The response to the referees

Comments from referees (black)

Author's response (green)

Author's changes in the manuscript (if easily presentable; blue)

RC1:

The manuscript of Ruuska et al. uses novel, quantitative methodology for analysing deformed Proterozoic rocks and their glacial cover to better evaluate how these rock sequences may impact civil engineering/infrastructure projects. This work is especially important for northern Scandinavia as glacially eroded bedrock sequences are omnipresent.

The main goals of the manuscripts are well summarised in lines 74 to 77 in the Introduction. However, I would also emphasise the importance of the results for civil engineering/infrastructure purposes.

Response #1 >>> The importance for civil purposes is emphasised in the last sentence of the Introduction.

"The results of this study show that a geologically realistic interpretation of the bedrock surface can be achieved, providing essential background knowledge for, e.g., civil engineering and infrastructure purposes"

Here are my main points for improving the manuscript:

1. It is not always clear to me whether the shear zones are brittle or ductile shear zones. A clarification early on in the manuscript might help to make this clearer and easier to follow for the reader.

Response #2 >>> Term "brittle shear zones" defined and added throughout the manuscript.

2. There is some issue with terminology, e.g., biotite foliation is not structural terminology and is used in the manuscript for a foliation made up by biotite (and other minerals I suppose).

Response #3 >>> Changed accordingly; biotite removed.

3. In the description of the shear zones in line 100ff is becomes clear that the dextral, E-W-striking strike-slip shear zones and the NE-striking (not trending) contractional shear zones acted in concert with each other during NW-SE shortening. The NE-striking shear zones were then reactivated by top-E extensional shear. One wonders whether this event also reactivated the dextral shear zones with sinistral kinematics?

Response #4 >>> Indeed, a good idea regarding relative timing and reactivation of the shear zones. Mention about the reactivation added based on Torvela & Kurhila (2022). However, there is no evidence in the literature about sinistral reactivation of the E-W striking shear zones during that time, only during the NW-SE extensional phase at 1.3 – 1.2 Ga (Nordbäck et al., 2024).

4. The classification of the foliation into high- and low-strain domains (line 150) is nice. I would use strain criteria to support this classification, i.e., the spacing of the foliation planes or the degree of flattening of minerals like quartz or feldspar in this foliation. Then the high- and low-strain foliations could be linked to the dip angle. The dip angle itself does not carry any information on the amount of strain in the rock.

Response #5 >>> We agree that criteria of strain domains were insufficiently presented. This topic is not an integral part of the study, and therefore, we excluded the strain domains from the manuscript.

5. The figures are generally of high quality and easy to read. For ignorant people like me it would help to highlight that inset in Fig.1A represents Finland.

Response #6 >>> Changed accordingly.

6. In Fig.3, F2 cuts SZ3 but seems to be cut off by SZ1. F1 does not appear to deform SZ1 and SZ2. The AFZ cuts SZ1 and SZ2. A bit of clarification would help.

Response #6 >>> The cross-cutting relationship of the shear zones is ambiguous. Therefore, the continuation of the shear zones was changed to be more coherent. See changes in Fig. 4 (previously Fig.3).

RC2

The paper by Ruuska et al. proposes a study on how the network of shear zones, faults, and fractures influences the morphology of a crystalline basement. This topic is of particular interest as the Authors attempt to provide a detailed analysis of the spatial relationships between depressions and various types of tectonic structures. However, the paper requires significant work before it can be considered ready for potential publication. Firstly, the English language used is of mediocre quality, with sentence construction that is often clumsy and unclear. The text lacks fluency and it is frequently difficult to understand the Authors' intended meaning. A thorough revision of the text and how concepts are expressed is necessary. There are also many inadequacies in terminology choices, as highlighted in the attached PDF, which are prevalent throughout the work.

Response #7 >>> The manuscript is reviewed for better fluency of the language and terminology. Detailed responses are provided in the attached PDF.

The Abstract does not provide information on what was done, how it was done, or what results were obtained, appearing more like as a part of the Introduction.

Response #8 >>> The abstract has been completely rewritten to provide better information on the workflow and results.

Regarding the methods, it is not at all clear how field mapping was conducted, how foliations and fractures were classified, and there is no reference to classical methods for structural mapping in metamorphic rocks. The proposed high- and low-strain division seems arbitrary; it is unclear how it was determined and lacks a clear basis. To make this division meaningful, it is necessary to document the types of schistosity, mineral assemblage, and fabric through descriptions and images.

Response #9 >>> Description of field mapping and classification of fractures clarified. Regarding the strain divisions, see response #5.

"Fractures are commonly divided into sets based on different criteria (e.g. Peacock & Sanderson, 2018), which guides analyses of the fracture networks, and helps us to determine potential inheritance relationships with fractures and ductile structures (e.g. Crider, 2015). During the field mapping, we investigated 152 horizontal and vertical bedrock exposures and collected structural measurements of the foliation and fractures (including outcrop walls). Fractures, observed both as traces and exposed fracture-controlled outcrop walls, were divided into major (R1) and minor (R2) groups based on the length of the fractures (e.g. Hamdani & Baali, 2019). R1 fractures present the most continuous fracture orientation per outcrop relative to the size of the outcrop exposure, whereas other fracture orientations are classified as R2. The number of subhorizontal fractures is limited due to the scattered locations of the vertical outcrops."

Furthermore, there is a complete lack of information on how photogrammetric surveys were conducted, how 3D models (DOMs) were processed, and how fractures were mapped. As a result, the results and discussion sections are not grounded in well-documented data, suggesting a need to improve the presentation of results before revisiting discussions. More field images and more effective yet concise descriptions are needed. The discussions currently are verbose and not engaging; they should aim to get straight to the point.

Response #10 >>> Information of the Photogrammetric data and fracture mapping process added to the manuscript (see Response #10). For the purposes of this manuscript, we believe that the modelling process of the DEMs is well enough described, and further description of the bedrock surface data processing is provided by Ahlqvist et al., 2026).

Improved field images added to Figs. 3, 5, and 13, which now better serve the study's purposes and support the results. The results chapter is compressed by removing the 4.6 chapter, which created unnecessary repetition. The results and discussion chapters have been mostly rewritten to improve the text.

"Aerial photographs were acquired using a UAV at a flight elevation of 20 m, with a minimum overlap of 60% to 70% between photographs. Agisoft Metashape software was used to generate an orthomosaic from the aerial photographs, with eight ground control points. The compiled ortomosaic covers the area of c. 100 × 100 m. 1185 fracture traces were manually digitised on the 2D-photogrammetry model, and nodes of the fracture topology were interpreted by using the NetworkGT plugin (Nyberg et al., 2018) in the QGIS software. The same plugin was used for the rose plots."

The influence of major shear zones and the F1 on the morphology is evident from the provided images. The impact of minor fractures is more questionable and requires better data presentation and documentation.

Response #11 >>> We have improved the presentation of the impact of fractures on the morphology. This is discussed in chapter 5.2 with improved figure presentation (Fig. 13).

The conclusions are not compelling for a broad audience of geoscientists and should be revised to highlight a broader significance beyond the local study. In summary, I suggest substantial revisions to make the paper presentable for a second review. I would provide a constructive criticism aimed at improving the clarity, and impact of the paper, focusing on the clarity of language, methodology, and the presentation of results and discussion. I emphasize the importance of using standard geological terminology, including detailed descriptions of the methods used, and suggests improvements in how the findings are presented to engage a wider audience.

Response #12 >>> Comprehensive revision of the manuscript is conducted with particular emphasis on clarity, methodology, terminology and method description.

RC3

The manuscript is on a very interesting and important topic but it has been submitted prematurely and needs more thorough proof-reading as there are numerous formality errors. This is a bit surprising considering the seniority of the co-authors. It might be an effect of different authors writing different sections of the manuscript, that would explain that the same (?) structure (it is a guessing game whether they are the same structure or not) have different names in different sections of the text. Are the Jaaninoja Fault (or Jaaninoja fault as it is also spelled, L369) the same structure as F2, and Aura River SZ (L368, Fig. 12) the same as SZ2?

The first author should make sure to harmonise the manuscript. Examples of incoherence can be given by spelling; LiDAR (L144; L197) is also spelled lidar (L147, L195) and Lidar (L155; L199), to highlight one of them and these spellings are mixed throughout. And the description that LiDAR (were used along with aeromagnetic maps) for lidar lineaments supported by field observations (L147) is rather difficult to understand. So is also sometime the phrasing like "For honouring the effect of the continuous 2D forms ..." at L166. Honouring what? Meaning "to include"?

Response #13 >>> Nomenclature is harmonised throughout the manuscript. F2 and SZ2 are removed. Jaaninoja Shear Zone (JaSZ) and Aura River Shear Zone (ARSZ) are now added throughout the manuscript.

In addition, there are references to a Fig. 2x at L180, to folds in Fig. 4 (L212) that is not present in this figure, and are also several spaces missing after brackets and between references, like at L82 or to many, like in "honour points -method" L179 (Figure caption 2B) for instance.

Response #14 >>> Changed accordingly. Technical issues in writing improved throughout the manuscript.

Normally, Figs. rather than Fig. is used when referred to more than one figure.

Response #15 >>> Changed accordingly.

The sentence at L243-245 should be rephrased.

Response #16 >>> Sentence rephrased together with the whole paragraph.

~~*"Within the well-exposed central parts of the 2D photogrammetric model, high amount of Y- and X-nodes indicates that the fracture network is very connective. Furthermore, I-nodes are regular at borders of the outcrop and in such places, where the bedrock surface dips underneath the vegetation, which indicates that many of the I-nodes may well continue outside of the outcrop and underneath the vegetation."*~~

"The topology analysis shows that NW-striking fractures often abut the NNE-striking ones (Y-nodes in Fig. 6b), and less frequently intersect (X-nodes in Fig. 6b). The isolated I-nodes are regular at borders of the outcrop and in places where the bedrock surface dips underneath the vegetation, which indicates that many of those fractures may well abut or intersect other fractures out of sight."

There are also unnecessary repetitions like the two following sentences at L323-326. Here, references to Figs. 2 and 3 should be included to guide the reader (L323). The last part of the paragraph ends with " ... SSE- and NNW-side". SSE- and NNW-side of what? A reference to Fig. 2 is also needed at the end of L344.

Response #17 >>> Repetition removed. SSE- and NNW-side of ARSZ added. Sentence at the end of L344 rephrased so that a reference to Fig. 2 is no longer needed. Instead, reference to Figs. 4 & 8 added accordingly.

Is Jaaninoja Fault/fault the same as F2 in Fig. 3?

Response #18>>> Answered in Response 13.

And why are "dummy points" used for sub-sea topography and not bathymetry data?

Response #19 >>> Bathymetric data would give some new information about sub-sea topography. However, the sea areas are elongated bays, so the bathymetric data would not reveal further evidence for this study about the bedrock surface. Even with bathymetric data, sediment cover would require dummy points on the bedrock surface along the elongated bays.

L115. At 1.3-1.2 Ga the central part of the shield was in an extensional setting with emplacement of the large Central Scandinavian Dolerite Group, present also in Finland. At this time interval all lithotectonic units to west of the Sveconorwegian Eastern Segment were located outboard.

Response #20 >>> Sentence rephrased and intrusion of the diabase sills added with appropriate references (Suominen, 1991; Elming & Mattson, 2001).

How is the damage zone defined?

Response #21 >>> Damage zones are estimated along the ARSZ and JaSZ based on fracture orientation within the T1-DEM and T2-DEM. Previous figure of damage zone interpretation of other brittle shear zones removed from the manuscript.

L366. There are no ductile or larger scale brittle structural precursor for the NNW and NNE R-1 fractures, but they are formed as a response to movements in the deformation zones. What deformation zones?

Response #22 >>> Inaccurate term changed to ARSZ and JaSZ.

L370 "The R2-fractures show similar ENE-strike **than** the foliation .."??

Response #23 >>> Sentence is rephrased.

~~*"The R2-fractures show similar ENE-strike than the foliation and shear zones, which suggest that the R2-fractures were largely localized into the existing ductile structures particularly near the ENE-striking shear zones."*~~

"The R2-fractures show parallel strike with the foliation, which suggests that the R2-fractures were largely localised into the existing ductile structures, particularly near the ENE-striking brittle shear zones."

Figures

Figure 1. Group II depressions in figure 1 are NE-SW trending but in the description on L122 they are NW-trending.

Response #24 >>> Orientation changed so that the description and figure correspond.

Figure 2. A) In the legend there should be dummy points in green squares, but the only green in the map are lines. B) Legend is missing.

Response #25 >>> Dummy points are changed to points instead of lines in the map, and the legend is added to the Figure. B.

Figure 3. Explanations to the sterogram and the grey field in the map are missing.

Response #26 >>> Explanations of the stereogram added to the caption.

Figure 6. According to L234 the most distinct R1 structures strikes in NNE and NNW, but in Fig. 6b R1 shows a max in N-S. The streograms need a legend.

Response #27 >>> R1 strike changed to N-S striking. Explanations of the stereogram added to the caption.

Figure 7. Green symbols (I-node) on green background should be changed to a better suited colour.

Response #28 >>> We believe that the green colour of the I-nodes is well visible from the background.

Figure 10. Add that the Aura River SZ equals to SZ2.

Response #29 >>> SZ2 deleted from the manuscript. Look at Response #13 for further details.