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# Insights into large slope failures in permafrost-glacier environments from the 2005 Mt. Steller slide, Alaska

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Landslides in high-mountain areas $>10^7$ m3 are rare, and accordingly, few occasions exist to document and analyze the failure causes of such events. We present here data on an exceptional slide from Mt. Steller (3236 m asl), located between the Bagley Icefield and the Bering Glacier, Alaska, that occurred on 14 September, 2005. The slide initiated in the South face of Mt. Steller and involved hanging glacier ice and underlying bedrock, with layering sub-parallel to the surface slope. The resulting rock-ice avalanche of a volume of about 50 million m3 traveled for 9 km horizontally with a vertical drop of 2.4 km until the mass was deposited on Bering Glacier. Based on seismic signals recorded at several Alaskan seismic stations, an avalanche velocity of up to 100 m/s could be reconstructed. Seismic signals of up to 0.5 hour before failure are interpreted as precursory slip movement of glacier ice, based on experience of similar recent slope failures in Alaska.

Mt. Steller is located in an extremely remote area in Alaska, and thus, any direct ground measurements are lacking. Nevertheless, learning from this large slope failure may be important in the context of impacts of atmospheric warming on permafrost and glaciers and related slope destabilization in more populated mountain regions. Beyond seismic data that helped constraining failure mechanisms, we therefore used available regional climate data to generate first-order models of thermal conditions and perturbations in bedrock and glacier ice. Subsurface thermal conditions at Mt. Steller are relevant to better understand the role of atmospheric warming and thermal

anomalies induced into the bedrock by overlying glaciers for the failure. Tectonic and geologic data of Mt. Steller are currently mostly lacking and therefore are not a focus here although they likely exerted an important control on the failure.

Extrapolations from regional climate stations suggest mean annual air temperatures (MAAT) at the failure site (˜2500-3150 m asl) of about -13°C to -19°C, with mean annual ground surface temperatures (MAGST) in the range of -10°C to -16°C. Regional radiosonde data, however, indicate a MAAT of about -10.5°C at 3000 m asl, and thus possibly better reflect the recent strong warming in Alaska, and filter local topographic climate effects of the climate stations. Such temperature conditions basically allow for infiltration in glaciers, a process that can strongly increase ice temperatures due to latent heat dissipation. In fact, observation of liquid water in the upper detachment zone immediately after the event points to a likely role of melt water in and at the base of the glacier ice. Our thermal modeling with a reconstruction of temperature distribution across a N-S cut of Mt. Steller indicates a large thermal perturbation of the bedrock due to polythermal glacier ice. Furthermore, the decade-to-century warming signal from the particularly strong temperature rise in Alaska has probably penetrated to a few tens of meters depth. Such strong thermal perturbations with parts of ice and bedrock close to phase equilibrium could have well contributed to slope destabilization. The possible physical processes effective for slope destabilization are currently under discussion.

Ongoing research of the Mt. Steller slide and other similar but about an order of magnitude smaller slides in the Alps may thus enhance the understanding of large slope failures in areas with permafrost and glacier ice, that with ongoing warming may increasingly evolve into significant hazards in regions with higher population density such as the Alps.