WP7 Water resources

Action 7.2 – Report

Hydrological discharge measurements, geophysical measurements for assessing the ice content of permafrost phenomena

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(1) Study Site Lazaun, Schnals Valley

Location

The Lazaunkar, a N-NE facing cirque in the upper Schnals Valley west of Kurzras, contains several fossil and three active rock glaciers. The uppermost part of the cirque is occupied by a glacier (Lazaunferner – Vedretta di Lazaun), just below the Saldurspitze, between an altitude of 3400 and 2800 m a.s.l. (Fig. 1).

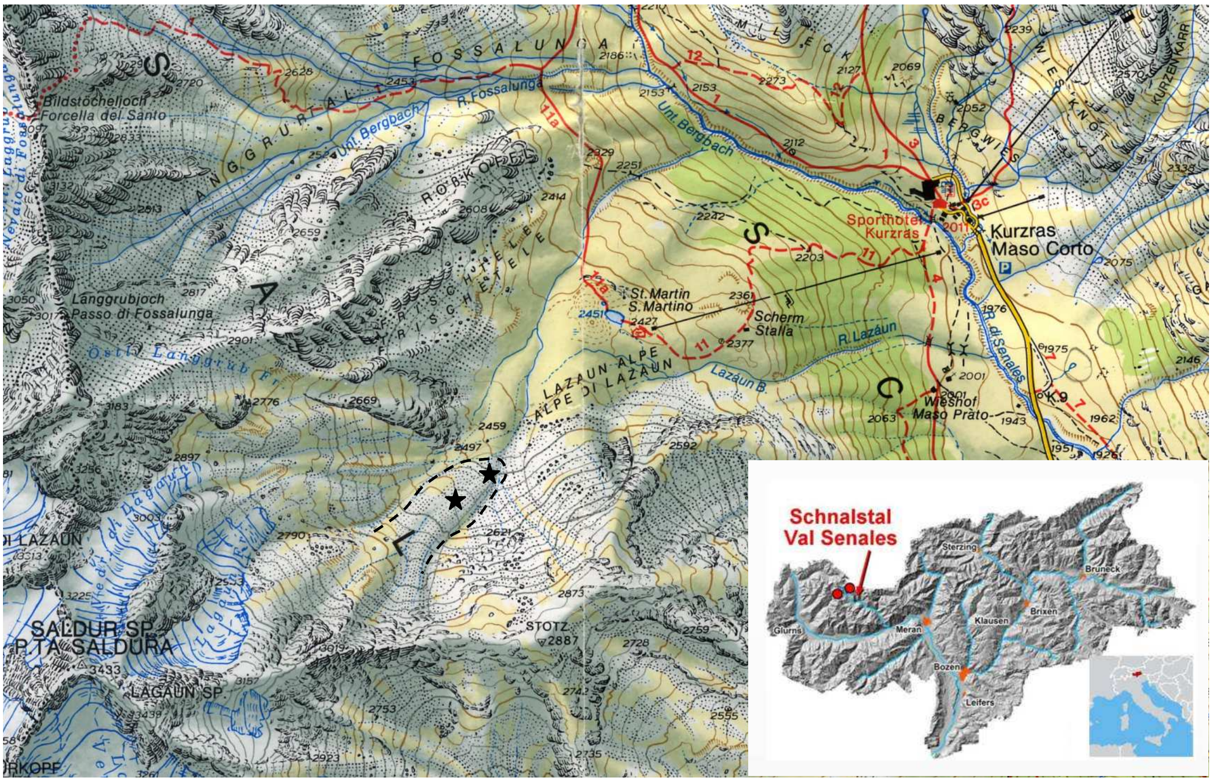

Fig.1: Topografic map with the location of the Lazaun cirque, indicated is the location of the two drillings.

Morphology

The cirque (Lazaunkar) is occupied by an active, tongue-shaped rock glacier, which is 660 m long, up to 200 m wide and covers an area of 0.12 km². The rock glacier extends from the rooting zone at 2700 m at the northern flank of the Stotz- to the front at 2480 m (Fig. 2).

The active rock glacier Lazaun is tongue-shaped, 660 m long, up to 200 m wide and covers an area of 0.12 km². The rock glacier extends from the rooting zone at approximately 2700 m above sea-level to 2480 m a.s.l. at the front. The rock glacier is supported with debris (mica schist and subordinately paragneiss) derived from frost weathering from the western part of the Stotz ridge.

The southern margin of the rock glacier is less steep than the northern margin. A depression in the frontal part divides the front into two lobes. The gradient of the front measures 35 – 45°. At the front the rock glacier is 29 m thick. The front of the rock glacier overrides an alpine meadow, on the northern margin a fan composed of debris flow deposits.

The surface of the rock glacier displays a pronounced morphology of longitudinal and transverse ridges and furrows. Longitudinal ridges and furrows occur in the upper part, transverse ridges and furrows are present in the lower part, particularly near the front.

Fig. 2: View on the active rock glacier at Lazaun (view towards SSW).

Hydrological discharge measurements

A gauging station was installed at the creek in front of the rock glacier briefly before the onset of the snowmelt period during mid June 2006 (Fig. 3).

During the beginning of the snowmelt daily discharge and variations are highest (Figs. 3, 4), from June 20 on discharge and daily variations decreased. Heavy rainfall events on June 24 and June 29 caused peak floods with the highest discharge of the entire melt season. After that discharge decreased continuously, and daily variations decreased significantly. Rainfall from July 6 until July 9 caused a slight increase in discharge. A rainfall event during the night of July 28/29, combined with high temperatures caused an exceptionally high peak flood. After this event discharge decreased slightly, daily variations were not recorded. Slightly increased discharge was recorded on Sept. 3 and Sept. 9, caused by fair weather with high temperatures (no precipitation).

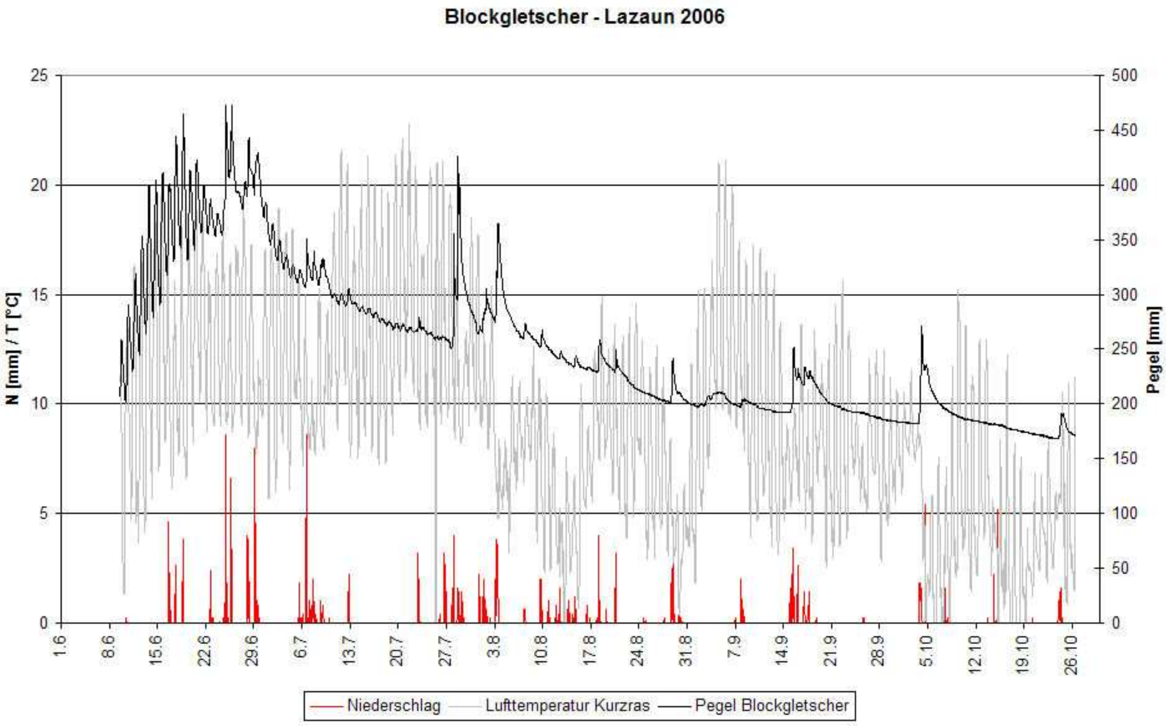

Fig. 3: Hydrograph of the meltwater stream in front of Lazaun Rock Glacier (black) and air temperature at Kurzras (gray). Red bars indicate precipitation at Kruzras.

The cool August was characterized by several events with high precipitation rates. A typical summer thunderstorm occurred on August 20, 2006, which started around 14.40 and lasted for 45 minutes. The heavy rainfall during this thunderstorm event caused a peak flood with its maximum at 17:00.

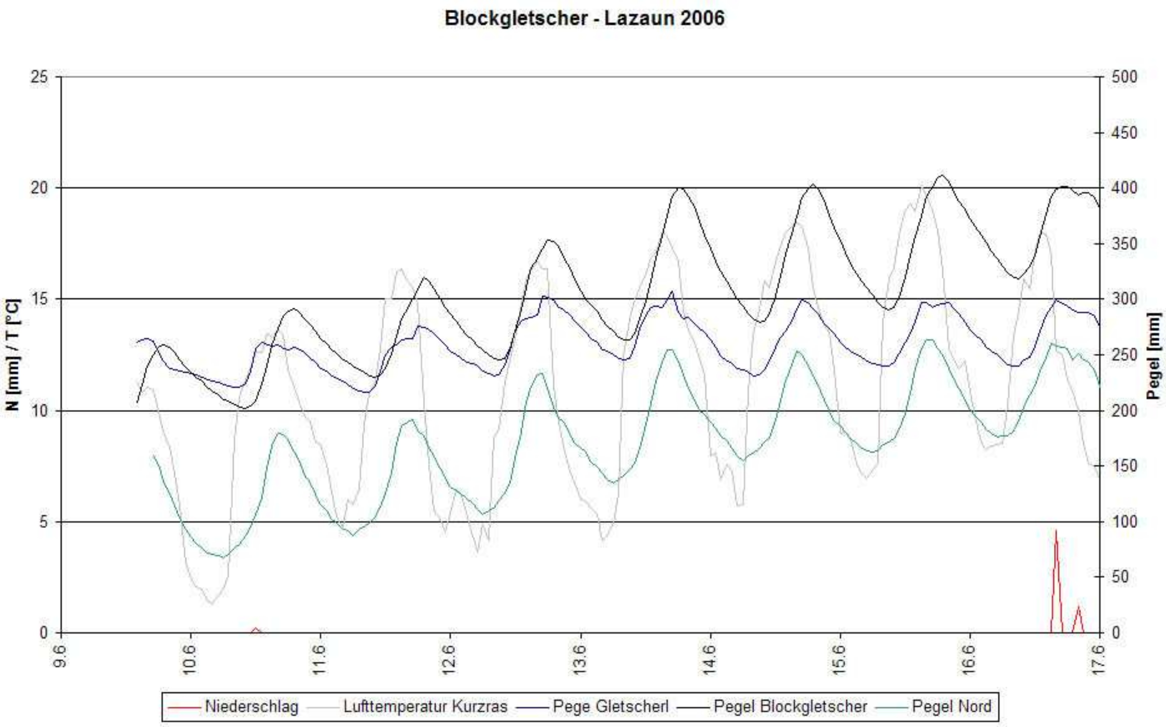

Fig. 4: Daily variations in discharge recorded at the gauging station in front of Lazaun Rock Glacier (black) with lowest discharge around noon and peaks during late evening (June 10 unti June 17). Blue: glacier stream, green: rock glacier in the cirque north of Lazaun, gray: air temperature at Kurzras, red: precipitation at Kurzras.

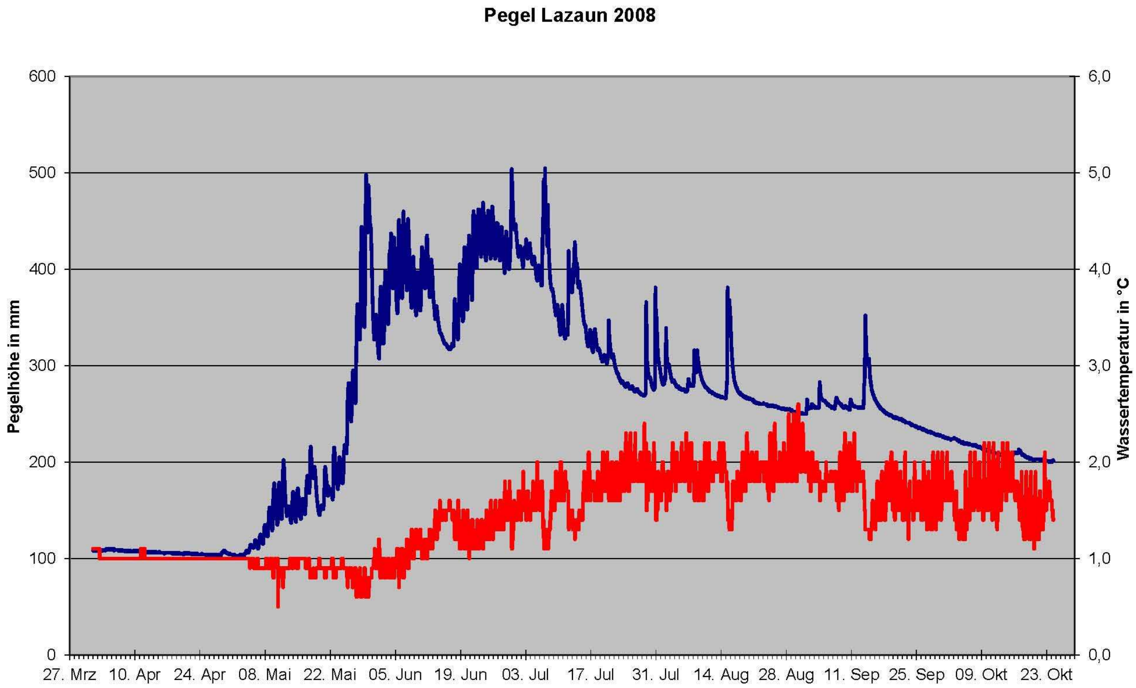

Fig. 5: Hydrograph of the meltwater stream in front of Lazaun Rock Glacier (blue) and water temperature at the gaging station (red) for the period April to October 2008.

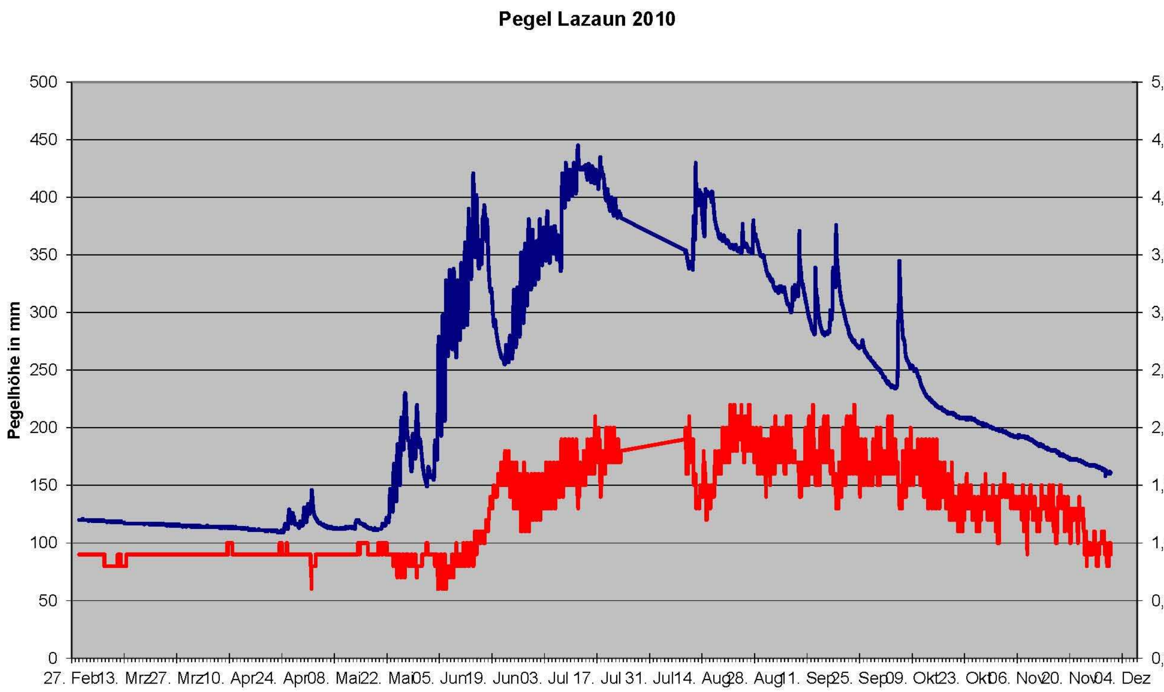

Fig. 6: Hydrograph of the meltwater stream in front of Lazaun Rock Glacier (blue) and water temperature at the gauging station (red) for the period February to November 2010.

Warm weather around Sept. 7 resulted in a slight increase in discharge. Rainfall events which caused increase in discharge occurred on Sept. 16 and Oct. 5.

The precipitation event on Oct. 15 which due to the cool temperatures probably fell as snow, had no effect on the discharge, whereas the precipitation event on Oct. 24, due to the warm temperature, fell as rain and caused a slight increase in discharge.

Compared to the air temperature, which reached its daily maximum between 14:00 and 15:00, the peak discharge of the rock glacier was recorded between 18:00 and 20:00.

Daily variations in discharge are highest during the snowmelt period during June with peak discharge of about 140 l/s, decreases until autumn and reaches its minimum of approximately 9 l/s during winter. The average discharge during summer (July to October) is approximately 26 l/s (Fig. 5, 6).

The frozen core of the rock glacier covers an area of approximately 0.1 km^2, the annual melting rate of the rock glacier ice according to GPS measurements is in the order of 10 cm on average resulting in a total ice volume of 10.000 m^3 (approximately 9.100 m^3 water) which the rock glacier looses by melting each year during the melt season from May until October (6 months). This results in an average discharge of 0.6 l/s which is only about 2.3% of the average discharge of the rock glacier (approximately 26 l/s).

This indicates that the amount of meltwater derived from the melting of permafrost ice is very low. Even if the melting rate of permafrost ice is 20 cm/year, the amount is less than 5% of the total discharge of the rock glacier. Discharge is mostly derived from snowmelt and summer rainfall with very small amounts of groundwater and melting of permafrost ice.

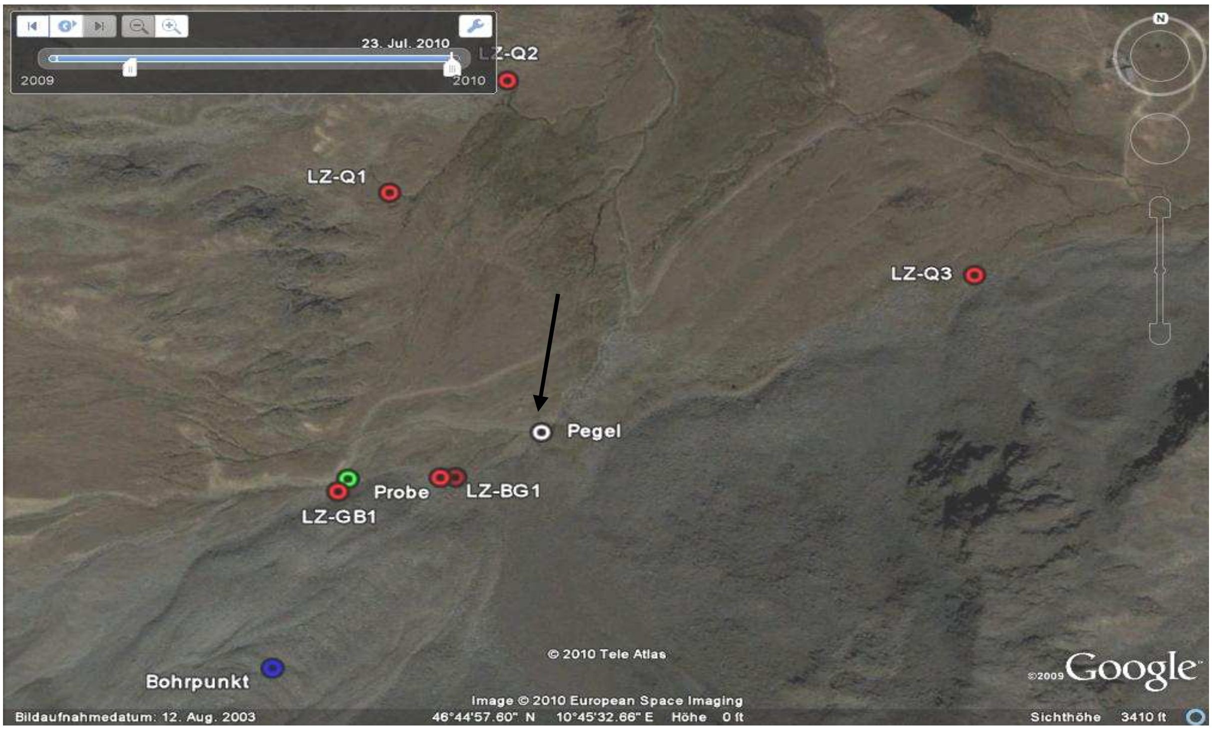

Fig. 7: Location of the gauging station.

Fig. 8: Gauging station.

Geophysical measurements

GPR (Ground penetrating radar) - Georadar

GPR (Ground penetrating radar) has been a standard procedure for investigating thicknesses and internal structures of glaciers since the 1970s (e.g. Arcone et al., 1995), despite the principles of the method already being put to use long before by Stern (1930). The exploration of permafrost also sees the application of GPR (e.g. Arcone et al., 1998; Berthling et al., 2003, Maurer & Hauck 2007, Mooreman et al. 2007).

The internal structure of rock glaciers has been studied by GPR since 1982 using centre frequencies between 50 and 300 MHz (Haeberli et al., 1982; Haeberli, 1985; King et al., 1987; Vonder Mühll, 1993). Penetration depths up to 40 m were obtained recently at rock glaciers using centre frequencies of 35 - 50 MHz (e.g. Berthling et al., 2000, 2003; Isaksen et al., 2000; Degenhardt, 2002; Degenhardt et al., 2003; Maurer and Hauck, 2007; Hausmann et al. 2007).

The basic principle of GPR is the transmission of a short electromagnetic pulse, with a specified frequency, down into the ground and the recording of reflected energy as a function of time, amplitude and phase. The specified central frequency is controlled by the transmitter and receiver antennae length.

The propagation of the electromagnetic waves is determined by material properties such as the electric permittivity, the electric conductivity and the magnetic permeability. If the electromagnetic wave velocity of the subsurface material is known the observed travel times to a reflector can be converted to depth.

The dielectric constant of earth materials usually varies from 1 (air) to 80 (water) representing wave velocities of 0.3m/ns (air) and 0.03m/ns (water). For subsurface materials in glacial and periglacial environment values of 0.09-0.11 (moraine), 0.10-0.14 (loose debris), 0.11-0.13 (granite) and 0.16 – 0.17 (glacier ice) are found (Davies and Annan 1989, Span et al. 2005, Hauck and Kneisel 2008). Typical values for the mean wave velocity of the ice-rich permafrost of rock glaciers range between 0.14 and 0.15 m/ns (Schmöller and Fruhwirth, 1996; Wale, 1999; Isaksen et al., 2000; Lehmann and Green, 2000; Berthling et al., 2003; Hausmann et al. 2007). Degenhardt and Giardino (2003) produced a different value (0.12 m/ns). Best results are achieved when GPR measurements are combined with other geophysical methods such as seismics or gravimetry (e.g. Hausmann et al. 2007).

A longitudinal section along the axis (A-B, 550 m long) and transverse section approximately in the middle of the rock glacier (C-D, 200 m long) were measured on the rock glacier in March 2006 when the rock glacier was covered with a thick snow pack.

Additional profiles were measured in front of the rock glacier, from the bedrock across the alluvial fan.

Due to the penetration depth of about 25 m surface of the bedrock was only detected in the rooting zone.

A prominent reflector was detected in the upper part of the profile at a depth of approximately 14 m, starting at 200 m and traceable for 75 m. A reflector was locally detected at a depth of 10 – 15 m.

According to the drilling these reflectors at depths of 10 – 15 m most probably document the unfrozen layer between the two frozen bodies. No reflectors were visible on the transverse section.

Fig. 9: Field campaign: georadar measurements at the Lazaun rock glacier.

Flow velocity measurements – DGPS measurements

On the rock glacier we established a geodetic network of 53 survey markers along 5 transverse profiles and 7 fixed control points in front of the rock glacier in August 2006. The survey markers were first measured on August 28, 2006 using differential GPS technique (the method is described in more detail in Hofmann-Wallenhof et al. 1994, Eiken et al. 1997, Lambiel & Delaloye, 2004). The survey markers were remeasured on July 10, 2007, July 23, 2008 and October 15, 2011.

Due to the morphology we already suggested before the GPS measurements that the highest flow velocities occur in the middle of the rock glacier along the axis, in the upper part of the rock glacier and at the northeastern part of the front. These suggestions were confirmed by the measurements (Fig. 10).

The flow direction is towards NE, highest flow velocities were recorded on the northeastern part of the front with maximum annual values at survey marker 4. Highest flow velocities were recorded at transect 1, flow velocities decreased upward and lowest flow velocities were recorded at transect 5.

Average daily flow velocities increased from 1.4 – 2 mm/day (2006 – 2007) to 2.7 – 4.5 mm/day (2008 – 2011) at transect 1. At transect 5 flow velocities increased from 0.3 – 1.7 mm/day (2006 – 2007) to 0.7 – 2.9 mm/day (2008 – 2011) (see table).

Flow velocities are low along both margins and increase towards the central part of the rock glacier.

		2006-2007	**2007 - 2008**	**2008 - 2011**
	marker points	318 days	379 days	1179 days
Transect 1	4 - 10	0,45 - 0,77 m	0,66 - 1,53 m	3,25 - 5,35 m
		(1,4 - 2,4 mm/day)	(1,7 - 4 mm/day)	(2,7 - 4,5 mm/day)
Transect 2	28 - 32	0,55 - 0,64 m	0,41 - 0,99 m	2,08 - 4,76 m
		1,7 - 2 mm/day)	(1,1 - 2,6 mm/day)	(1,7 - 4 mm/day)
Transect 3	16 - 21	0,18 - 0,55 m	0,45 - 0,86 m	2,43 - 4,33 m
		(0,6 - 1,7 mm/day)	(1,2 - 2,2 mm/day)	(2 - 3,7 mm/day)
Transect 4	38 - 44	0,20 - 0,54 m	0,31 - 0,82 m	1,74 - 3,92 m
		(0,6 - 1,7 mm/day)	(0,8 - 2,1 mm/day)	(1,5 - 3,3 mm/day)
Transect 5	52 - 66	0,11 - 0,55 m	0,16 - 0,75 m	0,82 - 3,44 m
		(0,3 - 1,7 mm/day)	(0,4 - 2 mm/day)	(0,7 - 2,9 mm/day)

Table: Flow velocities of transects 1 – 5 (central part) for the period 2006 - 2011

Highest flow velocities were recorded on that part of the rock glacier where transverse ridges and furrows are well developed.

Differences in height indicate that the thickness of the rock glacier decreased up to 30 cm on the northeastern part of the front and 20 – 5 cm in the central part of the rock glacier. An increase in thickness of the rock glacier was not observed; thickness of the rock glacier decreased on all markers. Markers with the highest horizontal displacements showed the highest vertical displacements.

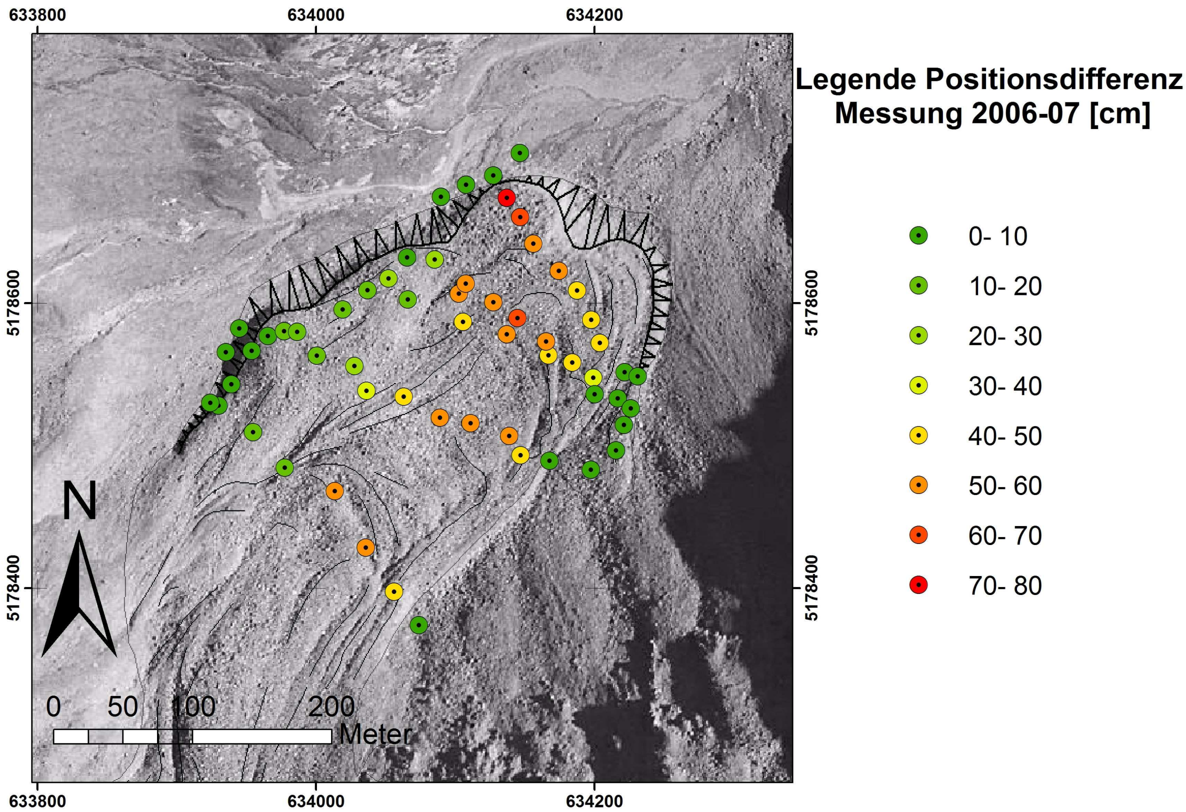

Fig. 10: Horizontal displacements (GPS data) on the lower part of Lazaun Rock Glacier for the period August 26, 2006 until July 10, 2007. Highest flow velocities were recorded along the axis, lowest velocities near the margin.

(2) Study Site Rossbänk, Ulten Valley

Location

Rock glacier „Rossbänk" is one of 17 rock glaciers (9 active, 4 inactive, 4 fossil) which were mapped in the Ulten Valley in the area of Oberweissbrunn. The area is located in Stelvio National Park. Rock Glacier „Rossbänk" is located in an east-facing cirque, surrounded by steep rock walls with Vordere Eggenspitze (3348m) being the highest summit (Fig. 11 - 12).

Fig. 11: Topografic map of the Rossbänk rock glacier in the Ulten valley.

Fig. 12: Lower and middle part of Rossbänk Rock Glacier in the uppermost Ulten Valley with steep front

Morphology

Rock glacier „Rossbänk" is 1700 m long, 200 – 600 m wide, extends from an altitude of 2310 m (fossile front) to 2840 m (rooting zone) and covers an area of 55 ha. The rock glacier is tongue-shaped, the front of the active part ends at an altitude of 2470 m and overrides two tongues of an inactive rock glacier, which end at 2375 m and overlie a fossil rock glacier which extends to an altitude of 2310 m. The slope of the front of the active as well as of the inactive and fossil rock glacier is up to 40° steep.

The rock glacier derives debris produced by frost weathering from the steep wall of the Vordere Eggenspitze. A depression is developed in the rooting zone which is filled with meltwater during summer.

The surface layer of the rock glacier is very coarse-grained. In the upper part of the rock glacier longitudinal ridges and furrows are well developed, in the middle and lower part transverse ridges and furrows (lobes) are present. The front of the active rock glacier is not well developed, the maximum slope measures 40°.

Hydrology

Water temperature was measured at the spring of the rock glacier several times. The water temperature always was below 1°C (0.4 – 0.7°C) which indicates the presence of permafrost. The water temperature of the the springs of the rock glaciers Nr. 6, 8, 9 and 12 also were mostly below 1°C, rarely increased to a maximum of 1.8°C at rock glacier Nr. 12 and to 1.4°C at rock glacier Nr. 6 (Juen 1999, 2000). These temperatures indicate that these rock glaciers very probably also contain ice. At the spring of rock glacier Nr. 2 the temperature ranges between 1.2 and 1.9°C also indicating that some ice may still be present. Significantly higher water temperatures of 2.3 – 5.1°C were recorded at the gauging station in front of the steep snout of the fossil rock glacier Nr. 4.

The gauging station was installed at a distance of about 30 m off the springs. Daily variations of the water temperature at the gauging station demonstrate that at this short distance the water temperature increases of up to more than 1°C on warm days during summer. During May the water temperature of the springs measured 0.2 – 0.8°C.

At the springs of the rock glaciers Nr. 4, 6, 8 and 12 the electrical conductivity was measured several times during summer. At all springs the lowest values (86 – 130 µS/cm) were recorded immediately after the beginning of the snowmelt during May and June and increased to values of > 300 µS/cm in autumn. The highest value of 360 µS/cm was recorded at the spring of rock glacier Nr. 12 in September.

In front of the fossil rock glacier Rossbänk a gauging station was installed from May until October 2007. During this time the discharge was characterized by pronounced seasonal variations. During May and June diurnal variations were recorded too. Due to snowmelt discharge is highest during May, June and July. Periods with cold weather cause a significant decrease of discharge to values < 20 l/s. Precipitation events during summer cause short peak discharge of more than 100 l/s. A pronounced rainfall event during August caused a significant peak discharge of more than 200 l/s.

During August and September discharge generally decreases, interrupted by few single peaks caused by rainfall events. During September discharge varied between 13 and 28 l/s. During October a rainfall event caused a peak discharge of 60 l/s, followed by a continuous decrease until the springs fell completely dry by the end of November (Fig. 13).

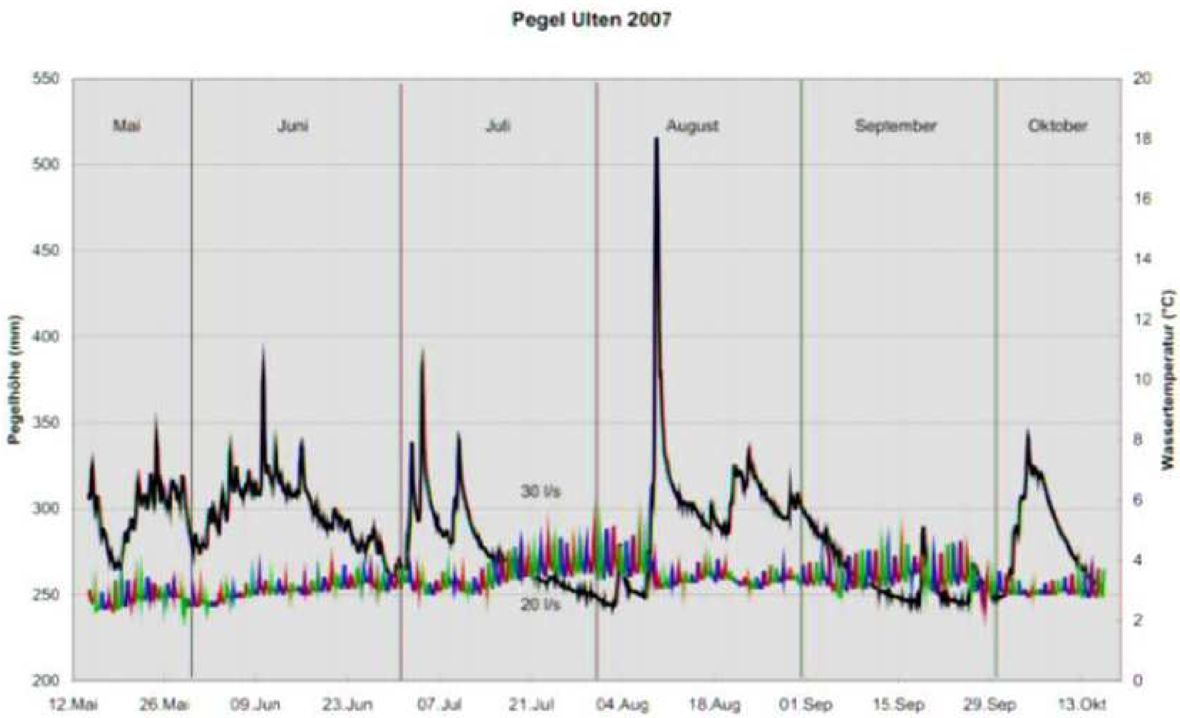

Fig. 13: Hydrograph (black line) and water temperature (red line) for the meltwater stream in front of Rossbänk Rock Glacier for the period May 12 until October 16 2007.

Flow velocities

On rock glacier Rossbänk 16 marker points were measured in the upper part. From 2005 to 2006 (316 days) horizontal displacements of 13 – 29 cm were recorded, resulting in average daily flow rates of 0.41 to 0.91 mm. At one marker (Z 1) the displacement was significantly lower (3 cm or 0.1 mm/day). Highest flow velocities were recorded along the axis of the rock glacier, the flow velocity decreased towards both margins.

During the consecutive year (2006 – 2007) (measuring interval of 347 days) higher displacement rates of 18 – 32 cm were recorded resulting in average daily flow rates of 0.52 – 0.92 mm. Also on marker Z 1 the displacement was higher (5 cm, 0.14 mm/day) than during the year before.

During 2005 – 2006 (316 days) the horizontal displacements on the middle part of the rock glacier measured 18 – 28 cm (0.57 – 0.89 mm/day) and during 2006 – 2007 (347 days) 21 – 37 cm (0.60 – 1.07 cm/day). Also on the middle part horizontal displacements were higher during 2006 – 2007 than in the year before.

The lowest horizontal displacements were recorded at the 13 marker points in the front part of the rock glacier: 0 – 5 cm (0 – 0.15 mm/day) in the period 2005 – 2006 and 2 – 11 cm (0.06 – 0.32 mm/day) in the following year 2006 – 2007. Also in the front part displacement rates were higher in the period 2006 – 2007 than in the year before.

Geophysical Measurements

In 2006 and 2008 several longitudinal and transverse georadar profiles were measured on the active and fossil rock glacier. Measurements were mostly done in March and April 2006 and May 2008 when the rock glacier was covered by snow. During October 2006 profiles were measured on the frontal part of the active and fossil rock glacier.

Due to a penetration depth of approximately 25 m the surface of the bedrock was only detected in the rooting zone of the rock glacier. The reflector disappears about 150 m downside the rooting zone. Down to a depth of approximately 20 m reflectors were locally detected in various depths in the longitudinal and transverse profile. These reflectors are difficult to interpret. As the active rock glacier overrides an inactive rock glacier and the inactive rock glacier overlies a fossil rock glacier in the middle and lower part of the active rock glacier the surface of the bedrock is expected to occur in a depth of at least 60 m.

In August 2005 RIBOLINI performed geoelectric measurements along two transverse profiles in the lower and middle part of the rock glacier.

In the upper profile various values of resistance were recorded down to a depth of about 4 m. This part is interpreted as “active layer”. Below the active layer down to a depth of approximately 15 m very high values of resistivity were measured. This part is interpreted as ice-rich debris and in the central part as massive ice-body. Parts with intermediate to high values of resistivity are interpreted to represent debris with low amounts of ice. The presence of water within this part cannot be excluded.

In the lower profile large variations of electric resistivity were recorded. Parts with high values of resistivity down to a depth of 10 m are interpreted as debris containing high amounts of ice. Interbedded layers with lower values of resistivity may represent meltwater channels. Below a depth of about 20 m values of electric resistivity and thus amounts of ice decrease (see AUSSERER 2009).

(3) Study Site Sella, Dolomites

Location

The studied active rock glacier “Murfreit” is situated at an elevation of 2670 m on a prominent terrace (Mittelterrasse, Meisules) on the northern side of the Sella massif west of the Rifugio Pisciadú in the Dolomites, northern Italy. The location is shown on Fig. 14.

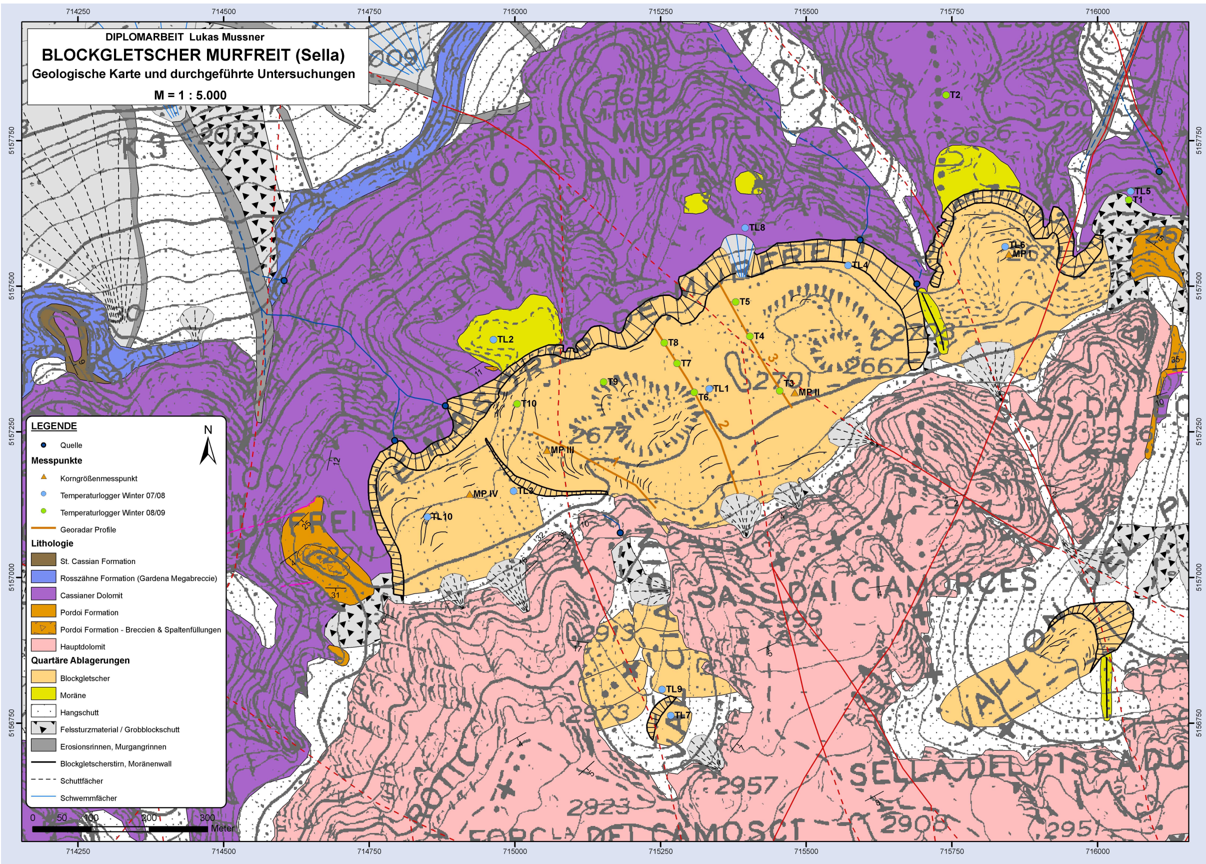

Fig. 14: Geologic-geomorphologic map of Murfreit Rock Glacier in the northern Sella Group (Dolomites).

Morphology

In the northern part of the Sella Group 10 rock glaciers were localized which cover an area of 53.5 ha. Four rock glaciers were classified as active, five as inactive and one as fossil. Among these rock glaciers Murfreit is by far the largest and also most active rock glacier. Another rock glacier termed

Sas dala Luesa is located immediately east of rock glacier Murfreit. Both rock glaciers are located on the prominent terrace west of Rifugio Pisciadú.

Rock glacier Murfreit (Fig. 15) is a lobate, ice-cored rock glacier which is 420 m long, 1100 m wide and covers an area of 33.6 ha. 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 towards the south is bordered by a steep wall which rises up to elevations of almost 3000 m. This steep wall is composed of Hauptdolomite which is cut by several steep faults. Particularly from the fault zones along which the Hauptdolomite is strongly tectonically disintegrated the rock glacier is supported with debris. Rock fall activity is also observed in the steep walls besides the fault zones. Consequently, the rock glacier is composed entirely of Hauptdolomite debris of varying grain size.

Fig. 15: Rock Glacier Murfreit (view towards north)

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. 16).

Fig. 16: Western part of Murfreit Rock Glacier with a steep fron which locally ends at the edge of the terrace. View towards the east.

In the rooting zone the debris layer ("active layer") at many places is only 10 – 15 cm thick. 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. 17).

Fig. 17: Small depression with small meltwater pond developed in the rooting zone of the western part of Murfreit Rock Glacier.

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 broke out several times. At times, during the 1950ies, Lake Dragon was partly bordered by a steep wall of banded glacier 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 (Figs 18, 19).

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 glacier ice is exposed. Along the banding (shear planes) thin, fine-grained layers of sediment occur. Larger blocks rarely are observed within the ice (Figs. 20, 21).
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. 22).

Fig. 18: Thermokarst lake on the western part of Murfreit Rock Glacier. Massive ice is exposed at the margin of the lake below a thin debris layer.

Fig. 19: Empty thermokarst lake with massive, banded ice exposed below a 0.8 – 1 m thick debris layer.

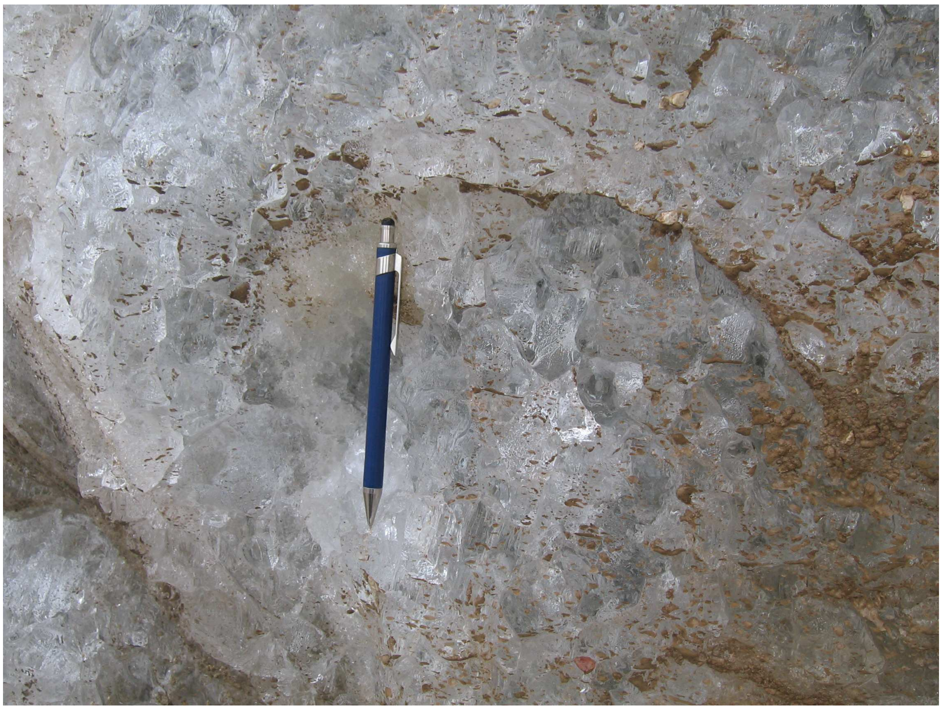

Fig. 20: Coarse-grained glacier ice composed of cm-large ice crystals, exposed at the margin of Lake Dragon at Murfreit Rock Glacier.

Fig. 21: South of Lake Dragon massive ice is exposed below a thin debris layer.

Fig. 22: Active western part of Murfreit Rock Glacier with well developed ridges and furrows on the surface. The steep front ends at the edge of the terrace.

Hydrological discharge measurements

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. Among these four springs only Cuela is easy to access, although it was not possible to install a gauging station.

At the spring Cuela which is located at the eastern end of the rock glacier at an altitude of 2640 m, 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/sec. Peak discharge was observed during early afternoon. Peak discharge was observed immediately after rainfall events. Discharge decreases from the end of July until the spring disappears during October/November. Also during summer cold weather periods cause a significant decrease in discharge.

At the rock glacier spring water temperature remains constantly below 1°C, mostly around 0.3°C during the entire summer. 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 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 spring 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 Cuela spring the Murfreit springs show higher discharges, but due to the steep front these springs are not accessible.

The total surface discharge of rock glacier Murfreit is significantly higher as that of the two active rock glaciers of the Hohe Gaisl massif.

Geophysical measurements

Velocity Measurements – DGPS 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.

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.

On the western part flow rates were significantly lower (mostly < 10cm, partly < 5 cm) in the period September 2007 – July 2008 than in the shorter period July 2008 – September 2008 (Fig. 23).

A comparison of the aerial photographs of 1953 and 2009 yielded horizontal displacements of distinct large blocks near the front on the western part of t 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 (Fig. 24).

On the markers also distinct vertical displacements were recorded which mostly range between -5 and -15 cm/year (Fig. 25). Comparison of photographs taken in 1899 and 2004 show 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 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.

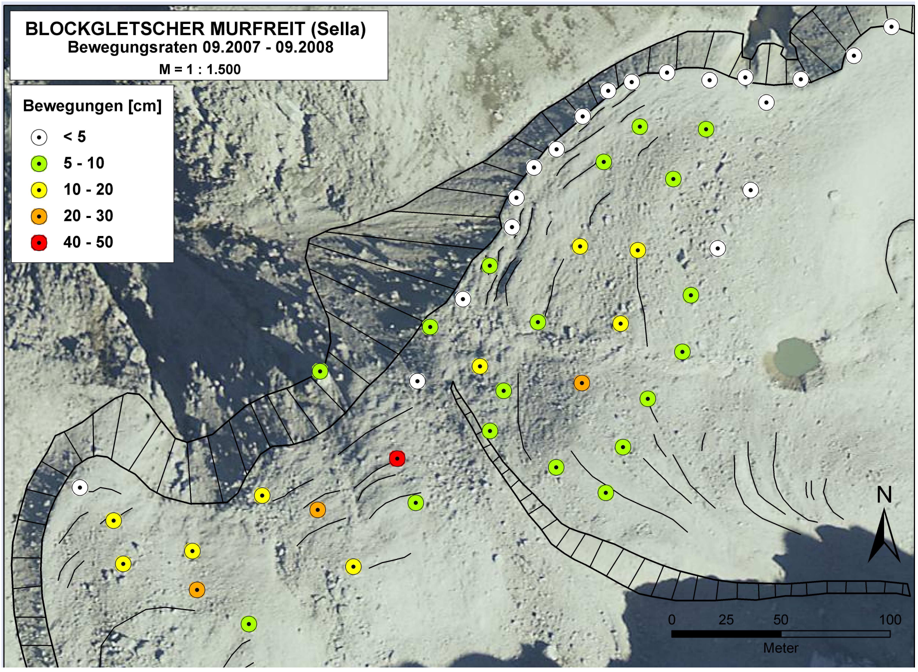

Fig. 23: Horizontal displacements (GPS data) on Murfreit Rock Glacier (western part) for the period September 2007 until September 2008.

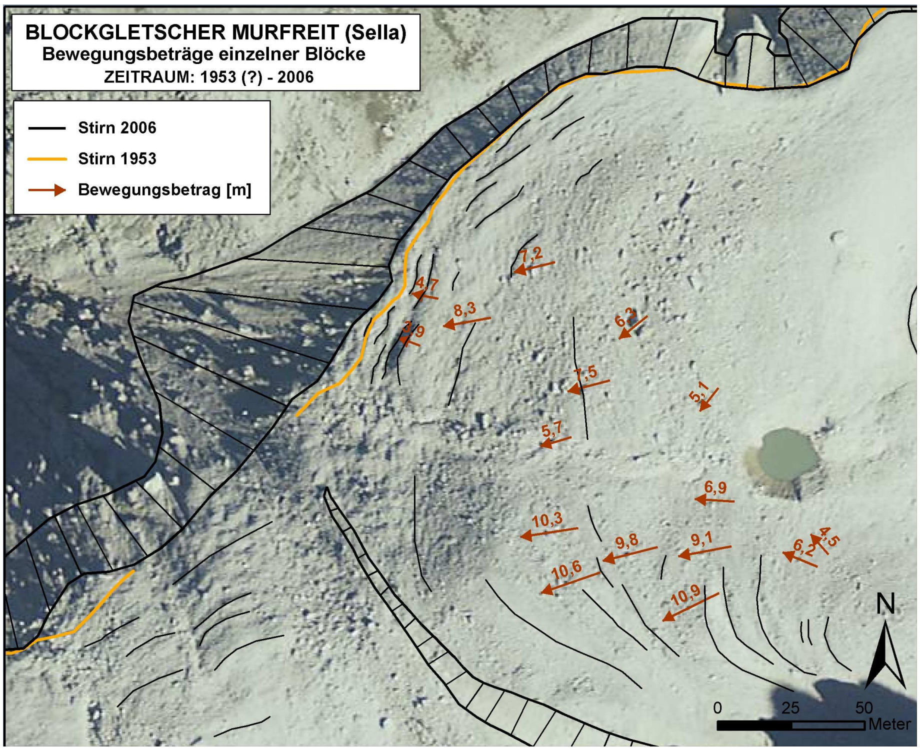

Fig. 24: Horizontal displacements (m) on the western part of Murfreit Rock Glacier for the period 1953 until 2006.

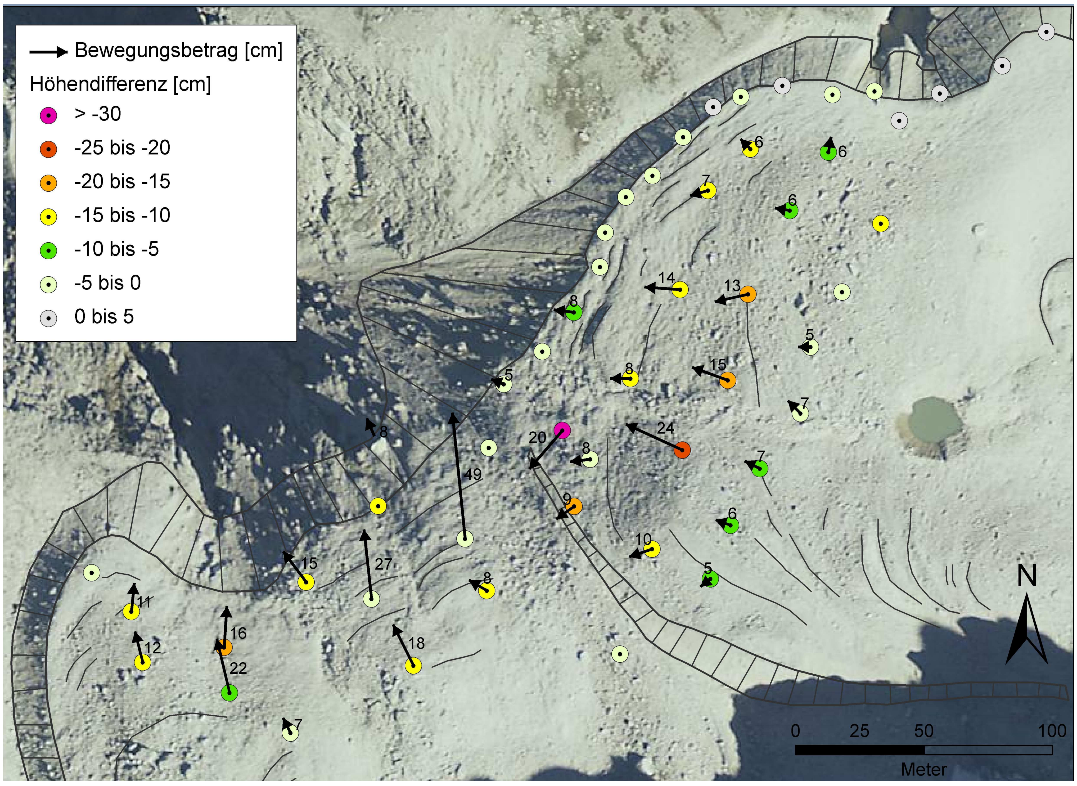

Fig. 25: Horizontal displacements (arrows) and vertical displacements (dots; cm) on the western part of Murfreit Rock Glacier for the period September 2007 until September 2008.

GPR Measurements - Ground Penetrating Radar

At rock glacier "Murfreit" three longitudinal sections were measured (Fig. 26). Section 1 is 250 m long, shows a basal reflector at a depth of approximately 25 m and numerous well developed continuous concave reflectors above this reflector in the middle part of the section (Fig. 27). In section 2 which is 330 m long, a basal reflector was identified at a depth of approximately 30 m and abundant well developed continuous concave reflectors above this reflector in the upper half of the section (Fig. 28). At section 3 a basal reflector is developed at a depth of about 25 m, concave reflectors as detected in the other sections were not observed (Fig. 29). As the rock glacier overrides bedrock which can be seen at the front, the basal reflector is interpreted as the permafrost to bedrock interface. 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. Similar results were obtained from Cadin del Ghiacciaio rock glacier at Hohe Gaisl, eastern Dolomites (Krainer et al. 2010).

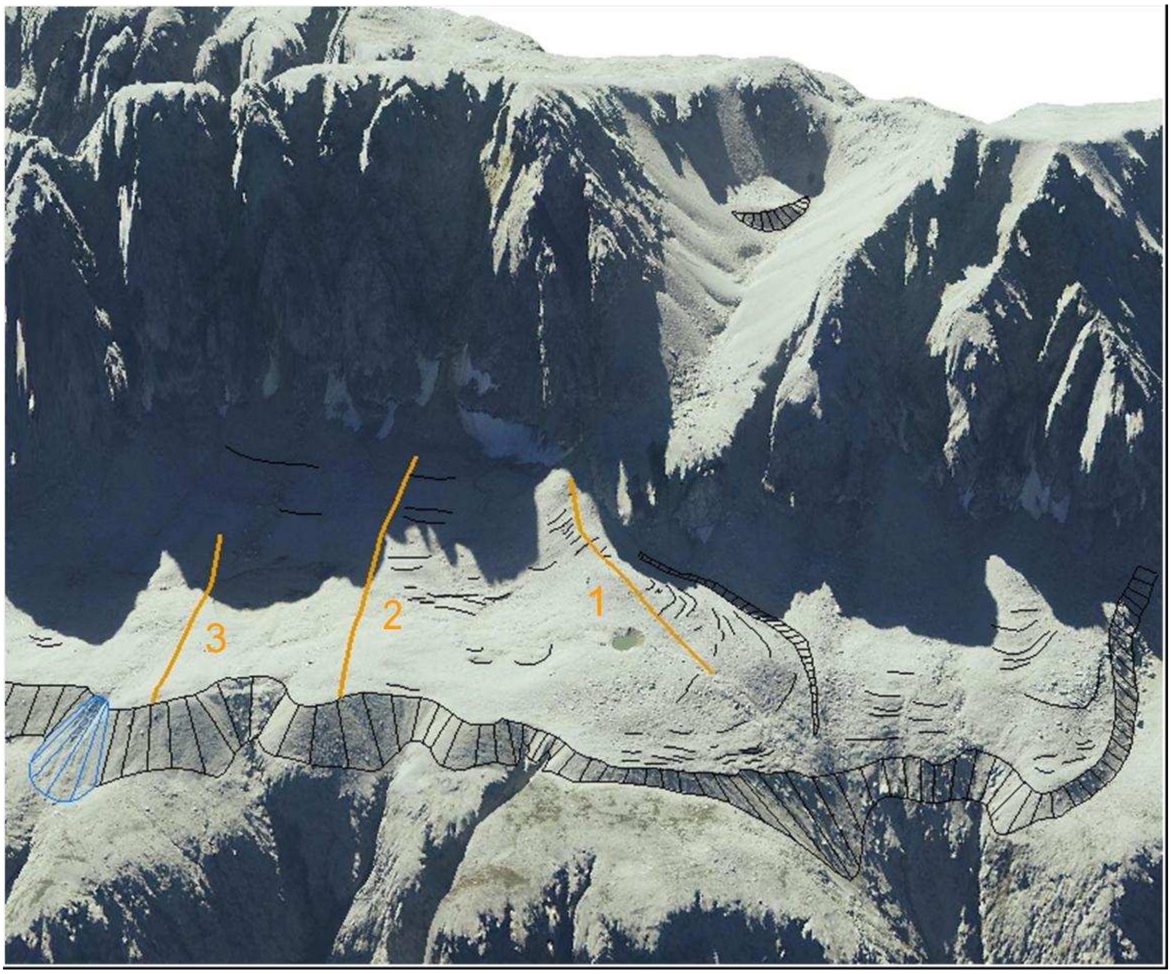

Fig. 26: Position of the georadar profiles on Murfreit Rock Glacier

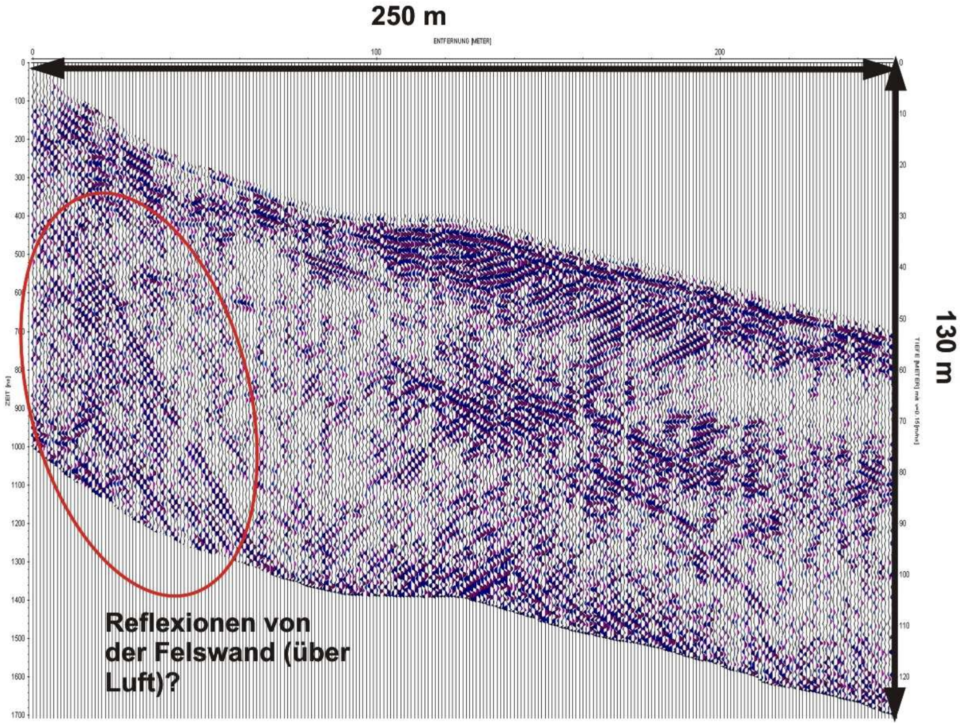

Fig. 27: Longitudinal georadar section (1) on Murfreit Rock Glacier with numerous, well developed reflectors. Reflectors within the circle are most probably caused by reflections from the steep rock wall.

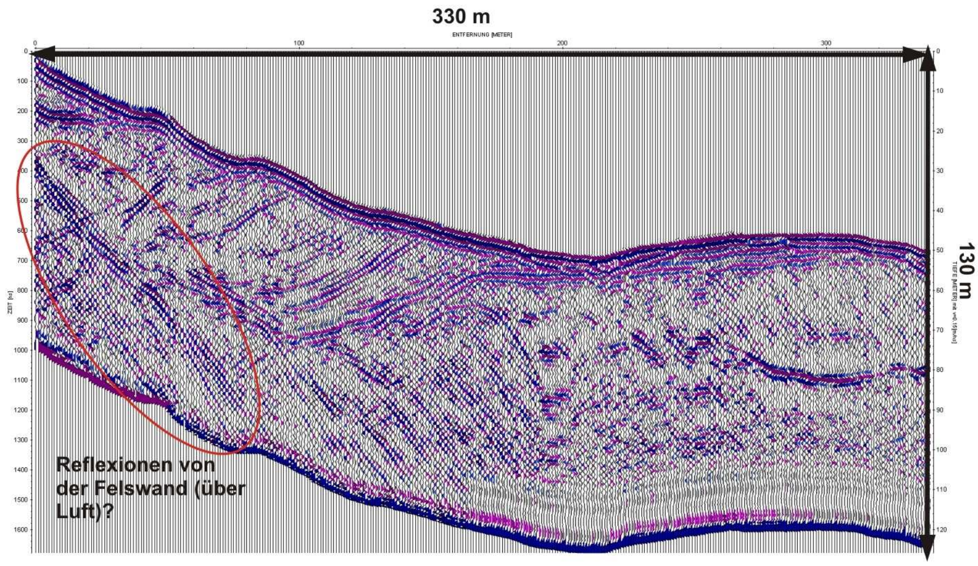

Fig. 28: Longitudinal georadar section (2) on Murfreit Rock Glacier with numerous, well developed reflectors. Slightly concave reflectors in the upper part indicate shear planes within the massive ice body. Reflectors within the circle are most probably caused by reflections from the steep rock wall.

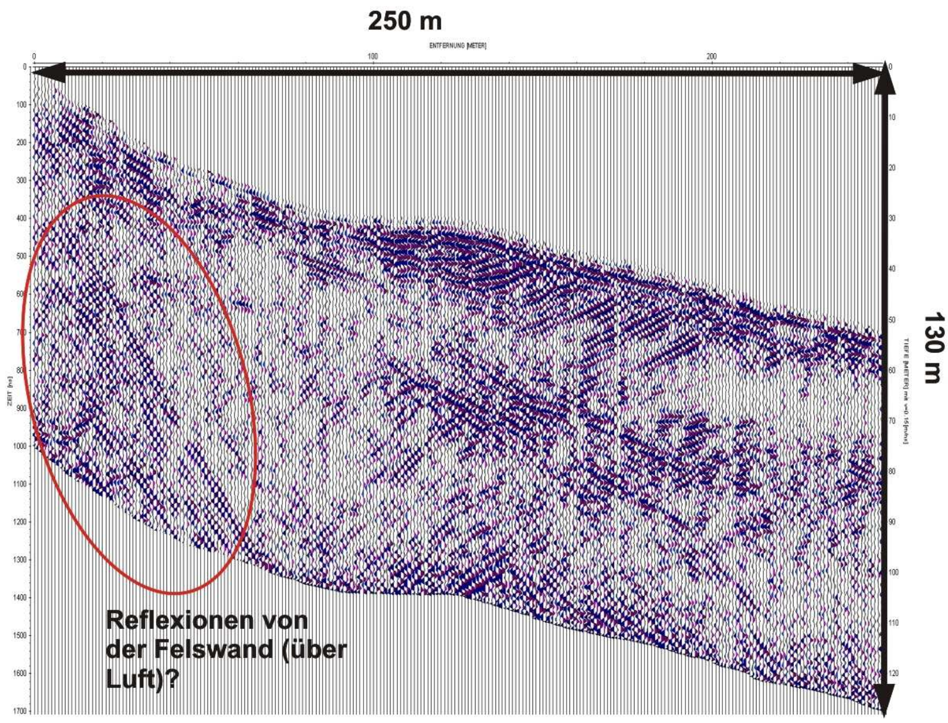

Fig. 29: Longitudinal georadar section (3) on Murfreit Rock Glacier with numerous, well developed reflectors. Reflectors within the circle are most probably caused by reflections from the steep rock wall.

Conclusions

The typical discharge pattern for active rock glaciers is characterized by strong diurnal and seasonal variations. During winter (October until May) discharge is extremely low and electrical conductivity high. Highest discharge is recorded during the snowmelt period in June and July, and during rainfall events. Pronounced diurnal variations in discharge are recorded in May and June.

From the end of July until October discharge decreases, interrupted by single peaks caused by rainfall events. Warm weather periods in autumn may also cause a slight increase in discharge (increased melting of permafrost ice).

Compared to the air temperature, which reached its daily maximum between 14:00 and 15:00, the peak discharge of the rock glacier was recorded between 18:00 and 20:00.

The frozen core of the Lazaun rock glacier covers an area of approximately 0.1 km². The average ice content of the Lazaun rock glacier is approximately 35 – 40 vol.%. Increased melting of permafrost ice causes a loss of approximately 10.000m³ ice/year which is 1.2 – 1.3 of the total ice.

The annual melting rate of the Lazaun rock glacier ice according to GPS measurements is in the order of 10 cm on average resulting in a total ice volume of 10.000 m³ (approximately 9.100 m³ water) which the rock glacier looses by melting each year during the melt season from May until October (6 months). This results in an average discharge of 0.6 l/s which is only about 2.3% of the average discharge of the rock glacier (approximately 26 l/s).

This indicates that the amount of meltwater derived from the melting of permafrost ice is very low. Even if the melting rate of permafrost ice is 20 cm/year, the amount is less than 5% of the total discharge of the rock glacier. Discharge is mostly derived from snowmelt and summer rainfall with very small amounts of groundwater and melting of permafrost ice.

Due to the morphology we already suggested before the GPS measurements that the highest flow velocities occur in the middle of the rock glacier along the axis, in the upper part of the rock glacier and at the northeastern part of the front. These suggestions were confirmed by the measurements.

Average daily flow velocities increased from 1.4 – 2 mm/day (2006 – 2007) to 2.7 – 4.5 mm/day (2008 – 2011) at transect 1. At transect 5 flow velocities increased from 0.3 – 1.7 mm/day (2006 – 2007) to 0.7 – 2.9 mm/day (2008 – 2011).

Highest flow velocities were recorded on that part of the rock glacier where transverse ridges and furrows are well developed.

Differences in height indicate that the thickness of the rock glacier decreased up to 30 cm on the northeastern part of the front and 20 – 5 cm in the central part of the rock glacier. An increase in thickness of the rock glacier was not observed; thickness of the rock glacier decreased on all markers. Markers with the highest horizontal displacements showed the highest vertical displacements.

Georadar data which show several reflectors within the frozen core support the idea that the Lazaun rock glacier has a glacial origin (e.g. LANG 2006).