Geogr. Fis. Dinam. Quat.
33 (2010), 25-36, 13 figg., 1 tab.

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ACTIVE ROCK GLACIERS AT CRODA ROSSA/HOHE GAISL, EASTERN DOLOMITES (ALTO ADIGE/SOUTH TYROL, NORTHERN ITALY)

Abstract: Krainer K., Lang K. & Hausmann H., *Active Rock Glaciers at Croda Rossa/Hohe Gaisl, Eastern Dolomites (Alto Adige/South Tyrol, Northern Italy).* (IT ISSN 0391-9838, 2010).

Two active rock glaciers occur in the eastern and northeastern cirques Cadin del Ghiacciaio and Cadin di Croda Rossa at Croda Rossa in the Eastern Dolomites, South Tyrol (northern Italy).

Both rock glaciers display a tongue-shaped morphology with typical surface morphology of transverse ridges and furrows. The rock glaciers are composed of limestone and dolomite debris derived from Upper Triassic and Lower Jurassic carbonate rocks. Compared to rock glaciers of regions with metamorphic bedrock the debris of both rock glaciers is finer grained and the surface morphology is less well developed. Due to the karstified bedrock beneath both rock glaciers almost all meltwater is released along karst cavities and there is almost no surface discharge. The thermal regime within the debris layer is strongly influenced by the local weather conditions. Ground temperatures are significantly lower than on permafrost-free ground outside the rock glaciers. Annual flow velocities are low compared to other rock glaciers, ranging mostly between 5 and 20 cm.

Internal structures (shear planes) interpreted by georadar data, flow velocities and particularly ice exposures at the upper part of Cadin del Ghiacciaio rock glacier clearly indicate that this rock glacier developed from a debris-covered cirque glacier and is under permafrost conditions still today. We suggest that Cadin del Ghiacciaio rock glacier has developed from a small avalanche-fed cirque glacier during retreat through inefficiency of sediment transfer from the glacier ice to the meltwater. Cadin di Croda Rossa rock glacier lacks ice exposures and shows different internal structures indicating that this is probably an ice-cemented rock glacier.

Key Words: Active rock glacier, Permafrost, Dolomites, Flow velocity, Ground penetrating radar.

Riassunto: Krainer K., Lang K. & Hausmann H., *Rock Glaciers attivi alla Croda Rossa/Hohe Gaisl, Dolomiti Orientali (Alto Adige/Sud Tirolo, Italia Settentrionale).* (IT ISSN 0391-9838, 2010).

Due rock glacier attivi sono presenti nel circo occidentale e nord-occidentale della Croda Rossa (Cadin del Ghiacciaio e Cadin di Croda Rossa), Dolomiti occidentali, Alto Adige (Italia del Nord). Entrambi i rock glacier presentano una forma allungata con una tipica, ma poco evidente, morfologia a dossi ed avvallamenti trasversali. I rock glacier sono composti di detrito calcareo e dolomitico, proveniente dalle rocce carbonatiche del Triassico superiore e Giurassico inferiore. Rispetto ai rock glacier situati in regioni con rocce metamorfiche il detrito dei due rock glacier risulta più fine e la morfologia è meno sviluppata. Dato che la roccia nelle vicinanze dei rock glacier è carsica quasi tutta l'acqua di fusione scorre dentro le cavità, non sono evidenti grandi deflussi superficiali. Il regime termale all'interno dello strato detritico è fortemente influenzato dalle condizioni meteoriche locali. Le temperature di base sono significativamente più basse rispetto alle zone prive di permafrost all'esterno dei rock glacier. Le velocità di movimento annuali sono basse in confronto ad altri rock glacier e comprese per lo più tra 5 e 20 cm.

Le strutture interne (piani di scorrimento) e particolarmente gli affioramenti di ghiaccio nella parte superiore del rock glacier di Cadin del Ghiacciaio indicano chiaramente che questo rock glacier si è sviluppato da un ghiacciaio di circo coperto da detrito che si trova in condizioni di permafrost ancora oggi. Presumiamo che questo rock glacier si sia sviluppato da un piccolo ghiacciaio di circo alimentato da valanghe in una fase di ritiro a causa del mancato trasferimento alle acque di fusione dei sedimenti trasportati dal ghiacciaio. Il rock glacier di Cadin di Croda Rossa non mostra affioramenti di ghiaccio e presenta strutture interne differenti indicando che probabilmente si tratta di un rock glacier con ghiaccio interstiziale.

Termini Chiave: Rock glacier attivo, Permafrost, Dolomiti, Velocità di movimento, Ground penetrating radar.

INTRODUCTION

Vitek and Giardino (1987) suggested to define rock glaciers by their morphology rather than their origin or thermal conditions. Following their proposal rock glaciers

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This work was funded by PROALP (Mapping and Monitoring of permafrost phenomena in the Alps - Autonomous Province of Bolzano-South Tyrol). We greatly appreciate the support of Volkmar Mair (Office for Geology and Building Material Testing, Autonomous Province of Bolzano-South Tyrol). We thank Wolfram Mostler (Innsbruck), Günter Chesi and Thomas Fontana (Institute of Geodesy, University of Innsbruck) for assistance in the field (Georadar and GPS-measurements). We are grateful to W. Haeberli and A. Ribolini for reviewing the manuscript and for their comments and suggestions.

can be defined as lobate or tongue-shaped, slowly flowing mixtures of debris and ice with steep sides and a steep front which slowly creep downslope (for summary see Barsch, 1996; Haeberli 1985; Haeberli & *alii*, 2006; Kääb, 2007; Whalley & Martin, 1992). Rock glaciers are striking morphological expressions of permafrost creep and belong to the most spectacular and most widespread periglacial phenomenon on earth (Haeberli, 1990) and are as well distributed on Mars (Colaprete and Jakosky, 1998; Masson & *alii*, 2001).

Concerning their formation a continuum exists between perennially frozen, ice-rich debris, also referred to as «ice - cemented rock glaciers» and debris covered glaciers, referred to as «ice-cored rock glaciers» as the two end members (Haeberli & *alii*, 2006). Rock glaciers are important agents of geomorphic modification of the landscape, particularly of alpine landscapes. They are widespread in alpine regions and much progress has been achieved during the last years concerning the dynamics and formation of active rock glaciers. (e.g. Ackert 1998; Isaksen & *alii*, 2000; Shroder & *alii*, 2000; Arenson & *alii*, 2002; Kääb & Reichmuth, 2005; Haeberli & *alii*, 2006; Kääb & *alii*, 2007; Hausmann & *alii*, 2007; Humlum & *alii*, 2007; Berthling & *alii*, 1998, 2000). Fukui & *alii*, 2008, studied the internal structure and movement mechanism of a polar rock glacier using GPR, geodetic survey and ice-core drilling to determine whether it is of talus or glacial origin. Remarkable are their interpretations on inter-bedded debris-rich layers similar to thrust structures of valley glaciers.

In the eastern part of the Alps a large number of rock glaciers is present (Lieb 1986, 1996), particularly in the central mountain ranges composed of metamorphic rocks («Altkristallin») like the Ötztal and Stubai Alps, the Deferegger Alps and Schober Group. Many of them are exceptionally large and highly active showing flow velocities from about 1 to 4 m/a (e.g. Hochebenkar, Reichenkar, Ölgrube; Schneider & Schneider 2001, Berger & *alii*, 2004, Krainer & Mostler 2000, 2006). Active rock glaciers are less common in the mountain ranges composed of carbonate rocks such as the Northern Calcareous Alps (e.g. Lechtal Alps) or the Dolomites. Although few active rock glaciers are present in the Dolomites, they have never been studied in detail.

The aim of this paper is to describe two active rock glaciers at Croda Rossa (eastern Dolomites) concerning the morphology, composition, thermal characteristics, hydrology, flow velocities and internal structures, and to discuss their dynamics and formation.

LOCATION

The studied active rock glaciers are situated in two cirques named Cadin del Ghiacciaio (Gletscherkar) and Cadin di Croda Rossa (Gaislkar) on the eastern and northeastern side of the Croda Rossa (Hohe Gaisl) in the eastern Dolomites (Braies Dolomites in the Fanes-Sennes-Braies Nature Park), northern Italy. The location is shown on fig. 1.

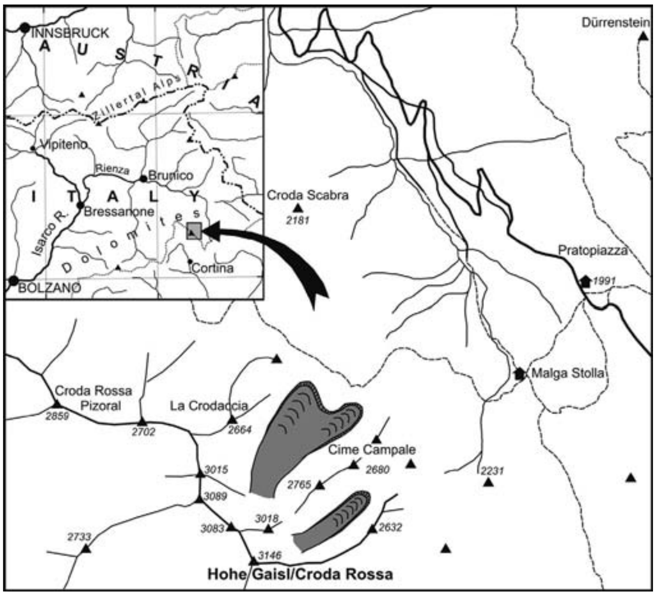

FIG. 1 - Location map of Cadin del Ghiacciaio and Cadin di Croda Rossa rock glaciers at Croda Rossa in the eastern Dolomites, South Tyrol (Northern Italy).

GEOLOGICAL SETTING

The bedrock of the Croda Rossa massif and the catchment area of the rock glacier in the Cadin del Ghiacciaio and Cadin di Croda Rossa are composed of carbonate rocks of the Upper Triassic (Norian - Rhaetian) Hauptdolomite (Dolomia Principale) and Dachstein limestone (Calcare di Dachstein) formations and uppermost Triassic to lowermost Jurassic Gray Limestone (Calcari Grigi) (fig. 2). The Hauptdolomite (Dolomia Principale) formation is a well bedded cyclic succession of intertidal stromatolite facies and thicker, subtidal mudstone beds locally containing abundant megalodonts and gastropods. The thickness is up to 1000 m.

The Dachstein limestone formation is about 300 m thick and composed of thick bedded gray limestone containing megalodonts. Intercalated are thin black pebble breccias. Locally the limestone is dolomitized. Limestone is intensively karstified and displays well developed karst morphology. The Gray Limestone is a 300 m thick succession of well bedded shallow marine grain-, pack- and wackestone locally containing abundant ooids and crinoids. The boundary to the underlying Dachstein limestone formation is gradational (see Bosellini 1998, Keim 1995).

The tectonic block of the Croda Rossa Massif is composed of flat lying Dolomia Principale and Dachstein limestone. This block was uplifted during the Neogene along two steep faults forming a positive flower structure. The ridge of the Cime Campale east of the Croda Rossa is strongly folded and faulted. Due to their orientation these folds are ascribed to the Dinaric compressional event (top SW) (Lang, 2006).

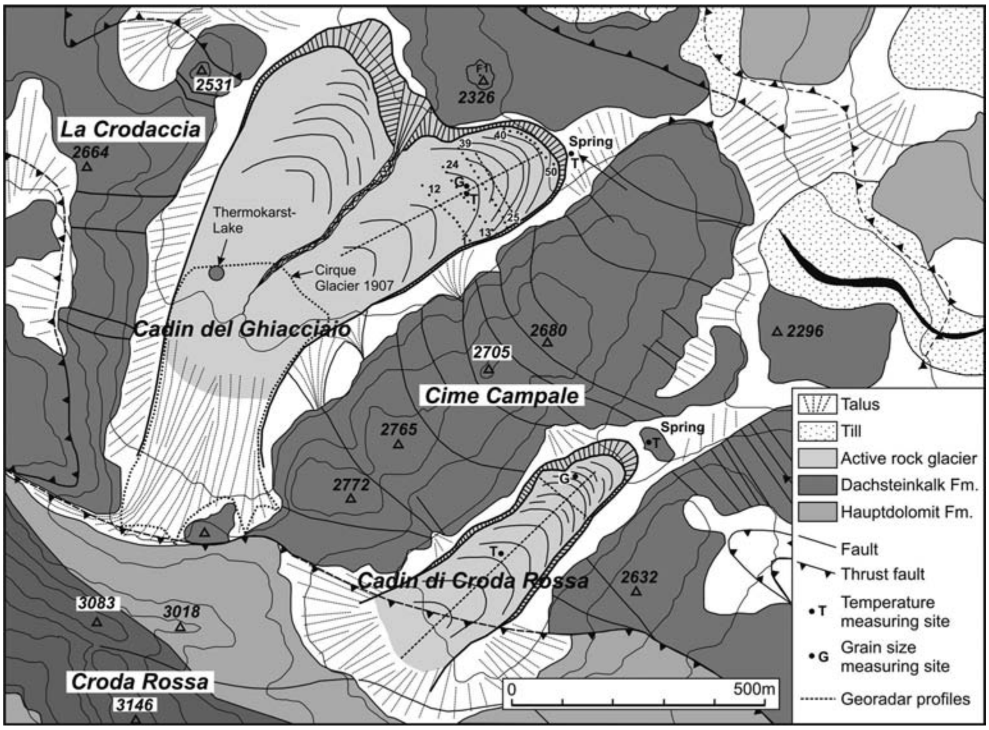

FIG. 2 - Geologic and geomorphologic map of the north-eastern part of the Croda Rossa massif in the eastern Dolomites with active rock glaciers Cadin del Ghiacciaio and Cadin di Croda Rossa.

METHODS

The first step was a detailed geologic/geomorphologic mapping of both rock glaciers and their catchment including the bedrock and the tectonic structures within the bedrock, supported by ortho-photos.

The grain size of the coarse-grained debris layer at the surface of both rock glaciers was measured at 4 locations of different grain-size (fine-to very coarse-grained) on each rock glacier. At each location the longest axis of 200 clasts lying side by side was measured in an area of 5 x 5 to 10 x 10 m. At the snout of Cadin del Ghiacciaio rock glacier three samples were taken from the fine-grained layer below the matrix-free coarse-grained surface layer to determine the grain-size and grain-size distribution by manual sieving.

Optic Stow Away temperature loggers (Onset Computer Corporation, USA) were installed at depths of 50, 100 and 150 cm on each rock glacier. Measurements were made every 2 hours with an accuracy of ± 0.2°C. During the winter, additional temperature loggers were installed at the base of the snow cover on the debris layer of both rock glaciers and outside near the spring to measure the temperature at the base of the winter snow cover (BTS).

During the melt season temperature loggers were installed at the spring of each rock glacier to record the water temperature of the meltwater released by both rock glaciers. Additional single measurements of the water temperature and electrical conductivity of meltwater on the rock glaciers, at the rock glacier springs and at other springs near the rock glaciers were carried out with a hand-held calibrated thermometer and electrical conductivity meter (WTW).

The flow velocity of the Cadin di Croda Rossa rock glacier was determined by using ortho-photographs of the years 1992, 2000 and 2003.

On the Cadin del Ghiacciaio rock glacier we established a geodetic network of 50 survey markers along four transects perpendicular to the flow direction on the eastern lobe of the rock glacier and two fixed control points on the hill in front of the rock glacier in July 2004. The survey markers were first measured on August 6, 2004 using differential GPS technique (Ashtec Z-Max) (the method is described in more detail in Hofmann-Wallenhof & *alii*, 1994, Eiken & *alii*, 1997, Lambiel & Delaloye, 2004). The survey markers were remeasured on September 19, 2005, August 11, 2006 and July 12, 2007.

For determination of the thickness and internal structures of both rock glaciers we used the Ground Penetrating Radar GSSI SIR System 2000 equipped with a multiple low frequency antenna. We measured two profiles on each rock glaciers (parallel and perpendicular to the flow direction) using antennas with a centre frequency of 35 MHz and constant antenna spacing in point mode (constant-offset profiling). Data were collected by fixed-offset reflection profiling. Distance between transmitter and receiver was 4 m, step size (distance between the data collection points) was 1 m. The antennas were oriented perpendicular to the profile direction. The main record parameters were 1000 ns time range, 1024 samples/scan, 16 bits/sample, and 32-fold vertical stacking. The data were processed with automatic gain control (AGC) function, bandpass-filter, migration velocity analyses, migration, time to depth conversion and elevation correction. In the case of identified air wave events (e.g. reflections from steep rock walls) we additionally applied an F-K filter to suppress this signals.

MORPHOLOGY

Cadin del Ghiacciaio rock glacier

The rock glacier is located in the Cadin del Ghiacciaio on the north-eastern side of the Croda Rossa (3146 m) (figs. 2, 3). The rock glacier and its two associated lobes lie in a cirque which is surrounded by steep walls composed of Upper Triassic to Lower Jurassic carbonate rocks of the Dolomia Principale and Dachstein limestone formations and Gray Limestone. Debris of the rock glacier is mainly derived from a prominent, NW-SE-trending fault, along which the bedrock is intensively deformed. The rock glacier is 850 m long, 300-550 m wide and covers an area of 0.3 km^2. The rock glacier extends from an altitude of 2340 m at the front to about 2500 m. The average gradient of the surface is 5°. The surface of the eastern lobe is characterized by transverse ridges and furrows (fig. 4). The grainsize of ranges from fine- to coarse-grained; the front is very steep (35-40°), 30 m high and composed of fresh, reddish material bare of vegetation.

A small alluvial fan is developed between the two lobes. Along the depression between the two lobes debris flow and sieve deposits formed during intensive rainfall events on the surface.

In the upper part massive ice is exposed during the summer months at several places below a less than 1 m thick debris layer (fig. 5). Locally the debris layer is only about 10 cm thick. The ice is coarse-grained, banded, and contains thin, fine-grained debris layers parallel to the banding. Rarely larger clasts occur within the ice.

During the melting season small thermokarst lakes may be developed on the upper part of the rock glacier (fig. 6). Meltwater streams may be present flowing over short dis-

FIG. 4 - The lower part of Cadin del Ghiacciaio rock glacier with poorly developed transverse ridges and furrows, steep sides and a steep front bare of vegetation.

FIG. 5 - Massive banded ice with thin, fine-grained sediment layers parallel to the banding, exposed in the upper part of Cadin del Ghiacciaio rock glacier.

FIG. 3 - The active rock glaciers at Cadin del Ghiacciaio, view toward the south.

FIG. 6 - Small thermokarst lake in the upper part of Cadin del Ghiacciaio rock glacier with ice exposed below a thin debris layer.

tances on the surface of the ice and within the thin debris layer. Downstream the meltwater disappears within the thicker debris layer and no meltwater is seen on the surface of the rock glacier on the lower and middle portions.

Gaislkar rock glacier

Another active rock glacier is located in the Cadin di Croda Rossa, an east-facing cirque surrounded by steep walls which are 200-600 m high (figs. 2, 7). The tongue-shaped Cadin di Croda Rossa rock glacier is 650 m long, 120-195 m wide and covers an area of 0.1 km^2. The rock glacier ends at an altitude of 2425 m and extends to the highest point at 2525 m. The average gradient of the surface is 9°. The front slope is up to 50 m high, the gradient of the front slope measures 35-40°. The surface is characterized by transverse ridges and furrows. A slight depression is developed in the root zone. Ice exposures, surface meltwater streams or thermokarst lakes like on Cadin del Ghiacciaio rock glacier were not observed.

DEBRIS PROPERTIES

Both rock glaciers are supported with debris from the steep wall of the Croda Rossa, particularly from faults and fault zones in the rooting zone along which the bedrock (limestone and dolomite) is intensively deformed and weathered. There is no debris supply from the steep walls at both sides in the lower parts of the rock glacier.

The debris layer («active layer») of both rock glaciers is composed of dolomite and limestone derived from Upper Triassic Dolomia Principale and Dachstein limestone formations and subordinate from the Liassic Gray Limestone. The debris layer is up to several m thick and consists of a gray, coarse-grained surface layer which is up to about 1 m thick and almost free of fine-grained material. Below this coarse, gray surface layer a reddish-coloured layer is present containing high amounts of fine-grained material. The grain size of the surface layer varies from place to place; coarse-grained areas alternate with finer grained areas. Due to the predominating pebbly grain size both rock glaciers are comparable to the «pebbly rock glaciers» of Matsuoka & *alii*, 2005 and Ikeda and Matsuoka (2006).

Cadin del Ghiacciaio

In coarse grained areas most grains range from 11 to 20 cm in grain size, abundant are also clasts measuring 1-10 and 21-30 cm. Clasts >50 cm are rare, those >1 m are very rare. In fine-grained areas clasts 1-10 cm in size constitute 80-90%; subordinate are clasts measuring 11-20 cm; clasts larger than 20 cm are rare.

In the upper, steeper part of the rock glacier the debris has locally been reworked by flowing water on the surface, probably during summer thunderstorms showing characteristic features of debris flows, rarely of sieve deposits.

The front of the eastern lobe of the rock glacier is steep, bare of vegetation and composed of debris containing a high amount of fine-grained sediment. Sieve analysis show that silt and mud (< 0.063 mm) constitute 6-16%, sand 10-28% and gravel 65-83%. The material is poorly sorted, the values of sorting («inclusive graphic standard deviation», Folk & Ward, 1957) range from 2.4 to 3.8.

Cadin di Croda Rossa

The grain-size and grain-size distribution of the surface layer is similar to that of Cadin del Ghiacciaio rock glacier. On coarse-grained areas clasts with diameters of 11-30 cm are most abundant. Larger clasts are rare and clasts exceeding 1 m are very rare.

In fine-grained areas clasts with diameters of 1-10 cm constitute almost 90%; clasts measuring 4-7 cm are most abundant and clasts > 20 cm are very rare.

GROUND TEMPERATURES

During summer the thermal regime of the active layer is mainly controlled by the air temperature (weather conditions), thickness of the frozen core, ice temperature, thickness, and grain-size (porosity and permeability) of the active layer.

Near the surface, down to a depth of about 1 m, the temperature of the debris layer is mainly controlled by the local weather conditions and characterized by pronounced diurnal and seasonal temperature variations on both rock glaciers. Cold weather periods result in a rapid fall of temperature in the debris layer causing a temperature inver-

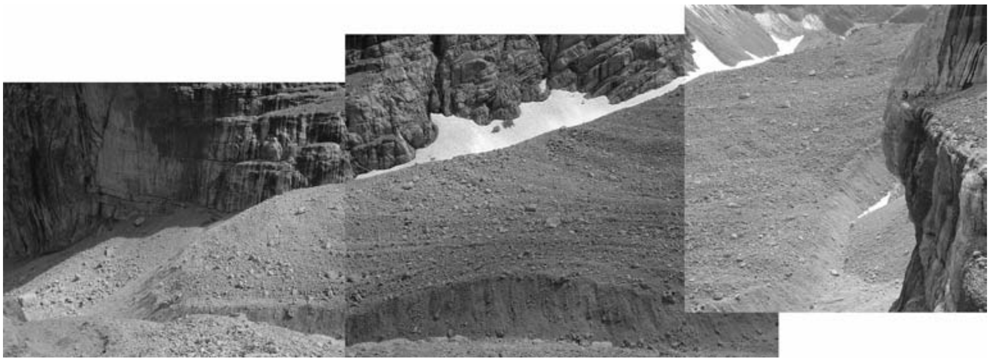

FIG. 7 - The active rock glacier at Cadin di Croda Rossa, view to wards the southwest.

sion within the active layer for 2-3 days. Near the surface of the active layer highest temperatures were recorded during the evening mostly between 18:00 and 20:00 and lowest temperatures during the morning between 06:00 and 12:00. The time delay results from the permeability and porosity of the debris layer and increases with depth. Daily temperature cycles are most significant during warm, sunny days.

At Cadin del Ghiacciaio rock glacier the temperature remained below 2°C at a depth of 150 cm during summer 2004, mostly fluctuating between 0.4 and 1.3°C. At a depth of 100 cm the temperature remained below 7°C and below 10°C at 50 cm, below 15°C near the surface.

During summer 2005 the temperature remained below 3°C at 150 cm, 9°C at 100 cm, 17°C at 50 cm and 21°C near the surface (fig. 8).

During winter the thermal regime of the active layer is additionally influenced by the thickness and duration of the snow cover. A thick (0.8-1 m) winter snow cover has a low thermal conductivity and thus acts as a thermal filter with respect to short-term variations of air temperature (Haeberli, 1985). Therefore no daily temperature variations are recorded at the base of the winter snow cover. During winter a temperature inversion within the active layer is observed on both rock glaciers. The deepest temperatures occur near the surface of the active layer at the base of the snow cover and higher temperatures are observed at a depth of 150 cm. Although a thicker snow cover acts as an isolating layer, temperature variations caused by changing weather conditions were also observed during winter due to thickness variations of the snow cover. Particularly on ridges the snow cover is thin or absent (wind-blown) and there also during winter air temperature may infiltrate into the active layer. Similar observations are recorded from many active rock glaciers (e.g. Berger & *alii*, 2003; Krainer & Mostler, 2000a, 2001, 2004).

At Cadin del Ghiacciaio temperatures ranged between 0°C and –6.2°C at a depth of 150 cm, between 1.3 and –8.8°C at 100 cm during winter 2004/05. Even higher variations were observed in 50 cm and near the surface. These data indicate that during winter 2004/05 the measuring site was covered by a rather thin snow pack and that the high permeability of the debris layer was responsible for the penetration and circulation of atmospheric air into the debris layer also during winter.

During winter 2005/06 temperatures varied between 0°C and –5.6°C at 150 cm, between 0.2°C and –8.0°C at 100 cm, and between 0°C and –13.9°C at 50 cm. Strong temperature variations were recorded until February 21 indicating that until this time the snow pack was also too thin to act as an isolating layer (fig. 9).

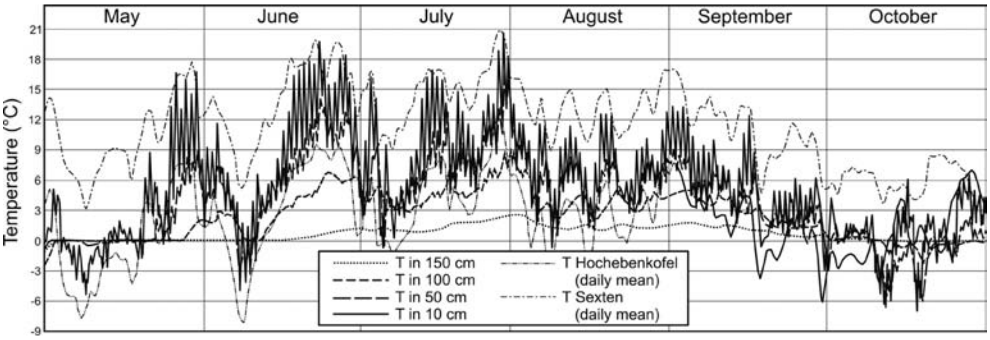

FIG. 8 - Temperatures at various levels within the debris mantle of Cadin del Ghiacciaio rock glacier recorded during summer 2005 (May-October), and temperatures of the meteorological stations at Sesto and Cima Piatta Alta (daily mean).

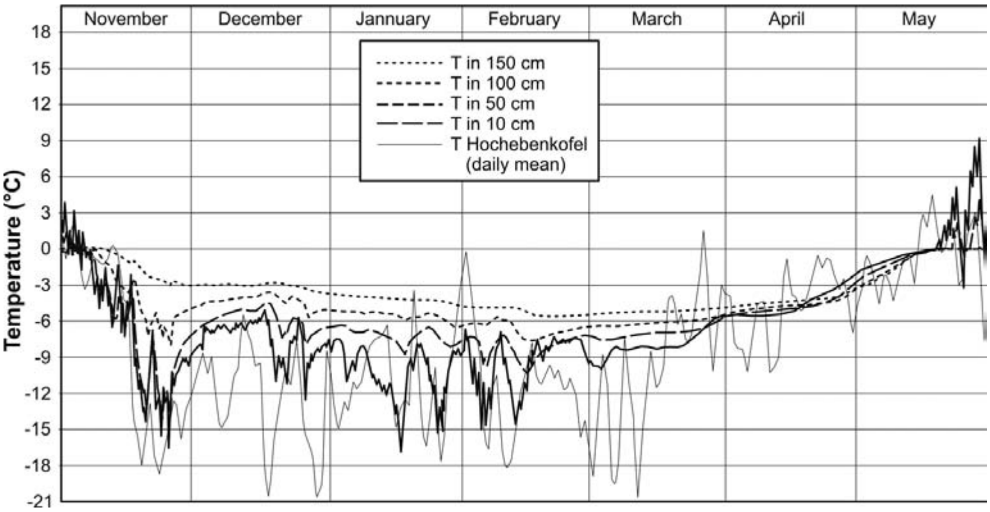

FIG. 9 - Temperatures at the base of the snow cover (BTS) and within the debris layer at Cadin del Ghiacciaio rock glacier from November 2005 to May 2006.

During winter lower BTS temperatures were recorded at the base of the snow cover on the rock glaciers than outside the rock glaciers, although temperatures were also considerably deep outside the rock glacier, probably resulting from the karstified bedrock and the formation of ice in the karst cavities during winter.

Between February and May 2006 BTS outside Cadin del Ghiacciaio rock glacier varied between –5.5 and –2.9°C, and between –14.5 and –4.5 on the rock glacier.

During winter 2004/05 and 2005/06 deep temperatures have also been recorded within the debris layer and at the base of the snow cover (BTS) of Cadin di Croda Rossa rock glacier (fig. 10).

HYDROLOGY

At the base of the steep front of both rock glaciers springs are present during the melt season which release only a small part of the meltwater. During the melt season discharge is mostly less than 1 l/sec, later in the season (August, September) the spring is mostly dry. The water temperature of the spring at the front of the rock glaciers remains constantly below 1°C during the entire melt season.

The meltwater released at the spring flows a few metres through the blocky material in front of the rock glacier and disappears along karst channels within a doline-like karst hole. The bedrock in front of and below both rock glaciers is composed of Dachstein limestone, which displays a typical karst morphology including karren, karst cavities and ponors.

VELOCITY MEASUREMENTS

The surface flow velocity of the rock glacier at Cadin di Croda Rossa was determined by comparison of orthophotos from 1992 and 2003. Distinct huge blocks on the surface of the rock glacier showed annual flow rates ranging from 11 to 21 cm. The average annual flow velocity measures 15 cm.

At the Cadin del Ghiacciaio rock glacier along all transects the surface flow velocities decrease from the axis to the rock glacier margins (fig. 11). From August 2004 to September 2005 the highest horizontal displacement was 22 cm measured at survey marker 32 of transect 3 yielding a mean daily flow velocity of 0.54 mm. Horizontal displacements along the axis measured 14-22 cm, decreased towards both margins to 5-15 cm. Lowest horizontal displacements of 2-7 cm were recorded near the northern part of the front. From September 2005 to August 2006 the highest horizontal displacement was 17 cm recorded at survey marker 18 (resulting in a mean daily flow velocity of 0.52 mm). Horizontal displacement varied between 9 and 17 cm along the axis and from 4 to 7 cm near the margins. From August 2005 to July 2007 highest horizontal displacement was 25 cm recorded at marker 5 of transect 1 (resulting in a mean daily flow rate of 0.74 mm). Low horizontal displacements of 1-7 cm were recorded at the northern part of the front at markers 40-46 of transect 4. Markers 47-50 of transect 4 on the southern part of the front yielded significantly higher displacements of 9-17 cm.

The mean daily flow rates did not change significantly from 2004 until 2007. The mean daily flow rates of transects 1-3 are mostly in the range of 0.3 mm/day, and of transect 4 in the range of 0.2 mm/day (see table 1).

GEORADAR MEASUREMENTS

At Cadin del Ghiacciaio rock glacier a longitudinal section (450 m) and a transverse section (150 m) was recorded on a 20 cm thick snow cover in autumn 2004. On the longitudinal section a well developed basal reflector at a depth of 26±6 m and numerous well developed

TABLE 1 - Mean daily flow rates of Cadin del Ghiacciaio rock glacier

Transect	Markers	6.8.04-19.9.05 410 days displ. cm (mm/day)	19.9.05-11.8.06 327 days displ. cm (mm/day)	11.8.06-12.7.07 336 days displ. cm (mm/day)
1	1-12 (12)	7-16 (0.17-0.39)	4-11 (0.12-0.34)	6-25 (0.18-0.74)
	average	12 (0.29)	7 (0.19)	10 (0.30)
2	13-24 (12)	5-19 (0.12-0.46)	4-17 (0.12-0.52)	7-13 (0.21-0.39)
	average	14 (0.35)	10 (0. 30)	10 (0.29)
3	25-39 (15)	9-22 (0.22-0.54)	4-14 (0.12-0.43)	6-14 (0.18-0.42)
	average	16 (0.40)	9 (0.28)	10 (0.31)
4	40-50 (11)	2-17 (0.05-0.41)	1-10 (0.03-0.31)	2-14 (0.06-0.42)
	average	8 (0.20)	6 (0.18)	7 (0.21)

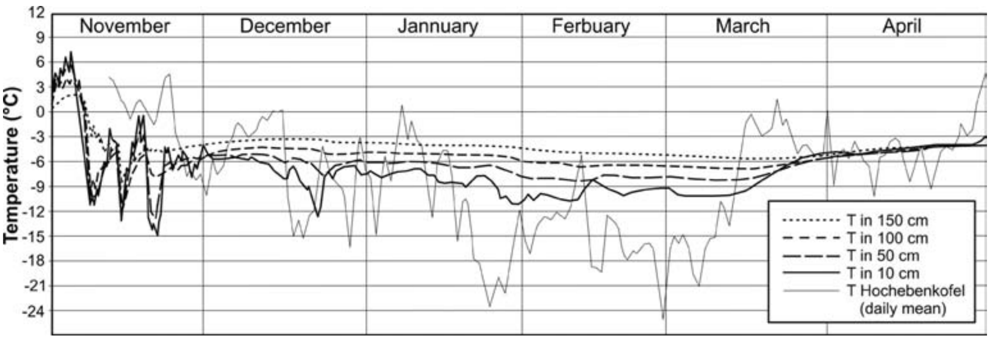

FIG. 10 - Temperatures at the base of the snow cover (BTS) and within the debris layer at Cadin di Croda Rossa rock glacier from November 2004 to April 2005.

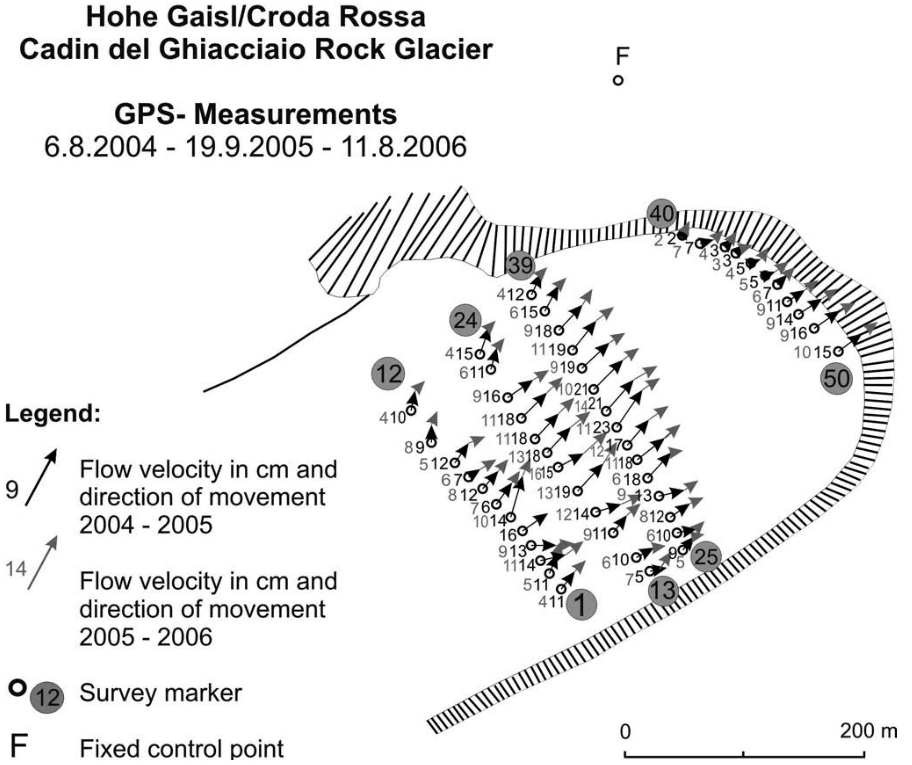

FIG. 11 - Surface flow velocities (horizontal displacements) on the lower part of Cadin del Ghiacciaio rock glacier recorded from August 6, 2004 to September 19, 2005 and from September 19, 2005 to August 11, 2006.

continuous concave reflectors above this reflector were identified (fig. 12). The central part of the section shows reflections with less amplitude than in the frontal part or in the upper (thinner) part of the rock glacier (fig. 12b). Close to the frontal slope the elevation corrected data display a set of continuous reflectors with high amplitude directed parallel to the basal reflector. In the transverse section the continuation of both the basal reflector and the concave reflectors were clearly identified and are well connected at the intersection point with the longitudinal section. The basal reflector in this section has a mean depth of 29±4.5 m. Since its surface is located in prolongation to the bedrock outcrops at the front (fig. 12c) and at the northern margin of the rock glacier it is interpreted as the permafrost to bedrock interface. For both profiles an exploration depth of up to 40 m was attained. Migrations velocity analyses and direct measurements of diffraction hyperbolas result in a mean wave velocity of 0.15-0.16 m/ns. Thus, we interpret the thick zone with distinct concave reflectors and less amplitude reflections to represent the frozen body of the rock glacier. The high contrast in dielectric permittivity and the shape of the concave reflectors can be explained by the presence of deformed, banded ice with thin intercalated debris layers which is documented by ice exposures in the upper part of the rock glacier. The high wave velocity, the good exploration depth and the internal structures are in accordance with the presence of a massive ice core.

In spring 2005 georadar data were collected on a 1-2 m thick snow cover at Cadin di Croda Rossa rock glacier along a 550 m longitudinal section and a 135 m transverse section. Both profiles recorded significant linear interspersions of air wave events which were interpreted by the high frequency content and their slope (fig. 13a). The migrated and F-K filtered longitudinal section is displayed in fig. 13b. In the upper part of the rock glacier a well developed continuous reflector dip down from the surface into a depth of ~15 m. Below a continuous reflector located parallel to the surface is identified in a depth of ~25 m (fig. 13c). In the middle part diffusive low amplitude reflections dominate whereas concave reflectors were not identified. Near the frontal part several vague and discontinuous reflectors with higher amplitude were found. The transverse section displays discontinuous reflectors in depths of up to 30 m according to the intersection with the longitudinal section. However the data exhibit a lower exploration depth than at the Cadin del Ghiacciaio rock glacier which is why the expected basal reflector (in ~45 m) could not be clearly identified.

DISCUSSION

In the Alps active rock glaciers composed of debris derived from limestone and dolomite are rare (see Ikeda and Matsuoka 2006), a few are known from the Dolomites (e.g. Sella, Croda di S. Croce) and from the Northern Calcareous Alps (e.g. Lechtal Alps) but have never been studied in detail. Most active rock glaciers in the Alps occur in mountain groups composed of metamorphic rocks such as mica schists, gneisses and amphibolites («Altkristallin»). In the Eastern Alps most active rock glaciers are known from the Silvretta Group, Ötztal and Stubai Alps, Defferegger Alps and Schober Group, all composed of metamor-

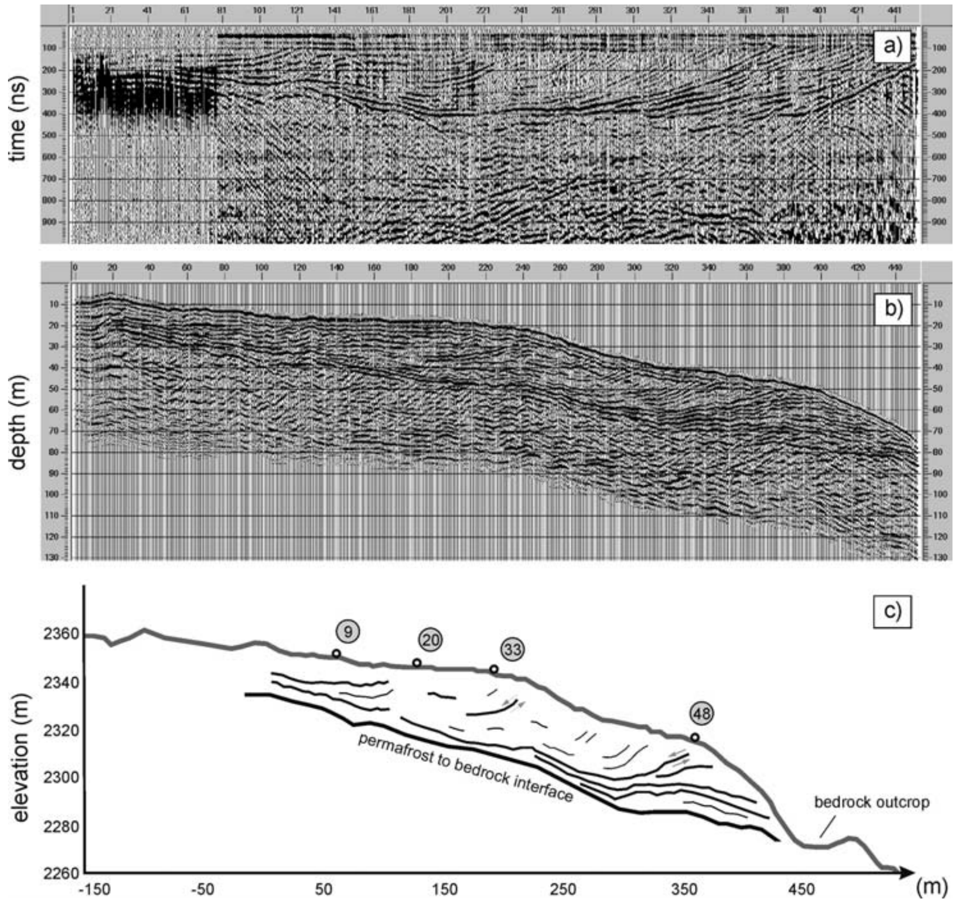

FIG. 12 - Longitudinal georadar section across Cadin del Ghiacciaio rock glacier with 35 MHz antennae: (a) raw data with constant gain; (b) Signal processed data (AGC, band pass filter, F-K filter) after migration, time to depth conversion and elevation correction; (c) Interpretation of major reflectors and shear zones. Symbols and numbers on the rock glacier surface denote the location of survey markers (fig. 11) along the section (fig. 2).

phic rocks (e.g. Lieb, 1986, 1996; Krainer & Mostler, 2000a, b, 2001, 2004; Berger & *alii*, 2004; Gerold, 1967, 1969).

The morphology of the two studied active rock glaciers at Croda Rossa is similar to other rock glaciers, although the surface morphology (furrows and ridges) is less well developed than on rock glaciers composed of metamorphic rocks such as gneiss and amphibolite (e.g. Reichenkar and Sulzkar rock glaciers in the Stubai Alps and Ölgrube rock glacier in the Ötztal Alps; Krainer and Mostler 2000a, b, 2004; Berger & *alii*, 2004).

The grain size of the surface layer is significantly smaller compared to rock glaciers derived from metamorphic bedrock where fine-grained parts are commonly in the range of 10-50 cm and coarse-grained parts up to 100 cm on average. Only on rock glaciers composed of debris derived from schists similar average grain sizes may occur on fine-grained parts (e.g. Schobergruppe). The sorting values of the layer below the coarse-grained surface layer, which contains considerable amounts of fine-grained material (mud-sand-size) are similar to rock glaciers composed of metamorphic rocks, ranging between 2.3 and 4 (very poorly sorted; e.g. Krainer & Mostler, 2000). According to Ikeda and Matsuoka (2006) a ridge and furrow topography is generally less developed or even absent on pebbly rock glaciers but common and well developed on bouldery rock glaciers.

Temperatures within the debris layer are mainly controlled by the local weather conditions, the frozen core of the rock glacier and the thickness of the debris layer. During summer the temperature decreases rapidly within the debris layer. At a depth of 150 cm no daily temperature variations are recorded and the temperature never exceeded +2°C during summer 2004 and +3°C during summer 2005. During the winter 2005-2006 the temperatures at the base of the snow cover (BTS) on both rock glaciers were significantly lower than outside the rock glacier. BTS indicate that permafrost conditions exist on both rock glaciers, also outside near the front of Gletscherkar rock glacier.

The hydrological system of both studied rock glaciers differs significantly from that of rock glaciers in metamorphic bedrock where conspicuous amounts of water are released at the rock glacier springs at the front during the melt season (e.g. Krainer & Mostler, 2002; Krainer & *alii*, 2007). Although high amounts of water derived from snow and ice melt as well as from precipitation (rainfall events) are released from both studied rock glaciers at Croda Rossa, particularly at Cadin del Ghiacciaio where small meltwater streams are present on the surface of the rock glacier in the upper part during the melt season, almost no water is released at the rock glacier springs at the front of the rock glaciers. The surface discharge of both rock glaciers is very small, measuring up to a few litres per second during the

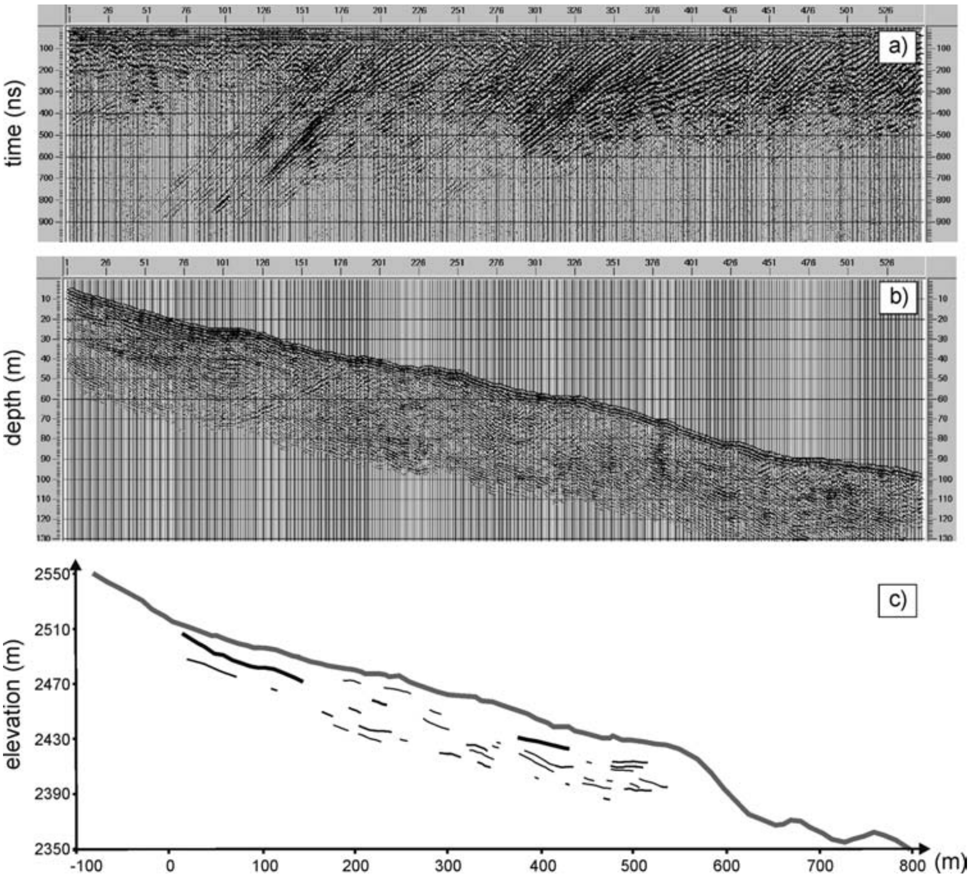

FIG. 13 - Longitudinal georadar section across Cadin di Croda Rossa rock glacier with 35 MHz antennae. (a) raw data with constant gain and interspersion from air wave events; (b) Signal processed data (AGC, band pass filter, F-K filter) after migration, time to depth conversion and elevation correction; (c) Rock glacier topography and interpreted reflectors. The profile location is shown on fig. 2.

melt season indicating that almost all water is released along karst cavities in the limestone below both rock glaciers. The water temperature of the rock glacier springs of both rock glaciers is typical for active rock glaciers, remaining constantly slightly below 1°C during the entire melt season.

Most active rock glaciers display annual surface flow velocities ranging from a few cm up to 1-2 m (summaries in Barsch, 1996; Haeberli, 1985; Vitek & Giardino, 1987; Whalley & Martin, 1992), few rock glaciers show higher flow velocities up to a few meters (e.g. Reichenkar rock glacier up to 3 m, Krainer & Mostler, 2006; Hochebenkar rock glacier up to 5 m, Schneider & Schneider, 2001; Delaloye & *alii*, 2008).

Since 2000 many fast and slow rock glaciers in the Alps display very similar annual velocity variations with exceptionally high flow velocities in 2003/04, followed by a significant drop in flow velocity during the subsequent years 2004-2006 (Delaloye & *alii*, 2008). These annual variations seem to be driven by climate, particularly the high flow velocities of 2003/04 seem to have been caused by the extremely warm summer of 2003.

The two active rock glaciers at Croda Rossa display relatively slow annual flow velocities which can be explained by the relatively slow gradient, by the thickness and by the internal composition of both rock glaciers. The observation period (2004-2007) is too short to see any annual variations in flow velocity, no significant variations were observed. For Cadin del Ghiacciaio rock glacier we calculated velocities from a creep model introduced in Hausmann & *alii*, 2007. The main input parameters were a 3 m thick debris layer, a 26 m frozen core, a dip of 8 ° for the basal reflector and a mean value for the temperature-depended parameter A (at 0°C). To match the observed surface velocities it was necessary to introduce a massive ice core (ice content >80%) in the model.

On both rock glaciers georadar measurements were collected with similar constraints (e.g. centre frequency, weather condition). However the data show large differences for their internal structures and composition. On Cadin del Ghiacciaio the internal structure is characterized by a set of continuous concave reflectors in the central part, parallel continuous reflectors elsewhere and by high wave velocity (0.15-0.16 m/ns). Ice exposures in the upper part of Cadin del Ghiacciaio indicate that the concave reflectors occur within the ice and are caused by numerous thin debris layers in the ice parallel to the banding of the ice. The banding seems to represent shear plains within the ice, indicated by the concave form of the reflectors. The zone of concave reflectors which extends to the front of the rock glacier indicates that the frozen body of the rock glacier contains large amounts of massive, banded ice with thin intercalated debris layers.

Thus, ice exposures, georadar data and creep velocities demonstrate that Cadin del Ghiacciaio rock glacier is an ice-cored rock glacier which developed from a debris-covered cirque glacier. This is supported by Richter (1888), Schulz (1906) Marinelli (1910) and Klebelsberg (1927) who report the presence of a small glacier at Cadin del Ghiacciaio covering an area up to about 0.26 km^2. According to these authors the lower part of the cirque glacier was strongly covered with debris. A small glacier is also shown on old topographic maps from the years 1874 (Wiedenmann) and 1902 (Freytag). The cirque glacier disappeared after 1927, and Meneghel (1994) notes that the cirque of the Cadin del Ghiacciaio is occupied by a rock glacier which contains ice from the former cirque glacier. We assume that Cadin del Ghiacciaio rock glacier developed from a debris-covered cirque glacier due to inefficiency of sediment transfer from glacier ice to meltwater. This model was recently proposed by Shroder & *alii* (2000) based on studies in the Nanga Parbat Himalaya. In early summer we observed that the steep snow field in the rooting zone of the rock glacier is covered by a thin debris layer which is derived by rock fall from the steep wall and particularly from the strongly deformed rocks of the fault zone. This indicates that the cirque glacier was mainly fed by snow avalanches and that the banding with the numerous thin debris layers in the ice reflects an annual layering. Due to the warm-ing since 1990 the cirque glacier disappeared and today only small remnants of the former glacier are present in the steep rooting zone of the rock glacier below a thin debris layer.

The redeposition of debris on the surface during intensive rainfall events by debris flows and rarely sieve deposits, particularly in the upper part of the rock glacier, has rarely been observed on other rock glaciers.

On Cadin di Croda Rossa the internal structure is characterized by a near surface reflector in the upper part, diffusive reflections in the central part, vague and discontinuous reflectors near the frontal part and by a lower wave velocity (~0.12 m/ns). The diffuse reflections and the low velocity exclude the presence of a core with high ice content. The lack of ice exposures and different internal structures obtained by georadar measurements indicate that Cadin di Croda Rossa rock glacier did not develop from a cirque glacier, but more likely represents an ice-cemented rock glacier. A cirque glacier is neither shown on old maps nor described by Richter (1888), Schulz (1907) and Marinelli (1910).

Both rock glaciers are supported by debris from the steep rock walls of Croda Rossa, and particularly by fault zones along which the limestone and dolomite are extensively deformed. Rock fall is the main process by which debris is transported into the rooting zone of the rock glacier.

CONCLUSION

Both rock glaciers display a tongue-shaped morphology with typical but less well developed surface morphology of transverse ridges and furrows. Locally at Cadin del Ghiacciaio surface debris is present which was redeposited during strong rainfall events as debris flows and rarely sieve deposits. Both rock glaciers are supported with high amounts of limestone and dolomite debris from the steep walls of Croda Rossa above the rooting zone and particularly from intensively deformed rocks of fault zones.

As both rock glaciers at Croda Rossa are composed of limestone and dolomite debris, significant differences exist in comparison to rock glaciers which are composed of debris derived from metamorphic rocks. The debris of both rock glaciers is finer grained; the surface morphology is less well developed. Due to the karstified bedrock beneath both rock glaciers almost all meltwater is released along karst cavities and there is almost no surface discharge. Temperatures at the base of the winter snow cover (BTS) indicate that permafrost conditions exist on both rock glaciers, also outside near the front of Gletscherkar rock glacier.

The thermal regime within the debris layer is strongly influenced by the local weather conditions.

Annual flow velocities are low compared to other rock glaciers, ranging mostly between 5 and 20 cm.

Internal structures (shear planes) interpreted by georadar data, flow velocities and particularly ice exposures at the upper part of the rock glacier clearly indicate that Cadin del Ghiacciaio rock glacier developed from a debris-covered cirque glacier. We suggest that the glacier has developed from a small cirque glacier during retreat through inefficiency of sediment transfer from the glacier ice to the meltwater. Cadin di Croda Rossa rock glacier lacks ice exposures and shows different internal structures indicating that this is probably an ice-cemented rock glacier.

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(Ms. presented 15 January 2009; accepted 15 November 2009)