The authors' replies on the comments are written in red, bold and italics

Review: Olsen *et al.*

Last Glacial ice-sheet dynamics offshore NE Greenland – a case study from Store Koldewey Trough.

This manuscript presents a mix of new and previously published (by the co-authors) geophysical, geomorphological and sediment core data from the continental shelf off NE Greenland – a region for which we have limited knowledge of ice extent, behaviour or retreat dynamics at and following the last glacial maximum. This sector merits investigation since it is presently drained by the largest ice stream in Greenland whose geometry is unusual and driving mechanism not well understood; it has a broad continental shelf (space to accommodate significant expansion) dissected by troughs (past ice streaming, potentially with a rather different regime to today); and ice-ocean feedbacks through deglaciation are potentially important/variable given the location near the zone of exchange between Atlantic and Arctic waters.

A large part of the geophysical data has been previously published (Laberg et al. 2017), and it should be made more explicit in this manuscript that mapping and interpretations from these data is not new (or should highlight explicitly if earlier interpretations are revised here). The mid-shelf dataset is, as far as I'm aware, new, as are the core data and interpretations.

I would contest some of the landform interpretations (detailed below) and think the sedimentological interpretations could be more specifically discussed with reference to both the authors' analyses and the literature. The Discussion is rather weak and the structure hops around from paragraph to paragraph, without building a sound argument that draws on the evidence presented or rigorously examines the literature. Potentially interesting themes (for example, drivers of retreat; role of melting vs calving; effect of bed slope) therefore aren't fully developed.

There are a handful of grammatical errors in the manuscript (largely subject – verb agreements). Figures are all well put together, but I am not sure that all of figs 8, 9 and 10 (interpretative figures) are required.

We included the data set from Laberg et al. (2017) into this manuscript with the purpose of improving the regional understanding of the bathymetry of Store Koldewey Trough. We have clarified what part of the data that is previously published by Laberg et al. (2017). As part of the inclusion, we have re-interpreted the published data from the outer shelf in greater detail.

We have restructured and rewritten the discussion chapter, by adding new paragraphs as well as reorganizing existing paragraphs. New paragraphs focus on possible drivers of retreat, the role local trough topography may have had on the retreating ice front, as well as calculations on GZW volumes and the relative length of time of grounding line stabilization.

We removed figure 10, a schematic landform-assemblage model for Store Koldewey Trough.

Interpretations

Sediment cores:

- You refer to grain size and sorting characteristics but present neither for the diamict units (or even diamict matrix) and no sorting data for any unit. Similar for clast count/abundance. ***When mentioning clast amount we refer to the relative abundance, based on visual observations in the X-ray images. We refrained from presenting clast counts as we regarded this irrelevant in the context of the current paper, as it lacks absolute chronologies.***

- How consistent is your interpretation of meltwater plumes & underflows with the characteristics of meltwater sediment facies reported elsewhere (eg Witus et al 2014, Smith et al 2017, Prothro et al 2018)? ***We think that our interpretation is consistent with the mentioned publications, given the data available.***

- The explanations offered for a lack of IRD in an ice-proximal setting (facies 4 vs 3) all assume an ice shelf wouldn't have any basal debris. Examine whether that is valid here. ***We have not excluded the presence of IRD in an ice shelf. However, we have provided possible explanations for an absence of IRD in such a setting and moved the previous suggestions in chapter 4.1.2 (Facies 4) to the discussion chapter (chapter 5.2 Glacial dynamics during deglaciation).***

Landforms:

- This section should make clear that the outer block of multibeam has already been reported on and interpreted by Laberg et al 2017 and isn't new here. I suggest this is acknowledged explicitly, or state that the earlier reported assemblages are re-interpreted here if that is the case (and in which case, why?). ***In the revised version of the manuscript we mention that the data set from the outer shelf has been published by Laberg et al. (2017), however, we have re-interpreted the data set in greater detail.***

- I question the 'megascale' interpretation of lineations in the mid-trough data. They are rather few, sparse, short and individually distinct compared to a more typically dense ridge-groove arrangement (such as those on the outer shelf shown in the Laberg paper). ***We understand the reviewer`s point. However, we keep our suggestion that the landforms are fragments of/partly buried MSGLs, because the lengths/width ratios exceed 10:1 (cf. Clark, 1993).***

- I am not convinced by the examples given of distinct differences between the interpreted recessional moraines, crevasse-squeeze ridges and multi-keel ploughmarks (and the consequent interpretation that they are formed by different mechanisms/in different environments).
  - In Fig 6, I see little difference between the recessional moraines that are slightly irregular (i.e. branch/merge, where part of the grounding line has retreated while pinned elsewhere) and the labelled CSRs. Similarly, the sinuous and (?) composite form of the curvilinear, transverse to ice flow ridges in 6B (interpreted as due to ploughing by icebergs) have the same kind of size and form as curvilinear ridges due to push at the grounding line (i.e. moraines). Most of the supposed ploughmarks in 6B seem to lack an 'inbound' scour that leads to the transverse ridge.
  - All three of these types are distributed throughout the assemblage. Is it not a simpler explanation that moraines are formed by push at the grounding line, and that spatially differential push (small differences in sediment mobility) will create a sinuous and potentially complex product? Three different landform types require fundamentally different ice flow dynamics or environments – how can these be reconciled in this setting?
  - E.g. Ploughing by icebergs requires a fundamentally different environment and time period to grounded, coherent ice approaching the grounding line. What strong evidence is there that these ridges were ploughed in front of (an) iceberg keel(s) rather than pushed up at the grounding line?
  - E.g. Moraines are interpreted here as a product of slow, steady retreat with repeated pauses. Crevasse squeeze ridges, on the other hand, are interpreted as infill of crevasses at the end of a fast flow episode, and the ridges are implicitly synchronously formed rather than in sequence. Yet these two landforms and dynamic interpretations intermingle. At least a discussion of this problem is warranted.
  - If moraines and CSRs are argued to be present here, then mapping them in the same class (same colour) is misleading.
  - Wedge C (? – mid Fig 4 – suggest label wedges A-D where appropriate on Figs 4&5) is superimposed by both (?) moraines and CSRs. Given that wedges are typically associated with prograding debris flows at the grounding line, moraines by local push, and CSRs by basal crevasse infill, how do you reconcile (dynamically) the three being formed on

top/immediately adjacent to one another?
We appreciate the extensive comment of the referee! Based on that, we revisited the data set and changed our interpretations from crevasse-squeeze ridges and multi-keel ploughmarks to saw-tooth moraines. Therefore, we rewrote the part of the result chapter regarding these specific landforms as well as the following discussion chapter.

Discussion:

- The non-topographically controlled (rather, exceeding topography) aspect of ice stream onset/source is under-developed. What amplitude topography does the ice stream have to override – what ice thickness would ignore a tendency to funnel either side of the higher ground (and is this a reasonable thickness)? Does SKT contrast with other troughs along the coast that are fjord-fed? Could this explain why it might exhibit a different style of retreat to 'typical' troughs? (I note that Laberg et al have already made this interpretation.) ***We have elaborated on this topic by providing information on the altitude that the Storstrømmen Ice Stream had to overcome to drain into Store Koldewey Trough (single peaks of 500-900 m), complimented with modelling results of paleo-ice sheet thickness on Germania Land during LGM (1000-1500 m; Fleming and Lambeck (2004) and Heinemann et al. (2014)).***

- Regular/many grounding line landforms are interpreted as a product of slow retreat. Why *slow*? Retreat proceeds in steps, yes, but is there independent evidence that these steps occurred slowly? The start of section 5.2 rather treats wedges and moraines (of quite different sizes) as providing the same sort of information: that the ice margin was stable "for a sufficient period" or "had a considerable flux" to build the landforms. I think this passage should explore the basis for "slow" retreat or prolonged standstills, and explain how this model of retreat fits with the later interpretation of surging. ***The terms "slow" and "episodic" retreat have been introduced by both Ó Cofaigh et al. (2008) and Dowdeswell et al. (2008) discussing styles of ice retreat accompanied with the formation of recessional moraines and grounding zone wedges, respectively. We wish to continue using these terms and have, therefore, rephrased the paragraph, hopefully making our use of terms more clear to the reader.***

- Arguments for drivers of retreat are muddled.
  - Laberg et al reject the hypothesis of retreat driven by sea level rise, yet here, based on the same data, you favour it. Why? I'm not convinced by the arguments for either (I don't think you have enough data), but they should be more rigorously discussed. If grounded ice is thick (which you argue for based on it passing over Germania Land) and its lateral extent is curtailed by the continental shelf break rather than because it is supply-limited, then it may be more resilient to sea level rise – the argument here is that a rise should cause ice to go afloat and the grounding line to make a large back-step, but this is contingent on ice thickness being close to the buoyancy threshold, and the bed topography allowing for such a back-step (difficult if landward-shallowing). On page 9, in fact, you point out contrasts between this system with others driven by sea level rise – so why do you call on this mechanism?
  - I wouldn't call on evidence for subglacial meltwater flow as the most immediate support of ocean warming-driven retreat (p8 final paragraph) – explain the logic for this.
  - A potentially interesting discussion of the roles of meltwater and/or calving doesn't really develop (p9 penultimate paragraph). Are these mutually exclusive modes of retreat? Facies 3 bears similar characteristics to facies 4, except with IRD: do we have continual meltwater with suppressed calving (absence of facies 4)? Or an increase in meltwater-related sediments? The Results report IRD in layers – are you detecting episodic calving events, or continuous delivery? If meltwater sediments and landforms are more abundant towards the inner shelf,

is this a temporal effect (i.e. more melt production later in deglaciation), or a spatial effect (e.g. preferential channelisation of water with a certain topography/substrate/ice surface profile)? You ought to be able to develop these ideas more than "retreat style was different" – in what way, and with what significance? ***We have rewritten this part of the manuscript, providing a more in-depth discussion of the relationship between local trough geometry and locations of the GZWs, as well as the sedimentary environments regarding the different lithofacies.***

- Comparisons of the numbers/positions of GZWs between troughs with very sparse multibeam/seismic data coverage (e.g. page 9) can at best lead to a speculative conclusion. Contrasting stabilisation points, if that is how a GZW is interpreted, also doesn't necessarily mean asynchronous retreat: retreat may be triggered by a synchronous forcing, but may be locally anchored in different ways. Contrasting pattern doesn't necessarily translate to contrasting timing (or forcing). ***We agree that there might be undiscovered GZWs in Norske Trough and Westwind Trough. We rephrased this paragraph, focusing on the presentations of facts, rather than speculating on differences in deglaciation dynamics between different troughs.***

- The discussion of surging is under-developed with respect to models for landform formation, drivers and with respect to both literature and the actual data. The basis for the surge interpretation here is the occurrence of crevasse-squeeze ridges. While I'm unconvinced by the figure examples shown, if these are present here then I think the discussion needs to:
  - Justify why these must indicate a surge. Is there a difference between a surge (in the sense used here) and a period of ice stream acceleration (externally driven?) which would cause extension and feasibly open up basal crevasses?
  - Address the spatial distribution, intermingled with moraines, wedges and iceberg scours – your actual data. Are there multiple patches of CSRs? Do these each, therefore, belong to a different surge? Why? How is this reconciled with "slow and steady" retreat indicated by the moraines? Why should a surge lead to ice front collapse *followed by* increased ice flux? And do you see any evidence for such ice front collapse? This seems at odds with the interpretation of slow, grounded retreat. ***We have re-interpreted the landforms initially suggested to be related to surging, to be saw-tooth moraines. Thus, the discussion of surges is irrelevant for the manuscript, so we have removed this section.***

Line-by-line

P1-line19: "exposed to" increasing ice loss? Rather, 'experienced', or simply 'has increasingly lost mass'… ***Corrected.***
1-20: 16% of the GIS is… ***Corrected.***
1-26: instability (also 2-45) – what do you actually mean by this? ***Here we use the term ´instability´ to refer to a possible disequilibrium within the GIS caused by external forces.***
1-27: identified as a tipping element ***Corrected.***
1-30: this sentence is awkward. '…precise predictions of the future potential decay of the GIS…' ***Changed.***
P2-first paragraph: you give almost as many references for 'sparse' as 'multiple studies'. ***We have added more examples of references.***
2-15: stepwise – this term isn't especially meaningful, since every pattern showing any kind of paused grounding line could be said to show 'stepwise' retreat. ***We use the term ´stepwise retreat´ to explain interruptions in the retreat. This term has been used in other articles and we therefore wish to keep it.***
2-19: *west* of Store Koldewey Trough, *reveals* that… ***Corrected.***
2-26: I have a bit of a problem with an objective being 'to confirm' something. And in this case, the data you have available with which to 'confirm' (or test) the interpretation of shelf-break glaciation is exactly the same data as has been used to propose it. ***Changed.***

3-10: episodic calving ***Corrected.***
3-12/13: this sentence isn't necessary, unless you make it relevant to your work ***We agree and have removed this sentence.***
3-30: were acquired ***Corrected.***
4-5: were estimated ***Corrected.***
4-9: chemical treatment…was conducted ***Corrected.***
4-35: it could help throughout the presentation of results to use inner/outer shelf or proximal/distal either instead of or as well as compass directions. i.e. here westernmost = innermost, or for example SE of wedge X = distal to or seaward of ***We have rephrased from compass directions where practical to make it easier for the reader to follow.***
5-15: Facies 3 interpretation – laminated mud with sandy layers sounds like Facies 4, interpreted as proximal, so if the 'background' sediments that are interrupted with IRD event layers are the same, does this not imply that the position is sufficiently proximal to still be receiving meltwater sediments? ***We have rephrased our interpretation, making it more clear that both suspension settling and iceberg rating is present.***
6-16: grounding zone wedges A-D ***Corrected.***
6-18: exceeds the… ***Corrected.***
6-21: wedge A (outermost) has more the shape of a moraine ridge – symmetric form, comparable to the more pronounced of the moraine ridges between here and wedge B. 'A' does not have the asymmetric shape typical of a prograding wedge. ***Noted. We base our interpretation on the fact that other ridges with similar dimensions and locations on the continental shelf of Greenland are interpreted as GZWs.***
7-13: what do you mean by meltwater runoff from the banks? Proglacial (ie bottom-hugging submarine flows)? Or subglacial from a semi-independent ice sheet sector? ***We believe the channels are not important for reconstruction the ice dynamics and have therefore made a simple interpretation of their origin, suggesting that they are formed during deglaciation and are related to meltwater. In order to further study their genesis, additional data is needed.***
7-29: can you distinguish between a buried bedrock surface and buried till surface (from previous glaciation)? ***We have included Petersen et al. (2015), showing that there is a thick Paleogene sedimentary succession offshore NE Greenland, ruling out bedrock sills.***
7-45: This conforms with… (or This is consistent with…) ***Corrected.***
8-3: covered a minimum length… ***Corrected.***
8-11: but this is the NE Greenland ice stream (or a distributary of) that you're talking about, so this 'comparison' is a little odd. ***We find it interesting that a similar flow feature is identified in modern day NEGIS.***
8-12: Once fast-flowing ice streams reach… ***Corrected.***
8-30: what sediment data? ***We have clarified that Stein et al. (1996) presented terrigenous, coarse grained material along the continental slope off NE Greenland.***
8-39: The occurrence … demonstrates ***Corrected.***
9-3: ii) trough narrowing ***Corrected.***
9-second paragraph: this repeats point (i) above ***Corrected.***
9-19: your high-res data reveal four wedges, but your data coverage is incomplete, so how can you reject the interpretation of six along the whole trough with full (albeit poorer resolution) coverage? You have also consulted IBCAO: do you agree with their interpretations of six wedges, and how does the expression of these in IBCAO compare to their expression in your high res data, where available? ***The paragraph has been altered and include now the possibility for GZWs outside our data coverage.***
9-fourth paragraph: how does this relate to the rest of your Discussion? ***We see your point and have removed this paragraph.***
10-5: what sedimentological evidence do you have for winnowing and resuspension? ***We have rephrased this statement.***
10-21: grounding zone wedges are not surge-indicative landforms ***Corrected.***
10-22: is consistent with ***Corrected.***

Figures

1. Present-day flow directions for Zachariae Isstrøm and Storstrømmen would be useful, and/or outline of NEGIS. ***Included.***

   Caption line 2: 'The small map shows…' ***Corrected.***

4&5. Suggest label wedges A-D on the illustrated mapping in each figure. I also don't think it's helpful or appropriate to show recessional moraines and crevasse-squeeze ridges as part of the same group, since you interpret their formational environment and palaeo-glacial significant differently. ***GZW A-D have been labeled, whilst the mapping of landforms have been updated.***

9&10. Both of these figures are not necessary – one or the other should suffice. I'm also not sure all panels of Fig 9 are really necessary – are these really all discrete, distinct 'stages' of retreat that can be clearly defined? ***We agree and have therefore simplified figure 9. Figure 10 has been removed from the manuscript.***