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EGUSPHERE-2024-2486
Final response RC1

*We thank Colby Smith for his thorough review of our work and, in responding to raised issues, we will be able to present an updated version of the manuscript that contains important improvements in its writing, arguments, and figures. Below we will address the reviewer comments in the order they were presented. The reviewer's comments are given in default font, with our original text, on which the comments were made, repeated in italics for reference. Our response is given in blue-, and suggested changes to the manuscript in red-type fonts.*

**RC1 – Colby Smith**

**General comments**
The manuscript is well organized around the geomorphic map, and draws conclusions related to the timing and dynamics of both the ice sheet retreat and the associated glacially induced faulting in northwestern Sweden. I recommend that the manuscript be published after minor revisions.

I have made some minor comments related to language, grammar, or general readability. These are included in the attached pdf of the manuscript.

All linguistic changes when adopted clearly improve the general readability of the manuscript. We would like to express our thanks for the reviewers' thorough check of the language.

Here, I will focus on the single larger issue that I believe needs to be addressed prior to publication. The authors make a case that different segments of the Pärvie fault ruptured at different times during or shortly after the late Weichselian deglaciation. Along Torneträsk, the authors present a strong case for fault rupture shortly after deglaciation based on the fact that older shorelines are displaced by the fault but not younger shorelines. Farther south, the other examples of where faulting either precedes or follows deglaciation are not as well presented. I do not question your conclusions, but that is because I have spent a lot of time looking at these faults in LiDAR. Other readers may need further convincing.

The crosscutting relationships are not obvious in figure 10 and they are not adequately described in the text. Thus, I suggest revising figure 10 to be more like figure 3 and clearly show the crosscutting relationships between the fault and glacial landforms, and the fault and the shorelines. Additionally, include text that explains the crosscutting relationships and the conclusions drawn from them.
This is a nice contribution to the deglacial history of northern Sweden, and I look forward to seeing it published.

First, we want to thank the reviewer for his kind words and encouragement. We are pleased that our work is considered a contribution to the deglacial history of northern Sweden. Second, we thank the reviewer for pointing out the issue regarding the crosscutting relationships and for giving us the opportunity to revise Figure 10. We will provide a detailed response and revisions further down in the document, where we present an improved Figure 10 and a suggestion for an additional panel to Figure 6.

**Specific comments (as annotated in PDF)**

- *Lines 74-76: “Finally, a refined history of ice-marginal retreat potentially enables future investigations of the interaction between the retreating ice sheet and the re-activation of faults through glacial isostatic adjustment (Fig. 1b).”*

The primary stress related to these faults is tectonic (ie related to the spreading of the Atlantic). Glacial isostatic adjustment is more the trigger than the cause. See: Stewart, I.S., Sauber, J. & Rose, J., 2000: Glacio-seismotectonics: ice sheets, crustal deformation and seismicity, Quaternary ScienceReviews 19, 1367–1389.

The sentence will be adjusted to emphasize how the total stress field is comprised of both the presence of a regional tectonic stress and the superimposed glacially-induced stress.

“Finally, a refined history of ice-marginal retreat potentially enables future investigations of the interaction between the changing configuration of the retreating ice sheet and its marginal positions and a re-activation of faults through the overprinting of the prevailing regional tectonic stress with glacially-induced stress”.

- *Line 80: “The Torneträsk Basin cuts through the Scandinavian mountain range, also known as the Scandes, and across the border to Norway forms the headwaters of Rombaksfjorden (Rombaken; Fig. 2).”*

There is no subject in this clause. It is incomplete. What forms the headwaters? It's also unclear because it sounds like the Torneträsk basin is the headwaters of the fjord. Torneträsk drains to the east, the fjord is over a pass to the west.

The sentence will be altered to emphasize that Torneträsk basin is draining to the east. The confusion probably stemmed from Fig. 2 showing that during deglaciation the Fennoscandian Ice Sheet drained westwards across the Torneträsk basin and across the water divide, providing meltwater to Rombaksfjorden.

“The Torneträsk Basin cuts through the Scandinavian mountain range, also known as the Scandes, and drains to the east. Across the border to Norway, over a pass to the west, the headwaters of Rombaksfjorden are found (Rombaken; Fig. 2).”

- *Line 119: “Additional azimuths of 90°, °and 180°”...*

Should there be another direction here?

Thank you for finding this mistake! The degree symbol will be removed, there was no other azimuth used than the two mentioned.

“Additional azimuths of 90° and 180°”

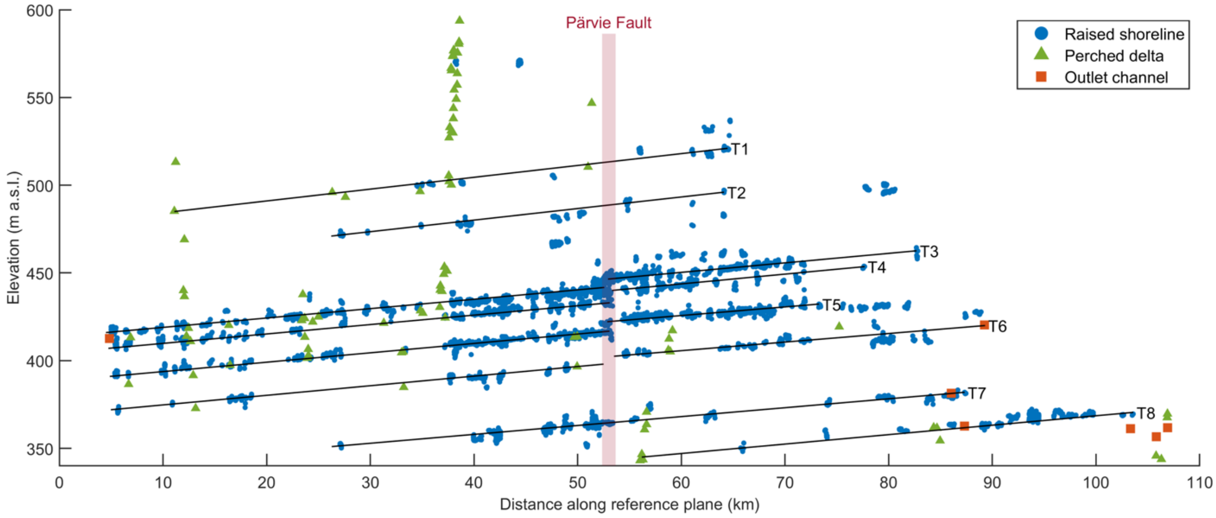
- *Line 259: “... there are no other geomorphological cross-cutting relationships that show the exact offset as well as the raised shorelines.”*

This is true, but the crosscutting relationship between fault and shoreline is not visible in the LiDAR imagery.

We suspect the confusion stems from the use of the phrase “as well as”, which was meant as “and also”, not as “as good as”. The crosscutting relationship between the fault and shorelines is only evident from regional analyses using the graph that plots the shoreline elevations along a reference plane (old and updated Figure 6, below), not from the LiDAR imagery itself due to the lack of continuity of the shorelines at the location of the fault scarp. This study is basically outlining a new technique to identify fault ruptures. The sentence will be changed to emphasize that the crosscutting is not visible in the LiDAR imagery.

“... there are no geomorphological cross-cutting relationships visible in the LiDAR imagery that show the offset of raised shorelines at the exact location of the fault scarp (Figure 6).”

Old Figure 6:



New Figure 6:

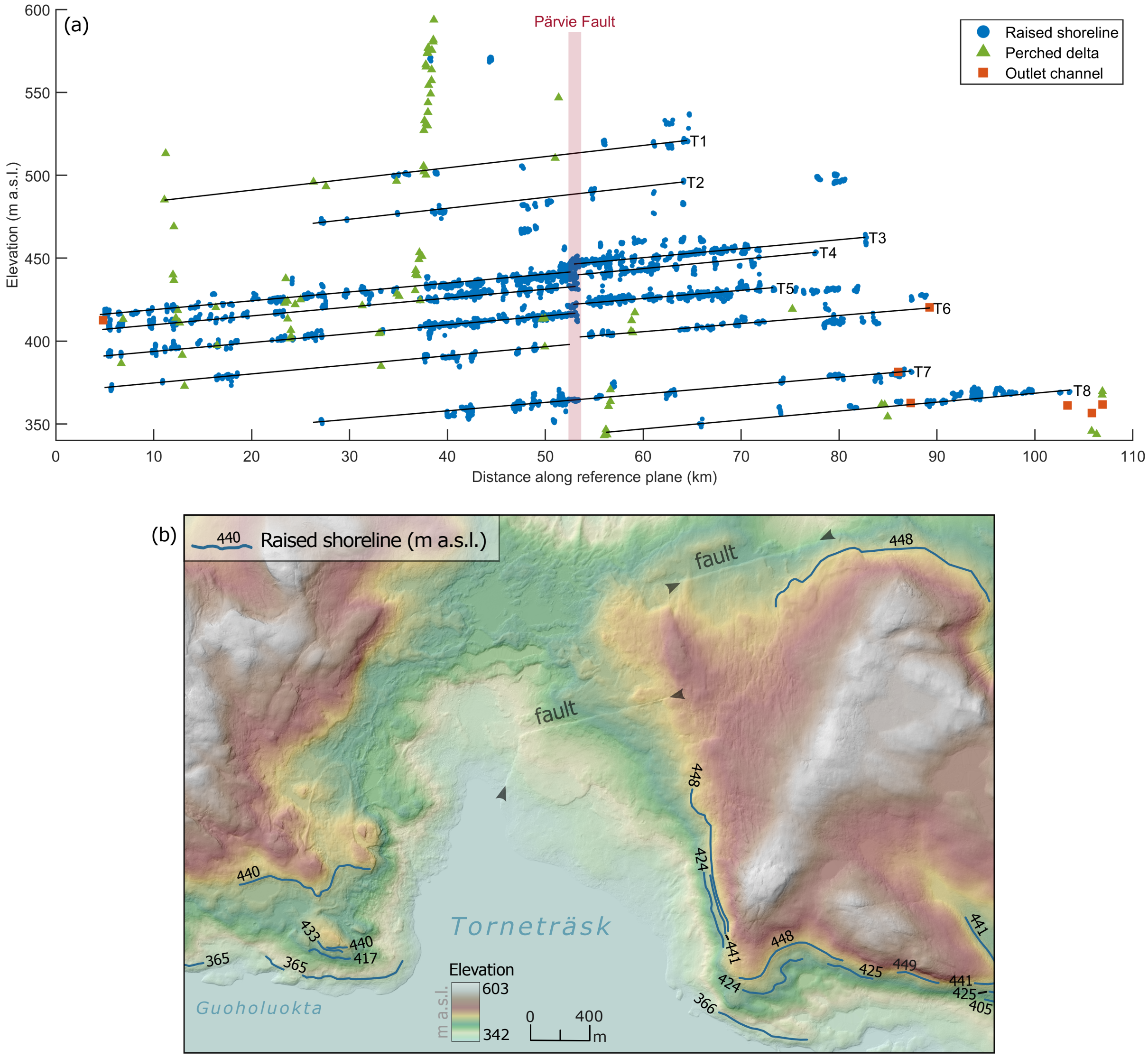



Figure 6. (a) Lake stages identified from the elevations of raised shorelines, perched deltas, and outlet channels of ice-dammed lake Torneträsk. At the Abscissa value of zero, the ordinate value is 342 m a.s.l., the current elevation of the surface of Torneträsk. The approximate location where the Pärvie Fault crosscuts the Torneträsk Basin is indicated by the red bar. The distance is calculated along an axis perpendicular to the isobases of postglacial rebound of the shorelines (see Fig. 1c). The corresponding elevation ranges are summarised in Table 2. (b) Elevations of raised shorelines of ice-dammed lake Torneträsk on either side of the Pärvie Fault where it crosscuts the northern shore of Torneträsk (see red bar in (a)), illustrating elevation jumps of around 8 m for the higher raised shorelines (T3-T6), while the lowest raised shoreline (T7) crosses the fault at 365–366 m a.s.l. The background is a shaded relief based on the DEM provided by ©Lantmäteriet.

- *Lines 260-261: "Remarkably, ice-dammed lakes T1 and T2 do not appear to have been offset by the Pärvie Fault, although this has perhaps remained unrecorded due to a lack of shoreline segments for these lake stages."*

I would revise this to indicate that these older shorelines do not record the fault displacement because of the lower resolution of the data. If there were continuous shorelines they would be crosscut by the fault.

We agree that the shorelines would be crosscut by the fault if they were continuous. The sentence will be adjusted to emphasize this argument.

"Ice-dammed lakes T1 and T2 do not record the offset by the Pärvie Fault due to the lower resolution of the data (Fig. 6)."

- *Line 283-284: "Mapping of surficial geology by the Geological Survey of Sweden (SGU, 2024a) shows that"* …

This is technically cited correctly if it came from the database this year. It is, however, significant that the mapping was carried out on aerial photos not lidar (in the 1990s I think).

First, while working on this comment, we concluded that the in-text citation refers mistakenly to the wrong SGU dataset (2024a instead of 2024b). Second, the original URL of SGU (2024b) links to a pdf with a product description of a surficial geology dataset at another scale. Both these errors will be corrected in the text and in the reference list.

"SGU: Product description: Surficial geology 1:250 000, northernmost Sweden (Swedish), https://resource.sgu.se/dokument/produkter/ jordarter-250000-nordligaste-sverige-beskrivning.pdf, 2024b."

We agree that the reference could be misleading to infer that the work in it was performed recently. However, it is correct to cite a product description from SGU which was last updated in 2024. Its maps are based on compilation and digitization of older surveys (the document does not clarify from which years), where the mapping was indeed mainly based on aerial photo interpretation together with field observations along the sparse road network. Elevation models were not used. The compilation was finished in 2011. In a separate guide by SGU to the surficial geology maps and databases of Sweden, it appears they started to use aerial imagery for mapping in the 1980s. In the digital map viewer, it shows that most of the mapping was finished in early 2000s.

"Mapping of surficial geology by the Geological Survey of Sweden (SGU, 2024b), carried out from the 1980s to early 2000s based on aerial imagery supported by sparse field observations, shows that vast amounts of glacio-fluvial sediments which form deltaic deposits are found 165 km downstream of the initial drainage location(s) along both Tornedalen and Kalixdalen (Fig. 8d)."

- *Lines 379-382: "These are favorable comparisons because GLOFs from Akkajaure and Sitojaure cut the Ancylus Lake highest coastline and are therefore in timing close to the youngest GLOF of Torneträsk (and so are their shoreline gradients) and lake evolution in central Jämtland spans 10.5–9.2 cal ka BP (Regnéll et al., 2023), which brackets ice retreat from the Torneträsk Basin, rendering it reasonable that the gradients of IDLT fall within the range of values from central Jämtland."*

This is too much information for one sentence. Break this up into smaller sentences and move the parenthetical text into the body of a sentence.

We appreciate the opportunity to revise this section. The study from Regnéll et al. (2019) did not trace the GLOFs from Akkajaure and Sitojaure (the two lakes we cited), but Pieskehaure and Mavasjaure, which are approx. 90 km farther south. These two ice-dammed lakes were, however, not reconstructed, so there are no shoreline gradients available to compare to. We will therefore remove this statement from our argumentation. Breaking up the sentence as the reviewer suggested will improve the readability as well.

"These are favorable comparisons because ice-dammed lakes Akkajaure and Sitojaure also formed in response to the final deglaciation of the Fennoscandian Ice Sheet. Their timing is closest to the youngest GLOF of Torneträsk, and so are their shoreline gradients. Additionally, lake evolution in central Jämtland spans 10.5–9.2 cal ka BP (Regnéll et al., 2023), which brackets ice retreat from the Torneträsk Basin, rendering it reasonable that the gradients of IDLT fall within the range of values from central Jämtland."

- *Line 386: "The reconstruction of the ice-dammed lakes in the Torneträsk Basin using LiDAR resulted in eight stages"* …

Add a sentence at the beginning of this paragraph that allows the reader to know where you headed. "Previously published work on ice-dammed lakes in the Torneträsk basin are broadly consistent with the results of this study but lack the detail allowed by use of the DEM."

Thank you for the helpful suggestion.

"Previously published work on ice-dammed lakes in the Torneträsk Basin are broadly consistent with the results of this study but lack the detail allowed by the use of the LiDAR-based DEM".

- *Lines 432-435: "The amplifying effect that ice-marginal lakes have on retreat rates of lacustrine-terminating ice sheets (e.g., Stokes and Clark, 2004; Utting and Atkinson, 2019), explains that the FIS experienced higher ice losses due to the ice-dammed lakes in the Torneträsk region, and helps explaining the pivoting motion of ice retreat in this region."*

Flip this sentence around. "Higher ice losses due to the ice-dammed lakes in the Torneträsk region can be explained by the amplifying effect…… Thus, the presence of the ice-dammed lakes led in part to the pivoting…"

This suggestion, when adopted, indeed helps improve readability.

"Higher ice losses of the FIS due to the ice-dammed lakes in the Torneträsk region can be explained by the amplifying effect that ice-marginal lakes have on retreat rates of lacustrine-terminating ice sheets (e.g., Stokes and Clark, 2004; Utting and Atkinson, 2019). Thus, the presence of the ice-dammed lakes led in part to the pivoting motion of ice retreat in this region."

- *Line 437-438: "The ice-marginal positions that dammed the successive ice-dammed lake stages of Torneträsk fall approximately in-between their 10.1 and >9.9 cal ka BP isochrons (Fig. 1b)"…*

How many dates actually constrain these isochrons?

Few, if any; there is a real dearth of data in this region. See Hughes et al. (2016) and Stroeven et al. (2016) for data compilations and resulting deglaciation histories.

- *Lines 460-461: "In fact, the fault may have ruptured subglacially as well while as much as 95 km of the fault trace was ice covered at that point."*

If the fault ruptured along its entire length at this time, then as much as 95 km.......

Thank you for pointing this out, because it is indeed questionable whether the fault ruptured along its entire length.

"In fact, if the fault ruptured along its entire length at this time, then as much as 95 km of the fault trace were ice covered at that point."

- *Line 466: ... "and pre-date deglaciation south of this ice sheet margin (Fig. 10)."*

As originally suggested by Lundqvist and Lagerbäck (1976).

Citing this paper highlights how the findings of our study are in contrast to the original school of thought.

"If all of the Pärvie Fault ruptured at once, such as is typically considered when calculating the amount of energy released, cross-cutting should post-date deglaciation north of the inferred ice sheet margin at the time of rupture (between T6 and T7, Figs. 9e and 9f) and pre-date deglaciation south of this ice sheet margin, as originally suggested by Lundqvist and Lagerbäck (1976) (Fig. 10)."

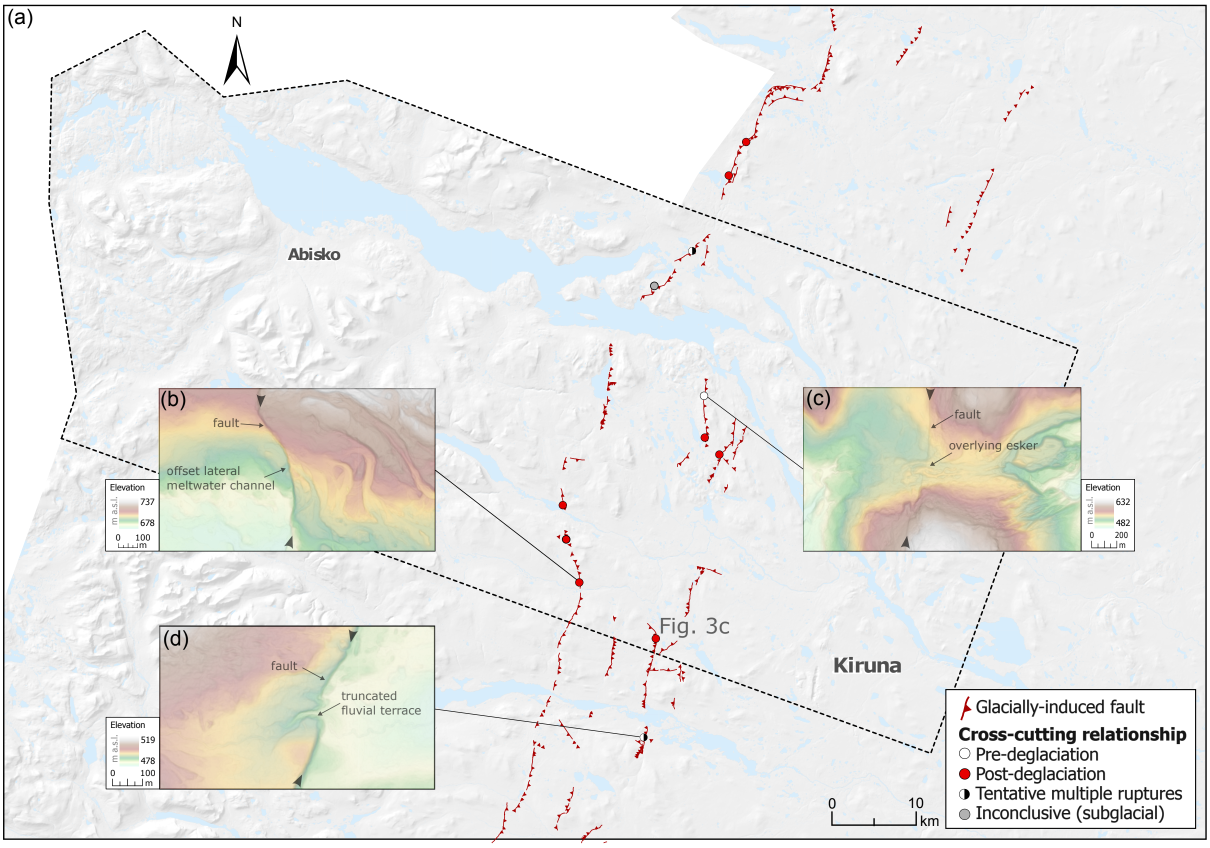
- *Figure 10*

I can't see these crosscutting relationships in the images provided. I suggest a revised figure similar to Fig. 3 with larger, clearer lidar images (perhaps without slope?). Additionally, to demonstrate the uncertainty involved here, include a lidar image of your crosscut shorelines. You present a convincing case that the shorelines are cut by the fault, but I can't see it in the imagery alone. This should be presented and discussed in the text as well.

We thank the reviewer for giving us the opportunity to revise Figure 10 to the standard of Figure 3. We have followed his suggestion, almost entirely. Below the former Figure 10 map, we now indeed will present four panels with significantly improved LiDAR imagery showing the cross-cutting relationships referenced in the manuscript. The four panels show one example of the Pärvie fault postdating (cutting) the glacial landforms or postglacial fluvial landforms, one instance where an esker drapes the fault trace, thus indicating faulting before esker formation, and two panels where we tentatively conclude that fluvial terraces have been offset multiple times. What is not included is a panel that shows the Pärvie fault cutting the shorelines and off-setting them on either side of the fault trace. If this evidence existed, we suspect this information might have been presented earlier-on. Rather, it is the painstaking reconstruction of the shoreline fault traces along the full length of the Torneträsk basin and across the full range of elevations that shows this jump in elevation of the oldest shorelines at the location of the Pärvie Fault. We include an additional map in our response (a panel that could be presented together with former Fig. 6) which illustrates the shoreline traces that are visible in the immediate surroundings of the Pärvie Fault trace (<1 km) and the elevation jumps (if any) that can be gleaned from these. Including this figure clarifies the question by the reviewer, but does perhaps not contain enough supportive information to warrant inclusion? Would the editor like to advise us on whether inclusion of this figure would be required, appreciated, or discouraged?

We believe that improved Figure 10 and its informative caption covers the information sought by the reviewer, and we abstain from further inclusion of a discussion paragraph as the imagery speaks the language and because this information aligns with excellent papers written by the reviewer himself (Smith et al., 2018, 2021), to which we direct the readers if they are interested in the Pärvie Fault.

Old Figure 10:



New Figure 10:

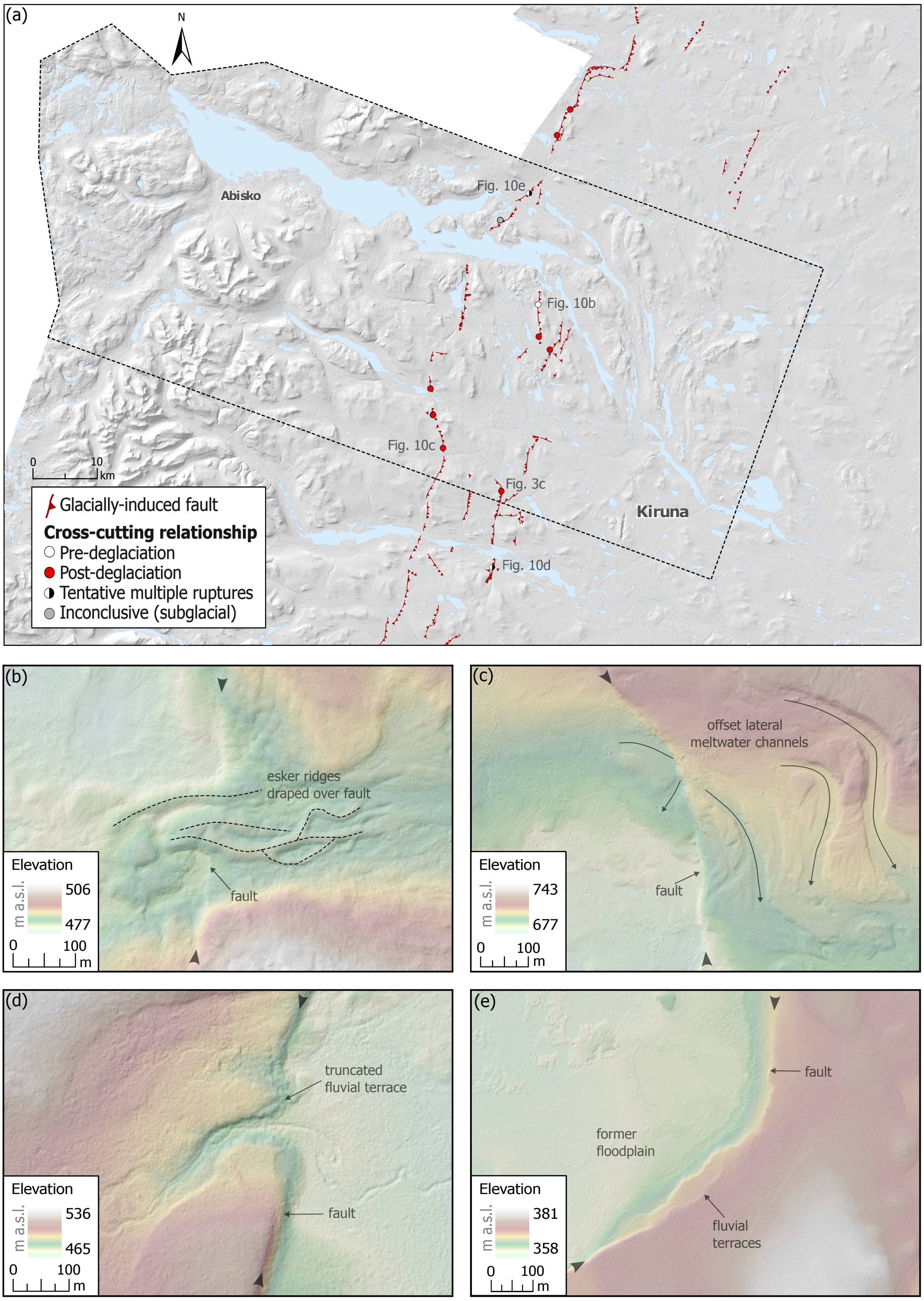



Figure 10. (a) Observed cross-cutting relationships between the glacial geomorphology and the fault scarp traces of the Pärvie Fault. Examples include cross-cutting (b) pre-dating deglaciation, where an esker drapes a fault scarp, (c) post-dating deglaciation, where glaciofluvial landforms are cut by a fault scarp, and (d-e) occurring, tentatively, multiple times, where fluvial terraces are offset by multiple ruptures (panel (d) is the same location as in Smith et al. 2021, Fig 12.4). The background is a shaded relief based on the DEM provided by ©Lantmäteriet.

New panel (b) in Figure 6:

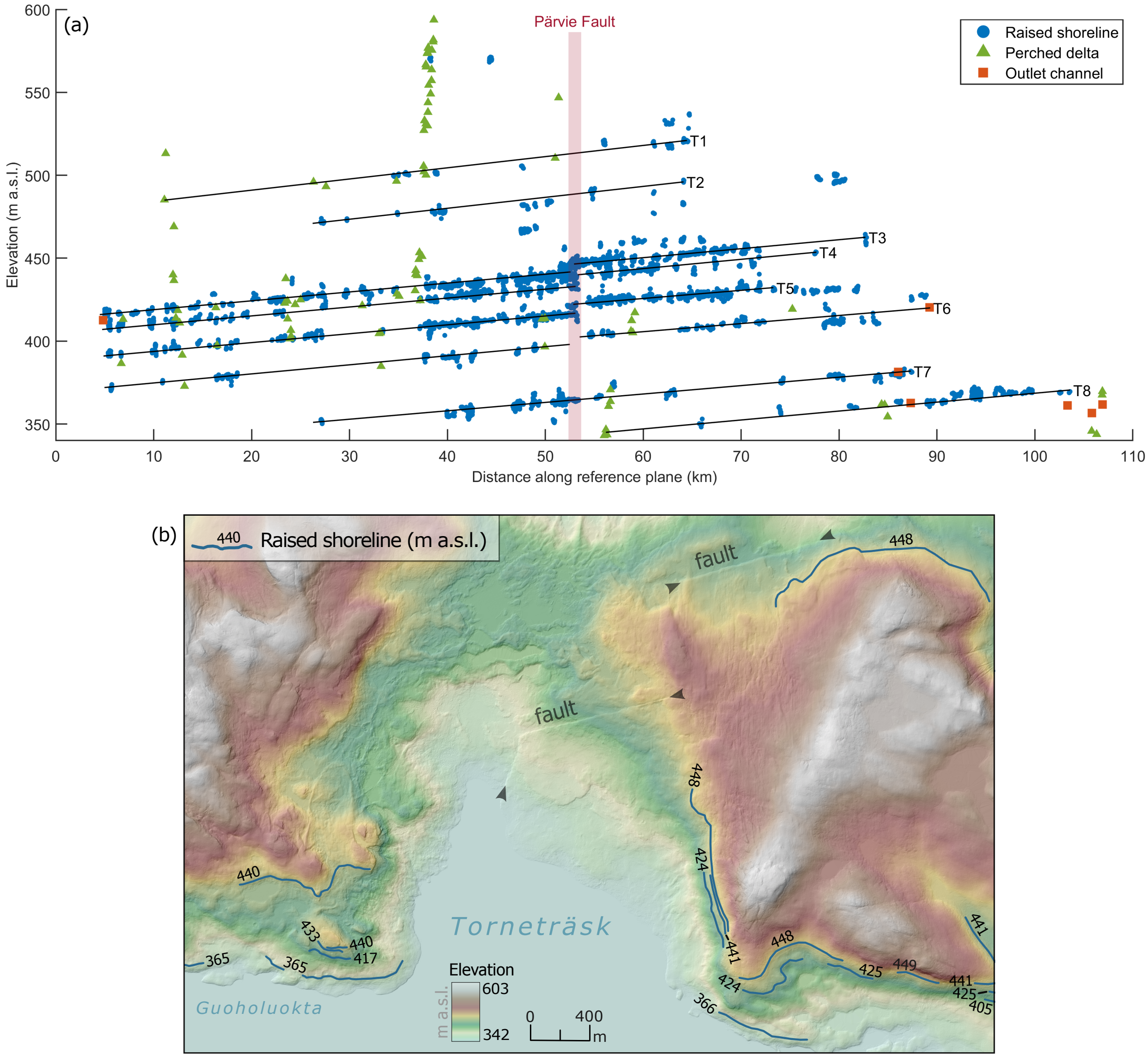



Figure 6. (a) Lake stages identified from the elevations of raised shorelines, perched deltas, and outlet channels of ice-dammed lake Torneträsk. At the Abscissa value of zero, the ordinate value is 342 m a.s.l., the current elevation of the surface of Torneträsk. The approximate location where the Pärvie Fault crosscuts the Torneträsk Basin is indicated by the red bar. The distance is calculated along an axis perpendicular to the isobases of postglacial rebound of the shorelines (see Fig. 1c). The corresponding elevation ranges are summarised in Table 2. (b) Elevations of raised shorelines of ice-dammed lake Torneträsk on either side of the Pärvie Fault where it crosscuts the northern shore of Torneträsk (see red bar in (a)), illustrating elevation jumps of around 8 m for the higher raised shorelines (T3-T6), while the lowest raised shoreline (T7) crosses the fault at 365–366 m a.s.l. The background is a shaded relief based on the DEM provided by ©Lantmäteriet.

- *Line 480: "Currently, such an approach appears unrealistic given the mounting evidence for different types of cross-cutting relationships (Fig. 10), reinforcing observations by Lundqvist and Lagerbäck (1976) that the Pärvie Fault ruptured both prior to, and after, deglaciation."*

This was published before people knew that there were multiple generations of glacial landforms in N. Sweden. Thus, their conclusion was that a single rupture occurred partially under the ice.

Thank you for this reminder. To avoid confusion, this citation will be removed together with the statement about the rupture being both prior and after deglaciation. Instead, we will add a sentence emphasizing how the cross-cutting evidence reinforces observations of multiple ruptures.

"Currently, such an approach appears unrealistic given the mounting evidence for different types of cross-cutting relationships (Fig. 10), reinforcing observations that the Pärvie Fault did not rupture at once."

- *Line 535-536: "Cross-cutting relationships between glacial landforms and fault scarps indicate that the Pärvie Fault ruptured multiple times during the last deglaciation and, indeed, before the last deglaciation."*

What do you mean by this? Before the last glaciation was complete?
You do not discuss evidence of pre-late Weichselian faulting.

Indeed, we have no evidence for pre-late Weichselian faulting. We only have evidence of faulting during deglaciation, where the rupture happened shortly after ice retreat. We will remove the latter part of the sentence that insinuated rupture before the last deglaciation.

"Cross-cutting relationships between glacial landforms and fault scarps indicate that the Pärvie Fault ruptured multiple times during the last deglaciation."

**References**

Regnéll, C., Mangerud, J., & Svendsen, J. I. (2019). Tracing the last remnants of the Scandinavian Ice Sheet: Ice-dammed lakes and a catastrophic outburst flood in northern Sweden. *Quaternary Science Reviews*, *221*. https://doi.org/10.1016/j.quascirev.2019.105862

Smith, C. A., Grigull, S., & Mikko, H. (2018). Geomorphic evidence of multiple surface ruptures of the Merasjärvi "postglacial fault", northern Sweden. *GFF*, *140*(4), 318–322. https://doi.org/10.1080/11035897.2018.1492963

Smith, C. A., Mikko, H., & Grigull, S. (2021). Glacially Induced Faults in Sweden: The Rise and Reassessment of the Single-Rupture Hypothesis. In H. Steffen, O. Olesen, & R. Sutinen (Eds.), *Glacially-Triggered Faulting* (pp. 218–230). Cambridge University Press. https://doi.org/10.1017/9781108779906.016