Reply to Dr. Truffer

This is a second review of the paper. The authors have made significant revisions and the paper has become much clearer and more focused in the process. I do recommend publication, but I still have a few issues that should be clarified.

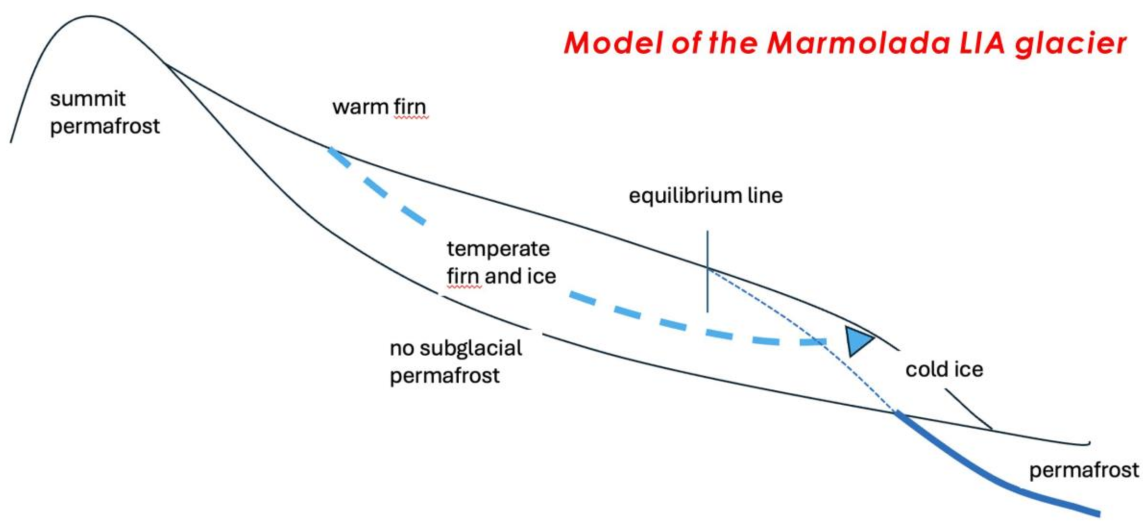
The authors are grateful to Martin Truffer for undertaking this second round of review.

General comments

Mostly, those revolve around the discussion of the role of permafrost that is, at times, still confusing. The paper claims on the one hand that glacier recession led from a temperate bed condition to a freezing bed condition since the LIA, and then more recently to a warming of the permafrost. I find that the paper presents little evidence for that. In fact, the authors present some evidence that during World War 1 the basal temperatures in the failure zone were below freezing. Borehole measurements immediately following the failure also show below freezing conditions.

We concur that the overall evolution of the thermal conditions cannot be definitively established from direct evidences, however, we present a logical and internally consistent reconstruction of the governing processes. The Little Ice Age glacier was most likely "polythermal" and predominantly "warm-based" except for the cold margins with underlying subglacial and adjacent proglacial permafrost.

In a steady-state condition, the summer meltwater percolates into the permeable firn of the accumulation area.

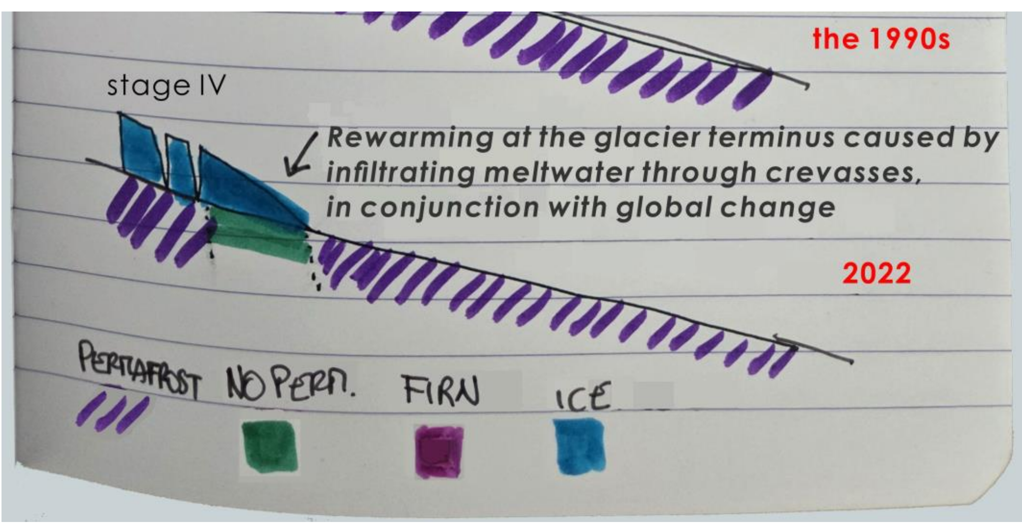


Subsequent refreezing of this meltwater within the firn releases latent heat, which warms the firn matrix and maintains it at the pressure-melting point (i.e., at phase-equilibrium temperature). This internal *refreezing process ensures that a significant portion of the energy absorbed at the surface, leading to melt, is retained as heat within the firn layer of the accumulation area.*

The temperate ice produced by the snow-firn-ice metamorphosis flows down underneath the equilibrium line to the ablation area. As the ice of the ablation area is impermeable, the meltwater flows off at the surface and takes with it the energy input from surface melting. The ice below the equilibrium line therefore cools down under the influence of negative surface temperatures forming an increasingly thick wedge of cold ice, which reaches the glacier bed near the ice margin, where permafrost penetrates into the ground. The Gruben glacier in the Swiss Alps provides a well-documented example of these conditions, and historical temperature records from World War I are consistent with such an incipient cooling stage

Global warming perturbs these equilibrium conditions. The equilibrium line rises rapidly, while the glacier typically retreats more slowly, reflecting its thermal and dynamic inertia. As a consequence, the warm firn area progressively diminishes and may eventually disappear completely. The glacier thereby transforms into an ice body situated entirely within the ablation regime. Influenced by recurrent sub-freezing ambient temperatures, this formerly temperate ice now cools and becomes cold ice. Where this cold ice is in contact with the bed, subglacial permafrost can begin to aggrade. This process tends to stabilize remaining glacier parts.

When the glacier finally disappears, the now exposed former glacier bed become perennially frozen , exhibiting newly formed permafrost. This is likely the current situation in deglaciated parts of the Marmolada massif, where bedrock has been exposed by glacier. Global warming, however, continues affecting permafrost worldwide. This means that the newly formed permafrost in the recently deglaciated areas including those surrounding our remaining glacieret, is also subject to warming.



In addition, meltwater infiltrating crevasses can induce refreezing (regelation) processes and convective heat transfer, contributing to the warming of sections of the glacier base. These factors, in conjunction *with associated hydraulic pressures, can affect the overall stability of the glacier —especially at the margins.*

We changed the sentences in section 5.1.3 and now they read:

P0

"Evolution of thermal conditions around the failure zone is crucial to get better insight into potential collapse mechanisms but involves complex transient glacier-permafrost interactions (Figs. 7-8). Where bedrock of the northern slope has remained free of glaciers during past decades, its temperature can be estimated at a few degrees Celsius below freezing, ranging from typically near 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). In the Alps, permeable 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 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 remained 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, already 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. These values suggest that moderately cold conditions prevailed at that time on the northern side of the Marmolada. Over the following decades, the progressive loss of insulating warm firn areas likely led to further cooling of surface ice. This cooling, in turn, is thought to have affected the thermal regime of the ice body from which the avalanche later detached."

"The long-term thermal evolution of the glacieret has, on one hand, caused the freezing of its ice base to the underlying rock, as confirmed by temperature measurements taken in the ice borehole throughout the upper portion last summer. On the other hand, the warming-induced permafrost degradation (Gruber and Haeberli, 2007), suggested by the fifteen-year temperature and active layer and permafrost thickness monitoring in the rock borehole at PZB (Fig. 7), is likely a contributing factor to weakening the basal interface in the frontal zone of the glacier. The curved geometry of the median crevasse, clearly visible after the failure, suggests that the glacier was primarily deformed under the influence of gravitational forces, with negligible basal sliding. This further supports the hypothesis of a locally cold ice base. Moreover, as clearly shown in Fig. 9B, a large portion of basal ice remained frozen to bedrock after the failure (see more details in subsection 5.2.2). Such recent subglacial freezing may likely have influenced the hydraulic permeability of the karstic subglacial rocks, potentially reducing drainage capacity beneath the cold ice. This permeability reduction could have helped building up high water pressures in the ice body."

To me, the most pertinent observations are the fully water-filled crevasse that would have created overpressure at the base of the crevasse, and the fact that no subglacial drainage occurred, which is consistent with a cold bed condition. Under such circumstances it should be expected that water pressure can progressively force a gap at the bottom of the glacier, leading to hydraulic jacking. The modeling section is useful in that it shows that the crevasse pressure cannot be considered as a sole independent cause of the failure. This is a significant result. One thing that is not clear to me, however, is how hydraulic jacking is considered as a separate factor from decreased ice-bedrock friction. If hydraulic jacking occurs, the friction would have to go to essentially zero.

Hydraulic jacking and the decrease in friction along the failure surface are considered separately due to the impossibility of otherwise incorporating the principle of effective stresses into the simplified model. This principle, enunciated by Terzaghi in 1922 and later in 1947, states that the mechanical behavior (including shear strength) of a granular material (e.g. sand) submerged under water pressure depends only on the effective stresses, which are equivalent to the total stresses minus the value of the water pressure. In other words, the Coulomb-like frictional behavior depends on the inter-particle contact forces that are only diminished and not totally cancelled out by the water pressure. Therefore, in the slope stability model reported in the article, the pore water pressure is simulated by hydraulic jacking, while the shear strength is expressed through the Coulomb criterion in terms of total stresses (i.e. the decreased ice-bedrock friction), assuming the principle of superposition of effects to be valid, without calculating the effective stresses along the failure surface.

Tergazhi K. Der grundbruch an stauwerken and seine verhiltung. Die Wasserkraft 17 (1922) 687445–449.

Terzaghi, K., Theoretical Soil Mechanics, John Wiley and Sons, New York (1943) ISBN 0-471-85305-4.

How about the following model that seems consistent with all the data and follows along similar lines as the one presented in the paper:

1) The glacier base in the failure area was frozen, presumably for many decades. This frozen condition prevents subglacial water drainage.

2) The opening of a full-depth crevasse allowed water to get to the base of the ice and over-pressure the system, progressively forming a gap that led to hydraulic jacking and a loss of basal friction.

3) General climate warming is leading to a general degradation of permafrost in the area that may have led to a warming of the ice base near the frontal area of the glacieret. This is a plausible contributing factor and might help explain why the crevasse filling event in 2003 did not lead to a failure.

We fully agree with the reviewer, and to some extent, similar considerations were already present in various section of the paper. We have now better conveyed this timeline by adding a sentence to the Conclusion section:

P1

In short, the base of the cold ice in the failure area was most probably frozen, presumably for many decades already. This frozen condition largely, if not entirely, prevented subglacial water drainage. The recent opening of a full-depth crevasse allowed water to get to the base of the ice and to over-pressure the system, progressively forming a gap that led to hydraulic jacking and a loss of basal friction. Continued atmospheric warming leading to a general degradation of permafrost in the area may have led to a warming of the ice base near the frontal and marginal area of the glacieret. This plausible contributing factor might help explain why the crevasse filling event in 2003 did not lead to a failure.

Specific comments:

l.37: ..., such as the degradation ...

The sentence was modified;

l.49: treats -> threats

Correction was made;

l.201: delete initials in reference

Correction was made;

Figure 3 caption: delete 'surface ablation' (none of these curves show surface ablation)

We replaced 'surface ablation' with 'surface lowering'; Panel C shows the lowering of the ice surface over time at the failure site … in my view this is still ablation but the word was changed.

l.269: explain the difference between 'surface' and 'area'. This was not obvious to me when I first reviewed the manuscript. I still think that reporting a 'surface' does not add additional information, and is, in fact, a scale dependent quantity, with no clearly defined meaning.

In general, we agree with the reviewer. The reason we included surface area in the graphs is that, in the case of dipping slopes, it can serve as an additional parameter to describe changes. This quantity was also required to compute ice volume changes over time, so it was already available and we decided to include it in the figure. The Topographic Surface Area (of a slope) is the actual two-dimensional measure of the slope's terrain surface, accounting for all inclinations and undulations. This definition was added to the caption.

l.276: a newer reference, such as Hugonnet et al may be more appropriate here

The reference was added.

l.292: delete 'as'

'as' was removed and the first part of the caption was reworded.

l.340-42: Rewrite sentence for clarity and correct grammar. Perhaps: Despite the uncertainty about the permafrost conditions at the Marmolada detachment site, we estimate the near surface temperature to be colder than at PBZ (at about -2 deg C), due to its northerly exposure.

The sentence was changed according to reviewer's suggestion.

Fig. 9 caption and elsewhere: how do you know this is regelation ice?

Primarily because it is a cryoconite-enriched layer. Evidence supporting this interpretation includes the following observations: (i) cryoconite was observed to be deposited at the bottom of the crevasses; (ii) the associated ice surface was evidently distinctly glassy, a typical characteristic of regelation ice; and (iii) this dark and thin layer mantled the crevasse floor.

l.437-444: I suppose it's ok to report these measurements, but it's hard for me to see how they should be interpreted. For example, on a clear night with strong radiative cooling, I would expect the surface temperature to be lower than the air temperature. But you are not really claiming that the ice temperature is -9 deg C, or is that the point? That would be significantly colder than any other direct measurement.

We understand the reviewer's observations. These IR data were repeatedly collected using drone-based high-end sensors, and I also personally took some IR shots from a helicopter while hovering just above the ground and directly in front of the ice scarp. The results from the different surveys were consistent and comparable, and in my opinion, for these reasons, it is worthwhile to report these data. We are NOT claiming that the ice is at –9 °C; we are simply suggesting that it is likely a few degrees below the freezing point, as recently confirmed by borehole temperature measurements. In the paper by Aubry-Wake et al. (2015), the authors report a negative bias exceeding 5 °C.

We changed the sentence that now reads:

P2

These temperatures, always taken in the early morning, represent skin temperatures, but they are significantly lower than the nighttime air temperatures. The values are relevant because they have remained consistent and comparable over time. Reliable quantitative interpretation requires complex calibration of the sensor along with specific processing. Corrections on the order of several degrees are often necessary (Aubry-Wake et al., 2015) especially in the case of rough surfaces. Despite potential biases of several degrees, these measurements still indicate —at least qualitatively—that the ice body is unquestionably cold, with temperatures several degrees below freezing.

l.442: complicate -> complicated

Correction was made;

l.442: delete 'Anyway'

Correction was made;

l.443: because THEY remain ...

Correction was made;

Fig. 16 caption: rewrite (I don't understand 'with evidenced the cross section'

The first part of the caption was changed in: Pre-failure model of the glacieret showing cross-sections HH', MM', and NN'.

l.553: what is the decimeter scale based on (estimated from what?)

Direct observation … the sentence was modified accordingly.

l.554: ... was performed along a cross-section that ROUGHLY follows ...

Correction was made;

l.539-542: I don't understand most of this sentence, including what you mean by 'heat waves propagating through the exposed rocks'. If you mean from the southern slopes on the other side, than this would imply longer time scales (many years)

This means that it's sometimes hard to distinguish between conditioning and triggering factors, as a predisposing factor can turn into a trigger over time—especially in the case of thermal effects. We do NOT refer to long-term heating effects from the southern face of the Marmolada; rather, we are talking about solar radiation directly warming the exposed bedrock at the front and on the eastern side of the glacieret. We change the sentence that now reads:

P3

It is important to emphasize that certain thermal effects can act as both predisposing and triggering factors. In particular, dynamic thermal processes—such as heat transported to the glacier base by meltwater percolating through crevasses, and heat absorbed by exposed rock surfaces—tend to function more as triggers than as underlying conditions.

l.546: delete 'glacial'

Correction was made;

l.569: sum -> total

Correction was made;

l.574: delete 'a' in front of precipitation

Correction was made;

l.576: I don't believe decade is used like this, 'in the second third of May'?

Correction was made;

l.577: ... absorbs less solar radiation THAN ICE, but ...

Correction was made;

l.577/78: is this correct in terms of mass of liquid water produced?

We found this a reasonable estimate;

l.580 there is a very -> there was very

Correction was made;

l.580: penetrate right into -> penetrates into

Correction was made;

l.582: is -> being

Correction was made;

l.584: in -> into

Correction was made;

l.589: do you mean 'permeable' (instead of pervious)?

We replaced pervious with permeable although the two words are often used as synonyms.

l.597-599: the sentence is not quite grammatically correct. But see also my overall comment. This statement is plausible, but it is not backed up by the observation of cold ice during WWI.

We have addressed this point in the overall comments.

In our opinion, these temperatures indicate that the ice body is progressively cooling; leading to the cold ice we measured last summer. This is consistent with our hypothesis about the overall glacier evolution. The sentence was changed to include these considerations (see new sentence P0 in the overall comments).

l.600-601: There is no evidence given for this statement

What we describe here is the typical behavior observed in other Alpine glaciers when the firn layer disappears. We have addressed this point in the overall comments.

l.603: I would state this as: ... is likely (or plausibly) a contributing factor to weakening the basal interface in the frontal zone of the glacier.

The sentence was changed accordingly.

l.605: I'm not sure if you could really conclude no basal sliding from that

This is an additional indication that basal sliding was absent or negligible. Further supporting elements include: the borehole drilled in 2024 just a few meters above the failure zone confirmed that the ice was frozen to the bedrock; aerial and satellite imagery from the past 30 years shows no evidence of sliding; and no water was observed at the glacier base, as indicated by the lack of frontal discharge between 1990 and 2022.

l.607: no evidence is provided for 'recent basal freezing'

See our response to the reviewer's comments on Fig. 9. The presence of a thin, cryoconite-enriched ice layer at the bottom of the crevasse provides evidence of regelation ice forming at the glacier base, directly above the bedrock.

l.614: reformulate this. I don't know what is meant by 'initial sliding of critical glacieret block thus triggering ...'

The sentence was reworded and now it reads:

P4

Among the possible triggers, we also evaluated whether a small earthquake could have caused the displacement of an ice mass that was already near its stability threshold, thereby leading to the full failure (Figs. 14-15).

l.621: ',' after before

Correction was made;

l.622: ... glacier on the day ...

Correction was made;

l.646: melting -> melt

Correction was made;

l.651: .. may ALSO have been ...

Correction was made;

l.651-53: There is no evidence for melting in the detachment zone. In fact, you present data that indicates cold basal conditions in that zone.

In reality we stated that the basal portion of the sliding surface—excluding the vertical and lateral ice scarps—consisted of three different units (see Fig. 9B): (a0) glacier ice, where failure occurred along an internal foliation; (s0) a thin, glassy, cryoconite-enriched ice layer, interpreted as regelation ice; and (e0) bedrock, where the failure occurred directly at the ice–bedrock interface. In summary, at the time of failure, the glacier was certainly frozen to the bedrock above the failure zone, to the west, and along its western front. Partly melting also induced by water forcing its way along the glacier base probably occurred at unit e0. The sliding surface of the Altels glacier failure (Failletaz et al., 2011) also consisted of different units, some of which contained residual ice still frozen to the bedrock.

l.660: this is in direct contrast to the statement above. Also, what is the evidence that the remaining ice was refrozen meltwater? It could also just be a failure within basal ice.

See comment above and see reply to reviewer's comment l.607 and to Fig.9.

l.674: delete 'Anyhow'

Correction was made;

l.708: delete 'tout court'

Correction was made;

l.708-12: These two statements directly contradict each other

This may be a matter of clarity, as we personally find no contradictions. Below is an attempt to establish the sequence of events:

At time t_0, the failed glacieret was still frozen—or mostly frozen—to its bedrock.

At time t_1, prolonged heating of the rocks on the eastern shoulder, along with the regelation of meltwater in the crevasse, caused progressive warming of the ice near the glacier base.

At time t_2, the water was able to force its way along this softened ice throughout the entire eastern sector (e0) and at the crevasse bottom (s0).

This should not be interpreted as the presence of a continuous water layer at the glacier base across the entire e0 sector. Instead: water that has made its way to the glacier base, likely driven by the overlying *ice pressure, appears to form an initial distributed drainage system. This system can be visualized as a micro-scale network of interconnected tiny rivulets—at times no more substantial than linked droplets—sparsely flowing directly over the bedrock.*

We hope this clarifies the apparent contradictions.

l.712: Why do you consider this most likely? As stated in the overall comments, I think there is a slightly different scenario that I personally find more likely, as it avoids some of the stated contradictions.

See comment above. The scenario suggested by the reviewer in the overall comments is fully consistent with ours. We are simply attempting a more in-depth reconstruction through a careful analysis of the available data.

l.717: I think you mean 'significantly' rather than 'largely'? In this context largely would mean 'mostly'

Correction was made;

l.721: I have a hard time imagining a scenario of hydraulic jacking without simultaneously losing basal friction (see overall comment)

We addressed this issue in the general comments.

l.724: Is that really surprising? It is the surface at which you apply the jacking

We are referring to the vertical scarp.

l.735: largely -> significantly

Correction was made;

l.769: is this known?

Images taken the day before the failure by UAV showed water flowing out the median crevasse. Post-failure images of the remaining edges of the median crevasse shows a clearly water-eroded inside with smooth rounded surfaces.

l.775-777: I'm personally more hopeful about the possibility of seismic monitoring, because some of these processes have different spectral signatures and could potentially be distinguished seems in terms of data the identification of large water filled crevasses would be indicative of a potentially hazardous situation that warrants detailed monitoring.

I fully agree with the reviewer, but I fear that seismic monitoring can only be applied when the potential collapse of the glacial mass threatens property or people. In all other cases, due to cost issues, it is very *unlikely that a local network of sensors will be set up, as is routinely done for dams or other critical infrastructures.*