Author Response to Review Round 2 Comments

March 31, 2026

We thank the referee for his second round of comments which help to further improve our paper. Below we provide a point by point response (black text) to the comments (blue text)

General comment 1: A very central problem is the use of precise, concise and adequate language and terminology. I have edited the first half of the manuscript (See detailed remarks below) but was exhausted by then (luckily, the quality improved somewhat later in the manuscript). It is important that all authors spend time in editing the paper carefully to improve its readability. Doing that you will also find several typos.

Where appropriate, we improved and clarified the terminology and we carefully edited and proofread the text throughout and improved the language and formulations.

General comment 2: The new version also contains some questionable and unproven hypothesis. Please avoid speculation if you could easily test if your statement is valid or not.

We tried to tone down/avoid such speculations or made clearer that these are open questions to be further studied in the future

General comment 3: My last detailed comment is about a finding, which I consider as very important. Generations of permafrost researchers have cited Glen's law. Some of them have violently misused Glens law to make it fit to their observations. No doubt, plastic deformation is one of several processes contributing to the deformation of rock glaciers (and most likely the process that initiates the deformation). However, you just showed that the deformation between the AL and the shear zone cannot be explained by a power law alone, even then when this zone consists of an almost pure ice core! This deserves more attention and some further thoughts and conclusions.

We agree that Glen's flow law does not explain all of our profile and made this clearer in the text as supported by our measurements.

Line 3 : “Understanding which processes lead to the observed displacement signal on the rock glacier surface is important because it is a parameter of the essential climate variable (ECV) ”permafrost”.”

Addressed and rephrased the sentence accordingly.

Line 30: Permos and Nötzli report that warming rates differ clearly between (warm) rock glaciers and permafrost with lower ice contents. This should be mentioned here, perhaps with a short explanation of this differences.

We briefly included the aspect that Nötzli et al. (2024) paper found colder permafrost sites to be warming faster than the warm ones.

Line 35:” The internal structure of rock glaciers is described to be heterogeneous and the displacement velocity changes non-linearly with depth. “

Addressed and rephrased the sentence accordingly.

Line 37: “The displacement signal at the rock glacier surface typically represents the combination of different deformation processes in three layers: the top coarse-blocky active layer(AL), the main permafrost ice core, and a frozen fine grained layer called the shear zone, where most of the deformation occurs.”

Addressed and rephrased the sentence accordingly.

Line 39/40: Delete: The surface movement of a rock glacier is an integrated signal of all these three components.

Deleted

Line 42: All the mentioned monitoring methods are “geodetic”. Either summarize as geodetic monitoring methods or specify all systems (total station, Lidar. . .)

Summarized the methods as geodetic.

Line 44: “RGV does not specify at which depth deformation occurs or where it changes over time.”

Addressed and rephrased the sentence accordingly.

Line 45: “Vertical deformation profiles of rock glaciers were first acquired at three sites in the Engadine. . . ”

Addressed and rephrased the sentence accordingly.

Line 47: This rare deformation data from boreholes showed that, depending on the site, “These measurements revealed that, depending on the site, about 60% to over 90% of the surface displacement happens in the shear zone (Arenson et al., 2002). “

Addressed and rephrased the sentence accordingly.

Line 51: “However, after 10 months all boreholes were destroyed because of the large displacement magnitudes at Furggwanghorn . . . .

Addressed and rephrased the sentence accordingly.

Line 55: Seasonal velocity changes cannot be attributed to a specific layer using periodic measurements; however, multiannual changes can be attributed (e.g. Ritigraben)

Addressed and rephrased the sentence accordingly.

Line 58/59: Repetition

We rephrased it to make it clearer that this paragraph is now about the driving processes of deformation.

Line 59: “Most recent studies improper if you cite studies from 2008.

Removed “recent” and rephrased the sentence slightly.

Line 61 ff: If you talk about plastic deformation and seasonal changes, you should mention that seasonal temperature changes only occur in within a limited depth and that in the meanwhile, many rock glaciers are almost isotherm (close to 0℃)

We added a sentence here to mention the role of the ZAA depth in determining the extent of seasonal variations in rock glacier temperature.

Line 72: “The large differences in temperature and internal structure between different rock glaciers and often even within one landform. . . .”

Addressed and rephrased the sentence accordingly.

Line 74: “The first objective of this study is to use the continuous high temporal resolution deformation record from the 2015 borehole drilled in Murtel-Corvatsch rock glacier to determine how the integrated components of deformation varies over different timescales and with depth. The second objective of this study is to explore the depth dependent thermo-hydrological controls of seasonal deformation changes with depth using the extensive data from at Murtel rock glacier. The third objective is to compare the surface displacements measured using the three systems available at Murtel rock glacier: borehole inclinometer, GNSS and geodetic survey using a total station.”

Addressed and rephrased the sentence accordingly.

Line 82: “located between 2640–2800 m a.s.l. in a north facing slope. The mean annual air temperature (MAAT) at the site during the period 1998–2022 period was -1.5℃ (PERMOS, 2024). “

Addressed and rephrased the sentence accordingly.

Line 84: “and is unique due to its characterized by its high ice content of . . . ”

Addressed and rephrased the sentence accordingly.

Line 107: “The bottom of the borehole is assumed to be anchored to its base” I do not understand what this should mean. You want to say that the bottom of the borehole is in stable bedrock?

We rephrased it and thereby clarified that the translational displacement at the bottom of the borehole is negligible, so it acts as a 'stable' reference point to integrate the SAA displacements upwards along each segment.

Line 109: Why is a displacement resolution given “per year”? spatial resolution is spatial resolution independent of time, isn't it?

The manufacturer reports a long-term accuracy after 1.5 years of operation of ±1.5 mm. We rephrased this accordingly.

Line 114: orthogonal? You mean horizonal?

We meant that the x and y components are perpendicular to each other, but that's redundant so we removed “orthogonal”.

Line 116 Displacements occur over time per definition

Addressed by removing the “with time” at the end of the sentence referring to the displacement calculation.

Line 128: What means “at each depth”?

Removed “at each depth” as then at the end of the sentence we explain that the shear strain is calculated between each SAA sensor.

Rest of Methods: partly difficult to read. Improve language and remove typos

Addressed by editing language in order to improve readability.

Line 166/167: Be careful, the initial thawing of a thermistor often appears unexpectedly, because the slow deepening of the AL in between two sensors isn't captured by linearly interpolating temperatures between them. This is because temperatures of the lowest sensor in the AL and the uppermost sensor in Permafrost are both in a diffuse zero curtain zone during the time of max. AL depth. Although you can't see it in the temperatures, it is more likely that the AL deepened slowly over the years in such an ice rich setting, than that it remained stable and suddenly dropped by more than 50 cm.

The phrasing here was misleading as the ALT does not suddenly drop by half a meter, but does so over a few years. We rephrased this to convey this message of continuous AL deepening clearer: 'The ALT extracted from the borehole temperatures is on average 3.5 m thick, until 2021 when it begins to deepen towards 4 m'.

Line 187: To make it very clear, perhaps add: While we observed an increase of the strain rate in one layer, there was a decrease of the strain rate in another layer during the same year. To support the following examples, you could add a table with strain rates of each layer and each year. That would make it more evident than in figure 4 and 5 where it is hard to extract this information.

A new table (Table 2 in revised manuscript) has been added and integrated in the text to ease and support the description of the interannual patterns of deformation across the three identified layers. However, this is not relevant for the line mentioned here which talks about absolute annual velocities at the surface versus at depth, and not layer-specific characteristics, which are described earlier in the paragraph.

Line 223: Last sentence is discussion already

We agree, and the sentence is removed.

Line 255: Why not "caused by a distinct weak zone/Layer in the stratigraphy, leading to. . . "

We have not directly tested the material properties within the shear zone, so we want to avoid calling it a weak layer, but rather phrase it as a general link between its high strain rates and the strong changes in stratigraphy observed around its depth range. However, we edited and added in this paragraph (linked also to other comments below) some more discussion on the effect of variable depth stratigraphy and debris content on the shear deformation and also set this into better into context of other rockglaciers with deformation observations.

Line 261: "The shallower shear zones are more likely to be above the depth of zero annual amplitude, and hence experience larger temperature variations. " This is speculative and – to my knowledge – not true for the mentioned landforms. If you make this statement, you must proof it. For the rock glaciers you are referring to, borehole temperatures are available.

We agree that this is likely to be rare case for individual steeper thinner rock glaciers, so the link between shear zone depth, temperature and fraction of deformation is removed from the discussion here.

Line 262: "This is important as it means that the bottom of the ice core above the shear zone will have higher plastic deformation, applying more shear strain to the underlying shear zone (Kaab et al., 2007)." This sentence makes no sense, neither logically nor physically. It refers to the previous statement about the ZAA (which I consider as wrong), but even if it would be true it does not mean that there is more plastic deformation above the ZAA than below. Moreover, strain cannot be "applied" by strain in another layer!? Stress can, but also this makes little sense in this setup. If you apply normal stress and the process in the shear layer is creep, it does not matter if you put a rigid or a plastic body on top of it. If you apply a shear stress over the entire depth profile, stress in the shear layer will decrease when plasticity of the permafrost body increases. This is then the opposite of what you wrote.

We agree that the terminology here was not precise. The concept was motivated by the discussion from Kaab et al. (2007) regarding the timing of shear zone peak deformation with that of the ice core above, however, the concept is not viable and thus has been removed.

Line 263-265: The other important consideration is that shallower shear zones are more likely to have seasonally-varying pore water pressures due to water infiltration (Kenner et al., 2020; Bast et al., 2024). This is again speculative and none of the two cited papers supports this statement. The temperature of the permafrost body (and the hydrological characteristics of the surrounding catchment) is very likely much more important for the hydrology in the shear layer.

We remove this connection between the hydrology and the depth of the shear zone, and limit the discussion to the role of the characteristics of the permafrost body in determining the hydrology of the shear zone, and hence its mechanical response.

266: That's it!

296: Two weeks from May to August?

As the range of the end of the seasonal melt (spring zero curtain) is highly variable from May-July, so it makes no sense to provide the number of weeks here. So we clarified that the time lag is on the scale of weeks.

Line 324: Caution! You compare different periods. It was not one of the lowest velocities measured at Schafberg but an intermediate deceleration.

We rephrased to say that it showed a strong deceleration instead of saying that it had one of its lowest velocities.

Line 342: "Note that in 2022 the temperatures in the ice core are not particularly high; however, the ice core deformation in 2022 was the highest of this period." Isn't that a contradiction of what you have said before and hereafter?

We remove this sentence to avoid the contradiction, and deem it to not be relevant as the correlation between ice core temperature and deformation is, on average, evident as seen in Fig Appendix B1.

Line 347ff: And suddenly everything looks so much different than expected. Good that you say that now, this is what brings us forward!

Thanks.

Line 355 to 368: Somehow confusing and hard to follow. It seems you jump between different topics, and it remains unclear what you actually want to say here. For me it is a bit disappointing, that the elephant in the room is little addressed: You just found out that plastic ice deformation described by a power law cannot explain the deformation observed in the ice core. There is not only a small deviation between observation and power law but a colossal gap. This is super interesting, but you only say a few words about it and in the last sentence you write again about "predominantly plastic deformation. Well there must be something else, of which temperature is again only a proxy and whose influence increases exponentially when "the annual mean ice-rich core temperature was the highest in other words when the temperature was closest to 0°C. Look

at your deformation profile in Figure 3. Does this look like pure plasticity? A smooth exponential curve? In the lower part of the “ice rich core”, the profile is curved convex towards the x-Axis! This is not what plastic deformation does. Do not focus too much on your local stratigraphy and think in 3D. There are at least a few evidences that there is some spatial heterogeneity also at Murtel. A few ideas more on that would be great.

The role of the few debris layers in the ice-rich core are now better discussed in context of the deviation found relative to Glen’s flow law. However, we believe it becomes too speculative to go further and explore 3D aspects of the internal structure given we only present the borehole stratigraphy.