Reply on RC1.

We thank the reviewer for their positive and constructive comments on this manuscript. In the response below, we address the comments made by Reviewer 1 (Edouard Ravier) and explain the changes we have made to the manuscript. Reviewer comments are in black, and our responses are in red.

References to line numbers relate to the revised track-changes document.

Review of Carter et al. – High-resolution DEM of the NEGIS Onset

In this study, Carter et al. present the first high-resolution (25 m) digital elevation model (DEM) of subglacial topography at the onset of the Northeast Greenland Ice Stream (NEGIS), derived from swath radar imaging. The data reveal the presence of mega-scale glacial lineations (MSGLs) beneath the ice stream onset zone—a truly relevant discovery given the relatively low present-day ice velocities (~60 m yr^{-1}), which are considerably lower than the velocities classically associated with the formation of MSGL formation.

The authors interpret a subglacial landscape composed of both soft-sediment features (e.g., MSGLs, sedimentary basins) and hard-bed landforms (e.g., crag-and-tails, drumlins), indicative of a complex, mixed-bed basal environment. The presence of these lineations far inland (~600 km from the coast) and near the ice divide (~200 km) challenges conventional associations between MSGLs and rapid ice flow, suggesting instead that relatively slow but sustained ice streaming may suffice for their development. This has important implications for the use of subglacial bedforms as indicators of past ice dynamics and flow velocities.

The manuscript is concise, clearly written, and well-illustrated. The unexpected discovery of MSGLs in an area with modest ice flow velocity is particularly significant, and the study will be of broad interest to the community, especially those reconstructing past ice-sheet dynamics from the morpho-sedimentary record. However, I have several comments and suggestions for strengthening the discussion and interpretations. Especially the discussion would benefit from greater clarity around MSGLs genesis and evolution, including mechanisms for MSGLs formation under varying basal conditions.

Major Comments

Interpretation of Sediment vs. Bedrock Features

The interpretation of landforms as either sedimentary or bedrock-based is critical to the study's conclusions. However, this distinction is primarily made using morphologies depicted in DEM. I recommend that the authors more clearly justify how these distinctions are made (give a guideline for identifying sediments or bedrock) and discussing the associated uncertainties.

In Section 3.1 (lines 230-233), we have added reference to Riverman et al. (2019) which identifies water-saturated, deformable sediment in a topographic low beneath the north-western shear margin, in an area where MSGLs are forming. We have also added the clarification in Section 3.1 that in the absence of seismic data directly overlying the areas of bedrock, this interpretation may have higher uncertainty (lines 216-217).

Timescales of MSGL Formation

The authors suggest that 2000 years is a short period for MSGL formation. Please clarify: short compared to what (other studies, modelling)? You could include comparisons with MSGLs associated with rough dating of ice stream duration in other settings (e.g., Margold et al., 2018; Laurentide ice sheet) to contextualize this assertion. Some of the ice streams are suggested to be short-lived in Margold studies while elongated streamlined bedforms are also described in some of them.

This is a relevant point, and we agree that the timescales of formation of MSGLs are not clearly known, however this dataset can provide a constraint on this. We have added this comparison at lines 363-366:

"As well, there is evidence from the palaeo record that ice streams can switch on and off over just a few hundreds of years. During deglaciation of the Laurentide Ice Sheet, it has been shown that around 40% of ice streams operated for <2,000 years (Stokes et al., 2016; Margold et al., 2018), although very few of these ice streams record MSGLs so close to the inferred ice divide."

Organization of Section 2.2

Much of the content in Section 2.2 introduces and describes landform characteristics from the swath radar images and should be part of the results section rather than the Methods. This reorganization would also reduce some redundancies between Sections 2.2 and 3.1.

We agree that there is some duplication between these two sections, so we have integrated the landform characteristics we use for interpretation into the results section 3.1. Sentences have been removed in Section 2.2 (lines 151-166) and reintegrated in Section 3.1 (lines 190-192, 206-211, 221-222).

Discussion of MSGL Formation Scenarios

The authors could expand the discussion by considering various combination of factors that could control the evolution of bedform metrics, i.e. ice flow speed, duration, sediment availability and deformability that could occur at the NEGIS:

Slow flow / long duration

This scenario has been discussed in Section 4.2 (lines 353-366).

Slow flow / short duration + highly deformable sediments (low cohesion, high dilatancy, high porewater pressure

We propose that the MSGLs described here are formed under slow flow within the last 2000 years in lines 371-372. However, we added a comment here (lines 374-375) that this could be enabled through the presence of highly deformable sediments with high porosity and dilatancy, which has been identified in an area where these MSGLS form by Riverman et al. (2019).

Episodic fast flow (e.g., surging phase of ice streams, maybe in relation with changes in subglacial hydrology) during short duration

Surging is defined as the active time of a glacier between quiescence phases. We lack any evidence that the NEGIS at its onset is surging or has surged in the past, and do not think that this term applies here. The analysis of the folds in the shear margin by Jansen et al. (2024) in terms of fold geometry and accumulated strain indicate a relatively steady flow after the onset of the NEGIS. Although we cannot rule out shorter periods of faster flow, which did not leave any noticeable imprint in the ice (e.g., folds) or basal morphology, the tentative correlation of the temporal length of an active surge period with the size of the catchment would rather indicate that a surge of a NEGIS-type ice stream would last several hundred years. Such a dynamic change would have left imprints in the ice. In contrast, for us it seems more plausible to consider the current state of NEGIS as an active surge period that initiated about 2000 years ago (Jansen et al. 2024) rather than that the present state could be considered a quiescence phase.

In terms of the subglacial hydrology, Karlsson and Dahl-Jensen (2015) show that ice-sheet geometry changes can lead to changes in subglacial water flow routing and this could potentially affect the conditions under which the subglacial landforms at NEGIS form. However, the how and when this may have occurred remains speculative.

Lateral variation in till thickness?

Although our interpretations indicate that bed properties vary, a variation in till thickness is something that we cannot quantitatively constrain at this point in time without additional data (e.g., spatially complete seismic surveys). Therefore, we would prefer to leave this out of the discussion at this stage because it would be too speculative.

Role of Meltwater

Could meltwater have contributed to the rapid formation of MSGLs, (erosion? Increasing ice flow velocity)? Is there any evidence for upstream subglacial lakes, as seen in Antarctica?

We have discussed the role of meltwater by adding a paragraph in Section 4.2 (lines 326-334):

“In addition, the role of subglacial meltwater and its potential contribution to MSGL formation in this context is difficult to constrain. Subglacial hydropotential modelling has indicated that water is concentrated into and along the shear margins (Christianson et al., 2014, Franke et al., 2021), and moves through this region in a distributed system with only limited regions of continuous channelisation (Riverman et al., 2019), suggesting that it has a limited role in bedform development. Observations from phase-sensitive radar measurements at the EastGRIP ice core site quantify basal melt rates at 0.19±0.04 m a-1 (Zeising and Humbert, 2021), which is suggested to arise from the subglacial meltwater system, but information on subglacial water volume is very limited. Subglacial drainage cascades have been observed albeit much further downstream (Andersen et al., 2023), so subglacial water is likely to exist further upstream, but in smaller amounts below the detection limit of this method, as the amount of subglacial water will cumulatively increase downstream.”

Minor Comments

The shear margin should be depicted as a band rather than a line; its width and evolution could influence the interpretation of some nearby landforms (being along the shear band rather than outside the ice stream).

The transition of ice flow velocity is illustrated in Figure 6, which can be seen relative to the location of the mapped geomorphological features. In Figure 5, we used a dashed line and note in the figure caption (lines 204-205) that this represents the central point of the shear zone (i.e. the maximum shear strain rate), and that the zone itself is much broader.

Terminology should be standardized early (e.g., "elongated ridges" vs. MSGLs vs. drumlins vs. crag-and-tails).

This is addressed in the reorganisation of sections 2.2 and 3.1 described above, where we clearly define these terms based on existing literature. Sentences have been removed in Section 2.2 (lines 151-166) and reintegrated in Section 3.1 (lines 190-192, 206-211, 221-222).

Consider including a rose diagram showing the orientation of MSGLs relative to present-day ice flow vectors and maybe relative to the axis of shear margins.

A rose diagram is present in the top left corner of Figure 6a, illustrating the orientation of the MSGLs.

If you can mark locations of sediment cores or previous seismic data from existing literature on Figure 1 to highlight how this survey area extends previous knowledge.

We have added the seismic points from Christianson et al. (2014) to Figure 1 (line 52) and added this information to the figure caption (line 56-57).

Maybe consider the possibility that oblique ridges seen are deformed ribbed bedforms (long axis 45° oblique to the MSGLs and shear margins (becoming oblique, or due to lateral strain variations in the shear zone, cf. lines and circles on Figure 7 on the annotated pdf).

We agree that the landforms referred to here may be deformed ribbed bedforms, and have added a sentence in Section 3.1 (lines 218-220):

"Some geomorphic ridges (e.g. in the centre of Figure 4e), with a long axis 45° oblique to the MSGLs and shear margins, may represent deformed ribbed bedforms, which are a transitional bedform resulting from the deformation of flow-transverse ridges (Vérité et al., 2024; Vérité et al., 2023)."

We have also labelled these ridges in Figure 5.

A brief overview of competing models for bedform formation (e.g., bed deformation vs. accretion/erosion) as a preamble for MSGLs explanation would strengthen discussion and interpretation

We have added a brief overview of models of MSGL formation in Section 1 (lines 90-101).

"In addition, different formational mechanisms for MSGLs have been proposed and there is, as of yet, little consensus in the literature. Early ideas tended to focus on their construction via processes of subglacial deformation under high ice velocities (a velocity-duration product) (Clark, 1993). Others have proposed an erosional mechanism through the catastrophic discharge of turbulent subglacial meltwater (Shaw et al., 2008) or via the erosion of pre-existing sediments to reveal a streamlined surface of megaridges (Eyles et al., 2016). Indeed, some have focussed on the grooves between the ridges and suggested that MSGLs may be the erosional remnants or intervening ridges from a 'groove-ploughing' mechanism, where roughness in the ice base passes over a bed of soft, saturated sediments (Clark et al., 2003). A more recent hypothesis invokes a rilling instability (Fowler, 2010), where the water flowing between ice and deformable subglacial sediment is unstable, and will form linear streams/rills separated by intervening ridges. Related to this hypothesis is the instability theory of the coupled flow of ice, water and till, which has successfully modelled the formation of a continuum of subglacial bedforms, including MSGLs (Ely et al., 2022). Although most work on MSGLs has utilised observations from the palaeo-record, geophysical data of their presence under extant ice sheets (e.g. King et al., 2009) offers a powerful tool to test some of these various formational hypotheses."

Line by line comments from annotated pdf

Line 70: precise the range of scale

We have added "(10s to 100s of metres)" after "small-scale" to this sentence in line 71.

Line 79: provide the range of scale of MSGLs to enable comparisons with the resolution of your data

The range of scales of our MSGLs are described in Section 3.1 (line 190), and we referred to the metrics of MSGLs from Vérité et al., 2024 now in line 320.

Line 81: not necessarily down-flow, this can also be lateral especially when crossing ice streams and their shear margins (Vérité et al., 2021).

This is a good point. We have added a sentence at line 85:

“Similar transitions in between evolution are also observed laterally, such as when crossing from the centre of an ice stream to its shear margin and beyond (Stokes & Clark, 2002; Vérité et al., 2021).”

Line 83: and duration of deformation, involved in cumulative strain, see Vérité et al., 2024.

This is a good point; we have changed the sentence as follows (lines 86-88):

“However, the inferred link between MSGLs, ice streaming, and the duration of their deformation related to cumulative strain at the base of the ice is largely qualitative with very few quantitative modelling studies (Jamieson et al., 2016, Ely et al., 2022, Vérité et al., 2024)”

Line 84: Most models tend to propose that that till deformation is responsible for MSGLs formation

We removed the last part of this sentence here (line 89).

Line 89: only spatial evolution? Do you have access to the temporal evolution?

We clarified this as spatial evolution (line 92).

Line 117: not sure to understand where does this number come from.

This angle correction was needed in order to overlap and accurately align each swath, so this is clarified here (line 122).

Line 130: Should it be part of the result sections?

in this section, you characterize the landscapes without giving the range of lengths, widths, elongation ratio, areas, etc... How many landforms and bedforms did you map ?

I saw that this is given later in the result section, I wonder if this section where you start describing the range of features you observed at the bed should not be in the "results" section.

This has been addressed as described above as we have integrated the landform characteristics that we use for interpretation into the results section 3.1.

Line 134: it would be better if could argument here, based on bedforms and landforms metrics why do you interpret lineations as being MSGLs rather than flutes or drumlins for examples. Based on Fig. 4a, I agree with you but maybe giving a few words on this will be relevant.

This explanation is now integrated into Section 3.1, where the characteristics of the identified MSGLs are described (e.g. elongation ratios in line 190).

Line 139: some of these types of landforms are made of sediments, some others are not? How do you make the difference on the DEM of the NEGIS bed.

Line 149: How did you differentiate bedforms (made of sediments) from other landforms (crag and tails, erosional drumlins, etc.)... Bed roughness ?

These two comments are addressed as described above in the changes to Section 3.1.

Figure 4c: could be seen as undulating ribbed bedforms depending on how you decided to delineate this contour. Figure 4e: some of the ridges seem to be elongated oblique to the ice flow direction given by the lineations…We saw similar things near the margins of some ice streams (Vérité et al., 2021, 2024)

The possibility of these landforms being deformed ribbed bedforms has been added in Section 3.1 (lines 218-220) as described above.

Line 164: please provide figure, here or in supplementary material, also provide the width of the shear margin

Our response to the representation of the shear margin is to edit Figure 5 as described above.

Line 179: again how do you differentiate bedrock from subglacial tills

This comment is addressed in Section 3.1 (lines 216-217, 230-233) as described above where we consider the seismic data available from Riverman et al. (2019).

Figure 5: channel long profile in supplementary material

Given the artefacts that cross-cut the channel long profile, we are not sure that this would give an accurate representation, and therefore had decided to omit this.

Line 187: is outcrop the right term?

To be more specific to this landform, we have changed this to ‘crag’ (lines 209, 210). In other cases, we think that the term outcrop is used correctly.

Line 199: not such a big difference between large meltwater channels and tunnel valleys, how would you differentiate this, is this just a matter of label rather than processes of formation

This reference to potential tunnel valleys is due to the scale of the channels, as they are much larger than Nye channels incised by meltwater, for example.

Line 205: do you mean that this shear moraine might probably continuous instead? How this "dissection artefacts" would affect other landforms and bedforms mapped in the area.

It’s unclear whether this shear moraine might be continuous or dissected. It may be a function of its orientation oblique to the flightlines, as the MSGLs mapped are less subject to this effect and appear continuous across multiple swaths. This is now clarified in the text (lines 225-227).

Figure 5b: Show this shear zone in (a)

As discussed above, the transition in velocity is visible in the colourmap of Figure 5(a).

Line 248: does this term encompass: crag and tails, MSGLs?

We have clarified this and change elongate ridges to crag-and-tails (line 284).

Line 253: Vérité et al., 2024 might be more relevant especially when discussing slip speed.

Thank you, we have corrected this reference.

Line 254: there is no consensus on the quantitative estimation of speed associated with the different types of subglacial bedforms, only few studies have numerically attempted to quantitatively associate deformation rate of subglacial till (not direct ice flow velocity) with bedform morphologies....and this is based on many assumptions...I would be therefore careful with the term typically here.

This is a good point, so we removed “typically” here (line 289).

Line 259: Vérité et al., 2024

This reference will be added here (line 295).

Line 259: same comment as above...In barchyn and Ely, this is the speed of the moving till layer I think.

We have clarified this sentence as follows (lines 293-296):

“When modelled, as ice base velocities and the speed of the moving till layer increase to 100s m yr^{-1}, drumlins have been hypothesised to evolve and elongate into MSGLs (Stokes et al., 2013, Barchyn et al., 2016, Ely et al., 2022, Vérité et al., 2024), but there is little work that quantitatively links bedform elongation to ice flow/slip speed and the assumptions are mostly qualitative.”

Line 277: this is a good argument for this and this should maybe a little bit more discussed. i.e. How the advection of the folding of the internal stratigraphy would suggest that NGEIS has unlikely experienced high ice flow velocity in the past.

This point was also raised by another reviewer, so we have proposed to explain this logic more thoroughly as follows from line 338-345:

“However, it is unlikely that the NEGIS experienced higher ice velocities prior to the localisation of the shear margins 2000 years ago (Jansen et al., 2024). The folds in the isochrone observed at the NEGIS onset in Jansen et al. (2024) are consistent with folding due to convergent flow of ice (similar to Petermann, for example), which are then sheared where they are intersected by the shear margins, causing them to rotate and tighten. The timing of this intersection of the folds by the shear margin is constrained to 2 ka by both the offset of ~55-75 km of the fold hinges (as they are advected with ice flow over ~2000 years) as well as the cessation of fold amplification at 2 ka.”

Line 285: very cautious

For us it is not fully clear what this comment is referring to or suggesting. If it refers to the sentence: “*Thus, we would consider the plausibility of these MSGLs being formed from a faster configuration of the NEGIS to be unlikely*.” or just the word “*unlikely*”, we do not see the necessity to rephrase. In our opinion it is a carefully phrased statement (“*would consider the plausibility*”), suggesting that based on our data and the literature at hand, we see no evidence why a faster configuration of the NEGIS should have been likely.

Line 292: It will be interesting to compare to bedforms in some of the short-lived palaeo-ice streams (Margold et al., 2018) ...For ice streams supposed to have been existing for very few thousand years, I think that very elongated bedforms are also observed.

This comparison has been added at line 363-366.

Line 301: compare to the bedform metrics database of Vérité et al., 2024 to have a more realistic range of MSGLs thickness

We have updated these numbers according to Vérité et al., 2024 (line 320).

Line 308: why not even during THIS glaciation?

As discussed in Section 4.2, we think that we have addressed the unlikelihood of a previous episode of faster flow in this glaciation (lines 335-352).

Line 327: Agree. We need to consider the cohesion and strength of sediments, their thickness, the porewater pressure, cumulative strain (recording either flow velocity, alternating coupling and decoupling and duration of deformation).

Thank you for this comment.

Table A1: same table for other landforms?

The morphometrics (lengths and elongation ratios) of the MSGLs are displayed in Figure 5b and 5c, and written in lines 190 and 195, therefore, we think that this would be a repetition of this information.

Reply on RC2.

We thank the reviewer for their positive and constructive comments on this manuscript. In the response below, we address the comments made by Reviewer 2 (Kiya Riverman) and explain the changes we have made to the manuscript. Reviewer comments are in black, and our responses are in red.

References to line numbers relate to the revised track-changes document.

This paper presents a novel and compelling dataset describing bedforms of the initiation of the NE Greenland Ice Stream (NEGIS). Studies of this ice stream are impactful because of the unique geometry and flow style of the ice stream: it extends deep within the interior of the Greenland Ice Sheet, and rapid flow initiates from a singular point, with flow widening downglacier. Interestingly, NEGIS does not flow within a bed trough — the locations of its shear margins are set by some process other than topographic forcing. This means that there is the potential for the ice stream to widen or shrink on rapid timescales. There has been a history of publications discussing the role of the bed in controlling the location and geometry of this ice stream using seismic and radar surveying. However, since those publications were released, radar surveying techniques have improved to now allow for much a much higher resolution look at the shape of the bed. What this enables is now a very compelling test of many of the hypotheses laid by prior work. With a more complete view of the bed of NEGIS, we can better understand how its subglacial geology and hydrology control its flow. The new radar dataset shows a streamlined bed with a variety of interesting features worthy of discussion. The dataset itself is well worthy of publications in TC, though I have some concerns about how the interpretation of the features is placed within the context of existing literature from the same field site.

As it stands, the paper draws strong conclusions from only one geophysical dataset instead of positioning itself as an excellent hypothesis test (our validation) of theories about controls on NEGIS that were developed with other geophysical data sets. The manuscript would be improved by incorporating the results of prior geophysical surveying (radar, common offset and common midpoint active seismic surveying) to strengthen the interpretations made here. With the incorporation of prior surveying into the analysis presented here, the paper will be a robust contribution to the literature on this important ice stream.

The radar survey of Christianson et al (2014) includes processed basal reflection strength within the survey area suggesting regions of wetter and drier bed, which could be used to support your hypothesis. The same radar survey was processed to focus on internal stratigraphy in Keisling et al (2014) which drew the conclusion that NEGIS has been a persistent feature across the Holocene and that modern flow is accommodated by a slippery bed. The active-source common offset survey of Riverman et al (2019a) identifies bed material across the ice stream (as seen in their Figure 2). These results alone, if incorporated into the existing manuscript, would strengthen the interpretation of bed materials across the ice stream. The seismic AVO work of Christianson et al (2014) could also be better incorporated.

We thank the reviewer for their constructive comments and have outlined our responses below.

199 What other evidence exists that these are large channels? These are LARGE channels — it would be somewhat of a surprise to find the sufficient volume of water necessary to carve them this far into the accumulation zone. Do the channels follow hydropotential lows? Or topographic lows? Whether or not the reflect subglacial water drainage or proglacial water drainage might be able to be determined from their relative positioning across the wider landscape.

To determine if these channels follow hydropotential or topographic lows, we would need hydrological modelling, which we think is outside the scope of this paper since the focus is mainly on MSGLs. In addition, the calculation of hydropotential routing would not be optimal with the DEM in its current configuration, due to the upwarping swath edge artefacts described in Section 2.1. However, this would be an interesting follow-up for future work.

The role of subglacial meltwater has also been discussed in more detail in Section 4.2 (lines 326-334), as detailed in the response to Reviewer 1.

201 Prior radar and seismic work across the shear margins at this location has identified these as shear margin moraines and discussed formation hypotheses — that work should probably be discussed here (Riverman et al 2019a). How does this new dataset either support or reject the formation hypotheses put forward in that paper (that ice 'drops' its subglacial sediments as it enters the ice stream and effective pressures drop).

We agree that this work should be discussed here, and will refer to the previously identified bedforms in more detail in this paragraph (lines 226-227). Since these data were not available online, it was difficult to ascertain whether the ridges we observe here were exactly the same bedforms that are described in Riverman et al. (2019). Whether this dataset supports or rejects the formational hypotheses proposed is unclear, and we would say that this would also be a potential for future follow-up work.

222-230 This section oversimplifies the conclusions of Christianson et al (2014). That paper finds a drape of subglacial till broadly across the entire region. Those sediments become dilatant within the fastest flowing section of the ice stream - but this is a result of fast ice flow (not the cause for fast ice flow). Christianson argues that the positioning of NEGIS is a more complicated hydrologic feedback — effectively, water is broadly present across the region, but routing of water to the shear margins (because of the hydropotential low set by the ice surface troughs) causes water to collect in the shear margins. This dries the region adjacent to the shear margins, slowing ice incorporation into the shear margins. Those ideas were then further supported by Riverman et al 2019a and 2019b, which performed detailed hydropotential analysis and meltwater routing modeling across the region and found that water indeed should be routed to the shear margins. Does this new dataset support this hypothesis for what sets the shear margin location of NEGIS?

Here we intend to make the comparison that the conclusions from the Christianson et al (2014) only infer subglacial till, whereas the swath data now allows us to visualise a much wider area of the subglacial bed and therefore we can infer the presence of bedrock outcrops. Therefore, we rephrased the last sentence as follows (lines 260-264):

"Christianson et al. (2014) infer from their observations that an underlying layer of dilatant till might explain the presence of the ice stream in this location and its lack of a major subglacial trough, but our observations of a mixed bed landform assemblage would suggest that the characteristics of the bed are perhaps more heterogenous than previously recognised."

We have also added a paragraph in Section 4.2 discussing the role of subglacial meltwater and its potential contribution to MSGL formation (detailed in the response to Reviewer 1), although we would not draw conclusions from this dataset regarding the location of the NEGIS shear margin.

245 Some of the main conclusions presented in this manuscript are that MSGLs can form at slower flowspeeds than previously thought — is it possible that they could even form at flow speeds down to 10-25 m/yr?

Given that no MSGLs are present outside of the shear margins, where the flow speeds are between 10-25 m yr^{-1}, we would assume that this would not be this case. If it were, then presumably MSGLs would be much more prevalent across deglaciated landscapes.

246 If the shear margin moraine forms through sediment rain-out during ice incorporation into the ice stream, then perhaps this could occur quickly, and this margin too could be a more transient feature.

This is a good point, although this is difficult to constrain from our data. Since the north-western shear margin has been observed in the radargrams to have shifted in Jansen et al. (2024), and no such jump is evident on the south-eastern side, we would think that it is more likely that the north-western margin is a transient feature in comparison to the south-eastern.

275-280 I found it difficult to track the logic through this section. I would expand on these arguments so that they are more clearly made. Specifically, how would we have observed higher shear strain rates within the margins at some point in the past? In the paleo record in some way?

We have added this clarification into this paragraph at lines 341-349 to better explain the logic:

"The folds in the isochrone observed at the NEGIS onset by Jansen et al. (2024) are consistent with folding due to convergent ice flow (e.g. similar to Petermann Glacier), which are then sheared where they are intersected by the shear margins, causing them to rotate and tighten. The timing of this intersection of the folds by the shear margin is constrained to 2 ka by both the offset of ~55-75 km of the fold hinges (as they are advected with ice flow over ~2000 years) as well as the cessation of fold amplification at 2 ka. When the shear margins localised in their current location, the ice stream was decoupled from the interior of the ice sheet, as the rotation of the orientation of the ice crystal basal planes lead to mechanical weakening in the shear margins (Gerber et al., 2023), which in turn facilitates localised deformation and the faster flow observed at present. Higher velocities would have produced higher shear strain within the margins, for which the analysis of the fold amplitudes by Jansen et al. (2024) did not show any evidence."

Figure 5 this figure reflects the sum of so much work — I could spend hour staring at it! No notes, just impressed.

Thank you for this kind comment.

Again, this work is impressive for its generation of a truly novel dataset that has the potential to really change the way we think about NEGIS. I apologize for being so 'you should better incorporate my work into this work' in this review — I usually try to avoid that! I also see that the seismic works I'm suggesting be incorporated here are not readily available online, which likely limited any efforts you would have made in that space. Dang! I am happy to provide any/all of the Penn State seismic surveying effort and processed results. Please do not hesitate to be in touch, riverman@up.edu

Citations for works mentioned above

Christianson 2014: Dilatant till facilitates ice-stream flow… EPSL

Riverman 2019a: Wet subglacial bedforms of the NE Greenland Ice stream shear margins. Annals of Glaciology

Riverman 2019b: Enhanced firn densification in high-accumulation shear margins of the NE Greenland Ice Stream… JGR Earth Surface

Keisling et al 2014: Basal conditions and ice dynamics inferred from radar stratigraphy… Annals of Glaciology

--Kiya Riverman

Reply on CC1.

We thank the commenter for their positive and constructive comments on this manuscript. In the response below, we address the comments made by Jessey Rice and others, and explain the changes we would make to the manuscript. Comments are in black, and our responses are in red.

References to line numbers relate to the revised track-changes document.

General comments:

The manuscript provides significant new insights into the subglacial geomorphology and subglacial evolution of the NEGIS. The identification of MSGLs under current low velocities and within relatively close proximity to an ice divide provides an important contribution to our understanding of subglacial dynamics. While this data provides invaluable details on subglacial landform geology and basal conditions, we feel this argument could be strengthened with a brief discussion of paleo-reconstruction from the LIS that has also highlighted warm-based, moderately fast-flowing conditions in relatively close proximity to ice divides (e.g., Hodder et al., 2019; Rice et al. 2020; McMartin et al. 2021). Specifically, Hodder et al. (2019) identified a complex till stratigraphy that suggested considerable till production in the vicinity of the last position of the Keewatin Ice Divide, possibly related to deposition as part of a large tributary ice stream flowing north toward the Arctic Ocean.

McMartin et al. (2021) identified that the Dubawnt Lake Ice Stream propagated back to an area where the Keewatin ice divide migrated over and is presumed to have been located. Paulen et al. (2017, 2025) documented mineral dispersal from a rare earth element deposit occurring in the trunk of the Kogaluk River ice stream at Strange Lake, Labrador, where the onset zone of that ice stream (IS #187 of Margold, 2015) was a mere 30 km from the mapped location of the Ancestral Labrador Ice Divide in the George River region (Dubé-Loubert et al., 2021). Finally, Rice et al. (2024) provided evidence of ice divide migration in close proximity to both the Ungava Bay Ice Streams, the Cabot Lake Ice Stream, and the Smallwood Reservoir Ice Stream. We believe these LIS comparative studies, especially their documentation of "mixed bed landform assemblages," provide particularly insightful examples for your manuscript, as they may have had similar glacial lineation formation to what you are observing in the NEGIS. Again, this manuscript provides important insights into the formation of these subglacial conditions, which offer unique insights into the broader subglacial mechanics at play, especially regarding ice flow velocities. However, we believe the examples from the LIS will also provide important insights into their formation and preservation. Please see specific examples below. If you have any questions or require any clarification on these comments, please feel free to reach out to me: jessey.rice@nrcan-rncan.gc.ca.

Jessey Rice, Geological Survey of Canada, Ottawa

We thank the commenters for their suggestions on how to strengthen the arguments in our manuscript, and agree that the some of the studies listed above are useful comparison points. We are very familiar with much of the work outlined above and completely agree that the onset zones of palaeo-ice streams in North America extended up-ice and very close to the position of the inferred ice divides. However, our key finding is that highly elongate bedforms (which we interpret as MSGLs) exist very close to the present-day ice divide. Few of the studies cited report evidence of MSGLs so close to an ice divide, although we would be happy to be corrected.

Specific examples:

Line 220 (Dowdeswell et al., 2014), the Amundsen Sea Embayment (Graham et al., 2009) and the North Sea (Roberts et al., 2019) (Fig. 7). These types of subglacial landscapes are characterised by the presence of crag and tails, drumlins, and highly elongate lineations, and thought to be formed under ice streams (Roberts et al., 2019; Dowdeswell et al., 2014; Graham et al., 2009)

Additional North American studies that could strengthen this argument: Margold et al. (2015), Eyles et al. (2018), Sookhan et al. (2021), Rice et al. (2024).

Thank you for this suggestion. We have also referenced Eyles et al. (2018) here (lines 253-254), as it demonstrates the combined presence of bedrock outcrops and deforming sediment. We are familiar with the inventory of ice streams in Margold et al. (2015) but, having inspected those ice stream beds in detail, very few record MSGLs so close to the inferred ice divide.

Line 266: To our knowledge, the only other high-resolution survey of an ice stream onset zone (King et al., 2007) revealed classic drumlin forms (elongation ratios 1:1.5 to 1:4) and a potential ribbed moraine under Rutford Ice Stream, West Antarctica, where velocities accelerate from 72 to >200 m yr-1. Furthermore, the location of the MSGLs in our study, 600 km from the grounding line and only ~200 km from the main ice divide, is also the furthest inland that MSGLs have been identified

Depending on the definition of high resolution, air photo interpretation (see Geological Survey of Canada Canadian Geoscience Maps (CGM) 410 and 429 (1:100 000 scale) produced from 1:60 000 scale air photos) indicates the onset zone of an ice stream in even closer proximity to the divide (summarized by Rice et al., 2024). Similar findings using higher satellite imagery were made by Dubé-Loubert et al. (2021).

Here we were referring to high-resolution DEMs of modern ice streams, rather than surveys in general, and have clarified this as follows (line 304):

"To our knowledge, the only other high-resolution survey DEM of a modern ice stream onset zone (King et al., 2007) …"

As noted above, we are aware of ice stream onset zones extending very close to ice divides, but these are not usually characterised by well-developed MSGLs and have made that point clearer in the revised manuscript.

Line 270: Furthermore, the location of the MSGLs in our study, 600 km from the grounding line and only ~200 km from the main ice divide, is also the furthest inland that MSGLs have been identified.

Assuming this is just for the NEGIS, as MSGLs have been identified further inland in other regions of former continental ice sheets (i.e., the Laurentide Ice Sheet), can you please clarify?

This again was only referring to surveys of modern ice streams, so we have clarified this and also refer to studies you have highlighted (Hodder et al., 2016; Rice et al., 2020; Dubé-Loubert et al., 2021; Rice et al., 2024) to show that onset zones can be located close to ice divides, although rarely with identified MSGLs (lines 311-313).

Line 308: Whilst we cannot rule out an episode of enhanced flow at this location in a previous glaciation, the sedimentary basins outside of the northwestern shear margin (Fig. 6) show little evidence of MSGL formation. This would mean that the ice stream would have to have formed in the same configuration as observed today in a prior glaciation, potentially with a higher velocity, to produce the observed MSGLs. Even so, if this had occurred, this would then suggest that MSGLs can be preserved for 100s to 1000s of years under relatively slow ice velocities.

We agree with this assumption, but postulate, is it potentially also possible that the lower velocity of the ice stream is due to ice divide migration closer to the study area? (i.e., was the divide previously further upstream and slowly propagated toward the study area, lowering velocity as it did so?

We would regard this possibility as unlikely, as the folding of the internal reflection horizons within the ice stream indicate a slower convergent flow regime prior to the localisation of the shear margins, after which the ice stream starts to flow faster (Jansen et al., 2024). In addition, the rotation of the orientation of the ice crystal basal planes lead to mechanical weakening in the shear margins (Gerber et al., 2023), which in turn facilitates localised deformation and faster ice stream flow. Also, modelling of the NEGIS and Greenland Ice Sheet would indicate that the ice stream propagates from its outlet glaciers upstream (Tabone et al., 2024), meaning that the velocities present at the onset now would have only increased to their current velocity, rather than decreased from a higher velocity. This is a highly difficult scenario to constrain, but with our current knowledge, we would not think this is not the case. This has now been discussed more thoroughly in Section 4.2 (lines 335-353).

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