Reply to reviewer #2 (Anonymous reviewer)

First, I would like to commend the authors for compiling extensive data related to the tragic collapse of the Marmolada Glacier. They have gathered information from multiple sources to evaluate the factors that triggered this catastrophic event. This manuscript is undoubtedly valuable and has the potential for high citation and recognition within the scientific community.

We thank reviewer #2 for the constructive comments.

However, before publication, the manuscript requires major revisions. This includes shortening and restructuring the content, as well as thoroughly checking for numerous redundancies. Additionally, the discussion of certain processes related to the glacier's thermal regime and permafrost needs re-assessment, as also addressed by M. Truffer in Review 1. While I started reading with eagerness to learn more about the event, I was somewhat disappointed because of obvious shortages. In my opinion, the manuscript is overly lengthy, the figures are not cited in order, and some are redundant and difficult to interpret. Below, I provide major and detailed comments. I have read M. Truffer's comments and fully support the points made, especially regarding the glacier's thermal regime and permafrost as possible triggers for the landslide.

The paper has been partially re-organized. The content was shortened and restructured and we worked on redundancies as well. The "Introduction" Section was shortened and the objectives clearly stated as well as the key methods. The "General Settings" Section was expanded adding geological and geomorphological settings. We carefully re-assessed many of our statements about the glacier's thermal regime (see the various replies to the review of Martin Truffer that's not copied here to avoid duplications). All figures were reworked to improve clarity and they are cited sequentially. The font size was increased, and some panels were removed. Panel C (graph from Davies et al.) was removed from Figure 8. Figure 11, which includes radar profiles and their interpretation, was split into two figures. The time series from the Himalaya avalanche were removed, while the spectral components of the Marmolada failure were added. Figure 15 was simplified (removing one cross-section) and Figure 16 was removed.

Specific comments:

Abstract: Move the sentence starting at line 17 to the end, after listing the methods used, as it is repeated there. Also, clarify whether the active layer in the permafrost is below the glacier, we do not have any "active layers" below ice.

The abstract was rewritten (see point P0 of our reply to Martin Truffer's at page i).

Introduction: This section is too long. Remove the initial list of collapses, including the ice shelf, as it is not relevant. Delete everything from line 65 onward related to "overall structure," as these discussions belong later. The introduction should end by stating the objectives of the paper and mentioning key methods (e.g., climate observations, thermal regime, seismicity) used to achieve these goals.

The Introduction was shortened and re-organized. The list of collapses was summarized. The objectives of the paper were clearly stated as well as our claim. The sentence stating the objectives now reads:

P1

"This study aims to partially address this gap with a dual objective: first, to identify the controlling factors of the collapse and classify them as predisposing or triggering; and second, to develop a numerical model to assess the relative influence of the different triggering factors. Multiple variables contributed to the catastrophic collapse that claimed several lives on July 3, 2022 (Chiarle et al., 2022; Olivieri and Bettanini, 2022; Bondesan and Francese, 2023). This required the collection and reorganization of various data into a comprehensive digital database to gain deeper insight."

We also reformulated the sentence indicating the focus of the numerical modeling that now reads:

P2

"We used a data-based back-analysis approach to infer the basal properties of the failure surface, aiming to understand the critical interactions among englacial water (which altered temperature and pressure fields within the glacier and at its base), permafrost in rocks and sediments, the glacier's thermal state, and the possible presence of a thin, heterogeneous, and discontinuous layer at the ice-bedrock interface."

And we better summarized the key methods:

P3

"Numerical simulations were conducted by means of the Limit Equilibrium Method (LEM), which is routinely used for slope stability analyses (Saim and Kasa, 2023) in geotechnical engineering. Particular attention was given in defining geometry and physical properties of the ice body, especially for those characterizing the interactions with the surrounding materials at the ice-rock interface. The purpose was achieved by re-processing and carefully analysing both existing and post-failure RES (Radio-Echo Sounding) profiles (Fretwell et al., 2013; Francese et al., 2019), which contributed to the conceptualization of the model for numerical simulations. Pre- and post-failure aerial and satellite imagery, along with aerial and terrestrial laser data, further contributed to conceiving the model. Available meteorological data (air temperature, rainfall, and snow cover) and cryospheric data (permafrost and ice temperature) were carefully analyzed. Finally, seismological observations were considered to evaluate the possibility of earthquake-induced triggering of the failure.

We prefer to leave the paper summary at the end of the "Introduction" as it helps the reader.

General Setting: The field area is not adequately introduced. Provide information about the overall geological and structural setting, climate (temperature and precipitation), and permafrost limits in the area. In Figure 1, the text is too small, there's no scale in (A), and the 3D plot's scale is not readable. It would help to include a regular image of the area and images from the collapse.

The geology, geomorphology, and climate of the study site have been described in greater detail. The font size in Figure 1 has been increased, and the scale bars have been enlarged for better readability. The scale in subpanel A was originally in degrees and minutes, which may have been difficult to interpret, so we enlarged its size. Additionally, a regular image has been included to replace the 3D model in Figure 2.

Data, Methods, etc.: Remove the initial paragraph listing methods, as these should be detailed with manufacturer information, resolutions, and other relevant details. Line 159 contains an interpretation that repeats throughout the manuscript; avoid such redundancies. The calculation starting from line 169 is unclear; specify if GPR was used and the strategy for filling in missing meteorological data. Figures are cited out of order (e.g., Fig. 9 on line 189), so ensure they follow a sequence. Important installations could be visualized in Fig. 1 or 2; consider using a standard map layout instead of complex 3D plots. I found it challenging to follow the glacier stability and back analysis. The discussion of parameters is confusing and should be reserved for the discussion section—just present the parameters used along with references and justification.

The list has been removed, leaving only the first introductory lines of the section, referring to the following paragraphs for the description of the available data and the methods used. We also removed the interpretation provided in the subsequent lines to avoid repetitions. Now the incipit of Section 3 reads:

P4

"The multi-disciplinary approach of the present study involves several research topics and different data types along with the specific methods of data acquisition, analysis and processing. Data were gathered in a large database comprising a wide range of glaciological and meteorological records, along with historical and modern topographic maps, aerial and satellite imagery, geophysical data, geological and geomorphological data collected and catalogued over the past two decades (see Supplementary Material for details)."

The calculation was better described, and the strategy for filling in missing meteorological data is outlined in the Supplementary Material and our previous paper; proper references have been added to the text. Figures are now cited in the proper order. Figures 1 and 2 were improved in both graphics and labeling, and the installations are now clearly visible. The theory of the back-analysis via the LEM approach was expanded (see reply to Martin Truffer). Parameters are now simply presented, with other considerations on selection criteria were shifted to the "Discussion" section as requested.

The ice temperature of -4°C seems low; is this value justified?

-4°C is a lower-bound value. We provide a best estimate of about -2°C and in Figure 8 a range from close to 0°C to -4°C. In the caption to figure 8, we write:

P5

"The large gray scale for the Marmolada detachment site indicates the uncertainty involved with applying temperature information from different times and obtained with different methods/accuracies."

Results: What is meant by "overall evolution"? Call it "development" or just "evolution." It is not interesting here who conducted the measurement (l. 251), just provide the results. Increase the font size in Fig. 3, as it is hardly readable. Fig. 4c is difficult to understand, and I cannot read the figure. What is meant by the "centroid of the glacier front"? Low readability also applies to Fig. 5—text within the figure is not clear. Ensure figures are readable on paper. I gave up on Fig. 6 because, while it looks nice, it is not understandable.

We changed "overall evolution" in "evolution" and removed the indications on who conducted the measurements. Font size has been increased in all figures (see above). Figure 4C represents the spatial migration of the centroid of the glacier front and its projection onto the EN, EZ, and NZ planes. The idea behind using the centroid is to provide a more robust representation of how the glacier front is changing over time, thus overcoming the limitations of describing the glacier front migration with a few sparse measurements taken at specific spots. The digitized 3D polyline representing the glacier front was first approximated with a 3D spline and then collapsed onto a single point (x, y, z), providing a much more accurate representation of the glacier front migration (this process is described in the Supplementary Material of Bondesan and Francese, 2023). A brief explanation and a reference were added to the caption.

Figure 6c presents a curve done for two cement blocks, not for the ice-bedrock interface. There's no certainty that the same relation is valid here; consider removing it. Furthermore, what is meant by "guessed thermal conditions"?

Panel C (graph from Davies et al., 2001) was eliminated from Figure 6. The term "guessed thermal conditions" was changed in "thermal conditions".

Line 346 and following contain interpretation, not results; this should be moved.

The sentence was moved to the "Discussion".

Chapter 4.3. is difficult to follow. Figs. 9 and 10 are very challenging; consider using color and clear color ranges. These are certainly important figures, but difficult to follow.

This description of the failure zone is a core component of this paper, as it forms the foundation for conceptualizing the numerical model used to assess stability and evaluate the different triggering factors. The validity of the model is strictly dependent on the settings of the failure zone. We attempted *to clarify the description by leaving out some of the details and focusing on the key issues. Additionally, we improved the line drawing overlay on the image by using wider lines and different colors for better clarity and distinction. These pre- and post-failure satellite imagery was provided in standard and widely accepted colors. RGB color-coding of the images does not enhance readability, and grayscale proved to be the most effective display choice.*

Fig. 11 is similar (especially parts A and D). What is RES? What does "very short wavelength" mean in line 400?

Figure 11 was split in two figures to improve readability. The acronym RES was already expanded in Radio-Echo Sounding in the "Introduction" Section. "Very short wavelength" is a common term in geophysics, indicating higher resolving capability. In wavenumber methods, the shorter the wavelength, the higher the spatial resolution.

Fig. 12 is very difficult to read. Line 425 should be revised, as surface temperature cannot be used to infer permafrost under the conditions mentioned.

Line drawing and labeling in Figure 12 were improved increasing the width of the lines and the size of the fonts. The sentence in line 425 has been completely revised and incorporated into the new discussion on subglacial permafrost. Please refer to our response to Martin Truffer's comment "A warming of subglacial permafrost is not really documented in this paper" on page vi of this document.

This chapter about seismology looks good, including the figures.

Ok; We included comments on the spectra of the failure event.

Slope Stability Back Analysis: I found this section difficult to follow—perhaps it is my fault—but the figures (e.g., Fig. 15) are not user-friendly.

The conceptualization was simplified as well as Figure 15 that now shows a single longitudinal cross-section to be used as a geometrical reference for the model. Figure 16 was removed. Figure 17 and Figure 18 are common representations of failure surfaces calculated according to Mohr-Coulomb's shear strength criterion.

Discussion: There is much redundancy here. The first paragraph provides a conclusion rather than a discussion. Section 5.1. is repetitive (line 574). How do you know the thermal regime of the LIA glacier (line 565)? Some observations have been mentioned before and seem redundant. The section on "triggering factors" is very lengthy; consider creating subheadings like "seismic factors," "thermal factors," etc.

The 'Discussion' section was reorganized and divided into more clearly defined subsections. Some sentences were removed to avoid redundancy, while others were relocated to different subsections for conciseness. Several statements were streamlined to enhance readability, and the first sentence was *moved to the 'Conclusion' section. The discussion on permafrost was simplified (see P3 of our response to Martin Truffer's comments on page iii). Subheadings were added to Section 5.2 (Triggering Factors), and the section was shortened.*

Conclusions: The conclusions contain much speculation and a few typos around line 740. I recommend using short conclusions with clear statements in bullet points rather than long text. You can omit the last paragraph, as it is not informative.

We have shortened the "Conclusions" Section avoiding speculations. We included just clear statements and removed the last paragraph. Now the core of the "Conclusions" Section reads:

P6

The detachment zone, as a consequence of the warming-induced disaggregation of the Little Ice Age glacier became an isolated cold glacieret—consisting of massive, impermeable, yet crevassed ice—at least over the past three decades. The progressive opening of a large median crevasse increased the glacieret capability of storing englacial water. Its ice temperature can be estimated at some -2°C, i.e., relatively close to melting conditions but with at least partially freezing or frozen bed. Additional conditioning factors included the steep slope inclination, the presence of low-angle discontinuities such as ice foliations and/or discontinuous basal till layers, along with the complex thermal conditions at the ice-bedrock interface.

The probably most influential triggering factors are associated with minimal winter snowfall and the prolonged positive thermal anomaly. The marginal thickness of low-permeable snow layers and especially the extreme air temperatures resulted in an excess of meltwater penetrating deep into the glacier. In fact, water filling the deep crevasses have produced subglacial water pressures in excess of floating conditions. The absence of a connected drainage network created the condition for the development of an increasing hydraulic over-pressure.

An earthquake, as the final triggering mechanism, can be excluded. Results from numerical simulations suggest that the triggering of the final collapse was most likely due to the simultaneous interaction of hydrostatic pressure, hydraulic jacking pressure, and a reduction in basal friction caused by the presence of a weak basal layer. This thin layer appears to be a key factor in the failure, as instability does not occur by hydraulic pressure alone. Its evolution is still under investigation, but it may be correlated with permafrost degradation at the ice-bedrock interface, leading to partial basal ice melting across the entire eastern flank of the glacieret's base.