Paraglacial Talus Slope Instability in Recently Deglaciated Cirques (Schober Group, Austria)

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Abstract

This paper presents observations on the paraglacial landscape adjustment in two recently deglaciated and neighbouring cirques (Kögele cirque/Kc and Hinteres Langtal cirque/HLc) in the Schober Group, Hohe Tauern Range, Central Austrian Alps (46°59'N, 12°47'E). During the Little Ice Age advance in the mid 19th century, both studied cirques have been covered by small glaciers and large perennial snow fields. Since then, these cryospheric landscape elements gradually disappeared almost completely at the surface leaving large talus slopes at the base of the headwalls behind. The evolution of surfaces covered by glaciers and perennial snow has been reconstructed for the years 1834, c.1850, 1872/73, 1928/29, 1969, 1982, 1997, and 1998 by using geomorphological evidences (terminal and lateral moraines), historical maps, and aerial photographs. Today, only few small patches of superficial glacier ice and perennial snow are found in radiation-sheltered locations. At both cirques, a number of vegetation-free small-scale and tongue-shaped landforms (STL) have evolved from these slope sediments during the last decades (Kc n=9, HLc n=13). Thus, all STLs are very young geomorphic features caused by paraglacial slope adjustment processes. Spatial distribution, geometry and possible genesis of the features in relation to the deglaciation history are discussed. It is suggested that the coverage of glacier ice by debris could possibly be a crucial process for the ice nourishment of the rock glacier Hinteres Langtalkar.

KEY WORDS: Paraglacial slope processes, deglaciation since the Little Ice Age, permafrost and buried glacier ice, small-scale tongue-shaped landforms, Schober Group, Central Austrian Alps

1. Introduction

The withdrawal of glacier ice commonly exposes a landscape that is susceptible to rapid morphological changes. The rates of erosion and sediment release in such 'paraglacial' landscapes are at rates greatly exceeding background denudation rates. The term paraglacial was first used by Ryder (1971) to explain the formation of alluvial fans by resedimentation of glacial deposits. Today, paraglacial geomorphology is defined as the 'study of earth-surface processes, sediments, landforms, landsystems and landscapes that are directly conditioned by former glaciation and deglaciation' (Ballantyne 2002). Paraglacial processes refer both to proglacial processes (ice marginal) and to those occurring outside the margins of a former glacier. Both para- and proglacial belong to the periglacial realm where geomorphic processes and landforms of cold, non-glaciated landscapes occur (French 1996). Morphologcial terrain changes in an alpine paraglacial environment can be expressed as rock slope adjustment due to stress-relief in form of steady mass shift, catastrophic mass-movement events, modification of debris-mantled slopes or morphological modification of glacier foreland (Ballantyne 2002). On cirque glaciers, where ice surfaces are overlooked by rockwalls, mass movements from slopes (i.e. rock falls, debris-charged avalanches) are by far the most important source for supraglacial debris input. This material is prone to intensive gravitational and meltwater reworking (Benn and Evans 1998).

A warming climate increases the areal extent of ice-free rock and slope area above such a glacier, thus, causes an increase of debris input on the remaining ice below. Furthermore, this effect causes the formation of a radiation protecting debris cover that possibly influences the dynamical behaviour of the glacier. In some cases, this effect may even cause a glacier advance (Benn and Evans 1998, Deline 2005). Degrading glacier ice can survive for a long period of time below a protecting debris cover (e.g. Gómez et al. 2003). In combination with a warming climate, the ratio of glacier-ice formation and rock debris accumulation at the foot of such a rockwall is shifting towards the debris side. Over time, at a high rate of debris input and through inefficiency of sediment transfer from glacier ice to meltwater (Shroder et al. 2000) a clean glacier may transform into a debris-covered glacier and finally into a moraine-derived/glacial rock glacier or ice-cored moraine (Benn and Evans 1998, Gómez et al. 2003, Frauenfelder et al. 2003). In terms of rock glacier relevance, the environment may shift from glacier-favouring to more rock glacier-favouring.

This contribution presents observations on the relationship between the recent retreat of small glaciers and perennial snow fields and the subsequent paraglacial modification of sediment-mantled slopes. In particular, the formation of unvegetated small-scale tongue-shaped landforms (STL) in the cirque headwalls of two recently deglaciated and neighbouring cirques (Kögele cirque/Kc and Hinteres Langtal cirque/HLc) is discussed. This study seeks to estimate the landscape dynamics after (superficial) deglaciation in a permafrost environment and contributes to the ongoing discussion on the ice nourishment of rock glaciers by presenting some observations on processes and landforms in the rooting zone of one active large rock glacier and one neighbouring cirque without a rock glacier. Field study results of the properties of the STLs (clast characteristics, stratigraphy) and photogrammetrically derived displacement rates will be addressed in a future publication (Kellerer-Pirklbauer and Kaufmann, in prep.).

2. Geographical Setting

The study area is located to the south of the main crest of the Hohe Tauern Range in the central part of the Schober Group and in the inner zone of the Hohe Tauern National Park at 46°59'N, 12°47'E (Fig. 1). The region is built of polymetamorphic crystalline rocks; different types of mica schists predominate (Lieb 1987). Due to the unsuitable topographic (steep rock faces, narrow crests, lack of flat surfaces at high elevations above the regional equilibrium line altitude) and climatic conditions (continental climate: low mean annual precipitation 1500mm at 2000m asl, mean annual air temperature/MAAT 0°C at 2300m asl) of the Schober Group, glaciation is limited to a few positions at the foot of rock faces in northern expositions and at high elevations. The mean size of all glaciers in the Schober Group does not exceed 0.18km^2 (1983: n=29, total area 5.23km^2) and most of the glaciers are partly covered by a prominent debris mantle (on average c.20%, Lieb 1987).

Since the Little Ice Age (LIA) advance in the mid 19th century the total glaciated area has decreased to <50%; some small cirque glaciers have even disappeared. The atmospheric warming since the end of the LIA is well documented by the data of the meteorological station Sonnblick (3106m asl) situated 15km east of the study area where the MAAT has increased by 1.6°C during the last 120 years (Auer et al. 2002). The lower limit of continuous permafrost in the wider study area is estimated to be at c.3200 m asl (Buchenauer 1990). The lower limit of discontinuous permafrost in the study area itself is generally not below 2600 m asl in northern expositions and at 2750-2800 m asl in southern expositions (Lieb 1987, Krobath 1999). Creeping permafrost features (i.e. active rock glaciers) are frequent. The abundance of rock glaciers (n=126, 67 contain permafrost, Lieb 1996) is further enhanced by the existing lithologies which favour the weathering of rocks to coarse grained debris. Some of the rock glaciers possibly

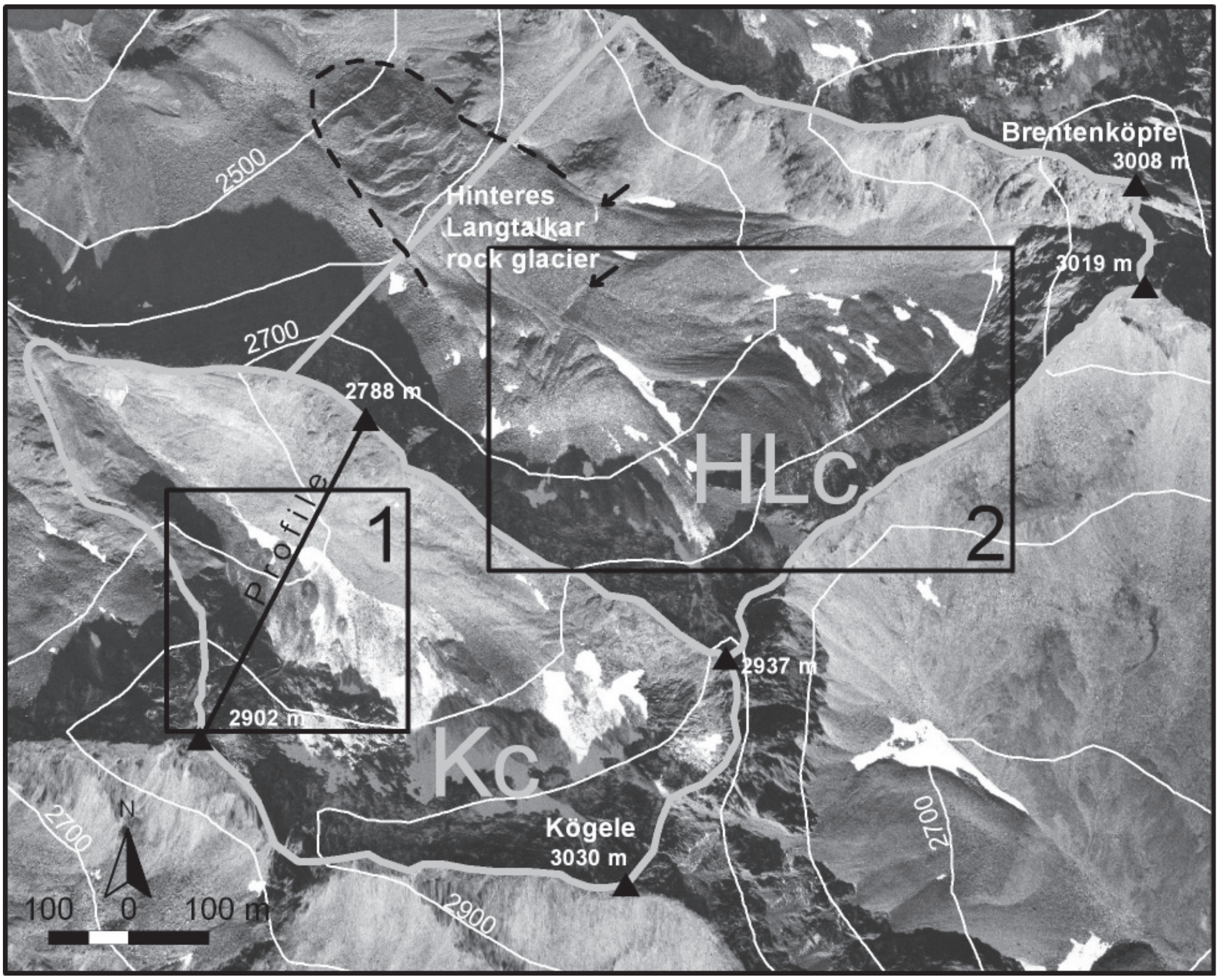

Figure 1: The two studied cirques: Kögele cirque (Kc) and Hinteres Langtal cirque (HLc) in the Hohe Tauern Range ('Hohe T.'), Central Alps, Austria. The two boxes in the main map - labelled as '1' (in Kc) and '2' (in HLc) - delineate the areas shown in Fig. 3. The black arrows indicate crevasses on the rock glacier Hinteres Langtalkar. Note the distinct transversal fissures at the frontal part of the rock glacier indicative for ongoing disintegration. The location of the profile shown in Fig. 6 is indicated (Orthophoto 16.09.1997, © BEV, Vienna).

contain remnants of glacier ice (Krainer et al. 2000).

Two neighbouring cirques - Kögele cirque (Kc) and Hinteres Langtal cirque (HLc) - have been investigated. Today, only small areas of superficial glacier ice and perennial snow patches are found in radiation-sheltered locations (cf. below). The orientation of both cirques is towards W-NW with high crests and mountain summits to the S and E in both cases. The Kc comprises 0.31km² and ranges in altitude from 2600 to 3030 m asl At the HLc, only the higher section of the cirque (2600-3019 m asl, 0.44km²) has been studied. The HLc is morphologically dominated by the tongue-shaped rock glacier Hinteres Langtalkar ('kar' is German for cirque). The rock glacier's lower margin reaches c.2450m asl indicating the local lower limit of discontinuous permafrost. Its dimensions (appr. length 850m, max. width 300m, area c.0.17km²) make it one of the largest rock glaciers of the Central Alps. The rock glacier features well developed longitudinal and transversal ridges and furrows on the surface and is nourished by active scree slopes which are separated from the rock glacier body by two distinct rooting zone depressions (Avian et al. 2005). The rock glacier creeps from the flat cirque over a cirque threshold causing an ongoing disintegration of the steep frontal part expressed as transversal fissures and gliding planes (Fig. 1).

3. Methods

3.1. Reconstruction and mapping of surface ice and perennial snow patches

The evolution of the extent of areas covered by glaciers and perennial snow at both cirques has been reconstructed for the years 1834, c.1850 (LIA-maximum), 1872/73, 1928/29, 1969, 1982, 1997 and 1998 by using morphological evidences (terminal and lateral moraines), historical maps, and aerial photographs. This information has been combined and analysed within a GIS (ArcView 3.3).

Situations in 1834, c.1850, 1872/73 and 1928/29: Since neither aerial nor terrestrial photographs of the glaciers are available for the period before the 1950s, the reconstruction of earlier glacial stages was based on field evidence (LIA-maximum) and historic topographical maps (1834, 1872/73 and 1928/29). The first cartographic document showing the two glaciers is dated with 1834 (franziszeische Landesaufnahme-'Kronlandskarte', at scale 1:28800). The second oldest historic map relevant for this study is dated with 1872/73 (franzisko-josephinische Landesaufnahme-'Sektionsblatt', sheet 5249/2 at scale 1:25,000). The cartographic representation of the two glaciers in the map is rather poor and fuzzy but the indicated spatial extents of glaciers and snow fields show that all STL-relevant areas have been covered by snow or ice. The first map showing contour lines and glacier boundaries with good quality is dated with 1928/29 (Österreichische Karte 1:25,000 der 5. Landesaufnahme, sheet 179/2 Debanttal; for detailed description of these historical maps refer to LIEB 1987). The 1850-stage was reconstructed on the basis of the LIA-moraines in both cirques. Furthermore, by use of the maps from 1834 and 1872/73, size and shape of the perennial snow field in the southern part of the HLc around 1850 has been estimated.

Situations in 1969, 1997 and 1998: Theses reconstructions are based on aerial photographs obtained from the Austrian Federal Office of Metrology and Surveying (BEV, Vienna). Additional aerial surveys were carried out by a private company in 1998 (Bildflug Fischer, Graz). Complementary information was taken from aerial photographs from 1974. This heterogeneous set of photographs shown in Tab. 1 was mapped into a common coordinate system (Austrian Gauss-Krueger map projection). In a first step all photographs were scanned with 10 µm pixel size using the UltraScan 5000 scanner of Vexcel Imaging Austria. Photogrammetric orientation was carried out on a digital photogrammetric workstation (ISSK) of Z/I Imaging. A high-resolution digital terrain model (DTM) with a grid spacing of 2m was derived from the stereo pair of 1998. This DTM was used to compute orthophotos (for 1969, 1997, 1998) from all photographs with a ground sampling distance (GSD) of 0.125, 0.25, 0.5 and 1m, respectively.

Date of acquisition	source	scale	film type
18.09.2002	Land Tirol	1:14,000	C
26.08.1998	Bildflug Fischer	1:10,500	BW
24.09.1997	BEV	1:11,700	CIR
16.09.1997	BEV	1:32,600	BW
05.09.1974	BEV	1:10,000	PAN
09.10.1969	BEV	1:29,100	BW

Table 1: Aerial photographs used in this study for surface ice/perennial snow reconstruction and mapping of the STLs.

Situation in 1982: For the reconstruction of the year 1982 the Österreichische Karte 1:50000, sheet 179 published in 1986 was used. This map is not useful for pure glacier studies because of the widespread occurrence of perennial (and late-lying) snow fields during the time of data acquisition (Lieb 1987); this was typical for the period around the 1980s ('1980-glacier advance'). However, for our study the 1983-map was useful. As pointed out by Lieb (1987), glaciation in the Schober Group during 1969 was most likely very similar to the one of the mid 1980s. Therefore, the overall spatial distribution of glaciers and snow fields in 1983 (published map) should be very similar to the one in 1969 (aerial photographs), which is roughly the case in both studied cirques (cf. Fig. 2).

3.2. Spatial distribution and morphometry of the STLs

All small-scale and tongue-shape landforms (STLs) have been mapped in the field by handheld GPS and differential GPS (DGPS) receiver. DGPS allows the continuous mapping of points or lines in the terrain with an error of a few centimetres. A GPS reference station was installed on a geodetic point with known coordinates approximately 1.2km to the SW (46°58.7'N, 12°45.7'E) of the study area close to the Elberfelder mountain hut. In addition to GPS/DGPS, morphological mapping was further improved by using the 2-m resolution DTM derived from the stereo pair of 1998. Further improvement of the delineation of the STLs was enabled by using the aerial photographs listed in Tab. 1. The combination of GPS/DGPS, different hillshade maps and orthophotos allowed accurate mapping. Based on these data sources and by use of a GIS, (i) average width, (ii) length and (iii) area of the tread (i.e. upper surface) and (iv) height of riser (i.e. frontal slope) has been mapped. The average width of the tread was measured across the slope. In this study, the length represents the downslope distance between the headwall or significant nickpoint of slope and the lower end of the STL (Matsuoka et al. 2005). The length-to-width ratio (L/W) distinguishes tongue-shaped forms (L/Wffl1) from lobate forms (L/W<1).

4. Changes of glaciation and perennial snow fields since 1834

During the LIA-maximum (c.1850), both cirques have been covered by glaciers and perennial snow fields (Fig. 2). The small cirque glaciers created distinct terminal and lateral moraines visible in Fig. 4 and 5B. In total, some 0.21km^2 of the Kc and some 0.18km^2 of the HLc have been covered in c.1850 by ice and perennial snow fields. As it has been pointed out by LIEB (1987) and visualised in Fig. 2, the areal coverage of snow and ice during the decades before and after 1850 was similar compared to the LIA-maximum. A time period of substantial glacier retreat started in the 1870s and was possibly not disrupted during the cooler last decade of the 19th century. The situation in 1928/29 can be regarded as the fading period of the 1920-advance (LIEB 1987). During that stage, the glacier in the Kc covered still some 0.19km^2, whereas the glacier in the HLc did not exist anymore; i.e. this small glacier has completely disappeared already in the first decades of the 20th century. The historic map of 1928/29 presents only glaciers; perennial snow fields are not shown on the map. This fact is very convenient for glacier studies but this is certainly not the case for the purpose of this study. Based on the perennial snow and glacier ice distribution pattern in 1969, it is hypothesised that some 0.09km^2 of the HLc (0.06km^2 HLc-S, 0.03km^2 HLc-N) have been covered by perennial snow during that time. During the following decades until 1965, the areal extent of snow and surface ice decreased dramatically.

By contrast, the time period 1965 to the beginning of the 1980s was quite stable with only minor changes. In 1969, surface glacier ice and snow still covered 0.12km^2 of the Kc and 0.06km^2 of the HLc, respectively. The situation in 1982 was very similar to 1969; perennial snow fields have been more common in the early 1980s. At that time, the remaining ice mass (0.08km^2) was a steep and concave niche glacier (slope at front 20° and close to the headwall 40°) with few crevasses. 35.9% of the glacier was covered with debris originating from rock falls and debris-charged avalanches from the Kögele-N-face. In 1997, surface ice and perennial snow patches covered less than 0.06km^2 of the Kc and only 0.01km^2 of the HLc. One year later, only in the Kc significant patches of surface ice have been mapped from the aerial photographs. Thus, by the end of the 1990s, the niche glacier mostly disappeared; at least superficially. Today, only very small patches of surface glacier ice and

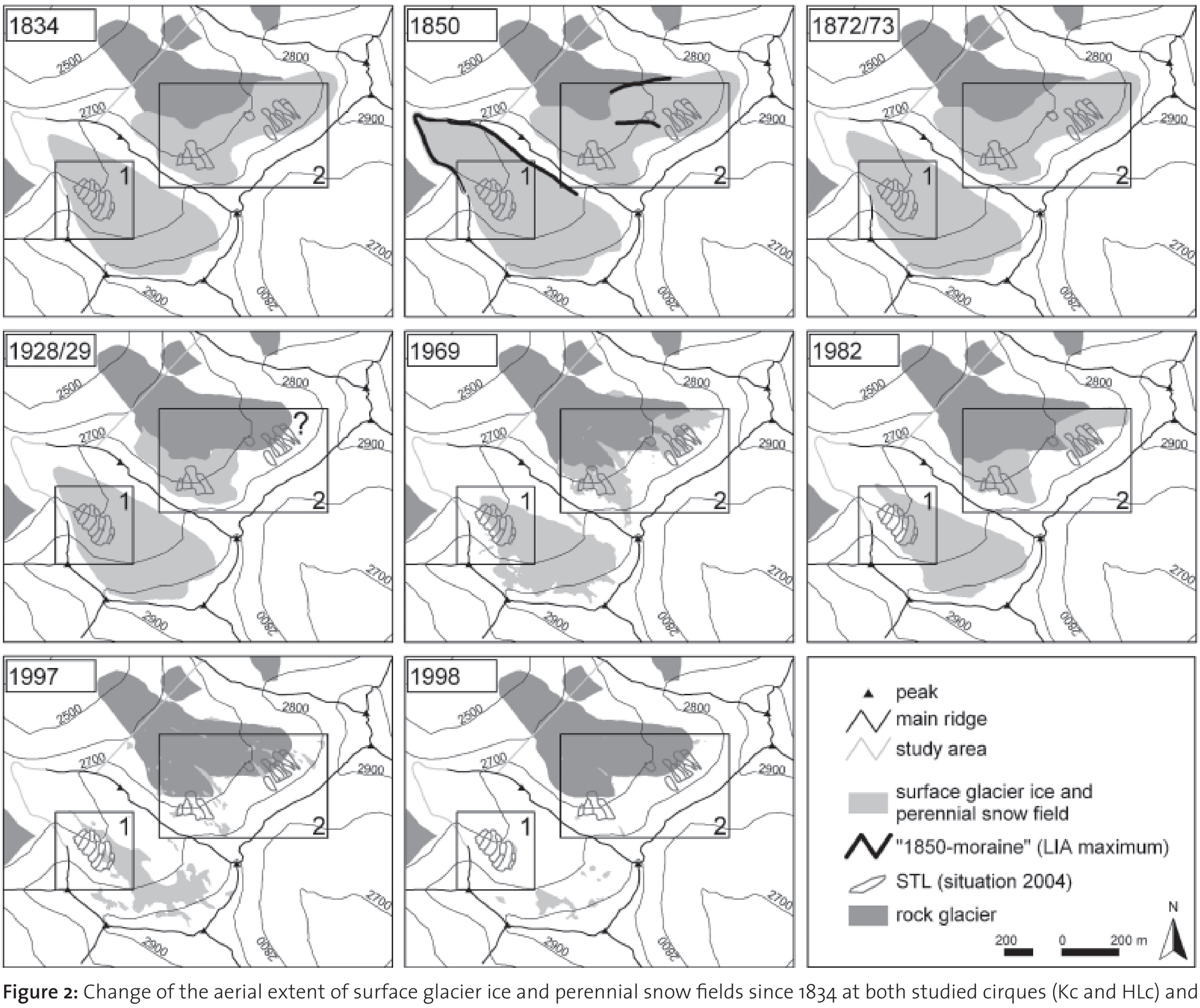

Figure 2: Change of the aerial extent of surface glacier ice and perennial snow fields since 1834 at both studied cirques (Kc and HLc) and its spatial relation to the studied STLs (cf. Fig. 3). The maps showing the situations in 1834, 1850 and 1872/73 should only be seen as approximations. The boxes '1' (Kc) and '2' (HLc) delineate the areas shown in Fig. 3. For explanation and data source refer to text.

perennial snow are found in the most radiation-sheltered locations in both cirques. Despite this fact, debris-covered dead-ice may be expected in both cirques due to permafrost conditions (cf. Lieb 1987, Buchenauer 1990).

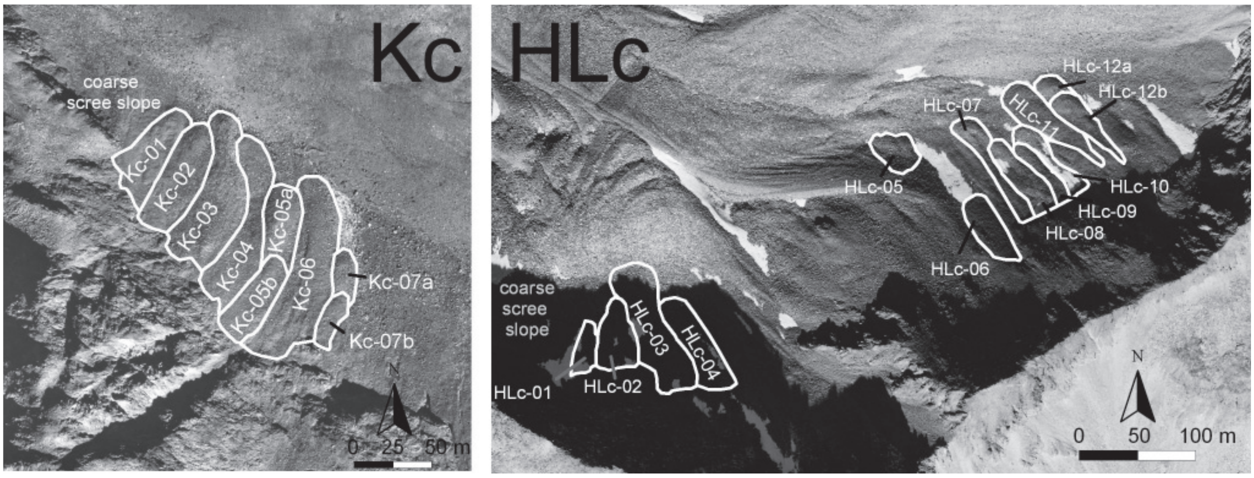

Figure 3: Spatial distribution of the STLs and distinct coarse scree slopes in both parts of the study area. Note the bended shape of most of the STLs in the Kc indicative for ongoing deformation of the remaining buried ice mass. For further explanation refer to text (Orthophotos: (i) Kc: 26.08.1998, © Bildflug Fischer, Graz; (ii) HLc: 24.09.1997, © BEV, Vienna).

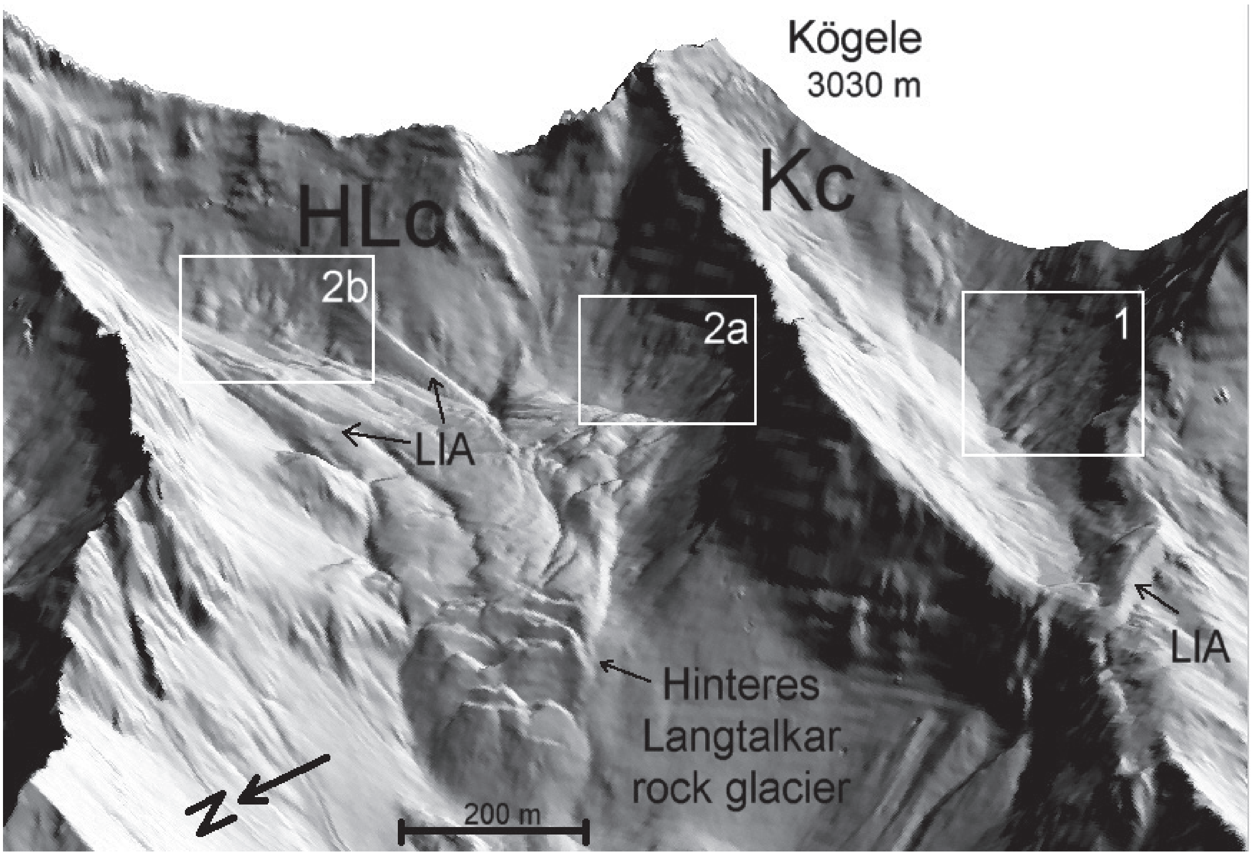

Figure 4: 3D-hillshade model showing the spatial distribution of STLs in the study area: box 1 – STLs in the Kc, box 2a – STLs in the SW-rooting zone of the rock glacier Hinteres Langtalkar, box 2b - STLs in the NE-rooting zone of the rock glacier Hinteres Langtalkar. Note the distinct LIA-moraine ridges (DTM based on orthophotos from 26.08.1998, © BEV, Vienna).

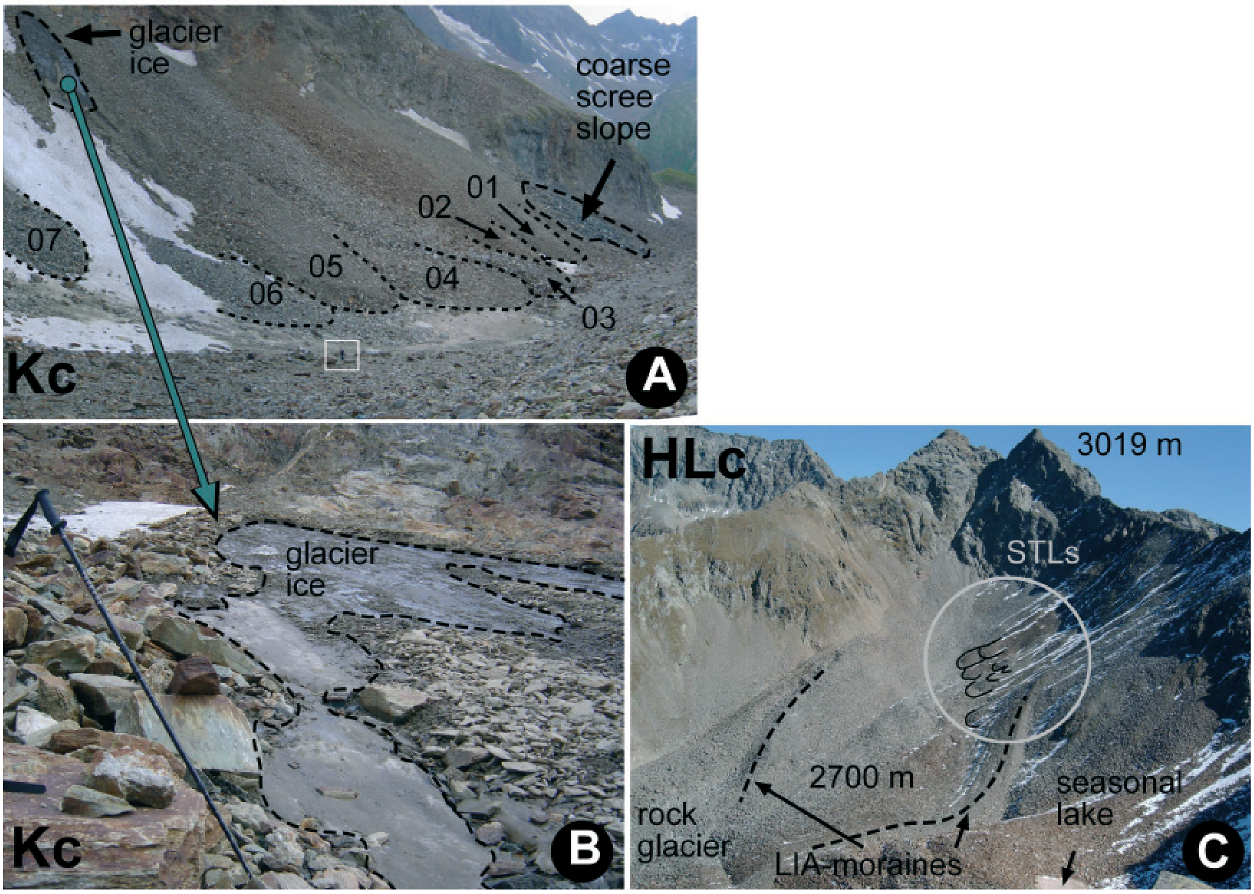

Figure 5: Field situation: (A) Kc: All seven STLs of the Kc; note the person in the white box for scale. Exposed glacier ice can be seen on the upper end of the talus slope. (B) Kc: exposed glacier ice under a thin veneer of debris close to the cirque headwall. (C) HLc: Some of the STLs in the HLc have been formed at the inner slope of the LIA-lateral moraine (all photos A. Kellerer-Pirklbauer: 18. and 19.08.2004).

5. Characteristics of the STLs

In both cirques, a number of vegetation-free STLs (n=22) have been formed from the slope sediments. In most cases this happened in rather close vicinity of the remaining patches of superficial ice and snow (Fig. 3-5). In the Kc, nine conspicuous STLs have been mapped. These features occur as one cluster at the SW-margin of the cirque. All are exposed to the NE; their lower limits reach 2675 to 2730 m asl Along longitudinal sections, most of the landforms (n=5) appear as one coherent unit ranging morphologically from the headwall area to the valley bottom with one distinct riser at their lower end. By contrast, along two longitudinal sections two distinct risers appear, thus, at those sites a lower (a) and an upper (b) unit of the STL can be distinguished. Morphometric studies of the STLs in the Kc show: (i) heights of the frontal slope 1-3m, (ii) lengths 66-125m, (iii) widths 15-31m, (iv) average slopes 26-30°, and (v) spatial extent 859-3,276m². All STLs in the Kc cover some 14,000m². Surprisingly, most of the STLs in the Kc have a downvalley-bended appearance at plane view which possibly indicates ongoing downward creep of the remaining buried glacier ice.

By contrast to the Kc, the STLs in the HLc occur in two different rooting zones of the rock glacier Hinteres Langtalkar. Four different STLs can be distinguished in the SW-rooting zone. All four features are orientated towards N and cover c.8400m² in total. Some 200 metres to the NE, along the NW-exposed slope of the second, more pronounced rooting zone depression, further nine STLs have been mapped. Here, only at one longitudinal section two distinct risers (i.e. two units) may be distinguished (HLc-11a and b). Morphometric studies of the STLs in the HLc show: (i) heights of the frontal slope 1-6m, (ii) lengths 38-116m, (iii) widths 13-34m, (iv) average slopes 24-35°, and (v) areas 722-3,789m². All STLs in the HLc cover c.19,100m² in total. By considering all mapped STLs, maximum values are: (i) height of the frontal slope 6m (HLc-06), (ii) length 125m (Kc-06), (iii) width 34m (HLc-05), (iv) average slope 34° (HLc-01), and (iv) area 3,789m² (HLc-03). Summing up, more than 33,500m² of both cirques are covered by STLs. Almost all STL are tongue-shaped (L/W >1), only the lower part (a) of the STL HLc-11 is slightly wider than long. All of the described STLs seem to be very active according to their fresh geomorphic appearance.

6. Possible ages of the STLs

Sediments which are covered by glaciers without subglacial movement (e.g. cold-based glaciers, small glacierettes or – at least in some areas – polythermal glaciers) or by perennial snow fields with low inclination are geomorphologically rather stable. Gómez et al. (2003) demonstrated at a comparable study site in Spain that the amount of summer snow cover can determine whether buried ice will decay and if other geomorphic processes will be triggered by melting. As soon as the snow/ice protecting layer is absent the landscape will change.

Based on our glacier/perennial snow field reconstructions, it can be stated that all areas where STLs occur today have been covered by snow and ice at least until the 1920s. According to historic maps, there was no glacier in the NE-rooting zone of the rock glacier Hinteres Langtalkar in 1928/29. However, it can be assumed that larger perennial snow fields still covered a substantial - if not the entire - area of this rooting zone. This assumption is based on the spatial distribution of surface ice and snow in 1969. During that stage, surface ice and perennial snow still existed extensively in both rooting zones in the HLc as well as in the Kc even though the areal extent of snow and surface ice decreased dramatically in the time period between the late 1920s and the mid 1960s (Lieb 1987). Thus, even in 1969 most areas where STLs occur today (in particular the lower parts of the tread including the riser) have been protected from geomorphic processes by snow and ice. Only few areas currently covered by STLs in the HLc (locations of HLc-05, HLc-11, HLc-12b) were free of surface ice and snow. By contrast, only the upper parts of some of the STLs in the Kc have been ice free in 1969. The situation was very similar in 1982. However, it must be considered that the spatial extent of surface ice and snow areas was minor during some of the years in-between 1969 and 1982. This is indicated by the distribution of snow and ice in early September 1974 (aerial photographs; no map shown). During that period, most locations of STL-relevance have been surface ice and snow free. Consequently, geomorphic processes may have affected those areas. Thus, the formation of the STLs possibly started sometime after 1969 in most locations. It is not unlikely that the more extensive snow fields around the 1980's re-buried some areas previously affected by the initial formation of STLs. However, at the beginning of the 1980's only the areas of the innermost STLs in the Kc (Kc05a+b, Kc06, Kc07a+b) where certainly covered by glacier ice. By the end of the 1990's, the niche glacier in the Kc disappeared almost completely - at least superficially. Thus, geomorphic process and formation of STLs eventually also affected those areas. Summing up, the formation of STLs in the study area was initiated between the beginning of the 1970s (northern part of the Hc) and the end of the 1990s (innermost STLs in the Kc), i.e. all STLs are very young geomorphic features formed very recently in highly active paraglacial environments.

7. Conclusion: Deglaciation and paraglacial landscape evolution

Our results indicate that both studied cirques are in a state of transition between a glacial and a periglacial environment. The evolution of the Kc since the end of the LIA is summarised and illustrated in the cross-profiles in Fig. 6. During the LIA-maximum around 1850 a small glacier covered most of the Kc. Small ice-free rock faces above the glacier produced only a small amount of debris by cryogenic processes. The retreat of the glacier increased the area of ice-free rock faces and consequently the input of debris on the shrinking ice mass. The glacier shrinkage reduced the glacier's ability to remove the debris. Until 2004, debris input on the glacier surface (periglacially weathered material and paraglacially reworked glacigenic slope sediments) buried almost completely the remaining glacier. The presence of this debris layer influences ablation rates by reducing the amount of ablation of underlying ice by shielding it from insolation and atmospheric heat. Furthermore, permafrost conditions in the study area favour the conservation of buried ice. Such a buried glacier remnant can be seen as a type of massive ground ice and, thus, a typical element of permafrost environments (French 1996). According to Etzelmüller and Hagen (2005), glacier ice with perennial sub-pressure melting point temperatures becomes part of the permafrost domain. Mass movement processes - gravitational and meltwater induced (creeping, sliding) - at the ice surface and within the debris layer caused the formation of the STLs. This process occurred predominantly at the lower end of the 'talus' slopes, thus, a concave-up slope profile evolved. Slow creeping of the buried glacier remnant generated an outward bend of the STLs in plan view (Fig. 3). In case that the thickness of the debris-cover equals the thickness of the active layer the glacier ice remnant will be preserved. A high rate of debris deposition on the Kc glacier remnant, a relatively stable local climate, permafrost conditions, and sluggish moving buried glacier ice will cause inefficiency of sediment transfer from glacier ice to meltwater. Over time this debris-covered glacier remnant could possible change into small moraine-derived/glacial rock glacier features (Benn and Evans 1998, Shroder et al. 2000, Frauenfelder et al. 2003). In case of atmospheric warming, the thickness of the active layer increases and the surface of the buried ice mass will be lowered by melting towards a new equilibrium, thus further disintegrating the buried ice mass. Such a complex of processes (glacier shrinkage

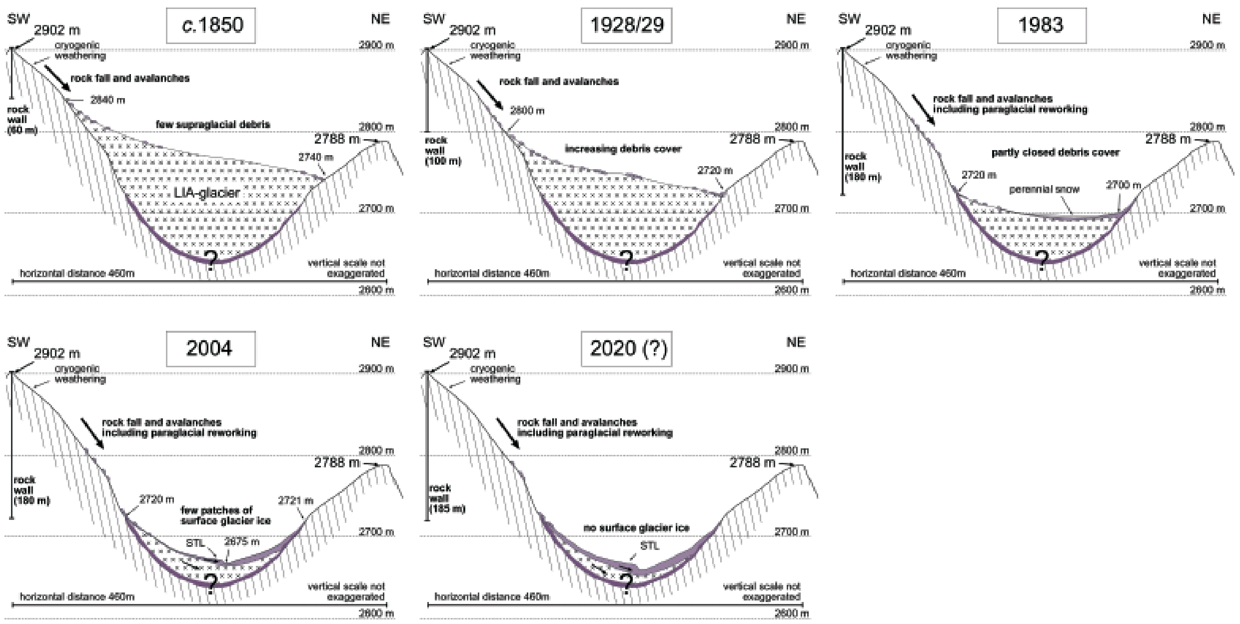

Figure 6: Landscape evolution of the Kc since the LIA-maximum and possible future changes: The cross-profiles illustrate the evolutions of (i) glaciation, (ii) ice free areas, (iii) supraglacial debris-cover, and (iv) movement of ice and debris perpendicular to the main flow direction of the glacier. The construction of the glacier is based on geomorphic and map information. For explanation refer to text, for location refer to Fig. 1.

-> closed supraglacial debris cover formation -> incipient rock glacier creation -> rock glacier downwasting) has also been observed in other recently deglaciated areas (e.g. GÓMEZ et al. 2003).

It is estimated that the active layer thicknesses in the study area are close to 1m in the more sheltered Kc and SW-corner of the HLc, but closer to 3m in the less sheltered NE-corner of the HLc. In the latter, i.e. the more radiation exposed location, no surface glacier ice has been observed in the field. Based on the evolution of the cirque and on the situation in the neighbouring SW-corner of the HLc as well a in the Kc, it seems to be very likely that glacier ice may still be preserved in this part of the HLc but covered by a thicker layer of debris. The recently buried glacier ice in the HLc might be seen as the uppermost part of the rock glacier Hinteres Langtalkar. Thus, it is suggested that coverage of glacier surface by debris could possibly be a crucial process for the ice nourishment of the rock glacier.

Acknowledgments

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