EGUSPHERE-2025-2906

Response to RC2: “Comments on egusphere-2025-2906” by Wolfram Geissler, 15 September 2025.

General comments

Dear authors, thank you very much for your study about the continental shelf glaciation off Northeast Greenland. Your study is an important contribution to understand the late Neogene-Quaternary evolution of the Greenland Ice Sheet despite the fact that drilling records are still too sparse in the study region. Especially impressive is that you are now able to map the development of individual glacial trough systems and related trough mouth fans throughout the studied time period. In comparison to an earlier study by Berger and Jokat (2009) using only sparse academic data, your study can build on an extensive combined seismic data set acquired by academic institutions and industry. This brings me already to my major points of criticism: (1) you do not consider the study of Berger & Jokat (2009) which was the first study about the late Neogene-Quaternary glaciations in NE Greenland based on marine seismic reflection data. Though referenced here and there throughout the manuscript mainly for data, it is even missing in the reference list. And (2), the seismic reflection data acquired by the Alfred Wegener Institute should be clearly referenced (e.g., Berger and Jokat, 2009; additional remark: maybe DOIs will be very soon available for the AWI data sets) and it should be documented in the section Data availability that the data is courtesy of the Alfred Wegener Institute and request should be directed to the institute and not TGS. A more technical point related to the various data sources, you should clearly mark the seismic profile names on the images.

Dear Geissler, thank you very much for your helpful comments. You will find that all of your comments have been addressed, and most are reflected as changes in the text. Thank you for your help to improve this manuscript.

1) Thank you for bringing this to our attention. We have added Berger & Jokat (2009) to the reference list and in the text as you have pointed out. We have also rephrased parts of sections 2.3 and 5.2.1 to accommodate your comments.
2) Thank you for bringing this to our attention. We have now made sure that the AWI data has been sufficiently acknowledged in the methods, figures, acknowledgments and data availability.
3) We have now added the seismic profile names to the figures.

I do not have any major criticism on the overall approach, results and interpretations. It is clearly documented that your seismic correlations are tied to only two (three) regional boreholes drilled by ODP and the KANUMAS consortium. In some cases, you mention that not all discussed horizons can be clearly tied to a lithological age in these boreholes; in that case you should further present and discuss these boundaries with their larger uncertainties (e.g., reflector NEG-3).

Thank you for your comment. To clarify, the NEG-3 reflection has been correlated with ODP Site 909 and has an approximate age of 4.1 Ma. However, NEG-2 has not been correlated with any of the ODP sites, and thus, we do not know the age of this bounding reflection. It was however correlated with Kanumas Site 13, which provides sedimentological information about the underlying seismic unit (MU-1), although not any age constraints. The age of NEG-2 lies between 6.4 and 4.1 Ma, and probably closer to the first than the latter. We have elaborated on this in section 5.1.1.

Some of the figures would benefit from minor revisions to make lines and individual features clearer. 1) The size of some figures could be enlarged (to full page size). 2) You should add profile names as mentioned before, and it would be great if SHOT/CDP numbers could be added. 3) For the conversion to depth/thickness and vertical resolution, you use a seismic velocity of only 1500 m/s. For a glacially overprinted shelf I suggest to use higher seismic velocities as documented by various seismic refraction data. At least you could indicate a range using a minimum and maximum velocity. 4) I would suggest that

you actually try to estimate true thicknesses in meters instead of only discussing difference in two-way travel times between reflectors. 5) Are there any data on seismic velocities available from TGS or KANUMAS?

1) Thank you, we have enlarged the supplementary figures 2 and 3.
2) We have added profile names to all seismic figures, however, we have not provided SHOT/CDP numbers.
3) Thank you, we have now calculated the resolution for our dataset using velocities of 1.5 km/s and 2.3 km/s, based on the velocity analysis on the shelf by Berger & Jokat (2008). This change had a few implications:
    a. The age uncertainty of NEG-1 and NEG-3 are based on the calculated vertical resolution in order to estimate tie-depth uncertainty. We have now re-calculated the resolution at each tie point to estimate the tie-depth uncertainty using the depth-velocity analysis for Site 909. We use the same method for Site 913 and Kanumas 13, but here we implement the average velocity of 1.66 km/s as provided from Site 913 (Myhre et al. 1995).
    b. Instead of the previous "±" age uncertainties provided, we now give the age uncertainty in a range (e.g. …. 6.4 Ma (age uncertainty ranging between 7.0 – 6.2 Ma)). based on the tie-depth (e.g. 652±31 m for NEG-1 in Site 909) (see Table 2).
    c. This changed the range of the age uncertainties. For NEG-1 from 6.4±0.4 Ma to 6.4 Ma with a range between 7.0 – 6.2 Ma. NEG-3 is changed from 4.1±0.3 Ma to 4.1 Ma with a range between 4.5 – 3.8 Ma.
    d. Note that the age estimations remain the same (i.e. 6.4 Ma and 4.1 Ma for NEG-1 and NEG-3, respectively).
    e. The uneven range (e.g. +0.6 Ma, -0.2 Ma for NEG-1) is due to the uneven slope of the age-depth model by Gruetzner et al. (2022). Thus, we think this way of presenting the uncertainties are more correct.
    f. We have updated the text, figures and tables accordingly.
4) We have now included thickness estimates of the seismic units using a simple average velocity of 2 km/s for consolidated (glacial) sediments (see section 3.3.1 and 4.2).
5) There have been no data on seismic velocities available to this study.

When you refer to ODP drill sites 909 and 913, make it clear that especially the deep hole at site ODP913 suffered from limited time towards the end of the expedition. Therefore, the upper part of the hole was not cored with the exception of short intervals. That does not mean that it is a poor recovery, it was sparse coring due to time constraints.

Thank you for bringing this to our attention. We have rephrased the text in section 3.2.2 according to your comment.

Please be correct in using terms, e.g., reflections define boundaries of intervals, not the intervals (e.g., line 251). And do not mix "reflections" and "unconformities", e.g, lines 273 & 274; both terms have different meanings, but reflectors could be interpreted as unconformities.

Thank you, we have made changes to the text where this was relevant. We feel that using unconformity in the headlines is informative to the reader. We establish the connection between seismic reflections and unconformable boundaries already in the very beginning of section 4. However, we have changes the heading of 4.1 and its subsections from "Regional reflections" to "Regional unconformities" to avoid mixing the two.

If you use geographical names, please make clear if they were defined earlier by others (e.g., IT-A/B/C inter-trough areas by Arndt et al. 2015). Maybe add bank features as documented in the Marine Gazetteer (e.g, Belgica Bank).

We have specified where the nomenclature has been adopted from in section 2.1.

The manuscript would benefit if you try to separate better between observations, interpretations and discussion. Sometimes, it is still a bit too much intermixed, in my opinion.

Thank you, we have made changes according to your suggestions in the text.

The Discussion section would need a bit more elaboration. Especially, (1) compare your results with the previous study of Berger and Jokat (2009) with respect to the overall timing of the NE Greenland shelf glaciations. (2) Also, make clear how you measure/interpret the intensification of the glaciations. (3) What could be the role of

erosion? (4) Why there is non-deposition (or reduced deposition) in some areas in specific time intervals? (5) Check the duration of deposition for your mega-unit MU-1? (6) Is it an interval or only a singular short-term event at about 6.4 Ma? (7) What is about the interval from mid to late Miocene, might there be glaciations in East Greenland as proposed by others before? (8) What is known about the sedimentary/basement structure beneath the IT areas? (9) How this could influence the glacial evolution of these areas?

Thank you, we have numbered your comments and elaborated on them as follows:

(1) Thank you, we have now elaborated on the comparison of our results to that of Berger and Jokat (2009) in section 5.2.1.

(2) Thank you, the intensification is not itself measured in this study. We imply an intensified glaciation/ice stream activity on the shelf for MU-3 due to increased size and thickness of depocentres as described in section 4.2.3 and 5.1.3.

(3) Thank you, onshore erosion has played a major role in order to provide the sediments which have been deposited on the shelf and slope. Subsequent erosion, after initial shelf glaciation and thus progradation, have eroded the topsets of some of the prograding sequences within the mega units. We believe that this erosion is primarily driven by subglacial erosion underneath fast flowing ice streams that reached the shelf edge in succession. Based on your comment in line 515, we have rephrased the paragraph slightly to clarify that we meant deposits on the palaeo-slope (i.e. underneath the present-day bank), and we added a sentence that we expect any deposits on the bank itself to be eroded by successive glaciations.

(4) Thank you, we suspect this is either due to the ice sheets dynamics and ability to transport sediments to the ice sheet terminus, where a cold based and sluggish ice would transport less sediments to the margin, than a warm based and fast moving ice stream. Another possibility is the absence of an ice margin at these locations, and thus reduced sedimentation rates compared to the TMFs where ice streams at the shelf edge deposit vast amounts of sediments. We have elaborated on this in section 5.1.

(5) Thank you, the time frame of MU-1 is not known, but we favour a late Miocene age, possibly coinciding with increases in IRDs into the Fram Strait between the interval 6.4 – 6.0 Ma. We have elaborated on this in section 5.1.1.

(6) Thank you, if you refer to the deposition of MU-1, we think the most likely scenario is that this was deposited during an interval, and not one single event. We have elaborated on this in section 5.1.1.

(7) Thank you, we do not see any evidence of glaciations on the shelf prior to 6.4 Ma. However, we have elaborated on this in section 5.2.1, referring to Berger and Jokat (2009).

(8) Thank you, the sedimentary successions below the IT-A bank is dominated by salt diapirs which folds and elevate the overlying sedimentary strata, which again has been eroded, forming strong truncated reflection boundaries. This salt is also present in the Norske Trough, although less so. This is already briefly described in section 2.1.

(9) Thank you, the underlying strata could definitely have affected the dynamics of the ice sheet, yet this paper does not aim to investigate the details of substrate-ice interactions. However, we have briefly elaborated on this topic in sections 5.1.2.

Please check the reference list for completeness. A few more relevant references are indicated in the annotated manuscript.

Thank you, we have updated the reference list with the reference that was missing, and we've added references as you suggested.

Line comments

31 all depocentres are trough mouth fans?

The depocentres mapped in this study are interpreted to represent trough mouth fans, dominantly formed during glacial maxima conditions when ice streams reached the shelf edge.

Figure 1a difficult to see (EGC) in figure

We have moved the "EGC" annotation to make it more visible.

53 just boreholes?

Tthe sentence has been rephrased to “cored boreholes”.

68 “form the first coherent stratigraphic framework**” ?**

We have rephrased the suggested sentence accordingly.

71-72 Rephrase? Check Berger & Jokat (2009).

We have rephrased the suggested sentence accordingly.

83 Does it not have a geographical name?

The whole of the Inter Trough area-A (IT-A), defined between Norske and Westwind troughs, does not have a geographical name that we are aware of. However, names for specific parts of the bank area have been used by previous studies, such as Belgica Bank (used for the southwestern parts), Northwind Shoal (western shallowest parts) and AWI Bank (northeastern parts). Although IT-A is not exactly an easy name, it is chosen because it encompasses the whole bank area, and not just smaller parts of it.

Figure 2 References

We have added the missing references accordingly.

115 all the Arctic Ocean?

We have rephrased the paragraphs regarding the opening of the Fram Strait in section 2.2 and 5.3.

117 & 121 Suggested reference: Jokat et al. (2016)

We have added the suggested reference in sections 2.2 and 5.3.

130 «Tributary ice streams**» Correct term?**

We have rephrased the sentence to avoid the word tributary. We have replaced the word with “branch”.

134-137 suggested reference: Winkelmann et al?

We have added the suggested reference.

138-144 what about evidence for Eocene IRD?

We have added a sentence including the Eocene and Oligocene IRD found in the Greenland Basin.

176 A higher velocity would make sense

We have now used a velocity of 2 km/s to calculate the vertical resolution of our data.

180 2000 m/s would make more sense

We have made changes according to your suggestions.

194-195 suggested rephrasing

We have rephrased the sentence accordingly.

215 drop stones?

We have rephrased the sentence accordingly.

221 which software?

We have added the software used in parentheses.

223-224 Rephrase

We have rephrased the sentence accordingly.

228 Automatic? How successful?

Assisted tracking is used to trace continuous horizons, such as the seafloor reflection. This dataset is not suitable for automatic tracking. we have rephrased the sentence to make this clear.

232 Why not estimate true thickness in metres?

We have included the estimated thickness in metres as well now.

237 There are seismic velocity models from seismic refraction studies, at least for the region to the south of study area. TGS or Kanumas?

Velocity data from Kanumas or TGS have not been available to us for this study. However, to estimate depocentre thicknesses, we have now used an average velocity of 2 km/s for glacial sediments on the shelf, similar to other formerly glaciated margins.

238 core & logging data

We have rephrased the sentence in hope that it will be more clear.

243 "1.66 km/s**" too slow**

The velocities we use for Site 913 are based on the numbers reported by Myhre et al (1995). At site 913 we expect to be in a depth range of 0 – 400 mbsf. This is comparable to ODP Site 909, which also yield an average velocity of 1.66 km/s for the interval 0 – 350 mbsf. We chose to use these numbers as these are the best velocity estimates we have.

250 reflections define boundaries of intervals!

Thank you, we have rephrased the sentence accordingly.

Table 2 "3.407 0±23.5**" Does not make any sense**

Tthe "±23.5" refers to depth uncertainties limited by the vertical resolution of the seismic (in this case 23.5 m). To avoid confusion, we have decided to remove the uncertainties for the seafloor depth.

Table 2 be consistent with numbers!

We have made changes to the table accordingly.

Table 2 Uncertainties, how are they decided?

Thank you, uncertainties in "Depth in borehole (mbsf)" are decided from the seismic resolution. The uncertainties from the "Age estimations" are for ODP Site 909 also decided from the seismic resolution (e.g. age span from 23.5 m above and below 310 mbsf for NEG-3 give an age of 4.4 to 3.8 Ma using the age model by Gruetzner et al. (2022)). However, the same approach cannot be used for the correlation to ODP Site 913, where the age model has a far lower resolution than the seismic, i.e. Pliocene to Pleistocene range, or middle to late Miocene range, both spanning millions of years. Thus, the age for the reflections correlated to Site 913 are given in intervals using the age model by Hull et al. (1996). This validates the correlations between the basins and

show that the NEG-1 and NEG-3 boundaries falls within the same age span in both the Molloy and Greenland basin.

Figure 3a lines not visible (maybe present without these)

We understand the confusion. the lines (interpretations) are not present in Figure 3a. We have moved the legend to the corresponding figure (3b).

Figure 3b add reflectors (names) here

The reflector names for all subfigures are now shown in the legend in Figure 3b.

Figure 3 Profile names should be added

We have added profile names in the first appearance of all seismic lines as suggested.

Figure 3 CDPs or shot numbers would be great to add

We have decided to not add CDPs or shot numbers at this point. However, we have complied with your recommendation on adding the profile name to each seismic profile.

Figure 4 Not the right term? (pre-shelf glaciation)

The term “pre-shelf glaciation” is here used to simply refer to sediments which were deposited prior to the first recorded shelf glaciation, as we have mapped in this study.

Figure 4 Add profile names (and CDPs/SHOTs)

Thank you, we have added profile name to the seismic lines. However, we decided to not add CDPs or shot numbers at this point.

Figure 4 GNPDR?

Thank you, GNPDR (Greenland Petroleum Depository) is a open access public site where seismic data can be downloaded. By using the portal, we agreed to acknowledge GNPDR as a data provider. The site (https://greenpetrodata.gl/) is however not available at this moment.

285 Not really obvious from figures

Thank you, the lithological subunits from the cores are not shown in the figure, thus maybe the confusion. We have rephrased the sentence to make it clearer.

292-293 Rephrasing

Thank you, we have rephrased the sentence.

307-308 any lithological changes in Site 13?

Thank you, Kanumas Site 13 is predominantly composed of matrix (silt) borne diamictite with thin (<1m) laminated intervals (described in section 3.2.3). Most of the core (30 – 114 mbsf) correspond to the base of MU-1, thus the composition of the core is repeated in section 4.2.1 where MU-1 is described.

308 How the age is then constrained?

Thank you, the age of NEG-2 is not constrained in this study, while NEG-1 and NEG-3 are. In Table 2 we suggest an age of NEG-2 to be within late Miocene, as we favour this to be the most likely age (section 5.1.1).

309-311 doubled?

We have rephrased the paragraph.

312-316 suggested rephrasing

We have rephrased the paragraph.

Figure 5c & d one subfigure!

We have rephrased the paragraph.

331 Figure 5 caption AWI!

We have made changes accordingly.

Figure 5 profile names

We have added profile names.

Figure 5 the subdivision is not easy to understand

We have made changes to the subdivision so the figure is easier to understand.

340-342 suggested rephrased

We have rephrased the paragraph.

345-347 rephrase

We have rephrased the paragraph.

347 Not clear how you define a plateau

We have rephrased the sentence, which hopefully makes in clearer.

355 coherent deposit **?**

We have rephrased the sentence accordingly.

366 suggested rephrased

We have made the change accordingly.

366 thickness in metres?

We have added thickness in metres in the text.

370 maybe add a figure illustrating better the shelf break advances?

Thank you, we have taken your suggestion into consideration, however we have decided not to create a new figure at this point as we feel it is illustrated sufficiently in Figure 6, and especially Figure 6d.

384-385 what is with the areas, where no MU-2 is interpreted?

Thank you, the lateral extent of MU-2 (Fig. 6g) is restricted by the NEG-3 reflection (Fig. 6c) at its upper boundary. On the shelf, this reflection is either truncated at the seafloor or it onlaps the NEG-1 reflection. We have rephrased this sentence to make it more clear.

391 Rephrase

We have rephrased the sentence accordingly.

400 definition of shelf break?

We have defined shelf breaks in section 4.1.1.

421 …….. in ….. detail in the beginning of sub section 4.2.3

We have added details of the age of MU-3 in the beginning of section 4.2.3, hoping this makes it more clear.

428-430 add Berger & Jokat (2009)

We have made the change accordingly.

441 everywhere?

We have rephrased this sentence.

444 Standard term?

Thank you, yes this is a normal term. deformation till refers to homogenised diamictic sediments transported subglacially to the ice margin.

449-454 MU-3 predominantly all glacial (?)

Thank you, and yes, the MU-3 is predominantly all glacial as stated in section 4.3.

453 sometimes too mixed (observations/interpretations/discussions)

Thank you, we have removed this part from the section 4.3 and elaborated on it in section 5.1.3.

Figure 7 How do you measure the intensification?

Thank you, the intensification is not itself measured in this study. We imply an intensified glaciation/ice stream activity on the shelf for MU-3 due to increased size and thickness of depocentres as described in section 4.2.3 and 5.1.3.

480-483 only the short event -> 6.4 -6.0 Ma?

Thank you, we have elaborated on this in section 5.1.1. The IRD input into the Fram Strait increases from 6.4 Ma, peaking around 6 Ma. This is a period of 400 ka of continuously increasing IRD in sedimentary records. In glacial context 400 ka is not considered one short event. For example, in the last 400 ka before present the Northern Hemisphere has had multiple glaciations of significant ice sheet growth, reaching the shelf edge. Similarily, the 400 ka period in late Miocene may have contributed to multiple shelf glaciations in NE Greenland. However, this study does not aim to go into further detail of each shelf advance.

484 how many subunits?

Thank you, in this study we have not divided MU-1 into subunits. Hence, the TMFs referred to here are solely divided geographically.

493-495 refer to Berger & Jokat (2009)

We have elaborated on the comparison with Berger & Jokat (2009) in section 5.2.

498-501 refer to Berger & Jokat (2009)

We have elaborated on the comparison with Berger & Jokat (2009) in section 5.2.

501 different time spans

We have rephrased this paragraph.

509 what means "most intense**"?**

By most intense we infer an ice stream which drained the most ice towards its terminus, and thus sediments. i.e. it can be large is size, velocity, duration or sediment flux. However, we do not know if this is because the ice stream stayed here for a longer period compared to other locations, or if the ice stream velocity/sediment flux were higher here. We have rephrased the sentence to make this more clear.

515-517 what about erosion?

We have rephrased the paragraph slightly to clarify that we meant deposits on the palaeo-slope (i.e. underneath the present-day bank), and we added a sentence that we expect any deposits on the bank itself to be eroded by successive glaciations.

532-533 why?

We have rephrased this paragraph to make it more clear.

535 IRD peaks might be related to terminations of glaciations?

We have rephrased this sentence accordingly.

537 rephrase

We have rephrased this sentence accordingly.

567-571 more observation than discussion

We have rephrased this sentence accordingly.

Figure 8 check the time periods for MU-1, 2, 3, especially MU-1

We have checked the time periods and they are in agreement with the data we present. The time frame of MU-1 is however uncertain. We suggests it was deposited during late Miocene, corresponding to increases in IRDs into the Fram Strait during this period. We have elaborated on this in section 5.1.1.

Figure 8d western?

The earliest glaciations occurred in the northern/northwestern Svalbard-Barents Sea region.

585 there are more relevant references for it

We have added the suggested references and rephrased the section.

Figure 8 explain all abbrevations clearly

We have checked and all abbreviations should now be explained in the text.

608-610 Berger & Jokat (2009)

We have rephrased this paragraph to better include the work by Berger & Jokat (2009).

614-615 what do you mean? What about the ….. …… early late Miocene before 6.4 Ma?

We have addressed this in the same rephrased paragraph as above.

624 ODP 907?

Butt et al (2001) used the core from ODP Site 987. We have added this in paranthesis.

637-640 what is the uncertainty range of NEG-3

We have added the uncertainty range of NEG-3 in the text.

645-654 limitations of seismic correlation without new drilling

We added a sentence on this at the end of the paragraph.

662 Berger & Jokat (2009)

We have rephrased the sentence.

699 what is the sedimentary structure below the bank?

The sedimentary structure below the bank at this site is dominated by salt diapirs which fold surrounding sedimentary rocks and possibly cause doming of the seafloor. However, this study does not aim to go into detail between the interactions between ice drainage pattern and subcropping sedimentary rocks/salt. However, we have briefly elaborated on this in section 5.1.2.

714-715 just add…….?

We have slightly rephrased the first sentence.

715 would prefer late Miocene cooling or LMC

We have made changes accordingly.

728 Not clear yet

We have rephrased the paragraph.

728 maybe not all is related to ice streams?

Based on the description of the units, their seismic facies, sediment distribution and geometry we interpret the depocentres to be TMFs deposited at the terminus of grounded ice streams as stated in section 4.3 and 5.1.

Figure S1 add profile names

We have made changes accordingly.

Figure S2 rotate figure to allow full page size

We have made changes accordingly.

Figure S2 +AWI

We have made changes accordingly.

Figure S3 + AWI. Add profile names

We have made changes accordingly.

Figure S4 Linear scales? Add labels to maps to allow more easy reading

We have made changes accordingly. Each map is labelled above the colour legend.