

Response to David Evans

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### **General comments**

This is an important report on, and interpretation of, new offshore data relevant to the reconstruction of MIS 6 glaciation of the North Sea. The interpretations are largely entirely logical and valid but I feel that the authors do not quite make the most of this important database in terms of implications for former glacier dynamics. A significant issue pertaining to the glaciation styles in the North Sea is the potential of surging versus normal active ice recession - this has been debated often for the MIS 2 glaciation and has been re-invigorated by the increasing amounts of offshore data becoming available. Particularly pertinent are the occurrences of large glaciotectionic thrust masses and widespread ice stagnation evidence (the latter not as convincingly demonstrated as the former in this paper), both diagnostic of surging glacial landsystems. The authors opt for active recession but the evidence begs further evaluation in this respect. In terms of details on glaciotectionic landforms, the authors might also want to consult some recent literature on the development of hill-hole pairs, whereby thrust masses aligned parallel to basins are termed paraxial ridges and are part of the overall development of hill-hole pair development and hence are not mutually exclusive with ridges aligned perpendicular.

I have added a number of queries and corrections on the pdf of the manuscript, which I attach here.

We thank the reviewer for their detailed, constructive, and useful comments. We have addressed all of the specific comments below and we have included the line numbers of the tracked changes version of the revised manuscript.

We have added a paragraph discussing surging as the origin of the thrust masses found in our study area. We have also clarified our interpretation of the presence of dead ice in the area and related it to the possibility of a surging ice-sheet terminus. We have also included references to supporting literature for such interpretations, and new references about the growing evidence of surge-type behaviour for ice-sheet masses in the North Sea. Additionally, we have also included the "paraxial ridges" terminology in the discussion and the appropriate references.

### **Specific comments**

Title: Here and throughout the text make sure that this is capitalised = The Netherlands. It is incorrect in many places.

Thank you for the correction. We have changed it throughout the text. (Lines 12, 19, 56, 99, 114, 398, 485, 521, 611).

L24-25: This is an ugly sentence. Try: .....data as records of process-form relationships preserved in buried landscapes, which can be utilised in refining palaeo-ice sheet margins and informing longer term drivers of change in low relief settings.

Thank you for the suggestion, we have changed the sentence. (Lines 24-25).

L27-37: This opening paragraph really doesn't work and because it is a token gesture on applications to future climate change predictions it is entirely out of context and provides no lead into what follows. The logic is also confused, because we use modern analogues to reconstruct the past, not the reverse - even if we did use ancient examples we would not use such a fragmentary record as that of MIS6! In short, you can pretty much just delete this paragraph.

We have deleted the paragraph and unused references. (Lines 29-39).

L52: So is yours! I'd be careful in what you imply here.

We imply that even onshore studying small sectors is sometimes the only option. Adding those up is what finally allows to get more robust and precise reconstructions. We have slightly changed the text regarding that point to make it clearer: "Over Germany and The Netherlands, the MIS 6 maximum ice advance was more extensive than the LGM and consequently relatively well preserved; and is known as the Saalian Drenthe substage ice limit in the regional stratigraphic schemes. These ice limits have been studied from spatially disparate field evidence onshore over a series of ice sheet subsectors". (Lines 56-60).

L84-85: add Dove et al 2017 here, as it pertains to your point and uses similar data types.

Reference added. (Line 98).

L206: What is a concave-up depression? This sounds like a contradiction in terms. Do you mean depression with concave-up floors?

This is probably confusing. We have simplified it, removing "concave-up". Now it reads: "above isolated depressions". (Line 222)

L217: A rather restricted and non-primary set of references on such a large topic. At least cite O' Cofaigh 1996 and maybe also Wingfield 1996 and Clayton et al 1999

We have added the following references which describe features of similar dimensions to those found in our study area: Clayton et al., 1999 and Ó Cofaigh, 1996. (Line 233).

L219: This is not specific enough - it is not actually loading, as that implies normal stress only. These features are created by compressive folding and thrust stacking. Phillips et al 2018 is a good example but you need to include some primary concept citations here also - like Mulugeta & Koyi 1987, Aber et al 1989, van der Wateren 1995

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. Thus, we have removed the reference to Phillips et al. (2018) and clarified the description and interpretation as follows: "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).

L221: This is a risky business! You can't definitively interpret the genesis of a diamicton from seismic records! The term "glacial" when put before the term "till" is also a redundancy. I suggest that this reads: ...are interpreted as glacial deposits, probably subglacial traction till.

Thank you for the suggestion. We have applied the suggested change in the sentence: "The patchy high-amplitude reflectors found at the base of the subglacial meltwater channel-fills, corresponding to matrix-supported diamicton in the boreholes, are interpreted as glacial deposits, probably subglacial traction till." (Lines 237-238).

L227: ...are likely to be... These can't possibly be subglacial. How would vegetation with oak trees exist up-ice in a landscape covered by an ice sheet? This makes no sense. I suggest you use: ...are likely to be channel infills laid down after deglaciation.

Yes, that was a mistake. We have modified it following the suggestion: "Given the seismic architecture, these sediments are likely to be channel infills laid down after deglaciation." (Lines 244-246).

L236: compressional deformation surely?

Yes, the ridge is consequence thrust stacking.

L237: There is no such word as "thrusted". This is a common error. The word is always "thrust" or "thrusting". This needs correcting in a number of places from hereon.

We have replaced the word "thrusted" with "thrust" throughout the manuscript. (Lines 257, 262, 280, 271, 291 and 417)

L377: is this not IJssel?

No, the correct term is IJssel, with capital I and J. This is because in Dutch the vowel IJ is one character.

L396: This is incorrect. The ridges represent the crests of individual thrust slices or fold noses - they are not indicative of active retreat. In fact large thrust masses are almost exclusively associated with surging - this needs to be considered and discussed, as you are likely looking at a surging glacial landsystem.

We have corrected the section regarding the interpretation of glacial landforms described by Mellett et al. (2020) and Phillips et al. (2018). It now reads as: "In the Dudgeon windfarm and the eastern sector of Dogger Bank, the glaciotectionised sequences form multiple parallel ridges extending over several kilometres, which are interpreted to be the result of surge-related marginal readvances during overall ice-sheet retreat (Mellett et al., 2020; Phillips et al., 2018)." (Lines 418-420).

We have also included a new paragraph discussing the interpretation of HKN as a surging glacial ice-sheet terminus: "Large thrust-block moraines are usually found at the margins of surging glacial landsystems formed due to rapid ice advance into proglacial and pre-existent sediments (Evans and Rea, 2005,1999). Surge-type behaviour has gained relevance in the discussion of marginal dynamics of former ice sheets (e.g., Bateman et al., 2015; Boston et al., 2010; Evans et al., 2019, 2020; Graham et al., 2009; Mellett et al., 2020; Phillips et al., 2018; Vaughan-Hirsch and Phillips, 2017). In HKN, a single thrust-block moraine is preserved and likely formed during a surge event when rapid advance of the ice sheet led to the pressurisation of groundwater within the underlying Quaternary sediments. In the northern sector, large subglacial meltwater channels (Figs. 3 and 4) were eroded in response to the over-pressurisation, while in the middle sector, the thick and laterally extensive mud and peat layers facilitated the development of a décollement and thrust staking in front of the advancing ice mass (Figs. 3 and 5). Although glaciotectionic thrust moraines cannot be taken as solely diagnostic of surging activity (Evans and Rea, 2005,1999), the glacial landforms identified in HKN (Fig. 3) is compatible with surging activity and therefore potentially indicative of a scenario of ice-marginal instability triggered by internal ice sheet dynamics rather than by external climatic forcing." (Lines 424-435).

L435: These are called paraxial ridges and are not mutually exclusive - they are part of hill-hole pair evolution. See Evans et al 2021 in QR for the establishment of this term and examples.

Thank you for the suggestion. We have included the term paraxial ridges (and the reference Evans et al., 2021) to describe ridges parallel to the glacial basins and removed the sentence pointing to these features being mutually exclusive. Now it reads: "The glaciotectionic ridges in HKN windfarm are oriented perpendicular to the P/Q-block basin, whereas onshore in the central Netherlands, there are large ridges that formed parallel to the basin rims. The later

correspond to paraxial ridges which are part of the evolution of hill-hole pairs (Evans et al., 2021). The glaciotectonic ridge identified in HKN seems to continue beyond the limits of the windfarm, and geomorphological features similar to the paraxial ridges may also be present beyond the areas covered by the dataset.” (Lines 472-4477).

L446: This is the first time we see the term V-shaped - surely they are U-shaped if they are subglacial/tunnel channels?

In the North Sea, tunnel valleys have been described both as U- and V-shaped in cross section using seismic data, see for example Kristensen et al. (2007), Lohrberg et al. (2020), Stewart et al. (2013), and van der Vegt et al. (2012). In the case of the features identified in HKN, they are V-shaped in cross section in the seismic profiles (Fig. 4A). We did not modify the text on this point. (Lines 489-490).

Kristensen, T. B., Huuse, M., Piotrowski, J. A. and Clausen, O. R.: A morphometric analysis of tunnel valleys in the eastern North Sea based on 3D seismic data, *J. Quat. Sci.*, 22(8), 801–815, doi:10.1002/JQS.1123, 2007.

Lohrberg, A., Schwarzer, K., Unverricht, D., Omlin, A. and Krastel, S.: Architecture of tunnel valleys in the southeastern North Sea: new insights from high-resolution seismic imaging, *J. Quat. Sci.*, 35(7), 892–906, doi:10.1002/JQS.3244, 2020.

Stewart, M. A., Lonergan, L. and Hampson, G.: 3D seismic analysis of buried tunnel valleys in the central North Sea: Morphology, cross-cutting generations and glacial history, *Quat. Sci. Rev.*, 72, 1–17, doi:10.1016/j.quascirev.2013.03.016, 2013.

van der Vegt, P., Janszen, A. and Moscariello, A.: Tunnel valleys: Current knowledge and future perspectives, *Geol. Soc. Spec. Publ.*, 368(1), 75–97, doi:10.1144/SP368.13, 2012.

L499- 502: This section of text is actually irrelevant as you don't expand on ice streaming anywhere else. Delete from "Geomorphological evidence..... to ....Winsborrow et al 2010)." And remove any of the references not used other than here.

We have deleted the sentence and the unused references. (Lines 547-550).

L504: Unless it surged? This concept needs to be examined. This is the first place that dead ice is mentioned - what is the evidence for this? If it is indeed strong, then you have another diagnostic criteria for surging.

We have removed the sentences about ice streaming, and a new paragraph discussing surging has been added to the previous section (Lines 424-435). We have clarified the interpretation of this section and the explanation for the presence of dead ice. This is inferred to explain the complex deglacial landscape, although other interpretations are feasible. This now reads: “Ice retreat left an unusual landscape preserved in HKN, characterised by the progressive filling of ice-advance and glacio-fluvial drainage depressions with laminated deposits recording postglacial climatic change through the preserved pollen (Figs. 3 and 4). The landscape is also characterised by a diffuse drainage network where only a few small deglacial channels are identified (Figs. 3 and 5). We interpret that this proglacial landsystem developed due to the presence of dead ice in HKN during deglaciation. Large masses of dead ice likely hindered development of a clear drainage network and favoured the formation of pools and small deglacial lakes that were progressively filled by fine outwash sediments as the ice melted. This interpretation is also coherent with a surge-type glacial behaviour, as distal parts become stagnant after a surge event leaving large masses of dead ice to melt in the formerly glaciated area. However, to improve understanding of ice margin retreat style in this southwest sector of the ice sheet, additional geomorphological and chronological data is needed, particularly towards the west and north of HKN and HKZ”. (Lines 552-568).

L508: This is just illogical - how does dead ice create severe winters? Consider deleting this as it makes no sense.

This sentence has been deleted. (Lines 558-559).

L511: Again - why? You need to provide evidence for stagnation.

As indicated above, we have removed the interpretation of ice margin stagnation, as this was a little bit speculative, and included discussion if ice surging. (Lines 552-568).

L539-540: consider citing Gibbard et al. 2018 (Royal Society Open Science) and Evans et al 2019 (PGA) here on the MIS 6 limit in eastern England.

We have not included such references here, as the section is on the Scandinavian-sourced southwesterly sectors of the ice-sheet in the North Sea and The Netherlands, not the more westward British-sourced parts of the ice-sheet. Therefore, we have not modified the text. (Lines 598-599).

L569: Surging needs to be a significant element of your conclusions.

Surging has been included in the conclusions: "We suggest that the preserved landscape assemblage is indicative of a surging glacial ice-sheet terminus. The thrust-block moraine preserved in the study area likely formed during a surge event when rapid advance led to the pressurisation of groundwater within the underlying Quaternary sediments, which led to the erosion of large subglacial meltwater channels and thrust stacking in front of the advancing ice mass. Surge-type behaviour in this distal sector of the ice sheet indicate ice margin instability independent of external climate forcing." (Lines 622-628).

### **Comments relating to Figures**

Figure 5: The single barbed thrust arrow symbols on the figures from hereon are too small. Enlarge to at least 3 times the size.

We have increased the size of the arrows.

Figure 8C: Glacitectonic ridge not ice pushed. Sea ice can push ridges so this term is very ambiguous.

We have changed the name to glaciectonic ridge in figures 1, 3, 8 and 9.

Figure 9: deglacial not deglaciation, glaciectonic ridges. Delete (this study) - obviously it's your figure!

Corrections done and caption changed. (Lines 499-512).

### **Technical corrections**

L19: and displaying

We have added "and". (Line 19).

L48: Delete "broadly speaking" = The MIS 6.....

We have deleted "Broadly speaking". (Line 54).

L52: relates

We have changed this sentence and the word "relate" is no longer present. (Line 60).

L59: close up space, ...stimulus for new research into late Quaternary submerged landscapes.

Changes done. (Line 68).

L63: ...offshore of the...

We have slightly modified this sentence. (Line 73).

L64: ..these data....

We have changed "this data" to "these data". (Line 73)

L79: basin, reaching

Comma added. (Line 92).

L93: ...deformation structures are....

Change done. (Line 106).

L184: ...were recovered....

Correction done. (Line 199).

L193: Surface S1 is.....

We have removed "In the northern sector,". (Line 209).

L194: elongate

Correction applied. (Line 210).

L226: ...the top of U2,...

We have added "of". (Line 244).

L233: ...of the HKN..., ...are faulted and distorted

Changes done. (Line 252).

L260: ...of thrust, faulted and folded....

Changes done. (Line 280).

L265: ...NE-SW drainage direction....

Word "drainage" added. (Line 285).

L270: overthrust

Changed. (Line 291).

L316: indicating deposition...

Change done. (Line 339).

L334: ...offshore of the... or "offshore The Netherlands"

Changed to "offshore of the Dutch coast". (Line 357).

L335: ice sheet-driven

Change done. (Line 358).

L370: offshore of the

Word "of" added. (Line 393).

L373: ..margins and marking...

Word "and" added. (Line 396).

L375: ...onshore glacial record in The Netherlands,....

Change done. (Line 398).

L378: stacked

Change done. (Line 401).

L405: ...comprised south....

"Of" removed from the sentence. (Line 441).

L410: comprising a thin....

Word "comprising" added. (Line 446).

L433: Glacitectonic ridge not ice pushed. Sea ice can push ridges so this term is very ambiguous.

"Ice push ridges" changed to "glaciotectonic ridges". (Line 455).

L434: Ditto

"Ice push ridges" changed to "glaciotectonic ridges". (Lines 471-472).

L445: offshore of the Dutch coast...

Change done. Now it reads: "into the nowadays offshore regions of the Dutch coast". (Line 488).

L449: ...sediments, leading....

Comma added. (Line 494).

L450: ..thrust-bound sediment packages (slices)

Word "packages" added. (Line 495).

L468: Unnecessary and ambiguous wording. ...1989), forming marginal.....

Unnecessary words removed ("releasing englacial debris"). (Line 514).

L469: A further advance then formed the maximum....Netherlands, creating the offshore HKN.....

Thank you for the suggestion. Change done. (Line 516).

L471: and the further

Word "and" added. (Line 518).

L472: position, the dominant

Word "also" deleted. (Line 518).

L473: HKN also suggests

Word "also" added. (Line 519).

L474: readvance followed

Word "has" deleted. (Line 520).

L475: observed in the northeast

Change done, word "in" added. (Line 521).

L478: ...area, there is no direct evidence for a change in ice flow direction. The.....

Change done. (Line 525).

L486: eroded

Correction done. (Line 533).

L490: which, with.....level, likely.....

Commas added. (Line 537).

L506: deglacial lake

Correction done to figure 9.

L509: become stagnant

This part of the text was removed. (Line 561).

L514: ....created a topography that.....

Word "inherited" deleted. (Line 570).

L515: Ijssel?

The correct name is IJssel. No changes done. (Line 571).

L517: formed

Correction done. (Line 573).

L532: reveals

Correction done. (Line 588).

L534: improves

Correction done. (Line 594).

L543: framework,

Comma added after framework. (Line 603).

L551: ice sheet-driven

Word "sheet" added. (Line 611).

L556: the word "glacial" is redundant when put in front of moraine. Its just "terminal moraine" here.

Word "glacial" deleted. (Line 616).