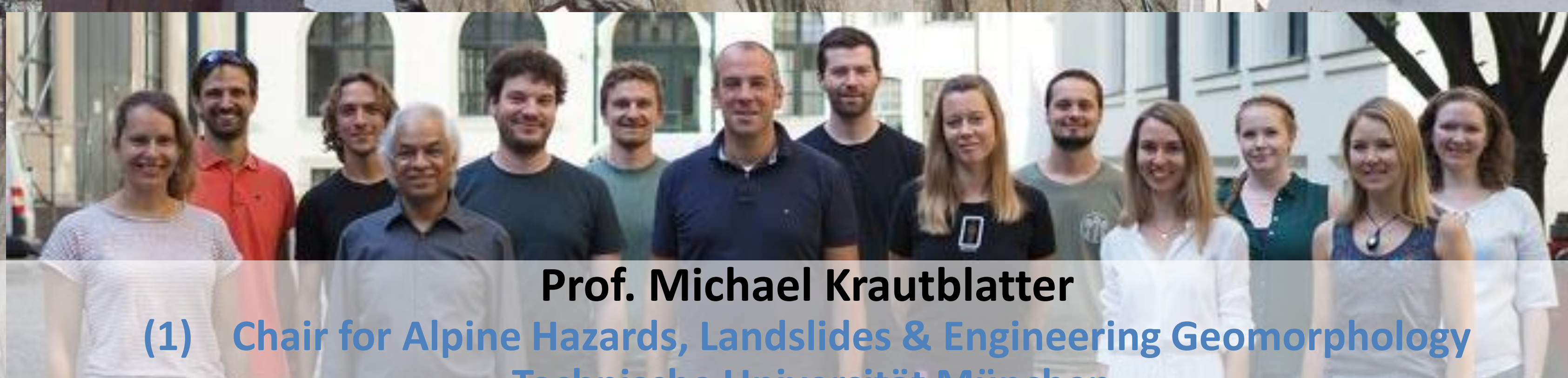
Alpine Naturgefahren im Klimawandel und rapide Anpassung

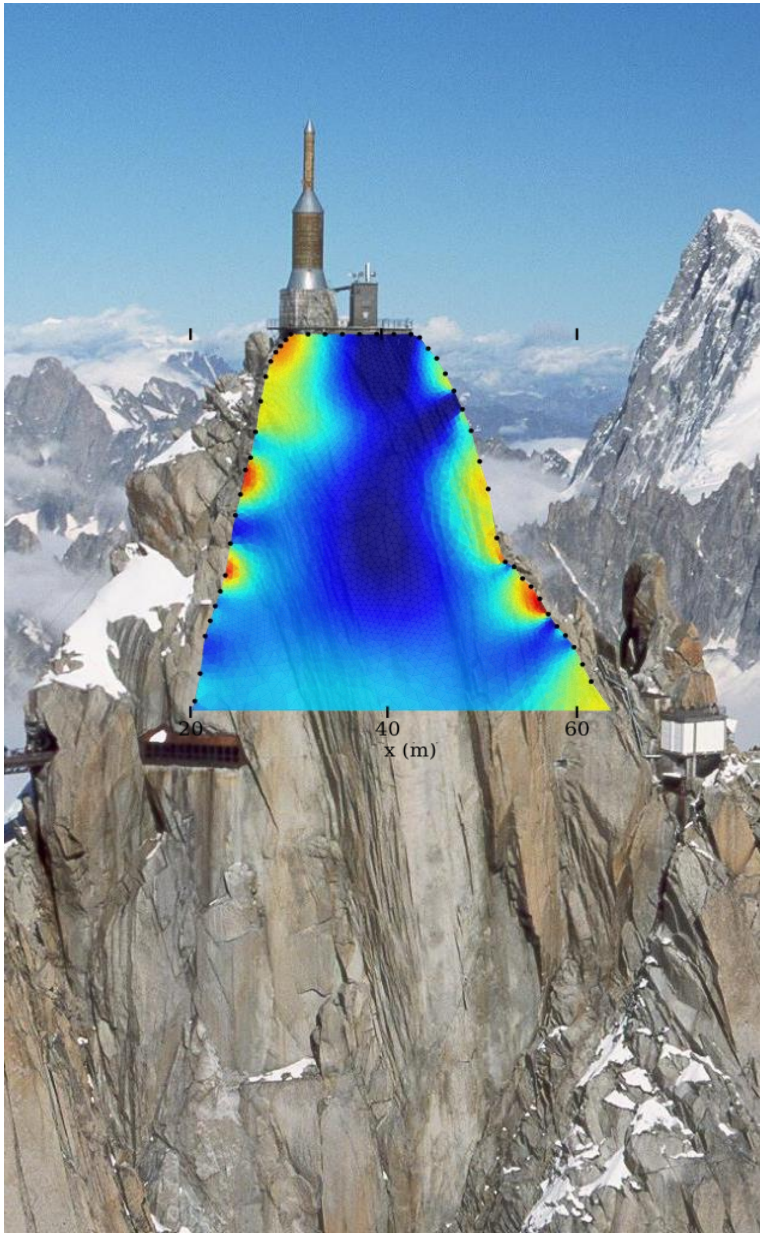
1. Bay. Naturgefahrentagung, DWD Naturgefahren 24.4.2026



Prof. Michael Krautblatter

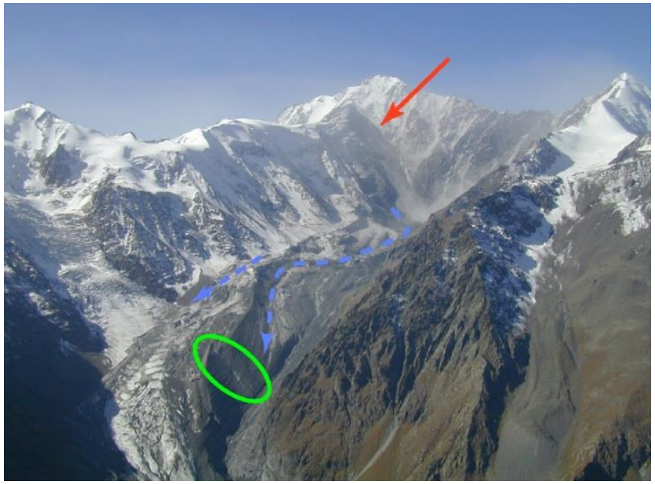
(1) Chair for Alpine Hazards, Landslides & Engineering Geomorphology
Technische Universität München

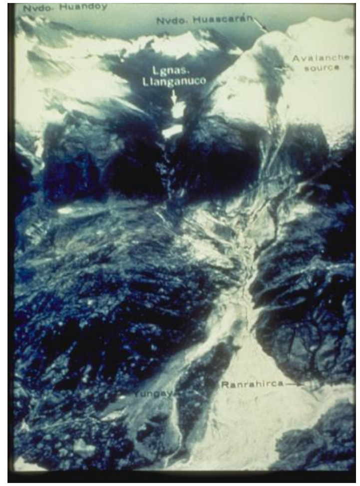
Alpine Hazards in the EUSALP Space



- **Key function**: global water, energy, and traffic infrastructure as well as tourism
- **Population:** 12% of the global population live in mountain areas
- **Water supply:** 50 % mountain regions contribute relvantly to foreland water supply
- **Tourism:** Alps 4% of the global tourism
- **Infrastructure:** Valleys, Tunnels and Passes vulnerable non-redundundant infrastructure
- **Landslides:** 32,322 fatalities in 2620 (non-seismic) landslides 2004-2011 (Petley 2012)
- **Debris flows:** 77,779 casualties in 213 debris flows 1950 to 2011 (Dowling and Santi, 2014)
- **European Alps:** 4000 fatalities and 46 billion € direct losses in 150 events 1951-2009
- **PlanAlp: 100 billion €** Alpine Nat. haz. protection structure in the Alps
- ***major reincestments (billions) in Alpine safety in the near future!***

Rock slope failure in permafrost rock walls



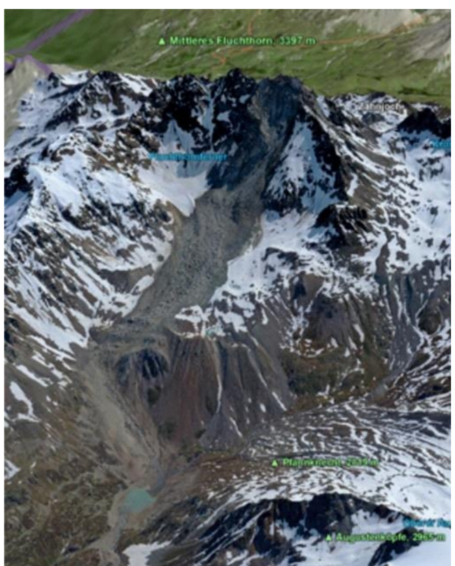


Kolka-Karmadon rock-/ice avalanche (Russ. Caucasus 2002, 100 mio. m³) 140 casualties
Huggel et al. 2005

Huascarán rock-/ice avalanche (Peru 1970, 50-100 mio m³) 20.000 casualties
Erismann & Abele 2001

Piz Cengalo Aug. 2017, 3.0 mio m^3 rock slope failure 8 casualties

Walter et al. 2020



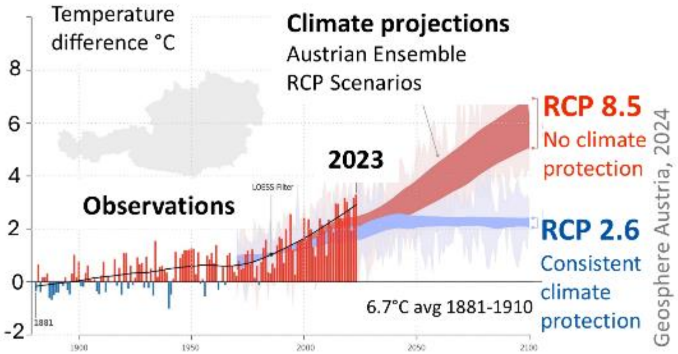
Fluchthorn

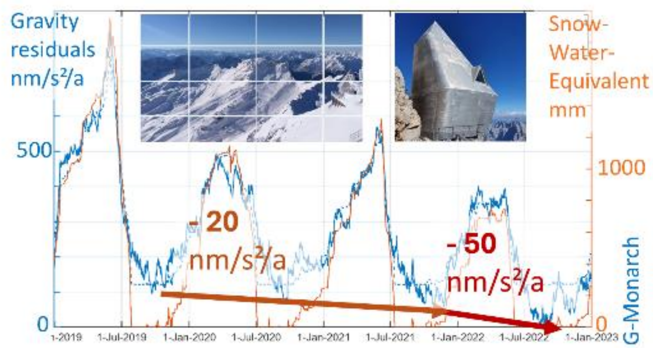
(Austria 2023, 1 mio. m³)

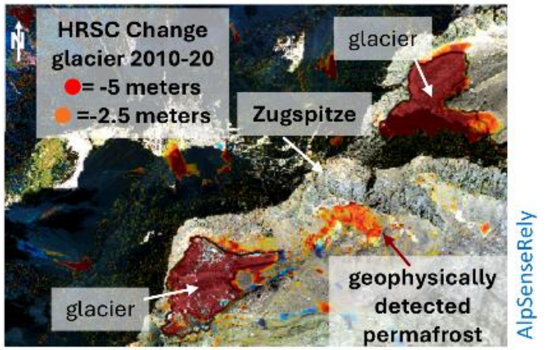
Kleines Nesthorn

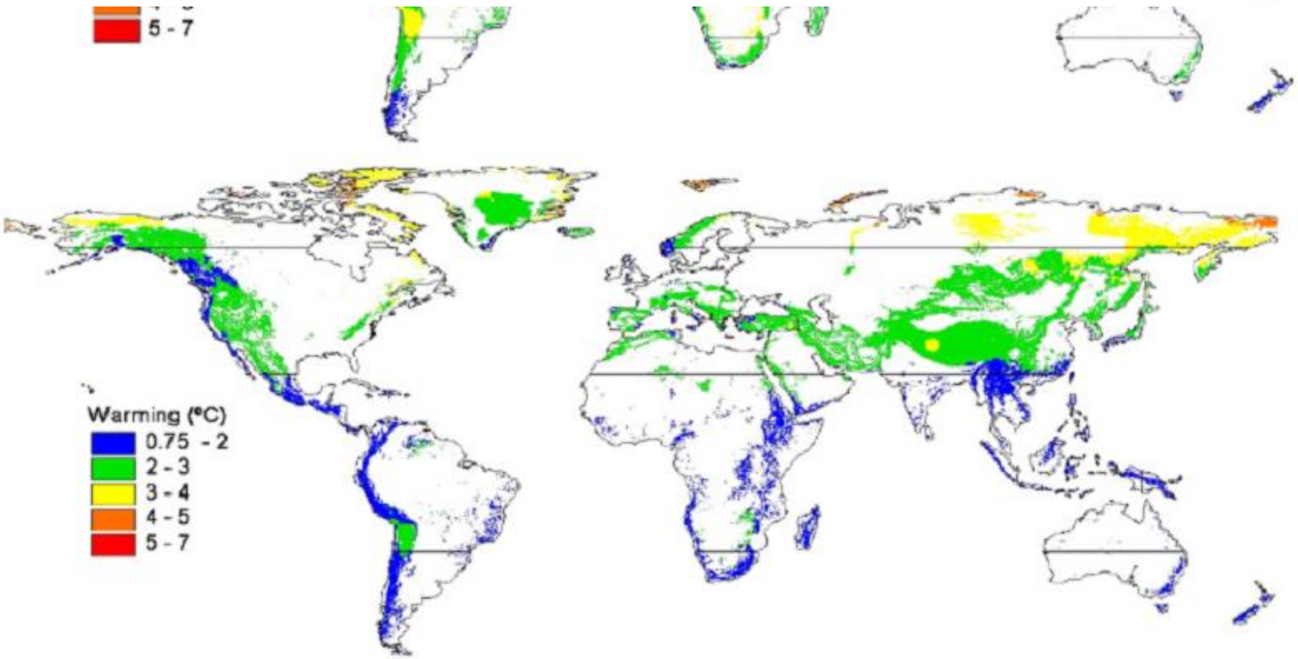
(Blatten, CH 2025, >3 mio. m³)

Anticipated climate change in mountains until 2055









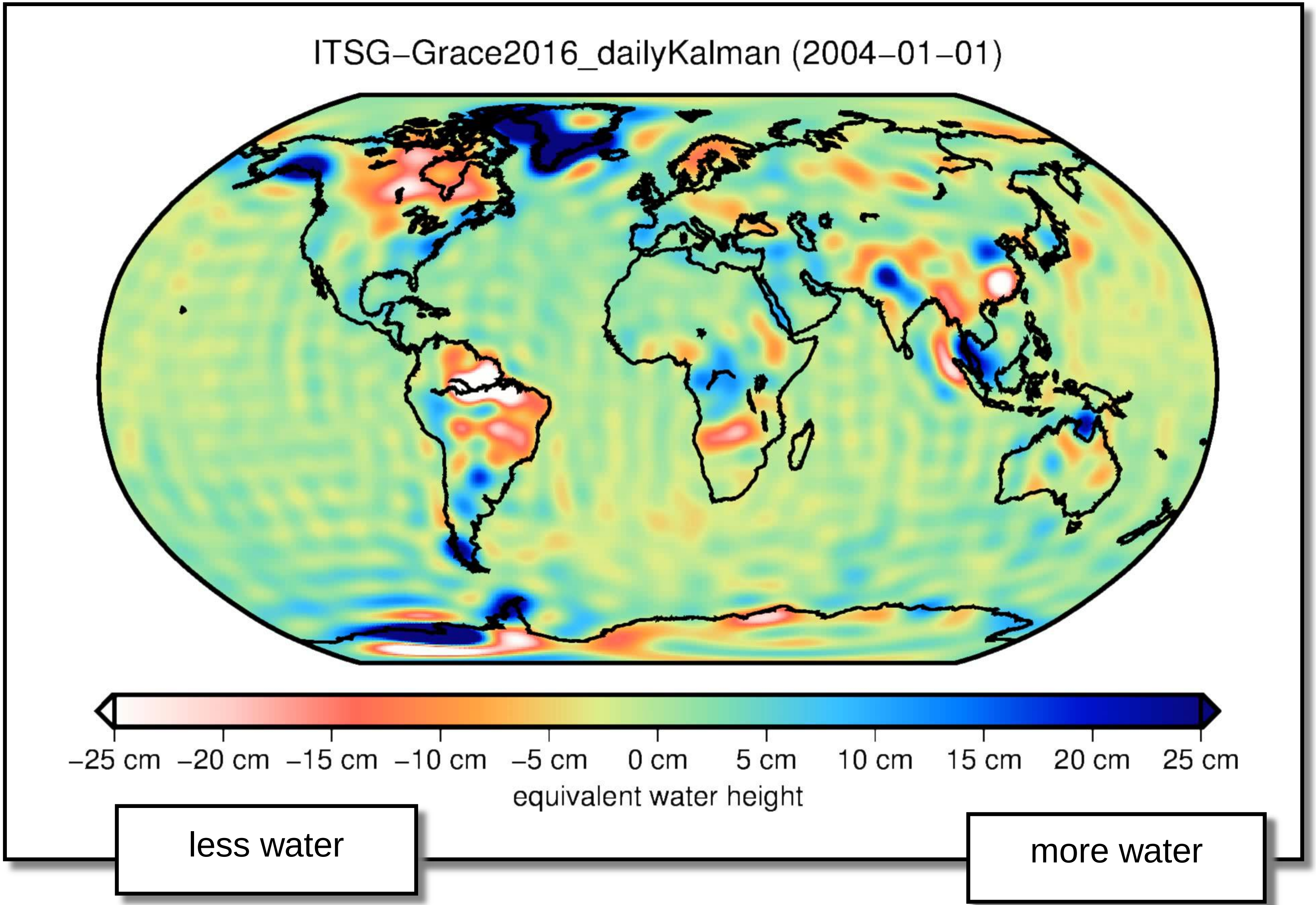
Im IPCC Szenario

„global environmental“

(rasche Einführung sauberer Technologien)

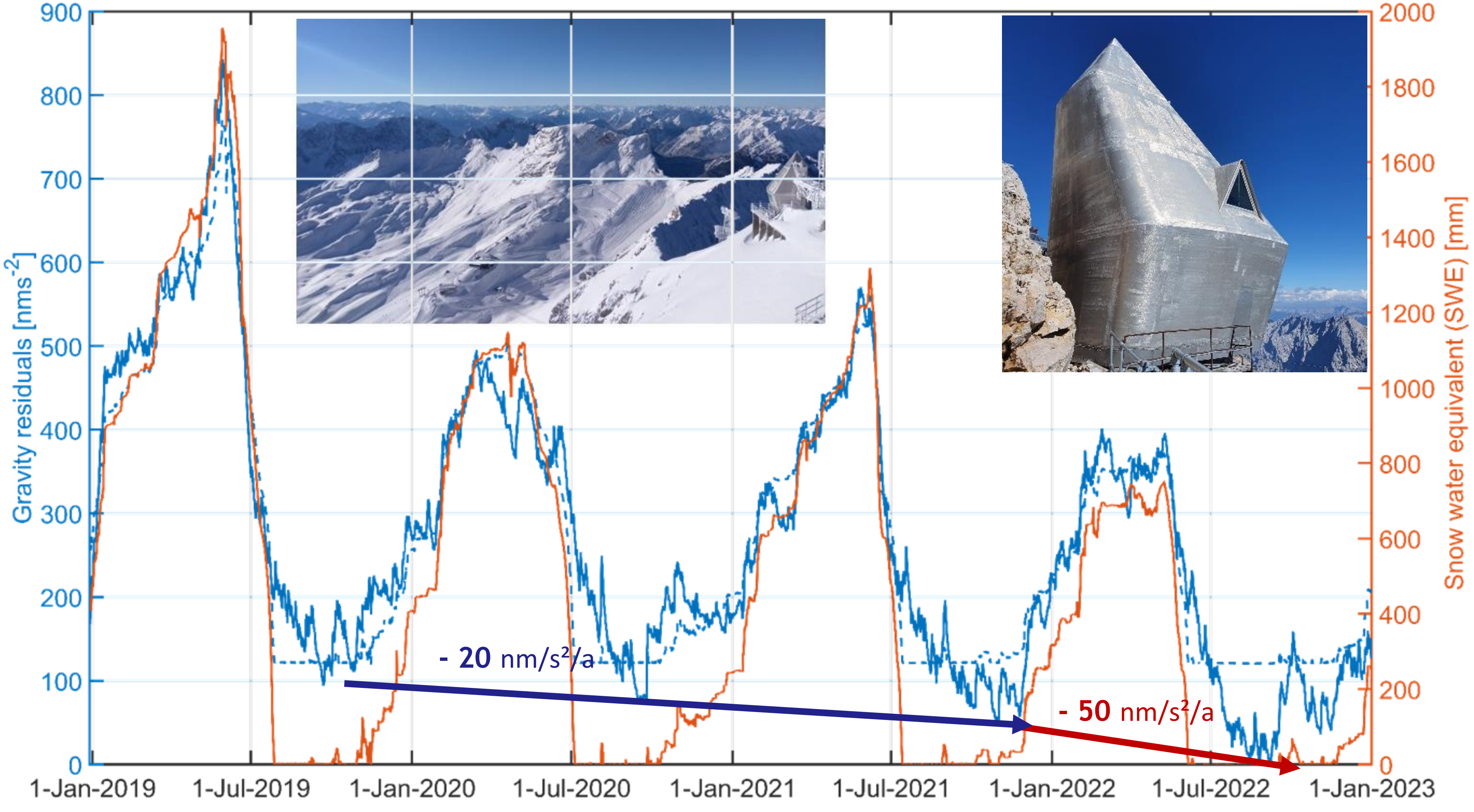
Nogués-Bravo et al. 2007

In a world of increasing fluctuations of water supply and droughts



Talk: R. Pail

Comprehensive effects of climate change beyond temperature & precipitation



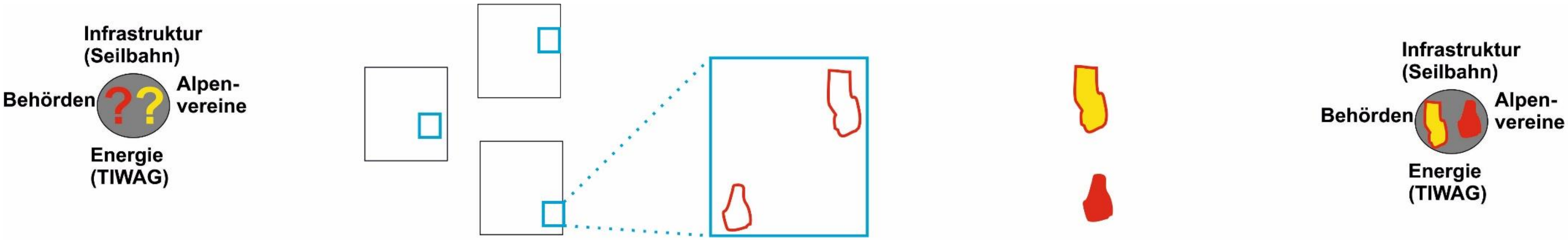
Coop: BOKU, HyWa, GFZ Helmholtz Centre Potsdam, TU Berlin, Universität Augsburg University, Umweltforschungsstation Schneefernerhaus, Technische Universität München

→ Potential reasons: Decline in glaciers, permafrost, and karst water, geomorphological redistributions, etc.

→ Decline in 2022 was 2.5 times larger enormous glacier mass losses

AlpSense: Alpine remote sensing of climate-induced natural hazards

A Benchmark Project in the EU Strategy for the Alpine Region (EUSALP) (STMWI -FUNDED)



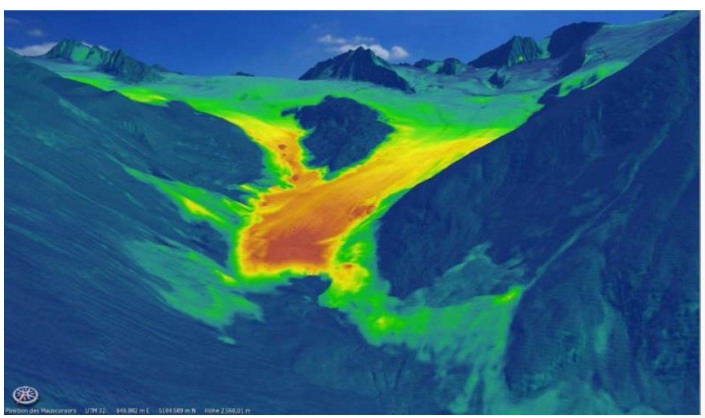
AP0 Nutzer- und Prozessoptimierte Strategie

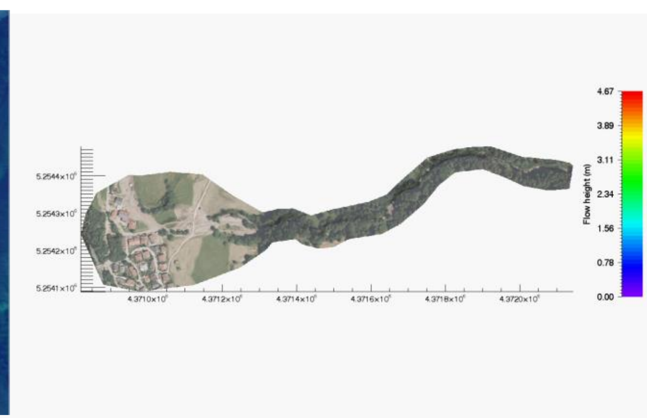
AP1 Identifikation Naturgefahren-Hotspots

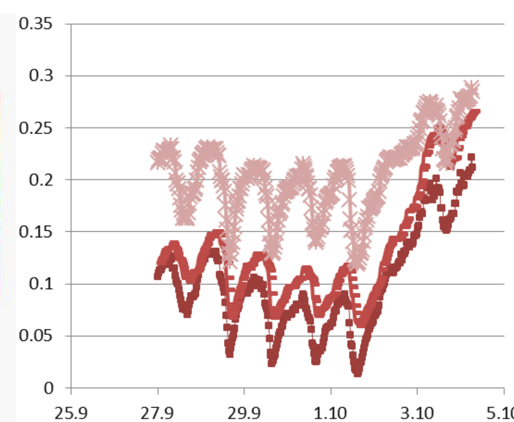
AP2: Prozessdynamik in den Naturgefahren-Hotspots

AP3: Near Real-Time Monitoring vorberei-tender Naturgefahren

AP4 Near Real-Time Visualisierung und Kommunikation

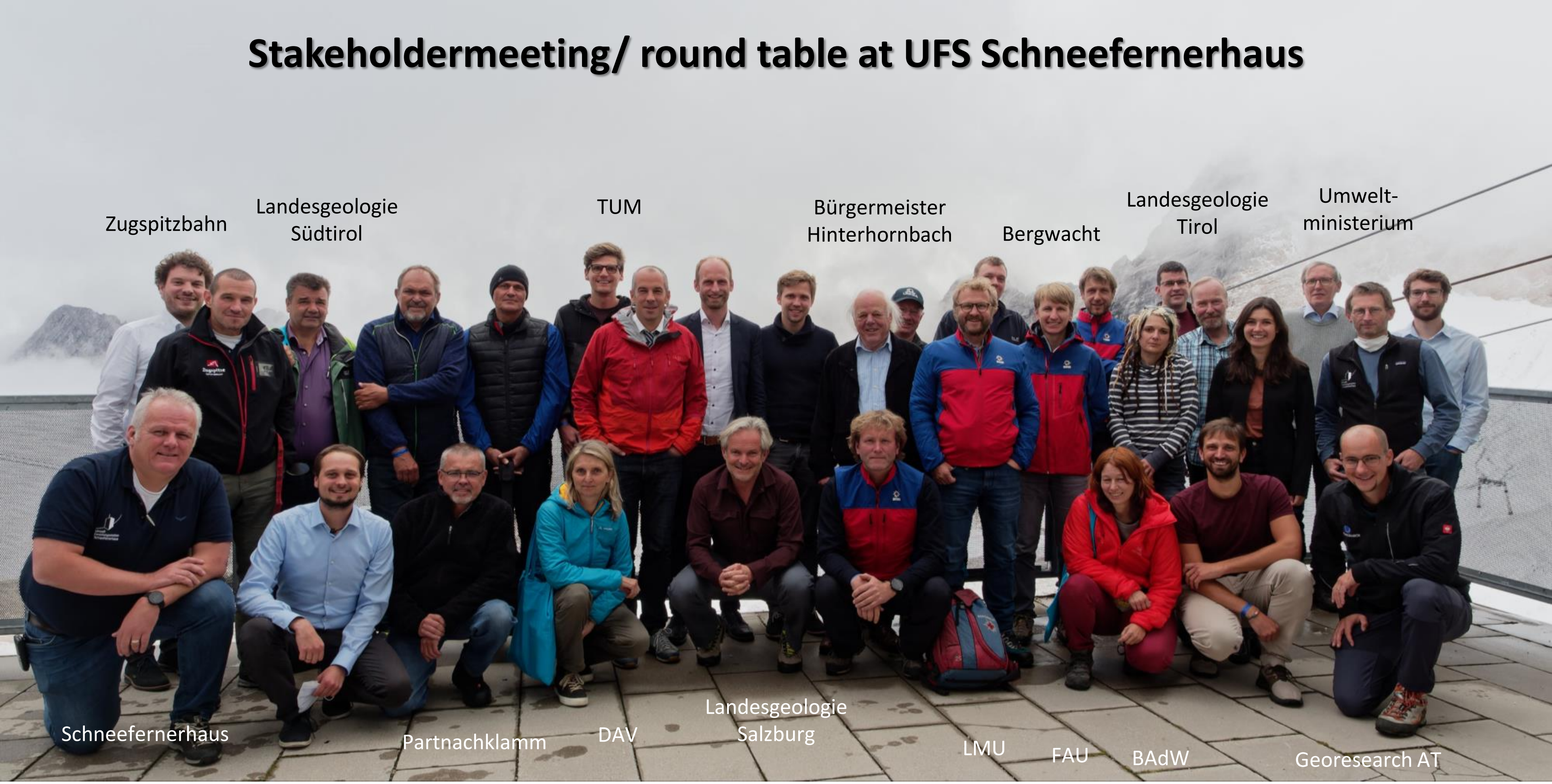






AP 0: User and Process Optimized Strategy

Cable Cars: Zugspitzbahn and Kitzsteinhornbahn
Alpine Clubs/ Alpenverein Garmisch-Partenkirchen
Alpine rescue service/ Bergwacht / DAV Luitpoldhaus / DAV Donauwörth Hochvogel
Landesgeologie Tirol/ Südtirol
Bayerisches Landesamt für Umwelt
Municipalities/ Mayors



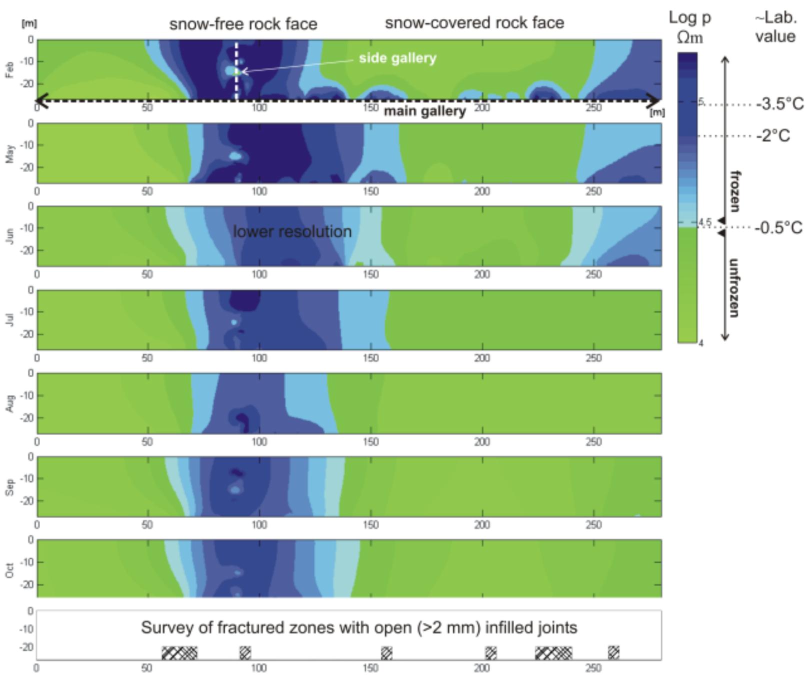
1. Climate-induced natural hazards: Glaciers and permafrost

Glaciers: fast melting of Schneeferner/ Höllentalferner

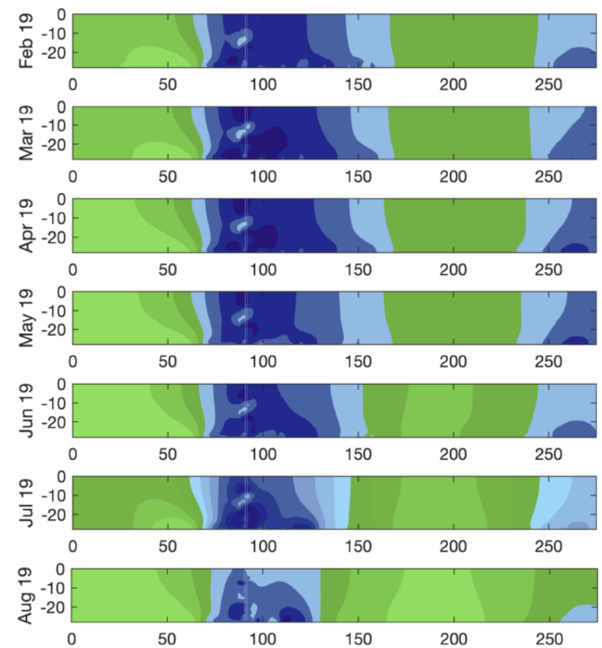
>yearly monitoring

Permafrost: fast degradation at Zugspitze/Wettersteingebirge
>continuous monitoring since 2007

2007



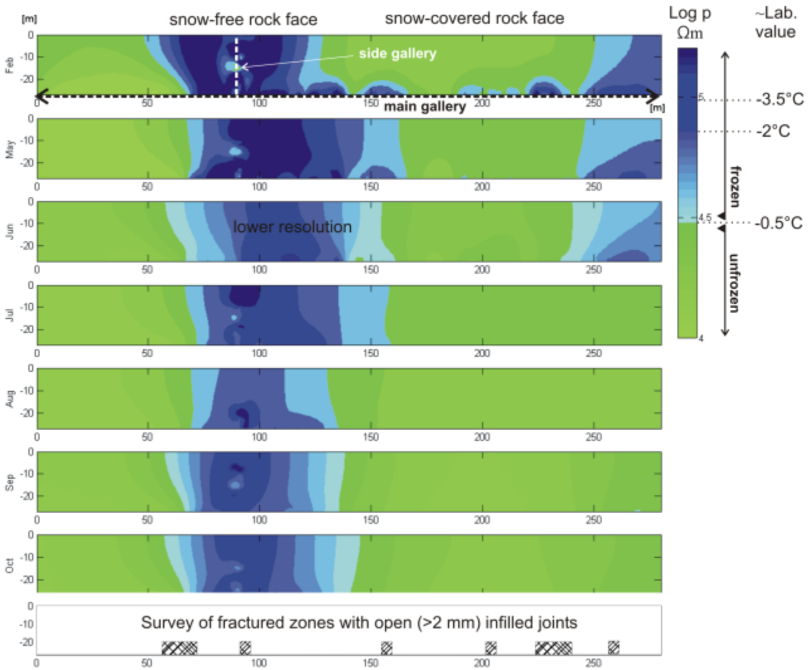
2019



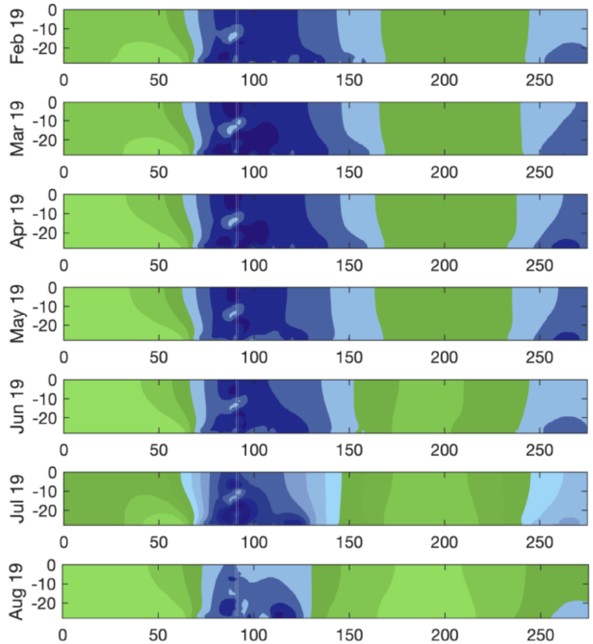
AlpSense: AP 1: Identification of Hazard Hotspots

1. Climate-induced natural hazards: Glaciers and permafrost

2007



2019

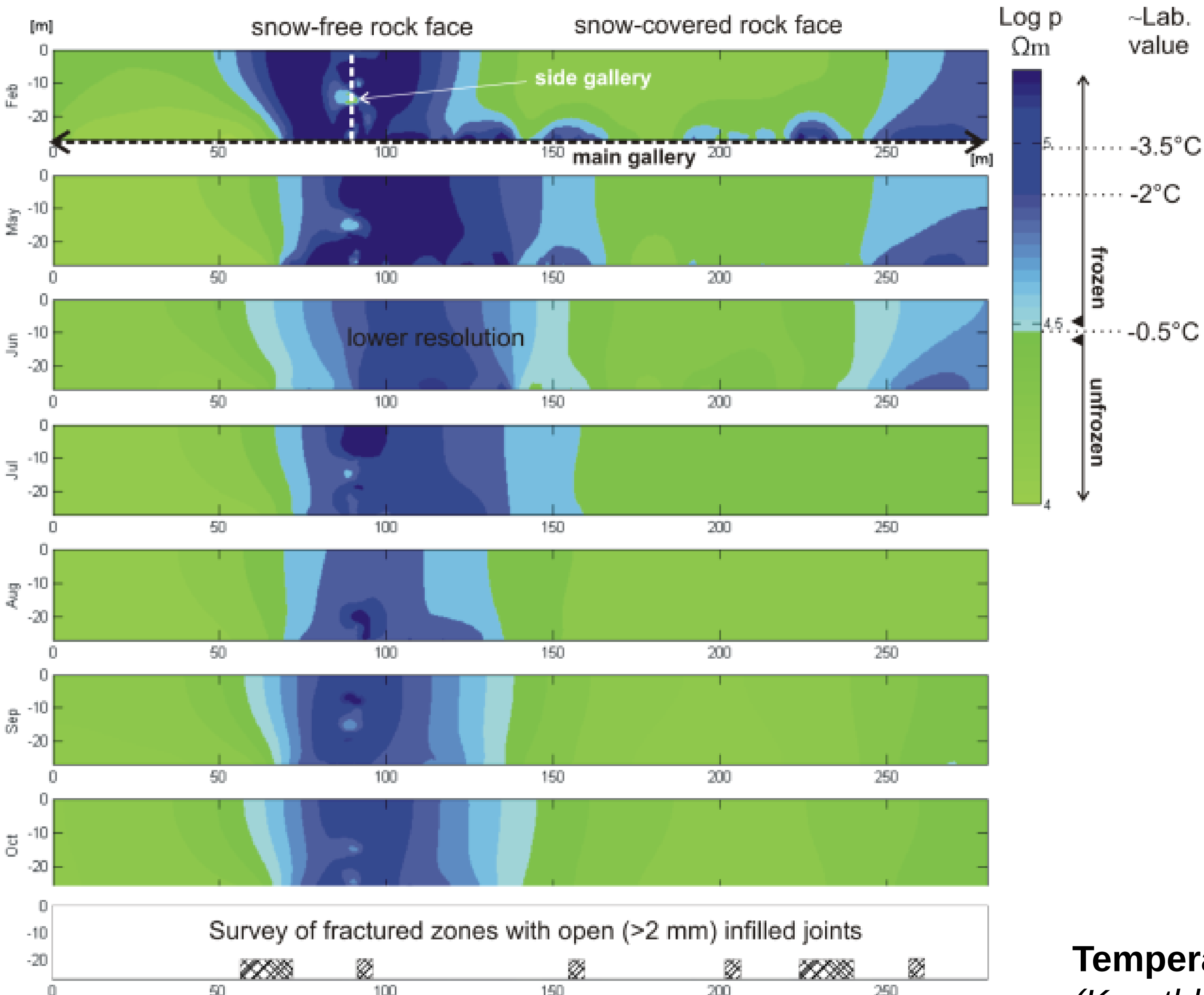


Rockfall scarp Zugspitze

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

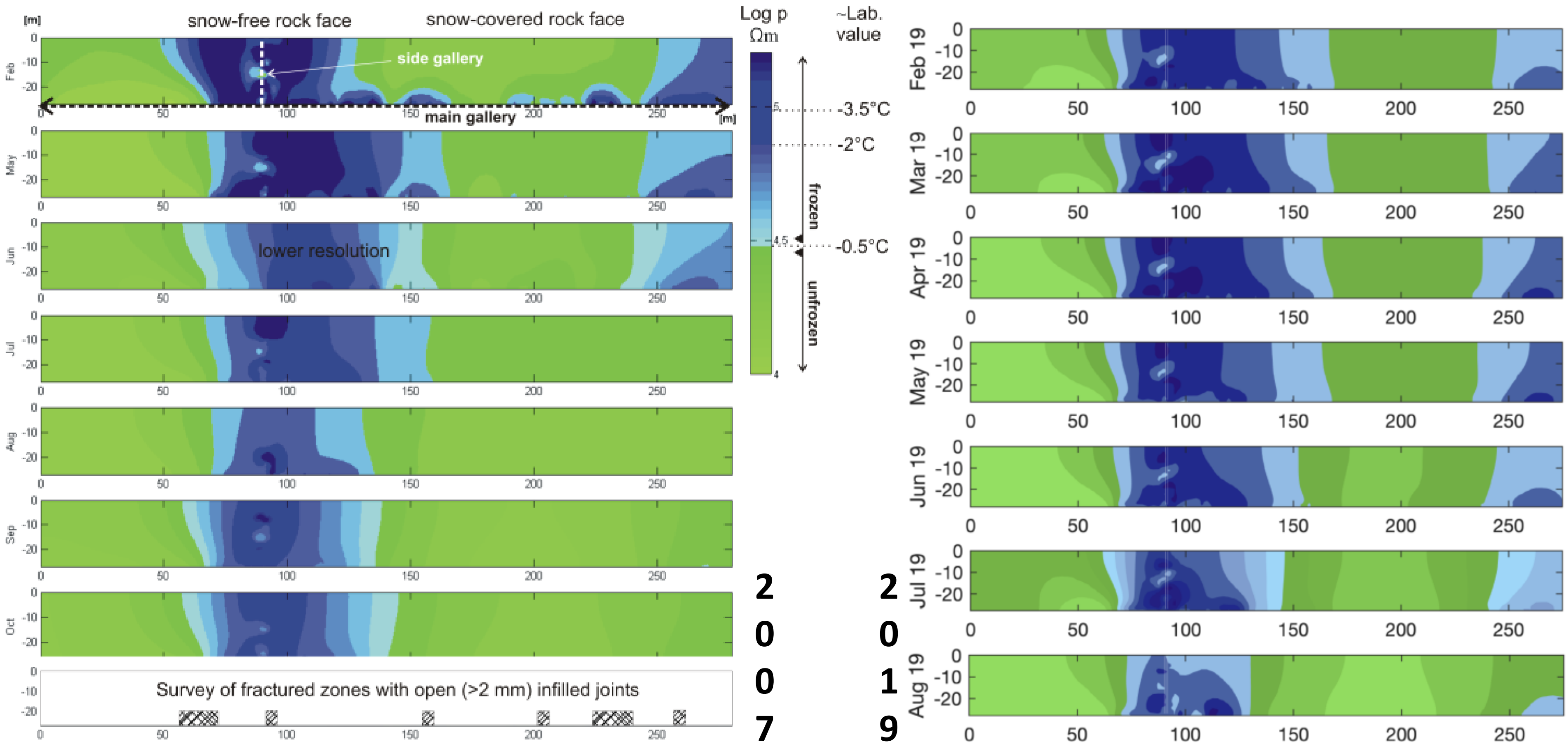
Do we understand the processes that link permafrost degradation and rock instability?

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



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

Permafrost Zugspitze 2007 & 2019

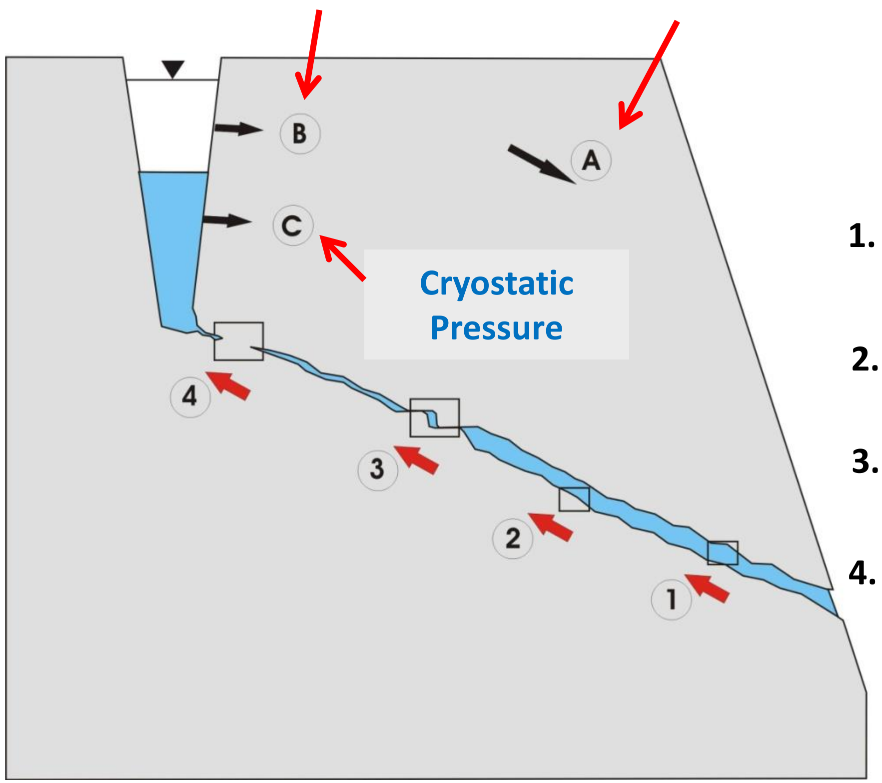


Rock-Ice mechanical model: puts relevant driving and resisting forces in a quantitative mechanical (Mohr-Coulomb) context

Driving forces

Hydrostatic Pressure

Gravitational mass -induced shear force



Resisting forces

1. Ice deformation in fractures
2. Rock-Ice interfaces
3. Friction of rock-rock contacts
4. Rock bridges

$$T_p = \varepsilon_w / A_0 \exp\left(-\frac{16700}{T_K}\right) + \left(-144 * T_C + 0.42 * \sigma' + 41.3\right) + \sigma' \tan\left(\mathrm{JRC} * \log_{10}\left(\frac{\sigma_u}{\sigma'}\right) + \varphi_r\right) + \frac{K_C\sqrt{\pi a}}{2w}$$

(yellow) = Temperature dependent

Krautblatter et al. 2013 ESPL

A preliminary rock-ice mechanical model

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

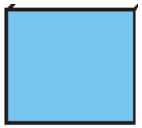
fracture of rock bridges

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

total friction due to fracture roughness

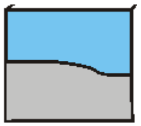
$$+ \frac{\varepsilon_w}{A_0 \exp(-\frac{16700}{T})}$$

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



<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

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

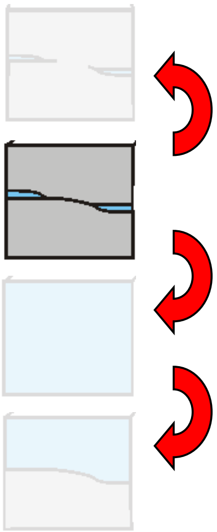
total friction due to fracture roughness

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

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

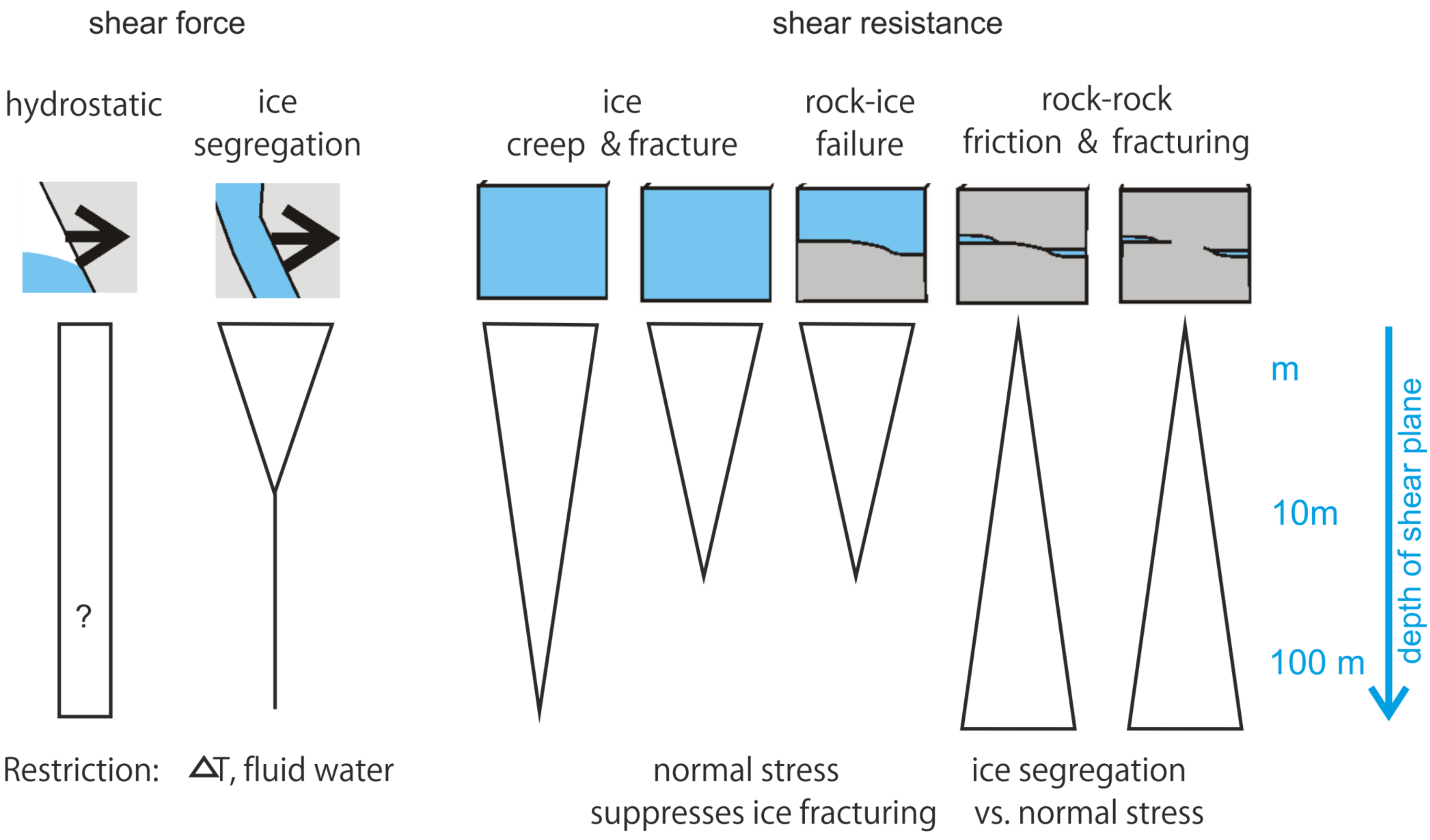
$$+(-145 * T_c + 0.47 * \sigma' - 3.5)$$

failure criterion of ice in rock clefts



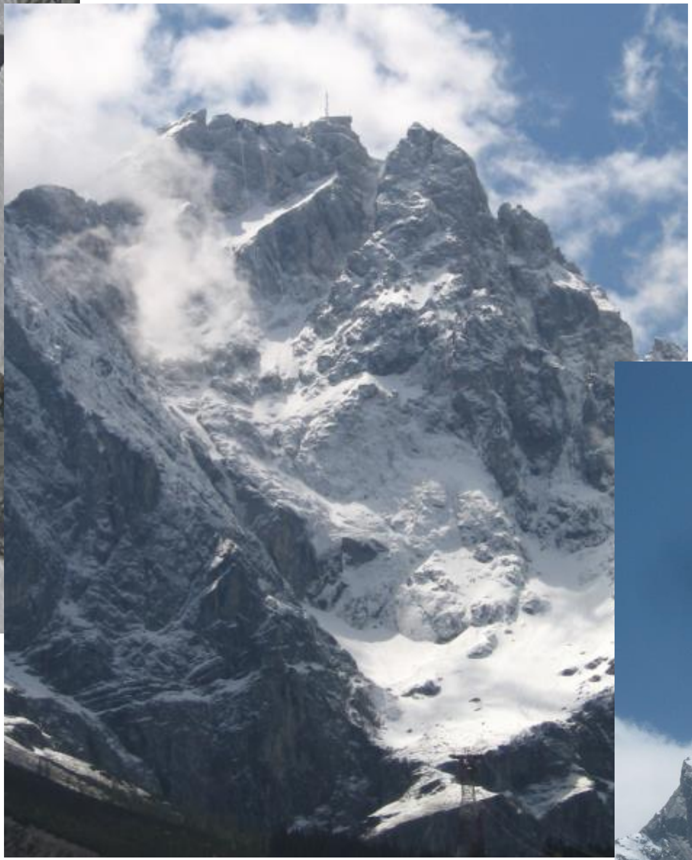
- At very low velocities (strain rates) rock-mechnical processes dominate initial destabilisation.
- Only at higher velocities ice-mechanical outbalance the importance of rock-mechnical processes.

Destabilisation in space



Sample sites

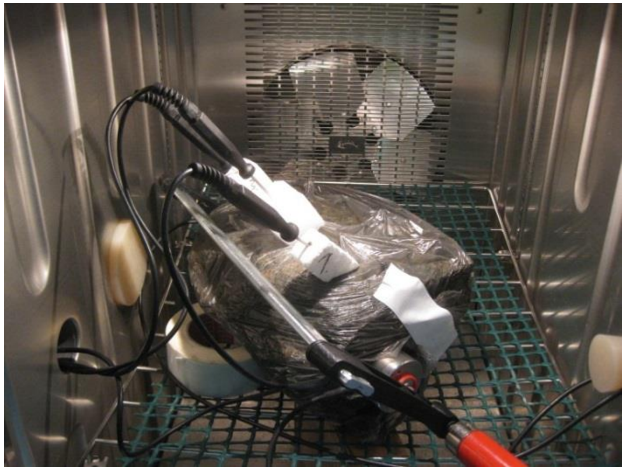
Steintälli, Mattertal, CH



Zugspitze, D/A

Kitzsteinhorn , A

Non-destructive and destructive testing techniques



Non-destructive:

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

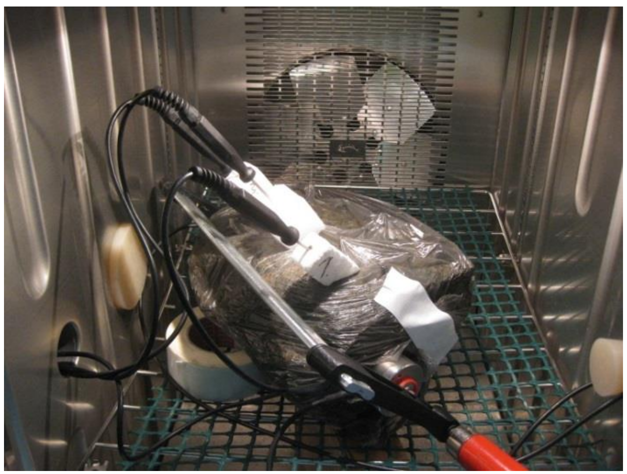
Destructive:

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

Inhomogneity, scale and anisotropy

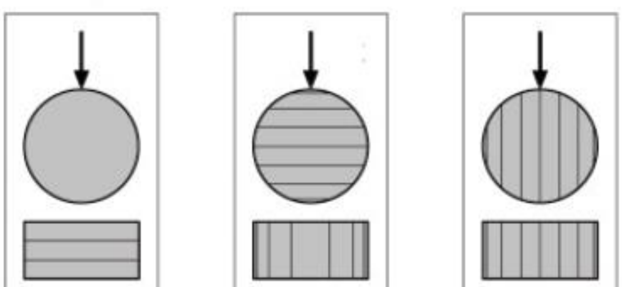
Inhomogeneity

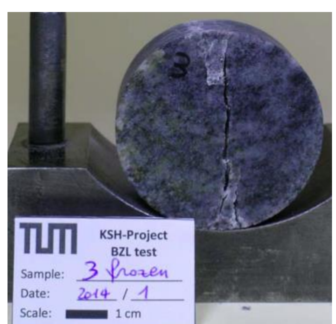
Statistic amounts of samples



Scale:

Differing testing scales with respect to fracture patterns or surface roughness

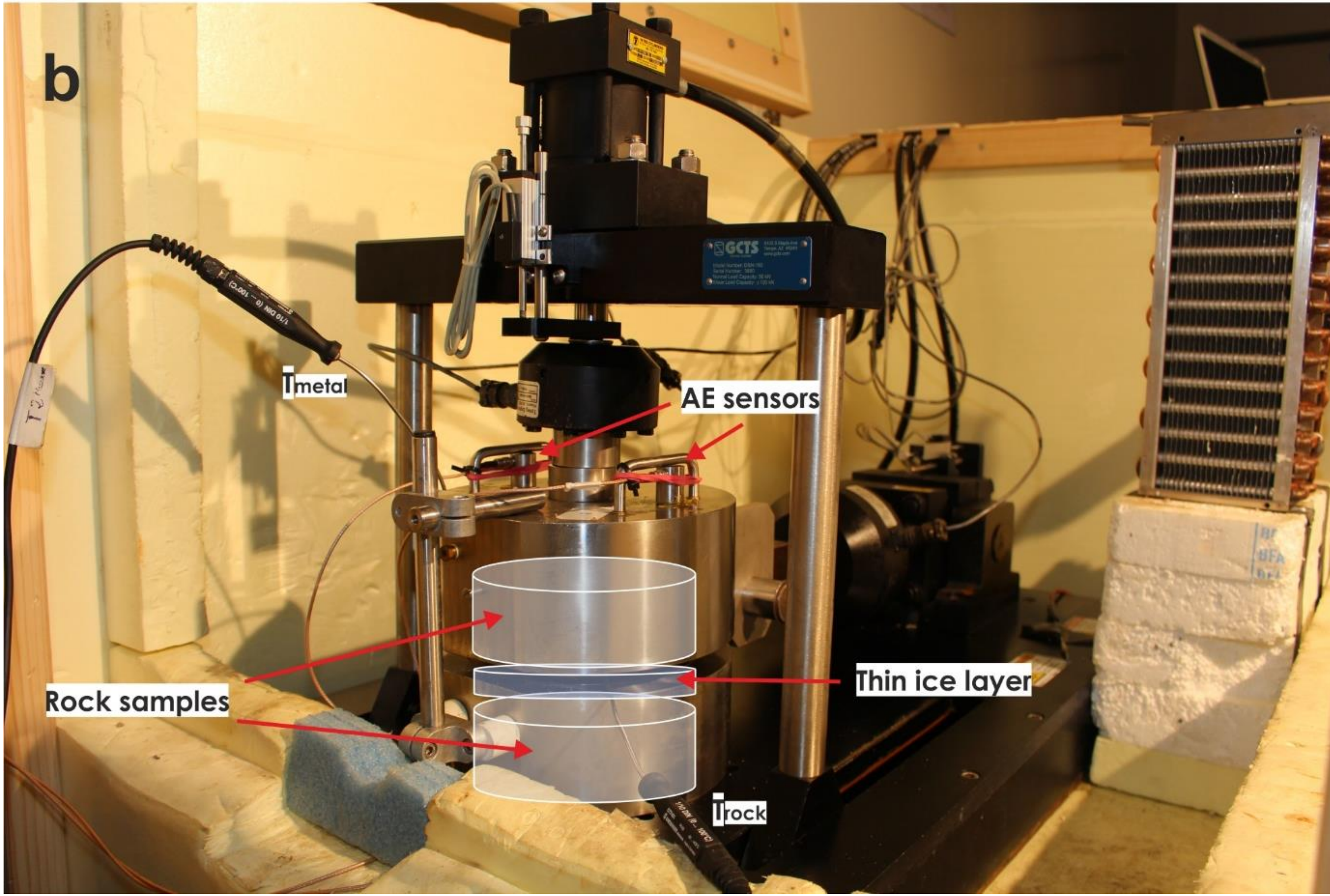




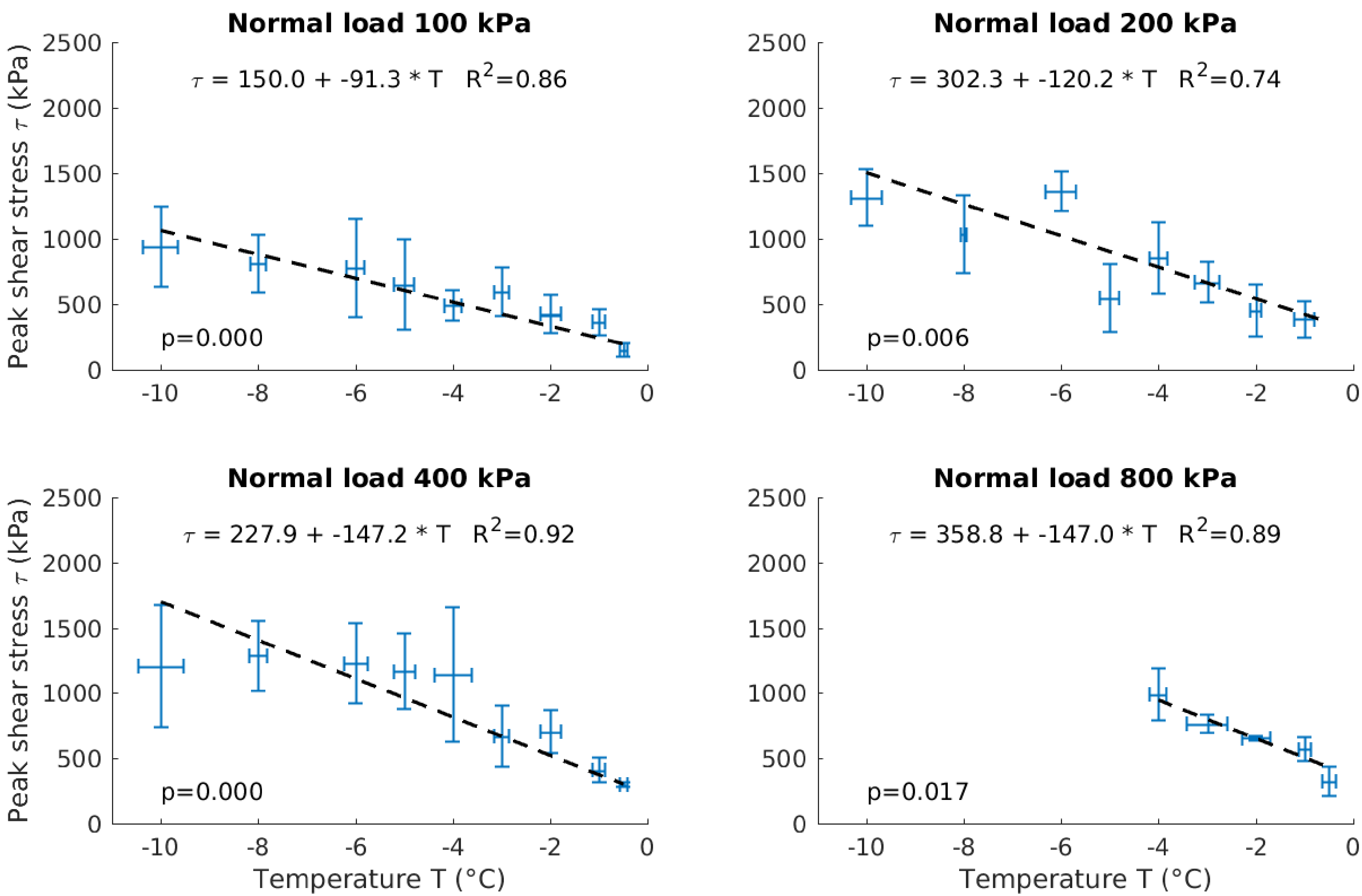
Anisotropy:

Differing testing directions with respect to fracture/ schistosity orientation

Rock-ice fracturing test

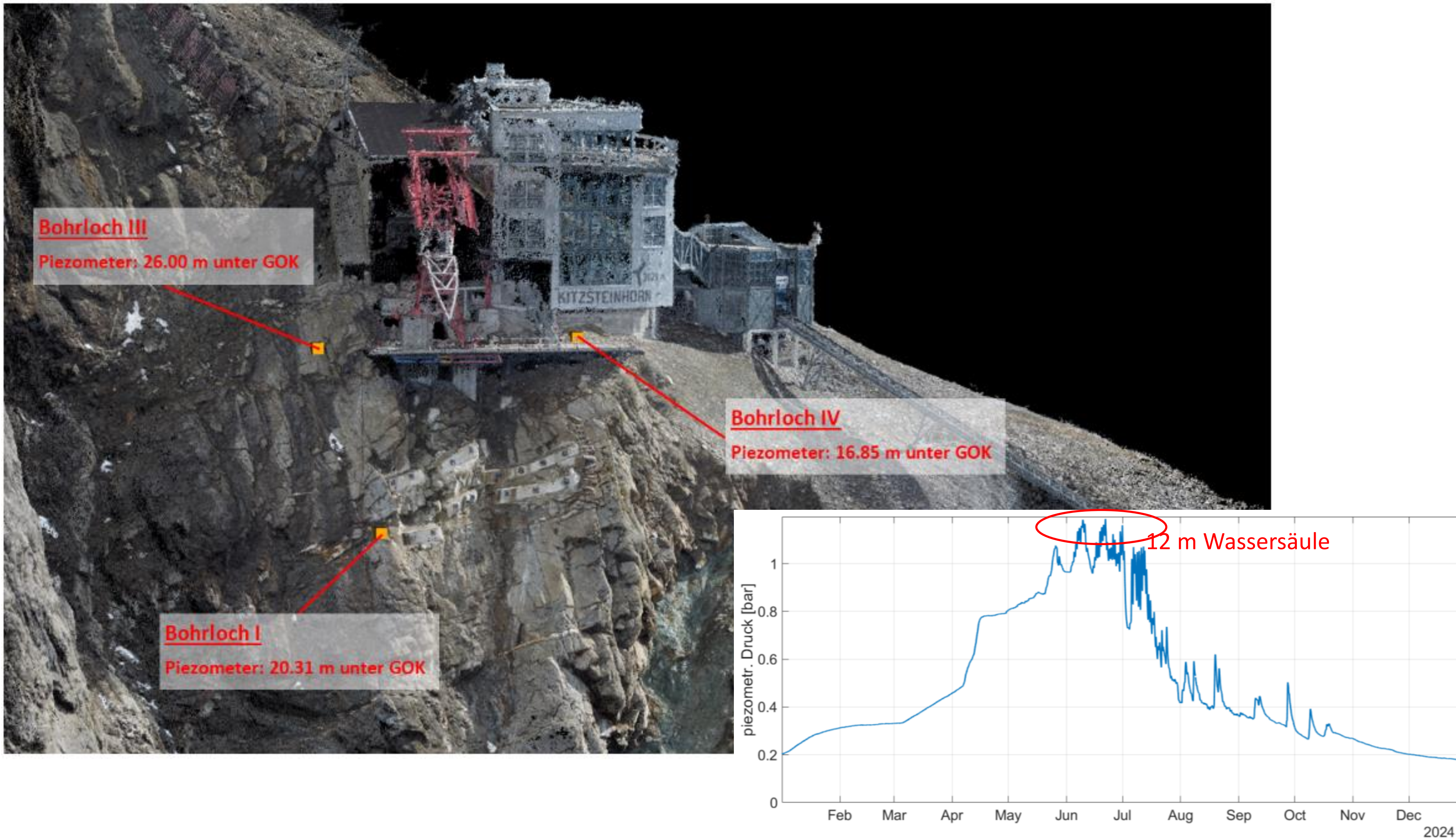


Rock-Ice-Fracturing: Temperature and stress dependence



Mamot, Weber & Krautblatter , Cryosphere, to be subm.

Hydrostatische Drücke am Kitzsteinhorn (3.029 m NN)



New freezing rock mechancial lab finished 10/25

Deriving a model of permafrost-related rock slope failure

Methodology

How could thawing permafrost influence slope stability at the Zugspitze summit crest?

Laboratory

Material parameter for modelling:
Temperature related change of rock-ice-mechanical properties (along discontinuities)

- Site specific -
...for the rock slope at the Zugspitze crest

Rock-ice-mechanical failure model

- Generalized -
...for degrading permafrost rock slopes

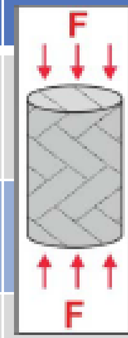
Field site

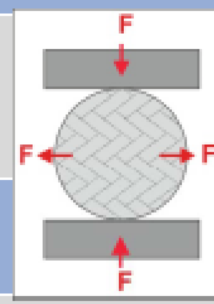
Spatial distribution of permafrost-affected rock

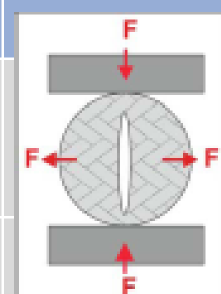
Spatial and temporal change in rock stability

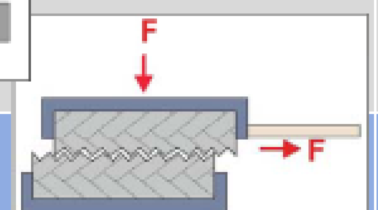
Mechanical change of frozen and unfrozen Zugspitze Limestone

Mechanical parameter	Sketch of test	decreases by	Temp. / Literature
Uniaxial compressive strength (UCS) of rock		20 - 50 % ca. 50 %	-10°C to 0°C: Mellor 1973, -20 to -5°C: Kodama et al. 2013
UCS of ice		293 %	-50°C to 0°C: Inada & Yokota 1984
Indirect tensile strength (ITS) of rock		15 - 70 % ca. 120 %	-10 to 0°C: Mellor 1973, -20 to -5°C: Kodama et al. 2013
ITS of ice		79 %	-50°C to 0°C: Inada & Yokota 1984
Fracture toughness of rock bridges		17 - 58 %	-10°C to 30°C: Dwivedi et al. 2000
Basic joint friction angle		14 - 17 %	-4.5°C to room temp.: Krautblatter et al. 2013
Shear strength of concrete-ice-contacts		(-144 kPa/°C) 255 %	-2.5 to 0°C: Krautblatter et al. 2013, -5°C to -0.5°C: Davies et al. 2000

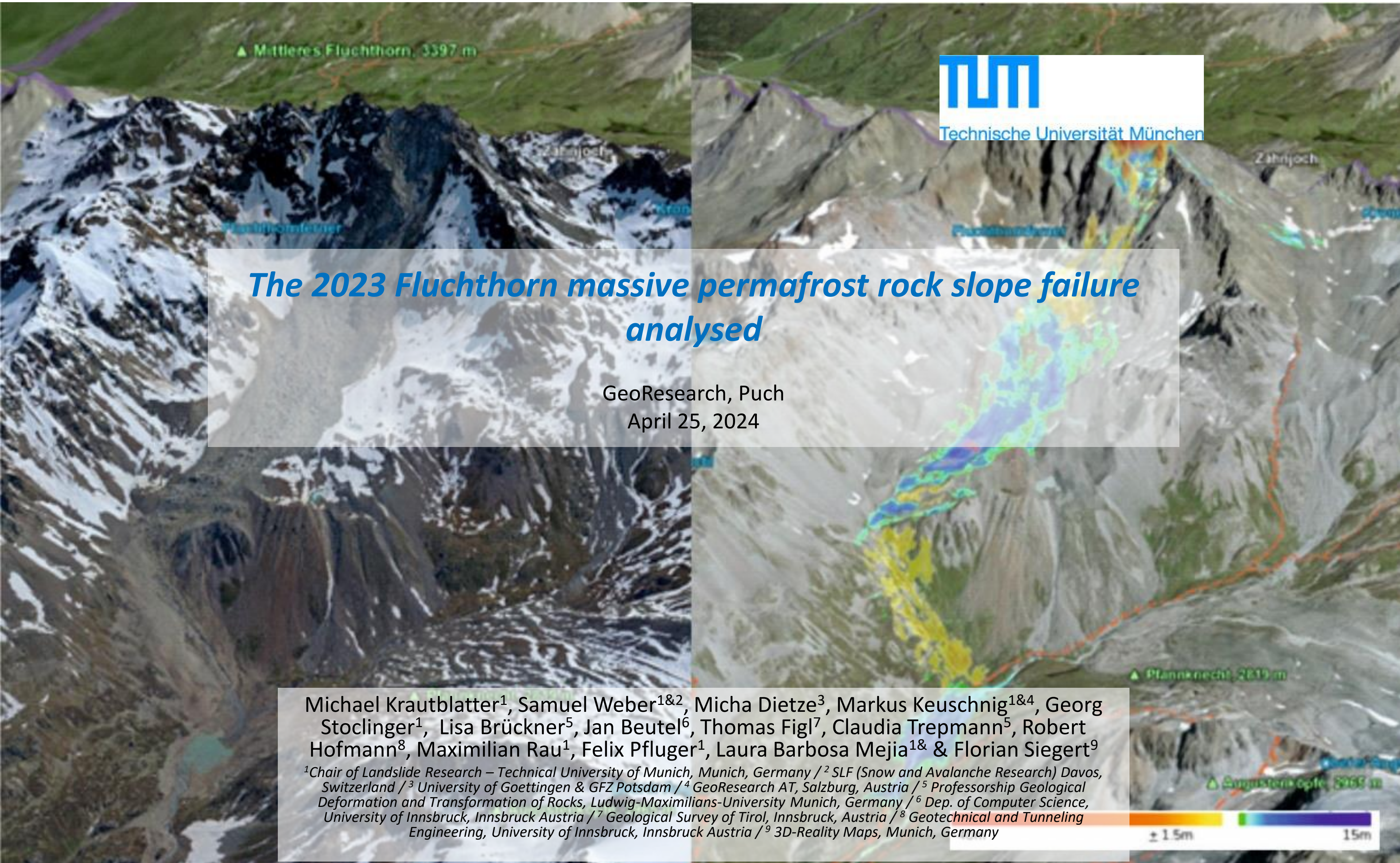








Mamot, Weber, Eppinger & Krautblatter 2021 ESurf



Technische Universität München

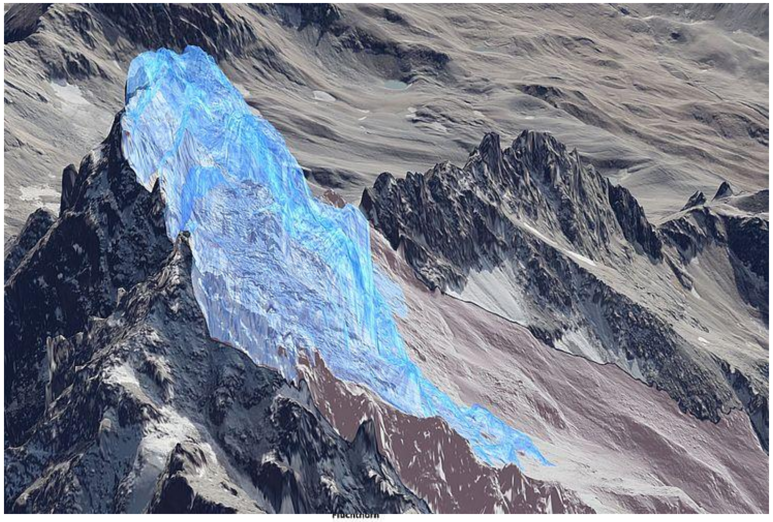
The 2023 Fluchthorn massive permafrost rock slope failure analysed

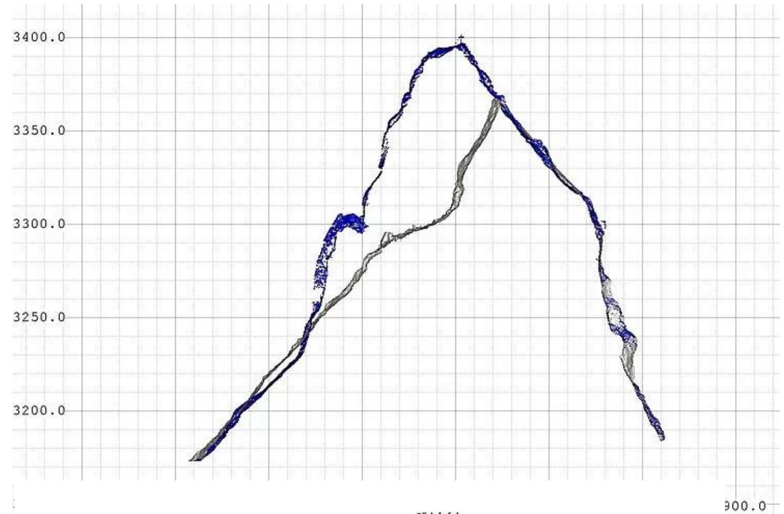
GeoResearch, Puch
April 25, 2024

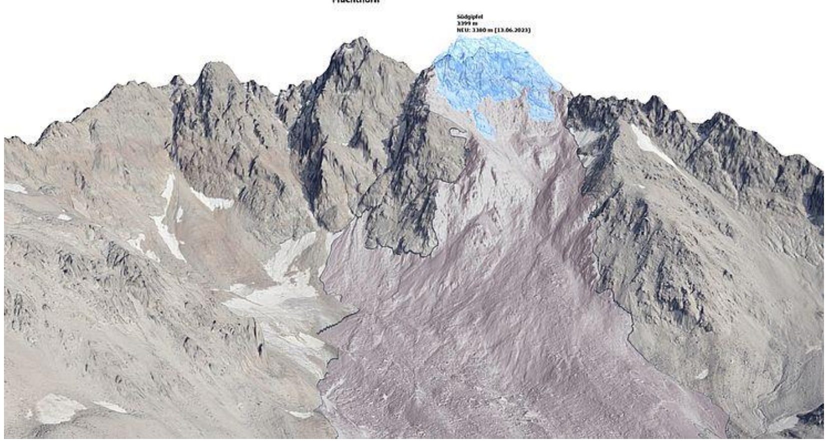
Michael Krautblatter[1], Samuel Weber[1&2], Micha Dietze[3], Markus Keuschnig[1&4], Georg Stoclinger[1], Lisa Brückner[5], Jan Beutel[6], Thomas Figl[7], Claudia Trepmann[5], Robert Hofmann[8], Maximilian Rau[1], Felix Pfluger[1], Laura Barbosa Mejia[1&] & Florian Siegert[9]

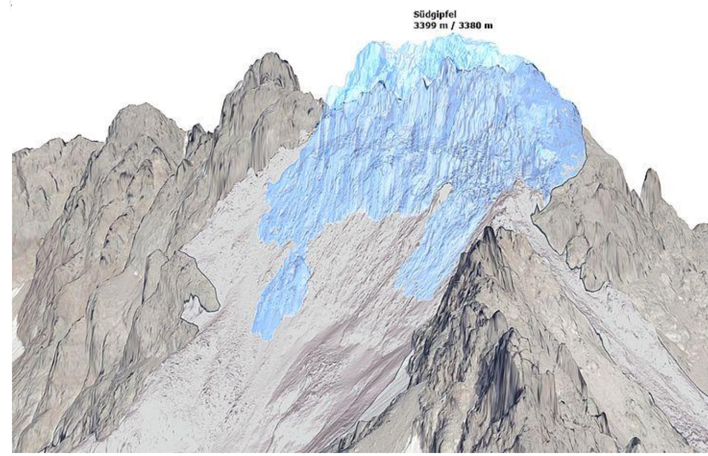
[1]Chair of Landslide Research – Technical University of Munich, Munich, Germany / [2] SLF (Snow and Avalanche Research) Davos, Switzerland / [3] University of Goettingen & GFZ Potsdam / [4] GeoResearch AT, Salzburg, Austria / [5] Professorship Geological Deformation and Transformation of Rocks, Ludwig-Maximilians-University Munich, Germany / [6] Dep. of Computer Science, University of Innsbruck, Innsbruck Austria / [7] Geological Survey of Tirol, Innsbruck, Austria / [8] Geotechnical and Tunneling Engineering, University of Innsbruck, Innsbruck Austria / [9] 3D-Reality Maps, Munich, Germany

1. Exact volumes of detached, deposited and eroded rock and ice volumes



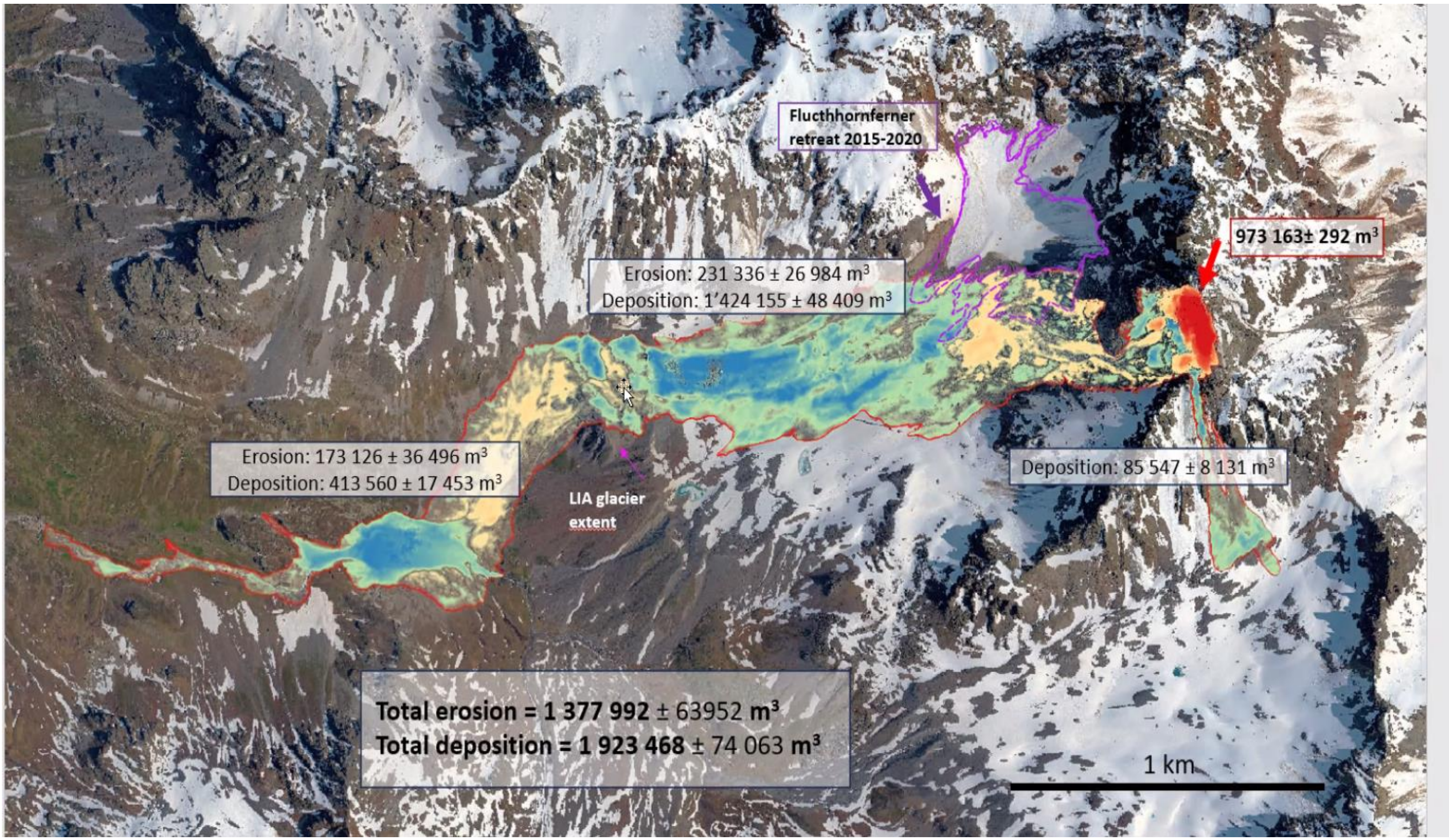






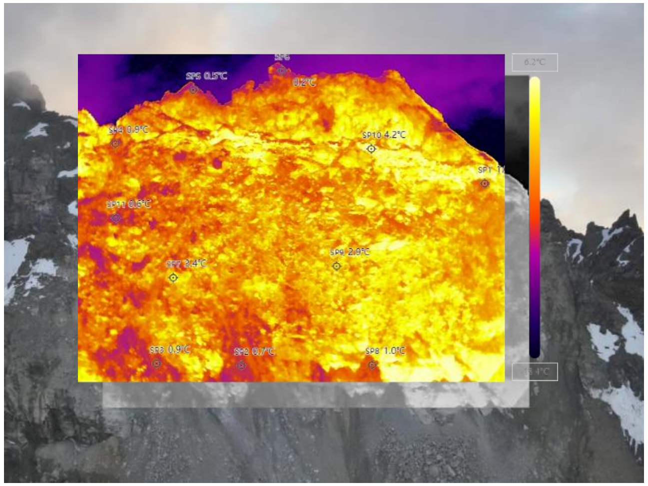
tirol.gv.at

1. Exact volumes of detached, deposited and eroded rock and ice volumes



2. Permafrost temperatures at the detachment surface

IR-UAV campaign 2d after failure



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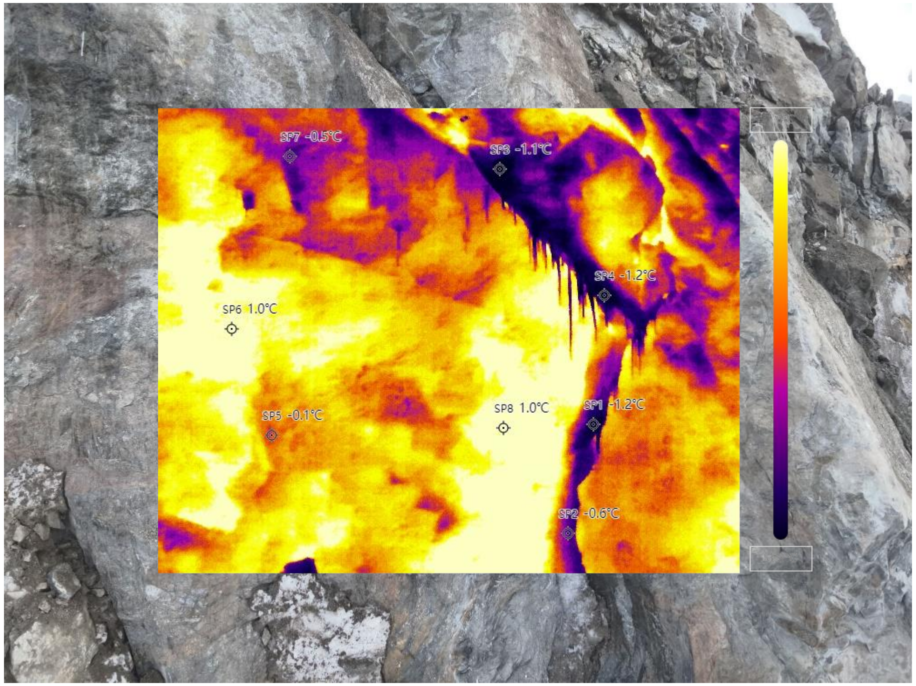
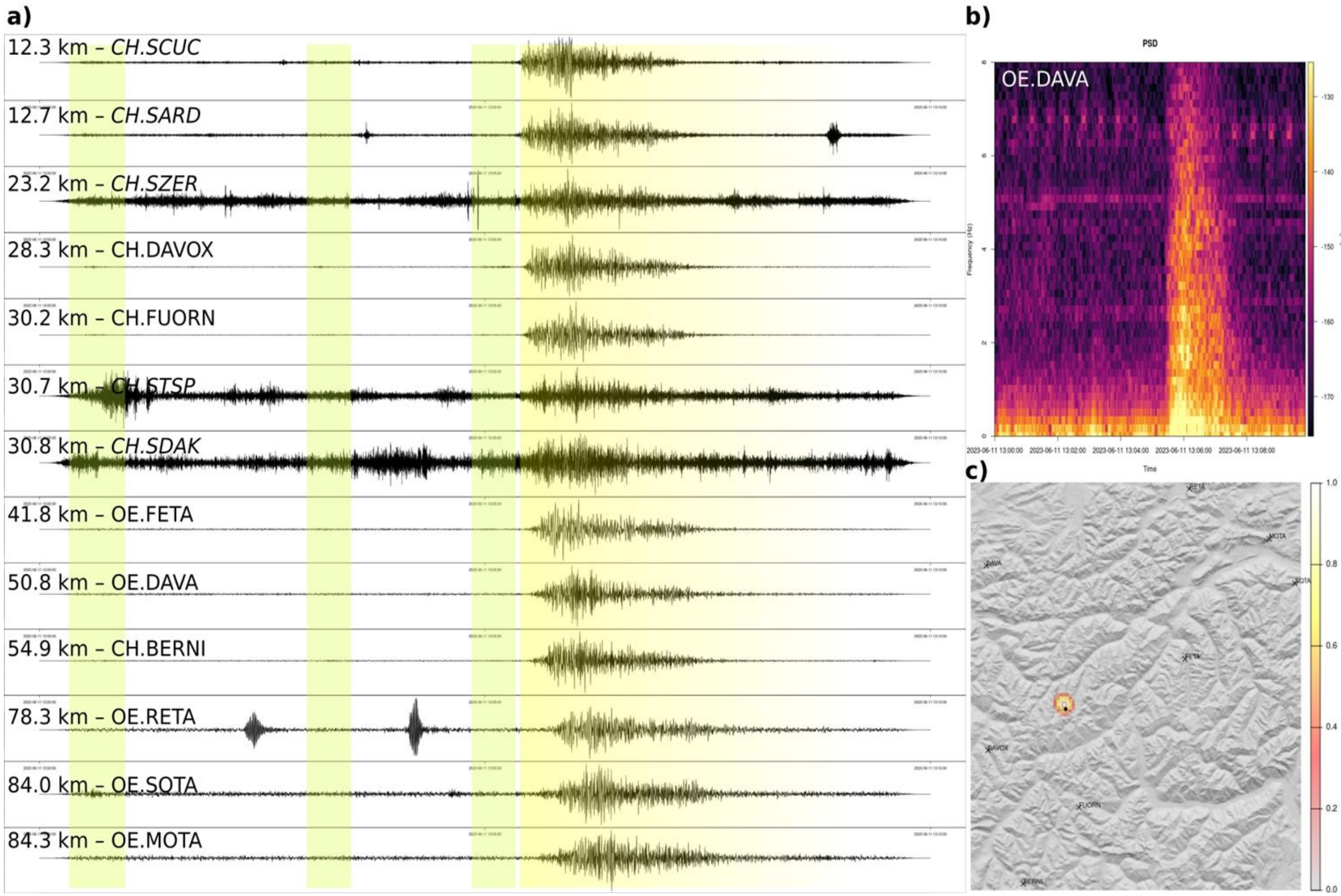


4 Timing and energy release of a single or multistage failure? (seismic analysis)



Start
2023-06-11 13:05:17 UTC

Duration (min)
144 s

Magnitude
M_L 2.3 (SED) or 1.4 (ZAMG)

Central frequency
0.56 Hz (at closest station)

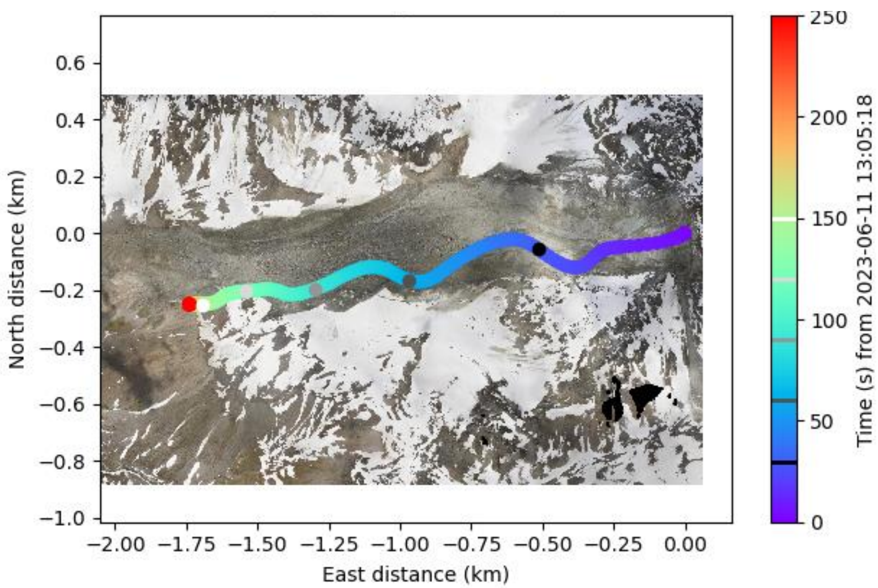
Number of sub-events
1

Precursor events
3

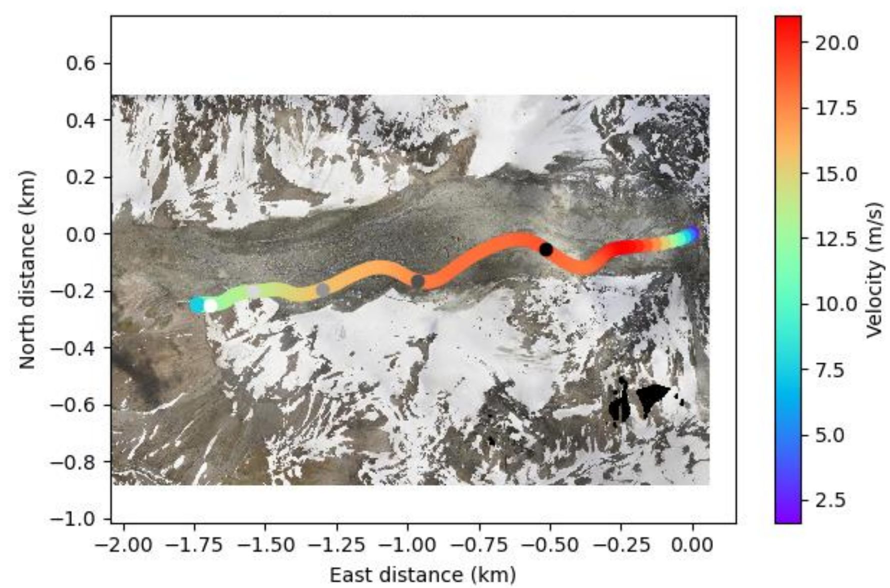
Radiated seismic energy
[pending]

4 Timing and energy release of a single or multistage failure? (seismic analysis)

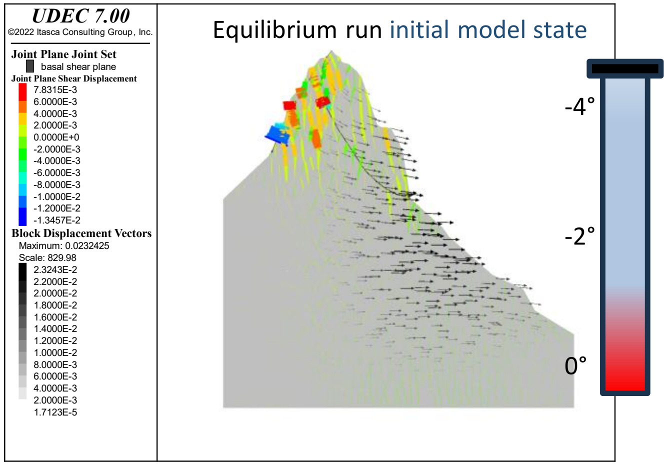
Timing of the rock avalanche front (seismic force inversion)

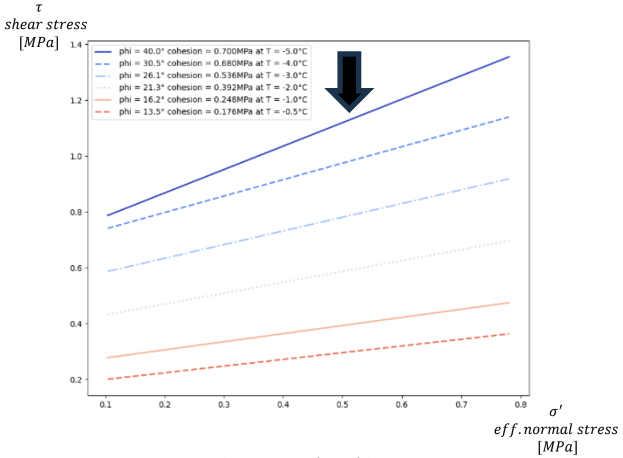


Velocity of the rock avalanche front (seismic force inversion)



6. Can we model the failure in a thermo-mechanic model?





Shear-criterion for icefilled joints
acc. to Mamot et al. (2018, 2020)

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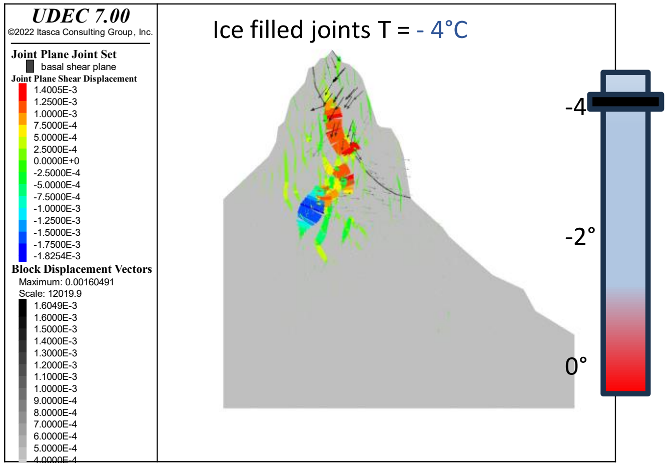

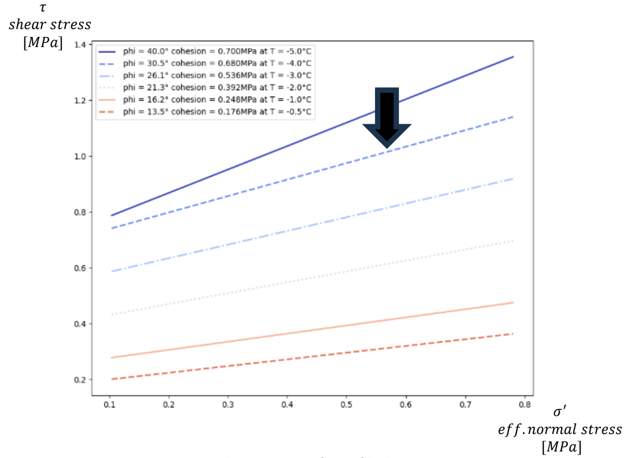

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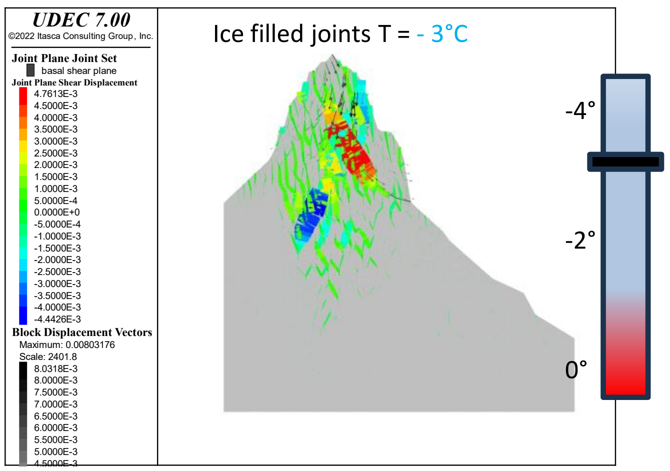

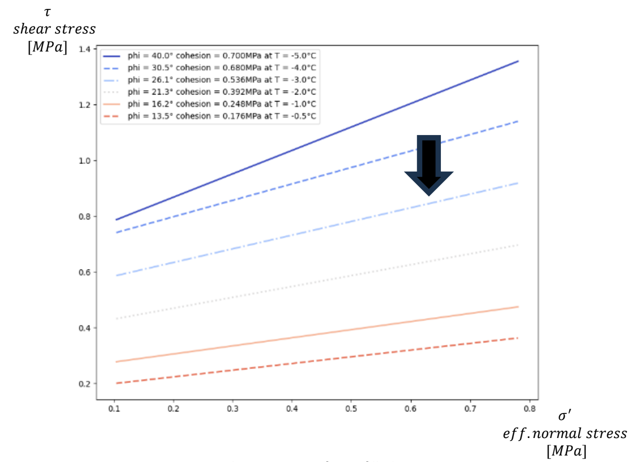

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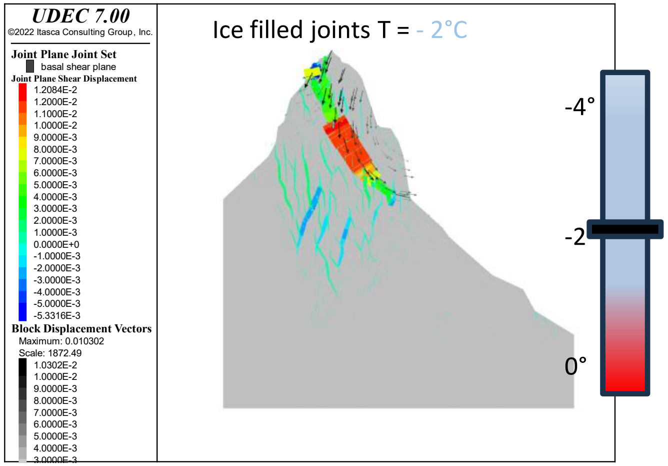

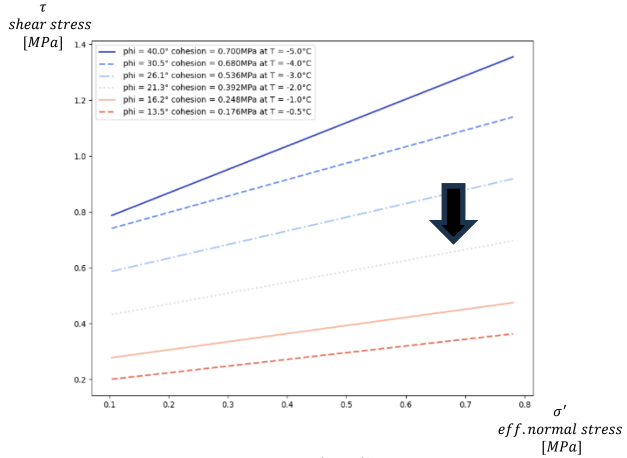

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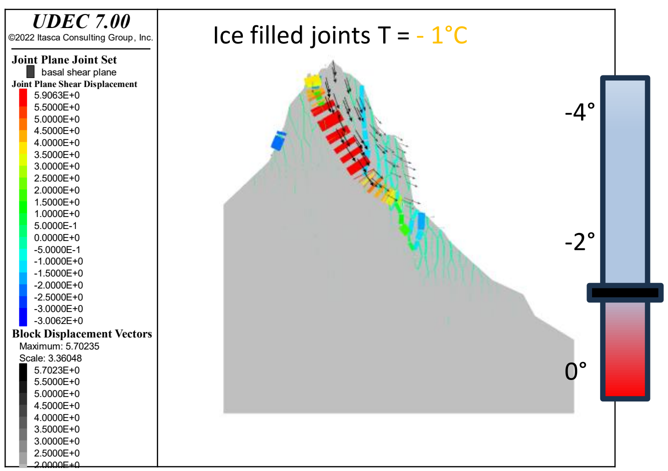

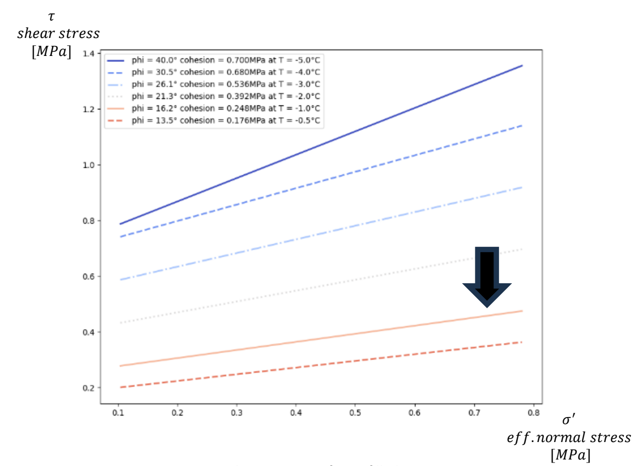

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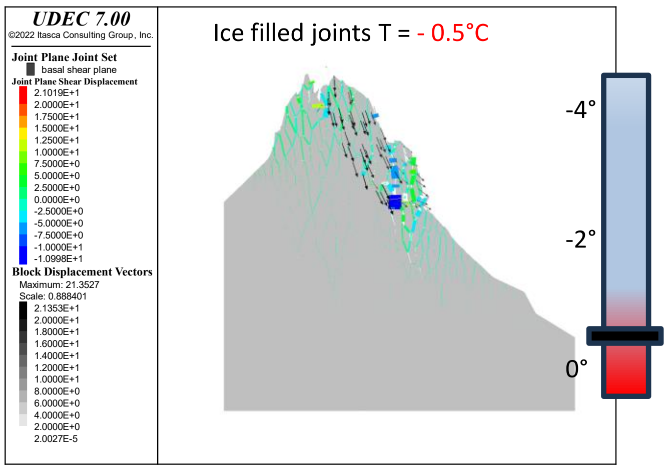

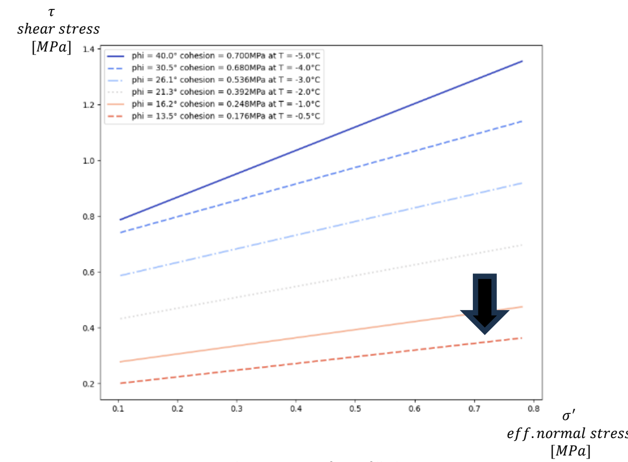

Shear-criterion for icefilled joints
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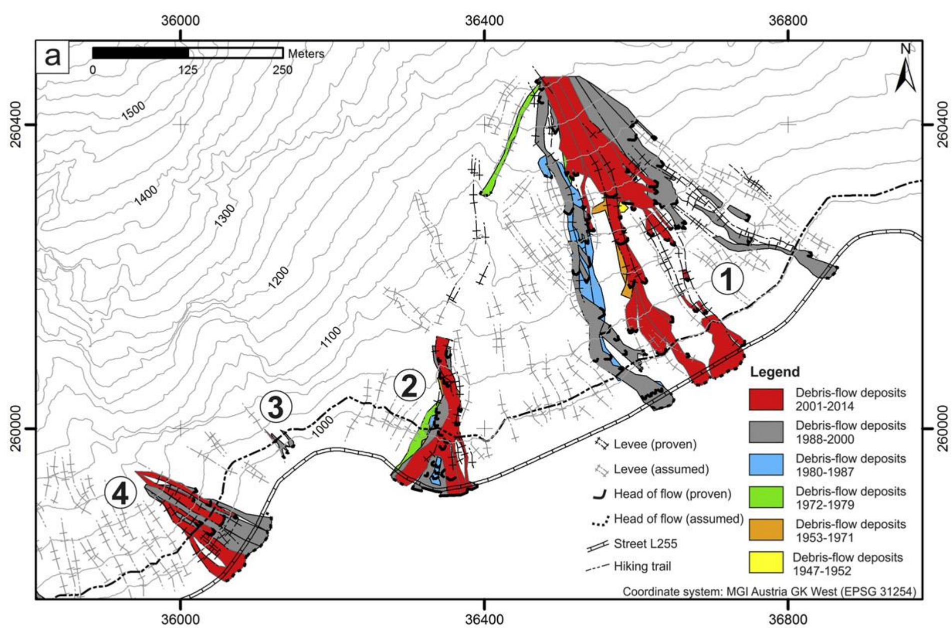
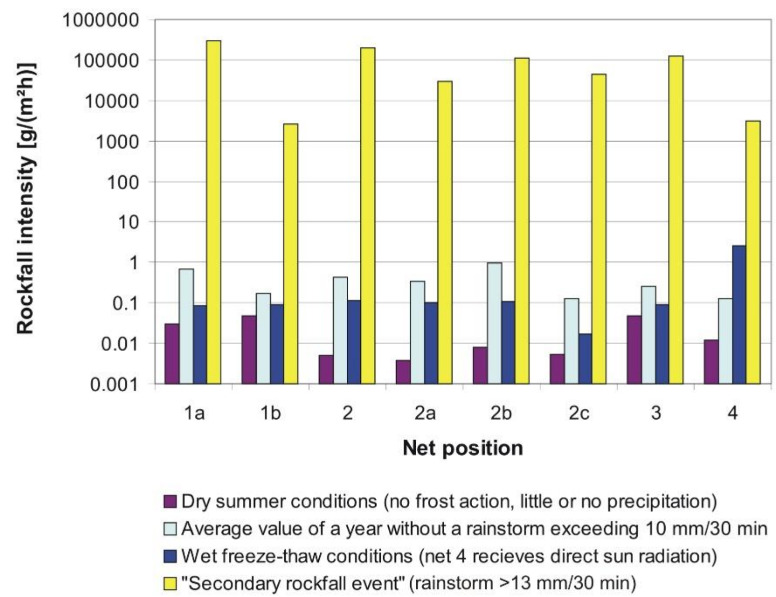
2. Climate-induced natural hazards: Debris flows and rockfall

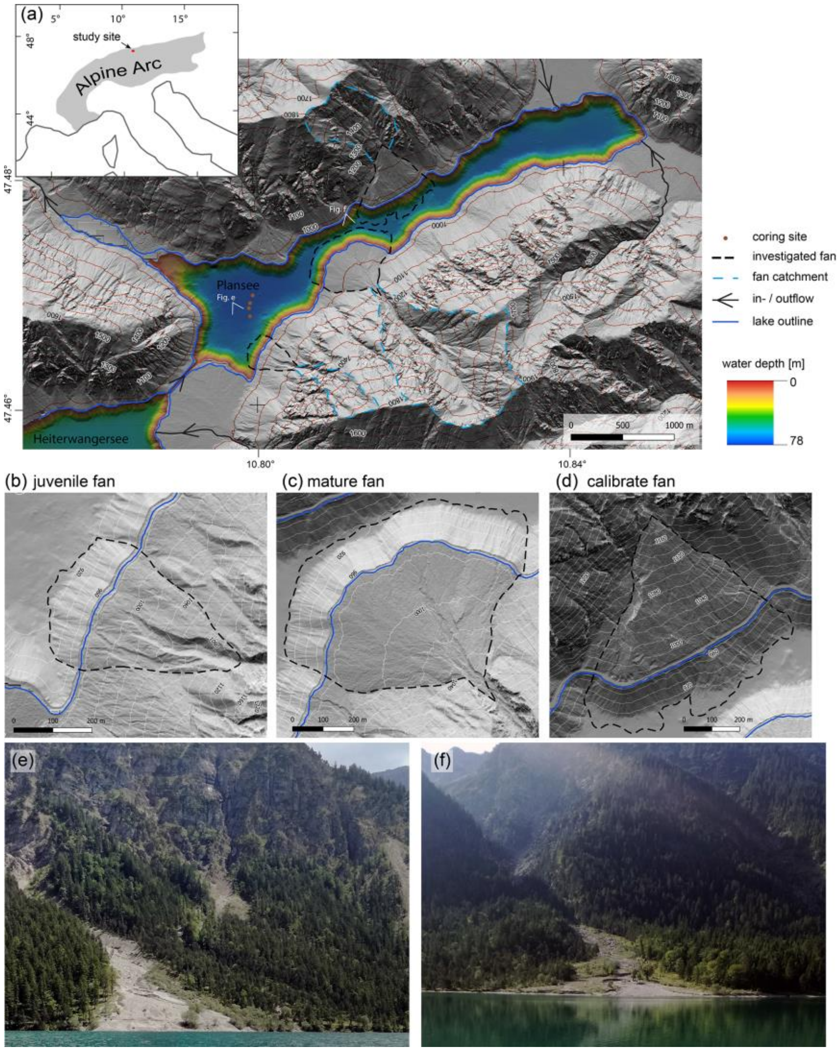
Debris Flows: clear increase since 1980s with heavy rainfall events

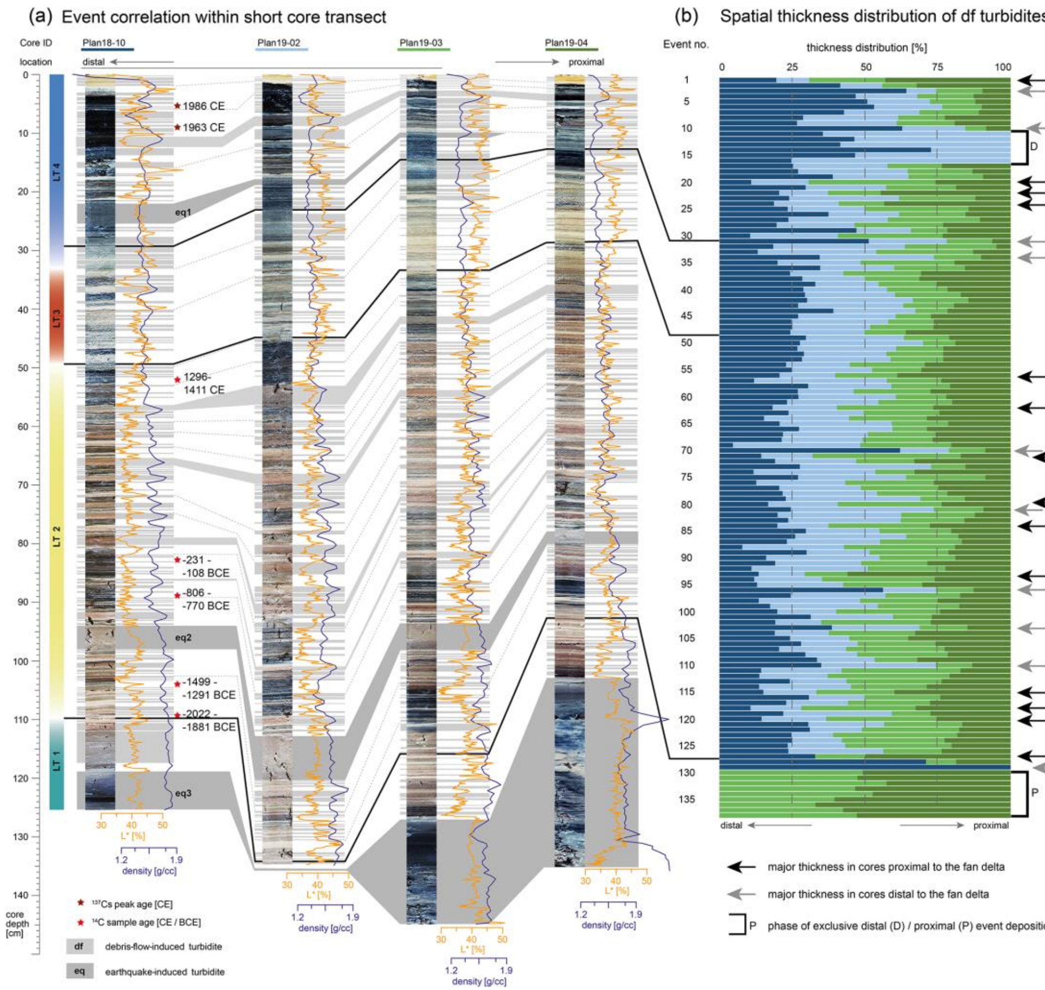
Rock fall: >90% coupled to heavy rainfall events





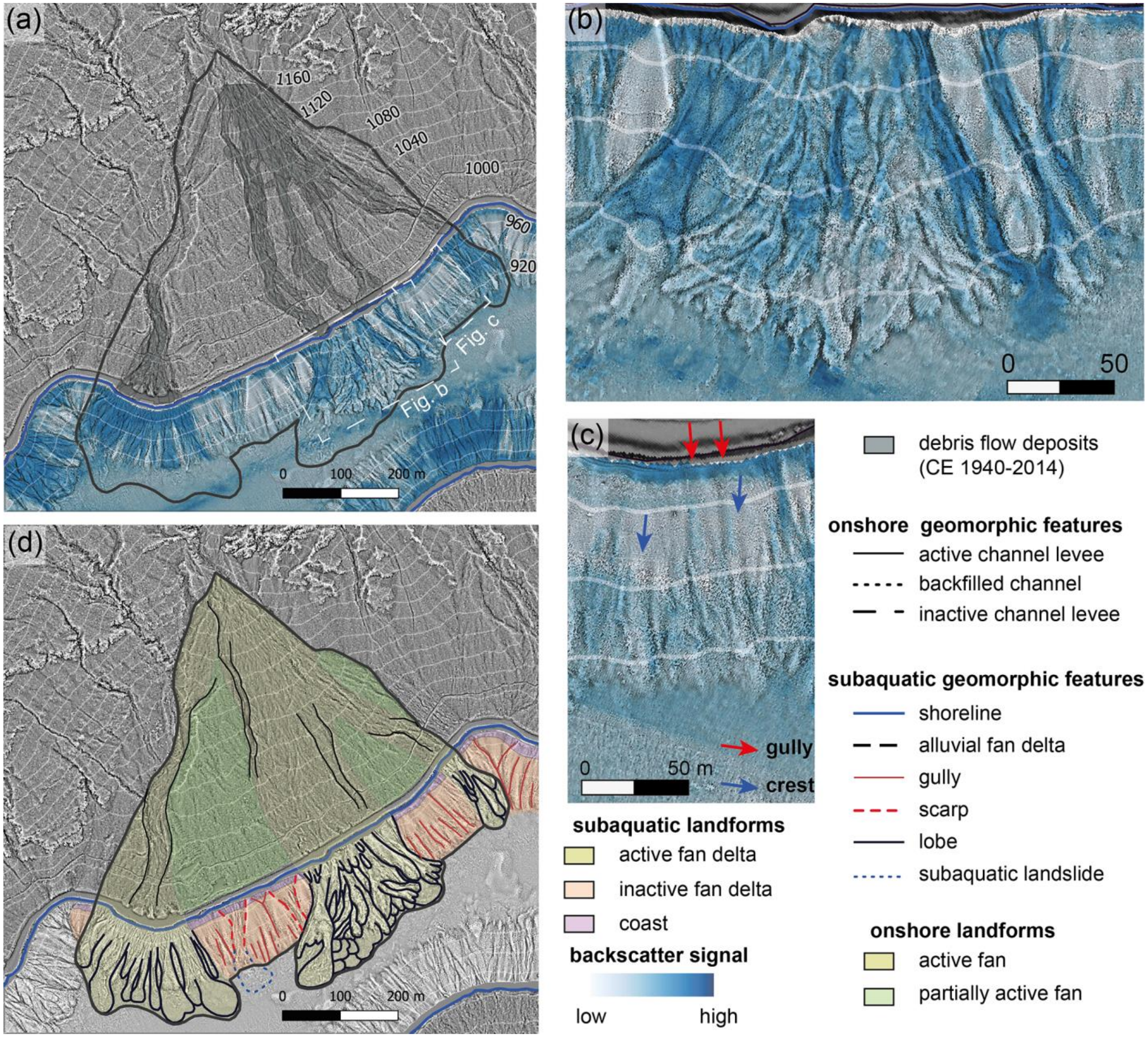
A 4000-year debris flow record based on amphibious investigations





Kiefer, Oswald… & Krautblatter ESURF 2021

A 4000-year debris flow record based on amphibious investigations



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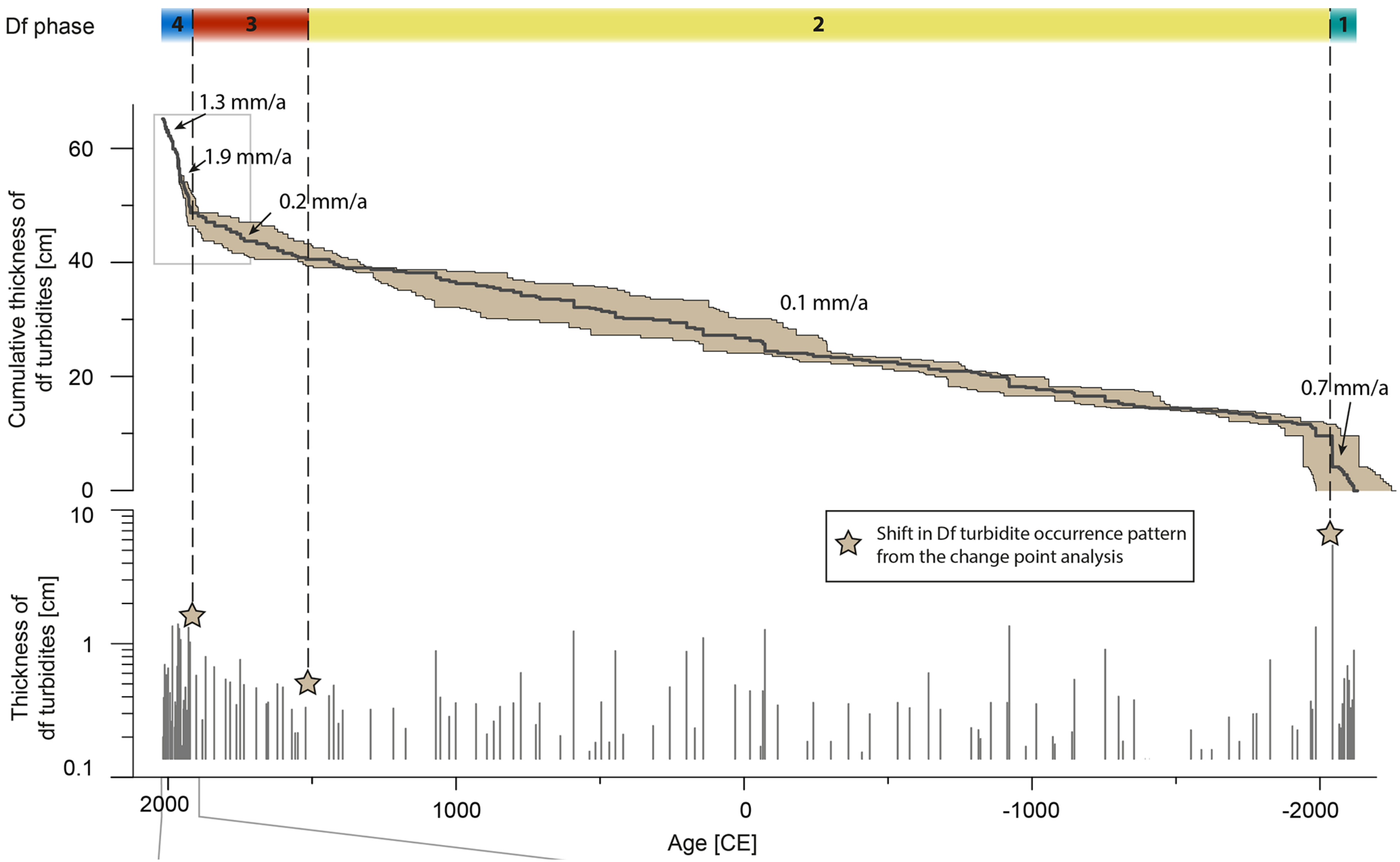
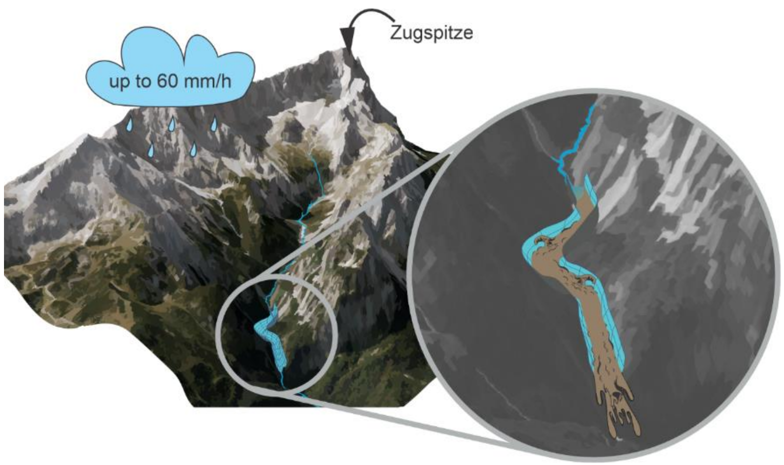
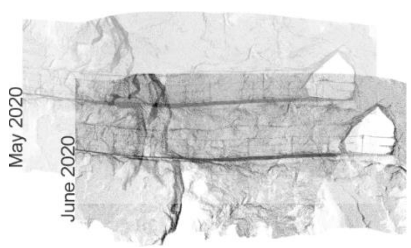


Kiefer, Oswald… & Krautblatter ESURF 2021

Höllentalklamm – Bedrock erosion due hyperconcentrated flow





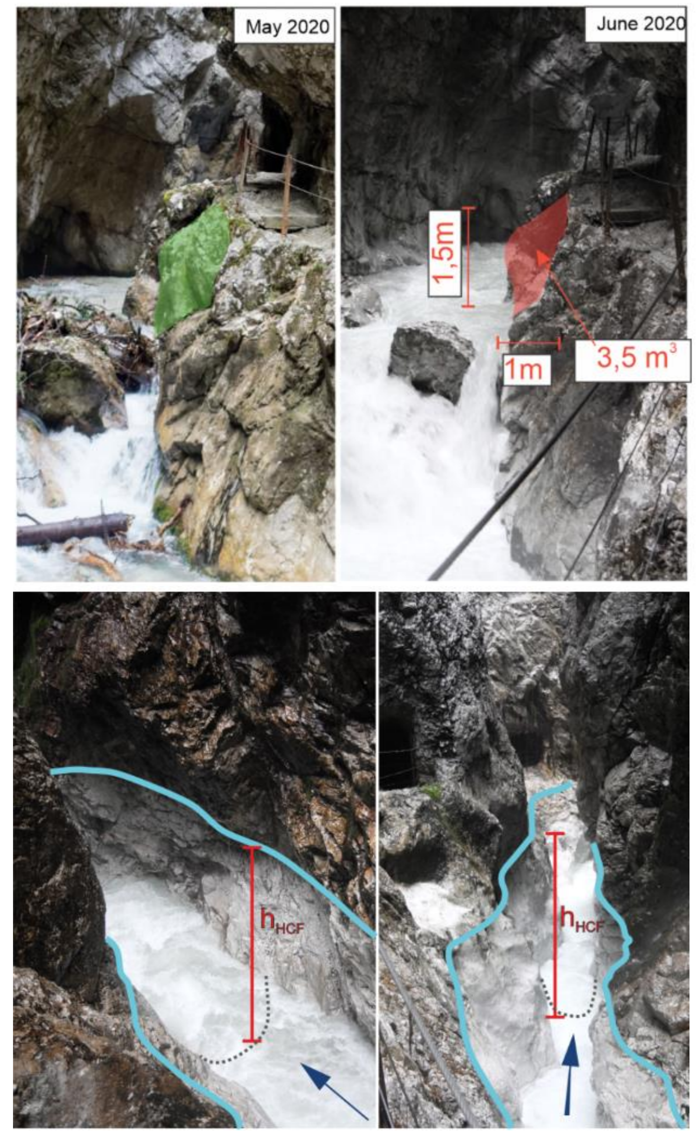
communications earth & environment **Article**

https://doi.org/10.1038/s43247-024-01353-3

Hyperconcentrated flows shape bedrock channels

Check for updates

Verena Stammberger, Benjamin Jacobs & Michael Krautblatter



Stammberger, Jacobs & Krautblatter et al. (2024) Nature Comm. E&E

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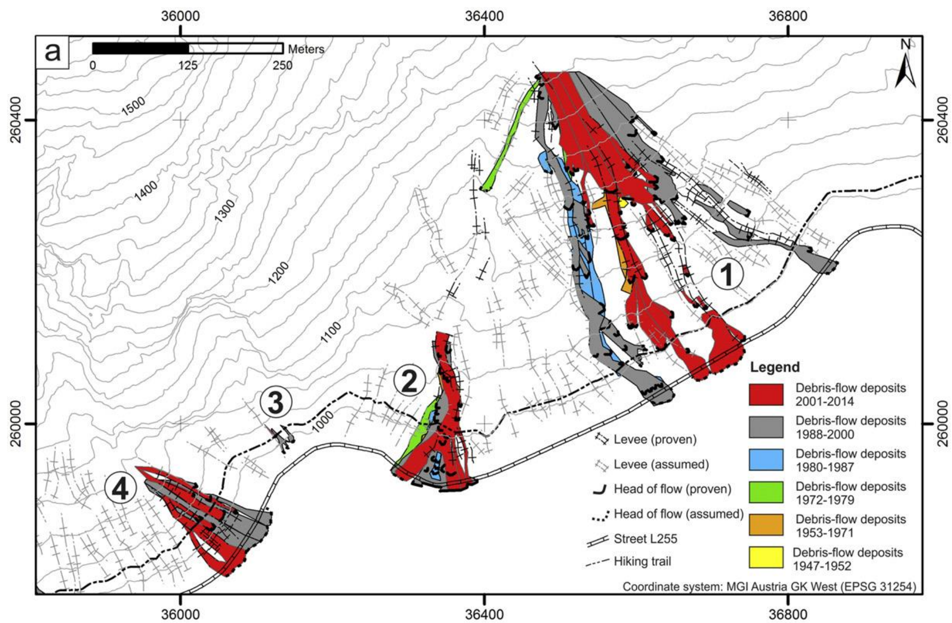
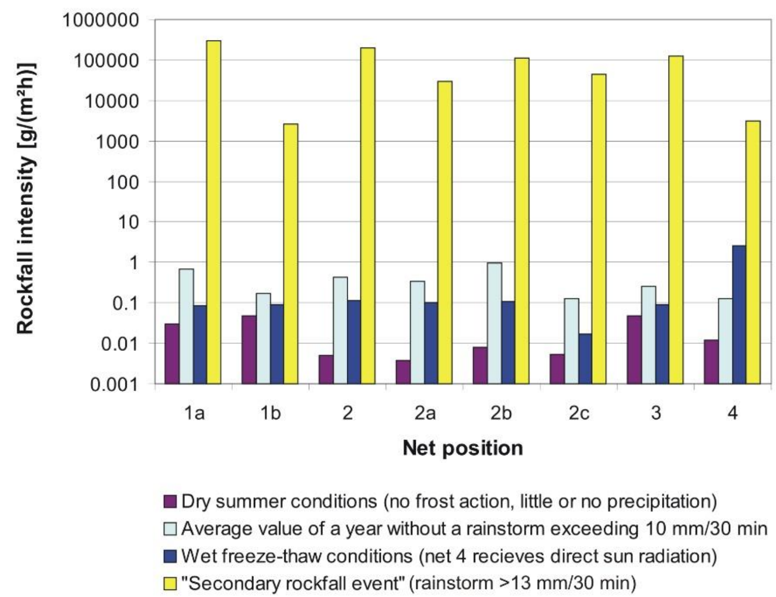


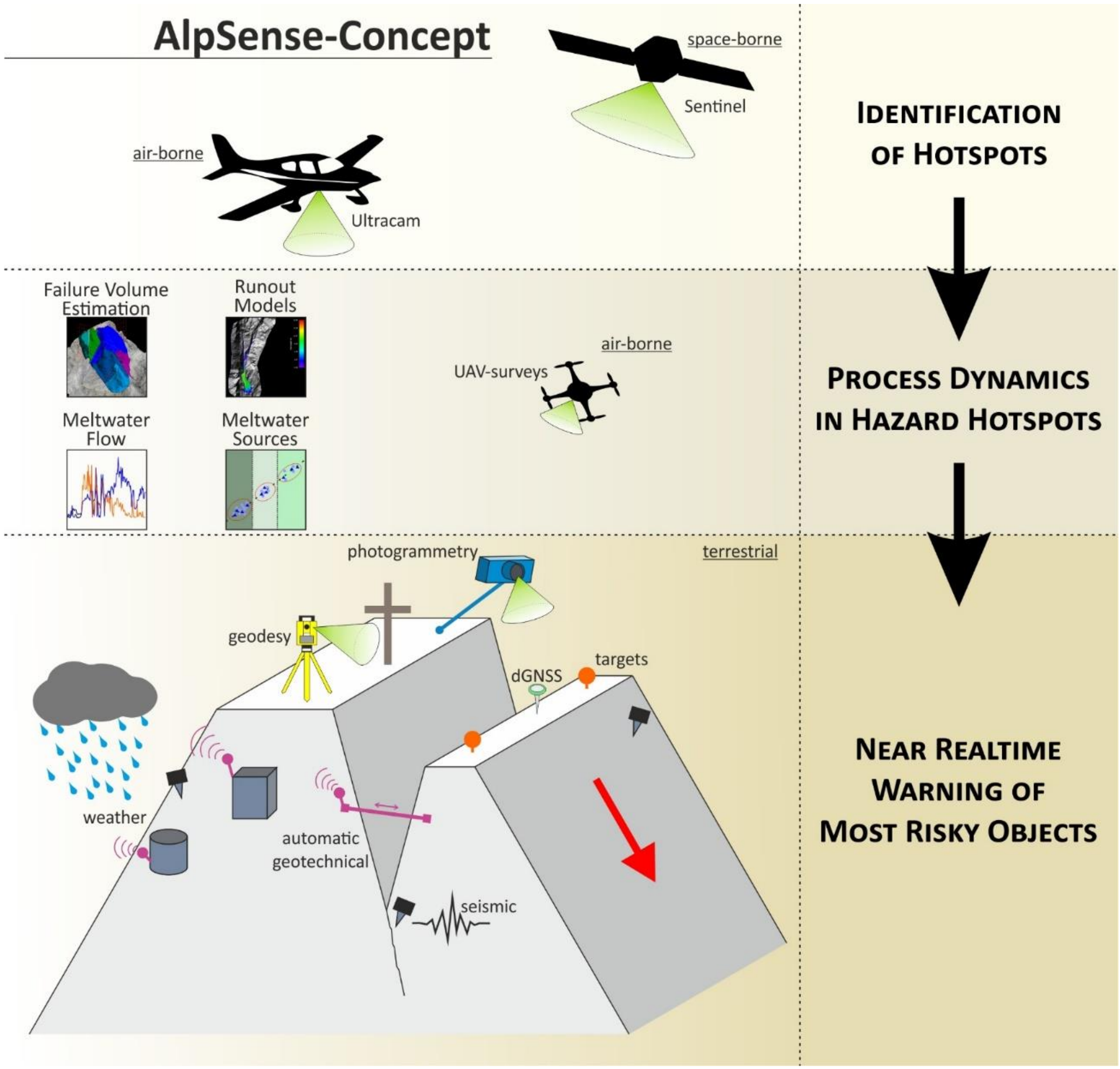


Rock fall activity from laser scanning (>50 positions) at Höllentalklamm

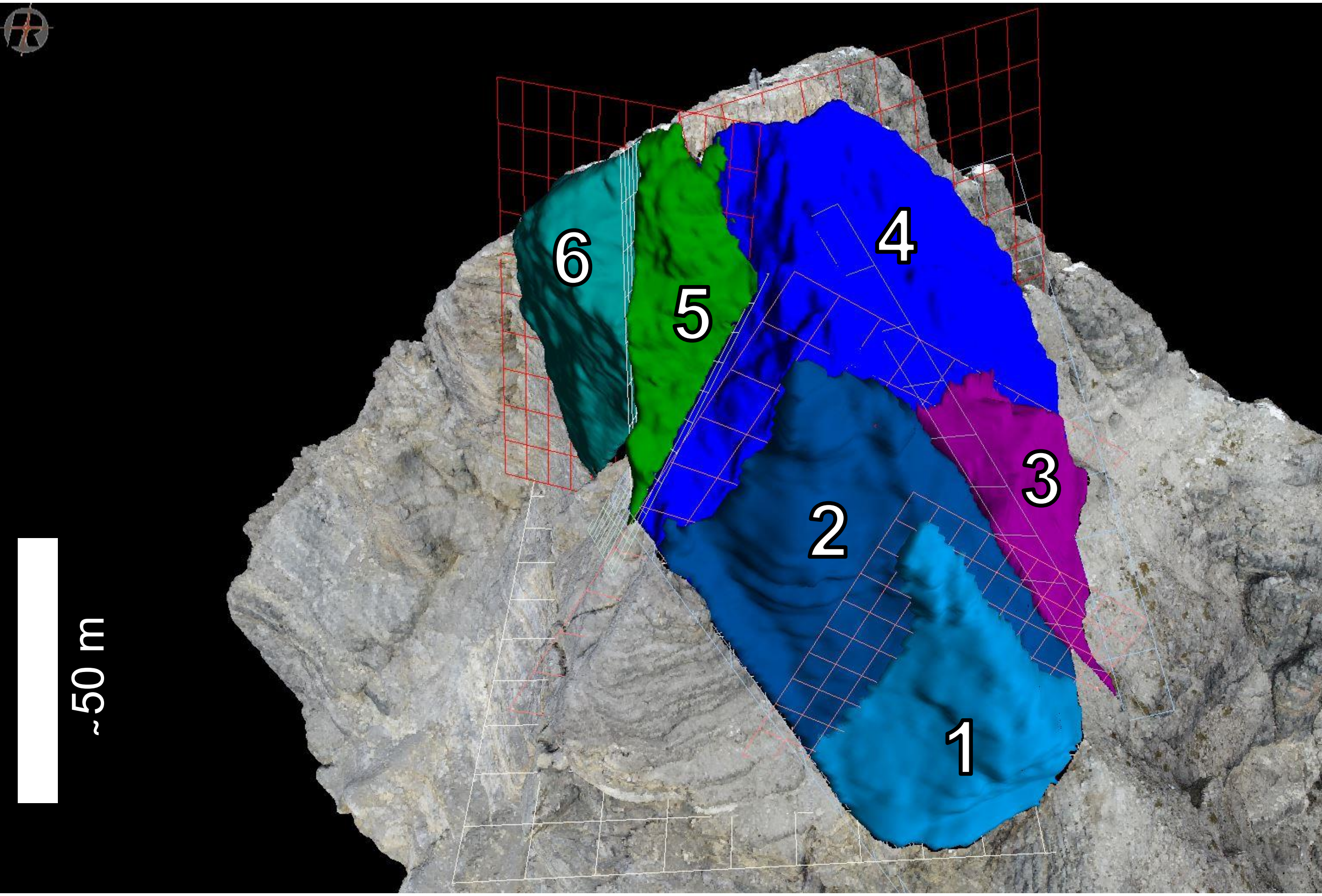
3. Climate-induced natural hazards: Felsstürze

Cliff fall: Hochvogel reacts with 2-3 days acceleration to enduring heavy rainfall

Hochvogel: Preparing 260.000 m^3 rock slope failure

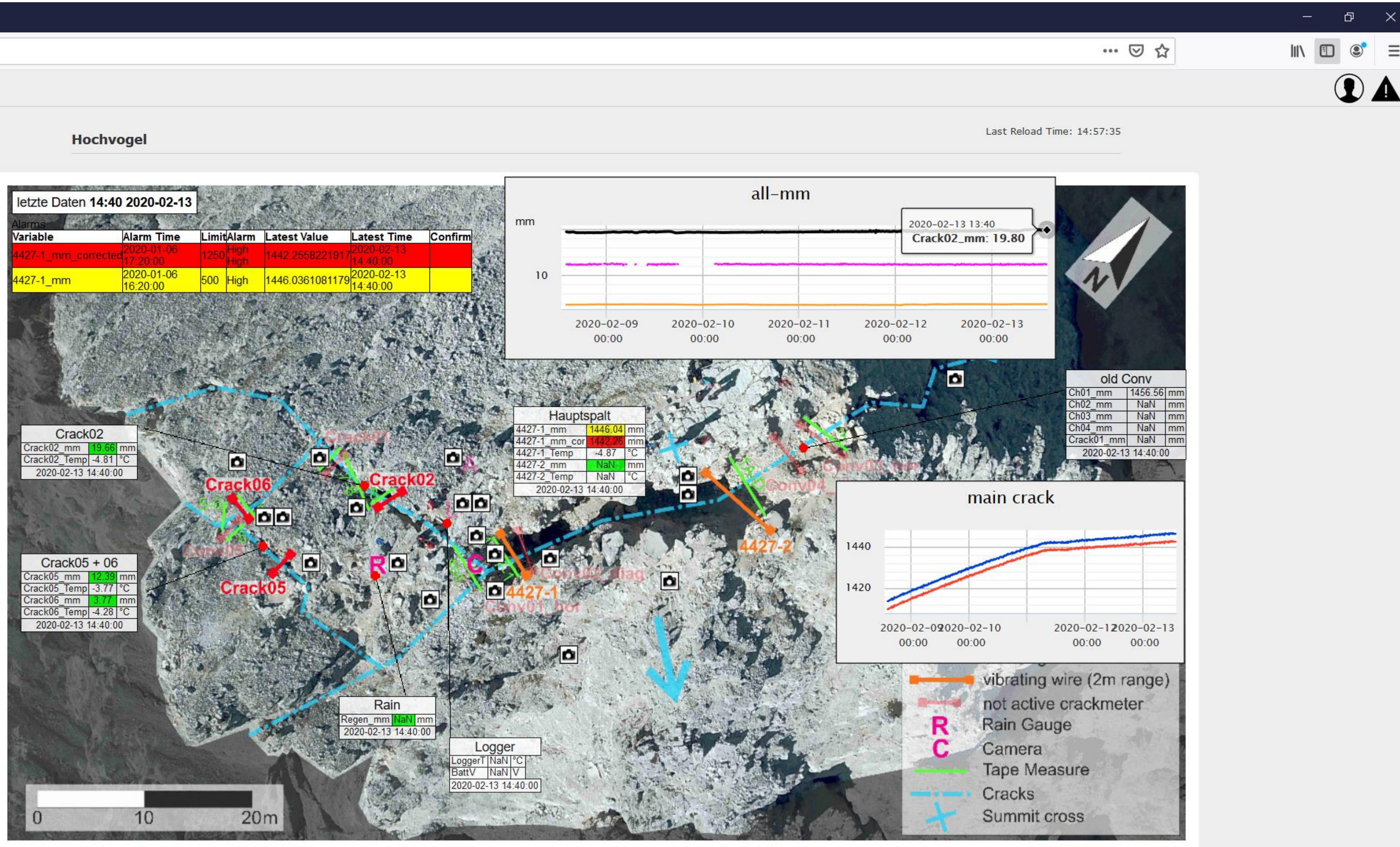

AlpSense-Concept
space-borne
Sentinel
air-borne
Ultracam
Identification of Hotspots
Failure Volume Estimation
Runout Models
Meltwater Flow
Meltwater Sources
air-borne
UAV-surveys
Process Dynamics in Hazard Hotspots
photogrammetry
terrestrial
geodesy
dGNSS
targets
weather
automatic geotechnical
seismic
Near Realtime Warning of Most Risky Objects

Volume of the instable rock mass



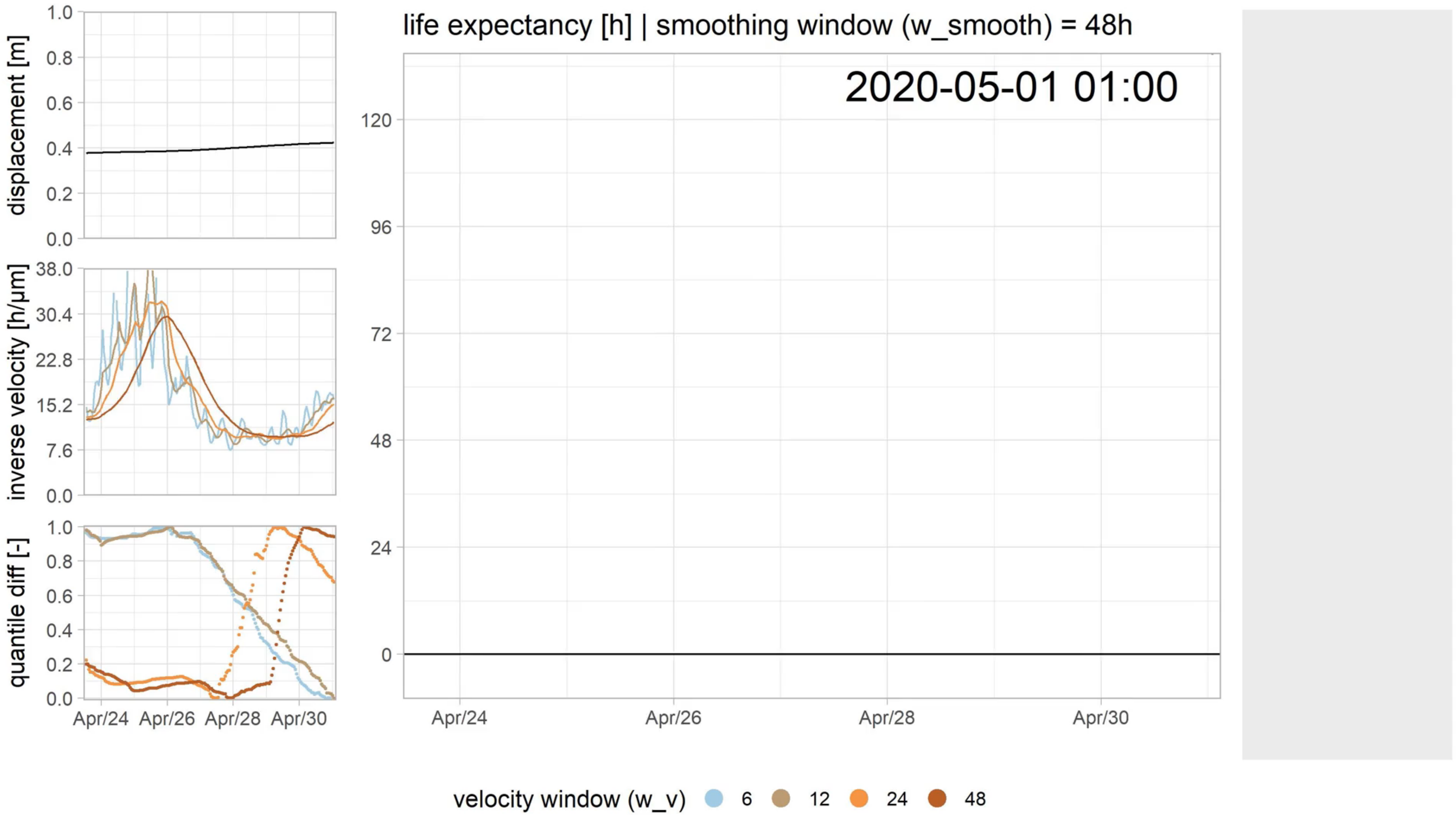
Subunit	m³
1	14.300
2	66.100
3	12.400
4	147.700
5	7.900
6	13.700
Sum	**262.100**

Measurement concept and data transfer at the Hochvogel



Prospective model: Rock block failure, Grabengufer (Randa, CH), 17.05.2020, ~500 m³

video animation of prospective failure time forecasting tool, input: hourly GNSS data



Leinauer, Krautblatter et al. (2024) Nature Comm. E&E

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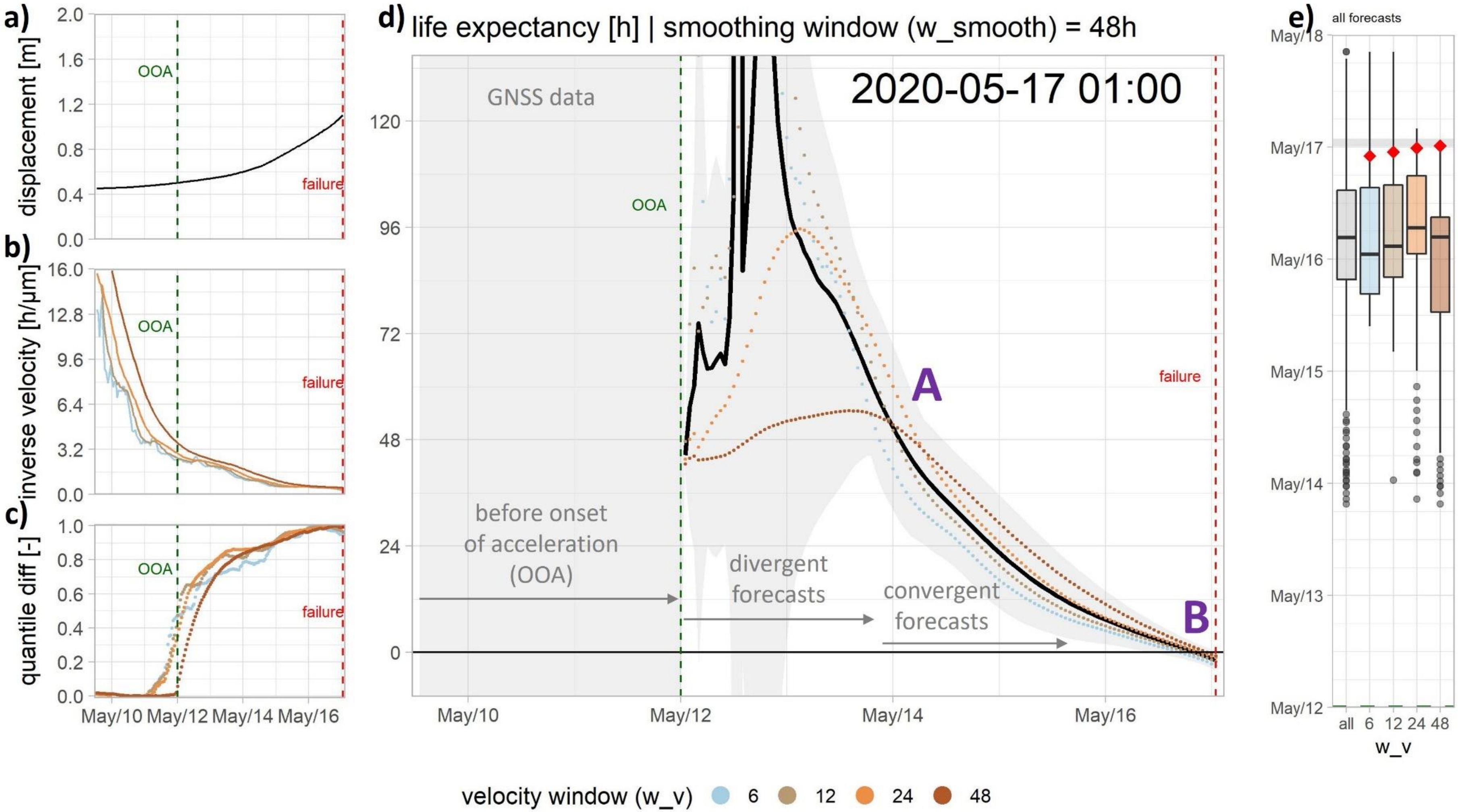


Leinauer, Krautblatter et al. (2024) Nature Comm. E&E

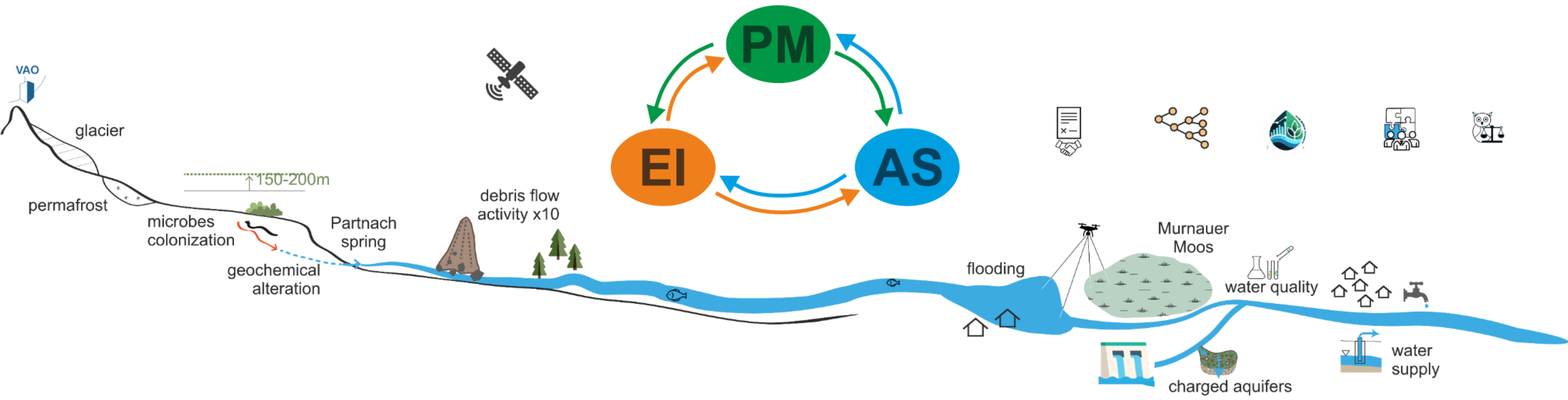
Alpine hazards in a changing climate and their predictabilty

- **Alpine temperature increase: up to 0.5°C per decade since 1980s, Austrian and Swiss Alps 2.9/3.1 °C since 1880**
- **Increase rainstorms: Frequency and intensity increases factor >2 in many stations in the Northern Alps**
- **Glaciers: Major glacier shrinkage and loss of most smaller glaciers until 2050**
- **Permafrost: slower thermal system that undergoes a major mechanical weakerning in the next 100 years**
- **Debris flows: First record shows a 10 fold increase in activity in the last decades**
- **Rockfall: reacts in some place quite strong to increase in rainstorm frequency and intensity**
- **Anticipation & Early Warning Systems: a key capacity to systematically adapt to climate change related alpine hazards**

Proposal for a Collaborative Research Centre

Rapid adaptation in a changing climate and environment (RACE)

in coupled cryo-, geo-, bio- and hydrosystems projected by natural, engineering and social science



The Virtual Alpine Observatory (VAO)
The Network of European High-Altitude Research Stations

Michael Krautblatter[1], Elke Ludewig[2], Johannes Knapp[3], Ashot Chilingarian[3], Markus Keuschnig[4], Christo Hangelov[5], Nina Nikolova[5], Jaroslav Chum[6], Jan Laštovička[6], Tuukka Petäjä[7], Nathalie Cotte[8], Didebulidze Goderdzi[9], Christoph Mayer[10], Birgit Einhellinger[11], Till Rehm[12], Peter Marton[12], Sabine Kraushaar[1], Reinhard Zeitler[11], Marc Zebisch[12], Kolbjørn Blix[14], Šimon Mackovjak[15], Ján Kubančák[15], Griša Močnik[16], Markus Leuenberger[17], Silvio Decurtins[18], Eliza Harris[19] and Verena Stammberger[1]

01 TU Munich, Chair of Landslide Research, Germany
02 GeoSphere Austria, Sonnblick-Observatory, Austria
03 Alikhanyan National Lab (Yerevan Physics Institute), Armenia
04 Georesearch, Austria
05 Bulgarian Academy of Sciences, Institute for Nuclear Research and Nuclear Energy, Bulgaria
06 Institute of Atmospheric Physics, Czech Republic
07 University of Helsinki, Institute for Atmospheric and Earth System Research, Finland
08 University of Grenoble Alpes, France
09 Ilia State University, Atmosphere-Ionosphere Physics, Georgia
10 The Bavarian Academy of Sciences and Humanities, Glaciology, Germany
11 Bavarian State Ministry of the Environment and Consumer Protection, Germany
12 Environmental Research Station Schneefernerhaus, Germany
13 EURAC Research, Italy
14 Andøya Space, Norway
15 Slovak Academy of Sciences, Institute of Experimental Physics, Slovakia
16 University of Nova Gorica, Centre for Atmospheric Research, Slovenia
17 University of Bern, Climate and Environmental Physics, Switzerland
18 University of Bern, Department of Chemistry, Biochemistry and Pharmaceutical Sciences, Switzerland
19 ETH Zurich, SDSC, Switzerland

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Why observing the Alps?

The Alpine region undergoes a **faster and more pronounced climate change** than surrounding lowlands and, therefore, is a **time machine** showing the things to come in a changing climate and environment. **Significant effects are visible and measurable** in atmosphere, biosphere, hydrosphere, and most apparently the cryosphere.

The Virtual Alpine Observatory

- Consists of 12 European Alpine Observatories, high alpine research facilities, data archives, and supercomputing centers spanning the Alpine landscape and analogous mountainous terrains in Europe
- **Shares** infrastructure and collaborative research pursuits
- **Paradigm:** interdisciplinary, cross-border collaborating research

Next Steps!

1. Expand the existing network and knowledge in a joint Interreg project 2025
2. Aanalyzing spatial disperse cryospheric data
3. Publish current available data in a joint paper

What are the Benefits?

The alliance

- explores data patterns **transcending national boundaries,**
- creates a data & knowledge **surpassing its individual understanding,**
- develops **precise high-alpine measurement tech with "open hardware" and ensures quality control for COPERNICUS satellite measurements.**

⇒ **features a novel transdisciplinary understanding of climate & environmental change controls, speed and processes to anticipate the near future.**

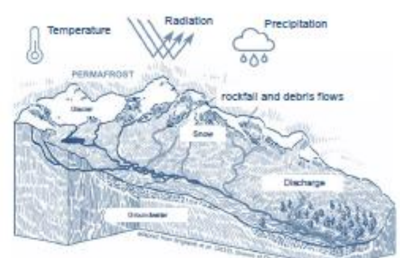
⇒ **delivers profound premises for policy makers, economy & society.**

VAO Core Aims

Observation	Understanding	Prediction	Action
We observe key environmental parameters at different sites, synchronized and long term.	We understand the complex Alpine Earth System and anthropogenic forcings.	We encapsule the knowledge into appropriate numerical/ statistical models.	We translate scientific advances into useful knowledge for politics and administration.

What Challenges do we Target?

- Athmospheric changes
- Cryospheric reactions
- Biospheric reaction patterns
- Geo- and hyrological risks
- Hydrological effects
- Biomedical effects
- Human impact of the environment



Atmosphere
Cryosphere
Biosphere
Geosphere
Hydrosphere
Lithosphere

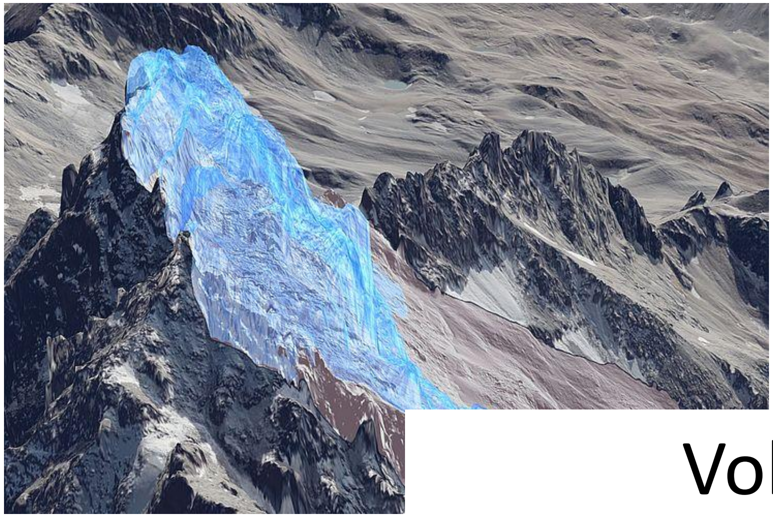
9. Symposium zu pot. Sonderforschungsbereich

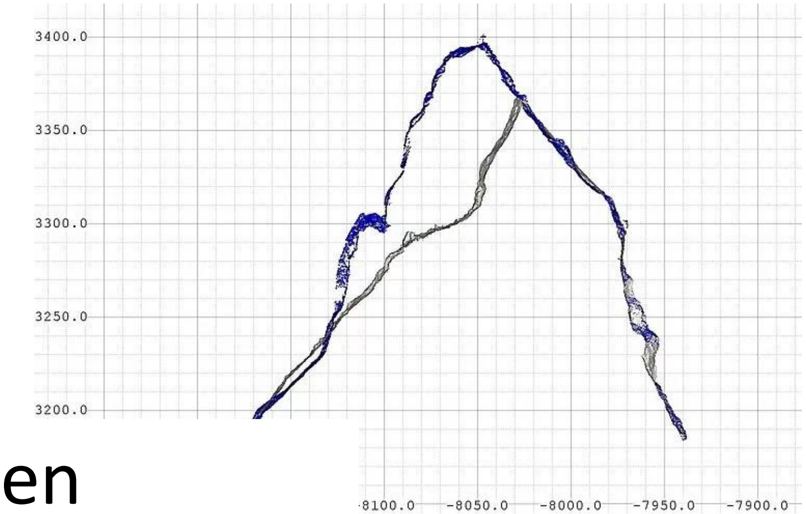
“Rapid adaptation in a changing climate and environment (RACE): coupled geo-, bio- and hydrosystems”

Institute of Andvanced Studies, TUM, Feb. 23, 2024

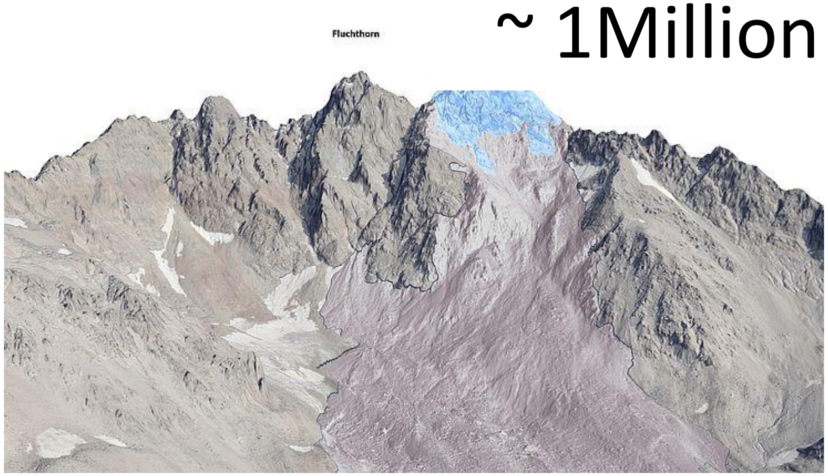
Hosted by M. Krautblatter (TUM ALPHA) & M. Elsner (TUM Wasser Cluster)

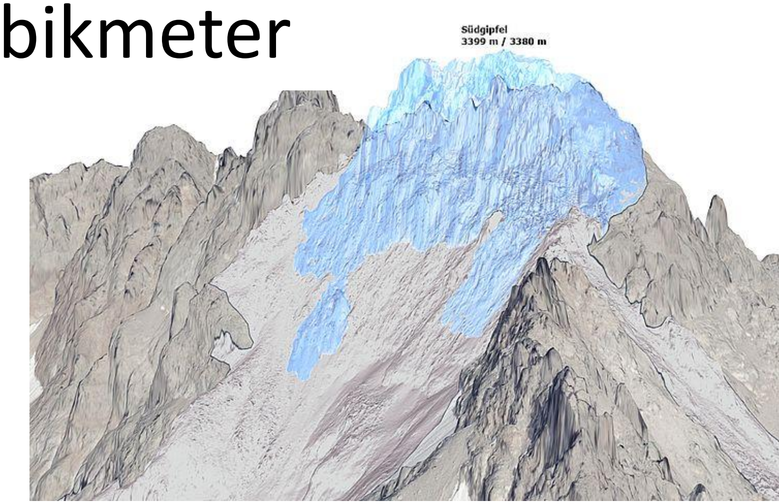

GEORESEARCH





Volumen
~ 1Million Kubikmeter





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Permafrost Research

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- Pudasaini, M. & Krautblatter, M. (2014). **A two-phase mechanical model for rock-ice avalanches**. JGR Earth Surface.
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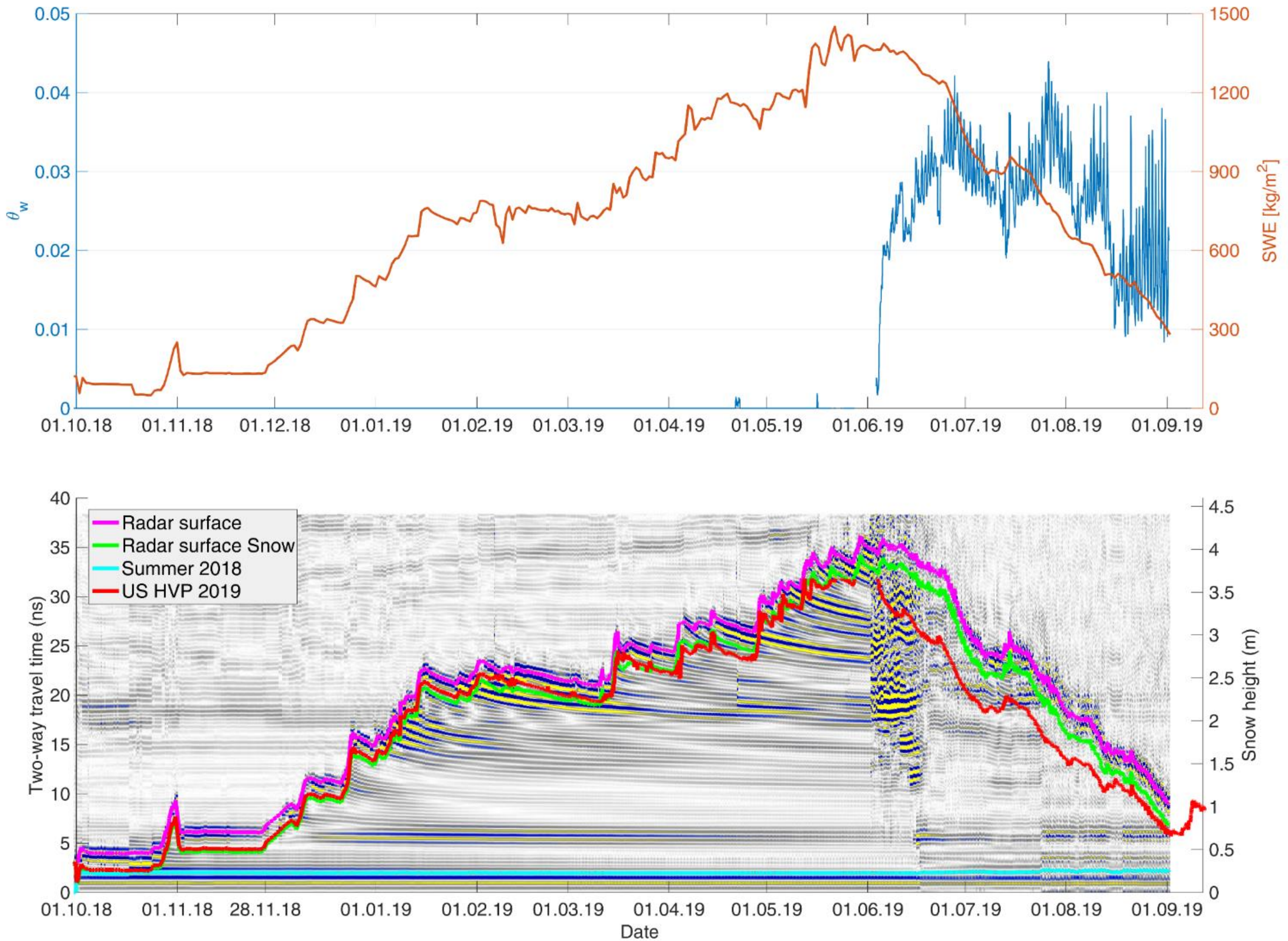
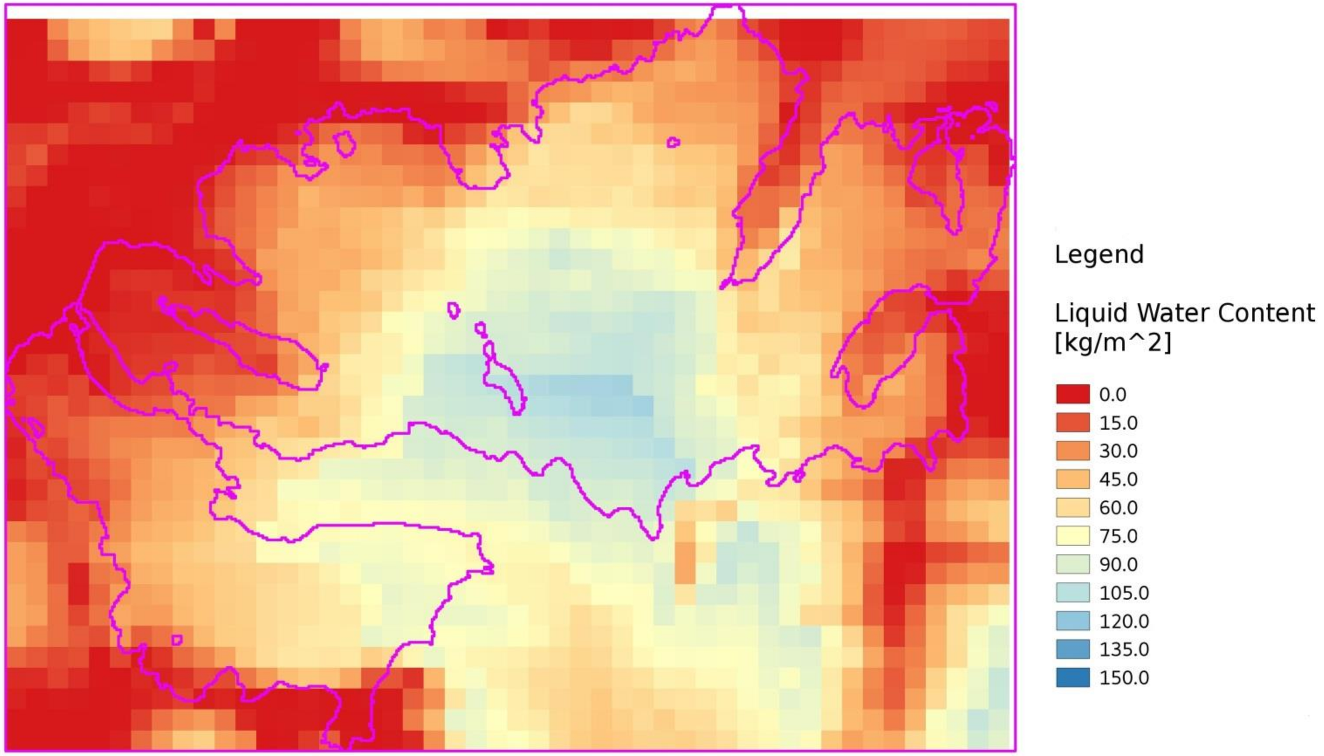
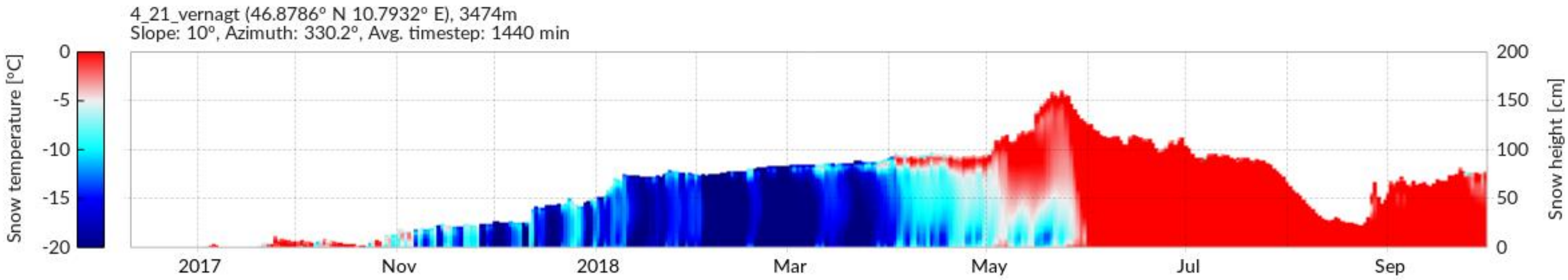
Snow and ice melt at the Vernagtferner (AlpSense-BADW)

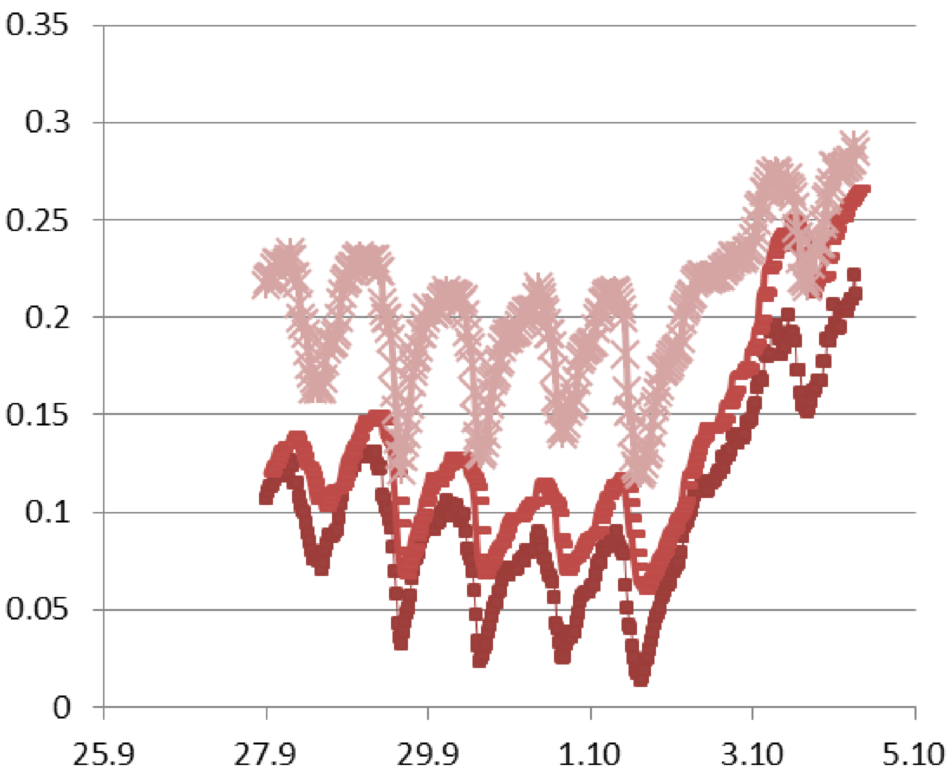


Vernagtferner: Prediction of extreme outflow events from glacial snow cover (AlpSense-BADW)



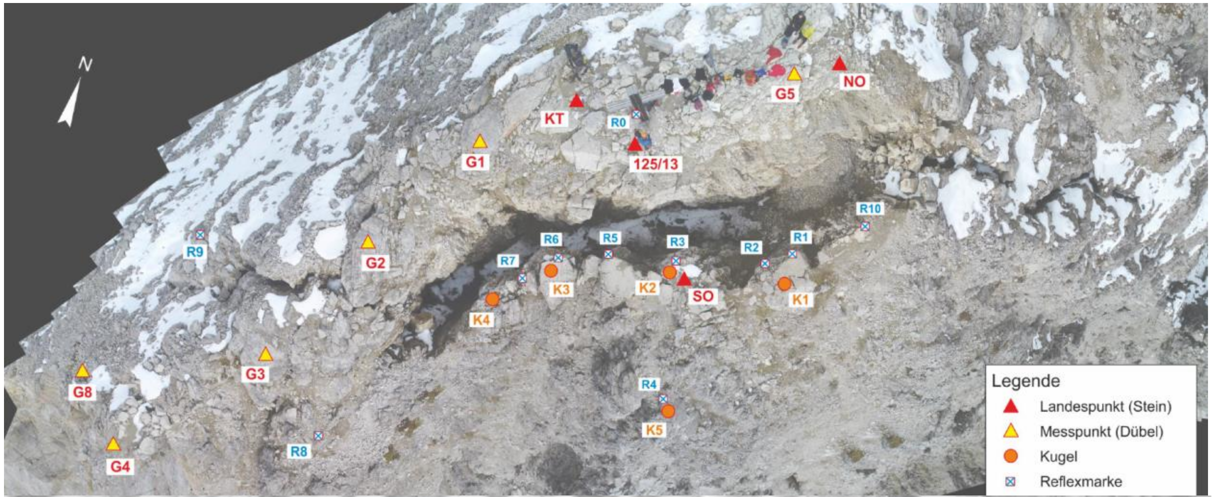


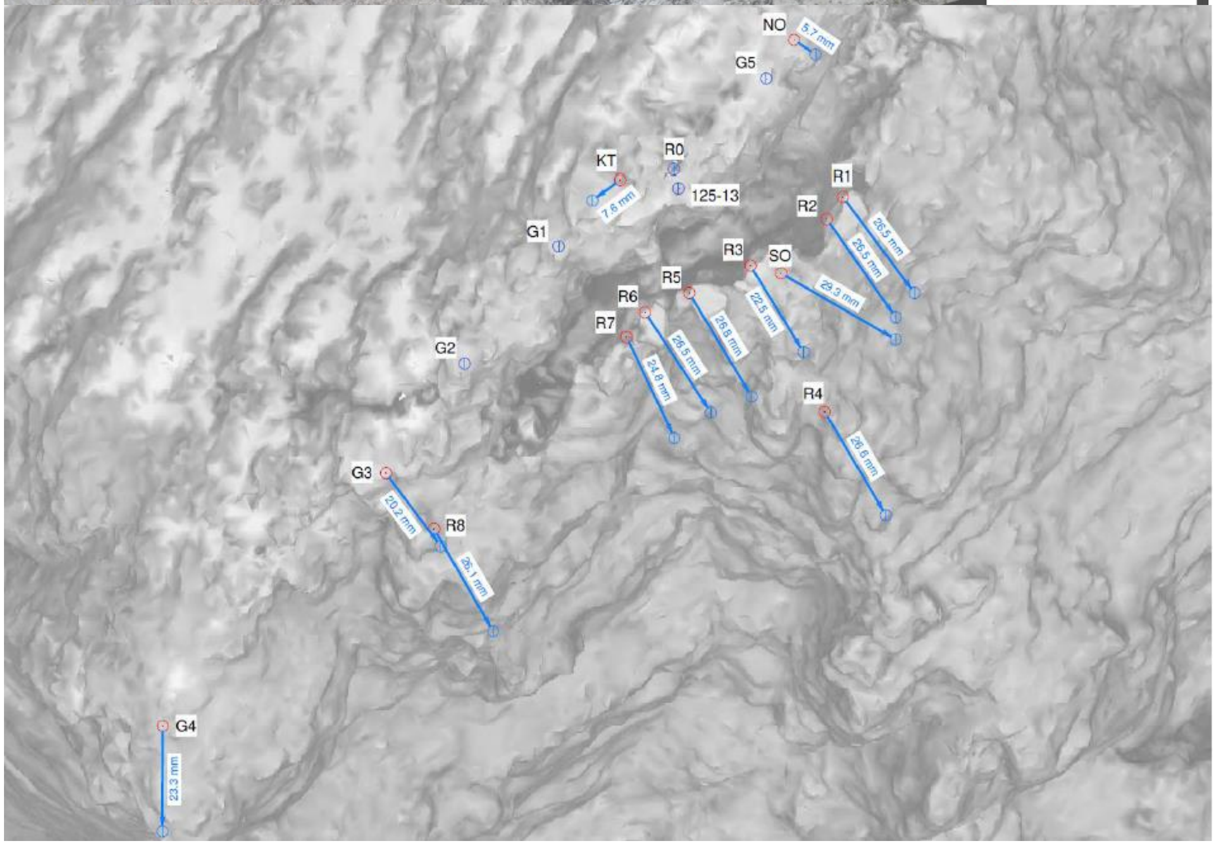
AlpSense: AP 3: Near Real Time Monitoring of MROs



10 min. automated wireless monitoring of a hazardous rock failure (Höllentalklamm, D)

Geodetic measurements





Reliability:

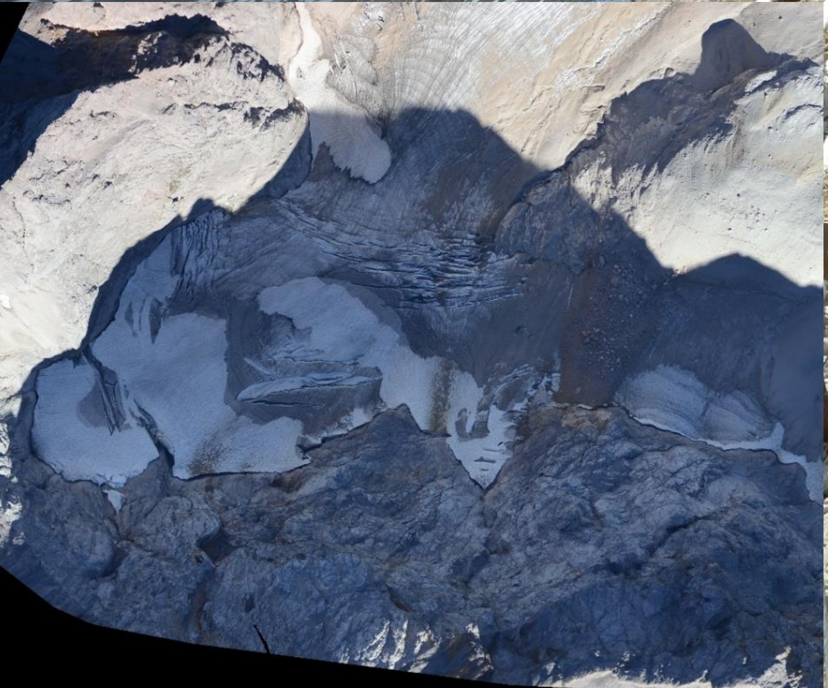
>(i) Scientific requirement for accurate prediction (mm)

>vs. (ii) technical performance

>Few scientific studies

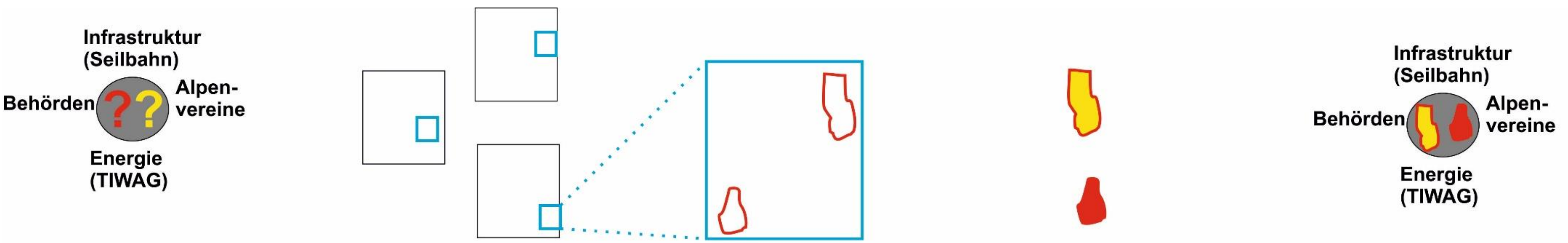
Consistency of geodetic and geotechnical measurements within 1 mm (26 vs. 27 mm.)

Coupled multi-risks



AlpSense: Alpine remote sensing of climate-induced natural hazards

A Benchmark Project in the EU Strategy for the Alpine Region (EUSALP) (STMWI -FUNDED)



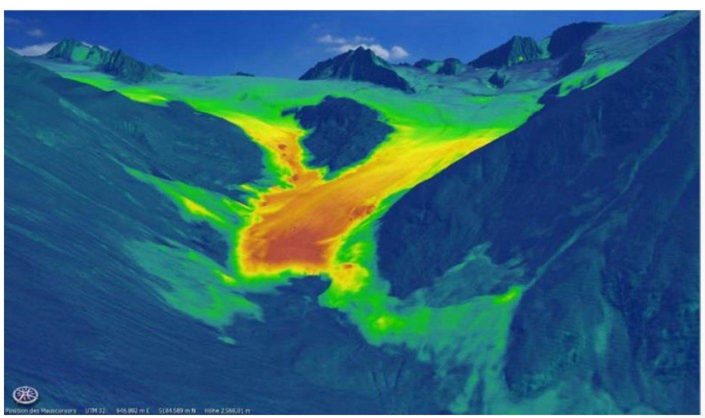
AP0 Nutzer- und Prozessoptimierte Strategie

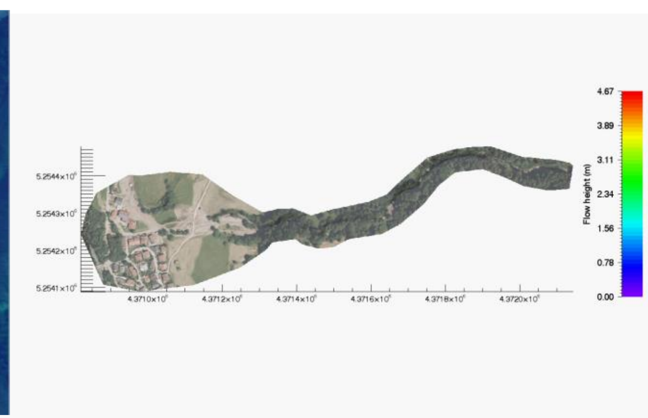
AP1 Identifikation Naturgefahren-Hotspots

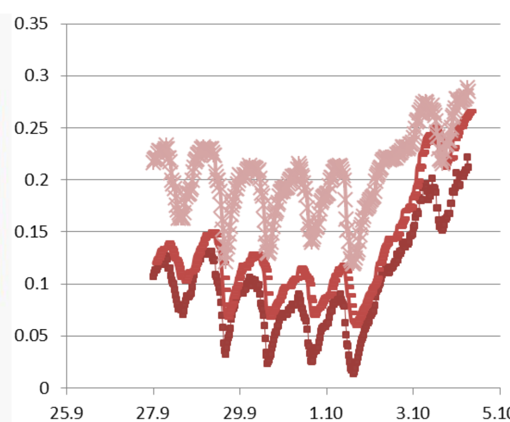
AP2: Prozessdynamik in den Naturgefahren-Hotspots

AP3: Near Real-Time Monitoring vorberei-tender Naturgefahren

AP4 Near Real-Time Visualisierung und Kommunikation







AP0: Integration Stakeholder

AP 0: User and Process Optimized Strategy

Zugspitzbahn und Kitzsteinhornbahn:

- Gespräche mit Vorstand ab Jan 2018;
- Messungen am Zugspitzplatt zu Permafrostgefahren der Zahnradbahn im Okt. 2018

Alpenverein Garmisch-Partenkirchen:

- 3 Treffen vor allem zur Naturgefahrensituation in der Höllentalklamm
- Operationelles Frühwarnsystem im Test und Laserscan der gesamten Klamm am 23/24.10.18

Bergwacht / DAV Luitpoldhaus / DAV Donauwörth Hochvogel:

- 5 Treffen mit Abstimmung der Wegsperrung im Ernstfall

Landesgeologie Tirol:

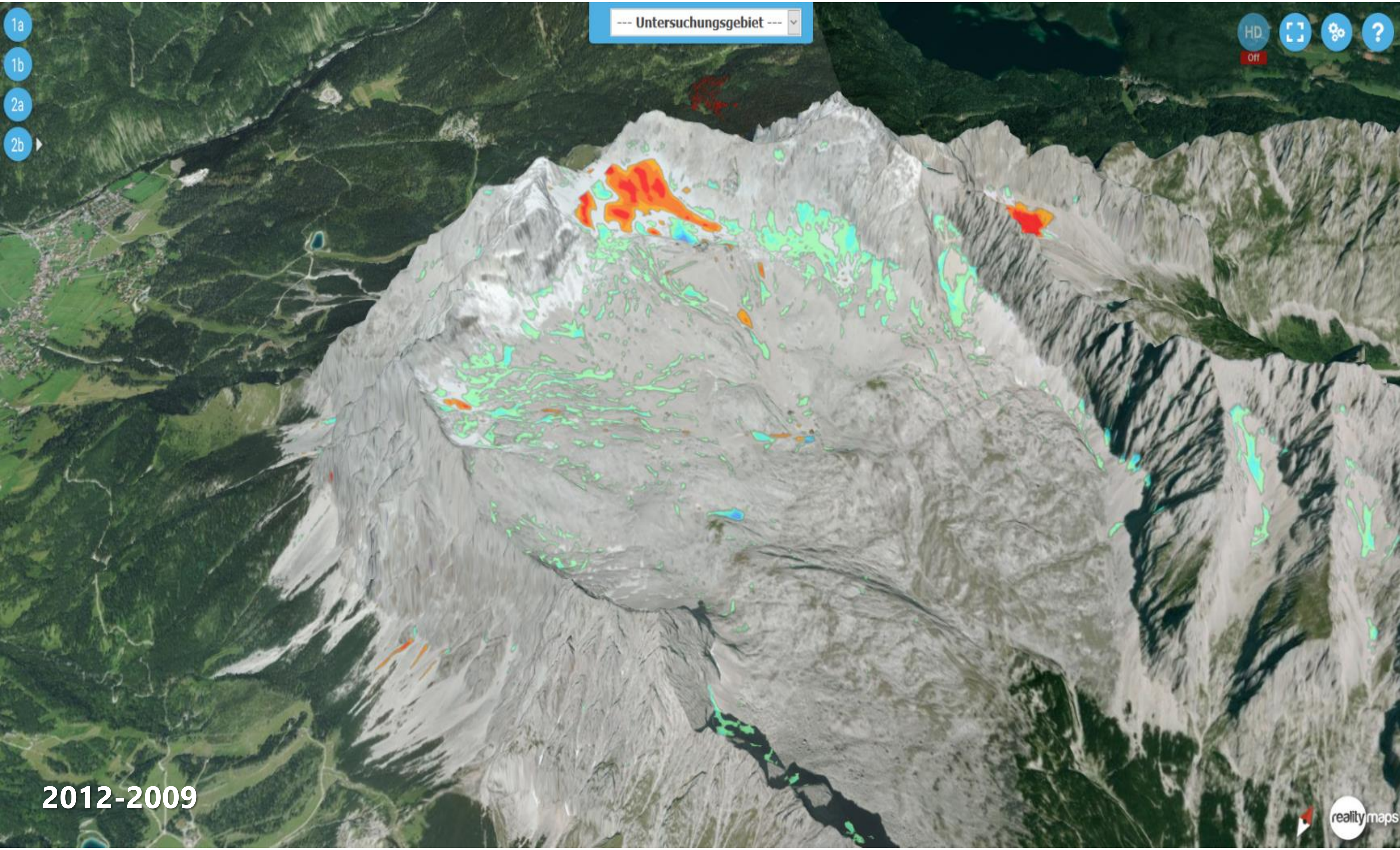
- Treffen in Innsbruck im April mit Abstimmung der Warnkette über die Landeswarnzentrale Tirol

Bayerisches Landesamt für Umwelt:

- Treffen im Oktober mit ausführlicher Information über die Möglichkeiten von Frühwarnsystemen Hochvogel/Höllentalklamm

AP 4: RUNDER TISCH IM DEZ. MIT STAKEHOLDERN UND STMWI

Glacier retreat & permafrost degradation at Zugspitzplatt/Höllental



AlpSense: Alpine remote sensing of climate-induced natural hazards

Benchmark-Study: 4 alpine Regions (Bavaria, Tirol, Salzburg and Southern Tirol)

Round Table Approach: Integrating Needs of User

Accessability of Data: By qualified users

Visualisation: For all user

Transferability: of instrumentation

Risk reduction: of climate-related alpine natural hazards

Cost reduction: for the sustainable alpine future

Systematic evaluation of predictive capabilities for different hazardous processes