Fracture dynamics in steep bedrock permafrost

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Debris fall summer 2003 1500 m$^3$, *ice-containing scarp*
Our patient does not fit into a laboratory.
So the laboratory has to go on the mountain.
Rock-slopes in alpine environments *debris, rock-glacier, rock-wall*

- **debris slope**
- **steep (structured) rock-wall**
- **near vertical rock-wall**

*snow, debris, heterogeneous*
Rockfall *rupture/failure* → different processes pre-condition and trigger

- *debris/boulder fall* → thermal forcing?
- *block fall* → thawing related failure?
- *bergsturz* → debutressing?

* volumetric classification by Whalley (1974, 1984)
Effect of rise in temperature on stability *Strength reduction by* warming ice-filled fractures

Davies et al. (2001)

At $-0.5^\circ C$:

$\tau_{\text{icefilled}} < \tau_{\text{icefree}}$

thawing permafrost bedrock

Mellor (1973)

Increase temperature ($-10^\circ C$ to $0^\circ C$):

$\rightarrow$ drop in compressive strength 20-50%  
$\rightarrow$ drop in tensile strength 15-70%
Summer deformation initiated by thawing

Hasler et al. (2012)

Blikra & Christiansen (2014)
Field site Hörnligrat, Matterhorn, Switzerland

Field site Matterhorn-Hörnliridge
- 3500 m a.s.l., north-east ridge
- main orientation SSE and NNW

Potential permafrost distribution
- Extensive permafrost likely, very thick in places
- Extensive permafrost likely, increasing thickness
- Extensive permafrost likely
- Local permafrost possible, patchy to extensive
- Local permafrost possible, frequent patchy distribution
- Local permafrost possible, patchy, discontinuous
Motivation
Gain better process understanding of rock-slope movement in ice-rich fractured bedrock permafrost.

Approach
Statistical analysis of relative fracture movement.

Target
Deciphering mechanical controls in steep frozen rock-walls.
Conceptual approach *driving forces vs. resistive forces*
Conceptual approach *driving forces vs. resistive forces*

**Driving forces**
- D1-Gravity: Fracture size
  - Fracture size
  - $-8^\circ$ to $3^\circ$ C

**Resistive forces**
- R1-Shear Resistance along Fracture
- R2-Fracture Toughness
- R3-Ice Deformation
- R4-Fracture Infill

S. Weber, Department of Geography, University Zurich, AK Permafrost, Hamburg, 2016
Measurement setup: *surface displacement and temperature*

**Crackmeter**
- accuracy: 0.01 mm
- relative displacement

**Temperature**
- ground surface temperature
- temperature at depth

Beutel et al. (2009)
Existing installation *crackmeter & temperature measurement (2’ intervall)*
Raw data *temperature and relative fracture movement*
Model fracture dynamics *apply linear regression and sum with trend*
Model fracture dynamics apply linear regression and sum with trend,
Model fracture dynamics apply linear regression and sum with trend.
Model fracture dynamics apply linear regression and sum with trend.
Model fracture dynamics apply linear regression and sum with trend
Model fracture dynamics *apply linear regression and sum with trend*
Model fracture dynamics *apply linear regression and sum with trend*

<table>
<thead>
<tr>
<th>Temperature$_{rock}$</th>
<th>Fracture$_{raw}$</th>
<th>LR$_{training}$</th>
<th>Fracture$_{reversible}$</th>
<th>Fracture$_{modeled}$</th>
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<tbody>
<tr>
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<tr>
<td>Temperature in °C</td>
<td>Fracture dynamics (mm)</td>
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<tr>
<td>2009</td>
<td>2010</td>
<td>2011</td>
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Summer creep offset in summer related to thawing
Summer creep offset in summer related to thawing
Limits of existing field experiment extend measurement setup

Fracture dynamics
- 7 years of data
- statistical analysis

⇒ limits
- point measurement
- “only” at surface
- 2’ sampling rate

MS/AE field experiment

pilot study 2011 on Jungfraujoch
pilot study 2012 at Matterhorn
Limits of existing field experiment  extend measurement setup

**Fracture dynamics**
- 7 years of data
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- MS/AE field experiment
  - pilot study 2011 on Jungfraujoch
  - pilot study 2012 at Matterhorn
Damage activity in rock \textit{micro-seismic/acoustic emission (MS/AE) approach}

powerful technique to early detect/track the evolution of damage
+ passive and non-destructive
+ look inside the rock mass

\textit{MS/AE} = transient elastic waves generated by the release of energy during rapid local changes of strains in solid materials
Thanks for your attention!

Overall aim: improve understanding of preconditioning processes in alpine environments that can result in rock-slope movements

Acknowledgment: S. Weber, Department of Geography, University Zurich

AK Permafrost, Hamburg, 2016
Surface displacement & temperature *in-situ*

**Crackmeter**
- accuracy: 0.01 mm
- relative displacement
- status quo: measures in 2’ interval

**L1-GPS**
- accuracy: few mm
- absolute displacement
- status quo: daily position solution relative to fix point
Surface displacement remote

Photogrammetry

Laserscan

Radarinterferometer

temporal resolution

spatial resolution

© PermaSense

© Andreas Hasler

© Andreas Vieli
Terrestrial Laser Scan  

1st scan autumn 2015
Terrestrial Laser Scan 1st scan autumn 2015
Modeled subsurface temperature (north-south cross section)

Modeled surface temperature (view on north-east ridge)

© Jeannette Nötzli
Damage activity in rock *micro-seismic/acoustic emission (MS/AE) approach*

**Powerful technique to early detect/track the evolution of damage**

+ passive and non-destructive

+ look inside the rock mass

**MS/AE** = transient elastic waves generated by the release of energy during rapid local changes of strains in solid materials

**Failure/Rupture** → **MS/AE**, source

**Detection range**

**Frequency**

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AK Permafrost, Hamburg, 2016
**Experiment setup** *installation overview*

**Measure/model temperature**
- ground surface temperature
- temperature at different depth

**Measure surface displacement**
- crackmeter *short time scale*
- GPS *long time scale*
- TLS *long time scale, spatial coverage*

**Capture acoustic/seismic activity in all frequency range**

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Continuous recording</th>
<th>Triggered recording</th>
</tr>
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<tbody>
<tr>
<td>Hz</td>
<td>1 Hz</td>
<td>10 Hz</td>
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<td></td>
<td>100 Hz</td>
<td>1 kHz</td>
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<td>100 kHz</td>
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- Geophone
- Accelerometer
- Acoustic emission
- Geophone
- CR
- Geophone
- Accelerometer

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Monitor rock-slope *work in progress*

**1 – data processing**  
*How to cope with attenuation?*

![Diagram showing acoustic sensors detecting a crack](image)

- Detection
- No detection
- Detection

Natural medium = low pass filter, depends on distance of the source

**2 – data analysis**  
*e.g. size frequency distribution with evolution of b-exponent*

![Graph showing size frequency distribution](image)

- $b = -1.9 \pm 0.1$
- $b = -1.9 \pm 0.08$
- $b = -2 \pm 0.08$
- $b = -2.9 \pm 0.1$

**3 – event detection**  
*How can we distinguish events from noise?*
MS/AE challenges *work under progress*

**Fracture dynamics**
- existing setup
- 6 years of data
- statistical analysis

⇒ limits
- point measurement
- “only” at surface
- 2’ sampling rate

**Longterm field experiment**
- pilot study 2011 on Jungfraujoch
- pilot study 2012 at Matterhorn

**MS/AE field experiment**
- spatial coverage
- information at depth
- high temp. resolution

⇒ challenges
- lot of noise
- big data (30 GB/day)
MS/AE challenges *work under progress*

**Longterm field experiment**

- Fracture dynamics
  - existing setup
  - 6 years of data
  - statistical analysis

⇒ **limits**
  - point measurement
  - "only" at surface
  - 2′ sampling rate

- MS/AE field experiment
  - pilot study 2011 on Jungfraujoch
  - pilot study 2012 at Matterhorn
  + spatial coverage
  + information at depth
  + high temp. resolution

⇒ **challenges**
  - lot of noise
  - big data (30 GB/day)
Boulder fall *small event on May 18, 2015*

**Before the event**

**After the event**
Fracture dynamics *summer 2015*

![Graph showing crackmeter measurements over months from March to September.]
Fracture dynamics *summer 2015*

- **Boulder fall**
- **Break off**
- **Summer**

Measurements Fieldsite MS/AE Boulder fall FBM Lab experiments

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Fracture dynamics *summer 2015*

- Boulder fall
- Break off
- Summer
MS/AE activity **August 14, 9-10 am**

Overview 14.08.2015 Nfft = 2¹¹ overlap = 0.8

- Piezo R4 alpha (35-80 kHz)
- Piezo R45 (5-30 kHz)

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What’s the source of the MS/AE signal?

- initiation of microcracks
- propagation of microcrack
- friction in existing clefts

→ need of lab experiments
MS/AE activity August 09, 20-21 pm

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Different types of rupture model dealing with heterogeneity exist.
(Percolation Model, Thermal Fuse Model, Sand Pile Model, Fiber Bundle Model, etc.)

choose to study **Fiber Bundle Models (FBM):**

(i) simplest model of rupture  
(ii) naturally includes heterogeneities  
(iii) effect of stress redistribution  
(iv) direct link to acoustic emissions

Fiber Bundle Model (FBM) = collection of elastic-brittle objects connected in parallel and clamped to a medium that transmits forces between the fibers.

Each fiber can deform linearly up to a threshold value.

When this value is reached, the fiber fails by no longer being able to carry any force. The force it carried is then *redistributed.*
Lab experiment *why?*

Fracture dynamics

- result of different processes
  - thermo-mechanical forcing
  - summer creep

- first melting day starts
  - needs investigation

Lab experiment
- investigate sensitivity of shear resistance in fractures to changes in water availability
Lab experiment *why?*

Fracture dynamics

- result of different processes
  - thermo-mechanical forcing
  - summer creep

summer creep starts

first melting day needs investigation

Lab experiment
investigate sensitivity
of shear resistance in fractures
to changes in water availability

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AK Permafrost, Hamburg, 2016
Lab experiment *why?*

Fracture dynamics

result of different processes

- thermo-mechanical forcing
- summer creep

first melting day starts

needs investigation

Lab experiment

investigate sensitivity of shear resistance in fractures to changes in water availability
Lab experiment *friction in fractures, sensitivity to changes*

**Motivation**
Linking field observations with mechanical laboratory observations

**Approach**
Friction test in lab

**Methodology**
Shear tests under different temperature condition with varying water/ice availability