

# Measuring and modelling permafrost at local and regional scales in the Kazbek region, Russian Caucasus

---

Regula Frauenfelder<sup>1</sup>, Christian Huggel<sup>2</sup>, Sonja Zraggen-Oswald<sup>3</sup>, Igor Galushkin<sup>4</sup>, & Sergey Chernomorets<sup>5</sup>

<sup>1</sup>*Department of Geography, University of Zurich, Switzerland; now at Norwegian Geotechnical Institute, Oslo, Norway*

<sup>2</sup>*Department of Geography, University of Zurich, Switzerland*

<sup>3</sup>*Department of Geography, University of Zurich, Switzerland; now at Amt für Tiefbau, Altdorf, Kt. Uri, Switzerland*

<sup>4</sup>*InfoTerra, Vladikavkaz, North Ossetia, Russia*

<sup>5</sup>*Lomonosov Moscow State University, Moscow, Russia*

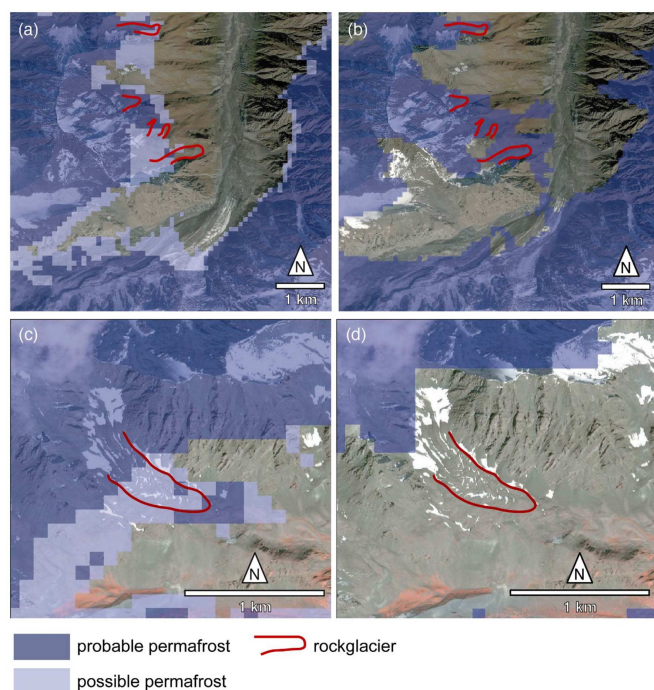
Widespread melting of glaciers and rising permafrost temperatures provide an early indication of the environmental and societal significance of global warming. In both high-latitude and high-elevation mountain ranges, glaciers commonly interact with permafrost, leading to potentially hazardous geomorphological processes at the temporal and spatial interfaces between them. Glacier retreat and thawing permafrost affect the stability of steep slopes in alpine mountain ranges. Detachment of hanging glaciers as well as glacier retreat can change the stress distribution of a slope and may induce destabilization. Several combined avalanche/rockfall events in high mountain regions during the 20th century are likely to have been connected to processes relating to glacier shrinkage and permafrost warming/thawing. With ongoing climate change, thermal conditions are becoming a critical aspect for slope stability in high mountains. Results from laboratory experiments and simulations have shown that the stability of ice-filled joints decreases with increasing ice-/bedrock temperature, with a presumed minimum stability between -1.5 and 0 °C. Phase transition from frozen to liquid water in rock fissures is therefore seen as an important factor influencing the slope stability.

A dramatic slope failure occurred on September 20th 2002, in the Kazbek massif of the Northern Caucasus (Republic of North Ossetia-Alania, Russia). After some precursory ice and rock avalanches on the Kolka glacier during the two months prior to the disaster, the main event started as a slope failure in the NNE face of Dzhimarai-khokh (4780 m a.s.l.) initially involving c. 10–20×10<sup>6</sup> m<sup>3</sup> of rock and ice from hanging glaciers. This mass fell onto the underlying Kolka glacier which was entrained to a major extent

by disruption and liquidization. The resulting extremely large rock-ice avalanche, on the order of more than 100×10<sup>6</sup> m<sup>3</sup>, devastated the valley for more than 30 km. The event caused the death of about 140 people and the resulting damage totalled nearly 20 million Euro. In May 2014, a similar, yet somewhat smaller event took place from the east face of Mount Kazbek where large amounts of ice and rock failed, transforming into a massive debris flow that travelled down the Devdorak glacier and valley and blocked the Terek River valley, which is the main connection between North Ossetia and Georgia (Chernomorets et al., 2007). Similar mass flow events from Devdorak glacier are reported from the 18<sup>th</sup> and 19<sup>th</sup> century.

The Kolka-Karmadon case is one of the largest rock-ice avalanches to have been documented. Due to the implications for worldwide glacier and permafrost hazard assessments, it was important to systematically analyze the event. The permafrost study presented here was initiated within the context of the hazard assessment and disaster prevention carried out shortly after the event. Previous studies (e.g., Evans et al., 2009; Huggel et al., 2005) have investigated the erosion and entrainment of Kolka glacier, the avalanche dynamics, possible trigger mechanisms and several post-disaster hazards. Publications emphasized the importance of the surface and sub-surface thermal conditions for the initial avalanche failure in the Dzhimarai-khokh NNE face but did not include in-situ observations or modelling. Based on data from a former weather station near the village of Karmadon, however, estimated a mean annual air temperature (MAAT) of -6±2 °C at the lower end and -11±3 °C at the upper end of the failure zone. Bedrock surface temperatures in the failure zone were thus

estimated to be about  $-5$  to  $-10$  °C. The thermal conditions, however, were complicated by the existence of hanging glaciers in the Dzhimarai-khokh NNE wall. Such steep ice bodies can induce significant thermal anomalies within the underlying bedrock.



**Figure 1:** Permafrost distribution modelling results overlaid on a QuickBird satellite image of the Upper Genaldon valley (a and b) and the south-west face of Chach-khokh (c and d). Active rock glacier tongues are outlined in red.

In the present study, near-surface temperature rock-wall loggers were installed to gain a better understanding of temperature conditions near the rock-ice avalanche failure zone. These temperature data, along with rock glaciers, mapped from satellite imagery of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and QuickBird, were used to validate spatial predictions undertaken with two existing permafrost models. The models were then applied to the mountainous terrain throughout North Ossetia-Alania, providing far greater detail on permafrost distribution in this part of the Caucasus than has been possible to date. The study represents an example of the level of permafrost assessment that can be achieved in a region with poor availability of climate data and ground information.

Our study provides an improved understanding of the permafrost distribution in the North Ossetian Caucasus in general, and in particular for the north-

ern slopes of Dzhimarai-khokh and Mt. Kazbek. For the 2002 avalanche thermal conditions of glacier ice and frozen rock likely played an important role. For the 2014 Kazbek/Devdorak avalanche disaster the results of this study can represent an important basis for an improved understanding of the characteristics and triggers of the slope failure.

The modelling approach used could be applied despite the paucity of field data. The results show that the two permafrost models developed in a climatically similar region, can be adjusted based on regional climate data to provide first-order estimates of the permafrost distribution. The employment of rock temperature loggers in this setting was a challenge, but the resulting temperature data were important, both for model validation and more detailed on-site information of the Kolka rock-ice avalanche failure area. The permafrost map developed for the territory of the Republic of North Ossetia is considered to be a useful instrument for regional planning purposes and for guiding further detailed investigations at critical sites. Any local use would require more in-situ measurements such as geophysical soundings and more extensive temperature measurements. Finally, the study showed the potential and limitations for permafrost assessments in high-mountain regions worldwide, many of which have similar limited data availability.

#### References

- Chernomorets S.S., Tutubalina O.V., Seinova I.B., Petrakov D.A., Nosov K.N., Zaporozhchenko E.V. 2007. Glacier and debris flow disasters around Mt. Kazbek, Russia/Georgia. / C.-L.Chen & J. Major (eds). Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment. Rotterdam, Millpress: 691-702.
- Evans SG, Tutubalina OV, Drobyshev VN, Chernomorets SS, McDougall S, Petrakov DA, Hungr O. 2009. Catastrophic detachment and high-velocity long-runout flow of Kolka Glacier, Caucasus Mountains, Russia in 2002. *Geomorphology* 105(3-4): 314-321.
- Huggel C, Zraggen-Oswald S, Haerberli W, Käab A, Polkvoj A, Galushkin I, Evans SG. 2005. The 2002 rock/ice avalanche at Kolka/Karmadon, Russian Caucasus: assessment of extraordinary avalanche formation and mobility, and application of QuickBird satellite imagery. *Natural Hazards and Earth System Sciences* 5: 173-187.