Alpine Permafrost And Related Geotechnical Aspects In West-Tyrol Austria

Master's Thesis
Presented to the
University of Innsbruck
Faculty of Geo- and Atmosphere Sciences

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Foreword

Recently, permafrost research has become an issue of national importance. As a result of climate change, thawing permafrost provides a potential of natural hazards, which could threaten any area in its proximity.
Several projects on permafrost research and climate change are in progress headed by the University of Innsbruck. Two projects dealing with permafrost research gave me the opportunity to investigate in this research area.

One mayor permafrost project was focusing on borehole drilling on two different rock glaciers in South Tyrol (Italy). This project is part of the Alpine Space Program, financed by the European Union. Its goal was to obtain more precise information about the internal structure of an active rock glacier, and its ice content and its age. I visited and documented both drilling sites.

'PermaNET', Permafrost Long-Term Monitoring Network, is the second project I was involved with. An overall permafrost distribution map in Tyrol (Austria) is the objective of this project. Rock glaciers, reliable indicators of permafrost, allow the installment of a rock glacier inventory in Tyrol. This is carried out by aerial photo interpretation. All rock glaciers on stock give information about their location, altitude, exposition and morphology. Within this project I inventoried all rock glaciers in the Samnaun Mountain Group (Austria).

Both projects have further developed my interest in Alpine permafrost, in particular in rock glaciers.

As a result I decided to write my Master's Thesis on this topic to expand my knowledge of permafrost, its mapping methods and as well as the impact of thawing permafrost in high mountain areas.

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1 Introduction

The goal of my master thesis is to characterize alpine permafrost, particularly active rock glaciers in a high alpine area of the Samnaun Mountain Range in the western part of Tyrol (Austria). This science is still very young and only few papers have been published on this topic within the Austrian Alps.

My study area lies in the Paznaun Valley with the UTM coordinates: 32 T E 602984, N 5205570. Geologically, it is a very unique area; the Penninic zone outcrop as a tectonic window within the Austroalpine basement. This particular tectonic window is called the Engadine Window, and it is comprised of sediments from the Alpine Tethys.

The emphasis of my work is focused on investigating the dynamics of active rock glaciers, the hydrology of springs released from rock glaciers, and the geology of the study area. Different kinds of permafrost mapping methods shall be described, applied, and interpreted.

The focus will lie on four rock glaciers, which are assumed to be active: the Idalp rock glacier, Buerkelkopf rock glacier, the Visnitz rock glacier and the Vesul rock glacier. By means of the above-mentioned measurements the activity state of the rock glaciers will be proven. Furthermore, impacts of permafrost on infrastructure in the area of my investigation are examined.

Another topic covered by my thesis is the analyses of core drillings of two active rock glaciers in South Tyrol (Italy). The drilling operation was carried out during the summer of 2010 by the international project (PERMANET) in South Tyrol (Northern Italy). Both drilling operations are documented and described within this master thesis.

1 Geographical Overview

The study area lies in the western part of Tyrol (Austria), within the Samnaun Mountain Range. This range stretches across 32 km with a strike of NE/SW from the town of Landeck (Austria) to the canton Graubuenden (Switzerland). The highest peak of this mountain range is the Muttler (3294m) and is located in Switzerland. Geographical boundaries are marked by the following valleys; to the north the Paznaun Valley, to the South the Inn Valley and to the West the Fimba Valley, respectively. The sketch below (Figure 1) shows the mountain group classification of the western Tyrol. The yellow area matches the Samnaun Mountain Range. Fig. 1: Basic Map of Tyrol with Mountain Groups in West-Tyrol. The black-dashed area outlines the Samnaun Mountain Group, (Ed. Hoelzl, 1985).

Fig. 1: Base Map of Tyrol. (Ed. Hoelzl, 1985)

1.1 Study Area

The area of investigation lies on the southern part of the SE trending valley called Paznaun. The Paznaun Valley is easily accessible by using the highway B188 from the city of Landeck. The main river Trisanna flows through the 30 km long valley. Several north facing side valleys end in the main Paznaun Valley.

The study area is situated at the orographic right side of the river Trisanna within the communities Kappl and Ischgl. Figure 2 shows a geographical overview of the county of Tirol. The study area is indicated by a black rectangle.

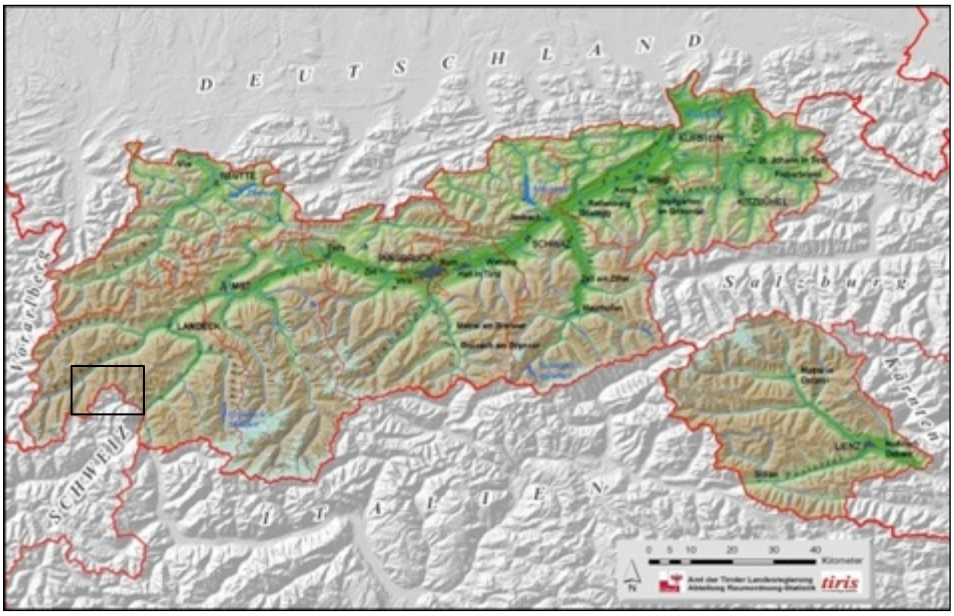

Fig.2: Geographical map of Tyrol with the study area indicated by a black rectangle (www.tirol.gv.at/tiris).

Side valleys of the Paznaun, the Visnitz and Vesul Valley and the location Idalp, a very famous ski area, lead to the investigated active rock glaciers.

The highest peak of the study area is the Vesulspitze at an elevation of 3089 m. The area surrounding the peak Vesulspitze is characterized by the occurrence of rock glaciers. The area of investigation is pointed out in the sketch below.

Fig.3: Aerial photograph of area of study area. (www.tirol.gv.at/tiris)

1.2 Historical Maps

Several historical maps are provided by the government of Tyrol and are available online with the following link: www.tirol.gv.at/tiris. By means of historical maps the rock glacier history can be observed.

Two historical maps, figure 4 and 5, of the Austrian-Hungarian Monarchy of the mapping episodes 1801/1805 – 1816/1821 and 1864/1887 give an overview of the glacier extent at that time. The surrounding of the mountains Vesulspitze, Buerkelkopf, Buerkelspitzen and Flimspitze were covered by big glaciers in the map of the first mapping episode of the early 19th century. The glaciers are indicated by a black rectangle in both figures. A slight decrease in glacier extent is noticeable in the middle to end of the 19th century. These glaciers were remnants of the Little Ice Age, which culminated around 1850. Comparing to the current topographical map in figure 6 below, the glacier retreat is remarkably. All big glaciers have disappeared and just a very small glacier at Buerkelkopf is still mapped; however this glacier is not present anymore.

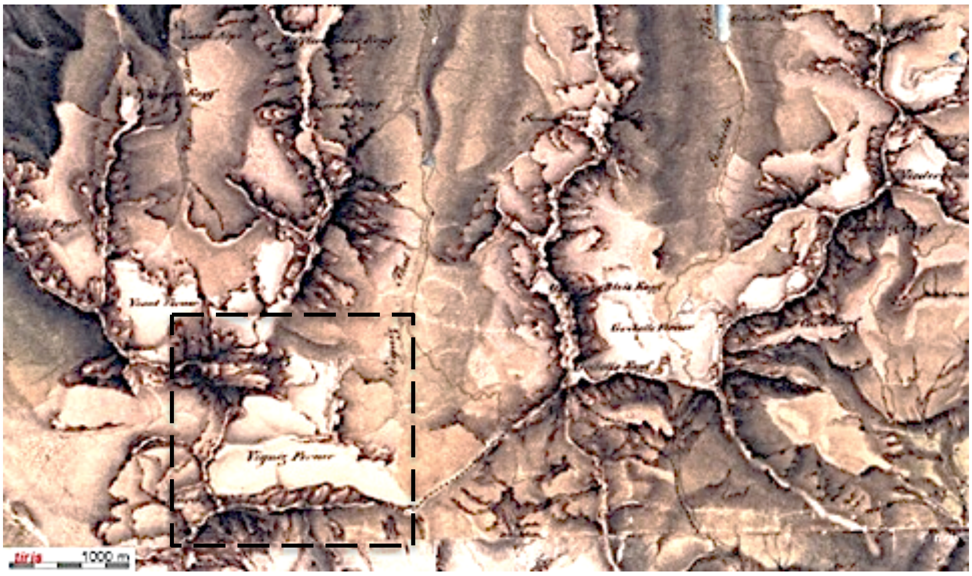

Fig.4: Historical map: “2. Tiroler Landesaufnahme 1801/1805 – 1816/1821”, showing several glaciers in the area of Vesulspitze and Buerkelkopf, indicated by a black rectangle.

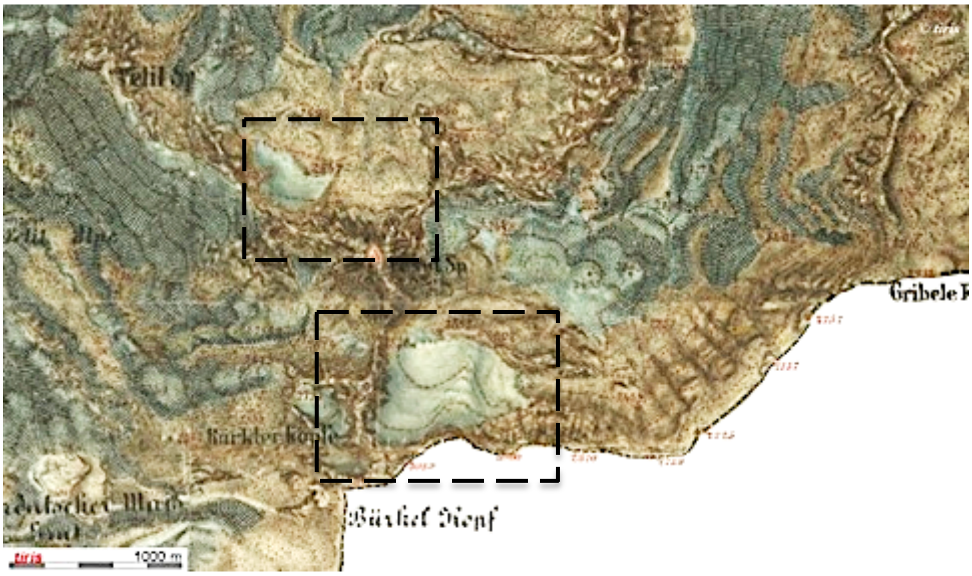

Fig.5: Historical map: “ 3. Landesaufnahme 1864/1887”, still documents the pre-sence of small glaciers north of Vesulspitze and Northwest of Buerkelkopf. The glaciers Visnitz and Vesul are indicated by black rectangles, with the Vesul gla-cier in the upper left and the Visnitz glacier in the lower right part of the map.

Fig.6: Current topographic map, which still shows a small glacier in the North facing cirque of Buerkelkopf. During the last few years this glacier has disappeared.

2 Geological Overview

The local geology offers an outstanding exposure and insight into the structure of the Eastern Alps and its tectonic history. Four major segments can be distinguished within the structure of the Alps (Schmid et al. 2004): the Helvetic zone, the Penninic zone, the Austroalpine zone, and the Southalpine zone.

The Helvetic zone represents the lowermost tectonic unit in the alpine architecture. It encompasses sediments of the European shelf and the upper slope, while the Penninic zone contains sediments of the alpine Tethys.

The upper plate of the alpine orogenic belt, is composed of rocks of the Apulian plate, the Austroalpine zone, and the Southalpine zone.

The Periadriatic Line divides the Austroalpine zone to the north from the Southalpine zone to the South. The investigated area exposes mostly the Austroalpine zone, however on the southern part rocks of the Penninic zone are exposed. Figure 7 shows the palaeogeographic distribution of the major tectonic zones of the Alps. The study area is pointed out by a red rectangle.

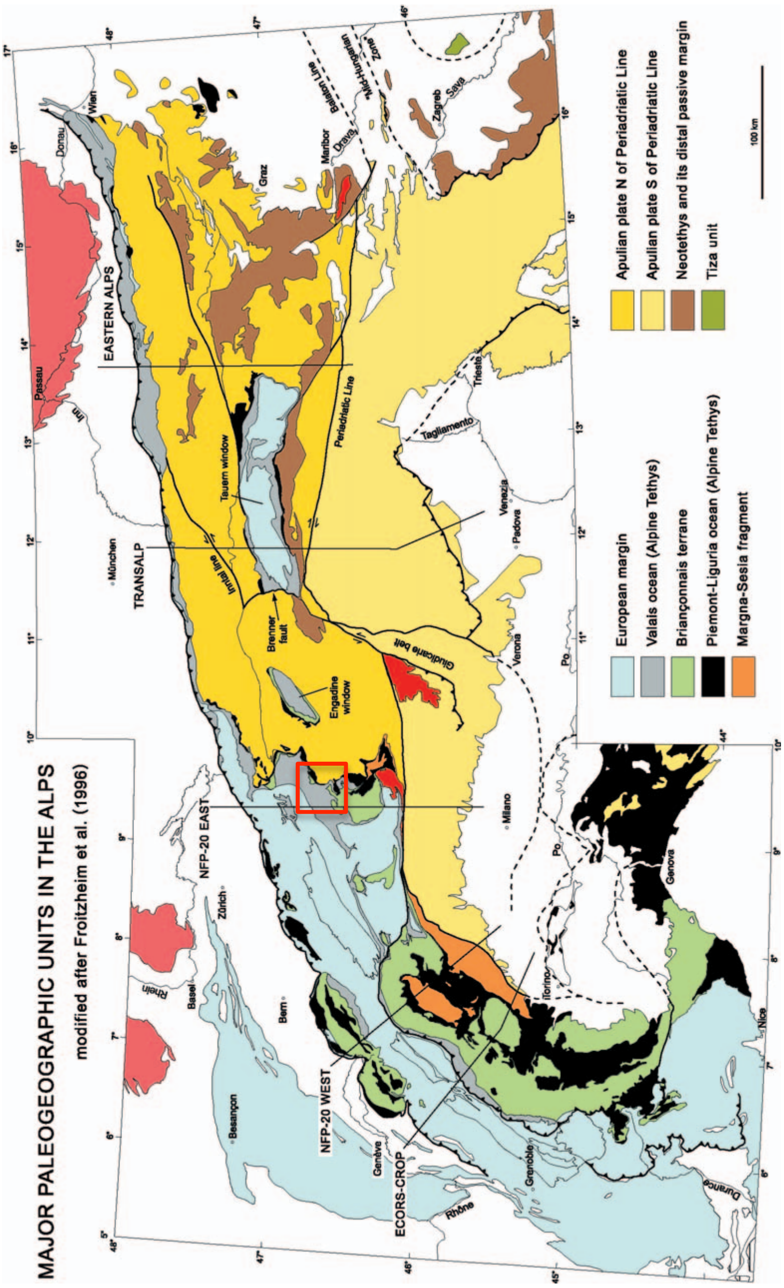

Fig.7: Map of the Palaeogegraphic units of the Alps (After Schmid et al. 2004).

Schmid et al. (2004) identifies three distinctive nappes within the Penninic zone: the lower-, middle-, and upper Penninic nappes. The lower nappe corresponds to the Valais Ocean, the middle nappe to the Briaconnais Terrane and the upper Penninic nappe to the Piedmont-Liguria Ocean.

Figure 8 shows the palaeogeographical locations of the European and Apulian plates as well as the Penninic depositional environment during the late Cretaceous.

The opening of the Piemont-Liguria Ocean (alpine Tethys) was thought to have occurred during the middle Jurassic, in kinematical context to the opening of the central Atlantic. The ongoing rift has led to the opening of a northern branch of the alpine Tethys "the Valais Ocean" during late Createaceous. This has resulted in a separation of the micro-continent "Brianconnais", which was a former part of the European continent. Sediments deposited within the Penninic realm range from late Jurassic to the Palaeogene.

The closing of the alpine Tethys took place in context of the Tertiary orogeny, when the north directed motion of the Apulian plate took place and the Penninic zones were overridden by the Apulian plate (Austroalpine and Southalpine Zone). Within the Eastern Alps, outcrops of the Penninic zones are found in tectonic windows: the Tauern Window, Gargellen Window, and the Engadine Window.

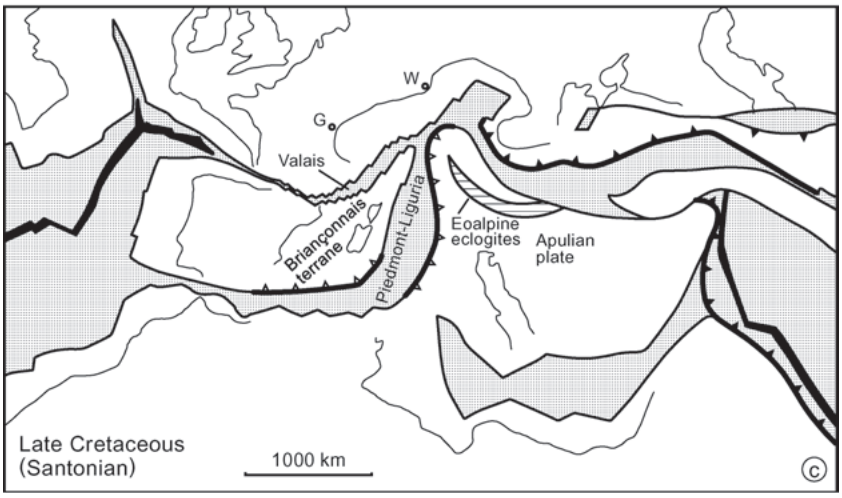

Fig. 8: Palaeogeographical situation during Late Cretaceous after Frank 1987, Stampfli 1993, Schmid et al. 1997 and Stampfli et al. 2001. The locations Vienna and Genevre are indicated by dots labeled with W, and G, respectively.

2.1 Geological Setting of the Study Area

The study area lies geologically in the Silvretta Crystalline Complex and the Engadine Window. The Silvretta Crystalline Complex is part of the Austroalpine zone and found in most parts of the study area, however the southernmost portion of the study area is composed of sediments from the Penninic zone, exposed as the Engadine Window. This offers an interesting insight to the tectonic transition from the Austroalpine zone, here the Silvretta Crystalline Complex

(SCC), and to the Penninic zone in the Engadine Window. The Engadine Window strikes NE/SW with a length of 55 km and a maximum width of about 17 km. It is surrounded and overlain by the Austroalpine units, to the north and west: the Sylvretta Crystalline Complex (SCC), to the East and South the Oetztal-Stubai Crystalline Complex. The Engadine Window is an anticlinal structure trending NE-SW, with the Buendnerschiefer exposed in the central part and a high diversity of rock types exposed at the northeastern margin of the window.

2.2 Silvretta Crystalline Complex (SCC)

The exploration history of the SCC goes back to the early 19th century (Escher & Studer, 1839; Theobald G., 1864, 1865). However, Koch (1875, 1876, 1877) carried out extensive field studies and investigations in the Austrian part of the SCC.

The SCC, as part of the Austroalpine tectonic unit, lies on top of the Penninic zone with a maximum thickness of 5 km (Gruber, 2010). The SCC is a polymetamorphic complex, composed of para- and orthogneiss, amphibolite, migmatite and eclogite. A Variscan metamorphic overprint dominates the SCC, however on the northern margin of the SCC a retrograde Alpine metamorphic overprint is observed.
Hurford et al. (1989) studied the thermo-tectonic evolution and distinguished three uplift styles by means of fission track analysis of apatite and zircon and K-Ar and Rb-Sr dating of white-mica and biotite.
From 110 – 35 Ma years an uparching of the SCC occurred, followed by a homogenous uplift from 35 – 2 Ma years and a recent eastward tilt of the SCC since 2 Ma years.

Petrographic studies indicate a predominant predominant amphibolite facies within the SCC and a greenschist facies at the northern margin.
Hoernes et al. (1971) carried out petrographic analysis on paragneisses of the SCC. They determined the following prealpine metamorphism zones: Staurolite zone, Disthen zone, Sillimanite zone and Sillimanite and Disthen zone.
The northernmost margin of the SCC is characterized by the Staurolite zone, to the west of the Arlberg the Disthenzone and Sillimanite-Disthen zone is present and East of the Arlberg to the eastern boundary of the SCC the Sillimanite zone is present. After Hoernes (1971) metamorphic zone classification, the study area is part of the Sillimanite zone.

Predominant rocks in the study area are metamorphic paragneiss and biotite-gneisses. The paragneiss occurs as very light colored rocks, from grey to crème, and rust-brown, when weathered. The rock is massive, banded, very fine grained and of homoblastic texture. Beside metapelites, bt-gneisses occur as dark very fine-grained greyish rocks. Figure 10 and 11 show the predominant rocks in the study area.

A tectonic overview of the study area is illustrated in figure 9. The NE-SW trending Engadine Window is located in the left right part of the map, and the Silvretta Crystalline Complex (in the map as “Silvrettadecke” mentioned) marks the northern and western boundary of the Engadine Window. The red rectangle outlines the location of the study area.

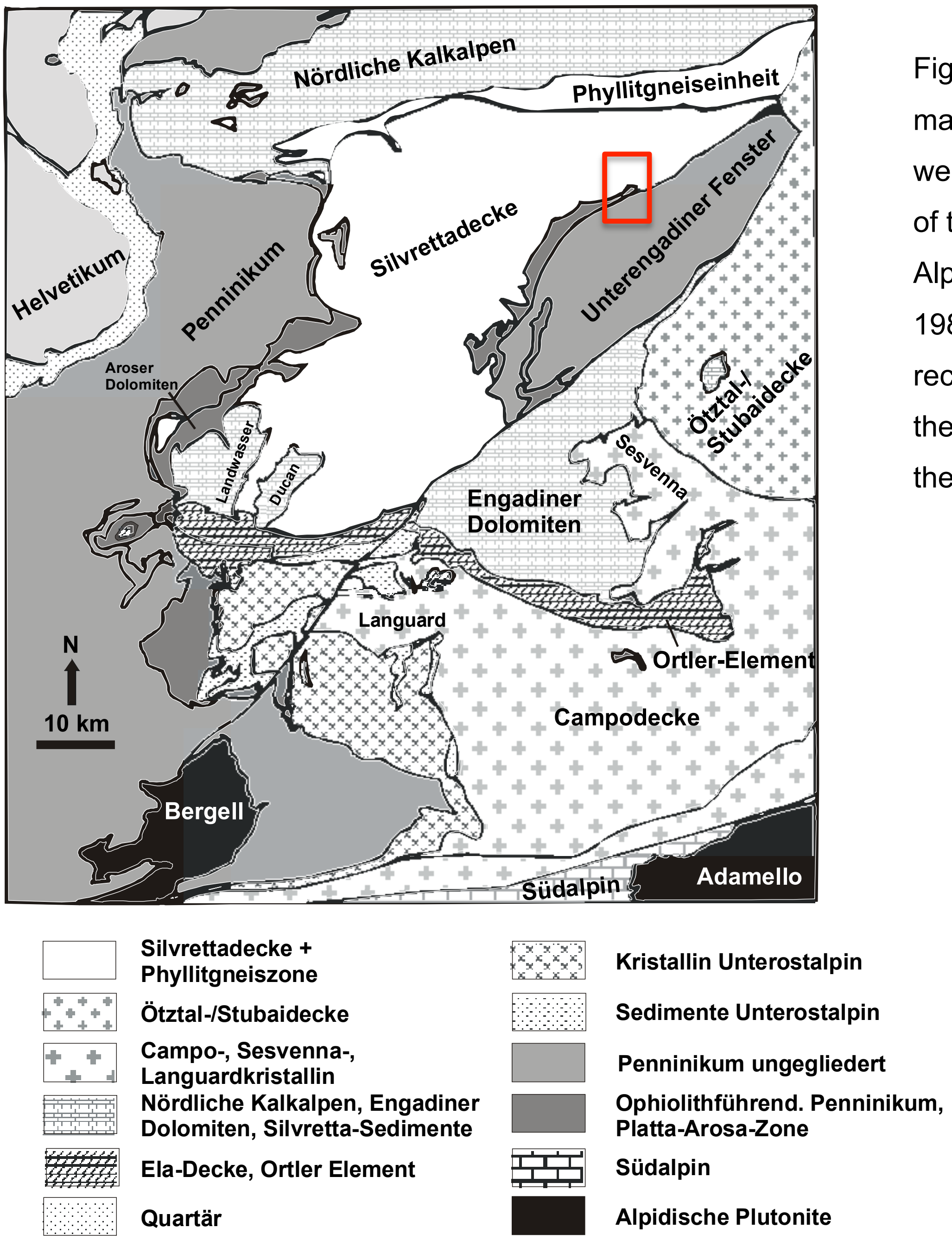

Fig.9: Tectonic map of the western margin of the Eastern Alps (Eberli, 1985). The red rectangle marks the location of the study area.

Fig. 10: Fine-grained paragneiss at the Visnitz cirque.

Fig. 11: Biotite – Gneiss at the foot of the Vesulspitze.

2.3 Engadine Window

The Engadine Window is characterized by a complex nappe system is divided into 3 distinctive parts: the lower, middle, and upper Penninic nappe (Schmid et al., 2004).
Oberhauser (1980) groups the Engandine Window into several distinctive zones: The Zone of Roz/Champatsch/Pezid, Pfundser Zone, Fimber Zone, Zone of Prutz /Ramosch, Buerkelkopf- and Flimspitz Zone.
A correlation of Oberhauser’s (1980) classification of the Penninic Zones and the lower, middle, and upper nappe by Schmid et al. (2004) is discussed in the report of Gruber et al. (2010).
The lower nappe, which is present in the central part of the Engadine Window, is divided into the Pfundser Zone and Zone of Roz-Champatsch-Pezid. Common rock types of the lower Penninic Zone are: Buendnerschiefer, quarzite, phyllite, limestone, calcareaous-micaschists. The Fimber Zone and the Zone of Prutz and Ramosch are correlated to the middle Penninic nappe, while the Buerkelkopf and Flimspitz Zone are ascribed to the upper Penninic nappe.

The study area comprises mostly upper Penninic units, in particular the Buerkelkopf Zone, and is represented by metamorphic oceanic lithosphere (ophiolite) of Jurassic-Cretaceous age.

Gabbro, pyroxenite, metabasalt, pillow basalt and radiolarite are common rock types. This section of rocks is known as the Idalp-Ophiolite.

To the East of the Buerkelkopf zone, the Fimber Zone is present with calcareous schists and limestones. To the West of the Buerkelkopf Zone the boundary to the Flimspitz Zone at location “Flimjoch” can be mapped. The boundary is characterized by slices of the Silvretta Crystalline Complex and units of the Idalp-Ophiolite.

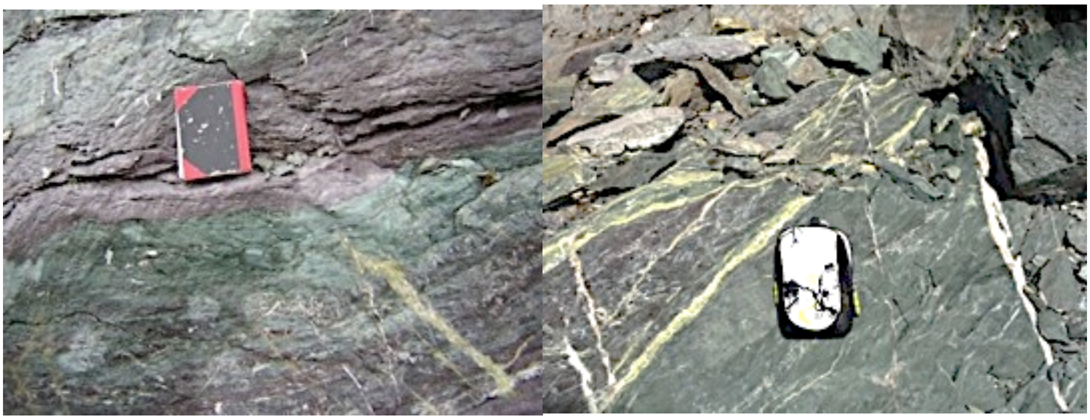

Fig.12 + 13: Dark green to purple metamorphic basalts at the locality Buerkelspitzen.

Two samples of the metamorphic basalts were analyzed by X-Ray diffraction indicating the following mineral assemblage:

Clinochlore + Albite + Epidote + Quartz + Calcite

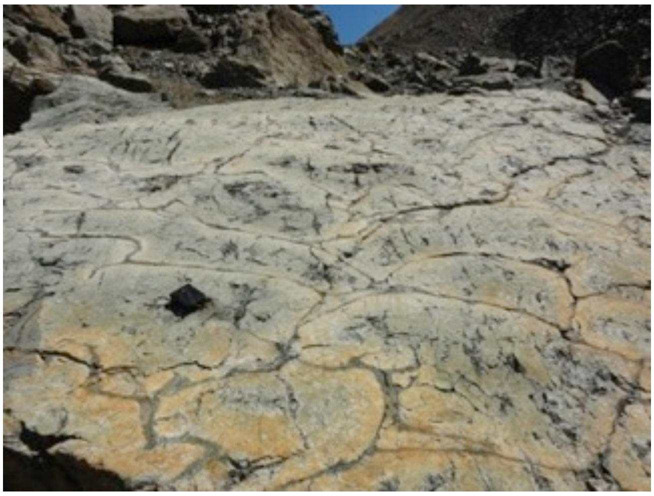

Fig.14: Well preserved pillow basalt (Idalp Ophiolite Complex) at location Flimjoch/Ischgl.

Fig.15: Calcareous Schists of Fimberzone at the location “Visnitzkopf”, east of the Buerkelspitzen.

3 Permafrost

Recently permafrost has become a highly covered media topic. Due to climate change, permafrost is of great importance in the Alps. Thawing of permafrost can cause several different types of hazards to all kinds of infrastructure such as settlements, traffic routes, tourist areas, mountain routes, and trails.

Traditionally, permafrost is defined as lithosphere material that remains at or below 0 °C for a minimum of one or even two years, irrespective of ice/water content (Häberli & King, 1987).

Permafrost used to be defined by its temperature, however French (1996) differentiates between temperature and its state condition, cryotic and non-cryotic. The term cryotic was implemented to describe the ground thermal condition, as the freezing point of included water may be < 0°C.

Perennially cryotic ground is, therefore, synonymous with permafrost, and permafrost may be ‘unfrozen’, partially frozen or frozen, depending upon the state of the ice/water content (French, 1996, p. 52).

The distribution of permafrost is controlled by the interaction of air temperature and ground thermal interactions. The ground temperature is directly related to the air temperature, however the air temperature is a product of the solar radiation, albedo, vegetation, and snow cover. Some authors use the term “mountain permafrost” to describe Alpine permafrost.

When talking about permafrost in alpine areas, some authors use the term “mountain permafrost”. This term is simply used to define permafrost in high altitude mountain areas, such as the Alps or the Himalayas.

While both permafrost and mountain permafrost are governed by climate, different factors are typically responsible for controlling their formation and creating a climate that is suitable to their formation (Gruber & Haeberli, 2009):

- Topography
    - Elevation and its geometric measures (slope, curvature, roughness)
- Ground conditions
    - Micro climate
    - Snow cover

All these factors influence the ground surface temperature and therefore the existence of mountain permafrost. Topography modifies the surface micro-climate and therefore the ground conditions. The occurrence of mountain permafrost is generally depending on elevation and exposition. For instance, the steeper a slope is, the less accumulation of snow is given and the better cold air temperature can penetrate into the ground. The winter snow cover is a key factor for the formation of permafrost.

A more than 1m thick cover of snow can interrupt the interaction of ground surface temperature and air temperature. This isolation effect could lead to an aggradation or degradation of permafrost in the ground. A cooling effect is just given, when first snowfall is in late fall, as cold air temperature can easily penetrate through the ground and the snow cover isolates it. Whereas a warming effect is fulfilled, when first snowfall occurs in fall, and the cold air temperature of fall cannot penetrate into the ground.

By definition, permafrost is influenced by both the ground surface temperature and the air temperature. Two different kinds can be distinguished, dry and wet permafrost. Wet permafrost can highly vary in ice content and in the form of the ice itself. Ice in permafrost areas occurs as ice cement, massive and/or thin ice lenses, as horizontal ice layers and/or ice wedges.

The volume of ice content in wet permafrost depends on the soil mechanics (pore volume, particle size), precipitation rate, and lithology.

Permafrost can be divided by its distribution that is primarily controlled by climate, particularly the mean annual air temperature.

Four different types of permafrost are listed below indicating the percentage of area covered by permafrost. (National Snow and Data Center, University of Colorado)

- Continuous permafrost: 90-100%
- Discontinuous permafrost: 50-90%
- Sporadic permafrost: 10-50%
- Isolated permafrost: 0-10%

Zhang et al. (2003) estimated that permafrost covers 24 % of the northern hemisphere, by using monthly air temperature isotherms. Permafrost typically occurs as far north as 84° latitude and as far south as 35-40° latitude (northern hemisphere) as an effect of high elevation, Zhang et al. (2003).

The “Circum-Arctic Map of Permafrost and Ground Ice Conditions” taken from the National Snow and Ice Data Center provides an overview of the distribution of permafrost in the northern hemisphere. The map is based on the distribution of the four different types of permafrost (continuous, discontinuous, sporadic and isolated) and the ground ice content in lowlands and mountainous areas.

In Figure 16, permafrost in lowlands is shown in bluish to greenish color, whereas mountain permafrost is given in brownish to reddish color.
Ice sheets and glaciers are matched in blue.
An increase in the intensity of the color indicates a higher amount of ice present.
The intensity of the colors indicates the amount of ice with more intense colors signifying the presence of more ice.

The distribution of permafrost in the Alps is indicated as a small band running through the alpine arc in the upper quadrant of the map. As indicated by figure legend, the permafrost in the Alps is described as discontinuous mountain permafrost with mostly high to medium ice content (>10%).

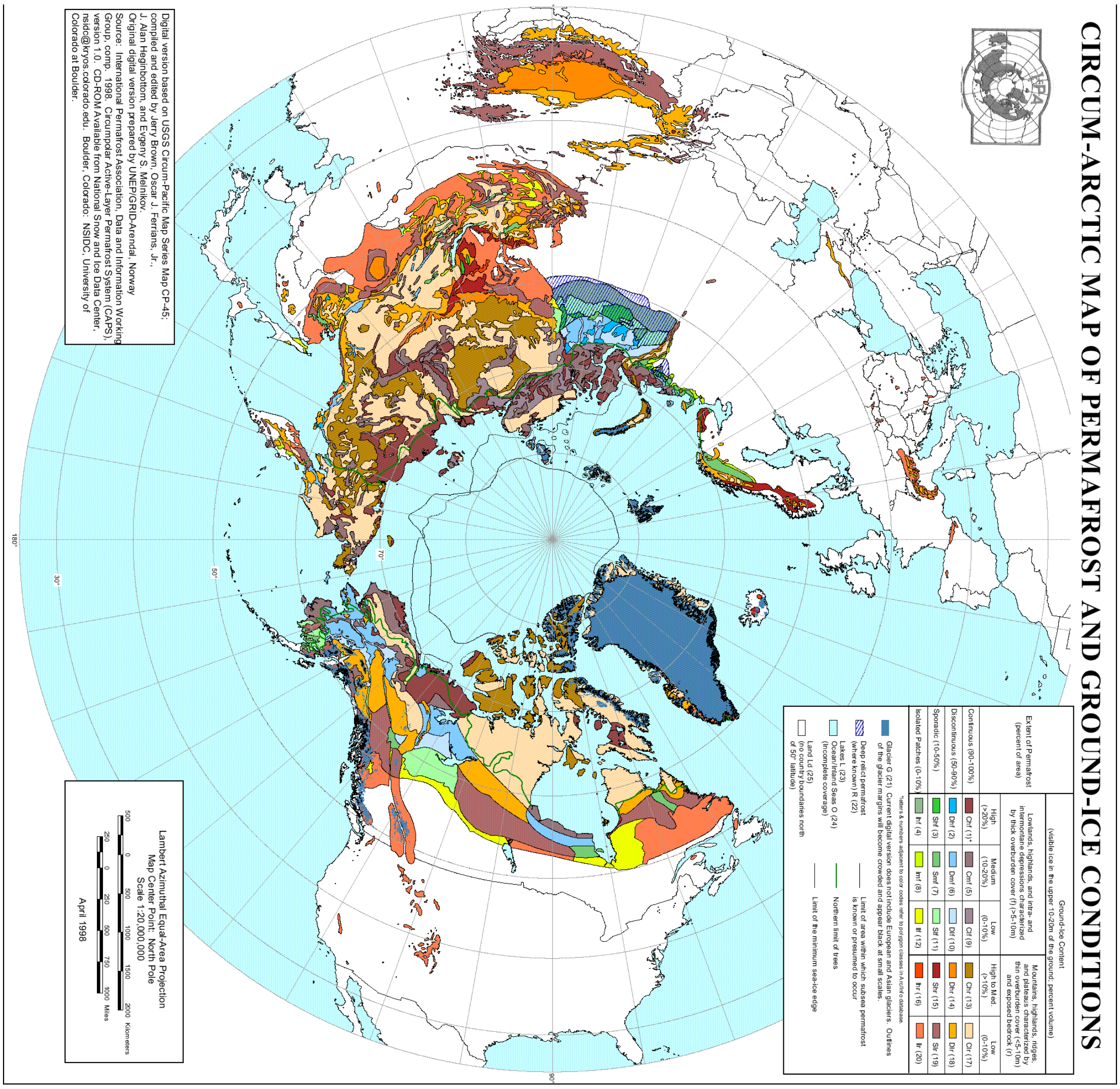

Fig. 16: Distribution of Permafrost in the northern Hemisphere. (http://nsidc.org/data/ggd318.html)

3.1 Permafrost Terminology

The most important terms related to permafrost are given in the schematic plot below (Noetzli & Gruber, 2005).

The active layer, which is prone to seasonal temperature variations, covers permafrost. As a result this layer thaws and freezes due to differences in air temperature. The typical thickness of this layer ranges from 0.5 – 8 m.

An increase in thickness of the active layer implies a decrease of seasonal temperature fluctuations. The temperature fluctuates less than 0.1 °C below the depth of zero annual temperature amplitude, (Gruber & Haeberli, 2009).

Below the active layer, the actual permafrost body is to be found. The seasonal temperature fluctuation is below 0.1 °C and it matches the ZAA – the depth of zero annual temperature amplitude. The permafrost table and the permafrost base are the markers of the permafrost body. Below the permafrost base, unfrozen bedrock or sediments occur.

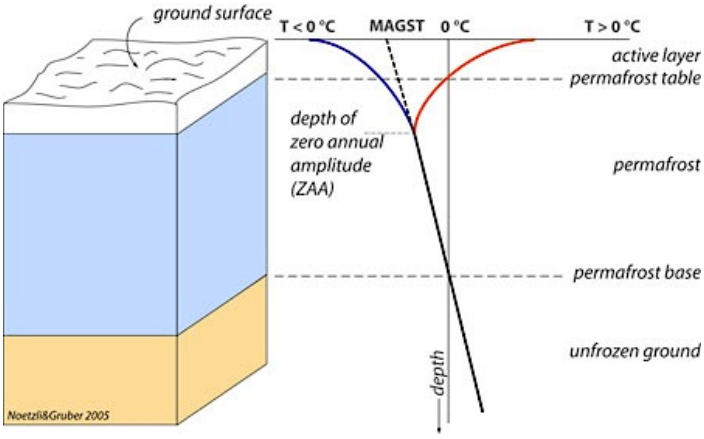

Fig.17: The most important terms related to permafrost. (Noetzli & Gruber, 2005)

3.2 Mapping of Permafrost

Mapping of permafrost can be a big challenge for scientists, as it is a thermal phenomena and therefore, mostly invisible. Active rock glaciers are crucial morphological features to detect permafrost activity.

Several methods can be used to attain information about the permafrost distribution.

Mapping methods can be placed into two different categories: Direct method and indirect methods. One direct method is borehole drilling accompanied by the installation of temperature loggers in the boreholes. This gives accurate information about the presence of permafrost through depth, however this method is quite expensive. As a result, most scientists use indirect methods to map permafrost.
Some indirect methods are listed below:

- Geophysical Measurements (Refraction Seismic, Ground Penetrating Radar, Electrical Resistivity)
- Bottom Temperature of Snow Cover (BTS)
- Mapping morphologic features and interpretation of aerial photographs
- Temperature of spring water (rock glaciers)

For achieving reliable results and interpretations, several indirect methods of data acquisition should be combined. Detailed information about mapping methods is given in chapter 7 applied methods.

4 Rock Glaciers

Active or inactive rock glaciers are a very common geological feature and generally a reliable indicator of mountain permafrost in the Alps.

The discovering history of rock glaciers goes back to the late 19th century. Steenstrup, a Danish scientist, described the phenomena of a rock glacier first as “dead glacier”, in his voyage to Disco Island, Greenland in 1883. He described dead glaciers as glaciers, which were buried under such a large mass of debris, that at first sight, they seem to be nothing but moraines.

Chaix (1919) was the first describing rock glaciers in the Alps (Engadin, Switzerland) followed by Solomon (1929), who introduced “Blockglätscher” into the German literature of rock glaciers.

In North America the term rock glacier was first introduced by Capps (1910), in his study in the Wrangell Mountains of Alaska.

Since then several studies on rock glaciers have been carried out all over the world and lead to a high variety of rock glacier nomenclature and classification schemes. (Barsch, 1996; Haeberli, 1985; Humlum, 2000; Wahrhaftig & Cox, 1959; Outcalt & Benedict, 1965).

4.1 Definitions of Rock Glaciers

Active rock glaciers can be described as tongue or lobate-shaped bodies, composed of debris and ice, which stand high above the adjacent terrain (> 20 m). Ridges and furrows mark the surface and are an expression of the downslope movement of the rock glacier. They are

several hundreds of meters long and move usually at a rate of 0,1 – 1 m/year. Preferred geographic directions of rock glaciers are NW, N, and NE in the northern hemisphere.
The upper part commonly shows longitudinal ridges and furrows; transverse ridges and furrows characterize the central and the frontal part. The slopes at the snout and on the side of a rock glacier are very steep exceeding the angle of repose, usually > 40°. Usually several springs are released from the rock glacier at its snout.

After Barsch (1996), rock glaciers can be seen as a two-layer phenomenon, the debris mantle and the frozen core. The debris mantle would therefore represent the active layer and the frozen core the permanently frozen body, respectively.

Barsch (1988) notes that: "Active rock glaciers are lobate or tongue-shaped bodies of perennially frozen unconsolidated material, supersaturated with interstitial ice and ice lenses that move downslope or down-valley by creep as a consequence of the deformation of ice contained in them and which are, thus, features of cohesive flow."

According to Haeberli (1985) "Active rock glaciers are the visible expression of steady-state creep of ice supersaturated mountain permafrost bodies in unconsolidated materials. They display the whole spectrum of forms created by cohesive flow."

Both definitions are process oriented and describe a creep of unconsolidated, ice-cemented material. When the volume of interstitial ice exceeds the volume of pore space of unfrozen debris, supersaturated ice is formed.

By this definition rock glaciers move downslope due to the creep of frozen, unconsolidated material; however, this theory was not always accepted. Scientists in the early years of rock glacier investigation have assumed that a rock glacier is a result of a sudden landslide (Howe, 1909) or a rock stream (Cross & Howe, 1905).

4.2 Debris Cover of Rock Glaciers

Coarse debris of angular rock fragments forms the surface of a rock glacier. Transverse and longitudinal ridges and furrows characterize the surface topography with a relief up to several meters. In the frontal part, ridges and furrows are typically oriented perpendicular to the flow direction of the rock glacier. The rock glacier mantle, a two-layer structure of distinctive grain size, covers the core of the rock glacier, which displays the permafrost body. The rough rock glacier surface ends in a steeply dipping frontal and side slope, exposing the two-layer structure of the rock glacier mantle. The upper layer with coarse boulders is underlain by a fine-grained, often frozen sediment body. The core mantle structure is depicted in figure 18.

The debris mantle of the rock glacier is usually 2 to 5 m thick and displays a mixture of gravels and boulders. Grain sizes may range from 0.6 m up to several meters (Barsch, 1996). The fine-grained part of the mantle displays mostly 60% sand and about 30% silt, which is classified as silty sand, after Barsch et al. (1979).

4.3 Rock Glacier Dynamics

The dynamics of a rock glacier can be arranged within four distinctive zones: root zone, the zone of longitudinal extension, the zone of longitudinal compression, and the front zone.

The movement of a rock glacier is based on the deformation of the internal ice. Albeit, in some cases basal sliding by melting of the permafrost base may take part of the movement of a rock glacier too (Haeberli et al., 1998).
The arrow in the sketch below indicates the direction of the permafrost creep.

The root zone is the source area of the rock glacier. The rock walls and cliffs supply debris produced by frost weathering. Longitudinal furrows in the zone of extension and transverse ridges in the compressional zone are typical elements on the surface of a rock glacier. A decrease in slope gradient often leads to a compression and hence to the development of the furrow and ridge topography, (Haeberli, 1998). According to Fukui et al. (2008), thrust movements along internal shear planes cause the ridges and furrows topography. In his work on a polar rock glacier on James Ross Island, Antarctica, he found out through a Ground

Penetration Radar profile, that internal ice layers, interbedded with debris, run towards the transverse ridges.

The compressional zone terminates with a sharp edge, where a steep plunging slope marks the rock glacier front.

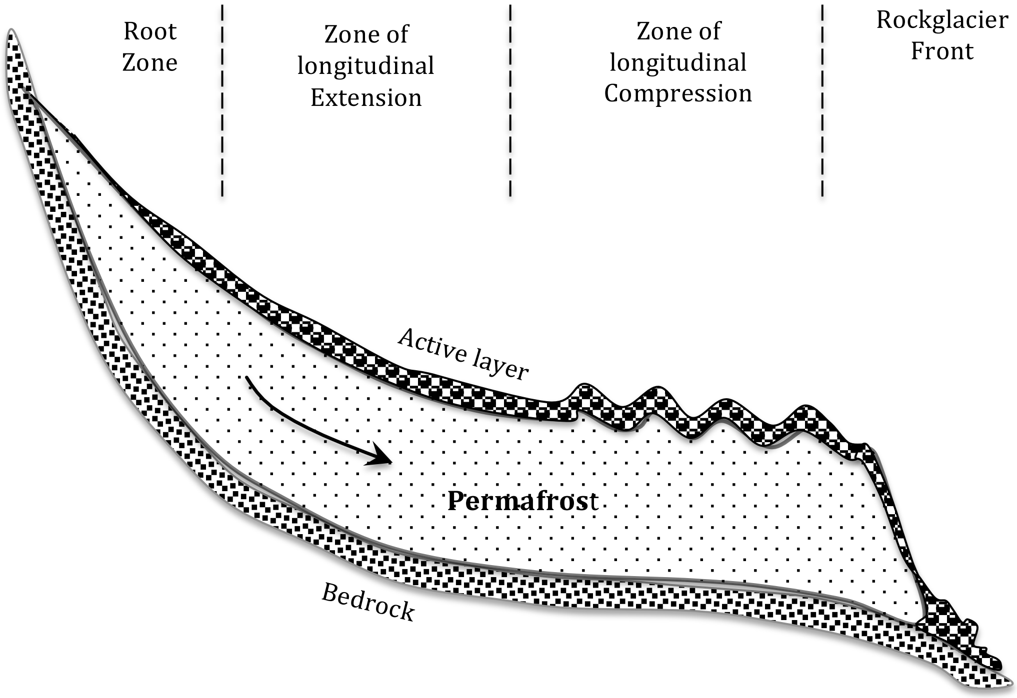

Fig. 18: Dynamics of rock glaciers, modified after Haeberli (1998).

4.4 Classification

Rock glaciers may have different morphologies (tongue shaped, lobate and complex); they occur in every topographic position (cirques and below cliffs), in every altitude and latitude, and may develop form every rock type or lithology. They are ice-cemented or ice –cored, may consist of moraine material (till) or debris from rock cliffs, and may be of glacial or non-glacial origin. Some scientists use the definition of a rock glacier as a descriptive term, whereas others tend to use the term as a formation of process: Humlum (2000), White (1971), Potter (1972), and Barsch (1988).

This has lead to a high variety in classification systems and hence made it quite difficult and sometimes controversial. The diverse classification system of rock glaciers can be arranged by the following criteria, modified after Hamilton (1995):

- Morphology: lobate, tongue-shaped, and spatulate rock glaciers
  Wahrhaftig & Cox (1959)
- Dynamics: active, inactive and fossil Rock glacier (intact, relict)
  Wahrhaftig and Cox (1959), Haeberli (1985)
- Genetics and process of formation:
  - Talus derived and glacier derived rock glacier; Humlum (2000)
  - Ice -cored and ice cemented; White (1971), Potter (1972)
  - Periglacial process: talus and debris rock glacier; Barsch (1988)
  - Glacial process: debris - covered glacier; Clark et al. (1994), Shroder et al. (2000)

4.5 Morphology

The classification of rock glaciers by Wahrhaftig & Cox (1959) is based on the shape of a rock glacier: lobate, tongue-shaped, and spatulate form.
The shape is defined by the length to width ratio (l: w).

- Lobate form: l:w < 1
- Tongue-shaped form: l:w > 1
- Spatulate form: tongue shaped with a broader lower part.

Figure 19 shows a combination of two classifications, the morphological proposed by Wahrhaftig and Cox (1959) and the topographical position introduced by Outcalt and Benedict (1965). The classification based on the topographic position after Outcalt and Benedict (1965) distinguishes two kinds of rock glaciers: valley wall and valley floor rock glaciers. The morphological classification shows three geometrical types of rock glaciers: lobate rock glaciers, piedmont or spatulate rock glaciers, and tongue shaped rock glaciers.
A protalus lobe, which is located at the valley wall may develop into a lobate rock glacier; rock glacier out of a cirque may develop into a piedmont/spatulate shape or into a tongue shaped rock glacier, and move onto the valley floor.

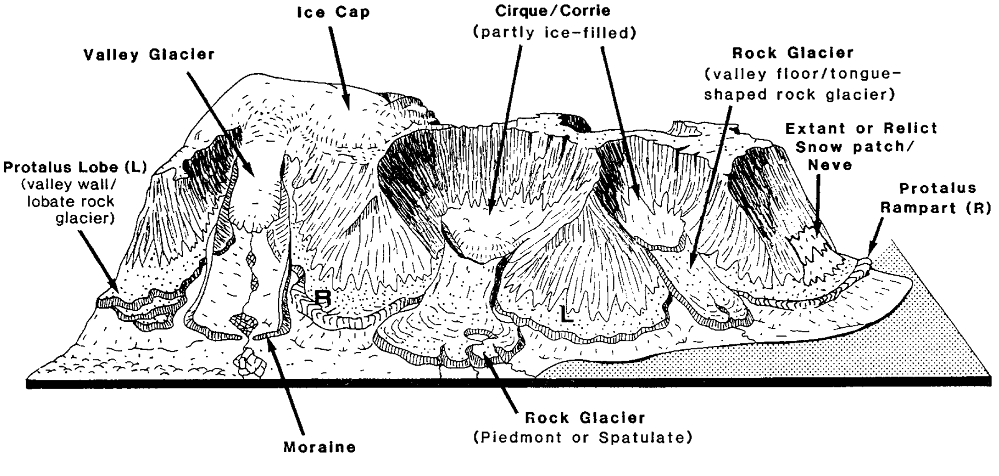

Fig. 19: The ice debris assemblage classification related to topographic form: L – Protalus Lobe; R- Protalus rampart. (Wahrhaftig & Cox, 1959; modified after Humlum, 1982).

4.6 *State of Activity*

Based on the activity of a rock glacier, Haeberli (1985) introduced the following classification. Three different states of activity can be observed: active, inactive and fossil. An active rock glacier by definition moves at a typical velocity of 0.1 – 1 m/year, whereas the inactive rock glacier does not show any movement, but still contains ice. No ice can be encountered at fossil rock glaciers.
The left figure below shows on the left hand side the active rock glaciers in Vesul Valley (Samnaun Mountain Range, Tyrol) and the right image shows the typical appearance of a fossil rock glacier, which is partly covered by vegetation.

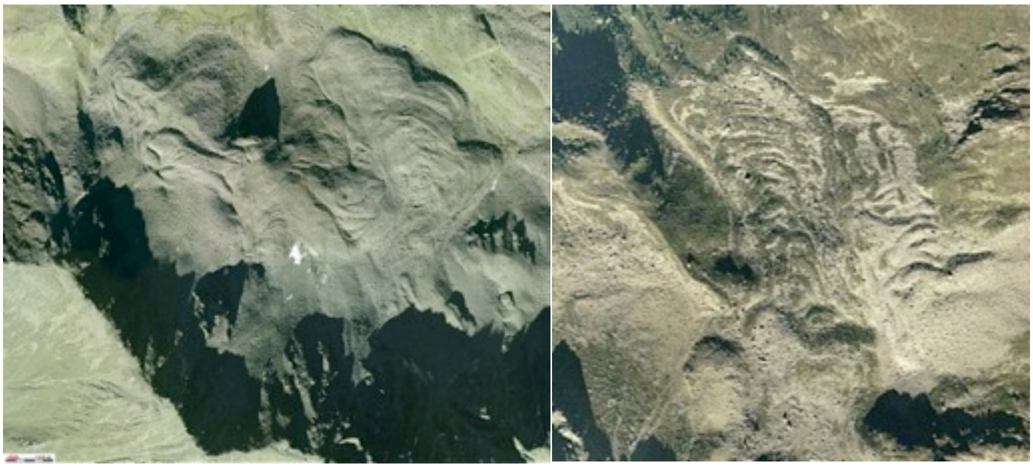

Fig. 20 + 21: Active Rock glacier in Vesul Valley and fossil Rock glacier at Thialkopf (www.tirol.gv.at/tiris).

The fossil/relict state implies no ice content, a well-developed relief with collapse structures. They can be observed as ridges and furrows. By observing the vegetation, the activity state between active and fossil rock glaciers may easily be identified. While fossil rock glaciers are mostly vegetated, active ones do not show any vegetation; particularly the steep frontal slope is bare of vegetation.

Commonly the slope of an active rock glacier is steeper than that of the inactive or fossil ones. It may even exceed its angle of repose, generally > 40°. In contrast, inactive and fossil rock glaciers have a smoother frontal angle of slope. The determination of the activity state of rock glaciers may sometimes be difficult to detect.

4.7 Genetics/Process of Formation

The origin of a rock glacier is extremely controversial, as the internal structure is not well understood and difficult to investigate.

On figure 18 below, the evolution of rock glaciers can be divided in two models: the glacier- and talus-derived models, after Humlum (2000). The glacier-derived model implies a glacial process (Shroder et al., 2000), whereas the talus-derived corresponds to a periglacial processes.

While Barsch (1996) proposes that rock glaciers are composed of two layers, Humlum (2000) distinguishes three different layers on both models: the 1-3 m thick top layer with coarse rock fragments, the ice rich permanently frozen core, and a basal unfrozen unit. This layer consists of debris that is deposited in the apron of the active rock glacier and is instantly overrun by the two uppermost layers. The uppermost active layer is given as thick black line in the figure below.

4.7.1 Glacier-Derived Model (Humlum, 2000)

The rooting zone of a glacier derived rock glacier is located in a cirque, wherefrom the rock glacier flows out onto the valley floor. Thereby the overridden scree of glacial till and debris may deform due to basal shear stress that may occur. Debris supply of the rock glacier is given by frost activity and dirty snow avalanches of the sidewalls, as well as by supra-glacial debris transport. The debris cover or active layer ranges from 1-3 m. The internal part of the glacier derived rock glacier is made up by a core of solid ice.

4.7.2 Talus-Derived Model (Humlum, 2000)

This rock glacier type develops out of a talus fan/slope with a high content of debris supply from the rock walls. Due to deformation of ice, the frozen core flows from the foot of a talus sheet downslope, while overriding the frontal scree.

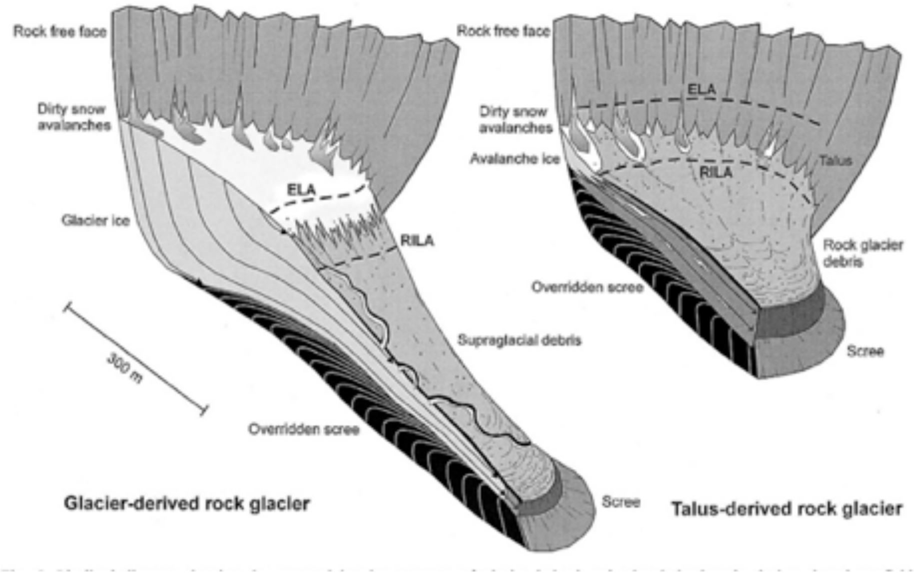

Fig. 22: Idealized diagram showing the internal structure of glacier-derived and talus-derived Rock glaciers (Humlum, 2000). The rock glacier initiation line altitude (RILA) indicates the altitude at which rock glaciers creep out from the slope down. The top active layer is matched as thick black line, the permanently frozen core is shown in greyish colors and the black unit corresponds to the lowermost layer. The dashed black line indicates the rock glacier initiation line altitude, the altitude at which rock glacier creep out from the slope above.

The rock glacier classification proposed by Potter (1972) includes ice-cemented and ice-cored rock glaciers. Ice-cemented rock glaciers form due to periglacial processes. The flow of the talus with interstitial ice can occur if climate requirements are given. The ice-cored rock glaciers on the other hand, develop from debris-covered cirque glaciers.

Barsch (1988) introduced two different kinds of rock glacier, the talus and the debris rock glacier. The talus-derived rock glacier comprises of debris from rock walls and cliffs; on the contrary, the debris rock glacier consists of moraine till sediments and is located adjacent to a glacier.

A very different approach to explain rock glacier formation is given by Clark et.al. (1994). Glaciers can turn into rock glaciers due to a single event (rockfall), high talus production under climatic conditions with high radiation.

While the periglacial processes correspond to the talus derived models, the glacial processes stick to the glacial derived models. The talus-derived rock glaciers after Barsch (1996) and Humlum (2000) are described as ice-cemented rock glaciers after Potter (1972). Conversely the glacier derived rock glaciers after Clark et al. (1994) and Humlum (2000) are equivalent to ice-cored rock glaciers after Potter (1972).

As a result of the combination of all models of rock glacier origins, the classification as suggested by Humlum (2000) has been applied in my study area.
Given these different ways of describing rock glacier origins, it is still a subject of debate.

4.8 Thermokarst - Lakes

Thermokarst lakes are quite common features on the surface of a glacier-derived rock glacier. By definition a thermokarst-lake is a result of the thawing of ice rich permafrost or massive ice (French, 1976; Washburn, 1980; Van Everdingen, 1998). Usually they form in small depressions or in areas, where clear ice is exposed and surrounded with debris. The water ponds enlarge due to ongoing thawing of ice beneath. As the water in these depressions is trapped above the permafrost body, no percolation with subsurface water flow is occurs.

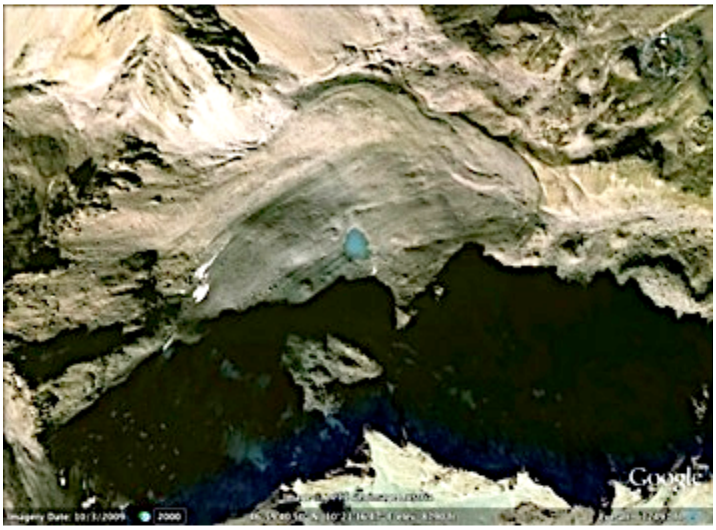

Fig. 23: Thermokarst lake on Buerkelkopf rock glacier – Paznaun Valley. (Google Earth Imagery)

4.9 Hydrology of Rock Glaciers

Research on hydrology of a rock glacier is very rare. Based on the work of Krainer & Mostler (2002), water is released from a rock glacier is either as a surface or a subsurface stream. The discharge of single or multiple springs in front of the rock glacier snout is mostly characterized by daily and strong seasonal variations. Water discharge is highest during spring and early summer and continuously decreases towards late fall, interrupted by single flood events caused by rainfall events.

Increase in discharge causes decrease in electrical conductivity. The water temperature of the rock glacier springs remains <1°C during the entire melt season until late fall. The water

temperatures from inactive rock glacier range from 1 – 3 °C, and indicate that ice is present in the rock glacier's interior (Krainer & Mostler, 2002).
Interestingly some of rock glacier springs in the Tyrolean Alps show high concentrations of heavy metals. The concentration for Ni in springs of the "Lazaun rock glacier" in South Tyrol (northern Italy) exceeds the upper limit for drinking water several times.

The source of Ni is still unknown; rock analyses of the bedrock in the catchment area did not yield higher Ni concentrations. It seems that the Ni is released from the ice of the rock glacier. Further research in the water chemistry of a rock glacier is therefore needed.

5 Investigated Rock Glaciers (RG)

All rock glaciers investigated lie in the westernmost part of the Samnaun mountain group. This part consists of northwards-trending ridges. The highest peaks in this area are Vesulspitze (3089 m) and the Buerkelkopf (3033 m).
Table 1 lists the investigated rock glaciers with their UTM coordinates, 5 of the total investigated rock glaciers are considered to be active.
Laserscan maps (www.tirol.org/tiris), which cover my study area, were used to create an ArcGIS map. The map shows the distribution of rock glaciers using a scale of 1:25.000. Investigated rock glaciers are indicated on the map with the presence of red stars. The map is enclosed in the chapter attachments.

Name of Rock Glacier	UTM Coordinates Zone 32T	
	E	N
Vesul 2	602766	5206935
Bürkelkopf	602984	5205570
Visnitz	603914	5205442
Visnitz fossil	604449	5206622
Idalp	601877	5204364
Vesul 1	602428	5206962

Table 1: UTM Coordinates of the investigated rock glaciers.

5.1 Rock Glacier Buerkelkopf

This rock glacier is located at in the end of the Visnitz Valley in a small cirque at the foot of the mountain “Buerkelkopf”. A small glacier occupied this cirque, probably since the little ice age until 1950. The map in figure 27 shows the glacier as it was in the year 1950.

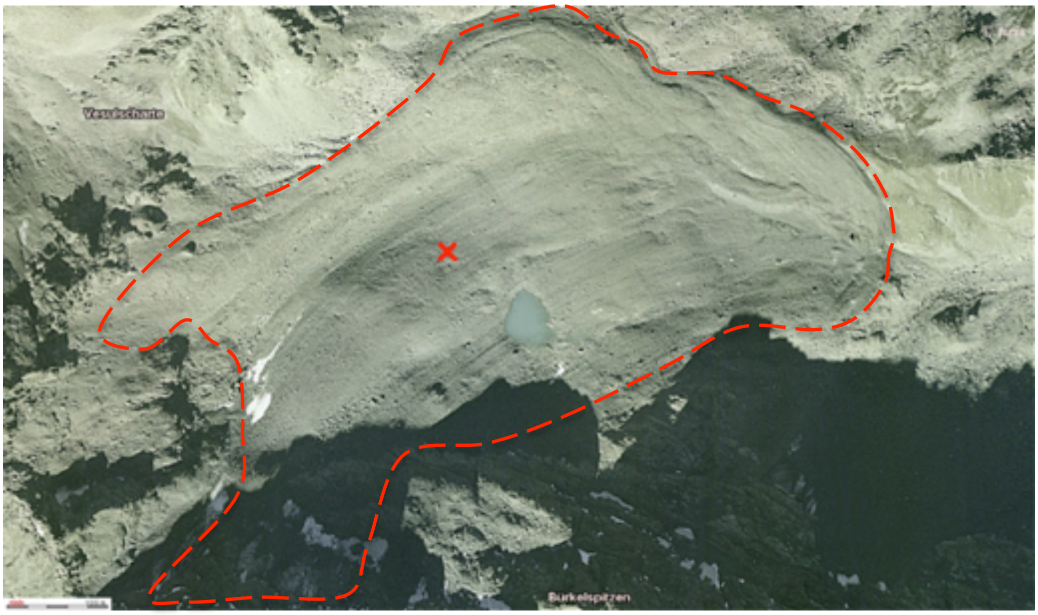

Fig. 24: Aerial photograph of the RG Buerkelkopf North of the Buerkelspitzen (www.tirol.gv.at/tiris).

This tongue shaped rock glacier has a length of 780 m, a width of about 400 m and an average thickness of about 20 m. A smooth surface with very poorly sorted angular debris is characteristic for it. The flow direction of the rock glacier is eastwards, and a few longitudinal ridges are located on the northern part. An outstanding feature on this rock glacier is the thermocarst-lake with a diameter of 60 m.

Fig. 25: Thermokarst-lake on rock glacier Buerkelkopf.

The rock glacier is supplied by debris from is the Buerkelkopf and the Vesulspitze. The debris derives from two predominant zones, the SCC and Penninic zone. Paragneiss, micaschists, gabbro, limestones, and sericite schists cover the rock glacier's surface.

The front reaches an altitude of 2610 m and the average altitude can be settled at 2700 m, hence the root area is at about 2790 m.
The dip of the frontal slope is about 30°. The frontal slope exposes the upper coarse-grained mantle and the fine and frozen debris of the interior.
Generally this rock glacier is fine grained, and shows a decrease in grain size from the front area to root area. About 90 % of the debris covering the rock glacier is < 30 cm, however the inner part is characterized by sandy gravel, with a mean composition of 59 % gravel, 29 % sand, and 12 % silt and clay.

The following measurements are carried out on this rock glacier:

- sieve analysis (2 samples)
- grain size analysis (root, center, and front) on the surface
- water analysis (thermokarst-lake & springs) of springs released from the rg

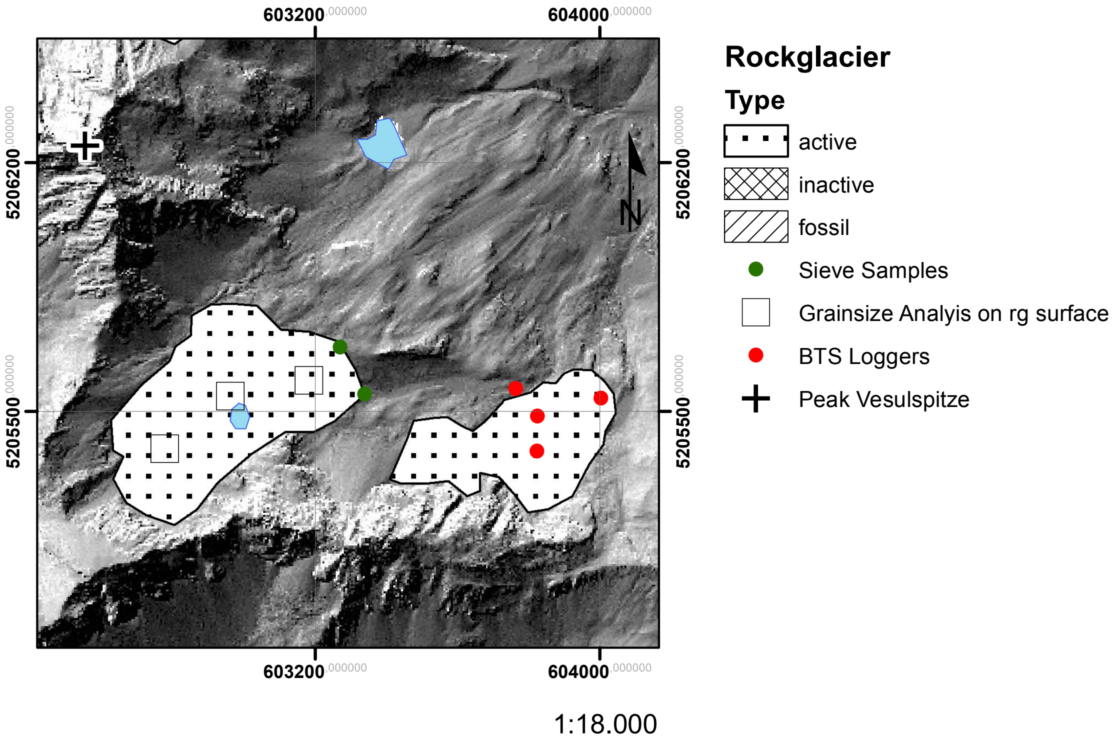

Fig. 26: Rg Buerkelkopf (left) and rg Visnitz (right) with locations of various measurements, which were carried out.

All results of the measurements are presented in chapter 7 (Applied Methods).

5.2 Rock Glacier Visnitz

The lobate shaped rock glacier Visnitz is situated adjacent to the rock glacier Buerkelkopf. It lies below the “Buerkelspitzen”, an ophiolitic rock cliff matching the border to Switzerland.
The rock glacier has two distinctive lobes, one extending down to 2480 m and the smaller one to 2600 m above sea level. The rooting zone lies at 2660 m. The maximum length of this rock glacier is about 390 m and its width about 520 m.

The rock glacier is very coarse grained and boulders as big as houses are quite common. Several transverse ridges and furrows can be found in the central and frontal regions.
Debris of both geological units, the Austroalpine and the Penninic zones, are found in the inner lobe of the rock glacier, whereas the outer lobe only comprises debris derived from the Penninic zone (gabbro). The steep front of rg Visnitz is prominent and shows angles of 45 – 50° at the inner lobe and 40 - 45° at the outer lobe.
Several springs are released at the outer part of the rock glacier, although a subsurface flow is noticeable at the front of the inner lobe.
The following measurements were carried out on this rock glacier:

- 3 BTS loggers
- water analysis of springs released from the rg

Fig 22 shows the locations of the measurements. All results of the measurements are given in chapter 7 applied measurements.

5.2.1 Aerial photograph documentation of Rock glacier Visnitz and Buerkelkopf

By means of historical aerial photographs the glacier history can be observed.
Several historical aerial photos are provided by the government of Tyrol and are available online at the following link: www.tirol.gv.at/tiris

The following aerial photograph documentation of the rock glaciers Buerkelkopf and Visnitz compares the images of the rock glaciers from the years 1950/1954, 2002 and 2010. In the oldest aerial photograph the cirque glacier at the Buerkelkopf is still present, but almost gone. At the bottom of the glacier, a rock glacier has already developed. While in 1950/1954 a small glacier was still evident at Buerkelkopf, however the following two aerial photos show a constant retreat of the glacier. On the contrary the rock glacier Visnitz does not show a remarkable change. On the oldest photograph, ice fields are visible in the rooting area, however in both younger photos this feature is gone. As shown by these images, no remarkable movement of both rock glaciers is visible. The existence of the rock glacier Buerkelkopf is documented since the recording of 1950/1954.

Fig.27: Aerial photograph of the year 1950/1954.

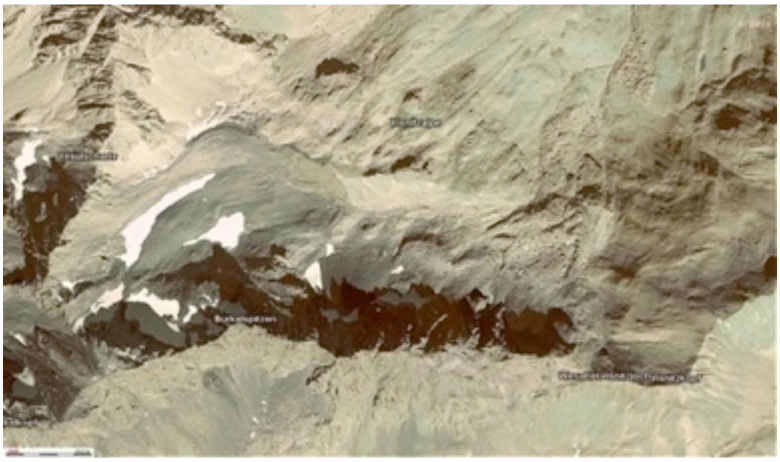

Fig.28: Aerial photograph of 2002.

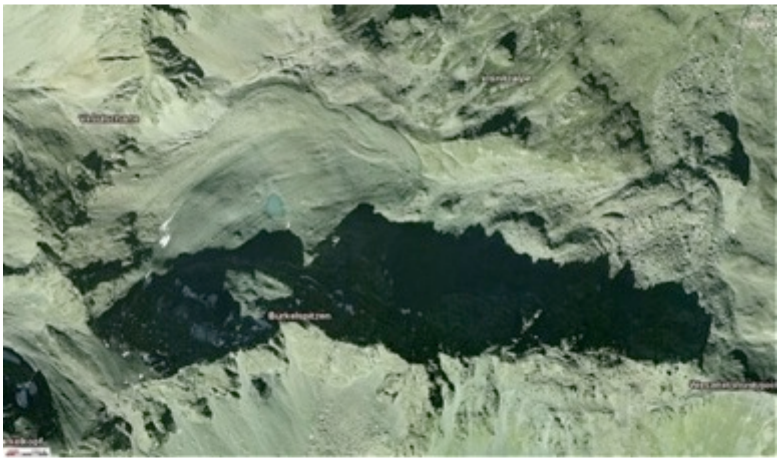

Fig.29: Aerial photograph of 2010.

5.3 Rock Glacier Vesul 1

With a length of 800 m and a width of 570 m, rock glacier Vesul 1 is the longest active rock glacier in the Samnaun Mountain Group. Rock glacier Vesul is located in a small cirque at the northern foot of the Vesulspitze (3089 m). The aerial photo, figure 30 shows the location of the rock glacier outlined by a red dashed line.

Fig 30: Aerial photograph of rock glacier Vesul 1 outlined by a red dashed line.

The debris supply is given by the mountain Vesulspitze, which is mostly comprised of rocks of the Silvretta crystalline Complex. Very few blocks can be found from the Penninic zone. The rock glacier is tongue shaped and has several lobes. Several longitudinal and transverse ridges mark the surface of this rock glacier. In the central part a small thermokarst lake can be found. The thickness of this rock glacier is greater than 40 m. The root area is located at an elevation of 2760 m and the maximum extent of the rock glacier lies at an elevation of 2440 m. The grain size of the outer mantle varies from several cm to > 1 m and is generally decreasing from the root zone to the frontal zone. The inner fine-grained zone comprises on average about 70 % gravel, 25 % sand and 5 % silt and clay.

Fig.31: Frontal part of rock glacier Vesul 1, with Vesulspitze in the background.

The frontal and side slope is very steep with gradients varying from 35° to 45°.

Fig.32: Frontal slope of the rock glacier Vesul 1.

Several springs released from the rock glacier show temperatures below 1° C.
Two ice outcrops could have been observed on this rock glacier.
In July 2009 the root zone exposed clear ice as the debris cover slipped down. Figure 33 shows the root zone of the rock glacier in 2009 and 2010. Another ice outcrop was displayed in the following year 2010. A debris covered massive ice layer or ice core was observed in the upper center portion of the rock glacier.

Fig.33: Root Zone with ice exposure on rock glacier Vesul 1 in 2009, indicated by a red rectangle.

Fig.34: Rock glacier surface with a small thermokarst-lake and root zone in 2010.

Fig.: 35 + 36: Both pictures show debris-covered ice. By removing the debris, clear ice is visible.

Figures 35 and 36 shows an ice layer of an uncertain thickness, but at minimum, it must be greater than 3 m. A 20 cm thick debris layer covers the ice.
A decreasing grain size from surface to ice layer shows the following range: boulders, coarse to medium gravel, fine-grained gravel, and sand.

Applied measurements and their distribution on the rock glacier are indicated in the ArcGIS map below:

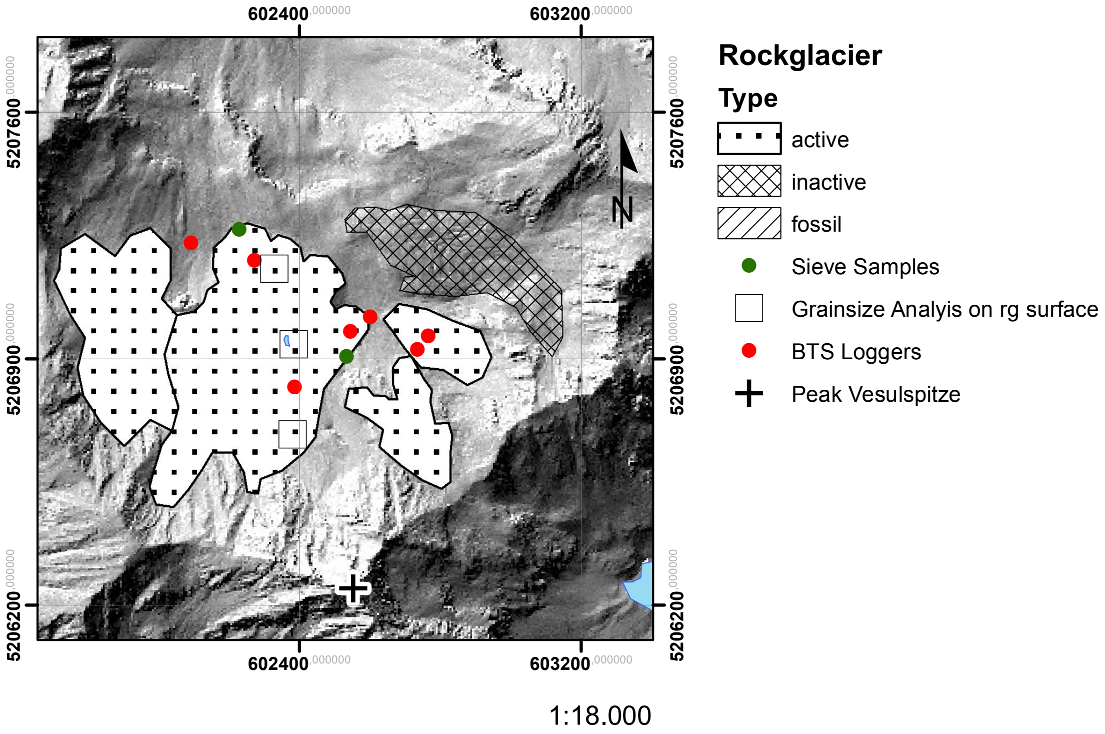

Fig. 37: Measurements on rg Vesul 1 and 2.

5.4 Rock Glacier Vesul 2

This tongue-shaped rock glacier is located east of the big rock glacier Vesul 1 with a length of 350 m, and a width of 153 m. It flows down from the rock walls at the orographic right valley side. Thereby it overruns an altitude of 140 m, with an elevation of 2660 m at the rooting zone. This rock glacier is composed of debris of the Silvretta Crystalline Complex and shows a similar grain size distribution as rock glacier Vesul 1.

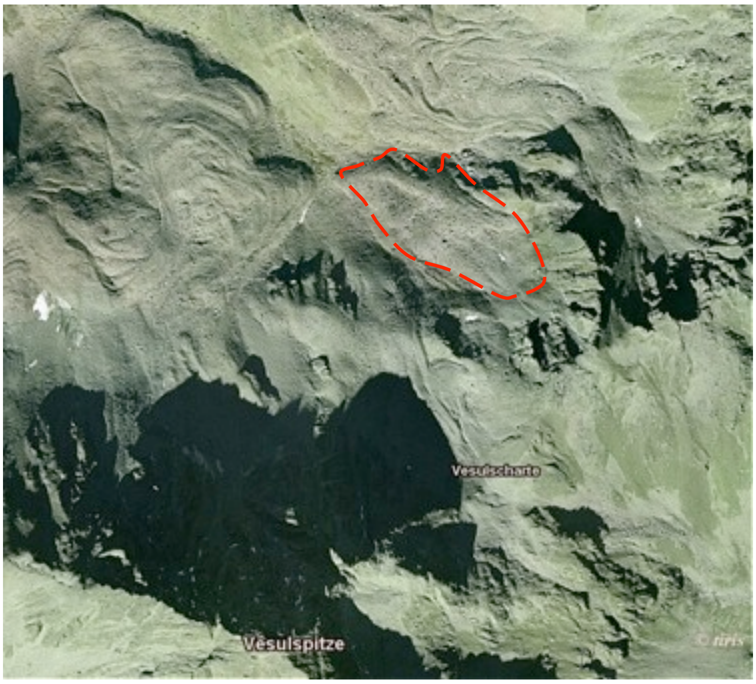

Fig.38: Aerial photo of rock glacier Vesul 2 outlined by a red dashed line.

Two BTS loggers have been installed on this rock glacier, indicated in figure 34.

5.4.1 Aerial photo documentation of Rock Glaciers in the Vesul-Cirque

Two aerial photographs of the cirque Vesul are shown in the figures below; the first one was taken in the time frame of 1950 to 1954, while the second shows the current extent. Significant differences are easily noticed between the images.

Snow and ice fields are covering the talus slopes of the Vesulspitze in the older aerial photographs, while the modern air photo does not show any evidence of ice or snow. A thermokarst lake is situated in the center of the rock glacier Vesul in the upper photograph. This surface feature is absent in the lower picture, however field observations in the year 2010 have shown a very small meltwater pond at the same location. Rock glacier Vesul 2 does not show any change in morphology or extent.

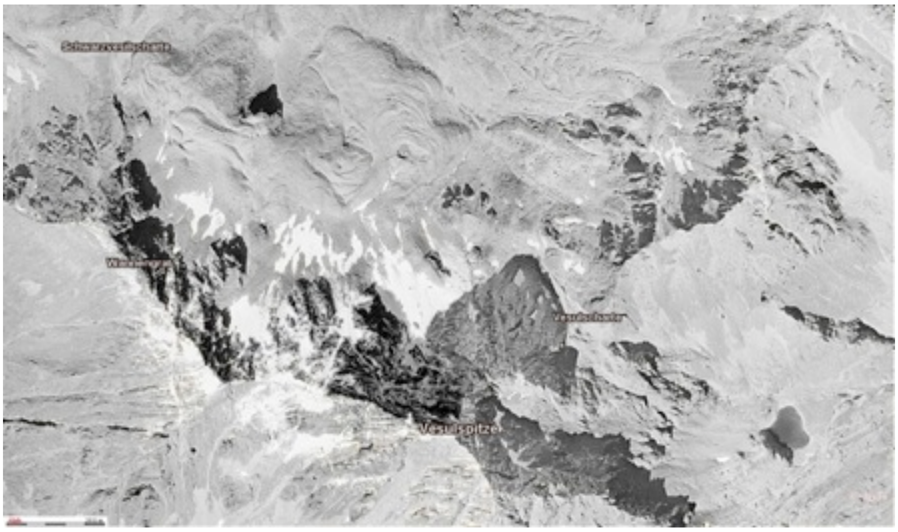

Fig.39: Aerial photograph of 1950/1954 of the rock glacier Vesul 1 and Vesul 2. (www.tirol.gv.at/tiris)

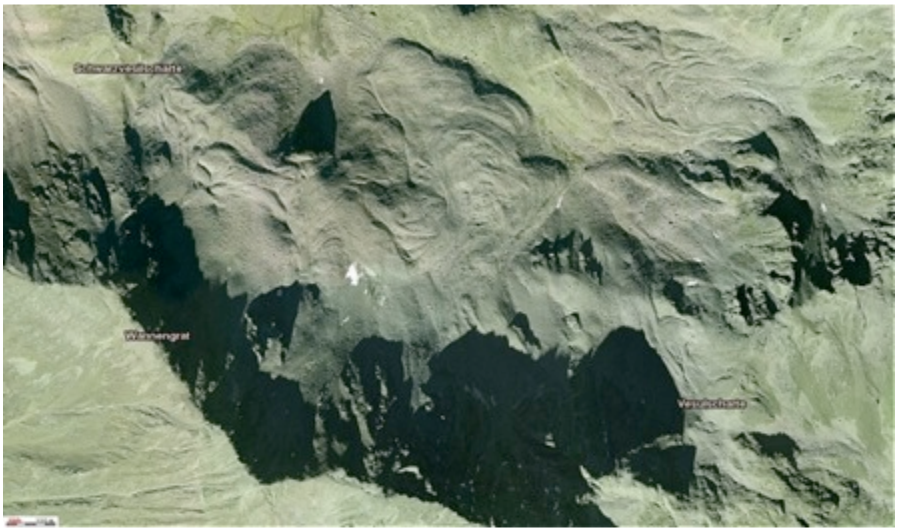

Fig.40: Aerial photograph of rock glacier Vesul 1, and Vesul 2 (www.tirol.gv.at/tiris).

5.5 Rock Glacier Idalp

This rock glacier is situated in a small cirque at the bottom of the mountain Flimspitze. Two rock glaciers can be distinguished; a very small one with a length of 220 m and a big one with a length of 500 m. Both rock glaciers share the same rooting zone located at an elevation of 2740 m. The thickness of the rock glacier is about 40 m with a frontal slope inclination of > 40 °.

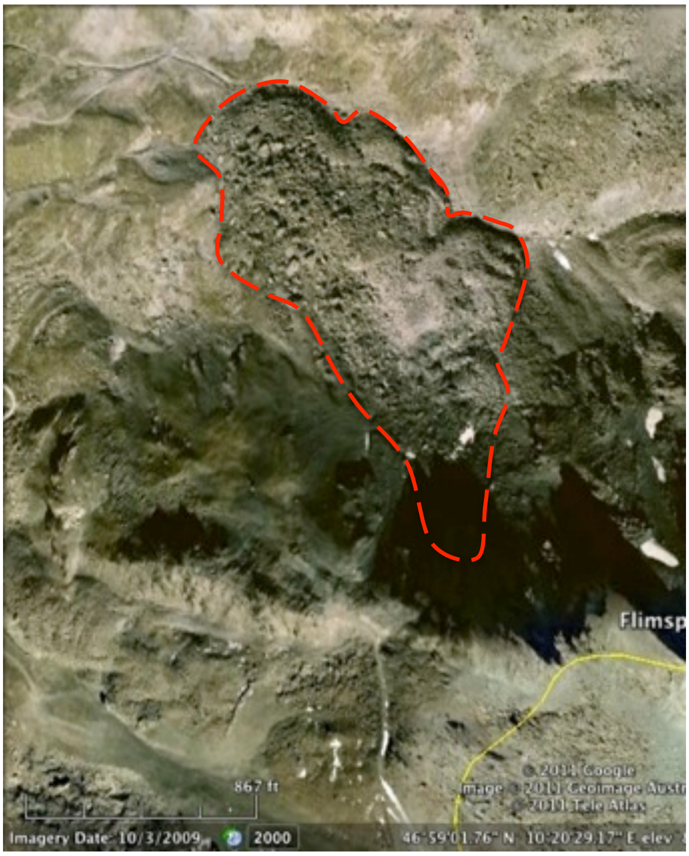

Fig.41: Aerial photograph of Idalp rock glacier (Google.Earth.Imagery).

This rock glacier was chosen for geophysical investigation, because of its accessibility, making it easier to gather geophysical measurements.

The following method were used:

- Refraction Seismic

Furthermore, the water temperature and conductivity of the water in the springs released from the rock glacier, were measured and recorded.