

## Reply to reviewer #1 (Dr. Martin Truffer)

This paper has a lot of interesting information about the catastrophic glacier failure of a piece of the Marmolada Glacier that caused several fatalities and must be rated as one of the bigger glacier related natural disasters in Europe. With the rapid change of glaciers in the current climate, it is important to better understand the mechanisms that lead to such an event. The paper does a good job in assembling a variety of data sets that allow for some conclusions. However, the paper would benefit from a significant reorganization and more detailed analysis. Parts of the paper go into great detail about things that may only be peripheral (parts of the permafrost discussion), while being really sparse on things that matter significantly (e.g. how the LEM model works). This review is rather long, because I think the paper needs major work. However, a clear paper on this topic is an important contribution to the literature and I hope it can be put into publishable form.

*We thank Martin Truffer for his extensive and constructive feedback.*

*The paper has been partially reorganized. The permafrost analysis has been simplified, while greater emphasis has been placed on the description of the LEM model. The authors acknowledge that several hypotheses were proposed without direct proof; however, this is an inherent part of the process of understanding natural phenomena. Moreover, these hypotheses have the potential to stimulate further discussion. Nevertheless, as per the reviewer's suggestion, the majority of the speculative statements have been removed, particularly in cases where the available data do not allow for reasonable estimate of the weight of the different controlling variables on the failure.*

*Regarding the different sections: the 'Introduction' has been slightly shortened to better focus on the topic; the 'General Settings' section has been expanded to provide a more detailed geological context of the site; the 'Results' section has been condensed, while the 'Discussion' has been expanded to better constrain the predisposing and triggering variables. The 'Abstract' was also modified avoiding speculations and now it reads:*

*P0*

*"A small, isolated portion of the Marmolada glacier broke off on July 3, 2022. The detached ice mass had an estimated volume of 70,400 m<sup>3</sup> and slid down the slope killing 11 mountaineers after having travelled for approximately 2.3 km along the northern slope. This event is considered among the deadliest ice avalanches historically recorded in the Alps.*

*The unusually high air temperatures in late spring and early summer of that year led to an excess of meltwater, which, since mid-June, overpressurized the englacial discharge network, partly blocked due to frozen conditions at its base. Cold ice and sub-glacial permafrost were among the primary variables controlling the thermal state of the sliding plane.*

*The cause of the collapse was investigated implementing a conceptual model that was further corroborated through simplified numerical simulations using the Limit Equilibrium Method. Pre- and post-failure satellite and aerial images, laser mapping, geophysics and morpho-climatic data were gathered in a comprehensive database and analysed to better understand the role and interaction of the predisposing and triggering factors as well as their mutual intercation. Particular attention was given to reconstructing the varying conditions of the failure surface, which partly developed along ice foliations near the glacieret's base and partly right at the ice-bedrock interface. An earthquake triggering the failure was excluded based on the processing of the available seismological observations.*

*It resulted that none of the three forces considered in the numerical analysis—namely, hydrostatic pressure in crevasses, hydraulic jacking, and basal friction reduction—individually caused the condition of instability. To reach this condition, it was necessary to invoke a combination of these actions, for which it was finally possible to estimate their relative weights”*

*A paragraph was added at the end of the Introduction to clarify the core framework of the paper (see P1 below).*

*All the figures have been updated based on the reviewers' comments. The 3D model in Figure 2 has been replaced with a map view (as suggested by reviewer #2). Subpanel C has been removed from Figure 8. Figure 11 (GPR scans) has been divided into two separate figures and a migrated version of the bedrock response was included. The time series from the Everest avalanche have been removed from Figure 14 and replaced with the spectral components of the Marmolada failure. Figure 16 has been removed. The captions have been revised and strengthened. The font size was increased in all figures to improve readability.*

The permafrost discussion is confusing. It appears that you argue that this glacier used to be temperate with a firn layer. Then it lost its firn layer and became cold-based. Then it started warming at the base again and weaken the ice, partially due to warming air temperatures and also heat infiltration through bed rock from the south facing side. While all of these are plausible at some level, this could be presented much more consistently. The Boeckli et al map is useful for context, but ultimately, the map and the nearby borehole will not allow much of an assessment of the thermal state. Neither do the thermal surface measurements. Those were acquired at a time when it could simply be cold surface temperatures that say nothing about the thermal state of the ground a few meters down. The most useful measurement is the borehole in the ice. This needs to be emphasized more. It clearly shows a cold ice base, although the base is barely below the level of where seasonal fluctuations would affect temperature.

*The permafrost aspect is indeed complex, involving a complicated transient thermal interaction between surface and subsurface conditions. We try to make it as clear as possible. We reworked the introductory sentence writing:*

*P1*

*“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 (Noetzi and Gruber, 2009; Rossi et al., 2022), the glacier’s thermal state, and most importantly the existence of a thin, heterogeneous, and discontinuous layer at the ice-bedrock interface (Zoet and Iverson, 2020; Huang et al., 2024).”*

**And later in the Materials & Methods:**

P2

*“The permafrost information for the study area was inferred from the 25 m x 25 m model for the Alpine chain (Boeckli et al., 2012) and from the nearby borehole of the Piz Boè (PZB) equipped with operational temperature sensors since the year 2011 (Crepaz et al., 2011).*

*The model devised by Boeckli (2012) is based on Mean Annual Air Temperature (MAAT) of the period 1960-1990. PZB data confirm this model and provide some information about ongoing permafrost warming in the region. The PZB borehole was drilled in 2011 at 2905 m asl, which is about 300 m lower than the failure site, on the warm eastern slope of the Piz Boè massif, about 8 km to the NNW.*

*Ice temperature estimates for the Marmolada glacier were inferred by using and updating published data (Haeberli et al., 2004a; Fischer et al., 2022). In early August 2024, a borehole was drilled in the residual ice body just above the failure scarp using a steam-based drill bit and was equipped with four temperature sensors. The sensors were located just above the ice-bedrock interface (at a depth of 11.5 m below the surface) and at -2.5 m, -5.5 m, -8.5 m from the ice surface respectively (Fig. 12).”*

**And in the Discussion:**

P3

*“Evolution of thermal conditions around the failure zone is crucial to get better insight in possible collapse mechanisms but involves complex transient glacier-permafrost interactions. Where bedrock of the northern slope has remained free of glaciers during past decades, its temperature can be estimated at a few °C below freezing temperature, probably close to 0°C at lower altitudes, around 2400-2600 m asl, and reaching -1°C to -4°C towards the uppermost parts. With such surface temperatures, permafrost depth may in places exceed several tens of m (Etzelmüller et al., 2020; Rossi et al., 2022).*

*In the Alps, pervious firn zones, warmed up by percolating and refreezing meltwater, are temperate up to altitudes between approximately 3400 and 3900 m above sea level (Haeberli and Alean 1985; Suter et al., 2001; Bohleber, 2019) while the impermeable ice of the ablation zones in areas with permafrost tends to be cold. The LIA glacier at the Marmolada site (Fig. 8A) with extensive warm firn areas may therefore have been polythermal and predominantly warm-based (cf., Wilson and Flowers, 2013) with only its lowest margins containing cold ice, partially frozen to bedrock. Higher parts of bedrock underneath the LIA glacier could therefore have been largely unfrozen. Interestingly, ice temperatures recorded several*

*tens of cm within the walls of some WWI tunnels, dug in the Marmolada glacier in 1917 (Hess, 1940), in the elevation range 2800-3200 m asl, showed average values of -1.32°C in tunnel “32” (located in the vicinity of the failure site) and of -1.27°C in tunnel “S” (located ~700 m west of the failure site), i.e., moderately cold conditions on the northern side of the Marmolada. With the progressive loss of warm firn areas, such cooling of surface ice especially also affected the small ice body, from which the ice avalanche later detached. Such cooling of surface ice over time must have induced the formation of subglacial permafrost, where it had been absent under LIA conditions. Such recent subglacial freezing may likely have influenced the hydraulic permeability of the karstic subglacial rocks and, hence, the drainage mechanisms of the cold surface ice body.”*

The influence of the southern slope on the other side of the mountain is an interesting hypothesis, but it is very difficult to see how that heat flux would have allowed the glacier base to first freeze and then later thaw again. There is a lot of potential for some simple thermal model here, but even in the absence of that, the various influencing factors and hypotheses need to be stated much more clearly.

*We acknowledge the reviewer's comments. Such strong asymmetries are quite characteristic near mountain ridges. The primary influence is not via heat conduction but could in many cases be through water infiltration. We nevertheless eliminated this aspect in order to focus on the already quite complex primary aspects (see P3 above). This paper does not include thermal modeling, as it was not our primary focus; however, it could be conducted in future works to gain a better understanding of the collapse.*

The model discussion also needs to be made clearer and many questions remain. First, little detail is given about the LEM model. Second, it is not clear to me whether the parameters from Huang et al are applicable here. That paper finds peak strength in shear tests that are conducted under very high constant strain rates. Applying such high strain rates leads to stresses that are very high and to a quick ductile/brittle transformation. However, in the situation of this glacier, the geometry imposes certain stresses that would lead to deformation of ice, and, in this case, failure. The high stresses obtained in the Huang paper probably explain why it is so difficult to obtain failure in the model.

*The LEM model used for the stability analysis has been explained in more detail in Section 3.5. Further details, especially on the method adopted to select the shear strength parameters, have been added also in Section 4.5. It is worth to underline that results from Huang et al. (2024) have been assumed only for reference. The model proposed by Huang et al. (2024) has not been used to calculate shear strength parameters, due to the lack of experimental measurements on specific ice content. Starting from the original Mohr-Coulomb's shear strength parameters of ice, cohesion was progressively reduced by 25% for each scenario C1-C5, while the friction angle was reduced by 11% for each scenario. Anyway, the adopted values of shear strength parameters in the LEM model are consistent with those experimentally measured by Huang et al. (2024) in similar stress conditions, i.e. with stresses normal to the sliding surface in the range of 150-250 kPa. In fact, considering the unit weight of the ice equal to 9.19kN/m<sup>3</sup> and a mean ice thickness of 20m, the mean vertical stress at the slip surface is around 184kPa. Huang et al. (2024) performed shear tests under normal stresses of 150kPa and 250kPa.*

We for instance write in Section 3.5:

P4

*“LEM is based on the principle that a rigid mass (in this case made by ice), will fail when the driving forces, due to gravity and external loads, exceed the resisting forces, due to shear strength along a defined failure surface. In the present study, the main driving force is the weight of the unstable mass, but further destabilizing actions, represented by hydrostatic forces in various configurations, were considered, as will be explained later. The calculated driving actions are compared to the available resistance, which is calculated according to Mohr-Coulomb's shear strength criterion. Referring to this shear strength criterion, specific strength parameters are assumed for the involved materials, i.e. ice and rock. The method considers the equilibrium of forces and/or moments along a predefined failure surface.”*

And later (in Section 3.5):

P5

*“In the framework of LEMs, slice methods are used to analyse the stability of slopes by dividing the unstable mass into vertical slices. These methods evaluate the equilibrium of each slice while considering forces acting within and between them. Each slice is analysed separately, considering its weight, normal force, shear force, and inter-slice forces. The stability of the entire slope is determined by calculating FoS based on shear strength and equilibrium conditions.”*

And finally (in Section 3.5):

P6

*“... by using the SLIDE2 software from Rocscience®. In particular, the Janbu's simplified method is based on equilibrium of slices along two orthogonal directions. It assumes only horizontal interslice forces and thus the interslice shear forces are zero (Janbu et al., 1956). The Janbu corrected FoS is obtained by multiplying the Janbu simplified FoS by a modification factor, which is function of the slope geometry and the strength parameters of the material. The Janbu modification factor is an attempt to compensate for the fact that the Janbu simplified method satisfies only force equilibrium and assumes zero interslice shear forces. Instead, GLE/Morgenstern-Price method assumes a half sine interslice force function to define interslice forces and is based on complete equilibrium of slices along two orthogonal directions and with respect to rotation. This is why this method is 'rigorous'. It should be noted that, although the failure surface was completely known, in the LEM model it was defined only at the base in contact with the rock, with the aim of comparing the failure scarp within the ice mass obtained from the model with that actually observed in situ.”*

Some of the mechanisms in the model are confusing. What exactly does plasticization of the basal layer mean? First, it is not clear what the mechanism for this is (see the permafrost discussion above). Second, a 'plasticization' would lead to increased deformation rates, which should be observable. Hydraulic jacking is also a strange mechanism as applied here, because it is inconsistent with a frozen basal

condition and a plugged drainage system. How does water access the entire base of the ice under these conditions?

*This is indeed intricate yet intriguing at the same time, as basal sliding or hydraulic jacking are not possible with perfectly frozen, hydraulically impermeable basal conditions. Instability may therefore have been caused by either partially non-frozen conditions or by a frozen but partially permeable state of the basal layer and subglacial rocks. In both cases, pressurized water at the base of the large median crevasse, combined with rising temperatures, could have forced its way through the thin basal moraine, increasing permeability in the basal layer without fully reaching the outlet at the frontal toe of the glacieret. This condition may have created hydraulic jacking in the eastern portion of the sliding surface (e0 in Figure 9). On the other hand, the southern and western portions of the sliding surface are frozen to bedrock, as inferred from helicopter images taken immediately after the collapse, LIDAR surveys from the following day, satellite images from July 7th, and direct observation. These differences in the sliding surface were already highlighted in our previous study (Bondesan & Francese, 2023). For these reasons, we incorporated hydraulic jacking and the weak basal layer into the model to account for the simplified effect of friction resistance reduction (which depends on effective stress) due to increased pore water pressure in a thin layer composed of ice, water, and debris. We have also attempted to clarify these concepts in the description of how the model was conceived.*

It is fair to assess how the LEM model does, since that is used in practice. But I think a first step is to use the fact that the glacier failed to estimate what stresses actually led to failure. You know that nature and magnitude of the failed surface, and you know all the relevant stresses (gravitational stress from the weight of the failed ice body and hydrostatic stresses from the water-filled crevasse. This allows you to calculate an average stress on the failed surface, which is a good place to start.

*We understand the observation; it is possible that we were not clear enough for those unfamiliar with this approach. "Using the fact that the glacier failed to estimate what stresses actually led to failure" is exactly what we call "back analysis". The failure happened because, along the sliding surface (whose geometry is known), the driving shear stresses were higher than the resistant shear stresses. Although in a simplified way, the comparison between driving and resistance forces (or stresses) is made by using LEM and by calculating the FoS along a specific failure surface. The average stress on the failure surface is calculated in the adopted model for different scenarios and it is compared with the basal shear strength.*

It seems overall, the extremely warm temperatures and the fact that a crevasse is filled with water to the top is probably the best indicator of how failure occurred. The excess pressure from the water-filled crevasse would have led to hydraulic jacking that would have progressively increased from the crevasse downward. In that area, shear strength would be lost entirely and the stress on the remaining intact surface would increase until failure.

*Agreed with some additional detail: The subglacial freezing process following the decoupling of the glacieret from the main glacier and with it becoming a cold massive ice body may have drastically reduced the hydraulic permeability of the subglacial karstic rocks and thereby prevented the water in the*

*crevasse to subglacially drain but to build up above-floating water pressure. This development may have over-stressed the warm-soft ice and water containing permafrost bedrock at the front of the glacieret.*

The abstract is full of speculation and conjecture. A warming of subglacial permafrost is not really documented in this paper. Neither is a 'plasticization of basal ice' or the presence of a subglacial active layer.

*The Abstract has been modified (see P0 above), with most speculations removed from the text. As for subglacial permafrost, we acknowledge that it is not confirmed by direct measurements. However, given the small size of the glacieret, it is highly probable that it has degraded—at least along the perimeter—following the overall Alpine trend, as supported by 15 years of observations at the PZB site.*

*Regarding the 'plasticization of basal ice', we agree that the expression is not appropriate. Anyway, we believe that the presence of a basal layer made by ice, water, and sediments, can reasonably explain the sudden and abrupt triggering of the failure. By disregarding any kind of deformation, the weak basal layer has been introduced to take into account in a simplified way the decrease of friction resistance (which depends on effective stresses) due to the increase of pore water pressure at the contact between ice and bedrock. There are at least three key pieces of evidence supporting this hypothesis.*

*- Back-analysis results indicate that instability conditions would not have been reached without the presence of a weak basal layer.*

*- The sliding surface analysis shows that, on the eastern flank, for 32% of the entire surface, the failure developed at the ice-rock interface. This suggests that, in this area, the glacier was not frozen to its base, unlike in the western sector and around and above the median crevasse.*

*- Infrared (IR) measurements taken the morning after the collapse indirectly support this hypothesis, as they reveal skin bedrock temperatures on the eastern flank very close to the melting point.*

### **Specific comments:**

The title is a bit of a mouthful; consider simplifying.

*In the title we would like to emphasize that multiple datasets are provided and analyzed, but the solution remains not-straightforward due to the complex conditions involved. We propose this new title:*

*Failure of Marmolada Glacier (Dolomites, Italy) in 2022: Materials for data-based back analyses of possible collapse mechanisms as related to recent glacio-climatic evolution and possible trigger factors.*

I.14: delete 'partially' (isolated portion and partially are redundant)

*The sentence was modified;*

I.22: ... understand THE role ...



*The sentence was modified;*

I.36/37: ice shelves are not collapsing due to acceleration and thinning of feeder glaciers, it's the other way around.

*The sentence was modified;*

I.48: neo-formation of -> formation of new ..

*The sentence was modified;*

I.48: is there really evidence for more subglacial lakes? I didn't look through the references carefully, but didn't see anything on a cursory look.

*The word "subglacial" was removed;*

I.65-70: a lot of this is unclear and speculative ('probably played a primary role', 'presumably', ...). How does active layer thickness affect glacier stability? Or are you referring to a subglacial active layer?

*The sentence was reworded (see P1 above):*

I.92: 'could be outlined' -> 'is'

*The sentence was modified;*

I.94 ; -> .

*Done.*

I.144: 'could be' -> 'was'

*The sentence was modified;*

I.161: delete 'a'

*We found the expression "As a result" to be correct;*

I.164: The hypothesis about changing plasticity appears out of thin air here. Perhaps it should be stated as a hypothesis to explore; same for active layer.

*The sentence has been modified, and the two distinct phenomena, as suggested by the reviewer, have been presented as hypotheses to be explored. The topic was also better stated in the Introduction (see also P1 above).*

Sec. 3.3: Satellite imagery and seismology is a bit of an odd combination for the same subsection



*The content was split in two sub-sections.*

I.194: define 'GSD'

*A definition was added;*

I.208: lately -> later

*The text was corrected;*

I.215: .. using a 0.05 m ...

*The text was corrected;*

I.216: define RES (or just use GPR throughout)

*RES (Radio-Echo Sounding) was already defined in the Introduction;*

I.221: functional -> used

*The text was corrected;*

I.233: by -> from

*The text was corrected;*

I.234: using values from sea ice studies seems odd; it has quite different strength

*We agree with the reviewer but we could not find other reliable data in the literature.*

I.237: 'could be probably considered': This kind of statement is very vague. Just state what exactly you assumed. Your borehole data provide justification for polythermal conditions.

*The sentence was reworded;*

I.238: Similar to what?

*The sentence was reworded;*

I.239/40: I am not convinced that PermaNet temperatures are directly indicative of polythermal glaciers. You actually explain this later; how firn refreeze processes can create warming conditions on glaciers that are not present on ice free ground and that are not incorporated in permafrost models.

*True. The sentence was removed. We now write in the Discussion:*

*P7*

*“Such recent subglacial freezing may likely have influenced the hydraulic permeability of the karstic subglacial rocks and, hence, the drainage mechanisms of the cold surface ice body.”*

I.247: A bit more detail on the model is warranted here. The Supplementary Materials don't help much. Say a bit more about the model, how it works, and what the differences are between the different versions.

*The LEM model has been described in much greater detail, including the key differences between the Janbu simplified, Janbu corrected, and GLE/Morgenstern-Price methods, which have been added in Section 3.5 (see P4, P5 and P6).*

Fig. 3 caption: .. for each OF the different ...

*The text was corrected;*

Fig. 4 and elsewhere: what is the difference between 'area' and 'surface'? Is one the map area and the other one actual surface area? If so, I would stick to map area. The actual surface area of a rough surface is actually not well defined and is scale dependent.

*The difference is “map area” and “surface area” as suggested by the reviewer. We are keen to retain both graphs, as the accurate measurement of surface area over the years was a long and rather complicated task to obtain reliable results. It was based on: digitization of contour lines from available maps, digital cartography, terrestrial and airborne laser scan data, and, finally, the correlation of satellite or aerial images (see SM for details and proper references).*

I.286: precipitations -> precipitation

*The text was corrected;*

Fig. 8: the grey shaded area for Marmolada seems large, given the altitude range of the glacier

*Yes. We added in the figure caption:*

*P8*

*“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.”*

I.337: after the mid of June -> after mid-June

*The text was corrected;*

I.339-345: several points are not clear here. You show temperature profiles for 3 July each year. These do not show the depth of the active layer. The active layer is the layer that changes from a frozen to a thawed state during the year. In mid-summer there is still part of the winter cold wave in the ground. I

don't think a single profile can be used to determine depth of the active layer. Overall, this profile does not contribute much of relevance to the paper. It shows that at a lower elevation and different exposure there maybe be some permafrost, but how transferable is this to the Marmolada Glacier with a layer of glacial ice?

*Temperature (T) data at the PZB site have been continuously collected since the borehole installation in late 2010. These data provide precise insights into how the active layer has changed over the years (2010–2025). We chose to present the data as shown in the figure to highlight the conditions in July 2022 compared to the same period in all other years. In 2022, T reached an absolute maximum within the depth interval between the surface and 3.5 m. These data offer some insights into how the thermal wave extended in depth in 2022 compared to the previous decade. Additionally, analyzing the PZB dataset allows for a local validation of the permafrost distribution map proposed by Boeckli et al. (2012) and, consequently, an assessment of its applicability to the Marmolada site.*

*We now write at Section 3.2:*

*P9*

*“The model devised by Boeckli (2012) is based on Mean Annual Air Temperature (MAAT) of the period 1960-1990. PZB data confirm this model and provide some information about ongoing permafrost warming in the region.”*

I.358/59: I'm having trouble identifying the 'traversel bediere' in the figure. This seems like a real oddity: how could a stream of water run in a transverse direction on a steep glacier?

*We understand reviewer’s observations. What we are trying to describe is not a bédrière strictu sensu but rather a crevasse filled with water, where the transverse water flow erodes the ice, creating a typical meandering morphology. The flow is transverse because the lower face of the crevasse forms a counter-slope, preventing the water from flowing in the longitudinal direction. At the end of the transverse section, the water overflows from the meander and flows over the ice surface, creating a true bédrière along the direction of maximum slope. We replaced “bédrière “ with “small torrent” and we added some explanation to the text and figure caption.*

I.381: 'Very little water evidences are' -> 'Very little evidence for water is'

*The text was corrected;*

I.382: delete 'somehow'

*The text was corrected;*

Fig. 11: I'm a bit skeptical about radar interpretations of bedrock under ice. These radar profiles are most likely influenced by out-of-plane reflections due to the shape of the glacieret. The v-shaped

troughs indicate that they should probably be migrated. The interpreted lines in the bedrock look quite a bit like the tails of hyperbolae created by point reflectors. Migration would shed some light on that.

*The authors are aware that out-of-plane reflections may occur in this geometry, with the crevasse signature c1 being a typical example. We collected the data using high-frequency (500 MHz) shielded antennas to partially mitigate this phenomenon in the bedrock response. The radius of the first Fresnel zone for this antenna frequency is approximately 1.5 m at a depth of about 15 m (the maximum depth of the bedrock), thus limiting the footprint size and the extent of backscattering from buried reflectors. We also recognize that some hyperbola tails are likely due to peaks and troughs in the bedrock morphology. However, as a first approach, we chose not to migrate the section to avoid the typical smearing of the radar image and enhance interpretation of the weak near-surface reflectors. Nevertheless, the post-failure radar profile was migrated. The new Figure 12 now shows both the un-migrated and migrated images of the bedrock. The bedrock geometry was reinterpreted based on the migrated data, resulting in a maximum vertical-lateral shift of 1 m. This re-interpretation led to a smoother representation of the bedrock morphology and it was validated comparing the buried bedrock morphology with the shape of the outcropping rocks nowadays visible just below the failure and in addition the maximum depth reached by the borehole in the ice nicely correlates with the RES interpretation in that position of the profile.*

Fig. 12: what's the colorscale?

*The color scale is "the normal" and it is commonly used to enhance surface orientation. RGB colors encode changes in surface normals.*

I.416: correct m3

*The text was corrected;*

I.418: could be -> was

*The text was corrected;*

I.421-24: can you conclude anything from these temperature measurements? This was imagery in the early morning and mostly reflects 'skin temperature', which would be very influenced by air temperature over the night.

*These temperature measurements always taken in the early morning are indeed skin temperatures. However, the values are consistent and comparable, despite having been collected in different seasons (summer and autumn). Furthermore, they are much lower than the minimum air temperature recorded during the previous night. At least in a qualitative sense, this information confirms that the ice body is cold. The above comment was added to the text.*

I.425-427: the surface temperature cannot be used to say something about permafrost conditions.

*We agree with the reviewer and have reprocessed the temperature of the exposed rock measured on the morning after the collapse, which ranged between 0 and -1°C. This temperature indicates thermal conditions close to the melting point (although influenced by nighttime air temperatures) and therefore could support the hypothesis of ice/sediment softening at the basal level over approximately 32% of the failure surface.*

Fig. 14: The seismic record is interesting. How well is the timing of the avalanche known? For example it looks like the seismic event records the initial failure (mostly in the horizontal components) and then the impact of the falling ice with both vertical and horizontal components about 20 sec later? Is this a reasonable interpretation?

*The error in the timing of the ice avalanche is approximately 0.3 s (0.27 s to be more precise) and it was estimated using multiple seismic stations. The reviewer's analysis is, in principle, correct but we are dealing with a rather complex wavetrain. The initial failure is primarily recorded in the horizontal component, followed by an ensemble of body (mostly S), converted and surface waves. The impact of the falling ice occurs on surface with an inclination of approximately 30 degrees thus generating high-amplitude transversal waves as well as lower-amplitude longitudinal waves. The time difference ( $\Delta t$ ) between these two events (initial movement and impact of the falling ice) was recorded more than 20 km away from the glacier. The differing velocities of body and surface waves, along with dispersion, cause this  $\Delta t$  to become larger as the recording distance increases.*

I.460-464: I fail to see the relevance of this paragraph and Fig. 14B. First, the figure shows no obvious similarity between the two events (for example the Everest event had a much larger vertical component). A thorough analysis would require looking at spectra and perhaps some force-momentum modeling.

*The paragraph was removed and the spectra of the Marmolada failure were included in the figure. A brief comment of the frequency content of the different spectral components was also added.*

Fig 15 caption: what does 'with evidenced the lower transversal crevasses' mean?

*The text was taken out for clarity*

There is a lot of overlap in Figs 15-18; these could be consolidated.

*The figure showing the schematization (conceptualization) of the numerical modeling was removed.*

I.510: what do you mean by 'uneven combination'?

*The text was changed in "unfortunate combination";*

I.518-520: Here is where you state your main hypothesis for the thermal state, but this is only weakly backed up (see discussion on permafrost above).

*The discussion regarding the thermal state has been simplified and re-organized to better align with the available data, avoiding hypotheses and speculations*

I.526: snow precipitation is mentioned here, but it is not well motivated.

*The sentence was expanded and now it reads:*

P10

*“The longer-term conditioning/predisposing factors are mostly determined by the relationships between the geometry of the glacieret and that of the carbonate bedrock. Further predisposing factors depend on the internal structure of the glacieret itself, on the physics and stratigraphy of the basal layers, the permeability of the frozen sub- and peri-glacial glacial rocks, and on the amount of winter-spring snow precipitation, which affects the timing of glacier ice exposure during the summer.”*

I.529-30: this is very much a hypothesis and conjecture and would require some thermal modeling to make a more definitive statement.

*The sentence was removed to avoid conjectures. Thermal modeling is a good idea for future work.*

I.544: second tens of -> middle of

*The text was corrected;*

I.556/7: Clarify what you mean here when you talk of 'thermal inertia in the exposed ice body'.

*The sentence was removed for clarity purposes;*

I.570: pervious -> previous

*In this sentence “pervious” was used as a synonymous of “permeable”;*

I.577-85: Again, there is quite a bit of speculation here

*The text describing the impact of permafrost changes on glacier stability was removed to avoid speculation;*

I.629: Altel -> Altels

*The text was corrected;*

I.634: Finding temperate ice with RES is a fraught subject with often questionable conclusions.

*The sentence was removed;*

I.664/5: Again, very speculative

*The part of the sentence referring to the 'transfer of heating from the outcropping rocks forming the east shoulder' was removed. The sentence was reworded to avoid hypotheses about the formation of the weak layer, instead focusing on describing the nature of the weak basal layer as reported in the literature.*

I.673/4: ditto

*The sentence was removed;*

I.711/2: this is an interesting observation and it needs some elaboration. It is not clear how a crevasse could penetrate to near the base in a cold glacier without the help of water. If the glacier is frozen to the bed, there are no longitudinal strain rates there, and failure under tension is not possible.

*The sentence has been modified and expanded to invoke the action of water as one of the agents for the opening of the crevasse.*

I.740: something is missing here.

*The sentence was reworded;*

The data statement reads odd. Every effort should be made to make data available publicly. That may not be possible with some of the proprietary imagery. But statements like 'data could be made available upon request' do definitely not meet modern open data requirements of most journals.

*The reason for this unusual statement is that we are dealing with a variety of datasets collected over the years from multiple public agencies, foundations, non-profit organizations, and private corporations. The authors can provide access to the geophysical data they collected after the failure, including RES profiles, IR images, and temperature measurements from the borehole drilled in the ice, as well as the seismological data. Additionally, they can share the DTMs generated by processing scanned historical maps, digital maps, and aerial/satellite images. The meteorological time series (temperature, snow cover, and rainfall) are publicly available, but a request must be submitted to ARPAV (<https://www.arpa.veneto.it/datirete.htm/richiasta-dati>). Finally, pre- and post-failure satellite images, which were purchased by the authors, cannot be made available.*