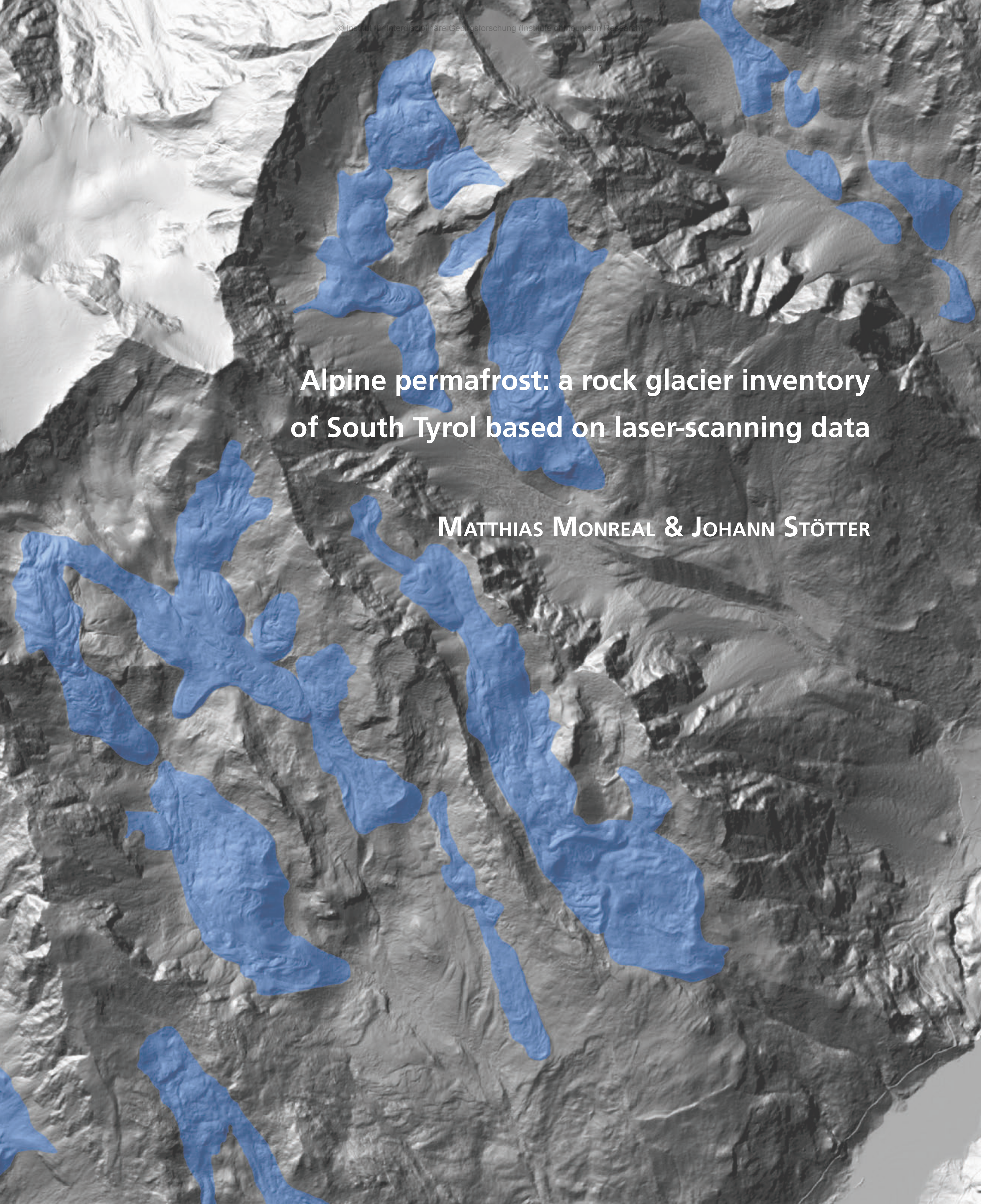

Alpine permafrost: a rock glacier inventory of South Tyrol based on laser-scanning data

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Permafrost, a periglacial phenomenon

"Permafrost is melting, the Alps are falling apart!" this or similar headlines have propelled the study of permafrost into public awareness, brought to light from its niche existence hitherto overshadowed by the more glamorous, more spectacular discipline of glaciology.

Where does this significant media hype and indeed rekindled scientific focus on a phenomenon entirely invisible to the naked eye stem from? From a sensationalist perspective, the increased potential for natural hazards as a result of melting alpine permafrost makes for a good reason. From a scientific point of view, however, permafrost is interesting for its twofold role in a warming world. While high latitude or polar permafrost is a significant driver of global warming due to the huge amounts of greenhouse gases, i.e. carbon-dioxide and methane, that are released as consequence of its thawing, the high-altitude alpine permafrost is a sensitive indicator for climate change. Furthermore, its thaw bears considerable potential for natural hazards. Wilfried Häberli from the University of Zurich was the first to make the important connection between climate change and the thawing of permafrost, following a dramatic mass movement event in the Swiss Alps in summer 1987 (Häberli et al. 1990).

But what is permafrost? It is defined as soil or rock that is permanently frozen for the duration of more than one year, with a mean annual air temperature below –1 °Celsius (see Muller 1945). Ground that fits this description makes up roughly 25% of all land surfaces with most of it situated in circumpolar regions of the northern hemisphere but also spanning large areas in the high mountain ranges at lower latitudes. The depth of the perennially frozen permafrost body varies from a few meters to approximately 1 500 meters in Siberia (see e.g. Embleton & King 1975) This ground ice cements otherwise loose sediment and fills the smallest fissures in solid rock. Besides frost weathering, the morphodynamic character of permafrost bodies is related to the so-called active layer, i.e. the upper part of three to at most four meters thickness that thaws during summer. Especially when exposed to the pull of gravity, melting permafrost can contribute to triggering serious natural hazards in the form of debris flows and rock falls.

Permafrost and natural hazards

Since alpine permafrost controls both the stability and hydrologic behaviour of rock and debris slopes, its thaw and the related loss of stability bear a significant potential for causing natural hazards by facilitating mass movement and initiating slope instability processes (Stötter 1994). Permafrost-related hazards include permafrost creep and the transportation of material into debris flow zones; thaw settlement and frost heave; debris flow from permafrost due to increased depth of active layer; destabilization of frozen debris slopes as well as rock fall and rock avalanches from frozen rock faces. Human life and settlements as well as infrastructure for high mountain tourism (huts, buildings, ski lifts, hiking trails, climbing routes, etc.) and hydropower plants (buildings, dams, reservoirs) are potentially threatened by these events (Krainer et al. 2007).

The occurrence of permafrost as such does not present a danger, but permafrost is inherently a transitory phenomenon. Given this situation, detailed knowledge of the distribution of permafrost-related slope activity on a local scale is fundamental to any statement about the potential of permafrost hazards and for developing strategies by decision makers in natural hazard management.

Mapping permafrost distribution

As expected, mapping an invisible phenomenon poses some difficulties. Defined as a thermal phenomenon and hidden beneath a seasonally freezing active layer, it cannot easily be captured directly. In addition, Alpine permafrost exhibits a high degree of spatial heterogeneity, largely driven by the complex high mountain topography but also due to the patchy thawing patterns.

Only on very rare occasions can permafrost be observed directly, mostly as a consequence of erosion processes uncovering the hidden ice.

First efforts to map the distribution of mountain permafrost in the European Alps were made more than three decades ago, much work having been pioneered in Switzerland (Barsch 1969). However, the spatially continuous distribution of permafrost in the Austrian Alps and for that matter in most areas outside Switzerland is still virtually unknown (Krainer et al. 2007).

Geophysical methods

The only controlled way of directly observing and verifying alpine permafrost is by geological means, i. e. by installing a deep borehole. Not only are boreholes notoriously difficult to install in high mountain terrain and thus cost intensive, but more importantly they are only of limited value for mapping permafrost distribution given their point sample character in complex spatial patterns.

Geophysical surveys are a step towards 2D mapping of permafrost. Various methods are employed and include seismic, radar, EM profiling and DC resistivity measurements. The strength of such geophysical methods is that they give an idea of the actual shape, size and thickness of the investigated permafrost body. They are however limited to covering relatively small areas. The only means so far by which an area-wide permafrost distribution map can be produced is through various computer modelling approaches.

Permafrost distribution modelling

Permafrost distribution models can broadly be categorized as physical models and empirical-statistical models (Etzelmüller et al. 2001). Physical models, often called process-oriented models, aim at describing the complex ground surface energy fluxes that govern the thermal regime that underlies permafrost. Such models are parameterized by a reasonable number of detailed, accurately measured, physical, geophysical and meteorological variables. In other words, a great deal of research needs to be undertaken before such physical models can be set up. This places them into the realm of process understanding and limits their feasibility for more applied mapping purposes. On the other hand, empirical-statistical models have successfully been employed for regional scale permafrost distribution mapping in the European Alps, Scandinavia, Canada and Japan. Given that only a limited number of relatively easy to obtain variables are needed for their computation, such models were "the only viable means" of mapping area-wide practical permafrost distribution (Gruber & Hölzle 2001) until recent developments of applying airborne laser-scanning technology to areas of permafrost melt. It has been shown that topo-climatic, biogeographic, geomorphological and geological proxy variables can serve as reliable indicators of permafrost. For example, models based on a set of rules of thumb developed by Häberli (1975) have successfully been employed to provide maps of probable and possible occurrences of mountain permafrost. The main underlying rationale is that permafrost occurrence may predominately be understood as a function of elevation, controlling the mean annual air temperature, and slope aspect, control-

Fig. 1: Typical lobate-shaped rock glacier. Photograph by M. Monreal.

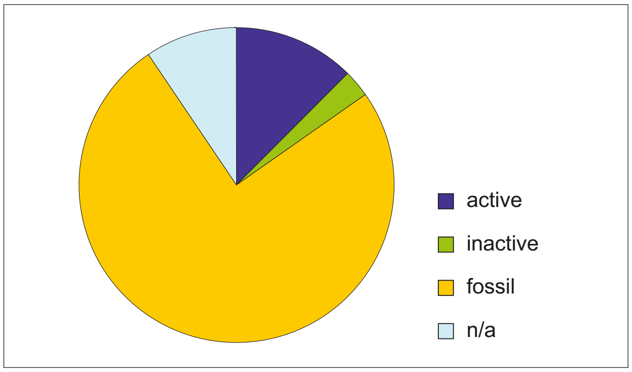

Fig. 2: State of activity of all rock glaciers in South Tyrol.

ling the incoming direct solar radiation. Thus it occurs at lower altitudes down to 2400 m in north-west facing slopes, while in southern and eastern exposition the thresholds may rise to 3000 m and more. Such indicator-based models are suitable for coarse-scale overview maps of permafrost distribution on a regional scale.

Periglacial landforms and geomorphometry

The predominant periglacial form of polar permafrost are patterned grounds, typically in the form of circles, nets or polygons of sorted stony material or pingos where ground ice is accumulated relative to the surrounding environment, resulting in hilly forms of moderate dimensions. In the context of alpine permafrost, the relationship between geomorphological surface processes and particular topographic characteristics finds its most obvious expression in rock glaciers but also in protalus ramparts, talus cones and thermokarst (Barsch 1969). Of such indicative periglacial landforms, rock glacier inventories have been widely used to indicate the distribution of permafrost and delineate lower limits of its occurrence (Lieb 1996).

The relationship between landform and the underlying process can be described in more abstract terms by geomorphometric analysis. Numerical instead of nominal description of the surface liberates this understanding from strict geomorphological classification and taxonomy. Pike (1988) states that 'the critical analytic tool is the geometric signature, a set of measures that describes topographic form well enough to distinguish among geomorphologically disparate landscapes'.

Etzelmüller et al. (2001) state that the distribution of certain periglacial landforms can be sufficiently described by relief parameters, thus allowing a prediction of the statistical likelihood of a particular process or landform in a certain topographical situation. Such relief parameters are derived from a Digital Elevation Models (DEM) and include altitude, slope, aspect, plan curvature, profile curvature, local relief, variance of altitude, skewness of altitude and distance to nearest ridge. This numerical approach has been extended by combining geomorphometric parameters with spectral information and object-oriented image classification to detect alpine landforms (Schneevoigt at al. 2008). However, despite their distinct shape and geomorphological expression, it still takes a human interpreter to identify rock glaciers in digital elevation data.

Geomorphological permafrost indicators

Amongst all periglacial landforms, the rock glacier sticks out, not only for its overall size and visual impact but also for its quality as reliable indicator of permafrost (see Fig. 1). Although all ice content lies beneath a layer of blocky rock material, its distinctive, lobate or tongue-like appearance immediately inspires glacial kinship. What looks like a doughy mass of rocks flowing downslope is indeed on the move. The ice content of a rock glacier, be it an actual ice core or ice lenses cementing the sediment, serves as the 'lubricant' upon which gravity pulls blocks and debris downslope at average surface velocities of several tens of centimetres up to five meters per year. Rock glaciers can be active, i.e. really moving downslope, inactive, i.e. no longer moving but containing ice, or fossil, i.e. the "shell" of the rock glacier in form of distinctly shaped accumulations of block material remains but without any ice.

Rock glaciers take on various distinct shapes. Most common is a lobate shape that, maybe even more so than regular ice glaciers, inspires the notion of gravitational pull and slow downslope movement. Depending on the particular terrain, rock glaciers can also take on tongue-like or spatula shapes. All rock glaciers have a root zone, the source of blocky material stemming from rock fall and making up the rock glacier. The body of the rock glacier can vary considerably in length and width, with the longest rock glacier in South Tyrol amounting to 2 974 m and the shortest to barely 26 m, the widest to 1 931 m and the narrowest to 29 m. The front of an active rock glacier can be several tens of meters high and often exhibits a slope angle of 40° and more due to the constant downward push of material. Indeed, the recent or still ongoing movement of rock glaciers gives them their striking, dynamic appearance and is obvious at first sight. However, the lack of consolidation and settling of the blocky material also makes rock glaciers an extremely uncomfortable, unstable and dangerous surface to walk across.

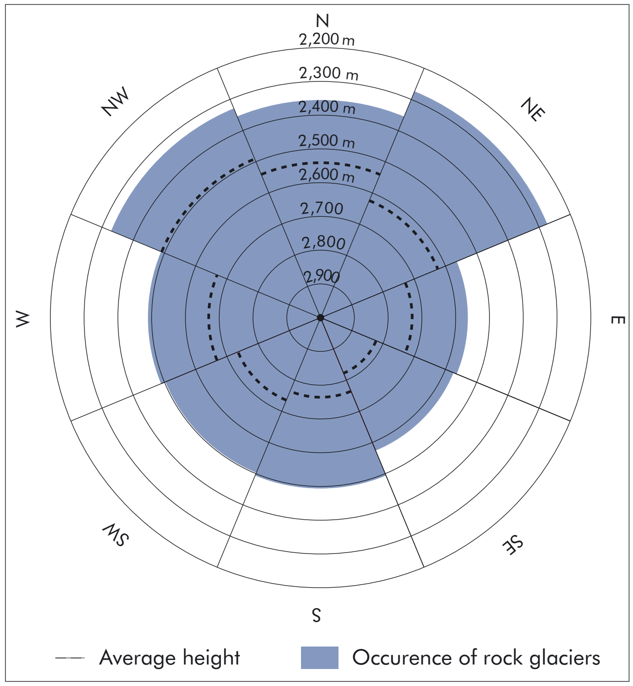

Fig. 3: Lower limit of permafrost as indicated by the occurrence of active rock glaciers reflecting the differential incoming solar radiation determined by aspect.

A rock glacier inventory in South Tyrol

As part of the project *PROALP – Kartierung und Überwachung von Permafrost-Phänomenen in den Alpen (PROALP – Mapping and Monitoring of Permafrost Phenomena in the Alps),* a comprehensive rock glacier inventory of South Tyrol has been compiled based on high resolution Airborne Laser Scanning (ALS) data (see title image). The study area comprises all areas above 2 000 m of the Autonomous Province of Bolzano, Italy, accumulating to 1 800 km². The actual mapping of the rock glaciers was carried out by combined interpretation of orthophotos, i. e. aerial photographs that have been corrected for terrain effects, and hill-shades derived from high resolution digital elevation models based on laser-scanning data (see Geist et al. 2004). Following visual interpretation, rock glaciers were manually delimitated within a GIS environment, resulting in 1 778 individual objects. Each object or polygon is further described by 25 attributes ranging from elementary metrics such as length, perimeter and area of the rock glacier, to more specific quantitative measures such as grain size, elevation, aspect and finally qualitative attributes such as shape, type and activity. The resulting database represents a fully comprehensive rock glacier inventory of South Tyrol that would not have been possible to produce in similar detail and completeness without the unique interpretation potential offered by high resolution laser scanning data.

Airborne Laser Scanning

Airborne Laser Scanning (ALS), also known as LiDAR (Light Detection and Ranging) data is captured by a sensor usually mounted on an aircraft. It offers an accuracy and precision previously only available from photogrammetrically derived DEMs. The actually achievable elevation accuracy of ALS data depends on the altitude above ground level during the measurement flight. At 1.1 km above ground, the elevation accuracy is best, reaching ±15 cm in vertical dimension and ±50 cm horizontally. To understand the quantum leap in resolution that this technology offers it helps to bear in mind that an ALS-derived DEM with a spatial resolution of 1 m is 625 times higher resolved than a conventional 25 m grid space DEM.

Image matching and feature tracking algorithms have already been developed and used for monitoring rock glacier and glacier movements using multi-temporal aerial photographs. While feature tracking based on aerial photographs is common in rock glacier analysis, image tracking using ALS data images represents a new research field that offers some advantages over conventional aerial photography. ALS data are basically very dense point data, not continuous photographic data. This implies different strategies in feature matching compared with the use of aerial photographs. Individual features will "look different" between different laser data capture campaigns as they are composed from different measurement points. However, the main advantage of the use of multi-temporal ALS data for rock glacier movement monitoring is the concept of directly comparing elevation features, not colour features.

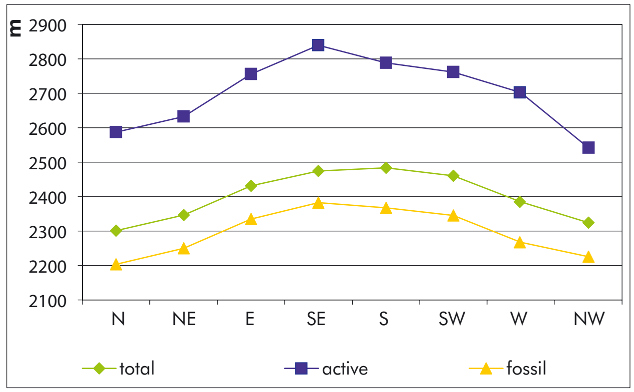

Fig. 4: Elevation distribution of active vs fossil rock glaciers reflecting impacts of global climate change.

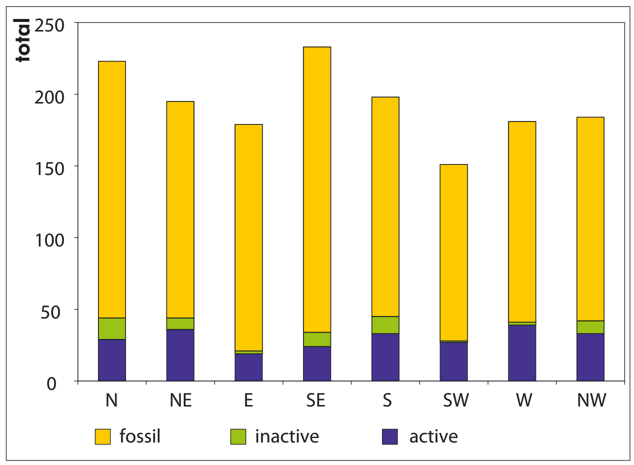

Fig. 5: Distribution of rock glacier occurrences at different states of activity by aspect.

Fundamental observations

The South Tyrolean rock glacier inventory represents the first comprehensive inventory of all rock glaciers in South Tyrol. From a total of 1 778 rock glaciers, 240 have been classified as active, 59 as inactive and 1 245 as fossil (see Fig. 2). 234 polygons have not been attributed in terms of their state of activity. The great number of fossil vis-à-vis active, moving rock glaciers illustrates the general warming trends of recent centuries. It can be inferred that many of the now fossil rock glaciers would have been active at the time of the last glacier climax around the year 1820.

A next step in the analysis of the data confirms the distribution of rock glaciers in line with the "rock glacier rose" produced for the first time by Wilfried Häberli for a rock glacier observed in the Swiss Alps. Here the distribution of rock glaciers is analysed according to their aspect and elevation. A lower average elevation in the sectors N, NW is due to the lesser amount of incoming solar radiation in these aspects (see Fig. 3). It is interesting that the general trend of elevation distribution according to aspect holds for active and fossil rock glaciers as well if analysed separately (Fig. 4). This fact further confirms a general upward trend of the lower limit of permafrost in all aspect sectors as a result of global warming trends.

Also, the fact that similar numbers of rock glaciers exist of all states of activity in all aspect sectors (Fig. 5) shows that the geomorphological processes that lead to the genesis of rock glaciers are not controlled by aspect, i.e. incoming solar radiation, per se, but only by the elevation at which these processes take place. The considerably greater number of fossil rock glaciers as compared to active ones is determined by the upper limit to the genesis of rock glaciers constituted by either glaciated terrain or rock walls close to the summit zone of the respective mountain ranges.

The proportions of 13% active, 3% inactive and 71% fossil (as well as 13% not classified) rock glaciers roughly holds for the proportional area distribution of the respective activity classes: 14.4 million km^2 active, 3.3 million km^2 inactive and 88 million km^2 (as well as 10.9 million km^2 unclassified) rock glaciers. This suggests the average size of rock glaciers have not changed significantly over time as temperatures became warmer.

Outlook

Further investigations on the regional permafrost distribution will be undertaken on the basis of this inventory. Given the comprehensiveness and accuracy of the data and keeping in mind that this is the first rock glacier inventory of its kind, it can be expected that not only regionally significant findings but also general statements on past and future development of mountain permafrost can be extrapolated.

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