Multi-disciplinary investigation of an active rock glacier in the Sella Group (Dolomites; Northern Italy)

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Abstract

The large active rock glacier Murfreit is situated on a prominent terrace in the northern Sella Group in the central Dolomites, South Tyrol (northern Italy). It is lobate-shaped and exhibits the typical surface morphology of transverse ridges and furrows on its western, most active part. The rock glacier is predominantly composed of dolomite debris derived from the Upper Triassic Hauptdolomit/Dolomia Principale. Compared to rock glaciers of regions with metamorphic bedrock the debris of the rock glaciers is finer grained and the surface morphology is less well developed. During the melt season thermokarst lakes appear on the surface. Meltwater is partly released as surface runoff at several springs, partly along fractures within the bedrock. Water temperature of these springs is permanently below 1°C during the melt season indicating that within the rock glacier the water flows in contact with ice. Temperatures at the base of the winter snow cover (BTS) are significantly lower than on permafrost-free ground outside the rock glaciers. Annual flow velocities in the western part are low compared to other rock glaciers, ranging mostly between 5 and 30 cm. On the eastern part annual flow velocities near the front are almost zero. Ice exposures on the middle and upper part and internal structures (shear planes visible in radargrams) clearly indicate that this rock glacier contains a frozen core of coarse-grained, banded ice. We use the glacier model to explain the formation of rock glacier Murfreit and suggest that the rock glacier has developed from a debris covered glacier during retreat. As the steep front terminates at the edge of the terrace and the rock glacier is still active in the western part, debris flows may be initiated at the front during heavy rainfall events. Such debris flows occurred in summer 2003 and blocked the road to Gröden Pass.

Auf der markanten Terrasse in der nördlichen Sella Gruppe in den zentralen Dolomiten (Südtirol, Norditalien) befindet sich ein großer aktiver Blockgletscher (Murfreit). Dieser besitzt eine lobate Form und zeigt im westlichen, aktivsten Teil eine deutliche Oberflächenmorphologie aus transversalen Rücken und Vertiefungen. Der Blockgletscher besteht aus Dolomitschutt, der vom obertriassischen Hauptdolomit stammt. Im Vergleich zu Blockgletschern mit metamorphen Gesteinen im Einzugsgebiet ist der Schutt des Blockgletschers Murfreit deutlich feinkörniger und die Oberflächenmorphologie ist auch weniger deutlich ausgeprägt. Während der Schmelzsaison sind an der Oberfläche Thermokarstseen ausgebildet. Die Schmelzwässer fließen großteils über Quellen am Fuß der Stirn oberflächlich ab, teilweise auch über Kluftsysteme unterirdisch. Die Wassertemperatur der Blockgletscherquellen liegt während der gesamten Schmelzsaison konstant knapp unter 1°C, was darauf hinweist, dass sich im Blockgletscher das Wasser in Kontakt mit Eis befindet. Die Temperatur an der Basis der winterlichen Schneedecke (BTS) ist am Blockgletscher deutlich tiefer als außerhalb auf permafrostfreiem Boden und zeigt ebenfalls das Vorhandensein von Permafrost an. Die jährlichen Fließgeschwindigkeiten sind im Vergleich zu anderen Blockgletschern relativ gering, liegen im östlichen Teil des Blockgletschers nahe der Stirn unter 5 cm, im westlichen Teil dagegen bei 5 – 30 cm. Eisaufschlüsse im mittleren und oberen Abschnitt des Blockgletschers und die im Radargramm deutlich erkennbaren internen Strukturen, die als Scherbahnen im Eis interpretiert werden, zeigen, dass der Blockgletscher Murfreit einen gefrorenen Kern aus massivem, gebändertem Eis besitzt. Wir interpretieren die Entstehung des Blockgletschers Murfreit nach dem Gletscher-Modell, offensichtlich hat sich der Blockgletscher durch den Rückgang eines stark schuttbedeckten Gletschers entwickelt. Da die steile Blockgletscherstirn stellenweise bis an die Abbruchkante der Terrasse heranreicht und der Blockgletscher im Westabschnitt noch deutlich aktiv ist, können im Sommer starke Regenfälle jederzeit Murgänge im Stirnbereich des Blockgletschers auslösen. Solche Murgänge ereigneten sich bereits im Sommer 2003 und blockierten die Straße zum Grödner Joch.

1. Introduction

According to Vitek and Giardino (1987) rock glaciers are defined by their morphology rather than their origin or thermal conditions. Following their proposal rock glaciers are 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 et al. 2006; Kääb, 2007; Martin and Whalley, 1987). Rock glaciers are striking morphological expressions of permafrost creep and belong to the most spectacular and most widespread periglacial phenomena on earth (Haeberli, 1990). 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 et al. 2006). The two models (permafrost and glacier model) which are generally used to explain the formation of rock glaciers are discussed by Whalley and Martin (1992) and Whalley and Azizi (1994). 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 et al. 2000; Shroder et al. 2000; Arenson et al. 2002; Kääb & Reichmuth 2005; Haeberli et al. 2006; Kääb et al. 2007; Hausmann et al. 2007; Humlum et al. 2007; Berthling et al. 1998, 2000). Fukui et al. (2008) studied the internal structure and movement mechanism of a polar rock glacier using ground penetrating radar (GPR), geodetic survey and ice-core drilling to determine whether it is of talus or glacial origin. Their interpretations of inter-bedded debris-rich layers are similar to thrust structures of valley glaciers. Woodward et al. (2007) also interpret internal and basal reflectors in glaciers by layers of sediments. Gently to strongly curved and upward dipping reflectors were imaged by GPR and interpreted as debris inclusions along thrust planes in the ice (Monnier et al., 2008; Krainer et al., 2010; Monnier et al., 2011).

Many rock glaciers exist in the eastern part of the Alps (Lieb 1986, 1996), in particular in the central mountain ranges composed of metamorphic rocks such as mica schists, para- and othogneisses, and amphibolites (e.g. Lieb 1986, 1996; Krainer and Mostler 2000a, b, 2001, 2004; Berger et al. 2004). Many of them are exceptionally large and highly active with flow velocities from 1 to 4 m/a (Schneider & Schneider 2001, Berger et al. 2004, Krainer & Mostler 2000a, 2000b, 2006). Active rock glaciers are less common in the mountain ranges composed of carbonate rocks such as the Northern Calcareous Alps or the Dolomites. In the Dolomites few active rock glaciers occur, of which two have been studied in detail by Krainer et al. (2010) in the Hohe Gaisl/Croda Rossa massif. Holzner (2011) studied active rock glaciers in the Fanes area east of St. Kassian/ San Cassiano in the eastern Dolomites.

The aim of this paper is to characterize an active rock glacier at the northern side of the Sella massif (Dolomites) by studying its morphology, composition, thermal characteristics, hydrology, flow velocities and internal structures, and to discuss its dynamics, formation and potential for natural hazards.

2. Location

The studied active rock glacier "Murfreit" is situated on a prominent terrace (Mittelterrasse, Meisules, "Raibl Terrace") on the northern side of the Sella massif west of the Rifugio Pisciadú in the Dolomites, northern Italy. The rock glacier extends from an altitude of 2590 m (front) to 2770 m (rooting zone), the average altitude is 2670 m. The coordinates of the rock glacier are 46°32´06´´N and 11°48´25´´E (Fig. 1).

3. Geological Setting

The „Raibl Terrace", on which the rock glacier is located, is most pronounced on the northern side of the Sella Group. The terrace is developed at the horizon of the Raibl-Group which, in the Sella massif, is represented by the Pordoi Formation (Figs. 2, 3). The terrace formed as a result of increased weathering of the rocks of the Pordoi Formation.

The Pordoi Formation itself is underlain by the Cassian Dolomite and overlain by the Hauptdolomit. In the northern Sella Group the Pordoi Formation is rarely exposed since it is mostly covered by talus and rock glaciers. The succession is approximately 30 m thick. The Hauptdolomit is a cyclic succession composed of meter-thick lime mudstone beds and thin stromatolitic beds. Locally thin breccias and marly layers are intercalated.

In the catchment area of the rock glacier the Hauptdolomit appears strongly jointed and is cut by several steep, NNE-SSW and NNW-SSE to NW-SE trending faults. Along these faults the Hauptdolomit is strongly fractured and the rock glaciers derive most of the debris from these fault zones.

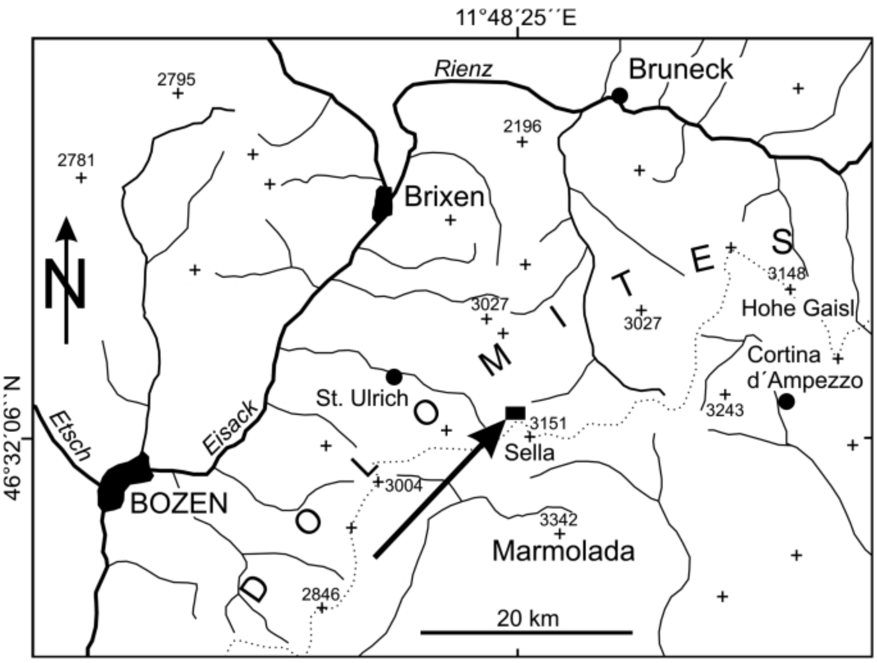

Figure 1: Location map of rock glacier Murfreit in the northern Sella massif, Dolomites (northern Italy).

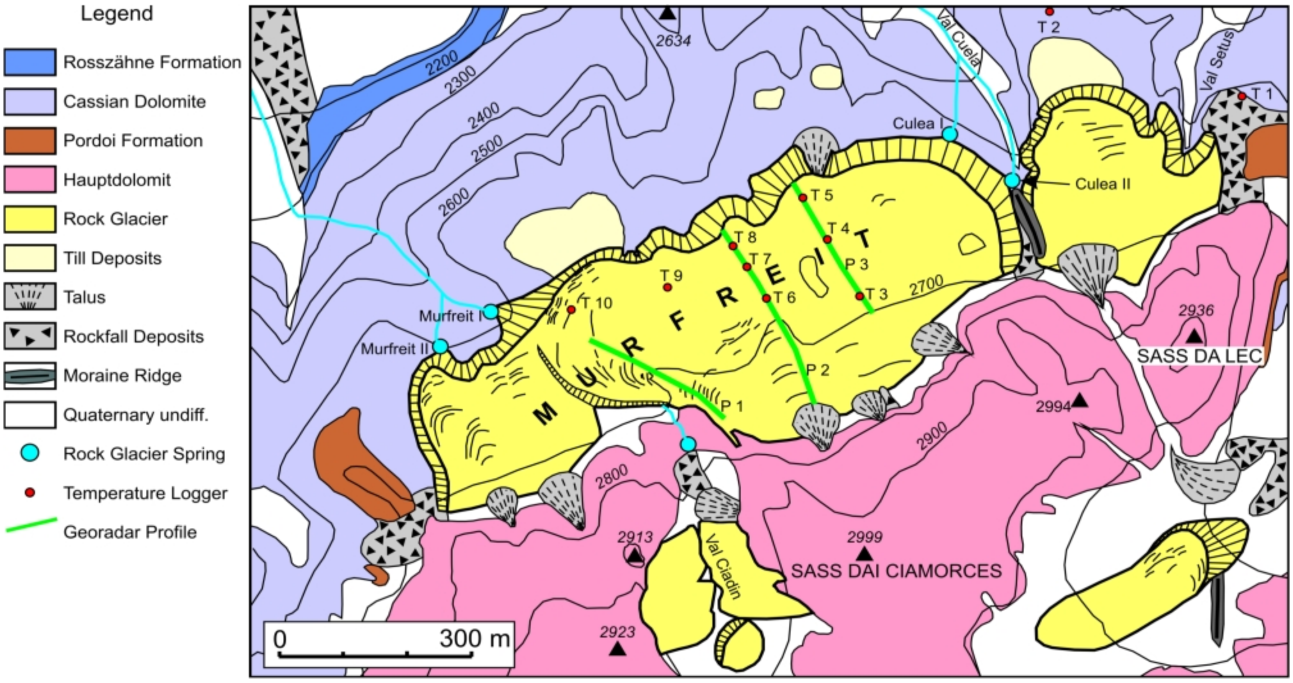

Figure 2: Geological/geomorphologic map of the northern part of the Sella massif showing rock glaciers including the studied rock glacier Murfreit which is developed at the prominent terrace.

4. Methods

The base for further studies was a detailed geologic/geomorphologic mapping of the rock glacier and the catchment including the bedrock and tectonic structures within the bedrock, supported by the study of orthophotos.

The grain size of the coarser-grained debris layer at the surface of both rock glaciers was measured at several locations of different grain-size (fine- to very coarse-grained) on the rock glacier. At each location the longest axis of 200 clasts lying side by side was measured in an area of approximately 4 x 4 m. At the snout of the rock glacier 5 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.

During the winter HOBO temperature loggers (Onset Computer Corporation, USA) were installed at the base of the snow cover on the debris layer of the rock glacier and outside to measure the temperature at the base of the winter snow cover (BTS). The locations are shown on Figure 2. Measurements were made every 2 hours with an accuracy of ± 0.2°C.

Single measurements of the water temperature and electrical conductivity of meltwater on the rock glacier and at the rock glacier springs (Fig. 2) were carried out with a hand-held calibrated thermometer and electrical conductivity meter (WTW).

The recent flow velocity of the rock glacier was determined by using ortho-photographs of the years 1953 and 2009. We established a geodetic network of 80 survey markers on the rock glacier and 5 fixed control points in front of the rock glacier in July 2007 (Figs. 14 and 15). The position of survey markers was initially determined on September 12, 2007 using differential GPS technique (e.g. Hofmann-Wallenhof et al. 1994, Eiken et al. 1997, Lambiel & Delaloye, 2004). The survey markers were measured again on July 23, 2008 and September 8, 2008.

Figure 3: Panoramic view on the terrace in the northern Sella massif with rock glacier Murfreit (right) and another small rock glacier (center left). The steep rock walls above the rock glaciers are composed of Hauptdolomit/Dolomia Principale, the terrace represents the horizon of the Pordoi Formation and the rock glaciers rest on Cassian Dolomite. View is towards South.

Figure 4: Western part of rock glacier Murfreit with steep sides and a steep front which locally terminates at the edge of the terrace (from Mussner, 2010).

For determination of the thickness and internal structure of the rock glaciers we used the Ground-penetrating radar GSSI SIR System 2000 in combination with a 35 MHz antenna. We measured three profiles on the rock glacier (P1, P2, P3; Fig. 2) parallel to the flow direction. Data were collected by fixed-offset reflection profiling. The distance between transmitter and receiver was 4 m, and the spatial sample interval was 1 m (point modus). The antennas were oriented perpendicular to the profile direction. The main record parameters were 1000 ns recording length, 1024 samples/scan, and 32-fold vertical stacking.

Figure 5: Steep front of rock glacier Murfreit in the central part, which terminates at the edge of the terrace. Debris may be mobilized at the steep front during heavy rainfall events causing debris flows (from Mussner, 2010).

5. Morphology

In the northern part of the Sella Group 10 rock glaciers were localized which cover an area of 0.54 km². Four rock glaciers were classified as active, five as inactive and one as relict. Among these rock glaciers Murfreit is by far the largest and also most active rock glacier. Another rock glacier (Sas dala Luesa) is located adjacent to the east of Murfreit. Both rock glaciers are located on the prominent Raibl terrace west of Rifugio Pisciadú (Figs. 2, 3).

Murfreit is a lobate, ice-cored rock glacier of 420 m length, and 1100 m width. It covers an area of 0.34 km². The front of the rock glacier terminates at an elevation of 2590 m; the rooting zone is at 2770 m. The rock glacier is exposed towards north – northwest, and it is bordered by a steep wall in its south (Fig. 3). The highest peaks of the wall reach an elevation of about 3000 m a.s.l. and it is composed of Hauptdolomit which is cut by several steep faults. In particularly these fault zones supply the rock glacier with debris. Rock fall activity is also observed in the steep walls besides the fault zones. Consequently, the rock glacier is composed entirely of Hauptdolomit debris of varying grain size.

The steep front with gradients of up to > 40° in the western part locally terminates at the edge of the terrace. The steep front as well as the surface of the rock glacier is bare of vegetation. Near the front the rock glacier is approximately 20 m, in the western part up to 40 m thick (Fig. 4, 5).

In the rooting zone the debris layer ("active layer") at many places is only 10 – 15 cm thick (Fig. 6). Thickness increases towards the front reaching values of several meters. Near the base of the steep wall in the rooting zone a prominent depression is locally developed (Fig. 7).

During summer a thermokarst lake ("Lake Dragon", Lech di Dragon) is commonly developed on the surface of the rock glacier, which is photographically documented since 1899. The outline of the lake changed during the years and during the last decades it broke out several times. At times, during the 1950ies, Lake Dragon was partly bordered by a steep

Figure 6: Massive ice is present in the upper part of the rock glacier beneath a thin debris layer (from Mussner, 2010).

Figure 7: A small depression filled with meltwater is developed in the rooting zone of the western part of the rock glacier. Avalanche snow is locally covered by fresh debris derived from the steep rockwall above the rock glacier (from Mussner, 2010).

wall of banded ice which was up to 25 m high. During 2004 the lake covered an area of approximately 1000 m². During the summer of 2006 another thermokarst lake formed west of Lake Dragon, which broke out in 2007 leaving a cone-shaped depression up to 12 m deep (Fig. 8, 9).

Around the thermokarst lakes the debris layer is 0.8 – 1 m thick. Below the debris layer up to > 10 m thick massive, coarse-grained, banded ice is exposed (Fig. 10, 11). Along the banding thin, fine-grained layers of sediment occur. Larger blocks rarely are observed within the ice. At the margins of the thermokarst lakes the debris layer is well exposed and composed of two layers: a layer containing high amounts of fine-grained material which directly overlies the massive ice is overlain by a coarse-grained layer in which fine-grained material is rare or absent. In the western part of the rock glacier transverse ridges and furrows are well developed on the surface (Fig. 12).

6. Debris Properties

In the eastern part the surface layer of the rock glacier is finer grained than in the western part. In general, the grain size varies from place to place; coarser grained areas alternate with finer-grained areas. The grain-size is mostly < 1 m, locally large blocks with diameters of several meters, which derived from rockfall events, occur on the rock glacier.

Figure 9: Thermokarst lake after the outburst showing banded ice covered by a thin debris layer (~ 1 m thick).

Figure 8: Thermokarst lake before the outburst in summer 2009.

The surface layer is dominated by grain-sizes of 1 – 10 and 11 – 20 cm. Locally, clasts with grain-sizes of 21-30 and 31-40 cm are also abundant. Clasts with grain-sizes > 60 cm are rare and those > 100 cm are very rare. The grain-size of the surface layer is similar to that of the rock glaciers at Gletscherkar and Gaislkar (Cadin del Ghiacciaio and Cadin di Croda Rossa) in the Hohe Gaisl massif of the eastern Dolomites (Krainer et al. 2010). Clasts > 60 cm are slightly more abundant at rock glacier Murfreit compared to the rock glaciers in the Hohe Gaisl massif. The cumulative curves of the five fine-grained samples show similar trends and similar grain-size distributions, comparable to those of other rock glaciers. All samples are poorly sorted and mainly composed of gravel, coarse sand and few pebbles. Fine sand, silt and clay constitute less than 10 percent.

7. Ground Temperatures

During winter 2007/2008 four temperature loggers were installed on the rock glacier Murfreit, one on each of the two small rock glaciers in the Ciadin Valley, one on the rock glacier Sas dala Luesa, and three on the ground in front of the rock glacier Murfreit where permafrost was considered to be absent.

As the snow pack was thin during this winter some of the installed temperature logger recorded distinct temperature variations at the base of the snow cover which made it difficult to distinguish between permafrost ground and permafrost-free ground.

The snow pack was thicker during winter 2008/2009, even when the temperature loggers were installed on October 11 the snow pack was 30 – 60 cm thick and was > 1 m thick at the beginning of December. Thus the temperature loggers were well isolated against the temperature of the atmosphere by a thick snow pack recording temperatures on the rock glaciers constantly ranging between -3 and -4°C. Outside the rock glaciers temperatures at the base of the snow cover were significantly higher; the temperature minimum was -1.5°C.

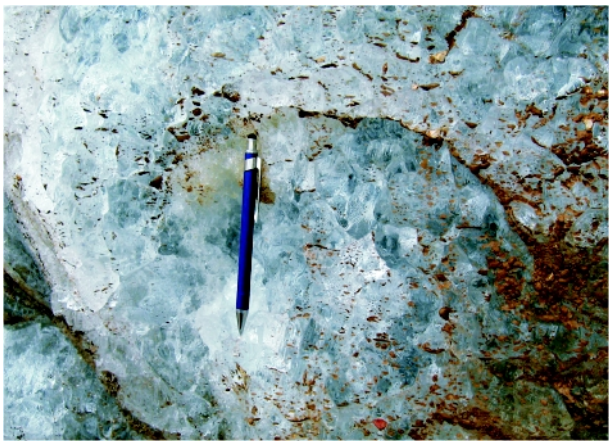

FIGURE 10: Coarse-grained massive ice with grain-size of individual ice crystals up to a few cm (from Mussner, 2010).

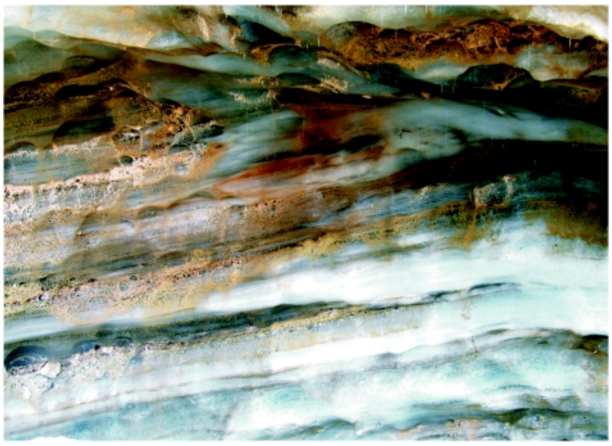

FIGURE 11: Banded ice with thin, fine-grained sediment intercalated.

Snowmelt started during the first half of May; within a few days the temperatures increased to 0°C and remained at this value until the snow completely melted at the measuring site (Fig. 13).

8. Hydrology

Several springs occur at the base of the front of the rock glacier Murfreit: Culea and Culea II in the eastern part, Murfreit I and II in the western part (Fig. 2). Among these four springs only Culea is easy to access, although it was not possible to install a gauging station.

At the spring Culea which is located at the eastern end of the rock glacier at an altitude of 2640 m (Fig. 2), water temperature and electrical conductivity was measured several times during summer. The discharge of this spring is characterized by pronounced seasonal, during early summer also by diurnal variations. During summer the discharge is mostly between 10 and 20 l/s. Peak discharge was observed during early afternoon and immediately after rainfall events. Discharge decreases from the end of July until the spring disappears in October/November. Also during summer cold weather periods cause a significant decrease in discharge. The discharge pattern is similar to that of other rock glaciers (Krainer and Mostler 2002, Krainer et al. 2007).

At the rock glacier spring water temperature remains constantly below 1°C, mostly around 0.3°C during the entire summer. Similar values have been recorded from other active rock glaciers (e.g. Krainer and Mostler 2001, 2002; Berger et al. 2004; Krainer et al. 2010). In contrast the water temperature of the Setus spring, a fissure spring in the Setus Valley at an altitude of 2550 m, varies between 2.3 and 4.9°C. There is no active rock glacier or permafrost in the catchment area of the Setus spring. The water temperature of Lake Dragon is very low during summer, mostly ranging between 0.4 and 1.5°C.

Electrical conductivity of the rock glacier springs is low during spring showing values of 82 – 100 µS/cm and increases to 162 µS/cm in autumn. Electrical conductivity of Lake Dragon was 83 – 99 µS/cm.

Compared to the Culea spring the Murfreit springs show higher discharges, but due to the steep front these springs are not accessible. The total surface discharge of water of rock glacier Murfreit is significantly higher than that of the two active rock glaciers of the Hohe Gaisl massif (Krainer et al. 2010).

9. Velocity Measurements

On rock glacier Murfreit 80 markers were installed. 49 markers are located along the front, just a few meters from the edge of the front. Three transects were installed additionally on the western part (Fig. 2).

From September 2007 until September 2008 the horizontal displacements on the eastern part of the front were < 5cm, mostly near 0 cm, whereas in the western, steeper part of the rock glacier annual rates of horizontal displacement were mostly between 5 and 10 cm, locally between 10 and 30 cm. At one marker a horizontal displacement rate of 49 cm was recorded (Fig. 14, 15). On the western part flow rates were significantly lower (mostly < 10 cm, partly < 5 cm) in the period September 2007 – July 2008 than in the shorter period July 2008 – September 2008.

A comparison of the aerial photographs of 1953 and 2009 yielded horizontal displacements of distinct large blocks near

FIGURE 12: Well developed transverse ridges and furrows on the lower part of the rock glacier in the western, most active portion. An empty thermokarst depression is visible on the right.

the front on the western part of the rock glacier of 3.9 – 10.9 m resulting in annual displacement rates of 7 – 20 cm. These annual displacements rates are in good accordance with those measured by GPS. In the period 1953 – 2009 the front advanced for 6 m in the western, most active part of the rock glacier.

On the markers also distinct vertical displacements were recorded which mostly range between -5 and -15 cm/year. Comparison of photographs taken in 1899 (Benesch) and 2004 show that during this period the glacier at the base of the steep wall strongly decreased. A comparison of absolute altitudes on the rock glacier indicates that during the last 100 years the surface of the rock glacier subsided significantly. The changes in altitude of five distinct points on the rock glacier between 1904 (map "Alpenvereinskarte") and 2008 are between -3 and -20 m, resulting in annual subsidence rates of -2.9 to -19.6 cm. These values are very similar to those determined by the GPS measurements.

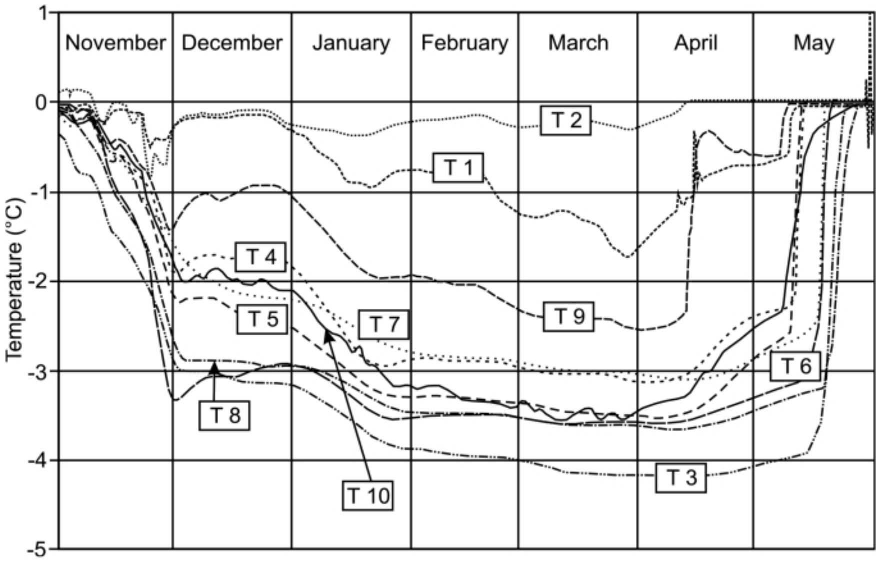

Figure 13: Temperatures at the base of the winter snow cover (BTS) recorded during the period November 2008 – May 2009. The position of the temperature loggers T 1 – T 10 is shown on Fig. 2.

10. Ground Penetrating Radar

The obtained data are of good quality, such that the processing could be kept simple. It comprised bandpass filtering (10-15-50-60 MHz)

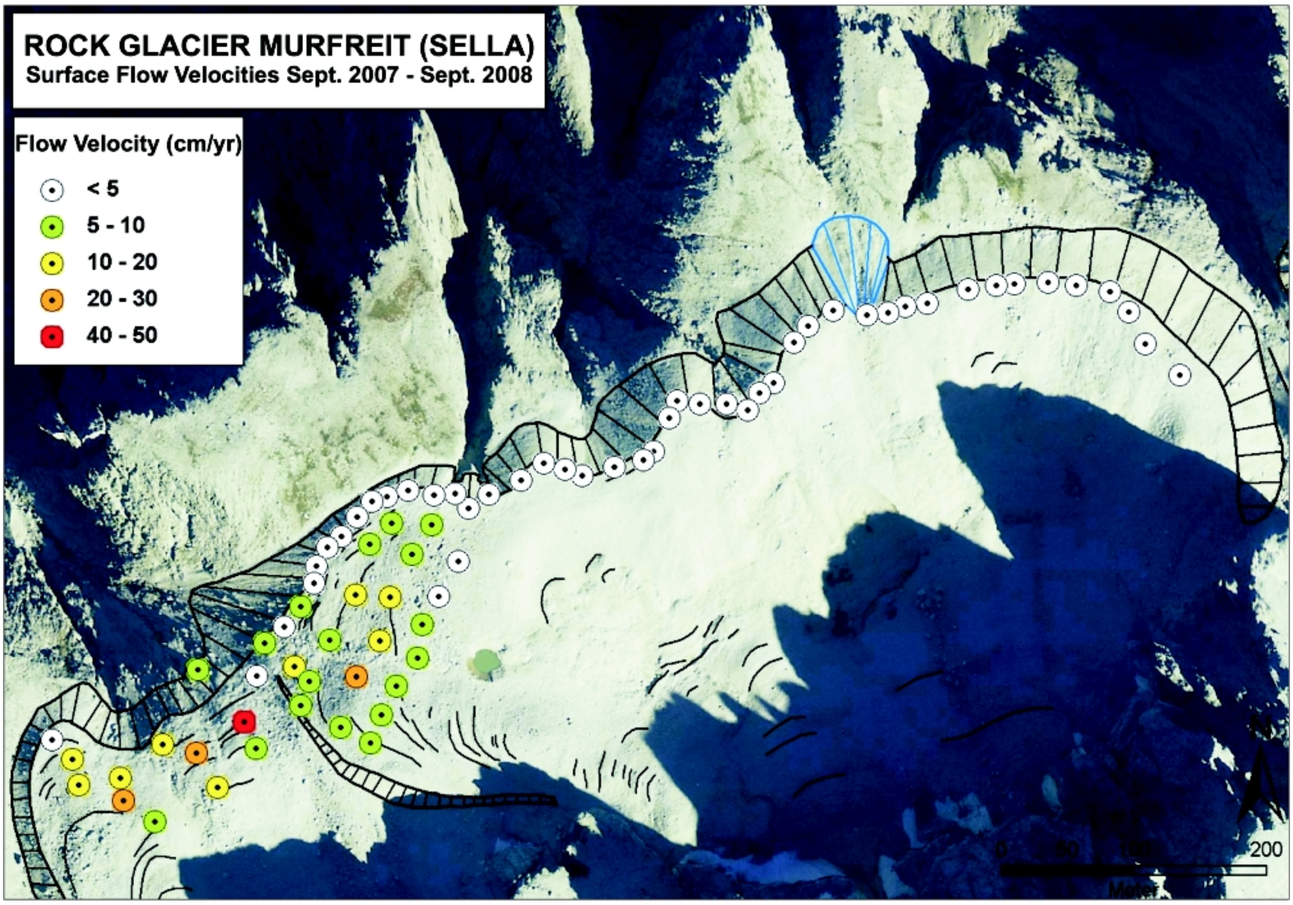

Figure 14: Surface flow velocities (horizontal displacements) on the lower part of rock glacier Murfreit from September 2007 to September 2008 (from Mussner, 2010).

and removal of the average amplitudes in the first 100 ns. An automatic gain control function (window lengths between 200 and 300 ns) was also applied to the traces to increase the amplitudes in the lower parts of the radargrams. Based on migration results, we chose a velocity of 0.14 m/ns as the average medium velocity. We show both the unmigrated and migrated images, and superimpose our interpretation on the latter one. All three profiles indicate several pronounced surface-parallel horizons down to depths of 45 m and upward dipping, curved, reflectors in the uppermost 20 m.

10.1 Profile 1

Profile 1 (Fig. 16) has a length of 250 m and starts close to a steep wall (P1 on Fig. 2). Along its last third, upward directed, concave-shaped reflection bands are observed. These are interpreted as ice intercalated with debris and fine-grained material as indicated by the ice exposures at the thermokarst lake which is located close to the profile. The reflection bands are terminated by horizon H1. H2 is observed from a depression at profile distance 75 m, where it has a depth of approximately 10 m, until the end. The maximum depth of H2 is about 30 m. Horizon H3 is somewhat parallel to H2, and has a maximum depth of 45 m. At the lower end of the profile the depth of horizon H3 fits with the bedrock outcrop at the rock glacier front. Here, the front slope has a thickness of ~ 35 m.

10.2 Profile 2

This profile is 330 m long (P2 on Fig. 2). The unmigrated section shows several diffraction hyperbolas, which indicate either the abrupt termination of layers or the inclusion of boulders (Fig. 17). The bulge in the middle indicates that the rock glacier comprises two parts. The upper part is bounded by horizon H2 (0 - 175 m). This horizon most likely connects to horizon H1 (the bulge) which almost reaches the surface at position 200 m. The lower part (125 - 330 m) comprises the bulge and thus partly underlies the upper part. Concave-shaped reflection bands are only observed at the upper part, where they reach depths down to 30 m. A prominent reflector (HH2) cuts through the lower part. HH2 is the lower boundary of a low reflectivity zone with few point sources. Horizon H3 (depth

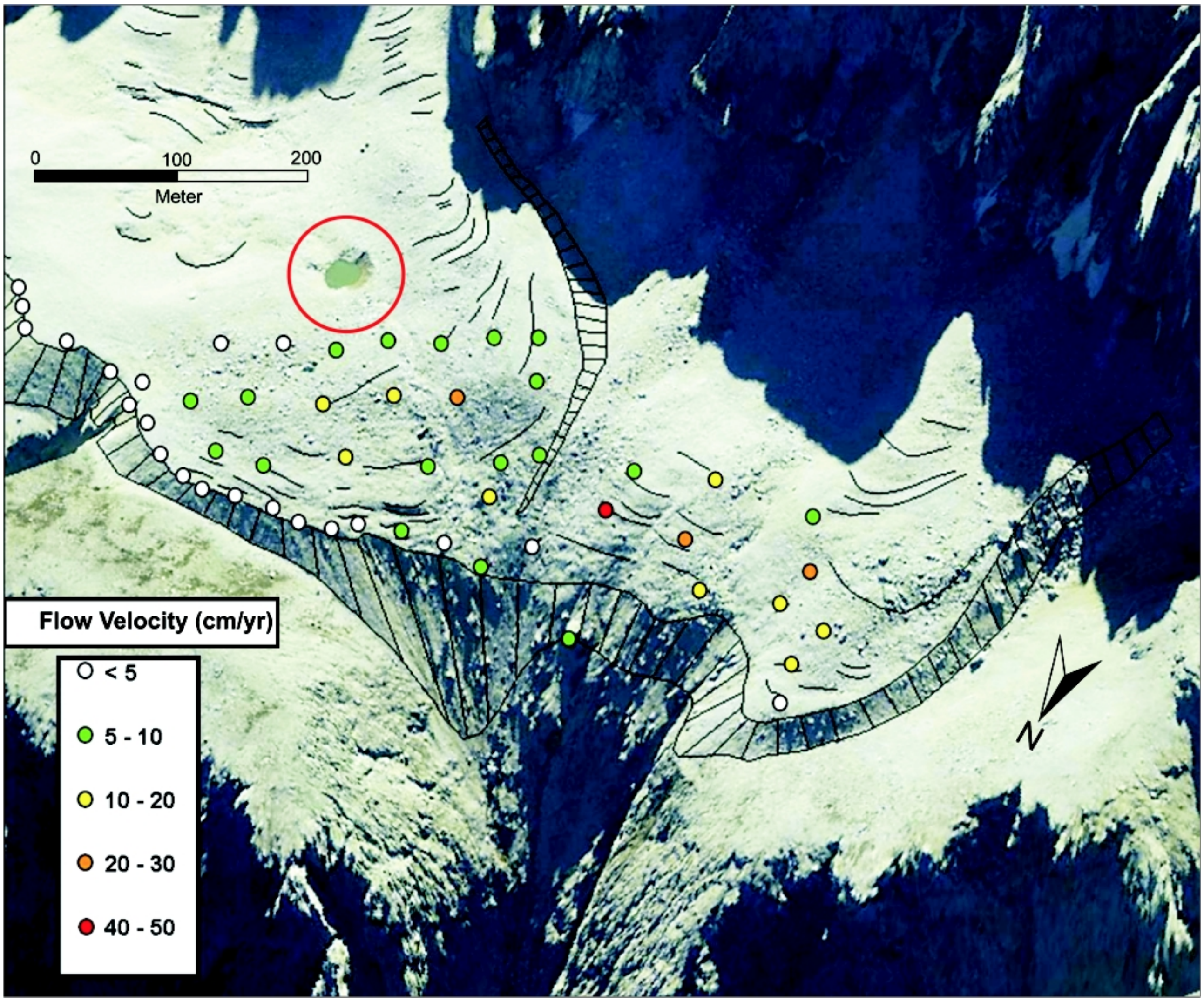

Figure 15: View on the western, most active part of the rock glacier showing flow velocities. The steep front of the most active part terminates at the end of the terrace. A thermokarst lake is visible in the upper left marked by a red circle (from Mussner, 2010).

~ 30 m) may represent the bottom of the lower part. The deepest horizon (>45 m) is associated with the onset of strongly ringing reflections. Such ringing is usually caused by the presence of liquid water, which could be explained by internal run-off of the thermokarst lakes. Additional reflections are observed at the beginning of the profile, e.g. a shallow horizontal layer and a steeply inclined feature. The apparent velocity of the latter one is significantly lower than the EM velocity of air, such that a reflection from the steep rock walls can be ruled out as its cause. We interpret this feature to represent the bedrock. The front slope near this profile has a thickness of ~ 25 m. The trend of the bedrock in this region remains unclear as horizon H3 as well as the union of H2 with HH2 run in the same direction and in similar depths.

10.3 Profile 3

The unmigrated section (P3 on Fig. 2) shows several diffraction hyperbolas, which in this case are most likely caused by boulders (Fig. 18). Similar to profile 2, profile 3 is also divided into a lower and an upper part. It does not indicate curved reflections, although horizon HH1 is of rather clear appearance. Similar to profile 2, a shallow horizontal layer is observed in the beginning and is connected with the depression. Horizon HH2 lies in the continuation of the steep part of the topography. Horizon H3 follows the shape of the topography with a rather constant depth of 40 m. At the lower end of the profile the depth of horizon H3 fits to the bedrock outcrop at the rock glacier front. Here the thickness of the front slope is ~ 40 m.

11. Related Natural Hazards

Several debris flows were initiated on the northern side of the Sella Group during the extreme warm summer of 2003 which partly covered the road from Wolkenstein to Gröden Pass (Fig. 19).

A heavy thunderstorm developed above the Sella Group on July 2, 2003 at 14:00. During the thunderstorm precipitation of 9 – 17 mm within 24 minutes was recorded by precipitation radar. Approximately 20 minutes after the begin of the thunderstorm a debris flow generated at the steep front on the western part of the rock glacier Murfreit which moved down the steep canyon and blocked the road to Gröden Pass.

Additional debris flows were initiated on this day on the northern side of the Sella Group which did not block the road.

In July 23, 2003 at 4:00 in the morning heavy rainfall mobilized a debris flow in the Culea Valley which also blocked the road to Gröden Pass. The debris flow mobilized approximately 500 – 600 m^3 sediment, which partly was derived from the steep front of rock glacier Sas dala Luesa.

Two small debris flows occurred on July 24, 2003 which partly also blocked the road to Gröden Pass.

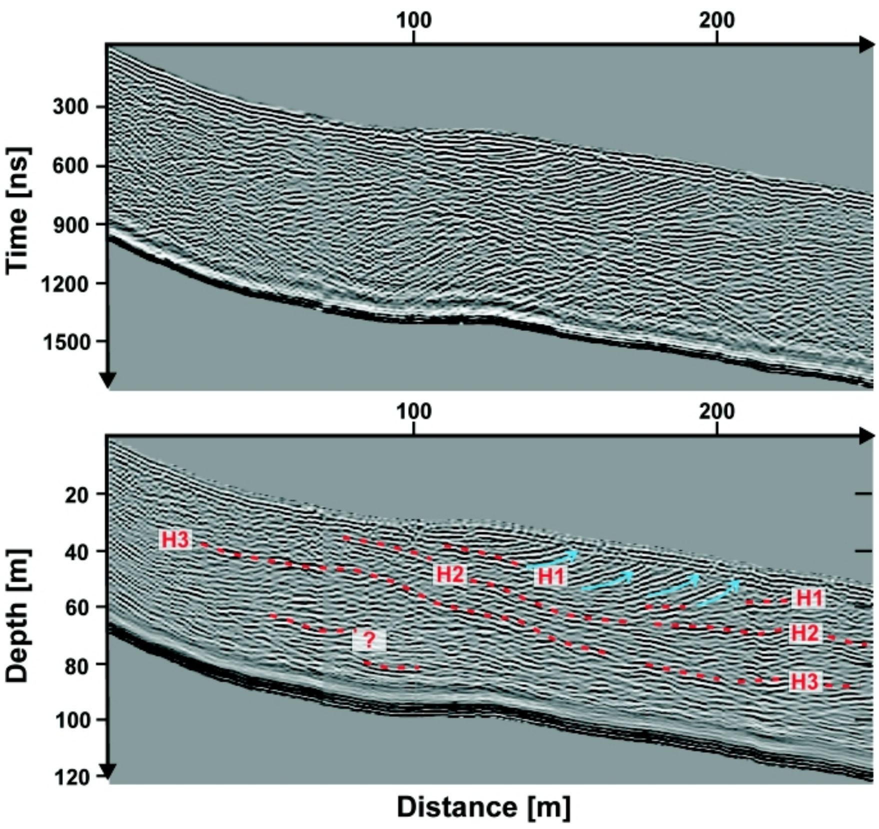

Figure 16: Unmigrated (upper row) and migrated (bottom row) radargram sections of GPR profile 1. Migration velocity was 0.14 m/ns. Broken lines are interpreted horizons. H2 probably marks the base of the massive ice core which is up to about 30 m thick. H3 has a maximum depth of 45 m and is caused by the surface of the bedrock. Between 120 and 210 m concave shaped reflection bands are well developed. Between H2 and H3 unfrozen debris is present.

12. Discussion

Due to the similar bedrock geology, rock glacier Murfreit is very similar in comparison to the active rock glaciers in the Hohe Gaisl and Fanes areas: at rock glacier Murfreit the surface morphology is characterized by poorly developed transverse ridges and furrows in the western, most active part, whereas in the eastern part these morphological features are lacking. The grain size of the surface layer is comparable to that of the Hohe Gaisl and Fanes areas but smaller than that of most rock glaciers composed of debris derived from metamorphic rocks (Krainer et al. 2010). The large blocks which locally occur on the surface are derived from rockfall events.

During winter 2008/2009 when a thick snowpack covered the rock glacier BTS on the rock glacier showed lower temperatures than besides the rock glacier indicating the presence of permafrost. Presence of ice is also documented by several outcrops, particularly at the thermokarst lakes which are developed during summer. The ice is coarse-grained, banded and almost free of debris probably indicating a glacial origin.

Four rock glacier springs occur at the base of the front in the eastern and western part of the rock glacier where water is released during the melt period (May – October). Surface runoff is highest during June and July and decreases towards autumn. In contrast to the active rock glaciers at Hohe Gaisl/ Croda Rossa (Krainer et al. 2010) where the bedrock is strongly karstified and the entire water is released along karst cavities, at rock glacier Murfreit a substantial amount of the water is released as surface runoff and only a small portion is released along joints and faults in the bedrock. The low water temperature of the rock glacier springs also indicates that the water released at the springs flows in contact with ice within the rock glacier. Electrical conductivity of the meltwater released at the rock glacier springs is typically low, with the lowest values recorded during May and June, and highest values in autumn. Even lower values are recorded at rock glacier springs where the bedrock in the catchment area is composed of metamorphic rocks (mica schist, gneiss, amphibolite) (Krainer and Mostler 2002).

Annual surface flow velocities near the front of the eastern part are almost zero indicating that this portion of the rock glacier is almost inactive. In the western part of the rock glacier where transverse ridges and furrows are developed on the surface, flow velocities up to 30 cm/a are recorded near the front indicating that the steep front is still advancing. The low gradient in the eastern part of the rock glacier may be responsible for the inactivity of the rock glacier.

We interpret thick zones with distinct concave reflectors and zones with less amplitude reflections - where an underlying reflector (e.g. profile 2: 270 - 330 m) could be clearly identified - to represent the frozen body of the rock glacier. This interpretation corresponds to findings from other studies (Arcone et al., 2002; Moorman et al., 2007; Krainer et al., 2010; Monnier et al., 2011; Hausmann et al., 2012) and indicate ice in depths of up to 10 and 30 m (zones above horizons H2 and HH2). 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. As the concave reflectors do not correlate with the location of ridges as reported by Monnier et al. (2011) and as high shear stresses in this shallow areas are too low to be of relevance we suggest that these structures do not represent the actual stress field. The reflectors could originate from the alignment of debris along thrusts (Fukui et al., 2008) which were active in former times when the frozen body reached its maximum thickness. The frozen body of the rock glacier above horizons H2 and HH2 which do not show distinct concave reflectors are assumed to be composed of a mixture of debris and ice lacking distinct internal structures. The high wave velocity, the good exploration depth and the internal structures are in accordance with the presence of a massive ice core. Similar results were obtained from Cadin del Ghiacciaio rock glacier at Hohe Gaisl, eastern Dolomites (Krainer et al. 2010). HH 3 probably represents the surface of the bedrock indicating that unfrozen debris is present between the frozen core of the rock glacier and the bedrock.

The lower parts of the GPR profiles 2 & 3 (north of the depressions) indicate that the rock glacier must have increased its thickness to keep creeping in former times. This formation also points to the presence of a massive ice core. In the western part the gradient is steeper also in the middle and lower part of the rock glacier, resulting in flow velocities up to 30 cm/a.

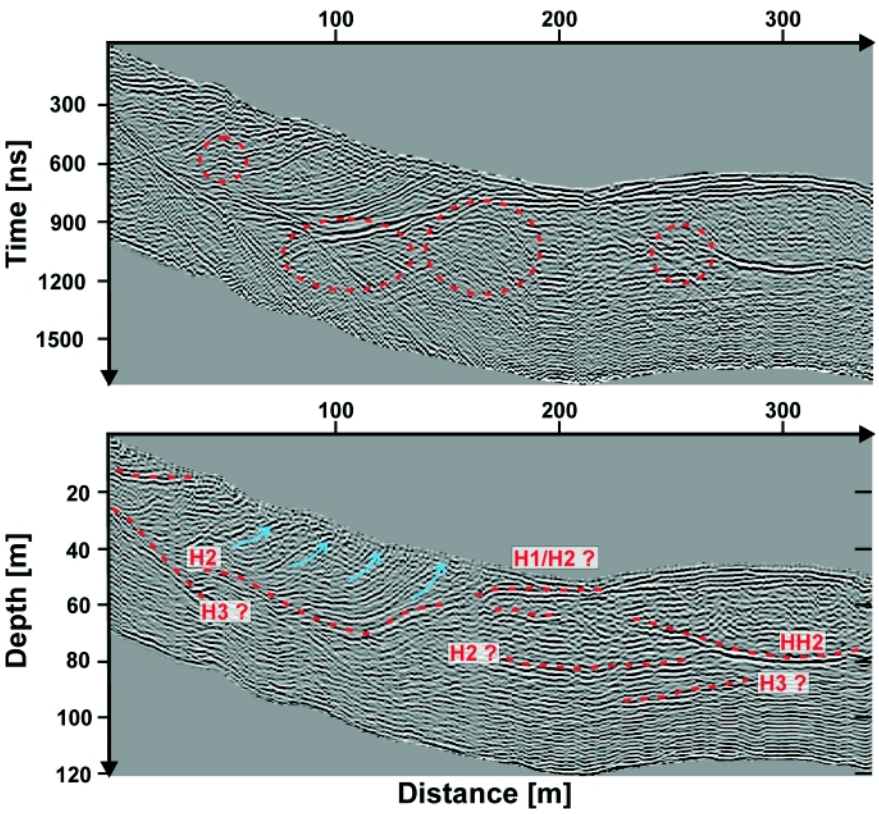

Figure 17: Unmigrated (upper row) and migrated (bottom row) radargram sections of GPR profile 2. Concave-shaped reflection bands are well developed between 50 and 125 m, representing the massive ice core with a maximum thickness of approximately 30 m. Circles indicate pronounced diffraction hyperbola. Horizon H2 marks the base of the frozen ice core and H3 the surface of the bedrock. In the lower part, from 180 to 330 m concave-shaped reflection bands are absent because in this part of the rock glacier the frozen core of the rock glacier is probably composed of a mixture of debris and ice.

The changes in altitude between 1904 and 2008, particularly in the middle and upper part indicate that the rock glacier lost substantial amounts of massive ice.

Debris flows which were mobilized at the steep front of the rock glacier during thunderstorm events in 2003 and blocked the road to Gröden Pass demonstrate that this rock glacier represents still a risk for natural hazards. Particularly at the western, active part of the rock glacier where the front is steep due to the movement of the rock glacier, large amounts of debris may still be mobilized during heavy rainfall events in summer. Debris may also be mobilized in the eastern part of the rock glacier where the steep front terminates at the edge of the terrace.

Thermokarst lakes which develop on the surface of the rock glacier during the melt season are a further source of danger. The outflow of a thermokarst lake in 2007 indicates that there is some potential for a sudden outburst of these thermokarst lakes. Such an outburst may also mobilize large amounts of debris at the front of the rock glacier. Outbursts of a thermokarst lake occurred at Gruben rock glacier (Switzerland) in 1968 and 1970 causing flooding and debris flows (Kääb et al. 1996, Haeberli 2005).

As a first action to minimize the risk for the road to Gröden Pass the retention dams immediately above the road were elevated to increase the capacity of the retention basins. As a further action the Government of South Tyrol plans to install a weather station at the rock glacier which automatically closes the road to Gröden Pass after exceeding a certain amount of rainfall.

Ice exposures and georadar data demonstrate that rock glacier Murfreit contains a massive ice core composed of coarse-grained, banded ice in the middle and upper part, which disintegrates towards the front. This indicates that rock glacier Murfreit developed from a debris-covered glacier, similar to the Cadin de Ghiacciaio rock glacier at Hohe Gaisl (Krainer et al. 2010). Although no glaciers are present in the Sella Group, Benesch (1899) reported the presence of a glacier in the northern Sella Group at that place where the rock glacier occurs. He published a photograph which shows a glacier which in the middle and lower part was covered by a thin debris layer. The thermokarst lake (Lake Dragon) was already present at that time. A glacier, which is covered by debris in the lower and middle part, is also shown on the topographic map of the Austrian Alpine Club (Alpenvereinskarte) published in 1904. The presence of a debris-covered glacier is also reported by Nangeroni (1938) and Klebelsberg (1956). These observations also indicate that rock glacier Murfreit is of glacial origin and is a remnant of the Little Ice Age. In the glacier inventory of Italy of 1957-1958 (Carta dei Ghiacciai Italiani, 1962) no glacier is reported from that place. We suggest that rock glacier Murfreit has developed from a debris covered glacier during retreat through inefficiency of sediment transfer from the glacier ice to the meltwater, a mechanism proposed by Shroder et al. (2000).

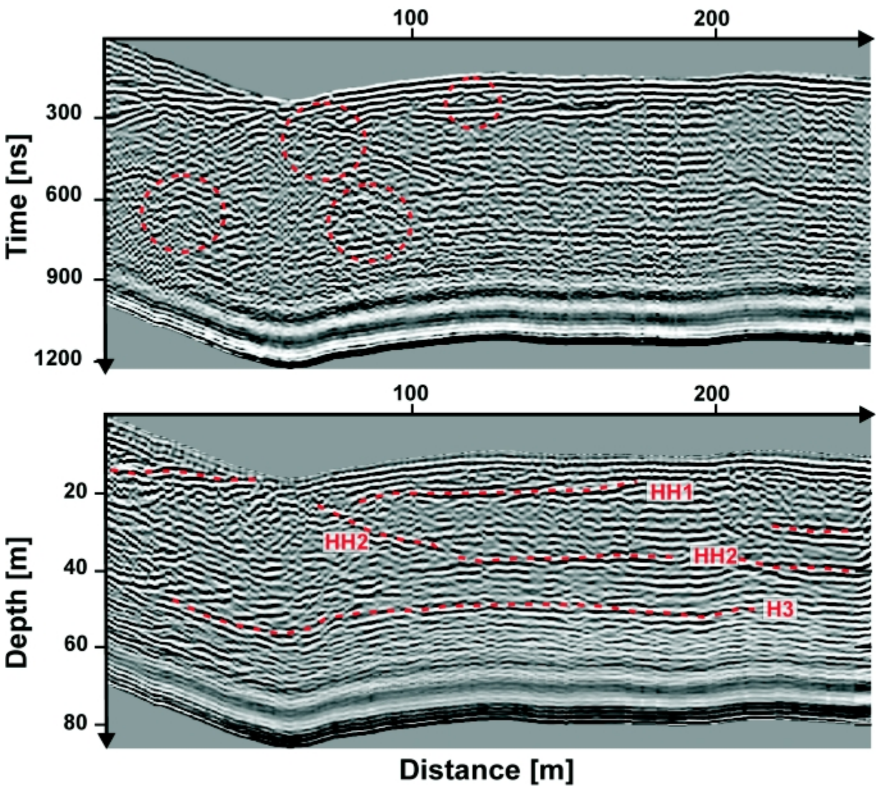

Figure 18: Unmigrated (upper row) and migrated (bottom row) radargram sections of GPR profile 3. Migration velocity was 0.14 m/ns. Broken lines are interpreted horizons. Circles indicate pronounced diffraction hyperbola. HH2 probably reflects the base of the frozen core of the rock glacier which is composed of a mixture of debris and ice. H3 is interpreted to represent the surface of the bedrock.

13. Conclusion

Rock glacier Murfreit is a large, lobate-shaped active rock glacier located on the prominent terrace on the northern side of the Sella massif in the Dolomites (Northern Italy). In general, the formation of rock glaciers is explained by using the permafrost model. The presence of banded, coarse-grained ice which is exposed at the margin of the thermokarst lakes, data from ground penetrating radar and old maps indicate that the origin and formation of Murfreit rock glacier can be explained by the glacier model rather than the permafrost model (similar to Marinet rock glacier described by Whalley and Palmer, 1988, and rock glacier Cadin del Ghiacciaio in the eastern Dolomites described by Krainer et al., 2010).

Clear banded ice with thin silt and sand layers beneath a relatively thin debris mantle has been reported

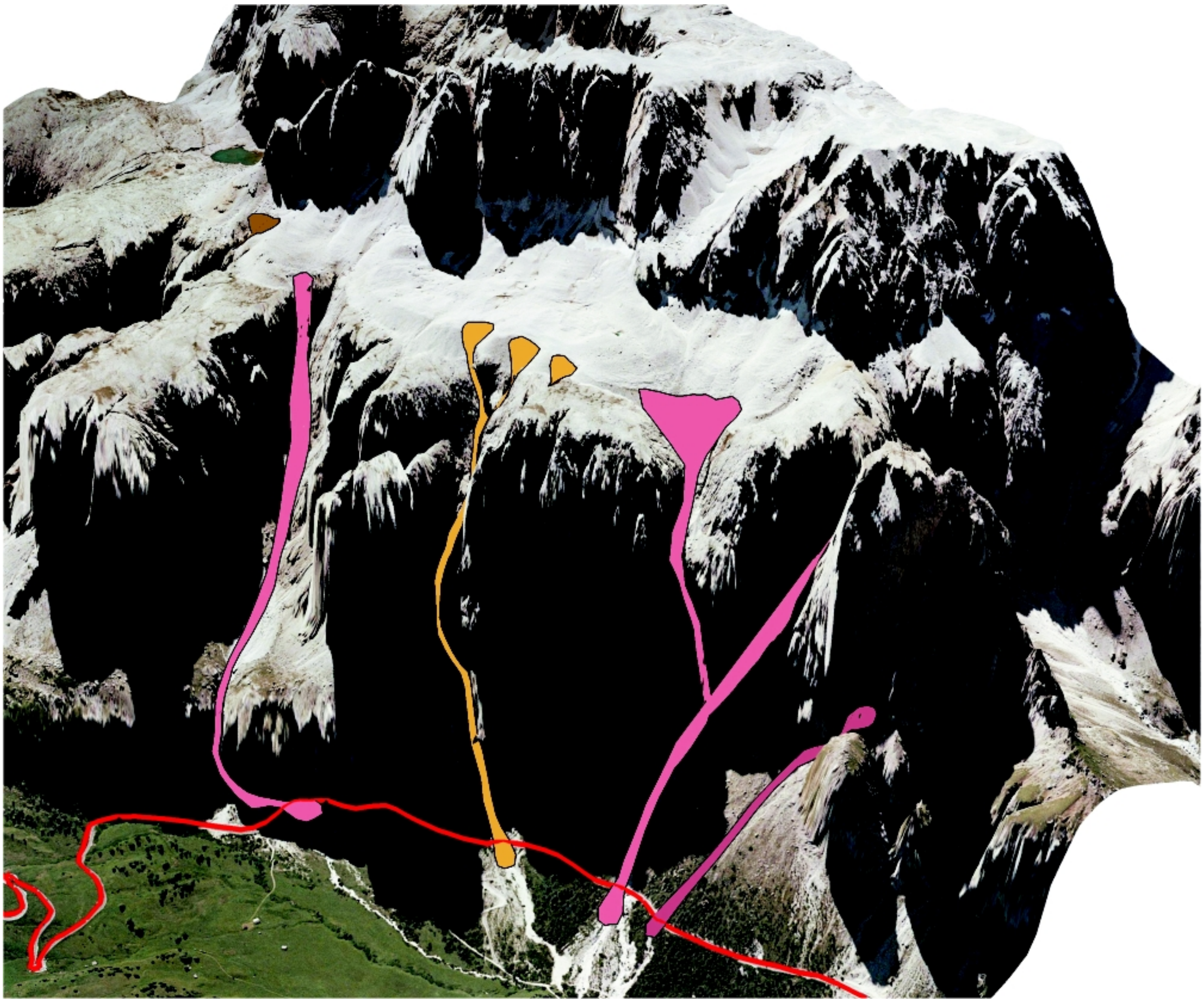

Figure 19: Panoramic view on the northern part of the Sella massif with rock glacier Murfreit. Debris flows were initiated from the steep front of the rock glacier where terminating at the edge of the terrace. As the rock glacier is still active in the western part, debris flows may be initiated there during heavy rainfall events (from Mussner, 2010). Pink: debris flows of summer 2003, light and dark brown: additional potential areas for the formation of debris flows. The red line marks the road to Gröden Pass.

from a few rock glaciers, e.g. Galena Creek (Ackert, 1998; Potter et al., 1998), Reichenkar (Krainer and Mostler, 2000a, Krainer et al. 2002), Hohe Gaisl/Croda Rossa (Krainer et al., 2010). The debris layers in the ice probably originated from summer ablation in the steep accumulation zone.

We suggest that during glacier retreat of the Little Ice Age the debris-covered glacier was transformed into an active rock glacier as the equilibrium line receeded upglacier and debris was concentrated on the glacier surface reducing ablation rates and preserving the underlying glacier ice.

Due to the activity and morphological situation at the front, rock glacier Murfreit is a very rare example of a rock glacier which is prone to natural hazards. Heavy rainfall events in summer may mobilize debris at the steep front of the rock glacier causing debris flows which may endanger the road to Gröden Pass. As a first step the retention dams were elevated and further measures are planned to prevent such natural hazards.

However, to get more information on the dynamics, two core drillings are planned on rock glacier Murfreit in summer/autumn of 2012 for detailed analyses of the ice core (chemistry, ice volume, palynology, radiocarbon dating) and to install instruments (temperature loggers, inclinometers) in the borehole.

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