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The 2023 Fluchthorn massive permafrost rock slope failure analysed

Michael Krautblatter[1], Samuel Weber[2], Michael Dietze[3], Markus Keuschnig[1,4], Georg Stockinger[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], and Florian Siegert[9]

[1]Chair of Landslide Research – Technical University of Munich, Munich, Germany
[2]WSL Institute for Snow and Avalanche Research SLF, 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

Warming in the last two decades has caused massive rockfall activity with limited mobility in the range of 10^{1-6} m³. However, only a few highly destructive and mobile rock avalanches above 1 Mio. m³ have been documented. Rock-ice mechanical models explaining high-magnitude rock slope failure in permafrost have been postulated but not validated on real failures.

This study combines complementary expert knowledge to decipher the 1 Mio. m³ Fluchthorn rock slope failure that detached on June 12, 2023, from the before 3399 m high summit causing a rock avalanche that additionally eroded ca. 120.000 m³ of ice. InSAR data shows deformation rates in the range 4.1 – 7.1 ± 0.13 cm/a from April 2021 to March 2023, but these are surprisingly linked to a westward deformation of the entire Silvretta nappe (in the range of 3 cm/a) oversteepening the Fluchthorn. Mountain guides have observed singular failures before the event. IR drone flights immediately after the event indicate rock temperatures at the failure planes in the range of 0°C - -2°C and ice-filled fractures. Solid, scarcely fractured pseudotachilitic sequences in the summit regions may have contributed to the massive oversteepening of the Fluchthorn Westface without significant pre-failures. The grain size compositions shows massive material take up of fine-grained material and fragmentation (Pudasaini & Krautblatter 2021).

In a seismic analysis we can for the first time exactly reconstruct the temporal and spatial trajectory of a rock-ice avalanche, velocities and energy release during the 120-second rock-ice-avalanche propagation consistent with fragmentation and deposits. High-resolution photogrammetry highlights massive ice erosion and accumulation patterns during the rock avalanche propagation. In addition, we analyse all precursors in the last two years before the failure in detail (Leinauer et al. 2023): These include small prefailure volumes, seismic precursors, kinematic precursors and kinematic precursors detected in UltraCam & LiDAR surveys.

In an IRAZU model, capable of nucleation and growth of fractures based on nonlinear fracture mechanics applied stresses act to produce a progressive fracturing path that closely resembles the real failure and we can show the impact of the solid pseudotachilitic roof on the oversteepening. In a discontinuum model (UDEC), we can show the stabilizing effect of permafrost on developing fracturing patterns in a combined rock-ice mechanical approach, including temperature-dependent rock mechanical (Krautblatter et al. 2013, Draebing & Krautblatter 2019, Jia et al. 2017, 2019) and destabilization processes in ice-filled fractures and along rock-ice interfaces (Mamot et al. 2018, 2020, 2021).

In summary, we show a unique combination of datasets deciphering pre-failure tectonic and geological controls and forcing, syn-failure permafrost-related mechanics, and second-resolution data on rock avalanche evolution in a cryospheric terrain with massive ice uptake.