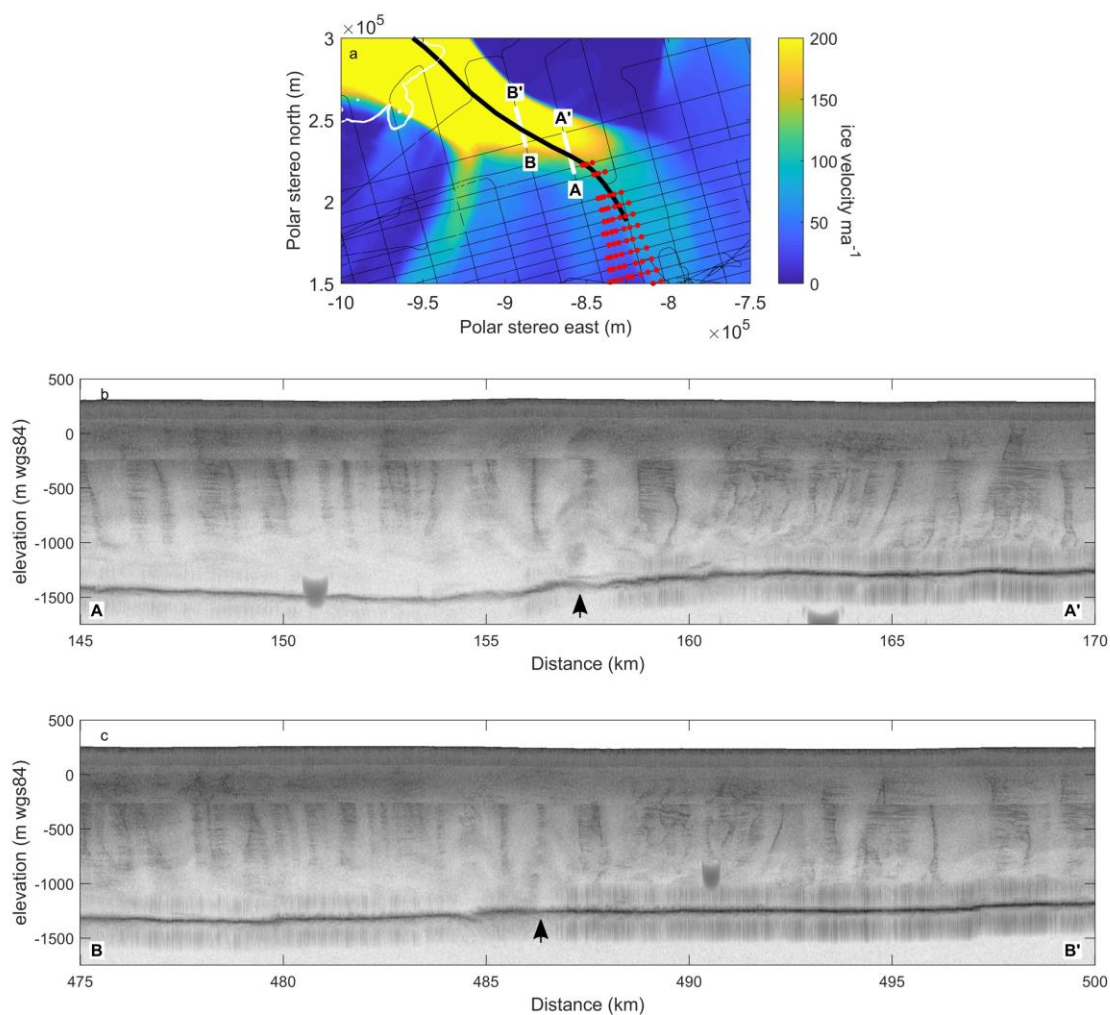


Figure 4. 3D visualisation of the picked (green lines) englacial layer R1 demonstrating 3D pattern of folding and density of survey lines: (a) radargram across ice flow lines 14-2; (b) radargram across ice flow line 7-2; (c) radargram across ice flow line 2. Ice flow is into page

and there is 105 km between across flow lines 14 and 2. Long down-ice 'tie' line radargram shown in a-c is tie line 9 (figure 2c). Tie lines 9, 10 and 11 are annotated

Figure 4. 3D visualisation of the picked (green lines) englacial layer R1 demonstrating 3D pattern of folding and density of survey lines: (a) radargram across ice flow lines 14-2; (b) across ice flow line 7-2; (c) across ice flow line 2. Ice flow is into page and there is 105 km between across flow lines 14 and 2. Long down-ice 'tie' line shown in a-c is tie line 9 (figure 2c).



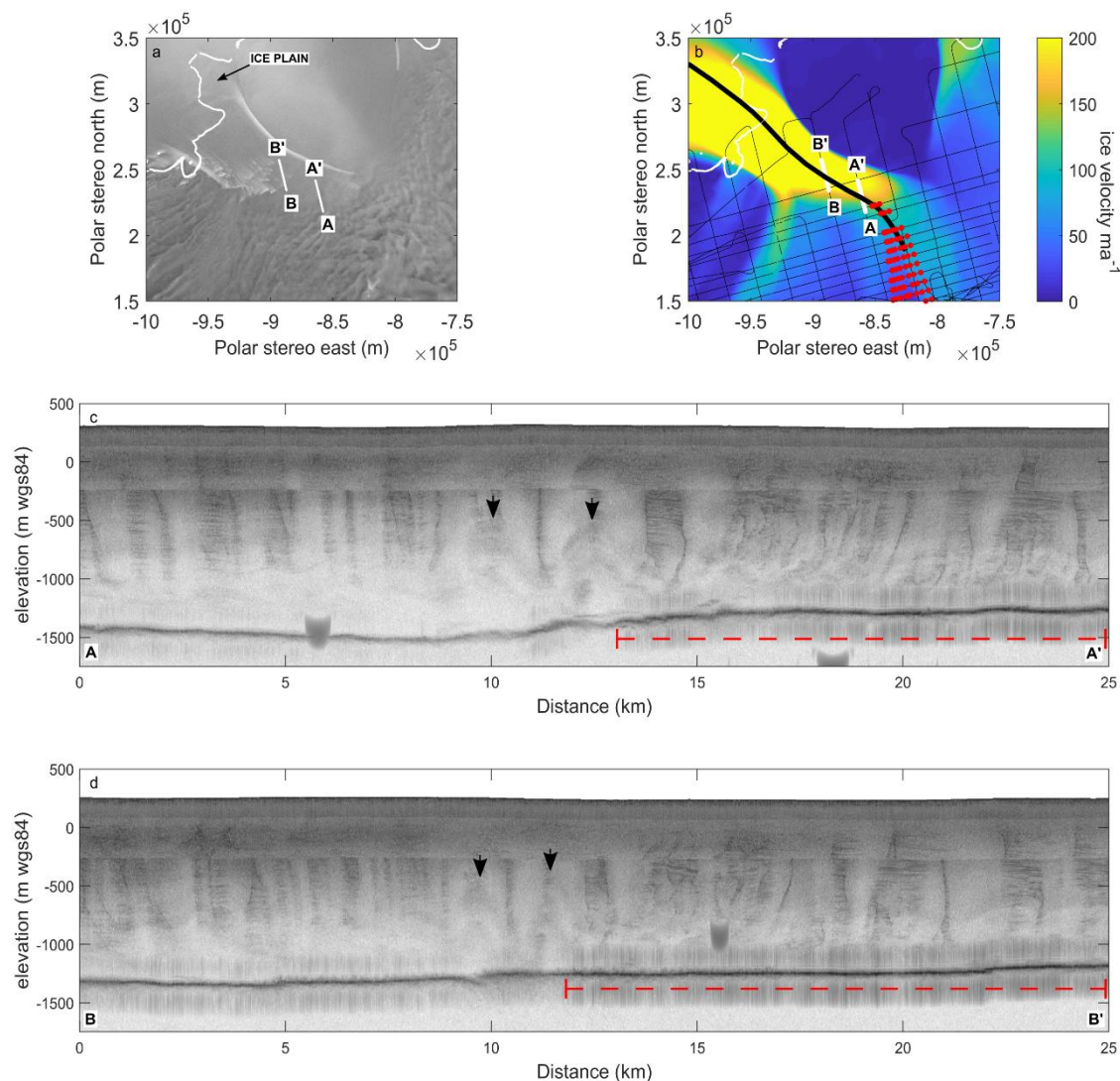
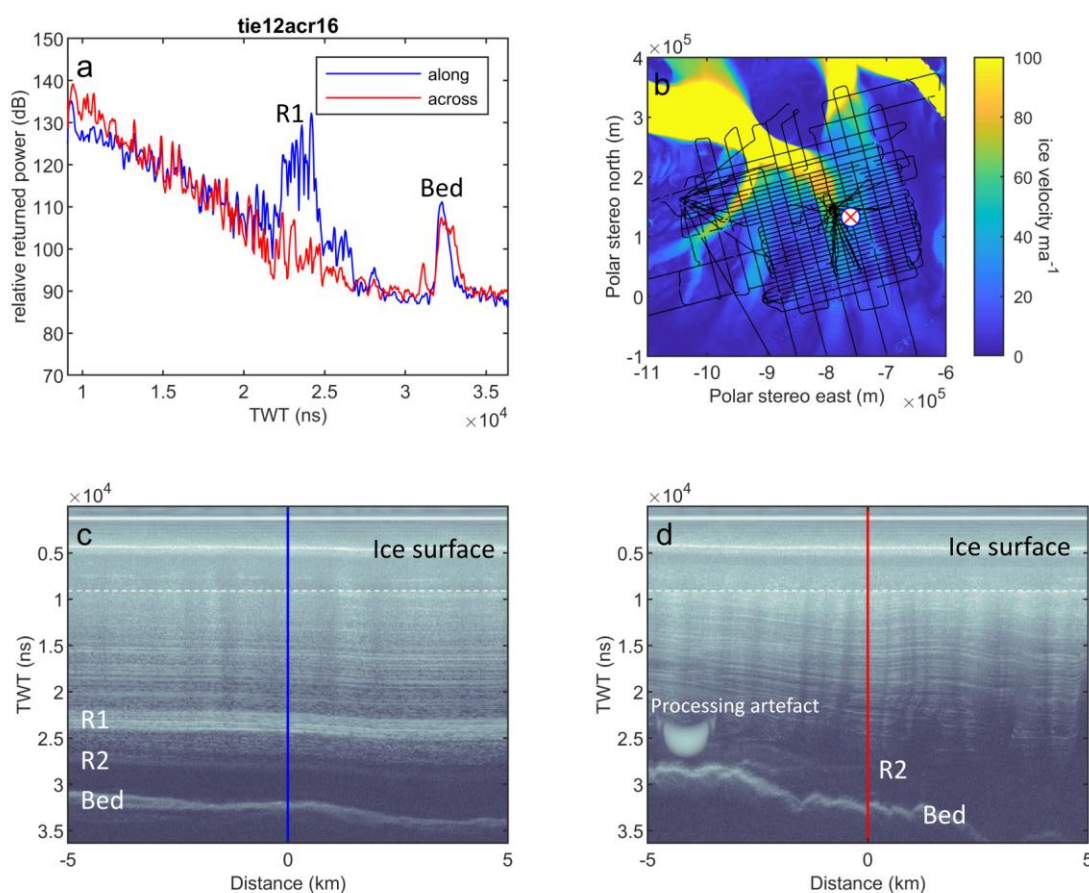


Figure 5. Englacial folds and ice flow of the IIS trunk: (a) RADARSAT image mosaic (Jezek et al., 2013) of the ice sheet surface of the IIS. Thick white lines show positions of radar data shown in 5c and 5d. Thin white line is grounding line (Rignot et al. 2011). The ice plain of the IIS is annotated; (b) mapped englacial fold axes (red dots) and prominent surface flow stripe (thick black line) mapped using RADARSAT and MODIS mosaics of Antarctica (Jezek et al., 2013; Haran et al., 2005), overlain on ice flow (Mouginot et al., 2019), IMAFI survey grid (thin black lines), and grounding line (thin white line) (Rignot et al. 2011). Thick white lines show positions of radar data shown in 5c and 5d; (c & d) radar data across the IIS trunk oblique to the flow stripe and ice flow, showing the subtle signature of the most apparent englacial folding (two black arrows) within the faster flowing trunk. The hand-shaped reflection (HSR) fold is the fold indicated by the right of two black arrows. A qualitative increase in basal reflectivity is apparent to the right of the HSR fold in both radargrams (indicated by two black arrows).



dashed redline. Figure 5. Englacial folds and ice flow of the IIS trunk: (a) mapped englacial fold axes (red dots) and prominent surface flow stripe (thick black line) mapped using RADARSAT and MODIS mosaics of Antarctica, overlain on ice flow (Mouginot et al., 2019), IMAFI survey grid (thin black lines), and grounding line (thin white line) (Rignot et al. 2011). Thick white lines show positions of radar data shown in 5b and 5c; (b & c) up-ice (b) and down-ice (c) radar data across the IIS trunk and perpendicular to the flow stripe and ice flow, showing the subtle, yet apparent, signature of englacial folding, including the hand-shaped reflection (HSR) fold (black arrows), within the faster flowing trunk.

A qualitative increase in basal reflectivity is apparent to the right of the HSR fold in both radargrams.



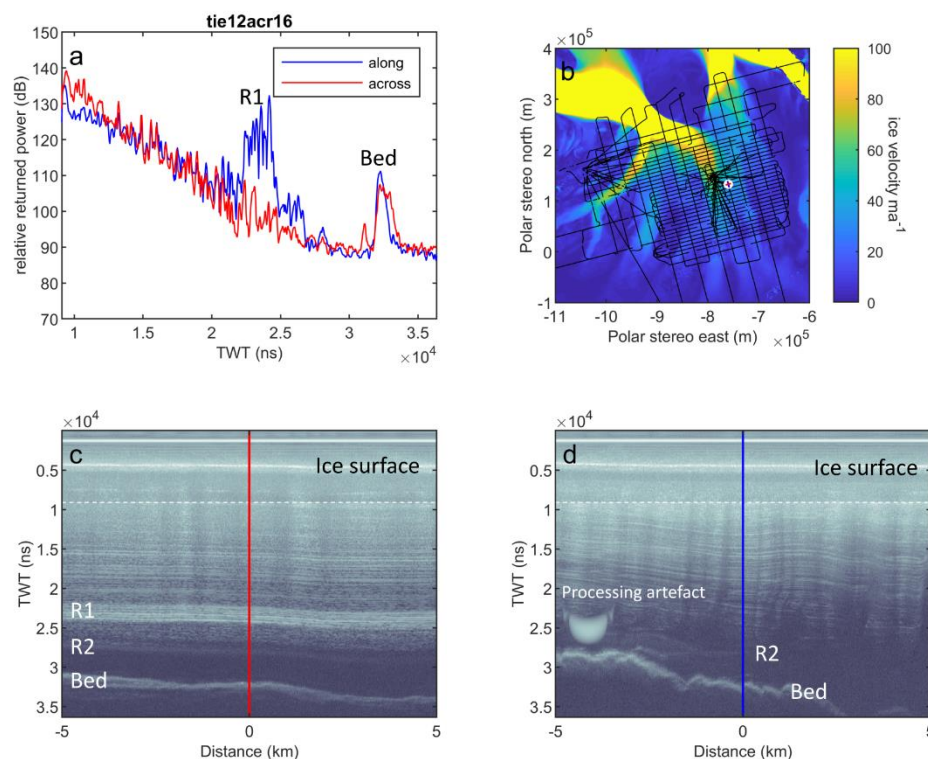


Figure 6. Example of the reflectivity of internal layering beneath Institute Ice Stream at cross over points: (a) relative returned power (dB) for eleven stacked 2D SAR processed traces (~ 100 m of radar data) along (blue) and across (red) ice flow. Reflection packages R1 and the bed of the ice sheet are annotated; (b) location of radar data crossover (white filled circle with location of across -red- and along -blue- flow), underlain by radar survey grid (thin black lines) and ice velocity (Mouginot et al., 2019), with colour scale saturated at 100 m s^{-1} . (c) radar data along ice flow. Ice flow is left-to-right along radargram. Cross-over with across ice flow radar data (Fig. 6d) shown with red vertical line. Blue profile in 6a is the returned power of the crossover trace stacked with 5 traces either side of this 'red vertical line' cross over location; (d) radar data across ice flow. Ice flow is into radargram. Cross-over with along ice flow radar data (6c) shown with blue vertical line. Red profile in 6a is the returned power of the crossover trace stacked with 5 traces either side of this 'blue vertical line' cross over location. Indistinct contrast to 6c, reflection package R1 is not imaged in these data. Along and across flow radar data (6c and 6d) were acquired with the same aircraft altitude, and therefore the same range to ice surface. This ensures that the geometry and anisotropy of the ice cannot be responsible for the pronounced anisotropy of the deep ice unit. White dashed lines in figures 6c and 6d define the boundary (200th vertical sample) between radar data SAR-processed (below line) and radar data not SAR-processed (above line). Information on SAR processing of the dataset is available in Jeofry et al., (2018a)

Figure 6. Example of the reflectivity of internal layering beneath Institute Ice Stream at cross over points: (a) relative returned power (dB) for eleven stacked 2D SAR processed traces (~ 100 m of radar data) along (blue) and across (red) ice flow. Reflection packages R1 and the bed of the ice sheet are annotated; (b) location of radar data crossover (red cross with white filled circle), underlain by radar survey grid (thin black lines) and ice velocity (Mouginot et al., 2019), with colour scale saturated at 100 m s^{-1} . (c) radar data along ice flow. Cross-over



with across ice flow radar data (Fig. 6d) shown with blue vertical line. Blue profile in 3a is the returned power of the crossover trace stacked with 5 traces either side; (d) radar data across ice flow. Cross over with along ice flow radar data (6c) shown with red vertical line. Red profile in 6a is the returned power of the crossover trace stacked with 5 traces either side. In distinct contrast to 6c, reflection package R1 is not imaged in these data. Along and across flow radar data (6c and 6d) were acquired with the same aircraft altitude, and therefore the same range to ice surface. This ensures that the geometry and anisotropy of the ice cannot be responsible for the pronounced anisotropy of the deep ice unit. White dashed lines in figures 6c and 6d define the boundary (200th vertical sample) between radar data SAR-processed (below line) and radar data not SAR-processed (above line). Information on SAR processing is available in Jeofry et al., (2018a).