Dear Sarah Greenwood et al.

We appreciate your detailed analysis of our mapping and your comments on the preprint (in black). We believe that your contribution will lead to improvement of the quality of our manuscript.

Please find our detailed response to your comments below (**in green**).

Exploitation of newly available terrain datasets in the Baltic region is undoubtedly welcome, since the offshore sector was both dynamically important to the last ice sheet and highly under-researched. However, we identify a number of concerning problems with the work presented here, notably the quality and rigour of the landform mapping. We comment only on internal issues in the manuscript. We do not discuss interpretations guided by any data not available to these authors, only what is presented as figures or text in the manuscript.

1. Mapping rigour

● We find numerous examples of erroneous landform interpretation: bedrock ridges (with little/no sediment cover), dolerite dykes, aeolian dunes, marine current bedforms, estuarine banks, among others, mapped erroneously as glacial landforms. We provide a selection of examples of mapping errors in the Figure, below, and note that these examples are just a few of those we encountered. Furthermore, with regards to mapping methods.

In general, we acknowledge some mistakes in the paper, but make the important point that mapping and interpretation in Earth Science is not an exact science, is subject to interpretations made and the time and resources available for checking and verification against other data sources (e.g. geological maps). Such sources can be very helpful and might indeed be correct in the specific cases you raise but we do not regard it universally true that previously published mapping is always the 'truth' and in many cases glacial landforms, for example, can get anchored on pre-existing bedrock structures so that they can, rather annoyingly of course, be both. Given the persistent gap in knowledge in the Baltic we were not aiming for 'definitive geological survey standard' mapping, but rather to gather enough information to act as a basis to build information about ice flow and ice margins. Indeed, we note the recent publication of Greenwood et al. (now online in press, Boreas), which reveals that although these papers proceeded entirely independent of each other, it is apparent that there is a very large degree of similarity in the findings, regarding the distribution and type of landforms identified and mapped, and especially so regarding the interpretations made of them regarding ice flow directions, sequencing and ice margins. In fact, the similarities are really rather reassuring and provide a nice example of scientific replication and with some additions and alternative interpretations that suggest both would be of value to the community.

Of specific concern are Swedish terrestrial examples where geological structures overlap with marine, lacustrine and glacial landforms. We could revise details of the mapping here, consulting data from the Swedish Geological Survey, or more simply exclude these terrestrial examples from our study.

Our mapping includes 22,500 features and reconstructions we derive are not based on single or small numbers of landforms and so even in case of misinterpretation when we do make the odd mistakes (a natural consequence of large-scale mapping – no one will be 100% correct), we still believe the conclusions hold, especially given that we concentrate on the Baltic Sea, not the terrestrial margin.

As for the seabed geology, the quality of EMODnet data also has its limits. The size of landforms is often smaller than the resolution of the geology data. In addition, geological maps indicate surficial sediments without providing detailed information on deeper compositions. There are numerous examples where post-glacial and glacial landforms occur together in the Baltic. In the example presented in Fig. F (Greenwood et al. comments to preprint), EMODnet geology does not allow for interpretation of the landform as a moraine. However, geological maps by Sviridov and Emelyanov (2000) in this region indicate moraine complexes, partly covered by sand, mud, and gravels. We interpreted their maps and topography as indicative of an ice margin. However, considering that the geology data is inconsistent in this area we could mark the moraine as uncertain or remove.

In some locations landforms were not clearly visible on the DEM, especially where there is a mixture of high and low quality data. In our interpretations we adopted the strategy of testing each area with several hillshade orientation angles and exaggeration. We also manipulated the colour palette, adjusting to particular areas in addition to checking each non obvious landform with terrain profiles. Fig. E (Greenwood et al. comments to preprint) represent a W-E chains of higher elevated bumps. The cross-profile (Fig. 1), the arcuate shape of this chain, the close vicinity of a potential tunnel valley and an accordance with the general moraine pattern in this part of study area leads us to interpret this chain as degraded moraine.

Fig. 1. Examples of cross-profiles along the chains of bumps interpreted as degraded moraine (cf. to Greenwood et al. comments to preprint Fig. E). In these cases, we see a change in elevation and texture that we interpret as degraded moraines, and which appears reasonable given the wider positioning in relation to other features and overall bathymetry. Others are free to disagree of course.

● We find numerous examples of inconsistent mapping choices: neighbouring landforms of similar appearance mapped or unmapped.

Fig. B from Greenwood et al. comments to preprint - Agree, it is a remnant polyline that was not removed from the database after checking the mapping.

Fig. G (bottom panels) from Greenwood et al. comments to preprint - The current erosional features from Kalmar Strait (Fig. G in Greenwood et al. comments to preprint) shown as an analogue for MSGLs along Odra Bank are two different landforms. The features along Kalmar Straight, are erosional with an anastomosing pattern of grooves and irregular shape (changeable width and general geometry) of 'positive' sections. MSGLs presented by us (Fig. 7D, Szuman et al. preprint), have more or less the same width along the whole profile and a regular shape. They have a potentially erosional and depositional origin as the ridges clearly overlap each other from different azimuths.

Fig. G (upper panels) from Greenwood et al. comments to preprint –

(i) The Ronne Bank is not mapped as a wedge because of its composition (mixture of sedimentary rock, sand, till; EMODnet geological maps) and the profile shape differs from the Odra Bank. The gravel stringers were not mapped as glacial lineations as indicated in Fig. G (Greenwood et al. comments), but the positive lineations on top of the bank that correspond well with and are close to lineations in the southern part of Bornholm are. According to geological maps our lineations are anchored both in sedimentary rocks (the MSGLs occur in hard bedrock; e.g., Krabbendam et al. 2016) and soft sediments (like till, sands). Erosional glacial lineations can have very different compositions (sand, diamicton, hard rocks; e.g., Hermanowski et al. 2019). The dimensions of mapped lineations are much greater than the stringers from Fig. G in Greenwood et al. comments to preprint.

(ii) The study of Kramarska (1998) along the Odra Bank indicates the geology of the structure as of various origin including glacial. It is true that the topmost layer of the southern margin (about 5 km) of the bank comprises Littorina sands (till below). However, the study only loosely corresponds with the lineations, both topographically and by location. The lineations are present up to c. 40 km from Kramarska's (1998) data and profiles. The elevation of the lineations is 5 m lower. Please notice, that in Kramarska's (1998) C-D profile (p. 281) the top of the till layer occurs at ridges, like in our case. These ridges are not a product of sea currents activity. Most of the lineations are located on a lower terrace similar to that of the elevated terrace of the Odra Bank from Kramarska (1988) study, so it is highly probable that the topmost layer of the lower terrace comprises sediments that are buried in the upper terrace. The features have a positive topographical expression (contrary to negative examples from Kalmar in Fig. G from Greenwood et al. comments to preprint), and there are also iceberg pits present on top of the lineations. So, we prefer to keep our interpretation that these linear features are of glacial origin.

However, taking into consideration the 'waviness'/overlapping nature of the features presented in our study we can add that more detailed analyses are needed to clearly determine the origin of these landforms.

● Landforms visualised in figures have not actually been mapped (e.g. Landsort Deep, Fig. 5G, 9F).

Thanks for noting this. The landforms were mapped, but switched off for figure preparation and mistakenly omitted when preparing Fig. 4. Please notice that in Figs 5G and 9F we show this area and state that there are glacial lineations present. In Figs 5G and 9F it was our intention not to blur the figure and not to add the lineations. We would be happy to attach a corrected Fig. 4 in the revised version.

● The approach to moraine mapping offshore is very unclear: it appears that all 'bumps' not considered a lineation, rib or esker are recorded as moraines, with little/no discussion of or motivation for the interpretation. This is problematic for the discussion of the retreat pattern (e.g. Section 4.5).

We did not interpret each bump that we did not consider as lineation, rib or esker as moraine. For the interpretations we analysed topographical expression of the landform with broader context of landform assemblages. We have gathered all studies on glacial landform in the Baltic (Szuman et al. preprint, Fig.

1 and Table 1) and where possible supported our interpretation of the topographic expression using seismic surveys and hydroacoustic profiles. When combined with the variable quality of the DEM over the study area, this results in areas that are more confident and less confident in the interpretation.

● Consultation of geological maps (easily and publicly available) would have avoided many mapping errors. (Statements like L264-5 - lack of information on composition - are false.)

We agree that the mapping could be improved by consulting geological maps and, if given the chance, would do this. Given the resolution and quality of geological data and inconsistency between different published datasets (cf. EMODnet geology and Sviridov and Emelyanov 2000), interpretation of some landforms will still have some degree of uncertainty and potentially can be interpreted in different way by different people or teams. However, we also note that given the total number of landforms mapped, which we base our interpretations on, the overall amount of mistakes are insignificant and our conclusions still hold (see main point above).

● There are three versions of the tiled EMODnet DTM product (2018, 2020, 2022); the authors do not state which version was used. These versions have noticeable differences in landform visibility stemming from differences in input datasets and (re-) gridding results. Comparing with visually obvious gridding artefacts, the base topography in their Fig 4 appears to be the 2018 version - did they use more recent data too?

We based our interpretation on EMODnet 2018, as we started mapping in 2019. The newer versions, in our opinion, are not significantly different for landforms recognition. However, we would be happy to verify landforms against the 2022 product in the revised version.

● L154: "Artifacts are common in the dataset and where these occurred, cross-checking in the data from hydroacoustic surveys and seismic profiles were used to help identify glacigenic landforms" - what hydroacoustic surveys, what additional data?

We analysed different published data i.e., hydroacoustic data and seismic profiles in searching for glacial landforms. Those that were useful are mentioned in the text and/or Table 1. Additional data – e.g., cross-profiles were mentioned in the Methods section.

2. Unsubstantiated or unqualified interpretations.

● While the authors acknowledge that low resolution data may preclude complete landform detection, they nonetheless make interpretations of ice flow behaviour and retreat style based on the apparent absence of landforms or landform traits, especially in the southern and eastern Baltic where the input data underlying the EMODnet terrain model are sparse or entirely absent. Such interpretations are false and misleading. For example, in the S/E Baltic: L221, absence of cross-cutting (in fact there is an absence of lineations altogether); L273, absence of eskers; L422, absence of ploughmarks (taken as indication for land-terminating margin).

L221: In this sentence we wanted to emphasise the same direction of two groups of lineations in the east (no cross-cutting, just overprinting) and different direction of the two groups of lineations in the west (cross-cutting). We do not make a statement on the lack of lineations but rather on the replacement of cross-cutting with overlapping. Please consider sentence in L221 with the following one in L222. "In contrast, no cross-cutting relationships are identified in the SE and E part of the study area. Typically, more delicate and shorter glacial lineations overprint more prominent ones." Both sentences could be rephrased to not confuse readers.

L273: In our opinion this comment also lacks perspective based on the full paragraph on eskers (L272-282) in which we note that eskers absence could be due to poor-quality DEM data and burying processes. I.e. "We speculate that such small landforms might not be distinguishable in the poor-quality DEM available for the offshore areas or that eskers could be buried by postglacial deposits (Uścinowicz, 1999)"

we note that

"Most of the eskers identified in this study occur onshore with only 2% of the total population located offshore."

In addition, we analyse the presence of eskers in coastal regions where good quality data are present.

We do not make interpretations of ice flow behaviour and retreat style based on the apparent absence of landforms. By including statements on the lack of landforms we instead look to emphasise that interpretations in the eastern Baltic are not strong and in need of better-quality data.

L422: In this sentence we indicate that ploughmarks are missing in the southern sector of the study region but are present in the north, and that this likely reflects a transition from a land-terminating to shallow lacustrine (aqueous) calving margin. It is true that here we make an interpretation based on a transition between absence and presence of landforms. However, since our southern sector comprises areas with high quality data where we are confident in our interpretations, we do not see what is false in this statement.

● L385: "MSGLs with locally splayed termini"… "ice streams that operated … behind a back-stepping ice margin" - these relationships have not been demonstrated, the interpretations are unsubstantiated.

In line 384 we refer reader to Figs 6 and 9C where locally splaying termini are present. In particular, we refer readers to inspect flowsets presented in Fig. 6 and our lineation mapping (Fig. 4 and partly in Fig. 6). We therefore do think that we identify locally splaying termini. We will refer more clearly to Fig. 4 in L384 to help clarify the statement.

● L388: "Ice marginal signatures … comprised overprinted lobes arising from oscillations and readvances of ice margins along with switching of flow orientations and changing lobe positions…" This has not been demonstrated (unclear if the statement reflects the authors' own observations or relates to the reference (Kjær) provided).

We do not understand this comment as there is no cited sentence present in L388. Possibly this refers to L398.

In our opinion, the study of Kjaer et al. (2003) is consistent with our manuscript. We could not provide landform level detail for every statement in the discussion. However, we provide the reader (in addition to numerous landform examples) with the mapping in Fig. 4, flowsets in Fig. 6 and possible margin retreat scenario in Fig 8. In particular, the flowsets (Fig 6) and landforms (Fig. 4) demonstrate flow switching and overprinting in the southern sector (zoom in Fig. 9B). We could clarify this by adding reference to those figures and to other publications with consistent statements (e.g. Gehrmann & Hardig 2018; Pedersen 2000).

We suggest replacing the sentence with a new one to better clarify what we mean: "Ice marginal signatures in the southern sector often comprise overprinted lobes arising from ice-margin oscillations and readvances (Figs 6, 9B) along with switches in flow orientation and changing lobe positions during overall retreat (cf. Pedersen 2000; Kjær et al., 2003; Gehrmann & Hardig 2018)"

● L432: "the Baltic depression is mostly floored with thick glaciolacustrine sediment" - this is not the case, demonstrated by publicly available substrate geological maps/data (e.g. EMODnet geology (Quaternary lithology) or seabed sediment classification layers; e.g. SGU 1:500,000 marine geology).

We agree, that 'thick' is a relative statement, as some areas have 5-15 meters of unconsolidated sediments (see e.g., Flodén 1997; Tulling and Flodén 2001; Sopher 2016) the others more than 20 m (e.g. Bjork 1990; Lemke 1995, 1998; Sopher 2016; Kramarska 2016). We will change this sentence to better correspond to these data presented in the geological datasets.

● L442-3: "the presence of lacustrine wedges and outwash fans, and large moraines in the central Baltic is consistently associated with these geological structures." This claim has not been demonstrated at all.

We agree that this statement could be better related to presented data. We do not provide a direct figure showing this, however, the statement is implicit when inspecting Figs 1, 4, 7E, 9D. We will provide more description in this paragraph in order to clarify.

● L454-5: "predominance of a western ice lobe over the West Gotland Basin in the earlier stages of deglaciation and a later switch to dominance of the eastern lobe." This relative chronology has not been discussed or demonstrated.

We provide relative timing based on superimposition of the landforms in Fig. 6C based on flowsets at Gotland where the density of the landforms is high, providing strong evidence for the statement. We indicate in the results that cross-cutting in Gotland is common (L219-220). We comment on it in the flowset section (L252-253).

"Overprinting (e.g., Figs 6B, C), on Gotland Island records 10 flowsets with orientations switching from N-S to NNE-SSW oriented, through NE-SW, ENE-WSW, and NW-SE (Fig. 6C)"

● L455: "The suture between the two lobes was located along Gotland Island." Beyond the figure citation, this has not been demonstrated; the figure caption does not discuss this "suture".

The reference here should be to Figs 8; 9C, E, F. Description of the suture zone could be added or rephrased from interstream zone, and better clarified on Fig. 9E.

3. Sloppy manuscript preparation

● Several instances of erroneous labelling within figures (which in some cases lead to opposing or contrasting conclusions) and mis-referencing figure numbers in the text.

○ Fig 3A: the West Gotland Basin label is incorrect - both these depressions are in the East Gotland Basin, with the topographic high Klints Bank in the middle.

Only East Gotland Basin should be included here.

○ Fig 3: "DEM conglometare margin"? Unclear what this means - data stitching boundary, data integration boundary, data seam…?

This label could be changed to data stitching boundary in order to clarify.

○ Fig 6: direction of flow lines in NW Skåne (green flowset) is arrowed south, instead of north (stated as north in text)

Direction of flow lines in NW Skåne (green flowset) is arrowed south.

○ Fig 8: also over Skåne, the same ice-marginal line has an arrow indicating retreat both to the north and the south

Here, there are 2 lines, the first indicates recession toward the SW, the second toward the N-NE, but it is true that they overlap each other. We will include a bigger space between the lines.

○ L298: Fig 7E is offshore, not onshore as stated

Thanks. Reference to figure should be offshore.

○ L427: Fig 7F, I ? (Not 8)

Should be Fig.7

● Unclear what the basis is for naming “phases” or “moraines” on Fig. 1B (described in the caption as “major moraine systems”).

Basis is for naming “phases” or “moraines” – should be unified to phases

● Reference for “the Baltic Ice Lake” given as Uścinowicz 2006 - the Baltic Ice Lake has been known and named since the early 1900s, this is lazy treatment of the literature. Sarah Greenwood, Carl

Reference for “the Baltic Ice Lake” – the amount of references could potentially be extended, but it is not necessary to cite the paper from 1900s.

In summary, we think that the most of the Greenwood et al. comments to preprint are technical and editorial rather than substantial for our general reconstruction and interpretations. Indeed the Greenwood et al. (now online in press, Boreas) paper published in Boreas independently has very similar findings to our results.

Kind regards,

Izabela Szuman-Kalita,
Jakub Kalita
Christiaan Diemont
Stephen Livingstone
Chris Clark
Martin Margold