Dear editor,

We have carefully addressed all mentioned comments and have improved significantly the structure and the language of the manuscript according to the comments. All detailed changes are listed hereafter.

Philipp Mamot and co-authors

Response by the author to comments of Referee 1

RC = Referee comment

AC = Author comment

Line 7:

RC: I assume you mean air temperatures in a general context here. – related to the term "warming"

AC: We reworded the sentence more concisely into *"Instability and failure of permafrost-affected rock slopes have significantly increased coincident to rising air temperature related to climate change in the last decades."*

Line 9:

RC: The referee suggested to delete the term "effects in"

AC: Changed as suggested

Lines 12-14:

RC: The referee…

(1) proposed to write "shearing experiments" instead of "shear experiments"
(2) proposed to present the information on the strain rate earlier in the sentence
(3) deleted the word "relevant"
(4) added the word "of" to "i.e. 4-30 m rock overburden"
(5) exchanged the word "i.e." by "representing"

(6) added the word “observed” to “typical for recent rock slope failures in alpine permafrost”

AC: We adjusted the proposed changes in the revised manuscript as follows:

“For this, we performed 141 shearing experiments with rock-ice-rock "sandwich" samples at constant strain rates (10^{-3} s^{-1}) provoking ice fracturing, under stress conditions ranging from 100 to 800 kPa, representing 4–30 m of rock overburden, and at temperatures from -10 to -0.5 °C, typical for recent observed rock slope failures in alpine permafrost.”

Before section 1 – Introduction

RC: Davies et al report that the lowest strength of an ice filled joint is reached not at but just below zero degrees. How does this compare to your results?

AC: As our tests are not performed at temperatures warmer than -0.5 °C a comparison to the study by Davies et al. (2000) will be difficult (see also below, comment to lines 387). We decided to point to the study by Davies et al. as follows (line 399 in the revised manuscript):

“We did not perform tests at temperatures warmer than -0.5 °C because we assume the ice to melt or be squeezed out of the rock cylinders which leads to shearing along rock-rock contacts. Cohesion will be absent at the melting point and shear strength values will rise. This is shown by the tests of Davies et al. (2001) when comparing shear strengths of ice-concrete samples with concrete-concrete samples.”

Line 34:

RC: The referee exchanged “e.g.” by “for example”

AC: Adjusted as proposed

Line 35:

RC: The referee proposed to check

a) Beniston, M., Farinotti, D., Stoffel, M., Andreassen, L. M., Coppola, E., & Eckert, N. (2018). The European mountain cryosphere: A review of its current state , trends , and future challenges. The Cryosphere, 12, 759–794. https://doi.org/10.5194/tc-12-759-2018 and

b) Baer, P., Huggel, C., McArdell, B. W., & Frank, F. (2017). Changing debris flow activity after sudden sediment input: a case study from the Swiss Alps. Geology Today, 33(6), 216–223. https://doi.org/10.1111/gto.12211.

AC: We checked and included the suggested references and modified the volume of the rock slope as follows:

“…as for example, the recent 3–4 $* 10^6$ m³ rock slope failure at Pizzo Cengalo, Graubünden, CH, on 23 August 2017 (Baer et al., 2017; Beniston et al., 2018; pers. comm. with Phillips, 2018).”

The citations are included in the reference list in chapter 11 (lines 638-639 and lines 642-643).

Line 41:

RC: Haeberli did not define the term, maybe use Müller 1947

AC: This might be a misunderstanding. The reference "Harris et al., 1988" refers to the Glossary of Permafrost and Related Ground-Ice Terms, Permafrost Subcommittee, published by Harris et al.

Hence, we stuck to the reference "Harris et al., 1988".

Lines 41-42:

RC: The referee

(1) deleted the term "fulfilled"

(2) wrote: Active layer thaw doesn't make sense. Either you say below the maximum active layer thickness, or, as I prefer, just use maximum thaw depth.

(3) proposed to be consistent with capital A or not – related to the term "Alpine"

AC: We adjusted the proposed changes in the revised manuscript to "Permafrost conditions are below the maximum thaw depth which typically ranges between 2–8 m in alpine environments…"

Further, we changed the first letter of "alpine" and adjusted this writing style (small letters) in the remaining manuscript.

Line 75:

RC: Any impact from stresses caused by thermal expansion of the bedrock as it warms?

AC: We added some sentences in section 1 (line 77 in the revised manuscript) to account for this information:

"Warming of permafrost in rock slopes reduces the shear resistance along rock joints in a chronological order by (i) reducing the fracture toughness of cohesive rock bridges, (ii) by lowering friction along rock-rock contacts, (iii) by altering the creep of ice infillings and (iv) finally reducing the fracture toughness of the ice itself and of rock-ice contacts (Krautblatter et al., 2013). Cyclic thermal expansion or contraction in the shallow bedrock occurs due to warming or cooling as a result of daily or seasonal variations in temperature. Variations of high frequency and magnitude can cause thermal gradients in the rock which leads to alterations in the stress field. This can induce thermal fatigue which, over long timescales, reduces the shear resistance along weakened discontinuities (Draebing et al., 2017; Gischig et al., 2011; Hall and Thorn, 2014; Jia et al., 2015; Weber et al., 2017)."

Further, we included a short comment on stresses induced by thermal expansion/contraction and their effect on the shear strength of ice-filled rock joints (section 4.1, line 477 in the revised manuscript):

"(iv) Rock minerals heat up differently and can generate thermal stresses (Gómez-Heras et al., 2006) in the intact rock and along discontinuities causing thermal fatigue and a reduction in the shear resistance (Dräbing et al., 2017). However, we do not expect an impact on the shear strength as repetitive temperature cycles with high magnitude and frequency are required for thermal stress fatigue (Hall and Thorn, 2014). During our tests, temperatures were kept constant."

The new citations are included in the reference list in chapter 11.

Line 90:

RC: At what strain rate? – related to the previous sentence

AC: The experiments by Schulson were performed at strain rates of 10^{-3} and 10^{-1} s^{-1}.

We added this information to the corresponding sentence in the revised manuscript, line 94: "…*The unconfined compressive strength of polycrystalline ice decreases by 82 % (from approx. 17 to approx. 3 MPa) with increasing temperature from -50 to 0 °C (at strain rates of 10^{-3} and 10^{-1} s^{-1}; Schulson and Duval, 2009)."*

Line 90:

RC: Asked to explain what commercial ice is.

AC: Commercial ice is artificially produced in the laboratory. Butkovich (1954b) described it with the following words: "…virtually free of air bubbles and the grains were prismatic in shape with dimensions of 5 to 20 mm by 40 to 70 mm." (Hobbs, 1974, page 329)

To clarify what we meant, we used "artificial" instead of "commercial" (line 95 in the revised manuscript)

Line 92:

RC: Explain relevance – related to *"The fracture toughness of polycrystalline ice decreases by 27 %..."*

AC: The fracture toughness describes the resistance of the ice to crack propagation and is important for tensile and compressive failure. As such, we added this parameter to the compressive and the tensile strength.

However, as the correlation between temperature and fracture toughness is rather weak with $r^2 = 0.22$ and errors are pretty big (Schulson and Duval, 2009), we deleted the sentence in the revised manuscript, line 96.

Line 123:

RC: Check Yamamoto and Springman CGJ 51(10) 1178-1195. 2014 – related to Eq. (3)

AC: We read the publication proposed by the referee and included it in the revised manuscript by adding references and information in...:

line 51: "*..and the ductile temperature- and stress-dependent creep of ice and ice-rich soils (Arenson and Springman, 2005a; Sanderson, 1988; Yamamoto and Springman, 2014) have been investigated in a number of studies,..*"

line 114: "*..AE events can indicate damage increase, i.e. microcrack generation and coalescence, initiation and propagation of fractures or shearing and failure along fractures (Cox and Meredith, 1993; Scholz, 1968). AE technology has been used extensively on rock samples in the laboratory (Lockner, 1993; Nechad et al., 2005; Yamamoto and Springman, 2014).*"

line 591: "*AE is generally well capable to anticipate rock-ice failure as (i) all failures are predated by an AE hit increase, (ii) the hit rate increases well before brittle failure starts and (iii) AE hits peak immediately prior to failure. This AE pattern coincides with observations in triaxial constant strain rate tests on frozen soil (Yamamoto and Springman, 2014). The experiments conducted clearly show that precursors before failure can be observed by the AE technique providing complementary information to the displacement measurements.*

line 596: "*It is interesting to consider that in ice, even secondary and tertiary creep are constituted by the generation and healing rate of microfractures (Paterson, 1994; Sanderson, 1988). The measured pre-failure increase in AE activity is, thus, an indication for damage increase, i.e. microcrack generation and coalescence (Fig. S3) typical for cryospheric damage propagation (Murton et al., 2016; Yamamoto and Springman, 2014).*"

The citation is included in the reference list in chapter 11.

Line 139:

RC: Assuming horizontal conditions. In steep rock faces the stress conditions are different. However, for the sensitivity study presented it is OK to use these assumptions. – related to the phrase: "*Normal stresses of 100, 200 and 400 kPa (corresponding to rock overburdens of approx. 4, 8 and 15 m) were chosen to reconstruct relevant stress conditions for ice- and rock-ice-fracturing processes in permafrost rock joints…*"

AC: We agree with the referee`s comment that in steep rock faces shear planes are often rather inclined than running horizontally and stress conditions are different. When we increase the inclination of a shear plane at a certain depth, the normal stress acting on it will decrease and downhill forces will increase. Certainly, shear planes with a specific normal stress but higher dips will also exist in greater depths. For example, a shear plane with an inclination of 60 ° and a normal stress of 100 kPa would occur in a depth of 8 m instead of 4 m, when oriented horizontally.

To prevent any misunderstanding, we rephrased this paragraph and shifted the paragraph to section 2.3 in the revised manuscript, line 229:

"In steep rock faces shear planes are rather inclined than horizontal. With increasing inclination of shear planes at certain depths, the normal stress acting on them will decrease and downhill forces will increase. Correspondingly, a shear plane with a normal stress of 200 kPa but a dip > 0° will also exist in depths greater than 4 m."

Lines 147-149:

RC: Not sure if this is correct. The ice to rock interface likely also also affected by the porosity of the rock and the chemistry. Both parameters affect the ice crystal growth, which in turn is responsible for the strength of the interface. – related to the sentence *"We assume that the shear strength of rock-ice interfaces is mostly affected by temperature, normal stress and joint surface roughness while the rock type is less important."*

AC: We shifted the respective paragraph to section 4.1 (line 452) because it makes more sense to discuss the topic there.

We agree that the porosity of the rock and the type of constitutive minerals could also affect the shear strength of an ice-filled rock joint. As no publication on this topic has been published yet, our assumption relies on observations during our experiments and on publications on specific and relevant characteristics of the different rock types. Hence, we listed a few arguments supporting the opposite opinion in the revised manuscript:

"So far the failure of ice-filled permafrost rock joints has been studied using concrete as a rock analogue (Davies et al., 2000; Günzel, 2008). For the first time, we use rock to closely reproduce real conditions along rock joints. Synthetic materials possibly deviate from shear strength values representative for rock joints in the field. For instance, ice sliding on granite shows a friction coefficient µ approx. 0.5 higher than ice sliding on glass or metals, all having a similar surface asperity roughness. The higher friction of the granite-ice interfaces is due to a higher effective adhesion (Barnes et al., 1971). We assume that the shear strength of rock-ice interfaces is mostly affected by temperature, normal stress, strain rate and joint surface roughness. However, the applied constant strain rate as well as the standardised preparation of a uniform joint surface roughness prohibit any potential effects on the shear strength. We postulate that the influence of the rock type on the shear strength is less important:

(i) The thermal conductivity of the rock may affect the shear strength by facilitated melting along heat-insulating surfaces causing a decrease in friction (Barnes et al., 1971). The thermal conductivity of rocks varies in a range of 0.3–5.4 W m-1 K-1 (Clauser and Huenges, 1993; Schön, 2015). A metal like brass, with a much higher thermal conductivity of 100 W m-1 K-1, would lead to a warming at the interface 14.5 °C lower than granite (Barnes et al., 1971). Due to the relatively small range of thermal conductivities for different rock types we do not expect a rock type-dependent effect on the shear strength.

(ii) The porosity of the rock and the type of constitutive minerals may play a role for the growth of ice crystals along the rock-ice interface which in turn affects the shear strength. The strain rate and the compressive strength of ice crystals are significantly higher for those oriented parallel to the applied stress than for those oriented randomly (Hobbs, 1974; Paterson, 1994). However, we assume any potential rock type-dependent orientations of ice crystals to be deleted before shearing starts due to the applied uniaxial compression during initial consolidation.

(iii) The strength of the constitutive minerals of the rock surfaces may control the friction of the rock-ice contact. However, we assume the strength of minerals to play a minor role for the shear strength, because at the rock-ice interface the ice will fail before the rock material and ice strength will control the failure process. In our tests we could not observe particles breaking off the rock surfaces. Elastic moduli of most rock minerals (bulk modulus k: 17–176 GPa; shear modulus μ: 9–95 GPa) are 2–20 times higher than of ice (k: 8.9 GPa; μ: 3.5 GPa) (Schulson and Duval, 2009; Schön, 2015). The small applied roughness of the shear surfaces additionally prevented any relevant impact of differing mineral strengths.

(iv) Rock minerals heat up differently and can generate thermal stresses (Gómez-Heras et al., 2006) in the intact rock and along discontinuities causing thermal fatigue and a reduction in the shear resistance (Dräbing et al., 2017). However, we do not expect an impact on the shear strength as repetitive temperature cycles with high magnitude and frequency are required for thermal stress fatigue (Hall and Thorn, 2014). During our tests, temperatures were kept constant.

Thus, the tests using limestone represent rock-ice fracturing along joints of all rock types. To use rock instead of other materials probably has a greater effect on the shear strength than different rock types. Still, a potential shear strength dependence on different rock types has to be proven in additional experiments."

We added the new references "Schön, 2015" and "Gómez-Heras et al., 2006" to the reference list (section 11).

Line 149:

RC: The referee marked the term "*we use limestone as a representation for all rock types*" with red colour.

AC: We modified the discussion on the application of the failure criterion to all rock types by adding more arguments supported by experimental observations and prior publications (see above, response to lines 147-149).

Line 150:

RC: Marked the words "small" in relation to the range in thermal conductivity of rocks" in the initial submission.

AC: We used the wording "small" because in comparison with other materials like metals, for example, the range of thermal conductivity is small. We tried to make our point clearer by adding more information (see above, response to lines 147-149):

"The thermal conductivity of the rock may affect the shear strength by facilitated melting along heat-insulating surfaces causing a decrease in friction (Barnes et al., 1971). The thermal conductivity of rocks varies in a range of 0.3–5.4 W m^{-1} K^{-1} (Clauser and Huenges, 1993; Schön, 2015). A metal like brass, with a much higher thermal conductivity of 100 W m^{-1} K^{-1}, would lead to a warming at the interface 14.5 °C lower than granite (Barnes et al., 1971). Due to the relatively small range of thermal conductivities for different rock types we do not expect a rock type-dependent effect on the shear strength."

Line 152:

RC: Refers to his previous comment on the thermal expansion (line 75) – related to *“As such, we do not expect any effect of the thermal conductivity on the shear strength…”*

AC: We added a short discussion on this as follows (see above, response to lines 147-149):

“(iv) Rock minerals heat up differently and can generate thermal stresses (Gómez-Heras et al., 2006) in the intact rock and along discontinuities causing thermal fatigue and a reduction in the shear resistance (Dräbing et al., 2017). However, we do not expect an impact on the shear strength as repetitive temperature cycles with high magnitude and frequency are required for thermal stress fatigue (Hall and Thorn, 2014). During our tests, temperatures were kept constant.”

Line 153:

RC: Unclear why since it isn’t just the surface roughness that affects the strength of the interface. – related to the phrase *“the standardised preparation of a uniform joint surface roughness for all rock samples in this study prohibits any potential effect of differing rock types.”*

AC: We agree with the referee´s opinion that more potential effects of differing rock types do exist. Therefore, we listed several characteristics and discussed them (see above, response to lines 147-149).

Line 167:

RC: Added the word “is” and deleted the words “deformation rates” in the sentence *“Since 2007, the rock mass creeps slowly at an average of 3.75 mm/year with more than five times higher deformation rates in July to October in comparison to the remaining months.”*

AC: We made two sentences out of one and formulated them in a way easier to understand (line 152 in the revised manuscript):

“Since 2007, the rock mass creeps slowly at an average of 3.75 mm/year. From July to October it moves more than five times faster than in the remaining months.”

Lines 176-184:

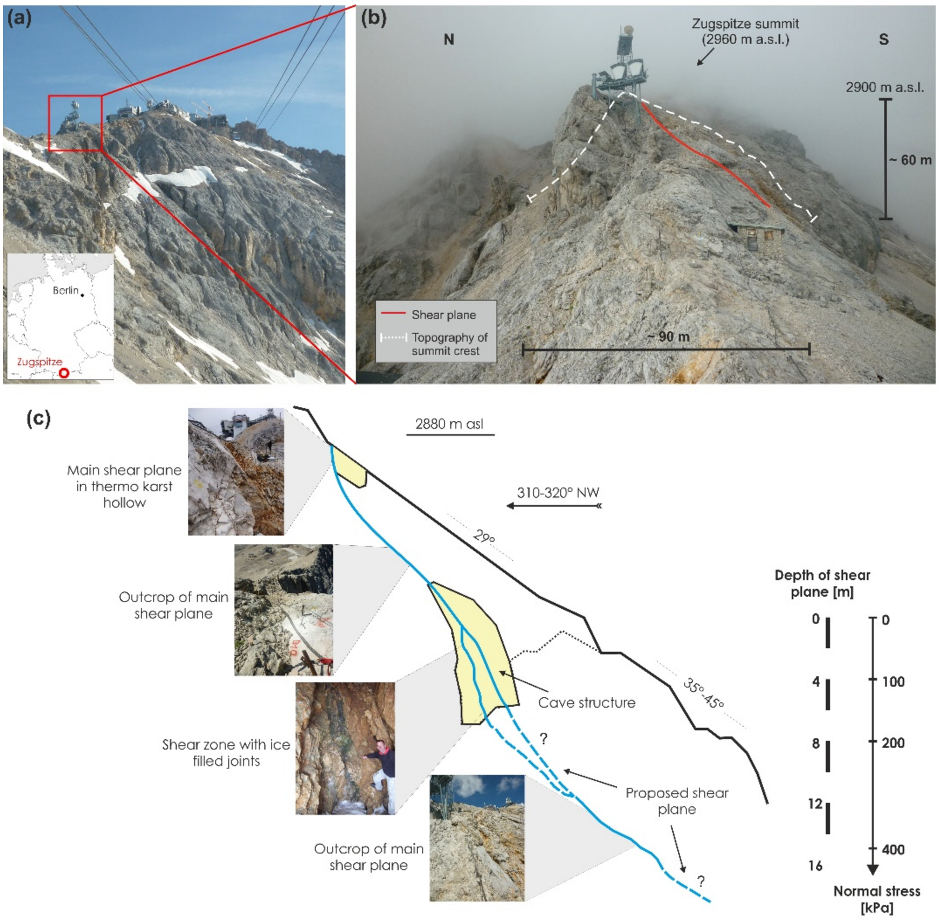
RC: The referee suggested to present the four points as a list instead within the running text.

AC: Adjusted as proposed

Line 177:

RC: It would be helpful to plot the principal stresses for the cross section. – referred to Fig. 1

AC: We changed Fig. 1 as proposed and included normal stresses (line 154 in the revised manuscript):



For a better link to the figure, we shifted its reference to another sentence (line 164 in the revised manuscript): *"(i) The depth of the main shear plane is assessed to a maximum of 10–15 m due to field mapping. The corresponding normal stresses on this shear plane (mostly ≤ 400 kPa) lie within the range of the tested stress levels (Fig. 1c)."*

Further, we increased the font and thickness of the lines for a better perceptibility (see Fig. 1).

Line 180:

RC: Not clear what depths you are referring to. Referred to *"Current borehole temperatures at the peak of the Zugspitze average -1.3 °C within the permafrost core area and approach minima of -6 °C at the margins…"*

AC: We added the information of the corresponding depths as follows (line 166 in the revised manuscript):

"(iii) The Zugspitze summit area is located at the lower permafrost extension limit. Current borehole temperatures at the peak of the Zugspitze average -1.3 °C within the permafrost core area (approx. 24 m away from the south face and 21 m away from the north face) and approach minima of -6 °C at the margins (ca. 5 m away from the north face) (Böckli et al., 2011; Gallemann et al., 2017; Krautblatter et al., 2010; Noetzli et al., 2010)."

Line 184:

RC: Be specific about the period. – referred to *"A climatic warming in the last century and an even stronger temperature increase since the 1990s can be observed at the Zugspitze, i.e. the mean annual air temperature (MAAT) in 1991–2007 was 0.8–1.1 °C warmer than in prior 20th century reference periods…"*

AC: We changed the sentence in order to give a more specific information on the reference periods (line 171 in the revised manuscript):

"(iv) A climatic warming in the last century and an even stronger temperature increase since the late 1980s can be observed at the Zugspitze, i.e. the mean annual air temperature (MAAT) in 1991–2007 was 0.8–1.1 °C warmer than in the three prior 30 year reference periods between 1901 and 1990 (Gallemann et al., 2017; Krautblatter et al., 2010)."

Lines 188-198:

RC: Deleted the second part of the sentence

AC: Deleted as suggested

Lines 192-193:

RC: Deleted the information in brackets

AC: Deleted as suggested

Line 198:

RC: Exchanged the word "basin" with "bath"

AC: Changed as suggested

Line 206:

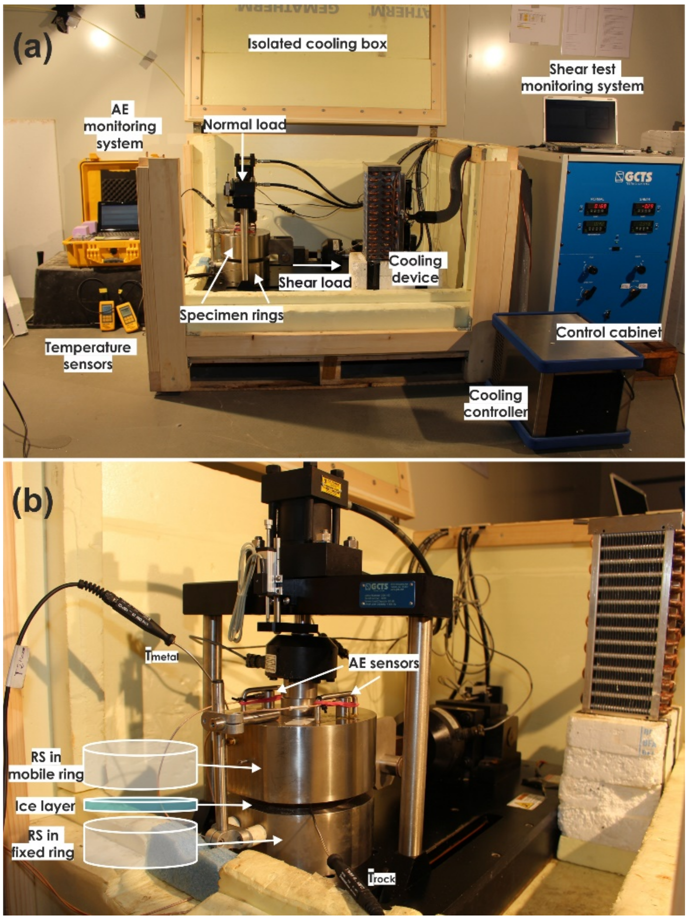
RC: Exchanged the expression "flowing out" with "draining"

AC: Changed as suggested

Line 224/Fig. 3:

RC: Perspective of the ice layer is off. – related to Fig. 3

AC: We changed Fig. 3b by shifting the overlain sketch of the specimen rings and the ice layer to the left. In this way the perspective onto the cylinders and the gap with the ice layer is good (see below):



In the caption of Fig. 3 we added two short explanations for abbreviations used in the figure (line 213 in the revised manuscript):

"Experimental setup showing the laboratory shear machine, acoustic emission monitoring system, the cooling device and the cooling box. RS = rock sample. T = Rock temperature sensor."

Lines 244-245:

RC: Also check Yasufuku, N., Springman, S. M., Arenson, L. U., & Ramholt, T. (2003). Stress-dilatancy behaviour of frozen sand in direct shear. In M. Phillips, S. M. Springman, & L. U. Arenson (Eds.), Proceedings of the 8th International Conference on Permafrost (pp. 1253–1258). Zurich, Switzerland: A.A. Balkema.

AC: We checked the study by Yasufuku et al. (2003) and added the reference to line 236 in the revised manuscript:

"As the shear and compressive strength of pure and dirty ice increase with the strain rate (Arenson et al., 2007; Sanderson, 1988; Schulson and Duval, 2009; Yasufuku et al., 2003), variations in the shear rate were kept as low as possible…"

The citation is included at the end of the reference list in chapter 11.

Line 268:

RC: Asked for the used version of MATLAB

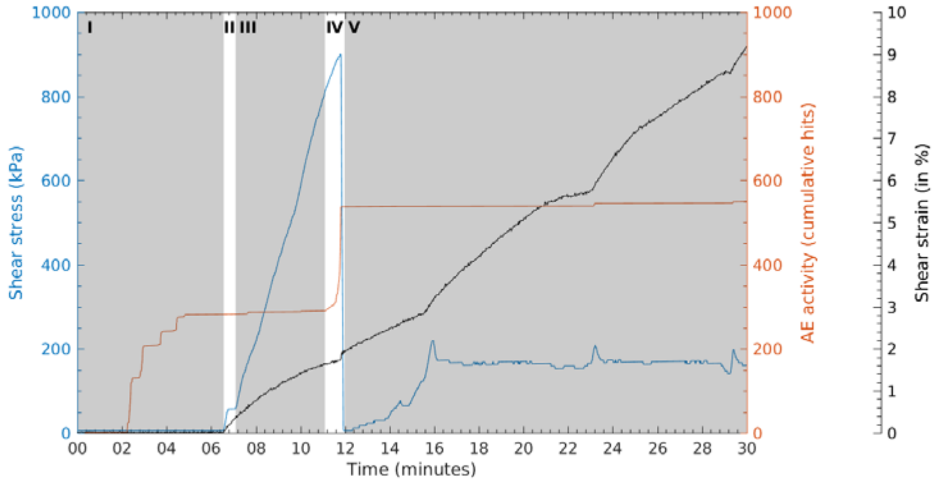
AC: The version of MATLAB was “R2017a (9.2.0.556344)”. We added this information to (line 260 in the revised manuscript):

“The linear fitting is estimated by a linear regression model using the LinearModel class of MATLAB (Version R2017a (9.2.0.556344)).”

Line 277/Fig. 4:

RC: “Would be better to show strain and not deformation.” – referred to Fig. 4

AC: We modified the figure by displaying the deformation of the sample with the shear strain in %, suggested by the referee:



Correspondingly, we slightly modified the first sentence of the caption (line 270 in the revised manuscript):

“Typical curves of shear stress, shear strain and acoustic activity for a shear test at T = -3 °C and σ = 200 kPa.”

Line 288:

RC: Exchanged the expression “deformation” with “failure”

AC: Changed as suggested

Line 292:

RC: Exchanged the expression "an" with "a minor"

AC: Changed as suggested

Line 292:

RC: Really? The AE signals represent ice healing? Or do you refer to the residual strength being ice healing, or the small increases are a indicating that some ice must have healed and are now braking?" – referred to the sentence *"…the post-failure shear stress exhibits several small peaks, which are often accompanied by a minor increase in AE hits and audible cracking (ice healing)."*

AC: When mentioning "ice healing" we primarily referred to the peaks in shear stress which are supposed to represent healed ice that breaks. More than 90 % of the tests with observed post-failure-peaks revealed failures within the ice or a mixture of failures in the ice and along rock-ice contacts. Thus, the peaks of shear stress could also be caused by ice-ice interlocking and subsequent failure when stresses exceed a threshold.

We changed the last sentence of the paragraph and added three ones for explanation (line 283 in the revised manuscript):

"In a few experiments (such as in Fig. 4), the post-failure shear stress exhibits several small peaks, which are often accompanied by a minor increase in AE hits, audible cracking and a pronounced rise in shear strain. The peaks in shear stress may refer to healed ice that breaks when stresses exceed a certain threshold. Further, more than 90 % of the samples with observed post-failure-peaks also failed within the ice or both in the ice and along the rock-ice interface. Hence, these peaks may also be caused by ice-ice interlocking leading to the observed decrease in shear strain (Fig. 4). Subsequent failure occurs when the shear stresses overcome the ice strength."

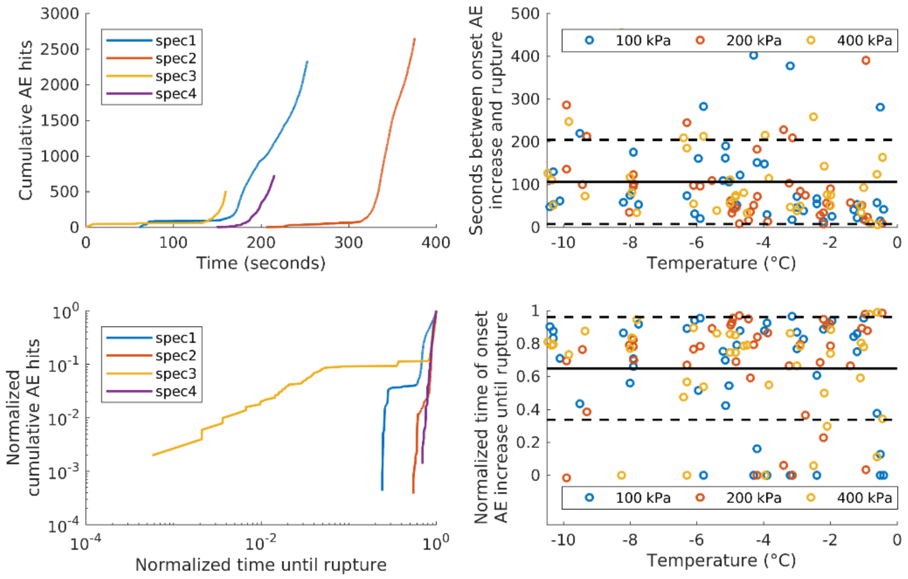
We also corrected the sentence in line 280 in terms of the description of the shear strain behaviour at failure:

"Correspondingly, the ice infill between the rock cylinders fails and shear deformation reaches one of its maximum values."

Line 294/Fig. 5:

RC: Can you show in a log-log plot? – related to Fig. 5c

AC: We plotted Fig. 5c as proposed (see below):



However, we still use the old version of Fig. 5c for the manuscript because in our opinion – with consistent time steps – it shows more clearly that the onset of AE increase starts rather shortly before failure. In this way, the stage of AE hit increase can be compared more easily with the rest of the remaining stages of the test. Further, the percentage of AE hits before the onset of increase (stages 1 and 2) and after it (stage 3 and 4) can be compared in a way that is more understandable.

Nevertheless, we changed the American "normalized" to the British "normalised" in the labels of Fig. 5c and 5d as the whole manuscript is written in British English.

Line 300:

RC: Exchanged the expression "rupture" with "failure"

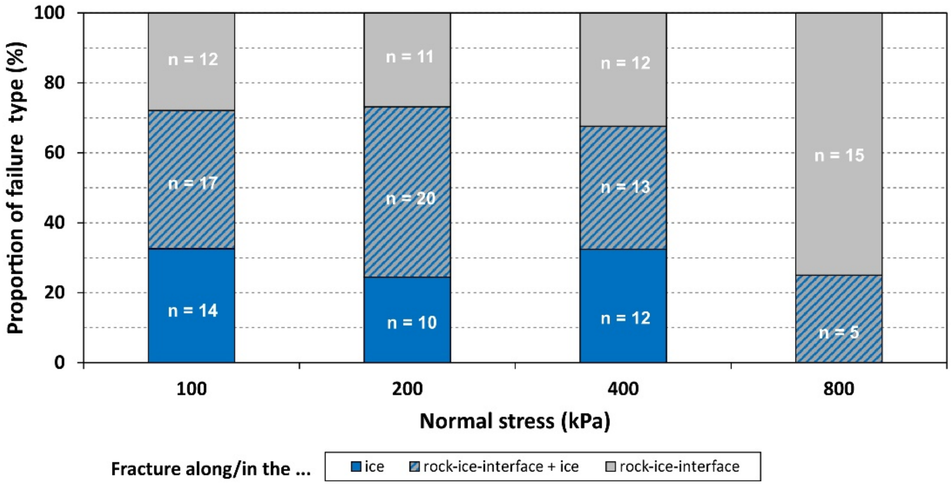
AC: Changed as suggested

Line 327:

RC: What about stress? – referred to the observations on the relationship between temperature and failure type

AC: To include our observations on the relation between normal stress and failure type we changed the title of section 3.2 into "*Observed failure type and its dependence on temperature and normal stress*".

Then we added a new figure (Fig. S6) to the supplementary material (line 97):



Within the supplement: We added a caption and a few sentences for explanation (line 98 and following):

"Figure S6: "Proportions and absolute numbers of failure types for normal stresses from 100 to 800 kPa and temperatures from -10 to -0.5 °C."

A new paragraph (lines 100 and following) was added:

"A relationship between failure type and normal stress could not be identified for stress levels 100–400 kPa (Fig. S6). However, at normal stresses of 800 kPa fracturing in the ice does not occur at all whereas fracturing of rock-ice contacts dominates with 75 %. This overrepresentation of failures along the rock-ice interface may be caused due to the absence of tests at 800 kPa and temperatures below -5 °C where (at ≤ 400 kPa) much higher proportions of failures within the ice were observed (Fig. 6)."

Further, the old numbers of the figures in the supplementary material were changed and we included the figure in the "legend" at the first page (line 18):

"(vii) the relationship between failure type and normal stress level (Fig. S6),"

In the main manuscript (line 325): In order to account for the referee`s comment we added the sentence

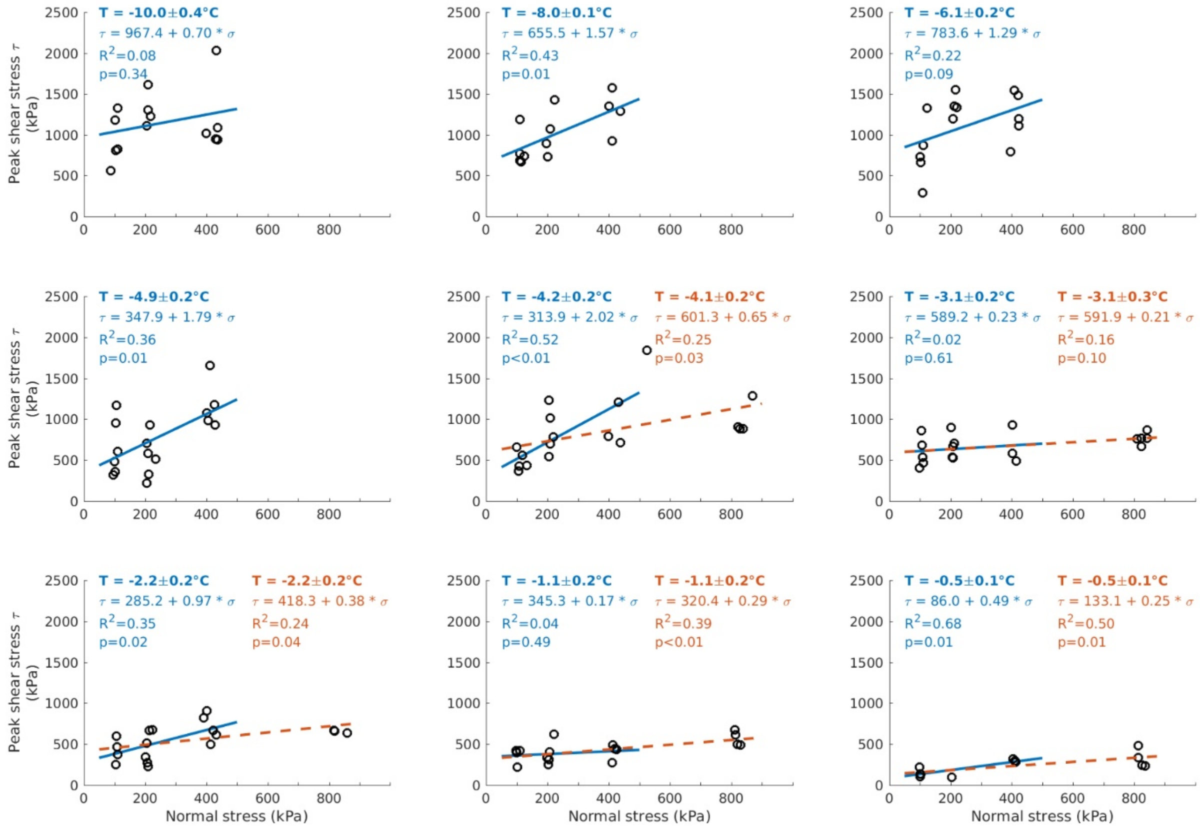
"A clear relationship between failure type and normal stress could not be identified (Fig. S6)."

Further, the old numbers of the figures in the manuscript were changed (lines 328, 360).

Line 349/Fig. 7:

RC: Combine a) with b) as illustrated – related to Fig. 7

AC: We modified Fig. 7 as suggested (line 341 in the revised manuscript):



As a consequence, we had to adjust the corresponding caption of Figure 7 as follows (line 342 in the revised manuscript):

"Measured shear stress at failure as a function of normal stress for temperatures between -10 and -0.5 °C. The temperature values are corrected by the means (including standard deviation) of the respective temperature level. Normal stress levels of 100, 200 and 400 kPa were applied for the whole temperature range. 800 kPa was additionally tested between -4 and -0.5 °C. Blue solid lines = calculated regression lines for normal stresses 100-400 kPa. Orange dashed lines = calculated regression lines for 100-800 kPa. Regression lines were used to derive temperature-specific cohesion and friction values. p = Probability of rejecting the null hypothesis (H0) although it is true."

Further, we had to change references to the respective figure from "Fig. 7a" or "Fig. 7b" to "Fig. 7", in lines 338 and 580.

Line 358:

RC: Suggested to add a reference to the Mohr-Coulomb equation

AC: We added three references of Coulomb (1773), Mohr (1900) and Jaeger et al. (2007) to the failure criterion (line 350 in the revised manuscript):

"To develop a shear strength description of ice-filled permafrost rock joints we used the linear and stress-dependent Mohr-Coulomb failure criterion (a combination of Coulomb (1773) and Mohr (1900); a discussion of its limitations is given in Jaeger et al. (2007)).."

Further, we extended the reference list by these three publications in section 11.

Line 360:

RC: Not sure if you can really apply the concept of effective stresses here as you don't know the pore water pressures. Please stay with total stresses. – referred to the explanation of Eq. (5)

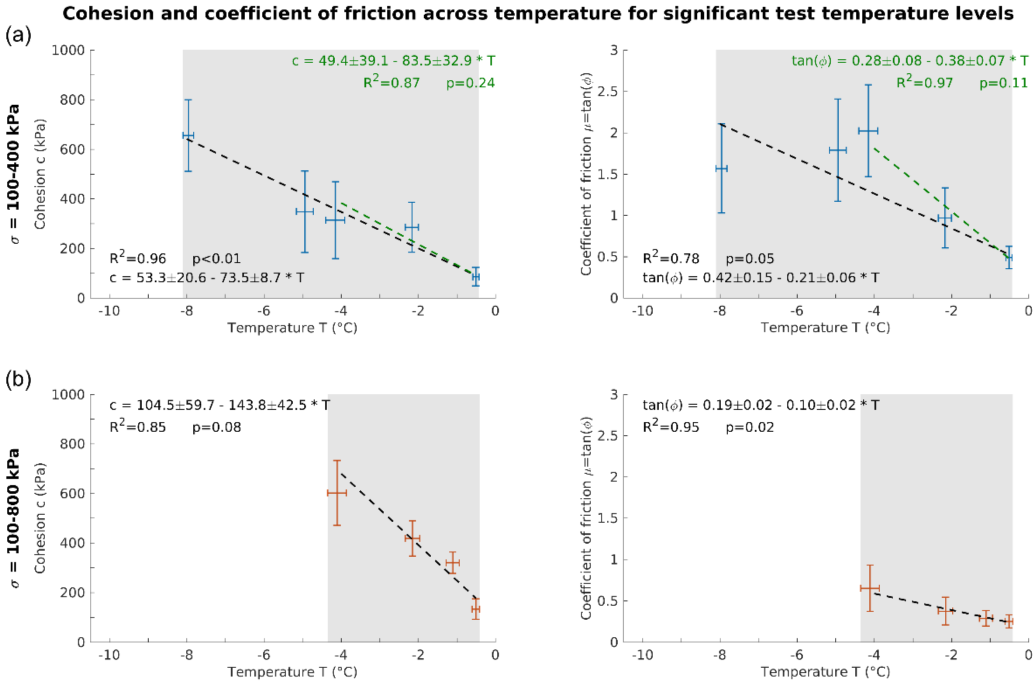
AC: We deleted the word "effective" and changed the symbol from effective σ´ to normal stress σ (line 356 in the revised manuscript).

Line 376/Fig. 8:

RC: The referee drew a red exponential curve into Fig. 8a and 8b giving an alternative to the linear curves by the authors. He commented on this with the following words: "For the cohesion I would not have expected a linear, but exponential trend. (b) makes most sense to me. Have you looked at such correlations? At 0 Degrees you shouldn't have a cohesion either".

AC: Considering the temperatures tested in our experiments, we do not know how cohesion and friction behave between -0.5 and 0 °C. As such, the valid upper boundary of temperatures for the calculated parameters and failure criterion is -0.5 °C. Correspondingly, the curves were not calculated/displayed for temperatures warmer than -0.5 °C. If we assume to have no cohesion at the melting point (where we fully agree with the referee), exponential curves are supposed to be very sensitive in the range of -0.5 to 0 °C. That is why we still keep to the linear curves.

In order to stress the fact that the equations for cohesion and friction are only valid for temperatures between -0.5 and -8 °C, we added grey areas displaying the valid temperature ranges (see below; line 371 in the revised manuscript):



Due to this change in the figure, we had to add further explanation in the caption of Fig. 8 (line 377 in the revised manuscript):

"…*The grey areas represent the valid temperature range for the respective parameter.*"

Line 387:

RC: This implies that at 0 degree you have a cohesion of 53.3 kPa. Where does it come from? – with reference to Eq. (6)

AC: We agree that no cohesion will be present at 0 °C and when the ice layer has melted. However, as the formula is just valid for temperatures from -8 to -0.5 °C (see sentence below Eq. (6)), cohesion values at a temperature of 0 °C are not supposed to be calculated with the formula. Tests at temperatures warmer than -0.5°C have not been performed as we assume the ice layer to be squeezed out of the rock cylinders leading to shearing along rock-rock contacts. In this case another surface material is involved in the shearing and may lead to different results. This can be observed in Davies et al. (2000, 2001) when comparing ice-concrete samples with concrete-concrete samples.

Hence, we would like to stick to this formula and added an explanation to prevent further misunderstandings (line 399 in the revised manuscript):

"We did not perform tests at temperatures warmer than -0.5 °C because we assume the ice to melt or be squeezed out of the rock cylinders which leads to shearing along rock-rock contacts. Cohesion will be absent at the melting point and shear strength values will rise. This is shown by the tests of Davies et al. (2001) where the shear strengths of ice-concrete samples closely approach the concrete-concrete sample line."

Line 407:

RC: It would be beneficial to include an error range, consider the large range in your test results. - with reference to Eq. (8)

AC: Changed as suggested

Lines 503-504:

RC: The referee deleted the term “thermal” and suggested to change the position of the bracket “(B1 in Fig. 11)”

AC: Changed as suggested (line 407 in the revised manuscript).

Lines 509-513:

RC: Suggested to present the five points as a list and not within the running text.

AC: Adjusted as proposed

Lines 521-527:

RC: Suggested to present the three points as a list and not within the running text.

AC: Adjusted as proposed

Line 544:

RC: What it? The number of signals or the rate? - referred to *“AE is generally well capable to anticipate rock-ice failure as (i) […], (ii) […] and (iii) it peaks immediately prior to failure.”*

AC: Changed to *“AE is generally well capable to anticipate rock-ice failure as (i) […], (ii) […] and (iii) AE hits peak immediately prior to failure.”* (line 590 in the revised manuscript)

Line 544:

RC: Suggested to exchange the term “this manuscript” by “the experiments conducted”

AC: Changed as proposed

Line 554:

RC: Added “ing” to the word “load”

AC: changed as proposed

Line 570:

RC: Be consistent with rock wall vs. rockwall

AC: As suggested by the referee, we wrote the term uniformly as “rock wall”

Line 578:

RC: Please do not simply copy - paste text from the manuscript, but prepare a condensed summary in the first paragraph – related to the conclusion

AC: As proposed by the referee we condensed the first two paragraphs of the conclusion as follows (line 617 in the revised manuscript):

“Most of the documented failures in permafrost rock walls are likely triggered by the mechanical destabilisation of warming bedrock, discontinuities with rock bridges as well as joints with or without ice fillings. The latter may evolve into shear planes supporting destabilisation on a larger spatial scale and leading to failure. To anticipate failure in a warming climate, we need to better understand how rock-ice mechanical processes affect rock slope destabilisation with temperatures increasing close to 0 °C.

This paper presents a systematic series of constant strain-rate shear tests on sandwich-like limestone-ice-limestone samples (i) to simulate the brittle failure of ice infillings and rock-ice interfaces along ice-filled shear planes of rockslides, ii) to study its dependence on temperature and normal stress and (iii) to develop a new brittle failure criterion for ice-filled permafrost rock joints. The setup and boundary conditions of our experiments are inspired by a 10^4 m³, ice-supported rockslide at the Zugspitze summit crest. Our tests apply to failures of permafrost rock slopes (i) with volumes of ≤ 2.3×10^4 m³, (ii) with ice-filled shear planes in a depth of 4–15 m, (iii) with bedrock temperatures between -0.5 °C and -10 °C and (iv) with high strain rates ($4.8 \pm 1.4 * 10^{-3}$ s^{-1}) coinciding with the accelerating final failure stage. Tests at a rock overburden of 30 m and temperatures from -4 to -0.5 °C were performed to study a potential stress-dependent transition from brittle fracture to creep. Of all the previous laboratory studies on the shear strength of ice-filled joints, the data set presented is the most extensive, containing 141 tests at nine temperature and four normal stress levels. For the first time, pre-conditioned rock from a permafrost-affected rock slope was used.”

We also condensed the last two paragraphs of the conclusion as follows (line 646 in the revised manuscript):

“The failure criterion contains a temperature-dependent cohesion and coefficient of friction decreasing by 12 % $°C^{-1}$ and by 10 % $°C^{-1}$ respectively with increasing sub-zero temperatures. The model fits well to the measured calibration means and even to the values excluded from the model development which mostly lie within or close to the calculated error margin. Further, we show that the failure type depends on the

temperature and is also affected by higher normal stresses (i.e. 800 kPa) above -4 °C which can presumably be explained by an enhanced pressure melting effect along the rock-ice interface.

The new failure criterion can be applied in numerical modelling and enables scientists and engineers to anticipate more accurately the destabilisation of degrading permafrost rock slopes, as it reproduces better real shear strength conditions along sliding planes."

Line 597:

RC: Added an "a" and "failure criterion" to the first part of the sentence *"It is based on a Mohr-Coulomb failure criterion, it refers…"*

AC: Changed as proposed (line 644 in the revised manuscript)