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Quantifying irreversible fracture deformation in steep fractured bedrock permafrost at Matterhorn

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Motivation and problem statement

Assessing and anticipating rock wall instability is a challenging task, mainly because of the incomplete understanding of precursory signals and the inherent rock-(and ice-)mechanical complexity of fractured inhomogeneous rock masses.

Fig. 1: Matterhorn rockfall

Goal

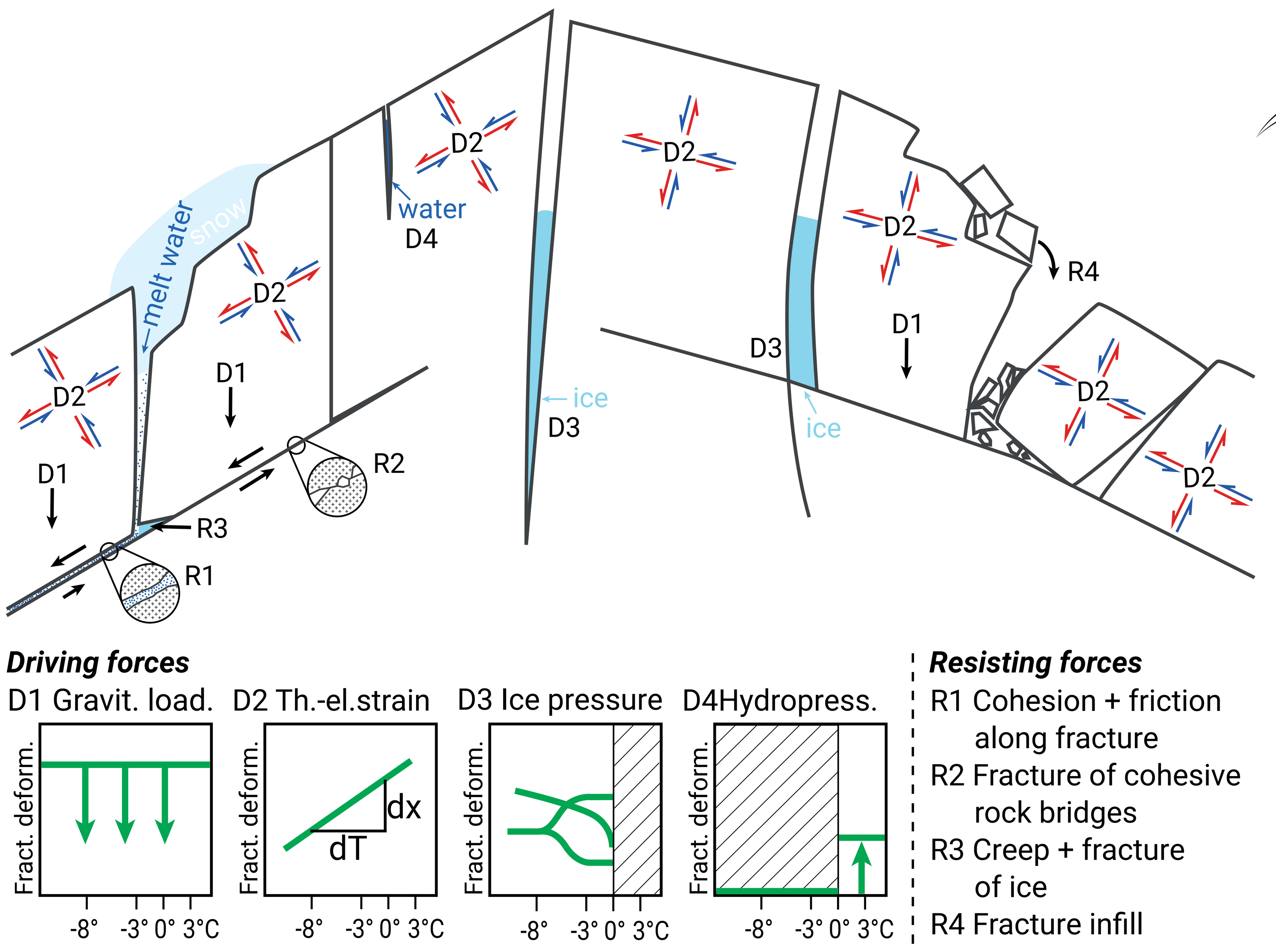
Transfer theoretical and laboratory understanding of rock fatigue and fracturing in cold environments to real conditions.

Main results

- statistical model describing the fracture deformation due to thermo-mechanical forcing and enabling the differentiation from the thawing-related creep
- irreversibility index is a proxy of impending rockfall activity revealing information of effective fracture deformation all year round, even if the total summer offset deformation is small
- irreversible enhanced fracture deformation during summer is triggered by percolating melt water, which changes the conditions in shear zone that leads to a decrease of friction along fracture

Which processes cause fracture deformation?

Surface displacements in steep fractured bedrock permafrost could reflect environmental processes that are controlled by temporally varying environmental forcing. Fracture dynamics consists of reversible and irreversible movement components resulting from a combination of temporal varying drinving and resisting forces (Fig. 2).

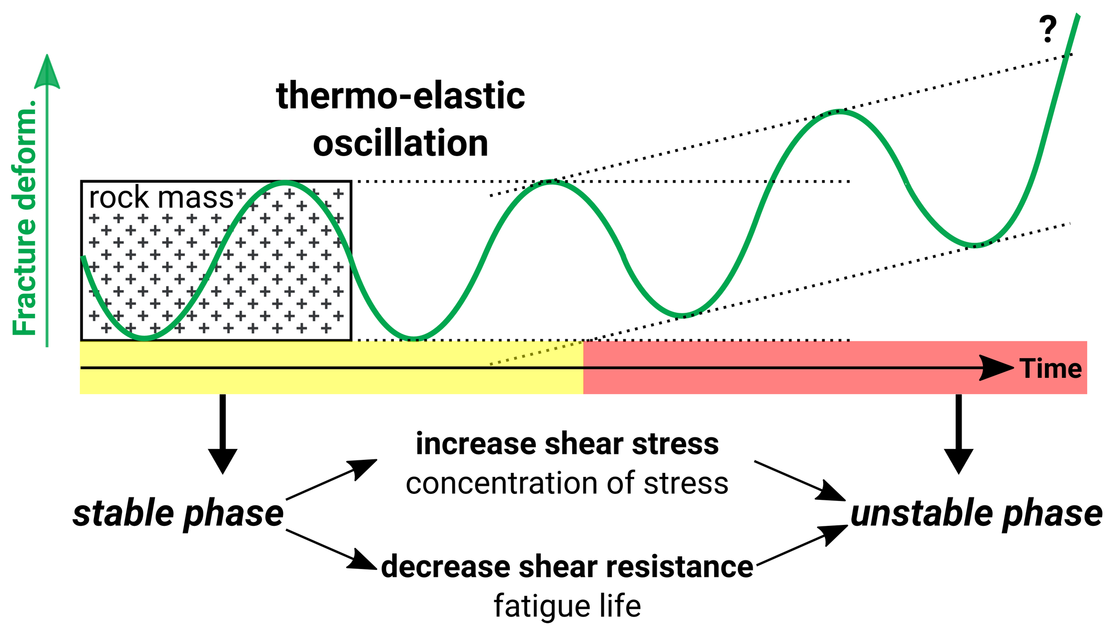


Driving forces
D1 Gravit. load.
D2 Th.-el.strain
D3 Ice pressure
D4 Hydropress.

Resisting forces
R1 Cohesion + friction along fracture
R2 Fracture of cohesive rock bridges
R3 Creep + fracture of ice
R4 Fracture infill

Fig. 2: Conceptual model of permafrost affected slope instabilities in steep fractured bedrock.

From reversible to irreversible deformation



Persistent thermo-elastic oscillations of an initially stable rock mass, 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).

Fig. 3: In long term, initially reversible deformation of rock mass can get irreversible

Monitor fracture deformation - field installation

Switzerland, Valais Alps, Matterhorn

- 3500 m a.s.l., NE-ridge, comprises both sides of the ridge
- steep fractured gneiss, partially debris covered ledges

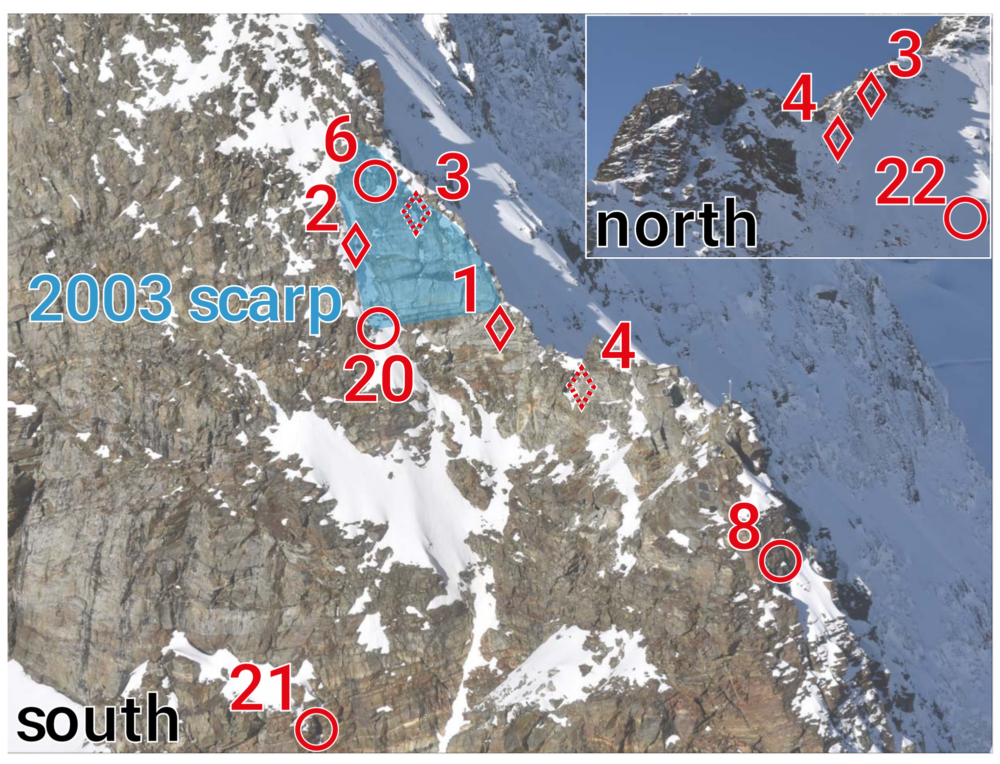


Fig. 4: Nine locations with crackmeters and thermistors

ForaPot crackmeter

- potentiometric measurements
- very high accuracy (≤ 0.01 mm)
- temperature-compensated
- multiple axes possible


Fig. 5: Crackmeter installation

Temperature

- rock surface
- at depth

Weather station

- Vaisala WXT520

7 years of field measurements

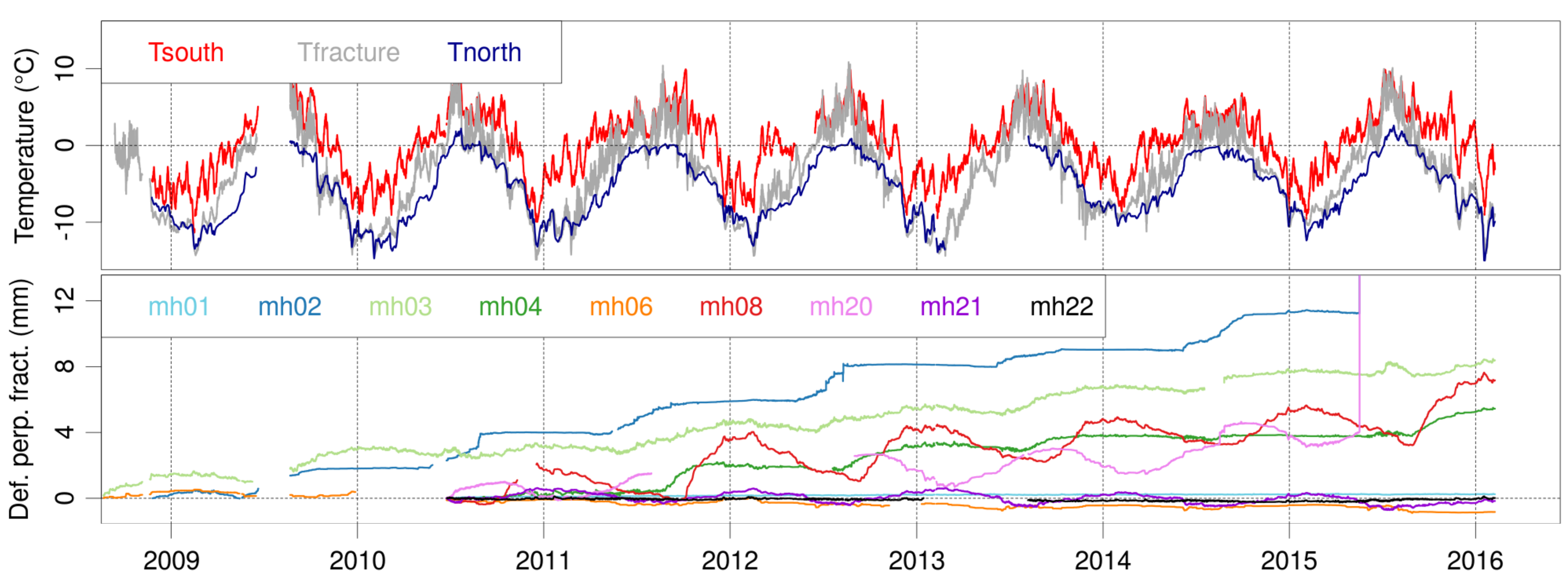


Fig. 6: Time series of the thermal conditions and fracture deformation at the field site Matterhorn

Quantify irreversible fracture deformation

Model temperature dependent fracture deformation (*LRM*)

As irreversible motion is suspected to occur prior to global gravity-driven slope failures, we developed a statistical model (*linear regression model LRM*) for computing the reversible thermo-mechanical induced fracture dynamics (Fig. 7) in steep permafrost bedrock calibrated with field measurements.

$$y_{lrm,t_i,k} = \beta_{0,k} + \beta_{1,k} \cdot T_{rock,t_i} + e_{i,k}$$

We apply this linear regression model with rock temperature as an input to isolate the ***irreversible deformation***, which is the ***residual*** $e_{i,k}$ of the model.

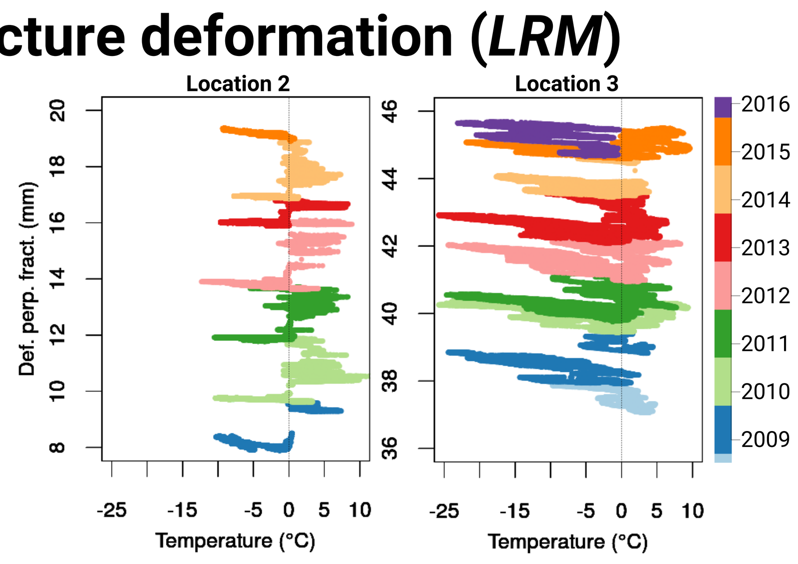


Fig. 7: Thermo-elastic induced strain

Model total fracture deformation (*LRM+*)

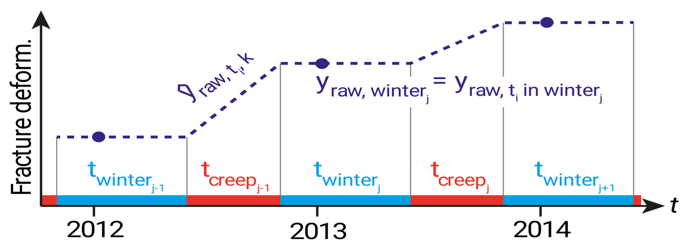


Fig. 8: Calculation of the LRM+ trend

The *Linear regression model plus (LRM+)* is a combination of LRM and irreversible trend ($\hat{y}_{raw,t_i,k}$, Fig. 8). It is given by one data point each winter ($y_{raw,winter_j}$) and a defined winter period (t_{winter_j}).

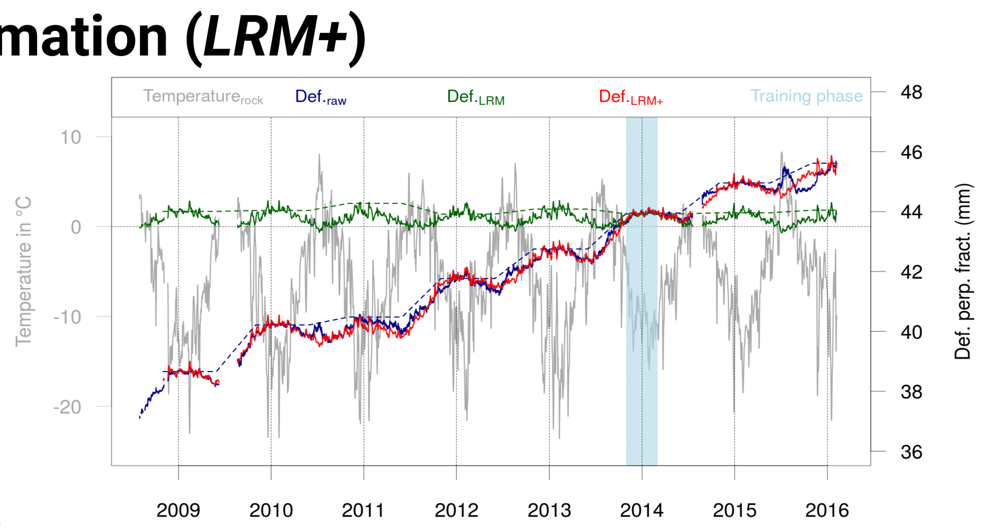


Fig. 9: *LRM+* applied to the deformation perpendicular to fracture of location 3 for 7 years.

Irreversibility index - new metric for stability

This index enables detecting periods when overall motion is not dominated by reversible thermo-elastic induced strains. It needs reversible and raw fracture deformation as input.

$index_{irrev.}$ = runmax$_{7days}(y_{diff})$ - runmin$_{7days}(y_{diff})$ | y_{diff} = |runmean$_{14days}(y_{raw})$ - runmean$_{14days}(y_{lrm})$|

The output *provides indications on rock wall stability and potential proxy of failure imminence*.

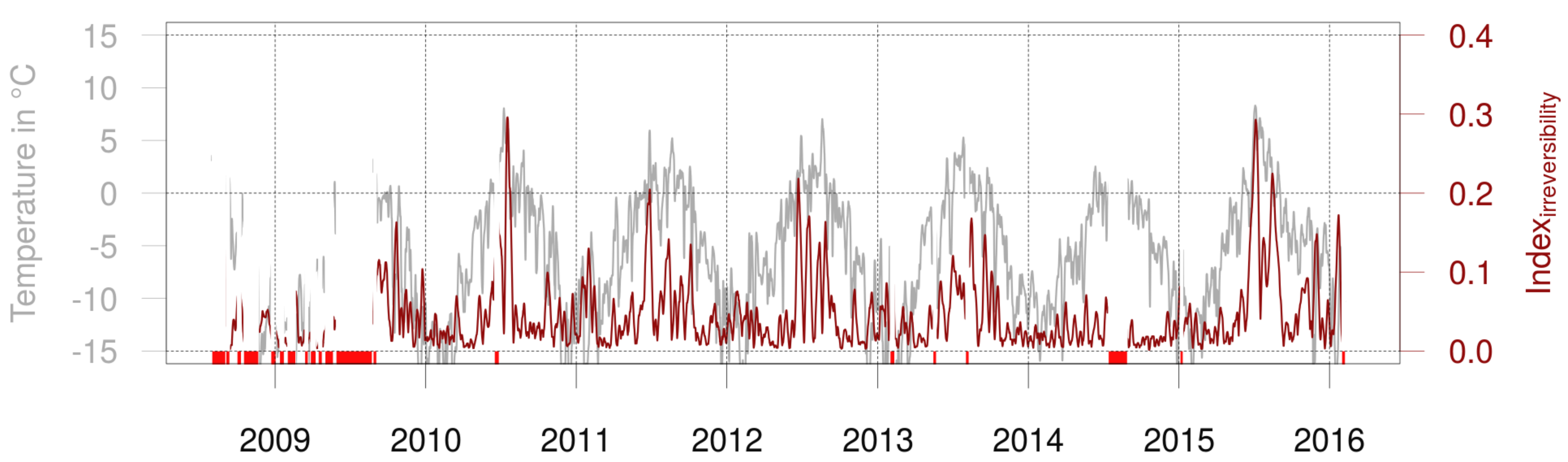


Fig. 10: Irreversibility index for location mh03. Red bars indicate periods with reduced data.

The result in Fig. 10 orchestrates:
- every year an increase in irreversible motion during melting periods
- location, creep and fracture of ice might attenuate the motion during freezing periods
- thawing related irreversible offset is visible during summer periods
- the irreversible fracture deformation is caused by a decrease of the cohesion and friction along
- fracture due to changing conditions in shear zone, triggered by percolating water