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

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Over the past 150 years almost half of the glacier volume disappeared in the European Alps. Besides glacier retreat, ice surface lowering reflects much of the volume loss and uncovers the adjacent rockwalls. In steep glacial cirques, this process 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 and the proportional contributions of low-, mid- and high magnitude rockfalls have remained poorly constrained.
We use terrestrial LiDAR to establish a rockfall inventory for the permafrost-affected rockwalls of two rapidly deglaciating cirques in the Central Alps of Austria (Kitzsteinhorn). During six-year monitoring (2011-2017) 78 rockwall scans were acquired. Overall, we registered 632 rockfalls ranging from 0.003 to 879.4 m^3, which concentrate along pre-existing structural weaknesses. 60 % of the rockfall volume detached from less than ten vertical meters above the glacier surface, indicating enhanced rockfall over tens of years following deglaciation.
Antecedent rockfall preparation is assumed to start when the rockwall is still ice-covered: Inside the Randkluft (gap between cirque wall and glacier) sustained freezing and sufficient water supply likely cause enhanced weathering and high plucking stresses. Following deglaciation, pronounced thermomechanical strain is induced and an active layer penetrates into perennially frozen bedrock, likely contributing to the observed paraglacial rockfall increase close to the glacier surface.
Observed mean cirque wall retreat 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 sections of the investigated rockwalls. Rockfall magnitude-frequency distribution, which has never been quantified before for deglaciating cirques, follows a distinct negative power law distribution 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. The present study thus demonstrates how recent climate warming shapes glacial landforms, controls spatiotemporal rockfall variation in glacial environments and indicates an exhaustion law over decades for rockfall activity immediately following deglaciation crucial for

future hazard assessments.

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