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The Cryosphere Discussions

# *Interactive comment on* "Large-scale englacial folding and deep-ice stratigraphy within the West Antarctic Ice Sheet" *by* Neil Ross et al.

**Anonymous Referee #1**

Received and published: 10 December 2019

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.

Specific Comments:

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

- 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.

- 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.

- 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.

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

- 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.

- 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 wich lateral boundary (I guess in the center - parallel to K'K and J'J)?

- 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.

- 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).

- 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.

- 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.

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

-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.

- 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-faceof basal hills. One can imagine that if locally basal freeze-on exists, then the plume of accreted ice pushing into the ice columne might act as an obstacle to the meteoric ice flow.

- 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.

- 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.

- 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 pusing up the entire ice column - with the vertical distance between the layers diminishing.

- 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?

- 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.

- 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?

- 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".

- 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.

- 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.

- 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.

- 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.

- 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).

- 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.

- 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).

- 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?

- 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.

- 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.

Technical corrections:

- Caption 2: Line 2 - "ubiquity and widespread" is this not the same message? - Caption 2: Line 2 - band of ice-layers rather than "deep-ice layers" - Caption 2: Line 4 - "thin black line" of grounding line is not easy to differentiate from the "thin black lines" of the survey grid. - Caption 2: Line 5 - "bifurcation of R2 into 3-4 layers" happens also earlier

around 50 km. - Caption 2: Line 5 - in (c) mention tie line 9 as used in Figure 4 and supplementary figures. - Caption 2: Line 6 - replace "show" with "shown".

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

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