# Status, dynamics and stability of rock glaciers in South Tyrol (Eastern Italian Alps)

PhD Thesis

Candidate: Christian Kofler

Supervisor: Francesco Comiti, Marc Zebisch

External supervision: Volkmar Mair, Stefan Steger, Stefan Schneiderbauer

## Abstract

Rock glaciers are complex geomorphic units of high-mountain landscapes. They are composed of a mixture of ice and debris at varying degrees, whose deformation enables a steady creep behavior. Glacial, periglacial and paraglacial mechanisms were proposed to be drivers of their origin. The present-day persistence of rock glaciers in the landscape however is enabled by cryotic environmental conditions. The internal deformation of rock glaciers influences directly the amount of debris they are transporting. Hence, rock glaciers can be considered to be active conveyors of sediment in high mountain areas. In the context of climate change, rock glaciers increasingly gained attention as their downwasting driven by rising atmospheric temperatures has implications for the management of natural hazards and freshwater resources. The decay of rock glaciers is often accompanied by an acceleration of their creep behavior, which can even end in their partial or complete destabilization. The importance of meltwater derived from presently ice-containing rock glaciers will increase in relevance as they were found to be more resilient to melting than clean glaciers. However, approaches to address these pressing and timely issues are still rare and often not transferable.

This thesis aims to respond to this need by proposing and applying novel assessment methods to evaluate rock glacier ice presence, sediment transfer and front stability. Following a state of the art review, three thematic chapters are responding step-by-step to this overarching aim. Firstly, a regional scale assessment method for rock glacier ice-presence is presented and applied in the region of South Tyrol (northern Italy). The paper shows strategies to exploit the increasing availability of appropriate data sources such as rock glacier inventories, high resolution terrain data or satellite data products and computational methods such as statistical and machine-learning based algorithms. Three classifiers of various complexity (logistic regression, random forest and support vector machines) are compared and evaluated on their ability to spatially predict the likelihood of rock glacier ice presence. Results show that elevation and vegetation presence are the most powerful covariates to assign a status of activity to rock glaciers. Surprisingly, the applied statistical classifier performed better than the more complex machine-learning based models. This study highlights also the need to apply a rigorously spatial perspective for training, testing and tuning the parameters of data-driven models.

Second, the capacity of ice-containing rock glaciers to displace and transfer sediment at their front was estimated for the Schnalstal and Ultental catchments, both located in South Tyrol. Given the absence of validation data, a simple and easily reproducible heuristic method is proposed. The capacity of a rock glacier to transfer sediment at its front is considered to be determined by (i) the annual rate of transported debris by the rock glacier itself and (ii) the potential travel range of mobilized material at its front. Both variables are then combined within a matrix-based integration scheme to an index that expresses on a qualitative level the capacity of a rock glacier to transfer sediment at its front (i.e. low, moderate, elevated). In a consecutive step, empirical relationships between the computed sediment transfer classes and independent topographic and environmental control variables are build.

# Paper 1: An inventory-driven rock glacier status model (intact vs. relict) for South Tyrol (Eastern Italian Alps)

## Introduction

Rock glaciers are cryogenic landforms of cold mountain landscapes that are formed by downslope creeping, perennially frozen debris (Haeberli et al., 2006). Presently ice-saturated rock glaciers are the visible expression of active "sediment conveyor systems" from sediment source areas towards their front (Müller et al., 2014). Besides their role as controlling landform of sediment cascades in cold mountain environments, ice-rich rock glaciers act as important fresh water storages and sources, especially in semi-arid and arid mountainous areas. As highlighted by Brenning (2003), the amount of water stored in intact rock glaciers might even exceed water volumes stored in glaciers within catchments of the Chilean Andes. Recently, Jones et al. (2018) emphasized the high resilience against climatic warming of rock glaciers compared to glaciers, as well as their future relevance for freshwater supply. Information on the spatial distribution, status and geometry of rock glaciers is usually stored in dedicated GIS-based inventories. However, time and cost constraints do not permit to assign the status to each rock glaciers in regional scale inventories based on in-situ evidence. Therefore, the determination of the status of an individual rock glacier is mostly carried out based on expert knowledge with support of aerial imagery, digital terrain models (DTMs), field investigations and other auxiliary material. This is a reasonable approach but makes the final inventory prone to biases related to subjective estimations of different operators in charge of defining the status of rock glaciers, as shown by Brardinoni et al. (2019).

The objective of this paper is was to present data-driven models to estimate the status of rock glaciers at the regional scale by integrating various geospatial datasets, such as high-resolution terrain data and satellite data products. Additionally, the paper aims at exploring the model results in terms of empirical relationships between rock glacier status and the controlling environmental variables.

## Materials and methods

The main data source was the inventory of rock glaciers for South Tyrol. It contains their spatial position as well as the training data on their status, which were necessary for this study. A total number of 1779 rock glaciers are in the inventory, of which 240 are listed as active, 59 as inactive and 1245 as relict. The status of 235 rock glaciers was not defined yet. The individual rock glacier status was assigned by interpreting geological maps, aerial photographs and the hillshade of the available high resolution (2.5 m) Light Detection and Ranging (LiDAR) digital terrain model (DTM). Many of the applied predictor variables in this study's modelling setup were derived from the same DTM mentioned above. It covers the entire province and refers to surveys carried out in 2005. In addition, semi-automatically mapped data on perennial snowfields were considered in the present study. The dataset was created by Zischg et al. (2012) on the basis of aerial images acquired in late summer (1996, 1999 and 2003). Information on the vegetation cover was approximated with the normalized difference vegetation index (NDVI). The NDVI derives from optical remote sensing imagery and can be used as indicator for vegetation presence. The NDVI maps used in this study are a product derived from openly accessible satellite scenes of the European Space Agency's (ESA) Sentinel 2 A/B mission.

A crucial step of this study consisted in the selection of potentially suitable variables to estimate the status of a rock glacier. Based on the available literature, we have identified several predictor variables that may influence the presence of ice within a rock glacier. These variables were subsequently grouped into three thematic fields, namely topographic controls, environmental controls and rock glacier appearance (i.e. the visually perceptible characteristics of a rock glacier).

Three data driven classifiers, namely the logistic regression model (GLM), support vector machine (SVM) and random forest (RM) were applied to discriminate between intact and relict rock glaciers. When dealing with georeferenced data, a spatially explicit partitioning of training and test samples is required to avoid overoptimistic performance estimates and to assess the spatial transferability of the model. Spatial k-fold cross validation (SCV) splits the initial data set into spatially independent training and test areas via a k-means clustering algorithm (Brenning, 2012). In the present work, the study region was split into 5 sub-regions and SCV was repeated 25 times for each fold (i.e. 25 x 5 = 125 tests per model). The discriminatory power of a binary classifier can be measured with the Area under the Receiving Operating Characteristic (AUROC).

## Results and discussion

Fitting performances for all models achieved a median AUROC higher than 0.95, which can be defined as an outstanding discrimination between intact and relict rock glaciers according to Hosmer and Lemeshow (2000)). The RF model reached a near perfect classification of training data, followed by the GLM and the SVM. SCV revealed that all models enabled to classify the rock glacier status of spatially independent test data with a very high accuracy (i.e. median AUROC > 0.92). In this context, the RF classifier (AUROC 0.93) achieved a lower performance than the SVM (AUROC 0.95) and the GLM (AUROC 0.96) and revealed a slight tendency to adapt too strongly to the training data set (i.e. to overfit).

Altitude or NDVI resulted to be the most important predictor variables in each of the model setups. With the altitude as a proxy for the elevation-dependent temperature gradient, one variable expressing a main driver for ice-presence and with the NDVI one variable expressing a visual discernible effect of rock glacier activity resulted to be most important. Nevertheless, the NDVI revealed to be a relevant variable to monitor the rock glacier status, also in practical terms. NDVI maps can be produced in a cost-effective way based on freely-available satellite imagery. Due to the high temporal resolution of data provided by recent missions such as the Sentinel-2 constellation, remote sensing based monitoring of the rock glacier status over time may become more effective when taking the NDVI into consideration.

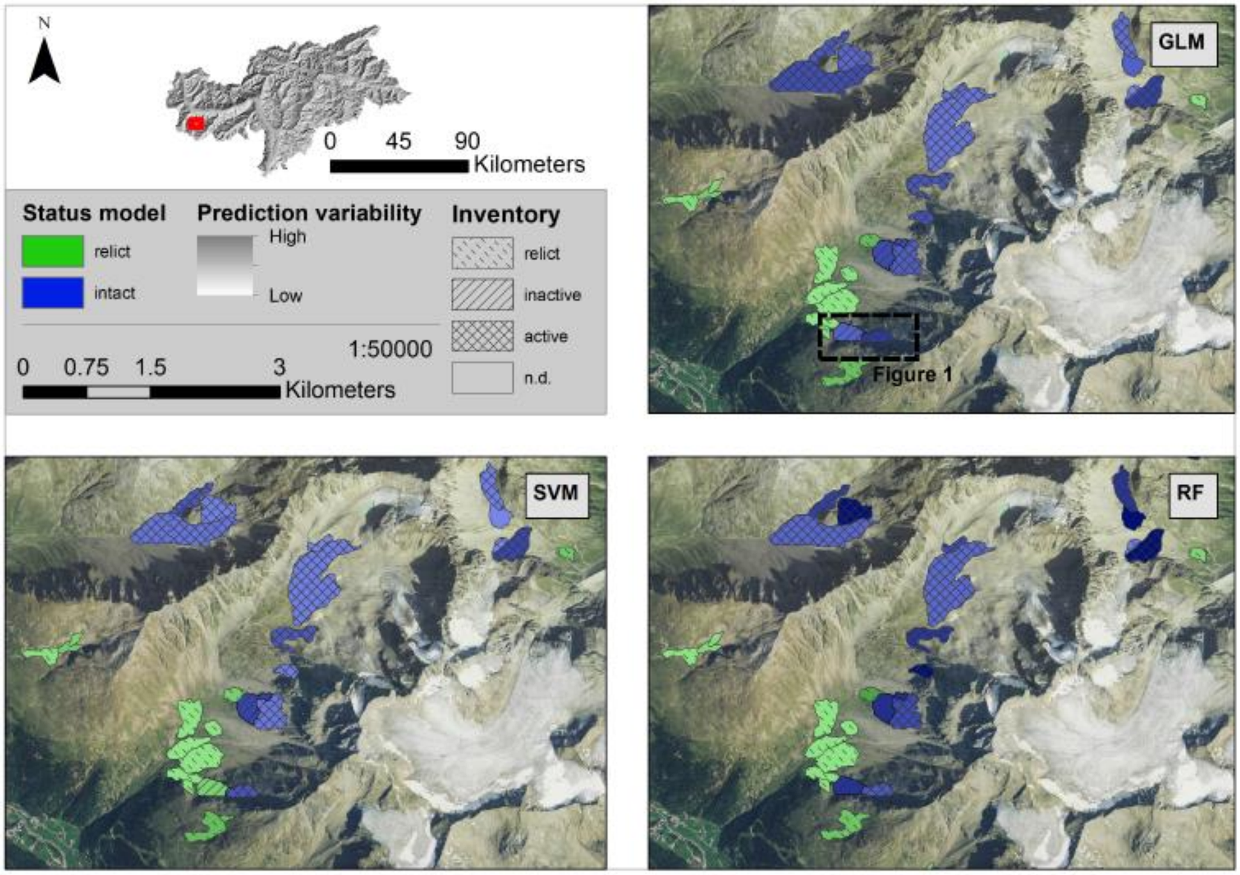


*Figure 1: Model application to rock glacier polygons*

# Paper 2: Sediment transfer capacity of rock glaciers: Examples from two catchments in South Tyrol, (Eastern Italian Alps)

## Introduction

Within the context of present-day atmospheric warming, high-magnitude sediment release from degrading glacial and periglacial systems is increasingly reported to be the source of far-reaching mass movements, often affecting infrastructure distant from their origin (Kofler et al., 2021). The coarse debris system proposed by Barsch and Caine (1984) comprises the transfer of coarse sediment from rock cliffs onto talus slopes and is predominantly found in dry continental environments. The lower boundary of the coarse debris system can be extended further downslope by the permafrost-ice driven debris convey capacity of rock glaciers, steadily moving tongue- or lobate-shaped bodies of ice-saturated debris (Barsch, 1996).

As the movement at a rock glacier's surface is usually faster than at its base, superficially transported debris falls down the steep front slope and accumulates at its toe. If the topographic characteristics of the fore field of a rock glacier do not predispose for a removal of the released sediment, a stiff layer of coarse debris builds up at the toe of the front slope and is subsequently overridden by the advancing of the landform. Hence, released sediment is ingested again by the rock glacier (Haeberli et al., 1998; Springman et al., 2012). Indeed, the coarse debris system introduced by Barsch and Caine (1984) considers rock glaciers as end-members of a closed system (cf. Müller et al., 2014). In the recent past however, scholars increasingly reported cases of rock glaciers being a sediment source as well (Kofler et al., 2021; Krainer et al., 2012).

In this paper, we consider rock glacier creep and its downward sediment connectivity as principal drivers of the debris transfer occurring at a rock glacier front. Therefore, the aim of this study is to explore this potential sediment transfer capacity of rock glacier fronts on a catchment scale. In this work we present (i) a reproducible GIS-based approach to generate proxy variables for the considered transport processes (i.e. steady-state rock glacier sediment transport and rapid mass wasting originating at rock glacier fronts), (ii) a matrix-based method to label entries of a rock glacier inventory according to their potential sediment transfer capacity.

## Materials and methods

An integrated assessment of the capacity of rock glaciers to transfer sediment required a detailed study of two types of transport processes: (i) slow moving (surface) deformation of the rock glacier body and (ii) rapid mass wasting occurring at the rock glacier front.

### Rock glacier sediment transport

The sediment transport rate of each individual rock glacier stored in our inventory was calculated based on the formula proposed by Lugon and Stoffel (2010):

$$A = 0.5 * (V * w * d)$$

, where V denotes the transported annual sediment volume [m3yr−1], v the rock glacier flow velocity [myr−1], W the width of the rock glacier [m] and d the depth of the shear horizon [m]. The factor of 0.5 accounts for the presence of air voids and ice in the rock glacier. As d was largely unknown, we assumed it to be at a depth of 65 % of rock glacier thickness below the rock glacier surface, as inclinometer data from six boreholes in the Swiss and Italian Alps suggests (Arenson et al., 2002; Krainer et al., 2015).

The reconstruction of v required the use of multi-temporal optical imagery. We tracked rock glacier creep from a series of co-registered orthophotos taken in 2006, 2008 and 2014. The "IMCORR" algorithm, developed by Bernstein (1983) and subsequently implemented in SAGA GIS (Conrad et al., 2015) was used to generate 2D surface displacement vectors on rock glaciers.

### Mass wasting processes at the rock glacier front

Reported types of rapid sediment transport processes at rock glacier fronts include hyperconcentrated flows, debris flows, debris slides and rockfall (Krainer et al., 2012; Kummert and Delaloye, 2018). We have reduced this wealth of reported processes to the process types “debris flows” (DF) and “rockfall” (RF). Potential travel ranges of sediment mobilized at the rock glacier front for rockfall LRF and debris flow LDF were computed by applying a combined physical-empirical modelling approach. The core module of the process modelling was the “Gravitational Process Path (GPP) v.1.0” tool, developed by Wichmann (2017) and implemented into the SAGA GIS software.

## Rock glacier sediment transfer capacity evaluation

In a subsequent step, each entry of our inventory was heuristically characterized in terms of its capacity to transfer sediment at its front. We performed this task on a catchment level, i.e. separately for Schnalstal and Ultental. Computed rock glacier sediment transport rates V and runout ranges of mass wasting processes LDF or LRF were aggregated to a single index by a two-dimensional matrix-based approach:

## Results and discussion

Sediment transfer capacity was estimated for Ultental and Schnalstal, differentiating between a hyperconcentrated flow-type and a rockfall-type of sediment transfer towards downward areas. Sediment transfer capacity could be estimated for 51 (DF) and 53 (RF) ice-containing talus generated rock glaciers in Ultental and 41 (DF) and 44 (RF) ones in Schnalstal. The matrix-based integration of rock glacier sediment transport and sediment provision to downward areas by rapid mass movements resulted in a dominance of a low sediment transfer capacity for all four integration schemes in absolute and relative terms. Surprisingly, for most rock glaciers V and L are allocated in the same class. In other words, most rock glaciers characterized by a low sediment transport V, have also rather short runout lengths L.

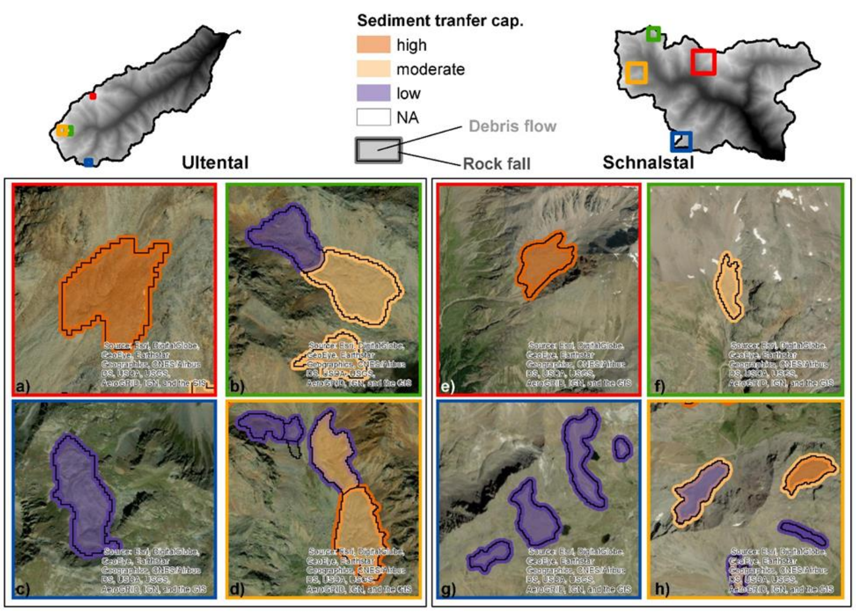


*Figure 2: Modeled sediment transfer capacity shown for selected sites in Ultental and Schnalstal*

# Paper 3: When do rock glacier fronts fail? Insights from South Tyrol (Eastern Italian Alps)

## Introduction

Climate change is strongly affecting the global cryosphere and leads to an increase in permafrost temperatures (IPCC, 2019). Permafrost influences livelihoods in Arctic and high mountain areas worldwide, and its thawing has already caused negative impacts in terms of an increased occurrence of geohazards and a deteriorating quality and supply of water (Hock et al., 2019).

Mass wasting at rock glacier fronts mainly affects the unfrozen domain of the landform, but it should not be viewed as process disconnected from its internal ice-driven deformation. If the terrain steepness at a rock glaciers toe favors the removal of such loose material, the latter may be transported downhill as debris flow, debris slide or rock fall (Krainer et al., 2012; Kummert and Delaloye, 2018; Marcer et al., 2020). Parts of the front slopes of two active rock glaciers - Hintergrat and Similaungrube - failed nearly simultaneously on August 13, 2014. The rock glaciers are about 50 km apart within the Vinschgau/Venosta Valley (South Tyrol, northern Italy).

In this paper, we aim to identify the factors controlling rock glacier front stability, to quantify their magnitude and to put them into an Alpine-wide context, specifically addressing the two front failures that occurred in South Tyrol in 2014.

## Materials and methods

A set of potentially destabilizing factors was identified based on previous findings in literature. We differentiated between temporally constant (predisposing), slowly-changing (preparatory) and rapidly-varying (triggering) destabilizing factors (Steger, 2017). This concept was recently used to discuss causes for collapses of rock glaciers (Bodin et al., 2017) and their front slopes (Marcer et al., 2020) in the French Alps. Within the context of this approach, we aim to test three hypotheses on interactions of destabilizing factors:

- Hypothesis 1: The predisposing sedimentary composition and the triggering rainfall event alone were the causes for the failure events.
- Hypothesis 2: Medium-term climatic and meteorological destabilizing preparatory factors affected the subsurface thermal and hydrological conditions of the study rock glaciers, in addition to the sedimentary composition and the triggering rainfall event.
- Hypothesis 3: The previous rock glacier displacement increased the predisposition to failure of the front slopes and acted together with the processes listed for Hypothesis 2.

A geotechnical study including material testing and slope stability modelling as well as a reconstruction of rainfall conditions during the failure events were conducted to test hypothesis 1. An analysis of ground temperature (GT) and key climate variables such as air temperature, precipitation and snow water equivalent (SWE) was carried out to test hypothesis 2. Hypothesis 3 was tested by reconstructing surface movement of both sites based aerial image correlation.

## Results and discussion

The triggering condition at both rock glaciers was a high-intensity rainfall event, estimated to be around the 95th percentile of all the recorded storms over the last 15 (Vernagt) and 11 (Madritsch) years. The simultaneous occurrence of several other events on August 13, 2014 originating in glacial or periglacial areas let us assume a prominent role of ice melting in high-altitude slopes besides the ones under investigation. Hence, the involvement of destabilizing factors acting on a time-scale beyond the short-term trigger was considered as very likely. Our data suggests that destabilization is to be expected if medium-term antecedent conditions are characterized by snow-rich and rainy conditions. The abundant 2013-2014 winter snowpack and the abnormally wet spring and summer in 2014 have probably thickened and saturated the active layer of both rock glaciers. The high-magnitude rainfall event was then the tipping point towards slope failure.

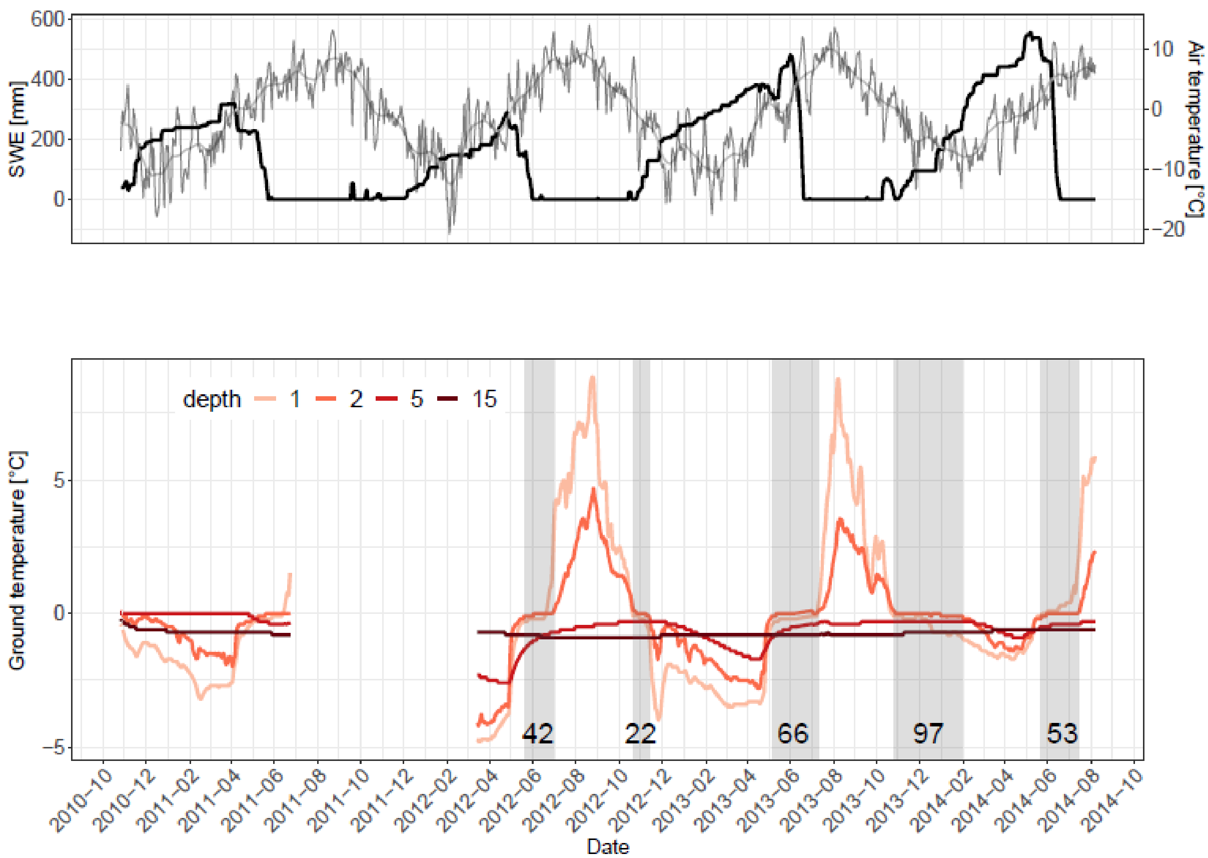


*Figure 3: Upper panel: SWE (black line), daily and 30 day running mean of TA (dark grey line and light grey line, respectively); lower panel: GT measured in borehole 1 of LAZ at 1 m, 2 m, 5 m and 15 m depth. The grey-shaded areas show the spring and autumn zero-curtains at 2 m depth and the black numbers within show the duration in days of the zero-curtains.*

## References

Arenson, L., Hoelzle, M., Springman, S., 2002. Borehole deformation measurements and internal structure of some rock glaciers in Switzerland. Permafrost Periglac. Process. 13, 117–135. https://doi.org/10.1002/ppp.414

Barsch, D., 1996. Rockglaciers - Indicators for the Present and Former Geoecology in High Mountain Environments, Springer Series in Physical Environment. Springer Berlin Heidelberg, Heidelberg.

Barsch, D., Caine, N., 1984. The Nature of Mountain Geomorphology. Mountain Research and Development 4, 287. https://doi.org/10.2307/3673231

Bernstein, R., 1983. Image geometry and rectification, in: Colwell, R.N. (Ed.), Manual of Remote Sensing. American Society of Photogrammetry, Falls Church, VA, pp. 881–884.

Bodin, X., Krysiecki, J.-M., Schoeneich, P., Le Roux, O., Lorier, L., Echelard, T., Peyron, M., Walpersdorf, A., 2017. The 2006 Collapse of the Bérard Rock Glacier (Southern French Alps): The 2006's Collapse of the Bérard Rock Glacier. Permafrost and Periglacial Processes 28, 209–223. https://doi.org/10.1002/ppp.1887

Brardinoni, F., Scotti, R., Sailer, R., Mair, V., 2019. Evaluating sources of uncertainty and variability in rock glacier inventories. Earth Surf. Process. Landforms 44, 2450–2466. https://doi.org/10.1002/esp.4674

Brenning, A., 2012. Spatial cross-validation and bootstrap for the assessment of prediction rules in remote sensing: The R package sperrorest, in: IGARSS 2012 - IEEE International Geoscience and Remote Sensing Symposium. Presented at the IGARSS 2012 - IEEE International Geoscience and Remote Sensing Symposium, IEEE, Munich, Germany, pp. 5372–5375. https://doi.org/10.1109/IGARSS.2012.6352393

Brenning, A., 2003. La importancia de los glaciares de escombros en los sistemas geomorfológicos e hidrológicos de la cordillera de Santiago: fundamentos y primeros resultados. Revista de Geografía Norte Grande 30, 7–22.

Colucci, R.R., Boccali, C., Žebre, M., Guglielmin, M., 2016. Rock glaciers, protalus ramparts and pronival ramparts in the south-eastern Alps. Geomorphology 269, 112–121. https://doi.org/10.1016/j.geomorph.2016.06.039

Conrad, O., Bechtel, B., Bock, M., Dietrich, H., Fischer, E., Gerlitz, L., Wehberg, J., Wichmann, V., Böhner, J., 2015. System for Automated Geoscientific Analyses (SAGA) v. 2.1.4. Geoscientific Model Development 8, 1991–2007. https://doi.org/10.5194/gmd-8-1991-2015

Haeberli, W., Hallet, B., Arenson, L., Elconin, R., Humlum, O., Kääb, A., Kaufmann, V., Ladanyi, B., Matsuoka, N., Springman, S., Mühll, D.V., 2006. Permafrost creep and rock glacier dynamics. Permafrost and Periglacial Processes 17, 189–214. https://doi.org/10.1002/ppp.561

Haeberli, W., Hoelzle, M., Kääb, A., Keller, F., Vonder Mühl, D.V., Wagner, S., 1998. Ten years after drilling through the permafrostof the active rock glacier Murtèl, Eastern Swiss Alps: Answered questions and new perspectives, in: Proceedings of the 7th International Conference on Permafrost. Presented at the 7th International Conference on Permafrost, Yellowknife, Canada, pp. 403–410.

Hock, R., Rasul, G., Adler, C., Cáceres, S., Gruber, S., Hirabayashi, Y., Jackson, M., Kääb, A., Kang, S., Kutuzov, S., Milner, A., Molau, U., Morin, S., Orlove, B., Steltzer, H., 2019. High Mountain Areas, in: Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, A., Okem, A., Petzold, J., Rama, B., Weyer, N.M. (Eds.), IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

Hosmer, D.W., Lemeshow, S., 2000. Applied Logistic Regression, Second Edition. ed, Wiley Series in Probability and Statistics. John Wiley & Sons, Inc.

IPCC, 2019. Summary for Policymakers, in: Pörtner, H.-O., Roberts, D.., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, A., Okem, A., Petzold, J., Rama, B., Weyer, N.M. (Eds.), IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

Jones, D.B., Harrison, S., Anderson, K., Betts, R.A., 2018. Mountain rock glaciers contain globally significant water stores. Scientific Reports 8. https://doi.org/10.1038/s41598-018-21244-w

Kofler, C., Mair, V., Gruber, S., Todisco, M.C., Nettleton, I., Steger, S., Zebisch, M., Schneiderbauer, S., Comiti, F., 2021. When do rock glacier fronts fail? Insights from two case studies in South Tyrol (Italian Alps). Earth Surf. Process. Landforms esp.5099. https://doi.org/10.1002/esp.5099

Krainer, K., Bressan, D., Dietre, B., Haas, J.N., Hajdas, I., Lang, K., Mair, V., Nickus, U., Reidl, D., Thies, H., Tonidandel, D., 2015. A 10,300-year-old permafrost core from the active rock glacier Lazaun, southern Ötztal Alps (South Tyrol, northern Italy). Quaternary Research 83, 324–335. https://doi.org/10.1016/j.yqres.2014.12.005

Krainer, K., Mussner, L., Behm, M., Hausmann, H., 2012. Multi-disciplinary investigation of an active rock glacier in the Sella Group (Dolomites, Northern Italy). Austrian Journal of Earth Sciences 105.

Kummert, M., Delaloye, R., 2018. Mapping and quantifying sediment transfer between the front of rapidly moving rock glaciers and torrential gullies. Geomorphology 309, 60–76. https://doi.org/10.1016/j.geomorph.2018.02.021

Lugon, R., Stoffel, M., 2010. Rock-glacier dynamics and magnitude–frequency relations of debris flows in a high-elevation watershed: Ritigraben, Swiss Alps. Global and Planetary Change 73, 202–210. https://doi.org/10.1016/j.gloplacha.2010.06.004

Marcer, M., Ringsø Nielsen, S., Ribeyre, C., Kummert, M., Duvillard, P., Schoeneich, P., Bodin, X., Genuite, K., 2020. Investigating the slope failures at the Lou rock glacier front, French Alps. Permafrost and Periglac Process 31, 15–30. https://doi.org/10.1002/ppp.2035

Müller, J., Gärtner-Roer, I., Kenner, R., Thee, P., Morche, D., 2014. Sediment storage and transfer on a periglacial mountain slope (Corvatsch, Switzerland). Geomorphology 218, 35–44. https://doi.org/10.1016/j.geomorph.2013.12.002

Rouse, J.W., Haas, R.H., Schell, J.A., Deering, D.W., Harlan, J.C., 1974. Monitoring the vernal advancement and retrogradation (greenwave effect) of natural vegetation (Technical Report No. E75-10354). Texas A&M University; Remote Sensing Center, College Station, Texas.

Springman, S.M., Arenson, L.U., Yamamoto, Y., Maurer, H., Kos, A., Buchli, T., Derungs, G., 2012. Multidisciplinary investigations on three rock glaciers in the Swiss Alps: legacies and future perspectives. Geografiska Annaler: Series A, Physical Geography 94, 215–243.

Steger, S., 2017. Spatial analysis and statistical modelling of landslide susceptibility – pitfalls and solutions (Doctoral Thesis). University of Vienna, Vienna, Austria.

Wichmann, V., 2017. The Gravitational Process Path (GPP) model (v1.0) – a GIS-based simulation framework for gravitational processes. Geoscientific Model Development 10, 3309–3327. https://doi.org/10.5194/gmd-10-3309-2017

Zischg, A., Mair, V., Lang, K., 2012. PROALP - Kartierung und Monitoring von Permafrost in der Autonomen Provinz Bozen Südtirol, Italien. Presented at the INTERPRAEVENT 2012, International Research Society INTERPRAEVEN, Grenoble, France, pp. 421–432.