General comments and response by authors

Dear Mr. Isaksen, Mr. Gischig and anonymous Referee,

We would like to thank for the detailed comments and constructive suggestions, which helped us to improve the manuscript. We hope that we have adequately addressed and answered all referee's comments and changed the manuscript accordingly.

In the revised manuscript we addressed all the referees' comments and added in the general response explanations and comments to the specific points of the referees. The comments made by Referee #4 related to training window/learning period refers to the Initial Submission and was strongly improved after the 1st Revised Submission. We tried to answer this comment satisfactorily. We addressed and clarified the remaining comments that are still relevant in the second revision. We also changed the figures in the manuscript according to the comments.

With kind regards

Samuel Weber

On behalf of all authors

Reply to comments made by Anonymous Referee #3
We thank Anonymous Referee #3 for its review and suggestions for improvement. Referee comments indicated as “RC:”, author reply as “AR:”. Only sections requiring a reply are reproduced.

RC: In the introduction, it may be appropriate to add a short paragraph/sentence about microseismic monitoring and fracture development, as this topic is also cited by the authors themselves in the last paragraph of the conclusions. As far as references are concerned, apart from the work by Murton and Matsuoka, I would consider: 1) Occhiena C, Coviello V, Arattano M, Chiarle M, Morra di Cella U, Pirulli M, Pogliotti P, Scavia C (2012) Analysis of microseismic signals and temperature recordings for rock slope stability investigations in high mountains areas. Natural Hazards and Earth System Sciences. 12: 2283-2298; 2) Arosio D, Longoni L, Mazza F, Papini M, Zanzi L (2013) Freeze-thaw cycle and rockfall monitoring. In: Margottini C et al (ed’s) Landslide Science and Practice, Vol.2, Springler, Berlin Heidelbergh, p 385-390. The first paper describes the relationship between acoustic emission and temperatures on the Matterhorn, while the second paper presents interesting lab tests, considering the role of ice expansion.
AR: Micro-seismic monitoring is for sure a way to complement the present study. In the recently published paper (Murton et al., 2016) 1000 micro-seismic events coincident to rock fracturing in a three year freezing experiment were analyzed and clustered according to presumable fracturing types (crack coalescence, initial fracturing…). A similar setup could in future reveal insights into relevant fracturing types. We only mentioned this method in outlook of this manuscript. This will be the scope of another paper that intends to link micro-seismic activity and irreversibility index given by the analysis of crackmeter measurements. Adding a short paragraph/sentence about micro-seismic might not be pertinent in the introduction section and be confusing for the reader, as we intend to separate and quantify the irreversible displacement only with crackmeter and temperature measurements. However we rephrased the last paragraph of the conclusion (page 20, line 23).

Murton, J., Kuras, O., Krautblatter, M., Cane, T., Tschofen, D., Uhlemann, S., Schober, S., Watson, P., 2016. Monitoring rock freezing and thawing by novel geoelectrical and acoustic techniques. Journal of Geophysical Research – Earth Surface.

RC: Page 3, line 5. Typo
AR Done.

RC: I would spilt Fig. 1 in sub-figures with proper labels and I would refer to them in the following paragraphs.
AR: Done.

RC: Page 4, line 4. “This is therefore a reversible mechanism”. The cause and effect relationship is not clear here. Could you please explain in more details?
AR: To clarify this point, we modified the sentence in the revised manuscript to (page 4, line 7): “This is therefore a reversible mechanism as it is driven by cycling temperature.”

RC: Page 5, line 16. What about the water lubricating the fractures? Could you comment on that?
AR: It seems that the lubrication mechanisms are investigated for fault rock by earthquakes. The effect of water lubricating the fractures is ambiguously discussed in the literature and therefore not included here. However, we don’t think that it is a dominant and relevant fact in such a field site. But the presence of water can reduce cohesion in clay, or possibly also rates of critically stressed fracture propagation in intact rock. We addressed this comment by rephrasing the paragraph (page 5, line 16):
“However, changing conditions in shear zones, e.g. from dry to wet, can lead to irreversible displacement, for example caused by water (melting snow or rain) percolating through preexisting fissures. Even with low hydrostatic pressure, the presence of water can reduce cohesion in fine-grained material containing clay and is expected to have a strong influence in fractures filled with fine-grained material.”

RC: Page 5, line 24. I would change into “could be assumed to be”. In some failures no

displacements are observed before ultimate collapse. Please consider also modifying sentence at page 6, lines 6-7.
AR: Done.

RC: Page 6, line 2. “(middle part of Fig. 1)”. Not clear. What do you mean?
AR: We modified the figure labeling in the revised manuscript and refer to Figure 1a.

RC: Page 6, line 17. What do you mean with “obvious”? Please clarify.
AR: We clarified this point by rephrasing the paragraph (page 6, line 15).

RC: Page 7, caption Fig. 3. What is an active layer of the permafrost?
AR: To clarify this point, we added a definition of active layer in the caption of Fig. 1 (page 3).

RC: Page 8, line 6. Information is singular.
AR: Done

RC: Page 9, line 5. Could you add a reference for the Pearson correlation?
AR: Done.

RC: Page 10, line 15. Why 21 days? Please explain.
AR: The length of the sliding window of 21 days was defined iteratively as a trade off between high noise-level and loosing important signals due to smoothing (page 10, line 14).

RC: Page 11, line 2. “rises”.
AR: Done

RC: Page 11, line 12. Please change into: “are not visible after mid 2015 as they are out of range (Fig. 6).”
AR: Done

RC: Page 11, line 13. Is 18 May 2015 early summer?
AR: To clarify this, we rephrased this sentence in the revised manuscript to (page 11, line 12): “This abrupt and large displacement is due to a small rock fall event with a volume of a few cubic meters on 18 May 2015.”

RC: Page 11, line 22. “according to”.
AR: Done

RC: Page 11, line 25. “exhibit”.
AR: Done

RC: Page 12, lines 1-2. Please rephrase this sentence.
AR: We rephrased the beginning of the caption to (caption Fig. 6, line 12): “Thermal conditions and fracture displacements at the Matterhorn Hörnligrat field site over a course of eight years”.

RC: Page 20, line 17. “superimposed on”.
AR: Done

Reply to comments made by Referee #4 Valentin Gischig.
We thank Valentin Gischig (Referee #4) for his review and suggestions for improvement. Referee comments indicated as “RC:”, author reply as “AR:”. Only sections requiring a reply are reproduced.

Page 1 Line 13; Comma after ‘Here, ...’
AR: Rephrased in the revised manuscript.

RC: Line 15: ‘variable rates’
AR: Rephrased in the revised manuscript.

RC: Line 16: Space after ‘...year.’
AR: Done.

RC: Line 19: remove ‘such’. This statement (also occurring elsewhere several times) needs to be reconsidered. What do you mean with ‘water’? Water pressure? I think it is far-fetched to say that thawing or the presence of water lowers cohesion and/or friction? There might be alternative mechanisms: increased water pressure would lower the effective stress along fracture but leave the strength (i.e. cohesion and friction) untouched. However, I doubt that significant water pressure can build up in such a heavily fracture and steep, ridge-shaped topography. I would agree that thawing of ice in fractures may have an effect on strength. But how? Reducing cohesion? tensile strength? Friction? All of them? What if ice melts in a fracture that has previously been ice-filled so that the blocks were separated? If the ice melts the blocks would get into contact again and hence friction would actually be higher than with presence of ice. I suggest refining/rewording the statement to describe a mechanism that is better funded.
AR: We agree to this point, it is not known how the availability affects cohesion or friction. This statement in the initial submission was reconsidered and clarified for the revised manuscript. Significant water pressures can build up even in fractured rock masses above permafrost bodies as perched water above ice-sealed fractures (Pogrebiskiy and Chernyshev, 1977) but there are no detailed empirical quantitative studies on how hydrostatic pressure affects rock walls in permafrost regions. Ice in fractures influences shear resistance due to creep and fracturing of ice itself and along rock-ice interfaces (Krautblatter et al., 2013) and produce tensile strength of typically up to 2 MPa. The performance of ice is controlled by stress, temperature and water/impurity content in the ice.

RC: Line 22: ‘... deformation cannot be explained by a single process even at close-by locations’ (check word order)
AR: Rephrased in the revised manuscript.

RC: Page 2, Line 8: ‘Assuming that warming ...’
AR: Done.

RC: Line 13: Improved monitoring strategies and hazard assessment for frozen ...’
AR: Done.

RC: Line 22: remove ‘hereby developed’. Is it known what components change the most to increase ‘shear resistance’? Cohesion or friction?
AR: We rephrased this statement to (page 4, line 31): “While ice-filled joints can form relatively tough ice bodies at low temperatures, the shear resistance decreases with rising temperature and reaches a minimum just below the thawing point (Davies et al., 2001).” The study of Davies only considers change in temperature and normal stress and does not provide further information concerning relative change in the different component (cohesion or friction).

RC: Line 28 and elsewhere: I find the term deformation for discontinuities or fractures confusing or problematic. I associate ‘deformation’ in rock mechanical contexts with a continuum, so a deforming fracture would be one that changes for instance shape from being planar to being curved. You are referring to movement of one side of the fracture with respect to the other one,

while the fracture itself remains undeformed. I suggest using to use the term ‘dislocation’ for fractures (i.e. infinite deformation along a nominally flat fracture with very small aperture), and leave the term deformation for intact rock.
AR: Dislocation is generally used in materials science to describe a defect within a crystal structure. Replacing deformation by dislocation would be therefore confusing for most of readers. However, reviewer is right, deformation in the context of discontinuities can be problematic. We therefore clarified this point by using the term fracture displacement and defining our terminology (page 6, line 6): “The term displacement used in the following refers to the movement of one side of the fracture with respect to the other.”

RC: Line 32: remove widespread or replace by widely. Here is another instance of the term ‘fracture deformation’.
AR: Done.

RC: Page 3, Line 1: ‘unbalance’
AR: Rephrased in the revised manuscript.

RC: Line 23: ‘sketched’ not sketched out.
AR: Rephrased in the revised manuscript.

RC: Line 31: ‘the observed motion’
AR: Rephrased in the revised manuscript.

RC: Page 4, Line 12 – 14: The sentence is somewhat trivial as nobody expects that this equation can readily be applied. I suggest omitting. Generally Section 2 could be shortened and written in a slightly more concise manner.
AR: Rephrased in the revised manuscript.

RC: Line 22: ‘stresses’ not ‘pressures’. Not sure that is necessarily has to lead to a ‘stress reduction’. I would replace this by ‘deformation/dislocation’.
AR: We rephrased this sentence to (page 5, line 23): “Deformation and fracture of ice can absorb stress along fractures and lead to dislocation...”.

RC: Line 28: ‘is’ not ‘get’. The sentence is not generally true. In first order, fracturing of cohesive rock bridges only stress intensity. How does the temperature dependence come in? Through presence of ice/water? The mechanism has to be explained in greater detail.
AR: We agree and removed this sentence as it is over simplified.

RC: Page 6: Line 10 ‘It depends, among other factors,...’
AR: Done.

RC: Line 8: ‘water’ not ‘hydro’ (also in process D4 in Figure 1), hydrostatic pressure (‘hydropressure’ is not a common term).
AR: We removed the term hydropressure and replaced it by hydrostatic pressure.

RC: Line 15: ‘ ...change the resisting forces defined by cohesion and friction ... ’.
AR: Rephrased in the revised manuscript.

RC: Line 16: ‘e.g. from dry to wet’ (Generally, it would be good check the manuscript for colloquial expressions).
AR: Done.

RC: Page 7: Line 8. Move sentence ‘Figure 3 gives ... ‘ before the sentence on the measurements locations ‘Fracture deformation perpendicular’ …. Also: it is not clear how dislocation parallel to a fracture is measured. I assume via extensometers spanned across fracture is an oblique manner. If that is the case, then these sensors would also measure a perpendicular component, and the parallel component has to be computed using the sensor perpendicular to the fracture. A sketch

and explanation would help.
AR: We changed the order of the sentences. In the revised manuscript, we adapted Figure 5 (page 8) and added a photo with a sketch that illustrates locations instrumented with two crackmeters.

RC: Page 8, Section 4.1: How large are the gaps? Do they occur often?
AR: We clarified this in the caption of Figure 6 (page 12)in the revised manuscript: "A gap in the rock temperature time series of location mh12 (T_{east}) is filled for the time period November 2012 until July 2013 and from August 2014 onwards applying quantile mapping using the best regressors approach (Staub et al., 2016) with a coefficient of determination R^2 = 0.92."

RC: Page 9: Line 4/5: Although a smoothed temperature may resemble temperature time series a greater depth, there are phase shifts of temperature cycles towards depth. I would omit that part of the sentence.
AR: This part was rephrased in the revised manuscript.

RC: Line 5: 'are' not 'get'.
AR: Rephrased in the revised manuscript.

RC: Line 6: training window: this needs to be explained better what you mean with it. Here also is my greatest criticism. I'm not sure if the concept of using a training window/learning period is applied in a sensible way. If the goal of the statistical model is to learn something about processes or timing of the dominant process (which I think it is the case here) it would be sufficient to calibrate the model with the entire dataset. If the goal is to demonstrate that the statistical model works as a predictive tool, it should be applied differently: to make predictions one has to use all data recorded up to a certain time, i.e. the model is calibrated against data from the start of the time series to the most recent data, and the training window is growing with time. You could for instance calibrate the model using the first 3 month, 6 month, 1 year, 2 years, etc. to show that it becomes better and better constraint or robust with time. However, choosing a training window in the middle and stating that periods in winter work better is a very arbitrary. I understand that this was done to illustrate the robustness of the model, but it does not tell anything about its predictive capability nor is it the best calibrated model (which would be one using the entire dataset). I suggest reconsidering this calibration strategy.
AR: We addressed the selection of the trainings phase in the revised manuscript. We added an additional correlation analysis for defining the trainings phase. We applied a best fit analysis using all available rock and fracture temperature data. Due to complete data availability at all instrumented locations, only the data in the time window between 1 Oct 2013 and 1 Jan 2015 is considered. We determined on this period the most representative temperature measurement for modeling the reversible thermo-mechanically induced fracture kinematics. The best trainings periods are shown in Table 2 on page 13. In our opinion it does not make sense to calibrate the model with the entire data set as the model only describe thermo-elastic strain. The correlation analysis shows that the coefficient of determination decreases if the training phase is too long. High coefficients of determination show that there are time periods dominated by thermo-elastic strains.

RC: Line 14: ' the difference between y and y is smoothed with a'
AR: This point was addressed in the revised manuscript.

RC: Section 4.4 I'm not sure if these variables do give much insight into the processes. Also the observations in Figure 8 are not very conclusive in terms of correlation between TDD and OFST. The article does not benefit much from it. However, it is up to the author if they leave it in or not.
AR: We added an additional figure to the appendix of the revised manuscript presenting the summer shift of kinematics perpendicular to fracture against yearly thawing degree days with a black line indicating the regression function (see Figure 14, page 23). We clarified this paragraph by rephrasing to: " ... TDD are not computed if the temperature time series contain a gap during summer. A weak correspondence is apparent (see Fig. 14 in appendix A) for locations with aspects to the north and east. This hints on a substantial influence of rock temperature and therefore

incoming conductive energy fluxes. Interestingly, …". (page 13, line 13)

RC: Page 10, Line 27: 'There are two options for the end...', 'when the rock temperature crosses' The choice of the end and start of the reversible period sound somewhat arbitrary. It relies on the pre-assumption that the irreversible period only occurs in summer or when temperatures are above -1°. Later this assumption is sold as a result / conclusion drawn from the data. A different strategy would be to let data tell, when to set the start / end of the irreversible period. The irreversibility index offers itself to guide the onset and end of the period. Replace 'get' or 'got' by proper passive tense.
AR: We revised and clarified the whole method section in the revised manuscript. In particular, the LRM+ model was removed. Although it reproduced quite well fracture kinematics, it was not crucial for the main focus and analysis of this manuscript and could confuse readers.

RC: Page 11, Line 22-25: 'the instrumented rock', 'the observed fracture deformation'
AR: Done.

RC: Line 22: Order of Figures: here Figure 10 follows Figure 5.
AR: The order of the figures is in this paragraph not consecutive as the first figure refers to the figure in the attachment.

RC: Page 12, Line 14: thermo-elastic would be a more appropriate term to talk about a reversible process. (also elsewhere)
AR: We rephrased all terms "thermo-mechanically induced strain" by "thermo-elastic strain".

RC: Page 13, Line 5: check sentence, there is something wrong here.
AR: This paragraph was rephrased in the revised manuscript.

RC: Page 14, Line 7: 'thermo-elastic' instead of 'therm-mechanical'
AR: Done.

RC: Line 12: 'distinct'
AR: Done.

RC: Page 17, Line 7: 'melt onset'
AR: Done.

RC: Line 5: what is the reason that mh02 does not show any temperature-dependent reversible movement? I think it is remarkable that a fracture does not react on temperature! Do the authors know the reason? I think an explanation would be warranted.
AR: A possible explanation could lie in the individual geometric mesoscale arrangement of each fracture. Actually we do not know for sure, but we guess that the fracture is more inclined and the thermo-elastic strain of the rock masses aside the fracture is detectable at the outer boundary of the rock mass. In this case, displacement occurs, but is not measured by the installed sensor setup. As this explanation is strongly hypothetical, we extended the paragraph with (page 18, line 18):
"..., the magnitude of the reversible fracture displacement, caused by thermo-elastic strain, is influenced by the individual geometric mesoscale arrangement of each fracture."

RC: Page 18, Line 6: 'rates'
AR: We rephrased this paragraph.

RC: Line 15: 'cannot' not 'can not' also elsewhere.
AR: Done.

RC: Line 19: Not only at mh02 and mh21 does OFST and TDD not correlate. How about mh08, or the last point at mh03?. As mentioned earlier I am not too convinced about the value of these

observations. Maybe if more explanation/analysis is offered it could be a good contribution to process understanding. However, you do not really elaborate much on the different behaviours.
AR: See author response to reviewer comment “RC: Section 4.4”

RC: Line 25: How many days before the rock fall did this increase occur? I think even without the irreversibility index the change in behaviour was readily visible from the fracture opening data. Do you know the volume of the break-off?
AR: We rephrased this paragraph in the revised manuscript (page 11, line 12): “This abrupt and large displacement is due to a small rock fall event with a volume of a few cubic meters on 18 May 2015. The functionality of both crackmeters was however not affected. But the thermistors at location mh02 were damaged by falling rocks. Hence the temperature time series ends on 18 May 2015. After this rock fall event, the fracture at location mh02 continued to deform in several small steps until late summer (14 August 2015) when the instrumented rock broke off completely during a bad weather period (see Fig. 12).” Unfortunately, we do not know the exact volume of the break-off.

RC: Line 32 ‘was not observed to close’
AR: This paragraph was rephrased in the revised manuscript.

RC: Page 19, Line 20: During additional phases, ...
AR: Done.

RC: Line 22: ‘suggesting a decrease of cohesion and friction’ as mentioned earlier this is a too far-fetched conclusion and is not directly supported by your data. It may also be that during summer, stress redistribute such that strength (i.e. friction and cohesion) is overcome and slip initiates, while friction and cohesion themselves do not change. If you compare with
Collins, B. D. & Stock, G. M. Nature Geosci. http://dx.doi. org/10.1038/ngeo2686 (2016).
or
Gunzburger, Y., Merrien-Soukatchoff, V. & Guglielmi, Y. Int. J. Rock Mech. Min. Sci. 42, 331–349 (2005).
irreversible fracture opening or slip does not have to be related to a change in strength (or not even to ice, although it may well be the case). To me it is not entirely clear by what mechanism irreversible movements in your case are induced: are the tensile fractures ‘glued’ with ice in winter (in this case it would be a change in tensile strength) or is it ice along sliding planes? Can something be deduced from your data and structural observations (block shapes, fracture orientations?)
AR: This comment refers to the initial submission and was rephrased for the first Revised Submission. Regarding the mechanism leading to irreversible displacement: Anyway, reviewer might be right, if , for any reason, local stress overcome strength (even constant), a slip might occur (i.e. irreveversible displacement). But based on only surface displacement and temperature measurements, it is difficult to decipher the process leading to irreversible displacement.

RC: Line 24-25: I suggest omitting this sentence. It does not conclude from your observations.
AR: This paragraph was rephrased in the revised manuscript.

Quantifying irreversible movement in steep fractured bedrock permafrost on Matterhorn (CH)

Samuel Weber[1], Jan Beutel[2], Jérome Faillettaz[1], Andreas Hasler[3], Michael Krautblatter[4], and Andreas Vieli[1]

[1]Department of Geography, University of Zurich, Switzerland
[2]Computer Sciences, ETH Zurich, Switzerland
[3]Department of Geosciences, University of Fribourg, Switzerland
[4]Landslide Research, Technical University of Munich, Germany

Correspondence to: Samuel Weber (samuel.weber@geo.uzh.ch)

Abstract. Understanding rock slope kinematics in steep fractured bedrock permafrost is a challenging task. Recent laboratory studies have provided enhanced understanding of rock fatigue and fracturing in cold environments but were not successfully confirmed by field studies. This study presents a unique time series of fracture kinematics, rock temperatures and environmental conditions at 3500 m a.s.l. on the steep, strongly fractured Hörnligrat of the Matterhorn (Swiss Alps). Thanks to ~~seven~~ eight years of continuous data, the longer-term evolution of fracture kinematics in permafrost can be analyzed with an unprecedented level of detail. Evidence for common trends in spatio-temporal pattern of fracture kinematics could be found: A partly reversible seasonal movement can be observed at all locations, with variable amplitudes. In the wider context of rock slope stability assessment, we propose to separate reversible (elastic) components of fracture kinematics, caused by ~~thermo-mechanically induced~~ thermo-elastic strains, from the irreversible (plastic) component due to other processes. A regression analysis between temperature and fracture displacement shows that all instrumented fractures exhibit ~~a reversible deformation that dominates~~ reversible displacements that dominate fracture kinematics in winter. Furthermore, removing this reversible component from the observed displacement enables to quantify the irreversible component. From this, a new metric – termed index of irreversibility – is proposed to quantify relative irreversibility of fracture kinematics. This new index can identify periods when fracture displacements are dominated by irreversible processes. For many sensors, irreversible enhanced fracture displacement is observed in summer and its initiation coincides with the onset of positive rock temperatures. This likely indicates thawing related processes, such as melt water percolation into fractures, as a forcing mechanism for irreversible ~~deformation~~displacements. For a few instrumented fractures, ~~an irreversible deformation was found with~~ irreversible displacements were found at the onset of the freezing period, suggesting that cryogenic processes act as a driving factor through increasing ice pressure. The proposed analysis provides a tool for investigating and better understanding processes related to irreversible kinematics.

Keywords

Fracture kinematics, steep bedrock permafrost, high mountain permafrost, fracture monitoring

1 Introduction

On steep high-alpine mountain slopes, the behavior of frozen rock masses is an important control of slope stability when permafrost warms or thaws and seasonal frost occurs. During the summer heat wave 2003, air temperatures across a large portion of Europe were $3°\,C$ higher than the 1961–1990 average (Schär et al., 2004), causing deep thaw and coinciding with exceptional rockfall activity in the European Alps (Gruber et al., 2004). In the last century, the upper tens of meters of Alpine permafrost in Europe have been warmed by $0.5-0.8°$C (Harris et al., 2003). Assuming that ~~this~~ warming will continue or even accelerate, rock slope instabilities are expected to become increasingly important for scientists, engineers and inhabitants in the vicinity of high mountain permafrost regions (Gruber and Haeberli, 2007; Keuschnig et al., 2015). A coexistent growth of vulnerable socio-economic activities in alpine areas potentially leads to rising risk (Jomelli et al., 2007). In the USA and Europe, global gravity-driven slope instabilities cause damage in the range of billions of euros each year (Sidle and Ochiai, 2006). Improved ~~assessment and monitoring strategies~~ monitoring strategies and hazard assessment for the dynamics of frozen rock walls are therefore needed and require better understanding of processes and factors controlling stability of potentially hazardous slopes.

Terzaghi (1962) postulated that the stability of steep unweathered rock slopes is determined by the mechanical defects of the rock such as joints and faults and not by the strength of the rock itself. In cold regions, rock is exposed to frost cycles of variable length, leading to mechanical rock damage caused by different processes, such as thermal gradients (Hall et al., 2002) or cryostatic pressure (Walder and Hallet, 1985). Ice formation is therefore an important driver of rock fracturing and can be produced by ice expansion or ice segregation. These two processes have been widely discussed, but it remains difficult to ~~incorporate~~ integrate this knowledge with field observations (Matsuoka and Murton, 2008). Assessing and anticipating rock wall stability is a challenging task, mainly because of the incomplete understanding of precursory signals and the inherent mechanical complexity of fractured inhomogeneous rock and ice masses (Arosio et al., 2009). Surface displacement measurements have been applied in several studies to survey fracture kinematics in permafrost revealing a clear reversible component related to thermal expansion (Wegmann and Gudmundsson, 1999; Matsuoka and Murton, 2008; Nordvik et al., 2010; Hasler et al., 2012; Blikra and Christiansen, 2014). Often, an additional irreversible displacement component is observed, which is relevant for the stability assessment of potentially hazardous slopes, but has so far not been thoroughly quantified in existing studies. In this study and based on a new ~~7~~ eight year continuous data set of fracture kinematics, we propose and apply a methodology for separating and quantifying such irreversible displacements.

1.1 Permafrost rock slope kinematics and environmental controls

Fracture displacements, reversible and irreversible, is controlled by a variety of processes and external environmental forcing which are outlined in Fig. 1 and discussed in more detail in this section. The schematic in Fig. 1a combines the concept of destabilization by warming ice-filled rock joints developed by Gruber and Haeberli (2007), the rock-ice-mechanical model by Krautblatter et al. (2013) and the permafrost controlled rock slide model by Blikra and Christiansen (2014), in which topographically controlled thermally induced stresses, ice and water pressure act as driving processes. The resisting mechanisms are shear resistance and fracture infill. The shear resistance is given by cohesive rock bridges, ice deformation/fracture that reduces stresses through plastic work and cohesion/friction along fractures. All processes strongly depend on temporal fluctuating environmental forcing as well as the static geological or geotechnical characteristics. Many of these processes interact and result in complex combinations of individual contributions. The observed fracture kinematics usually consists of a reversible (elastic) and irreversible (plastic, creep and rupture) component. ~~An individual relation~~ The corresponding specific relations between fracture kinematics and temperature ~~(see bottom~~ are indicated in more detail below (see plots in Fig. 1~~) is proposed for the main mechanisms described in in more detail below~~b).

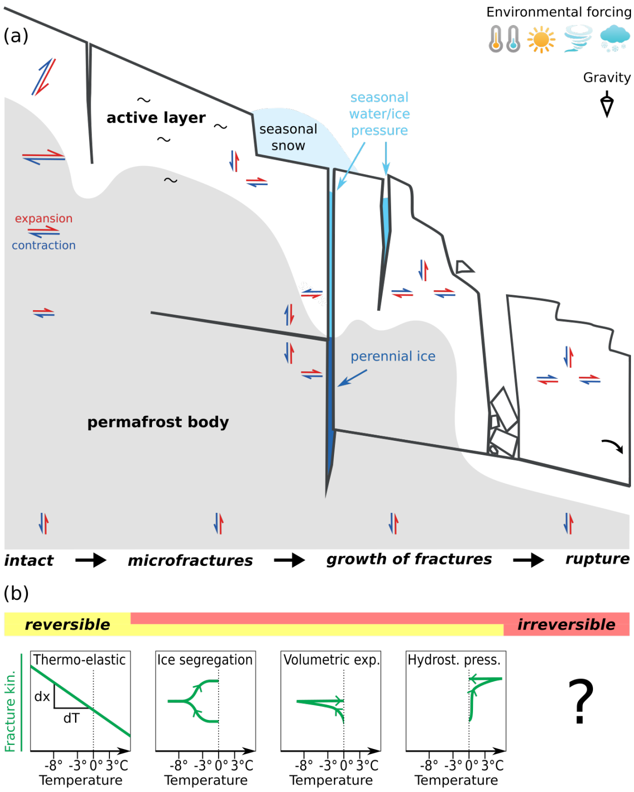

Figure 1. Schematic visualization of kinematics in steep fractured bedrock permafrost shows the main acting mechanisms influenced by varying environmental forcing. (a) The gray area indicates permafrost, which is thermally defined as ground with a temperature below 0° C for at least two consecutive years. The ~~overlying rock mass~~ overlaying active layer is exposed to ~~seasonal~~ sub-annual freezing and thawing. (~~top~~b) ~~.~~The indicated mechanisms can lead to fracture kinematics and each isolated mechanism causes specific movement patterns, illustrated with the schematic plots showing the relation between fracture kinematics and rock temperature~~(bottom)~~.

Thermally induced stress

Rock tends to expand on warming and to contract on cooling and results in a reversible displacement behavior. Assuming homogeneous thermal conditions, a change in length ΔL of rock in all directions can be described by a linear function of temperature:

$$\Delta L = L_0 \cdot \alpha \cdot \Delta T \qquad (1)$$

where L_0 is the initial length, α the material dependent linear expansion coefficient and ΔT the temperature change of the material. In laboratory experiments, Wolters (1969) showed a linear strain-temperature relation for different rocks (marly limestone, limestone, claystone, granite and basalt) between -20 and $+80°$C. Short-lived ~~thermo-mechanically induced~~ thermo-elastic strains accommodate volume changes as displacements, typical for fractured bedrock in non-permafrost (Watson et al., 2004) as well as in permafrost areas (Hasler et al., 2012). This is therefore a reversible mechanism as it is driven by cycling temperature. Equation 1 is a highly simplified approximation and ignores: (i) anisotropy and heterogeneity of the rock mass, (ii) complex 3D temperature regimes, (iii) the unknown behavior of fractured bulk rock masses and (iv) a potential non-linear expansion coefficient of rocks containing ice-filled pores (Jia et al., 2015). However, several studies in permafrost bedrock with different measurement setups (e.g. Wegmann and Gudmundsson, 1999; Matsuoka, 2001; Matsuoka and Murton, 2008; Nordvik et al., 2010) confirm a simple relation between fracture kinematics and (rock-) temperature at different time scales ranging from diurnal to annual. Further, Nordvik et al. (2010) applied a multiple regression analysis with aggregated sinusoidal air temperature to model the seasonal fracture kinematics and propose this approach for predictions of fracture kinematics in the context of early warning systems.

Thermally induced stress may cause rock fracture either by repetitive low-magnitude temperature cycles that lead to thermal stress fatigue or by a rapid temperature change (Murton, 2007). This might lead to irreversible ~~deformation~~displacement.

Cryogenic ~~deformation~~ kinematics during freezing periods and related ~~deformation~~ kinematics during warming

~~Deformation~~ Kinematics in partly frozen rock masses may also be caused by increasing ice pressure evolving in ice-filled fractures or pores by cryogenic processes. Volumetric expansion or ice-segregation are the most common explanations here. Volumetric expansion in laboratory experiments is only effective if freezing leads to sealing of rock fractures or porous samples before ice can extrude (Davidson and Nye, 1985). However volumetric expansion also applies in pores which are on average saturated by much less than $91\,\%$. Due to the heterogeneous moisture distribution, some pores will always have a higher saturation and thus have insufficient space for the volumetric expansion of freezing water (Jia et al., 2015). Ice segregation, which is most effective between $-3°$ and $-6°$C with sustained water supply (Hallet et al., 1991), describes the freezing of the migrated water at the freezing site, which results in lenses or layers of segregated ice due to ice growth (Matsuoka and Murton, 2008). Ice formation induces pressure variations in rock pores and cracks at a level that is sufficient to crack intact high porosity rocks (Murton et al., 2006). Based on numerical simulations, ice segregation can even occur in low porosity rocks in an estimated temperature range from -4 to $-15°C$ if liquid water is available (Walder and Hallet, 1985). In nature, conditions required for ice segregation are more commonly met than the conditions required for volumetric expansion. It has to be considered that ice pressure and its release by melting can also produce reversible fracture displacements.

While ice-filled joints can ~~develop~~ form relatively tough ice bodies at low temperatures, the shear resistance decreases with rising temperature and reaches a minimum just below the thawing point (Davies et al., 2001). ~~Independent of the occurrence~~

of ice, fracture of cohesive rock bridges is temperature dependent and influenced by warming during slow deformation (Krautblatter et al., 2013). Mellor (1973) showed a significant reduction in strength when intact water-saturated rock thaws. Periodic loading of discontinuities due to thermo-mechanical effect acts as a mesoscale fatigue process. This can result in enhanced deformation displacement and progressive rock slope failure (Gischig et al., 2011). After a certain fatigue life, tensile and compressive strength reduce to residual values (Jia et al., 2015). Besides the relatively slow process of heat conduction, the warming of frozen fractured bedrock is influenced by advective heat transport by percolating water. This process efficiently transfers heat from the surface to fractures (Hasler et al., 2011). Such advective heat transport produces rapid variations in mechanical properties, which can potentially deform frozen discontinuities and consequently prepare rock-slope failures. But the potential formation of basal ice layers between the snow and the rock prevent prevents percolation of snow melt water into fractures (Phillips et al., 2016).

Hydro deformation kinematics occurs during summer months and during snow melt

Irreversible deformation caused by hydro-related displacement caused by water-related processes can only be observed in summer, because the availability of liquid water is very limited during winter. Water can increase the effective stress through hydrostatic pressure but leave the strength (i.e. cohesion and friction) untouched, whereby hydrostatic pressure is mostly determined by the height of the water column. It depends amongst other factors on the hydraulic permeability of the rock mass. Hydraulic permeability is much lower in rock masses with frozen and ice-filled fissures than unfrozen fissures and often causes high hydrostatic stress due to perched water (Pogrebiskiy and Chernyshev, 1977). But there are no detailed empirical quantitative studies on how hydrostatic pressure affects rock walls in permafrost regions (Krautblatter et al., 2013). However, hydrostatic pressure is presumed not to dominate in the near-surface layer of strongly fractured steep bedrock, where the ability for drainage is quite high. However, changing conditions in shear zones, e.g. dry-wetfrom dry to wet, can lead to irreversible displacement, for example caused by water percolating due to (melting snow or rain. This) percolating through preexisting fissures. Even with low hydrostatic pressure, the presence of water can reduce cohesion in fine-grained material containing clay and is expected to have a strong influence in fractures filled with fine-grained material.

Long term evolution

In the long term, deformation displacements along fractures act to change the persistent gravitationally-induced stress distribution in the rock mass controlled by the bulk material stiffness and rock mass strength properties. Deformation and fracture of ice can absorb pressure stress along fractures and lead to stress reduction dislocation (Matsuoka, 1990) while fracture infill by debris or fine grained material can significantly alter shear resistances of fractures in a frozen or unfrozen state. Persistent reversible thermo-elastic oscillations of an initially stable rock mass (stable phase in Fig. 2), in combination with an increase in shear stress due to concentration of stress at rock bridges or a decrease in shear resistance, leads to irreversible surface displacement (unstable phase in Fig. 2). Therefore, irreversible displacements are assumed to could be a first indication for the initiation of rock slope failure.

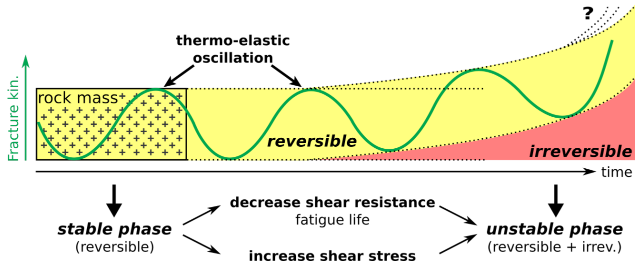

Figure 2. Evolution of a permafrost affected rock mass with persistent thermo-elastic oscillations: initially reversible ~~deformation~~ displacement of rock mass can develop an additional irreversible component either by an increase in shear stress or by a decrease in shear resistance.

However, reversible and irreversible displacements are often superimposed and it is difficult to interpret ~~deformation~~ kinematics data and relate them to external forcing. Furthermore, failure of heterogeneous natural materials often results from the culmination of progressive irreversible damage involving complex interactions between multiple defects and growing microcracks (Faillettaz and Or, 2015). Therefore quantifying the irreversible component of the overall fracture displacement is expected to give valuable information in the context of rock slope stability assessment (Fig. 1).

1.2 Aim of this study

This study focuses on the kinematics of fractured bedrock permafrost (~~middle part of~~ Fig. 1a). It aims at quantifying irreversible fracture displacements in relation to environmental forcing. For this, the reversible (elastic) components of fracture displacement, due to ~~thermo-mechanically induced~~ thermo-elastic strains, are separated from the irreversible (plastic) component, due to other processes. Using a statistical model for the reversible component, we are able to investigate the kinematics in fractured bedrock permafrost with a focus on enhanced opening and shearing of fractures. The term displacement used in the following refers to the movement of one side of the fracture with respect to the other. Irreversible displacement refers to slow rock slope deformation, which ~~is~~ could be seen as a part of slope instability, potentially preparing slope failure. ~~This statistical model~~ The statistical model introduced here has been developed and tested ~~using 7~~ on the base of eight years of continuous high resolution temperature and fracture kinematics measurements from the Matterhorn Hörnligrat, a high mountain permafrost monitoring site. This study addresses three main questions:

1. How can we statistically separate reversible from irreversible fracture kinematics?

2. Is there a common inter-annual pattern of irreversible fracture displacements in all instrumented fractures?

3. Under what environmental conditions do enhanced irreversible fracture displacements occur?

2 Site description, instrumentation and field data

The relative fracture displacement and thermal conditions were measured at Matterhorn Hörnligrat (Swiss Alps) at an elevation of 3500 m a.s.l. (see Fig. 3) using the experimental setup by Hasler et al. (2012). The field site is suitable for such measurements due to: (1) the occurrence of ice-filled fractures indicated by an ice-containing scarp after a block fall event (approx. $1500\,\mathrm{m}^3$) in summer 2003, (2) strong fracturing ~~, (~~and (3~~) obvious indicators of rock deformation and (4~~) a large gradient of surface thermal conditions allowing installation of thermistors and crackmeters at locations with contrasting conditions (cf. Hasler et al., 2012).

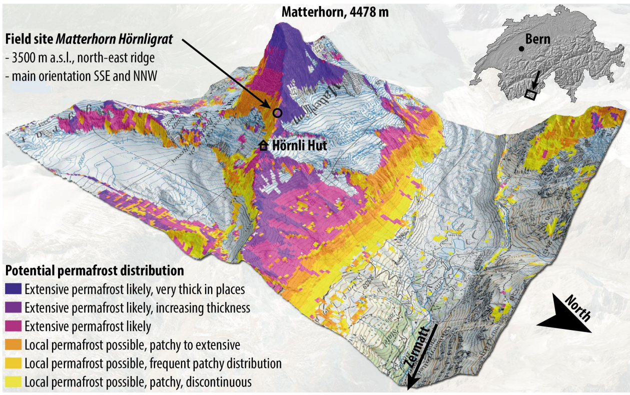

Figure 3. 3D overview of the Hörnligrat field site on the north-east ridge of the Matterhorn, in Valais, Switzerland (based on map.geo.admin.ch, Google Earth and SRTM). Colors indicate the potential permafrost distribution (FOEN, 2005). At this field site, extensive permafrost with a thin active layer is expected on the north side of the ridge. On the south side of the ridge, local permafrost is possible with a considerable active layer.

This field site consists of spatially heterogeneous steep fractured bedrock with partially debris covered ledges. The mean annual air temperature is $-3.7°\,\mathrm{C}$ for the time period $2011-2012$ (see Fig. 11 in appendix A). The precipitation mostly falls as snow with occasional infrequent rainfall events in summer. Winter temperatures (down to $-27°\,\mathrm{C}$ in $2011-2012$) in combination with exposure to strong wind (up to $88\,km/h$ in $2011-2012$) results in a preferential snow deposition in fractures, on ledges and at other concave micro-topographical features, which can be observed using the webcam images (see Fig. 4). ~~The~~ On the south side the accumulated firn disappears completely ~~on the south side during summerwhile snow patches persist~~ during summer, while on the north side ~~all year~~snow patches persist all year round. These factors lead to a complex temperature regime ~~due to variable surface characteristics with temporal variations~~ and therefore need a correspondingly large amount of precisely measured data (Krautblatter et al., 2012).

In this study three types of data were recorded at different locations: relative fracture displacements perpendicular to and along fractures at 2 min intervals (temperature compensated, accuracy of ±0.01 mm over entire temperature range), temperature at different depths in rock and in fractures at 2 min intervals (accuracy of $\pm0.2°\,\mathrm{C}$) and meteorological data using a Vaisala WXT520 weather station (location *mh25* in Fig. 5). The time series of the weather station is interrupted for brief periods

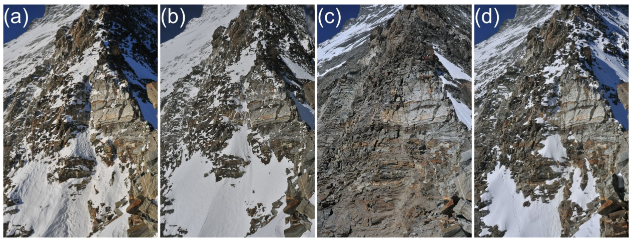

Figure 4. Four webcam pictures, taken in the morning on (a) 01 Jan 2015, (b) 03 Apr 2015, (c) 01 Jul 2015 and (d) 01 Oct 2015, illustrate the varying snow deposition patterns.

(several weeks) due to technical problems with the electronics, but a complete continuous time series is available for the years 2011 and 2012. Seven high resolution images per day (12.0 MP, giving an approximate pixel resolution of 1.5 cm) serve for visual inspection of the instrumentation and also provide information on snow deposition.

~~Fracture displacements~~ Figure 5 gives a spatial overview of all installations and measurement locations. Basic meta information of the measurement locations is given in Table 1 for all locations. Displacements perpendicular to the fracture are measured at locations *mh02–mh04* while ~~fracture~~ displacements perpendicular and parallel to the fracture are measured at locations *mh06*, *mh08* and *mh20–mh22*. Crackmeter at location *mh01* is installed next to a fracture on a rock mass with several microcracks (sub-millimeter scale). Temperature in fractures at different depths are available at all crackmeter locations, except at locations *mh20–mh22*. Rock temperature at different depths $(0.1 - 0.85\,\mathrm{m})$ is measured at the additional locations *mh10–mh12*. ~~Figure 5 gives a spatial overview of all measurement locations. Basic meta information of the measurement locations are given in Table 1 for all locations.~~ All sensors are embedded in a low power wireless sensor network that provides all year-round data at near real-time (Beutel et al., 2009). The observed temperature and fracture kinematics measurements were aggregated as 10 min averages to reduce noise. A detailed description and explanation of the measurement setup is given by Hasler et al. (2012, Section 3).

Instrumentation started in autumn 2007 and continuous time series are available since summer 2008 for locations *mh02*, *mh03* and *mh06*. The measurement network was extended in Summer 2010 with additional sensors and by establishing new measurement locations (*mh01*, *mh04*, *mh08* and *mh20–mh22*). This results in up to ~~7~~ eight years of data for rock and fracture temperatures, fracture kinematics and environmental conditions.

3 Data analysis method

3.1 Correlation analysis

In a first step, we investigate the linear relation between fracture displacements and temperature. We looked for a time period, during which fracture kinematics are best described by temperature. For the evaluation of these temperature dependent fracture kinematics, we compute the Pearson correlation (LeBlanc, 2004, p. 292) for varying time periods (different start time and

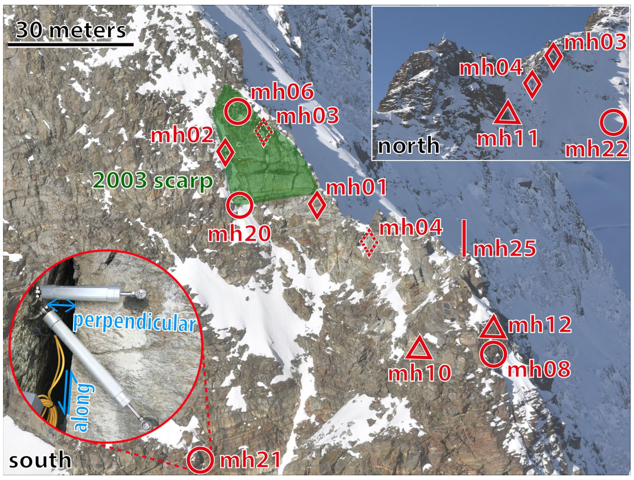

Figure 5. Overview of crackmeter installations. Location *mh01–mh04* (indicated with ◇) are instrumented with one crackmeter perpendicular to the fracture. Location *mh06*, *mh08* and *mh20–mh22* (indicated with ◯) are instrumented with two crackmeters to calculate displacements perpendicular to and along fracture. Temperature measurements in fractures exist at most location. Locations with only rock temperature measurements are indicated with △ while for the weather station | is used. Scarp of the 2003 rockfall is shaded green.

Table 1. Meta information for all measurement locations providing characteristics, type, orientation and instrumentation. If type is "fracture", thermistors are installed in fracture. Otherwise the thermistors are drilled in rock.

Location	Characteristics	Type	Aspect	Slope	Crackmeter	Depth of thermistors $T1$, $T2$, ... (m)
*mh01**	intense solar radiation, microcracks	fracture	95° N	75°	1 axis	0.1, 0.4, 0.7, 0.5
mh02[†]	concave, often snow, wet	fracture	80° N	50°	1 axis	0.1, 0.3, 0.4 – 0.8 [3, 1, 2]
mh03	lower part snow	fracture	350° N	65°	1 axis	0.1, 0.4, 0.6 – 0.8 [5]
mh04	saddle north	fracture	320° N	70°	1 axis	0.05, 0.2, 0.2 – 0.5 [3, 1]
mh06	corner, often snow	fracture	90° N	60°	2 axes	0.1, 0.8, 1.5, 1.8
mh08	wide, ventilated, close to ridge	fracture	50° N	90°	2 axes	0.1, 1, 2, 3
mh10	intense radiation, fracture 1 m beside	rock	140° N	90°	—	0.1, 0.35, 0.6, 0.85
mh11	occasionally snow, no fracture	rock	340° N	70°	—	0.1, 0.35, 0.6, 0.85
mh12	snow free, fracture beside	rock	45° N	85°	—	0.1, 0.35, 0.6, 0.85
mh20	corner, often snow, wet	fracture	70° N	70°	2 axes	—
mh21	wide, south side	fracture	70° N	85°	2 axes	—
mh22	wide, north side	fracture	70° N	85°	2 axes	—

* installed next to a fracture across microcracks

† rock instrumented broke off completely during a bad weather period (14 August 2015)

$[X]$ number in square brackets indicates number of thermistors in the given depth range without exact depth information

X, [X] depth information or number in gray indicates problems with thermistor duration). Each location instrumented with crackmeters is individually correlated with all available fracture and rock temperature data (depths of used thermistors are indicated black in Table 1). As additional constrain time periods (1) have to be at least 70 days, (2) have to be in the time window between 1 Oct 2013 and 1 Jan 2015 (complete data availability at all instrumented locations) and (3) the temperature range must exceed 8° C. This optimal time period is determined independently for displacements perpendicular and along fractures.

3.2 Linear regression model (LRM)

In a second step, we aim to reproduce the reversible component of fracture kinematics caused by ~~thermo-mechanically induced~~ thermo-elastic strain. For each measurement location, the linear regression function and its parameters are computed for the optimal time period (trainings phase) determined by the correlation analysis (see Section 3.1). The linear regression model (LRM) applies this function with temperature T $[^\circ \mathrm{C}]$ for the complete time series to reproduce the reversible fracture displacement y_{rev} [mm]:

$$y_{\mathrm{rev}} = \beta_0 + \beta_1 \cdot T + e \tag{2}$$

where intercept β_0 [mm] and slope β_1 $[\mathrm{mm}/^\circ \mathrm{C}]$ are the regression parameters and e [mm] is the residual. This model is based on the assumption of a constant linear elastic rheology in the considered temperature range for all consecutive years. Irreversible kinematics is assumed to be negligible during the trainings phase. Note that the LRM is applied indistinctly perpendicular or along fracture.

3.3 Irreversibility index

We build a metric (termed irreversibility index) that aims at detecting periods ~~when~~ during which overall kinematics is not dominated by ~~thermo-mechanically induced~~ thermo-elastic strains. This index uses the absolute difference (Δy) between the observed fracture data (y_{obs}) and the modeled reversible fracture kinematics component (y_{rev}) given by the LRM as input:

$$\Delta y = |y_{\mathrm{obs}} - y_{\mathrm{rev}}| \tag{3}$$

Finally, index I is calculated applying the following function to Δy:

$$I = (\mu + 2 \cdot \sigma) - (\mu - 2 \cdot \sigma) = 4 \cdot \sigma \tag{4}$$

where the sliding functions μ (mean) and σ (standard deviation) are evaluated over all data points in the past 21 days. The length of the sliding window is a trade off between high noise-level and loosing important signals due to smoothing. The two standard deviation range considers 95% of data around mean and thus ignores outliers. The output value of the irreversibility index is a positive number of unit mm/year. A value of zero means that the displacement is fully reversible. The higher the number, the higher the proportion of irreversibility.

3.4 Thawing degree days (TDD) and fracture kinematics summer shift (SHT)

In order to put the fracture kinematics data in context of thawing or freezing, we use the concept of thawing degree days (TDD). The TDD concept takes into account the amount of energy available for thawing/melting over the course of the year (Huybrechts and Oerlemans, 1990). It is here used as a rough approximation of the total energy available for melting ice or thawing permafrost. The thawing degree day sum (TDD) is defined as the total sum of daily average rock temperature above 0° C over one year.

The fracture kinematics summer shift y_{SHT} represents the shift in kinematics between two consecutive winters and is calculated as:

$$y_{\mathrm{SHT}} = \overline{y}_{\mathrm{obs,winter+}} - \overline{y}_{\mathrm{obs,winter-}} \tag{5}$$

with the mean fracture kinematics during winter given by

$$\overline{y}_{\mathrm{obs,winter}} = \sum_{k=t_1}^{t_2} y_{\mathrm{obs}}/n \tag{6}$$

where $t_1 = Nov 1$ $t_1 = 1\,Nov$ and n the number of measurements. The end time t_2 is usually defined by a fix date $t_2 = May 1$ $t_2 = 1\,May$ unless the rock temperature rise rises above a defined threshold value of $-1°$ C before this date. If this is the case, the end time is given by the date when the rock temperature reaches this threshold ($t_2 = \mathrm{date}(T_{\mathrm{rock}} < -1°\,\mathrm{C})$).

4 Results and interpretation

Figure 6 shows the rock temperatures at 85 cm depth for different aspects (a) and the fracture displacements, relative to the start of the measurements, for all locations perpendicular to the fractures (b) and along the fracture fractures (c). Partly reversible fracture displacement can be observed at all locations with different seasonal movement amplitudes, except for location *mh02*. Most of them also show a long term trend indicating an additional irreversible component of variable magnitude and sign. The individual deformation displacement pattern of each location may be influenced by differences in geometric mesoscale arrangement of rock, where different combinations of processes dominate. An irreversible deformation displacement is indicated at most locations in early summer (e.g. *mh02*–*mh04*, *mh06*, *mh08* and *mh20*) but the exact timing and pattern is difficult to quantify. The fracture displacements of *mh02* and *mh20* are not visible after mid 2015 not visible in Fig. 6 as they are out of range (Fig. 6). This abrupt and large displacement is due to a small rock fall event with a volume of a few cubic meters in early summer (on 18 May 2015). 2015. The functionality of both crackmeters was however not affected. But the thermistors at location *mh02* were damaged by falling rocks. Hence the temperature time series ends on 18 May 2015. After this rock fall event, the fracture at location *mh02* continued to deform in several small steps until late summer (14 August 2015) when the instrumented rock broke off completely during a bad weather period (see Fig. 12). The observed variable spatial and temporal patterns in fracture displacements (Fig. 6) indicate that a field site can not cannot be described by a single measurement location and a short measurement period. Therefore, longterm monitoring of several fractures is essential to observe different modes of kinematics and accordingly to improve the process understanding of the fracture kinematics.

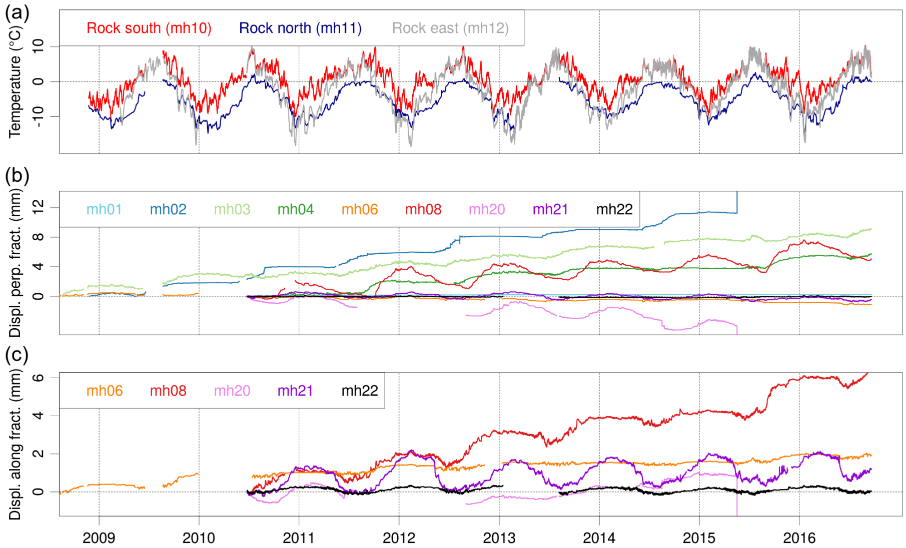

Figure 6. ~~Time series of the thermal~~ Thermal conditions and fracture displacements at the ~~field site~~ Matterhorn Hörnligrat ~~with up to seven years~~ field site over a course of ~~data.~~ eight years: (a) The thermal conditions are ~~represented~~ shown by characteristic rock temperatures ~~at 0.85 m depth (a)~~ for the south, east and north side of the ridge measured at a depth of 0.85 m. The ~~relative~~ fracture ~~displacements~~ kinematics are ~~represented~~ shown as normalized displacements (b) perpendicular to and (c) along fractures. A gap in the rock temperature time series of location *mh12* (T_{east}) is filled for the time period November 2012 until July 2013 and from August 2014 onwards applying quantile mapping using the best regressors approach (Staub et al., 2016) with a coefficient of determination $R^2 = 0.92$.

In the following paragraph, we present the analysis of a set of 3 locations in more detail, namely *mh02* (South), *mh03* (North) and *mh08* (East, on ridge). These locations were selected according to their contrasting modes of ~~deformation~~ kinematics and their variations in aspect and cover all different patterns of observed fracture displacements.

4.1 Regression analysis of ~~irreversible~~ fracture displacement with temperature

The time periods during which fracture displacements ~~exhibits~~ exhibit best correlation with temperature are shown in Table 2 and have a typical duration of three to 5 months. The variation in length of 1–2 weeks results in similar correlation coefficients. The regression analysis between temperature and fracture kinematics (perpendicular to and along fracture) shows negative correlation coefficient between -0.90 and -0.99 for all instrumented fractures. The fracture displacements at most locations correlate best with rock temperatures at 0.85 m, while the correlation with the other available rock temperatures are much lower. Only a few instrumented fractures correlate best with fracture temperatures (between 0.2 and 0.8 m). In general, all determined time periods for fracture kinematics perpendicular to fracture are in winter or early spring. The time periods for fracture kinematics along fracture are either during winter or almost during the whole year. Note that these determined time periods constitute for the further analysis.

Table 2. Regression analysis between temperature (rock or fracture) and observed fracture displacements (perpendicular and along fracture). Regression parameters intercept β_0 and slope β_1, correlation coefficient r and coefficient of determination R^2 for the time period with the highest correlation coefficient are listed. Depth of the most representative temperature (thermistor T) is described in Table 1.

Location	Temperature (thermistor)	Kinematics	Time period		β_0 (mm)	β_1 (mm/°C)	r	R^2
mh01	fracture @ *mh06* ($T2$)	perpendicular	13 May 2014	– 22 Jul 2014	8.6	-0.0035	-0.88	0.77
mh02	fracture @ *mh04* ($T5$)	perpendicular	28 Oct 2014	– 30 Dec 2014	19.0	-0.0127	-0.96	0.92
mh03	rock @ *mh12* ($T4$)	perpendicular	01 Oct 2013	– 28 Feb 2014	43.5	-0.0404	-0.96	0.92
mh04	fracture @ *mh04* ($T4$)	perpendicular	30 Sep 2014	– 16 Dec 2014	13.4	-0.0038	-0.95	0.91
mh06	rock @ *mh11* ($T4$)	perpendicular	01 Oct 2013	– 07 Jan 2014	11.2	-0.0274	-0.98	0.97
mh06	fracture @ *mh06* ($T2$)	along	22 Jul 2014	– 23 Dec 2014	-134.0	-0.0313	-0.90	0.82
mh08	rock @ *mh12* ($T4$)	perpendicular	21 Jan 2014	– 01 Jul 2014	19.8	-0.0829	-0.99	0.97
mh08	rock @ *mh11* ($T4$)	along	22 Oct 2013	– 18 Feb 2014	43.9	-0.0407	-0.95	0.91
mh20	rock @ *mh11* ($T4$)	perpendicular	13 May 2014	– 15 Jul 2014	72.2	-0.1202	-0.98	0.98
mh20	rock @ *mh11* ($T4$)	along	15 Oct 2013	– 17 Dec 2013	-19.6	-0.0696	-0.98	0.96
mh21	fracture @ *mh02* ($T6$)	perpendicular	31 Dec 2013	– 18 Mar 2014	33.0	-0.0947	-0.99	0.97
mh21	rock @ *mh11* ($T4$)	along	07 Jan 2014	– 09 Sep 2014	-127.6	-0.1620	-0.99	0.97
mh22	fracture @ *mh03* ($T4$)	perpendicular	10 Dec 2013	– 18 Feb 2014	21.3	-0.0085	-0.94	0.89
mh22	rock @ *mh11* ($T4$)	along	24 Dec 2013	– 14 Oct 2014	81.4	-0.0363	-0.97	0.93

4.2 ~~Thermo-mechanically induced~~ Thermo-elastic reversible response and LRM

Figure 7 shows the relation between observed fracture kinematics and rock temperature. Applying the LRM, we obtain the linear regression coefficients that describe the reversible temperature dependent fracture displacements (black lines in Fig. 7). The fracture displacement at location *mh02* (South, Fig. 5) is almost temperature independent (regression coefficient of $-1.2 \cdot 10^{-2}\,\mathrm{mm/^\circ C}$) except for the winters 2008/2009 and 2014/2015. In contrast, location *mh03* (North, Fig. 5) shows a stronger temperature dependency of $-4.0 \cdot 10^{-2}\,\mathrm{mm/^\circ C}$. At *mh08* (East, Fig. 5), the coefficients are with $-8.3 \cdot 10^{-2}\,\mathrm{mm/^\circ C}$ perpendicular to fracture and $-4.1 \cdot 10^{-2}\,\mathrm{mm/^\circ C}$ along fracture. These temperature dependencies are likely influenced by the combination of geometric arrangement and acting mechanisms. A potential lack of temperature dependency in the LRM analysis would mean that no reversible or negligible ~~deformation caused by thermo-mechanically induced strainoccurs~~displacements occur that are caused by thermo-elastic strain. Or in other words, irreversible ~~deformation dominates~~displacements dominate.

Reversible fracture displacement is now modeled for the whole dataset with the *LRM* (see green lines in Fig. 8) using the regression parameters given in Table 2 (light blue shading in Fig. 8). The red line in Fig. 8 represents irreversible ~~displacement~~displacements, obtained from subtracting reversible displacement (green line) from the observed displacement (blue line). This analysis clearly shows that the evolution of irreversible fracture displacement is described for every year by ~~single phases~~ a single phase of quiescence (or solely reversible displacements) followed by ~~phases~~ a phase of almost linear

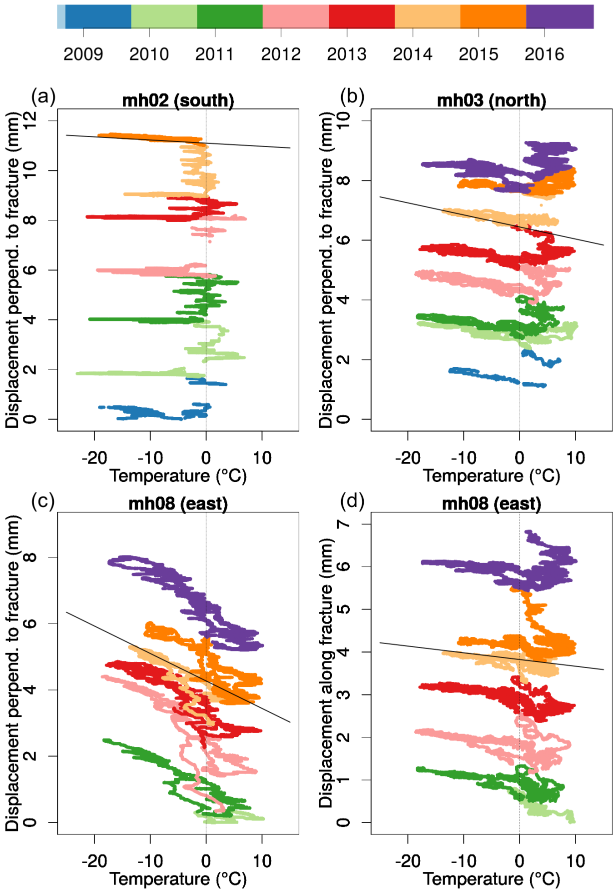

Figure 7. Temperature dependency of fracture displacements for location *mh02* (perpendicular to fracture), *mh03* (perpendicular to fracture) and *mh08* (perpendicular to and along fracture). Discrete colors indicate hydrological years (1 October – 30 September). Black lines indicate the linear regression function determined by the regression analysis (see Table 2).

irreversible displacements once a year. For most locations, including *mh03*, the distinct irreversible phase occurs during the summer, starting when rock temperatures rise above 0° C. This likely ~~indicates~~ refers to thawing related processes with melt water that percolates into fractures as a potential cause for this irreversible ~~deformation~~displacement. At a few locations, such as *mh08*, this linear irreversible phase occurs in autumn when rock temperatures reach freezing conditions, suggesting cryogenic processes (i.e. ice pressure, see Section 1.1) as the causing mechanism. There are however discrepancies to this simple temporal pattern, for example for location *mh03* (see Fig. 8a, black arrows) additional small excursions in displacement occur in summer 2010 and 2015, when summer temperatures are exceptionally high. Although these excursions seem to be reversible, they are not explained by the LRM approach. Furthermore, for location *mh08* in summer, the full amplitude of reversible ~~deformation~~ displacement is not always reproduced by the LRM.

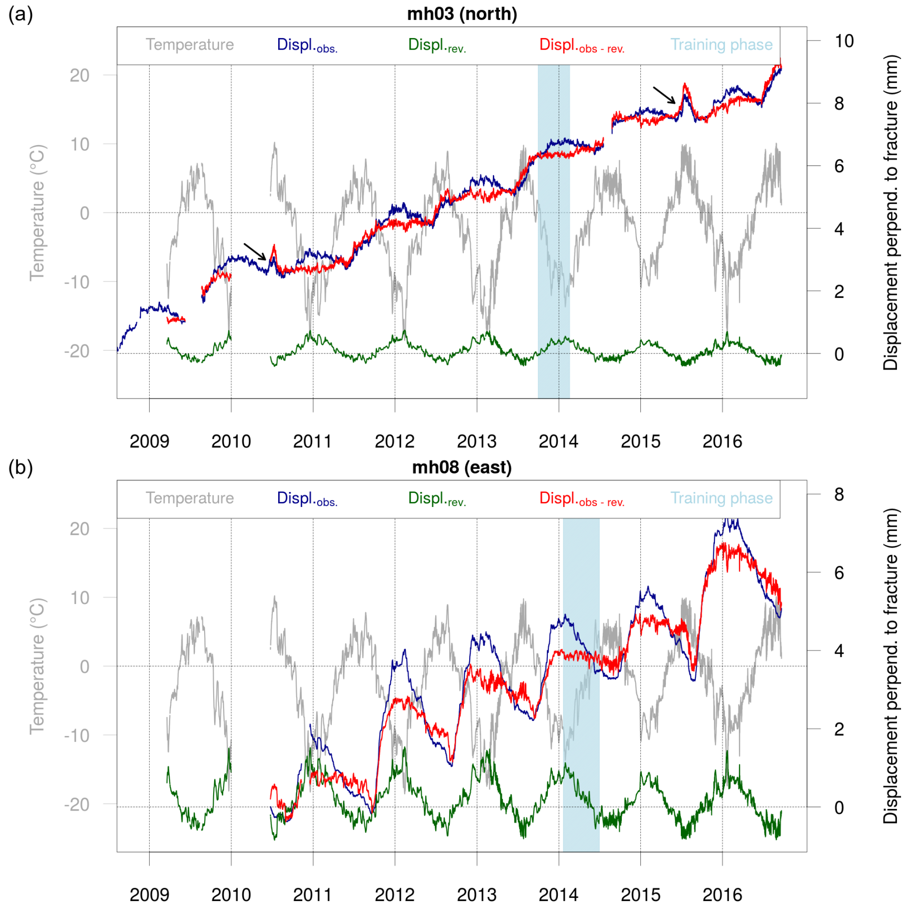

Figure 8. LRM (green) applied to the observed displacements (blue) perpendicular to the fracture at location *mh03* (a) and *mh08* (b). The reversible component (green) due to ~~thermo-mechanically induced~~ thermo-elastic strains in rock can be modeled by a linear regression model (LRM) with temperature ~~as input data~~ (dark gray) and ~~deformation~~ displacement measurements during a training period of several months (light blue shading) as input data. Subtracting these reversible displacements from the observed data results in the red line, referred to as irreversible fracture displacement.

4.3 Thawing degree days and summer shift

The summer shift of the fracture kinematics (SHT) and the thawing degree days (TDD) are parameters, allowing to analyze and interpret the inter-annual evolution (Fig. 9). TDD are not computed if the temperature time series contain a gap during summer. A weak correspondence is apparent (see Fig. 14 in appendix A) for locations with aspects to the north and east. This hints on a substantial influence of rock temperature and therefore incoming conductive energy fluxes. Interestingly, at locations exposed to the south, SHT seems independent of TDD. The local break-off at location *mh02* occurred in summer 2015 (described in first paragraph of Section 4, page 11). This summer exhibits a record high in TDD at all locations.

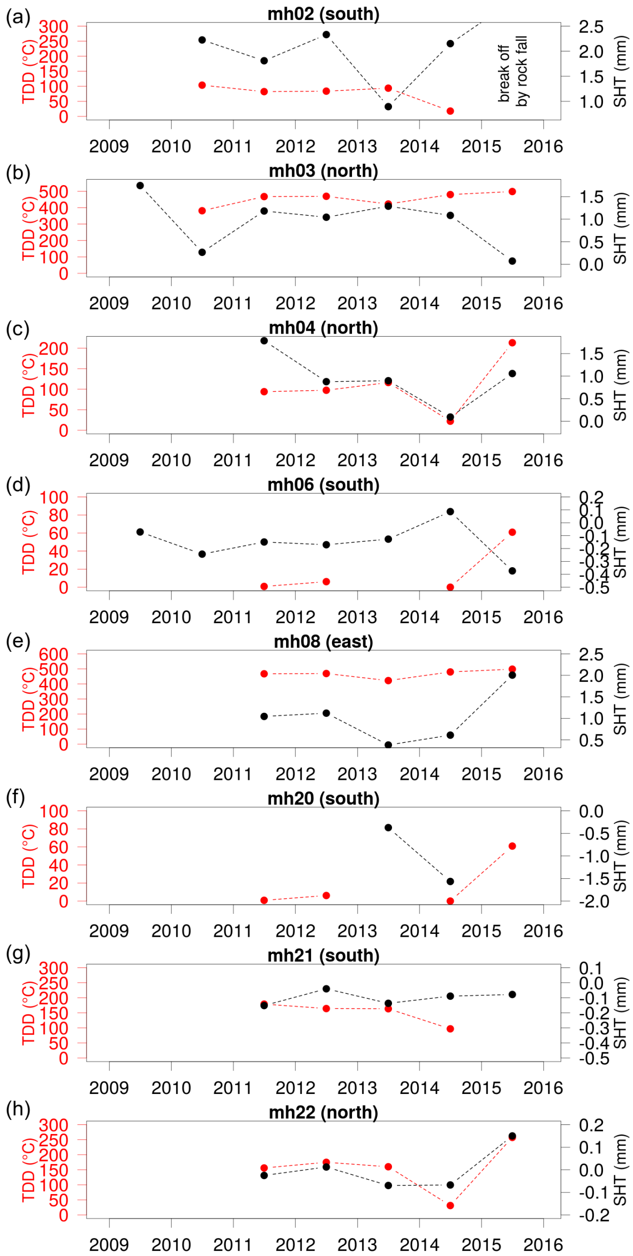

Figure 9. Inter-annual variability of thawing degree days (TDD) and summer shift of fracture kinematics (SHT) perpendicular to fractures for all locations. Data at location *mh02* is missing from 2015 onwards due to the break-off and the TDD values at a few locations for the year 2014 are removed due to missing or incomplete temperature data.

4.4 Irreversibility index

The irreversibility index indicates the onset of irreversible deformation displacement and is shown in Fig. 10 for displacements perpendicular to fractures. In general, this index shows once a year a period with sudden increases of irreversible deformation displacement at all locations. High index values can be observed in summer (positive temperatures) at location *mh02* (South) and *mh03* (North), during thawing period, while in winter low indices occur without any peaks (see Fig. 10a and 10b). The irreversibility index shows that irreversible displacement is related to positive temperatures, which further supports our findings from the relation between SHT and TDD (Fig. 9).

In contrast, for location *mh08* a high irreversibility occurs in autumn when temperatures drop below 0° C, suggesting freezing as a dominant process. Note, these periods of high indices correspond to the irreversible displacement phase obtained from the LRM.

The reversible excursions from the LRM at location *mh03* in summer 2010 and 2015 are picked up by increased indices. However, they are reversible deformation displacements that are not represented by the LRM. This points to a potential additional reversible process that can not cannot be explained only by the thermo-mechanically induced thermo-elastic strain.

5 Discussion

This study aims at quantifying and separating reversible and in particular irreversible fracture kinematics in relation with environmental forcing. The main processes leading to fracture deformation kinematics are presented in Fig. 1, enabling to isolate different processes from the field observations. Possible interactions between the different processes are not considered but may well occur in nature. Thanks to Using our quantitative approach, we are able (i) to separate reversible from irreversible fracture kinematics and (ii) to produce a new irreversibility index. This new metric provides useful indication on a useful indication for the occurrence and timing of irreversible displacement and thereby contributes towards rock slope stability assessment. In the following, we discuss the research questions formulated in Section 1.2.

5.1 Separation of the reversible fracture kinematics

Very high coefficients of determination given by the regression analysis (see Table 2) support the suggested linear relation between temperature and fracture kinematics (see Fig. 1b). The regression analysis is only based on few assumptions (see Section 3.1), thus preventing coincidental relations. The duration of the training periods (set to a minimum of 70 days) prevent such high coefficients caused by an irreversible process. As the best coefficients are obtained in winter, reversible thermo-mechanically induced thermo-elastic strain dominates during this period. It further supports the postulated existence of intra-annual periods with negligible irreversible deformationdisplacements. Temperatures deeper in rock/fracture might cause even higher correlation coefficients, as the correlation coefficient mostly increases with increasing depth of the temperature measurement. But it is difficult to estimate a representative depth for temperature measurements as the temperature variations are attenuated with increasing depth and the deepest available rock temperature measurement on Matterhorn is at 0.85 m depth.

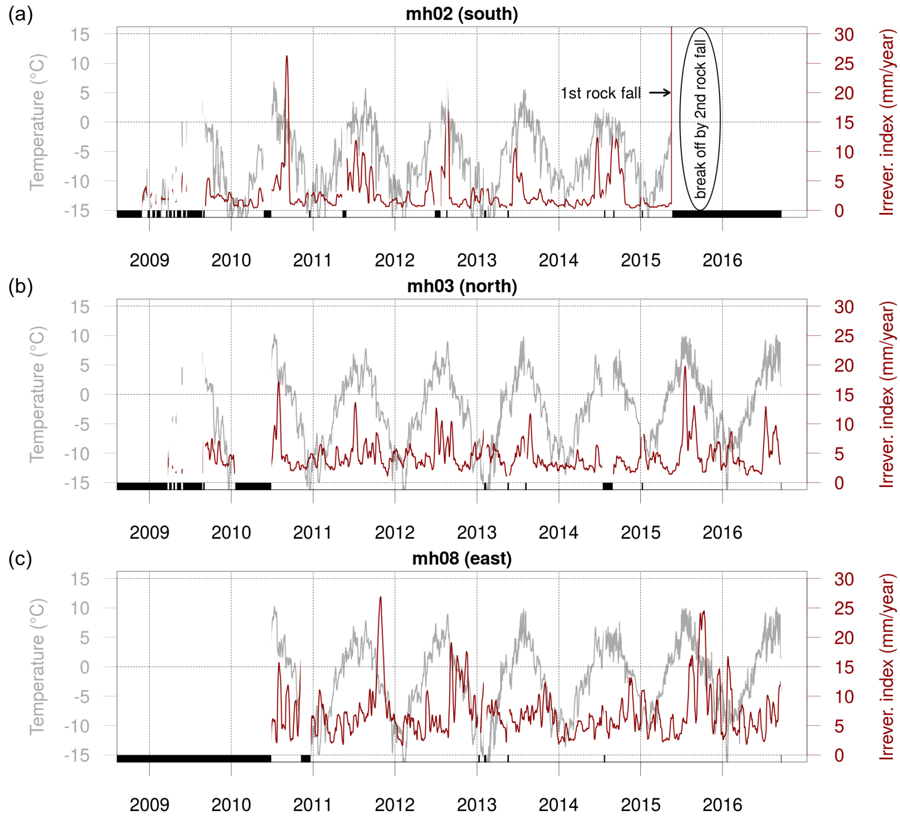

Figure 10. Irreversibility index for (a) location *mh02* (south), (b) location *mh03* (North) and (c) location *mh08* (East, on ridge) as an indicator for periods, where the irreversible displacement dominates. Black bars indicate periods where no or reduced data is available.

The linear regression model (LRM) can reliably reproduce the ~~thermo-mechanically induced strain for given temperature. Although LRM~~ thermo-elastic strain for a given temperature, and therefore can be used to describe the observed reversible ~~deformation~~ displacement component in all instrumented fractures. Furthermore our analysis shows that a selected single time period of a few months is representative for the reversible component in ~~deformation~~ displacement for the whole time series when the process ~~thermo-mechanically induced~~ thermo-elastic strain strongly dominates (e.g. winter). Therefore, such a quiescent time period can be used as the training phase for the LRM. The exception is at location *mh02* (see Fig. 12) where the reversible fracture ~~displacements are~~ displacement is almost negligible apart from winter 2014/2015 after which the small failure occurred. This location ~~even~~ further shows an annually changing relation between fracture displacement and temperature (see Fig. 7), which is ~~a singular case~~ an exception in this data set. Otherwise, the amplitude of reversible ~~deformation~~ displacements varies strongly from location to location. Although we expect the thermal expansion coefficient of pure rock material to be very similar, we explain this variation by highly variable volume or length of rock wall material influencing an individual fracture and by the spatial heterogeneity in thermal conditions at depth. Hence, the magnitude of the reversible fracture displacement, caused by thermo-elastic strain, is influenced by the individual geometric mesoscale arrangement of each fracture.

In principle, LRM can be applied the same way to fracture kinematics perpendicular to and along fracture (see Fig. 13 in appendix A). But the kinematics along fracture is much more sensitive to the geometric mesoscale arrangement of the fracture. Assuming for instance the rock masses aside the fracture have the same size and thermal condition, the ~~thermo-mechanically induced~~ thermo-elastic strain is also the same and no relative displacement along fracture is measured.

Observed reversible excursions in displacement at location *mh03* in summer 2010 as well as in summer 2015 are not caused by ~~thermo-mechanically induced stress and also visible in~~ thermo-elastic stress which is also evident from the high values of the irreversibility index (Fig. 10)~~with high values. It~~. These excursions in displacement may be caused by a non-local effect or points to an additional unidentified process causing reversible displacement. These excursions sporadically occur during summer with very high temperatures. Ice pressure and its release by melting can also produce reversible excursions with a fracture opening during freezing and a fracture closing during melting. However, the closing phase would have to start at the ~~onset of melting~~melt onset, which is clearly not observed. Thus ice formation is not playing a dominant role for reversible fracture kinematics.

5.2 Inter-annual pattern of irreversible fracture kinematics

Close to a decade of field measurement provides enough data for inter-annual analysis of fracture kinematics. In general, all instrumented locations show a trend of fracture opening or closing perpendicular to fractures, but with different rates. At each individual location, the temporal pattern of ~~deformation~~ displacements is very similar every year, but the irreversible summer shift (SHT) slightly varies over time. According to our analysis, this summer shift seems at least for north facing locations to correlate slightly with an increasing total amount of available energy (TDD). This suggests that further warming and therefore increasing TDD's cause thawing of permafrost at greater depth, potentially leading to an increase in summer shifts (SHT). Percolating water allows effective heat transport along fractures leading to faster temperature increase in fractured rock mass than in intact rock. Additionally, water percolation can affect the shear resistance along fractures and lead to a decrease in friction, which can cause irreversible ~~deformation~~displacement. For example at location *mh02*, enhanced availability of water from snow melt after summer snowfall events seems to cause accelerated irreversible ~~deformation~~displacements.

As TDD derived from mean daily rock temperature, relation between summer shift and TDD in south exposed and warmer rock should be interpreted carefully. Rapid variation of temperature with short peaks above 0° C can lead to thawing even when the mean daily temperature stays below 0° C. This is often the case at locations exposed to strong solar radiation (south facing), even at winter time, and might explain why the TDD at the south exposed locations do not correlate with the summer shift (e.g. *mh02* or *mh21*).

The presented summer shift only provides total ~~deformation~~ displacement between two winters without any intra-annual information. In contrast, the irreversibility index can be seen as a proxy of impending rockfall activity and reveals information on the short term evolution of the irreversible fracture kinematics all year round, even if the total summer shift (SHT) is small. Despite based on local measurements, such an index can help to identify periods of enhanced irreversible fracture kinematics or risk for failure (see Fig. 2). For example, a strong increase was observed in early summer 2015 at location *mh02*, followed by several small rockfalls and a final break-off (approx. $2-3\,\mathrm{m}^3$, timing indicated in Fig. 10a). Similar at location *mh03*, irreversible ~~deformation~~ displacement occurs during the melt period, which is likely related to a reduction of friction along a fracture line.

However, there are also irreversibility index peaks in autumn, e.g. at location *mh08* (East, on ridge, Fig. 10c), which do not correlate with thawing days but with rapid cooling and freezing in autumn. In this case, the growth of ice in late autumn acts as a driving factor through increasing ice pressure by cryogenic processes. Interestingly no fracture closing is observed during ice melt period in the subsequent summer indicating irreversibility of such a process. Such ~~thermo-mechanically~~ thermo-elastic and cryogenic forcing of fracture kinematics has been hypothesized by Hasler et al. (2012), but their data was not fully conclusive on this point due to the short duration of the data set (1–2 years).

5.3 Environmental controlling of irreversible fracture kinematics

Combined analysis of LRM and irreversibility index exhibits distinct periods of solely reversible fracture kinematics and others with additional irreversible fracture kinematics. Irreversible ~~deformation~~ displacement seems to be driven by environmental conditions, namely by rock temperature above $0°\,\mathrm{C}$ (indicating thawing) or less commonly by periods of freezing conditions. In the main winter time (temperatures well below freezing) after the initial cooling phase, none of the instrumented fractures shows irreversible displacement. Seasonal freezing and thawing of the rock mass in the active layer can influence fracture kinematics in several ways and can lead to irreversible displacements. On the one hand warming influences the fracture toughness of rock bridges, creep of ice and total friction along existing shear zones (Krautblatter et al., 2013). On the other hand, water from the surface mainly by snow melt can percolate into fractures. This increased water availability can refreeze at the permafrost table and cause cryogenic pressure. If the water and/or heat supply is high enough, the water column can rise and enhance hydro pressure. But high water columns are rather unlikely at the Matterhorn field site, because it is located on the ridge with steep, laterally open fractures. Therefore, the suggested patterns for cryogenic and hydrostatic processes in Fig. 1~~can not be proved~~b cannot be confirmed. These patterns may be oversimplified, as this study shows that the related processes are often superimposed on and not clearly distinguishable.

6 Conclusions

Knowledge of processes and factors affecting rock slope stability is essential for detecting and monitoring potentially hazardous rock slopes. A unique ~~7~~ eight year time series of fracture kinematics is presented, providing new insights on fracture kinematics with respect to thermal conditions on steep high-alpine rock slopes. The intra- and inter-annual behavior of the fracture kinematics strongly varies between locations, but patterns at individual locations are consistent over the entire observation period. Longterm monitoring at multiple fractures thus essentially helps to improve the process understanding of fracture kinematics.

The regression analysis highlights periods with a significant negative correlation between fracture kinematics perpendicular to fracture and temperature for all locations. Interestingly, the most representative time periods used for training the LRM occur in winter and early spring. The proposed LRM approach provides a tool for systematic analysis of fracture kinematics and was successful in separating reversible from irreversible displacements. An irreversibility index was built to detect irreversible displacement and its link to environmental forcing. ~~Seven~~ Eight years of relative surface displacement measurements show that reversible fracture kinematics caused by ~~thermo-mechanically induced~~ thermo-elastic strains of the material is occurring at all locations except one all year round, but are temporarily superimposed by other processes. ~~In addition~~ During additional phases of irreversible ~~deformation~~ displacement with a stepwise behavior occur mostly during periods with temperature above 0° C suggesting a decrease in friction along fractures as a responsible process. At one location, ice formation due to freezing during the onset of the winter also causes irreversible ~~deformation~~displacements. These results are supported by the developed irreversibility index. As irreversibility can lead to rock slope failure, quantifying irreversible kinematics is a first step toward assessing rock slope stability.

However, this approach to measure relative surface displacement has limited time resolution and provides only point information from near the surface and with a limited spatial coverage. ~~Additional~~ Ongoing analysis of micro-seismic activity, currently measured on this field site, could potentially give insights with a very high temporal resolution and ~~some spatial coverage, which is going to give another mean to characterize damage and irreversible displacement~~a extended spatial coverage. Clustering of micro-seismic events coincident to rock fracturing (Murton et al., 2016) could reveal insights into relevant fracturing types. Coupling spatio-temporal characterization of irreversible ~~deformations~~ displacement with internal progression of microcrack activity could significantly improve process understanding and be applied in the context of early warning system.

Appendix A: Supplementary figures

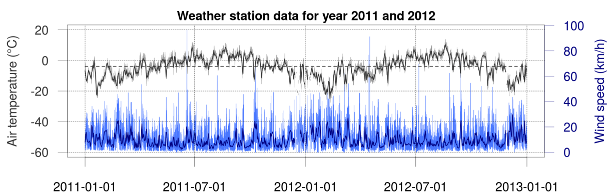

Figure 11. Time series of the in situ installed Vaisala WXT520 weather station providing air temperature and wind speed for the years 2011 and 2012. 10 minutes averages are shown in gray (air temperature) and lightblue (wind speed) whereas weekly averages are shown in darkgray (air temperature) and darkblue (wind speed). Dashed darkgray line represents the mean temperature.

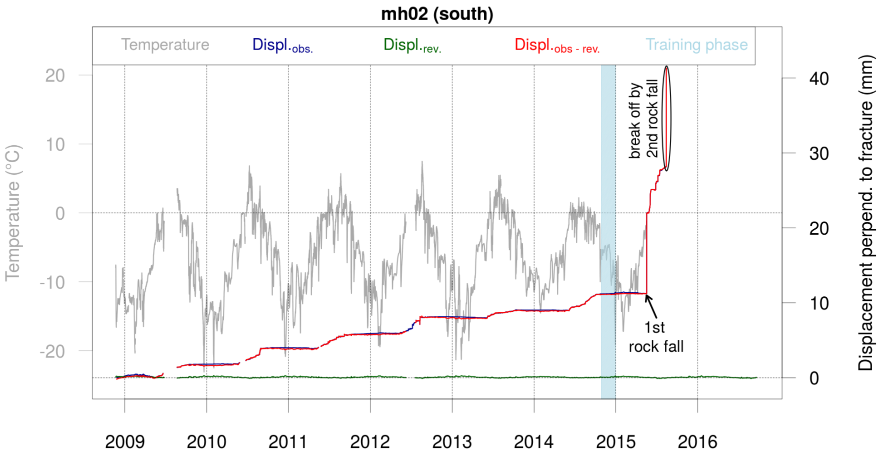

Figure 12. LRM (green) applied to the observed displacements (blue) perpendicular to the fracture at location *mh02*. The reversible component (green) due to ~~thermo-mechanically induced~~ thermo-elastic strains in rock can be modeled by a linear regression model (LRM) with temperature as input data (dark gray) and ~~deformation~~ displacement measurements during a training period of several months (light blue shading). Subtracting these reversible displacements from the observed data results in the red line, referred to as irreversible fracture displacement.

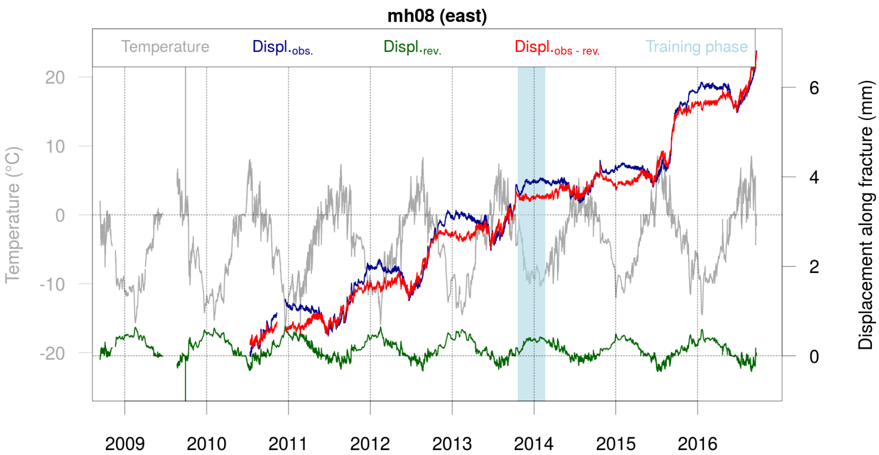

Figure 13. LRM (green) applied to the observed displacements (blue) along the fracture at location *mh08*. The reversible component (green) due to ~~thermo-mechanically induced~~ thermo-elastic strains in rock can be modeled by a linear regression model (LRM) with temperature as input data (dark gray) and ~~deformation~~ displacement measurements during a training period of several months (light blue shading). Subtracting these reversible displacements from the observed data results in the red line, referred to as irreversible fracture displacement.

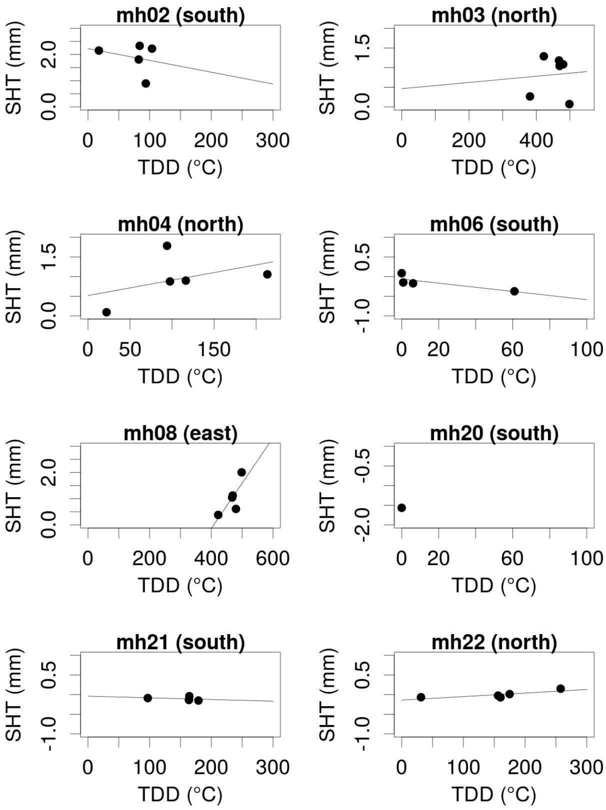

Figure 14. Summer shift (SHT_{summer}) of displacement perpendicular to fracture against yearly thawing degree days (TDD_{year}) for locations *mh02*, *mh03*, *mh04*, *mh08*, *mh21* and *mh22*. The black line indicates the regression function.

Appendix B: Data availability

All used data (processed and aggregated as 10 min averages) is available in the supplementary as csv-file for each location. The meta information is given in Table 1 on page 9. Additional data can be accessed via the PermaSense GSN data portal (data.permasense.ch). A system documentation and tutorial for online data access is available on the PermaSense project web page (www.permasense.ch/data-access/permasense-data.html).

Author contributions. Jan Beutel and Andreas Hasler designed the field experiment and installed the sensors in 2010 and 2012. Jan Beutel and Samuel Weber have done maintenance work and data management tasks since spring 2012. The analysis code in R was written by Andreas Hasler and Samuel Weber. Samuel Weber developed the model code as well as the irreversibility index and performed the data analysis. Samuel Weber prepared the manuscript with substantial contribution of all co-authors.

Acknowledgements. ~~We thank Max Maisch for providing us geomorphic considerations for Fig. 3 and Marcia Phillips for editing the English~~The work presented in this manuscript is part of the project X-Sense 2 and was financed by nano-tera.ch (Ref.: 530659). We acknowledge the PermaSense team, namely Tonio Gsell and Christoph Walser, who provided valuable support with the development of measurement devices, in the field and with data management. ~~The work presented in this manuscript is part of the project X-Sense 2 and was financed by nano-tera.ch (Ref. : 530659)~~We thank Max Maisch for providing us geomorphic considerations for Fig. 3 and Marcia Phillips for editing the English. Reviews from Valentin Gischig and three anonymous referees provided valuable comments that helped to improve the manuscript substantially.

References

Arosio, D., Longoni, L., Papini, M., Scaioni, M., Zanzi, L., and Alba, M.: Towards rockfall forecasting through observing deformations and listening to microseismic emissions, Natural Hazards and Earth System Science, 9, 1119–1131, doi:10.5194/nhess-9-1119-2009, 2009.

Beutel, J., Gruber, S., Hasler, A., Lim, R., Meier, A., Plessl, C., Talzi, I., Thiele, L., Tschudin, C., Woehrle, M., and Yuecel, M.: PermaDAQ: a scientific instrument for precision sensing and data recovery in environmental extremes, in: The 8th ACM/IEEE International Conference on Information Processing in Sensor Networks, San Francisco, California, USA, 2009.

Blikra, L. H. and Christiansen, H. H.: A field-based model of permafrost-controlled rockslide deformation in northern Norway, Geomorphology, 208, 34–39, doi:10.1016/j.geomorph.2013.11.014, 2014.

Davidson, G. and Nye, J.: A photoelastic study of ice pressure in rock cracks, Cold Regions Science and Technology, 11, 141–153, doi:10.1016/0165-232X(85)90013-8, 1985.

Davies, M., Hamza, O., and Harris, C.: The effect of rise in mean annual temperature on the stability of rock slopes containing ice-filled discontinuities, Permafrost and Periglacial Processes, 12, 137–144, doi:0.1002/ppp 378, 2001.

Faillettaz, J. and Or, D.: Failure criterion for materials with spatially correlated mechanical properties, Physical Review E, 91, doi:10.1103/PhysRevE.91.032134, 2015.

FOEN, Federal Office for the Environment: Map of potential permafrost distribution in Switzerland, www.bafu.admin.ch/naturgefahren/06140/06149/, 2005.

Gischig, V., Moore, J. R., Evans, K., Amann, F., and Loew, S.: Thermomechanical forcing of deep rock slope deformation: 1. Conceptual study of a simplified slope, Journal of Geophysical Research, 116, F04 010, doi:10.1029/2011JF002006, 2011.

Gruber, S. and Haeberli, W.: Permafrost in steep bedrock slopes and its temperature-related destabilization following climate change, Journal of Geophysical Research, 112, F02S18, doi:10.1029/2006JF000547, 2007.

Gruber, S., Hoelzle, M., and Haeberli, W.: Permafrost thaw and destabilization of Alpine rock walls in the hot summer of 2003, Geophysical Research Letters, 31, L13 504, doi:10.1029/2004GL020051, 2004.

Hall, K., Thorn, C. E., Matsuoka, N., and Prick, A.: Weathering in cold regions: some thoughts and perspectives, Progress in Physical Geography, 26, 577–603, doi:10.1191/0309133302pp353ra, 2002.

Hallet, B., Walder, J., and Stubbs, C.: Weathering by segregation ice growth in microcracks at sustained subzero temperatures: Verification from an experimental study using acoustic emissions, Permafrost and Periglacial Processes, 2, 283–300, doi:10.1002/ppp.3430020404, 1991.

Harris, C., Vonder Mühll, D., Isaksen, K., Haeberli, W., Sollid, J., King, L., Holmlund, P., Dramis, F., Guglielmin, M., and Palacios, D.: Warming permafrost in European mountains, Global and Planetary Change, 39(3-4), 215–225, doi:10.1016/j.gloplacha.2003.04.001, 2003.

Hasler, A., Gruber, S., Font, M., and Dubois, A.: Advective heat transport in frozen rock clefts: Conceptual model, laboratory experiments and numerical simulation, Permafrost and Periglacial Processes, 22, 378–389, doi:10.1002/ ppp.737, 2011.

Hasler, A., Gruber, S., and Beutel, J.: Kinematics of steep bedrock permafrost, Journal of Geophysical Research, 117, F01 016, doi:10.1029/2011JF001981, 2012.

Huybrechts, P. and Oerlemans, J.: Reponse of the Antarctic Ice Sheet to future greenhouse warming, Climate Dynamics, 5, 93–102, doi:10.1007/BF00207424, 1990.

Jia, H., Xiang, W., and Krautblatter, M.: Quantifying rock fatigue and decreasing compressive and tensile strength after repeated freeze-thaw cycles, Permafrost and Periglacial Processes, doi:10.1002/ppp.1857, 2015.

Jomelli, V., Brunstein, D., Grancher, D., and Pech, P.: Is the response of hill slope debris flows to recent climate change univocal? A case study in the Massif des Ecrins (French Alps), Climatic Change, 85, 119–137, doi:10.1007/s10584-006-9209-0, 2007.

Keuschnig, M., Hartmeyer, I., Höfer-Öllinger, G., Schober, A., Krautblatter, M., and Schrot, L.: Permafrost-related mass movements: Implications from a rock slide at the Kitzsteinhorn, Austria, in: Engineering Geology for Society and Territory, edited by Lollino, G., Manconi, A., Clague, J., Shan, W., and Chiarle, M., vol. 1, chap. 48, pp. 255–259, Springer Internaional Publishing Switzerland, doi:10.1007/978-3-319-09300-0_48, 2015.

Krautblatter, M., Huggel, C., Deline, P., and Hasler, A.: Research Perspectives on Unstable High-alpine Bedrock Permafrost: Measurement, Modelling and Process Understanding, Permafrost and Periglacial Processes, 23, 80–88, doi:10.1002/ppp.740, 2012.

Krautblatter, M., Funk, D., and Günzel, F.: Why permafrost rocks become unstable: a rock-ice-mechanical model in time and space, Earth Surf. Process. Landforms, 38, 876–887, doi:10.1002/esp.3374, 2013.

LeBlanc, D.: Statistics: concepts and applications for science, Jones and Bartlett Learning, band 2 edn., 2004.

Matsuoka, N.: Mechanisms of rock breakdown by frost action – an experimental approach, Cold Regions Science and Technology, 17, 253–270, doi:10.1016/S0165-232X(05)80005-9, 1990.

Matsuoka, N.: Direct observation of frost wedging in alpine bedrock, Earth Surface Processes and Landforms, 26, 601–614, doi:10.1002/esp.208, 2001.

Matsuoka, N. and Murton, J.: Frost weathering: recent advances and future directions, Permafrost and Periglacial Processes, 19, 195–210, doi:10.1002/ppp.620, 2008.

Mellor, M.: Mechanical properties of rocks at low temperatures, in: 2nd International Conference on Permafrost, Yakutsk, pp. 334–344, International Permafrost Association, 1973.

Murton, J.: Rock Weathering, in: Encyclopedia of Quaternary Science, pp. 2249–2256, Elsevier, Oxford, 2007.

Murton, J., Peterson, R., and Ozouf, J.-C.: Bedrock fracture by ice segregation in cold regions, Science, 314, 1127–1129, doi:10.1126/science.1132127, 2006.

Murton, J., Kuras, O., Krautblatter, M., Cane, T., Tschofen, D., Uhlemann, S., Schober, S., and Watson, P.: Monitoring rock freezing and thawing by novel geoelectrical and acoustic techniques, Journal of Geophysical Research: Earth Surface, doi:10.1002/2016JF003948, 2016.

Nordvik, T., Blikra, L. H., Nyrnes, E., and Derron, M.-H.: Statistical analysis of seasonal displacements at the Nordnes rockslide, northern Norway, Engineering Geology, 114, 228–237, doi:10.1016/j.enggeo.2010.04.019, 2010.

Phillips, M., Haberkorn, A., Draebing, D., Krautblatter, M., Rhyner, H., and Kenner, R.: Seasonally intermittent water flow through deep fractures in an alpine rock ridge: Gemsstock, Central Swiss Alps, Cold Regions Science and Technology, 125, 117–127, doi:10.1016/j.coldregions.2016.02.010, 2016.

Pogrebiskiy, M. and Chernyshev, S.: Determination of the permeability of the frozen fissured rock massif in the vicinity of the Kolyma hydroelectric power station, Cold Regions Research and Engineering Laboratory – Draft translation, 634, 1–13, 1977.

Schär, C., Vidale, P., Lüthi, D., Frei, C., Häberli, C., Liniger, M., and Appenzeller, C.: The role of increasing temperature variability in European summer heatwaves, Nature, 427, 332–336, doi:10.1038/nature02300, 2004.

Sidle, R. C. and Ochiai, H.: Landslides: processes, prediction, and land use, vol. 18 of *Water Resources Monograph Series*, American Geophysical Union, Washington, DC, doi:10.1029/WM018, 2006.

Staub, B., Hasler, A., Noetzli, J., and Delaloye, R.: Gap-filling algorithm for ground surface temperature data measured in permafrost and periglacial environments, Permafrost and Periglacial Processes, doi:10.1002/ppp.1913, 2016.

Terzaghi, K.: Stability of steep slopes on hard unweathered rock, Géotechnique, 12, 251–270, doi:10.1680/geot.1962.12.4.251, 1962.

Walder, J. and Hallet, B.: A theoretical model of the fracture of rock during freezing, Geological Society of America Bulletin, 96, 336–346, doi:10.1130/0016-7606(1985)96<336:ATMOTF>2.0.CO;2, 1985.

Watson, A. D., Moore, D. P., and Stewart, T. W.: Temperature influence on rock slope movements at Checkerboard Creek, in: Proceedings of the ninth International Symposium on Landslides, vol. 2, p. 1293–1298, 2004.

Wegmann, M. and Gudmundsson, G. H.: Thermally induced temporal strain variations in rock walls observed at subzero temperatures, in: Advances in old-region thermal engineering and sciences, edited by Hutter, K., Wang, Y., and Beer, H., vol. 533, pp. 511–518, Springer Berlin Heidelberg, doi:10.1007/BFb0104208, 1999.

Wolters, R.: Zur Ursache der Entstehung oberflächenparalleler Klüfte/Some Reflections on the Cause of the Formation of Joints Parallel to the Surface, Rock Mechanics, 1, 53–70, doi:10.1007/BF01247357, 1969.