Rockfall in permafrost-affected cirque walls: New insights on spatial variability and potential causes derived from a 4-year LiDAR monitoring campaign, Kitzsteinhorn, Austria

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Thermal changes in permafrost-affected rock significantly alter the mechanical properties of rock and ice along potential failure planes. Within the context of recent climate warming the thermal state and stability of frozen rock walls have therefore become a key issue not only for rockfall risk considerations but also for high-alpine landscape evolution and periglacial geomorphology.

In the European Alps numerous, largely visual, observations indicate an increasing occurrence of rockfall events that may be connected to rising temperatures. However, long-term data on rockfall patterns and ground thermal conditions is scarce for these steep, inaccessible environments. Understanding of the controlling factors of climate-sensitive high-alpine rockfall has therefore remained elusive.

The presented study tackles the need for high-precision field data by analyzing a four-year terrestrial LiDAR time series from a high-alpine (peri)glacial environment. The study area is located in the summit region of the Kitzsteinhorn (3203 m a.s.l.), Hohe Tauern Range, Austria. LiDAR monitoring campaign was started in July 2011, since then six side- and backwalls of two glacial cirques were scanned at an interval of approximately two months during the snow-free summer season (June to October). The scanned rock faces predominantly consist of calcareous mica-schist and differ in terms of height, slope inclination, slope aspect, and discontinuity orientation. The rock faces are underlain by permafrost, their combined surface area is approximately 100000 m^2. All investigated rock faces are situated directly adjacent to the Schmiedingerkees cirque glacier, which has retreated and thinned significantly in recent decades (downwasting rate 1.5 m/a). The interpretation of the acquired terrestrial LiDAR data is supported by extensive in-situ borehole temperature measurements from depths of up to 30 m. LiDAR data acquisition was performed using a Riegl LMS-Z620i. For data acquisition a quick, flexible methodology was applied that does not require fixed installations and/or artificial, reflective markers. For data post-processing a procedure was developed which allows point cloud alignment by surface geometry matching and objective, automated discrimination between measurement errors und real surface changes.

From 2011 to 2014 a total number of 104 rock fall release zones were identified (LiDAR data of the 2015 summer season is currently analyzed, final results are not available yet). The total rockfall volume was 1130 m^3, the largest rockfall event reached a volume of about 250 m^3. The distribution of the rockfall release zones displays a distinct spatial pattern: Rock surfaces that were exposed by the thinning Schmiedingerkees glacier in recent years and decades show a significantly increased rockfall activity: 66 % of the detected rockfall release zones and 80 % of the detected rockfall volumes were triggered from areas located less than 20 m above the current glacier surface. The annual rockwall retreat rate within this 'active belt' (= 0–20 m above glacier) is approximately 7.5 mm. This clear correlation suggests that glacial thinning exerts a major destabilizing influence on the adjacent rock faces.

Permafrost degradation and glacial debuttressing, two frequently cited causes for high-alpine rockfall, do not provide conclusive explanations for most of the detected rockfall events. Maximum active layer thickness during the summer season (> 3 m) is larger than the depth of the failure plane for the majority of the detected rockfall events (95 %). Thus, permafrost degradation is an unlikely trigger for most events. While glacial debuttressing (i.e. loss of support at the base of a rock face due to glacial melting) certainly plays an important role for some of the observed events there are two relevant counter-arguments: the existence of a distinctly opened randkluft at the base of most of the scanned rock faces necessarily implicates that there is no effective debuttressing impact at the time of the 'emergence' of a rock surface above the lowering glacier surface. The debuttressing effect, if relevant at all, should therefore occur subglacially in the bottom sections of the randkluft, which cannot be covered by LiDAR monitoring; (ii) glacial debuttressing fails to explain the observed high rockfall activity several meters above the glacier surface.

Frost cracking and thermo-mechanical forcing may provide alternative, more convincing explanations for the observed rockfall pattern. Sustained periods of subzero temperatures are likely to lead to intense frost cracking within the randkluft causing extensive fracturing of intact rock. When rock surfaces are exposed to atmospheric influences due to pronounced glacial thinning, ground thermal conditions are modified significantly. Newly exposed rock surfaces are subject to greater temperature amplitudes, leading to pronounced thermomechanical strain along critically stressed discontinuities and potentially to rockfall detachment.