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.

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, we will add 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 will also add 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.

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 would add this comparison at line 296:

"In addition, short-lived ice streams have been identified as part of the deglaciation of the Laurentide Ice Sheet, with around 40% operating for less than 2 kyr (Stokes et al., 2016, Margold et al., 2018), but this study could indicate that the velocities of these ice streams may not have been extremely fast."

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 will integrate the landform characteristics we use for interpretation into the results section 3.1.

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 the fourth paragraph of Section 4.2.

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 and a relatively short duration (i.e. within 2000 years) in line 313. However, we will add a comment here 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, and the reorientation of flow direction of an ice stream, for instance, does not imply a surge. 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 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 would discuss the role of meltwater by adding a paragraph before the last paragraph of Section 4.2:

“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 will use a dashed line and note in the figure caption 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 will be addressed in the reorganisation of sections 2.2 and 3.1, where we will clearly define these terms based on existing literature.

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 will add the seismic points from Christianson et al. (2014) to Figure 1.

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 will add a sentence at the end of the second paragraph in Section 3.1:

"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 will also label 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 will add a brief overview of models of MSGL formation in Section 1, ~line 85.

"Different formational mechanisms for MSGLs have been proposed, for example, through a constructive process involving the deformation of existing landforms composed of subglacial sediment under rapid ice velocities (Clark, 1993). Others propose an erosional mechanism through the catastrophic discharge of turbulent subglacial meltwater (Shaw et al., 2008), or a 'groove-ploughing' hypothesis, where roughness in the ice base passing over a bed of soft, saturated sediments would carve elongate grooves and deform the material up into intervening ridges (Clark et al., 2003). A rilling instability theory has also been put forward (Fowler, 2010), where the water flowing between ice and deformable subglacial sediment is unstable, and will form streams separated by intervening ridges."

Line by line comments from annotated pdf

Line 70: precise the range of scale

We will add "(10s to 100s of metres)" after "small-scale" to this sentence in line 69.

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, and we refer to the metrics of MSGLs from Vérité et al., 2024 now in line 301.

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 will add "or lateral morphological continuum…. (Vérité et al., 2021)" here.

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

This is a good point; we would change the sentence as follows:

"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 would remove the last part of this sentence here.

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

We will clarify this as spatial evolution.

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 will be clarified here.

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 will integrate 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 will now be integrated into Section 3.1, where the characteristics of the identified MSGLs are described (e.g. elongation ratios in Line 173).

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 as described above. We will also add some discussion of this possibility in Section 4.2.

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 will be 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 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 will change this to 'crag'. 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 will be clarified in the text.

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 will clarify this and change elongate ridges to crag-and-tails.

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

Thank you, we will correct 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 will remove "typically" here.

Line 259: Vérité et al., 2024

This reference will be added here.

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

We will clarify this sentence as follows:

"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)."

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 propose to explain this logic more thoroughly as follows from line 276:

"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 will be added at line 296 as per a comment above.

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

We will update these numbers according to Vérité et al., 2024.

Line 308: why not even during THIS glaciation?

As discussed in the third paragraph of Section 4.2, we think that we have addressed the unlikelihood of a previous episode of faster flow in this glaciation.

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, therefore, we think that this would be a repetition of this information.