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Paraglacial responses in deglaciating cirque walls: Implications for rockfall magnitudes/frequencies and rockwall retreat

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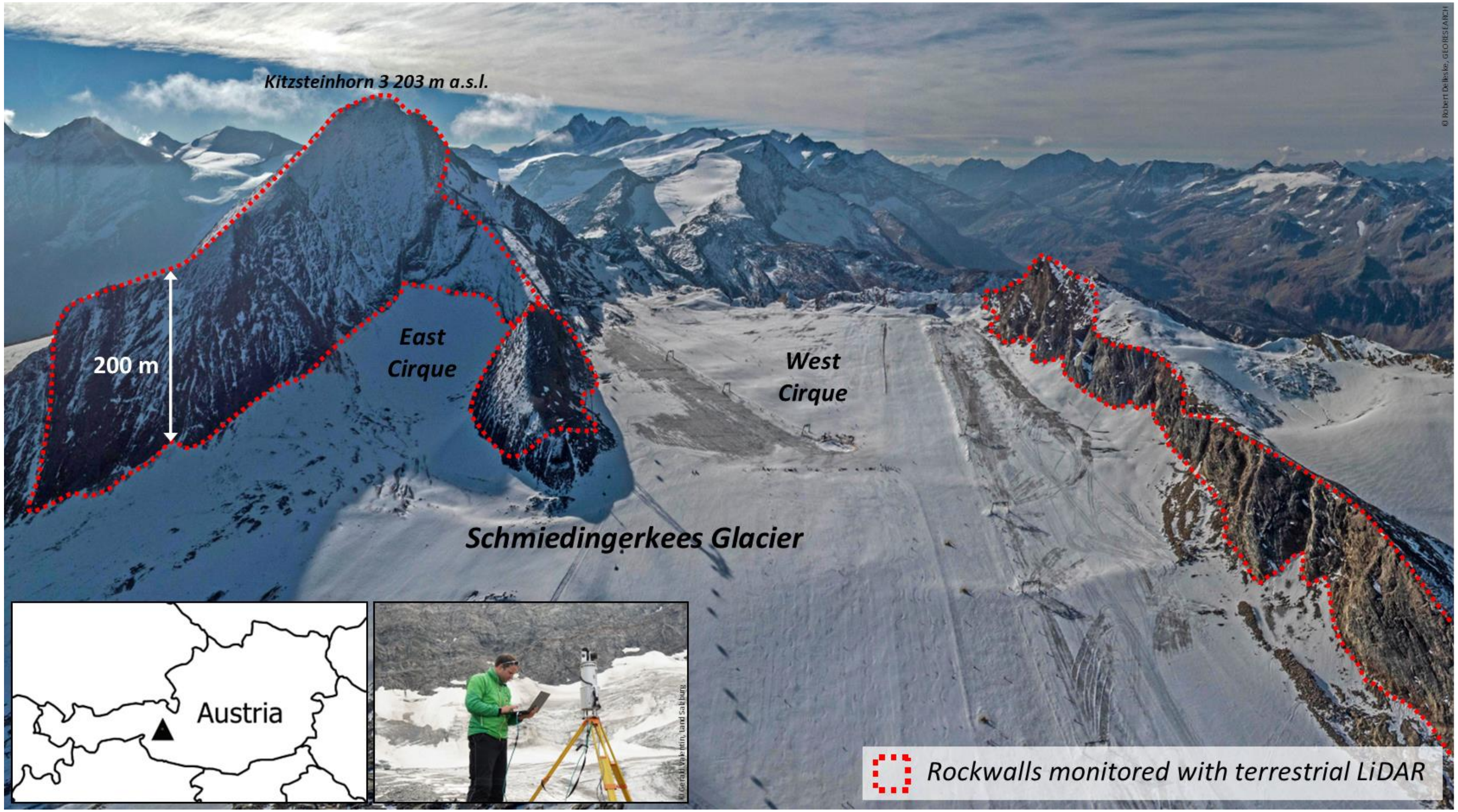
In a nutshell…

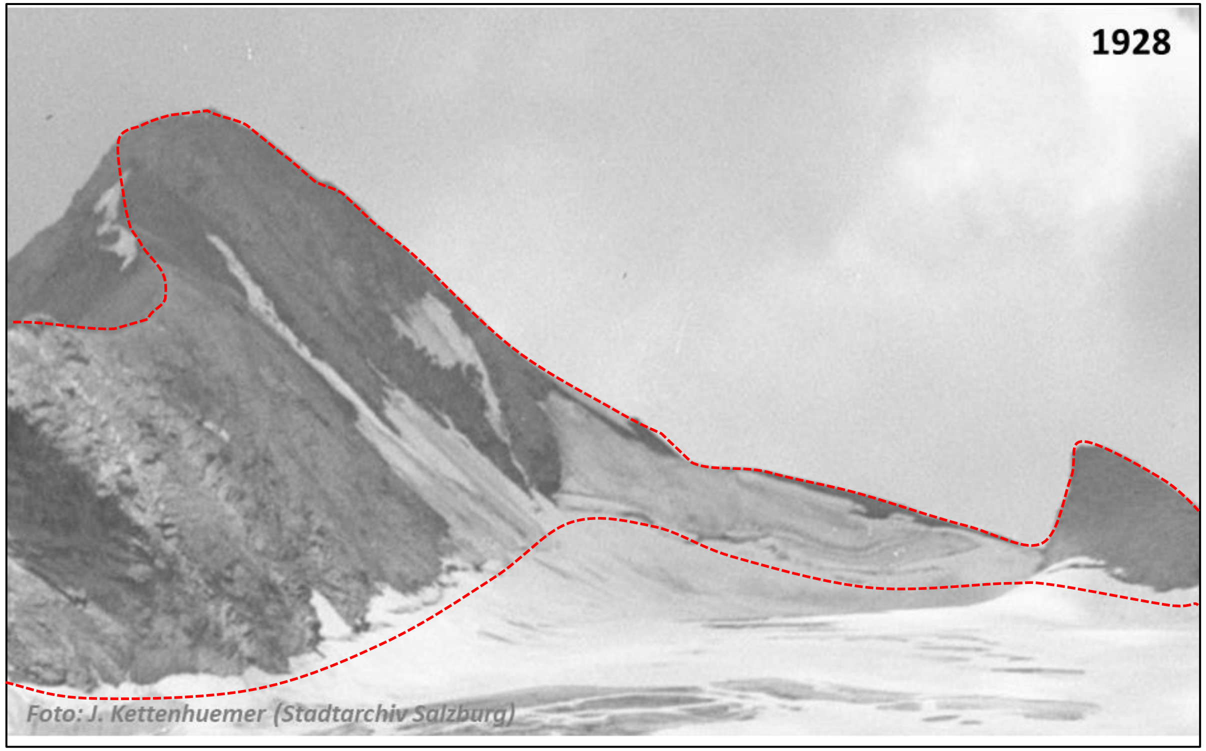
- We present a unique rockfall inventory from a **six-year terrestrial LiDAR campaign (2011-17)** for permafrost-affected rockwalls of two glaciated cirques in the Central Alps of Austria (Kitzsteinhorn).
- The inventory represents the **most extensive published dataset** of high-alpine rockfall to date and the first quantitative documentation of a cirque-wide erosional response of glaciated rockwalls to recent climate warming.
- 60 % of the rockfall volume detached from less than ten vertical meters above the glacier surface, indicating **enhanced (paraglacial) rockfall activity** over tens of years following deglaciation.
- The mean cirque wall retreat rate of **1.9 mm a^{-1}** ranks in the top range of reported values and is mainly driven by enhanced rockfall from the lowermost, freshly deglaciated rockwall sections.
- The **rockfall magnitude-frequency distribution** – the first such distribution derived for deglaciating cirques – differs significantly between glacier-proximal and glacier-distal rockwall sections due to an increased occurrence of large rockfalls in recently deglaciated areas.

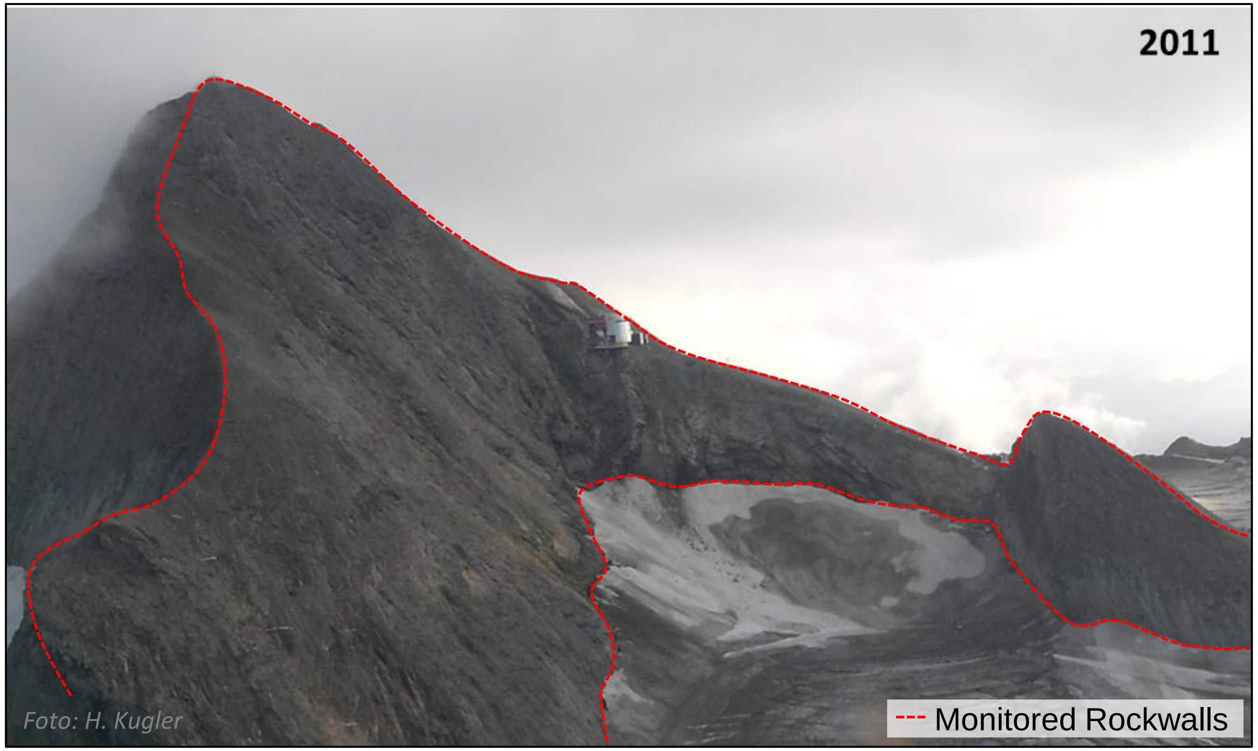
Study Site & Methods



- The rockwalls of two neighboring cirques were monitored for **six years (2011-17)** with terrestrial LiDAR.
- All monitored rockwalls are located **adjacent to the local cirque glacier.**
- *Rockwall surface area*: **235 000 m²**
- *Lithology*: **Calcareous micaschists**
- *Elevation range:* **2700-3200 m a.s.l.**
- *Dominant slope aspects:* **N, NW, E**

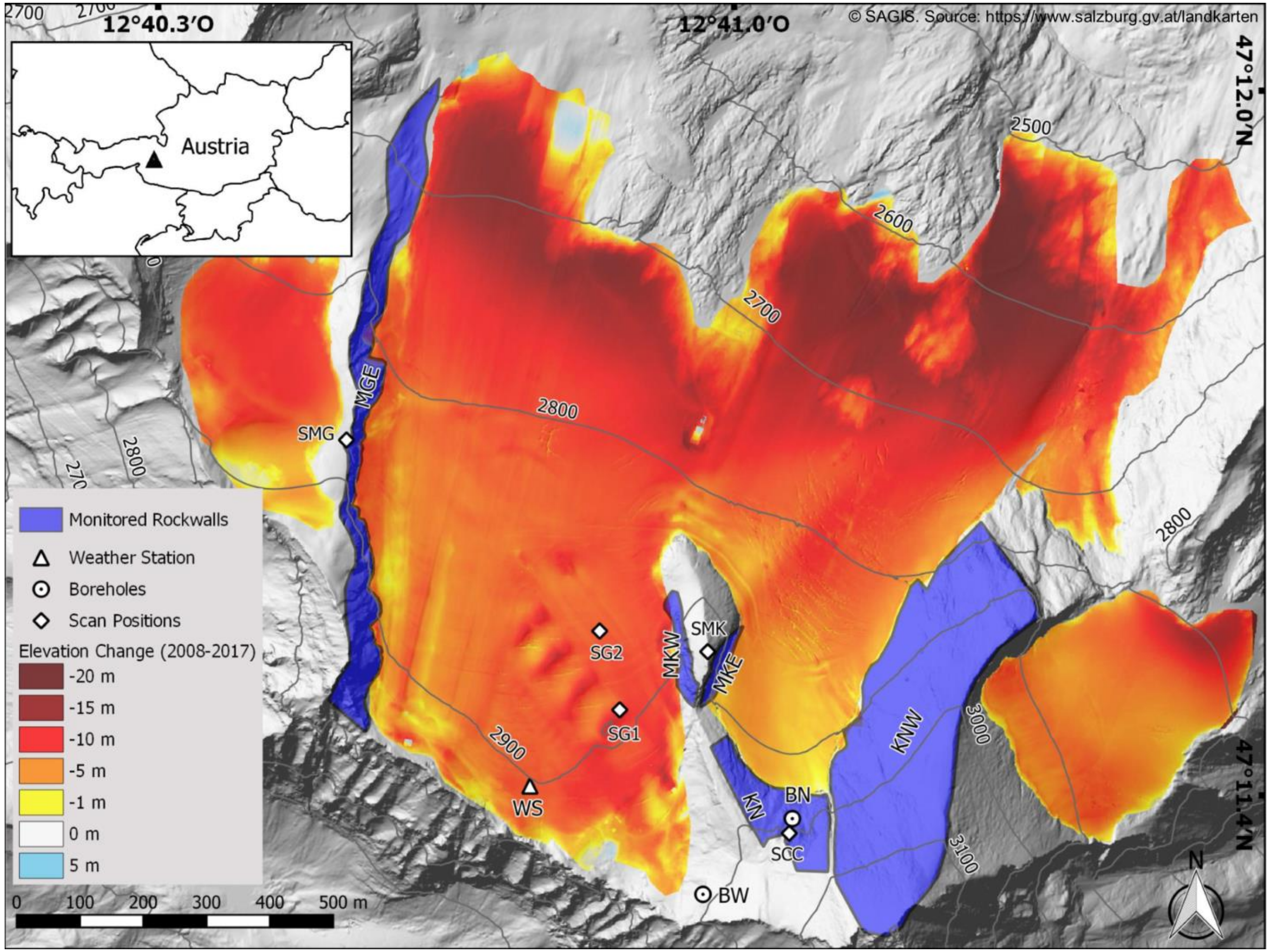
Deglaciation



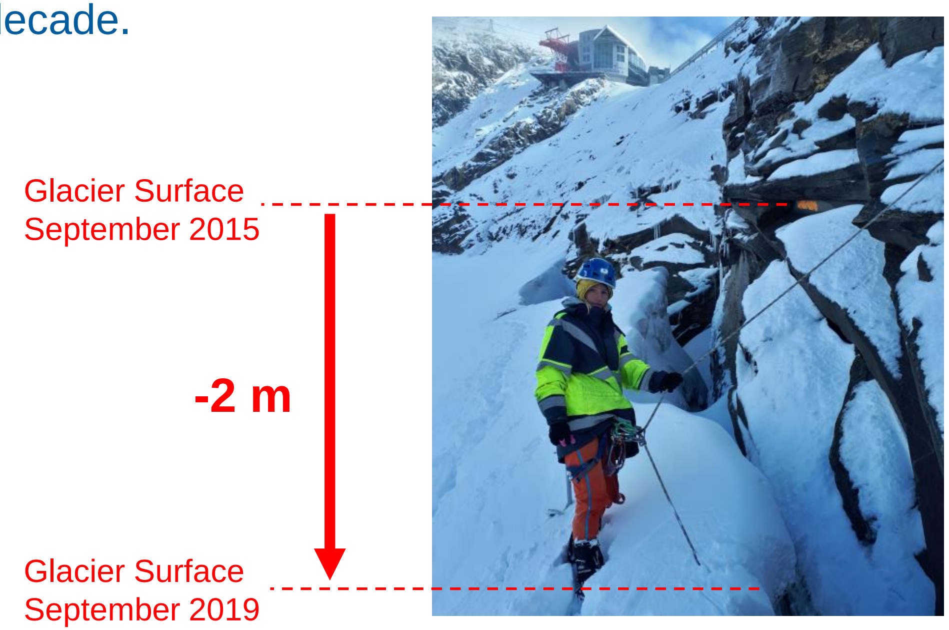


- In the last 150 years mean temperature rise in the European Alps more than doubled the global mean (Böhm 2012) and over this period approximately **50 % of the glacier volume has disappeared** (Haeberli et al. 2007).
- Glacier retreat rates increased since the 1980s and have been exceeding historical precedents in the early 21st century (Zemp et al. 2015).

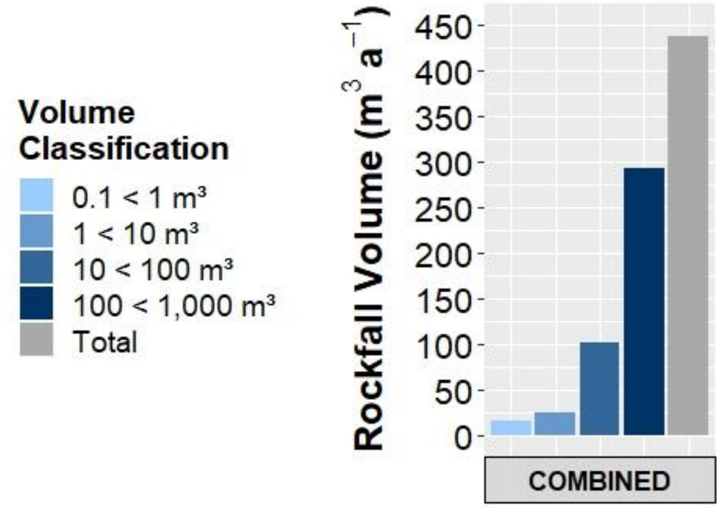
Deglaciation

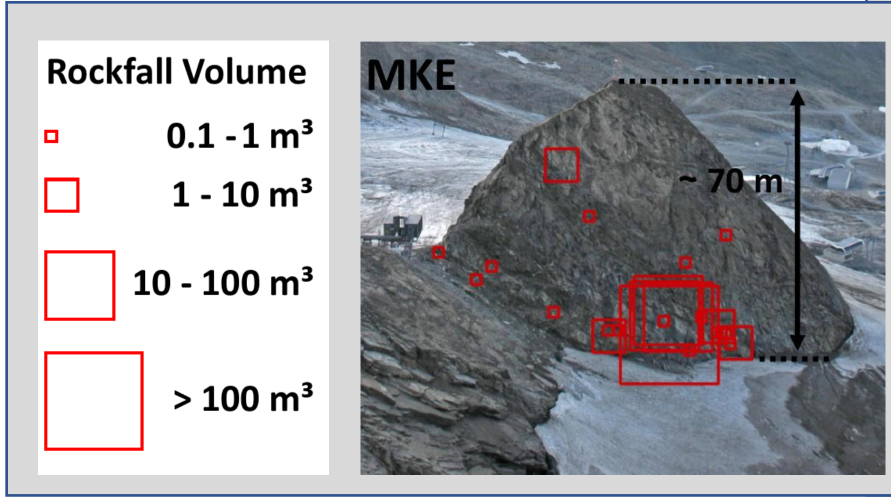


- The Schmiedingerkees glacier (1.4 km² in size) loses around 0.5 million m³ of ice each year.
- Ice loss is most pronounced near the terminus of the glacier but also in the root zone – i.e. adjacent to the monitored rockwalls – high surface lowering rates around **0.5 m a^{-1}** were observed over the last decade.



Rockfall Magnitudes/Frequencies

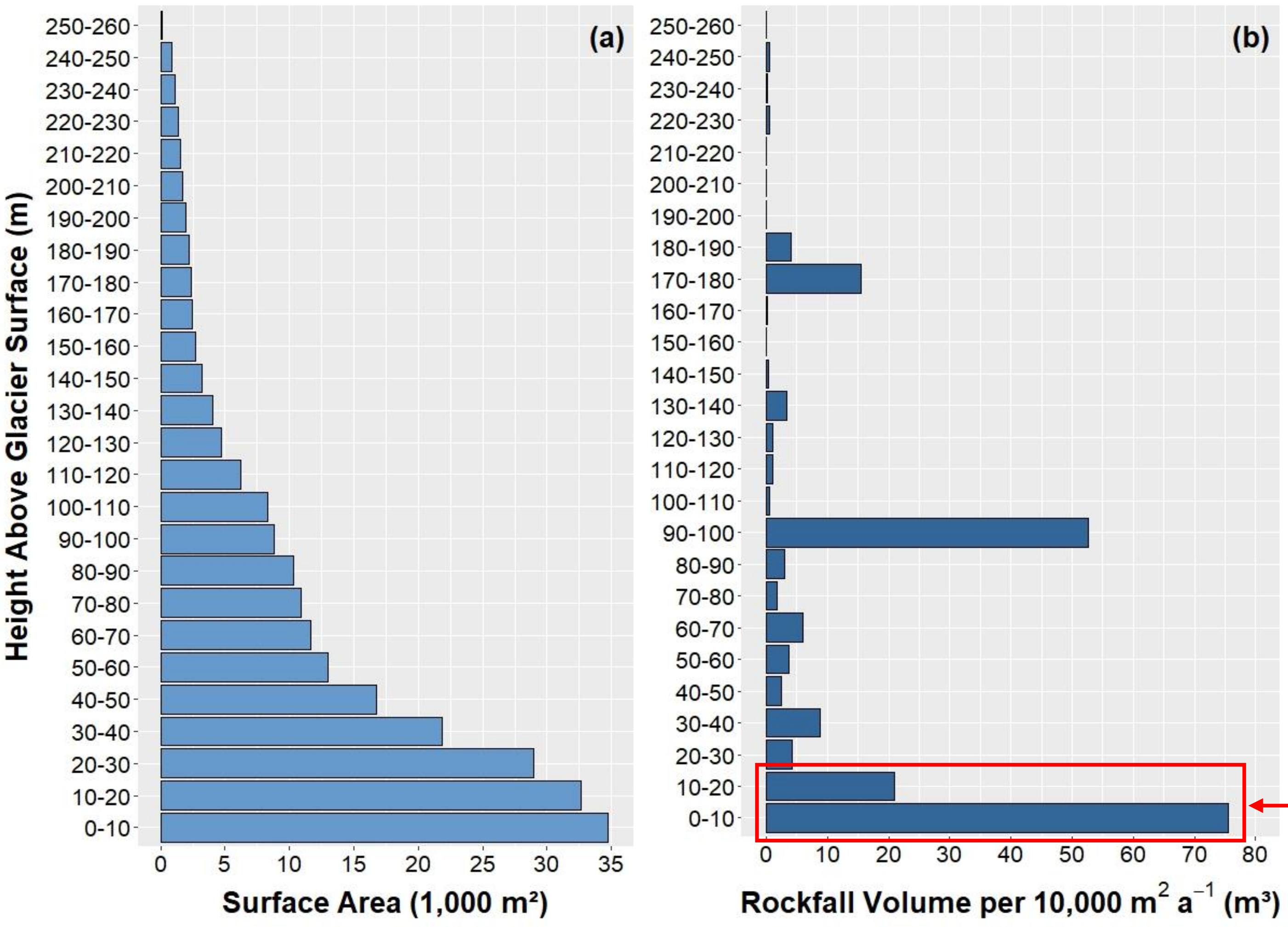




The compiled inventory represents the **most extensive (published) dataset of high-alpine rockfall to date** and the first direct documentation of a cirque-wide rockfall response to glacier retreat.

- 374 rockfalls identified (> 0.1 m³)
- Total rockfall volume: 2 551 m³
- Rockfalls > 100 m³ (n = 5) represent 67 % of the total rockfall volume.
- Rockfalls < 10 m³ (n = 349) represent 10 % of the total rockfall volume.
- Largest single rockfall: 879 m³
- Rockfall activity concentrates along pre-existing structural weaknesses

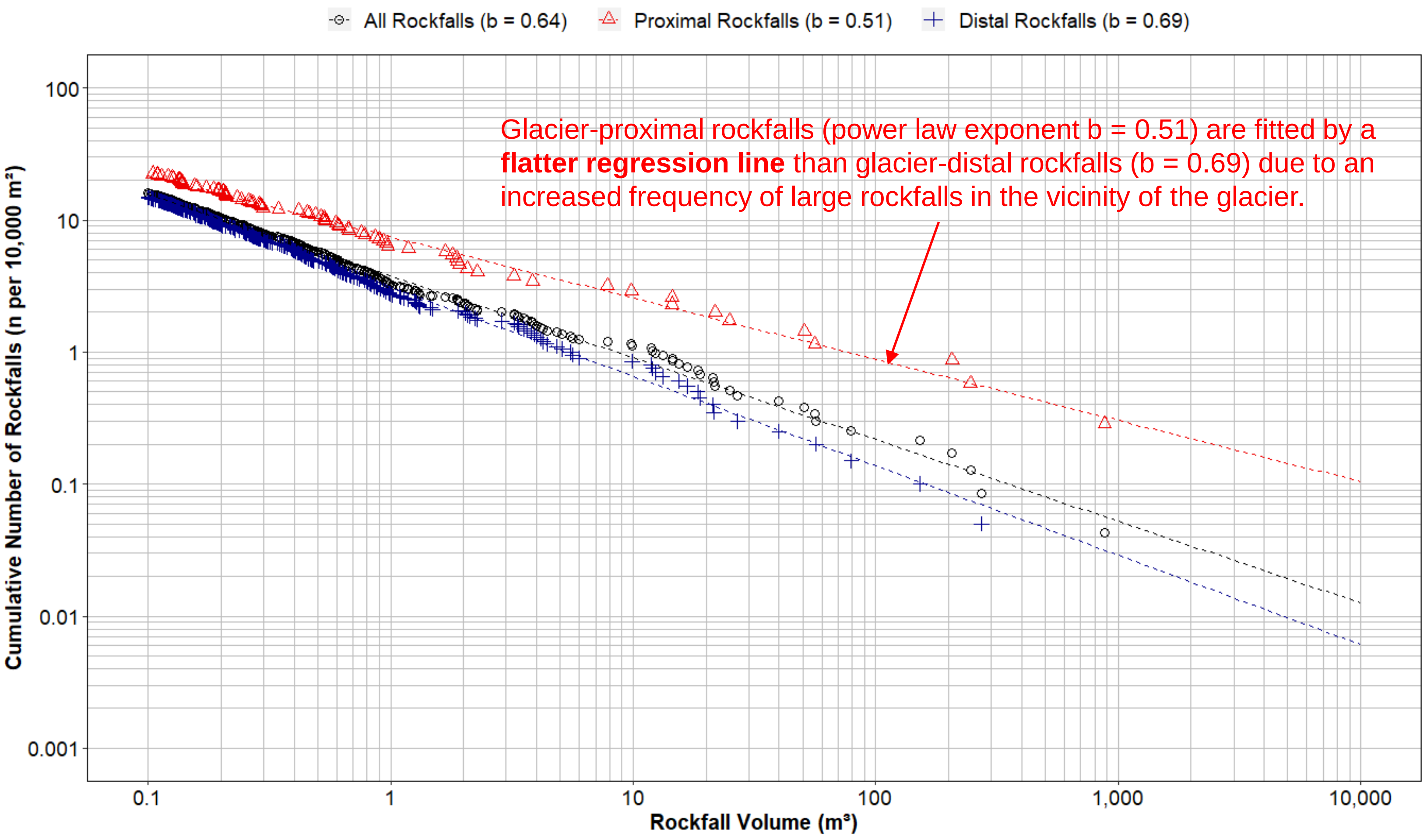
Rockfall Magnitudes/Frequencies



- **60 %** of the rockfall volume detached from less than ten vertical meters above the glacier surface.
- High rates 10-20 m above the glacier indicate enhanced rockfall activity **over tens of years following deglaciation.**
- Increased mass wasting activity in recently deglaciated areas, such as discovered here, is typical of **paraglacial environments**, where slope systems gravitationally adjust to new, non-glacial boundary conditions.

Significantly increased rockfall activity in recently deglaciated terrain

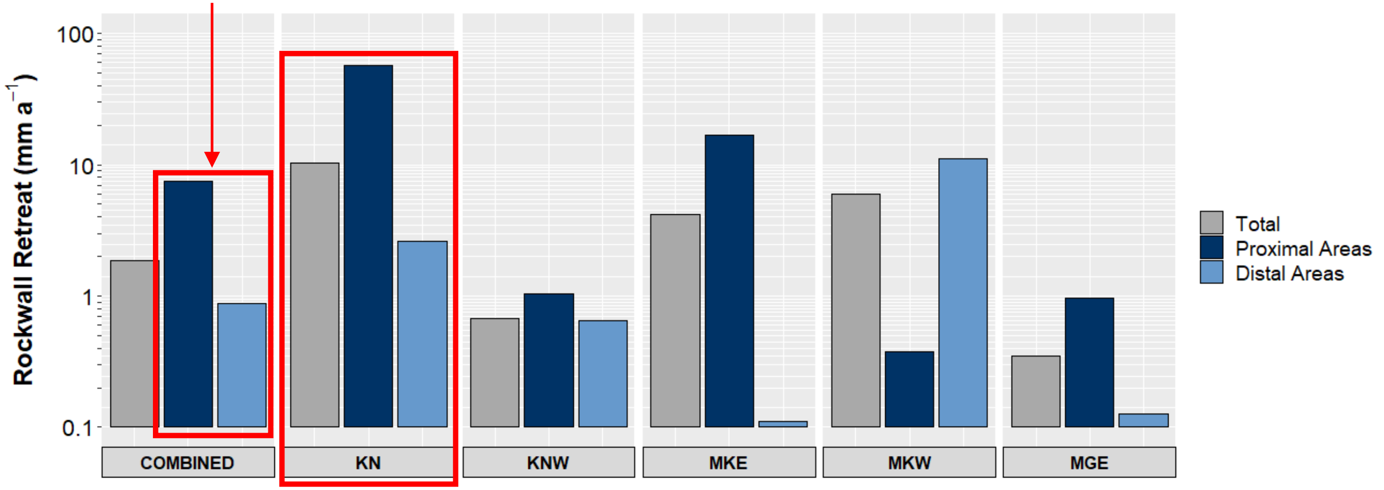
Rockfall Magnitudes/Frequencies

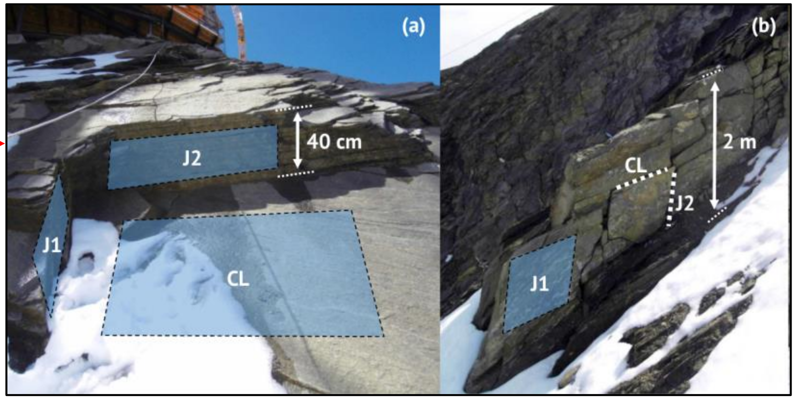


- The rockfall magnitude-frequency distribution – the first such distribution derived for deglaciating cirques – follows a distinct **negative power law over four orders of magnitude**.
- Magnitude-frequency distributions in glacier-proximal (0-10 m above glacier) and glacier-distal (> 10 m above glacier) rockwall sections differ significantly due to an **increased occurrence of large rockfalls in recently deglaciated terrain.**
- Historical rockfall patterns may thus no longer be used **as indicators for future events** (in rockwalls affected by glacier retreat).

Rockwall Retreat Rates

Rockwall retreat in proximal areas (0-10 m above glacier; dark blue) is an order of magnitude higher than in distal areas (> 10 m above glacier; light blue).





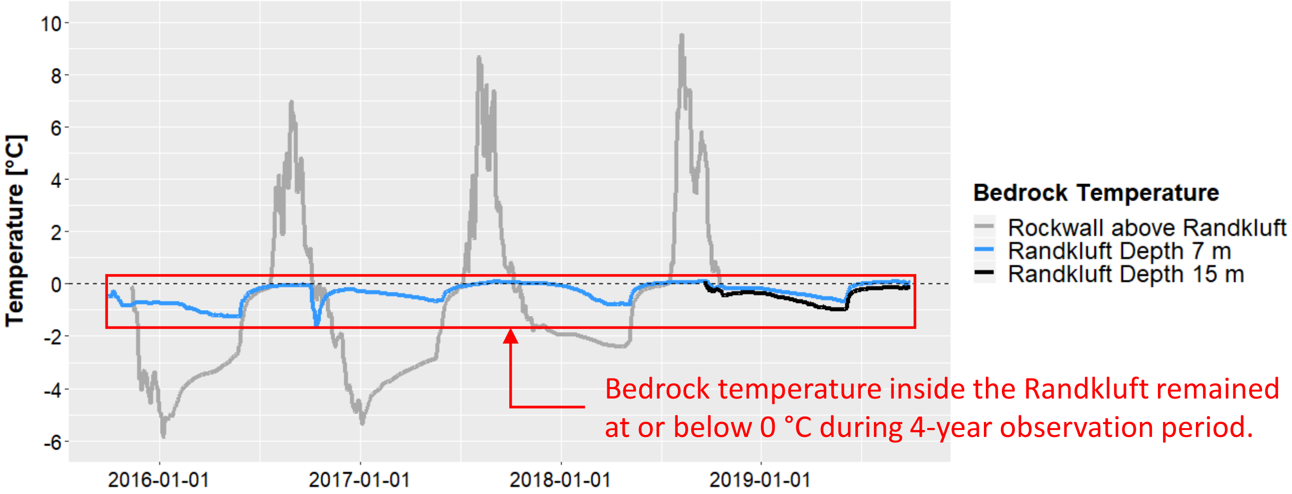
Retreat rates are significantly elevated where the direction of cleavage facilitates large dip-slope failures (catalinal setup).

- Mean cirque wall retreat of **1.9 mm a^{-1}** ranks in the top range of published values and is mainly driven by enhanced rockfall from the lowermost, freshly deglaciated rockwall sections (**7.6 mm a^{-1}**).
- Retreat rates in glacier-distal rockwall sections (**0.9 mm a^{-1}**) are an order of magnitude lower than in proximal areas.
- Enhanced cirque wall dismantling in recently deglaciated rockwall sections supports concepts of **increased cirque growth during deglacial periods** (Delmas et al. 2009, Crest et al. 2017).

Paraglacial Rockfall Increase: Potential Causes

Distinct Randklufts separate glacier and headwall.

Installation of bedrock temperature sensors 7 m below glacier surface level.



- The observed paraglacial rockfall increase **cannot be explained by debuttressing effects** as the investigated cirque walls are separated from the adjacent glacial ice by distinct Randklufts.
- Rockfall preconditioning may start **inside the Randkluft** where sustained freezing and ample supply of liquid water likely cause enhanced physical weathering (ice segregation) and high plucking stresses (refreezing of meltwater at the Randkluft bottom).
- As the glacier is wasting down strong diurnal and seasonal temperature variations induce pronounced **thermal stress** (Hall 1999), cause **rock fatigue** (Jia et al. 2015) and lead to the first-time formation of a **deep active layer**, which is expected to exert a significant destabilizing effect on glacier-proximal areas (Krautblatter et al. 2013).

Further Reading

For more details and analyses check out our two discussion papers (preprints) available online at *Esurf*.

Hartmeyer, I., Delleske, R., Keuschnig, M., Krautblatter, M., Lang, A., Schrott, L., and Otto, J.-C.: Current glacier recession causes significant rockfall increase: The immediate paraglacial response of deglaciating cirque walls, Earth Surface Dynamics, 2020.

Hartmeyer, I., Keuschnig, M., Delleske, R., Krautblatter, M., Lang, A., Schrott, L., and Otto, J.-C.: Enhanced rockwall retreat and modified rockfall magnitudes/frequencies in deglaciating cirques from a 6-year LiDAR monitoring, Earth Surface Dynamics, 2020

https://doi.org/10.5194/esurf-2020-8
Preprint. Discussion started: 9 March 2020

Current glacier recession causes significant rockfall increase: The immediate paraglacial response of deglaciating cirque walls

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Abstract. In the European Alps almost half the glacier volume disappeared over the past 150 years. The loss is reflected in glacier retreat and ice surface lowering even at high altitude. In steep glacial cirques surface lowering exposes rock to atmospheric conditions for the very first time in many millennia. Instability of rockwalls has long been identified as one of the direct consequences of deglaciation, but so far cirque-wide quantification of rockfall at high-resolution is missing. Based on terrestrial LiDAR a rockfall inventory for the permafrost-affected rockwalls of two rapidly deglaciating cirques in the Central Alps of Austria (Kitzsteinhorn) is established. Over six-years (2011-2017) 78 rockwall scans were acquired to generate data of high spatial and temporal resolution. 632 rockfalls were registered ranging from 0.003 to 879.4 m^3, mainly originating from pre-existing structural rock weaknesses. 60 % of the rockfall volume detached from less than ten vertical meters above the glacier surface, indicating enhanced rockfall activity over tens of years following deglaciation. Debuttressing seems to play a minor effect only. Rather, preconditioning is assumed to start inside the Randkluft (gap between cirque wall and glacier) where sustained freezing and ample supply of liquid water likely cause enhanced physical weathering and high plucking stresses. Following deglaciation, pronounced thermomechanical strain is induced and an active layer penetrates into the formerly perennially frozen bedrock. These factors likely cause the observed paraglacial rockfall increase close to the glacier surface. This paper presents the most extensive dataset of high-alpine rockfall to date and the first systematic documentation of a cirque-wide erosion response of glaciated rockwalls to recent climate warming.

1 Introduction

High-alpine, glacial environments are severely affected by recent climate warming (WGMS, 2017). This is especially true for the European Alps, where mean temperature rise over the last 150 years more than doubled the global mean (Böhm, 2012) and over this period approximately 50 % of the glacier volume has disappeared (Haeberli et al., 2007). Glacier retreat rates increased since the 1980s and have been exceeding historical precedents in the early 21st century (Zemp et al., 2015). The consequences of these changes are most visible in lower lying glacierized cirques where ice-surface lowering in the ablation

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https://doi.org/10.5194/esurf-2020-9
Preprint. Discussion started: 9 March 2020

Enhanced rockwall retreat and modified rockfall magnitudes/frequencies in deglaciating cirques from a 6-year LiDAR monitoring.

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Abstract. Cirque erosion contributes significantly to mountain denudation and is a key element of glaciated mountain topography. Despite long-standing efforts, rates of rockwall retreat and the proportional contributions of low-, mid- and high magnitude rockfalls have remained poorly constrained. Here, a unique, terrestrial LiDAR-derived rockfall inventory (2011-2017) of two glaciated cirques in the Hohe Tauern Range, Central European Alps, Austria is analysed. The mean cirque wall retreat rate of 1.9 mm a^{-1} ranks in the top range of reported values and is mainly driven by enhanced rockfall from the lowermost, freshly deglaciated rockwall sections. Retreat rates are significantly elevated over decades subsequent to glacier downwasting. Elongated cirque morphology and recorded cirque wall retreat rates indicate headward erosion is clearly outpacing lateral erosion, most likely due to the cataclinal backwalls, which are prone to large dip-slope failures. The rockfall magnitude-frequency distribution – the first such distribution derived for deglaciating cirques – follows a distinct negative power law over four orders of magnitude. Magnitude-frequency distributions in glacier-proximal and glacier-distal rockwall sections differ significantly due to an increased occurrence of large rockfalls in recently deglaciated areas. In this paper we show how recent climate warming shapes glacial landforms, controls spatiotemporal rockfall variation in glacial environments and indicates a transient signal with decadal scale exhaustion of rockfall activity immediately following deglaciation crucial for future hazard assessments.

1 Introduction

Cirque erosion contributes significantly to the morphological appearance of glaciated mountain ranges. It controls rockwall retreat and creates emblematic high-alpine landform features such as horn-type peaks and sharp-edged ridges. Erosional processes operating in glacial cirques are widely recognized as important agents of high-alpine landscape evolution (Benn and Evans, 2010; Sanders et al., 2012; Scherler, 2014). Rockfall from cirque walls represents a primary source of debris for glacial systems and thus supplies tools for effective glacial erosion (Hallet, 1981). The disposal of sediment from cirque walls also

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