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Creep of Two Alpine Rock Glaciers – Observation and Modelling (Ötztal- and Stubai Alps, Austria)

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Abstract

Our study concentrates on two active rock glaciers in the Eastern Alps, where displacements were observed by the comparison of aerial photographs and GPS (RTK) measurements. The structure of these rock glaciers was also explored by geophysical methods (GPR, refraction seismology and gravimetry). Additionally comprehensive geological, geomorphological, and hydrological studies were carried out. The two studied examples are Reichenkar (Stubai Alps) and Ölgrube (Ötztal Alps) rock glaciers. The source areas of these rock glaciers are situated at altitudes of 2700 to 2800 m a.s.l. The fronts of the tongues extend down to elevations of 2300 - 2600 m a.s.l. Their total areas vary between 0.22-0.27 km^2, the maximum thickness measures 30 - 50 m.

At Reichenkar rock glacier GPS measurements on 37 markers were taken in an interval of one year from 1997 to 2005. A continuous acceleration of 1.8 - 3 m/a was observed at all markers. During summer 2002 a continuous GPS measurement (46 days) shows that the flow velocities (~6 mm/d) are independent from the strongly varying melt water flow and equal to the annual average. Ölgrube rock glacier also shows an increase in flow velocity from 2000 to 2005 (from 0.9 m/a to 1.5 m/a). In contrast to Reichenkar rock glacier the flow velocities of 166 surveying markers show lateral variations and decrease from the toe to the head. For a period of 57 days in summer 2003, daily mean flow rates were significantly higher compared to the daily mean flow rates computed from the yearly data. This indicates significantly less displacements during the winter period. Flow velocities generally increased from 2000 to 2004, but decreased in 2005, a similar pattern to Reichenkar rock glacier.

Models of the internal structures of the rock glaciers were derived from integrated geophysical studies (thickness and density of the debris layer, thickness and debris-content of the frozen core). On the basis of these geophysical models and the rheology of ice the observed creep velocities were successfully modeled. During the last decades the thickness and inclination, and therefore the internal states of stress of the rock glaciers did not change significantly. Therefore, the increase in creep velocity is assumed be a consequence of either higher internal deformation due to higher temperature, or of higher basal sliding due to higher pore water pressure. Support for the theory that higher internal deformation of the frozen core due to higher temperatures caused an increase of flow velocity comes from the observation that the P-wave velocities of the accelerating rock glaciers (Reichenkar, ~3300 m/s; Ölgrube, ~3300 m/s) are below the P-wave velocity of pure ice (3750 m/s). P-wave velocity below the velocity of pure ice indicates reduction of the solid (frozen) contacts between ice and debris within the frozen core and formation of a water film along these contacts.

KEY WORDS: Rock glacier, creep, sliding, climate change, global warming, internal deformation, geophysics, GPR, refraction seismology, gravimetry, water film, Reichenkar, Ölgrube

1. Introduction

Several Alpine rock glaciers exhibit increasing creep velocities since about 1990 (Schneider and Schneider 2001, Ikeda et al. 2003, Lambiel and Delaloye 2004, Roer 2005, Hausmann 2005). It is notable that these rock glaciers nearly show a simultaneous acceleration despite of different internal structure and elevation. An interrelation may be supposed between the increasing flow velocity of rock glaciers and global warming. The relation between various rock glaciers in the Turtmann valley shows a clear correlation between altitude (of the front) and the mean annual horizontal velocity (Roer et al. 2005). For dynamic processes on rock glaciers internal deformation, sliding (on discontinuities) and deformation at the base could act as mechanisms.

2. Location, description and earlier investigations

The location of the three studied rock glaciers is the western part of Austria (Tyrol) (Fig. 1). Ölgrube rock glacier is situated in the Ötztal Alps whereas Reichenkar rock glacier is situated in the western Stubai Alps.

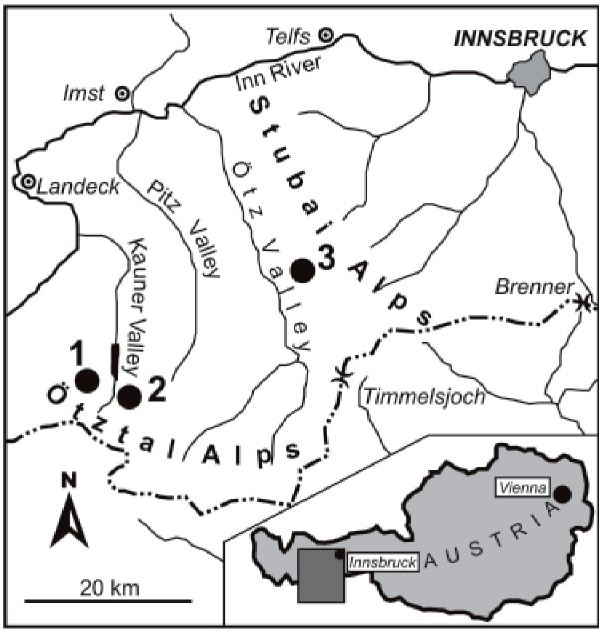

Figure 1: (a) Location map of rock glacier Reichenkar (3) and Ölgrube (2). (b) Photography from Reichenkar rock glacier (July 2004). (c) Photography from rock glacier Ölgrube.

All two rock glaciers are composed of debris derived from metamorphic rocks such as amphibolites, eclogites (Reichenkar), gneisses and micaschists (Ölgrube) (Krainer and Mostler 2000a). Their surface is characterised by well developed longitudinal and transversal ridges and furrows (see Fig. 2a, Fig. 2b). The meltwater is released at the foot of the front slope of all two rock glaciers. Hydrological information on the meltwater flow is available since 1998 (Reichenkar) and 2000 (Ölgrube).

Reichenkar is a 1400 m long, tongue-shaped ice/debris cored rock glacier. It covers an area of 0.27 km^2 and extends from 2750 m to an altitude of 2310 m. The front slope has a steep gradient of 40-41°. Analysis of aerial photographs from 1954, 1990 and 2003 show that the rock glacier is accelerating (from 0.64 m/a to 2.2 m/a). RTK - GPS measurements from 1998 to 2004 show a steady rise in the annual horizontal velocities (Fig. 4a). Continuous GPS observations (in summer 2002) show that the flow is independent from seasonal variations. The strongly varying meltwater discharge does not cause any seasonal variations in the rock glacier movement (Krainer and Mostler 2002).

Ölgrube consists of two tongue-shaped lobes of varying activity produced by two headwall source areas divided by a ridge. This composite rock glacier is 880 m long, 250 m wide and extends from 2800 m to an altitude of 2380 m. The front slope is very steep and active with gradients of 38°. GPS measurements from 2000 to 2005 show a steady rise in the annual horizontal velocities (excepting 2004/2005) (Fig. 2.a). Fig. 2.b displays the increasing flow velocities from the head to the toe during the period 2003/2004. A continuous measurement of 57 days (in summer 2003) indicates less displacement during the winter period. Thus seasonal variations in flow velocities are assumed. In the lower part mean annual horizontal velocities of 1.5 m/a are representative for the period 2003/2004.

	v (m/ns)	**derived from**
Reichenkar	0.145	literature
Ölgrube	0.15	diffraction hyperbolas

Table 1: Mean wave velocities for the time to depth conversion.

	vo (m/s)	**v1 (m/s) L**	**RMS**	**v1 (m/s) T**	**RMS**
Reichenkar	869	3429	± 65	3255	±65
Ölgrube	707	3257	±159	3397	±97
		longitudinal profile		transverse profile	

Table 2: P-wave velocity and standard deviation for the first two layers..

	Longitudinal profile		**Transverse profile**
	Density (Ice Content)	Layer 1 / Layer 2 thickness (m)	Density (Ice Content)
Reichenkar	1.75 g/cm^3 (~58 %)	5 m / 24 m	1.85 g/cm^3 (~53 %)
Ölgrube	1.60 g/cm^3 (~60 %)	5, 7 m / 32 m	1.50 g/cm^3 (~66 %)

Table 3: Mean values for the density (ice content) for the ice-rich permafrost.

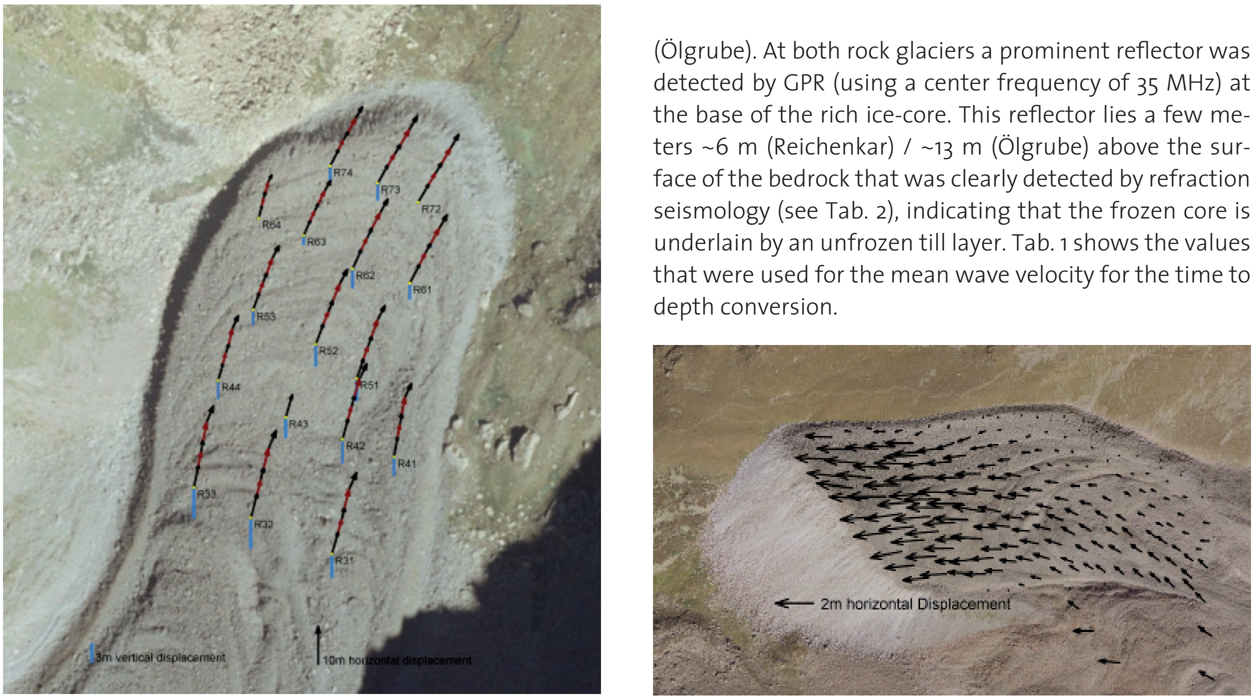

Figure 2: (a) Reichenkar: Horizontal and vertical displacements at each point from 1998 to 2004. (b) Ölgrube: Horizontal displacements from 2003 to 2004. Aerial photographs from 2003 (with by permission of the Administration of Tyrol / tiris)

3. Internal structure - Geophysics

Internal structure and composition of Reichenkar rock glacier was explored by a combination of GPR, refraction seismology and gravimetry. The result of an integrated interpretation of the geophysical data is that Reichenkar and Ölgrube rock glacier consists of three layers. The uppermost debris layer has an average thickness of 5 m (Reichenkar) / 7 m (Ölgrube) and is underlain by a rich ice-core with an average thickness of 24 m (Reichenkar) / 32 m (Ölgrube). At both rock glaciers a prominent reflector was detected by GPR (using a center frequency of 35 MHz) at the base of the rich ice-core. This reflector lies a few meters ~6 m (Reichenkar) / ~13 m (Ölgrube) above the surface of the bedrock that was clearly detected by refraction seismology (see Tab. 2), indicating that the frozen core is underlain by an unfrozen till layer. Tab. 1 shows the values that were used for the mean wave velocity for the time to depth conversion.

After subtracting the regional trend a density model was created in which only densities of the permafrost body were changed. High residual Bouguer anomalies up to -1 mGal (Reichenkar) and -1,3 mGal (Ölgrube) were calculated. The resulting models indicate ice-rich permafrost under the two rock glaciers (Tab. 3).

4. Constraints on Creep Mechanism

The vertical displacements along the longitudinal profile of both rock glaciers show different length and dip angle. On Reichenkar all vectors are directed between the surface topography and a ~3° steeper angle. The active layer has varying thickness, but does generally show a greater thickness under ridges. Measuring points that are located above ridges show clearly a steeper angle than the mean surface.

On rock glacier Ölgrube the vertical displacements increase from the upper to the lower part. In the upper part (0 - 190 m) small horizontal velocities (~ 0,5m/a) and vertical displacements were observed. The lower part (190 - 360m) displays high horizontal and vertical displacements. This behavior, especially the larger vertical changes in the lower part, could be explained by extensional flow. On both rock glaciers positive vertical displacements were not observed.

Increase in MAAT from about 1990 (short time scale, Fig. 4b) correlates well with the increase in flow velocities shown in Fig. 4a. Nevertheless the rock glacier speed up fits also well with the general rise in temperature (long time scale) (Roer et al. 2005).

To get more information about the dynamics of rock glacier, the amount of internal deformation must be computed first. One can use Glen's flow (Glen 1955) law to model the ice/rock matrix as pure ice body (Kääb 2005, in press). The effect of cohesion and the friction angle must be considered if dense ice saturated masses (solid content > 40%) will be modelled (Ladanyi 2003).

We applied Glen's law to describe the rheology of ice in the case of simple shear. For the rock glacier we have been introduced Φ and r_0. The porosity Φ allows flow only where ice exists. r_0 is the shear stress that is caused by the load of the boulder layer. Eq. (1):

$$v_x = \phi \cdot 2 \cdot A \cdot \int_0^{h_{mix}} \left(\tau_0 + \frac{g \cdot d_{mix} \cdot y \cdot \sin(\alpha)}{1000} \right)^n dy$$

In Equation (1) v_x is the surface velocity, g is the gravity acceleration and α is the (surface) slope. Further symbols in Equation (1) are d for density, h for the thickness of the ice/debris mix. To consider the temperature dependency of parameter A we used an exponential expression given by Kääb et al. (2005, in press) (Fig. 4). Eq. (2):

$$A = A_0 \cdot \exp^{(0.4 \cdot T)}$$

The observed values for the surface velocity during the periods 1954-1990 and 2003-2004 are shown in Fig. 5 as horizontal (grey dashed) lines.

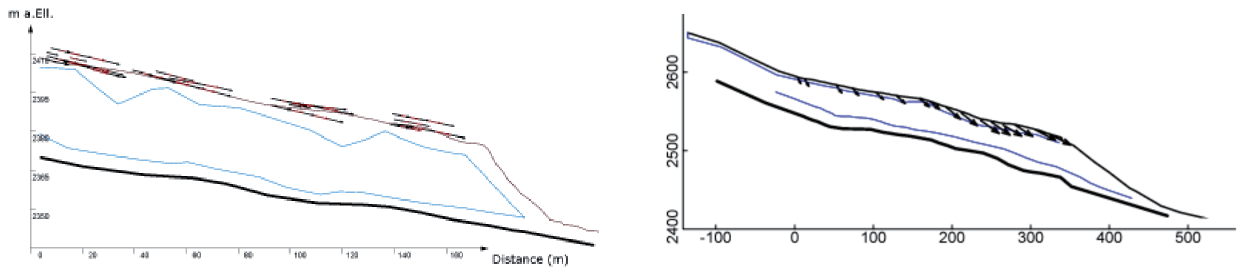

Figure 3: (a) Reichenkar: Horizontal displacements projected to longitudinal section (1998-2004). The length of each arrow is multiplied by the value of two. (b) Ölgrube: Displacements projected to longitudinal section (2003-2004). The length of each arrow is multiplied by the value of ten.

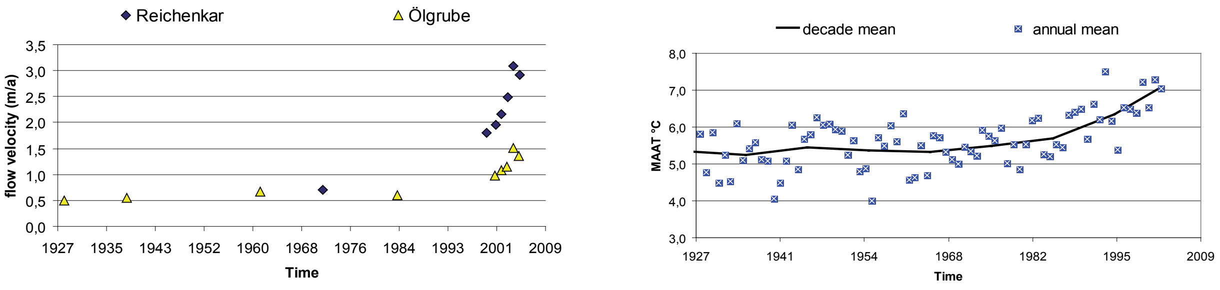

Figure 4: (a) Flow velocities on rock glacier Reichenkar and Ölgrube. (Finsterwalder 1928, Pillewizer 1957, Gerhold 1969, Krainer and Mostler 2006, in press). A steady rise in flow velocity from about 1990 to 2004 and a decrease from 2004 to 2005 is shown. (b) Mean annual air temperature of Längenfeld (Ötztal Alps).

For Reichenkar rock glacier the following two processes are consistent with our observations:

(a) Increasing ice temperature increases parameter A and increases the amount of internal deformation, which causes increasing surface velocities. Our model only fits the observed data if $A_o = A_{max}$ is used (Fig. 5, thick red curve).

(b) To explain the difference between computed and observed surface velocities we combine process (a) with sliding as additional process (yellow area in Fig. 5). This model is consistent for following values of A_o: $A_{min} \leq A_o < A_{max}$. The combination of internal deformation and sliding is shown as blue curve in Fig. 5.

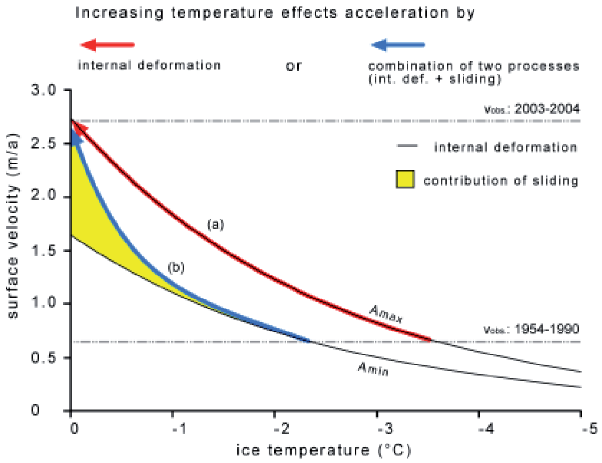

Figure 5: Effect of increasing ice temperature on surface velocity. (a) Acceleration by increasing internal deformation; $A_o = A_{max}$; (b) Acceleration by a combination of necessary internal deformation and additional sliding; $A_{min} \leq A_o < A_{max}$.

For rock glacier Ölgrube the model calculates too high values if temperatures at the melting point were used for parameter A_o. On the other hand the distribution of the ice/debris concentration could also explain the deviation.

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