General comments and response by authors

Dear Mr. Isaksen and anonymous Referees,

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 reviewer comments and changed the manuscript accordingly.

The referees state the topic is interesting and based on a very interesting 7 year time series of fracture displacements recorded at several locations at the Matterhorn. They highlighted several concerns which mainly concerned the clarity of the methodology, the focus and main result of the study and the introductory background information.

We addressed all these issues (and all the specific ones) raised by the referees and briefly outline here the more substantial changes/ revisions below.

- Regarding the misinterpretation of the focus: The focus of this study is not to predicting rock slope instabilities. To address this, we clarified the focus, purpose and novelty of this study in the abstract and introduction.
- Regarding the weakness of the initial conceptual model: We agree, the initial conceptual model was not consistent and contained some weaknesses. To be more precise, we now use the term “fracture kinematics” instead of “fracture dynamics”. We rewrote and shortened the conceptual model to an overview of the processes and related environmental controls and clarified the aim and research questions of the study in a separate section.
- Regarding difficulty in understanding methodology: We simplified and clarified the methods. We revised and clarified the whole method section. 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. We also changed the term “summer offset” to “summer shift” with the abbreviation “SHT”. We further extended and improved the regression analysis to investigate the relation between fracture kinematics and temperature.
- Regarding the criticism of referee 2 that a qualitative analysis of raw data would have brought the same observations/conclusions, but the proposed model does not bring significant contributions or advantages: We disagree on this point. This work provides a new quantitative analysis based on a significantly longer time series (7 years vs. 2 years). The scientific advance of this contribution is to distinguish phases as well as the timing of irreversible displacements. Timing of irreversible kinematics is crucial to link the acting mechanisms to environmental forcing. Furthermore, the developed irreversible index provides useful indication on rock wall stability.

In the revised manuscript we addressed all the reviewers’ comments and added in the general response one by one explanations and comments to the specific points of the referees. We also added additional figures and 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 #1 (doi:10.5194/tc-2016-136-RC1).
We thank Anonymous Referee #1 for its review and suggestions for improvement. Referee comments indicated as “RC:”, author reply as “AR:”. Only sections requiring a reply are reproduced.

RC: GENERAL COMMENT 1. Analysis methods are in places not understandable: e.g. Section 4.2. Some newly defined terms (e.g. OFST, LRM+) also do not seem to represent the actual features, so they are difficult to understand.
AR: We revised and clarified the whole method section. 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. We changed the term “summer offset” to “summer shift” with the abbreviation “SHT”. An improved explanation of this shift is given on page 10, line 25.

RC: GENERAL COMMENT 2. Why temperature is represented by data at 85 cm depth (instead of surface T)? Does the value best correlate with deformation? If it is true, why?
AR: Surface temperature is strongly influenced by daily fluctuations. The temperature is strongly attenuated with depth and is a more suitable representation of a seasonal signal. We added a table (Table 1 in manuscript on page 9) with an overview of all available temperature measurements (rock temperature at different depths and temperature in fractures). In the revised manuscript, we applied a best fit analysis using all available rock and fracture temperature data. With this we determined 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.

RC: P1 L8 Insert ‘that’ after assuming.
AR: Done.

RC: P2 L32 Does ‘thermal expansion’ here mean D2 or include also D3? Ice pressure and its release by melting can also produce reversible movement.
AR: We agree, the initial conceptual model was not consistent and contained some weaknesses. To be more precise, we now use the term “fracture kinematics” instead of “fracture dynamics”. We refocused the the conceptual model to an overview of the processes and related environmental controls and clarified the aim and research questions of the study in a separate section. We also clarified in the manuscript that ice pressure and its release by melting can also produce reversible fracture kinematics.

RC: P3 L4 Insert ‘us’ after allows.
AR: Done.

RC: P6 L31 . . .strong wind results in a preferential snow deposition in fractures. . . (Insert ‘s’ and delete comma.)
AR: Done.

RC: P7 L4 Does ‘along fracture’ mean that the crackmeter does not cross a fracture? A photo or illustration of the installation will be helpful.
AR: We adapted Figure 3 (new Figure 5 on page 8) and added a photo with a sketch that illustrates locations instrumented with two crackmeters.

RC: P8 Fig.3 caption Scap of the 2003 rockfall.
AR: Done.

RC: P8 L9 Why did you use T at 85 cm depth?
AR: This point was addressed in detail in GENERAL COMMENT 2.

RC: P9 L3 Where is ‘ti’ in Eq. 2?
AR: This was a mistake. We have removed it.

RC: P10 L8 Insert ‘of’ after ‘approximation’?
AR: Done.

RC: P10 L16 What does ‘date(Trock < −1 C)|May 1’ mean?
AR: This issue was addressed and clarified by a more detailed explanation on page 11, lines 1-3.

RC: P10 L27-29 Should this be described in Section 4.4 (equation 6)?
AR: This is correct and addressed in the previous referee comment RC: P10 L16.

RC: P11 L19 Perhaps ‘installation’ could be deleted.
AR: Done.

RC: P12 Fig. 5 caption L2: I suggest to insert (a) after ‘at 85 cm depth’.
AR: We inserted labels referring to all subfigures.

RC: L3: I suggest ‘. . . represented by (b) perpendicular to and (c) along fracture’.
AR: We inserted labels referring to all subfigures.

RC: P13 Fig. 6 Why deformation does not start from zero (cf. Fig. 5).
AR: The observed crackmeter data represents the extension of the crackmeter itself. Dealing with fracture kinematics, we changed the initial deformation and set it to zero at beginning of measurements (Figure 6-8).

RC: P13 Fig. 6 caption Replace ‘parallel’ by ‘along’?
AR: Done.

RC: P13 L4-5 Note that. . .: I cannot understand this sentence.
AR: This section was removed.

RC: P14 L3 Insert comma after ‘Assuming’.
AR: Done.

RC: P14 L13-14 Hinting on. . .: Also not understandable. Lacking a verb.
AR: This paragraph has been clarified 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, …". See 13, lines 13-15.

RC: P14 L17 Replace ‘Section 5’ by ‘Figure 5’?
AR: We wanted to refer to the first paragraph of “Results and interpretation”, which describes the evolution to the rock fall event at location *mh02* in a few sentences. We rephrased the text in the brackets to: "… The local break-off at location *mh02* occurred in summer 2015 (described in first paragraph of Section 4, page 11).". See page 14, lines 1-2.

RC: P15 Fig. 7 Why deformation does not start from zero?
AR: This issue is addressed. See author response AR to RC: P13 Fig. 6.

RC: P18 L8-9 Which data do show ‘this summer offset seems to correlate slightly with an increasing total amount of energy available (TDD)’?
AR: We added an additional figure to the appendix 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.

RC: P18 L32 What is ‘the hypothesis of Hasler et al. (2012)’?
AR: Hasler et al. (2012) hypothesized a thermo-mechanically and cryogenic forcing of fracture kinematics. We addressed this issue by rephrasing the sentence to: “… Such thermo-mechanically

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)" See 19, lines 22-24.

RC: P19 L7-8 'the water can easily drain through the strongly fractured rock and the water availability is limited': Does this situation fit any places in the rockwall? Aren't there any locations topographically favorable for water storage?
AR: The investigated field site is very steep and strongly fractured. We tried to measure water pressure in fractures without success. But we agree there might be topographically favorable spots for water storage, even close to the ridge and limited water supply. To clarify it, we rephrased this paragraph to: " 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. " See page 19, lines 34ff.

Reply to comments made by Anonymous Referee #2 (doi:10.5194/tc-2016-136-RC2).
We thank Anonymous Referee #2 for its review and suggestions for improvement. Referee comments indicated as "RC:", author reply as "AR:". Only sections requiring a reply are reproduced.

GENERAL COMMENTS
RC: The authors propose an empirical/statistical model aimed at separating reversible components of fracture deformation, due to thermo-elastic strains in alpine high-elevation permafrost environments, and the irreversible (plastic) component due to other processes. The topic is interesting and of interest for The Cryosphere. The work is based on a very interesting 7-year time series of fracture displacements recorded at several locations at the Matterhorn (Switzerland) by a monitoring network set up by Hasler et al (2012). Nevertheless, my review pointed out a number of serious scientific issues, which are listed in the following general comments and in the following "Detailed comments" section. I suggest that these points must be carefully addressed before the manuscript can be published in a high-level journal as The Cryosphere.

RC: GENERAL COMMENT 1. The abstract is quite too long and should be more focused and to-the-point;
AR: We shortened the abstract and focused more on the main results of our analysis. See page 1.

RC: GENERAL COMMENT 2. English could be generally improved using shorter and more focused sentences;
AR: We addressed this comment. The re-submitted manuscript was revised by a native speaker.

RC: GENERAL COMMENT 3. The "mechanical conceptual model" (Section 2) is characterized by some weaknesses and is not used later in the paper, which then focus on an empirical/statistical model. The authors seem to want to add a "rock mechanics taste" to the work, but tend to mix some different concepts and quantities and use terms as "fracture dynamics" which sound ambiguous to people from the geological and engineering rock mechanics communities (see detailed comments);
AR: We agree, the initial conceptual model was not consistent, contained some weaknesses and lacked clear link to the main work undertaken in this study. We replaced the conceptual model by a schematic visualization and a description of kinematics in steep fractured bedrock permafrost and the related main acting mechanisms influenced by varying environmental forcing. This part leads now more clearly to the research questions and includes the assumption for the developed linear regression model. To be more precise, we now use the term "fracture kinematics" and "fracture displacements" instead of "fracture dynamics".

RC: GENERAL COMMENT 4. The empirical/statistical model, making the core of the work, is biased by strong assumptions leading to somehow obvious results and poor predictive capability (see different detailed comments below). Actually, it is difficult for me to see either the scientific advance or the practical contribution of this work. In fact, the statistical model aims at discriminating thermo-mechanical elastic displacements, which are indeed small and of the same order of magnitude of possible precursors of rock slope instability (the latter can also follow very different patterns). This seems to suggest that the reliability of the method is low for small irreversible displacements and useless when irreversible displacements become larger. Finally, irreversible displacements are not investigated themselves thus the method cannot be used to predict rock slope failures (as promised in the abstract).
AR: We agree that the original manuscript was not clear enough on the aim and main focus. This point helped to improve the manuscript. The main results stay the same, which indicates that the previous assumptions were not invalid. We agree, the applied model is based on assumption and has limitations, but the main target is to separate reversible thermo-mechanically induced (elastic) displacements from the residual irreversible (plastic) displacements and not to predict. This model is rather a tool for fracture kinematics analysis than for prediction of rock slope failure. The focus and aim of this manuscripts are now clarified and assumptions and limitations are discussed in more detail in the revised manuscript and is investigated by a separate correlation analysis.
The scientific contribution of this manuscript is to distinguish phases as well as the timing in relation to potentially acting processes. Timing of irreversible kinematics in relation to environmental forcing is crucial for investigating and identifying the acting mechanisms and to assess rock slope stability. The results clearly show, that thermo-mechanically induced strain dominates in winter. Further, the irreversible displacements are investigated in relation of environmental forcing using the available data. This allows some inferences on potential causing mechanisms. But as referee 2 rightly points out, we can not investigate the actual causing process in detail (this point has been clarified in the manuscript).

RC: GENERAL COMMENT 5. The most interesting contribution seen here is monitoring, providing a continuous, 7-years long time series of displacements. Nevertheless, this contribution originates from the previous work by Hasler et al 2012.
AR: The data in this manuscript is based on the initial experimental and installation setup by Hasler et al. (2012). But the analysis of Hasler et al. (2012) was based on a very short time series (5 locations under 2 years and 5 locations under one year). Due to the limited duration of the data set, Hasler et al. (2012) provided only a qualitative analysis. Here, we present a much extended data set of 7 consecutive years of most sensors. Further, with this data set we undertake a much more detailed and quantitative analysis. All data used in this paper is openly available.

RC: Page 1, line 4: (and elsewhere in the manuscript): "fracture dynamics" is a confusing term to members of the rock mechanics communities (both geoscience and engineering): in fact the term "dynamics" usually refer to fracture mechanics (micro- or meso-modes of failure and related mechanical models and parameters; see e.g. Paterson & Wong) under dynamic loading conditions. Instead, the author simply refer to the temporal pattern of movements along or perpendicular to fractures. Why not use a simple term as "fracture kinematics"?
AR: We appreciate this advice. We replaced "fracture dynamics" by "fracture kinematics" or “fracture displacements” everywhere in the manuscript.

RC: Page 1, line 9: "gravity-driven slope failure": Rock slope failure? Landslide?
AR: “gravity-driven slope failure” has been removed by shortening the abstract.

RC: Page 1, lines 12-13: "enables a local assessment of rock wall stability": actually, the presented work just aims at depurate a time series of displacement along fractures from the elastic thermal component. No analysis of the spatial-temporal patterns, mechanisms and triggers of irreversible displacements is proposed, thus I do not understand how rock wall stability is dealt with here.
AR: We agree with the referee that our investigations are not focused on stability. However, the analysis includes measurements with a high temporal resolution at multiple locations with different characteristics as exposition or slope. This gives an idea of the spatial variability, but no common pattern could be detected. As irreversible kinematics can lead to instabilities, the temporal

evolution of the irreversibility provides a first indication for stability assessments. We adjusted the text accordingly.

RC: Page 2, line 4: "frozen rock masses": the authors focus on rock masses with ice-filled discontinuities and exclude ice-free frozen rocks, where a thermal elastic strains indeed occur. This is ok, but I suggest that this should be declared clearly as an assumption at the beginning of the analysis, also suggesting the expected differences in the behaviors of ice-filled and ice-free rock masses with respect to slope instability. This would be very useful to non-permafrost-experts involved in the analysis of slope instability at high altitudes.
AR: In our interpretation, the adjective “frozen” refers to the aggregate state of potentially available water in a rock mass. In permafrost regions, three layers are expected. In the top layer (active layer), ice can occur seasonally if water is available. At the permafrost table (boundary between active layer and permafrost body), the percolating water freezes and stays perennially. The ice content in the permafrost body mainly depends on the water availability during permafrost aggradation. We fully agree that there are differences in the behavior of ice-filled and ice-free rock masses with respect to slope instability. But it is difficult to quantify the occurrence of ice in fractures, as the visible part of the fracture lays in the active layer and is ice-free in summer. Visual observations during field visits in winter support the seasonal availability of ice in some fractures.

RC: Page 2, line 21: "Intact high prosity rocks": and what about low porosity rocks, which form most of the Alps?
AR: We fully agree on this point, also the Matterhorn consists of low porosity rock. Unfortunately, there are limited studies investigating low porosity rocks. The same mechanism is also expected to act in rock masses with flaws in rock. We addressed this point by adding the following sentence to the manuscript: "Based on numerical simulations, ice segregation can even occur in low porosity rocks in an estimated temperature range from −4 to −15° C (Walder and Hallet, 1985)." See page 4, lines 25-26.

RC: Page 3, line 25 "thermo-elastic induced strains": the conceptual model of the authors is based on a balance of driving and resisting forces. Strains are not forces, but are related to forces by a specified rheology and geometry (i.e. Stress distribution). Balancing the contribution of strains is formally incorrect, although this has no consequence on the analysis because the mechanical model is actually not used in the following (but it is another weakness of this work; see General Comments)
AR: We agree that there was a confusing use of language/terminology in this section. We replaced the conceptual model by a schematic visualization and a description of kinematics in steep fractured bedrock permafrost and the related main acting mechanisms influenced by varying environmental forcing. This new approach built the basis for the linear regression model and the hypothesis. Based on the 7 year time series, we analyzed and discussed the influence of environmental forcing on the acting mechanisms.

RC: Page 3, line 27: "creep and fracture of ice": here the authors include among resisting forces some processes and quantities that are not forces. Creep is a time dependent deformation of materials, including a large variety of physical processes at micro to macro scales. Fracture is brittle failure of solids. I understand that ice deformation and failure reduces stresses through plastic work, but again it is formally not correct to include these processes as forces.
AR: We agree, a detailed answer is given in the previous point and the text has been revised accordingly.

RC: Page 3, line 27: "fracture infill": strength of fracture infill?
AR: Fracture infill is interpreted as a mechanism that blocks the fracture and prevents a closing of the fracture, unless there are other mechanisms which reduce the amount of infill.

RC: Page 3, line 31: "reversible and irreversible": elastic and plastic?
AR: Reversible kinematics refers to thermally-induced strain, while irreversible describes the residual kinematics. Thus, the reversible part is elastic strain, but the irreversible part can also include creep and rupture beside plastic strain. We addressed this comment by modifying the

manuscript: "... The observed fracture kinematics usually consists of a reversible (elastic) and irreversible (plastic, creep and rupture) component. ..." See page 3, lines 3-4.

RC: Page 3, line 33 and Page 4, line 1: I am not convinced about the physical consistency of the "temperature-fracture deformation relationships". It is well known from a huge laboratory rock mechanics literature that the rheology (stress-strain relationships, brittle vs ductile behavior) of rocks depends on temperature. Thus, it would not be possible in principle to define unique temperature-strain relationships, especially when dealing with creep, which is non-linear and time dependent even at constant temperature. I understand that authors just refer to individual existing fracture deformations and guess that they assume linear elastic-perfectly plastic rheology in the considered temperature range. Nevertheless, the authors *should clearly state and support their assumptions and related limitations*: are they sure that stress-strain-temperature relationships for ice filled fractures (and even more for fractured rock masses!) are as simple as they state? Are they able to provide experimental data or literature to support that?
AR: We think there is a misunderstanding in scale and temperature here. The laboratory experiment of Wolters (1969) showed a linear temperature-strain relation for the temperature range from -20 to +80° C, which covers the temperature range measured at Matterhorn. 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) reported a simple correlation between fracture kinematics and (rock-) temperature at different time scales from diurnal to annual. The field site Matterhorn consists of fractures with and without ice, but the stress induced by ice pressure might be limited due to the high degree of fracturing. For our model describing the reversible fracture kinematics, we assumed a linear relationship between thermo-elastic strains in rock and temperature (we modified and clarified this point in the manuscript). It is clear that reversible kinematics can not be split up in different processes, but high coefficients of determination resulting from the regression analysis indicate that it works.

RC: Page 6, line 23: "these statements are validated": in the following, the authors switch from a conceptual mechanical model to a simplified statistical one to discriminate reversible and irreversible movements along monitored fractures. Nevertheless, the postulated origins of irreversible movements, i.e. "Cryogenic" in winter and "hydro" in summer, although reasonable, are not validated by data and analysis. No information is provided about the state of ice filling in fractures, and there is no correlation between hydrological parameters (e.g. Rainfall) and irreversible movements.
AR: We agree that these statements are not explicitly validated due to limited data describing environmental conditions and no reliable data providing information about the state of ice infill in fractures is available. The paper was refocused and the hypotheses were removed, as they mainly supposed the same as the research questions.

RC: Page 6, line 29: "heterogeneous": in which sense?
We addressed this point by rephrasing this sentence: “This field site consists of spatially heterogeneous steep fractured bedrock with partially debris covered ledges.” See page 6, line 19.

RC: Page 6, line 30: rainfall, cold winter temperature, exposure etc.: please provide quantitative values/ranges typical of the studied environments.
Unfortunately, we have limited weather data for this field site and no representative weather station of the Swiss Meteo Station Network, which is close to the field site and in a similar elevation. But we inserted the MAAT and maximum wind speed locally measured in the years 2011-2012 (see page 6, lines 19ff). We added three pictures distributed over a year (taken in the morn on 01 Jan 2015, 03 Apr 2015, 01 Jul 2015 and 01 Oct 2015) to illustrate the variability of snow deposition (see Figure 4).

RC: Page 7, line 5: could the authors explain why they measured temperature down to 85cm and not deeper? This also applies elsewhere in the manuscript. Which are the other measuring depths, and why temperature profiles are not used / presented?
AR: The depth of rock temperature measurements (0.1, 0.35, 0.6 and 0.85 m) are given by the installation of Hasler et al. 2012. The extended Table 1 on page 9 gives an overview of the

available temperature in rock and fracture at different depths. A selection of the rock temperature time series are shown in Figure 6 (at the end of this reply a similar figure with temperature gradients calculated by ($T_{0.85\,m}$ – $T_{0.1\,m}$)/0.75 m is shown). For the new analysis, temperature measurements in fractures at different depth are included. Applying a best fit analysis using all available rock and fracture temperatures, we determined the most representative temperature measurement (which are in most cases at 0.85 m depth) for modeling the reversible thermo-mechanically induced fracture kinematics. The optimized trainings windows are shown in Table 2 on page 13.

RC: Page 7, lines 5-6: "high resolution images": what are these used for, also considering that pixel resolution is of the same order of magnitude of the fracture displacements recorded in seven years?
AR: These images are mainly used for inspection of the instrumentation, but also provide information about the snow deposition. Currently, we do not derive displacements. This would be the scope of an other project.

Page 7, line 13: "aggregated": cumulated or averaged?
AR: The data was aggregated by averaging.

RC: Page 8, line 4: "Staub et al": manuscripts in review are not citable.
AR: This publication is accepted now and published as early view article.

RC: Page 8, line 9: "Used temperature ....at 85cm depth": why?
AR: This point was addressed in detail in the author response to the referee comment RC Page 7, line 5.

RC: Page 9, lines 3-10: the statistical linear model for the reversible deformations is poorly explained and supported: does it apply at the same way to shear and normal fracture displacements? How is the data population related to reversible movements separated from the irreversible movements occurring in winter for fitting purposes? Which are the best-fit statistical parameters of the model and related measures of statistical performance? These are not reported and the reader is forced to believe that the model is robust. This is a major scientific weakness of the work and the authors should work more on this.
AR: We addressed this point and explained the linear regression model in more detail. We added an additional correlation analysis for defining the trainings phase and a table with the statistical performance (Table 2, page 13). In principle, LRM can be applied the same way to shear and normal fracture kinematics, but 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 strain is also the same and no kinematics along fracture is measured. For one location (*mh08*), we added in the supplements a figure illustrating the modeled reversible, thermo-mechanically induced kinematics (Figure 13, page 22).

RC: Page 9, line 14: 28 days window length: one month is a long smoothing period, could the authors explain why they used such a long time interval? In general, one could expect that excessive smoothing may "kill" some important signals on shorter timescales.
AR: We agree that smoothing over 28 days may attenuate variations on short timescales. We adapted the irreversibility index, run the index function (Equations 3 + 4 on page 10) with a sliding windows of 21 days and do not explicitly smooth the data any further. Anyway, the irreversibility index aims at detecting periods, when the irreversible fracture kinematics dominates. On the one hand, it helps to interpret potential forcing and on the other hand, it should enable to assess the stability and not to predict rock slope instabilities.

RC: Page 10, line 11: “due to creeping”: this part is obscure and, again, I cannot understand how the authors are able to separate the population of reversible vs. irreversible winter deformations.
AR: We rephrased this sentence and do not refer to a process anymore. The referee is right, we can not separate the population of reversible vs. irreversible kinematics during the training phase. We assumed that the irreversible kinematics is negligible during the trainings phase, which is

confirmed by the coefficient of determination given by the regression analysis (see Table 2, page 13).

Page 10, line 21: “in winter. . ...we assume that deformation by the thermos-mechanical induced strain dominated”: this indeed remains a strong assumption, possibly significantly biasing the model. The authors should try to support this better.
AR: The LRM+ model was removed. See comment above.

RC: Page 11, Figure 4 (and related text): the piecewise linear regression model sounds over-simplified and biased by different strong assumptions including the following: 1) winter deformation is always reversible (or, at least, the same reversible deformation fitted in an early “training period” occur every winter – this may be not true as the rock mass accumulates damage); 2) the beginning of the “creeping” phases can be predefined and is the same every year; 3) displacement time series in the creeping phase are linear. I suggest that these assumptions pose too many constraints on the model and hampers its application to prediction/forecasting, except in very simple cases.
AR: This figure was removed according to the explanation in RC: P10, lines 21. Instead, we analyzed the whole time series, focusing on the irreversible fracture kinematics after removing the reversible part from the raw data.

RC: Page 11, line 23: “. . .a field site can not be described by a single measurement location. . ..”: this seems quite obvious, and things are even worse when dealing with rock masses instead of individual fractures.
AR: We think this statement is still valuable and very well supported by data. Individual fractures seem to respond quite differently. Multiple spatially distributed locations with different characteristics as exposition or slope, including fractured rock masses, give an idea of spatial variability. Single measurement points enable to investigate the kinematics at small scale, while an array of measurement points can help to assess the stability of the instrumented area.

RC: Page 12, lines 9-10: “indicated by a black line in Figure 6”: this is unclear or incorrect. The black lines seem linear regression functions, not their coefficients (which are never reported in the paper; instead, the authors should provide tables of best-fitting function parameters and regression quality statistics or indices to demonstrate the performance of their statistical model). Moreover, it is difficult to understand why the black lines are plotted at these positions (why don’t they intersect the x-axis in zero? What is actually fited?)
AR: We appreciate this note. We clarified this in the caption of Figure 7: “Black lines indicate the linear regression function determined by the regression analysis (see Table 2).” Table 2 provides the regression parameters (selected temperature, trainings phase, parameters intercept and slope of regression function, correlation coefficient and coefficient of determination).

RC: Page 13, lines 4-5: “note that. . ...deformation”: incomplete statement.
AR: The LRM+ model was removed (see previous comments).

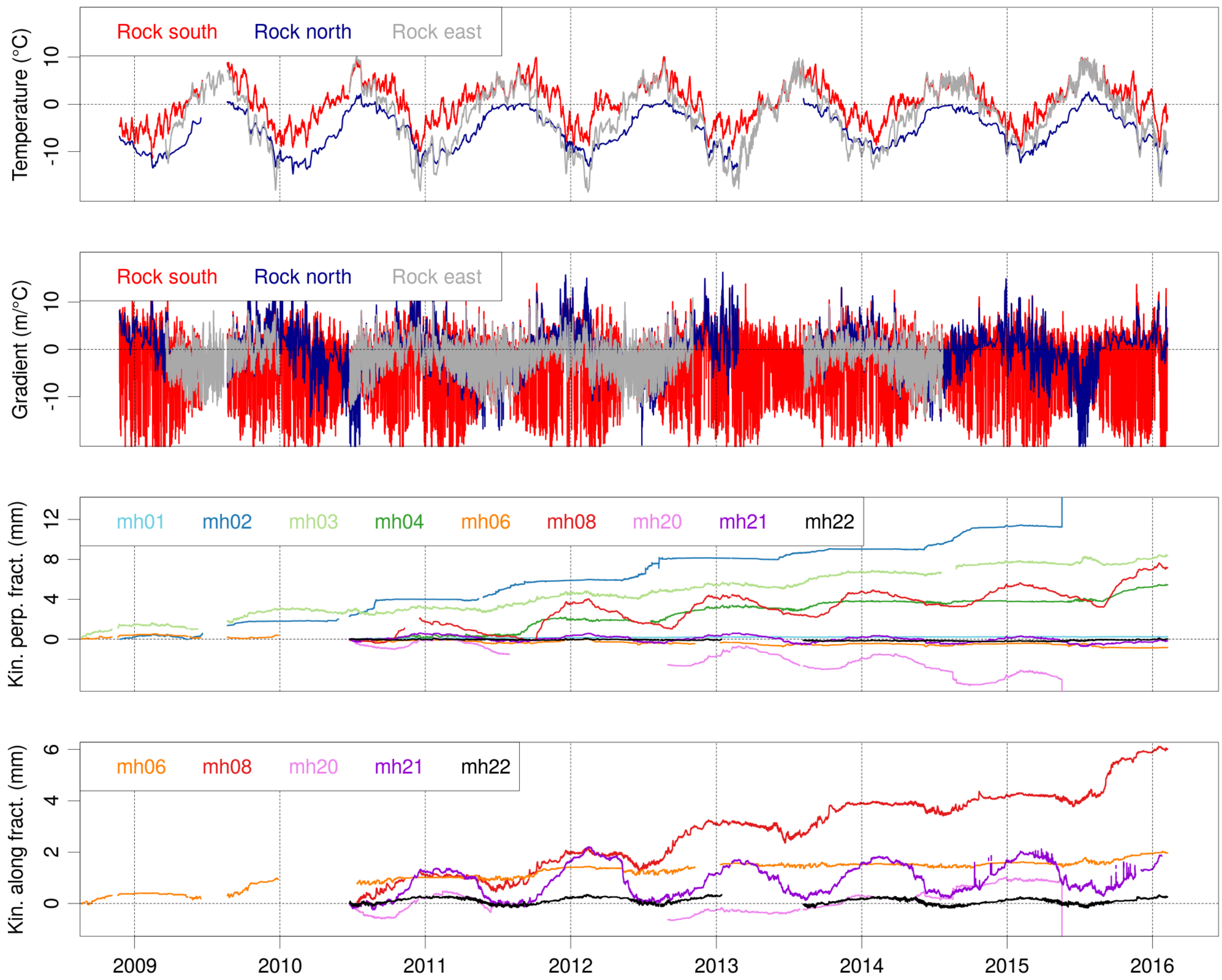
RC: Page 13, lines 5-6: “reduced data input”: the authors’ approach is to fit very limited time windows and then extrapolate the results. But in this way, they are not able to obtain a model fitting the entire dataset, which is particularly important to empirically fit time-dependent movements (creep). Also, in this way the potential of the beautiful 7-year presented monitoring series is not exploited.
AR: This section was removed and the full 7-year monitoring series without reduction is now discussed/explored in more detail. However, we end up with similar results showing that fracture kinematics at most locations consists of reversible thermo-mechanically induced strain, creep phase during thawing period and fracture opening in autumn when temperatures drop below 0° C.

RC: Page 14, line 1: “this likely indicates thawing related processes”: this is obviously reasonable, but but still unsupported by specific analyses. “assuming that water is available. . ...deformation”: same comment.
AR: We don t really understand this comment: We specifically build an index to analyze our data,

and could eventually link its variations to environmental conditions. Moreover, we specifically mention this as a possible interpretation.

RC: Page 17, lines 4-5: “one single. . .. . .fracture deformation”: the result is reasonable in some specific conditions (individual fracture displacements vs. rock mass, low strain, low damage, simple failure kinematics causing block movements), but is biased by the strong assumptions on which the model is based (what is reversible or irreversible deformation?)
AR: See comments above.

RC: Page 18, section 6.2: a qualitative analysis of raw data would have brought the same observations / conclusions, suggesting that the data (following the work of Hasler et al 2012) are very interesting, but the proposed model does not bring significant contributions or advantages (especially in a predictive perspective)
AR: We disagree on this point. With a qualitative analysis, it is very difficult to assess the relative contribution of reversible versus irreversible displacement and in particular the timing/evolution of irreversible displacement. This timing is however crucial in relation to the environmental forcing (melt, freezing, precipitation, …) and hence relating it to potential responsible processes.
This work provides a new quantitative analysis based on a significantly longer time series (7 years vs. 2 years). Furthermore, the developed irreversible index may be a useful measure for evaluating on rock wall stability.



Quantifying irreversible movement in steep fractured bedrock permafrost ~~at~~ 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. ~~Identifying precursors of gravity-driven slope instabilities in inhomogeneous fractured rock masses~~ Understanding rock slope kinematics in steep fractured bedrock permafrost is a challenging task. Recent laboratory studies have ~~brought upon an~~ provided enhanced understanding of rock fatigue and fracturing in cold environments but were not successfully confirmed by field studies. ~~In this study we monitor environmental conditions~~This study presents a unique time series of fracture kinematics, rock temperatures and ~~fracture dynamics~~ environmental conditions at 3500 m a.s.l. on the steep, strongly fractured Hörnligrat of the Matterhorn (Swiss Alps). ~~Here we analyze~~ Thanks to seven years of continuous data~~of the long term~~, the longer-term evolution of fracture ~~dynamics in permafrost offering~~ kinematics in permafrost can be analyzed with an unprecedented level of detail~~and observation duration. The fracture dynamics consists of reversible and irreversible movement components resulting from a combination of temporal varying driving and resisting forces. As irreversible motion is suspected to occur prior to global gravity-driven slope failure, we developed a statistical model, assuming the reversible deformation is caused by thermo-mechanical induced strain, and tested it successfully with field measurements from steep permafrost bedrock. We apply this linear regression model to our data set of fracture dynamics and rock temperature in order to separate the residual irreversible movement~~. 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 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 fracture kinematics in winter. Furthermore, removing this reversible component from the observed displacement enables to quantify the irreversible component. From this, ~~we produce~~ a new metric ~~that quantifies~~ – termed index of irreversibility – is proposed to quantify relative irreversibility of fracture ~~dynamics and enables a better interpretation of the data. This index of irreversibility is based on in situ measurements and enables a local assessment of rock wall stability. Here we show how environmental forcing causes reversible and irreversible rock mass deformations that might be relevant in preconditioning rock slope instability. In general, all locations instrumented show a trend of fracture opening, but at variable rate between locations. At each individual location, the temporal pattern of deformation is very similar every year.All but one sensors show a~~

~~reversible deformation component caused by thermo-mechanical induced strain~~kinematics. This new index can identify periods when fracture displacements are dominated by irreversible processes. For many sensors, ~~we observe an~~ irreversible enhanced fracture ~~deformation in summer , starting when rock temperaturesreach above zero~~displacement is observed in summer and its initiation coincides with the onset of positive rock temperatures. This likely indicates thawing related ~~process~~processes, such as melt water percolation into fractures, as a forcing ~~mechanisms~~ mechanism for irreversible deformation. ~~Most likely, such water or thawing leads to a decrease of the cohesion and friction along fracture in the shear zone.~~ For a few ~~fractures instrumented , we find~~ instrumented fractures, an irreversible deformation was found with the onset of the freezing period, ~~which suggest~~ suggesting that cryogenic processes act as a driving factor through increasing ice pressure. ~~It further highlights that irreversible fracture deformation can even at locations in close proximity not be explained by one single process.~~ The proposed analysis provides a tool for investigating and better understanding processes related to irreversible kinematics.

Keywords

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

1 Introduction

On steep high-alpine mountain slopes, the behavior of frozen rock ~~mass~~ masses is an important control of slope stability when permafrost warms or thaws and seasonal frost occurs. During the ~~hot summer of~~ summer heat wave 2003, air temperatures across a large portion of Europe were $3° C$ ~~warmer~~ 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 ~~observed to warm~~ warmed by $0.5-0.8°$ C (Harris et al., 2003). Assuming that this warming ~~continues or even accelerates, gravity-driven~~ 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). ~~An improved~~ Improved assessment and monitoring strategies for the dynamics of frozen rock walls ~~is~~ are therefore needed and ~~requires~~ require better understanding of processes and factors controlling ~~slope~~ 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~~(Haeberli, 1996)~~, 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 ~~known to be~~ 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 this knowledge with field observations (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). Ice-filled joints hereby developed may inherit relatively tough ice bodies at low temperatures with the shear resistance decreasing with rising temperature and reaching a minimum just below the thawing point (Davies et al., 2001). When intact water-saturated rock thaws, fracture toughness and compressive and tensile strength decrease by up to 50% (Krautblatter et al., 2013). Besides the relatively slow process of heat conduction, the warming of frozen fractured bedrock is influenced by advective heat transport by percolating water, which efficiently transfers heat from the surface to the level where fractures become impermeable (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.~~

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). ~~Measuring surface displacements has been applied widespread~~ Surface displacement measurements have been applied in several studies to survey fracture ~~deformation~~ kinematics in permafrost revealing a clear ~~temperature dependent~~ 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). ~~Slope failure is the final stage of irreversible motion, resulting from a disbalance between driving and resisting forces. Reversible and irreversible motion are often superimposed and therefore it is difficult to interpret deformation data and relate to external forcing factors.~~

~~This study presents a statistical model for computing the reversible thermo-mechanical induced fracture dynamics in steep bedrock permafrost derived from measured fracture deformation. This approach allows to separate the irreversible movement components and to investigate the dynamics of fractures in ice-rich fractured bedrock permafrost with focus on enhanced fracture opening and shearing observedduring summer. Irreversible movement refers to slow slope deformation~~Often, an additional irreversible displacement component is observed, which is ~~seen as a part of slope instability, potentially preparing slope failure. This statistical model has been developed and tested using~~ 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 ~~years of continuous high resolution temperature and fracture deformation measurements from the Matterhorn Hörnligrat, a high mountain permafrost monitoring site. This study addresses three main questions:~~

1. ~~How can we separate reversible from irreversiblefracture movements by statistical means?~~

2. ~~Is there a common inter-annual pattern of irreversible fracture movement at all fractures instrumented?~~

3. ~~What kind of environmental conditions lead to enhanced irreversible motion?~~

~~In the first part of this paper we illustrate a conceptual model that describes fracture dynamics in steep fractured bedrock permafrost (Section 2) and describe a novel field measurement setup (Section 3). We pinpoint a quantitative way to distinguish between reversible and irreversible movement by temperature dependent statistical analysis and model (Section 4).This approach is used to analyze the data set comprising seven years (Section 5). We further elaborate on inter- and intra-annual fracture dynamics and finally build and discuss a new index of irreversibility, a novel metric providing useful indications on rock wall~~

~~stability.~~ year continuous data set of fracture kinematics, we propose and apply a methodology for separating and quantifying such irreversible displacements.

2 ~~Conceptual model~~

~~Surface displacements in steep fractured bedrock permafrost could reflect environmental processes controlled by temporally varying environmental forcing. To better isolate the individual processes, it is necessary to separate them in space and time as well as to relate them to the forcing mechanisms. Based on~~

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. The schematic in Fig. 1 combines the concept of destabilization by warming ice-filled rock joints developed by Gruber and Haeberli (2007), the rock-ice-mechanical model ~~of Krautblatter et al. (2013) , a new conceptual model of permafrost affected slope instabilities in steep fractured bedrock is proposed, sketched out in Fig. 1. This model tries to link spatial and temporal patterns of movements to related processes. Herein topographically controlled~~ ~~*gravitational forces*~~ ~~(D1),~~ ~~*thermo-elastic induced strains*~~ ~~(D2),~~ ~~*ice pressure*~~ ~~(D3) and~~ ~~*hydrostatic pressure*~~ ~~(D4)~~ 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 ~~forces. Resisting forces are composed of~~ ~~*cohesion and friction along fractures*~~ ~~(R1),~~ ~~*shear resistance of cohesive rock bridges*~~ ~~(R2),~~ ~~*creep and fracture of ice*~~ ~~(R3) and the~~ ~~*fracture infill*~~ ~~(R4). The driving and resisting forces~~ 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 ~~fluctuating environmental~~ temporal fluctuating environmental forcing as well as ~~static geological/~~the static geological or geotechnical characteristics. ~~As long as the driving forces are compensated by the resisting forces, there is no relative motion. But if the forces become unbalanced, either by increasing the driving force or by decreasing the resisting force, deformation occurs.~~

~~In general, the motion observed , consisting of reversible and irreversible movement components, results from a combination of several forces. When looking at each of these driving forces separately, it is possible to obtain~~ ~~*rock temperature – fracture deformation relations*~~ ~~(see~~ 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 between fracture kinematics and temperature (see bottom plots in Fig. 1~~a) for different environmental conditions. The gravitational loading is constant with time and temperature independent and the thermo-elastic induced strain is expected to cause cycles in fracture deformation that are linearly related to temperature. Ice pressure induced forcing only occurs at negative temperature while hydrostatic pressure acts at positive temperature. These relationships between temperature and process in combination with environmental forcing allow to interpret the observed movement patterns~~) is proposed for the main mechanisms described in in more detail below.

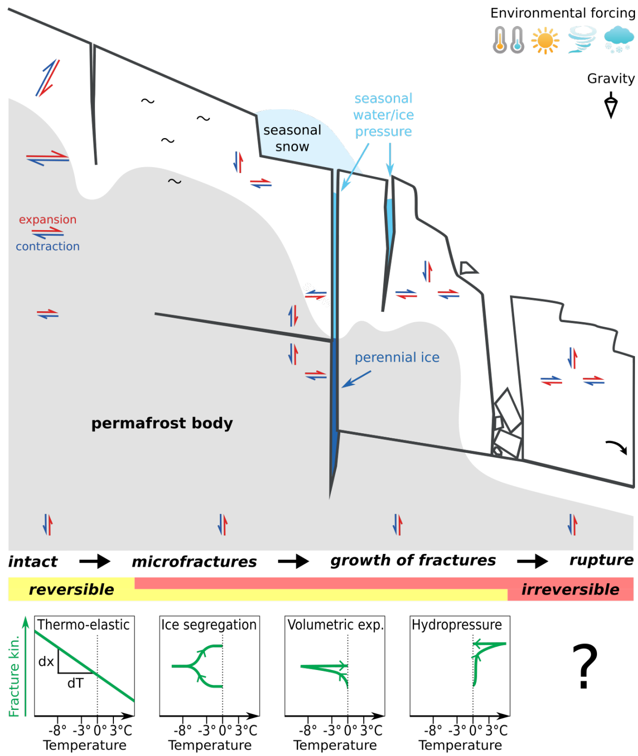


Figure 1. ~~Conceptual model~~ Schematic visualization of ~~permafrost-affected slope instabilities~~ kinematics in steep fractured bedrock ~~. (a) Cross-section through a fractured rock ridge in an alpine environment (top) and~~ permafrost shows the main acting mechanisms influenced by varying environmental forcing~~(bottom) to describe the relative fracture deformation~~. The gray area indicates permafrost, which is thermally defined as ground with a ~~result of driving~~ temperature below 0° C for at least two consecutive years. The overlying rock mass is exposed to seasonal freezing and ~~resisting forces~~thawing (top). ~~Each driving force~~ The indicated mechanisms can lead to fracture kinematics and each isolated mechanism causes ~~a~~ specific ~~motion pattern~~movement patterns, ~~which is~~ illustrated with the schematic plots showing the relation between fracture kinematics and rock temperature ~~and fracture deformation.~~ (~~b~~bottom)~~In long term, initially reversible deformation of rock mass can develop an additional irreversible component either by an increase of shear stress or by a decrease of shear resistance~~.

~~Short-lived *thermo-elastic induced strains* (D2) accommodate volume changes as movements, typical for fractured bedrock in non-permafrost (Watson et al., 2004) as well as in permafrost areas (Hasler et al., 2012) and is therefore an irreversible process. This volumetric expansion~~

Thermally induced stress

Rock tends to expand on warming and to contract on cooling and results in a ~~change of~~ reversible displacement behavior. Assuming homogeneous thermal conditions, a change in length ΔL of rock in all directions ~~that can theoretically be described~~

~~, assuming homogeneous thermal conditions, by~~ can be described by a linear function of temperature:

$$\Delta L = L_0 \cdot \alpha \cdot \Delta T \tag{1}$$

where L_0 is the initial length, α the material dependent linear expansion coefficient and ΔT the temperature change of the material. ~~This formula is difficult to apply in real world due to~~ 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 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. Equation 1 is a highly simplified approximation and ignores: (i) anisotropy and heterogeneity of the rock mass, (ii) complex 3D temperature regimes~~and~~, (iii) the unknown behavior of fractured bulk rock masses ~~as well as the fact that rocks with ice-filled porosity might have a~~ and (iv) potential non-linear expansion coefficient ~~(Jia et al., 2015).~~

~~Several~~ 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) ~~report a correlation between fracture deformation~~ confirm a simple relation between fracture kinematics and (rock-) temperature at different time scales from diurnal to annual. Further, Nordvik et al. (2010) applied a multiple regression analysis with aggregated sinusoidal air temperature to model the seasonal fracture ~~dynamics. They~~ kinematics and propose this approach for predictions of fracture ~~dynamics in~~ kinematics in the context of early warning ~~system.~~ systems.

~~In the long term, deformations 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. Creep and fracture of ice (R3) can absorb pressures along fractures and lead to stress reduction (Matsuoka, 1990) while fracture infill (R4) by debris or fine grained material can significantly alter shear resistances of fractures in a frozen or unfrozen state. Persistent thermo-elastic oscillations of an initially stable rock mass (stable phase in Fig. 1b), in combination with an increase of shear stress due to accumulation/concentration of stress at remaining rock bridges or a decrease of shear resistance, leads to irreversible surface displacement (unstable phase in Fig. 1b). Therefore, irreversible deformationis assumed to be a first indication for the initiating of slope failure~~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.

~~*Fracture of cohesive rock bridges* (R2) is temperature dependent and get influenced by warming during slow deformations (Krautblatter et al., 2013). Mellor (1973) showed a significant reduction in strength when frozen rock thaws. Periodic loading of discontinuities due to thermo-mechanical effect acts as a mesoscale fatigue process, which can result in deformation 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). Repeated stress on fractures caused by cryogenic processes in permafrost can also lead to fatigue.~~

Cryogenic deformation during freezing periods and related deformation during warming

Deformation in partly frozen rock masses may also be caused by increasing ~~*ice pressure* (D3)~~ ice pressure evolving in ice-filled fractures or pores by cryogenic processes. ~~Hereby, volumetric~~ 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 ~~fractures of~~ rock fractures or porous samples before ice can extrude (Davidson and Nye, 1985). However volumetric expansion also ~~works~~ applies in pores which are on average saturated by much less than ~~91 per cent, but due to the unequal~~ 91 %. Due to the heterogeneous moisture distribution, ~~always~~ 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 $-15^\circ C$ 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 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 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 percolation of snow melt water into fractures (Phillips et al., 2016).

Hydro deformation occurs during summer months and during snow melt

Irreversible deformation caused by ~~hydro related~~ hydro-related processes can only be observed in summer, because the availability of liquid water is very limited during winter. ~~On the one hand, water can act as the driving force through *hydrostatic pressure* (D4), which describes the fluid pressurein rocks,~~ Water can increase the effective stress through hydrostatic pressure, whereby hydrostatic pressure is mostly determined by the height of the water column. It ~~depend~~ depends amongst other factors on the hydraulic permeability of the rock mass~~, which~~ . Hydraulic permeability is much lower in rock ~~mass with frozen~~

masses with frozen and ice-filled fissures than unfrozen fissures and often causes high hydrostatic stress ~~levels~~ 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 ~~supposed to not be dominating in the surface~~ presumed not to dominate in the near-surface layer of strongly fractured steep bedrock, where the ability ~~to drain~~ for drainage is quite high. ~~On the other hand, water can change the resisting force *cohesion and friction along a fracture* (R1), which is elementary in steep fractured bedrock. Changing conditions in the shear zone~~However, changing conditions in shear zones, e.g. dry-wet, can lead to irreversible ~~motion~~displacement, for example caused by water percolating due to melting snow or rain. This is expected to have a strong influence ~~at~~ in fractures filled with fine-grained material.

~~Based on this conceptual model, we postulate that (i)rock movements can be separated into~~

Long term evolution

In the long term, deformation 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 along fractures and lead to stress reduction (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 be a first indication for the initiation of rock slope failure.

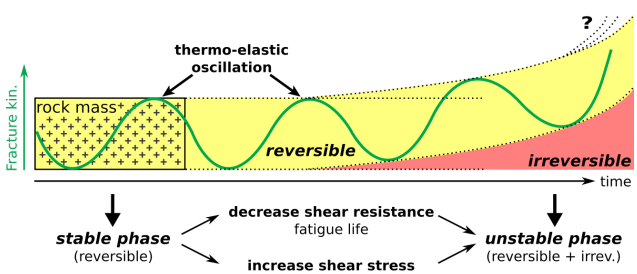


Figure 2. Evolution of a permafrost affected rock mass with persistent thermo-elastic oscillations: initially reversible deformation of rock mass can develop an additional irreversible component either by an increase in shear stress or by a decrease in shear resistance.

However, reversible and irreversible ~~movements, (ii)reversible thermo-elastic strains occur during the whole year, (iii)irreversible cryogenic deformations dominantly occur during freezing periods and (iv) irreversible hydro deformations during summer months and periods of snow melt. Using the continuous~~ displacements are often superimposed and it is difficult to interpret deformation 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. 1). 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 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. Irreversible displacement refers to slow rock slope deformation, which is seen as a part of slope instability, potentially preparing slope failure. This statistical model has been developed and tested using 7 ~~year deformationand temperature data set, these statements are validated.~~ 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 ~~altitude~~ elevation of 3500 m a.s.l. (see Fig. 3) using the experimental setup by Hasler et al. (2012). The field site is ~~predestined~~ 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 m^3) in summer 2003, (2) strong fracturing, (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).

This field site ~~is heterogeneous~~ consists of spatially heterogeneous steep fractured bedrock with partially debris covered ledges~~in steep fractured bedrock~~. The mean annual air temperature is $-3.7°$ C for the time period $2011-2012$ (see Fig. 11 in appendix A). The precipitation ~~almost exclusively~~ mostly falls as snow with occasional infrequent rainfall events in summer. ~~Cold winter temperature~~ Winter temperatures (down to $-27°$ C in $2011-2012$) in combination with exposure to strong wind ~~result~~ (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 accumulated firn disappears completely on the south side during summer while snow patches persist on the north side all year. 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). ~~The accumulated firn disappears completely on the south side during summer while snow patches persist on the north side all year.~~

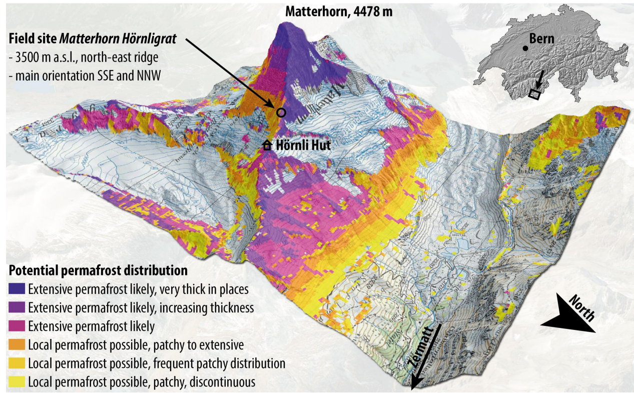


Figure 3. 3D overview of the Hörnligrat field site on the north-east ridge of the Matterhorn, in Valais, Switzerland (based on map.geo.admin.ch, Google Earth and SRTM). Colors indicate the potential permafrost distribution (FOEN, 2005). At this field site, extensive permafrost with a thin active layer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

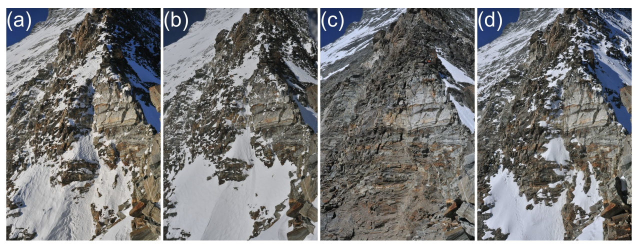


Figure 4. ~~3D overview of field site Hörnligrat, north-east ridge of Matterhorn~~Four webcam pictures, ~~located~~ taken in ~~Valais~~the morning on (a) 01 Jan 2015, ~~Switzerland~~ (~~based on map.geo.admin.ch~~b) 03 Apr 2015, ~~Google Earth and SRTM~~(c) ~~. Colors indicate the potential permafrost distribution~~ 01 Jul 2015 and (~~FOEN, 2005~~d) ~~. At this field site~~01 Oct 2015, ~~extensive permafrost with a thin active layer is expected on the north side of the ridge. On the south side of~~ illustrate the ~~ridge, local permafrost is possible with a considerable active layer~~varying snow deposition patterns.

In this study three types of data were recorded at different locations: relative fracture ~~deformation~~ displacements perpendicular to and along fractures ~~in a~~ at 2 min ~~interval (accuracy of 0.01 mm~~intervals (temperature compensated, accuracy of ± 0.01 mm over entire temperature range), temperature at different depths in rock ~~in a~~ and fractures at 2 min ~~interval (from surface down to 85 cm;~~ intervals (accuracy of $\pm 0.2°$ C) and a Vaisala WXT520 weather station (location *mh25* in Fig. 5). The time series of the weather station is interrupted for brief periods (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, ~~which gives~~ giving an approximate pixel resolution of 1.5 cm) ~~7 times per day. Fracture deformation~~ serve for visual inspection of the instrumentation and also provide information on snow deposition.

Fracture displacements perpendicular to the fracture are measured at locations ~~*mh01*~~*mh02*–*mh04* while fracture ~~deformation~~ displacements perpendicular and parallel to the fracture are measured at locations *mh06*, *mh08* and *mh20*–*mh22*. ~~Rock temperature measurements at 85 cm depth~~ 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 ~~locations~~ all crackmeter locations, except at locations ~~*mh02*~~*mh20*–~~*mh04*~~*mh22*~~and~~. Rock temperature at different depths ($0.1-0.85$ 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 ~~?? for the three locations with only temperature and in Table ?? for all crackmeter locations. If there is no co-located temperature measurement, a nearby measurement with similar topography is used.~~ 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 ~~raw~~ observed temperature and fracture ~~deformation~~ kinematics measurements were aggregated as 10 min averages to reduce noise. A detailed description and explanation of the measurement setup ~~, data processing as well as filtering~~ 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 years of data for rock and fracture temperatures, fracture kinematics and environmental conditions.

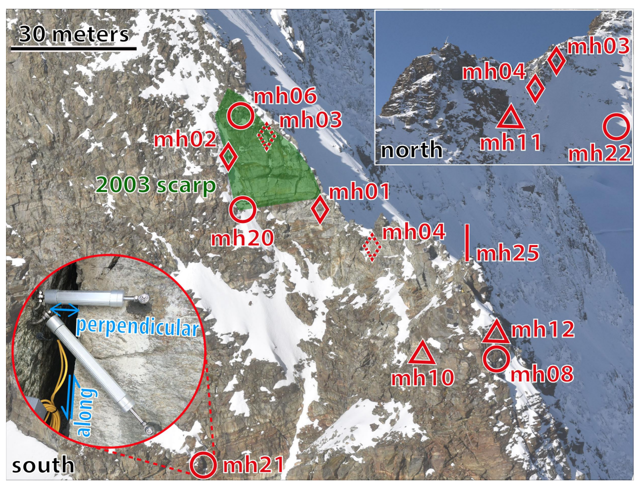


Figure 5. Overview of crackmeter installations. Location *mh01*–*mh04* (indicated with ◊) are instrumented with one crackmeter perpendicular to the fracture. Location *mh06*, *mh08* and *mh20*–*mh22* (indicated with ◯) are instrumented with two crackmeters to calculate ~~motion~~ displacements perpendicular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

Table 1. Meta information for ~~temperature~~ 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	~~Aspect Slope Thermistors at Label *mh10* 140° N 90° 10, 35, 60, 85 cm T_{south} *mh11* 340° N 70° 10, 35, 60, 85 cm T_{north} *mh12* 45° N 90°~~
*mh01**	intense solar radiation, microcracks
mh02†	~~8° N~~ concave, often snow, wet
mh03	lower part snow
mh04	saddle north
mh06	corner, often snow
mh08	wide, ventilated, close to ridge
mh10	intense radiation, fracture 1 m beside
mh11	occasionally snow, no fracture
mh12	snow free, fracture beside
mh20	corner, often snow, wet
mh21	wide, south side
mh22	wide, north side

* 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

3 ~~Analysis~~ Data analysis method

~~Temperature gap fillingGaps in the time series of temperaturesensors can occur due to interrupted power supply. To fill long gaps in the temperature time series at 85 cm depth, we apply quantile mapping using best regressor approach (**?**, in review). To select a representing reference time series, we look for measurement locations with similar properties, i. e. altitude, exposition, slope and surface conditions.~~

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 for varying time periods (different start time and 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)

~~To quantify the temperature dependent~~ In a second step, we aim to reproduce the reversible component of ~~the fracture dynamics, we modify the approach of Nordvik et al. (2010). Instead of air temperature, we use rock temperature T_{rock} at 85 cm depth~~fracture kinematics caused by thermo-mechanically induced strain. For each measurement location, ~~we then apply a~~ the linear regression function ~~with rock temperature T_{rock} and model~~ 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 [°C] for the complete time series to reproduce the reversible fracture ~~deformation y_{lrm}:~~ displacement y_{rev} [mm]:

$$y_{\cancel{\mathrm{lrm}}\mathrm{rev}} = \beta_0 + \beta_1 \cdot T_{\cancel{\mathrm{rock}}} + e_{\cancel{i}} \quad (2)$$

where ~~β_0 and β_1 are the unknown regression parameters for a fracture, t_i is the time and e_i~~ intercept β_0 [mm] and slope β_1 [mm/°C] are the regression parameters and e [mm] is the residual.

~~The temperature values were smoothed with a running window over seven days to reduce the noise, which likely represents temperature at greater depth. The length of the trainings windows get optimized iteratively for each location by searching for the best correlation coefficient, whereby the training window length is constraint to be between 3 months and one year. We also prefer training windows for which the temperature range from -3 to -6°C is passed very rapidly for excluding fracture deformation by ice segregation (Fig. 1, D3)~~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 ~~resulting best training windows periods occur during winter time with temperature below zero. For each fracture instrumented, the optimized correlation coefficient is used for the whole time series in order to model the reversible fracturedeformation by thermo-mechanical induced strain~~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 overall ~~motion~~ kinematics is not dominated by ~~thermo-elastic~~ thermo-mechanically induced strains. This index uses the ~~raw~~ absolute difference (Δy) between the observed fracture data (~~y_{raw}) after removing~~ y_{obs}) and the modeled reversible fracture ~~dynamics component (y_{lrm}~~kinematics component (y_{rev}) given by the LRM as input~~. This difference between y_{raw} and y_{lrm} is applied to running mean values (28 day window length) to reduce noise:~~ :

$$\Delta y = |y_{\mathrm{obs}} - y_{\mathrm{rev}}| \quad (3)$$

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

$$\cancel{y_{\mathrm{diff}}}I = \cancel{\mathrm{runmean}_{28\,\mathrm{days}}}(\cancel{y_{\mathrm{raw}} - y_{\mathrm{lrm}}}\mu + 2\cdot\sigma) - (\mu - 2\cdot\sigma) = 4\cdot\sigma \quad (4)$$

where the ~~function runmean$_{X\,days}$ is evaluated as the centered running mean~~sliding functions μ (mean) and σ (standard deviation) are evaluated over all data points in the ~~time window $\pm\frac{X}{2}$ days Finally, the index is calculated from the difference~~

~~between the running maximum and running minimum of y_{diff} over 7 days to reduce fluctuations:~~

$$\cancel{\text{index}_{\text{irreversibility}} = \text{runmax}_{7\,\text{days}}(y_{\text{diff}}) - \text{runmin}_{7\,\text{days}}(y_{\text{diff}})}$$

past 21 days. 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 ~~at~~ of zero means that the ~~motion~~ displacement is fully reversible. The higher the number, the higher ~~is~~ the proportion of irreversibility. ~~The benefit of this approximation is the temporal sensitivity to the intra-annual fracture dynamics and can therefore be used to detect unstable time periods.~~

~~3.4 Thawing degree days (TDD) and fracture dynamics summer offset (OFST)~~

~~A thawing degree day model~~

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 ~~dynamics summer offset y_{OFST_i} represents the movement between two winters due to creeping~~ kinematics summer shift y_{SHT} represents the shift in kinematics between two consecutive winters and is calculated as:

$$y_{\cancel{\text{OFST}_i}\,\text{SHT}} = \overline{y}_{\cancel{\text{raw,winter}_{i+1}}\,\text{obs,winter}^{+}} - \overline{y}_{\cancel{\text{raw,winter}_i}\,\text{obs,winter}^{-}} \qquad (5)$$

with the mean fracture ~~deformation~~ kinematics during winter given by

$$\overline{y}_{\cancel{\text{raw,winter}_i}\,\text{obs,winter}} = \sum_{k=t_1}^{t_2} \cancel{y_{\text{raw}}}\, y_{\text{obs}}/n \qquad (6)$$

where ~~$t_1 = Nov\,1, \text{year}_{i-1}$, $t_2 = \text{date}(T_{\text{rock}} < -1°\text{C})\,|\,May\,1, \text{year}_i$~~ $t_1 = Nov\,1$ and n the number of measurements.

~~3.5 Linear regression model plus (LRM+)~~

~~The presented LRM only describes the thermo-elastic induced reversible deformation and does not include an irreversible behavior. The *Linear regression model plus (LRM+)* aims to reproduce the total fracture deformation. It is a combination of the LRM (y_{lrm}) and periods of linearly approximated irreversible deformation. For a specific time period in winter, which we refer as the reversible phase ($P_{\text{reversible},i}$), we assume that deformation by the thermo-mechanical induced strain dominates. For the residual time period each year, which we refer as the creeping phase ($P_{\text{creep},i}$), we assume that the irreversible movement is active and linear during the whole creeping phase.~~

~~The deformation trend function $\hat{y}$(data) (see Fig. ??) is constant every winter during the reversible period $P_{\text{reversible},\imath}$, ranging from $t_{\text{reversible},\imath,\text{beg}}$ to $t_{\text{reversible},\imath,\text{end}}$, with the first available data point (see blue point) at the beginning of every year. The beginning of the reversible phase is essentially constraint by the start date of the earlier determined training period (see Section 3.2). There are two option for the end, either by the end of the hydrological year or when~~ The end time t_2 is usually defined by a fix date $t_2 = May1$ unless the rock temperature ~~cross~~ rise above a defined threshold value of ~~$-1°$C. The hydrological year approach is suitable for locations where the irreversible deformation is likely caused by cryogenic processes while the temperature threshold approach is applicable for locations melt water related fracture deformation. The deformation trend function $\hat{y}$(data) for the creeping phase $P_{\text{creep},\imath}$ then get piecewise linearly interpolated from the end of a reversible period ($P_{\text{reversible},\imath}$) to the beginning of the next reversible period ($P_{\text{reversible},\imath+1}$).~~

~~Super-imposing the reversible component of the LRM (y_{lrm}) on the irreversible piecewise linear trend, which is~~ $-1°$C before this date. If this is the ~~difference between the deformation trend of the raw data $\hat{y}$(raw) and the deformation trend of the modeled reversible data $\hat{y}$(lrm), results in the enhanced LRM+:~~

$$y_{\text{lrm}+} = y_{\text{lrm}} + \hat{y}_{\text{raw}} - \hat{y}_{\text{lrm}}$$

~~The resulting piecewise linear function represents the combination of reversible fracture deformation due to thermo-elastic induced strains and enhanced seasonal irreversible linear creep. Note that this model assumes a constant reversibility every year and all irreversible deformation is linear during the creeping phase~~case, the end time is given by the date when the rock temperature reaches this threshold ($t_2 = \text{date}(T_{\text{rock}} < -1°\,\text{C})$).

~~Schematic illustration how the piecewise linear deformation trend function $\hat{y}$(data) for the LRM+ get determined.~~

4 Results and interpretation

Figure 6 shows the rock ~~temperature~~ temperatures at 85 cm depth for different ~~exposition~~ aspects (a) and the fracture ~~dynamics, set to zero at start of measurement, of~~ displacements, relative to the start of the measurements, for all locations perpendicular to the fractures ~~and parallel to the fracture . A partly reversible movement~~ (b) and along the fracture (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 pattern of each location may be influenced by differences in geometric mesoscale arrangement of rock, where different combinations of processes dominate. An irreversible deformation 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 ~~dynamics~~ displacements of *mh02* and *mh20* are ~~not plotted completely for the year~~ after mid 2015 ~~, because there is a large jump in displacement~~ not visible in Fig. 6 as they are out of range. This abrupt and large displacement is due to a small ~~debris~~ rock fall event with a volume of a few cubic meters ~~of rock~~ in early summer (18 May 2015). ~~For~~ The functionality of both crackmeters was however not affected. But the thermistors at location *mh02* ~~, the crackmeter installation continued measuring reliably, while the thermistor got damaged by the falling rockswith a resulting interruption in~~ were damaged by falling rocks. Hence the temperature time series ~~. After this debris~~ ends on 18 May 2015. After this rock fall event, the fracture at location *mh02* continued to deform ~~with~~ in several small steps until late summer (14 August 2015) when the ~~rock instrumented~~ instrumented rock broke off completely during a bad weather period (see Fig. 12). The ~~variable patterns of fracture deformation observed~~

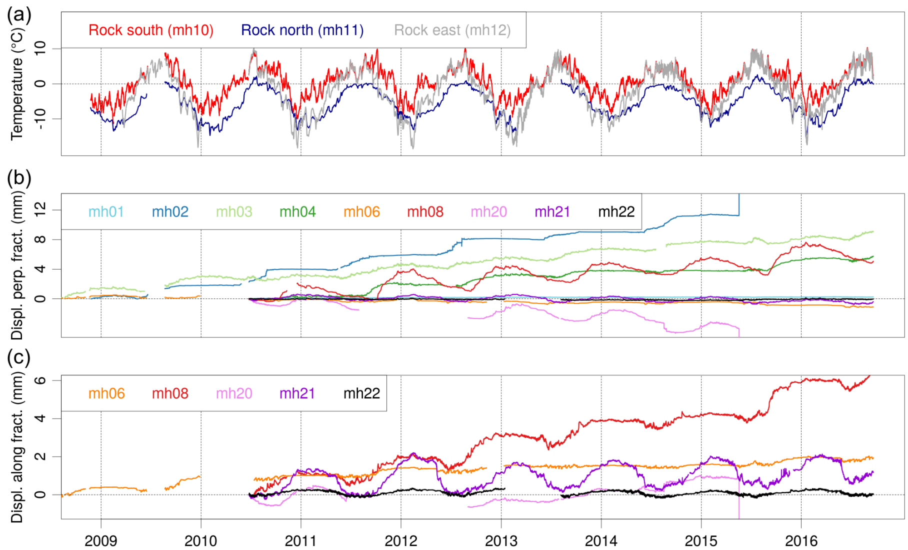


Figure 6. Time series of the thermal conditions and fracture ~~deformation~~ displacements at the field site Matterhorn Hörnligrat with up to seven years of data. The thermal conditions are represented by rock temperatures at 0.85 m depth (a) for south, east and north side~~at 0.85 m depth~~. The relative fracture ~~dynamics is~~ displacements are represented (b) perpendicular to and (c) along ~~fracture~~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 ~~the temperature gap filling method~~ quantile mapping using best regressors approach (Staub et al., 2016) with a ~~correlation~~ coefficient of determination $R^2 = 0.92$.

observed variable spatial and temporal patterns in fracture displacements (Fig. 6) indicate that a field site can not 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 ~~motion~~ kinematics and accordingly to improve the process understanding of the fracture ~~dynamics~~kinematics.

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

4.1 ~~Thermo-elastic response and LRM~~Regression analysis of irreversible displacement

The time periods during which fracture displacements exhibits 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 reversible response and LRM

Figure 7 shows the ~~relationship and evolution between fracture dynamics~~ relation between observed fracture kinematics and rock temperature. Applying the LRM, we obtain the linear regression coefficients that describe the reversible temperature dependent fracture ~~deformation indicated with a black line in Figure 7~~displacements (black lines in Fig. 7). The fracture ~~deformation~~ displacement at location *mh02* (South, Fig. 5) is almost temperature independent (regression coefficient of ~~$5\cdot10^{-2}$ mm/100°C~~$-1.2\cdot10^{-2}$ mm/°C) except for the winters 2008/2009 and 2014/2015. In contrast, location *mh03* (North, Fig. 5) shows a stronger temperature dependency of ~~-3.0 mm/100°C~~ $-4.0\cdot10^{-2}$ mm/°C. At *mh08* (East, Fig. 5), the coefficients are with ~~-9.0 mm/100°C~~ $-8.3\cdot10^{-2}$ mm/°C perpendicular to fracture and ~~-1.8 mm/100°C along fractureeven higher~~$-4.1\cdot10^{-2}$ mm/°C along fracture. These temperature dependencies are likely influenced by the combination of geometric arrangement and acting ~~forces. The~~ mechanisms. A potential lack of temperature dependency in the LRM analysis ~~, e.g. at location *mh02*, means~~ would mean that no reversible or negligible deformation caused by ~~thermo-mechanical~~ thermo-mechanically induced strain occurs. Or in other words, irreversible deformation dominates.

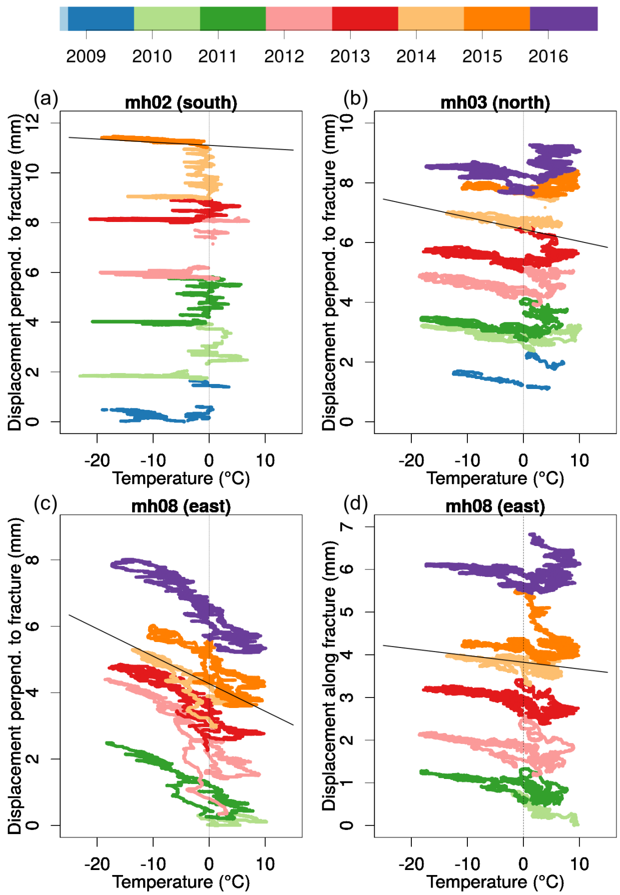


Figure 7. Temperature dependency of fracture ~~deformation~~ displacements for location *mh02* (~~perp. fract.~~perpendicular to fracture), *mh03* (~~perp. fract.~~perpendicular to fracture) and *mh08* (~~perp.~~ perpendicular to and ~~parallel fract.~~along fracture). Discrete colors indicate hydrological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

4.3 ~~Piecewise linear trend and LRM+~~

~~We model the reversible movement~~ Reversible fracture displacement is now modeled for the whole dataset with the *LRM* (see green lines in Fig. 8) using the ~~training phase in winter 2013/2014~~ regression parameters given in Table 2 (light blue shading in Fig. 8). The ~~total fracture dynamics approximated with the LRM+ model is shown in red and results from the LRM added to the~~

~~piecewise linear trend.Note that for producing the LRM+ deformation data (red line) , only the temperature data, a few months of training data and 1 winter value of fracture deformation. With this reduced data input, the original fracture deformation is well reproduced including short term variations.~~

red line in Fig. 8 represents irreversible displacement, obtained from subtracting reversible displacement (green line) from the observed displacement (blue line). This analysis clearly ~~show that we are able to describe~~ shows that the evolution of irreversible ~~deformation by~~ fracture displacement is described for every year by single phases of quiescence (or solely reversible displacements) followed by phases of ~~linear irreversible deformation~~almost linear irreversible displacements once a year. For most locations, including *mh03*, ~~this~~ the distinct irreversible phase occurs during the summer, starting when rock temperatures ~~reach above zero~~rise above 0° C. This likely indicates thawing related processes ~~, such as melt water percolation into fractures , cause~~ with melt water that percolates into fractures as a potential cause for this irreversible deformation. At a few locations, such as *mh08*, this linear irreversible phase occurs in autumn when rock temperatures ~~drop below zero. Assuming water is available, this points to~~ reach freezing conditions, suggesting cryogenic processes (i.e. ice pressure, see Section ~~??) as likely cause irreversible fracture deformation.~~

1.1) as the causing mechanism. There are however ~~some discrepancies between the LRM+ and the measured signal. For~~ 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 ~~thermo-mechanical induced strain (LRM). For~~ the LRM approach. Furthermore, for location *mh08* in summer, the full amplitude of reversible deformation is not always reproduced by the LRM.

4.3 Thawing degree days and summer ~~offset~~shift

The summer ~~offset~~ shift of the fracture ~~dynamics (OFST~~kinematics (SHT) and the thawing degree days (TDD) are parameters, ~~which allow~~ 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. ~~For most, a rough correspondence between OFST and TDD seems visible and some distinctive discrepancies are observed.For locations with aspect~~ A weak correspondence is apparent (see Fig. 14 in appendix A) for locations with aspects to the north and east~~, a correlation is apparent (negative for location *mh03*). Hinting~~ . This hints on a substantial influence of rock temperature and therefore incoming conductive energy fluxes. Interestingly, at ~~location~~ locations exposed to the south, ~~OFST~~ SHT seems independent of TDD.

~~Summers with very high TDD, such as in 2015, although showing the highest OFST values, result in a~~ The local break-off at ~~one location (~~location *mh02* ~~, see~~ occurred in summer 2015 (described in first paragraph of Section 4~~). The opposite behavior is observed for summer 2014, when TDD were exceptionally low due to a cold summer, and the summer offset low as well~~, page 15). This summer exhibits a record high in TDD at all locations.

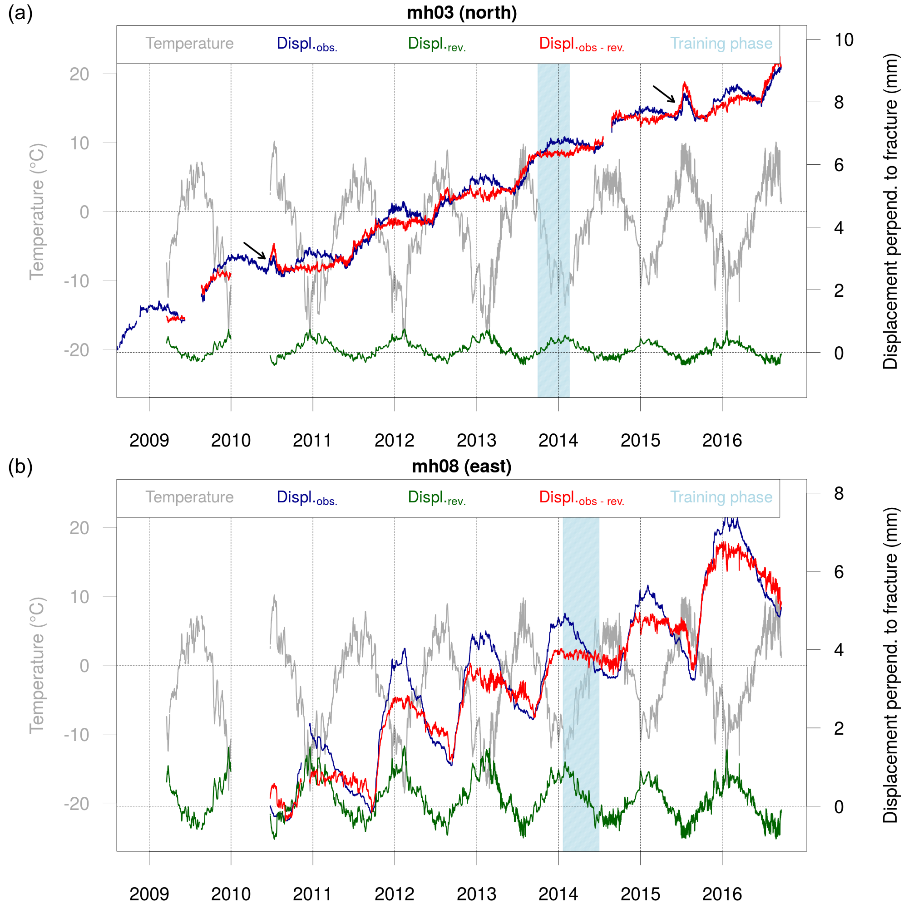


Figure 8. LRM (green) ~~and LRM+ (red)~~ applied to the ~~deformation~~ observed displacements (blue) perpendicular to the fracture at location *mh03* (a) and *mh08* (b). ~~Raw deformation measurements perpendicular to fracture (blue).~~ The reversible component (green) due to ~~thermo-elastic~~ thermo-mechanically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

4.4 Irreversibility index

The irreversibility index ~~(see Fig. 10)~~ indicates the onset of irreversible deformation ~~perpendicular to fracture~~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 at all locations. High index values can be observed in summer (~~temperature above zero~~positive temperatures) at location *mh02* (South) and *mh03* (North), during thawing period, while in winter low indices occur without

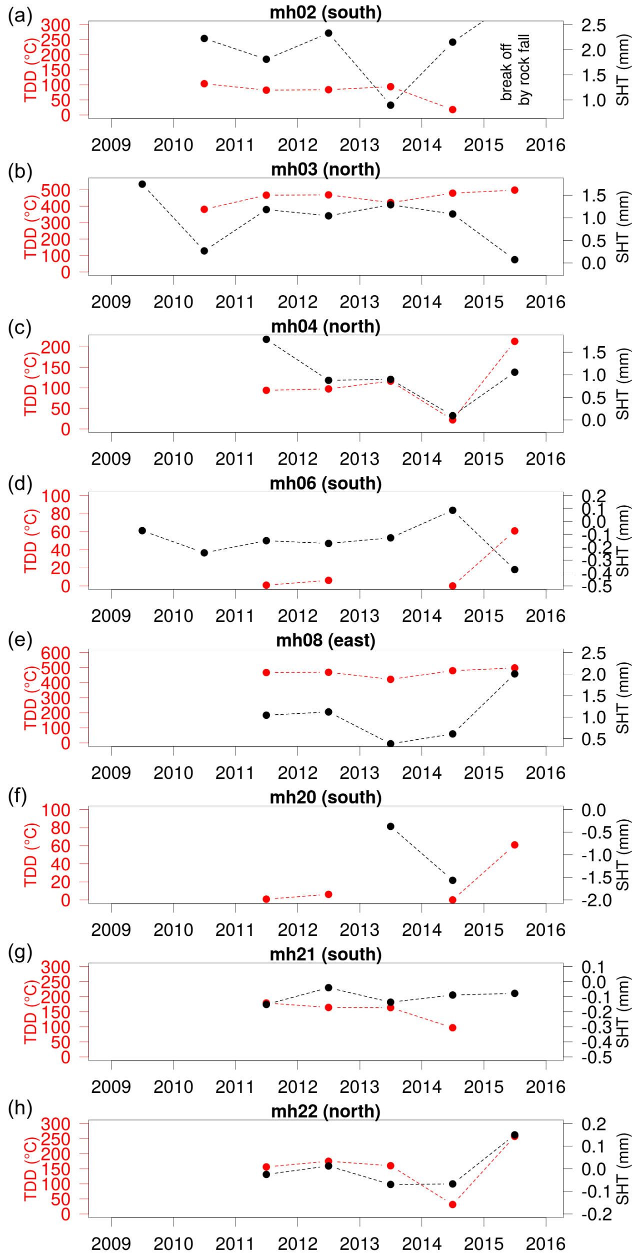


Figure 9. Inter-annual variability of thawing degree days (TDD) and summer ~~offset~~ shift of fracture ~~deformation~~ kinematics (~~OFST~~SHT) perpendicular to ~~fracture~~ fractures for all locations~~, except for location *mh20* due to many data gaps~~. Data at location *mh02* is missing from 2015 onwards due to the break-off and the TDD ~~value~~ values at ~~location *mh02*~~ a few locations for the year 2014 ~~is~~ are removed due to missing ~~measurements~~or incomplete temperature data.

any peaks (see Fig. 10a and 10b). The irreversibility index ~~indicates that irreversible motion is influenced by warm~~ shows that irreversible displacement is related to positive temperatures, which further supports our findings from the ~~relationship between OFST~~ relation between SHT and TDD (Fig. ~~??~~9).

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

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

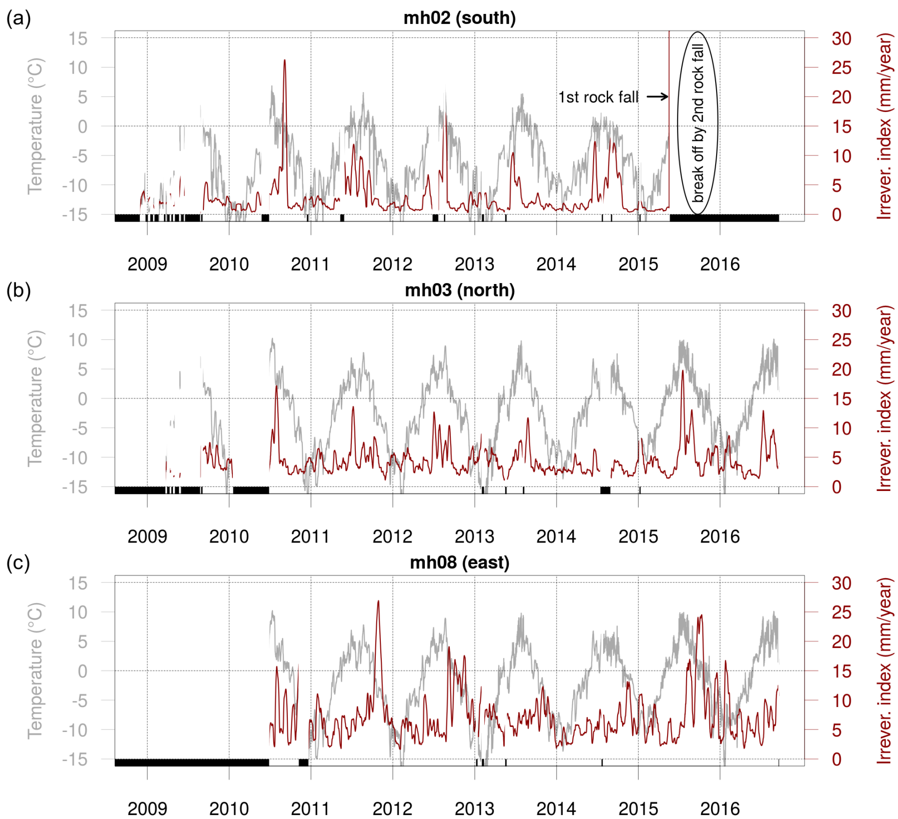


Figure 10. Irreversibility index for (a) location *mh02* (south), (b) location *mh03* (North) and (c) location *mh08* (East, on ridge) as an indicator for periods, where the irreversible ~~movement is dominating~~displacement dominates. Black bars indicate periods where no or reduced data is available.

5 Discussion

This study aims ~~to investigate the relationship between thermo-mechanical forcing and deformation and to separate irreversible from reversible processes. The presented conceptual model describes the dominating~~ at quantifying and separating reversible and in particular irreversible fracture kinematics in relation with environmental forcing. The main processes leading to fracture ~~dynamics in steep bedrock permafrost and builds the basis for isolating~~ deformation are presented in Fig. 1, enabling to isolate different processes from the field observations. Possible interactions between the different processes are not considered ~~. With the quantitative approachwe developed here~~but may well occur in nature. Thanks to our quantitative approach, we are able (i) to separate reversible from irreversible fracture ~~dynamics and produced~~ kinematics and (ii) to produce a new irreversibility index~~, which is a novel metric for assessing rock wall stability~~ . This new metric provides useful indication on 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 ~~deformation~~kinematics

~~Based on thermo-mechanical induced strain , using the LRM we are able~~ 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. 1). 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 strain dominates during this period. It further supports the postulated existence of intra-annual periods with negligible irreversible deformation. 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.

The linear regression model (LRM) can reliably reproduce the thermo-mechanically induced strain for given temperature. Although LRM can be used to describe the observed reversible deformation component ~~at all fractures instrumented . This confirms the assumption of periods with negligible irreversible movement. Further~~ in all instrumented fractures. Furthermore our analysis shows that ~~one single such quiescent phase (training phase)~~ a selected single time period of a few months is representative for the reversible component in deformation for the whole time series when the process thermo-mechanically induced 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 ~~almost no reversible motion occurs~~ the reversible fracture displacements are almost negligible apart from winter 2014/2015 after which the small failure ~~event occurred.~~

~~The process of ice formation can also cause fracture opening with decreasing temperature , but the closing phase would have to start at the onset melting~~occurred. This location even shows an annually changing relation between fracture displacement and temperature (see Fig. 7), which is ~~clearly not observed. This leads to the conclusion that ice formation is not playing a dominant role for reversible fracture deformation.~~

~~The~~ a singular case in this data set. Otherwise, the amplitude of reversible deformation varies strongly from location to location. Although we expect the thermal expansion coefficient of ~~the~~ 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~~vary spatially~~.

~~Reversible motion, which is not caused by thermo-mechanical forcing, is observed~~ 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 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 ~~at location *mh03*. This reversible motion is~~ are not caused by thermo-mechanically induced stress and also visible in the irreversibility index ~~in~~ (Fig. 10) with high values~~and~~. It may be caused by a non-local effect or points to an additional unidentified process causing reversible ~~motion.~~ 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, 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 ~~deformation~~kinematics

~~Almost~~ Close to a decade of field measurement provides enough data for inter-annual analysis of fracture ~~deformation~~kinematics. In general, all instrumented locations show a trend of fracture opening ~~, but at variable rate between locations~~or closing perpendicular to fractures, but with different rates. At each individual location, the temporal pattern of deformation is very similar every year, but the irreversible summer ~~offset (OFST~~shift (SHT) slightly varies over time. According to our analysis, this summer ~~offset seems~~ shift seems at least for north facing locations to correlate slightly with an increasing total amount of ~~energy available~~ available energy (TDD). This ~~implies~~ suggests that further warming and therefore increasing TDD's cause thawing of permafrost at greater depth, potentially leading to an increase ~~of summer offsets (OFST).~~

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 ~~of cohesion and~~ in friction, which ~~may~~ can cause irreversible deformation. For example at location *mh02*, enhanced availability of water from snow melt after summer snowfall events seems to cause accelerated irreversible deformation~~, whereby this observation can not be described with the piecewise irreversible motion of the LRM+ (see Fig. 12)~~.

As TDD ~~is defined using~~ derived from mean daily rock temperature, ~~relationship between summer offset~~ 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 ~~activity whereas~~ 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 ~~offset~~ shift (e.g. *mh02* or *mh21*).

The presented summer ~~offset~~ shift only provides total deformation between two winters without any intra-annual information. In contrast, the irreversibility index ~~is~~ can be seen as a proxy of impending rockfall activity and reveals information on the short term evolution of the irreversible fracture ~~deformation~~ kinematics all year round, even if the total summer ~~offset (OFST) deformation~~ shift (SHT) is small. ~~Even if such an index is~~ Despite based on local ~~measurement, it~~ measurements, such an index can help to identify periods of enhanced ~~creep~~ 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 ~~(approx. $2-3\,\mathrm{m}^3$)~~ and a final break-off (approx. $2-3\,\mathrm{m}^3$, timing indicated in Fig. 10a). Similar at location *mh03*, irreversible ~~creep~~ deformation occurs during the ~~melting~~ melt period, which ~~likely links~~ is likely related to a reduction of friction ~~and cohesion~~ 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 ~~rapidly~~ rapid cooling and freezing in autumn. In this case, the growth of ice in late autumn acts as a driving factor ~~(Fig. 1 D3)~~ through increasing ice pressure by ~~volumetric expansion. In this case, if the ice melts~~ cryogenic processes. Interestingly no fracture closing is observed during ice melt period in the subsequent summer ~~, the fracture does not observed to close due to missing compressing force.~~

~~This study confirms the hypothesis of Hasler et al. (2012) that at the time was based on a much more limited data set~~ indicating irreversibility of such a process. Such thermo-mechanically 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 ~~deformation~~kinematics

~~Our~~ Combined analysis of LRM ~~+ and the irreversibility index both support the idea that there are~~ and irreversibility index exhibits distinct periods of solely reversible ~~deformation periods~~ fracture kinematics and others with additional irreversible ~~deformation~~fracture kinematics. Irreversible deformation seems to be ~~strongly linked to environmental conditionsof, either~~ driven by environmental conditions, namely by rock temperature above ~~zero degrees~~ 0° C (indicating thawing) or less ~~common~~ commonly by periods of freezing conditions~~, whereby the piecewise linear trend introduced also fits this modal behavior~~. In the main winter time (temperatures well below ~~zero~~freezing) after the initial cooling phase, none of the ~~fractures instrumented show irreversible motion. Water pressureis likely a marginal process~~ 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 ~~the water can easily drain through the strongly fractured~~

~~rock and the water availability is limited~~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. These patterns may be oversimplified, as this study shows that the related processes are often superimposed and not clearly distinguishable.

6 Conclusions

Knowledge of processes and factors affecting rock slope stability is essential for detecting and monitoring potentially hazardous ~~slopes. Here we present a~~ rock slopes. A unique 7 year time series of fracture ~~deformation~~kinematics is presented, providing new insights on fracture ~~dynamics in relation~~ kinematics with respect to thermal conditions on steep high-alpine rock slopes. The intra- and inter-annual behavior of the fracture ~~dynamics~~ kinematics strongly varies between locations, but patterns at individual locations are consistent over the entire observation period~~of several years. This implies that longterm~~ . Longterm monitoring at multiple fractures ~~is essential~~ thus essentially helps to improve the process understanding of fracture ~~dynamics~~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 ~~deformation~~ kinematics and was successful in separating reversible from irreversible ~~motion. After the removal of the reversible deformation component by LRM, we constructed the irreversibility index as a new metric that allows the detection of irreversible motion and link it~~ displacements. An irreversibility index was built to detect irreversible displacement and its link to environmental forcing. Seven years of relative surface displacement measurements show that reversible fracture ~~deformation caused by thermo-elastic~~ kinematics caused by thermo-mechanically induced strains of the material is occurring at all ~~location~~ locations except one all year round~~apart from one~~, but are temporarily superimposed by other processes. In addition phases of irreversible deformation with a stepwise behavior occur mostly during periods with temperature above ~~zero degrees~~ 0° C suggesting a decrease ~~of cohesion and~~ 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. These results are ~~confirmed~~ 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 ~~information from surface with a bad~~ point information from near the surface and with a limited spatial coverage. Additional analysis of micro-seismic activity could potentially give insights with a very high temporal resolution and some spatial coverage, which ~~could get considerably improved by micro-seismic measurements.~~ is going to give another mean to characterize damage and irreversible displacement. Coupling spatio-temporal characterization of irreversible deformations with internal progression of microcrack activity could significantly improve process understanding and be applied in the context of early warning system.

Appendix A: Supplementary ~~figure~~figures

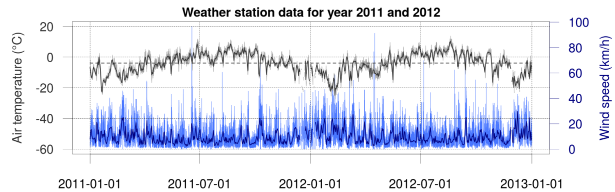


Figure 11. Time series of the in situ installed Vaisala WXT520 weather station providing air temperature and wind speed for the years 2011 and 2012. 10 minutes averages are shown in gray (air temperature) and lightblue (wind speed) whereas weekly averages are shown in darkgray (air temperature) and darkblue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

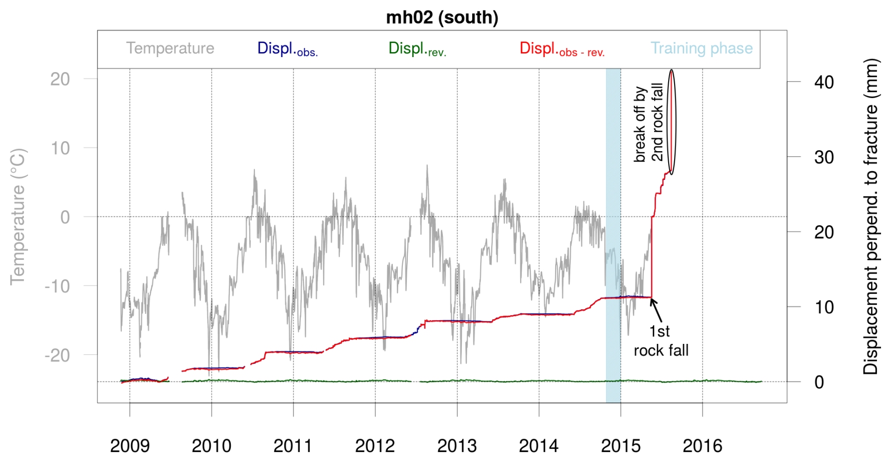


Figure 12. LRM (green) ~~and LRM+ (red)~~ applied to the ~~deformation~~ observed displacements (blue) perpendicular to the fracture at location ~~*mh03* (a) and *mh08* (b). Raw deformation measurements perpendicular to fracture (blue)~~*mh02*. The reversible component (green) due to ~~thermo-elastic~~ thermo-mechanically induced strains in rock can be modeled by a linear regression model (LRM) with temperature as input data (dark gray) and deformation measurements during a training period of several months (light blue shading). ~~The combination of the LRM (green) and the piecewise linear deformation trend (blue dotted line, given by a reversible and creep phase, a fracture deformation measurement in each~~ Subtracting these reversible ~~phase and a linear interpolation in~~ displacements from the ~~creep phase)~~ observed data results in the ~~modeled fracture deformation LRM+ (~~red ~~). The discrepancies between the LRM+ and the field measurements occur during melting periods can not be described with the piecewise~~ line, referred to as irreversible ~~motion of the LRM+~~fracture displacement.

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 12. Additional data can be accessed via the PermaSense GSN data portal

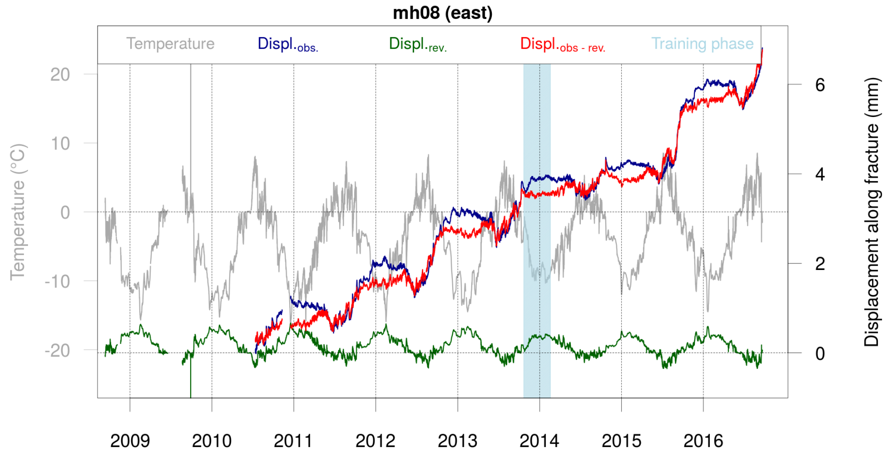


Figure 13. LRM (green) applied to the observed displacements (blue) along the fracture at location *mh08*. The reversible component (green) due to thermo-mechanically induced strains in rock can be modeled by a linear regression model (LRM) with temperature as input data (dark gray) and deformation measurements 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.

(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 figures. 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. 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 ~~paper was scientifically evaluated by the SNSF, and financed by the Swiss Confederation and by~~ manuscript is part of the project X-Sense 2 and was financed by nano-tera.ch ~~.~~ (Ref.: 530659).

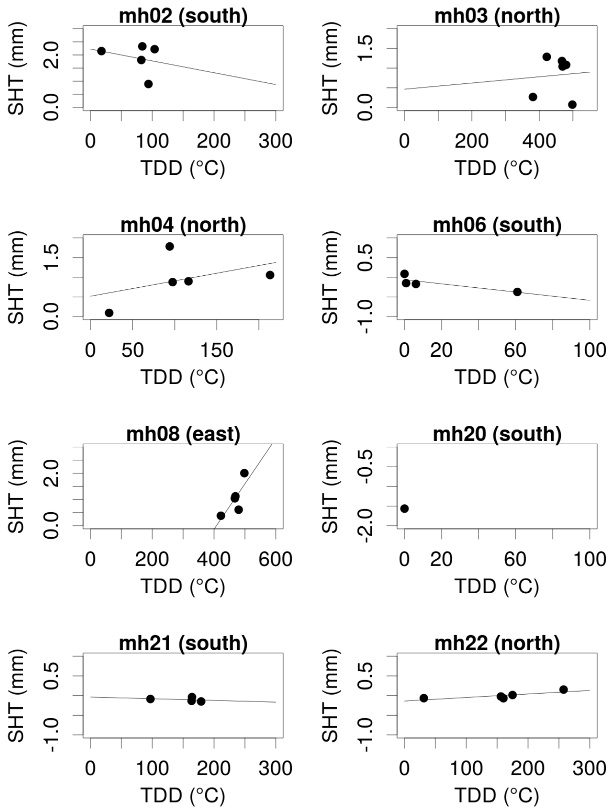


Figure 14. Summer shift (SHT_{summer}) of displacement perpendicular to fracture against yearly thawing degree days (TDD_{year}) for locations *mh02*, *mh03*, *mh04*, *mh08*, *mh21* and *mh22*. The black line indicates the regression function.

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.

Haeberli, W.: On the morphodynamics of ice/ debris-transport systems in cold mountain areas, Norsk Geografisk Tidsskrift, 50, 3–9, doi:10.1080/00291959608552346, 1996.

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.

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.

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 heataves, 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.