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LiDAR for monitoring mass movements in permafrost environments at the cirque Hinteres Langtal, Austria, between 2000 and 2008

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Abstract. Permafrost areas receive more and more attention in terms of natural hazards in recent years due to ongoing global warming. Active rockglaciers are mixtures of debris and ice (of different origin) in high-relief environments indicating permafrost conditions for a substantial period of time. Style and velocity of the downward movement of this debris-ice-mass is influenced by topoclimatic conditions. The rockglacier Hinteres Langtalkar is stage of extensive modifications in the last decade as a consequence of an extraordinary high surface movement. Terrestrial laserscanning (or LiDAR) campaigns have been out once or twice per year since 2000 to monitor surface dynamics at the highly active front of the rockglacier. High resolution digital terrain models are the basis for annual and inter-annual analysis of surface elevation changes. Results show that the observed area shows predominantly positive surface elevation changes causing a consequent lifting of the surface over the entire period. Nevertheless a decreasing surface lifting of the observed area in the last three years leads to the assumption that the material transport from the upper part declines in the last years. Furthermore the rockglacier front is characterized by extensive mass wasting and partly disintegration of the rockglacier body. As indicated by the LiDAR results as well as from field evidence, this rockglacier front seems to represent a permafrost influenced landslide.

1 Introduction

The creep of frozen ground in high mountains is best expressed in the landforms of rockglaciers. The creeping process itself is determined by e.g. material properties, thermal conditions or the slope angle of the underlying bedrock resulting in characteristic deformation patterns visible on the rockglacier‘s surface (Haeberli, 1985; Barsch, 1996). “Surging” or destabilized rockglaciers have been detected in many regions in the Alps in the last decade. All of these particular landforms show typical surface topography such as e.g. surface subsidence at the upper part or fast growing transversal crevasses (Roer et al., 2005). Knowledge about three-dimensional surface movements supports the understanding of internal processes in permafrost dynamics and is widely used in different applications (e.g. Kääb et al., 1997; Roer et al., 2008). Photogrammetry and geodetic surveys can be regarded as classical techniques for monitoring the surface dynamics of rockglaciers. Photogrammetry provides sufficient spatial and – in case of a good data base – temporal resolution (e.g. Kääb et al., 1997; Kaufmann and Ladstädter, 2009). Geodetic surveys are cheaper to carry out but implicate a lower density of measurement points on the rockglacier surface (e.g. Kaufmann et al., 2006). Differential GPS (DGPS) is a further terrestrial method which is increasingly used for this monitoring purpose although it has the same spatial drawback as geodetic surveys (Lambiel and Delaloye, 2004). Space-borne differential synthetic aperture radar (DinSAR) interferometry offers very accurate measurements especially of vertical surface displacements (cm to mm) (Kenyi and Kaufmann, 2003). LiDAR (Light detection and ranging) or Laserscanning – airborne (ALS) as well as terrestrial (TLS) – is a rather new technique to survey periglacial processes. Usage of TLS on rockglaciers in the European Alps started at the beginning of this decade and allows acquiring 3-D surface data with a high spatial sampling rate. Long-range TLS (more than 400 m) is of particular interest for measuring high mountain environments as it offers very detailed digital surface models in non-accessible terrain (e.g. Bauer et al., 2003). A measuring range of up to 2000 m allows hazardous sites to be easily

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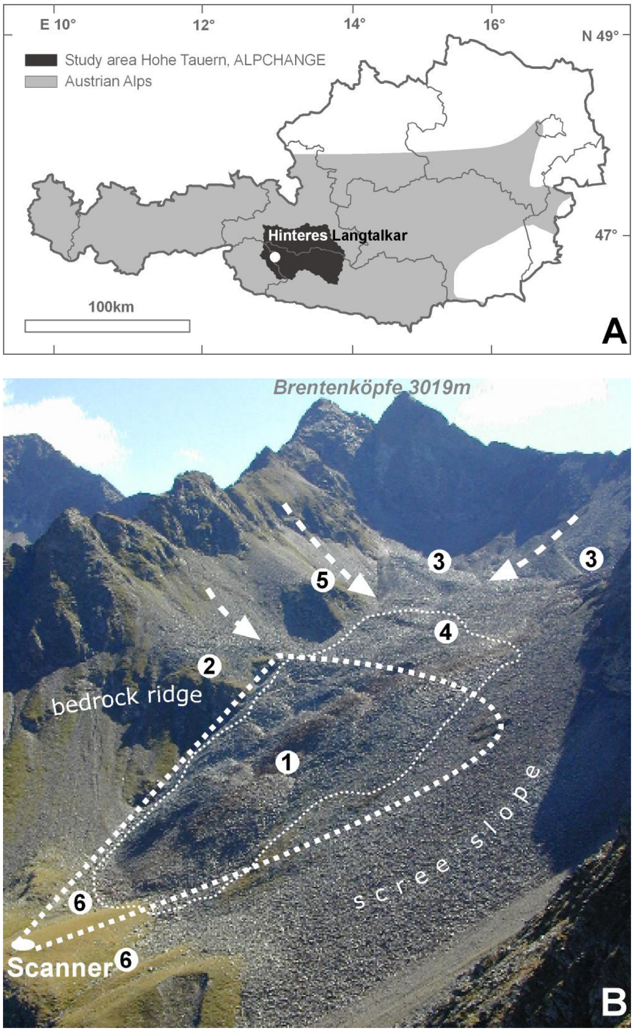

Fig. 1. Location of Hinteres Langtalkar within Austria **(A)** and the monitoring configuration **(B)**. Numbers in the photograph: (1) Area of very high rockglacier movement (bordered with the thin dashed line), (2) prominent bedrock ridge, (3) latero-terminal moraine ridges (Little Ice Age, ∼1850 AD), (4) several transversal crevasses on rockglacier indicating high strain rates, (5) meteorological station and (6) recently deposited boulders spreading over alpine meadows. Scanner‘s position appr. 90 m distance to rock glacier front (Photograph kindly provided by Viktor Kaufmann 24 August 2003). White arrows indicate material transport from the adjacent slopes to the rockglacier.

measured from a safe distance. TLS provides high resolution, adequate accuracy and high availability over long periods of time at comparably low cost. Despite these advantages, TLS has rarely been used in characterizing rockglacier movement (Bauer et al., 2003; Avian et al., 2008; Bodin and Schoeneich, 2008). An extensive overview of remote sensing applications in monitoring permafrost related hazards give Kääb et al. (2006). The objective of this study is to (a) present a multi-temporal analysis of TLS data of the collapsing frontal area of the very fast moving rockglacier Hinteres Langtalkar covering the period between 2000 and 2008 and to (b) discuss the results in a broader context.

2 The rockglacier Hinteres Langtalkar

The studied rockglacier Hinteres Langtalkar (N46°59′, E12°47′) is located in the Schober Mountains, Hohe Tauern Range, Austria, and has been subject of geomorphological studies since the mid 1990s. A remarkable movement over a prominent bedrock ridge starting most likely in 1994 (reported from M. Krobath in Avian et al., 2005) was the scientific reason for initiating geodetic, photogrammetric and LiDAR measurements. The rockglacier‘s length and width are 900 and 300 m, respectively. The landform itself covers an altitudinal range from appr. 2700 m a.s.l. – covering two root zones – to 2455 m a.s.l. at the front. The collapsing area of the rockglacier has a longitudinal range of appr. 230 m with a difference in elevation of appr. 150 m. The 150 m wide rockglacier front has reached flat terrain covered by well developed alpine meadows appr. in 1997 (Avian et al., 2005; Kaufmann and Ladstädter, 2009). A geodetic network was established in 1998, annual measurements have been carried out since (Kienast and Kaufmann, 2004). Multi-temporal photogrammetric analyses with data from 10 epochs (1954, 1969, 1974, 1981, 1991, 1997, 1998, 1999, 2004 and 2006) were carried out (e.g. Kaufmann and Ladstädter, 2009). Mean horizontal movement rates calculated for the entire rockglacier increased from 0.11 $\mathrm{m\,a^{-1}}$ in 1999/2000 to 0.18 $\mathrm{m\,a^{-1}}$ in 2003/2004 and have decreased since then to 0.10 $\mathrm{cm\,a^{-1}}$ in 2007/2008 (Kaufmann and Ladstädter, 2009). The lowest part of the rockglacier shows very high horizontal displacement rates. Maximal movement ranges from 1.75 $\mathrm{m\,a^{-1}}$ (derived from TLS for the lowest part by surface structure matching, Avian et al., 2008) to 3.60 $\mathrm{m\,a^{-1}}$ (derived from automatic photogrammetry for adjacent areas covered by TLS (Kaufmann and Ladstädter, 2009).

3 Data acquisition and digital terrain model (DTM) extraction

The integrated LiDAR system is capable of describing 3-D surface within a one hour measurement and in terms of multi-temporal data sets 3-D motion, and deformation of rockglacier surface. LiDAR is a time-of-flight system that measures the elapsed time of the laser pulse emitted by a photodiode until it returns to the receiver optics. Maximum range mainly depends on the reflectivity of surface (which is excellent for snow, rock or debris), and atmospheric visibility (best for clear visibility, bad for haze and fog). Since each single measurement consists of a multitude of laser-pulses, different measurement modes (first pulse, last pulse, strongest pulse) give proper results even during bad weather conditions and

Table 1. Scanner parameters and values of Riegl LPM-2k Long Range Laser Scanner.

Scanner parameter	Value (range)
Measuring range for: – good diffusely reflective targets – bad diffusely reflective targets	up to 2000 m >800 m
Ranging accuracy	+50 mm
Positing accuracy	Measuring time/point 0.25 s to 1 s
Measuring beam divergence	1.2 mrad
Laser wavelength	900 nm
Scanning range – horizontal – vertical	400 gon 180 gon

on poor surfaces that may otherwise lead to ambiguous measurements like vegetated, moist or roughly structured terrain (Baltsavias et al., 1999).

3.1 Data acquisition

The LiDAR instrument used in this study represents a long range scanner (Riegl LPM-2k, wavelength 900 nm, ranging distance up to 2000 m) and therefore the frequency is limited to 4 Hz (for more information see Table 1). For exterior orientation of the sensor a geodetic network of five reference points was established. For each of the measurements the sensor orientation was obtained independently. The sensor location itself was selected at a distance of about 90 m to the front of the rockglacier. A region of interest (ROI) defines both the measurement raster, and the distance measurement parameters like integration time and mode. The laser scanner performs tasks of a predefined measurement schedule to automatically measure regions of interest. The resolution (point density) of the measurements was mainly limited by the acquisition time. A grid width of 0.5 m could be established at the centre of the front slope, corresponding to 140×200 single measurements.

First methodological measurements using TLS in the study area were carried out in July and August 2000 at the rockglacier Hinteres Langtalkar and the nearby debris covered glacier Gössnitzkees and were repeated in July and August 2001. Beginning with 2004, annual measurements with focus on periglacial analyses started and were afterwards implemented in the project ALPCHANGE which was initiated in 2006.

Measured point density varies due to problems with energy supply in 2006, 2007 and 2008 (Table 2), as a consequence the scanning increment had to be reduced. Larger shadowed areas occur in the upper part of the scanning sector due to a pronounced surface topography of transversal ridges and furrows (Fig. 1).

Table 2. Periods of data acquisition and quality parameters (mean deviation of translation after regression analysis).

Period	total pts	valid pts	PR (1)	OA (2)
07/2000	27 048	26 517	0.98	0.07
08/2000	27 048	26 437	0.98	0.06
07/2001	27 048	26 274	0.97	0.02
08/2001	26 910	26 312	0.98	0.02
08/2004	20 424	19 818	0.97	0.02
08/2005	27 048	17 843	0.65	0.02
09/2006	7836	6048	0.77	0.02
09/2007	6384	5739	0.90	0.02
08/2008	6384	9315	0.90	0.02

(1) PR: point ratio=numbers of points used/total number of points measured (2) OA: orientation accuracy [m]

3.2 Data processing

3.2.1 Pre-processing

The classification of the raw laser measurements allows the examination of the quality and reliability of the distance measurements. Uncertain measurements are weighted smaller or even dismissed for the subsequent data evaluation. The classification is based on an analysis of the reflectivity, the RMSE (as each single measurement consists of a multitude of laser-pulses), the structure (e.g. detected artefacts due to moisture), and external sensors (e.g. meteorological stations to estimate atmospheric influences to laser distance measurement).

3.2.2 Orientation

To guarantee the comparability of measurements, both orientation (e.g. due to subtle misalignments of the scanner platform) and distance measurements (due to atmospheric

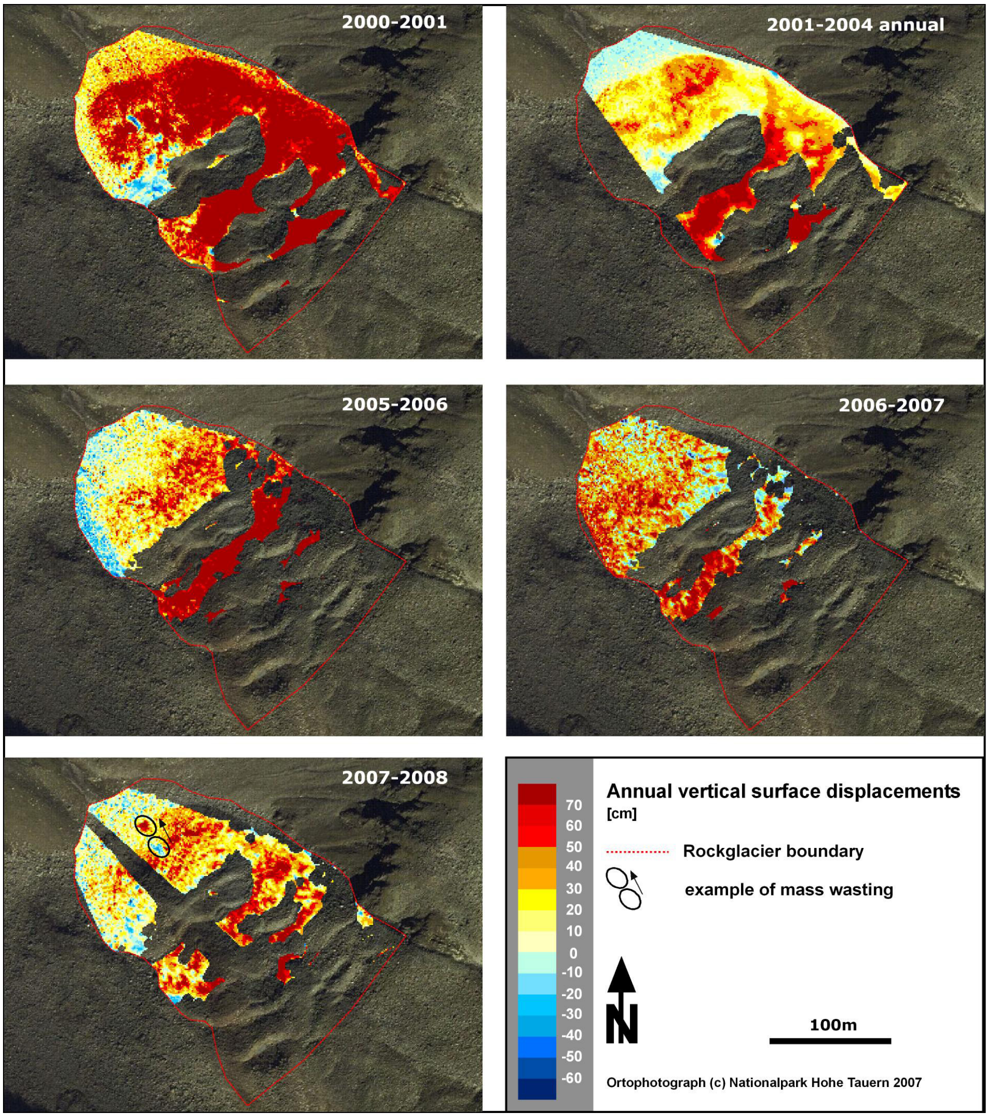

Fig. 2. Annual vertical surface displacements in [cm a^{-1}]. Parts of obvious material shifting are indicated with black circles and arrows showing direction of movement. Orthophotograph 2002, kindly provided by Nationalpark Hohe Tauern © 2007.

influences) are compensated. Repeatable sensor orientation is performed continuously using reflective targets fixed on stable surfaces in the spherical field of view of the sensor (five targets at a distance of 30 to 75 m to scanner position). A centroid localization algorithm on the laser reflectance image gains the angular components of the target coordinates. The distance is calculated as weighted average of all individual distance measurements covering the target. Since our version of LPM-2k does not contain an electronic levelling sensor like standard theodolite, we determine all unknown position and orientation parameters using the reference targets. As a consequence the following tasks are crucial for precise orientation and the essential components of our orientation process:

- stable distribution of the orientation targets (strongly depending on study site conditions)
- robust automatic evaluation of the usability of target measurements
- stable mathematical methods and algorithms for sensor orientation under various restrictions

3.3 DTM generation

To represent each measurement in a user selected reference coordinate system, we convert the oriented laser point cloud to a dense DTM. A DTM is a regularly spaced grid in desired resolution on an analytical model of the local surface, in the simplest case a horizontal or vertical plane. It is used to store the elevation as a vertical distance at the grid points. We generalize the DTM to an arbitrary reference surface, to be able to represent the surface data in best resolution, since most of the potentially insecure surfaces are characterized by steep fronts. In case of the presented study the rockglacier front is approximated by a best-fit plane based on the global 3-D point cloud.

Direct mapping from the sensor spherical system to the DTM cartesian coordinate space would result in a sparse and non-uniform elevation map, especially at large distances. To avoid interpolation artefacts, the Laser Locus Method (Kweon and Kanade, 1992) for DTM generation (Bauer and Paar, 1999) proves to be a robust tool for data acquisition from flat angles, and supports error detection and utilization of additional confidence values provided by the range sensor.

Since the DTMs of (temporally) different surface measurements are geo-referenced, simple differences between the DTMs reflect the changes in elevation (Fig. 2). As a consequence we derive a full description of change in elevation, as well as spatial distribution of resulting patterns, or arbitrary profiles on the surface.

4 Results

TLS in first place delivers a 3-D point-cloud from which afterwards a DTM with user specified spatial resolution is calculated. Since the point density of acquired data varies from area to area the quality of the reproduction of the real surface in a DTM is heterogeneous. The DTM of rockglacier Hinteres Langtalkar delivers a spatial resolution of 1 m, therefore surface roughness is sometimes represented accurately (with boulder sizes exceeding the spatial resolution) or only approximated (smaller boulder sizes, small cracks).

The analysis of the surface dynamics of the rockglacier Hinteres Langtalkar is based on vertical surface elevation changes which have been calculated annually over six time periods and two times inter-annually beginning with 2000 to 2008. Annual vertical surface elevation changes are presented in Table 3 and Fig. 2. The results of the observed sector at the rockglacier are not representative for the entire landform in magnitude due to the outstanding character of the ongoing frontal processes. Mean surface elevation changes are positive over the entire observation period with 75 cm (2000/2001) to 30 cm of surface elevation changes in 2007/2008.

The period 2000/2001 shows strong positive surface elevation changes almost over the entire scanning sector (>70 cm). Only a marginal area at the left boundary zone presents negative values (<−40 cm). In the period 2001/2004 annual surface elevation changes decrease in most parts of the rockglacier front but mean values are still positive. The surface of the lowest part of the rockglacier front shows elevation changes of ∼25 cm, some parts at the right margin still more than 60 cm. The upper part of the scanning sector remains in strong positive annual elevation changes of >70 cm. The period 2006/2007 does not show clear patterns of surface elevation changes. Values are positive over the entire front (up to 70 cm) with minor exceptions in the right middle part (−10 cm). In 2007/2008 the surface of the middle part of the rockglacier front shows strong positive surface elevation changes (>60 cm) while vertical surface changes of the lowest part and parts of the left margin are significantly smaller (−10 cm to 20 cm). In 2005 problems with sensor levelling inhibited the acquisition of comparable data.

Table 3. Periods of data acquisition and statistical parameters (values are not distributed normally, so the median represents mean rates).

[cm]	00/01	00/04	04/05	05/06	06/07	07/08
			Vertical displacements			
min	−70	−39	−195	−95	−125	−90
max	250	151	135	215	125	155
median	**75**	**28**	***−10***	**35**	**15**	**30**
modal	85	23	−10	20	15	20

5 Discussion on surface dynamics

Results of the vertical surface dynamics demonstrate a mostly uniform behaviour of the tongue of the rockglacier Hinteres Langtalkar. Due to the lack of a long-term monitoring of the near-surface and subsurface thermal conditions a rheological model for the rockglacier Hinteres Langtalkar is not available yet. As a consequence only surface elevation changes were used to simply characterise the ongoing modification of the rockglacier front with its sliding processes. It has to be addressed that in terms of the question of the assumed influence of the ongoing global warming on rockglacier behaviour, surface elevation changes of rockglaciers do not automatically indicate permafrost degradation (Kääb, 2005).

The example of the rockglacier Hinteres Langtalkar shows distinct patterns in vertical surface dynamics in corresponding areas like changes from surface subsidence to a lifting of the surface. This can be addressed as an evidence of mass wasting as well as an indication for potential shear zones causing the process of sliding (Roer et al., 2008).

5.1 Movement patterns

The lowermost part of the rockglacier is characterised by different zones of vertical elevation differences. Considering Fig. 2 annual patterns of surface elevation changes are almost uniform over the rockglacier front, an obvious switch

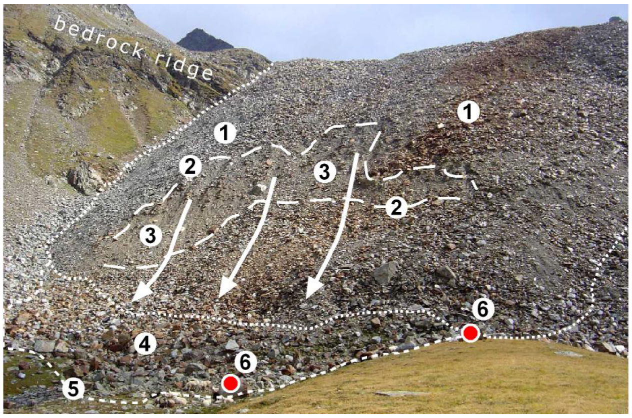

Fig. 3. Terrestrial photograph of the rockglacier front from scanner position. Codes: (1) Coarse blocks on rockglacier surface, (2) edge of ridge (3) exposed fine debris and sand in potential shear zones, (4) deposit area of blocks on alpine meadow (5) active rockglacier spring (6) reflective targets for exterior orientation of the sensor (red dots), white arrows indicate possible motion of mass wasting.

from a decrease of surface elevation to a growth of areas which show surface subsidence. This coincides with results from photogrammetry at the middle part of the rockglacier, where positive horizontal surface displacements significantly decrease since 2004 (Delaloye et al., 2008; Kaufmann and Ladstädter 2009). A decreasing positive volume change of the lower part of the rockglacier indicates that the material transport from the upper part obviously declined in recent years (Avian et al., 2005; Kaufmann and Ladstädter, 2009). As a consequence of the observed mass wasting the meso-scale surface characteristics changed from a convex to a concave surface topography (Roer et al., 2008). Unfortunately measurements were affected by shadowing of crucial parts in the upper part of the scan-sector inhibiting a comprehensive view at the entire part (Fig. 2). Generally, vertical surface dynamics are expressed by decreasing high positive surface elevation changes until 2007 which coincides with photogrammetric analysis (Kaufmann and Ladstädter, 2009).

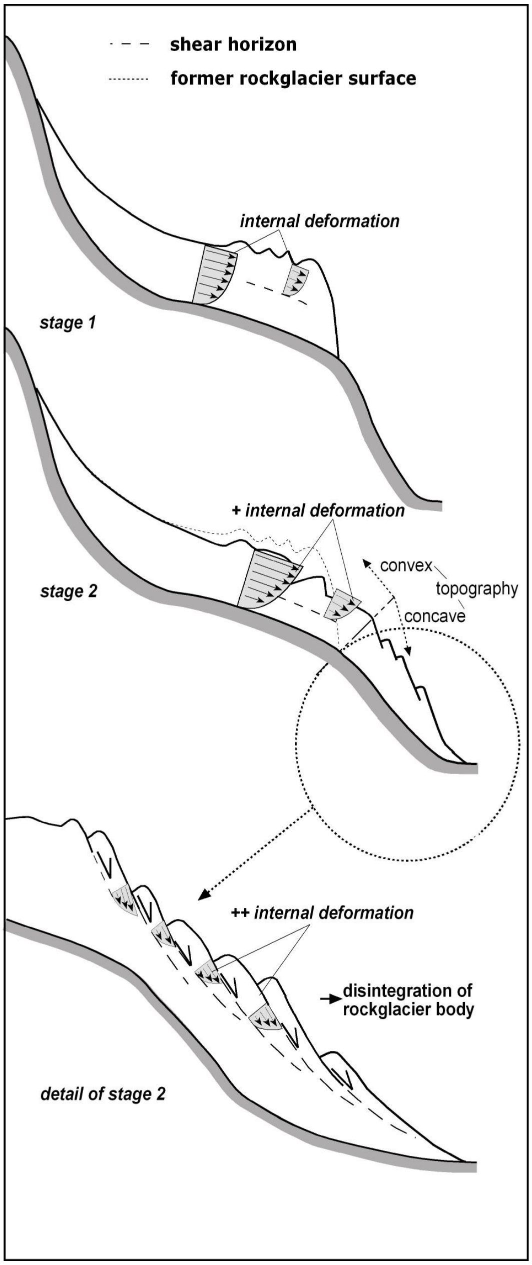

Fig. 4. Schematic profile of the evolution of the disintegration of the front of the rockglacier Hinteres Langtalkar. Stage 1 presents a rockglacier at steady state conditions with typical surface topography in permafrost conditions containing transversal furrows and ridges. Stage 2 (and the detail below) presents the recent situation at the rockglacier Hinteres Langtalkar showing significant surface elevation changes at the upper part of the rockglacier with typical convex surface characteristics. The lower part is expressed by a concave surface topography and an extensive disintegration of the rockglacier front (Roer et al., 2008). Note: The slope situation is exaggerated and does not represent the real situation.

5.2 Shear zones

The assumed disintegration of parts of the rockglacier front and frequent shifting of material is expressed by surface elevation changes with apparent surface subsidence and adjacent surface lifting (Fig. 2, e.g. 2000–2001, 2007–2008). Figure 3 shows several areas of mass wasting at the rockglacier tongue. We presume shear horizons in a rather shallow depth which are expressed by exposed fine material at the individual root zones of mass wasting (Fig. 3). These evidences are frequent over the entire lower part of the rockglacier and are visible in different patterns of surface elevation changes. These patterns are expressed by areas showing high or moderate rates with adjacent areas showing low positive or even negative rates in surface elevation changes (Fig. 2). As the landform rockglacier is defined as a frozen sediment body consisting of ice and debris, we presume that the upper part (in the vertical profile) of the tongue consists of several rotational slides occurring within permafrost conditions (Fig. 4).

Summarizing all evidences, the observed patterns in surface elevation changes, which show sliding on several shear horizons within shallow depths of the rockglacier body, can be addressed as landslides in probable changing permafrost conditions (Arenson et al., 2002; Roer et al., 2008).

5.3 Methodological improvements

From a methodological point of view the selection of an oblique plane adjusted to the real situation is recommendable compared to the usage of a defined vertical or horizontal plane as a reference surface. The scanner's position tends to be unsatisfying for some applications due to shadowed areas in the upper part of the disintegrated rockglacier front. In terms of an effective measuring configuration a stable sensor levelling, bedrock or other stable surfaces within the scanning area ("natural targets") and a uniform distribution of the reference targets are of crucial importance. To validate acquired data especially the availability of stable surfaces or independent measurements like geodetic surveys improve the quality of the generated DTM.

6 Conclusions and outlook

The rockglacier Hinteres Langtalkar shows a striking phenomenon with a rapid advance during the last 14 years. The high movement of the rockglacier stresses the internal structure of the rockglacier leading to deformations on several shear horizons most likely in the active layer or in shallow depths of the consistent permafrost body. Especially the lowest part of the rockglacier is characterized by disintegration and extensive mass wasting. Shallow and deep slides on shear horizons (Figs. 3, 4) are visible exposing fine material from the lower active layer of the permafrost body. The overall process, best described as a landslide in permafrost conditions, seems to decelerate in the last 2 years which is expressed by decreasing surface elevation changes and decreasing volume of the lowest part (Fig. 2).

In terms of the accuracy of the measurements a crucial factor is the availability of independent measurements to validate the acquired data. Furthermore stable bedrock areas – forming "natural targets" – are rare in the scanning sector, but will be integrated in future measurements. An airborne LiDAR survey was carried out in late summer 2008. These data will be compared with TLS data to validate results and accuracy. The next monitoring campaigns will be carried out with a new sensor system (Riegl LMS-Z620, scanning rate up to 11 kHz, ranging distance up to 2000 m) which allows faster data acquisition to avoid problems concerning sensor levelling during the measurements. Furthermore, the faster sensor offers new perspectives to establish a second scanner position to cover larger parts of the rockglacier within a single day‘s campaign.

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