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Interactive comment on "Fracture dynamics in an unstable, deglaciating headwall, Kitzsteinhorn, Austria" *by* A. Ewald et al.

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We thank Robert Kenner for his insightful and constructive comments. The expressed criticism is substantial and points to a lack of novelty and originality in the submitted manuscript. We therefore consider a complete revision of our manuscript. The intended new manuscript will no longer focus on recent deglaciation, instead we will explore the relation between fracture kinematics and active layer dynamics in steep, frozen rockwalls. For this purpose we will now concentrate on regression analyses between data from the described crackmeter station and an adjacent permafrost borehole. We consider the immediate vicinity of a deep borehole and a crackmeter station a novel measurement setup that has the potential to advance the current knowledge on kinematics in steep bedrock permafrost. To increase the significance of the new analysis we will expand the time series to four years (2016-2019) as opposed to 2.5 years in the current manuscript. To model thermo-elastic deformation we will resort to the linear regression model published by Weber et al. (2017), and will no longer derive the thermo-elastic deformation component from cracktop temperatures below -10 °C, which has been criticized by all reviewers. To identify potential discrepancies between measured and modeled fracture kinematics we intend to implement state-of-the-art ice segregation models driven by borehole temperature data. Below, we respond to the major concerns/points of criticism of Robert Kenner only. Facing significant changes of the revised manuscript we assume that most minor comments will no longer apply, therefore we will not comment on here. More general comments of this section will be considered in the revision process.

REVIEWER COMMENT: [. . .] Furthermore, I have the feeling that the significance of the paper could be clearly increased if the authors establish a link to the really central question: What is role of deglaciation?

REPLY: Former glacial occupation led to a change in slope form. The schrundline dissects the headwall into an upper, flatter (45°) and a lower, steeper (90°) part. Headwall retreat, presumably driven by periglacial weathering in the randkluft system (Sanders et al., 2012), likely created the steep, lower section. With the onset of deglaciation, atmospheric forcing is hypothesised to significantly contribute to the widening of pre-existing fractures and thus to a destabilisation of the deglaciated rock slope. (We will add a sketch with a cross section of the headwall from the summit station to the recent glacier surface to better illustrate the whole setting.) As we are not able to compare the fracture kinematics of this paraglacial setting with a periglacial one, we decided to rather focus on active layer dynamics and its mechanical response.

REVIEWER COMMENT: [...] However, to stick out and become a really important paper the authors have to interpret their results with respect to glaciation. Are the observed processes particularly related to a deglaciered rock wall or can I observe the same in the upper parts of the rock wall which was never covered by glacier ice?

REPLY: What we observe in our data may also be observed in other (never glacier covered but permafrost affected) parts of the rock wall. Freeze-thaw action as well as ice segregation are common processes acting to destabilise permafrost affected rock walls. The question is whether these processes are particularly efficient in a rather unfavourable geotechnical setting (vertical rock wall with steeply outdipping fractures) preconditioned by glacial erosion. However, again, we will shift the focus away from deglaciation.

REVIEWER COMMENT: What is difference to rock wall kinematics below the glacier line or in the Bergschrund? Is the erosion faster above or below the Bergschrund? In particular the last question is considered by too many authors as obvious but the answer is not obvious at all.

REPLY: As we present a point data set from a location above the bergschrund, links to the bergschrund environment are more likely to be seen as an outlook. A comparison of the efficiency of erosion above or below the glacier line is beyond the limits of this study but we are working on that.

REVIEWER COMMENT: Abstract: I miss some information about permafrost presence or absence. This is an important factor that should be mentioned in the Abstract. Searching "permafrost" in the rest of the document gave no clear answer on this question neither.

REPLY: We added detailed information about the ground thermal regime based on the borehole temperature data to address the permafrost occurrence in our study site.

REVIEWER COMMENT: Introduction: P1 l29: This is an interesting (and correct) description but do you have some explanations or references why these headwalls are often oversteepened? I think there is a term for it called schrundlines. See e.g. sanders et al 2012 (cited by you). These schrundlines have obviously developed during glaciation and not after glaciation or during deglaciation. Any thoughts on that?

REPLY: Schrundlines, as the name says, mark the location of the (former) bergschrund which divides the glacier body into a dynamic, presumably warm-based glacier and an upper, cold-based hanging glacier (citation). The type of glacier cover is of crucial importance, since the static, upper part may prevent erosion whereas the lower, dynamic part may favour plucking, abrasion and periglacial weathering inside the bergschrund. The discrepancy of favoured and prevented erosion may be expressed by this distinct "knickpoint"/schrundline. The resulting form is preserved by high rock mass strength (permafrost!) and destabilised by permafrost thaw following deglaciation. To better demonstrate the link between the form of the headwall, the importance of the schrundline and the location of our instrumentation, we will add a sketch with a cross-section of the headwall similar to figure 10 in Keuschnig et al., 2017.

REVIEWER COMMENT: P2 l6ff: I would distinguish these processes more carefully. Debuttressing is probably not a driving factor at headwalls but is more related to lateral (valley) slopes of tongue shaped glaciers. Oversteepening occurs at headwalls as well as on lateral slopes but the type of glacial erosion is very different between both locations. (Perhaps rather a type of plucking behind the bergschrund!? See again sanders et al.) If you want to focus on headwalls, I think it is important to go more into detail here.

REPLY: Oversteepening due to glacial erosion may dominate over debuttressing as preconditioning/ preparatory factor but the toe of a headwall may still be buttressed by the cirque glacier (ice-rock contact). However, as we decided to readjust our research focus we feel that this discussion is beyond the scope of this publication.

REVIEWER COMMENT: Furthermore, I feel it is a pity that all rock slope failures taking place in the vicinity of a glacier are lumped together by most of the studies in this field. Oversteepening is obviously a result of glacier erosion and not of glacier retreat. Rock slope instabilities caused by oversteepening are thus just secondarily or not related to glacier retreat. This is probably different for rock slope failures whose kinematic was not related to oversteepening or which were previously covered by glacier ice in large

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parts (especially the discontinuities) as it is the case at your study site. Just recently we observed a rock fall at Flüela Wisshorn in Switzerland where more than 250'000 m3 collapsed in an old glacier cirque (you can google some pictures of it). This cubature was never covered by glacier ice, not even during the last cold period. However, the cubature was kinematically free, as the release plane (dip slope) cropped out below the cubature already before the event. This was because the lower end of the cubature was built by a terrain step which was part of a distinct schrundline. In such a case it makes absolutely no sense for me to talk about a slope failure related to glacier retreat. This instability originates most likely from glacial erosion during the last glacial maximum and collapsed now, several decades after the LIA glaciation and several thousands of years after its initiation. I claim it would have collapsed as well if the LIA glacier below the cubature would still have been present. Maybe you can consider those differences somewhere in the introduction and perhaps also in the discussion

REPLY: As you mentioned, the locations of rock slope failures observed in the headwall at our study site were formerly covered by cold-based glacier ice (above the schrundline). Consequently RSFs may be a result of glacier retreat. This discussion is outside the scope of this study.

REVIEWER COMMENT: Data Acquisition P4 l16: Why just in 3 depth if the borehole is 30 m deep? Why not deeper and why not closer to the surface (to track freezing fronts)?

REPLY: As mentioned above, we will add borehole temperature data from thermistors at least up to a depth of 10 meters.

REVIEWER COMMENT: Data Analysis P5l5: "(i) fracture deformation by ice segregation is of minor importance" Can you give an explanation for this? CTT are a weak indicator for the temperature profiles in greater depth aren't they?

REPLY: To model thermo-elastic deformation we will resort to the linear regression model published by Weber et al. (2017), and will no longer derive the thermo-elastic deformation component from cracktop temperatures below -10 °C, which has been criticized by all reviewers. By carrying out correlation analyses between fracture displacements and rock temperatures from the borehole at different depths we will be able to see at which temperatures in which depth significant fracture displacements occur.

REVIEWER COMMENT: 4 Results

Figure 3: The rock temperatures show distinct zero curtains in Autumn but not in spring. This is interesting and important. Is this somewhere discussed? There must be a lot of water somewhere in the rock that caused the long autumn zero curtain by freezing...? But why is there no ZC in spring? Where has the ice gone!? Or has the water percolated away in autumn without freezing??

REPLY: Meltwater may percolate away in spring due to active layer thaw from bottom to the top (see Keuschnig et al. 2017). Surface freezing in autumn may lead to huge amounts of perched water within the rock mass. We will include these issues in the discussion.

REVIEWER COMMENT: P5 l22 Anomalies during zero curtain period? You are talking about ZC at which depth? Increase of 1K during zero curtain at 3m depth means +1°C what is not possible as active layer depth was 3m in 2016!? Along with shorter zero curtain period... Where? When? Unclear! Section is hard to follow, try to formulate more precise.

REPLY: Zero curtain is detected at the crack top. We will formulate the chapter more precisely and include a sketch to better illustrate the setup.

REVIEWER COMMENT: Figure 6: Again, what is zero curtain here? Is it zero curtain at the surface or CTT??? But then snow cover and zero curtain period would occur simultaneously. There is a zero curtain during the snow melt and you couldn't separate these two periods as you did it in the figure ... Completely unclear to me....

REPLY: We tried to clarify the use of the term “zero curtain” in the manuscript. In this figure the term may be misleading. Classes in figure 6 are related to temperature ranges and not solely to snow cover. However, we translate positive temperature to snow free conditions and negative temperatures to snow covered conditions. In this case the period of ZC represents a phase where snow cover is still present, but in a melting phase. We will modify this figure accordingly to avoid this overlap.

REVIEWER COMMENT: Discussion

P11 l15: I am quite skeptical about the relevance of debuttressing in headwalls of glaciers. This is an often heard hypothesis which established more by repeating it again and again than by sound research on it. You cited Keuschning et al but in this paper debuttressing is once more mentioned as important factor without giving any sound justification. The efficiency of debuttressing was shown for lateral slopes of valley glaciers but not for headwalls. Here we see erosion processes like plucking in the bergschrund causing oversteepening.

REPLY: Do we really see plucking in the bergschrund? Can you provide any reference for this? Our observations do not reveal indication on plucking.

REVIEWER COMMENT: This is a sign for glacial forces that rather act in the same direction as the critical rock slope deformation and not against the rock slope deformation. Rock masses obviously detached from the headwall as they were still covered by glacier ice, otherwise there would not appear an oversteep rock wall under the melting glacier. Rock masses still detach during deglaciation and after glaciation. Perhaps they detach more often than, as the atmospherically forced processes which you have measured in your nice dataset are more efficient than. But perhaps this is wrong and we are completely of the track! Perhaps the rock falls in freshly deglaciert areas are just an adaption process following oversteepening!? This is the big question that we should try to answer!

REPLY: Since we are not able to answer this important question with our data set we are not going to enhance the discussion on whether glacial debuttressing is a preparatory factor or not. However we are recently trying to tackle these questions in our further research activities. Since we will not stress the deglaciation aspects in the revised version of the manuscript, this will no longer apply here.

REVIEWER COMMENT: P12 l16 I think it is absolutely right that you emphasize shallow instabilities. But are you sure that erosion increased after deglaciation compared to the period during which it was ice covered? How do you know? Erosion during glacier coverage was obviously strong as well, as I said before: otherwise there would not appear an oversteep rock wall under the melting glacier. The only difference is that you can see the rock slides now and before they were invisible because they took place below the glacier line. I do not say that the one thing or the other is right or wrong but I consider it as an open question on which your paper could not give a satisfying answer so far.

REPLY: Here again, it is to add that the part of the headwall, which we instrumented, has been covered by cold-based glacier ice which presumably prevented extensive fracture displacements. The location of our crackmeter is not within the randkluft, therefore other processes may apply.

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