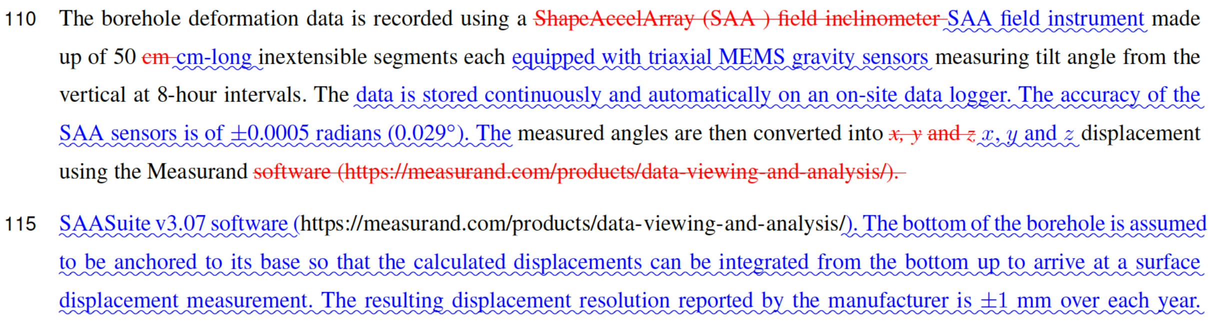
Author’s response

RC1

First, we would like to thank the reviewers for their contributions in making this revised version of the manuscript a stronger case. The main changes implemented are: the more detailed discussion on the accuracy assessment of the borehole deformation data, along with resampling its daily data to monthly, restructuring the discussion for improved clarity, more consistency with technical terms used, and more implications of the findings for the “permafrost” ECV parameter. The relevant comment/s of the reviewer for the following response will be grouped based on the topic and written in *italics* while the response below will be in normal text. The comments which we felt were self-explanatory were excluded from this response, the corresponding changes made can be found in the *latexdiff* PDF.

“One of the most important issues is the need for a more careful treatment of the SAA dataset. A general assessment of the challenges and limitations of this measurement system, along with an accuracy analysis, is sorely lacking. Inconsistencies in some of the given values are evident.”
“135: It is essential to add a paragraph about the accuracy of the Inclinometer somewhere to proof the significance of the results.”
“178/179: This is weird. A deformation can’t become negative. A directional displacement can but it won’t happen in this case. What you describe here is a measurement artefact which calls for an accuracy analysis even before presenting any results”
“4.3: It is important that you finally say at least something about challenges of the measurement system. The section is however rather confusing with a lot of speculation. Since this dataset is the core of your paper, this section must be transformed into an extensive analysis of the measurement system, including its accuracy and limitations. Therefore, a literature review is necessary and this section must be placed before the result section and not in the discussion. All results must be reconsidered under the light of this evaluation of the measurement system.”

In the methods we elaborated more on the SAA instrument specifications and uncertainty.



The borehole deformation data is recorded using a ~~ShapeAccelArray (SAA) field inclinometer~~ SAA field instrument made up of 50 ~~cm~~ cm-long inextensible segments each equipped with triaxial MEMS gravity sensors measuring tilt angle from the vertical at 8-hour intervals. The data is stored continuously and automatically on an on-site data logger. The accuracy of the SAA sensors is of ±0.0005 radians (0.029°). The measured angles are then converted into ~~x, y and z~~ x, y and z displacement using the Measurand ~~software (https://measurand.com/products/data-viewing-and-analysis/).~~ SAASuite v3.07 software (https://measurand.com/products/data-viewing-and-analysis/). The bottom of the borehole is assumed to be anchored to its base so that the calculated displacements can be integrated from the bottom up to arrive at a surface displacement measurement. The resulting displacement resolution reported by the manufacturer is ±1 mm over each year.

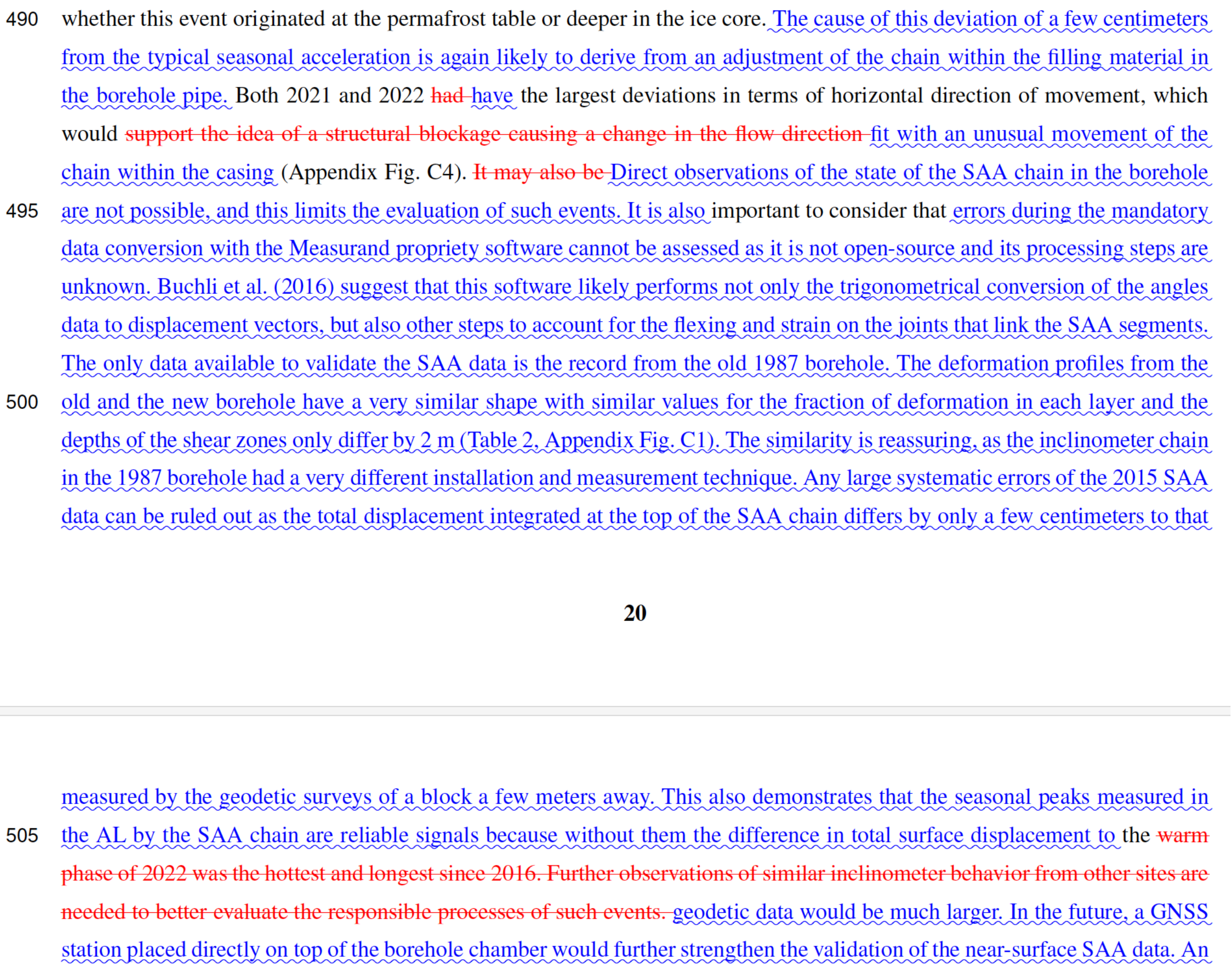
This is, then, further explored in the section 4.3, where we calculate a measurement accuracy for the SAA data using the displacement measured below the shear zone where there should be no deformation.

station placed directly on top of the borehole chamber would further strengthen the validation of the near-surface SAA data. An accuracy assessment of the SAA data can be done using the measurements at depths below the shear zone, where it is assumed that there should be no displacement. There, the observed maximum total displacement measured over the 7.25 years is 2 cm, and this can be used to estimate an annual velocity uncertainty of 0.3 cm/year which is three times more than that reported by the manufacturer. This, then, can be considered as an upper bound of the instrument uncertainty, and it remains well below the typical surface velocity magnitudes of 1-5 cm/month. This gives confidence in the kinematic patterns and processes inferred from the SAA data throughout this study.

We resampled the daily SAA data to a monthly resolution which shows still the same seasonal patterns and does not alter our conclusions, while ensuring the signal amplitudes are well above the accuracy limits of the instrument.

~~inclinometer~~ chain with time, resulting in a cumulative daily time series of ~~total~~ horizontal displacement. ~~Differences between daily measurements are then applied~~ The daily displacement of Murtèl rock glacier is generally at the sub-centimeter scale, so the daily series is resampled to a monthly resolution. The GNSS displacement data is corrected for the rotational movement

In section 4.3 of the Discussion, we explained in more detail the validity of the SAA data in context of the old inclinometer data and the unusual events of 2021 and 2022. We emphasized that we can use the fact that over the whole measurement period the integrated surface displacement from the SAA chain is very similar to that of the geodetic data to be confident that there are no large systematic errors in the SAA data and that the enhanced AL deformation component is a true signal.



whether this event originated at the permafrost table or deeper in the ice core. The cause of this deviation of a few centimeters from the typical seasonal acceleration is again likely to derive from an adjustment of the chain within the filling material in the borehole pipe. Both 2021 and 2022 ~~had~~ have the largest deviations in terms of horizontal direction of movement, which would ~~support the idea of a structural blockage causing a change in the flow direction~~ fit with an unusual movement of the chain within the casing (Appendix Fig. C4). ~~It may also be~~ Direct observations of the state of the SAA chain in the borehole are not possible, and this limits the evaluation of such events. It is also important to consider that errors during the mandatory data conversion with the Measurand propriety software cannot be assessed as it is not open-source and its processing steps are unknown. Buchli et al. (2016) suggest that this software likely performs not only the trigonometrical conversion of the angles data to displacement vectors, but also other steps to account for the flexing and strain on the joints that link the SAA segments. The only data available to validate the SAA data is the record from the old 1987 borehole. The deformation profiles from the old and the new borehole have a very similar shape with similar values for the fraction of deformation in each layer and the depths of the shear zones only differ by 2 m (Table 2, Appendix Fig. C1). The similarity is reassuring, as the inclinometer chain in the 1987 borehole had a very different installation and measurement technique. Any large systematic errors of the 2015 SAA data can be ruled out as the total displacement integrated at the top of the SAA chain differs by only a few centimeters to that

measured by the geodetic surveys of a block a few meters away. This also demonstrates that the seasonal peaks measured in the AL by the SAA chain are reliable signals because without them the difference in total surface displacement to the ~~warm phase of 2022 was the hottest and longest since 2016. Further observations of similar inclinometer behavior from other sites are needed to better evaluate the responsible processes of such events.~~ geodetic data would be much larger. In the future, a GNSS station placed directly on top of the borehole chamber would further strengthen the validation of the near-surface SAA data. An

“Later you are talking about “daily deformation rate”, what I assume is the deformation velocity of a certain layer on a daily basis? Again, an accuracy analysis is absolutely essential here. If you later calculate the daily deformation velocity changes in the AL, which deforms 26 millimeter per year, this makes on average 70 micrometer displacement per day and of these 70 micrometers per day you calculate seasonal deviations!? I do not believe that your system is that accurate. In contrast, referring to the findings of Buchli et al. we are far of an accuracy that would allow such interpretations: https://doi.org/10.2136/vzj2015.09.0132”

“Line 180: With 0.25 mm/day deformation velocity you end up with 9.1 cm deformation per year, which deviates strongly from the 5.9 cm given as annual deformation rate. This shows again that an accuracy analysis is very important to distinguish a measurement signal from noise and systematic errors.”

The confusion regarding the terminology used for the layer-specific velocity values reported is clarified in the methods section by clearly defining a *layer-specific velocity difference* as the difference in velocity from the top to the bottom of the given layer, not an layer-averaged velocity. This is more similar to a shear strain rate variable, but without normalizing it by the layer thickness to provide more readable values.

based on the calendar year. ~~For~~ Using the SAA data, layer-specific ~~deformation rates are calculated~~ velocities differences for the AL, the ice-rich core, and the shear zone are calculated by taking the difference of the ~~deformation rates between the top and the bottom values~~ velocity from the top to the bottom of the given layers. The fraction of deformation that occurs in a given layer relative to the surface displacement is calculated by dividing the layer-specific ~~deformation rate by the total~~

In the results where these values are presented, we make it again explicit that these are velocity differences from the top to the bottom of each layer. We also add the strain rate values to show that these two variables describe the same quantity.

The interannual variability of the borehole deformation varies across different depths. The ~~AL-specific annual deformation rate~~ annual velocity difference from the top to the bottom of the AL ranges from approximately 1 cm/year to 6 cm/year (Fig. 4a). In other terms, the average annual strain rate ($\dot{\varepsilon}$) in the AL varies from 0.003 year^{-1} to 0.018 year^{-1}. The ice-rich core ~~deformation~~ velocity difference ranges from approximately 1 cm/year ($\dot{\varepsilon} = 4 \times 10^{-4}$ year^{-1}) to 5 cm/year (0.002 year^{-1}), and the ~~shear zone deformation~~ velocity difference from the top to the bottom of the shear zone stays relatively constant, ranging from approximately 6 cm/year (0.04 year^{-1}) to 7 cm/year (0.05 year^{-1}). A similar pattern of decreasing interannual

The seasonal deviations we observed at a daily resolution still hold at a monthly resolution as illustrated in the updated Figure 5.

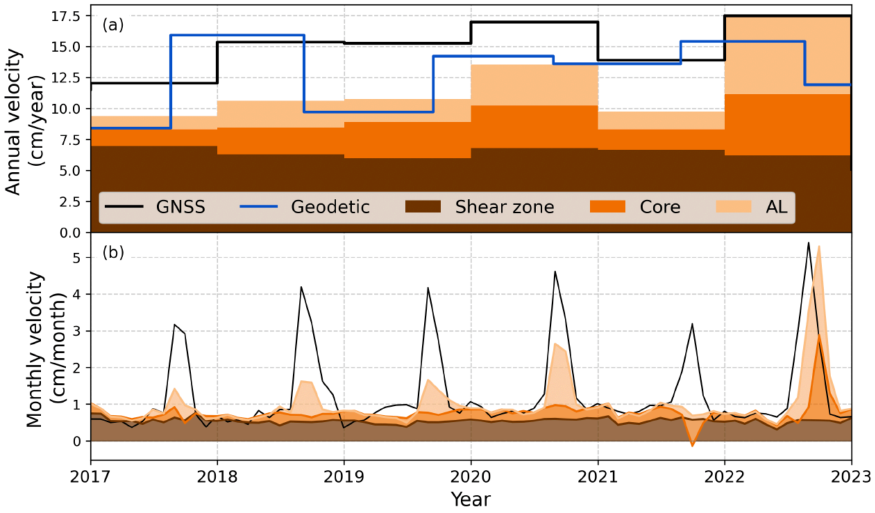


Figure 5. Layer-specific cumulative ~~deformation rates~~ velocity over time: (**a**) at an annual resolution and (**b**) at a ~~daily~~ monthly resolution. Measurement are from the borehole SAA, the GNSS station and the geodetic marker (only with an annual resolution).

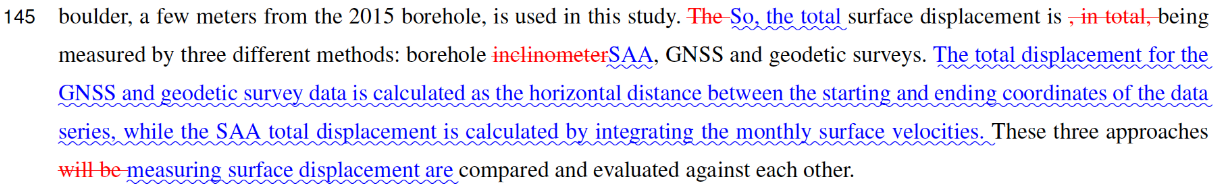
"Comparing an inclinometer with a GNSS sensor/Total station sounds a bit odd. Perhaps comparing the surface displacements measured by system xyz."

"4.4: This is all very descriptive and speculative. Why do you suggest correcting the rotational component in future studies but don't do it yourself? You could then easily say if tilting is the main reason for the observed differences between GNSS and SAA displacements!"

"Good that you have summed up the daily GNSS displacements. I have not checked in Cicoira how GNSS was processed but I am sure velocities are somehow calculated over a longer basis than daily. Otherwise the difference between the sum of daily displacements and total

displacement would have been more than 11cm. It is impossible to calculate significant daily velocities using GNSS. GNSS can’t measure submillimeters, your device not even subcentimeters. However, the same applies to SAA!”
“At least we know that GNSS can measure the total displacement over the entire monitoring period accurate to a (few) centimeter. So 101 cm (102 cm in figure 8, what is correct??) total displacement is the benchmark!”
“89 cm for the total station (~13cm error) reflect the sum of annual errors. You have to recalculate the total displacement from the raw coordinates instead of summing up the annual observations. This gives a horrible error propagation. The fact that GNSS and the surveyed total station prism were mounted on the same boulder, strongly indicates that the 13 cm are indeed a measurement error.”

As for the SAA data, the GNSS data has also been resampled to monthly and the total displacement value integrated is now integrated from the monthly velocities instead of daily. Also, the net total displacement is measured from the horizontal distance from the initial to final coordinate produced by the GNSS and geodetic data.



boulder, a few meters from the 2015 borehole, is used in this study. ~~The~~ So, the total surface displacement is ~~, in total,~~ being measured by three different methods: borehole ~~inclinometer~~SAA, GNSS and geodetic surveys. The total displacement for the GNSS and geodetic survey data is calculated as the horizontal distance between the starting and ending coordinates of the data series, while the SAA total displacement is calculated by integrating the monthly surface velocities. These three approaches ~~will be~~ measuring surface displacement are compared and evaluated against each other.

The two different approaches to retrieving a total displacement value are better illustrated in the updated Figure 8. The SAA data does not measure local coordinates so a net total displacement from the distance of initial to final coordinates cannot be calculate.

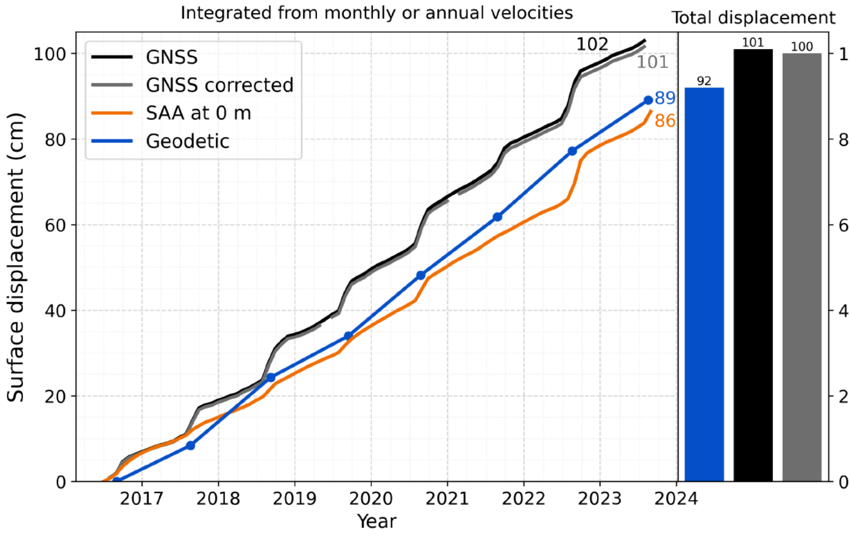


Figure 8. ~~The cumulative~~ Comparison between the surface displacement measured by the GNSS~~station~~, ~~the~~ SAA ~~over the entire depth,~~ and ~~the~~ geodetic station. The GNSS ~~and SAA are available are daily resolution~~ corrected data subtracts the rotational movement of the mast from ~~July 2016 to August 2023, while~~ the ~~geodetic data is limited to an annual resolution~~horizontal displacement. The cumulative lines are the integrated displacement from the monthly ~~GNSS~~ or yearly velocity data~~is also shown for comparison~~. The total displacement (cm) measured over the entire observation period by ~~each technique is also noted. Note~~ the ~~divergence of the~~ GNSS ~~from~~ and the ~~inclinometer data~~ geodetic station is ~~due to~~ shown on the ~~higher displacement during the summer periods~~right. Data source: PERMOS and PermaSense.

The GNSS displacement data has now been corrected for the rotation of its mast as explained in the methods.

the daily series is resampled to a monthly resolution. The GNSS displacement data is corrected for the rotational movement of the boulder using basic trigonometry and the tilt data from its inclinometer. The direction of the mast inclination relative to the direction of the rock glacier movement was taken into account to only subtract the rotational component in displacement parallel to the direction of motion. The monthly displacement data is then differentiated to calculate the ~~daily velocity~~ monthly

The results of the correction do not significantly lower the translational displacement measured by the GNSS station. We better explain the methodological differences between the GNSS and SAA-derived surface total displacements to claim that the observed differences are acceptable.

~~velocity data, which requires less noise filtering, is used instead of the daily then the peaks are smaller. The~~ a). The corrected

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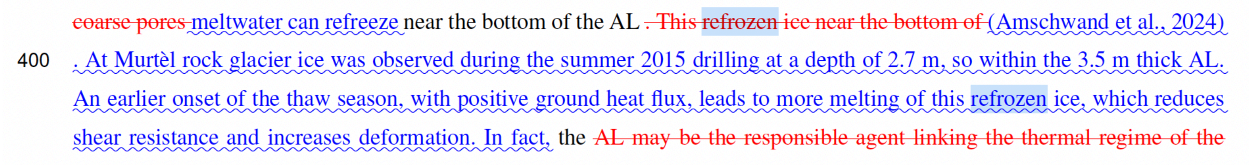
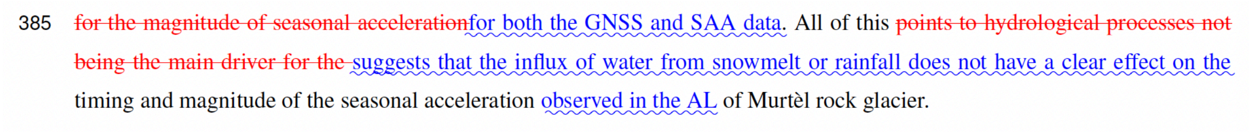
GNSS total displacement by removing the rotational component is 1.5 cm lower, providing a slight improvement (Fig. 8). A difference in the total displacement of 14 cm over seven years between a GNSS system and a SAA chain which integrates the movement of 80 segments over 40 m to estimate surface displacement is an acceptable result. Moreover, even with these methodological differences, the timing of the seasonal surface velocity peaks is very similar between the GNSS and ~~borehole inclinometer~~ the borehole SAA data (Fig. 5b).

“Line 206: The discussion about the displacements in the active layer is rather poor. The fact that so much displacement occurs in such flat terrain in such a shallow depth (most likely no high pore pressures) is very remarkable and calls for an explanation. A possible explanation was given in the study of your colleague Marcel Frehner et al., which convincingly explains the formation of ridges and furrows in the active layer on top of the ice core, due to a compressional flow regime. The formation of such a structure is of course a major reason for deformation in the active layer.”
“322: Melting and not only warming the ice at the bottom of the AL. At one point, the refrozen water (independent if it originates from the snowmelt or from the previous summer) must melt again, if the AL depth stays constant. And as you wrote before, frozen debris with low ice contents deforms slower than ground with high ice contents. Here however, you measure higher strain rates in the ice poor AL than in the ice rich core. The acceleration is thus likely to be triggered by melting of ice in the AL. This melting strongly weakens the shear resistance of the water saturated fine materials at the base of the AL and this is the explanation for the increasing strain rates. The argumentation in this paragraph is very lengthy but does not get to the point. You can shorten this clearly. Be more precise and only show correlations which are relevant.”

We incorporate the addition here regarding the role of the melting of the refrozen water in the active layer for reducing shear resistance at its base and driving deformation. We agree that given strong thermal connection found this must be the driving agent for the seasonal acceleration in active layer movement. The role of the buckling of the active layer we still believe is not relevant for the timescales considered in this study, as explained in the original response to the comment.


~~coarse pores~~ meltwater can refreeze near the bottom of the AL ~~. This refrozen ice near the bottom of~~ (Amschwand et al., 2024) . At Murtèl rock glacier ice was observed during the summer 2015 drilling at a depth of 2.7 m, so within the 3.5 m thick AL. An earlier onset of the thaw season, with positive ground heat flux, leads to more melting of this refrozen ice, which reduces shear resistance and increases deformation. In fact, the ~~AL may be the responsible agent linking the thermal regime of the~~

We also make more clear that our data only suggests that snow meltwater and rainfall specifically do not show a statistical connection to the acceleration of the active layer movement and this does not mean that hydrological processes are not important in general.


~~for the magnitude of seasonal acceleration~~for both the GNSS and SAA data. All of this ~~points to hydrological processes not being the main driver for the~~ suggests that the influx of water from snowmelt or rainfall does not have a clear effect on the timing and magnitude of the seasonal acceleration observed in the AL of Murtèl rock glacier.

“Line 107: There is also data from Ritigraben, where we did a similar analysis here: doi: 10.1002/ppp.1953”

The borehole inclinometer data from the Ritigraben rock glacier will be included in Table 2.

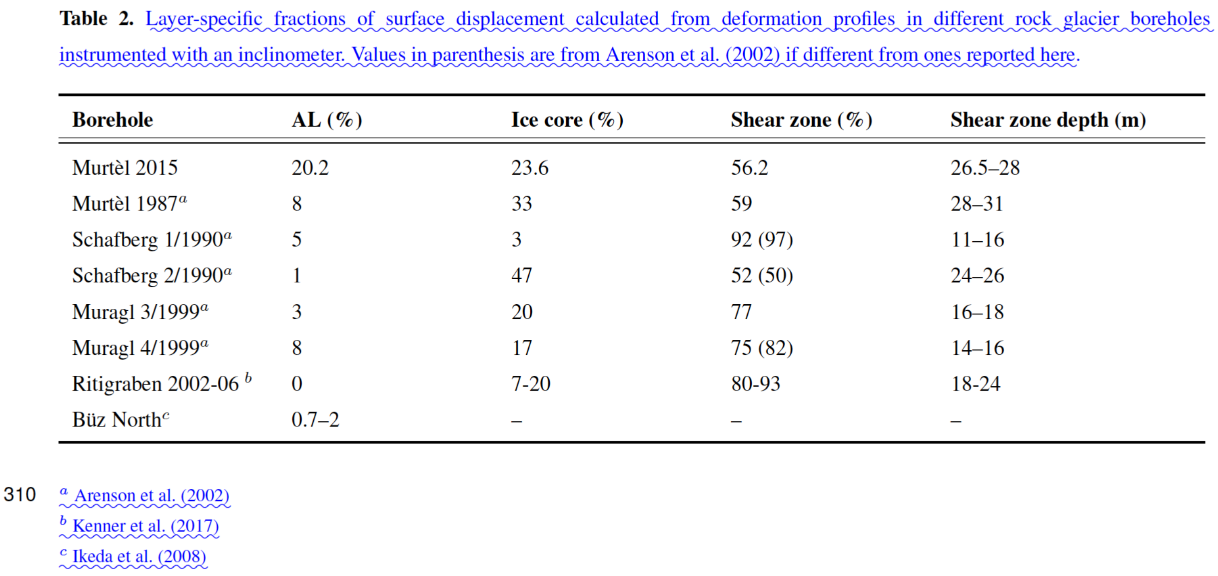


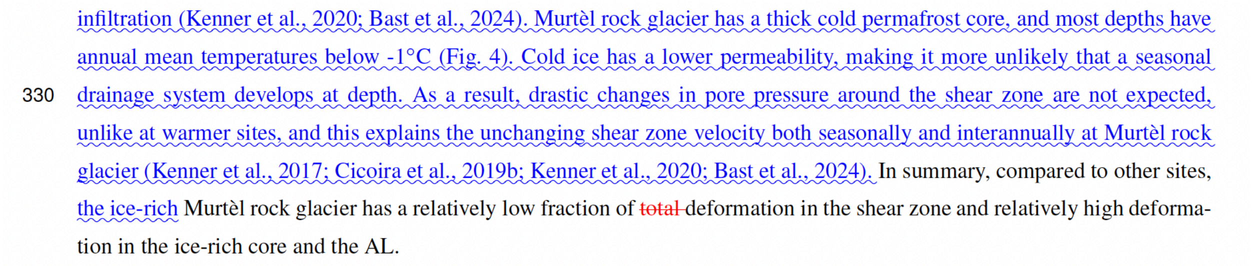
Table 2. Layer-specific fractions of surface displacement calculated from deformation profiles in different rock glacier boreholes instrumented with an inclinometer. Values in parenthesis are from Arenson et al. (2002) if different from ones reported here.

Borehole	**AL (%)**	**Ice core (%)**	**Shear zone (%)**	**Shear zone depth (m)**
Murtèl 2015	20.2	23.6	56.2	26.5–28
Murtèl 1987[a]	8	33	59	28–31
Schafberg 1/1990[a]	5	3	92 (97)	11–16
Schafberg 2/1990[a]	1	47	52 (50)	24–26
Muragl 3/1999[a]	3	20	77	16–18
Muragl 4/1999[a]	8	17	75 (82)	14–16
Ritigraben 2002-06 [b]	0	7-20	80-93	18-24
Büz North[c]	0.7–2	–	–	–

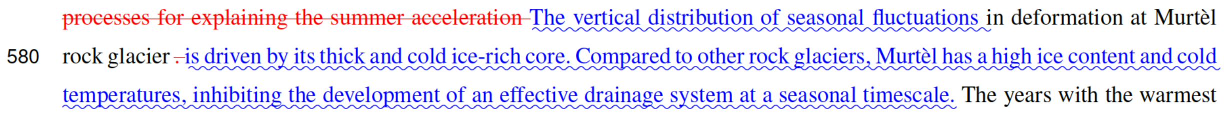
[a] Arenson et al. (2002)
[b] Kenner et al. (2017)
[c] Ikeda et al. (2008)

“On top of it all, this broader discussion of the driving processes could lead to a final, overarching interpretation of your results from the Murtèl site, which I would personally find very interesting. Murtèl is a very famous permafrost study site. How representative is it for rock glaciers in general? [...] Should we compare it to other rock glaciers, or is it even justified to compare its dynamics to those of cold glaciers? Have you looked at this?”
“Line 118/119: If you have such a good dataset, why don’t you calculate a (winter) surface energy balance instead of working with such statistical approximations?”

We have added more discussion on the fact that Murtèl rock glacier has thick ice-rich and cold permafrost core which has implications on the driving processes for its creep. So, some of the inferred processes may not be representative for rock glaciers with warmer permafrost, or lower ice content.



infiltration (Kenner et al., 2020; Bast et al., 2024). Murtèl rock glacier has a thick cold permafrost core, and most depths have annual mean temperatures below -1°C (Fig. 4). Cold ice has a lower permeability, making it more unlikely that a seasonal drainage system develops at depth. As a result, drastic changes in pore pressure around the shear zone are not expected, unlike at warmer sites, and this explains the unchanging shear zone velocity both seasonally and interannually at Murtèl rock glacier (Kenner et al., 2017; Cicoira et al., 2019b; Kenner et al., 2020; Bast et al., 2024). In summary, compared to other sites, the ice-rich Murtèl rock glacier has a relatively low fraction of ~~total~~ deformation in the shear zone and relatively high deformation in the ice-rich core and the AL.

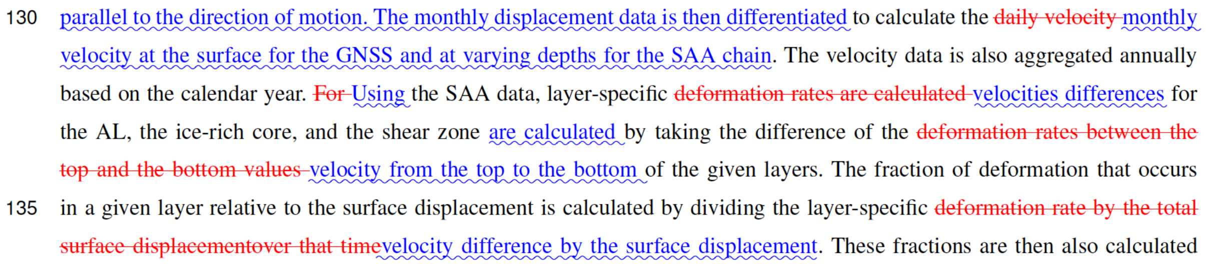


~~processes for explaining the summer acceleration~~ The vertical distribution of seasonal fluctuations in deformation at Murtèl rock glacier ~~.~~ is driven by its thick and cold ice-rich core. Compared to other rock glaciers, Murtèl has a high ice content and cold temperatures, inhibiting the development of an effective drainage system at a seasonal timescale. The years with the warmest

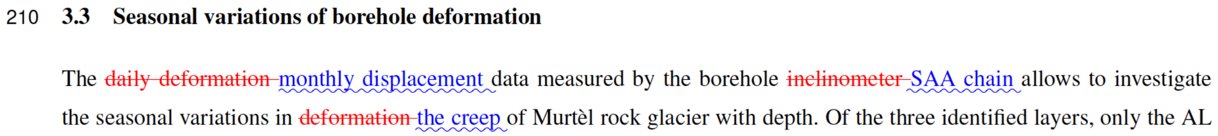
We still believe that an energy balance calculation is out of scope for this study, as explained in the original author’s response to the comments.

“171: What are daily deformation data? Be precise with “rate”, “deformation”, “velocity”, “strain”… throughout the text. I think you are talking about total deformation per layer here, right? So, it would be best if you define a term such as deformation velocity at the beginning and use it consequently afterwards.”
“Line 177: it will increase the readability and clarity a lot if you stick to a predefined term such as deformation velocity instead of daily deformation rate or other paraphrases”
“Line 214: Vertical strain rate? If I understood right, you measure horizontal strain in a vertical borehole.”

We ensured that the terms used to describe the kinematic data from the SAA chain are consistent and descriptive and avoided using terms such as “deformation rate”.



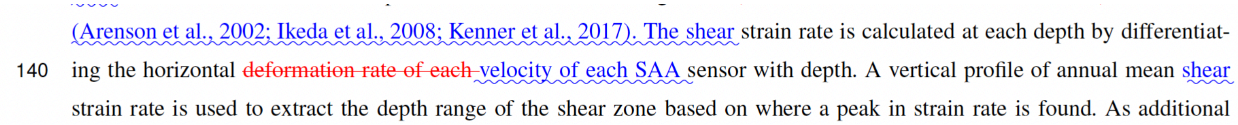
parallel to the direction of motion. The monthly displacement data is then differentiated to calculate the ~~daily velocity~~ monthly velocity at the surface for the GNSS and at varying depths for the SAA chain. The velocity data is also aggregated annually based on the calendar year. ~~For~~ Using the SAA data, layer-specific ~~deformation rates are calculated~~ velocities differences for the AL, the ice-rich core, and the shear zone are calculated by taking the difference of the ~~deformation rates between the top and the bottom values~~ velocity from the top to the bottom of the given layers. The fraction of deformation that occurs in a given layer relative to the surface displacement is calculated by dividing the layer-specific ~~deformation rate by the total surface displacementover that time~~velocity difference by the surface displacement. These fractions are then also calculated



3.3 Seasonal variations of borehole deformation

The ~~daily deformation~~ monthly displacement data measured by the borehole ~~inclinometer~~ SAA chain allows to investigate the seasonal variations in ~~deformation~~ the creep of Murtèl rock glacier with depth. Of the three identified layers, only the AL

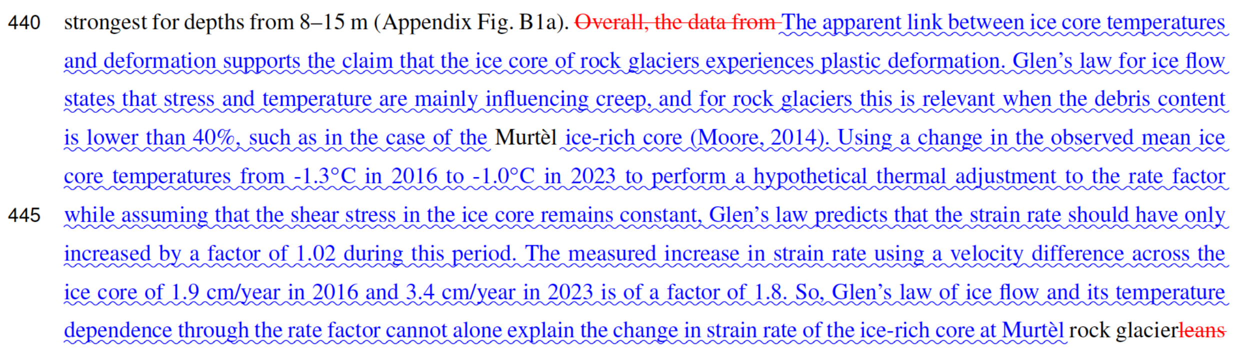
The term “vertical strain rate” is replaced by “shear strain rate” to better convey that it is a measure of how horizontal velocity changes with depth.



(Arenson et al., 2002; Ikeda et al., 2008; Kenner et al., 2017). The shear strain rate is calculated at each depth by differentiating the horizontal ~~deformation rate of each~~ velocity of each SAA sensor with depth. A vertical profile of annual mean shear strain rate is used to extract the depth range of the shear zone based on where a peak in strain rate is found. As additional

“Line 233/234: If you bring that into connection here, you should not only cite Glens law but apply it to show, if the implied connection is indeed reasonable. 3.2 mm Y^(-2) is a deformation increase by 10% per year in the ice core. Can this be caused by 0.03°C/y warming?”

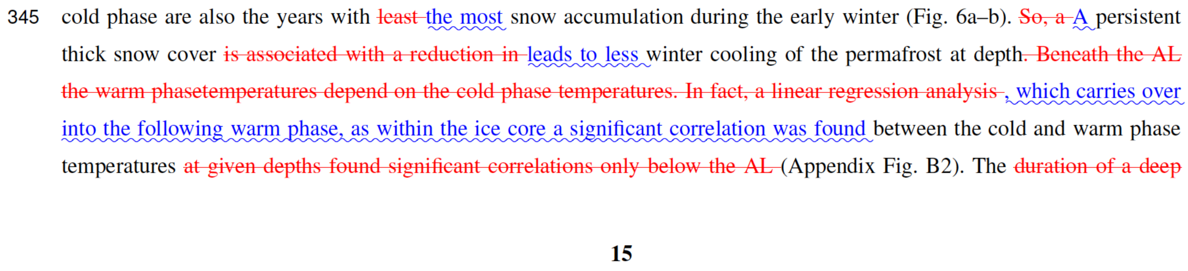
As suggested, we did an hypothetical calculation using the measured increase in temperature in the ice core to estimate the response in strain rate and compared it to the measured change in strain rate from the SAA data.



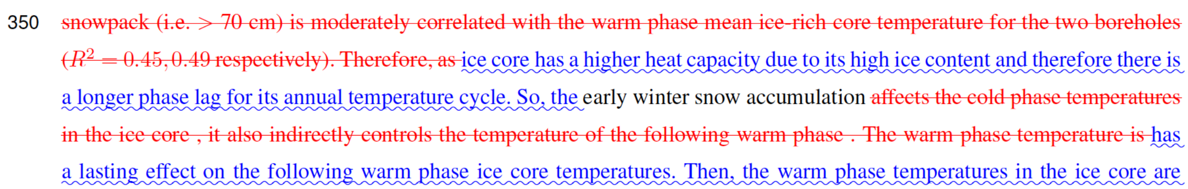
strongest for depths from 8–15 m (Appendix Fig. B1a). ~~Overall, the data from~~ The apparent link between ice core temperatures and deformation supports the claim that the ice core of rock glaciers experiences plastic deformation. Glen's law for ice flow states that stress and temperature are mainly influencing creep, and for rock glaciers this is relevant when the debris content is lower than 40%, such as in the case of the Murtèl ice-rich core (Moore, 2014). Using a change in the observed mean ice core temperatures from -1.3°C in 2016 to -1.0°C in 2023 to perform a hypothetical thermal adjustment to the rate factor while assuming that the shear stress in the ice core remains constant, Glen's law predicts that the strain rate should have only increased by a factor of 1.02 during this period. The measured increase in strain rate using a velocity difference across the ice core of 1.9 cm/year in 2016 and 3.4 cm/year in 2023 is of a factor of 1.8. So, Glen's law of ice flow and its temperature dependence through the rate factor cannot alone explain the change in strain rate of the ice-rich core at Murtèl rock glacier~~leans~~

"271/272: This is more results and misses interpretation. This might be because the ice core is a heat sink and damps the temperature signal in both directions due to its high heat capacity, while the AL is much closer coupled to atmosphere"

We clarified how winter permafrost temperatures carry over to the next summer due to the longer phase lag in the temperature cycle at depth.



cold phase are also the years with ~~least~~ the most snow accumulation during the early winter (Fig. 6a–b). ~~So, a~~ A persistent thick snow cover ~~is associated with a reduction in~~ leads to less winter cooling of the permafrost at depth~~. Beneath the AL the warm phasetemperatures depend on the cold phase temperatures. In fact, a linear regression analysis~~ , which carries over into the following warm phase, as within the ice core a significant correlation was found between the cold and warm phase temperatures ~~at given depths found significant correlations only below the AL~~ (Appendix Fig. B2). The ~~duration of a deep~~



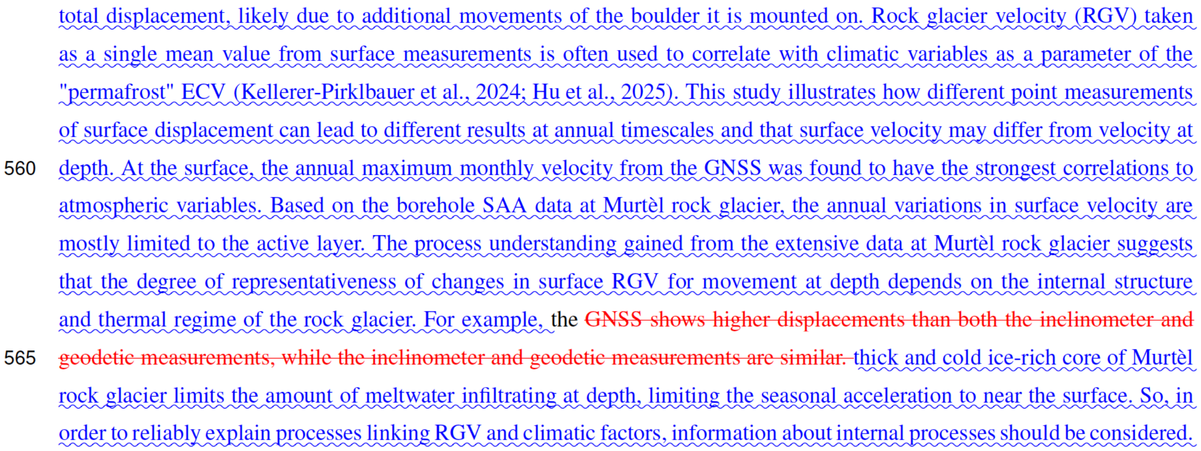
~~snowpack (i.e. $>$ 70 cm) is moderately correlated with the warm phase mean ice-rich core temperature for the two boreholes ($R^2 = 0.45, 0.49$ respectively). Therefore, as~~ ice core has a higher heat capacity due to its high ice content and therefore there is a longer phase lag for its annual temperature cycle. So, the early winter snow accumulation ~~affects the cold phase temperatures in the ice core , it also indirectly controls the temperature of the following warm phase . The warm phase temperature is~~ has a lasting effect on the following warm phase ice core temperatures. Then, the warm phase temperatures in the ice core are

RC2

"I would have like to see a critical discussion on the ECV Rock Glacier Velocity in the light of your findings. I do believe that this ECV is very important, but your data highlight that things are often very complex, and rock glaciers can be different. What we measure at the surface originates from different processes. And in some instances, it is simply the response of the active layer dynamics and the deformations within the rock glacier remain constant, unaffected from interannual variability. Others react immediately to runoff, because water can likely infiltrate to the shear horizon, something that doesn't happen at Murtel rock glacier. Hence, this example shows us that we have to be very careful when relying on surface deformations only as they may not provide the full picture and they must be evaluated in combination with the rock glacier

characteristics and morphology. Your work offers a unique opportunity to add these points, and I think that this would add value to your manuscript beyond simply presenting data."

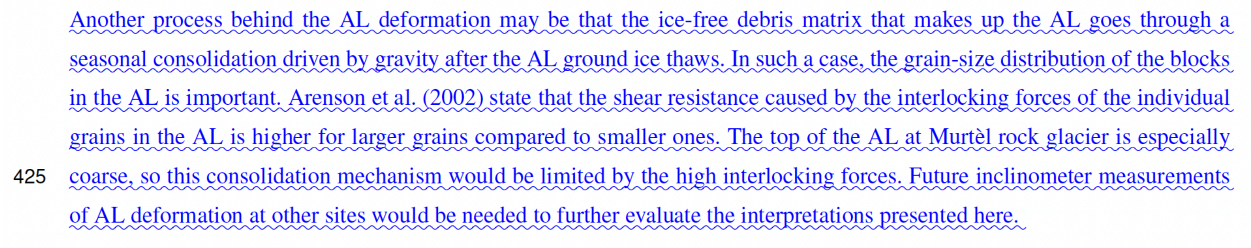
We expanded on the implications of the findings from the Murtèl rock glacier super-site in the context of RGV being a parameter of the "permafrost" ECV. As suggested, we discussed how the processes controlling rock glacier kinematics are complex and differ from site to site. The importance of having data about internal processes is emphasized here.



total displacement, likely due to additional movements of the boulder it is mounted on. Rock glacier velocity (RGV) taken as a single mean value from surface measurements is often used to correlate with climatic variables as a parameter of the "permafrost" ECV (Kellerer-Pirklbauer et al., 2024; Hu et al., 2025). This study illustrates how different point measurements of surface displacement can lead to different results at annual timescales and that surface velocity may differ from velocity at depth. At the surface, the annual maximum monthly velocity from the GNSS was found to have the strongest correlations to atmospheric variables. Based on the borehole SAA data at Murtèl rock glacier, the annual variations in surface velocity are mostly limited to the active layer. The process understanding gained from the extensive data at Murtèl rock glacier suggests that the degree of representativeness of changes in surface RGV for movement at depth depends on the internal structure and thermal regime of the rock glacier. For example, the ~~GNSS shows higher displacements than both the inclinometer and geodetic measurements, while the inclinometer and geodetic measurements are similar.~~ thick and cold ice-rich core of Murtèl rock glacier limits the amount of meltwater infiltrating at depth, limiting the seasonal acceleration to near the surface. So, in order to reliably explain processes linking RGV and climatic factors, information about internal processes should be considered.

"Yes, but as the transition layer is thawing, additional deformation can occur at depth, which then result in rocks within the active layer also being able to move and slowly consolidate under their own weight. It isn't a simple static system."

We have included now a short paragraph about the potential role of the readjustment of individual blocks in the active layer after the seasonal thaw to contribute to its deformation.



Another process behind the AL deformation may be that the ice-free debris matrix that makes up the AL goes through a seasonal consolidation driven by gravity after the AL ground ice thaws. In such a case, the grain-size distribution of the blocks in the AL is important. Arenson et al. (2002) state that the shear resistance caused by the interlocking forces of the individual grains in the AL is higher for larger grains compared to smaller ones. The top of the AL at Murtèl rock glacier is especially coarse, so this consolidation mechanism would be limited by the high interlocking forces. Future inclinometer measurements of AL deformation at other sites would be needed to further evaluate the interpretations presented here.

"Slope inclinometers and SAAs are different and it is suggested to differentiate between the different deformation measurement types."

We omitted from using the term "inclinometer" when referring to the borehole SAA chain as we understand that technically a SAA chain is not made up of inclinometers, but produces inclinometer-equivalent data.

formation with depth (Fig. 2). The drilling was non-destructive~~(for more details see Noetzli et al. (2021))~~, allowing to gather more data about the internal structure of Murtèl rock glacier (Noetzli et al., 2021). The borehole is equipped with thermistor sensors to 60 m depth and ~~an inclinometer chain to a depth of~~ the 40 ~~m with sensors every 50 cm~~m-long SAA chain producing inclinometer-equivalent data. The borehole temperature data is provided directly from the PERMOS data portal

~~bend in the rigid~~ the SAA chain itself buckled backward within the filling material inside the casing of the borehole. ~~Another alternative is that the inclinometer chain itself buckled backward within the casing due to the filling material moving~~During these few months, the SAA chain only moved backwards by about 1 cm, which is well within the 11 cm-wide casing pipe.