6 Applied Methods & Results

This table gives an overview of all measurements that were carried out on the rock glaciers in the study area:

Rock glacier	Sieve & Grain size analysis	BTS	Water Chemistry	Spring Temperature & electrical Conductivity	Refraction Seismic	Water discharge
Vesul 1	x	x	x	x		
Vesul 2		x		X		
Buerkelkopf	x		x	X		x
Visnitz		X	x	X		
Visnitz fossil		X		X		
Idalp			x	X	x	

Table 2: Overview of measurements carried out on rock glaciers.

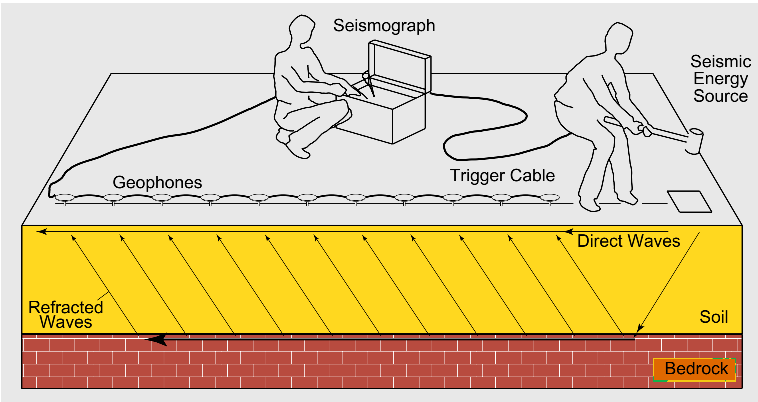
6.1 Refraction Seismic

Refraction seismic is a commonly used geophysical method in engineering geology to determine the depth of water table and bedrock and other seismic velocity boundaries. However, recently seismic methods have been applied in permafrost and rock glacier investigations to measure the depth of the active layer, the permafrost body, and the bedrock.

The principle of this method is based on the generation of seismic waves through an impulsive energy source (hammer, explosive substance), which travels through the subsurface with a specific velocity. Different subsurface velocities are caused by differences in mechanical properties of the individual layers. The density is the crucial factor of differences in the velocity of the layers.

As the wave front travels through the earth, it encounters layers of higher velocities, causing a refraction of the seismic wave. A head wave travels along the boundary of the refracted layer at the velocity of the refracting layer. The head wave returns to the surface at the critical angle of refraction (Kearey, 2002).

Along a predetermined profile a line of geophones detects the arrivals of the head waves, while the seismograph records the data. The time required for the waves (direct and refracted) to travel from the source to a series of geophones is measured. Figure 42 illustrates the alignment of the refraction seismic using a hammer as energy source.



from: Benson, 1983

Fig. 42: Alignment of refraction seismic, using a hammer as energy source, (Benson, 1984).

The seismic survey in the study area was carried out on September 2, 2010 in cooperation with Daniel Landskron of Vienna University of Technology, who focused his bachelor thesis on the seismic measurements at the rock glacier Idalp. The investigated rock glacier is located at the Idalp in Ischgl; further information about its morphology is given in chapter 6. This image shows the rock glacier Idalp; in the upper right lobe of the rock glacier the seismic profile was measured. The yellow line marks the border between Austria and Switzerland.

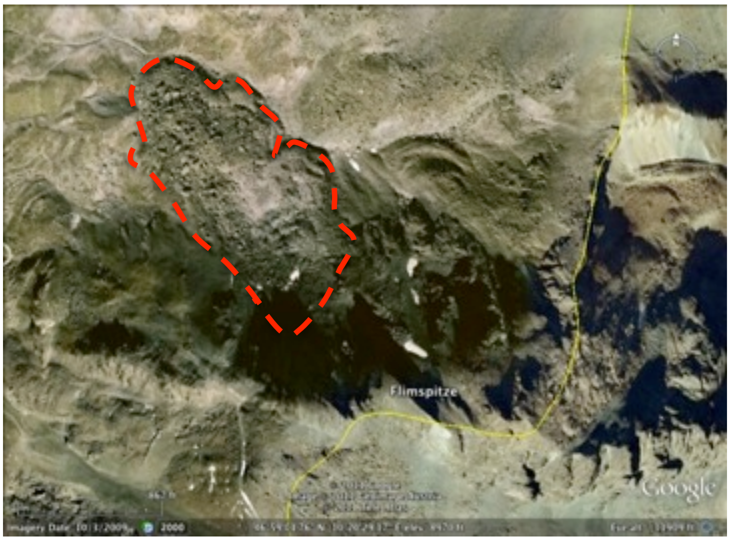


Fig.43: Aerial image of rock glacier Idalp, indicated by the red dashed line (Google.Earth Image).

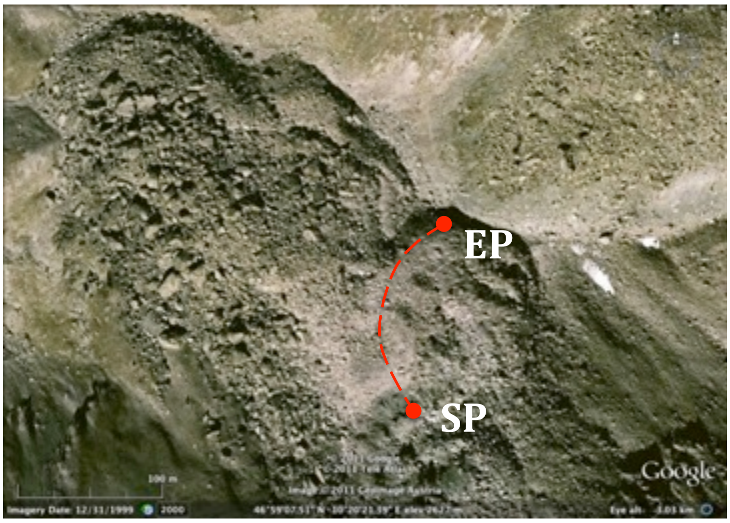


Fig.44: Profile path on rock glacier Idalp. SP: Starting point, EP: Endpoint. (Google.Earth Image)

Fig. 45: Upper right lobe of rock glacier Idalp.

One set of data along a profile length of 100 m was collected. The survey used 12 geophones set up in a linear array to record the arrival times of seismic waves. The energy source was a hammer, which was connected with a cable to the recording device. Two different types of recording devices were used: the Reftek 130-01/06 and a 6-channel recorder. Two geophone chains with 3 geophones respectively were arranged with each recording device. The 12 geophones were spaced in 8 m intervals, and shot points were spaced in 4 m intervals. The shot points were spaced between the geophones so that at any given point, they were placed at a distance of 2 m from the seismic source.
16 shots were carried out at 24 shot points along 12 geophones. The recent snowfall hindered the work in the field and all shot points and places, where geophones were located, had to be uncovered of snow.

Fig. 46: Uncovering snow along profile.

Fig.47: Admeasuring the profile length.

Barsch (1996) measured typical P-wave velocities for rock glaciers:

- active layer: 300 – 800 m/s
- frozen core: 2800 – 4000 m/s

Hausmann et al. (2007) carried out seismic Investigation on Reichenkar rock glacier and estimated velocities for:

- V_{debris}: 950 m/s
- $V_{ice\ permafrost}$: 3300 m/s
- $V_{bedrock}$: 4100 m/s

6.1.1 Evaluation and Results

The evaluation of the data was performed by Helmut Hausmann and Daniel Landskron (Vienna University of Technology). First, the geometry of the rock glacier at the profile length was determined, followed by the evaluation of the seismic waves with the program "ProMax". The first arrival time of seismic data was picked and plotted into a time-distance diagram, as shown in figure 48. The distance is given on the x-axis and time on the y-axis. The green line matches the direct wave, which has a velocity of 490 m/s, whereas the red line indicates the refracted wave, with a velocity of 3610 m/s. The velocity of the refracted wave may be a good index for a massive ice core in the interior of the rock glacier. The low velocity of the direct wave is caused by the presence of unconsolidated debris.

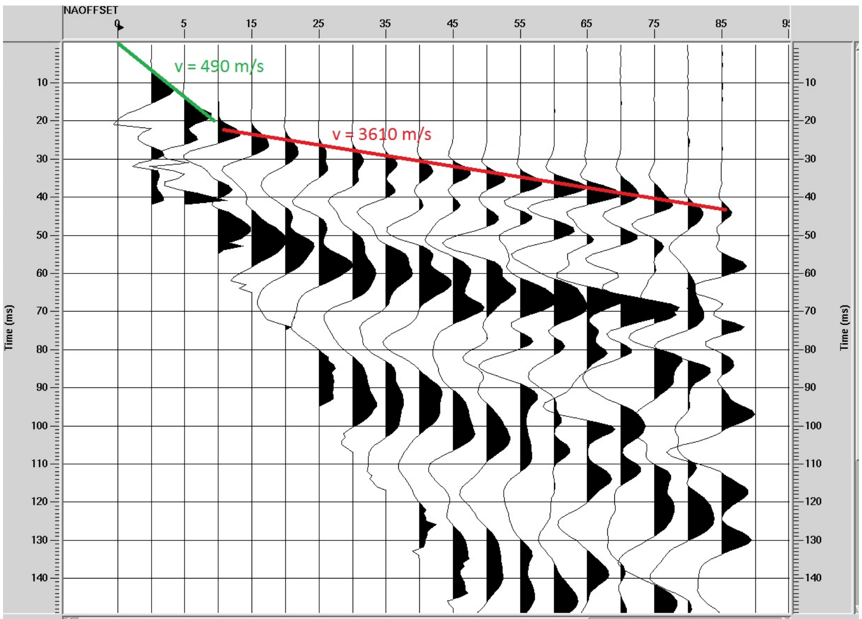


Fig. 48: Time-distance diagram of seismic waves (Landskron, 2011).

The 2-D evaluation of the refractor depicts the elevation of the profile (y-axis) versus the distance (x-axis) in Figure 49. The blue dots indicate the surface geometry, while the purple squares show the profile length, and distribution of the geophones on the surface. The yellow triangles represent the depth of the refracted surface calculated from each shot point. By means of delay times, Landskron (2011), calculated the depth of the refractor and gives values of 4,5 m and 3,4 m.

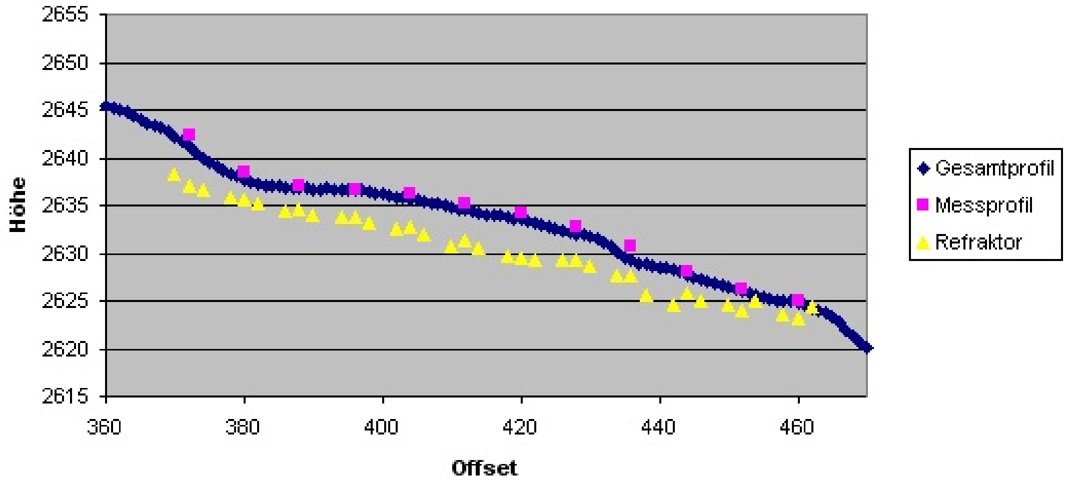


Fig.49: 2-D Refraction Model of the rg Idalp (Landskron, 2011).

Figure 50 shows a 2-D tomography based on velocities of the survey. The velocities of the subsurface are put on the offset (x-axis) versus the depth (y-axis).

A sharp contrast in transition from green to yellow/orange is clearly visible in the velocity tomography in figure 50. This contrast indicates an increase from about 2000 m/s, which is the unfrozen active layer, to about 3000 m/s, the frozen core. The black marker runs in accordance to the likely debris/ice boundary, (Landskron, 2011). In the mid section of the profile, bedrock is encountered below 17 m, while the depth of bedrock is shallower towards both margins.

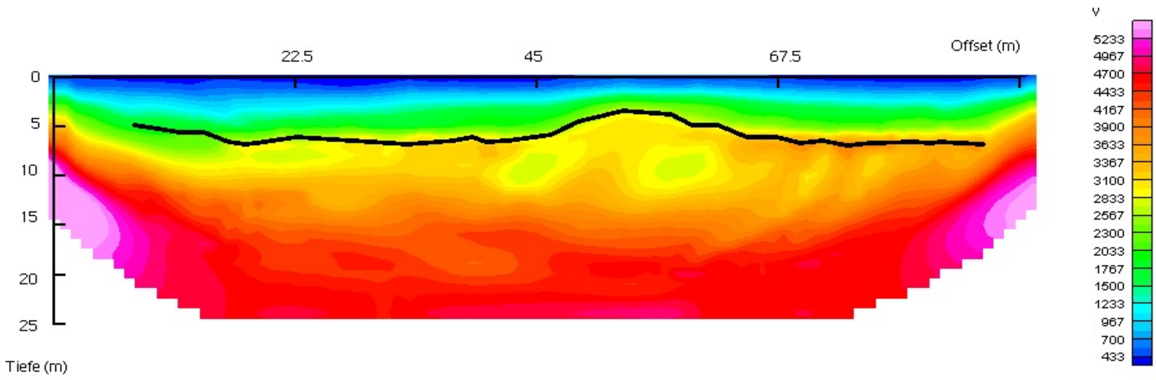


Fig. 50: Differences in velocities based on 2-D tomography (Landskron, 2011).

6.1.2 Interpretation

The seismic survey on this rock glacier shows a clear boundary between the debris cover (active layer) and the rock glacier interior (frozen core). The debris cover comprises the active layer of the rock glacier and shows velocities of 490 m/s, while the velocities of the internal section of the rock glacier show an abrupt jump in value up to 3610 m/s. This most likely indicates a mixture of ice and debris or possibly a massive ice core may be encountered in the interior of the rock glacier. The thickness of the active layer, which was calculated by means of delay times, gives an average depth of 3.9 m. This indicates that the boundary of the active layer and the permafrost body of the rock glacier is located about 3.9 m below surface. Velocities over 4000 m/s indicate bedrock. Bedrock depths range from 8 m below the surface at the ends of the profile and up to 18 m in the midsection of the profile. The maximum thickness of the rock glacier Idalp is about 18 m.

Typical velocities for permafrost bodies are 2300 – 4000 m/s according to Barsch (1996), while Hausmann et al. (2007) report seismic velocities on Reichenkar rock glacier, Tyrol (Austria), of about 3300 m/s. Using a seismic velocity of 4000 m/s of the permafrost body, the maximum thickness of the permafrost body is about 10 m. The data produced by the seismic survey indicates that the upper right lobe of the rock glacier Idalp is active with a massive ice core or a mixture of ice and debris. The area around the mountain Flimspitze and at the current location of the rock glacier Idalp was glaciated during the early 19th century, indicated in the historical map of the 2nd mapping period in Tyrol (1801/1805 – 1816/1821).

This glacier is totally retreated by 1887, which is indicated by the map "3rd Landesaufnahme of Tirol in chapter "Historical maps". The knowledge of the glacial history at rock glacier Idalp attributes to a maximum age of ~ 150 years, assuming that a fast glacier retreat after the little ice age with its maximum ~1850, occurred in this area, as in the year 1877 no glacier was mapped in that area.

The glaciation history and the geophysical exploration data lead to the assumption that the rock glacier is derived from of a glacier. However, further investigation is required to determine the ice content and activity state of the entire rock glacier.

6.2 Bottom Temperature of Snow Cover

This method is based on ground surface temperature measurements below an insulating snow cover of at least 0,8 to 1 m. The snow cover is acting as an insulator, preventing the surface of daily temperature influences. Hence, the temperature recorded reflects the ground temperature of the soil and bedrock. This method has been used first by Haeberli (1973). Due to the temperature record and the data obtained the existence of ice in the rock glacier can be determined. BTS measurements have been used frequently to get information about the existence of ice in rock glaciers.

The existence of permafrost at a temperature < -3° C is very probable, from -3 °C to - 2 °C it is possible, whereas temperatures > - 2 °C it is not probable to encounter permafrost.

Haeberli and Patzelt (1982) show the relationship between the thickness of the active layer and the BTS. This correlation has been carried out on the rock glacier “Aeusseres Hochebenkar” near Obergurgl (Tyrol). An increase in the thickness of the active layer shows an increase in temperature. For instance, the BTS shows -7 °C with a thickness of 2 m, in comparison to a thickness of 4,5 m the BTS shows a temperature of – 3 °C.

6.2.1 Installation

A total of 12 BTS-loggers were installed in July/August 2010 on four rock glaciers. Therefrom three are assumingly active rock glaciers and one fossil. 3 BTS- loggers have been set up adjacent to the rock glaciers as referencing temperature. The loggers record the air temperature in a two-hour interval frame with a +/- 0.2° C accuracy of measurement. The distribution of the temperature loggers on the rock glaciers Vesul 1 and 2, Visnitz, and Visnitz fossil is pointed out in the Google.Earth images below.

Fig. 51: Location of BTS – loggers on rock glacier Vesul1 and Vesul 2.

Fig. 52: Location of BTS loggers on rg Visnitz and Visnitz fossil.

All temperature loggers were collected in August 2011 and read by the Software HOBOWARE. The data is drawn by excel charts with the date (mm/dd/yy) at the x-axis and the temperature (°C) at the y-axis. The measuring period has started at Nov. 1, 2010 and has ended at August 25, 2011.

The results of the temperature records of the rock glaciers Vesul 1, Vesul 2, Visnitz and Visnitz (fossil) are shown as graphs and described below. Every temperature record will be classified within Haeberli's (1973) BTS classification system of permafrost.

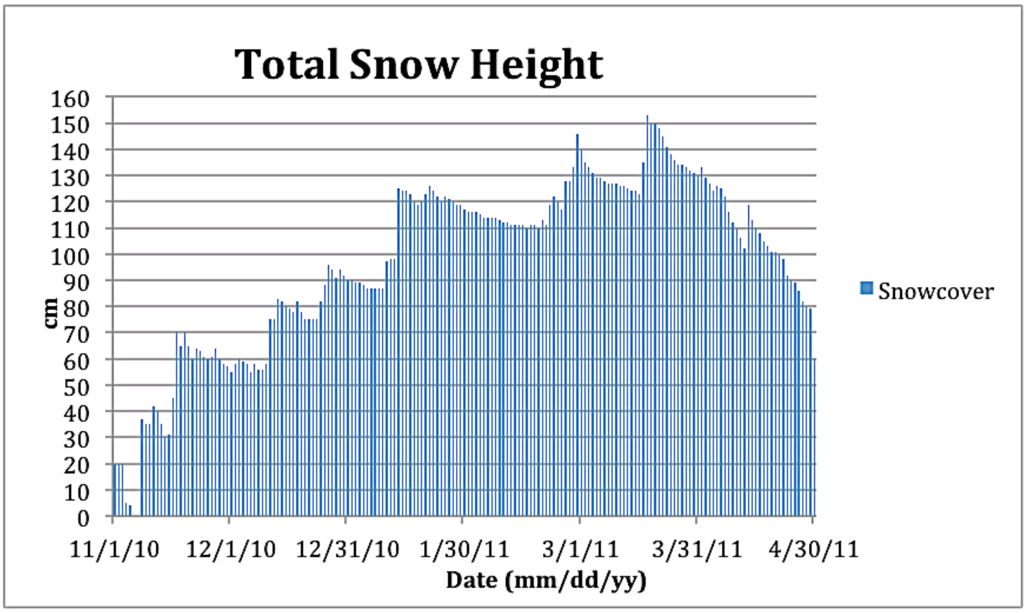


Chart 1: Total snow height at meteorological station Idalpe (www.zamg.ac.at).

The data for snow height at the meteorological station Ischgl/Idalpe (2319 m) was kindly provided by the federal meteorological office of Austria (Zentralanstalt fuer Meteorologie und Geodynamik). Meteorological data from station Ischgl/Idalpe is available for the time frame of 11/1/10 – 4/30/11. A closed snow cover has been recorded since the beginning of November (11/8/10) until the end of April with a height of 60cm. On 18th of March the maximum height of 153 cm was reached. The mean snow height within the measuring period was 97 cm.
From December 24, until the end of April, the snow height reached > 80 cm. Since mid of April the snow cover is receding constantly, from 119 cm to 60 cm in end of April.

6.2.2 Results

The charts 2 + 3 show the result of the BTS measurements from November 2010 to April 2011 of rg Visnitz, Visnitz fossil, Vesul 1 and Vesul 2. The date is given by the x-axis; the temperature by the primary y-axis and the snow height is indicated at the secondary y-axis.

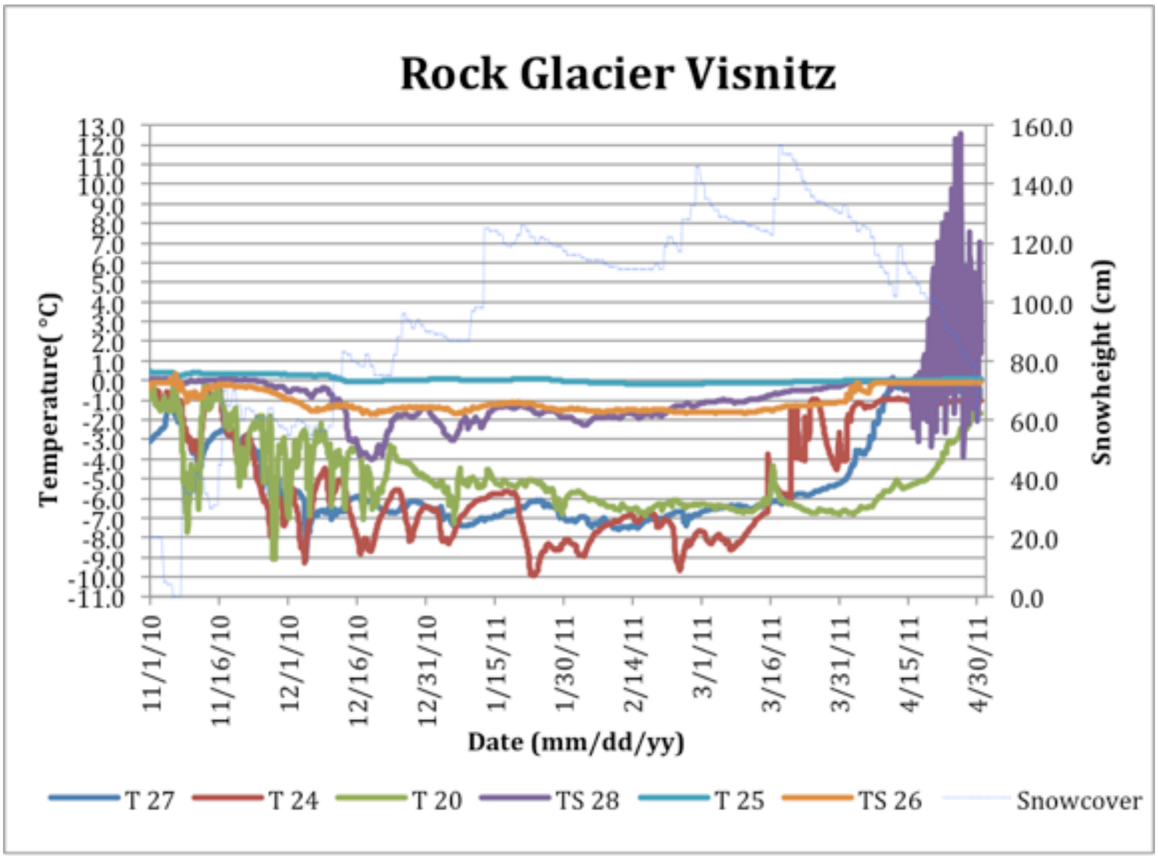


Chart 2: BTS - Temperatures of Rock Glacier Visnitz and Visnitz fossil.

TL # 20, 24, 27, and 28

Loggers # 27, 24 and 20 were placed on the rock glacier Visnitz and # 28 adjacent to the rock glacier. The lowest temperature on the rock glacier was -9.2 °C (#27), -9.1 °C (#20) and -10 °C (#24) and # 28 reached a minimum temperature of -3 °C. Between the period 11/19/10 – 4/15/11 the temperature on the rock glacier remained mostly below - 3 °C. The temperature on the rock glacier remained mostly < - 6 °C from mid of January until the end of March.

TL # 25 & 26

Logger 26 has been installed on a fossil rock glacier in the Visnitz Valley and #25 is placed permafrost free ground adjacent to the rock glacier. Both show a similar trend, however the temperature on the rock glacier was slightly lower during winter than adjacent to it. The lowest temperature recorded on the rock glacier was – 1.7 °C in January, and adjacent to it – 0.2 °C. Throughout the winter month the temperature was slightly below 0 °C at the bottom of the snow cover. At the end of March the snowmelt started slowly and a steady increase in temperature was recorded. Daily temperature cycles are clearly visible.

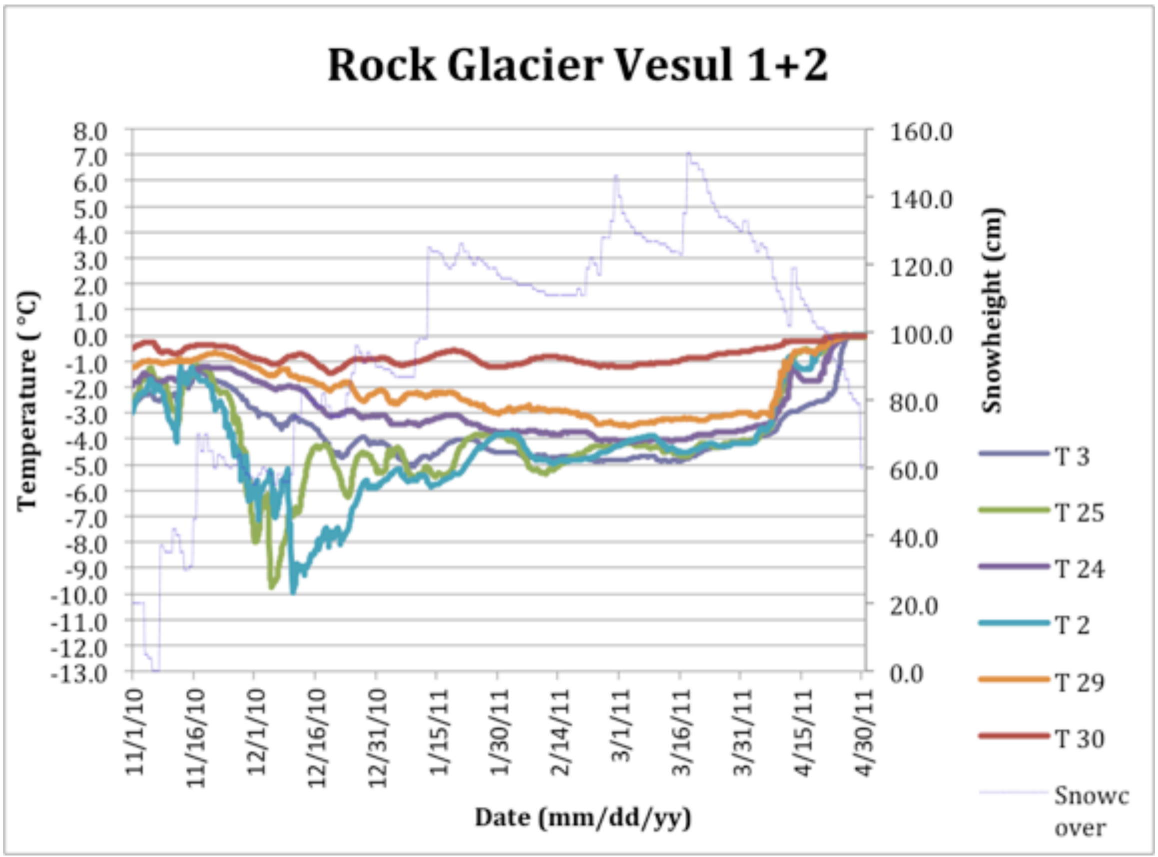


Chart 3: BTS - Temperature of Rock Glacier Vesul 1 and 2.

TL # 2, 3, 24, 25, 29 and 30

This graph shows the BTS-temperature of 6 loggers, placed on two rock glaciers: Vesul 1 and Vesul 2. One logger (#30) was placed on permafrost free ground and is the reference temperature to the rock glaciers. The temperatures of all loggers placed on Vesul 1 (#3, 25, and 24) remain below -3 °C from the end of November until the beginning of April. The lowest temperature recorded on this rock glacier. Was – 9.8 °C. The mean temperatures below a minimum snow-cover of 80 cm can be found within -4 C° to -3 °C.

The temperature loggers of rg Vesul 2 (#2, 29) differ widely from each other. The mean temperature of logger 2 is distinctly lower than of logger 29; -4 °C was recorded for logger 2 and logger 29 had a mean temperature of – 2.5 °C. Logger 2 remained below -3 °C within the same time period as of loggers of Vesul 1 (#3, 25, 24). Logger 29 only stayed from mid of

February until the end of March below this temperature. The lowest temperature recorded of the reference station is -1.5 °C.

Comparing the loggers of the active rock glaciers, a similarity in daily fluctuations is noticeable. The loggers from rg Visnitz (27,24,20), rg Vesul 1 (3, 25, 24) and rg Vesul 2 (2) recorded strong daily fluctuations in temperature until the end of December. Due to Haeberli (1973), the snow cover has an insulation effect at a height of max. 80 cm. Is this insulating effect not given, the BTS loggers interfere with the air temperature. Prior to December the temperature loggers are influenced by the air temperature, as the snow height stays over 80 cm from end of December on. The reaction time of daily temperature differences past December become less intense. Since mid of April the temperature of the loggers increased constantly with the increase of air temperature and constant snow melt.

Table 3 gives an overview of the mean BTS temperature between 12/24/10 – 4/30/11. The measuring period is based on the minimum snow height required for achieving an insulating effect to prevent interactions of air temperature with the BTS loggers. The minimum temperature is calculated from the period of 11/1/10 – 4/30/11.

Rock Glacier	TL	Mean Temperature* (°C)	Minimum Temperature (°C)
Visnitz	T 27	- 5.4	- 9.2
Visnitz	T 24	- 5.5	- 10.0
Visnitz	T 20	- 5.6	- 9.1
RL Visnitz	T 28	- 0.9	- 5.8
RL Visnitz fossil	T 25	0.0	- 0.2
Visnitz fossil	T 26	- 1.1	- 1.7
Vesul 1	T 3	- 4.1	- 5.1
Vesul 1	T 24	- 3.2	- 4.1
Vesul 1	T 25	- 3.9	- 9.8
Vesul 2	T 2	- 4.0	- 10.0
Vesul 2	T 29	- 2.5	- 3.5
RL Vesul 1+2	T 30	- 0.8	- 1.5

*Mean temperature of period 12/24/10 – 4/30/11. (TL: Temperature Logger, RL: Reference logger)

Table 3: Mean BTS – Temperature and minimum temperature on investigated rock glaciers.

6.2.3 Interpretation

The detection of permafrost on rock glaciers based on the BTS measurements can be described as followed: Rock glacier Vesul 1 and Visnitz show clear evidence for permafrost activity. The temperature of the loggers placed on the rock glaciers is significantly lower than of the reference temperatures and the temperature of rg Visnitz fossil. Table x lists all loggers with their mean temperature.

Mean temperatures of rg Visnitz, Vesul 1+2 stay below 5 °C and below 3 °C, respectively. Two temperature loggers were placed on rg Vesul2, wherefrom one shows permafrost activity (#2) and the second (#29) does not.

This might indicate that this rock glacier is on the transition from active state to inactive.

These rg are considered to be active as permafrost occurrence is very probable. However, The presence of permafrost at rock glacier Visnitz fossil, is not very probable. After Haeberli's classification, at rg Vesul 1 and Visnitz the permafrost occurrence is very probable.

6.3 Hydrologic Measurements

The following table shows the hydrologic measurements carried out on each rock glacier. In the chapter attachment an ArcGIS created map, with the investigated rock glaciers and springs is enclosed.

Name of Rock glacier	Gouging System	T & EC	Water Chemistry
Buerkelkopf	x	X	x
Visnitz		X	x
Vesul1		X	x
Idalp		X	x

Table 4: Hydrologic Measurements on the investigated rock glaciers. (T: Temperature, EC: electrical conductivity)

By installing a gouging system the water depth is recorded. This gives information about the daily and seasonal variations in discharge. Furthermore the temperature and electrical conductivity is measured simultaneously. By sampling spring water released from the rock glaciers the water chemistry was analyzed, focusing on the detection of heavy metals.

6.3.1 Spring Temperature (T) and Conductivity Measurements (EC)

These measurements were carried out in summer 2010-2011 with a conductivity meter of the type WTW LF330.
The temperature and conductivity of springs released of five distinctive rock glaciers were measured and given in the tables below. The date is presented in the format mm/dd/yy.
An overall map of investigated springs can be found in the attachment.

Rock Glacier Buerkelkopf
The measurements were carried out at two springs and the thermokarst-lake.
The coldest temperature of 0.5 °C was measured at the spring released within the rock glacier. However, all measurements show a very low conductivity value of < 77 μS/cm. In comparison to the spring temperatures, the lake temperatures are remarkably higher.

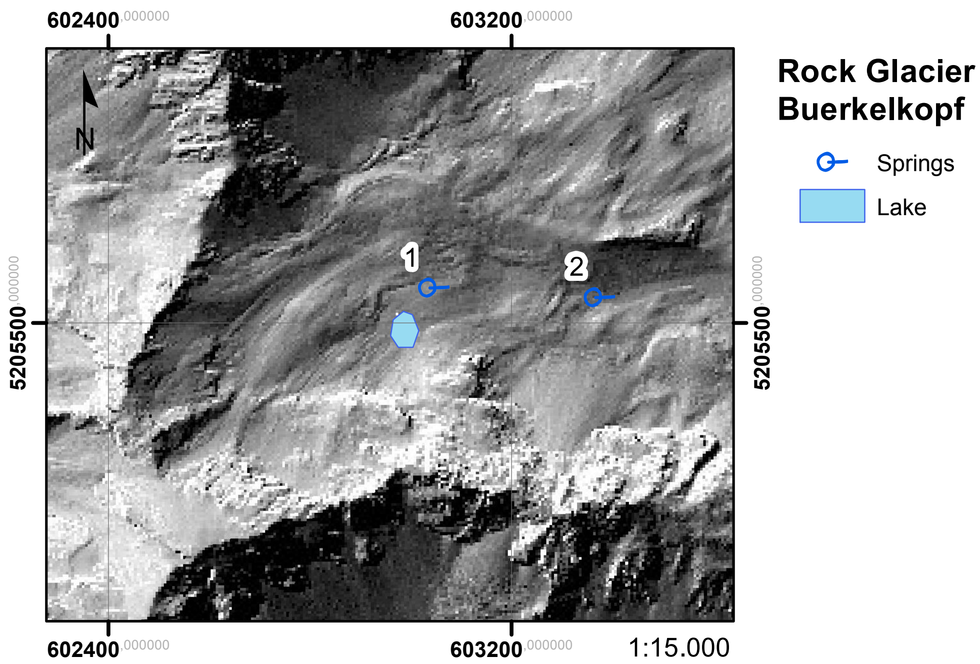


Fig.53: Investigated Springs at rg Buerkelkopf.

	7/26/10		8/19/11	
Spring	T °C	EC µS/cm	T °C	EC µS/cm
Tkl*	2,3	75,5	10,6	70,5
1, on RG	0,5	76,7	-	-
2	0,9	68,3	2,8	71,3

Table 5: Temperatures and EC of investigated springs from rg Buerkelkopf. (* Thermokarst lake)

Rock Glacier Vesul

The temperature of the majority of springs remained below 1°. The spring, released on the rock glacier itself shows the lowest temperature of 0.1 °C and the highest conductivity of 163,5 µS/cm. The conductivity of all other springs are rather low. The highest temperatures are measured in the meltwater pond with the lowest conductivity with 17,4 µS/cm. The water discharge of the spring 1 is low and just present during periods of warm weather.

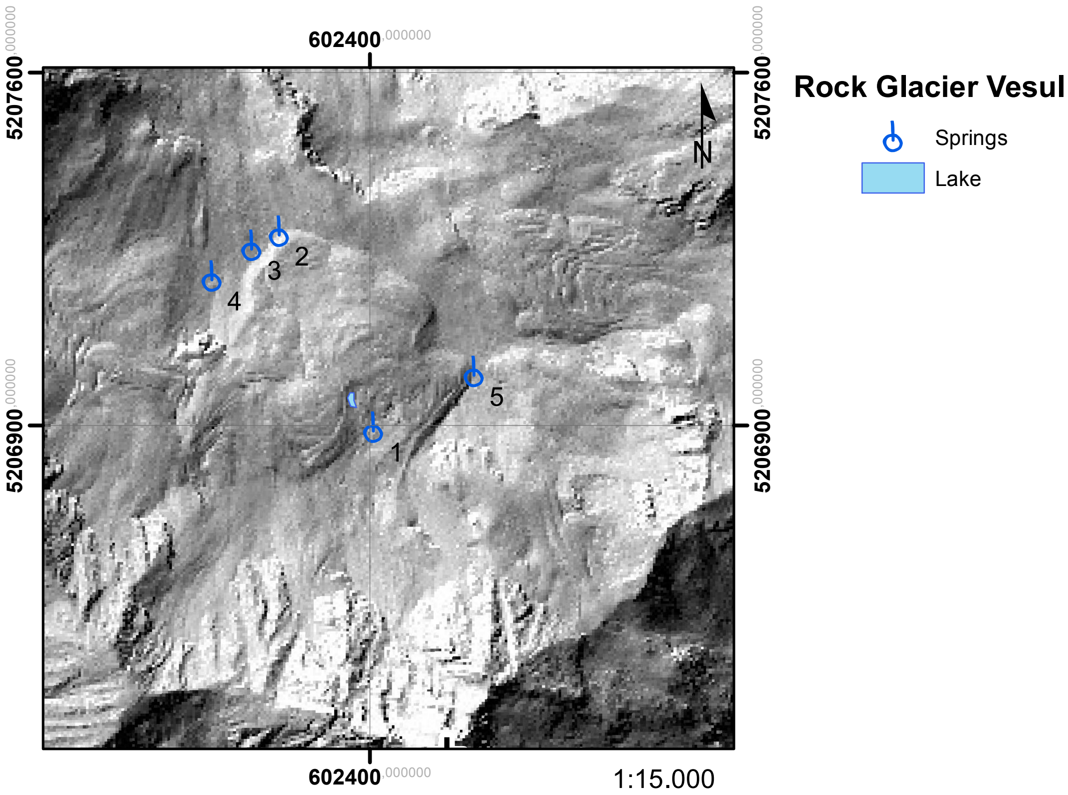


Fig.54: Investigated Springs on rg Vesul 1.

	9/10/10		8/19/11	
Spring	T °C	EC µS/cm	T °C	EC µS/cm
Meltwater pond	2,7	17,4	3,2	19,8
1	0,1	163,5	-	-
2	1,5	36,5	-	-
3	0,6	81,4	0,6	78,8
4	0,9	54,0	0,6	79,6
5	0,5	42,6	0,9	55,6

Table 6: T & EC of investigated springs of rg Vesul 1.

Rock Glacier Visnitz

Two springs released from the rock glacier show quite high temperatures > 2 °C, however the temperature of one spring is < 1 °C.

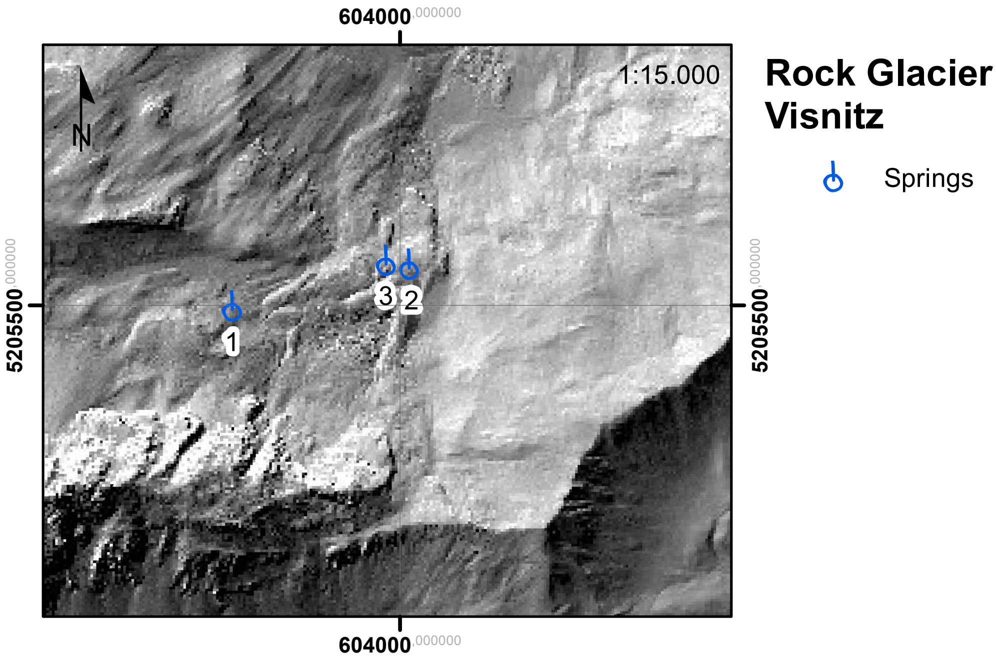


Fig.55: Investigated Springs on rg Visnitz.

Date	Spring	T°C	EC µS/cm
7/28/10	1	0,6	95
7/28/10	2	2,5	153,7
7/28/10	3	2,6	147,5

Table 7: T & EC of investigated springs of rg Visnitz.

Rock Glacier Idalp

The rg Idalp releases three springs, thereof is one with a remarkably low temperature < 0.5°C. The EC is similar at all springs with a value of 95 µS/cm.

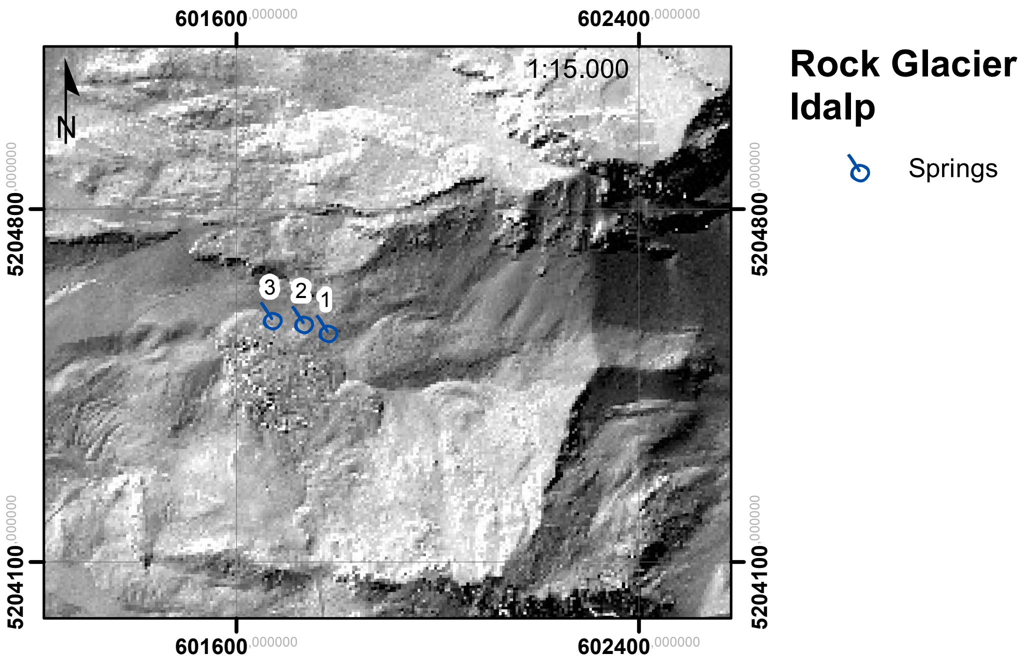


Fig.56: Investigated Springs on rg Idalp.

	8/26/10		9/15/11	
Spring	T°C	C µS/cm	T°C	C µS/cm
Sp 1	0,4	101,4	0.9	25
Sp 2	2,2	94,4	1.2	23.9
Sp 3	1,2	91,8	1.3	25.3

Table 8: T & EC measurements of the Investigated springs of rg Idalp.

Rock Glacier Visnitz – fossil

Data of measurements on spring of this rock glacier is given below:

Date	Spring	T°C	C μS/cm
7/25/10	Sp 1	2,6	37,3
7/25/10	Sp 2	1,9	37,5

Table 9: T & EC measurements of the Investigated springs of rg Visnitz fossil.

6.3.2 Interpretation

Krainer & Mostler (2002) report in their research about hydrology of active rock glaciers, that temperatures of active rock glaciers stay constantly < 1 °C throughout the melt season, while spring temperatures from inactive rock glaciers may vary from 1 – 3 °C. Several springs released from the investigated rock glaciers were measured throughout 2 years.

The lowest spring-temperatures were recorded at rg Vesul 1. Four out of five springs of rg Vesul and the two investigated springs of rg Buerkelkopf show temperatures <1°C. One out of three investigated springs released from rg Idalp and Visnitz show temperatures below 1°C, however the rest ranges within temperatures of 1,2 – 2,6 °C. This data indicates that both rock glaciers contain ice. This might indicate that some segments of both rg are free of ice. In this respect, the small left segment of rg Visnitz and the upper right part of rg Idalp seem to contain ice. The springs of the fossil rg have temperatures of 2,6 and 1,9, which confirms that no ice can be encountered within the rg.

6.3.3 Water Chemistry

Generally the water released from the rock glaciers is very low mineralized.
Water samples were taken from eight springs and two thermokarst-lakes. The samples were filled in a 250 ml PET bottle.

The results from all springs were quite alike. The table below shows the minimum and maximum value of the 10 samples.

Element	Minimum Value mg/l	Maximum Value mg/l
Na	0,124	0,275
Mg	1,4	7,461
Al	< 0,001	
Si	0,269	0,501
K	0,059	0,776
Ca	4,698	9,773

Table 10: Water chemistry with minimum and maximum values.

The heavy metal concentrations of all samples did not show any remarkably high concentration. The heavy metals listed show the maximum values reached:

Element	Value mg/l
Ni	< 0.005
Ag	< 0.001
Pb	< 0.005
As	< 0.005

Table 11: Heavy metals listed with maximum values.

6.4 Grain size analysis & Sieve analysis

To characterize the grain size of the upper mantle and the inner core of the rock glacier grain size measurements have been carried out. These measurements were carried out on rg Buerkelkopf and rg Vesul 1.

- Grain size measurements have been done on the root, central and front part of each rock glacier. Within 9 m^2 the biggest diameter of 200 boulders was admeasured.

- Sieve analysis of fine-grained sediment was carried out of samples from the frontal and side part of the snout of the rock glacier. The samples were dried in the oven and 2 kg therefrom was sieved and weighed.

Both rg are active with a quite different lithology. The former one is mostly composed of debris from the Penninic zone, whereas Vesul 1 rock glacier mostly comprises debris from the Silvretta Crystalline Complex.

6.4.1 Results of grain size analysis

The following two charts show the grain size of three distinctive areas on both rock glaciers: root area, center and front.

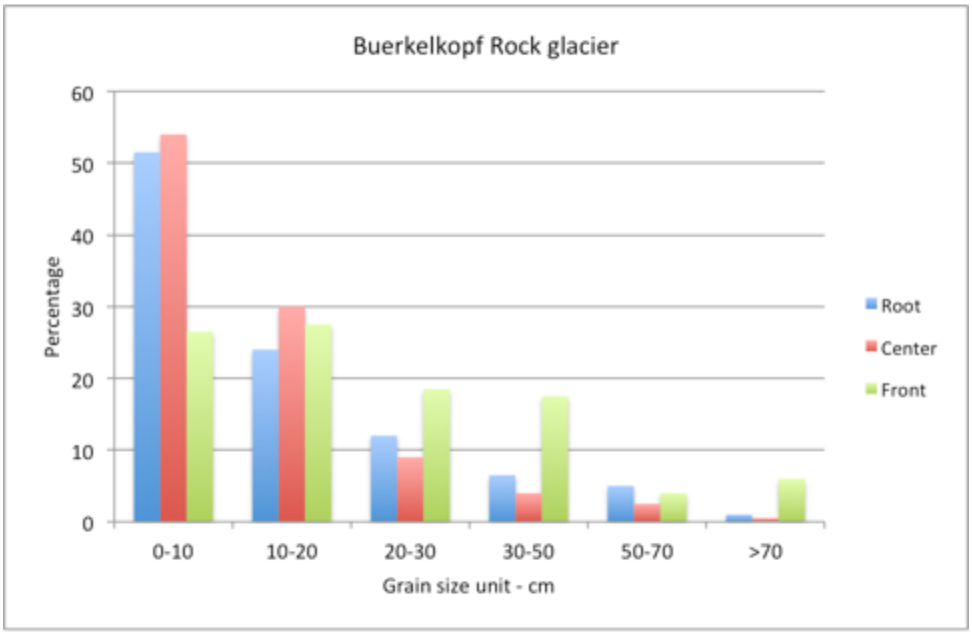


Chart 6: Grain size distribution on Buerkelkopf rock glacier.

At Buerkelkopf rg there is a general increase in grain size from the root to the front part of the rock glacier. The distribution of the grain sizes from the root and central part are very similar showing about 90% below 30 cm. Both show a maximum in the grain size unit 0 – 10 cm.

Over half of the rock fragments of both areas and even a quarter in the front part are below 10 cm. In contrast to the root and center part, the front part 7 % of the clasts have diameters > 70 cm.

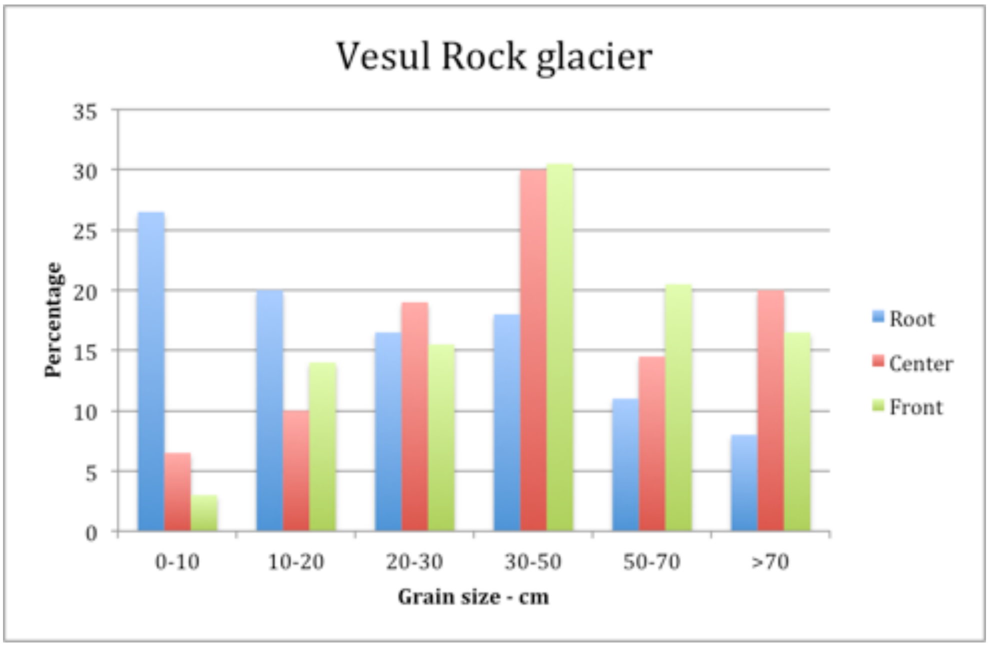


Chart 7: Grain size distribution on Vesul rock glacier.

At Vesul rg, a slight increase in grain size from the root to the center area is apparent, however a slight decrease from the central to the front part is given. The distribution of grain sizes of the root area peaks in the first grain size class. About 45% of the rock fragments diameters are below 20 cm and 90 % are below 70 cm. The central and front part peaks with a total of 30 % in the grain size unit 30 – 50 cm. More than 65% of the grain sizes of the central and frontal part are bigger than 30 cm. The front part however lies with about 70 % between 20 and 80 cm. The root and front area show both a quite low percentage of rock fragments over 1 m, in contrast to the center, where the reach about 10 %.

6.4.2 Results of sieve analysis

As the boulder size of the rock glacier mantle is given by the grain size measurements, the inner fine-grained part is analyzed by sieve methods. Two samples, one taken from the frontal and one from the side slope, of the Buerkelkopf and Vesul rock glacier were sieved. The x-axis gives the grain sizes in a phi logarithmic scale after Krumbein & Sloss (1963) and the y-axis gives the cumulative percentage of the grains.

The scale is based on the equation:

$$\varphi= - \log_2 D/ D_0$$

φ is the Krumbein phi scale

D: Diameter of the Particle

D_0: reference Diameter.

φ scale	Size range (mm)	Aggregate name (Wentworth Class)
< −8	> 256 mm	Boulder
−6 to −8	64–256 mm	Cobble
−5 to −6	32–64 mm	Very coarse gravel
−4 to −5	16–32 mm	Coarse gravel
−3 to −4	8–16 mm	Medium gravel
−2 to −3	4–8 mm	Fine gravel
−1 to −2	2–4 mm	Very fine gravel
0 to −1	1–2 mm	Very coarse sand
1 to 0	½–1 mm	Coarse sand
2 to 1	¼–½ mm	Medium sand
3 to 2	125–250 µm	Fine sand
4 to 3	62.5–125 µm	Very fine sand
8 to 4	3.90625–62.5 µm	Silt
> 8	< 3.90625 µm	Clay
>10	< 1 µm	Colloid

Table 12: Scheme of particle size, phi and metric scale and the aggregate name (Wentworth, 1922).

The sediment size distribution is described for every sieve sample as well as the dispersion (sorting) is calculated according to Folk and Ward (1957).

$$D = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

Values from	To	Equal
0.00	0.35	very well sorted
0.35	0.50	well sorted
0.50	0.71	moderately well sorted
0.71	1.00	moderately sorted
1.00	2.00	poorly sorted
2.00	4.00	very poorly sorted
4.00	∞	extremely poorly sorted

Table 13: Classification of degrees of sorting according to standard deviation values.

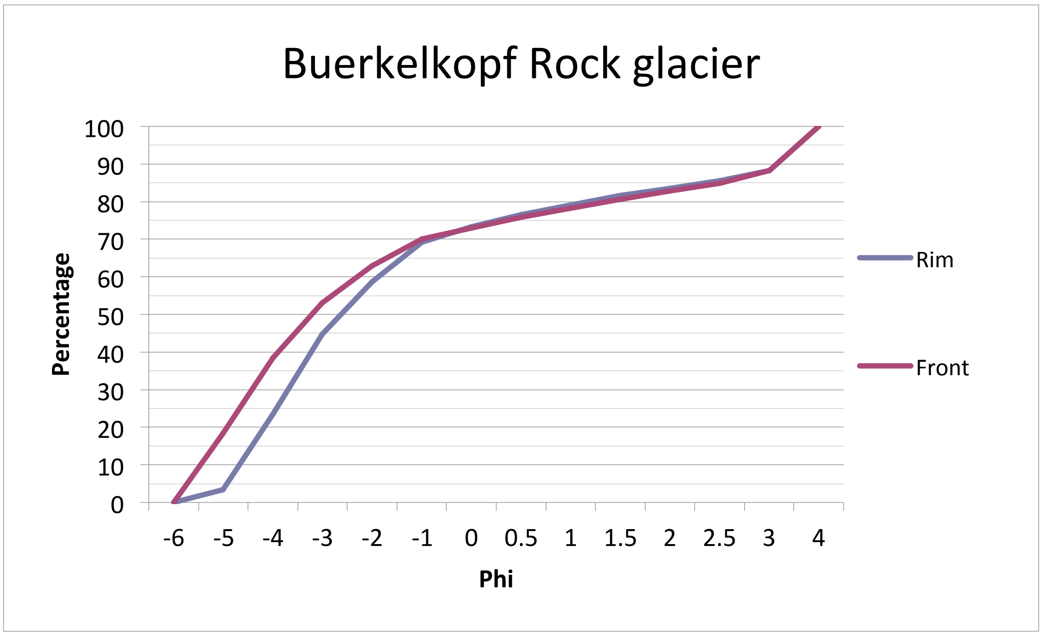


Chart 8: Particle size curve of samples from rg Buerkelkopf.

	Front	Rim
Dispersion	3,31	2,97

After Folk and Ward 1957, both samples can be classified as very poorly sorted.
The grain size distribution curve of the rim and the front are quite similar, however the sample taken from the front part has a higher value in coarse gravel.

Very coarse gravel (32 - 64 mm) is absent in both samples. The rim sample shows 59 % gravel, 29% sand and 12 % silt and clay. While the front shows the same amount in silt and clay, the value for gravel is slightly higher, 63 % and lower for sand, 25 %. Both can be characterized as very poorly sorted, sandy gravels.

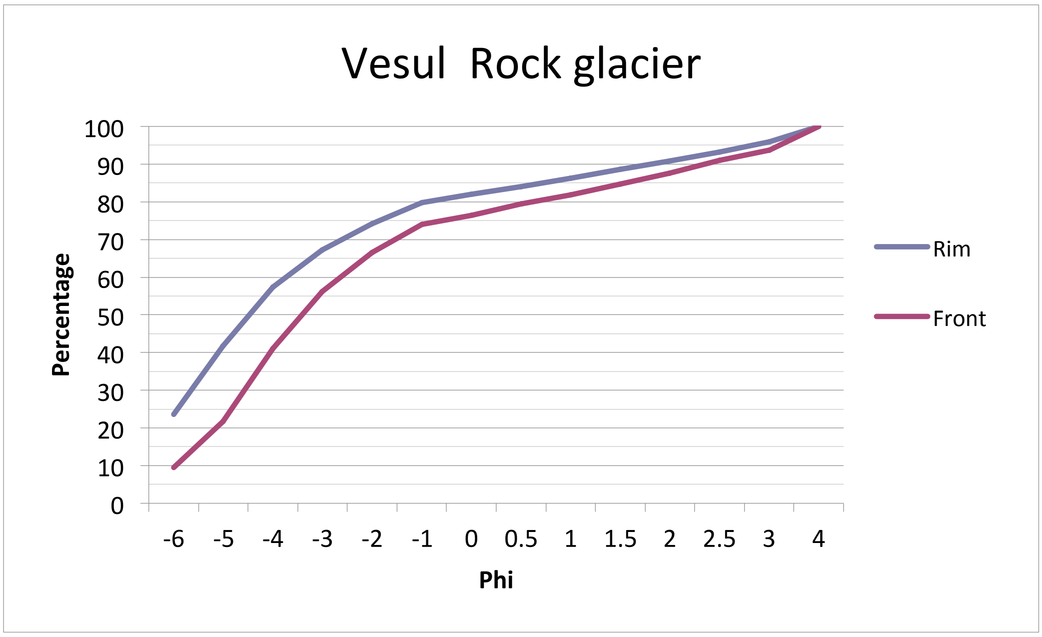


Chart 9: Particle size curve of samples from rg Vesul 1.

	Front	Rim
Dispersion	2,94	2,95

The values for the dispersion of the sieve sample are similar and classified as very poorly sorted.

The grain size distribution line of the rim is coarser, than the one of the front. The front sample just has 9 % of very coarse gravel (32 – 64 mm), while the rim has 24 %. The total amounts of gravel in both samples vary between 75 % for the rim and 66 % for the front sample. Furthermore the rim shows 21 % of sand and 4 % of silt and clay, whereas the front shows 28 % sand and about 6 % of silt and clay. Both can be characterized as very poorly sorted, sandy gravels.

6.4.3 Summary

The measurements on the grain sizes on top of the rock glacier and the sieve analysis of the rock glacier front are descriptive measures.
The measurements were carried out on two individual rock glaciers, which comprise of different rock types.
The sieve results of both rock glaciers are similar and classified as very poorly sorted sandy gravel.
A general increase in grain size from the rock glaciers root to the front, however no interclass correlation between both rock glaciers is visible. The grain size of rock glacier Buerkelkopf is significantly lower than of rock glacier Vesul. Lithological and structural differences in bedrocks influence the grain size on rock glaciers.

Berger et al. (2004) carried out measurements on debris properties on rg “Oelgruebe”. The fine-grained layer is characterized as very poorly sorted silty sand or sandy silt. The rg surface shows high variations in rock diameters, however most rocks range from 20 – 40 cm. Results from rg Reichenkar show similar results regarding the fine grained layer, which is similar to till, very poorly sorted sand and silt (Krainer, 2000).

Results of sieve samples from rg Buerkelkopf and Vesul 1 are equal to rg Oelbrube and Reichenkar regarding their sorting. All samples are very poorly sorted, however rg Buerkelkopf and Vesul 1 are sandy gravels, while rg Oelgrube and Reichenkar are silty sands or sandy silts.

The coarse grained layer on the surface show at all rg a high variety in grain sizes. Most common rock diameters vary from 25 – 50 cm, similar to rg Vesul 1.

7 Impacts of Permafrost

Thawing and freezing of permafrost may generate difficulties in constructing and maintaining high mountain infrastructures. The distribution of permafrost is controlled by the following factors: air temperature, ground thermal conditions and climate change. These factors play a key role in thawing and freezing of permafrost.
Natural hazards, such as rockfall and slope instability may occur due to degradation of permafrost in the Alps. Gruber and Haeberli (2007) mention several mechanisms for the degradation of permafrost: loss of bonding, ice segregation, volume expansion, increased hydrostatic pressure and the reduction of shear strength.

7.1 Pardorama Restaurant

Using the example of the “Pardorama Restaurant” in the ski area of Ischgl, the impacts of permafrost and hence geotechnical solutions will be explained. The Pardorama Restaurant is located in the skiing area of Ischgl, on the Pardatschgrat, at an elevation of 2624 m. This restaurant is the third construction on the mountain “Pardatschgrat”, as severe damages on the prior restaurants occurred due to slope instability.

History of restaurants on the Pardatschgrat with the construction year:

1. Restaurant 1972
2. Restaurant 1985
3. Pardorama 2004

The old restaurant was built on an armored concrete foundation. Thawing and freezing of permafrost caused differential settlement of the ground.
As a result, the building had opened cracks (up to 5 cm/year) and deformed, as the foundation was rigid and hard to adjust to the subsurface movement.

The maintenance of the restaurant was at some point not cost-effective and the new "Pardorama" restaurant was built.

Fig. 57: Old Restaurant on the Pardatschgrat

Fig.58: Deformation of old restaurant.

Fig. 59 + 60: Damages on Building (open Cracks and Deformation of roof).

7.2 Geological Situation

The mountain Pardatschgrat is located on the boundary of an overthrust zone with two major units, the Silvretta Crystalline Complex (SCC) and the Penninic unit. The SCC is composed of gneisses, mica-schists, while the penninic unit is prominent in two thrust sheets with the ophiolite complex to the East and the "Buendnerschiefer" to the South.

On the mountain top an orthogonal joint system is prominent as a result of mountain splitting. Permafrost was encountered in joints as ice layers and ice-cemented fillings. The percolation of water through predominant joints, enforce the settlement, as water decreases the friction on

the sliding plane of the gravitational mass. The ongoing process caused continuative joint opening and hence an increase in permafrost as joint ice.
In addition to mountain splitting, thaw and frost activity causes sloped instability and settlement.

7.3 Solution

At the Pardatschgrat a conventional construction method is not applicable due to the geologic background. A flexible construction to build on permafrost was required.
The new restaurant, a complex structure of steel frame, is built on a three-point-foundation. The steel framework is based on three concrete pillars on a special dynamic bearing construction supported by concrete foundation. Figures 62 and 63 below show the foundation and construction of the project. Steel plates are assembled on top of the fixed reinforced concrete foundation, on which the complex steel construction is fixed. The highlight of this 3-point foundation system is the ability to perform individual adjustment of ground settlements, through the use of hydraulic pumps, shown in figure x. Inserting steel plates below the three bases levels the differences in foundation-settlement. Figure x shows the adjustment of foundation through the use of steel plates. The fundament can be raised at individual foundation points and the stability of the construction is provided.
Height measurements on 13 survey points are carried out every year to determine height variations of the foundations. Since the construction of the restaurant until 2009 the settlement of the three foundations is considerable. The height variation of the left front foundation is about 40 cm, 15 cm at the front left and about 130 cm at the rear foundation. The adjustment of the foundation settlement is carried out yearly.

Some facts
Constructor: Silvretta Seilbahn AG
Architect: Arch. Dipl. Ing. Manfred Jaeger, Kappl
Structural Engineer: ZT-Ingenierbuero Guertler, Mayrhofen
Construction Company: Swietelsky Landeck
Construction Time: 8 Month
Construction Costs: 10 Mio. Euro

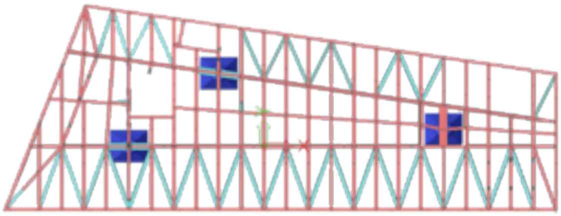


Fig. 61: Ground Plan of Construction (www.ihrarchitekt.com)

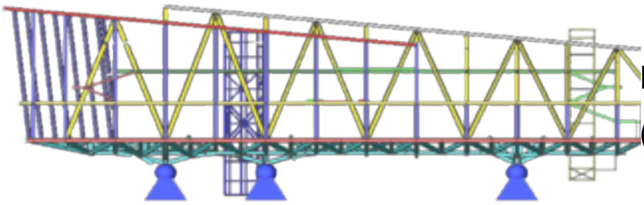


Fig. 62: Profile of Construction; (www.ihrarchitekt.com)

Fig. 63: Hydraulic pumps lifting up the steel construction; (www.ihrarchitekt.com)

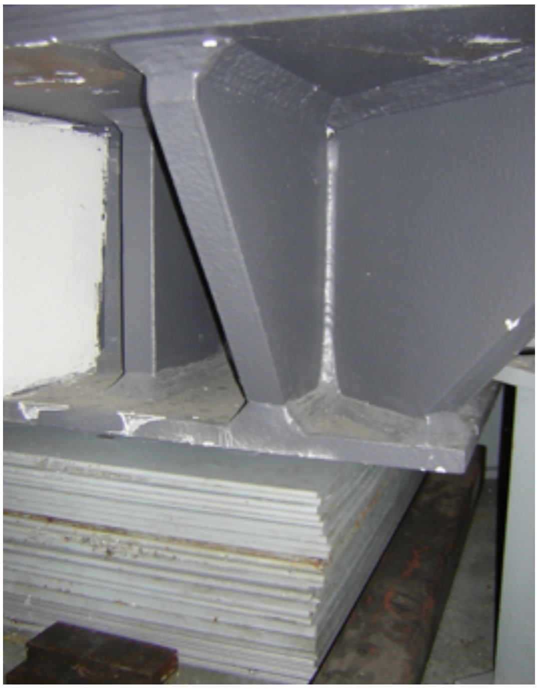


Fig. 64: Steel plates adjusting surface settlements.

The flexible structure of the Pardorama restaurant is one solution to build on permafrost. A three-point-foundation system is implemented to compensate differences in settlement with zero potential. Despite the geological challenge, after 7 years the restaurant is free of damages.

Fig. 65: The Pardorama Restaurant.

The data were provided with the kind support of

- Dipl. Ing. Manfred Jaeger, www.ihrarchitekt.com,
- Silvretta Seilbahn AG, Dipl. Ing. Markus Walser.

8 Conclusion

The area of investigation comprises a total number 21 rock glaciers, therefrom 11 are active, 3 are inactive and 7 are classified as fossil. All active rock glaciers can be encountered at an elevation > 2500 m and cover an area of 1.13 km^2.

The determinations of the permafrost at rock glaciers are based on three different methods: measurement of spring temperature, the bottom temperature of snow cover and refraction seismic.

BTS measurements have proven, that rock glaciers do show drastically lower temperatures than reference stations on permafrost-free ground. The occurrence of permafrost at rock glacier Visnitz and Vesul 1 is evident, and partially evident at rg Vesul 2 based on the BTS measurements.
Based on the spring temperatures, the presence of permafrost is given for rg Vesul 1, Buerkelkopf, Visnitz and Idalp. However, temperatures of rg Vesul 1 and Buerkelkopf remain below 1 °C, while spring temperatures of rg Visnitz and Idalp vary from 0.5 – 3°C. Spring temperatures of rg Visnitz fossil indicate that no ice at the rock glacier will be encountered.
The results of the refraction seismic on rg Idalp point out an active state. This is partially proven by spring temperature measurements. A maximum thickness of the permafrost body of 10 m could have been calculated from data provided by the refraction seismic. This permafrost body is most likely a composition of ice and debris, or ice layers alternating with debris layers.

The grain size and sieve analysis characterize the surface layer of the rock glacier. The grain sizes of the outer mantel decreases from the front to the root area of the investigated rock glaciers. However, the grain sizes are highly depending on the rock type, weathering rate and tectonic history of the area.
The fine-grained interior consists of very poorly sorted, sandy gravel. The inclination of the frontal slope of the investigated rg is greater than 40°. An exception is the slope of rg Buerkelkopf, which inclines with about 30°.
The investigated active rock glaciers are either facing to the NW, to the N or to the NE. The same trend of exposition is pointed out in the chapter “Rock Glacier Inventory”. The inventory

depicts a total number of 80 active rock glaciers in the Samnaun Mountain Group exposing towards the NW, N, and NE.
All investigated rock glaciers are lobate-shaped except of rg Buerkelkopf. Rock glacier Buerkelkopf also varies in respect to its thickness. Most rock glaciers show a thickness of approximately 40 m, despite rg Buerkelkopf whose thickness is < 25 m. Generally, the grain size of this rock glacier is significantly lower than that of the rest of the active rock glaciers.

These morphological features could also lead to the conclusion that this rg is a basal moraine, with a side moraine to the northernmost part. Barsch's (1996) debris derived model could be another approach to explain the morphology of this rg. The debris-derived model explains the formation of a rg out of moraine material. Supraglacial debris support would provide enough debris supply for the formation of a rock glacier. Unfortunately no data of the BTS measurements could be recorded, which might have given a better understanding of this rock glacier. The activity state of a rock glacier could furthermore be detected by means of geodetic measurements. Active rock glaciers show movements of less than 1 ma^{-1} (Barsch, 1996). This method would give further information of the activity state.

Comparing the historical maps and the aerial photograph from 1950 to 2010 the age of the rock glacier can be estimated. The historical maps in chapter 1 (Geographical overview) document the glacial history of the area of investigation. In the oldest map of the year 1805, cirque glaciers covered the present rock glacier sites. In the map of the 2nd mapping period of Tirol (Fig. 4) the glaciers have already retreated. In the oldest aerial photograph from 1950 rock glaciers replaced the sites of glaciers. The aerial photographs of rock glacier Buerkelkopf strongly indicate that the transition of the glacier to the rock glacier occurred after 1950. The aerial picture of that year shows a small ice shield in the root zone of the present rock glacier. This documentation concludes that the formation of the active mapped rock glaciers took place after the Little Ice Age (1850) and therefore a maximum age of 150 years can be approximated and therefore reflect a young Holocene landform.

Based on the glacial history and the ice outcrop on rg Vesul the formation of the active rg is out of a glacier, as Humlum (2000) described it in his glacier derived model.

Further measurements such as geophysical exploration and drilling at rock glacier sites are needed to determine the interior structure of the active rock glaciers. An estimation of the ice content and the age of the ice could be concluded out of ice analysis. The results of the analysis reflect the present state of all the investigated rock glaciers. The observation period has to be prolonged in order to observe changes in the activity state of rock glaciers.

9 Projects

9.1 Drilling on Rock Glaciers in South Tyrol - Italy

Two drilling sites were chosen at rock glaciers in South Tyrol (Italy) to investigate their internal structure and composition. This project was part of the Alpine Space Program, which is a European transnational cooperation program for the Alps. The program period began in 2007 and will conclude in 2013. It has a funding of 130 Mio. € and is financed by the European Union. All information about this program is given at "http://www.alpine-space.eu".

- PermaNET

One project within the Alpine Space program is called Permafrost Long-Term Monitoring Network (PermaNET). The Autonomous Province of South Tyrol (Italy) led the project and worked together with several partners including the University of Innsbruck.

This project deals with the distribution of permafrost; it relates to both the highly sensitive topic of climate change and to natural hazards. Degradation of permafrost can cause natural hazard to traffic routes, touristic areas, settlements and infrastructure. Establishing a permafrost monitoring system in the overall alpine space should help to prevent the above mentioned risks.

Drilling sites

Within the framework of the project PermaNet two drilling sites were selected at active rock glaciers located in South Tyrol. The drilling was carried out over 3 month from 7/15/2010 to 10/15/2010. Figure 66 below shows the location of both drilling sites.

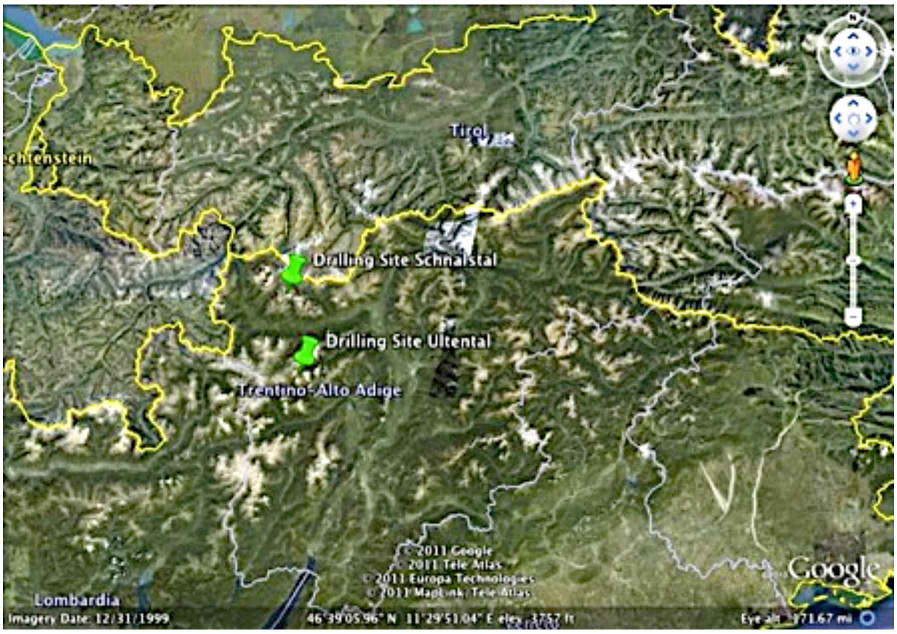


Fig. 66: Drilling sites in the Province of Bozen Italy (Google Earth Imagery).

The first drilling site was located in the Schnals Valley, on the “Lazaunalm” at an elevation of 2550 m. This location is quite remarkable due to the springs that emerge from the rock glacier. They are highly saturated in heavy metals such as nickel (Bressan, 2007). The reason for their occurrence is still unknown, but the drilling project may reveal additional information, which could help to explain it.

The second drilling site is located in the Ulten Valley on the rock glacier “Rossbaenk”.

The objectives of this drilling project are to obtain a better understanding of different layers within the rock glacier, and detection of the amount of ice content, and ice structure and its chemistry. Furthermore, stable isotope and pollen analysis will be performed to determine the age of the ice within the rock glacier.

9.1.1 Drilling Site Ulten Valley: active rock glacier "Rossbaenk"

This majestic, northeastward exposed rock glacier is > 35 m thick, 1,7 km long and is located in the Ulten valley, near proximity to Weissbrunn. The geographic coordinates of this rock glacier are: UTM WGS84 E 637964, N 5147898.

Fig.67: Rock Glacier "Rossbaenk" – View to the Southwest. The red dot indicates the drilling location.

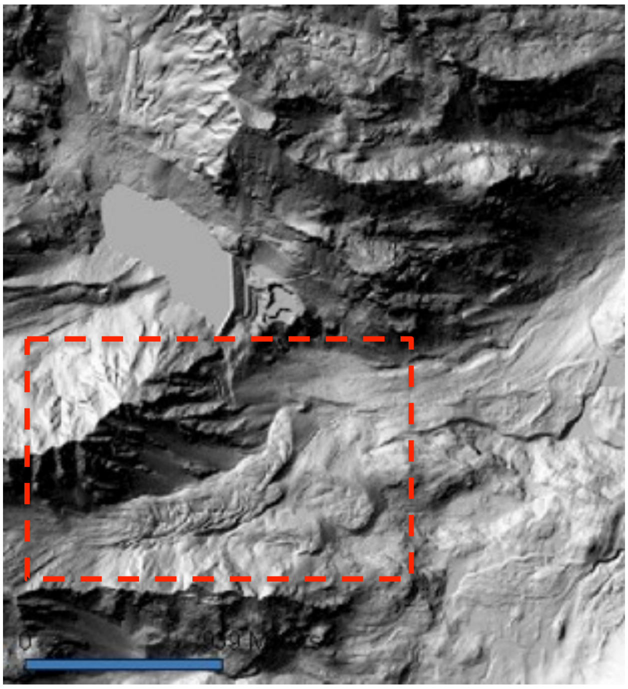


Fig. 68: Infrared photograph of the rock glacier "Rossbaenk".

This rock glacier has a total length of 1700m and a width ranging from 200 – 600 m from root to frontal area respectively. Three activity states can be observed on the rock glacier "Rossbaenk"; active, inactive and fossil, distributed over a 530 m range in elevation.

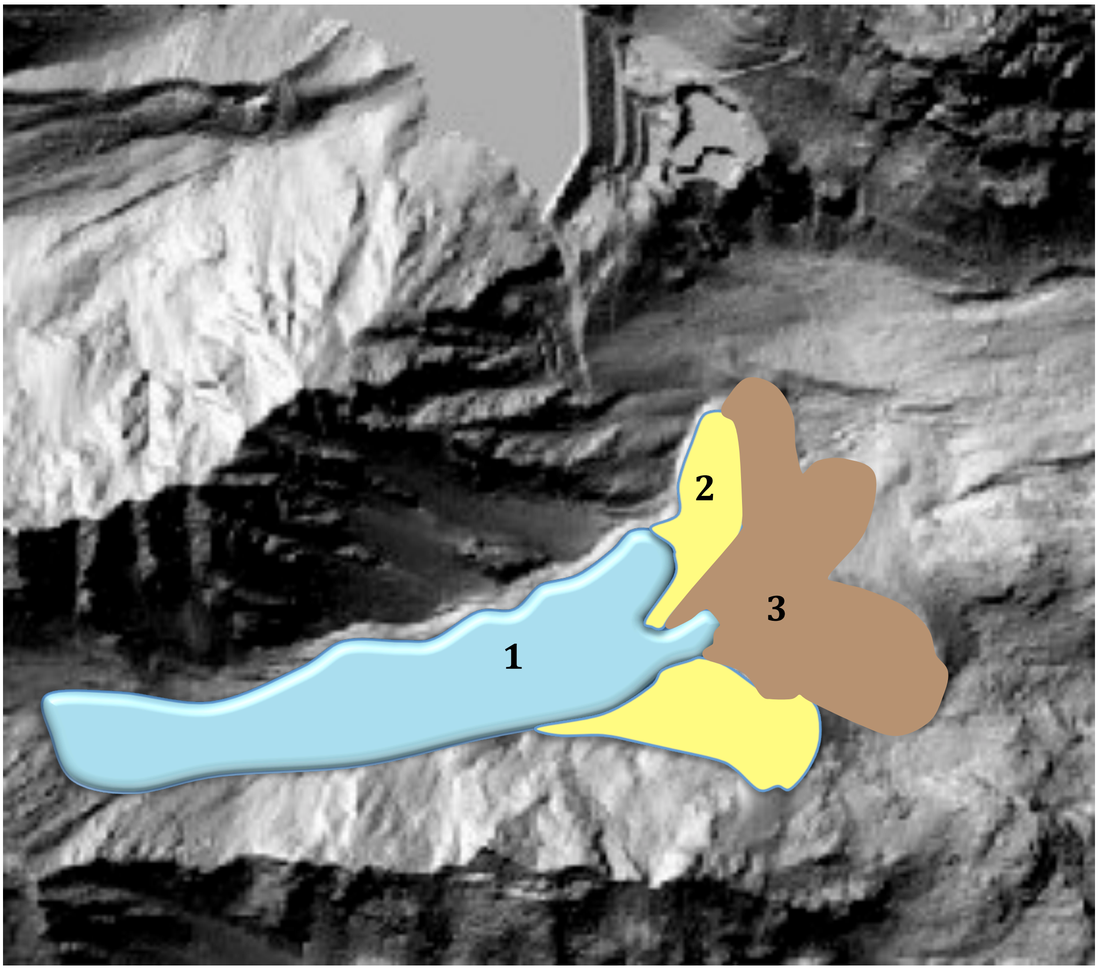


Fig. 69: States of activity of the rock glacier „Rossbaenk". 1: Active; 2: Inactive; 3: Fossil; (www.provinz.bz.it)

The altitude of the root area reaches as high as 2840 m while the frontal area falls to as low as 2310 m. The mean altitude of the active segment is at 2655 m while the frontal area at 2470 m. The frontal part of the active rock glacier has no vegetation cover and a dip of 35 - 38°. Mountain "Eggenspitze" supplies the rg with debris. Geologically, the area is part of the Ortler-Campo-Crystalline Complex with predominately paragneiss, tonalites and garnet - micaschists.

The origin of the rock glacier is most likely a glacier-derived type, as the western most part of the Eggenspitze is still glaciated. But the drilling results will show more detail of the interior of the phenomena rock glacier.

Ausserer has performed previous work on this rock glacier in 2005 and 2006. The results have been recorded in his master's thesis.

Some data from his thesis are listed below:

Bottom temperature measurements (BTS)

BTS measurements on the rg record a temperature of - 11° up to – 7 °C, while a temperature of max. – 4 °C is given by installed temperature loggers beyond the rock glacier area. Two geo-electric profiles were accomplished, whereof one runs in the proximity to the drilling site. According to the profiles, the active layer is at a max. depth of 4m. High electric resistances were measured in the depth of - 4 to – 15 m. This area is interpreted as debris, enriched in ice or a massive ice layer. Below 15 m the electric resistance decreased and gives advice of an ice-free area.

Drilling

The drilling was operated by "Landservice", a company based in Bozen (Italy). The drilling was carried out within 3 weeks, beginning with 09/14/2010. The drilling machine and the equipment was transported by helicopter onto the rock glacier. The drilling site is located at 2555 m on the active part of the rock glacier.

Water containers for cooling the drilling machine and two freezers for cooling the ice-cores were set up on the drilling site. The cooling fluid for the drilling machine was water, transported by helicopter from the nearby lake to the drilling site.

Alternatively two different drilling methods had to be conducted, the rotary-core drilling and the air hammer drilling method. The diameter of the bore barrel is 148 mm. The difficulty in drilling a rock glacier lies in the right application of the cooling medium. As the rock glacier has layers of ice, the risk of contamination with cooling water is given. Therefore air should be used as cooling medium for drilling ice enriched layers, whereas layers with no ice get cooled down with water.

Fig. 70: Drilling Site.

Fig. 71: Casing the borehole.

Fig. 72: Drilling machine.

The figure below shows meter drilled from 16 - 18, with boulders and stones.

Fig. 73: Core from 16 – 18 m.

Difficulties

Casing the borehole has emerged severe problems, as the borehole lapsed constantly. The big grain sizes of this rock glacier and the abundance of fine grain fraction might be a reason for it. Bad weather conditions have led to delays and complications in drilling. A two-meter core with debris-enriched ice was pulled out. This could also be a matter of the drilling methods used. Mostly the air hammer drilling method was applied; this could have led to an additional load and an early melting of ice in the borehole.
The two figures below show the ice cores of this drilling site, while the University of Innsbruck inventoried them.

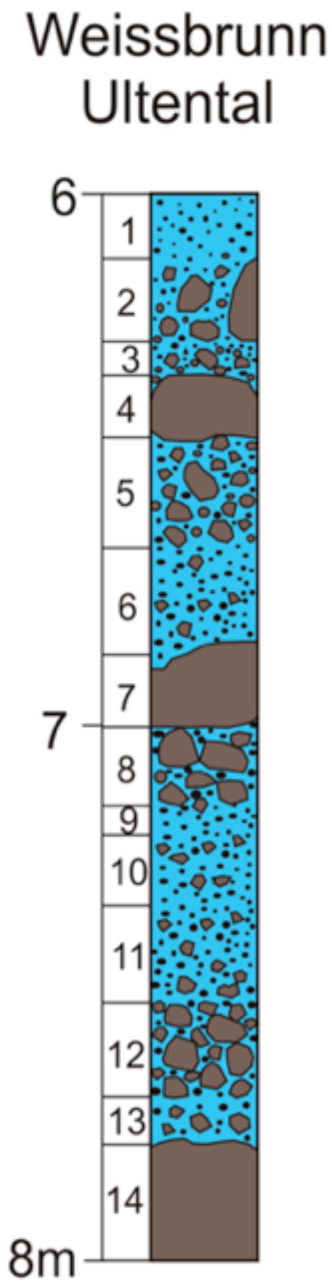
Fig. 74: Ice-core Inventory.

Fig. 75: Brownish Ice of Ulten core.

Core Profile Ulten Valley

The results of this drilling site were non-satisfying. A 2 m core out 30 m reached depth could be pulled out. An overall estimation of the ice content and distribution within the rock glacier is therefore impossible. Based on the measurements of Patrik Ausserer this rock glacier indicates to be active.

Core Profile – Ulten Valley Rockglacier “Rossbaenk”; (Tonidandel, D. et al. 2010)



G: Gravel, I: Ice

1) Quite clean and clear ice,
few smallpebbles

2-3) Gravel and ice mixture,
G: angular, prolate
I: brownish color, clear, air bubbles

4) boulder, prolate, rotund

5) Gravel and ice mixture,
G: angular, prolate
I: brownish color, clear, air bubbles

6) Ice (clear, air bubbles) with few Gravel (angular, mm)

7) Boulder, angular, prolate

8) Gravel with ice embedded
G: angular, prolate
I: brownish, air bubbles

9-11) Quite clear, transparent ice,
few mm-sized gravel

12-13) Gravel, with ice embedded

14) Boulder, angular

9.1.2 Drilling site – Schnals Valley, Rock Glacier Lazaun

Rock glacier Lazaun is located in the back of the Schnals Valley west of the village Kurzras/Maso Corto. The satellite and laserscan photographs below gives a geographical overview of the village and the drilling sites (red dots). A comprehensive work on this rock glacier is given by Bressan (2007).

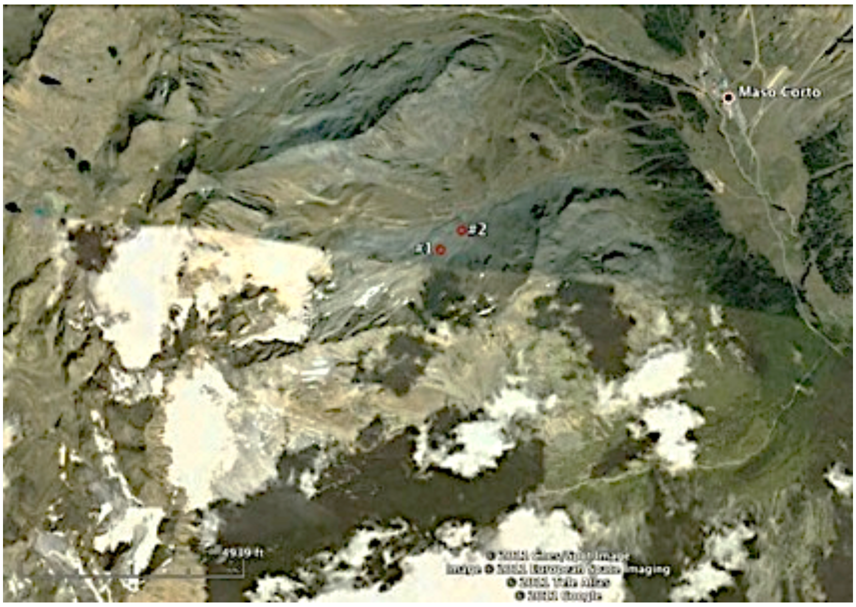


Fig. 76: Satellite photo with general overview of Maso Corto (Kurzras) and the drilling sites (Google.Earth Imagery).

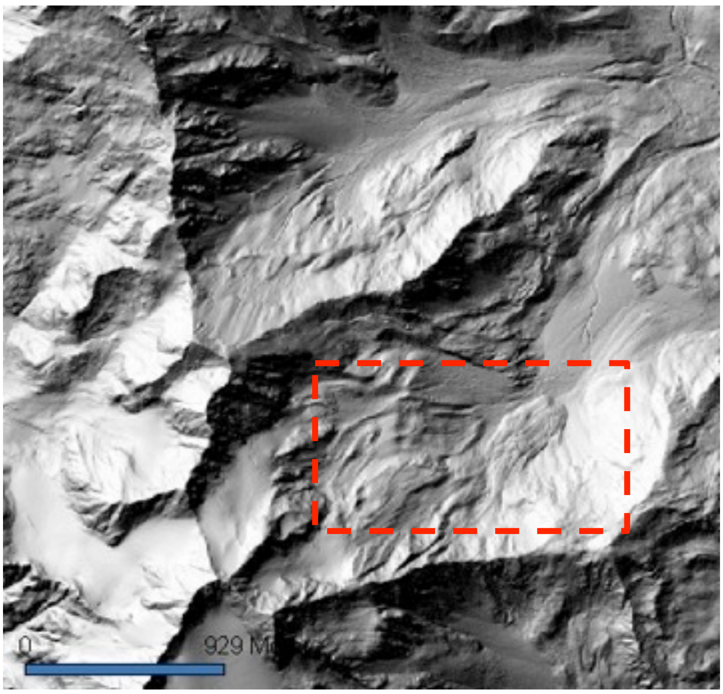


Fig. 77; Laserscan photograph of the rock glacier Lazaun, the red rectangle marks the rock glacier of the Schnals Valley

The morphological, majestic rock glacier has a length of 660m and a width of 200m. The figure below shows an overall view to the Southwest with the peak Saldurspitze (3433m) and the rock glacier front.

Fig. 78: Lazaun rock glacier with the mountain “Saldurspitze”.

On the Lazaun rock glacier two holes were drilled, and the result of the first core was overwhelming. In comparison to the drilling site in the Ulten Valley, the drilling site of this rock glacier generated less complication. On the Lazaun rock glacier only the rotary core drilling method was used and the projected depth was reached. The cooling fluid for the drilling machine was water pumped from the nearby stream to the drilling site, so no helicopter transport was needed for the water supply. The satellite photo below shows the majestic rock glacier Lazaun with its two drilling sites, one located in the center and the other at its front.

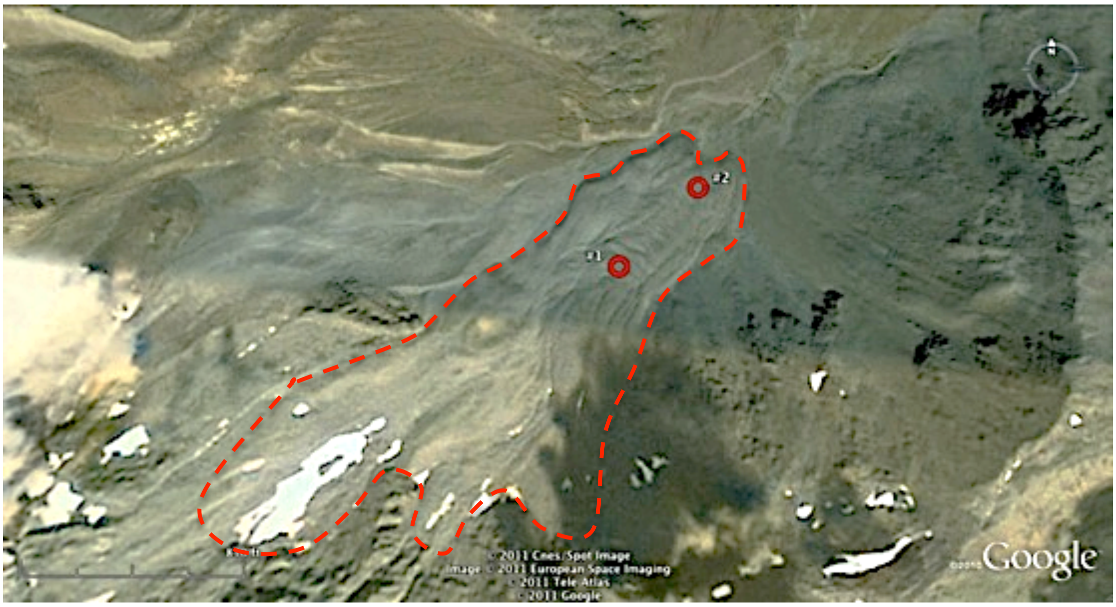


Fig. 79: Rock Glacier Lazaun with location of the two drilling sites.

The final depth of the first drilling site was 40 m and for the second was 32 m. The compact and massive ice-cores as well as ice-enriched debris could be pulled out, packed in plastic foil and stored in the freezer on the drilling site. Every day the packed ice cores were transported to a storage room in the valley and then transported to the University of Innsbruck, where they will be further analyzed. Inclinometer sensors and temperature loggers were installed in the boreholes to measure the flow velocity and temperature of the rock glacier.

Fig. 80: Drilling site 1 on RG Lazaun.

Fig. 81: Drill bit set with diamonds.

Fig. 82: Freezer with packed ice cores.

Fig. 83: Debris enriched ice core from drilling site #1.

Fig. 84: Packing – Station on the rock glacier.

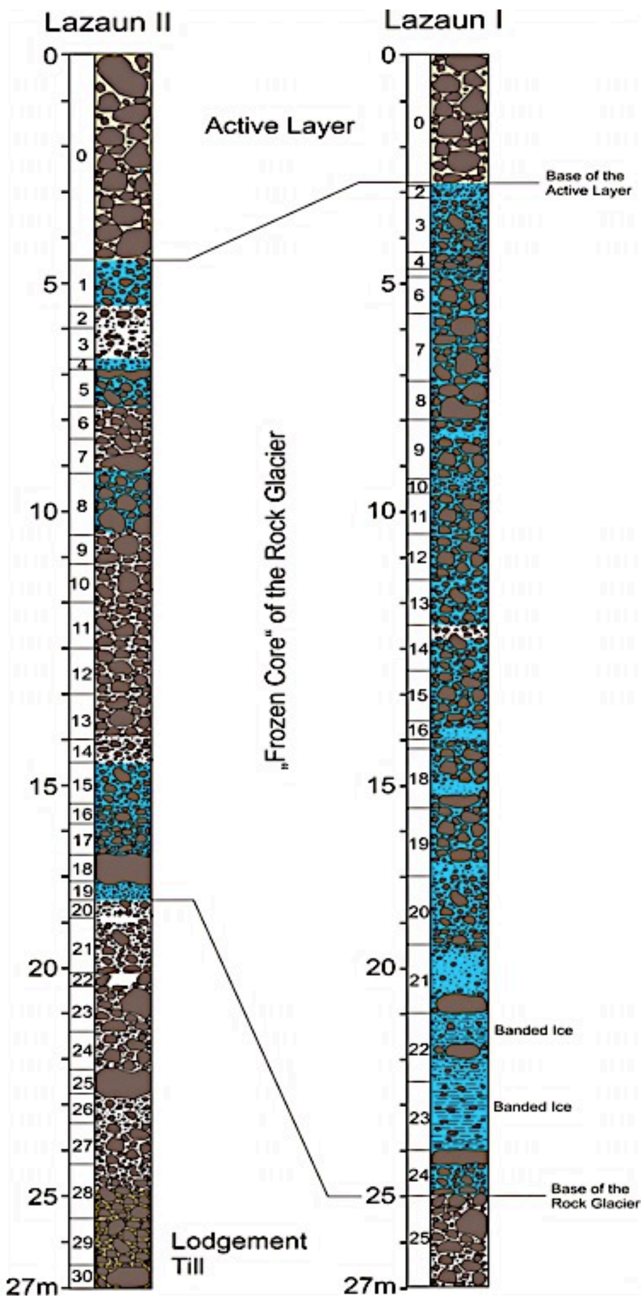
Description of the drill cores Lazaun

Both cores are divided into three zones: the active layer, the frozen core of the rock glacier, and the base of the rock glacier.

Both cores show a high ice content or ice as matrix within the debris. The core Lazaun 1, shows two massive ice layers separated by a small debris layer at 14 m depth. The thickness of the active layer at core Lazaun 1 is about 3 m and, about 4.5 m at Lazaun 2. The maximum depth of the frozen ice body differs by 7 meter: from 25 m depth of core 1 to 18 m depth of core 2.

Underlying this ice-cored body, a ground moraine is likely, since fine-grained, silty material was pulled out. The upper ice lens shows a thickness of 11 m and is located at 3 m depth. Towards the snout of the rock glacier the thickness of the lens decreases down to 8 m and is covered by a 5 m thick debris layer. A 2 – 6 m thick debris layer is separating both ice lenses. The lower lens can be encountered at a depth of 16 m, with a thickness of 8 m in the upper part and 2 m in the lower part of the rock glacier.

Core profiles of Drilling site Lazaun – Schnals Valley; (Tonidandel, D. et al. 2010)



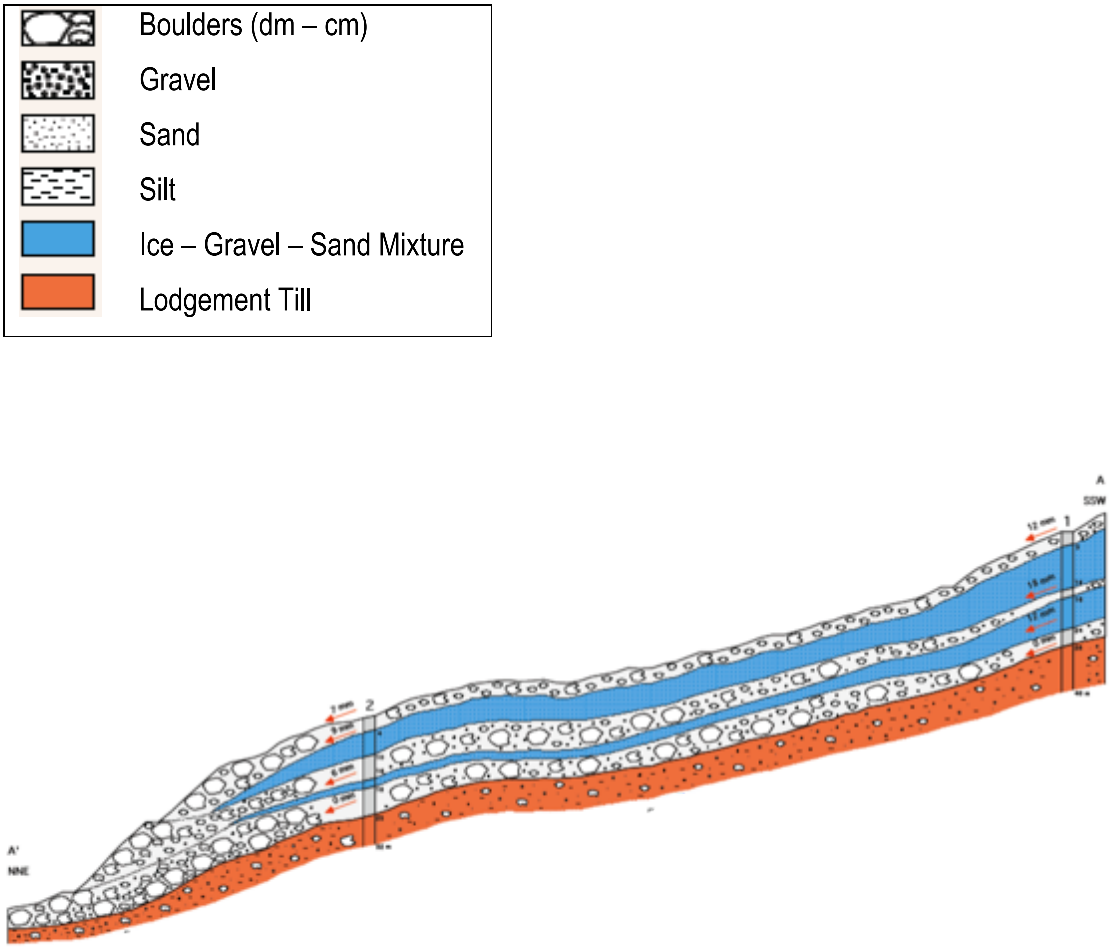


Fig. 85: NNE – SSW Profile of Rock Glacier Lazaun. (Tonidandel, D. et al. 2010)

Based on the two cores a NNE – SSW profile through the rock glacier was drawn by the team of geologists at the Bureau of Geology of the Autonomous Province of Bolzano. The rock glacier interior shows an alternate bedding of boulder layers and ice lenses, which are underlain by a ground moraine. The uppermost layer of rock fragments with a thickness of 3 – 4 m is very coarse, mostly of boulders and coarse to medium sized gravel. Below this layer are two massive ice lenses with a 20° dip towards NNE. Both ice lenses are thinning out towards the snout of the rock glacier. The red arrows with the numbers indicate the flow direction and flow velocity of the rock glacier. Flow velocities of the upper part of the rock glacier are generally greater than of the lower part. For example, the surface movement in the upper and lower parts, show 12 mm and 7 mm, respectively. Inclinometer measurements show the greatest movement of 18 mm at the base of the thicker ice lens in the upper part of the rock glacier. Towards the base of the rock glacier no movement was measured.

Direct measurement of the rock glacier's movement has proven, that it is active. Both cores show a high ice content and the data of the inclinometer measurements also indicate an active and quickly moving rock glacier.
Most likely this rock glacier is derived from a cirque glacier: the cores show a massive ice layer within the rock glacier.

Scientist from the University of Innsbruck will carry out further analysis on the ice cores of both drilling sites in autumn 2011. Stable isotopes ($^{16}O/^{18}O$) and pollen analysis should give information about the age of the ice. These results will be published on the Alpine Space Program website this fall. http://www.alpine-space.eu

9.2 Rock Glacier Inventory

Inventorying rock glaciers is part of a long-term ongoing project, on permafrost research in the Alps. The project, Permafrost Long-Term Monitoring Network (PermaNET), is part of the Alpine Space Program, aiming to create an overall permafrost distribution map of the Alps.

Rock glaciers, a phenomenon of permafrost, can easily be mapped and described on the basis of aerial and laserscan photos. Every rock glacier documented inside the database contains the following information:

- UTM Coordinates
- Air photo documentation
- Root-, frontal and average elevation
- Length/Width
- Area
- Exposition
- Morphological description
- Shape

- Origin
- Activity
- Bedrock composition of the catchment area
- Springs of the rock glacier front
- Watershed
- Analysis of water, heavy metal concentration
- Literature of the rock glacier

9.2.1 Introduction

My study area was in the Samnaun Mountain Group, which contains 257 known rock glaciers of various types and compositions. Most information can be obtained through the analysis of aerial photos. However certain information can not be gathered in this way, such as the classification of the rock glacier origin. Most rock glaciers are talus derived, however a sizable minority, ~20% are developed out of glaciers. An exact classification requires more literature research, comparison of old and new topographical maps, and data collected from geophysical measurements.

The longest rock glacier in this area is fossil and extends ~910 m in length, and located at Kappl, at the Huehnerbergkopf with the following UTM Coordinates 32 T 603175/5210023. It ranges from 2300 m to 2020 m elevation, with an average elevation of 2140 m. This rock glacier is tongue-shaped and shows both longitudinal and transversal ridges and is exposed to WNW.
The dashed line in the aerial photograph below marks the outline of this rock glacier.

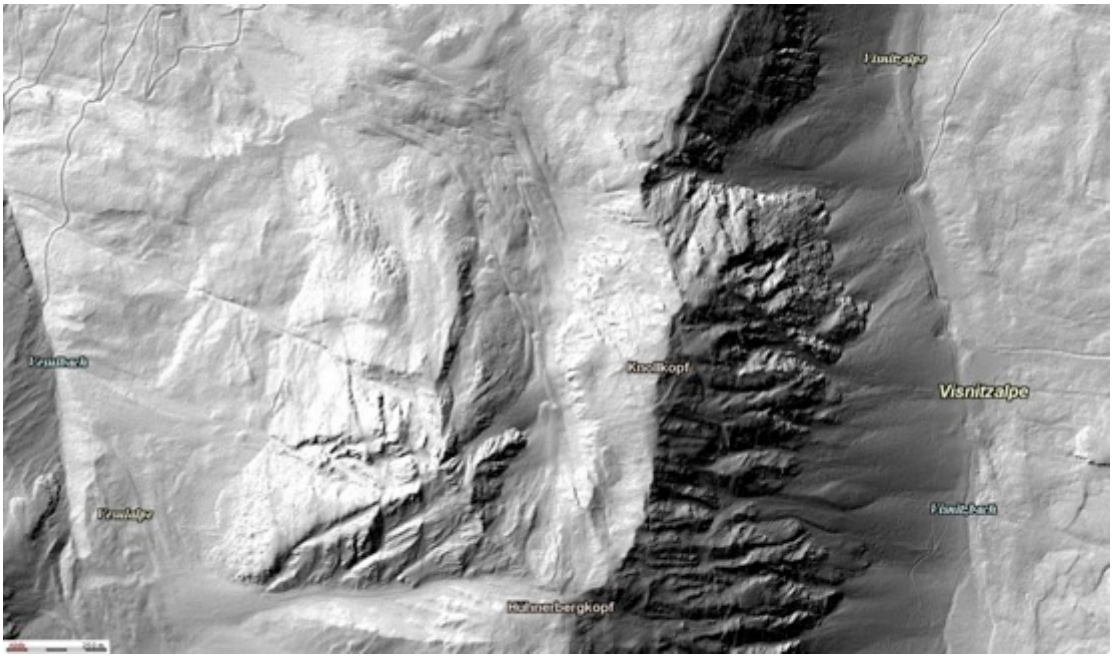


Fig. 86 + 87: Aerial- and laserscan photograph of the longest rock glacier.

Despite being a fossil rock glacier, the relief and morphology is quite smoothened and the surface is highly vegetated.

The longest active rock glacier, with a length of 800 m is located in the Vesul Valley. This giant rock glacier is not only the longest within the active rock glaciers it has the maximum width of 570 m too.

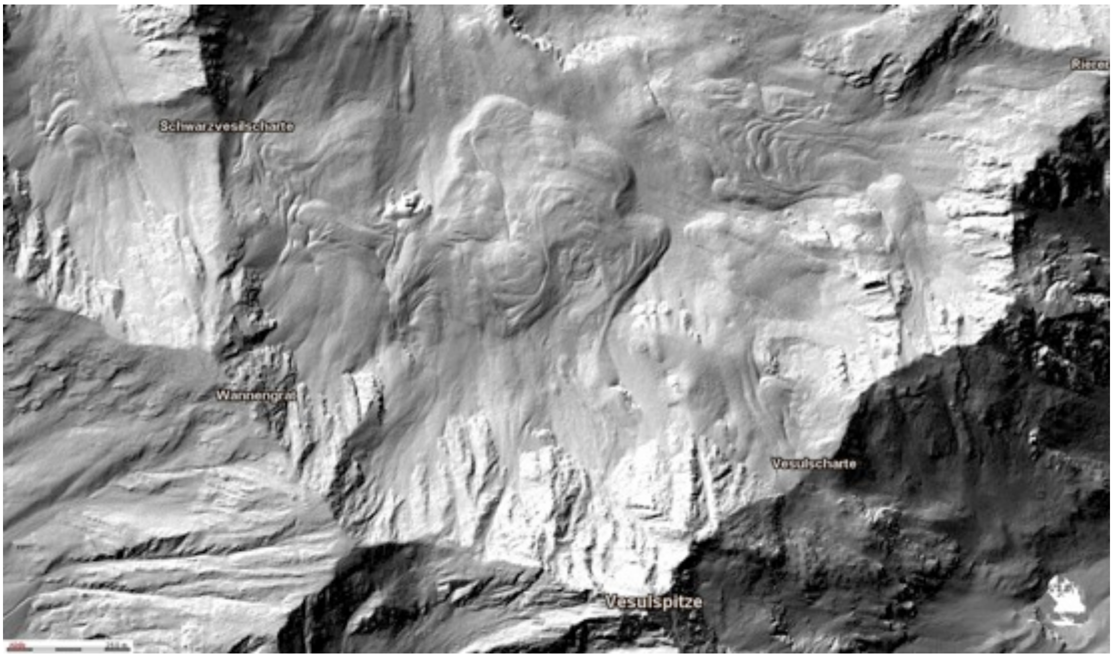


Fig. 88 + 89: Aerial- and laserscan photograph of the longest active rock glacier Vesul.

In comparison to the longest fossil rock glacier the morphology and thickness of the active one is much better developed. It is located in the Vesul Valley within my study area. This rock glacier will be described in detail in the chapter “investigated rock glaciers”.

9.2.2 Results

Out of a total number of 257 investigated rock glaciers 80 are classified active, 71 inactive and 106 are fossil rock glaciers. 60 % are active or inactive. The following chart gives an overview of the activity state of the rock glaciers in the Samnaun Mountain Group.

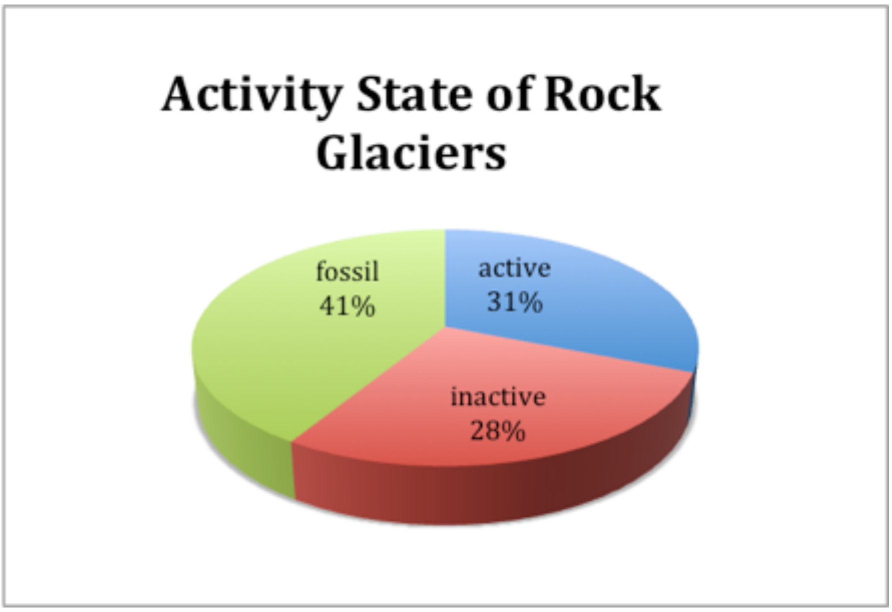


Chart 10: State of activity of rock glaciers in the Samnaun Mountain Group.

Figure 90 illustrates the distribution of the location of all rock glacier in the Samnaun Mountain Group classified as active (blue dots), inactive (brown dots) and fossil (green dots). The rock glaciers cover an area of about 12.933 km^2.

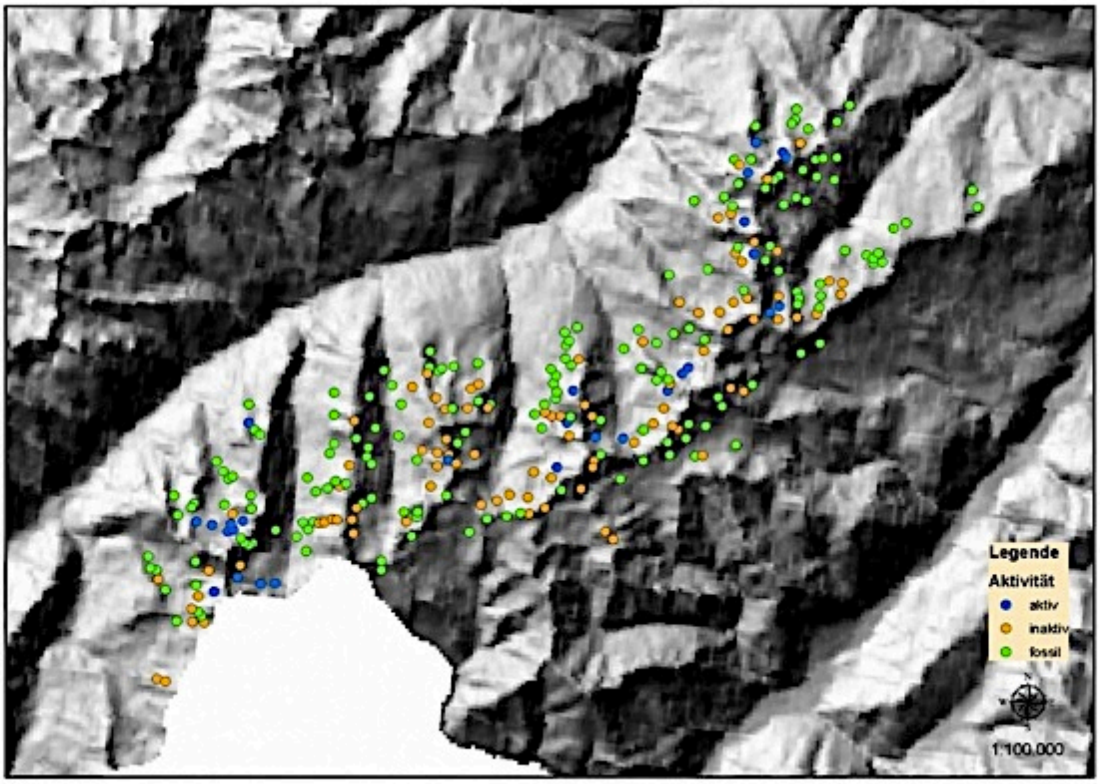


Fig. 90: Location of rock glaciers in Samnaun Mountain Group.

Altitude and Activity State of Rock Glaciers

The following chart shows the elevation (y-axis) and the exposition (x-axis) of all rock glacier activity state; active, inactive and fossil.

The average altitude correlates with the state of activity of the rock glacier.

Fossil rock glaciers can be found within the following altitude range: 2045 – 2770 m, but over 60% are located below 2400 m. A quarter of the fossil rock glaciers lie between 2400 and 2500 m and ~20 % are located above 2500 m.

Inactive rock glaciers tend to be located at higher elevations in comparison to fossil rock glaciers. The rock glaciers in this grouping have elevations ranging from 2250 m at the lowest and 2810m at the highest. The mean altitude averages at 2560m. 80 % of the inactive rock glaciers can be found within 2400 and 2700 m, and more than 60 % of are located above 2500 m.

Active rock glaciers are on average, located at the highest elevations. The lowest active ones are found at an elevation of 2320 m, while the highest are at 2810 m. More than 60 % are located above 2600 m, and more than 90 % are above 2500 m. 70 % are exposed to the NW, N or NE.

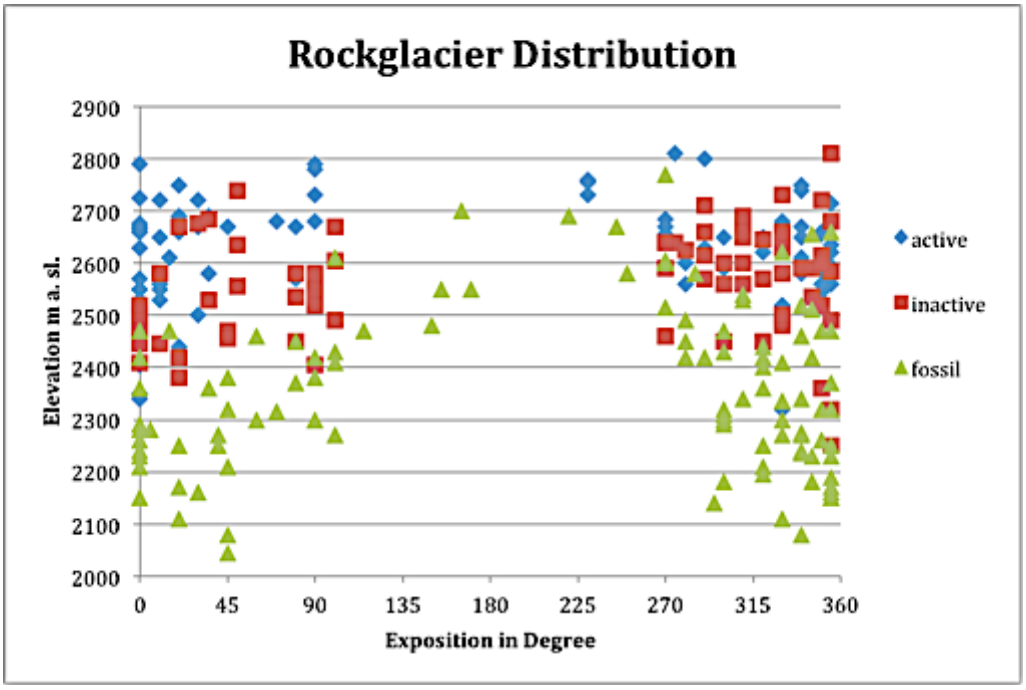


Chart 11: Elevation and exposition of all activity states of rock glaciers.

Exposition of Rock Glaciers

Remarkably, ~75 % of all rock glaciers in the Samnaun Mountain Group are exposed towards the NW, N and NE, while the NW matches the peak of this group. Extremely few rock glaciers face to the South or Southeast. Roughly 15 % of the rock glaciers are facing either the East or West.

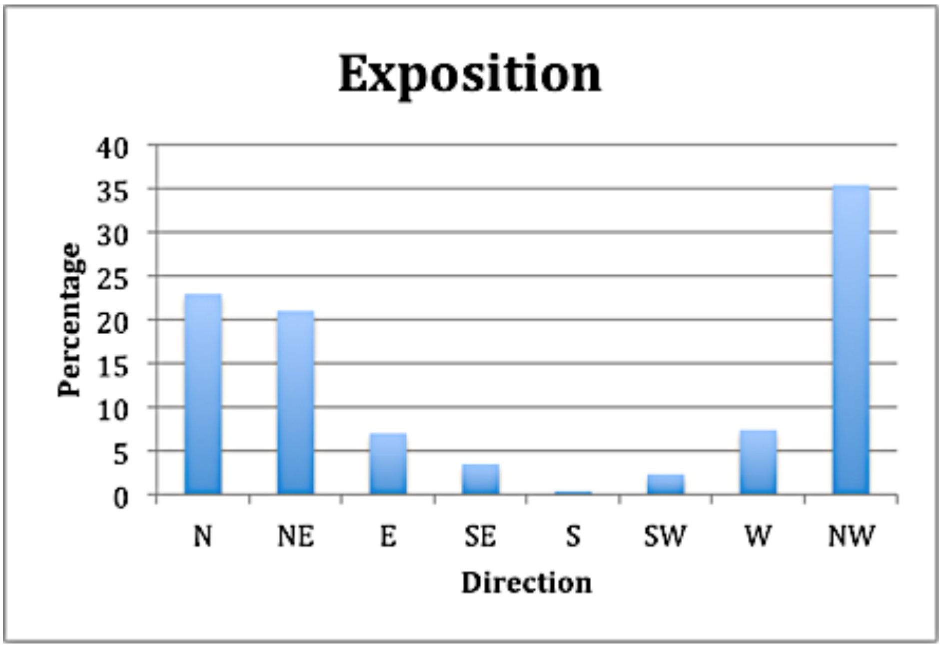


Chart 12: Exposition of all rock glaciers in the Samnaun Mountain Group.

A combination of all three types of activity state in one chart gives a clear overview of the distribution oft he rock glacier exposition.

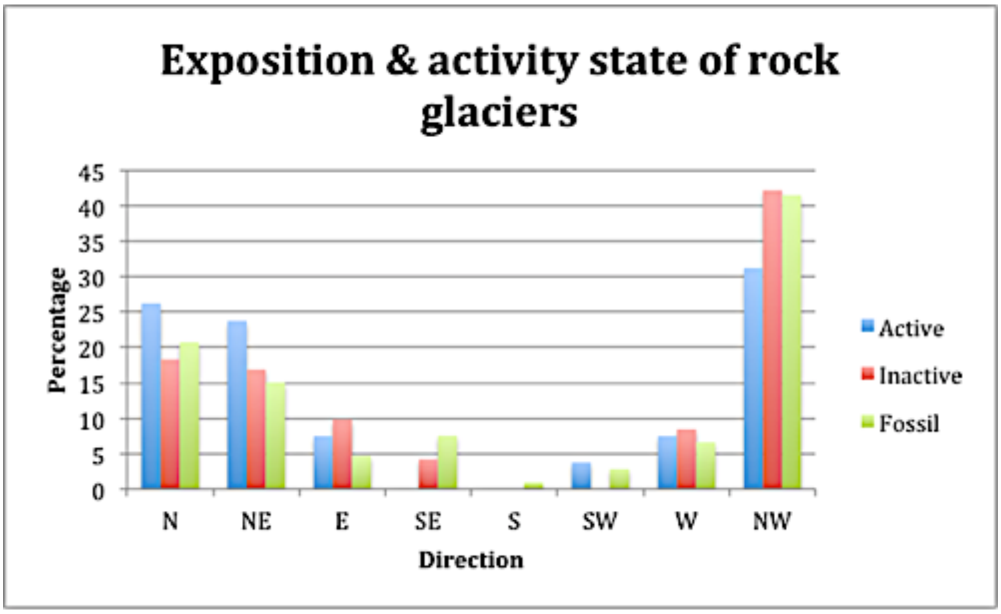


Chart 13: Exposition and state of activity of all rock glaciers in the Samnaun Mountain Group.

There is a notable peak in the NW direction in all kinds of activity states; active, inactive and fossil rock glaciers. However inactive and fossil rock glaciers are more common than active rock glacier in this direction. The two other major directions are N an NE. About 80% of the active rock glaciers are facing the main the most common three directions NW, N and NE. Around 75% of both, inactive and fossil rock glaciers face the northward directions. No rock glaciers of type active and inactive are facing the South, except very few (<2 %) of the fossil rock glaciers do.

Morphology

Rock glaciers can be classified within two morphological types: a tongue shaped and lobate shaped. In the Samnaun Group lobate rock glaciers are the majority, accounting for 60% of the total.

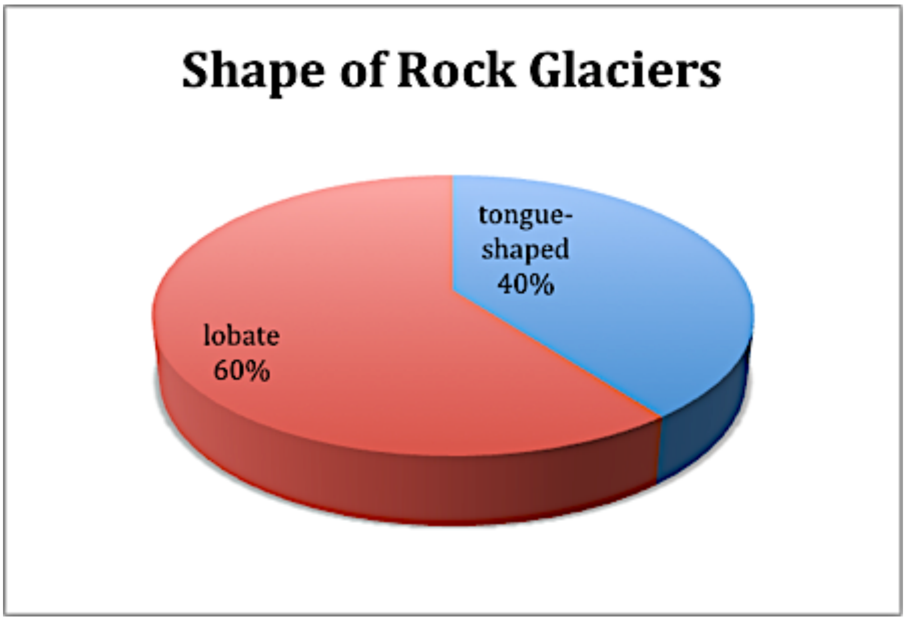


Chart 14: Shape of Rock Glaciers in the Samnaun Mountain Group.

Chart 15 shows the three activity states with the shape distribution for each.

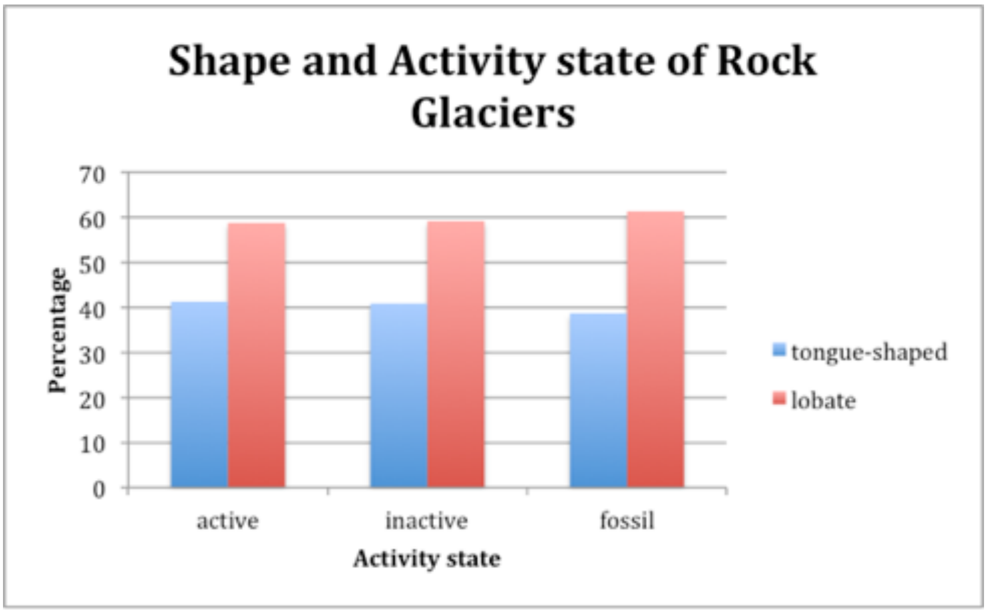


Chart 15: Shape and state of activity of Rock Glaciers.

This comparison indicates, that about 60% of rock glaciers are lobate-shaped while 40% are tongue-shaped in all three states of activity. This shows a lack of statistical correlation between the activity state of the rock glacier and its shape.

Features

A substantial number of rock glaciers show additional morphological features; common features include longitudinal lobes, transversal ridges or both.

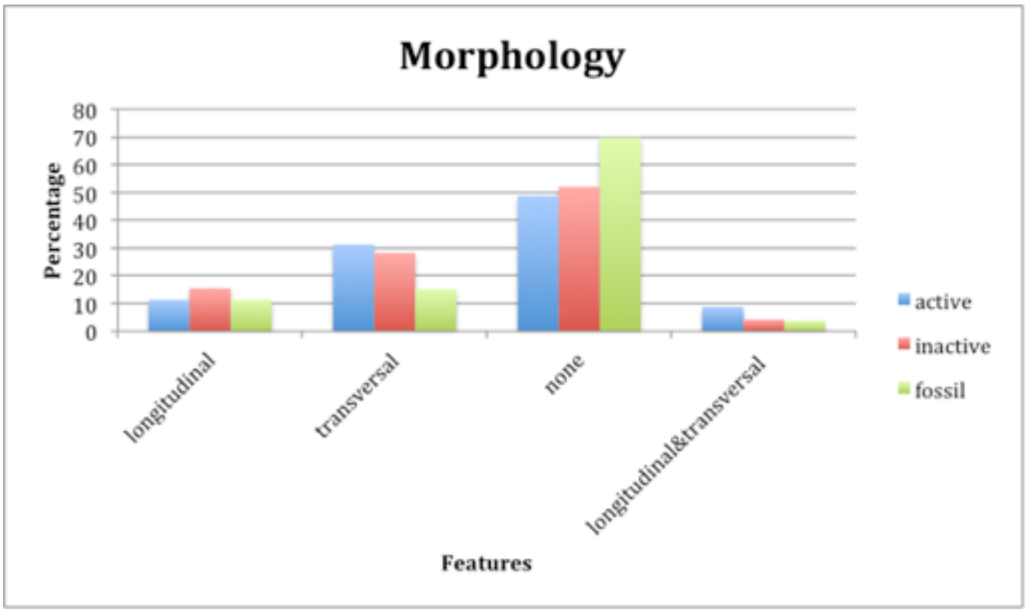


Chart 16: Morphological features on all rock glacier types.

Interestingly, no features can be found on half of the active and inactive rock glaciers, and the majority of the fossil rock glaciers. The lowest amount of rock glaciers, whether they are active, inactive or fossil, show both features, longitudinal and transversal. Longitudinal ridges and furrows are on the average found on 10% of the rock glaciers, while transversal features match about 30% of inactive and active rock glaciers. The inventory of rock glaciers was built based primarily on the analysis aerial photographs, as a result most rock glaciers are not described in the field itself. Therefore the number of rock glaciers containing additional morphological features may be underestimated because smaller features may not be visible on the aerial photographs. A key role on fossil rock glaciers might the vegetation play, as highly vegetated fossil rock glaciers make the determination of features difficult.

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Silvretta Seilbahn AG, Dipl. Ing. Markus Walser.

11 ATTACHMENT

11.1 Map with investigated rock glaciers in the study area

6.2 Map with investigated springs at rock glaciers