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Glacier-permafrost relations in a high-mountain environment: 5 decades of kinematic monitoring at the Gruben site, Swiss Alps

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Abstract. Digitized aerial images were used to monitor the evolution of perennially frozen debris and polythermal glacier ice at the intensely investigated Gruben site in the Swiss Alps over a period of about 50 years. The photogrammetric analysis allowed for a compilation of detailed spatio-temporal information on flow velocities and thickness changes. In addition, high-resolution GNSS (Global Navigation Satellite System) and ground-surface temperature measurements were included in the analysis to provide insight into short-term changes. Over time, extremely contrasting developments and landform responses are documented. Viscous flow within the warming and already near-temperate rockglacier permafrost continued at a constant average but seasonally variable speed of typically decimetres per year, with low average surface lowering of centimeters to decimetres per year. This ~~quite~~ constant flow causes the continued advance of the characteristic convex, lava stream-like rockglacier with its over-steepened fronts. Thawing rates of ice-rich perennially frozen ground to strong climate forcing are ~~obviously~~ very low (centimetres per year) and the dynamic response strongly delayed (time scale decades to centuries). The adjacent cold debris-covered glacier tongue remained an essentially concave landform with diffuse margins, predominantly chaotic surface structure, intermediate thickness losses (decimetre per year) and clear signs of down-wasting and decreasing flow velocity. The former contact zone between the cold glacier margin and the upper part of the rockglacier with remains of buried glacier ice embedded on top of frozen debris exhibits complex phenomena of thermokarst in massive ice and backflow towards the topographic depression produced by the retreating glacier tongue. As is typical for glaciers in the Alps, the clean glacier part shows a rapid response (time scale years) to strong climatic forcing with spectacular retreat (>10 meters per year) and mass loss (up to >1 meter water equivalent specific mass loss per year). The system of periglacial lakes shows a correspondingly dynamic evolution and had to be controlled by engineering work for hazard protection.

1 Introduction

High alpine environments are characterised by perennial surface and subsurface ice, typically found in glaciers and permafrost. Glacier and permafrost related processes can interact in a number of ways (Haeberli, 2005). Both, glaciers and permafrost are

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important for landscape evolution, the hydrological cycle, the mountain sediment budget, the stability of mountain slopes and associated natural hazards. Due to their characteristic thermal conditions, close to melting or thawing temperature, the occurrence and preservation of glaciers and permafrost is strongly affected by atmospheric temperature rise (IPCC SROCC, 2019) which appears to be stronger in cold mountain areas than on a global average (UNEP, 2007; MRI, 2015).

Mountain glaciers and their fluctuations are recognised as key indicators of climate change; their mass balance primarily reflects a direct response to changing atmospheric conditions, while their volume and length changes (advance/retreat) represent an indirect, delayed and filtered signal (Zemp et al., 2015). Debris cover is present on 44 % and prominent (covering > 1 km^2) on 15 % of the glaciers worldwide (Herreid and Pellicciotti, 2020). Glaciers with a thick debris cover are limited in terms of their use as climatic indicators, since the debris cover influences the energy balance, delays the dynamic response, and influences the ablation rate as well as the discharge of melt water (Nakawo et al., 2000; Reid and Brock, 2010; Ragettli et al., 2015; Ayala et al., 2016). When melting rapidly, the glaciers waste down or back where they have a clean surface, while changes in the debris-covered part typically are significantly smaller and the processes more complex (Benn et al., 2012; Mölg et al., 2020). Corresponding process differences can, for instance, enhance the potential of lake formation in the contact zone of clean and debris-covered ice and may cause glacier lake outburst floods (Kääb et al., 2005; Benn et al., 2012).

Together with long-term measurements of borehole and near-surface temperatures, the monitoring of changes in ice-rich perennially frozen debris and related viscous flow – here called "permafrost creep" concerning the process, and called "rockglacier" concerning the landform – is a key element within long-term observation programmes for mountain permafrost such as PERMOS (2019) in the Swiss Alps. In accordance with the IPA Action Group "Rock glacier inventories and kinematics" (RGIK, 2020), rockglaciers as landforms are defined here by their characteristic morphology exhibiting long-term cohesive creep with reduced internal friction, their convex shape with over-steepened fronts resulting from continued advance, their composition of talus or debris with variable but generally high (excess) ice contents, as well as by their complex flow behaviour as affected by negative subsurface temperatures and highly anisotropic material properties (Haeberli, 1985; Haeberli et al., 1998; Florentine et al., 2014; Merz et al., 2015, 2016; Wahrhaftig and Cox, 1959). Typically, rockglaciers creep downslope with velocities of several decimetres up to some meters per year (e.g., Roer, 2007). This creep behaviour results from internal deformation of the frozen debris and shearing in a narrow horizon at typical depths of around 20 m (Arenson et al., 2002; Cicoira et al., 2021). Reliable information on the kinematics of rockglaciers provides insights into the evolution of ice-rich permafrost on mountain slopes and facilitates the analysis of its dynamics (Roer et al., 2005b; Kääb et al., 2007). Therefore, terrestrial as well as remote sensing techniques are applied to quantify the kinematics of permafrost creep, i.e. horizontal surface velocities and vertical surface changes, respectively (Lambiel and Delaloye, 2004; Kääb, 2005; Haeberli et al., 2006; Roer, 2007; Strozzi et al., 2020; Kääb et al., 2021).

In regions with moderately continental climatic conditions, relations between polythermal glaciers and permafrost are widespread (e.g., Reynard et al., 2003; Haeberli, 2005; Kneisel and Kääb, 2007; Bosson et al., 2014; Bolch et al., 2018; Kunz and Kneisel, 2020; Falatkova et al., 2020). The full spatio-temporal complexity, however, of such relations and sometimes even interactions between surface and subsurface ice in high-mountain areas still remains far from being well understood. This

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can become important also for applied purposes in the context of formation and evolution of potentially dangerous periglacial lakes. Due to repeated historical outburst floods from such lakes in an environment with interacting glaciers and permafrost, the Gruben cirque (Fig. 1) in the Saas Valley, Swiss Alps, has been intensely investigated over many years and using numerous comprehensive field measurements, many of them in connection with protective construction work carried out by the responsible authorities (Haeberli and Röthlisberger, 1976; Röthlisberger, 1979; Haeberli et al., 2001; Kääb and Haeberli, 2001).

To monitor the evolution of the formerly dangerous periglacial lakes, special large-scale aerial photographs were taken annually by the Federal Office of Topography swisstopo since 1970. A first detailed aerophotogrammetric analysis of the flow field caused by permafrost creep at Gruben rockglacier and its former contact zone with Gruben glacier was published by Haeberli et al. (1979). A detailed analysis of the vertical and horizontal changes at the rockglacier surface between 1970 and 1995 was given by Kääb et al. (1997). Results from numerous geophysical soundings (seismic refraction, ice-penetrating radar, geo-electrical resistivity, gravimetry), permafrost mapping using the BTS method (Bottom Temperature of winter Snow cover; Haeberli, 1973; Lewkovicz and Ednie, 2004), core drilling, and lichenometric studies all document conditions in the periglacial areas and nearby glacier forefields (Barsch et al., 1979; Haeberli et al., 1979; Haeberli, 1979, 1985; King et al., 1987; Haeberli et al., 2001). The monitoring of kinematics and ground-surface temperatures (GST) on the Gruben rockglacier is systematically documented within the framework of the Swiss Permafrost Monitoring Network (PERMOS - http://www.permos.ch/) since 2012 and 2015, respectively. On the directly adjacent Gruben glacier, radio-echo soundings, numerous hot-water drillings with borehole observations (englacial temperature, glacier bed-resistivity, subglacial water pressure) and aerophotogrammetric observations on thickness changes provided rich information reported by Haeberli (1976), Haeberli and Fisch (1984), Haeberli et al. (2001), and Kääb (2001).

The purpose of the study presented here is (i) to extend the kinematic monitoring series on the tongue of Gruben glacier and the adjacent Gruben rockglacier by another 21 years to describe the observed horizontal and vertical changes for a 46-year period (1970-2016; additional in-situ monitoring on the rockglacier provides information until 2020), (ii) to analyse and compare the creep characteristics of the periglacial and the glacier-affected parts of the rockglacier, and (iii) to analyse and compare the morphological structures and flow of the rockglacier and the debris-covered polythermal glacier adjacent to it in order to differentiate the characteristics of the two landforms and their evolution in time. ~~In sum,~~ our study aims to analyse a 50-year time series of interconnected periglacial, paraglacial and glacial processes and their morphological expressions in a typical high mountain environment.

2 The Gruben site

A comprehensive overview of the glaciological and geomorphological situation of the study site is given by Haeberli et al. (2001), based on results from a large number of field measurements. The polythermal Gruben glacier and the adjacent perennially frozen rockglacier are situated below the western face of Fletschhorn (3993 m a.s.l.) in the canton of Valais,

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southern Swiss Alps (~~at around~~ 46° 10'N / 7° 58' E; Fig. 1). The southern Valais, in between the Great St. Bernhard, the Rhone valley and the Simplon area is formed by the St. Bernhard and Monte Rosa penninic nappes. The Gruben site is characterised by the Siviez-Mischabel sub-nappe, where polymetamorphic rocks dominate (Labhart, 1998). The climate of the study area is predominantly influenced by air masses from South-West and has an inner-Alpine, moderately continental character. According to meteorological measurements at high elevations in the Swiss Alps (MeteoSwiss) and applying a thermal gradient of -0.55°C/100m, mean annual air temperature at the site (2700 – 3000 m a.s.l.) can be estimated at some -2 to -4°C for the ~~time~~ period 1980-2010. This has most likely been colder by about 2°C during the Little Ice Age, whereas the last decade (2011-2020) has been warmer by about 0.8°C. Regional precipitation has not been measured on site, but is probably below or around 1000 mm per year as the Gruben area is particularly shielded by high-mountain ridges in all directions within a few tens of kilometres.

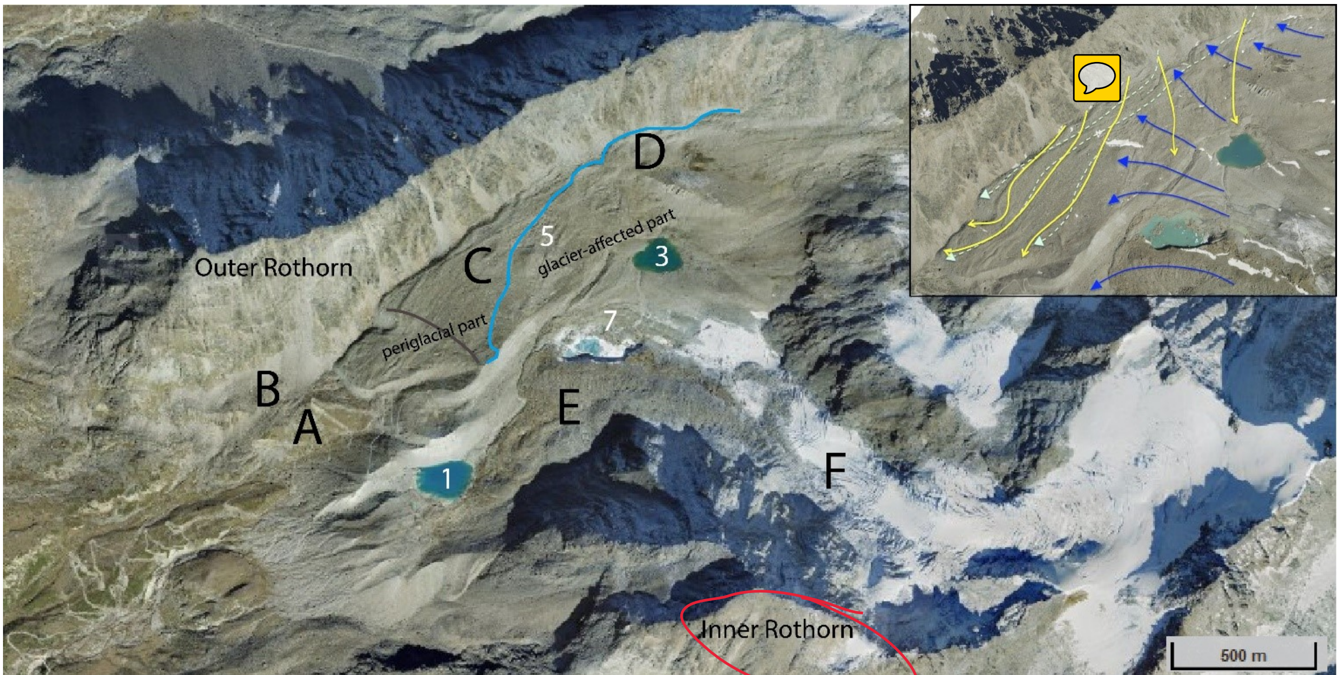

Figure 1: Geomorphological description of the Gruben site as shown on an orthophoto from 2017 (Source: SWISSIMAGE, geodata@swisstopo) The blue line indicates the approximate outline of Gruben glacier at the time of the Little Ice Age (LIA). The grey line on the rockglacier represents the subsurface bedrock riegel. Landforms: A = inactive rockglacier; B = actively creeping protalus rampart; C = Gruben rockglacier; D = deformation of frozen talus; E = debris-covered tongue of Gruben glacier; F = Gruben glacier; 1, 3, 7 = existing lakes; 5 = former thermokarst lake. The inset in the upper right shows the flow trajectories in frozen debris as determined by aerophotogrammetry with the yellow lines (cf. Figure 14 in Haeberli et al., 1979) and flow trajectories in frozen debris as derived from topography with the yellow dotted lines. The blue arrows indicate the estimated flow direction of the LIA glacier.

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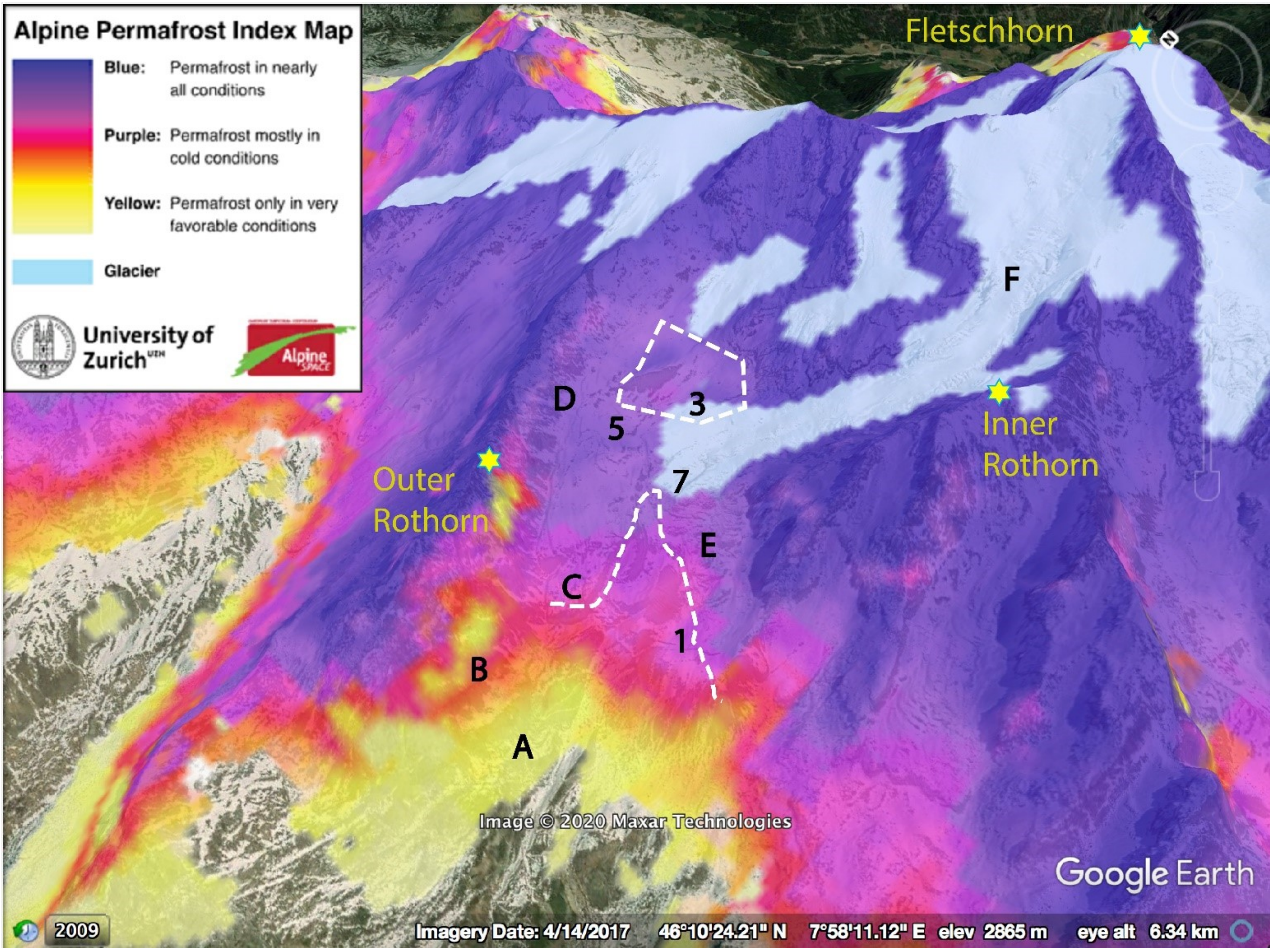

Figure 2: Permafrost distribution at the Gruben site as derived from the Alpine Permafrost Index Map (Böckli et al. 2012), overlay on GoogleEarth (© Google Earth 2009). Landforms: A = inactive rockglacier; B = actively creeping protalus rampart; C = Gruben rockglacier; D = deformation of frozen debris; E = debris-covered tongue of Gruben glacier; G = Gruben glacier; 1, 3, 7 = existing lakes; 5 = former thermokarst lake. White dashed lines indicate transition to permafrost-free terrain as documented by BTS measurements and geophysical soundings.

Under such cold-dry conditions, mountain permafrost is widespread (Fig. 2; cf. spatial model results at 25 m resolution by Boeckli et al., 2012 for the entire Alps; ~~Obu et al., 2019 (Northern Hemisphere) or Gr[illegible]be, 2012 (worldwide) have a 1 km resolution~~). Especially cold local microclimates exist thereby for two situations: (a) in steep rock faces with thin winter snow and exposed away from the sun, and (b) below surfaces with large blocks where the advection of latent heat by burial of snow in widely-open pore spaces together with efficient convective ventilation in wintertime can locally reduce mean ground temperatures by several ~~°C~~ (Hanson and Hoelzle, 2002). Warm conditions relate to more fine-grained surface materials in topographic depressions with thick accumulation of winter snow (e.g. Schneider et al., 2013). Conditions at the Gruben site

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closely correspond to this differentiation: the forefields of the polythermal but largely warm-based glaciers, with their finer materials and flat to partly even concave topography are permafrost-free as indicated with white dashed lines in Fig. 2, while the shady northwest-oriented rock faces below the Inner Rothorn and the blocky "foot-of-talus" situations below the Outer Rothorn are perennially frozen. The constituting lithic materials of the rockglacier are derived from the long-term (i.e. Holocene) erosion of the headwall reaching from Outer Rothorn to Senggchuppa and through various sediment transfer processes varying over time. Near-surface borehole temperatures in the upper part of Gruben rockglacier were about -1°C from 1977-1982 and BTS values were about -5°C (Haeberli, 1985). Recent GST values at the rockglacier surface (Fig. 3) document that the rockglacier permafrost was still active in 2015-2020, with an active layer ~~which was~~ regularly freezing through during wintertime as documented by near consistently cold BTS values.

The surface thermal behaviour at the Gruben rockglacier is well in accordance with the observations on other permafrost sites in the region (Valais-Cervinia-Furka-Gotthard), which show a consistent warming trend by about +0.36°C/decade over the last 20 years (Fig. 3; PERMOS, 2020). With mean annual near-surface temperatures close to and even above 0°C, the thickness of the frozen materials reaching up to about 100m must be inherited from colder phases of the Holocene and the Little Ice Age (cf. Haeberli, 1985; Haeberli et al., 2001) and is not in equilibrium with today's climate. In view of pronounced thermal offsets within the active layer (ventilation, balch effect) and at the permafrost table (latent heat), mean annual permafrost temperatures at the depth of zero annual amplitude (about 15m) can be expected to be close to thawing conditions but still slightly negative even today.

Viscous creep of perennially frozen talus produces a large number of active rockglaciers in the region (Frauenfelder, 1998; Barboux et al., 2015). Smaller permafrost landforms, such as an actively moving protalus rampart and an inactive but still frozen rockglacier, exist at Gruben down to altitudes around 2600 m a.s.l. Cohesive deformation of frozen talus/right-lateral moraine is also indicated in the uppermost part of the cirque (Fig. 1; Haeberli, 1979). From the electrical resistivities (high kΩm-range), the strong attenuation of electromagnetic waves, the high but variable P-wave velocities, frontal advance rates of the rockglacier (Kääb and Reichmuth, 2005), and shallow core drilling (7m) on top of it, overall volumetric ice contents of the frozen talus material are estimated to characteristically vary within about 60 to 85% by volume (cf. similar values reported from geophysical soundings and core drillings at comparable sites by Florentine et al., 2014; Krainer et al., 2014; Merz et al., 2015, 2016). Extrapolating back in time, the photogrammetrically determined advance rate of 0.15 times the surface velocity at the front, the development of Gruben rockglacier can be estimated to have taken place during major parts of the Holocene, i.e. over millennia. This is in accordance with exposure, luminescence and radiocarbon datings at other rockglaciers in the Alps (Haeberli et al., 2003; Fuchs et al., 2013; Krainer et al., 2014; Amschwand et al., 2021). The Gruben rockglacier front now advances over vegetation-covered, permafrost-free terrain.

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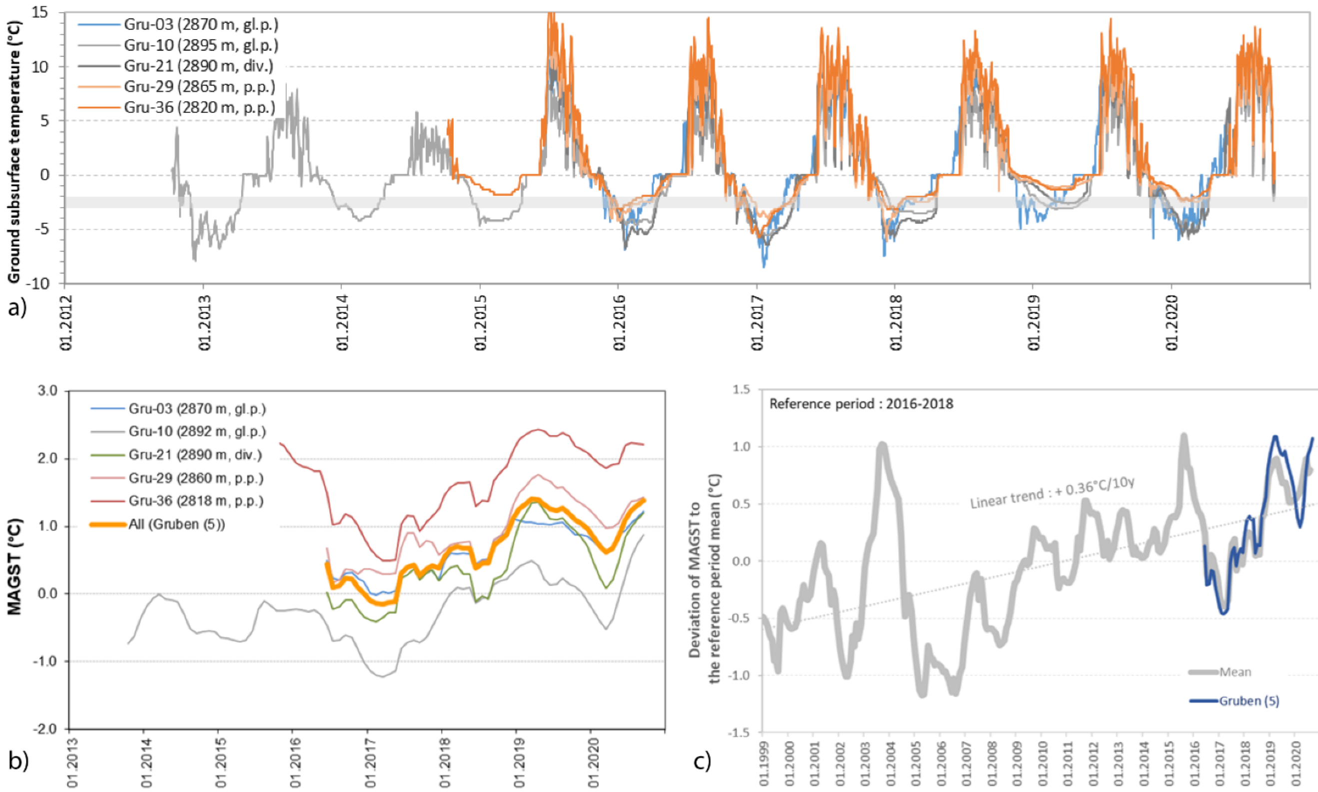

Figure 3: Daily ground surface temperature on the Gruben rockglacier (gl.p.: glacier-affected part; p.p.: periglacial part; div.: transition zone) since 2013, with indication of the upper limit of BTS for permafrost conditions (grey bar) (a), mean annual ground surface temperature (MAGST) (b) and deviation to the reference period 2016-2018 in comparison to the overall signal measured on rockglaciers and debris landforms (n= 2 to >20) in the surrounding region (c) (data: PERMOS and UniFR).

Gruben glacier flows down from the Fletschhorn in the shape of a mirrored "S" and has its active tongue at about 2880 m a.s.l., while its *debris-covered* part on the orographic left side reaches down to 2780 m a.s.l. (see Fig. 1). The glacier is polythermal with firn temperatures close to -10°C in its highest parts, temperate firn in the steep lower accumulation area, and a partially cold tongue with 10m - borehole temperatures of -1 to -2°C (Haeberli, 1976). The rapidly vanishing flat part of the ablation area is/was frozen to its bed at the margins but otherwise warm-based; it rests on relatively fine sandy sediments exceeding in places a thickness of 100 m (Haeberli and Fisch, 1984). Artesian water has been observed in hot-water drillings at the transition zone between warm- and cold-based ice (Haeberli et al., 1992, 2001). The artificial tunnel through the cold glacier margin at lake 3 established after the outburst events in 1968 and 1970 for lake-level lowering had been carved into the frozen part of this subglacial bed material. The orographic left part of the tongue is heavily covered with debris from intense rock-fall activity in the rock walls to the south of it, which is affected by strong glacial debuttressing and probably also by permafrost degradation.

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During cold periods of the Holocene as well as during historical advances, the upper part of the rockglacier was partly in contact with the orographic right margin of the polythermal Gruben glacier, which deposited some extended, debris-covered ice (up to about 20 m~~eters~~ thick; Kääb and Haeberli, 2001) on top of the permafrost. This upper part of the rockglacier is called the *glacier-affected* part, whereas the lower part is described as the *periglacial* part (Kääb et al., 1997; see Fig. 1 and 4), both being separated by a transition zone, which cannot be bounded by ~~any~~ clear geomorphological limit. Between 1970 and the mid 1990s, changes in geometry and movement have been pronounced for the clean part of Gruben glacier, minimal for the periglacial part of Gruben rockglacier and intermediate for the glacier-affected part of the rockglacier (Haeberli et al., 2001; Kääb, 2001), indicating different dynamics of glacial, periglacial and paraglacial processes.

Since the early 20th century, several periglacial lakes had developed and in cases disappeared again in the Gruben cirque at altitudes between 2770 and 2900 m a.s.l. (lakes 1, 3, 5 and 6 in Fig. 1 and 4). Lake outbursts and associated floods and debris flows through the Fällbach Creek had repeatedly threatened and damaged the village of Saas Balen (1500 m a.s.l.) in the Saas Valley. Lake 1 is a moraine-dammed lake in front of the debris-covered glacier tongue of Gruben glacier (proglacial lake). In the years 1968 and 1970, outburst floods in combination with the sudden emptying of Lake 3 into Lake 1 formed a deep breach in the large moraine threshold and developed into important debris flows. With the construction of a reinforced and controllable outlet structure, Lake 1 was later turned into a retention basin with a capacity of about 100,000 m^3 for floods from the upper parts of the cirque (Haeberli et al., 2001). Lake 3 was long situated directly at the cold margin of the glacier tongue at 2860 m a.s.l. Following the outbursts of 1968 and 1970, an artificial outflow tunnel through ice and subglacial permafrost of the glacier margin was constructed for lake-level regulation. This tunnel was replaced in 1996 by an open channel along the retreating glacier margin. In the following year, continued and even enhanced thinning and melting back of the glacier margin eliminated direct ice contact of the remaining water in the lake, the level of which was further lowered in 2003 through a shallow artificial cut in morainic material of the former glacier bed. Lake 5 – a classical thermokarst lake – started developing in the 1960s in buried massive ice on top of the rockglacier in its glacier-affected part. It continually migrated with, and grew on top of, the underlying permafrost (Kääb and Haeberli, 2001). In autumn 1994 the lake had a surface of about 10,000 m^2 and was filled with up to 50,000 m^3 of water. Due to its increasing hazard potential, the lake was artificially emptied in 1995; partially by pumping ~~out~~ and by draining trough an excavated trench. Lakes 2, 4 and 6 were temporary and of less importance with respect to geomorphological and hazard considerations. In 2016, lake 5 is still empty and also lake 3 is of less importance due to the retreating Gruben glacier. ~~But a~~ new proglacial lake (lake 7) formed in the connection zone between the clean ice and the debris-covered part of Gruben glacier, building a 20m high ice cliff at its southern bank (Fig. 4).

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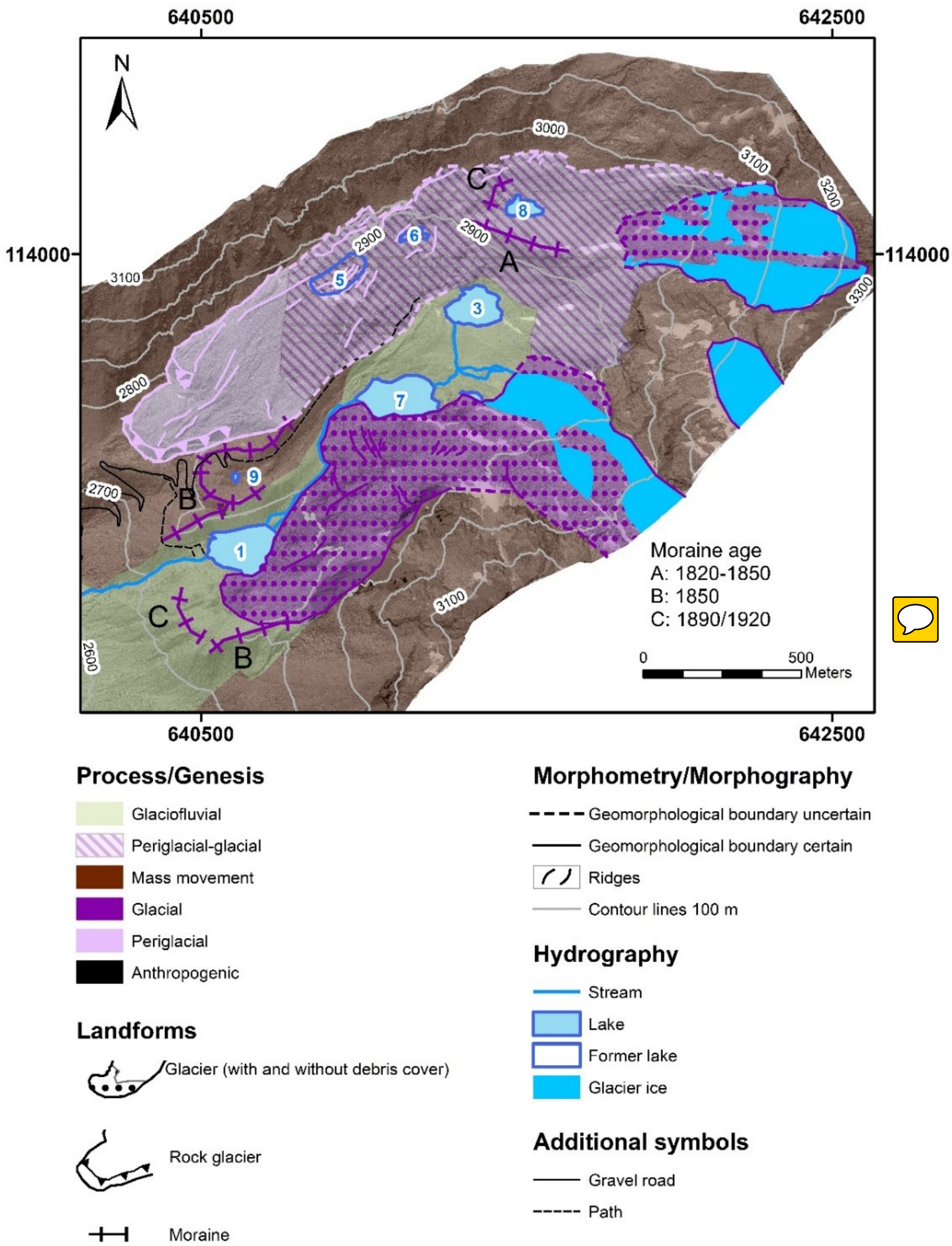

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Figure 4: Geomorphological map of the Gruben site. The moraine ages are taken from Whalley 1979 (age A) and Haeberli et al. 1979 (ages B and C). The numbering of lakes 1 to 9 follows the historical sequence of lake formation and denomination; lakes 2 and 4 are not anymore present.

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3 Data & methods

Geometry changes of Gruben rockglacier and the debris-covered part of Gruben glacier were quantified by the application of digital photogrammetry based on digitized or digital aerial photographies. In order to continue the existing kinematic monitoring series (1970-1995) at the Gruben site (Kääb et al., 1997; Kääb, 2001)), large-scale aerial images of the years 1994, 2000, 2006, 2010, and 2016 were selected for this study. Image orientation, automatic generation of Digital Elevation Models (DTMs) and digital orthoprojection were performed within the digital photogrammetry software SocetSet (BAE Systems, UK). DTMs with 1 m spacing and orthophotos with 0.32 m ground resolution were compiled for the 1994, 2000, 2006, and 2010 imagery, while the 2016 data from aerial digital sensor (ADS) were already processed to DTMs and orthoimages. The accuracy of the DTMs is estimated to lie within the range of 1-3 pixels for moderate high mountain topography (Kääb, 2005). The DTMs were co-registered according to the procedure by Nuth and Kääb (2011). For the quantification of vertical changes, the DTMs of the respective years were differenced within ArcGIS. Thus, loss of excess permafrost ice and glacier ice, as well as the topographic expressions of mass transfer can be quantified. The horizontal velocities were calculated using standard digital cross-correlation as implemented in the software CIAS (Correlation Image Analysis Software; Kääb and Vollmer, 2000; Heid and Kääb, 2012). Detailed information on raw data, processing steps, resampling methods and data accuracy is given in (Kääb, 2005; Roer et al., 2005a; Brunner, 2020). The horizontal velocities shown in this study are given for values above a maximum correlation coefficient determined as the 30% quantile, as detailed in Brunner (2020).

In addition, on the rockglacier repeated GNSS (Global Navigation Satellite System) measurements were started in 2012 (Barboux et al., 2015). At 46 locations, measurements have been taken twice a year around 1st of July and 1st of October to estimate seasonal as well as annual and decadal changes. The measurement points are distributed over different zones in the periglacial and the glacier-affected part of the rockglacier (Fig. 6). According to the recurrent measurement of four stable control points outside the rockglacier, the accuracy (standard deviation) in positioning is 0.8 cm in horizontal coordinates and 1.0 cm in elevation. The uncertainty in horizontal velocity as well as in vertical displacement rate, without taking into account any tilting or specific movement of the marked boulder, is about 2 cm/a over a year, but rises to 3 cm/a when the velocity is computed over the 9 winter months and 9 cm/a over the three summer months. These GNSS data can be compared with the multi-annual velocities obtained from cross-correlating repeat orthophotos of the rockglacier.

4 Results

4.1 Gruben rockglacier – *periglacial part*

For the period 1970 – 1995, Kääb et al. (1997) showed horizontal velocities of several decimetres per year for the central part of the rockglacier (= upper part of the periglacial part) and maximum values of about 1m/a directly above the rockglacier front. The vector field depicted a uniform pattern over the years and a sharp velocity increase as the rockglacier creeps over a bedrock riegel about 250 m above the front (see Fig. 1) indicated by (unpublished) seismic refraction soundings (Kääb, 2005).

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In the following years (1994-2016), as investigated in the present study, the overall pattern of the vector field is ~~very~~ similar (Fig. 5). Towards the rockglacier lateral margins the horizontal velocities are below 0.1 m/a and mostly in the range of measurement uncertainty. Especially the orographic left part of the rockglacier seems to be hardly active. As in the previous study, velocities between 0.2 – 0.4 m/a occur in the central part of the rockglacier and higher rates of 0.7 – 1 m/a at and below the bedrock riegel (Fig. 1). Mean horizontal velocities of the periglacial part of the rockglacier for the period 1970 to 2016 are given in Fig. 8a and indicate only little changes (about 0.3 m/a). The in-situ measurements in the last decade (2012-2020) give similar results and show ~~in addition~~ that the rockglacier surface near the front (points 040-043) is moving about 25% slower than the tongue behind (points 032-039). Only small changes in horizontal velocities are observed over time with an almost constant trend around which limited seasonal and interannual variations occur, whereas the very terminal part of the rockglacier above its front tends to decelerate by about 2.5 cm/y (Fig. 7).

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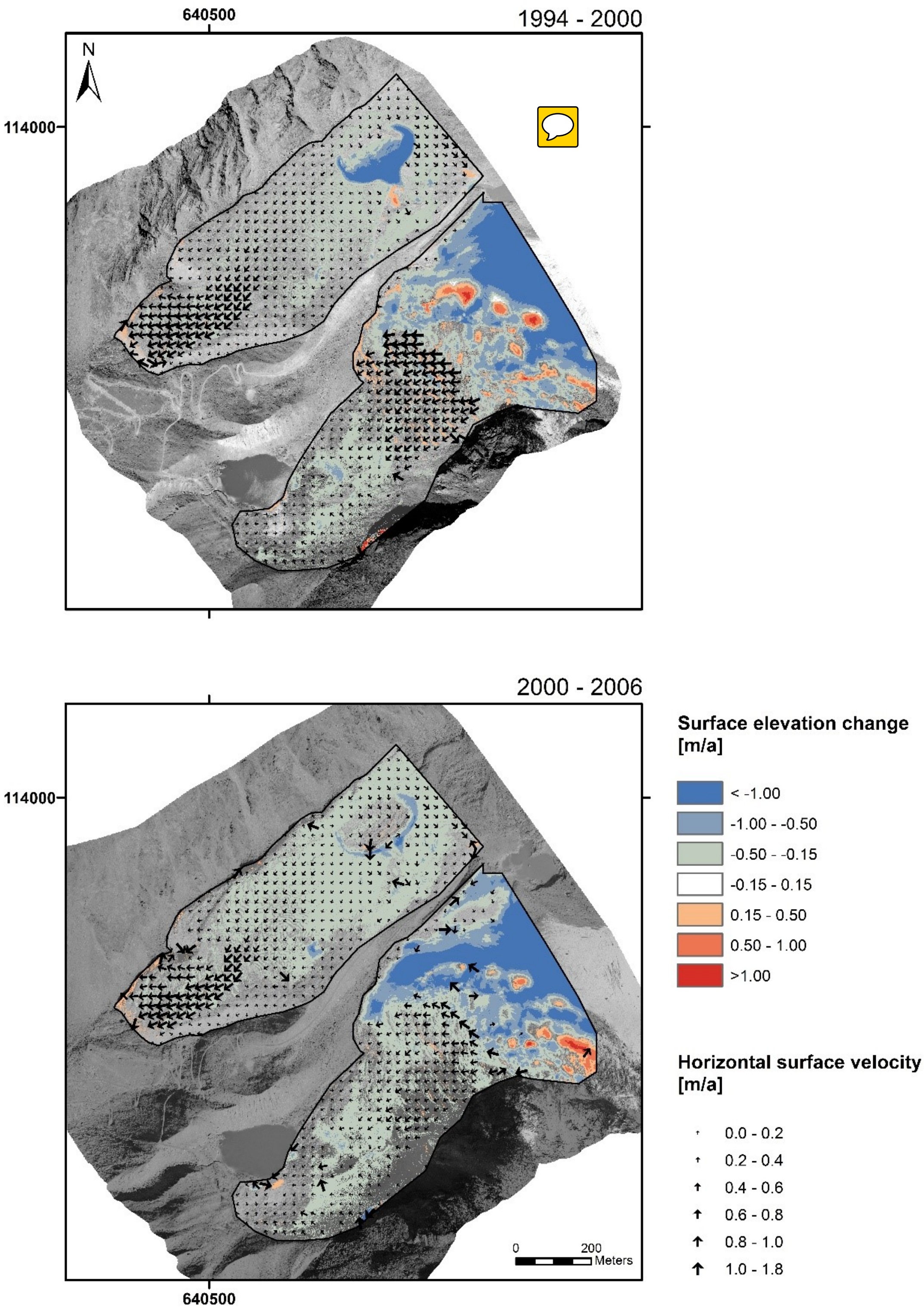

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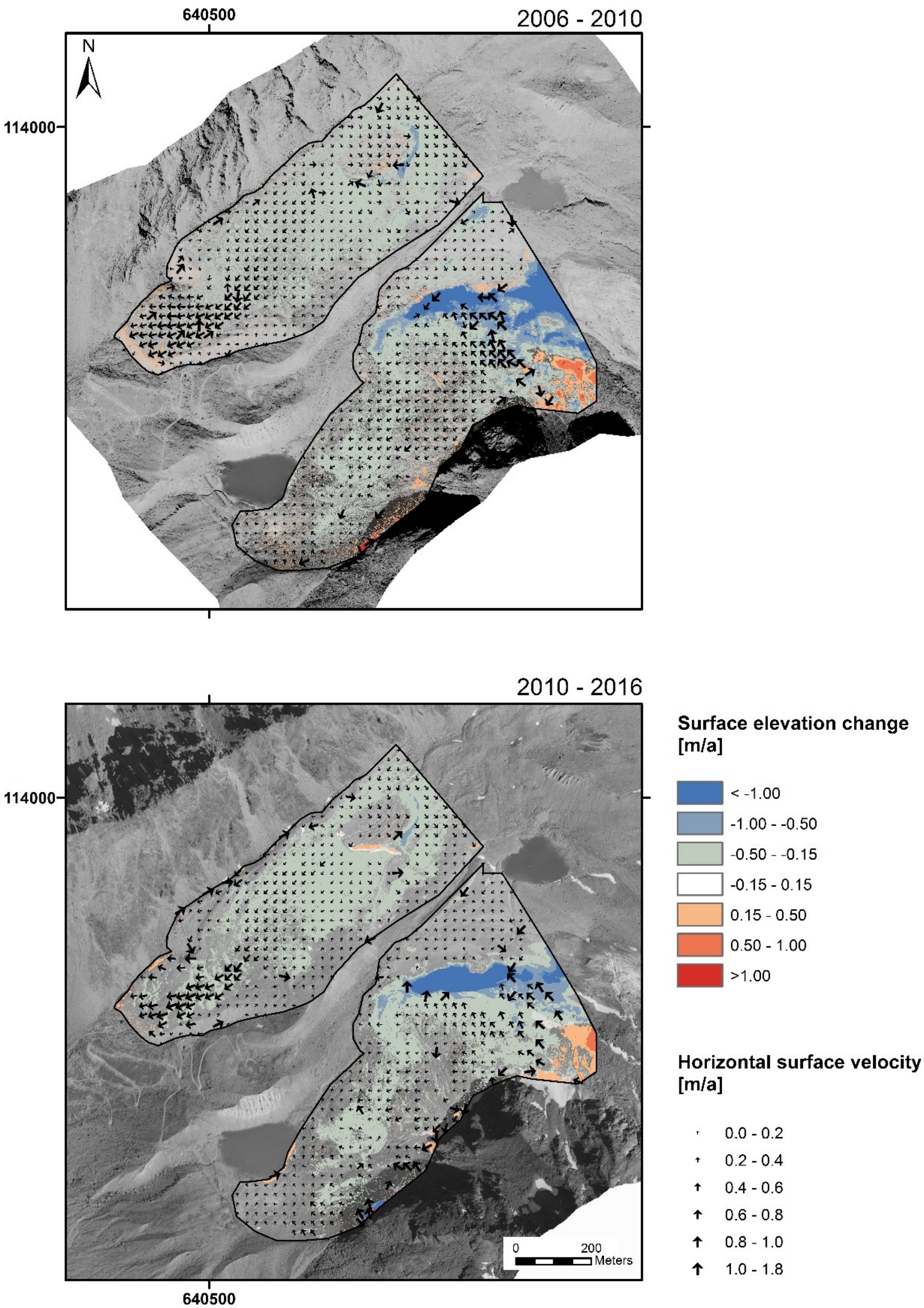

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Figure 5: Overlay of the horizontal surface velocities (vectors) and the colour-coded changes in surface elevation, for 1994 to 2000, 2000 to 2006, 2006 to 2010, and 2010 to 2016 (for each observation period the later orthophoto is shown; 2000, 2006, 2010, and 2016, respectively).

The vertical changes in the central part of the rockglacier reflect surface lowering (-0.1 to -0.5 m/a) between 1970 and 1995, whereas the lower tongue seems to remain almost constant in thickness (Kääb, 2005). In the period 1994 – 2016 the vertical changes show the same pattern and are in about the same range of -0.1 to -0.5 m/a (in total between -2 and -10 m). The lower part of the rockglacier shows little vertical changes (Fig. 5). Mean vertical changes for the period 1970 to 2016 are given in Fig. 8a and indicate almost constant surface lowering.

The GNSS measurements of the period 2012-2020 show that the trajectories of the marked boulders at the rockglacier surface are all 10 to 30° inclined, ~~what is close, but in most places somewhat~~ steeper than the surface topography (Fig. 7). The trajectories are often steeper in summertime, indicating ice-melt induced subsidence between 0 and -0.3 m/y. The absence of a relative height gain caused by the compression related to the slow down of the creep velocity in the last tens of meters above the front indicates the occurrence of an ice-melt induced subsidence, which can reach ~~here~~ up to 0.5 m/y.

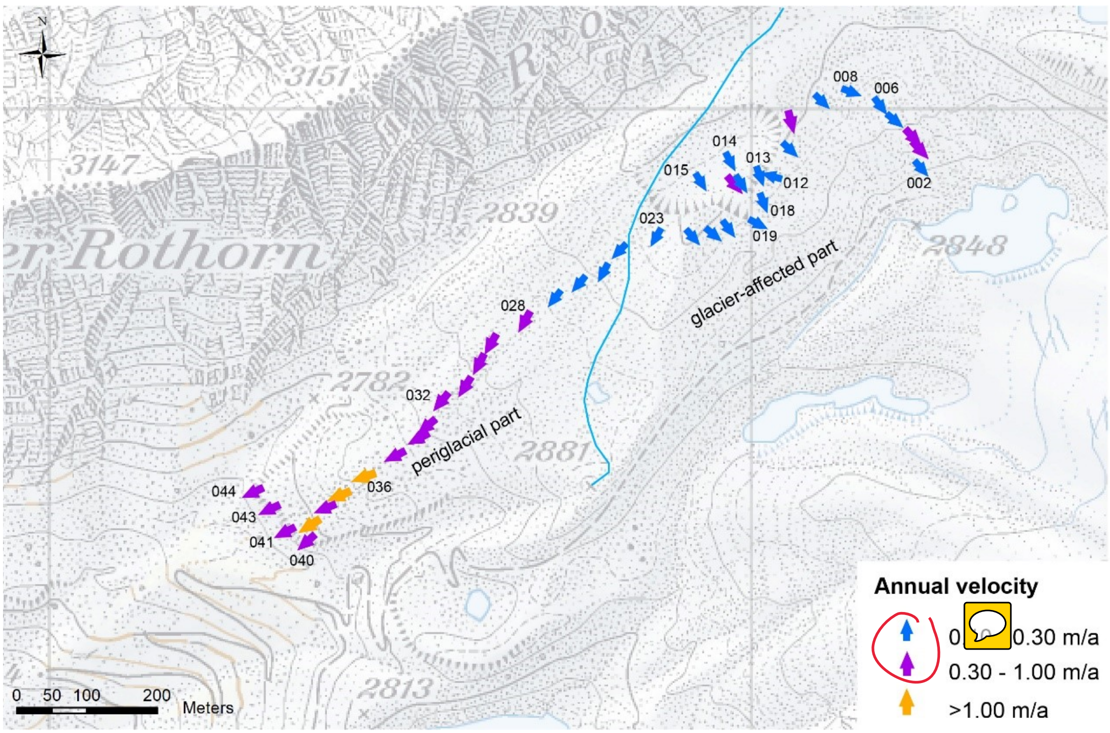

Figure 6: Overview on horizontal flow fields on Gruben rockglacier, measured by GNSS for the year 2019/2020. Numbers are referring to GNSS measurement items. The blue line separate approximately between the glacier-affected and periglacial parts of the rockglacier (cf. Fig. 1). Basemap © Swisstopo, updated 2005.

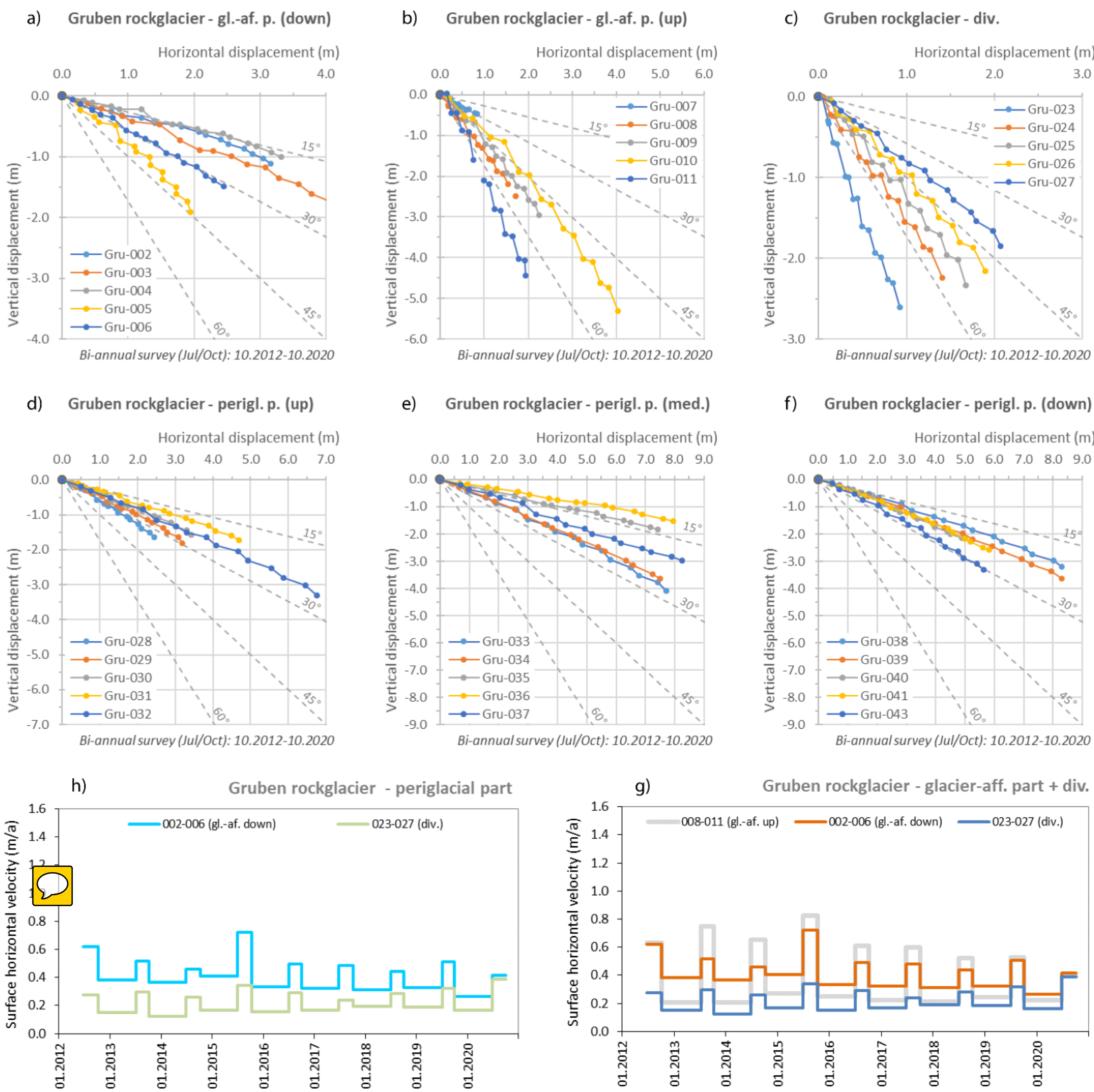

Figure 7: GNSS-based rockglacier kinematic behaviour in both glacier-affected (gl.-af.) and periglacial (perigl.) parts of the Gruben rockglacier as well as in their transition zone (div.). a)-f): Horizontal versus vertical displacement of selected items. g)-h): Seasonal horizontal velocities in specific sections. The numbers or identifiers are referring to the GNSS-surveyed items; location in Fig. 6.

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4.2 Gruben rockglacier – *glacier-affected part*

The former contact zone between the polythermal Gruben glacier and the periglacial permafrost of Gruben rockglacier is here called glacier-affected part. The cold glacier margin most likely pushed the permafrost upslope during its extended Little Ice Age stages, while ~~the~~ changes in slope and stress fields induced by the retreating glacier margin ~~more recently~~ have caused permafrost to creep back into the direction of the topographic depression formerly filled with the glacier tongue. As detailed by Kääb et al. (1997), the horizontal velocities between 1970 and 1995 in this part of the rockglacier-glacier contact were significantly higher than in the periglacial part and reached up to several meters per year near the glacier-dammed lake 3. These high creep rates were accompanied by strong vertical changes resulting from melting of dead ice and the formation and growth of thermokarst lakes. In the former contact zone of the glacier and the rockglacier (now the proglacial area), the retreat of the glacier caused a strong but decelerating surface lowering over the 25-years period (Kääb et al., 1997; see also Fig. 8).

In the following years (1994-2016), the mean horizontal velocities in the glacier-affected part of the rockglacier remained almost stable at about 0.2 m/a (see mean horizontal velocities in Fig. 8b). The flow is still directed towards the clean-ice part of the glacier. The vertical changes show the highest mean value of -0.3 m/a between 1994 and 2000, followed by a decreasing trend of vertical losses reaching a mean value of 0.14 m/a. The area of the thermokarst lake 5 (Fig. 1) indicates high vertical losses of up to 25 m between 1994-2016 at the southern lake outlet related to the artificial draining of the lake and the collapse of its former lake margins (Fig. 5). In addition, vertical changes related to the engineering works carried out in 1995 (road construction and trench digging) are clearly visible in the comparison of the 1994 and 2000 DTMs. Due to the former lake surface and the collapse of lake margins, accompanied by a loss in visual coherence, tracking of blocks and quantification of horizontal displacements could not be conducted in this part of the landform (especially between 1994 and 2000).

The GNSS measurements of the period 2012-2020 show most of the area, except the transition zone toward the periglacial part, is still back-creeping at a mean rate which has tended to decrease from about 0.4 to 0.3 m/y. The trajectories of the marked surface boulders are 40 to more than 70° inclined in the uppermost glacier-affected part (thermokarst lake area) and in the transition zone toward the periglacial part. The steepness of the trajectories is essentially caused by a strong ice-melt induced subsidence in summertime combined to an almost low rate of horizontal movement. The subsidence is ranging from 0.25 to more than 0.5 m/y, thus showing slightly higher values than the photogrammetric analysis. Trajectories in the downstream part of the back-creeping zone (pts. 002-004) are 15-20° inclined (Fig. 7), which is much closer to the topographical slope angle. Steeper trajectories in summertime cannot be evidenced, showing the absence of any significant ice loss at depth.

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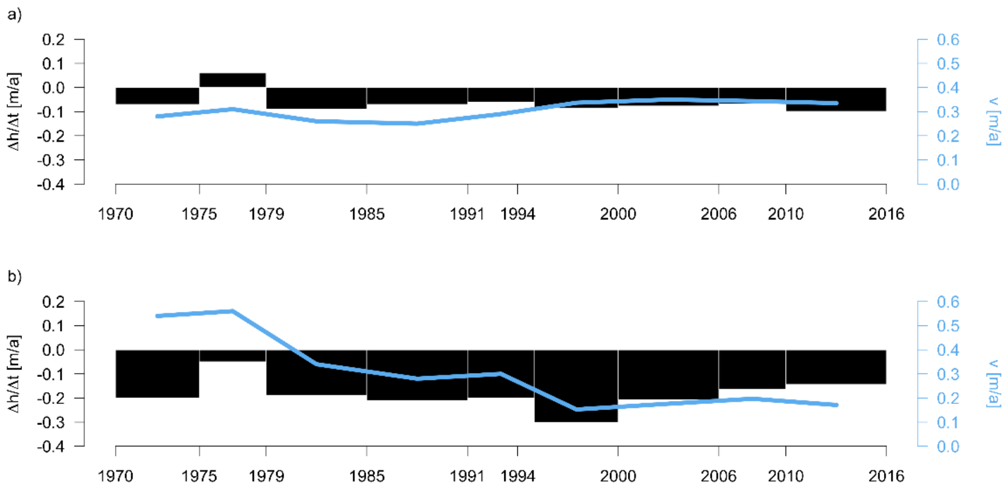

Figure 8: Mean vertical changes (black columns) and horizontal velocities (blue line) of the periglacial part of the rockglacier (a) and the glacier-affected part of the rockglacier (b) from 1970 to 2016. The values of the period 1970 to 1995 result from Kääb et al., 1997.

4.3 Gruben glacier – *debris-covered tongue*

In prior studies, the research focussed on the debris-free tongue of Gruben glacier, on the rockglacier and on the development of lakes, and only Kääb (2001) compiled a few measurements on the debris-covered tongue on Gruben glacier. In the study presented here, detailed horizontal velocities were not only quantified for the rockglacier, but also for the entire debris-covered part of Gruben glacier, in order to compare spatio-temporal patterns of the different landforms and to analyse the ongoing processes. As it becomes apparent in Fig. 1, the debris-covered glacier tongue has the same orientation as the rockglacier as well as a similar altitudinal range but receives much more shadow from the Inner Rothorn. The surface roughness of both landforms is comparable, with a high percentage of large blocks (> 1m in diameter). In relation to the sediment input by rock falls, the boulders appear to be less sorted on the debris-covered glaciers than on the rockglacier. The surface topography of the debris-covered glacier tongue shows regular ridges perpendicular to the flow lines, which are probably related to a combination of compressing flow, thrusting, and differential ablation and downwasting of the glacier, which consists here of cold ice and is likely frozen to the subglacial sediments. The surface structure strongly contrasts with the striking longitudinal structures of the rockglacier with its predominantly extending flow (Fig. 1; cf. also Kääb and Weber, 2004). In addition, the terminal part of the debris-covered glacier constitutes a diffuse transition to its foreland at lake 1 and does not exhibit the characteristic sorting of material as it is the case for the striking over-steepened fronts produced by creeping masses of frozen talus/debris of actively advancing rockglaciers.

For the debris-covered tongue, a general decrease in velocity from 0.27 m/a (1994-2000) to 0.17 m/a (2010-2016) is described by the median horizontal surface displacements (Brunner, 2020). In addition, the vector field depicts a division into two parts. The lower part shows surface velocities of 0.3 m/a decreasing towards zero at the lower ice margin and vectors show a whirl-

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like orientation, indicating stagnation of flow. The upper part shows much higher but ~~clearly~~ decelerating velocities, and has a flow field essentially following the main slope. Vertical changes on the debris-covered tongue lie in the range of -0.1 to -0.8 m/a apart from the uppermost part which is in close connection to the main body of the glacier, where mean surface lowering amounts up to 17 m between 1994 and 2016 (about -0.77 m/a) (Brunner, 2020). Here, at the glacier margin, lake 7 with a pronounced ice cliff heavily affected by thermokarst processes recently formed.

4.4 Gruben glacier – *debris-free tongue*

On the ice tongue of Gruben glacier, only a few horizontal velocities were quantified in this study, due to unsuitable temporal resolution of the aerial images with respect to glacier flow. But glacier retreat of about 370 m (about 17 m per year) is quantified for the measurement period 1994-2016. In addition, surface changes measured from DTM comparison indicate a lowering of up to 47 m at the glacier front in this period (about 2 m per year), much more than found for the 1970s – 1990s (Kääb, 2001). This quantification allows for a comparison with earlier studies measuring and modeling ice thickness and analyzing the glacier bed, such as Haeberli and Fisch (1984), who applied a combination of thermal drilling and electrical resistivity soundings of subglacial material and observed an ice thickness between 25 m and 80 m along a 400-m profile over the glacier tongue. A thick layer of unconsolidated sediments (about 150 m) occurs in the glacier bed underneath the tongue (Haeberli and Fisch, 1984). Comparing the ice thickness of about 35-40 m as measured in 1979 at the former glacier tongue with the same area (now ice free) and the ice loss of more than 40 m between 1994 and 2016 indicates a good coincidence.

5 Discussion

5.1 Periglacial processes

~~The perennially frozen~~ Gruben rockglacier ("periglacial part") shows a coherent flow field, a thickness remaining nearly constant in time and a steadily advancing over-steepened front, pointing to continued creep of ice-rich permafrost with its pronounced thermal inertia (Kääb et al., 1997; Kääb, 2005). With annual velocities of 0.5-1.0 m/a it lies within the range of typical rates for permafrost creep in rockglaciers of Switzerland (Delaloye et al., 2010). The advance rate of the front is significantly smaller than the surface velocities, which also resembles a typical pattern and links to a probable shallower shear horizon and/or melting processes at the front. The spatial pattern of its flow field essentially remained constant with only small temporal variations in the last two decades. Characteristic rates of surface lowering are in the range of centimeters to few decimeters per year, remain relatively constant over time (Fig. 5 and 8) and are ~~similar~~ to observations on other rockglaciers (Fey and Krainer, 2020; Kääb et al., 2021). The annual in-situ measurements allow for an interpretation and distinction of different processes causing vertical changes, such as extension/compression, melt-induced subsidence or topographic influences (Arenson et al., 2002; Lambiel and Delaloye, 2004). The overall extending flow regime of the rock glacier is generating a subsidence of a few centimeters along most of the GNSS longitudinal profile, reaching up to 20 cm/y above the bedrock riegel, whereas a compression heave of more than 20 cm/y should occur close to the front. This rate is proportional to

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spatial velocity contrasts and, because the flow field is constant over time and the velocity not dramatically changing over the seasons, it is not expected to vary significantly over the year. The in-situ measurements indicate however significantly higher rates of vertical motion during the summer months, e.g. in the hot summer of 2015 (Fig. 7), which seem to ~~evidence~~ ice melt-induced subsidence in large sections of the periglacial part of the rockglacier. Part of the vertical change must be related to the predominantly extending flow and related mass transfer. In reaction to increasing air and ground temperatures, pronounced flow acceleration and surface lowering or even flow destabilization (Roer et al., 2008) have been observed at a ~~good~~ number of rockglaciers in the Alps (Delaloye et al., 2010; PERMOS, 2020; Fey and Krainer, 2020) and other mountain ranges (Darrow et al., 2016; Eriksen et al., 2018; Kääb et al., 2021). The most plausible reason is that progressive permafrost warming causes subsurface ice to become softer, to contain higher amounts of unfrozen water and to increase the hydraulic permeability of the ice-rock mixtures (Kääb et al., 2007; Cicoira et al., 2019). The steady behavior of Gruben rockglacier over the last 50 years is in contrast with such warming-induced acceleration of viscous creep in perennially frozen debris but resembles long-term developments in the Tien Shan (Kääb et al., 2021). There, marked acceleration is observed for large rockglaciers with the exception of a glacier-affected case (Gorodetsky), where glacier retreat and dead-ice melting may decouple landforms of viscous permafrost creep from debris supply and induce changes in the stress field (unloading). In the case of Gruben, the retreating orographic right part of the clean glacier never supplied much debris to the rockglacier as clearly recognizable from Fig. 1 and from old maps (publicly available at Swisstopo (https://www.swisstopo.admin.ch/en/maps-data-online/maps-geodata-online/journey-through-time.html). Rather, the retreat of the glacier margin induced a south-orientated backflow of the upper rockglacier part towards the now exposed topographic depression (overdeepening) of the former glacier bed, away from the generally southwestern flow direction towards the rockglacier. Other possible influences remain highly speculative and require further investigation or modelling efforts. Thinning of the rockglacier, which can reach up to 3 meters per decade in the transition area between the periglacial and glacier-affected parts, is graduall~~y~~, but significantly decreasing the stress at the shear horizon. Very high ice contents could, in principle, dampen the temperature penetration ~~to~~ depth due to latent heat exchange caused by thaw at depth and hence prevent the warming from reaching shear horizons at depth, where most of the deformation takes place (Kääb et al., 2007). In addition, a high ice content can influence the hydrological system and dampen the water flow and connectivity within the rockglacier, thus making the landform insensitive to seasonal and interannual temperature forcing. The information from ~~the~~ geophysical soundings, however, provides no evidence of extraordinary high ice contents or even large bodies of massive ice as documented e.g. from the rockglacier Murtèl (Hoelzle et al., 2002; PERMOS, 2020). The role of the bedrock riegel, which regulates and limits flow depth in the lower rockglacier part, is also difficult to judge. Ultimately, ~~however,~~ continued atmospheric temperature rise will unavoidably cause progressive permafrost degradation and thaw during the upcoming decades and centuries, accompanied deceleration and inactivation of rockglaciers, as the melting of excess subsurface ice will lead to a loss of cohesion, an increase in internal friction, and ultimately slow down and stop movement through viscous flow. However, a significant flow acceleration could occur in a first stage. Continued thermal and kinematic monitoring at this well-documented site can shed more light on the involved processes.

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The periglacial part of the rock glacier shows a striking coincidence of modern flowlines and (longitudinal) structures from long-term cumulative deformation. In strong contrast to this, the former glacier-affected part exhibits a rather extreme divergence between modern flow directions and surface structures from long-term cumulative deformation (Fig. 1, 5, 6). Due to glacier vanishing and unloading with related topographic changes, this part experienced - since LIA - a marked reorientation of the stress ~~distribution~~ and the corresponding flow field. During the entire observation ~~period~~ and probably much longer ~~back in time~~, the strikingly convex landform "rockglacier" underwent slow cumulative deformation and advance through viscous creep of the frozen talus material but essentially kept the same appearance. Characteristic features are perfectly preserved such as (i) an "organized" surface structure strikingly reflecting a coherent field of cohesive viscous creep with large-scale stress transmission, here primarily under a regime of extending longitudinal flow, and (ii) an over-steepened, unstable front of the continuously advancing frozen mass where fresh material from the inner parts of the rockglacier is continuously being exposed. In sharp contrast to this conservative landform evolution, clear signs of down-wasting and collapse characterize the debris-covered, cold part of the Gruben glacier tongue. When directly comparing orthoimages from the 1970s to those from 2016~~, for example,~~ one can easily track individual rocks or patterns of rocks over time on most areas of periglacial rockglacier part, something that is significantly more difficult on the glacier-affected part, and on the debris-covered glacier tongue only possible over smaller disconnected areas.

5.2 Glacial and proglacial processes

The changes on the clean-ice part and the debris-covered part of Gruben glacier indicate typical processes in reaction to the changing climate with increasing temperatures (Zemp et al., 2015). The clean-ice part of Gruben glacier has been thinning by tens of meters and retreating by hundreds of meters. In analogy to Alpine glaciers in general, characteristic thinning rates during the observation period (1970-2016) are several decimeters per year (cf. Haeberli et al., 2001; Sommer et al., 2020). In the former contact zone between the polythermal glacier and the creeping frozen material small transverse ridges point to compression by the cold ice margin during maximum LIA glacier advance of frozen material "upslope" – towards the talus at the foot of the Outer Rothorn crest, while the flow trajectories are ~~now~~ again in the opposite direction, i.e. from the talus towards the now ice-free topographic depression of lake 3. This is likely a consequence of the approximately 180° change in slope and corresponding stress re-orientation induced by glacier retreat. Where the glacier disappeared, completely new landscapes form. The occurrence of fluted moraines in the northern part of the cirque serves as a testimony that the polythermal glaciers had been partially warm-based and largely debris-free. The debris-covered, cold part of the Gruben glacier shows similar developments as the clean-ice part, but strongly lagged and partly hidden due to the protecting cover of debris influencing near-surface heat exchange. Similar to the contact zone between the polythermal Gruben glacier and the permafrost of Gruben rockglacier it mainly shows intermediate thinning rates. The uppermost part of the debris-covered glacier tongue, which is still in contact with the active glacier, shows strong signs of down-wasting. Here, the velocities still indicate a coherent flow field with decelerating velocities over the observation period, while the lower part of the debris-covered tongue shows a marked decrease in velocity towards stagnation. This documents the retrogressive influence of the retreating glacier. Despite

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somewhat vague indications of compression in the probably frozen debris cover (rather weakly pronounced transverse ridges), the surface structure remains predominantly chaotic and the margins of the landform remain diffuse to such a degree that judging the exact position of the "ice margin" becomes hardly possible without the use of additional data, such as radar imagery (Fischer et al., 2014). Even under similar conditions of permafrost, the difference between the perennially frozen rockglacier and the debris-covered glacier is striking.

For both parts of the glacier, the retreating and down-wasting ice is the driving process exposing and forming a new landscape. The proglacial area is typically dominated by gravitational and fluvial processes, but is still conditioned by the former glaciation. This adjustment from glacial to non-glacial conditions is formulated by the paraglacial concept and describes a transition towards new equilibrium conditions (Ballantyne, 2002; Curry et al., 2006; Slaymaker, 2011). There is a scientific need to observe and quantify geomorphological changes, characteristic successions, as well as long-term trends in order to better understand the evolution of proglacial systems during this transition phase (Carrivick and Heckmann, 2017). In our study we provide insights into glacial, periglacial and paraglacial dynamics over a period of 50 years. One interesting feature of the glacial system is the delayed ~~reaction~~ of the debris-covered tongue to the atmospheric changes (several decades) and the related deceleration of ongoing geomorphological processes.

The ice in the former contact zone ("glacier-affected part") between the polythermal Gruben glacier and the permafrost of Gruben rockglacier generally shows intermediate thinning rates. Locally, vertical changes are higher in relation to the artificial emptying of the thermokarst lake and the melting of glacier remains. Horizontal velocities show a marked decrease with time. These observations indicate the fading interaction of glacial and periglacial processes and the rapid stabilization of the ground, as typically found in proglacial systems (Carrivick and Heckmann, 2017). Assuming characteristic mean thicknesses of several tens of meters for both, the glacier and the ice-rich frozen ground, the time scale for complete ice loss as derived from such quantitative rates of subsidence and mass loss is decades to centuries for the clean glacier while it is an order of magnitude longer for the rockglacier ice. ~~With~~ other words, subsurface ice in perennially frozen rockglaciers will continue to exist under conditions of continued warming when most surface ice in glaciers will already have disappeared. The creeping permafrost body is thereby most likely far out of thermal equilibrium already today and in its lower part could indeed now be approaching near-isothermal thawing temperatures at depth.

5.3 Future perspectives and related hazard aspects

Since the earlier 20th century, the complex evolution of glaciers and permafrost in the Gruben cirque has led to the development of an interconnected system of smaller but nevertheless dangerous lakes. Engineering construction work as combined with thorough scientific prospection and monitoring enabled successful prevention of further damaging incidents after the outburst floods in 1968 and 1970. The situation should nevertheless be carefully kept under observation. In general terms, with the accelerated glacier shrinking and the related destabilization of adjacent slopes, rock avalanches, landslides or debris flows can be triggered (Huggel et al., 2005; Deline et al., 2021; Curry et al., 2006). One difficult aspect thereby concerns the ~~obvious~~ destabilization of the shady rock walls at the Inner Rothorn with strong effects from glacial de-buttressing and permafrost

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degradation. Activation of rock fall~~s~~ has been obvious during field work for many years already and future large-volume events cannot be ~~safely~~ excluded. Such events could in principle have the potential to suddenly and entirely squeeze out water bodies with the dimensions of the lakes at the site. The early transformation of lake 1 into a flood retention basin with a capacity of about 100,000 m^3 of water has so far been an assurance against floods in the valley but the basin should better not be full of water in case of a large rock avalanche potentially reaching it. Since both, the glacial as well as the periglacial systems are highly dynamic, new lakes may form in future at the immediate foot of the destabilizing rock wall; e.g. between the debris covered part of the glacier and the active glacier tongue assuming an ongoing retreat of the glacier (cf. Frey et al., 2010). In comparison with rapid developments, the creeping rock glacier permafrost is quite a conservative landscape element. Whether current and future warming accelerates or stops the rockglacier creep remains to be observed. Continued monitoring of lake developments, further down-wasting and retreat of glacier ice, and of permafrost creep in the rockglacier tongue is conducted by national (PERMOS, GLAMOS) and local authorities and will allow for assessments (cf. GAPHAZ, 2017) of future hazard situations, if applicable.

6 Conclusions

Long-term monitoring of glacial and periglacial processes, materials and landforms at the Gruben site using modern geomatics methods opens unique insights into past and ongoing climate-related dynamics of complex ice-related system responses to rapid atmospheric temperature rise and corresponding landform evolution under moderately continental climatic conditions. The measurements document that over the past 50 years:

- the polythermal Gruben glacier retreated significantly as a rapid response to climate change and in accordance with Alpine glaciers in general;
- the cold debris-covered tongue of Gruben glacier degraded gradually from the front backwards and is now containing ice that is far out of equilibrium with the current climate – a situation which is in accordance with other debris-covered glaciers;
- the creeping perennially frozen talus of the Gruben rockglacier showed a steady behavior with a coherent flow field and limited surface lowering: as a result of the continued viscous flow it advanced at a rate which remained practically constant during the observation time;
- the striking lack of an acceleration trend due to permafrost warming and softening is not easily explained but may be related to unloading (thinning is still ongoing) and re-oriented stress fields in its upper part, to very efficient draining of melt water, or to very high ice contents;
- the geomorphological changes affected the hazard potential at the Gruben site, necessitating human intervention and careful observation combined with regular assessments.

Our analysis of glacial and periglacial processes and landforms and their interactions provides a better understanding of landform dynamics, in particular the current responses of cryospheric landforms to climate forcing. It highlights the various response times in relation to material properties, physical conditions and related process interactions. In addition, it underlines the importance of longterm, integrative monitoring of glacial and periglacial systems, for scientific as well as applied reasons.

Data availability

GST and GNSS measurements are partly available on the PERMOS Data Portal (www.permos.ch/data.html). All other data are available upon request.

Author contributions

IGR, WH and AK conceived the study. AB, IGR and AK analyzed the digital elevation models (DEMs) and orthophotos. RD added recent in-situ data. WH contributed all his data and knowledge from earlier investigations. PT supported the processing of digital elevation models and orthophotos. IGR and WH wrote the paper and AB, RD and IGR produced the figures, with support and contributions from all other co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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