Brief Comment: Revealing the former bed of Thwaites Glacier using sea-floor bathymetry
Submitted to The Cryosphere Discussions
Commenter: Nicholas Holschuh

The authors present an incredible data set capable of characterizing both the large-scale, morphometric controls on Amundsen Sea circulation as well as the fine-scale morphology of the sea floor downstream of Thwaites and Pine Island Glaciers. These data will undoubtedly improve our ability to model ocean forcing of glacier change and provide an analogue for understanding the subglacial environment of Thwaites glacier. I've spent a fair amount of time thinking about bedforms under Thwaites, and really enjoyed reading the analysis presented here – I only have a brief set of comments for the authors, in an effort to clarify their (a) characterization of the landscape so readers like me can learn to see the same features they do and (b) interpretations of the landscape, to make clear what aspects of the morphology are *definitive* indicators of physical properties, and which are just assumed to be (but not yet proven to be) bedrock/sediment/water-carved/gravity-flows/or glacially reworked.

Lines 185-218: I appreciate the thorough description of landforms here, but often found it hard to link the text to the figures (and differentiate landforms) the way the authors did. I understand that looking at these things is interpretive, and at times as much an art as a science, but I think it would be helpful if the authors put forth an image for a type example for each of the described features. Crag-and-tails, glacial lineations, grooves, gulleys, channels, troughs, grounding-zone wedges, slide scars, crescentic scours; linking them to the figures is often very challenging, and figuring why one elongate feature is called a groove and one a lineation in these data is often difficult to do. When I was faced with my own data from swath radar under Thwaites, trying to differentiate features, I really wished I had a clearer articulation in the literature of how others defined features in their data from morphology alone.

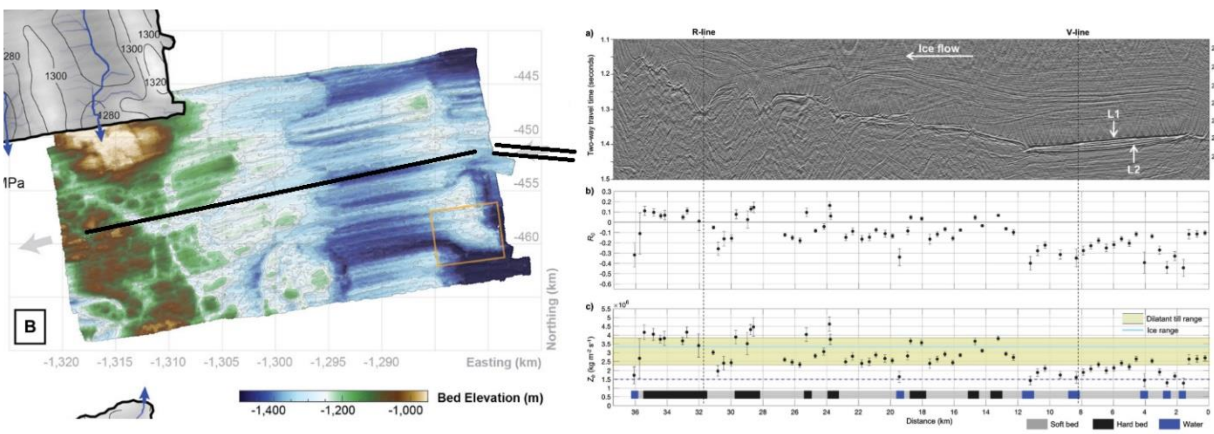
Lines 195-197: These moats are gorgeous, and really interesting to think about. In the reviews of our swath radar paper at Thwaites (Holschuh et al., 2020), we were challenged on the interpretation that they must be carved by water, and have spent a fair amount of time since thinking about that problem. There are reasons to believe that ice might be the primary actor here. Is there a reason you only mention meltwater and till slurries, when Graham and Hogan list "meltwater erosion, erosion by a saturated till slurry, or the direct action of mobile basal ice"?

Lines 477-480: What specifically indicates that flat-topped surfaces are erosional? Given that tablelands have been described in many places under Antarctica (as far back as Drewry 1975), I think more evidence might be required to call them planed-off. In general, features that act as ice rises are thought to have been areas of uniquely low erosion rates (Matsuoka et al., 2015). The fact that they interrupt deep glacial troughs seem to imply that those features are in fact more resistant than their surroundings. I would just like more (or clearer) evidence before arguing there is some new, unique positive feedback here, distinct from existing discussion of erosion / ice-flow feedbacks (e.g., Kessler et al, 2008).

Lines 493-495: This was a problem we were having comparing swath radar data with the terrestrial record – sediment in-fill of crescentic features was making it hard to evaluate their true depths in the paleo record. Definitely interesting to see the same challenges here!

Line 509: Again, it seems unlikely that (after all of Antarctica's growth and retreat cycles) we might catch a very transient pinning point now. Doesn't it seem more parsimonious that there is no such thing as a particularly weak pinning point? Either that, or the authors should expand on the idea that erosion of pinning points requires ungrounding (maybe higher velocities in ice shelves/ice rises, as opposed to fully grounded ice are required to erode the underlying pinning point, or slump events are a required precursor, and so this feedback is unique to ice rises as opposed to the general erosion/ice flow feedback already described in the literature).

Line 532-533, 537-539, and 544-545: Without seismic data or rock cores, I do not think you have the data required to validate Muto et al.'s work (although I do think it has interesting implications for your data set). Muto was looking at features within a region of the Thwaites bed that, if interpreted morphologically, would have been assumed to be uniformly hard bedded. Below, you can see a figure from our swath radar paper (Holschuh et al., 2020), that shows that the bed looks like in the vicinity of Muto et al.'s seismic line:



You can see the upstream region, characterized by crag-and-tails and MSGL, is uniformly weak in the seismic data. It is in the downstream half of the Thwaites grid that is described in detail by the authors, showing that (in a region that might be interpreted as uniformly hard by the morphology alone), the lee and stoss sides of bed features show variable bed properties. I think the only way to actually validate the Muto et al. study is to look in more places with coincident high-resolution morphological data and acoustic property or rock property measurements, it is not possible to validate or contradict their results with morphological data alone.

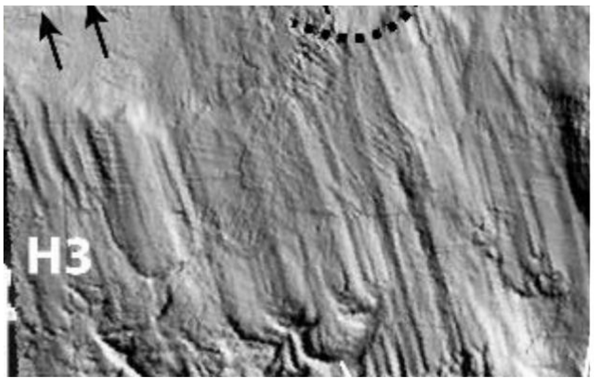
Line 563-564: I have always been jealous of how nice multibeam data look – you are right that conventional radar sounding and seismic sounding can't compare. But swath radar data are finally giving sea-floor observations competition! I know you mention the substance of the Holschuh et al., 2020 paper below, but some of the predecessors deserve mention here. (Paden et al., 2010; Jezek et al., 2011).

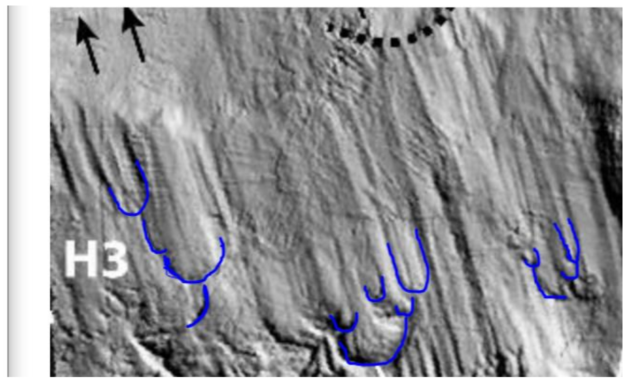
Line 566-567: Again, I'm not sure you have the data required to do more than assume variability in bed type.

Line 591-594: I worry that there is something that I missed– do you have direct observation of substrate type from acoustics or coring? If so, that needs to be described in more detail, because I really think Muto et al., 2019 cannot be validated without them.

Lingering Questions:

Because we are interested in moats generally, we noticed a commonality between your data and our swath radar data at Thwaites. Moats on the leading edge of bedforms often meet exactly at the center of a downstream mot, at the head of a new bedform. I find this to be a really curious pattern – any thoughts on why this might be the case?





As one last note – due to the highlands you've pointed out (H1/H2/H3), the main trough and pathway for CDW to route in toward the ice-sheet terminus is actually to the true west of the modern Thwaites shelf. Do you have any thoughts on what implications that has for Thwaites retreat? It looks as though there are available high-spots for shelf regrounding to the west, but perhaps the Thwaites tongue was never resilient enough, given its closer proximity to this CDW pathway? I think some more discussion of the oceanographic implications of these data could be a really useful addition.

These data are really phenomenal, I look forward to all the science they enable.

References:

Drewry, D.J., 1975, Radio Echo Sounding Map of Antarctica, (~90°E-180°): Polar Record, v. 17, p. 359–374, doi: 10.1017/S0032247400032186.

Holschuh, N., Christianson, K., Paden, J., Alley, R. B., & Anandakrishnan, S. (2020). Linking postglacial landscapes to glacier dynamics using swath radar at Thwaites Glacier, Antarctica. *Geology*, *48*, 1–5. https://doi.org/10.1130/g46772.1

Jezek, K., Wu, X., Gogineni, P., Rodríguez, E., Freeman, A., Rodriguez-Morales, F., & Clark, C. D. (2011). Radar images of the bed of the Greenland Ice Sheet. *Geophysical Research Letters*, *38*(1), 1–5. https://doi.org/10.1029/2010GL045519

Kessler, M.A., Anderson, R.S., and Briner, J.P., 2008, Fjord insertion into continental margins driven by topographic steering of ice: Nature Geoscience, v. 1, p. 365–369, doi: 10.1038/ngeo201.

Matsuoka, K., Hindmarsh, R.C.A., Moholdt, G., Bentley, M.J., Pritchard, H.D., Brown, J., Conway, H., Drews, R., Durand, G., Goldberg, D., Hattermann, T., Kingslake, J., Lenaerts, J.T.M., Martín, C., et al., 2015, Antarctic ice rises and rumples: Their properties and significance for ice-sheet dynamics and evolution: Earth-Science Reviews, v. 150, p. 724–745, doi: 10.1016/j.earscirev.2015.09.004.

Muto, A., Anandakrishnan, S., Alley, R. B., Horgan, H. J., Parizek, B. R., Koellner, S., … Holschuh, N. (2019). Relating bed character and subglacial morphology using seismic data from Thwaites Glacier, West Antarctica. *Earth and Planetary Science Letters*, *507*, 199–206. https://doi.org/10.1016/j.epsl.2018.12.008

Paden, J., Akins, T., Dunson, D., Allen, C., & Gogineni, P. (2010). Ice-sheet bed 3-D tomography. *Journal of Glaciology*, *56*(195), 3–11.