

Response to Anonymous Referee #1

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### **General comments**

The paper is well written and presents timely, interesting and new insights into the lateral extent and ice marginal dynamics of the MIS 6 palaeo-ice sheet in the southern North Sea using both geophysical and sedimentological data. The paper is thorough in its assessments of available sedimentary and geotechnical data from engineering boreholes and shallow, high resolution 2D seismic and I would recommend it for publication with some relatively minor revisions listed below.

Framing of the research question or gap in knowledge that this paper will address has to be tightened in the Introduction section. At the moment when reading through the intro it sounds like the paper will tackle MIS6 ice sheet forcing mechanisms, ice sheet dynamics, spatial and temporal advance and retreat of the ice sheet and palaeo-sea-level. Of course it is fine to mention wider implications of the research but actually this paper focuses on the southerly extent of the ice sheet and ice marginal dynamics within one marine sector of the MIS6 ice sheet. This is by no means a weakness of the paper, as is eloquently described in the final section of the paper (5.4), focusing in on specific ice sheet sectors where detailed, high resolution data is available can lead to i) far greater certainty in ice sheet extent, ii) revision of previous reconstructions based on older low res data sets, iii) better interpretation/reinterpretation of ice marginal dynamics and iv) highlight the complexity of nearsurface geology in the North Sea. I would try and frame the intro more towards these very important focused questions which are dealt with throughout the rest of the paper rather than far more general possible ice sheet dynamics/sea level implications.

We thank the reviewer for their clear, insightful, and constructive review comments. We have replied individually to specific remarks and technical corrections below. We have also included the line numbers corresponding to the tracked changes version of the revised manuscript.

We have rewritten the first paragraphs of the introduction in response to RC1's remarks on our framing, also following suggestion from another reviewer. In the new version we introduce early on that the focus of the paper is to study a distal sector of the ice sheet where data of high resolution is available and highlighted in the framing the relevance of preserved landforms and deposits to reconstruct ice-sheet extent and dynamics. We have also clarified the objectives of the paper, now more specific and including findings from section 5.4.

### **Specific comments**

L59: Avoid using the term "late Quaternary" throughout the manuscript. Use either Late Pleistocene or Late Pleistocene and Holocene since these are officially recognised epochs and subepochs.

Thanks for the advice, we have changed the terms accordingly. (Lines 68, 96, 601 and 610)

L61: What time period is covered by the "late Saalian"? State this at first use. In addition state what time period or age ranges are covered by "pre-late-Saalian" and "post-Saalian".

We have included that the late Saalian corresponds to MIS 6 the first time that the late Saalian is mentioned. (Line 71).

L64-65: This relates to the comment above. Firstly how does this study investigate ice sheet morphology? This study is focused on the margin of one sector of the very large MIS6 ice sheet so I don't think you can make this claim. What do you mean by the "style" of an ice sheet as

oppose to the “dynamics” of an ice sheet? I think this sentence needs a slight refocus. I don’t think this paper gives so much information of broad scale advance and retreat of the ice sheet since the dataset used is from a very localised ice marginal area. Again, I don’t necessarily think this is a weakness, looking at modern polar ice sheets, it is the highly complex 3-5 km marginal zone of these ice sheets that models struggle with and that are so crucial to understand ice sheet dynamics. However, I think large scale MIS6 ice sheet dynamics are beyond the remit of this paper. Thus, I would focus on the fact that you have a very detailed dataset from the ice sheet margin to allow corresponding detailed interpretation of ice margin dynamics which in turn is useful to e.g. palaeo-ice sheet modellers etc.

We have removed the first paragraph of the introduction, which was too broad, and instead introduce early that the focus of the paper is the study of a distal sector of the MIS 6 ice sheet. We have also highlighted the importance of preserved landforms and deposits to reconstruct past ice sheet extent and dynamics, and the relevance of investigating specific sectors where high-resolution data is available. We have also clarified the objectives of the paper, and are now more specific: “We use these data to revise previous reconstructions based on older or low-resolution datasets, to constrain the maximum extent of the ice sheet in the marine sector, to provide insights into the regional marginal dynamics of the ice sheet and to investigate the complexity of the near-surface geology of the North Sea and its implications for offshore infrastructure development and palaeogeographical reconstructions.” (Lines 73-77).

L93: by “glaciotectonic deformations” do you mean glaciotectonic structures?

Yes, we have changed it accordingly. (Line 106)

L215: I think it is significant that mapped tunnel valleys are V-shaped, in the North Sea they can be both V- and U-shaped relating to various hydrological and/or geological factors, there are several papers on tunnel valley morphology from the North Sea (e.g. Kristensen et al. 2007; Lohrberg et al. 2020) so possibly one additional sentence could be added regarding the significance of the V-shape?

Thank you for the suggestion. We have included the interpretation of the V-shape in the discussion: “Several authors suggested that V-shaped subglacial channels are eroded mainly by pressurised subglacial meltwater rather than direct glacial abrasion (Jørgensen and Sandersen, 2006; van der Vegt et al., 2012).” (Lines 492-493).

L217: why would tunnel valleys “typically form during phases of ice advance”? Surely there would be larger volumes of meltwater during deglaciation?

Yes, that was incorrect. We have changed the sentence, which now reads as: “, which typically form as the result of erosional processes occurring beneath continental ice sheets.” (Line 234).

L218-219: What kind of “glaciotectonic deformation”? Is this a thrust sequence? If so considering the gridded seismic data it should be possible to provide some structural measurements or the orientation of the thrusts to provide useful information on ice flow direction as has been done in the paper that is referenced by Phillips et al.

We apologise, as this is a mistake due to a misplaced reference. Deformation found in the northern sector of HKN only corresponds to distorted reflectors, slightly wavy sometimes, found in U1 (as part of seismic facies sf2). There is no thrusting in this sector, only some faulting, although difficult to characterise due to the weak acoustic signal. We have clarified the description: “The disrupted aspect of reflectors from the underlying seismic unit (U1, sf2), with some inferred faulting and possibly folding, is interpreted as glaciotectonic deformation of the pre-existing deposits”. (Lines 235-236).

L220: Maybe worth quickly mentioning something about the peat layers from the borehole log in Fig 4 found in U1.

The peat layers from the borehole log in figure 4 found in U1 are mentioned above in section 4.1.1. (Lines 198-200)

L260: Something that needs to be clearly explained here and throughout the manuscript is the orientation of the thrusts within the glaciotectionic ridge and the relation of these thrusts to the orientation of the ridge. From Figure 5 it seems that the thrusts within the ridge suggest ice flow from the NE while the orientation of the ridge suggests ice flow from the N.

The orientation of the thrusts and the ridge are explained in the description section above (4.2.1, lines 252-256). We have further clarified that the thrusts indicate a S to SW sense of displacement (ice flow coming from the N-NE). The orientation of the mapped ridge in figure 3 is not only consequence of the ice flow, but also the subsequent erosive and depositional processes. The northern side of the ridge has been intensively eroded by deglacial meltwater channels (Fig. 5), removing large sectors of it, and most of the western sector of the ridge only corresponds to a few preserved deposits, as the area suffered intensive erosion during deglaciation and transgression.

L283: I think you have an interesting result here: a transparent or semi-transparent acoustic facies (sf1) that corresponds to a laminated and interbedded sedimentary facies. Similar transparent or sometimes termed “chaotic” acoustic facies are commonly found in the North Sea (and many other formally glaciated continental margins) and often they are simply linked to “till” or diamictons. This result highlights how important it is to be able to ground truth seismic interpretations. This very point, that transparent or chaotic acoustic facies cannot be assumed to represent till was made in a paper by Stewart and Stoker (1990, Problems Associated with Seismic Facies Analysis of Diamicton-Dominated, Shelf Glacigenic Sequences) where they demonstrated that several stratified glaciomarine sequences can give a similar transparent/chaotic acoustic response. Here it seems you have evidence of this and even more diverse sets of laminated/interbedded sediments that can appear acoustically transparent. It may be worth an extra sentence highlighting this here or in the interpretation.

Thank you for the suggestion. We have included a few sentences about this observation as part of section 2.4 when we discuss the need to revise palaeogeographic reconstructions using legacy seismic reflection data: “Similarly, we have identified transparent and semi-transparent seismic facies, which are usually interpreted as subglacial diamicton on formerly glaciated continental margins (Stewart and Stoker, 1999), that correspond to diverse sets of laminated and interbedded glaciofluvial or coastal sedimentary facies (sf1 and sf3, Table 1). These results further highlight the importance of being able to ground truth seismic interpretations.” (Lines 589-593)

L301: what is “slightly erosive”?

With “slightly” we were meaning of minor order, however, it is not needed as they are found within the seismic unit, so we have deleted the word slightly. (Line 323)

L356: Here it is stated that chronostratigraphic connection was made between the study site and onshore chronological frameworks but earlier in the manuscript it is stated that “The low resolution sub-sampling for palynological assessment in the RVO-commissioned surveys prevented a detailed correlation with established chrono-biostratigraphic frameworks.” This seems somewhat contradictory.

Yes, it is somewhat contradictory, so we have decided to delete the earlier sentence from methodology section (Lines 152-153). It was present to indicate that the palynological data were

of too low resolution to do traditional pollen-based chronostratigraphy 'within interglacials', but this is a detail explaining limitations of the data. The later sentence is retained (lines 359-360). That sentence relates to the overall glacial-interglacial Pleistocene framework, separating individual cycles and tying a numeric age to them.

L340-349: I wonder if there is any explanation for the lack of till in U1? Obviously S1 is a product of glacial erosion but it is interesting that only a thin till layer is present in borehole HKN10. Was this the case for other boreholes in HKN? Acoustic facies sf4 corresponds to till but that seems to be laterally discontinuous? Another point, sf4 appears to be relatively uniform in thickness at least from the seismic profiles? All of this would have interesting wider implications for subglacial processes/ice flow (i.e. the "bed mosaic" model of ice flow and depth of deformation).

The diamicton layers were recovered in several boreholes in the northern sector of HKN, not only in HKN10, but always thin layers associated with S1. We mapped the preserved diamicton/till following seismic facies sf4 that were associated with surface S1, appearing as patchy deposits, picking S1 always at the base of such deposits. Of course, there is a degree of uncertainty in the interpretation considering that more detailed analyses and testing were not possible in the boreholes. The mapped distribution may also be strongly related to preservation and depends on the spatial resolution of the seismic grid. Given the uncertainty and limitations, we consider that it is difficult to discuss wider implications without additional data. We did not modify the text on this point. (Lines 364-372).

L448: ridge morphology suggests ice flow from N, and thrusts from the NE, see comment above.

The orientation of the mapped ridge in Figure 3 is not only a consequence of the ice flow, but also the subsequent erosive and depositional processes, and therefore, we consider that this cannot be taken as strong evidence of ice flow coming from the N. The thrust indicate ice coming from N to NE, and subglacial meltwater channels, which are larger and therefore easier to characterise in the seismic grid, indicate ice flow from NE. We did not modify the text on this point. (Lines 489-490).

L478-479: but detailed structural analysis of the thrust blocks within the ice push ridge may indicate variation in flow direction?

The thrusts blocks indicate a S to SW sense of displacement (ice flow coming from the N-NE), but it is not possible to refine this orientation even more (and distinguish N from NE ice flow) as it is limited by the spatial resolution of the seismic grid and the orientation of the seismic profiles. We have only slightly modified the text on this point following suggestions from another reviewer: "In the HKN windfarm area, there is no direct evidence for a change in ice-flow direction" (Line 525).

L507-512 and figure caption 9: There seems to be quite a bit of speculation here regarding ice sheet margin stagnation. Just because there is evidence of dead ice does not necessarily mean stagnation of the ice sheet margin. Surely a rapidly retreating ice margin could also leave behind areas of dead ice. Secondly, while the NCIS switched on and off numerous times during multiple ice advances throughout the Mid and Late Pleistocene, it is not known when streaming switched on or off during individual ice advances and what influence the NCIS had on other parts of the ice sheet in terms of ice dynamics. The referenced Sejrup et al. (2003) paper relates to specific dynamics of the NCIS. For interpretations of ice margin retreat style in this SW sector of the ice sheet, either better geomorphological data or chronological data is needed.

We have removed the section discussing ice margin stagnation and clarified the interpretation of dead ice presence in the study area, which we suggest as an explanation for the unusual deglacial landscape preserved in HKN (Lines 547-563). We have also included a new paragraph

discussing the possibility of surge-type behaviour in this marginal sector of the ice sheet in line with comments from another reviewer. (Lines 424-435 and 563-568).

L527: Section 5.4 is strong, I think the questions relating to these findings should be more clearly integrated with the aims in the Introduction (see general comments above).

Thank you for the kind words. We have integrated this as part of the rewritten objectives: “We use these data to revise previous reconstructions based on older or low-resolution datasets, to constrain the maximum extent of the ice sheet in the marine sector, to provide insights into the regional marginal dynamics of the ice sheet and to investigate the complexity of the near-surface geology of the North Sea and its implications for offshore infrastructure development and palaeogeographical reconstructions.” (Lines 73-77).

L563: again I assume “ice margin stagnation” is linked to dead ice but could surely equally relate to rapid retreat?

Yes, it was linked to the presence of dead ice, however, we have now removed the discussion of ice stagnation and included a new discussion of surging glacial landsystems in line with comments from another reviewer. (Lines 424-435 and 547-568).

L567-568: why would “flat subglacial topography” equate to stagnation of an ice sheet margin? There are numerous examples of rapid ice retreat across “flat” continental shelf areas. Several areas of the North Sea, Irish Sea, Norwegian Sea, Barents Sea etc. were deglaciated relatively rapidly after the LGM with a highly dynamic ice margin over the continental shelf. In fact I am not aware of any direct geological or chronological evidence that suggests ice margin stagnation during retreat along the NW European continental shelf other than to stabilise long enough to form grounding zone wedges or ice marginal moraines.

As indicated above, we have removed that section from the manuscript. (Lines 424-435 and 547-568).

### **Comments relating to Figures**

Fig 1. The key/legend should have a space between “Hijma et al. (2012)” and “Batchelor ...” The colour schemes in several of the figures don’t seem to correspond very well. In fig 1 till is outlined in green, in fig 2 till is a stippled yellow/brown and diamicton interpreted as till in the core log HKN10 is dark grey. Why not stick to dark grey for diamicton/till deposits for all figures.

Correction to the legend done. We apologise for the changes in the colour schemes. Till/diamicton is now dark grey in all the figures (colour changed in figures 1, 3 and 8) and glaciotectonic ridges light red (changes done in figures 3 and 8).

Fig. 3 Again, ice-pushed ridges appear purple in my version whereas the same feature in other figures is pink.

The colour of the glaciotectonic ridges has been changed to light red (same as figure 1).

Fig 4. Both clay and U3 appear to be the same green colour, they should be different colours.

We have changed the colour for clay in figures 4, 5, 6 and 7.

Fig 5. Is there any diamicton in core log HKN56? If not it should be removed from the key. In the figure caption should it read “In seismic section C-C’, the side of the ridge....”?

No, there is no diamicton in HKN56 and has been removed from the key. The caption should read “side of the ridge”, so the correction has been done.

Fig 6. Again, diamicton appears to be obsolete in the key so remove.

Diamicton removed from the key.

Fig 8A. Again, colours are slightly confusing, the same glaciotectonic ridge is light grey in Fig 5 but here it is dark grey. Choose one and be consistent. Also, since you provide a colour key for all other units also include a legend for U1, even if it just says multiple sedimentary facies (I realise it is more challenging to group these sediments).

We have used the darker grey colour to be able to differentiate the deformed strata from other deposits of U1. In the new version we have included the legend for U1, as older deposits with multiple facies, and we have changed the colour of the deformed strata to light red (same as glaciotectonic ridges).

Fig 8B and 9B. At first glance the reader may wonder where the ice-push ridges across HKZ shown in Fig 1 are. Obviously you have reinterpreted these features as glaciofluvial so I think you should include them here in Fig 8B and 9B in a different colour and label them as such to highlight that this too is a key finding of your study, i.e. reinterpretation of legacy data.

We have added the channel and bars fills identified in HKZ to figure 8B, to highlight our reinterpretation of these deposits. However, we have not included these bars in figure 9B as most of these are found as part of unit U1 and therefore correspond to a time before that depicted in figure 9B.

#### **Technical corrections**

L59: Delete space after “investigations”.

Space deleted. (Line 68)

L89: remove space after “Offshore”.

Space deleted. (Line 103)

L122: “and” should be “at”? and “conducted” should be “drilled”.

Changes done. (Line 135)

L371: replace “or” with “of”.

It should be “or” as it refers to two different terms usually found in the literature for the same feature. (Line 394)

L475: should be “..observed to the northeast..”

Changed to “..observed in the northeast...”. (Line 521)

L556: remove “is”

Removed. (Line 616)