Technische Universität München

Alpine Naturgefahren und Herausforderungen für alpine Infrastruktur in der Zukunft

Bauen mit Holz im alpinen Raum

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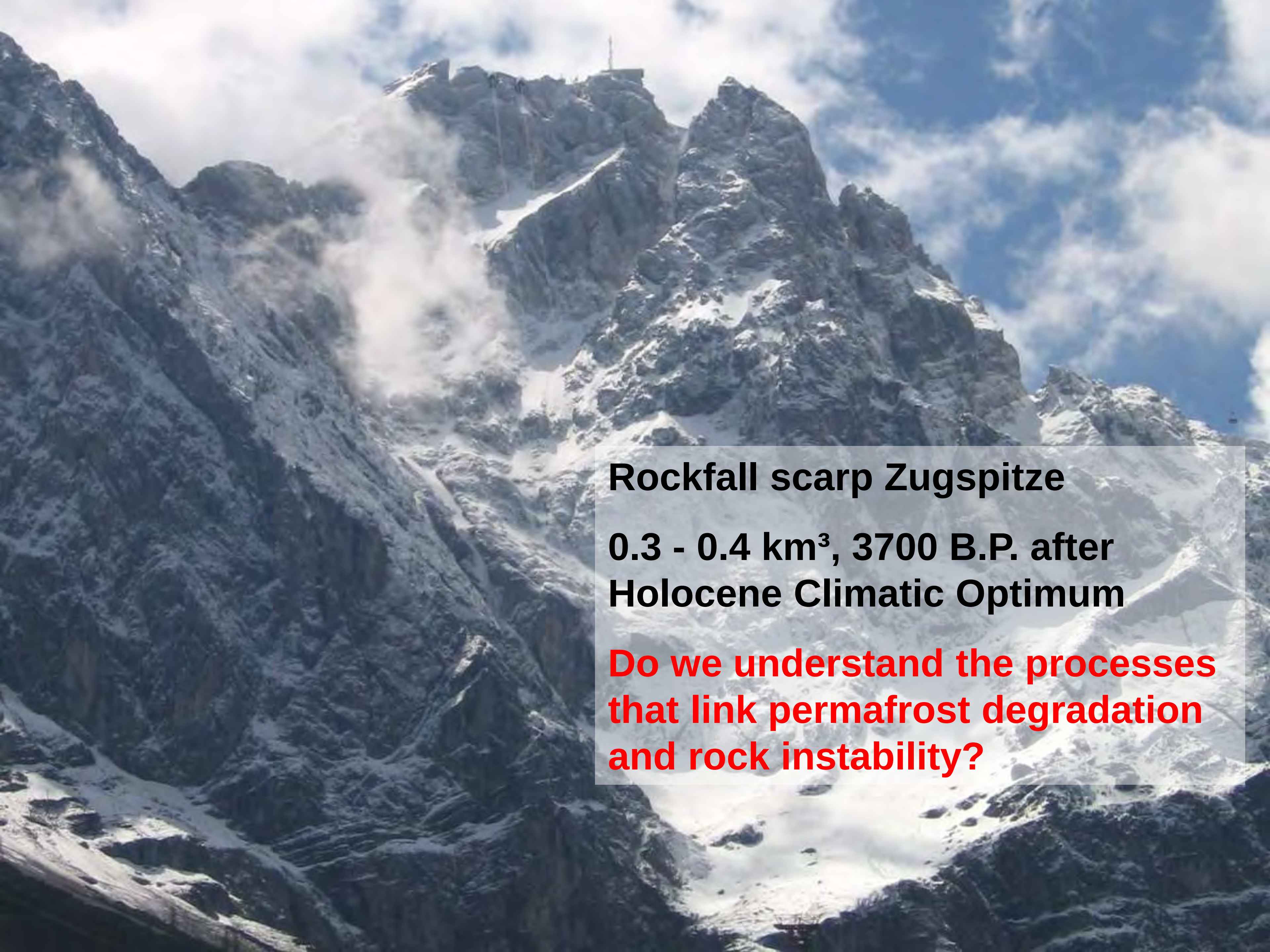
Technische Universität München

Abschätzung zukünftiger Naturgefahren:

1. Degradierung Permafrost

2. Murgangaktivität

3. Steinschlagaktivität

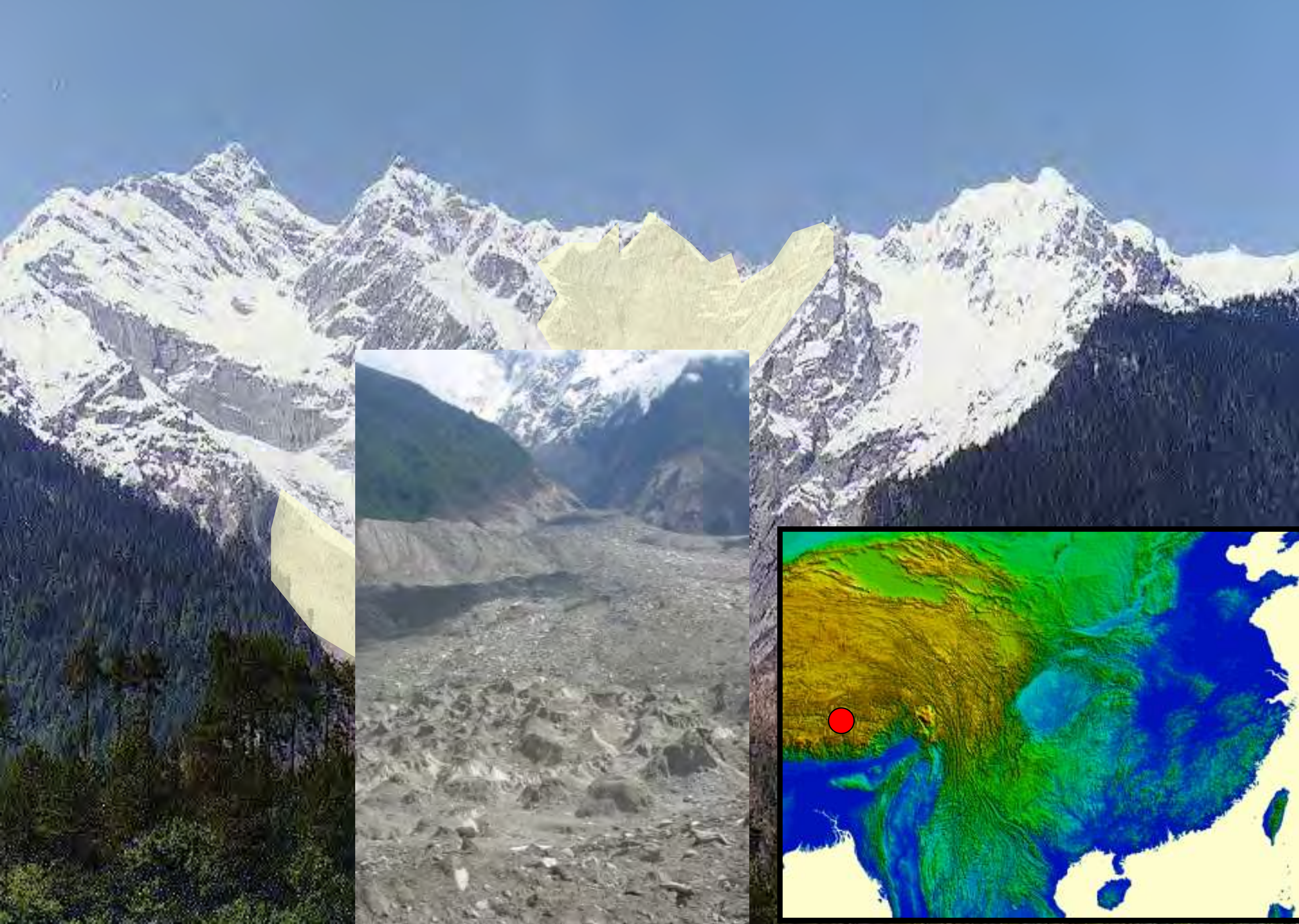


Rockfall scarp Zugspitze

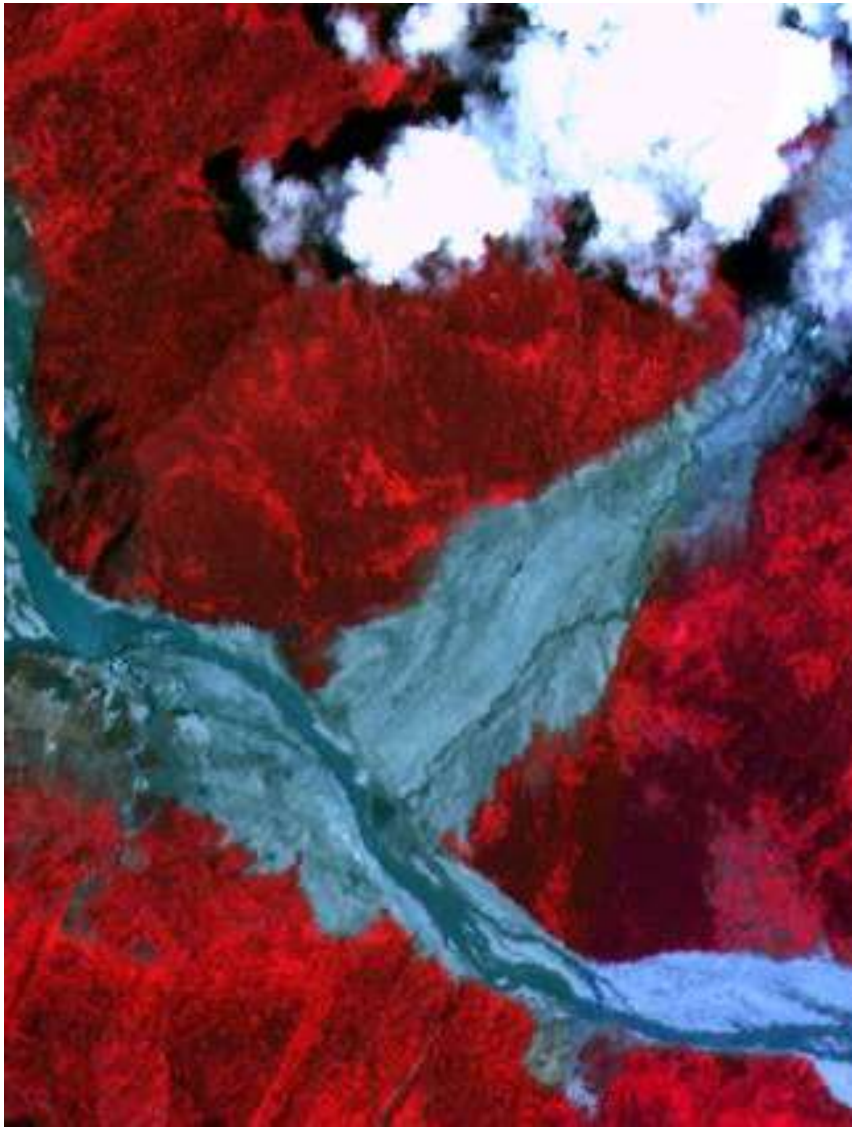
0.3 - 0.4 km³, 3700 B.P. after Holocene Climatic Optimum

Do we understand the processes that link permafrost degradation and rock instability?

Yigong Rock Avalanche April 2000 (Foto by Runqiu Huang)



Hazard due to the 2000 Yigong (Bomi, Tibet, China) rock avalanche



Rock slope failure: April 9, volume 0.28 km^3

Landslide dam: 60-100 m high

Blocking of Yigong Zangbo River

Upstream flooding: affected 4000 people, several schools/villages & Yigong tea garden

Channel construction May 3-June 3: 1000 m long, 150 m wide top, 24 m deep, 1.4 mio m^3

Catastrophic breach starting June 10

Max. discharge June 11: discharge 120,000 m^3/s at Tongmai bridge 17 km downstream, water level 34 m above bridge deck

Flood distance: 216 km China, 284 km India, flash flood 450 km downstream 5 m high

Effects (India): >20 bridges destroyed (including steel suspension bridges), > 50000 people rendered homeless

Rock slope failure in permafrost rock walls

Kolka-Karmadon rock-/ice avalanche (Russ. Caucasus 2002, 100 mio. m³)

140 casualties

Huggel et al. 2005

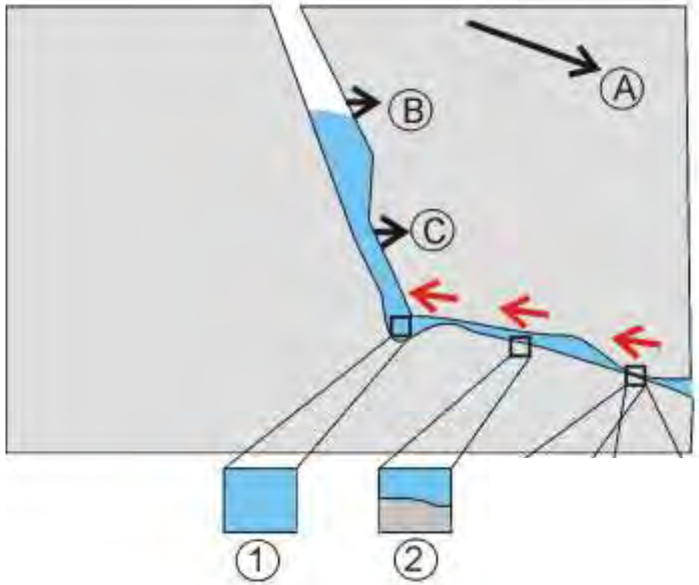
Huascarán rock-/ice avalanche (Peru 1970, 50-100 mio m³)

20.000 casualties

Erismann and Abele 2001

Rock creep in permafrost rocks

Deformation Gipfelseilbahn
(Gemsstock, Andermatt, CH)



Davies et al. 2003/Fischer et al. 2006

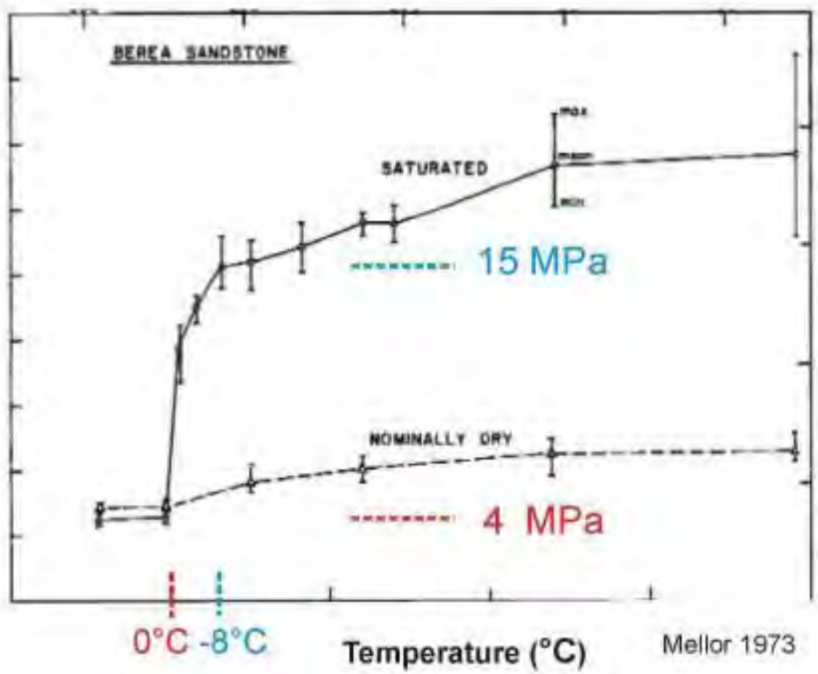
Murton et al. 2006/ Gruber & Haeberli 2007

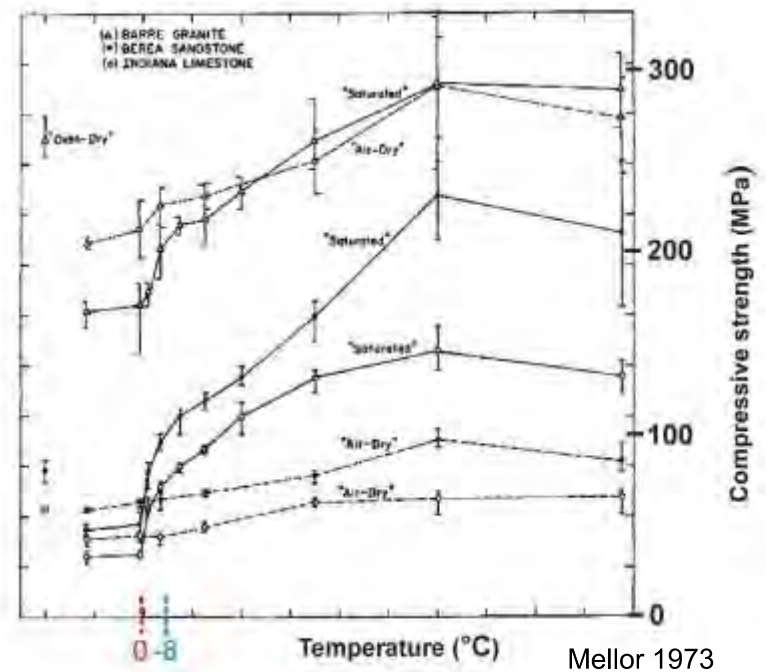
Davies 2000/Arenson& Springman 2005

Guenzel 2008

1. Why/How does thawing affect rock-mechanical properties (friction/fracturing)?
2. At what time and spatial scales of destabilisation do rock- or ice-mechanical processes dominate instability behaviour?
3. Empirical evidence for rock mechnical destabilisation when thawing?

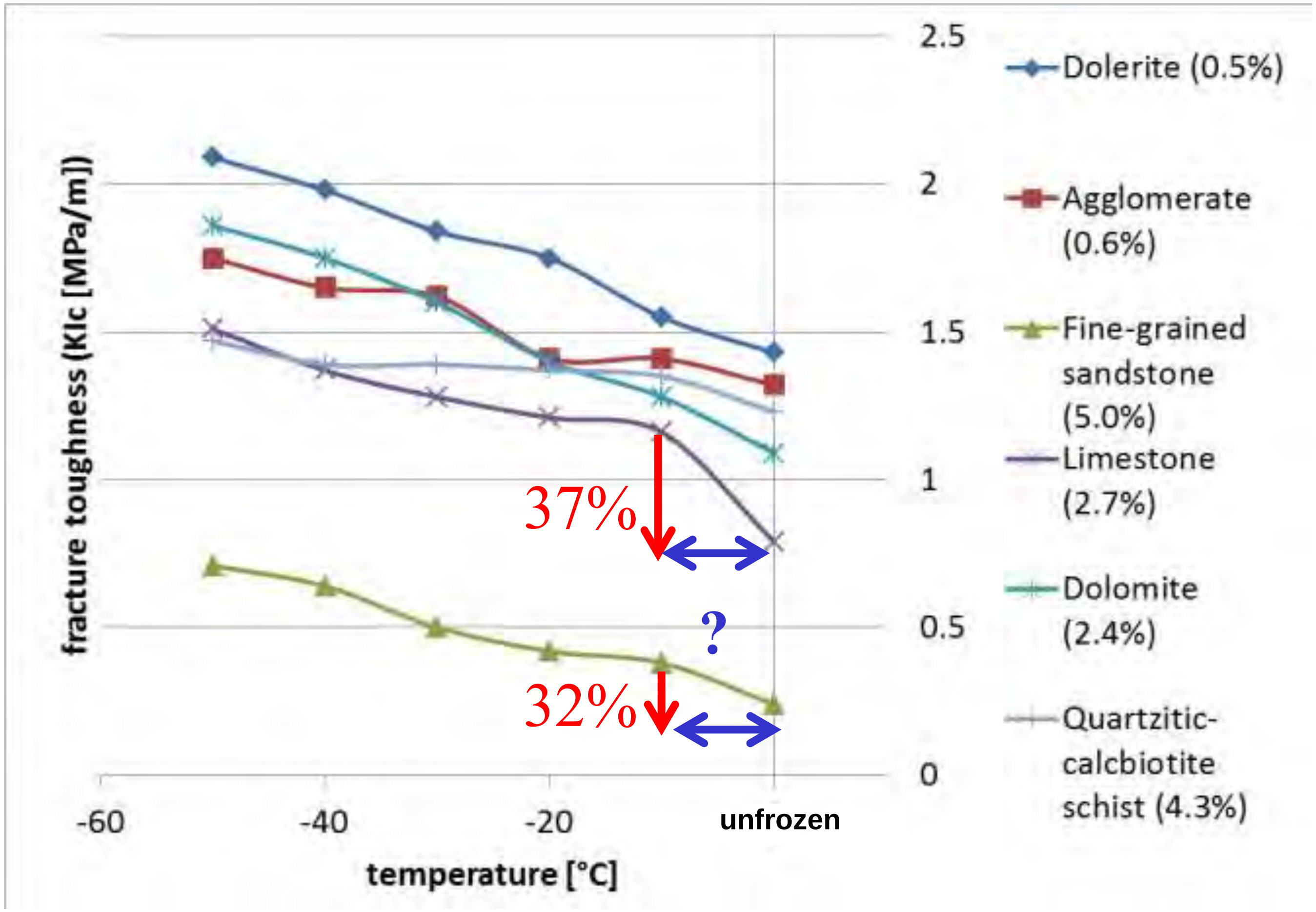
Compressive and tensile rock strength during thaw





- Compressive and tensile strength of saturated intact rock decrease by 25-75% when thawing (Mellor 1973).

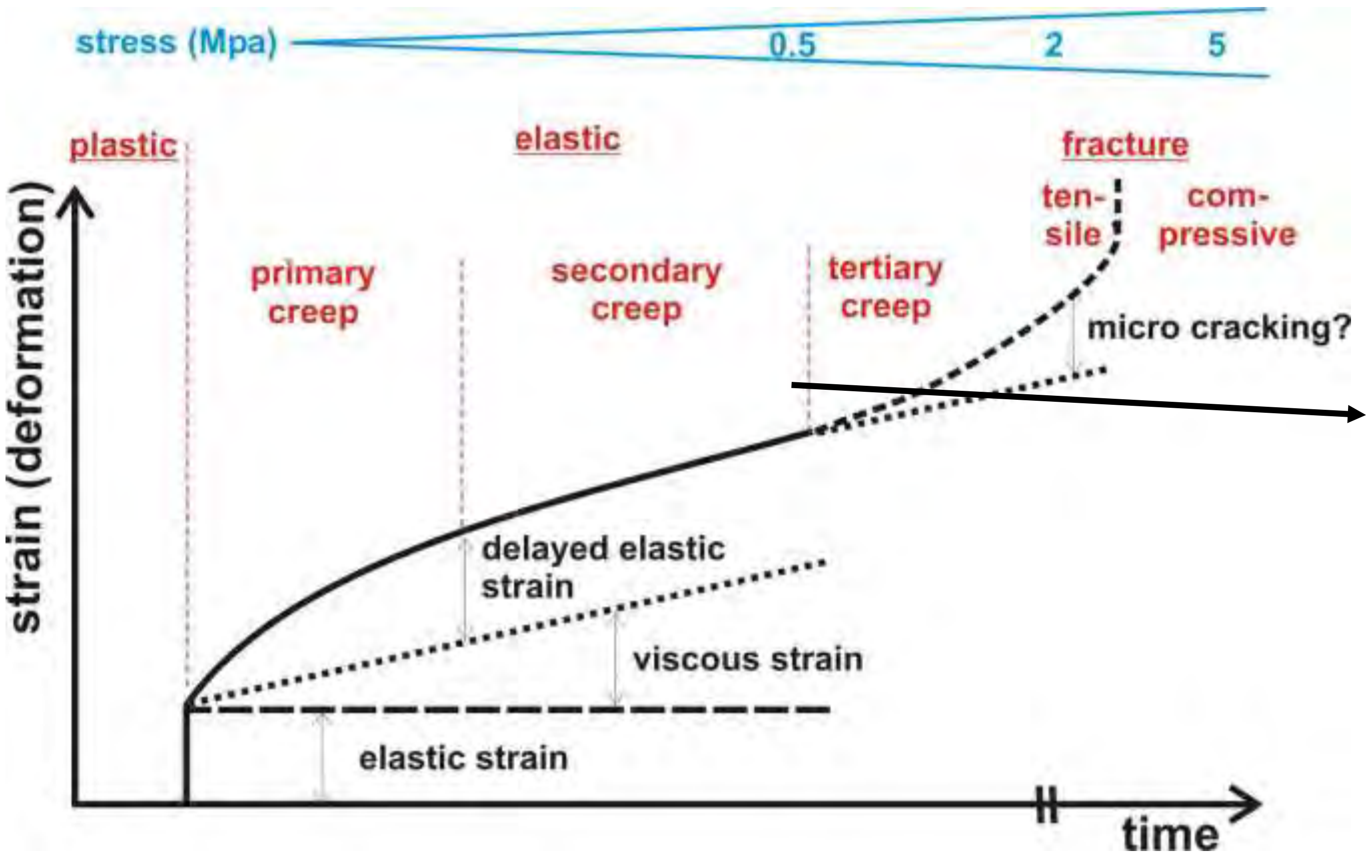
Fracture toughness during thaw



Dwivedi et al. 2000

- Fracture toughness in water-saturated rocks decreases by up to 40% when thawing (Dwivedi et al. 2000)
- This effect is more pronounced for repeated freezing (Inada&Yokota 1984)

Shear resistance of ice itself



$$\tau_{xy}^{n} = \varepsilon_{xy} / A$$

ε_{xy} strain rate

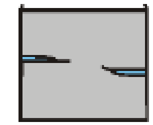
τ_{xy} shear stress

- At very low velocity (i.e. strain rate), at which e.g. subcritical cracking of rock bridges occurs, the shear resistance of ice due to creep is negligible.
- Fracturing only occurs at higher velocities (strain rate $>10^{-3}$ s^{-1}; Sanderson, 1988).

A preliminary rock-ice mechanical model

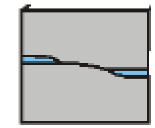
$$|\tau| = \frac{K_c\sqrt{\pi a}}{2w}$$

fracture of rock bridges



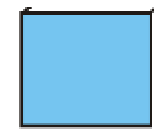
$$+\sigma'\tan(\varphi + JRC * \log10(\frac{\sigma_c}{\sigma'}))$$

total friction due to fracture roughness



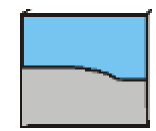
$$+\frac{\varepsilon_w}{A_0\exp(-\frac{16700}{T})}$$

reduction of effective shear stress due to secondary/tertiary creep of ice



$$+(-145 * T_c + 0.47 * \sigma' - 3.5)$$

failure criterion of ice in rock clefts



<u>Dynamic components (yellow):</u>

| τ | shear stress at failure, Kc critical fracture toughness, σ_c compressive strength and temperature T_c [°C] und T [K]

Processes act individually, in succession or in combination

Destabilisation in time

$$|\tau| = \frac{K_c \sqrt{\pi a}}{2w}$$

fracture of rock bridges

$$+ \sigma' \tan(\varphi + JRC * \log 10(\frac{\sigma_c}{\sigma'}))$$

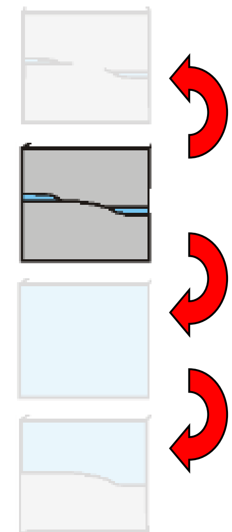
total friction due to fracture roughness

$$+ \frac{\varepsilon_w}{A_0 \exp(-\frac{16700}{T})}$$

reduction of effective shear stress due to secondary/tertiary creep of ice

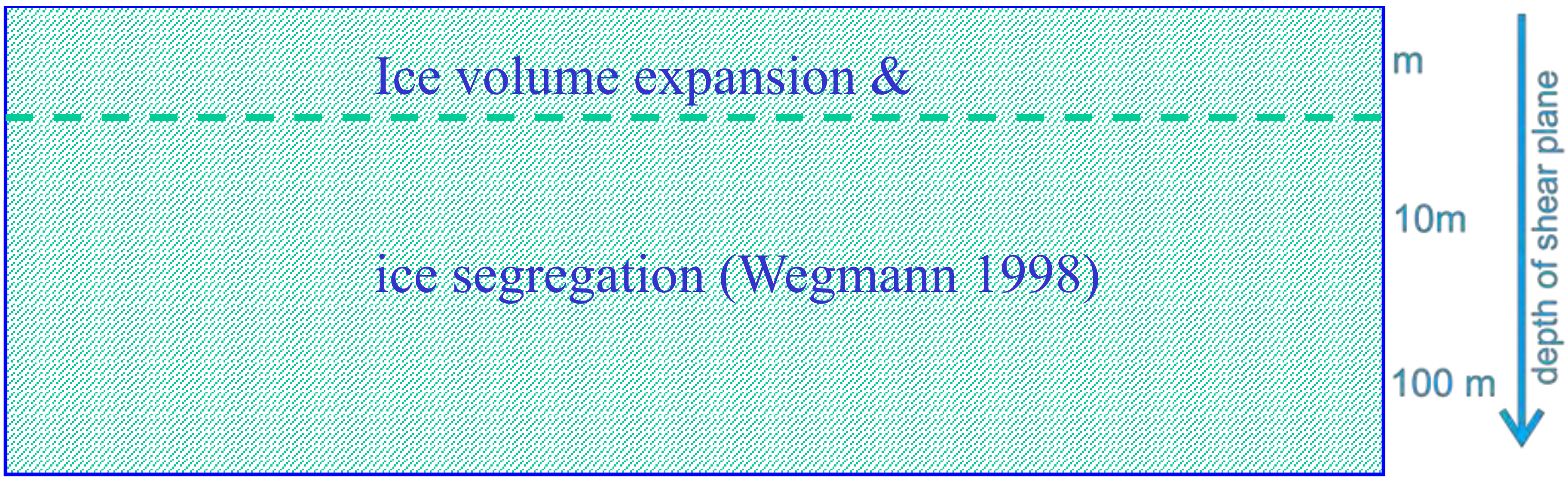
$$+ (-145 * T_c + 0.47 * \sigma' - 3.5)$$

failure criterion of ice in rock clefts



- At very low velocities (strain rates) rock-mechnical processes dominate initial destabilisation.
- Only at higher velocities ice-mechanical outbalance the importance of rock-mechnical processes.

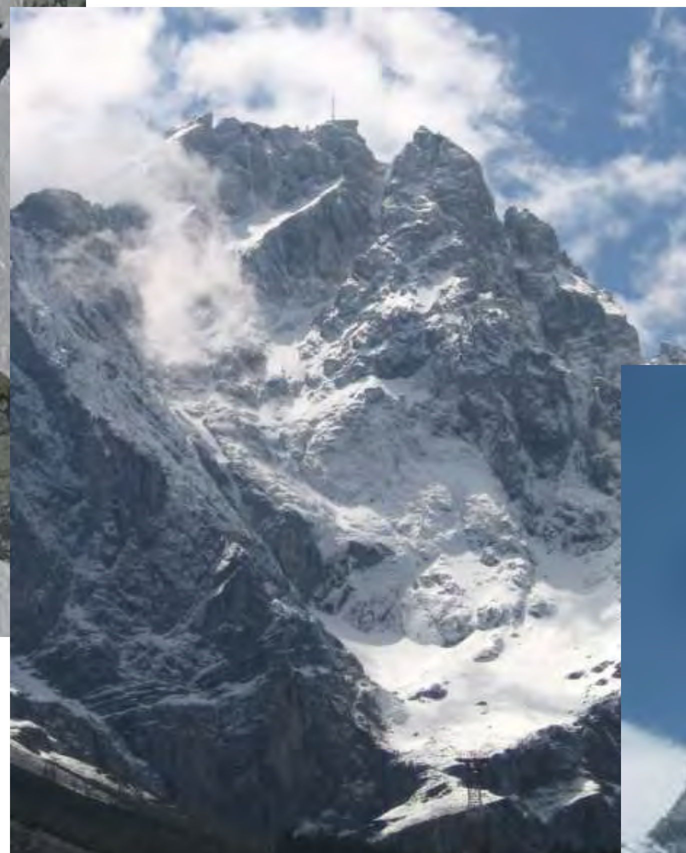
Destabilisation in space



Restriction:

Sample sites

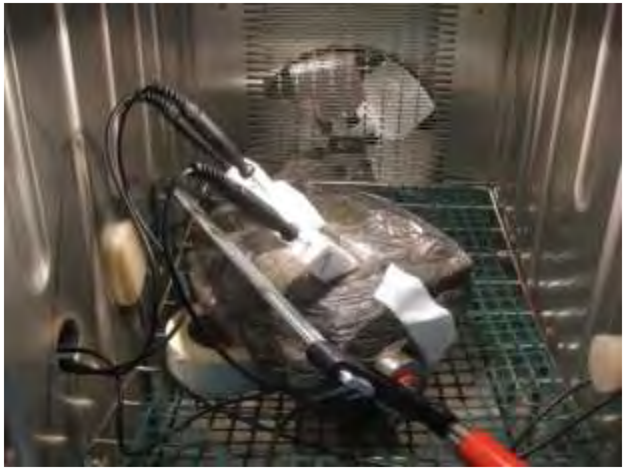
Steintälli, Mattertal, CH



Zugspitze, D/A

Kitzsteinhorn , A

Non-destructive and destructive testing techniques



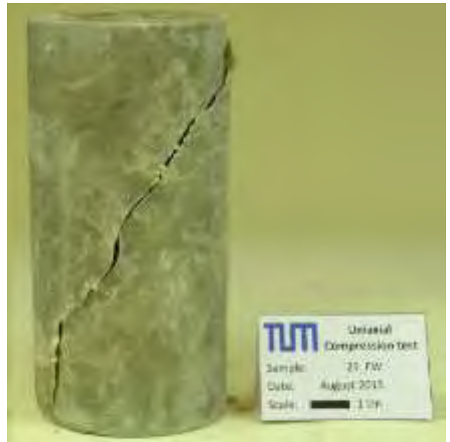
Non-destructive:

- **P- wave velocity**
- **S-wave velocity**
- **>Elastic moduli**

Destructive:

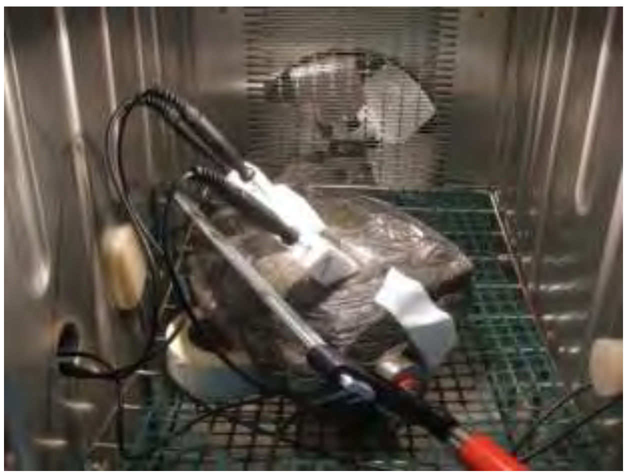
- **Compressive strength (Uniaxial)**
- **Tensile strength (Brazilian)**

Inhomogneity, scale and anisotropy



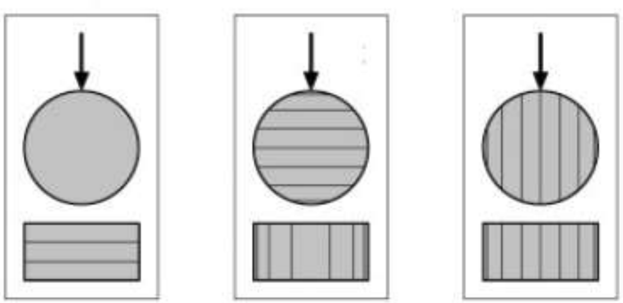
Inhomogeneity

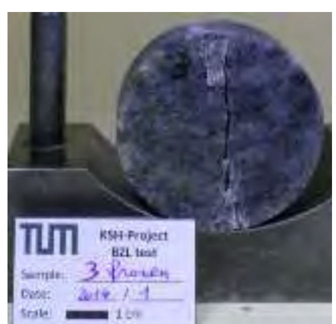
Statistic amounts of samples



Scale:

Differing testing scales with respect to fracture patterns or surface roughness

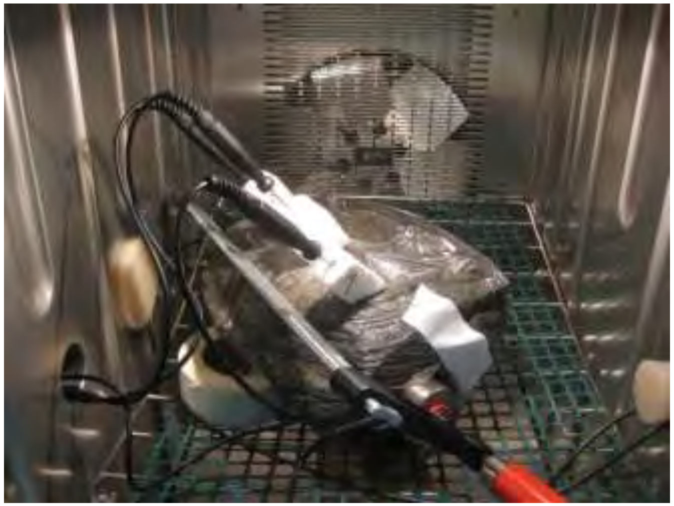


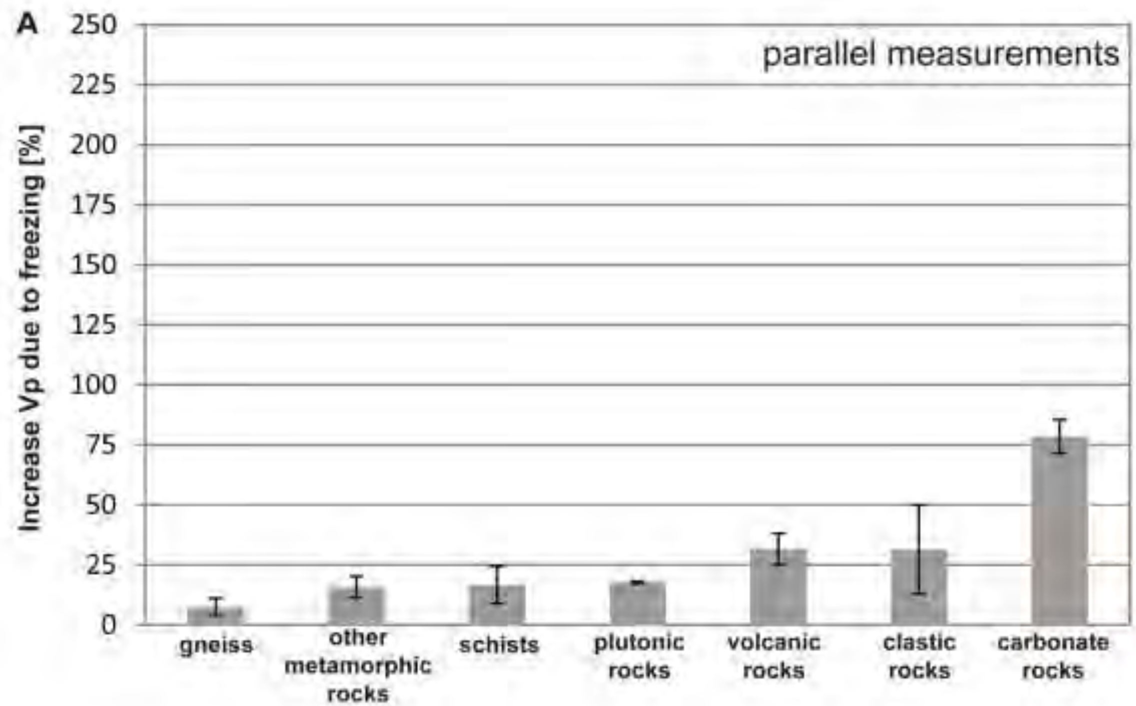


Anisotropy:

Differing testing directions with respect to fracture/ schistosity orientation

Increase in fracture toughness: P-Wave velocity as a proxy





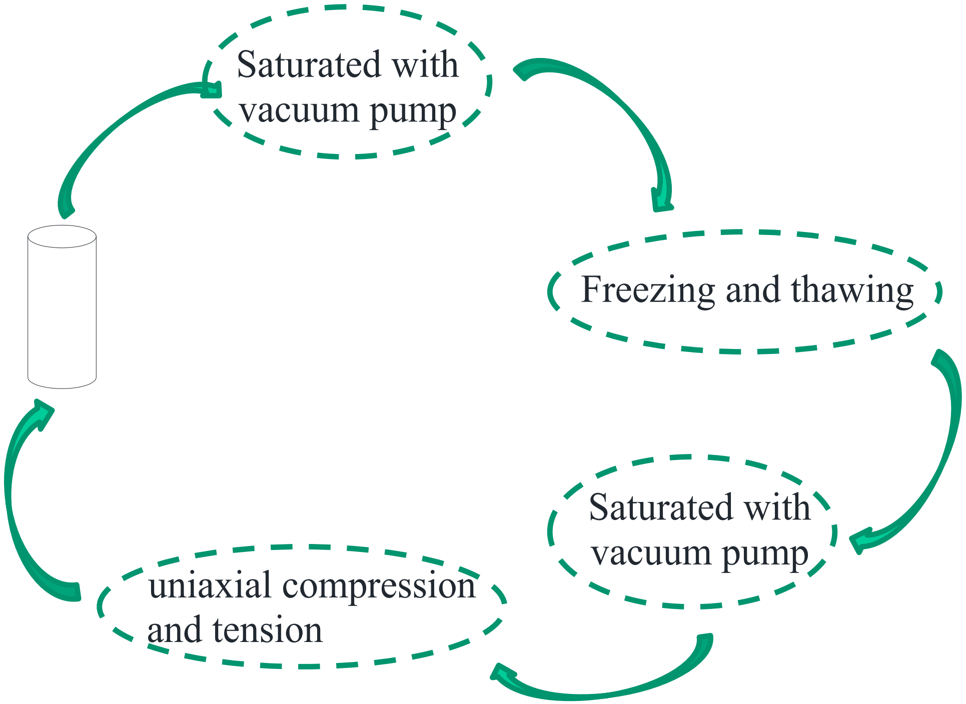
P-wave velocity is the best correlated factor with K_{Ic} fracture toughess (Chang et al. 2002, R^2=0.8).

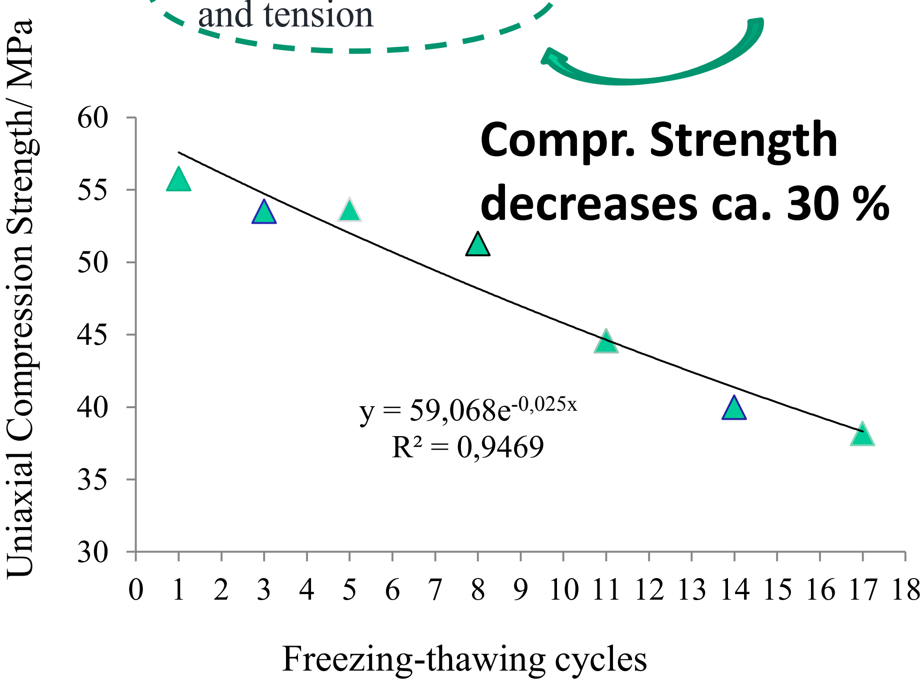
P-wave velocity can be measured non-destructively and in different directions.

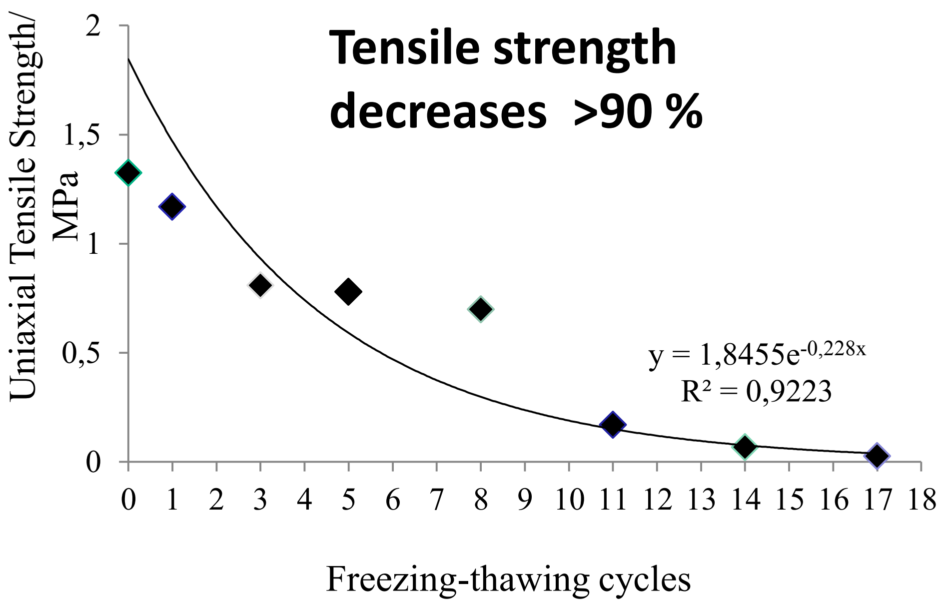
High-resolution (0.2°C increments) changes in P-wave velocity were measured in 22 alpine and arctic rock samples (Dräbing & Krautblatter, 2012, *The Cryosphere*)

3D - Field application (Krautblatter&Draebing, 2014)

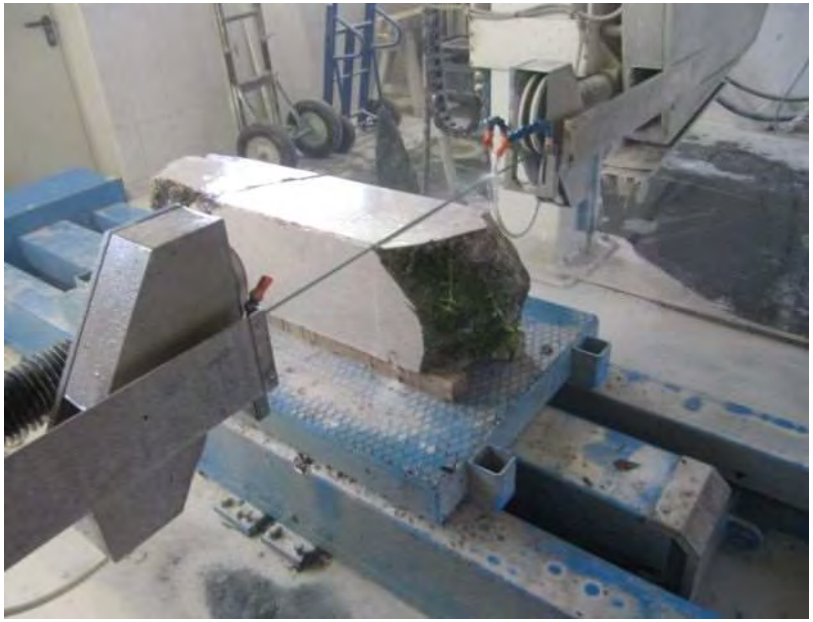
Fatigue: Reducing mechanical strength upon repeated freezing





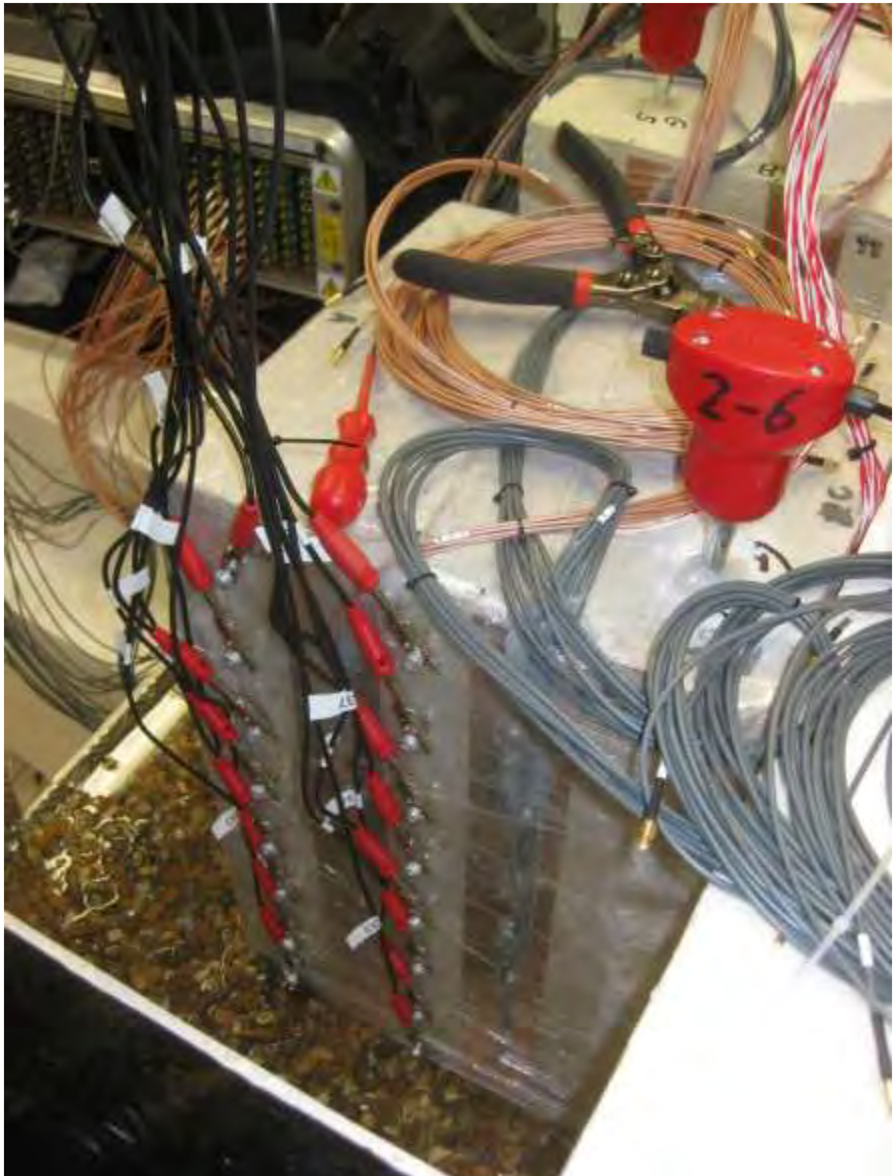


Field-lab analogue testing



Experimental setup: 4 soft chalk blocks, 2 Wetterstein limestone blocks

Instrumentation on each block

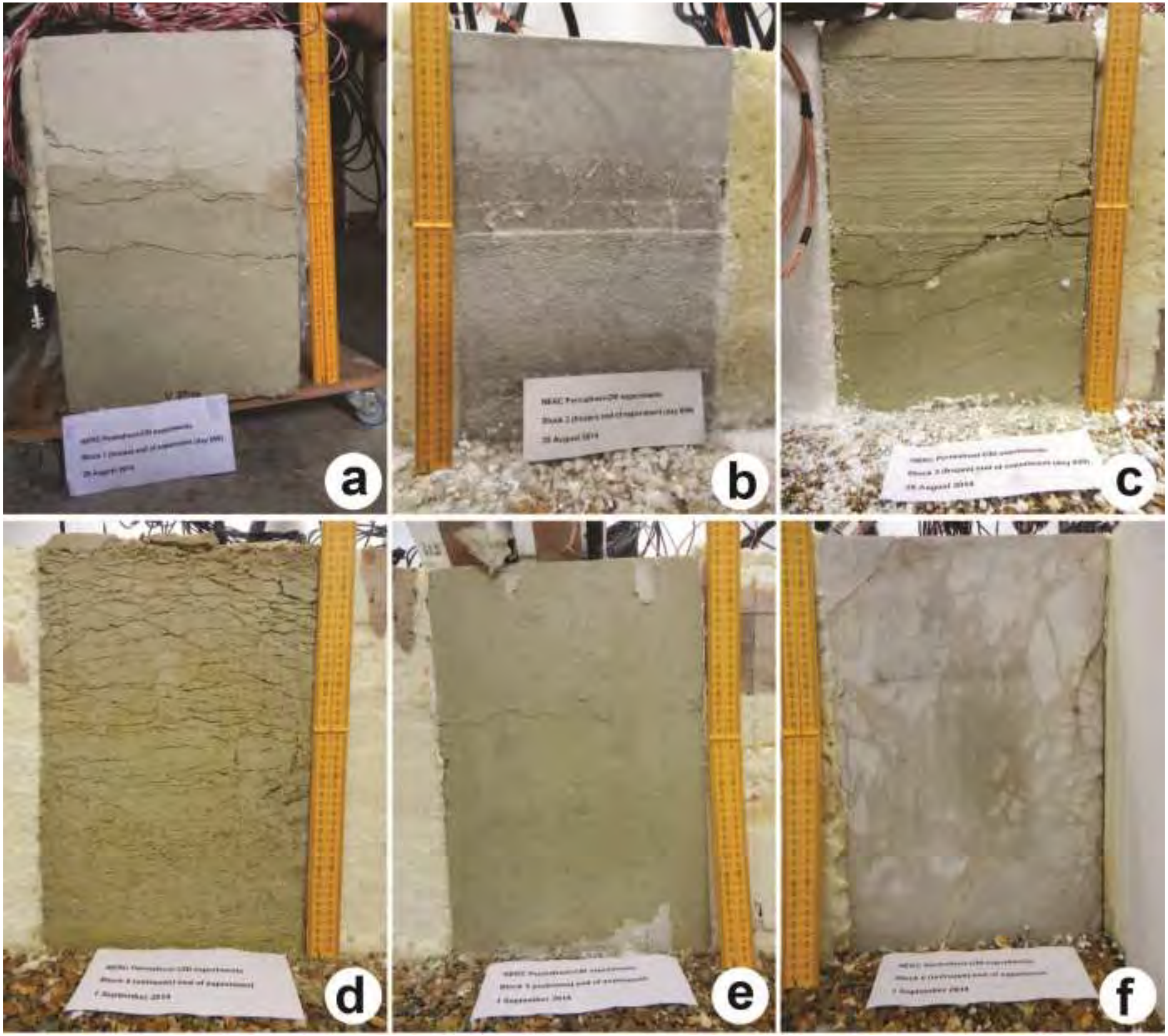


Instrumentation:
- **32 galvanic electrodes for ERT**
- **32 copper plates for capacitive EIT**
- **8 TDR sensors (rock moisture)**
- **8 platinum temperature sensors**
- **1 heave sensor (0.01 mm)**
- **1 geophone (1000 Hz, cont. recording)**

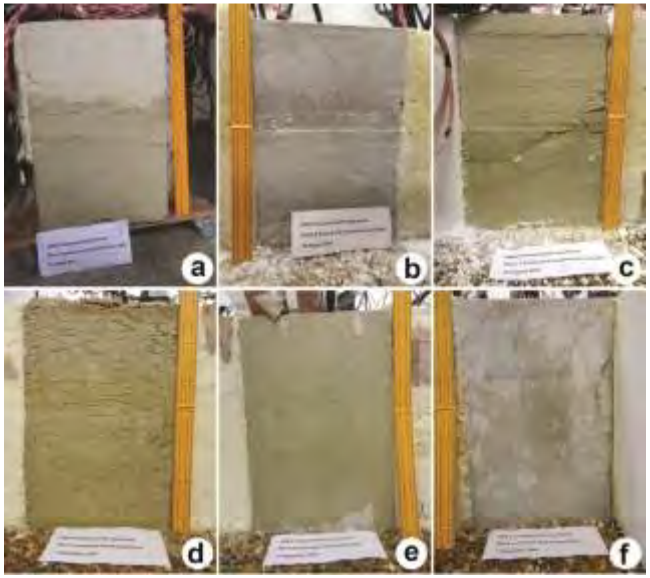
Schedule:
- **Installation: April 2011 – April 2012**
- **Start of test: April 25, 2012**
- **Duration: 900 days - 2015**

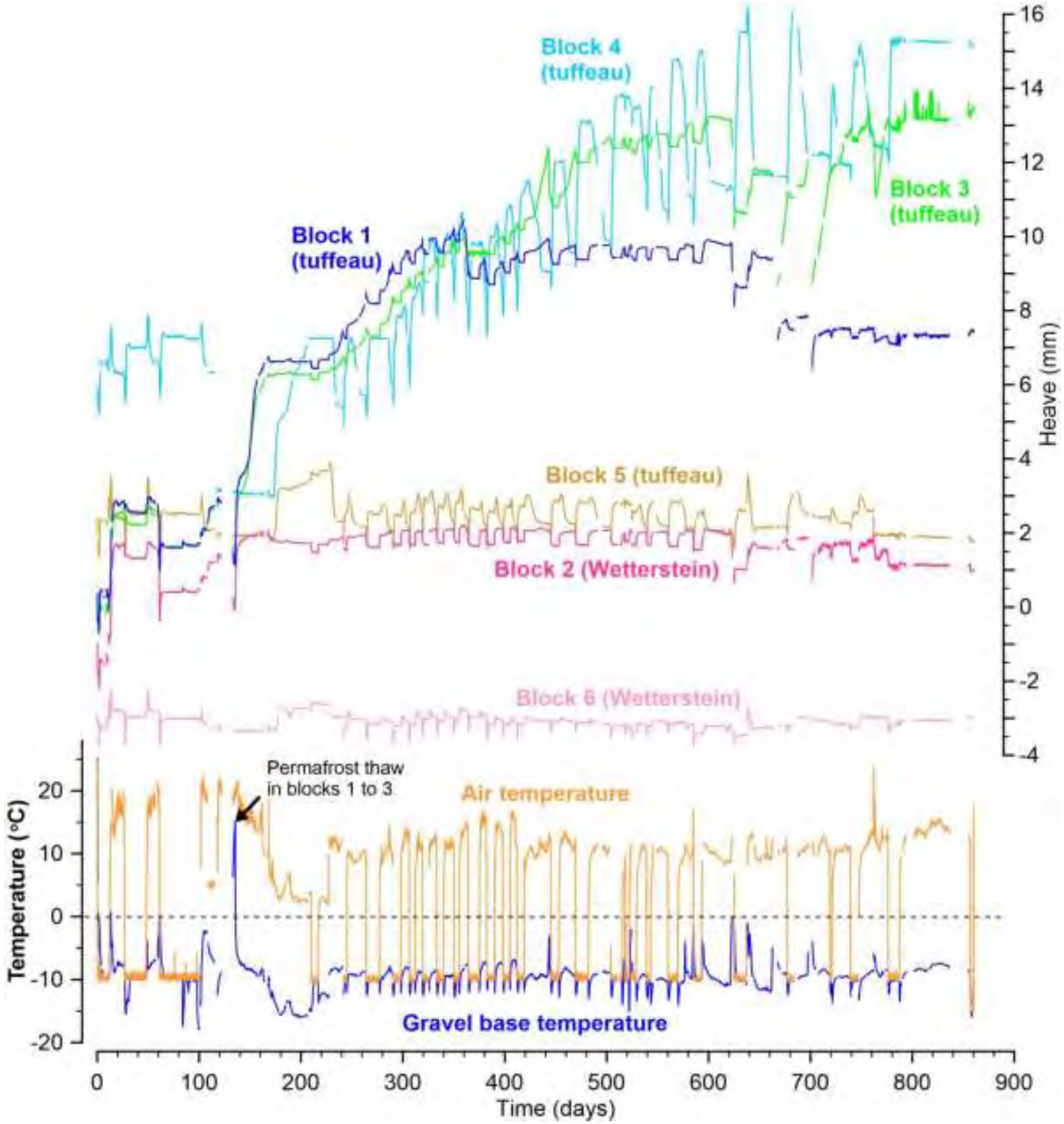
Project: CRI-Permafrost, NERC:
Prof. J. Murton, U. of Sussex,
Dr. O. Kuras, Brit. Geol. Survey
Dr. M. Krautblatter, TUM

900 days, > 20 freezing cycles and resultant shattering



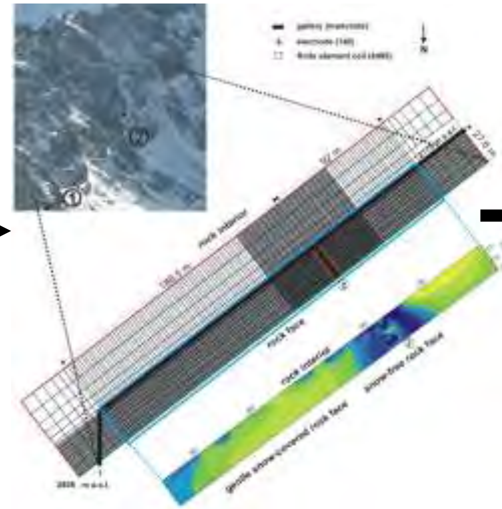
Heave signal



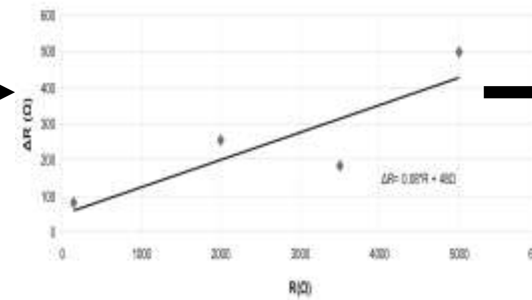


Quantitative ERT (Zugspitze, 2800 m a.s.l.)

High-res. resisitivity measurement (3000 datums)

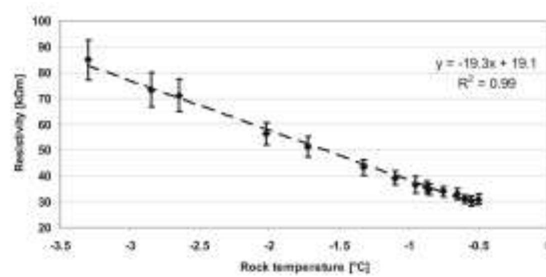


Finite element grid

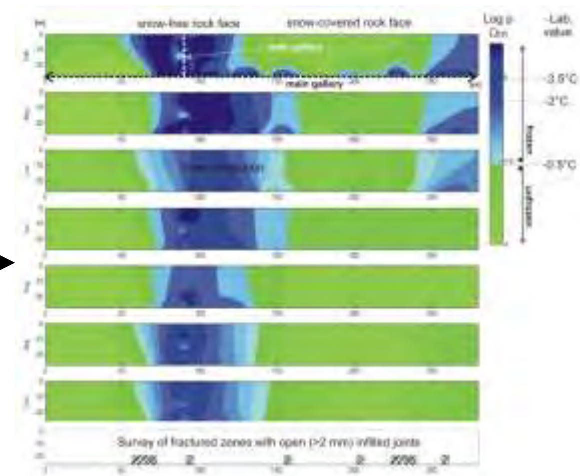


Empirical error model

Laboratory calibration

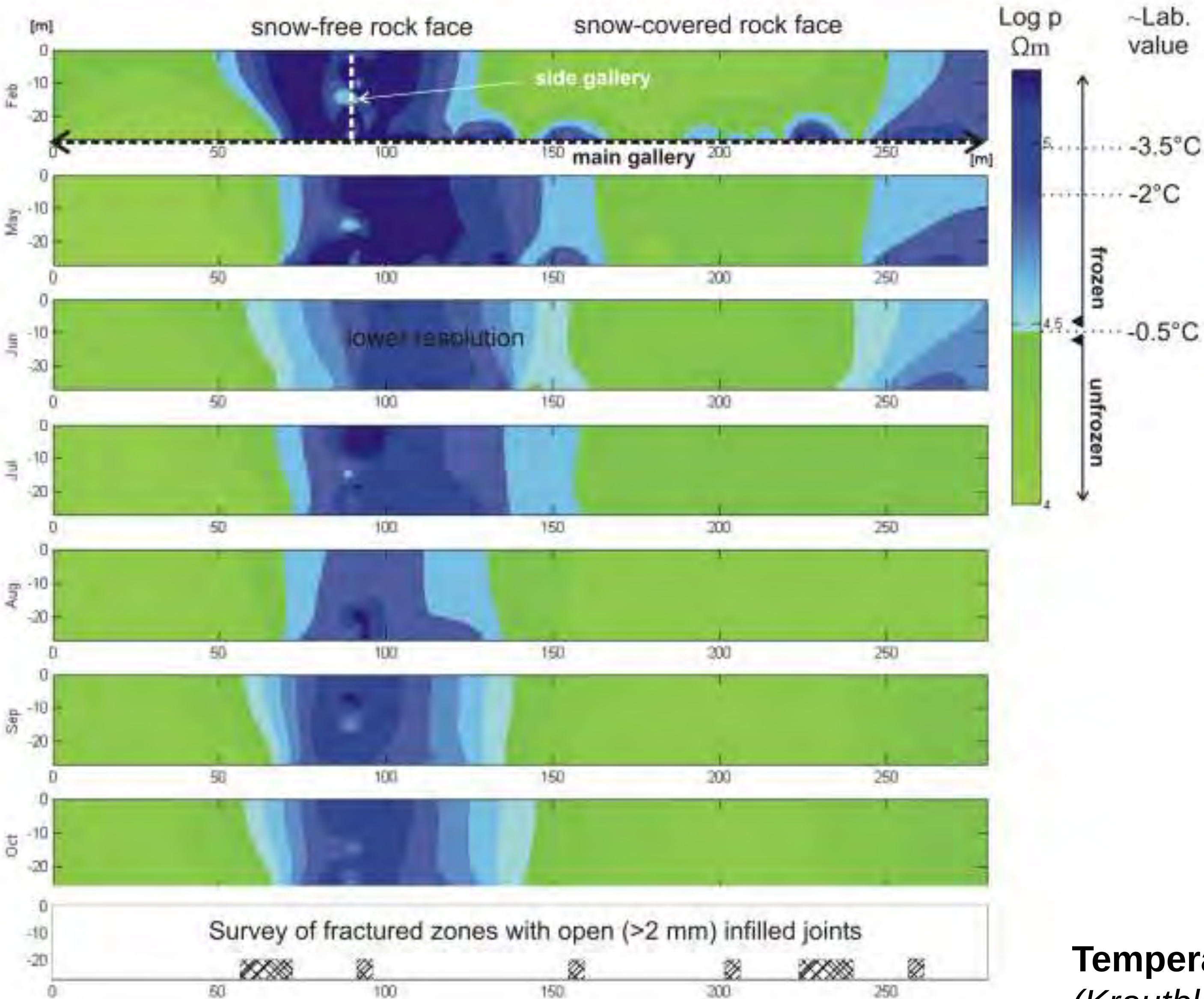


Temperature-resistivity function



Temperature-calibrated ERT *(Krautblatter et al. 2010 JGR)*

Quantitative ERT (Zugspitze, 2800 m a.s.l.)



Temperature-calibrated ERT
(Krautblatter et al. 2010 JGR)

Field work

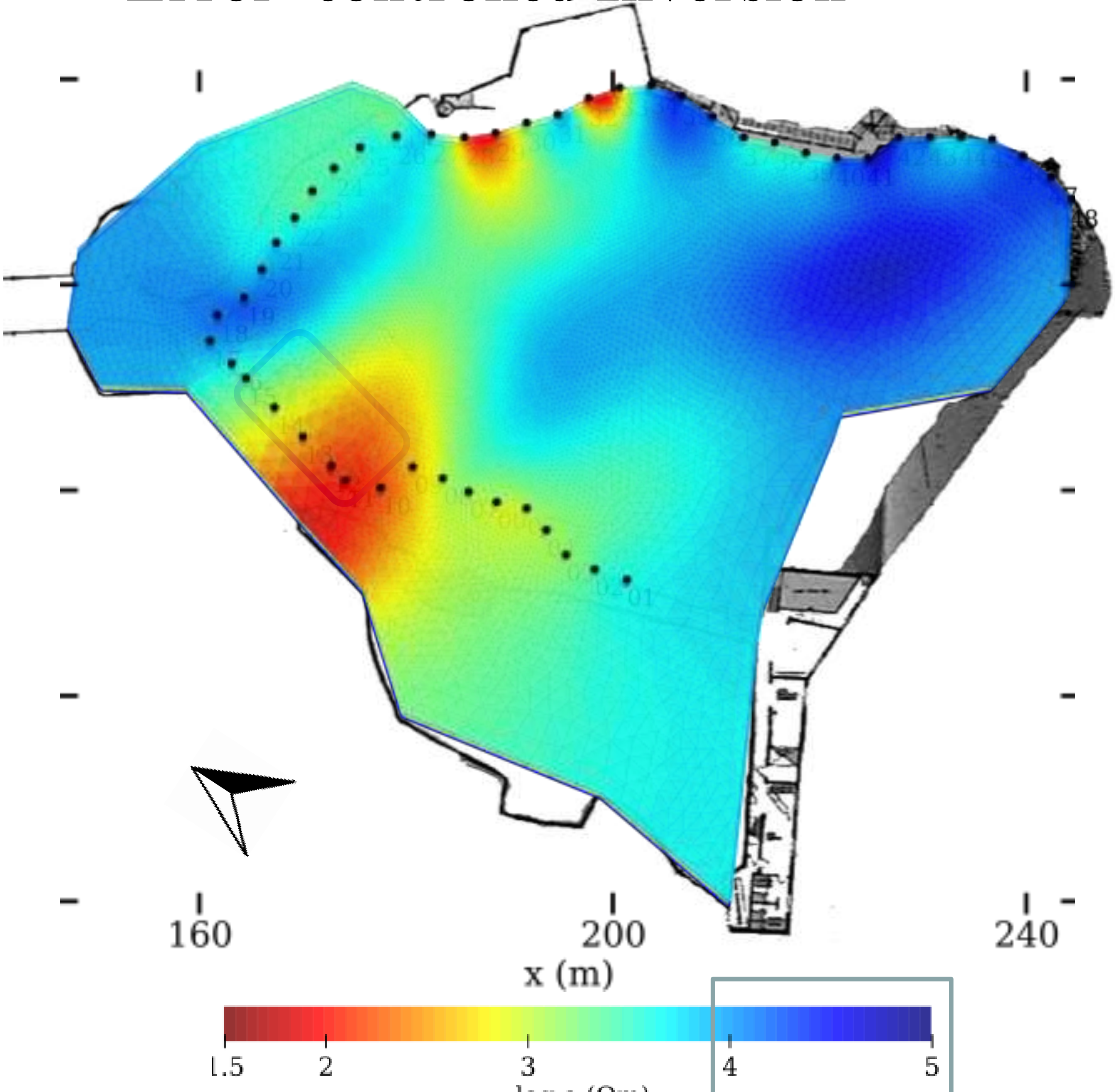
Transects Aguille du Midi (3842 m a.s.l.)

Measurements

- Dec 2008
- Jun 2009
- Oct 2009
- Oct 2010

Error- controlled Inversion

Piton Central
Oct 2010



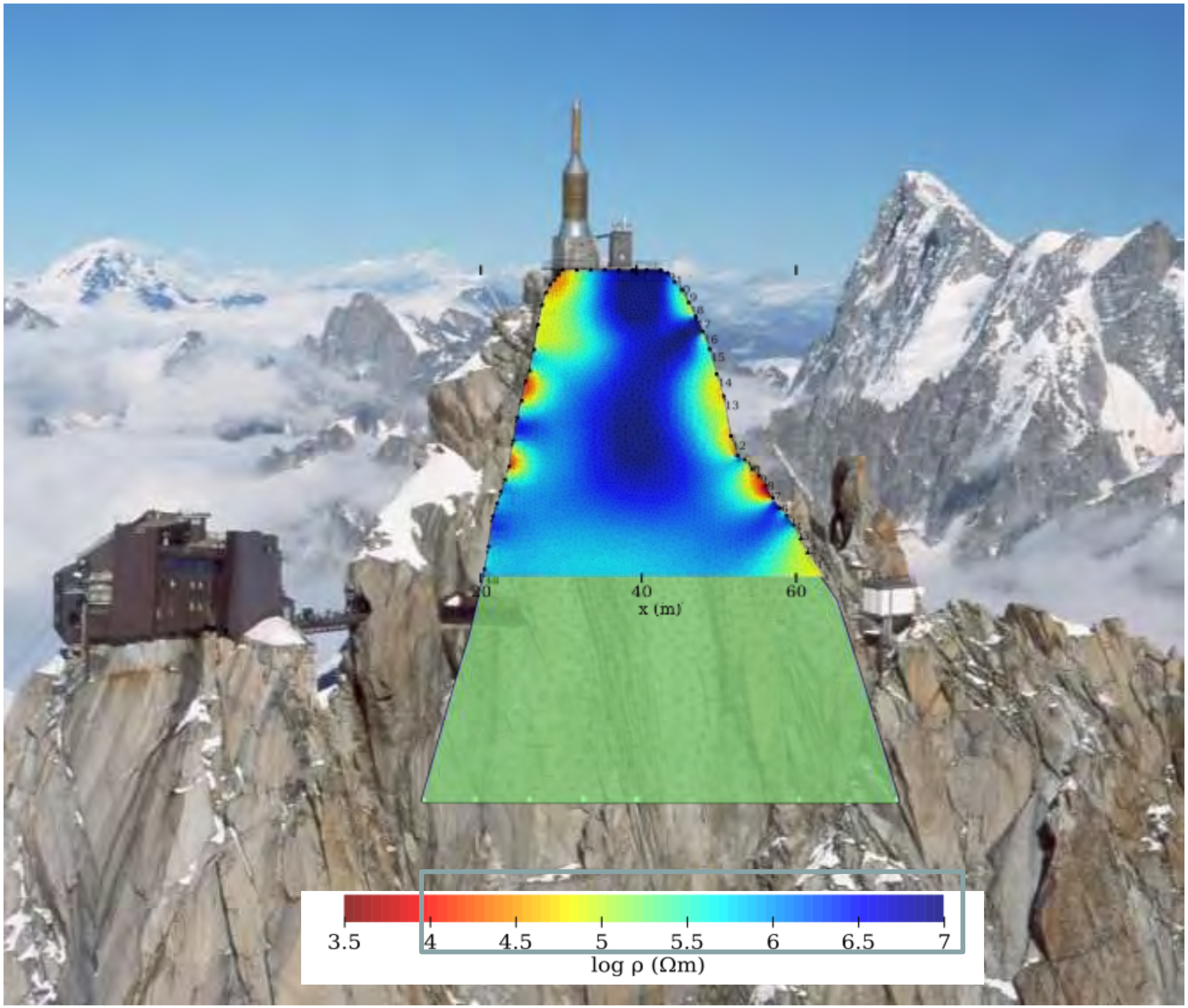
- Skip 3
- Robust inversion

- Rel. error: 26,97 %
- Abs. error: 0,12 Ω
- Background resistiity: 10.000 Ωm

- Electrode gap 12-15 (storage room)

- 318 datum points

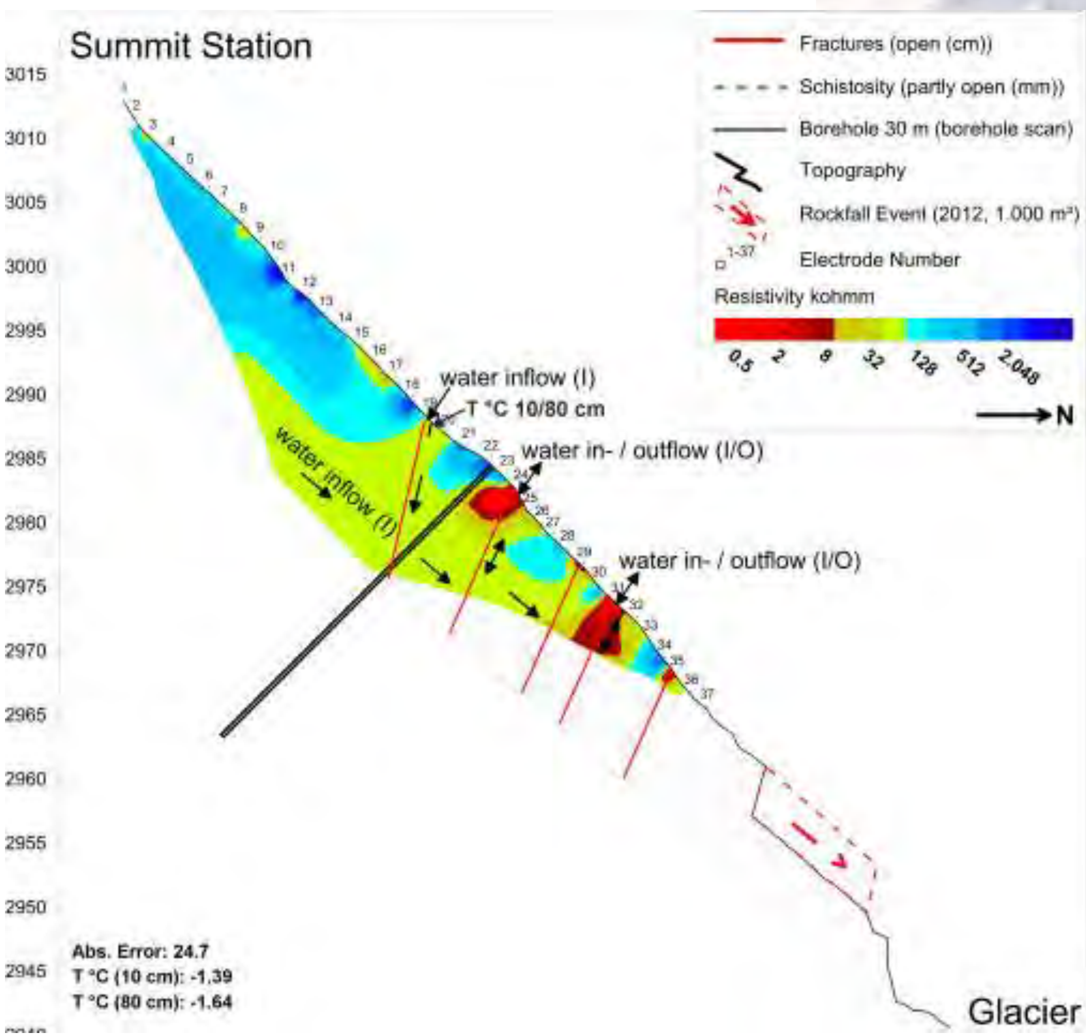
Piton Central
Oct 2010

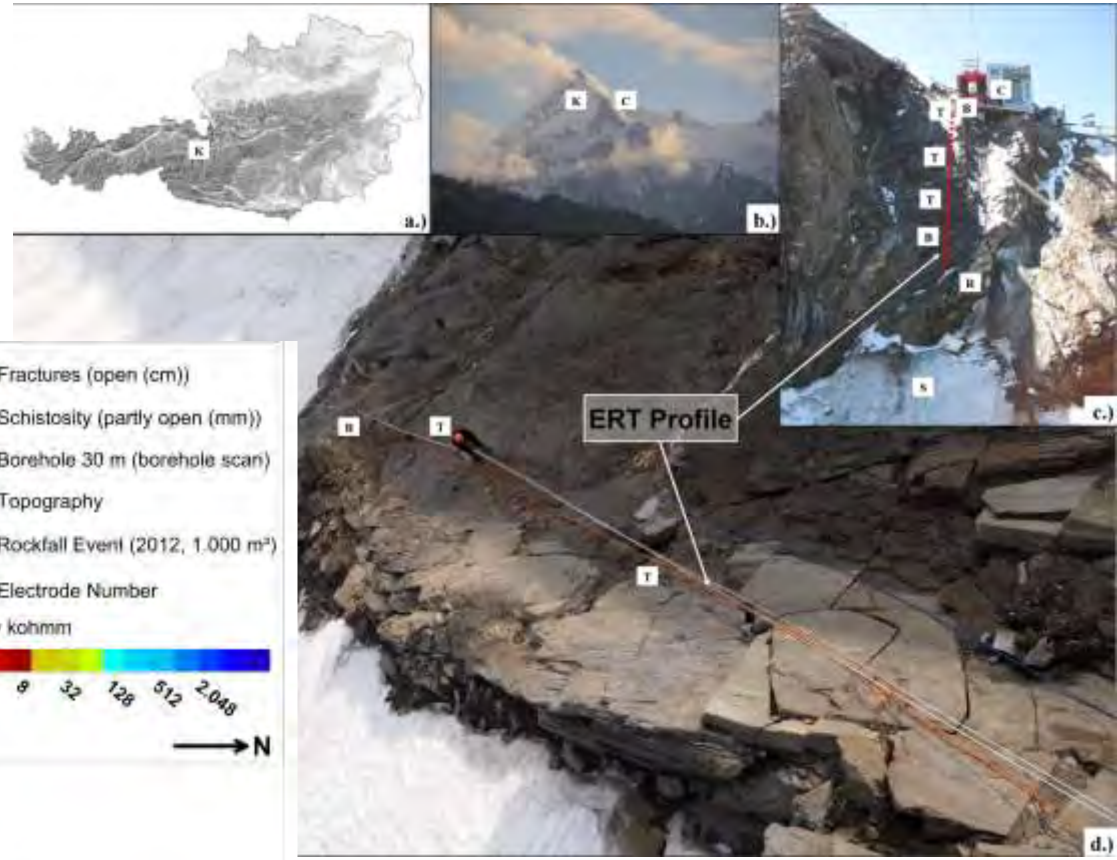


Altered Colour Scale!

- Skip 3
- Robust inversion
- Rel. error: 36,19 %
- Abs. error: 23,07 Ω
- Background resistivity: 10.000 Ωm
- 156 datum points

Continuous ERT monitoring for cable car infrastructure





Keuschnig, Krautblatter et al. (in review), PPP

Deriving a model of permafrost-related rock slope failure

Mechanical failure model

Fig. 4: Study site with profile used for modelling.

- first modelling results: higher xy-displacements and lower factor of safety for „unfrozen condition" (fig. 5)
- next step 1: assign „frozen material parameter" to frozen zones identified by i) geophysics (ERT, SRT) and ii) direct rock temperature monitoring (fig. 6, right)
- next step 2: calculate with complex topography and joint set configuration

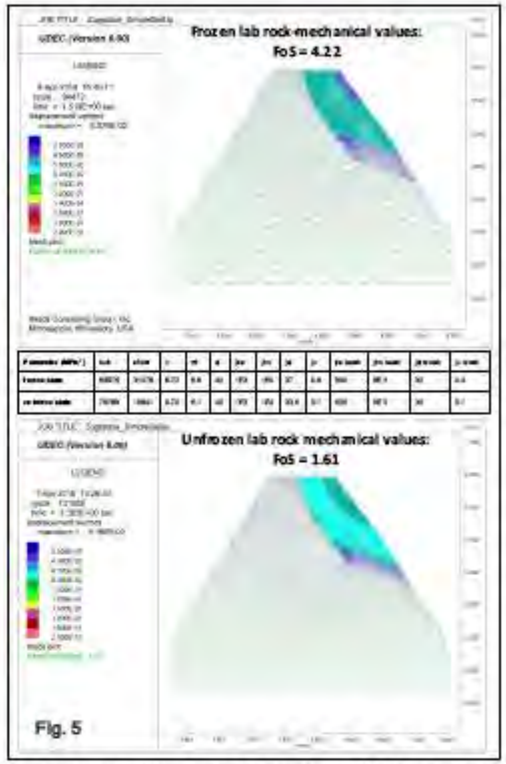
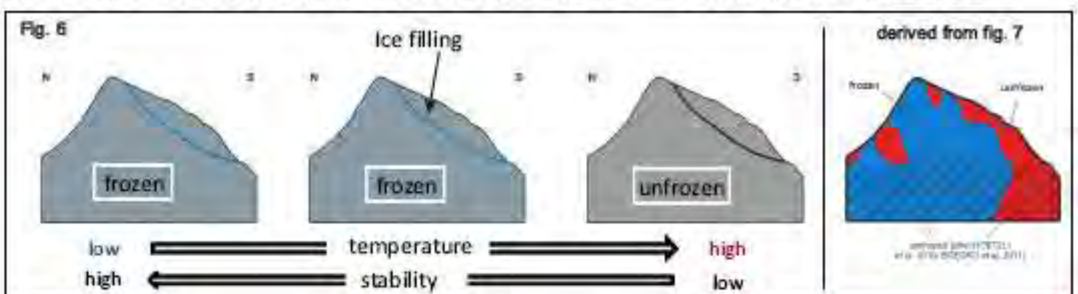


Fig. 5: Two UDEC models with simple geometry of the Zugspitze crest, displacement vectors (in meters) and calculated factors of safety for frozen (above) and unfrozen conditions (below).
Fig. 6: Sketch of the same rock slope as in fig. 5 with various temperature - stability states corresponding to modelling results in fig. 5.



PhD P. Mamot

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