

## **Reply to the reviews of Anonymous Referees 1 to 2 on our manuscript " Paleo ice flow and subglacial meltwater dynamics in Pine Island Bay, West Antarctica "**

We thank all reviewers and the editor for their constructive comments and edits. We were able to address all their points, which lead to significant improvements of our manuscript.

Here we address the comments of both reviewers, including language and clarifying the sentences.

### **Detailed reply to comments by reviewer #1:**

With regard to considering more options for the origin of the basin to be discussed (geology, ice erosion), we expanded on possible origins/controls of the large basins.

p 4269: line 2:

*Comment:* it is "mainly" instead of "most" of the WAIS

*Response:* We changed "mostly" to "mainly"

p 4269: line 10:

*Comment:* as recently observed under?

*Response:* We changed the sentence accordingly, adding "observed".

P 4270: line 17:

*Comment:* Can the authors provide a few more details on the cosmogenic surface exposure ages – what dates, when was thinning greatest, do these agree with the marine dates?

*Response:* So far there are only few published dates. The available dates confirm the marine dates, but don't provide much additional detail, e.g. on episodes of higher or lower thinning rates. We provide this information for completeness and to confirm that the overall picture seems consistent with the different methods. To clarify we have changed the text to "And cosmogenic surface exposure ... yielded a record of progressive ice thinning for the last ~14.5 ka BP that is consistent with the marine record, although so far the few available dates do not provide much detail of variations in thinning rates or different episodes of thinning of the Pine Island-Thwaites drainage basin (Johnson et al., 2008)".

p 4271, line 1:

*Comment:* I find this sentence quite difficult to follow and therefore perhaps needs a re-write. Otherwise, I am not sure if it is needed at all.

*Response:* We rewrote the sentence to make it clearer.

p 4273, line 20:

*Comment:* I am not sure if a striation is a useful term to use in this context as the authors are referring to a different scale of bedform. I would just stick to grooves or gouges as has been referred to in the past.

*Response:* We deleted striations to avoid confusion about the terms

p 4274, line 9:

*Comment:* Refer to Fig. 7.

*Response:* We added a reference to Fig 7

p 4275, line 10-11:

*Comment:* You refer to the undulating profile in the sentences below, so suggest: and are 200-400 m deep, 1-2 km wide and 10-15 km long.

*Response:* We have changed the text following the reviewer's suggestion.

p. 4277, line 5:

*Comment:* Or is it a composite signal of the ice stream shifting around?

*Response:* We think it is unlikely that the observed lineations were created by shifting of the ice stream location, because it is more likely to stay in the main trough, and older lineations would be overprinted by newer ones. However, we cannot completely rule out that ice stream shifting occurred and thus have added "or, less likely, shifted their location" to the text.

p. 4277, line 17:

*Comment:* The authors could refer to the review by Livingstone et al. (2012) in Earth-Science Reviews for some of these gross Antarctic comparisons.

*Response:* We replaced the list of references here with "(s. Livingston et al. 2012 for a review).

p. 4278, line 3:

*Comment:* in Fig. 2 the topography seems to have a series of smooth zones in-between rugged lineated substrate. This might hint at buried basins – especially given Fig. 6, which should be referred to at this point. Is there other acoustic data in this region, which would help support or disprove a buried basin-channel network?

*Response:* We have added a reference to Figure 6 here and added a note that the smooth morphology of the bottom of other basins suggests that they might also be partly filled by sediments.

P. 4278, line 18:

*Comment:* Or bedrock poking through the sediments?

*Response:* Figure 3e does show some bedrock sticking out in places. But here we refer to the elongated, very smooth ridges marked as GL. Their shape and appearance are more similar to features formed over sediment substrate than hard bedrock outcrop. We have added text "which closely resemble sedimentary features of the mid- and outer shelf areas" to make this clearer.

P. 4279, line 24-25:

*Comment:* The section on the retreat since 11 ka BP could probably go in a separate sentence to help distinguish between the modern observed record and that delineated by marine cores.

*Response:* To distinguish modern observed record better from the marine record we joined the statement about the 11ka BP retreat with some earlier text that describes earlier parts of the marine record.

p. 4279, line 25:

*Comment:* a stable grounding line. Could this relatively stable position be a function of a change in slope gradient (depths shallower than area 2 – p4272)? Or does the trough narrow at this point? Maybe worth expanding on possible mechanisms (as you start doing in L19-21).

*Response:* There are again different mechanisms that could have keep the grounding line stable. One is that the main trough is more confined in the inner Pine Island Bay by shallow sides (fig. 2). Another possibility is that ridges like the one described by Jenkins et al, 2010 act as a pinning line. We don't really observe much of a slope gradient. We have included the text ", which could be caused by buttressing from the surrounding land (Fig. 1) or by pinning on the shallower ridges in this area (Jenkins et al., 2010)" to point these options out in the text.

p. 4280, line 14-15:

*Comment:* Could channelization of meltwater along discrete portions of the bed not also maintain slow ice-flow (as opposed to broad sheet-flow)? Could also relate the spatially variable bed signature to research that has been done on sticky-spots.

*Response:* We agree. In general we would expect that channelized meltwater flow could leave the majority of the bedrock between channels dry and thus reduce lubrication and result in slow ice flow. On the other hand, the large channels might indicate the presence a significant amount of meltwater. If not all the meltwater drained trough the channels, there might have been enough to lubricate parts of the ice stream. We have added ", if not all meltwater drained through the channel system" to the text to clarify this.

p. 4280, line 24:

*Comment:* mechanism (without the s)

*Response:* We removed the 's' at the end of 'mechanism'

p4281, line 3:

*Comment:* Why alternatively? Could water films (and shallow canals) develop when the sediment is no longer able to transmit all the meltwater downstream. See Noormets et al. (2009) for a detailed discussion.

*Response:* We did not intent to describe an exclusive (one or the other) option, just another possible mechanism. Most likely both options played a role. To avoid this misunderstanding we changed "alternatively" to "In addition" and added the reference (Noormets et al. 2009).

p. 4281, line 19:

*Comment:* I find it interesting to think how these basins formed in the first place as well? Especially as they are also observed elsewhere around the continental shelf. Is there a geological control, and is it meltwater erosion or focused bedrock erosion (or both)?

*Response:* While we don't really know the formation process of these basins, it seems likely that these basins have formed by a combination of "overdeepening" processes and meltwater activity. A good review of possible formation processes just published by Clark and Swift (2012) has been added, along with a statement in section 4.4 on meltwater flow and channel development.

p. 4281, line 25:

*Comment:* And frictional heating due to rapid ice flow.

*Response:* Following the reviewers suggestion, we have added "and frictional heating due to rapid ice flow" to the text.

p. 4283, line 4-6:

*Comment:* But as the floors of the basins are sometimes lineated could erosion by ice also have aided enlargement/formation?

*Response:* The main point here is that meltwater contributions to the channel/basin formation are most likely caused by episodic flow rather than continuous flow. Other factors like ice erosion most certainly played a role, as stated in other parts of the text. We have changed the text to "... "... meltwater involved in forming of the observed large basins and channels was produced ..."

p. 4283, line 13:

*Comment:* delete indicates

*Response:* Done.

p. 4283, line 17:

*Comment:* similar channels and basins instead of similar features

*Response:* We have changed the text to "similar channels and basins"

p. 4284, line26:

*Comment:* The authors do not just refer to meltwater networks on the Antarctic Shelf.

*Response:* We changed this to "Antarctic meltwater networks" and deleted the non-Antarctic meltwater examples (s. response to next comment).

p. 4285, line 4-9:

*Comment:* I find this section and especially the choice of references a bit odd here. The authors refer to only one example of a bedrock channel in North America, but do not mention the influence it has on ice-dynamics. A broader review of the meltwater channel geometries beneath the North American and European ice sheets would be more appropriate here. The Boulton and Hagdron (2009) reference refers to modelling of the British-Irish Ice Sheet, not terrestrial evidence of subglacial meltwater flow. Suggest deleting or expanding.

*Response:* Our intention was to show that those channels also occur outside of Antarctica. Since a broad review of meltwater channels in the Northern Hemisphere would be outside of the scope of this paper we deleted this segment.

p. 4285, line 9-11:

*Comment:* It would be interesting to discuss this further, in terms of channel formation mechanisms.

*Response:* We added more details of formation mechanism proposed by Lewis et al 2006 in the text as "through erosion by fast-flowing subglacial meltwater during multiple flow events".

p. 4285, line 19:

*Comment:* Analogous

*Response:* Changed 'Analogue' to 'Similar to the proposed ...'

Figures:

Fig. 2:

*Comment:* I find the red annotations to be extremely difficult to see. Perhaps a white colour would stand out better?

*Response:* We changed the coloring of the labels from red to white or black to make them better readable.

Fig. 6:

*Comment:* This figure needs explaining in more detail in the caption. I think the right hand panel should be on the left as it highlights the physiography of the region imaged. What are the dotted black lines? Instead of two-way travel time can this be converted to a depth scale?

*Response:* We switched the order of (a) and (b), added labels in NW and SW direction and explained the dotted lines. We prefer to keep the vertical scale in TWT since seismic velocities in the sediments and underlying basement are not known. Instead we added an approximate scale bar with an explanation in the caption that this would only apply to 2000 m/s for sediment.

Fig. 7:

*Comment:* Is this a generalized map of the mapped features? The basins are difficult to make out with the light blue - maybe try a different colour. It is also interesting to note the channels cutting across the basins. This is not mentioned in the text, but is an interesting feature, which perhaps deserves a comment.

*Response:* We changed the coloring of the features to make the basins more clearly visible. And added a note to the figure captions about smaller channels cutting into the main basins.

### **Detailed reply to comments by reviewer #2:**

*General comment:* Most of the figures are both necessary to the story and clearly explained. With that said, most of this data has been previously published in smaller pieces and is simply compiled and integrated here. Thus, most of my suggestions below are focused on better development of the literature review and citations of other work.

*Response:* This paper does build on previous work by adding a significant amount of new data. There is a large amount of new multibeam bathymetry data, seismic data from the inner shelf that has not previously been published in this detail. The subbottom data have

been worked up as part of a term paper but not published in the general literature. The earlier work by Lowe and Anderson 2002, 2003 is based on cruises NBP9902 and NBP0001 and describes the basins and channels that they observed, but they did not have the data to find and describe the network of these features and the relationship between them.

We now summarize and highlight the previous work better to clarify this. We have modified the text accordingly and added an inset to figure 2 emphasize the differences in data coverage.

p. 4268: Line 25:

*Comment:* Understanding behavior of past ice streams as a way to understand future behavior has been stated goal of many papers. Why pick these particular two papers to cite?

*Response:* We are aware of many papers on this topic, but wanted to limit the number of references in the manuscript to overview papers. Stokes and Clark, 2001 is a good review while Vaughan and Arthern provide a good summary of why understanding ice streams is critical for understanding possible future ice sheet behavior. To broaden the coverage we have added two additional review papers Anderson et al 2002 and Livingston et al. 2012, which focus more on the Antarctic shelf.

p. 4269: Line 2:

*Comment:* Is most of the WAIS really grounded below sea level? Or, just a lot? Can a % be cited?

*Response:* We changed 'mostly' to 'mainly' (as reviewer #1 suggested). The area with grounded ice below sea-level is probably 55% - 65% of the WAIS according to our estimates, but we didn't find an accurate value to cite. Mainly because defining the boundary between EAIS and WAIS is a tricky problem, which most studies avoid.

p. 4269, Line 10-11:

*Comment:* Explain the end of that sentence.

*Response:* added observed (s. rev#1)

p. 4269, Line 16:

*Comment:* Retreated "considerably." How much?

*Response:* To avoid confusion of this statement, which did not contribute much to the manuscript, we deleted it here.

p. 4269, Line 28:

*Comment:* Retreat dates cited without any reference. The retreat dates and discussion of cores need to be better explained and better cited throughout paper. Understood this paper only geophysics. But, if want to call on cores as additional evidence, need to do it more thoroughly. As it is, core information is just tossed in as a crutch, without being developed. In this particular location the retreat dates are cited with no reference at all.

*Response:* The goal of the dates here was simply to provide a general time frame for the LGM and not to provide specific dates for the retreat history.

The dates cited are from Lowe and Anderson 2002, and Kirshner et al 2012 and have been moved from the end of the paragraph to the end of this sentence for clarifications.

p. 4270: Lines 5-15:

*Comment:* Cite Lowe and Anderson and explain original dates vs. newer dates. (Line 14: "Respectively" not need there, but it is at end of sentence.)

*Response:* This paper does not introduce any new dates, but uses existing dates and sediment core information to place the described bathymetric features into a chronological context (as much as possible, i.e. the sparse dates allow). The original dates from Lowe and Anderson are consistent with the updated interpretation described in Kirshner et al: ~16k BP for leaving the outer shelf and a stop of the retreat near Burke Island around ~12k BP. We have added the Lowe and Anderson ref to the reference list here.

p. 4270, Line 24:

*Comment:* Mention of subglacial substrate not given context or explanation or reference.

*Response:* We have added a sentence describing substrate changes with references: " The change in seafloor morphology is linked to changes in subglacial substrate from crystalline bedrock to sediment (Wellner et al., 2001; Lowe and Anderson, 2002)" and added a brief explanation of the consequences: ' as lubricated beds and sediment substrate tend to allow faster ice flow whereas dryer beds exposed bedrock results in higher bed friction'.

p. 4271: Line 24-25:

*Comment:* What does that sentence mean?

*Response:* The maximum penetration depth, which can be interpreted as thickness of consolidated sediments, was digitized manually. We added some text to clarify this.

p. 4271, bottom:

*Comment:* the other cruises from which swath data is being used also collected subbottom data. Explain that only certain cruises are being used, but others also collected.

*Response:* While we are aware that other cruises collected some subbottom data in this area as well, those data were either not available for this study or of much poorer quality. We added some text to clarify this.

p. 4273: Line 2-10:

*Comment:* Why alternate from drumlin-shaped ridges, then drumlinoids, then later drumlins? If they are being used to mean different things, explain. Otherwise, be consistent.

*Response:* To make it more consistent and avoid confusion we have changed all occurrences to drumlin-shape.

p. 4273, Line 16-18:

*Comment:* Again, the core date is totally unexplained and just tossed in. If want to mention sediment information, it needs to be much more developed.

*Response:* We added the sentence ". The occurrence of diamicton in such shallow depth also indicates that some of these features were formed subglacially" to explain the significance of the sediment information. However further development of such data is beyond the scope of this paper and we refer to the cited references for this.

p. 4275: Line 4-7:

*Comment:* Give context for cores, explain and develop.

*Response:* We mention these cores here because they are consistent with our interpretation that some of these basins contain unconsolidated sediment, which have been deposited after grounded ice left the basins (otherwise the sediments would be more consolidated by the overriding ice). We added the explanation: "This suggests that these pockets of unconsolidated sediment have been deposited after grounded ice retreated from these basins" to the text. Other details of the cores are described and discussed in the cited Ehrmann et al. 2011.

p. 4275, Line 20:

*Comment:* Is the core number from Lowe and Anderson important? Why do we need to know it was PC46? It would be much more helpful to know location, or length, or more than just "it was consistent" and what number it was.

*Response:* We use the naming convention established in other publications, to which we refer for details (PC46 is also used as label on the map (Fig. 2)). We rearranged the text and added the details about the core that are relevant for this paper here, e.g. that the top gravel and sand unit was ~0.5m thick. Other details can be found in the reference Lowe and Anderson 2003, where the core is described in detail.

p. 4276: Line 9:

*Comment:* Why "must" the sediment be of post-glacial origin? Explain, don't just make claims.

*Response:* We added an explanation in the form of " most of these sediment layers visible in the PARASOUND data are probably sands, silts, and mud that have not been consolidated by overriding ice and therefore likely to be of post glacial origin"

p. 4277: bottom:

*Comment:* Could a figure show previously published data limits and highlight the new data? Or, show the Lowe and Anderson zones? Hard to follow the discussion of differences in the new compilation with just the figures here.

*Response:* We have added an inset to figure 2 that shows the previously published data (and thus the amount of new data that is the focus of this study) and that also shows the zone boundaries by Lowe and Anderson.

p. 4283: 4.4 header:

*Comment:* "flow events" too vague. Give clearer header.

*Response:* We changed the header to "Timing of meltwater flow and channel development".

Figure 5:



*Comment:* Needs to be darker to be seen.

*Response:* We increased the contrast and darkened the image as recommended.

Figure 6:

*Comment:* Seismic line should have NW and SW labels.

*Response:* We switched the order of (a) and (b), added labels in NW and SW direction and explained the dotted lines. We prefer to keep the vertical scale in TWT since seismic velocities in the sediments and underlying basement are not known. Instead we added an approximate scale bar with reference in the text that this would only apply to 2000 m/s for sediment.

Figure 7:

*Comment:* Very interesting and I would like to study details, but can't see the difference in the colors.

*Response:* AS noted above we have changed the coloring of the features to make the different features more clearly visible.