Distribution and kinematics of rock glaciers in the Southern Alps of New Zealand

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The Southern Alps of New Zealand is an elongated mountain range, around 800 km long and 80 km wide, crossing almost all the South Island from north-east to south-west. The climate is strongly influenced by the atmospheric perturbations coming from the West. Consequently, the glacier coverage is extensive in the Western part of the mountain range and decreases strongly towards the East, allowing the presence of rock glaciers. These landforms are widespread in the Southern Alps of New Zealand but have been only marginally studied.

In this study we inventoried and mapped the active rock glaciers of the central part of the Southern Alps using Sentinel-1 InSAR data and following the guidelines produced by the IPA Action Group Rock Glacier Inventorying and Kinematics. We used a total of 43 interferograms acquired between 2015 and 2019 with time intervals between 6 days and 2 years along with orthoimage analyses.

A total of 115 active rock glacier have been identified. However, only 33 of them can be qualified as strictly active, i.e. displaying velocities higher than 10 cm/y. The remaining landforms are considered as transitional, with velocities below 10 cm/y. Besides, hundreds of rock glaciers are relict. The mean annual air temperature at the rock glacier locations is comprised between +1.4°C and +4.3°C, with values higher for transitional landforms. This indicates a strong climatic control on rock glacier kinematics: air temperatures are too warm for allowing faster velocities. Moderate altitudes in the dryer Eastern part and humidity of the climate in the Western part, which allows low ELA, hinder the presence of rock glaciers at higher and more favorable elevations. Rock glaciers in the Southern Alps are thus in a degrading phase, which is expressed by typical morphologies such as stable fronts.

Tracking active rock glaciers in Utah with satellite-based InSAR

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Rock glaciers are a common landform in many alpine landscapes that play an important role in alpine hydrology and landscape evolution, principally through the release of seasonal meltwater and the downslope transport of coarse material. Here, we use satellite-based interferometric synthetic aperture radar (InSAR) to identify and monitor rock glaciers in the Uinta and La Sal Mountains, Utah between 2015 and 2021. Using the new framework established by the IPA Action Group community, we identified 255 active and transitional rock glaciers in the ~10,000 km^2 Uinta Mountains, and 45 active and transitional rock glaciers in the ~350 km^2 La Sal Mountains. In the Uintas we found that the rock glaciers are 10.8 ha in area on average, and located at a mean elevation of 3290 m, where mean annual air temperature is 0.12 ˚C, while in the La Sals the rock glaciers are 9.5 ha on average, and located at a mean elevation of 3150 m, where mean annual air temperature is 2.5 ˚C. The mean line-of-sight (LOS) velocities for individual rock glaciers in both mountain ranges are ~1 to 6 cm/yr. We also examined the time-dependent relationship between the motion of select rock glaciers and local climatic drivers such as temperature and precipitation. We found that rock glaciers exhibit seasonal velocity changes, presumably driven primarily by snowmelt, with motion that is more than 5 times faster during the late summer compared to the rest of the year. Our findings demonstrate the ability to use satellite InSAR to monitor rock glaciers over large areas and provide insight into the environmental factors that control their kinematics.

Repeated annual UAV-based measurement of the surface creep velocity of Leibnitzkopf rock glacier (Austrian Alps) without the use of geodetically measured ground control points (GCPs)

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The kinematic state of a rock glacier is best described by its surface velocity field. Rock glacier monitoring often includes annual measurements of the surface creep velocity. Due to time constraints and, in recent years, accessibility, in-situ geodetic measurements (total station, GNSS-based) are usually restricted to a limited number of observation points. In contrast, UAV-based rock glacier mapping allows the flow velocity field to be remotely derived, without stepping on the rock glacier's surface. Nowadays, the georeferencing of UAV-based aerial images is facilitated by measuring camera positions using RTK/PPK-GNSS techniques. However, UAV images taken with consumer-grade cameras generally require camera self-calibration during bundle block adjustment. Consequently, around 3-4 GCPs are commonly used to model systematic offsets and to eliminate strong correlations between unknowns. The present study is based on a field campaign planned for August 2021, and comparison with last year's UAV-based aerial survey of the highly active Leibnitzkopf rock glacier in the Austrian Alps. We will use a hexacopter twinFold Geo carrying a Sony Alpha ILCE-6000 and a PPK-GNSS module for data acquisition. However, this time we will not use any GCPs. Georeferencing of the 2021 UAV-based image data will be done using the PPK-GNSS-measured camera positions, and the UAV-based images from the 2020 aerial survey which have already been georeferenced. We intend to carry out a bi-temporal (2020-2021) joint bundle block adjustment, connecting both the reference and the follow-on image data using stable ground in the surroundings of the rock glacier. We are also investigating whether the 2021 image data can be georeferenced using plain co-registration and completely disregarding the 2021 PPK-GNSS-measured camera positions. The accuracy of the obtained creep velocities for 2020-2021 will be assessed using contemporary geodetic measurements. A further quality control will be to compare the digital orthophoto and digital elevation models with older ones obtained from previous aerial surveys, both conventional and UAV-based. This study emphasizes that annual (in-situ) geodetic measurements on highly active rock glaciers such as the Leibnitzkopf rock glacier can be replaced by UAV-based aerial surveys without the use of GCPs where high-quality UAV-based image reference is available.

INTERNAL STRUCTURE, DYNAMIC BEHAVIOR AND HYDROLOGICAL CHARACTERISTICS OF A ROCK GLACIER IN THE SEMIARID ANDES OF ARGENTINA

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This work aims to present the analysis of the internal structure, dynamics and hydrogeology of a large-sized, complex, multi-lobate and multi-root rock glacier located in the southwest of the San Juan province (31°52'59.75""S; 70°15'8.62""W), Central Andes of Argentina. The study was conducted combining electrical resistivity tomography (ERT), Differential Interferometry Synthetic Aperture Radar (DInSAR) and hydrochemical data. A total of 8 ERT profiles have been carried out in the El Gigante rock glacier which have been distributed to be representative for various lobes. ERT surveys shows a marked irregular geometry for the upper sector of the permafrost with electrical resistivity values ranging from 7 to 142 kΩm. This low electrical resistivity values recorded could be influenced by the high metallic concentration present in the environment, reflecting ionic enrichment to varying degrees during water circulation and subsequent re-freezing.

The horizontal displacement from October 2014 to April 2017, exhibits its greatest magnitudes in the upper sector of both tongues, reaching speeds of up to 150 cm/year. The active frontal sector shows a displacement rate of 2 to 4.5 cm/year. The analysis of 28 interferograms shows minimal seasonal and inter-annual variability for the “The Giant” rock glacier. Part of this time span corresponds to a period of extreme drought in the Andes, which directly influences the availability of water. Hydrochemical data show both the existence of different disconnected water flow pathways inside the rock glacier and the remarkable ionic concentrator effect of this landform.

This study contributes to the knowledge of the material properties of rock glaciers, which represent important reservoirs/water resources, and their influence on the distribution of mountain permafrost, hydrology and dynamics. The presence of large areas of hydrothermal alteration, such as in the Andes, constitutes an additional challenge in the interpretation of cryogenic processes and a key factor in water quality.

Keywords: Rock glacier, mountain permafrost, Central Andes, DInSAR, Geoelectrical prospecting.

Statistical prediction modelling of rock glacier distribution in Norway

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Knowledge about rock glacier activity and distribution is valuable to understand and explore the evolution of permafrost throughout the Holocene. In this study, we updated the existing rock glacier inventories of Norway by interpreting publicly available aerial photos, and by acquiring surface velocities from the free public service InSAR Norway (https://insar.ngu.no/). This updated inventory, together with suitable explanatory variables like air temperature, direct solar radiation, topographic roughness and curvature, was further used to fit a statistical prediction model to rock glacier existence in Norway. The Holocene and late-Pleistocene distribution of intact rock glaciers has subsequently been explored by adjusting the temperature in the model to climatic conditions during the Younger Dryas (YD – ca 12 ka BP; -6 °C), the Holocene thermal maximum (HTM – ca 8 ka BP; +2 °C) and the Little Ice Age (LIA ca 0.2 ka BP; -1 °C). Our model indicates that at present, intact rock glaciers exist at 300 to 400, 600 to 800, and 1300 to 1500 meters above sea level in Finnmark, Troms and southern Norway, respectively. The adjusted model runs predict that rock glaciers could have existed in 1) low-lying, coastal areas in a YD climate, 2) areas at or inside the YD ice sheet margins in an LIA climate, and 3) at high elevation continental areas during the HTM. From these results, we suggest that rock glaciers that were predicted to have existed in the YD were probably also initiated during this time period and remained active a couple of thousand years until they turned relict before or during the Preboreal or the HTM. Rock glaciers attributed to an LIA climate were probably formed after the HTM, and rock glaciers associated with an HTM climate have likely existed continuously since the YD, throughout the HTM and until today as either active or inactive landforms.

Operational monitoring of rock glacier kinematics: insights from the PERMOS network

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Rock glaciers are characteristics landforms associated with mountainous periglacial landscape and have been widely used since the mid-20th century as a visual indicator of mountain permafrost. Recently, studies have shown that the velocity of rock glaciers responds sensitively and synchronously to inter-annual and decennial changes in ground temperatures. An ongoing initiative lead together by GTM-P and the IPA Action Group on Rock Glacier Inventories and Kinematicss, intends to make rock glacier kinematics a new associated parameter within the ECV permafrost.Within the Swiss Permafrost Monitoring Network (PERMOS), rock glaciers have been operationally monitored using terrestrial geodetic surveys for more than 20 years for the longest time series. Results show a consistent regional evolution for the entire Swiss Alps: over the past decades, a general increasing trend has been observed with significant interannual variation such as the velocity peak in 2015 and the velocity decrease from 2016 to 2017. This evolution fits well with the in-situ near-surface surface temperature as well as the permafrost temperatures observed in boreholes. In this contribution, we will present the detailed results of the PERMOS monitoring sites as well as highlight some of the challenges we faced collecting and processing this outstanding dataset. Cécile Pellet Department of Geosciences, University of Fribourg Jeannette Noetzli WSL Institute for Snow and Avalanche Research SLF, Davos

An estimation of past and present air temperature conditions, water equivalent, and surface velocity of rock glaciers in Cordillera Volcanica, Peru

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Rock glaciers (RG) are one of the most important geomorphological features in the Peruvian Andes. However, the local characteristic of RG have barely been studied or remain unknown. The aim of this research was to characterize past and present conditions of the RG located in Cordillera Volcanica in the southern of Peru. For this purpose, an inventory of rock glaciers was carried out and a modern and past regional mean air annual temperature (MAAT) were calculated. We estimate the water equivalent of RG to assess their importance as possible stores of frozen water for past and present conditions using an empirical rule. In addition, the surface velocity of RG was obtained from Landsat 8 imagery. Within the study area, 200 RG were identified (8.25 km2). Of these, 101 were classified as intact and 99 as relict forms. The altitudinal distribution of RG ranges between 4252 to 5554 m a.s.l. where modern MAAT is close to a positive level (0.73°C). In the current conditions, relict RG are located in positive MAAT levels around 1.2°C, however, for the past conditions, relict RG were located in negative MAAT levels around -5°C. The amount of water stored in intact RG is between 16 and 37 km3. Meanwhile, for past conditions, we estimated that volume stored within rock relict RG was between 18 and 53 km3 (We assume an ice-rich layer of RG permafrost has between 20-45%). On the other hand, the average surface velocities of the active RG have been estimated between 2 cm/month to 16 cm/month. The finding of this research contribute to increasing knowledge about RG in the Peruvian Andes, however, further research is needed to understand the importance of RG as stores of frozen water during the past and present conditions.

Strengths and Limitations of Rock Glacier Inventories

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Rock glaciers have globally been described and monitored for many decades. Recently, the attention has increased rapidly in the scientific community, but also within the general public, related to an inferred hydrological resource. In an effort of developing widely accepted guidelines to inventory rock glaciers on a global scale, the IPA Action Group on rock glacier inventories and kinematics recently developed baseline concepts.

The development of such a guiding document is extremely valuable. In particular, the distribution of rock glaciers may allow to estimate the extent of permafrost within a mountainous region. However, it is crucial to communicate and respect limitations of such inventories. Specific caution must be applied when a rock glacier inventory is used to draw conclusions on the state of the cryosphere and hydrological resources. It must be emphasized, that rock glaciers are not glaciers, and when inventories include both types of cryoforms or when different inventories are compared with each other, conclusions may be misleading. For example, changes in glacier areas are comparatively easy to monitor. It is also known that those changes are linked to current changes in climate, such as precipitation and air temperatures. However, the rock glacier morphology dependents on other parameters, such as local geology, topography and historic climate. The insulating effect of the active layer and the lack of ice exchange significantly delays the response of a rock glacier to changes in climate. In addition, it is not possible to correlate rock glacier area with its thickness nor its ground ice volume, as both depend on multiple parameters. The outlining of a rock glacier, specifically in the upper section where the exact beginning can often not be identified, is often confusing, which results in a significant uncertainty in its area, limiting further interpretations.

Based on multiple examples, this presentation will provide an overview of the strengths and the limitations of rock glacier inventories and offers suggestions on how to communicate those.

Review of the inventory and kinematic analysis of Aosta Valley (Italy) rock glaciers

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ARPA Valle d'Aosta is conducing a general review of the regional rock glacier inventory, realized about 10 years ago. The review, based on the analysis of DEMs and more recent and detailed aerial images allowed to better delineate the contour of numerous bodies, as well as to detect several others, not identified in the first inventory. The mapped rock glaciers are more than a thousand, with planar dimensions ranging from less than 2.000 m2, up to 60.000 m2. About 50% of them are classified as active. A first evaluation about the driving factors controlling the spatial distribution and areal density of the rock glaciers was carried out. Besides aspect and elevation, a significant factor is represented by the fracturing degree of rock masses that supply the talus, frequently in close proximity to tectonic regional features, such as major faults and overthrusts. Furthermore, an analysis on a sample of intact rock glaciers has been performed, in order to identify the percentage of active rock glaciers and quantify their surface velocity. This will allow the integration of the inventory with kinematic data. This study is based on the analysis of aerial images covering a temporal range of 10 years (flights of 2005, 2012 and 2015). The horizontal ground displacements and the velocity rates of each of the selected rock glacier were computed through manual identification of well recognizable corresponding boulders in the medium-frontal part of each rock glacier. This approach shows good results for significant displacements over the whole time period. For smaller ranges, the uncertainty due to frame resolution, georeferencing and orthorectification of aerial photograms can be greater than the observed displacement.

Systematic monitoring of rock glacier kinematics from satellite SAR interferometry: insights from case studies in the European Alps and Disko Island

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Recent observations have shown that rock glaciers located near the lower limit of discontinuous permafrost move downslope with velocities between a few cm/a and several m/a. The majority of the surveyed rock glaciers, irrespective of their size and velocity, respond sensitively and almost synchronously to inter-annual and decennial ground temperature changes. Change in rock glacier motion is thus considered a suitable proxy for short- to medium-term response to environmental change and an indicator of mountain permafrost conditions in general. Satellite radar interferometry (DInSAR) has been efficiently used for the estimation of the rate of motion of rock glaciers. Previous work dealing with rock glaciers at the single-valley or the regional scale has been mainly concerned with the manual delineation of rock glacier outlines and the morphologic or InSAR-based evaluation of their degree of activity. The ESA Copernicus Sentinel-1 constellation, specifically designed for SAR interferometric applications and displacement monitoring, allowed to move from punctual surveys to a more spatially-distributed and systematic monitoring scenario.

In this contribution, we analyse the performance of Sentinel-1 InSAR time-series for the monitoring of the rate of motion of selected active rock glaciers in the Swiss and Italian Alps and over Disko Island (Greenland). The line-of-sight displacement in 6 to 48 days derived from the interferometric pairs is converted to rates of motion along the slope. Reliable displacement information can be derived for the snow-free season and in winter during stable, cold conditions. The typical annual cycle of rock glacier velocities, with higher values in autumn and lower values in spring, with reference to existing in-situ measurements, can be observed with an estimated accuracy on the order of 0.2 m/a. We conclude that Sentinel-1 DInSAR can complement in-situ data collection on rock glacier kinematics and expanding, with a degree of independence, in-situ monitoring networks.

Multi-method approach to inventorying rock glaciers and features of interest in Banff and Jasper National Parks, Alberta, Canada

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Rock glaciers are perennially frozen masses of ice and unconsolidated material that creep downslope as a result of cyclic freeze-thaw mechanisms and weight due to gravity. These features are often tongue-shaped, lobate landforms containing longitudinal or transverse flow structures, with a surface that consists of poorly sorted, angular, rock debris. Although rock glaciers are abundant geomorphological features in the alpine periglacial environments of the Rocky Mountains, their spatial distribution and characteristics are largely unknown. As rock glaciers contain frozen fresh water and can be potential geohazards, inventories are crucial in the assessment of the activity status and distribution of these landforms. This inventory will also provide an estimate on the potential cubic meters of water equivalent storage within the rock glaciers for cryospheric reserves as freshwater depletes. To date, over 800 intact (active/inactive) rock glaciers were successfully identified within the study areas, as well as over 204 features of interest requiring further validation of surface kinematics and morphometric quantification. Grid-based manual inventorying of these features was completed using high-resolution satellite imagery that is readily available through the ESRI World Imagery Base Layer, then subsequently verified manually with Google Earth Pro. This methodology proved crucial and supports the idea of both multi-temporal and multi-method approaches to the inventorying of rock glaciers and features of interest within the alpine terrains of Canada. Using a digital elevation model of 10m resolution and climate re-analysis products (ie. ClimateNA, ERA5), geomorphometric and climatic parameters will be extracted for all identified features. This multi-method approach to rock glacier inventorying and classification developed a proof of concept within the study area that verifies the applicability of this method at a regional scale. This work represents the first component of our rock glacier monitoring network within Canada, as there currently are none to date. The inventories completed with this initiative will be shared with the International Permafrost Associations Rock Glacier Inventorying Action Group.

Keywords: Rock Glacier, Inventory, Alberta, Rocky Mountains, Google Earth

Accelerating rock glacier threatens critical infrastructure

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The Pretty Rocks rock glacier in Denali National Park has the potential to disrupt transportation at the mid-point of the dead-end park road, impact the regional economy, and affect public safety. Approximately 90 m of the full width of the park road crosses the rock glacier. Impacts to the road have been experienced at Pretty Rocks since at least the 1960s and, until recently, only required maintenance every 2-3 years. The park first noticed an increasing impact to the road in 2014. Between 2016 and 2017, the road slumped up to 15 cm/month, creating a slump that steepened the road gradient and limited sight lines for drivers. Road displacement increased to approximately 5 cm/day in 2019, then to almost 9 cm/day by August, 2020. Numerous borings and their associated monitoring equipment indicate that most displacement occurs at a discrete failure plane, there is abundant massive ground ice, and temperatures are near thawing. Analysis of nearby climate monitoring sites indicated a step-wise increase in temperature of 2.4°C in mid-2013; this shifted mean annual temperatures to near or above 0°C in the area. Denali maintenance staff and contractors maintained a safe drivable surface during these years by placing up to 4,500 cubic meters of gravel to repair the road. The NPS and Federal Highways Administration are developing long-term solutions to the increasing road displacement at Pretty Rocks.

Reconstruction of rock glaciers dynamics in alpine environment, from modern to holocene timescales

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Rock glaciers are one of the most frequent cryospheric landforms in mid-latitude mountain ranges. Their dynamics strongly influence the evolution of alpine environments over short (years to decades) and long (centuries to millennia) time scales. Being conspicuous expressions of mountain permafrost [1] and important water reserves in the form of ground ice [2], rock glaciers are seen as increasingly important in the geomorphological and hydrological evolution of mountain systems in the context of climate change and deglaciation [3, 4]. Over longer time scales, rock glaciers transport rock boulders produced by headwall erosion and therefore participate in shaping mountain slopes [5]. Despite their importance, the dynamics of rock glaciers and their evolution over different timescales still need to be better constrained. In this study, we address two main questions:

1) How has the dynamics of rock glaciers changed over time?

2) What is the origin of rock glaciers and what is their influence on the evolution of alpine environments?

Addressing these two questions require a quantitative evaluation of the surface velocity field of rock glaciers by relating short and long-time scales. Accordingly, we combine methods including remote sensing, geochronology and numerical modelling of rock glacier dynamics [6], and apply this approach to the rock glacier system of the Vallon de la Route in the Combeynot massif (French Alps). Remote sensing employing image correlation document the displacement field of the rock glacier over modern time scales [7]. Over longer periods (103 to 104 years), we use cosmogenic terrestrial nuclides (TCN) dating (10Be in quartz) of rock-boulder surfaces at different positions along the central flow line of the rock glacier, from the headwall to its terminus. The 10Be exposure ages may then be translated into mean surface speeds.

Preleminary results show exposure ages ranging from 1.88 ± 0.14 to 13.10 ± 0.51 ka. They reveal a first order negative correlation between 10Be age and elevation; and a positive correlation between 10Be age and horizontal distance to the headwall. These correlations validate the hypothesis that rock boulders fall from the headwall and remain on the glacier surface as they are transported down valley. The further from the headwall (the lower in elevation) the boulder is, the older its surface exposure will be.

Prelimary results show exposure ages ranging from 1.88 ± 0.14 to 13.10 ± 0.51 ka. They reveal a first order negative correlation between 10Be age and elevation; and a positive correlation between 10Be age and horizontal distance to the headwall. These correlations validate the hypothesis that rock boulders fall from the headwall and remain on the glacier surface as they are transported down valley.

The further from the headwall (the lower in elevation) the boulder is, the older its surface exposure will be.

The use of numerical modelling of rock glaciers [6] allows us to relate the surface kinematics at different time scales with the overall aim to discuss the age; the origin of rock glaciers and how topo-climatic and geomorphological processes control their evolution in an Alpine environment. While the ages in the upper reaches of the rock glacier can be explained by modern measured speeds, those in the lower reaches are far too old, and suggest significant slowing of the rock glacier over the late Holocene.

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Remote Detection of Buried Ice Masses; Transantarctic Mountains, Antarctica

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Glacial ice can yield information on paleoclimate, paleo atmosphere, and ancient organisms. Throughout the Transantarctic Mountain Range (TAM), a minimal number of buried ice masses have been discovered which have the potential to be much older than most glaciers. An example of such is found in Ong Valley, Antarctica covered by a sublimation till that is >1.1 Ma years old, consequently making it one of the oldest known ice masses on Earth. In addition to a few known locations, no systematic effort has been made to map such ice masses in Antarctica.

We visually analyzed >8,000 high resolution satellite images covering the TAM from Victoria Land to Pensacola Mountains. The multispectral imagery has sub-meter resolution (0.32-0.5 m) which allowed for permafrost polygon detection. The satellite imagery contains bands 1-3 (Red, Green, Blue) covering a spectrum from 400 to 745nm.

On those images we inspected all land areas that were not covered by exposed ice and looked for land areas with polygonal patterned ground which is known to occur only when regolith either covers ice or the regolith is cemented by ice (ice cementation refers to the regolith that contains only interstitial ice, but no massive ice is necessarily present). Once we discovered the polygonal surface pattern the corresponding digital elevation model (REMA) was inspected.

When a massive ice body is present in a U-shaped glacial valley it forms a convex shape on the bottom of the otherwise U-shaped valley cross profile. The REMA DEM was used to determine whether the given valley floor had a convex pattern that reveals the presence of buried ice body.

Based on these analyses, we identified 28 individual field sites that all fill both the above-mentioned criteria, and thus have a strong likelihood of containing a massive buried ice body.

Rock glaciers throughout the French Alps accelerated and destabilised since 1990 as air temperatures increased

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In the past decade, the research community on alpine periglacial landforms reported several cases of increasing rock glacier displacement rates up to abnormally high values. This process is often bond with the development of surface features typical of landslide processes, as crevasses and cracks. Existing studies of this phenomenon, commonly referred as “destabilization”, have been limited to a small number of landforms and short time spans. This study aims to contribute to our understanding of rock glacier destabilization using a regional scale approach over a long period. Our methodological pillar is displacement rates evaluation based on orthophoto comparison. First, we spotted destabilizing landforms by coarsely evaluating displacement rates on all rock glacier in the French Alps since the 50s using readily available orthoimages provided by the national geographical institute. We then computed a database of orthoimages at high temporal resolution (5-10 years interval) for all destabilized rockglaciers in the region in the past seven decades, allowing to evaluate the evolution of their displacement rates in greater detail. Our analysis shows that rock glacier velocities have significantly increased since the 1990s, concurrent with the development of destabilization in 18 landforms that represent 5% of the 337 active rock glaciers. This pattern of activity correlates with rising air temperatures in the region, which suggests that a warming climate may play a role in this process. Surface crevassing shortly preludes the acceleration phase most of the times, although few landforms show “dormant” crevasses for decades before destabilization onsets. Destabilized landforms can reach displacement rates up to 25 m/y, although most common values range around 3-5 m/y. Destabilizing landforms show sliding dynamics, and this process lasts until the destabilized mass is depleted or reaches flat terrain

Novel subsurface measurement setup to investigate heat transfer processes within the debris mantle of rock glacier Murtèl (Engadine, eastern Swiss Alps)

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The summertime runoff from melting ground ice stored in debris-covered permafrost landforms is an increasingly important water resource in dry, deglaciating mountain regions. However, annual melt rates in these landforms are hardly known. Lacking quantitative process understanding on how energy flows across the surface debris mantle down to the permafrost table impedes the modelling and prediction of annual permafrost melt water availability.

Evidence from, e.g., warming-resilient rock glaciers and crushed rock railroad embankments indicates that air convection within the permeable debris mantle has a cooling effect, thus creating overcooled ground thermal conditions. We investigate heat exchange processes including air circulation and longwave radiation across the openwork debris mantle down to the permafrost table on rock glacier Murtèl. At this Swiss Permafrost Monitoring Network (PERMOS) key site, borehole temperatures down to a depth of 58 m and meteorological conditions have been measured since 1987 and 1997, respectively.

In August 2020, we instrumented natural cavities between the coarse blocks with a variety of sensors such as thermistors, hygrometers, pyrgeometers, sonic anemometers, hot-wire anemometers, and heat flux plates. This unique ‘subsurface weather station’ measures heat exchange processes within the debris mantle. We complemented the ongoing PERMOS atmospheric measurements by eddy flux, precipitation, and snow temperature measurements. In addition, a visible light and thermal infrared dual camera provides hourly images of snow cover and surface temperatures. To verify the energy balance calculations, we track the water provenance of the outflow in the rock-glacier forefield with electrical conductivity measurements and estimate the discharge from permafrost melt.

The huge amount of collected data will allow to explicitly model the energy balance within the debris mantle. While our project will provide more reliable ice-rich permafrost runoff forecasts at a yearly resolution, the gained process understanding will also contribute to improved predictions on downwasting rates of debris-covered glaciers and on the delayed response of cold rocky landforms to climate change.

Consensus-based rock glacier inventorying in the Torngat Mountains, northern Labrador

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The Torngat Mountains of northern Labrador are an Arctic Cordillera mountain range located at the southern limit of the Canadian Arctic. Fretted coastal relief and cold-maritime climate conditions promote continued existence of small mountain glaciers and widespread periglacial activity. However, apart from brief archaeological investigations and ecological monitoring, there is no baseline information on permafrost in the region. Sparse observations of periglacial landforms in the Torngat Mountains, including rock glaciers and ice-cored moraines, imply permafrost may be widespread but to date there has been no comprehensive inventory of these features. In this study, we provide preliminary results from the first feature inventory of rock glaciers in the Torngat Mountains National Park and adjacent areas of Nunavik and Nunatsiavut, northeast Canada. Feature inventorying used high-resolution imagery recently made available through ArcGIS Online. A multi-step inventorying approach was used, with initial feature identification performed by eight mappers, and quality-control and feature-grouping completed by an independent review team. A total of 932 unique features (875 after quality-control) were identified in Stage 1, but considerable disagreement existed between mappers. For example, only 100 of the 875 features were identified by four or more mappers in Stage 1. Stage 2 required mappers to independently re-evaluate all 875 unique features identified from Stage 1. The total number of features characterized as rock glaciers by one or more mappers decreased in Stage 2 (n = 760), with 546 features categorized as a rock glacier by four or more mappers. All eight mappers identified the same 167 and 115 features as rock glaciers and non-rock glaciers, respectively. Comparison against an earlier unpublished (coarse) rock glacier inventory showed general agreement but a significant underestimation in the earlier inventory of the number of probable rock glaciers present in the Torngat Mountains ecoregion.

Rock glaciers and contributing area parameters in the Front Range of Colorado

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Rock glaciers, a component of the coarse debris system, exist in many different forms which are often dependent upon talus production and topography. Rates of creep/flow also vary considerably, ranging from 1 to more than 100 cm/yr. Here, we examine the relationship among contributing area parameters (width, length, area, slope, headwall height, etc.) and rock glacier variables (width, length, area, thickness, slope, creep/flow and temperature) in the Front Range of Colorado in order to better understand formation factors and kinematics. Rock glacier width had the strongest correlation with contributing area width because of an abundance of lobate rock glaciers (r=0.78). Rock glacier area and contributing area size were also related (r=0.74) and are a function of talus production factors. Mean surface velocity appears to be better correlated with thickness (r=0.58) and length (r=0.62), rather than slope (r=0.33). Mean annual air temperature had a stronger exponential relationship with maximum velocities (r=0.76) compared to mean annual velocity (r=0.60). Front Range rock glacier velocities tend to decrease with warming, whereas a global inventory of rock glaciers indicate greater rates of deformation with warming. Given their relatively slow rates of flow (10-20 cm/yr), Front Range rock glaciers may lack sufficient ice content, experience minimal rates of shear in plastic layers, or enhanced sliding via meltwater compared to rock glaciers found in other parts of the world.