Discriminating viscous creep features (rock glaciers) in mountain permafrost from debris-covered glaciers – a commented test at the Gruben and Yerba Loca sites, Swiss Alps and Chilean Andes

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Abstract. Viscous flow features in perennially frozen talus/debris called rock glaciers are being systematically inventoried as part of global climate-related monitoring of mountain permafrost. In order to avoid duplication and confusion, guidelines were developed by the International Permafrost Association for discriminating between the permafrost-related landform "rock

15 glacier" and the glacier-related landform "debris-covered glacier". In two regions covered by detailed field measurements, the corresponding data- and physics-based concepts are tested and shown to be adequate. Key physical aspects, which cause the striking morphological and dynamic difference between the two phenomena/landforms concern:

- tight mechanical coupling of the surface material to the frozen rock-ice mixture in the case of rock glaciers as contrasting with essential non-coupling of debris to glaciers they cover;

20 - talus-type advancing fronts of rock glaciers exposing fresh debris material from inside the moving frozen bodies as opposed to massive surface ice exposed by advancing fronts of debris-covered glaciers; and

- increasing creep rates and continued advance of rock glaciers as convex landforms with structured surfaces versus predominant slowing down and disintegration of debris-covered glaciers as concave landforms with primarily chaotic surface structure.

25 Where debris-covered surface ice is, or has recently been, in contact with thermally-controlled subsurface ice in permafrost, complex conditions and interactions can develop morphologies beyond simple "either-or"-type landform classification. In such cases, remains of buried surface ice mostly tend to be smaller than the lower size limit of "glaciers" as applied in glacier inventories, and to be far thinner than the permafrost in which they are embedded.

1 Introduction

30   Application of modern technologies enables climate-related science and long-term monitoring of mountain permafrost on Earth to evolve in a rapid, fascinating and important way. Absolute age determination using radiocarbon, luminescence or exposure dating (e.g., Haeberli et al., 2003; Fuchs et al., 2013; Krainer et al., 2015; Nesje et al., 2021; Amschwand et al., 2021) document the multi-millennial, typically Holocene time scale related to the often-spectacular landforms usually called "rock glaciers", which reflect cumulative deformation through slow viscous creep of perennially frozen talus/debris rich in ice

35   (Wahrhaftig and Cox, 1959; Haeberli, 1985; Barsch, 1996; Haeberli et al., 2006, Berthling, 2011; Kääb, 2013). Sophisticated borehole observations and laboratory experiments together with results from high-precision geodetic-photogrammetric and interferometric measurements (e.g., Arenson et al., 2002; Roer et al., 2008; Springman et al., 2013; Cicoira et al., 2021; Kääb et al., 2021; Kaufmann et al., 2021; Cusicanqui et al., 2021; Noetzli et al., 2021; Thibert and Bodin, 2022; Fleischer et al., 2023) provide detailed and crucial quantitative information about the corresponding flow mechanisms and flow fields with

40   remarkable indications of recent warming-related flow acceleration.

        Increasing creep rates of rock glacier permafrost can be attributed to permafrost warming down to tens of meters below surface as systematically measured in boreholes (Harris et al., 2009; Etzelmüller et al., 2020; Hoelzle et al., 2022). Warming-induced reduction in strength of subsurface frozen materials parallels increasing amounts of unfrozen water as reflected by repeat geophysics (Mollaret et al., 2019; Buckel et al., 2023), a phenomenon and long-term climate impact which

45   also affects the stability of perennially frozen rock walls (Davies et al., 2001; Gruber and Haeberli, 2007; Krautblatter et al., 2013; Mamot et al., 2021; Shugar et al., 2021). In striking contrast to enhanced creep rates in rock glacier permafrost, flow dynamics in lower parts of debris-covered glaciers are decreasing as a consequence of stronger thinning in their upper boundary zone with related reduction of driving stresses (Clayton, 1964; Anderson et al., 2021) and of continued warming-induced ice loss.

50   In its responsibility for the Global Terrestrial Network for Permafrost (GTN-P) as part of the Global Climate Observing System (GCOS), the International Permafrost Association (IPA) undertakes focused efforts via an Action Group (Rock Glacier Inventories and Kinematics; RGIK/IPA, 2022a, 2022b) to internationally coordinate the development and compilation of rock glacier inventories and the long-term monitoring of rock glacier kinematics (https://www.unifr.ch/geo/geomorphology/en/research/ipa-action-group-rock-glacier/). This action group consisting of

55   numerous experts from around the world develops, through consensus, technical guidelines including recommendations on how to discriminate the landform "rock glacier" as expression of viscous creep in perennially frozen subsurface materials (Haeberli et al., 2006; Cicoira et al., 2021; Arenson et al., 2021) from debris-covered glaciers with their surface ice monitored as part of the Global Terrestrial Network for Glaciers (GTN-G). An objective way of differentiating corresponding landforms and kinematics is essential in creating clarity when utilizing such landforms to assess where and how climate change impacts

60   our planet, specifically the cryosphere, or when used in a regulatory/legal context, for example in view of hydrological significance; or generally, to avoid confusion and duplication. The present note attempts at testing the proposed technical

recommendations/guidelines and at commenting on them using two practical examples: i) the Gruben site in the Swiss Alps (Figure 1) and ii) the Yerba Loca Valley in the Chilean Andes (Figure 5). At the Gruben site, detailed and comprehensive field investigations of permafrost, glaciers and complex contacts between the two have been carried out for more than half a century

65 in connection with hazardous lakes and flood-protection work (see for details Haeberli et al., 2001; Gärtner-Roer et al., 2022; Wee et al., 2022). While less information exists for the Yerba Loca Valley, it is a valuable site for which some data is available, and it helps demonstrating that similar conditions exist in different mountain ranges.

2 Rock glacier and cold debris-covered glacier at the Gruben site

The continuously advancing *Gruben rock glacier* (Figure 1) with its strikingly coherent flow field is a convex landform

70 exhibiting a regular surface pattern of ridges and furrows – here lengthwise following the predominantly extending flow –, and has over-steepened talus-like fronts and margins continuously exposing fresh material from the interior parts of the moving body. It neither exhibits ice cliffs, nor surface streams, visible crevasses exposing ice or thermokarst/surface lakes as it would be characteristic for debris-covered glaciers. Older, as well as recent geophysical soundings document permafrost tens of meters deep (Figure 2; cf. supplement) and still thermally active in that winter freezing reaches down through the active layer

75 to the top of the permafrost (cf. ongoing GST-measurements reported by Gärtner-Roer et al., 2022). As a consequence of global warming, however, ground temperatures are currently in strong thermal imbalance, with only slightly negative near-surface temperatures and a near-zero vertical geothermal gradient/heat flow at depth as it appears to be characteristic for present-day mountain permafrost (Haeberli, 1985, cf. Etzelmüller et al., 2020). These geothermal conditions have been confirmed for many permafrost sites in the Swiss Alps (Mollaret et al., 2019; Phillips et al., 2020; PERMOS, 2022) and are

80 indicative of the degrading state of permafrost at this site causing characteristic rates of surface subsidence (thaw strain / settlement) in the range of centimeters per year. Due to the slow process of heat diffusion with latent heat exchange at depth, complete thawing of the ice-rich rock glacier permafrost would most likely need centuries if not millennia (cf. early calculations reported by Haeberli, 1985).

In strong contrast, the continuously slowing-down and decaying debris-covered cold tongue of *Gruben glacier*

85 (Figure 1) with its progressive loss of coherent flow is a concave landform with a chaotic rather than regular surface pattern, with diffuse and hardly recognizable frontal and lateral margins but with, in places, local ice cliffs, visible crevasses exposing ice and thermokarst/surface lakes. Detailed long-term measurements of horizontal and vertical surface displacements (Gärtner-Roer et al., 2022) for the past decades document characteristic subsidence rates in the range of tens of centimeters per year due to ice melting. From earlier measured radio-echo soundings (Haeberli and Fisch, 1984) and borehole temperatures (Haeberli,

90 1976), the remaining ice underneath its debris cover can be estimated to be about -1 to -2°C cold and its present-day thickness to decrease from a maximum of about 20 m at the upper end of continuous debris cover to zero at the diffuse margins close to Lake 1 (Figure 2). Complete vanishing of the presently existing remains of the glacier tongue is most likely a matter of a few

decades. Subglacial permafrost may presently penetrate into the thick sediment bed (Haeberli and Fisch, 1984) underneath the rapidly thinning and vanishing cold glacier remains.

95   The differences are obvious, and the morphological criteria proposed by the IPA action group are adequate: The subsurface ice contained in the striking viscous creep feature of *Gruben rock glacier* is a permafrost (periglacial) phenomenon and as such part of global permafrost monitoring. The increasingly indistinctive feature of the down-wasting debris-covered *Gruben glacier* tongue is a (glacial) phenomenon of surface ice and as such part of global glacier monitoring. Comparison between the measured kinematics of the two features at this site documents strikingly different characteristics and dynamics

100   of the two domains under conditions of global warming and highlights the importance of separating these two different features when developing inventories. The situation is clear and the differentiated treatment of the two phenomena within the framework of internationally coordinated global climate observation perfectly appropriate. Comments are, however, needed concerning two special aspects:

- complex contact zones between debris-covered surface ice and thermally controlled subsurface ice; and

105   - the sometimes still maintained idea that covering of surface ice by debris alone can produce striking viscous flow features called "rock glaciers".

3 Complex zones with contacts between surface and subsurface ice

Where mean annual air temperatures are, or have until recently been, below zero centigrade, various types of surface ice - especially cold perennial snow fields or ice patches, glacierets and mostly small, cold to polythermal glaciers - can be in contact

110   with thermally controlled, creeping ice-rich mountain permafrost, contributing debris and in cases remains of buried ice to deeply frozen materials. This had already been recognized by Wahrhaftig and Cox (1959), Fisch et al. (1978), Haeberli (1985) or Barsch (1996) and in the meantime became the subject of intense and detailed quantitative investigations by various authors (cf., for instance, Kneisel and Kääb, 2006; Bosson and Lambiel, 2016; Monnier and Kinnard, 2017; Bolch et al., 2020; Falatkova et al., 2020; Kunz et al., 2021; Vivero et al., 2021; Wee and Delaloye, 2022; Wee et al., 2022). At the Gruben site,

115   a former contact zone exists between the polythermal Gruben glacier during its maximum LIA/Holocene advances and the permafrost of the Gruben rock glacier (Figure 1; cf., Kääb et al., 1997; Gärtner-Roer et al., 2022). Contacts and interactions between glaciers and rock glaciers can give rise to a diverse range of landforms, exhibiting a wide spectrum of characteristics. These landforms encompass structured surface morphology, such as glacitectonics or back-creep, which can either align with or oppose the original stress exerted by the advancing glacier. They can also encompass diffuse and often chaotic topography

120   with thermokarst features in degrading or aggrading permafrost. Furthermore, the local surface coarseness can be smoothed due to the deposition of fine-grained sediments (Wee and Delaloye, 2022; Kneisel and Kääb, 2007).

Such complex and highly variable landforms can mostly not be attributed in a straightforward "either-or" scheme to the terms "rock glacier" or "debris-covered glacier" but constitute what could better be called "complex contact zones of (viscous creep in ice-rich) permafrost with remains of buried surface ice". Various forms of surface ice must thereby be treated

125   in a differentiated way – not every piece of surface ice is a "glacier". A number of potentially interconnected effects and processes can take place as related to loading/unloading, reorientation of stress and flow fields, intermittent burial of surface ice in frozen debris with, in cases, thermokarst development due to its warming-induced vanishing, penetration of permafrost into previously unfrozen parts of now exposed glacier beds, etc. Understanding the full spatiotemporal complexity of relations and interactions and heat fluxes between surface and ground ice in such areas by far exceeds possibilities of intuitive/simplistic

130   landform interpretation from visual or remotely-sensed surface inspection alone. Combinations of sophisticated quantitative measurements are needed, especially geophysical soundings, geotechnical drillings with undisturbed core extraction and geodetic measurements, in order to define subsurface physical conditions (thermal, hydrological and mechanical; stress conditions), material properties and characteristics (especially ice content, unfrozen water, cohesion and internal friction) and related physical processes (creep, shearing, cumulative long-term deformation, infiltration/advection, latent heat exchange)

135   with their changes in time.

       Neither the term "rock glacier" nor the term "debris-covered glacier" would be appropriate for such complex contact zones with their characteristically diffuse landforms. A practicable approach for internationally coordinated inventory work to deal with such overlapping/combined contact zones still needs development. An important if not decisive aspect may thereby be that remains of surface ice buried in permafrost are – as the Gruben and Yerba examples document – mostly smaller than

140   the lower size limit applied to the term "glacier" in glacier inventories and much thinner than related permafrost depths (cf. also the Kintole conditions documented in Haeberli, 1985).

4 Debris-covered glaciers remain debris-covered glaciers

Few authors continue postulating that the burial of massive surface ice alone, i.e., in the absence of long-term freezing at depth, can produce rock glaciers (Anderson et al., 2018) or even that rock glaciers are nothing else than debris-covered LIA glaciers

145   (Whalley, 2020, 2023). Such concepts primarily stem from the side of intuitive landform interpretation as it had been more common before the development of readily available measurement techniques that allowed data- and physics-based approaches for quantitative research on mountain glaciers and permafrost (cf. the literature overview provided by Janke and Bolch, 2022). They were never supported by results from adequate, quantitative field measurements about subsurface thermal or ice conditions with their fundamental effects on geophysical/geotechnical properties, and essentially remained entirely speculative

150   beliefs. A never discussed implication of these beliefs is the rather astonishing, tacit assumption that debris-covered glaciers have two options of possible developments:

      (a)   they can remain *debris-covered glaciers* with predominantly chaotic surface structure, slowing down their flow, and decaying/disintegrating under conditions of global warming as increasingly concave landforms with diffuse margins; or

155   (b)   they can become *rock glaciers* by maintaining or even accelerating their flow and advance under conditions of atmospheric temperature rise, adopting a coherent flow pattern of their surface debris and becoming convex landforms

with strikingly lavastream-like "organized" surface structures and over-steepened talus-type margins/fronts continuously exposing fresh debris (instead of massive ice) from their inner parts.

Option (a) is documented in a rich, quantitative scientific literature (e.g., Iwata et al., 1980; Anderson and Anderson, 2018;
160   Mölg et al., 2020; Shokory and Lane, 2023) and needs no further discussion. Version (b), on the other hand, has never been safely documented in nature by any adequate subsurface prospection and is even in full contradiction with the wealth of quantitative information available from decade-long sophisticated measurements all over the world (cf., the community comments in The Cryosphere related to Whalley, 2023). Nevertheless, it is useful to understand the reason why this is the case, and what the physical causes are for the striking differences in appearance and dynamic evolution of rock glaciers and debris-
165   covered glaciers. Could perhaps permafrost and cold ice conditions constitute a possibility for debris-covered glaciers to "learn" how to turn into something so strikingly different from what they are initially?

Debris covers on both, rock glaciers and glaciers, are usually predominantly coarse-grained. Frost-susceptible, fine material tends to be washed out and/or to accumulate at the bottom of the debris cover/permafrost active layer. In addition, the source zones of the debris, which are typically steeper rock faces, favour the generation of coarse material. Excess ice formation
170   inducing cohesion and reduced internal friction can therefore not take place throughout coarse-grained surface layers. As a consequence, material properties of the debris cover themselves can hardly make a decisive difference. The key for understanding the striking difference between the involved processes and structures relates to the formation of the ice-debris combination and the corresponding mechanical and thermal coupling between the surface layer of debris and the moving mass underneath (Figure 3). While freezing processes induce the formation of ice inside the rock material and, hence, induce a
175   tightly interconnected mixture of ice and rock particles, largely pure surface ice in debris-covered glaciers or ice patches forms first, and rock components covering it are added independently in a second step as a fundamentally different process and without any tight connection to the ice.

5 The key role of ice-debris coupling …

On *rock glaciers*, the rock components in the lower part of the "cover", which includes the thermally defined active layer,
180   reach down beyond the permafrost table and are firmly frozen within the creeping mass. Unless the permafrost is in an advanced state of degradation, mean annual temperatures just below the permafrost table are substantially colder than zero centigrade, adding to the strength of this mixed rock-ice layer. The coherent movement pattern of the perennially frozen mass at depth with its excess ice in fine material, strong cohesion and reduced internal friction is thereby directly transmitted to the rock components of the active layer. Components of the upper active layer, which may intermittently reach positive
185   temperatures during summertime, are firmly interlocked with the deeper, frozen-in components and, hence, directly coupled with the creep movement of the frozen body underneath. This effect is especially strong in zones of compressing flow, which generally occurs in lower and flatter reaches of rock glaciers, causing buckle folding and the creation of characteristic arcuate transverse ridges and furrows (Frehner et al., 2015). Where movement speeds increase along the flow direction, especially in

steep root zones of rock glacier flow, extending flow with tensile stresses weakens the interlocking effect between rock
190   components at the surface, thereby often making surface structures somewhat diffuse or producing longitudinal rather than
transverse ridge-and-furrow structures. The decisive fact related to the striking viscous appearance of rock glaciers is the large-
scale stress coupling which is transferred from the cohesive creep of the thick perennially frozen body at depth to the partially
frozen-in and interlocked surface layer.

Components of the debris cover resting on the surface of *massive ice* have hardly any contact with the rare major rock
195   components inside the ice underneath. They are, therefore, not directly coupled with the movement of the ice underneath but
typically remain freely mobile at the ice-debris interface (Figure 3). Relative displacements of individual components at
smallest spatial scales are easily possible and tend to follow spatially variable, local melt patterns of the underlying ice (cf.,
Alean et al., 2020), which are further impacted by water flow patterns that develop at the surface of the ice, and thermokarst
(cryokarst) processes leading to the collapse of the overlying ice (and debris) layers (Thompson et al., 2016; Mölg et al., 2020).
200   Rather than coherent flow patterns, the debris cover on glaciers or on other buried massive ice tends to develop chaotic surface
structures following small-scale features of ground ice melt. The mostly chaotic surface structure of debris-covered glaciers is
due to the non-transmission of large-scale stress-coupling from the massive ice body at depth to its loose and unconstrained
debris cover. This also applies to cold or polythermal ice conditions such as they exist at the Gruben site (cf. also Miles et al.,
2018 for Khumbu glacier), because the thickness of the debris layer on glaciers (typically decimeters) is mostly much smaller
205   than that of the thermally controlled active layer (typically meters) in the permafrost of rock glaciers. With other words: debris-
covered glaciers have no choice – they remain debris-covered glaciers.

6 … as visible at advancing fronts …

A key element for understanding and recognizing the differences between creeping frozen debris and glaciers covered by
debris is the morphology of over-steepened, advancing fronts (Figure 4).
210   Advancing fronts of creeping perennially frozen debris are presently widespread under conditions of atmospheric
temperature rise and related permafrost warming/softening with resulting creep acceleration. Ongoing movements create their
characteristic talus-like morphology with freshly exposed debris from inside the creeping mass in their over-steepened upper
parts (cf., the detailed analyses by Wahrhaftig and Cox, 1959; Kääb and Reichmuth, 2005; Kummert et al., 2021). Direct
exposures of frozen materials are only observed in connection with extraordinary erosional processes such as detachment slides
215   (Haeberli and Vonder Mühll, 1996; Arenson and Jakob, 2015) or extreme fluvial erosion (Elconin and LaChapelle, 1997).

Advancing debris-covered glaciers have become exceptional under conditions of atmospheric temperature rise and
predominating glacier shrinkage. In such increasingly rare cases, massive ice of the flowing glacier is usually visible at near-
vertical fronts where debris cannot accumulate (Figure 4). Massive ice is also often visible at terminal margins of shrinking
debris-covered glaciers.

220   The advantages of adequately interpreting over-steepened fronts of creeping frozen talus/debris can be illustrated with an example from the Andes of Chile (Yerba Loca Valley; cf. Marangunic et al., 2022). Numerous typical advancing fronts (yellow arrows in Figure 5) document active creep behavior of perennially frozen talus as confirmed by animations using recent aerial lidar scans (cf., supplement). Near points 4 and 5 in Figure 5, at an elevation of about 4150 m, a mean annual air temperature of -4.4°C was measured in 2014 and -2.5°C at 0.4 m depth (in the active layer). These temperatures are significantly colder

225   than at Gruben. Occurrences of buried massive ice with thermokarst ponds are documented by visual observations and core drilling (Ugalde et al., 2018). The landforms 1, 2 and 3 can clearly be defined to be "rock glaciers", while the large debris mass marked with the numbers 4 and 5 neither shows clear characteristics of the landform "rock glacier" nor of the landform "debris-covered glacier". Here, thermokarst ponds develop in remains of massive surface ice from perennial ice patches/avalanche cones and small glacierets on top of creeping and hydraulically impermeable, perennially frozen materials in deep-reaching

230   permafrost. Three primary conclusions can be drawn from this example:

- Complex or doubtful landforms with combinations of surface ice and frozen ground represent conditions in nature that vary beyond limits of "either-or"-type landform categorization.
- Definition and measurement of material properties, ground thermal regimes and physical processes can provide more differentiated insights than applying simple landform schemes.

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- Creep phenomena in mountain permafrost are more widespread than the occurrence of specific rock glacier landforms.

7 … and its effects on ice loss as a response to long-term warming trends

Ice melting and ground thawing processes are again fundamentally different in thermally controlled permafrost as compared to debris-covered massive ice (Figure 3; cf. Haeberli and Vonder Mühll, 1996). As a response to surface warming caused by

240   changes in time of atmospheric conditions, by creeping out of shadows towards warmer areas in the sun and/or at lower altitudes, or by a combination of both, active layer thickness on rock glacier permafrost increases and thereby adjusts to (near-) equilibrium conditions (e.g. long-term measurement series as reported by PERMOS, 2023). Thawing into the *perennially frozen ice-rock mixture* underneath sets free the necessary debris for active-layer thickening. Thaw settlement primarily results from melting of excess-ice within the frozen debris, i.e., the ice occupying space within the frozen subsurface matter that

245   exceeds the naturally available pore space, while melting of ice within its pore space alone would not lead to settlement. This process coupling is among the principal reasons for the remarkably low subsidence rates typically observed during recent decades on rock glacier permafrost (Fey and Krainer, 2018; Vivero et al., 2021; Gärtner-Roer et al., 2022). Latent heat effects (energy required to melt ice), together with the increasing thermal protection of permafrost as active layer thickness increases, make the response to climate change through degradation of ice-rich permafrost extremely slow. Further, a thickening of the

250   coarse active layer allows increased air flow and with that additional cooling through air convection (Wicky and Hauck, 2020).

The debris cover on *glaciers or buried massive ice* tends to be much thinner than the active layer on permafrost (Figure 4, cf. McCarthy et al., 2022), providing much smaller insulation capacity and potential for cooling effects by air convection. Most importantly, however, it can generally not significantly increase in thickness as a consequence of ice melting alone, because no significant mass of debris is provided from the vanishing of the underlaying massive ice. Assuming 0.1%

255 average debris content inside the ice as an upper-end value based on Bozhinskiy et al. (1986), Nakawo et al. (1986), Kirkbride and Deline (2013), Miles et al. (2021) or Anderson et al. (2021), the melting of a 100m column of ice would result in a thickening of surface debris by only 10cm. Continued warming therefore unavoidably leads to marked thermal imbalance and irreversible ice melting with enhanced surface subsidence until complete vanishing of the covered massive ice. The melting of ice thereby has a heterogenous spatial pattern as it directly responds to the highly variable thickness of the debris cover with

260 its spatially heterogenous sources from rock falls, debris flows or various local displacements, furthered through ice melting caused by thermal and mechanical erosion through water flow at the ice surface (Iwata et al., 1980; Moelg et al., 2020). This is in strong contrast with the thermally controlled active layer of rock glacier permafrost, which responds to climatic conditions in a much more homogeneous way. As a logical consequence, for which more measured evidence is still needed, bodies of massive ice buried in rock glacier permafrost are expected to disappear more quickly in response to warming surface conditions

265 than surrounding frozen debris which can continue to exist over extended time periods (centuries, millennia). This may be the primary reason why such massive buried ice seems to primarily occur, if at all, in upper reaches of presently existing rock glaciers (Haeberli and Vonder Mühll 1996; cf. Bosson and Lambiel, 2016) and hardly ever appears at advancing fronts.

The here-described material-process coupling causes the striking difference in the response of rock glaciers and debris-covered glaciers to ongoing atmospheric warming trends. It constitutes another reason why debris-covered glaciers have

270 no choice – they can be in contact with creeping frozen materials but cannot, by themselves, become rock glaciers. They remain debris-covered glaciers even under permafrost conditions with cold or polythermal ice, and can quite easily and safely be discriminated from the remarkable viscous creep features usually called rock glaciers. The technical guidelines developed by RGIK/IPA (2022a, 2022b) rightly state that confusion between the two phenomena must be avoided. This is of particular importance when assessing and projecting how different components of the cryosphere respond to climate change and in the

275 context of their hydrological role within a watershed.

8 Summary and recommendation

The rich available quantitative knowledge basis from borehole and geophysical data in combination with advanced material-/process-related understanding enables safe and straightforward discrimination between rock glaciers as viscous creep phenomena in ice-rich mountain permafrost and debris-covered glaciers. The corresponding strategies recommended by

280 experts of the International Permafrost Association are clear and easy to follow. The treatment within internationally coordinated global climate observation of thermally controlled subsurface ice in rock glaciers as part of the Terrestrial Network for Permafrost (GTN-P) and of surface ice in debris-covered glaciers as part of the Terrestrial Network for Glaciers (GTN-G)

is fully appropriate and such a differentiation shall be followed into the future. Complex contact zones of surface ice (mostly perennial snow and ice patches, glacierets or small glaciers) with creep phenomena in ice-rich permafrost in cases constitute diffuse landforms beyond "either-or"- type landform classification. Investigating the thereby involved materials and processes with their interactions is a challenging research field beyond simplistic landform attribution.

The key physical phenomenon relates to the fundamentally different distribution of ice and debris: subsurface frozen ice-rock mixtures in rock glaciers versus massive surface ice with debris on top in debris-covered glaciers. The related mechanical coupling between the moving body at depth and the surface layer of debris is tight in the case of perennially frozen rock glaciers but virtually inexistent in the case of surface ice with a debris cover. The strikingly different morphologies of advancing fronts of rock glaciers and of debris-covered glaciers result from this difference and are in most cases easily recognizable. The difference in ice-debris distribution also explains the extreme contrast in reactions to global warming: Slow thaw subsidence, increasing creep rates and continued advance in the case of warmed-up and softened frozen debris/talus in rock glaciers versus down-wasting, slowing down and disintegration/collapse/vanishing of debris-covered glaciers.

Data availability: Results from ongoing field measurements carried out by JW at the Gruben site are planned to soon be published in detail.

Team list and author contribution: WH and LA developed the original concept and prepared a first draft. JW and CH provided information about the most recent field campaign at the Gruben site. All co-authors, including NM, were actively involved in the discussion and in the preparation of the submitted version.

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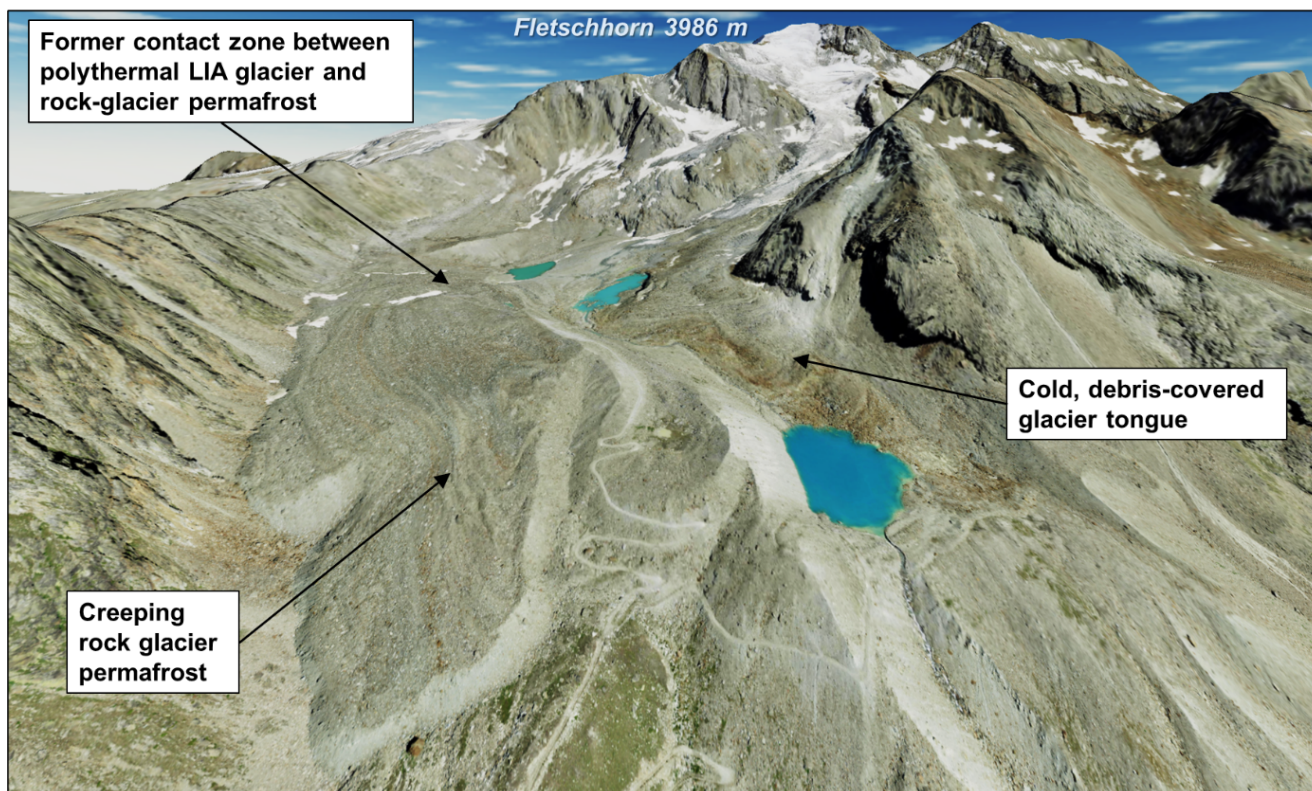


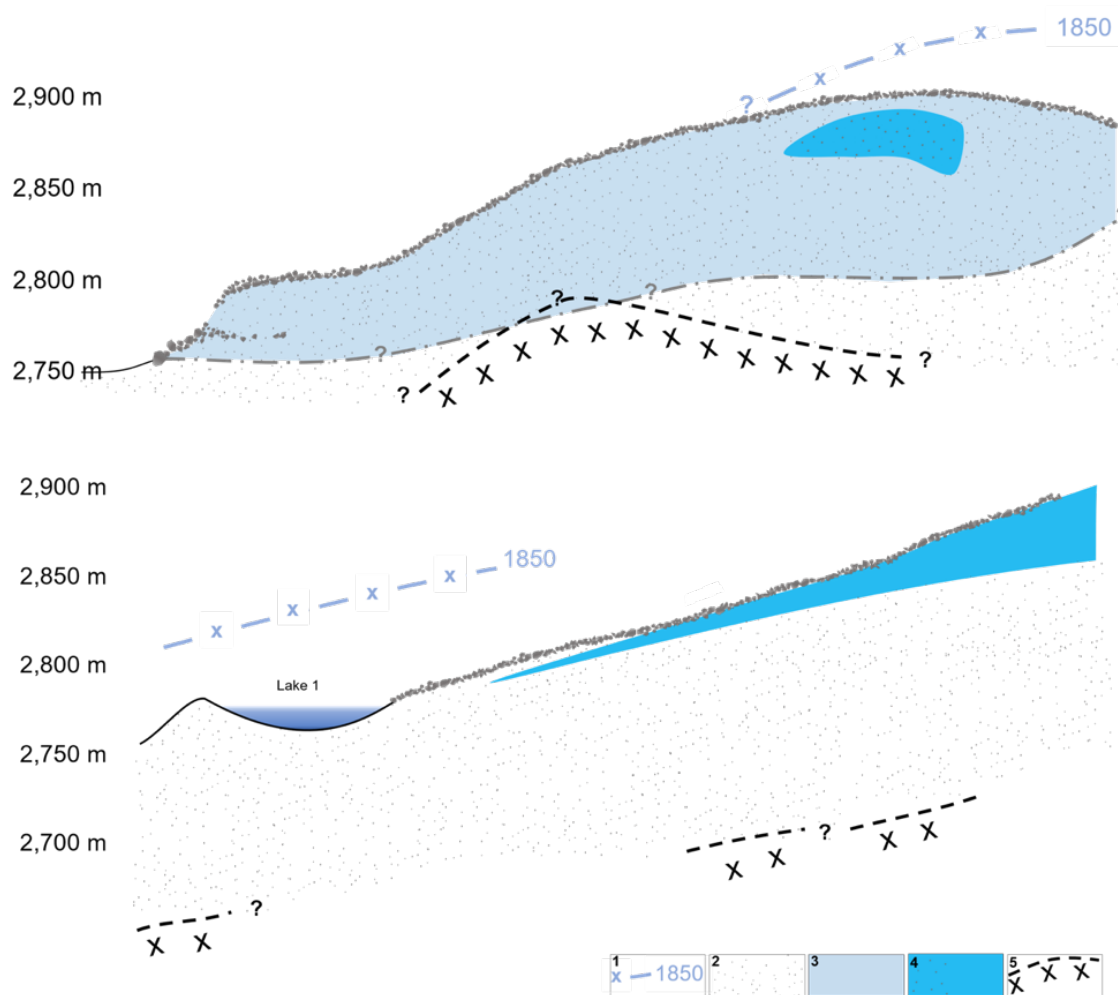
Figure 1: Continued viscous creep of perennially frozen debris, rich in ground ice at Gruben rock glacier (left), decaying debris-covered, cold tongue of Gruben glacier (right), and former contact zone (center) between the polythermal Little Ice Age (LIA) glacier and the creeping permafrost of the Gruben rock glacier. World Imagery available from Global Mapper V23.1; recent, but exact date unknown.

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Figure 2: Schematic longitudinal profile through the Gruben rock glacier (top) and the cold debris-covered tongue of Gruben glacier (bottom) based on extensive geophysical prospection (electrical resistivity, seismic refraction, radio-echo-sounding as compiled by Haeberli et al., 2001; Gärtner-Roer et al., 2022; and on recent soundings by Wee et al., 2022). The upper part of the rock glacier presentation reflects the complex contact zone between the polythermal LIA Gruben glacier and the rock glacier permafrost (Kääb et al., 1997); flow direction in this zone is not parallel to the profile but somewhat towards the viewer, leading to the orographic right LIA moraine of Gruben glacier rather than to the advancing rock glacier front. Quantitative information about the debris-covered part of Gruben glacier is from a combination of earlier glacier-bed resistivity and radio echo soundings (Haeberli and Fisch, 1984) with measurements of long-term changes in surface elevation as reported by Gärtner-Roer et al. (2022). Vertical exaggeration is by a factor of 2. Legend: (1) maximum Little Ice Age extent of Gruben glacier; (2) talus, debris; (3) permafrost conditions; (4) buried massive ice of uncertain origin (Gruben rock glacier) and glacier ice (debris-covered part of Gruben glacier); and (5) bedrock after unpublished seismic refraction (Gruben rock glacier) and glacier-bed resistivity soundings (Gruben glacier).
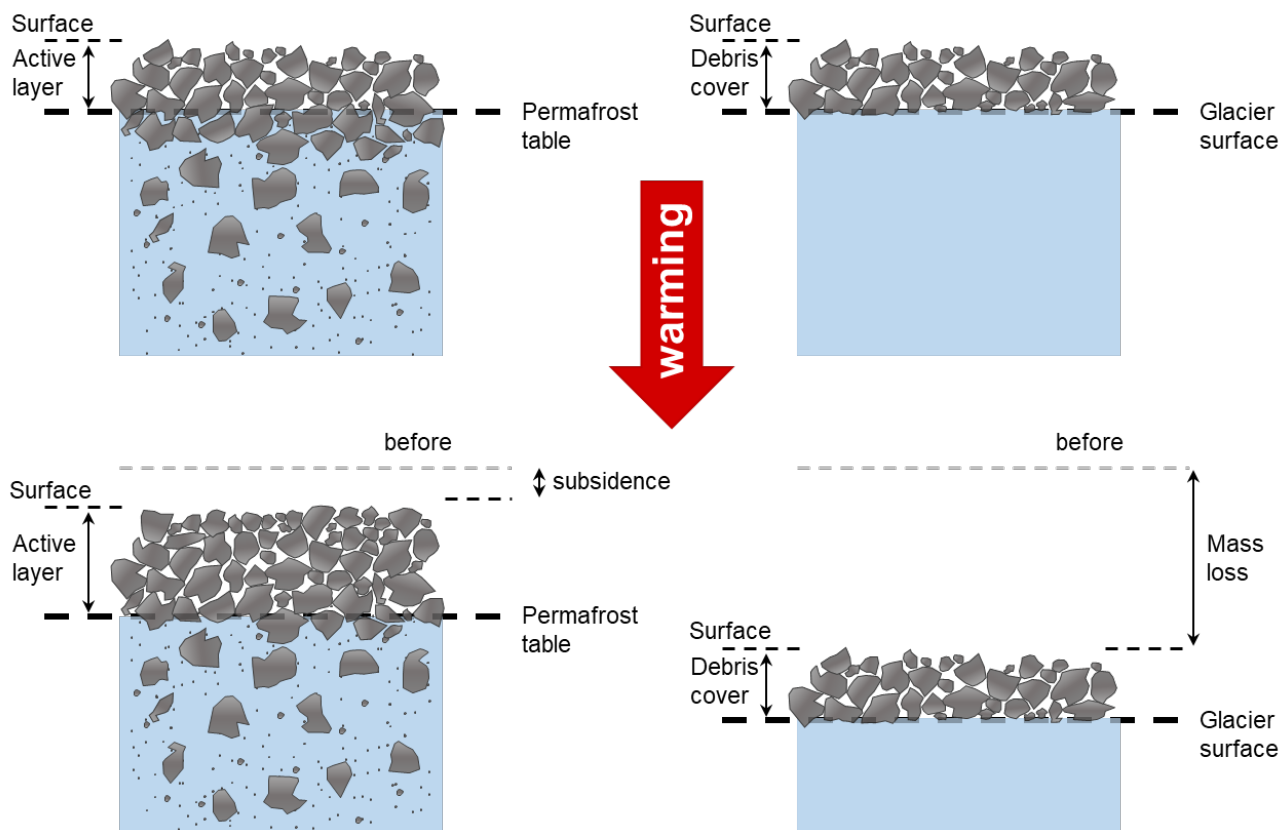
Figure 3: Types of ice-debris coupling and adjustment to warming effects in the cases of perennially frozen debris with excess ice (left), and debris-covered massive ice (right). As the ice melts, the thermal insulation in the form of the active layer increases for the permafrost case, but remains unchanged in the case of a debris-covered glacier, where the debris thickness largely remains constant. Modified from Haeberli and Vonder Mühll (1996).

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Figure 4: Advancing fronts of creeping perennially frozen debris at Gruben rock glacier (top; fall 2009, © Google Earth) and of a debris-covered glacier at Belvedere glacier in the Italian Alps (bottom; summer 2005).
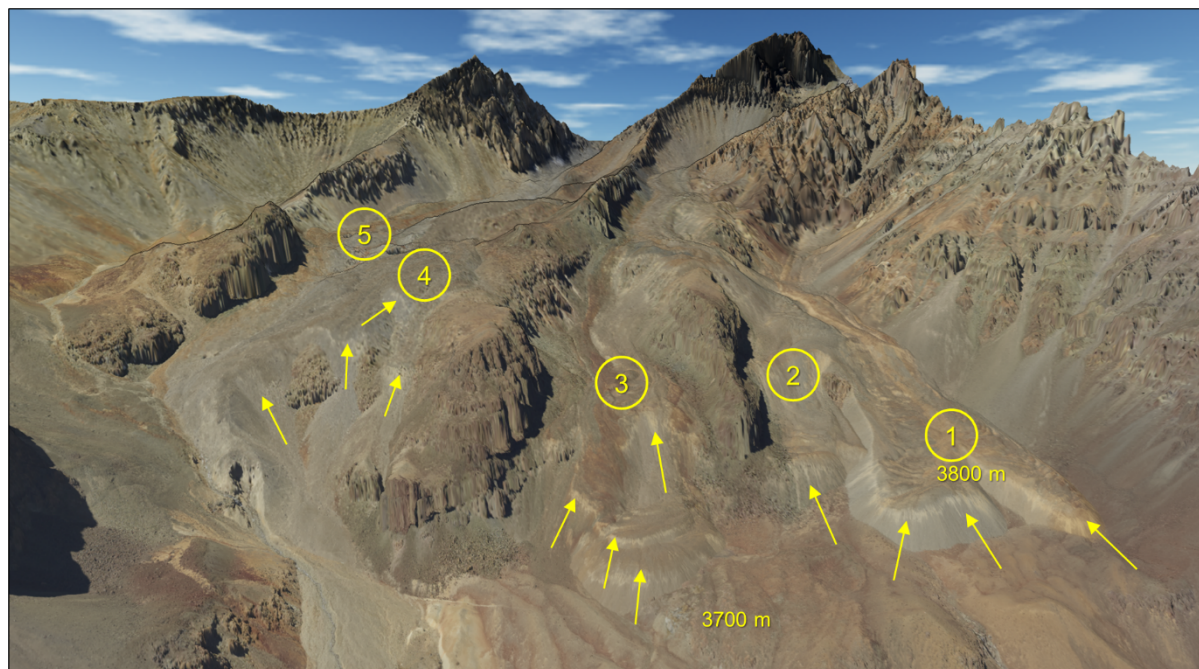
Figure 5: Creep phenomena in the upper Yerba Loca Valley, Andes of Chile. Yellow arrows point to over-steepened advancing fronts of creeping perennially frozen talus/debris, numbers in circles point to landforms as discussed in the text. © DigitalGlobe available in GlobalMapper, modified.