Active Rock Glaciers near the Franz-Senn Hütte
(Oberberg Valley, Stubai Alps, Austria)

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Institute for Geology and Paleontology
of the Leopold-Franzens-University Innsbruck

Master thesis in the major of Earth Sciences

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Innsbruck, September 2011
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APPENDIX
Geological map
1. Introduction

1.1. Introduction and assignment of tasks

In context of this master thesis an area in the Stubai Alps (a side valley of the Stubai Valley in Tyrol/ Austria) was investigated from summer 2009 until fall 2011. The main goal of this thesis was to characterize and describe the morphology and to study the dynamics of rock glaciers and the geology of their catchment area. The investigations of this thesis were focused on grain size analysis of the debris layer, the thermal regime of the debris layer (particularly the temperature at the base of the winter snow cover – BTS), the hydrological regime and the dynamics of active rock glaciers. Additionally other quaternary phenomena, like moraines and solifluction lobes, will be discussed and described in particular.

A main issue was the compilation of a geological and geomorphological map of the study area. The data of this thesis will be compared to published results of other rock glaciers in the eastern Alps, particularly the Ötztal/ Stubai Alps.

In summer 2010 an international core drilling project in South Tyrol / northern Italy was carried out to study the internal structures and in particular the ice content of two active rock glaciers. The documentation and conclusions of the drilling will be explained and compared with the rock glaciers in the study area.

In the study area remains of the Little Ice Age (between 15th and 19th century) are observed and there are also many indications of late glacial variations such as lateral moraines, rock drumlins, glacial striations, cirques and cirque lakes and at least rock glaciers.

In general, rock glaciers can be described as tongue- to lobate-shaped bodies, consisting of frozen debris, which is derived from frost weathering or moraine material and contain ice in form of cement, lenses or ice bodies. They are slowly creeping down slopes as a result of internal deformation of the frozen core. Basal gliding is also estimated to be an important factor for the movement of active rock glaciers. Rock glaciers are an eye catching and common phenomena in high mountain areas and they are spread in the Central Alps from an altitude of about 2500 meters. According to Haeberli (1985, 1990) and Barsch (1996) rock glaciers are
defined as pure permafrost phenomena, but they are also suggested to develop from debris-covered cirque glaciers (Outcalt and Benedict 1965; White 1971; Potter 1972; White 1976; Johnson and Lacasse 1988; Whalley and Martin 1992; Clark et al. 1994; Whalley et al. 1994; Humlum 1996; Ackert 1998; Potter et al. 1998; Whalley and Palmer 1998; Shroder et al. 2000). Rock glaciers of the western Alps were studied intensively, whereas only few rock glaciers of the eastern Alps were examined in detail.

1.2. Importance of local and global permafrost

Permafrost is defined as perennially frozen ground which remains frozen at least for two consecutive years at or below 0°C (32° Fahrenheit) and it occurs normally in regions, where the mean annual temperature does not increase over 0°C. Permafrost is mainly present on the Arctic and Antarctic continental shelves and also covers approximately 22% of the land of the northern hemisphere. The distribution of permafrost is restricted to high latitudes, and in high altitudes in the form of mountain permafrost (Harris, 1988).

In general permafrost can be regionally divided into two main types (Fig. 1.1 and Fig. 1.2):

a) Continuous permafrost in higher latitudes (Arctic and Antarctic), which is extensive and can be hundreds of meters thick. Permafrost in Polar Regions is thousands of years old. In case of continuous permafrost in all localities, except locally thawed zones or taliks, is present. About 90% of the permafrost appearance in the northern hemisphere occurs in form of discontinuous permafrost.

b) Another type of permafrost occurs in areas of high elevations in lower latitudes, which is discontinuous, less thick (commonly tens of meters) and appears patchy. This means, that the permafrost-bodies are separated and isolated by unfrozen ground. This type is called alpine or mountain permafrost and exists all over the world and typically occurs beneath peaty, organic sediments (French, 2007).
Fig. 1.1 The permafrost distribution in the northern hemisphere (taken from Pêwè, 1975)

Fig. 1.2 Distribution of permafrost areas referring to the latitude. The solid line represents variations of the permafrost area; the short-dashed line displays the fraction of the land surface, and the long-
The thickness of permafrost is controlled by the snow cover, vegetation, water supply, geothermal heat and the air temperature. The uppermost layer of perennially frozen ground is called the “active layer”. This layer usually thaws during summer and freezes during winter, whereas the permafrost body beneath this layer remains frozen. The thickness of the active layer typically varies from year to year and especially in discontinuous permafrost it often does not reach the uppermost part of the permafrost body, the permafrost table. This can happen, when permafrost is relict and a residual thaw layer (thawed, and non-cryotic layer of the ground) divides the active layer from the permafrost.

In areas of unfrozen zones the seasonal frost often does not reach the permafrost table and zones of unfrozen soil inside the permafrost body can occur. This phenomenon is called “talik” (Fig. 1.3) and appears between the bottom of seasonal frost and the permafrost table and also within and below permafrost (French, 2007).

![Fig. 1.3 Relationship between permafrost, the permafrost table, the active layer and supra-, intra- and subpermafrost taliks (modified from Ferrians et al., 1969)]
The lower limit of the permafrost body is controlled by the heat of the Earth’s interior and the thickness is determined by the relationship between the internal heat and the loss of heat from the surface. The internal heat increases with the depth (Lachenbruch, 1968) with 1°C per 30 to 60m. Thus, the thickness of the permafrost body decreases with an increase of the mean annual temperature (MAAT) on the surface and vice versa (French, 2007). For example, it may be less than 30cm thick in cold areas like the polar belt, whereas in high mountain areas the thickness is mostly between 0.5 and 5m, like in the Alps. Therefore, the thickness of the permafrost body increases towards the north in the northern hemisphere, where it can extend down to hundreds of meters (for example in Siberia, where the thickness can reach 1450m).

The relationship between temperature and depth can be demonstrated in a typical ground temperature profile (Fig. 1.4). In this profile higher temperatures are plotted from 0°C (displayed as a dashed vertical line) towards the right and lower temperatures are plotted towards the left. The thicker and darker curves represent current conditions which imply that the temperature in summer remains above the freezing point near the ground surface. The winter profile is represented by the curves on the left.

**Fig. 1.4** Typical temperature profiles from the ground surface to the base of permafrost, (Permafrost Task Force Report, 2003).
The temperatures at the surface are expected to be the lowest and increase to a depth where both curves intersect. Below this point there is no influence by the seasonal fluctuations at the surface. Where the temperature curves intersect with the vertical line of 0°C, the base of the permafrost body is reached, which is controlled by geothermal heat. The grey curves in the diagram represent the permafrost conditions due to global warming.

The distribution and change of permafrost is mainly controlled through climatic terms. The fast and articulate reaction of permafrost on marginal climatic change makes this phenomenon to an important climate-indicator. Besides air temperature and radiation the thickness of the snow cover is another important factor for permafrost due to its isolating property. In alpine or high mountain areas slope gradient, slope exposition, altitude, vegetation and the subsurface quality are additional important factors for the occurrence of permafrost phenomena, which results in a complex and patchy disposition.
2. Rock glaciers generally

2.1. History of rock glacier research

Rock glaciers are impressive landforms in high mountain areas. Nevertheless they aroused attention of scientists since the 17th century, when the first glacial historical models appeared. In 1883, the Danish scientist Steenstrup published a paper, in which he defined active rock glaciers in northern Greenland for the first time as “dead glaciers” (Humlum, 1982; Vitek and Giardino, 1989). Then Spencer (1900), who mapped in the San Juan Mountains in Colorado, described this special landform more as a “peculiar form of talus”, than a former, true glacier, and in 1910 Rohn studied the “movement of talus glacier”. The term “talus glacier” was finally characterized by Chamberlin and Salisbury (1906, p.474), who compared a “rock glacier” with a “real glacier”. Also in 1910 investigations in Alaska were made by Capps (1910), who delivered the first written definition of a “Rock glacier” (p.359, 360). Like Russel (1895) he believed that rock glaciers are not equal as true glaciers. His definition was accepted by other authors and scientists for a few decades. The term, “rock glacier”, which is still accepted by scientists all over the world, has its origin in a work of Cross and Howe (1905) (Giardino and Shroder, 1978, p.446). Observing rock glaciers in non-glacial regions, Patton (1920) and Tyrell (1920) believed that rock glaciers are periglacial phenomena. Due to the appearance of translations in different languages and the increasing international interest into rock glaciers, several terms, like the German “Blockgletscher” (Högbom, 1914, p.356; Krebs, 1925; Salomon, 1929), the French “glacier rocheux” (de Martonne, 1920), or the Spanish “lithoglacial” (Catalano, 1923) were established. As a result of the confusions about the origin of rock glaciers, many difficult terms and models referring to their formation have been suggested. Models like “ablation complexes” (Johnson, 1974) or “glacier-cored, tongue-shaped rock glacier” (Calkin et al. 1987, p.73). Humlum (1982) idealized the terms of these models and designated talus-derived rock glaciers as talus rock glaciers, and furthermore he defined glacier-derived rock glaciers as debris rock glaciers. However, the term debris rock glacier in this sense is not correct, because it is only a transport-system for glacial deposits and not glacial derived. Today, the term “rock glacier” (Barsch, 1988) is still present and is used all
over the world, but there are still ongoing discussions about rock glacier-investigations (summarised from Barsch, 1996). Whereas Haeberli (1985) and Barsch (1996) consider rock glaciers as true permafrost phenomena, Shroder et al. (2000), Humlum (1988) and others state that rock glacier may also develop from debris-covered glaciers.

2.2. Introduction – Rock Glacier

Rock glaciers are the most common phenomena of alpine permafrost in high mountain systems. Active rock glaciers are of a high geodynamic and geo-ecologic importance and they are a good indicator for alpine or mountain permafrost. They contain permafrost-ice beneath a more or less thick, during summer unfrozen layer of debris (=active layer). Huge masses of debris may be stabilized by the freezing of these debris layers and global warming may cause increasing mass movements in high mountain areas. As a result debris flows, landslides, and rock falls may occur and get hazardous for roads, cable ways and ski slopes, for example. Active rock glaciers work like transport systems of debris in high mountain regions, and they often contain a huge storage of frozen water (Barsch, 1977; Krainer and Mostler, 1999, 2001). However, fossil rock glaciers do not contain ice anymore.

Due to increased melting of permafrost the geophysical properties of rock glaciers change, that is why these phenomena are also of great importance for engineering in high mountain areas. The melting of permafrost ice can also lead to floods. (Krainer, 2007)

Rock glaciers also give references to climate and climate changes (Hölzle, 1994; IPCC, 1996).

2.3. Definition and Classification of Rock Glaciers

Various definitions of rock glaciers exist, as some people define them only as debris-covered glaciers (Lliboutry, 1965; Klaer, 1974; Whalley, 1987a), and others also believe in features with a non-glacial origin, like rock glaciers, which derived from talus slopes. Normally rock glaciers are defined through 3 main concerns, which are process, material and morphology.
The following definition by Barsch (1988, 1992 p.176) contains all of these concerns and represents only periglacial forms, as he, like some other authors (Wahrhaftig & Cox, 1959; Haeberli, 1985 and King, et al. 1987), excludes a glacial origin of rock glaciers. He defines active rock glaciers as *tongue-shaped or lobate bodies of perennially frozen, unconsolidated material (talus or morainic material) and ice lenses or ice bodies, which move downslope by creeping.*

The movement is affected by processes, which are similar to those of glaciers and occur as a consequence of internal deformation. As a phenomenon of alpine permafrost, rock glaciers are among the most common and most important appearances of permafrost in high mountain areas (summarized from Barsch, 1996; Haeberli, 1985a; Schroder et al, 2000).

The commonly tongue- or lobate-shaped form of rock glaciers is controlled by the topography and the input of debris. The surface relief of an active rock glacier may be characterized by transverse and longitudinal ridges and furrows, which reflect the flow processes. The morphology of the surface is an expression of compressive stress and extending flows (Wahrhaftig and Cox, 1959, Potter, 1972; Haeberli, 1985).

Due to the shape, topography and debris input, rock glaciers can be classified into 3 types (Barsch, 1996):

1) **Active rock glaciers** (Fig. 2.1) consist of frozen rock fragments and move at velocities of 0.1 to 1m/yr. After Barsch (1996), there are some factors controlling the activity of a rock glacier, which are ice-content, ice-temperature, the gradient of the slope and the debris-supply. The gradient of their front can be very high, and sometimes exceeds 45°. Due to repeating break out of boulders from the front and the movement in the blocky mantle of an active rock glacier, the material at the surface always gets displaced. Thus the growth of vegetation on the surface is mostly not possible. This may be an indicator for the activity of a rock glacier. However, this needs more geophysical investigations to make sure, that a rock glacier is still active.
2) **Inactive rock glaciers** still contain ice but are stationary. Their inactivity can be caused by the melting of ice contained in them. These rock glaciers are called “climatic inactive” (Barsch 1973). The influence of the surrounding topography and the further extension from their source area may also be a reason for inactivity (Ellis 1982; Chalkin et al. 1987; Solid and Sörbel 1992). In the first case, the friction inside the rock glacier is too high for further movement. The latter can even happen in areas of continuous permafrost, where further movement is not possible as a result of increasing tangential stress due to the slope gradient, the thickness of the deposit and its bulk density. When these factors decrease under a certain limit, further movement is not possible anymore. These rock glaciers are called “dynamic inactive”. The gradient of the front can be still high, but due to the lack of movement vegetation appears. This is an important indicator for the inactivity of a rock glacier.

3) **Fossil or relict rock glaciers** do not contain ice anymore and they are stationary. Due to their origin and development differences between talus-rock glaciers and rock glaciers, which have their origin in moraines, such as lateral moraines and terminal moraines (Barsch, 1996), can be made. They may extend down to the tree line and indicate the climate change through time (van Tatenhove & Dikau, 1990; Barsch, 1996, Humlum, 1998; Frauenfelder & Kääb, 2000). Fossil or relict rock glaciers are estimated to have their origin between the Pleistocene and Holocene (Barsch, 1996). Their topography is mostly characterized by collapse-structures and the front slope is
strongly flattened. Vegetation is growing on the surface and makes it often difficult to recognize fossil rock glaciers in the field.

Rock glaciers may also be classified based on their shape. After Barsch (1996), rock glaciers can be divided into three different types:

- Tongue-shaped rock glaciers (length : width > 1)
- Lobate rock glaciers (length : width < 1)
- Complex rock glaciers display numerous lobes, even of different activity.

However, the classification of some rock glaciers is difficult, as their length and width are similar, and complex rock glaciers may be composed of different types, even of different ages and stage of activity.

2.4. Morphology

There are some important morphological parameters defining a rock glacier. These are length and width, thickness, gradient of the front, the surface area of the rock glacier and the surface area of the catchment area. Other important parameters are the elevation of the front and of the rooting area, and the average elevation in comparison to the local snow line and the tree line. The volume of a rock glacier is defined by the relationship between the debris layer and the ice content.

Dimensions of rock glaciers
The dimension (length and width) of a rock glacier varies from mostly several tens of meters up to several hundreds of meters. Some rock glaciers even reach dimensions up to several kilometres in length (Humlum, 1996 and 2000). For example the Reichenkar rock glacier in the Stubai Alps, Austria is 1.7 km long (Krainer and Mostler, 2000). Near the front rock glaciers are mostly between 10 and 30 m thick and the front and side slopes of active rock glaciers are usually more than 35° steep. Tongue-shaped rock glaciers are normally bigger as lobate rock glaciers and they normally have a typical surface topography, with altitude differences in the relief.
between 2 and 10 m. The thickness of the unfrozen layer on the surface is usually between 0.8 and 2 m.

**Thickness**

The thickness of rock glaciers is mostly difficult to establish, as the underlying topography is rarely well known. Very helpful are geophysical measurements, like seismics or ground-penetrating radar, or exploration through drillings. Accordingly, the thickness of a rock glacier has only been determined at a few sites, like some in the Swiss Alps (Haeberli, 1989b), the USA (Rocky Mountains, Alaska) (Bucki et al., 2004; Leopold et al., 2011), in Austria (Hausmann et al., 2007) and the Dolomites in South Tyrol/Italy (Krainer and Lang, 2007). The bigger the rock glacier, the thicker it generally is. Thus, a rock glacier with an area of less than 0.01 km² may be up to 20-30 m thick, and a rock glacier, which covers an area between 0.01 km² and 0.1 km² may be up to 50 m thick (Barsch, 1977a, d). If the rock glacier is bigger than 0.1 km² it may even reach a thickness of about 150 m, such as the El Salto rock glacier in the Andes (Barsch and King, 1989).

**Surface Topology**

Almost all rock glaciers show a more or less well developed surface topography with altitudinal differences between 1 and 10 m, which is an indicator for the movement of the rock glacier (Barsch, 1996). Longitudinal furrows and ridges run parallel to the flow direction and transversal furrows and ridges run perpendicular to the flow direction. Longitudinal ridges occur because of extensional flow in the rooting area. Furthermore, crevasses in steeper sections probably result from extremely extensional flow. Transverse ridges occur due to compressional flow. They are characteristic for the flat frontal part of a rock glacier. (Wahrhaftig and Cox, 1959)

### 2.5. Composition and internal structure of rock glaciers

**Composition**

Two main layers are distinguished in the “active layer” with regard to temperature and texture. In terms of the textural composition, a layer of blocky material lacking fine-grained sediment on the surface of the rock glacier can be distinguished from a
layer with high amounts of fine-grained material beneath this 2 to 5 m thick upper layer. With regard to the temperature differences between the active layer of debris, which is expected to be unfrozen during the summer period, and the frozen, interior part can be made. The thickness of this active layer decreases towards the rooting zone to less than 1 m and is well developed in the area of transverse ridges, whereas it almost disappears in furrows (Barsch, 1973). The grain size decreases from the surface, where decimetre to meter size is present, towards the frozen core. The pore space of active rock glaciers contains ice. Rock glaciers may be undersaturated, saturated, or even supersaturated depending on the amount of ice. Some rock glaciers even contain a massive core of coarse grained, layered ice or ice-lenses. The development of a rock glacier is controlled through two main factors, which are climate and debris supply. The type of bedrock in the catchment area (in the Alps mostly metamorphic rocks, subordinately sedimentary rocks) is very important for the development of rock glaciers.

**Grain size**

The grain size of a rock glacier may differ from place to place. The surface layer of many rock glaciers is composed of very blocky, coarse-grained material. The grain size reaches decimeters to meters and can even reach the size of a small house. Normally the boulders are within an order of 0.6 – 1 m (Barsch, 1996). Barsch (1969a) suggests that the transition into a pure bouldery layer can be an indicator of movement at this point.

A separation of boulders from fine-grained material is expected to occur due to downwashing of the smaller grain size. But this factor seems to be secondary, as Washburn (1979) claims, that frost heave is the principal factor of the blocky appearance on the surface of a rock glacier. Humlum (1988a) describes “cairns” as a result of frost heave, which means, that boulders get lifted up above the “normal” topography. In his opinion this phenomenon is an indicator for a massive ice core.

Below the coarse surface layer finer grained, silty to sandy material is present, which can be visible at the steep front and side slopes of the rock glacier.
Internal structure
The internal structure of rock glaciers is very complex and can only be investigated through drillings and geophysical methods, like seismics, gravimetric analyses, ground penetrating radar, geoelectrical measurements or exploratory excavations (Hausmann et al., 2007; Krainer et al., 2007). The proportions of debris to ice seem to be highly variably and the amount of ice may be up to 80% higher than that of the debris. Investigations on permafrost in the USA demonstrate rock glaciers with a core of thin-layered, coarse-grained glacier ice containing only a small amount of rock fragments. At the base of the rock glacier a layer of low viscous material is present, which seems to be responsible for basal sliding of the rock glacier body.

The thickness of the active layer of a rock glacier reaches its maximum at the frontal part, with 3 to 5 m. In its rooting zone it only reaches normally about 1 m or less. The development of the active layer mainly depends on the climate and short-time climate change.

Hydrology
Some important parameters control the hydrologic system of high mountain areas, like precipitation, snowfields, glaciers, firn, soil, vegetation, bedrock, sediments and permafrost phenomena. Active and inactive rock glaciers may have a huge storage capacity for frozen water within the pore-space. The melt water runs off through one or more springs at the front of the rock glacier and the delivery of a rock glacier spring is, according to Barsch (1996), estimated to be 5 to 250L per second, whereas the averaged discharge should be between 8 and 15L per second. The water within a rock glacier derives from precipitation in terms of rain and snow, or from melt water of permafrost ice, and ground water. During the spring season the discharge is estimated to be highest (Evin & Assier, 1983) and it decreases during late summer and autumn. In winter some rock glacier springs are often observed to be frozen and without any discharge. Due to the filter effect of a rock glacier the spring water is usually very clear and lacking suspension, so that it can be used as drinking water. The water temperature at the spring of an active rock glacier is normally close to or slightly below 1°C and it remains constant during the melt season.

The electric conductivity of the outflowing water of rock glaciers is generally higher than the conductivity of glacier water. If water stays in contact to rocks for a long time, minerals get dissolved, which causes a higher conductivity due to the higher
amount of ions in rock glacier water. The discharge is usually characterized through high seasonal and daily variations. The highest rates are measured in June and July due to the snow melt. (Krainer et al., 2007)

Movement
Flow velocity measurements have been done on only a few rock glaciers since about 70 years. There are numerous methods of measurements existing and there are almost the same as on glaciers. An inexact method because of the vague boundary of the snout is the observation of the shifting of fixed points at the frontal part. Although it is not a very accurate method it was used for a long time, for example by Chaix (1919, 1923 and 1943). Another, more exact method is the measuring of the change of marked profile lines, which are specified across the rock glaciers and are measured through fixed points in the bedrock. This method is described in works of Wahrhaftig and Cox (1959), White (1987) and Vietoris (1972). Changes are also measured through aerial images and geodetic surveying, like measuring with the help of theodolites or GPS. Pillewitzer (1957) initiated terrestrial photogrammetric measurements in 1936. In different years aerial photographs have been taken and following the position of individual boulders on rock glaciers can be compared and so the movement can be traced back. This method was first used by Messerli and Zurbuchen (1968). The measurement of velocity is always connected with the problem of missing accuracy as the control points are marked on boulders and the movement of individual boulders often cannot be used for the entire rock glacier. Furthermore, long-term and short-term measurements have to be discussed seperately, as same as the vertical and the longitudinal displacement of boulders. (Barsch, 1996)

The first measurements of rock glacier velocities were made in Switzerland in Graubünden by Chaix (1919, 1923). He investigated an annual downslope movement of between 0 and 2 m for the rockglacier Val Sassa. Lower velocities of rates between 65 and 155 cm per year were reported from rock glaciers in the Alaska Range by Wahrhaftig and Cox (1959). Since then, more scientists (like White, 1971b; Chalkin, 1987) started to report about velocity measurements on the surface of rock glaciers. Short-term measurements were carried out, for example, on the rock glacier
Äußeres Hochebenenkar in Austria. Pillewitzer (1957) and Vietoris (1972) report unusual high velocities up to 500 cm per year. Another short-term investigation, carried out by Haeberli et al. (1979) gives also very high velocities of more than 3 m per year from the Gruben rock glacier in Switzerland. (Barsch, 1996)

Summarizing rock glaciers usually move at velocities up to 2 m per year, rarely up to 5 m. Their movement depends on topography, climate and alteration of the delivery of debris and is not constant, but may vary seasonally. (Krainer and Mostler, 2006)

**Rheology**

The flow behavior of rock glaciers act similar to the flow behavior of glaciers and follows parameters, which are shear stress inside of the frozen material, the density of ice and rock fragments, the thickness of the rock glacier, temperature, grain size and shape of the material, and size and form of the ice crystals. Like glaciers, the movement of rock glaciers results from internal deformation and probably also from basal sliding. However, rock glaciers contain higher amounts of rock fragments and debris material, so that their viscosity is much higher and hence their flow velocity is lower. (Krainer and Mostler, Hausmann et al., 2007)

### 2.6. Genesis of rock glaciers

There are special assumptions for the development of rock glaciers, which are special climatic conditions, supply of debris, which is controlled by rock type, weathering, erosion, and topography. Rock glaciers can occur under periglacial conditions, through infiltration and freezing of precipitation and melt water. If the slope gradient also exceeds a certain limit the mass of rocks and frozen water begins to flow due to internal deformation. Rock glaciers mostly evolve out of talus-material, more than out of moraines or cirque glaciers, which would be the same like a debris-covered glacier (Schroder et al. 2000, Berger et al. 2004, Krainer and Mostler 2004).

There are glacier-derived rock glaciers known from the eastern Alps, which are definitely still in connection with cirque-glaciers. Examples are the rock glaciers at Inneres Reichenkar, Sulzkar (Krainer and Mostler, 2000 and 2006) and the rock glacier Innere Ölgrube (Berger et al., 2004). This thesis of a glacial origin is also represented by Llibourty (1965 in Barsch, 1996), Whalley (1974), Potter (1972) and
Humlum (1998) and meanwhile the existence of glacier-derived ice-cored rock glaciers is documented for several rock glaciers. An example is the Reichenkar rock glacier in the western Stubai Alps (Krainer and Mostler, 2000).

In context of their origin and following their building material, Barsch (1988, 1996) divides rock glaciers into talus-rock glaciers and debris-rock glaciers, which have developed out of moraine material. Both of them represent the periglacial or rather non-glacial origin.

**Fig. 2.2** different types of rock glaciers related to their origin and associated features; L = Protalus lobe, R = Protalus rampart (After Hamilton and Whalley, 1995)

**Talus rock glaciers (Fig. 2.3)**
This type developed beneath talus slopes and consists of alternating layers of debris from the slope, snow (from avalanches) and refrozen meltwater. Due to the increasing of the pressure, the lower and the basal, ice-supersaturated parts of the talus slope, becomes unstable. When the slope exceeds a certain limit and the thickness climbs over 15 m the mass of debris and ice starts to creep and the first ridge forms (Protalus lobe). Further talus production and input of snow and ice can lead to the formation of additional ridges (Barsch, 1988, 1996).
Debris rock glaciers (Fig. 2.4)

After Barsch (1996) debris rock glaciers have their origin in moraine material. Moraines develop into rock glaciers when they are supersaturated on ice (frozen meltwater), and temperature, material and relief allows creeping. The supply of rock fragments is controlled by the glacier, pushing material against the inner part or the top of the moraine. Debris rock glaciers are not considered as glacier-derived rock glaciers, as they are only a transport-system for moraine material and do not contain a massive core of glacial-ice.
However, there are also glacial models discussed by Potter (1972) and Johnson (1974), who accept debris-covered glaciers also as a type of rock glaciers.

Glacier-derived rock glaciers
Neither a talus-rock glacier, nor a debris-rock glacier contains a massive glacial ice-core, which can reach a thickness of 20 to 30 m and distinguishes this controversial type of rock glacier totally from other rock glacier-types. Glacier-derived rock glaciers are also estimated to own a different rheological character. As they are not bound on a permafrost-origin, they are often not accepted as permafrost phenomena. Debris covered glaciers often display a surface topography, which is not typical for rockglaciers with a permafrost-origin. A very reliable indicator for this rockglacier type is the appearance of thermokarst, which can occur as depressions, thermokarst lakes or the exposure of clear glacier ice (Fig.2.5). (Barsch, 1996)

Fig. 2.5 Rock glacier development out of a retreating cirque glacier. This model also explains the development of a typical depression, a thermokarst phenomenon in the rooting area. (modified after Krainer and Mostler, 2000)
2.7. Age of rock glaciers

Dating of rock glaciers, active as fossil, is very difficult, as there is a lack of good dating material for relative and absolute dating. In case of rock glaciers, which are mesoforms (Barsch 1983a, Thorn and Loewenherz 1987) there seem to be a relationship between size and age. Due to this fact, the development of active rock glaciers is estimated to need thousands of years. According to Höllermann (1983), the time a rock glacier needs to develop does not have to be the same time in which they were active. They may be reactivated during colder periods within warm periods, like during the younger late-glacial “Egesen” (Younger Dryas) in the Alps (10.000 - 11.000 years ago). Kerschner (1978) suggests that the climate during this period may have been more continental and more ideal for rock glaciers to develop, than today. In North America ice samples were taken from the core of some rock glaciers and were investigated through dating methods. Scientists found out, that these samples were several 1000 years old. The rock glaciers in the alpine region are normally all younger than 10.000 years, except of glacial territories, and fossil rock glaciers. These are very difficult to date and they are probably older than active rock glaciers. Some rock glaciers evolved from debris-covered cirque-glaciers of the Little Ice Age, like Ölgrube in the Kaunertal in Tyrol (Berger et al. 2004) and Hohe Gaisl in the Dolomites of South Tyrol /Italy (Krainer and Lang, 2007).

The age of active rock glaciers

Due to the lack of organic material direct dating of active rock glaciers is very difficult. According to Birkeland (1973) relative dating, like lichenometry on weathering rinds and weathering pits of boulders on the surface of rock glaciers can be used. Lichonometric studies, which are used to study the growth of a special species of lichens (*Rhizocarpon geographicum*), deliver only young ages and can, according to King and Lehmann (1973), mainly be used for dating of up to 300 years old boulders. Additionally present-day movement extrapolation and the relationship to Holocene lateral or end moraines can be used to substantiate lichonometric dating. The dating with present-day movement is also problematic as the movement rates can change from more than 160 cm per year down to zero (Barsch, 1996).

A more precise way of exploring the age of active rock glaciers is the dating of the ice cores of rock glaciers, with the disadvantage of very high costs. For example, pilot
analyses were carried out on an ice core taken from rock glacier Murtèl I in the Swiss Alps (Haeberli, 1989b). In terms of these analyses the rock glacier was dated back to several thousands of years. The age at a depth of about 32 meters, where a shear zone is located, seems to be Holocene. These data show that the rock glacier was formed during the Holocene. According to the model created by Haeberli (1990) permafrost ice on the toe of a rock glacier is the oldest and gets younger to towards the rooting zone.

The age of inactive rock glaciers
Due to the fact that dynamic inactive rock glaciers may have the same age as active rock glaciers, only the age of climatic inactive rock glaciers will be discussed. According to Patzelt (1972, 1977b), there was an altitudinal belt between alpine and nival regions existing during the Holocene, with variations of about 200 m. Inside this belt the difference of the MAAT (mean annual air temperature) between colder and warmer periods amounts 1 to 1.5°C. Both, inactive and active forms of Holocene age are found in this same altitudinal belt, climatic inactive rock glaciers lower than active ones. It is likely that the global warming of the last decades affected rock glaciers, which are observed as climatic inactive, in the lower belt first. They mark the beginning of the Holocene cryogenic belt, “where mountain permafrost is not in equilibrium with climate during the warmer periods of the Holocene” (Barsch, 1983).

The age of fossil rock glaciers
Fossil or relict rock glaciers originate out of active or inactive rock glaciers and their interstitial ice content is completely melted. They may have been active for several thousands of years, whereas they are estimated to have developed into fossil rock glaciers during the Holocene. An activity during this time is considered to be impossible, as the climatic situation did not allow the appearance of active rock glaciers at those altitudes. Thus they probably formed during the Pleistocene. However, relict rock glaciers in the Alps are suggested to be much older than inactive and active ones, because they normally appear well below the present timberline. Relict rock glaciers are described from the Würm period by Kerschner (1976, 1978). Their $^{14}$C- age is dated of about 13.000 to 12.000 years (Daun) and 11.000-10.000 years (Egesen). Rock glaciers were also dated within late glacial moraines of the Egesen by Maisch (1981), who describes ages between 11.000-10.000 years.
Summarizing, relict rock glaciers in the Alps are accepted to have been active during the Pleistocene and thus they are older than 11,500 years B.P. They are estimated to have become inactive 9,000 years B.P. at the boundary between the Pleistocene and the Holocene. (Summarized from Barsch, 1983)

2.8. Climate and rock glaciers

There are many thesis and studies about the development of rock glaciers in connection with the climatic conditions. In general active rock glaciers are estimated to exist only in high mountain regions between about 2500 meters above sea level up to more than 3000 meters. Thereby, the averaged annual temperature should not climb over 2°C and the maximum precipitation per year is expected to be 2500 mm. In the Alps there are fossil rock glaciers present about 600 meters lower than the altitude, at which recent active rock glaciers occur. This lets assume, that the permafrost line used to be much lower in former times than today.

Humlum (1998) summarizes studies and opinions of different authors, who are investigating rock glaciers all around the world. Some of them (King, 1986; Barsch, 1992, 1996) claim, that rock glaciers only evolve in cold and continental mountain regions. But rock glaciers are also described from maritime regions (Eyles, 1978; Birnie & Tom, 1982; Humlum, 1982; 1984; 1988a; 1988b; 1996; Martin & Whalley, 1987a). Some scientists, like Wahrhaftig and Cox (1959) or Barsch (1987a, 1987b) have different views about their origin and claim a periglacial origin of rock glaciers, whereas others, like Whalley (1974), White (1976) or Humlum (1982) suggest, that rock glaciers may contain a massive ice core of glacial origin.

There is just little knowledge about the climatic situation in connection with rock glaciers, as they are usually not used for paleoclimatic studies. In his paper about the climatic significance of rock glaciers Humlum (1998) distinguishes rock glaciers into talus-derived rock glaciers and those which are glacier-derived. He mentions previous works of several authors, who are investigating in different areas around the world and therefore under different climatic conditions. There are some investigations in the Swiss Alps made by Haeberli (1983), who requires ice-cemented rock glaciers, which can only exist at MAAT between -4°C and -10°C and with annual precipitations
between 500 and 1000 mm. He suggests ice-cored rock glaciers to occur in areas with an MAAT between 1°C and -10°C. Whalley (1974) claims that rock glaciers also develop in maritime climates if there is a high supply of debris available. According to Birnie and Thom (1982) active rock glaciers can also exist in areas with a MAAT above 0°C. Some authors (Eyles, 1978; Guglielmin et al., 1994; Whalley et al., 1995b; Kirkbride and Brazier, 1995;) suggest, that the development of active rock glaciers is closely linked to the regional precipitation, which should be in the range of 1000 - 1700 mm per year.

In the Swiss and Austrian Alps maps of the distribution of rock glaciers were prepared (Barsch, 1980; Höllermann, 1983) and compared to the reconstructed snowline of the Little Ice Age (Jegerlehner, 1903) with the result, that the ELA (equilibrium line altitude) between 1850 and 1856 is nearly the same as the lower limit of rock glaciers today. (Summarized from Humlum, 1998)

According to Höllermann (1983) the Central Alps seem to be climatically and geologically optimal for the occurrence of active rock glaciers, whereas there are obviously poor conditions in the zones of carbonate rocks in the Northern, Western and Southern Alps. He also suggests, that rock glaciers are periglacial phenomena, which prefer the climate of marginal glacier territories but avoid the rim of the Alps with its oceanic climate.
3. General Overview of the study area

3.1. Geographical Position

The area of investigations (Fig. 3.1) is located in the central part of Tyrol/ Austria, in the Oberberg Valley, which is a side valley of the Stubai Valley. It is located in the Stubai Alps, a mountain range in the Central Eastern Alps. The border of the Stubai Alps is characterized through the Inn river Valley in the north, the Sill river Valley in the east and the Ötz Valley to the west. The southern border runs along tributaries of the Passeier river.

The Franz-Senn Hütte, which belongs to the Austria Alpine Club, in the Oberberg Valley can be reached by car, by driving the B183. From the village Milders it is possible to enter the Oberberg Valley. After parking at the Oberriss Alm it is possible to reach the area of investigations by hiking on an unofficial trail or an official trail to the Franz-Senn Hütte within an hour.

Fig. 3.1 Aerial photograph of the Ötztal and Stubai Alps; the study area is marked with a red square (Reference: www.tirol.gv.at)
The Oberberg Valley is the largest side valley in the Stubai Alps and the valley ends with the glaciers of the Alpeiner Mountains. This glacier and some other side glaciers are surrounded by the highest summits in this area, which are the summits of the Schrankogel (3.497m), the Ruderhofspitze (3.474m), the Östliche Seespitze (3.416m) and the Westliche Seespitze (3.354m). Due to glacial erosion the Oberberg Valley is mostly trough-shaped, except the lower part of the valley, which is more eroded by the Alpeiner creek, which runs through the Oberberg Valley. In the entire Oberberg Valley different features of erosion remind on the last ice age in the Holocene, like glacial polished rocks or the huge side moraines of the Alpeiner Ferner.

Description of the study area
From the west to the east the area can be divided into 4 main parts: the Stiergschwetz, the Kuhgschwetz, the Unnützes Grübl and the Platzengrube. The southernmost part of the area is partly occupied by a cirque glacier, the Sommerwandferner. Northeastwards are remains of another cirque glacier located, which is called the Knotenspitzferner. In the cirque of the Kuhgschwetz and the Unnützes Grübl there have also been glaciers, which disappeared not long ago.

Fig. 3.2 Overview map of the study area with the territory names
The study area is bordered by a mountain ridge in the south, which divides the Oberberg Valley from the Stubai Valley and runs from the *Alpeiner Knotenspitze* through the *Östliche Knotenspitze* and the *Uelasgratspitze* to the *Basslerjoch*. The western border is marked through the *Sommerwand* and the eastern border is characterized by the *Platzenturm* and the *Platzenkopf*. The northern border can be described by the Alpeiner creek.

### 3.2. Geological overview

The area of investigations is located in the Ötztal-Stubai Crystalline Complex (ÖSCC), which occupies almost a quarter of the surface area of Tyrol. Tollmann (1977) describes the Ötztal-Stubai unit as a nappe with a thickness of 5 to 7km, which presents a part of the Austroalpine Basement. The ÖSCC is located between the Tauern Window in the east and the Unterengadiner Window in the west. The border of this unit runs along the Brenner line - which is a west-dipping detachment fault - along the Tauern Window in the east and along the Northern Calcareous Alps with the Inntal line in the north. The western border is formed by the Engadine line along the Penninic units of the Engadine Window. In the south the ÖSCC is bordered towards the Old Gneiss Zone and the *Schneebergerzug* and tectonically by the Schlinig-line in the southwest. (Konzett, Hoinkes & Tropper, 2003)
The Austroalpine Basement is divided into 3 subunits, the Ötztal-Stubai unit, the Scarl-Campo unit and the Ulten unit, which are all separated through tectonic lines. The Ötztal-Stubai unit is separated from the Scarl-Campo unit along the Schlinig-line, which runs from the NNW to the SSE, and the Peio-line divides the Scarl-Campo Complex from the Ulten-unit (Hoinkes and Thöni, 1993).

Geological history and ages
All of these units consist of acid to intermediate metamagmatites and metasediments enriched by quartz and feldspar. Metasediments like paragneiss and mica schist are dominating. The Scarl unit is basically composed of acidic metamagmatites of variscan age. Late variscan pegmatites are dominating in the Scarl-Campo Unit and also variscan peridotites in the Ulten Unit. The middle- to high-grade metamorphism
in the Scarl-Campo and the Ötztal-Stubai Complex is suggested to be pre-alpine. However, the Ulten unit has been transformed under granulite facies conditions. During the alpine orogeny the Ötztal-Stubai and the Scarl-Campo units were overprinted from the north to the south with higher intensity.

The ÖSCC was overprinted by 3 main metamorphic events: the caledonian, the variscan, and the eo-alpine event.

The caledonian event can be only locally observed in a few places, for example in the area of the Reschenpass, where it is recorded in the migmatites of the “Winnebach-Granite”. These rocks were formed under extreme conditions with temperatures up to 750°C and pressures up to 8kbar (upper amphibolite/ lower granulite facies) (Elias, 1988).

The rocks of variscan age were overprinted under conditions of amphibolite to eclogite facies with temperatures between 500 and 650°C and pressures between 4 and 8 kbar. The pre-variscan eclogites in the ÖSCC are characteristic for this unit (Miller and Thöni, 1995).

The eo-alpine metamorphic event shows an increasing trend of the metamorphic grade from sub-green schist conditions in the northeast to amphibolite-eclogite conditions in the southwest, where eclogites are located in the area of the Schneeberger Zug (Hoinkes and Thöni, 1993).

Regional geology
The rocks of the Austroalpine Basement are of high importance because the alpine metamorphism has been mostly not as intensive as the variscian metamorphism was. Accordingly in many cases the pre-alpine mineral paragenesis has still remained. The units of the Austroalpine Basement include the Silvretta Crystalline Complex (SCC), the ÖSCC, the Scarl-Campo Complex and the Ulten Complex. These units remained as a result of the breakup of a bigger Austroalpine Basement during shearing-off, nappe-stacking and tectonic transport during the alpine orogeny. However, the original positions of the units are still almost the same. The tectonic series of the Mesozoic Penninic-ocean and the distal European continental border
The Ötztal-Stubai Complex

The Ötztal-Stubai Complex is a tectonically bounded Austroalpine tectonic unit, located immediately west of the Penninic units of the Tauern Window. The basement only crops out on the southwestern border, the Schlinig-thrust, between the Sesvenna-Unit and the ÖSCC. Due to increasing temperatures during the last tectonic event, in the area of the city of Meran, in South Tyrol, this kind of tectonic line is changing to a local-shearing and high-scale folding (Schmid and Haas, 1989). As a possible border of the Ötztal-Stubai Complex, a pre-alpine border between the Schneeberg-Syncline and the Laas-Series could be considered. The tectonic line Passeier-Sterzing, which divides the pre-alpine basement in the east from the alpine-metamorphic basement in the west, represents the southeastern border of the ÖSCC.

The Ötztal-Stubai Complex is primarily composed of amphibolite-facies, metasedimentary rocks, enriched on quartz and feldspar, and secondarily metapelites. Subordinately there are also acid to intermediate metamagmatites, amphibolites, eclogites and metacarbonates.

There are four phases of deformation (D1 to D4), which are defined by different structural elements. Van Gool (1987) defined these phases of the Ötztal-Stubai Basement. The first phase is very rare observable and it only exists as relict microstructures. However, D2 is characterized by intensive foliation and microlayers. The whole ÖSCC shows the result of the third deformation-phase D3, expressed through typical chevron-folds.

It is still unsure how old these deformations are, whereas the age is estimated to be late-variscan in the alpine, low-temperature regions (Thöni, 1988) and cretaceous in alpine, high-temperature regions in the south. After Thöni (1986, 1988) local shear zones and open folds of probably alpine age are recorded by deformation-phase D4. (summarized in Hoinkes and Thöni, 1993).
3.3. The rock glaciers in the area near the Franz-Senn Hütte

In the south and the southeast of the Franz-Senn Hütte, the area of investigations, some rock glaciers are located, which can be classified as active, inactive and fossil (Table 1).

<table>
<thead>
<tr>
<th>Name (rock glacier)</th>
<th>Identification</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiergschwetz</td>
<td>ST</td>
<td>Inactive</td>
</tr>
<tr>
<td>Franz-Senn Hütte 1</td>
<td>FSH 1</td>
<td>Fossil</td>
</tr>
<tr>
<td>Franz-Senn Hütte 2</td>
<td>FSH 2</td>
<td>Fossil</td>
</tr>
<tr>
<td>Franz-Senn Hütte 3</td>
<td>FSH 3</td>
<td>Fossil</td>
</tr>
<tr>
<td>Kuhgschwetz 1</td>
<td>KU 1</td>
<td>Active</td>
</tr>
<tr>
<td>Kuhgschwetz 2</td>
<td>KU 2</td>
<td>Active</td>
</tr>
<tr>
<td>Kuhgschwetz 3</td>
<td>KU 3</td>
<td>Active</td>
</tr>
<tr>
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<td>KU 4</td>
<td>Fossil</td>
</tr>
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<td>UG 1</td>
<td>Inactive</td>
</tr>
<tr>
<td>Unnützes Grübl 2</td>
<td>UG 2</td>
<td>Inactive</td>
</tr>
<tr>
<td>Unnützes Grübl 3</td>
<td>UG 3</td>
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</tr>
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<td>Unnützes Grübl 4</td>
<td>UG 4</td>
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</tr>
<tr>
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<td>Inactive</td>
</tr>
<tr>
<td>Platzengrube</td>
<td>PL</td>
<td>Inactive</td>
</tr>
</tbody>
</table>

Table1 List of the rock glaciers (from the west to the east) within the study area and their identification and expected status of activity

Stiergschwetz (ST):
This rock glacier heads in the southernmost part of the study area in the apron of the Sommerwandferner in a north-facing cirque. The catchment area seems to be the slopes of the Sommerwand in the southwest and the slopes of the Alpeiner Knotenspitze and the Falbesonder Knotenspitze in the south. It consists of rock fragments of orthogneiss which is recognized in this area as “Alpeiner Granite”. The rock glacier of the Stiergschwetz is a 260m long and 220m wide, tongue-shaped rock glacier and seems to be inactive. One indicator for its inactivity is the steepness of the front slope, which shows an angle of about 35°. It is possible, that this rock glacier has developed from a debris-covered glacier but also the theory of a morainic origin seems to be possible. Probably there is no contact with the ice of the Sommerwand glacier. Its exposition is about 20° to the NNW. The highest point of
the rock glacier is approximately 2510m and the lowest point is about 2455m above sea level. The surface is characterized by longitudinal, inarticulate furrows and ridges, which display the former movement of an active rock glacier. The thickness of the rock glacier seems to be less than 10 m and there are some depressions which indicate, that most of the ice contained inside is melted. A spring at the snout of the rock glacier is present but the water, which is very milky, seems to discharge the melt-water of the Sommerwand glacier (Fig. 3.4). There is also a small lake of melt-water in the apron of the rock glacier (Fig. 3.5).

This rock glacier is important for measurements and will be discussed in particular.

![Fig. 3.4 Runoff at the front of the rock glacier in the Stiergenschwetz](image1)

![Fig. 3.5 Aerial photograph of the rock glacier in the Stiergenschwetz with the melt-water lake in the northeast.](image2)
**Franz-Senn Hütte 1, 2, 3 (FSH):**

Those three rock glaciers are located in the southwestern part of the Franz-Senn Hütte and on the western slope of the Gschwetzgrat (Fig. 3.6). All of them seem to be fossil, i.e. they do not contain permafrost-ice anymore. They are probably talus derived and evolved through the supply of rock fragments from the slope, which got supersaturated with ice delivered through precipitation and avalanches. The rock fragments of the debris-mantle consist of two-mica augen gneiss from the Gschwetzgrat. The average altitude of all three rock glaciers is about 2400m. There are no springs of melt-water on the base of these rock glaciers observed.

FSH1 is a lobate-shaped rock glacier with a length of about 80m and a width of about 440m. Its exposition is 270° to the west. There are no furrows or ridges visible and the surface of the debris shows vegetation of moss, which is an indicator for the inactivity of a rock glacier.

FSH2 is a tongue-shaped rock glacier and located in the north of FSH1. It is probably also talus derived and about 370m long and 190m wide. A surface-topography in form of ridges can be suggested at the frontal part. The exposition is 345° to the NNW.

FSH3 is also a tongue-shaped, fossil rock glacier and it is located in the north of FSH1 and FSH2. Its length is about 75m and its width about 70m. The rock glacier is exposed with 300° to the northwest.

![Fig. 3.6 Rock glaciers FSH 1, 2 and 3 near the Franz-Senn Hütte](image)
Kuhgschwetz 1 (KU1):
The rock glacier KU1 is an active rock glacier and is located in the cirque of Kuhgschwetz, which is exposed to the north (Fig. 3.7). Its body is tongue-shaped and about 1280m long and 240m wide. The lowest point at the front is 2320m in altitude, the highest point 2800m. The rock glacier seems to be ice-cored, so it may have developed out of an old cirque glacier. A depression in the rooting zone is the typical indication for a glacier-derived rock glacier and it marks the border between the rock glacier and the beginning of the debris delivering talus slope behind it. Today there is no glacier in this cirque anymore, which could feed the rock glacier with ice. The surface morphology is characterized by mostly transversal lobes and on the western part of the rock glacier a second, small front has developed. The debris, which consists of the mantle of the rock glacier consist mainly of amphibolite, which crops out in the Gschwetzgrat in the west of the rock glacier at an altitude of about 2640m. It seems that the rock glacier transports the debris from this altitude and from the cirque downwards. There is only a little amount of two-mica augen gneiss in the debris of the lower part of the rock glacier. The amphibolite-debris, which appear closer to the cirque are more and more mixed up with schist. There is probably alternating stratification between amphibolite and mica schist. There are four springs of melt water on the snout of the rock glacier, which are of seasonally activity and not always running. The front slope is about 42° steep which is very typical for active rock glaciers.

This rock glacier is also important for measurements and will be discussed in particular.

Kuhgschwetz 2 (KU2):
The active rock glacier KU2 is located between KU1 and KU3 (Fig. 3.7). It is tongue-shaped and shows inarticulate lobes on its surface. It is exposed directly to the north and 575m long and 160m wide. The maximum altitude is about 2520m at the front and 2720m at the rooting zone. KU2 probably has developed out of a talus slope but in this case it seems to be very unsure as it is lying between two rock glaciers, which are estimated to be glacier-derived. The rock fragments on the surface mainly consist of amphibolite and mica schist from the cirque. But there are also debris of two-mica augen gneiss, which is derived from the Uelasgrat, located in the east. The
hydrological system of this rock glacier probably runs together with the system of KU1 and KU3, as there are no springs observed at front of the snout.

**Kuhgschwetz 3 (KU3):**
This tongue-shaped rock glacier lies next to rock glacier KU2, and it also seems to be active (Fig. 3.7). The surface is characterized through transversal lobes, which are an indicator that the rock glacier is probably still moving. The exposition is 5° to the North and it is 1005m long and 370m wide. The altitude of the rock glacier is 2340m at the snout and 2800m at the rooting zone. KU3 also might have developed out of a cirque glacier like KU1, but a talus-derived origin should not be excluded. On the frontal part the rock glacier is very wide and it narrows towards the rooting zone. The rock fragments on the surface seem to originate from the Uelasgrat, which is located to the east of KU3 and delivers rock fragments of two-mica augen gneiss. There are also springs in front of the snout which indicate, that there is still ice inside.

![Aerial photograph of the rock glaciers KU 1, 2 and 3 in the Kuhgschwetz](image)

*Fig. 3.7 Aerial photograph of the rock glaciers KU 1, 2 and 3 in the Kuhgschwetz*
Kuhgschwetz 4 (KU4):

KU4 is a fossil, tongue-shaped rock glacier, which is located in the lower part of the area of the Kuhgschwetz at an altitude of about 2125m at the front and 2270m at the highest point. It is 550m long and 150m wide. On its surface there are many furrows and ridges visible, showing the former activity of this rock glacier. The exposition is 300° to the northwest and the rock glacier seems to have its origin in the northernmost part of the investigation area, the Platzengrube. It is covered by vegetation, which indicates, that it has been inactive or even fossil for a long time (Fig. 3.8 and Fig. 3.9). There are no rock glacier springs, which indicates, that there is no hydrologic system beneath the surface anymore. There is also no contact to talus slopes anymore.

Fig. 3.8 Rock glacier KU4 in the area of the Kuhgschwetz

Fig. 3.9 The fossil rock glacier Kuhgschwetz 4; view towards the northeast
Unnützes Grübl 1 and 2 (UG):
These probably inactive rock glaciers are located at the eastern slope of the Uelasgrat, on the border to the rock glacier UG3 and will not be discussed in particular, as they are not important for measurements or mapping in this area (Fig. 3.10).

Fig. 3.10 Rock glaciers UG1 (in the north) and UG2 next to the Uelasgrat

Unnützes Grübl 3 (UG3):
The rock glacier UG3 is located in the area of Unnützes Grübl on the eastern slope of the Uelasgrat and the northern slope of the Schrimmenkopf (Fig. 3.11). UG3 is an active, tongue-shaped rock glacier with a steep snout (45°) and it is exposed with 5° to the north. It is about 870m long and 305m wide and the altitude is about 2410m at the front and about 2800m at the rooting zone. The rocks on the surface of the rock glacier consist of two-mica augen gneiss, which is derived from the slopes of the Schrimmenkopf and the Uelasgratspitze in the south. Maps from 1970 of the Austrian Alpine Club show remnants of a glacier in this cirque. So it is likely that this rock glacier has developed out of a cirque glacier and it probably contains a massive ice core. The topography of the surface represents abundant transverse lobes which indicate, that the rock glacier is still moving. There are also springs on the snout suggesting, that the rock glacier still contains ice.
Unnützes Grübl 4 (UG4):
Rock glacier UG4 is also an active, tongue-shaped rock glacier, which is located next to UG3 (Fig. 3.11). Both rock glaciers are divided through bedrock and they merge on the front. Its exposition is 345° to the NNW. The northern slopes of the Schrimmenkopf and the western slopes of the Schrimmennieder deliver rock fragments of two-mica augen gneiss, which builds up the mantle of the rock glacier. It is about 670m long and 240m wide and its altitude is 2420m at the front and 2720m in the rooting zone. The surface topography shows inarticulate, longitudinal furrows and transversal lobes. There is also no vegetation visible, indicating that the rock glacier is still active and probably contains a massive ice core. There are also springs in the apron of the rock glacier, which probably deliver melt water from the frozen core of the rock glacier.

Unnützes Grübl 5 (UG5):
This lobate-shaped, talus derived rock glacier is located in the eastern part of the Unnützes Grübl, in the north of the rock glacier UG4 (Fig. 3.12). It is probably inactive and will not be discussed in particular, as it is not important for measurements or mapping in this area.
Fig. 3.12 Rock glacier UG5 located in front of UG4 in the eastern part of the Unnützes Grübl

**Platzengrube (PL):**

This tongue-shaped rock glacier is located in the easternmost part of the study area and is supposed to be inactive (Fig. 3.13). It shows a diversified surface topography of transversal ridges and furrows in the frontal part and longitudinal ridges in the rear part. Its exposition is 340° to the NNW, its maximal length is 640m and its width is 240m. The lowest part of the front lies at an altitude of 2370m and the rooting zone is located at 2700m. The slopes of the Schrimmennieder support the rock glacier with rock fragments of ortho gneiss. In the middle part, where the track crosses the rock glacier water can be heard running inside and there is also a spring at the front of the rock glacier, suggesting that there is still permafrost ice inside the rock glacier. The vegetation covering the side slopes of the rock glacier also indicates that rock glacier PL is not moving anymore and thus inactive. Due to the existence of a side moraine westwards beside the rock glacier a glacier-derived origin is likely, but a talus-derived origin can not be excluded.

Fig. 3.13 Rock glacier PL in the north of the Schrimmennieder and the east of the Unnützes Grübl
4. Research methods and conclusions

4.1. Development of the glaciers in the study area

Today there is located just one bigger glacier within the study area, the Sommerwand glacier (Sommerwandferner) in the Stiergschwetz. Also in the area of the Stiergschwetz another glacier was located. This glacier was called the Knotenspitz glacier (Knotenspitzferner), which is today represented by two remains in the east of the Sommerwand glacier.

To illustrate the influence of the climate on the cryosphere in the study area the different phases of glaciation, from the beginning of the 20th century until the beginning of the 21st century, were compared. Therefore, topographic maps of the alpine club from the years 2003, 1970, 1937 and 1896 were used to display the retreat and following the change of the glacier-covered areas. The different stages of glaciation were compared and calculated with the help of the program ArcGIS.

Fig. 4.1 Laser scan shot of the study area. The different stages of glaciation between 1896 and 2003 are marked based on the topographic maps of the alpine club. The different glaciers are colored in different shades of blue. Regarding to their stage the transparency of the colors differs.
According to the map (Fig. 4.1) the glaciation in the study area decreased mostly between 1896 and 1937. Considering the retreat of the Sommerwand glacier at the first sight it is obvious, that the biggest change with a loss of 630m happened in the length of the glacier. According to the topographic maps of the Austrian Alpine Club the glacier was shorter but wider in 1937. Following the surface area, the Sommerwand glacier did not change a lot. In the same time period the glaciers located in the Unnützes Grübl and the Kuhgschwetz almost disappeared. Already in 1970 there are only remains left of these glaciers and they are totally missing in 2003.

<table>
<thead>
<tr>
<th></th>
<th>1896</th>
<th>1937</th>
<th>1970</th>
<th>2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sommerwandferner</td>
<td>1.501.514 m²</td>
<td>1.134.796 m²</td>
<td>915.766 m²</td>
<td>715.699 m²</td>
</tr>
<tr>
<td>Knotenspitzferner</td>
<td>576.085 m²</td>
<td>349.960 m²</td>
<td>374.617 m²</td>
<td>161.465 m²</td>
</tr>
<tr>
<td>Kuhgschwetz</td>
<td>125.794 m²</td>
<td>39.956 m²</td>
<td>10.293 m²</td>
<td>-</td>
</tr>
<tr>
<td>Unnützes Grübl</td>
<td>282.241 m²</td>
<td>35.458 m²</td>
<td>62.510 m²</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2 The table shows the change of the area of the different glaciers

According to Table 2 the Sommerwand glacier lost about one third of its surface area between 1937 and 2003. Related to these data it could be possible, that this glacier disappears within the following 120 years and in 30 years the Knotenspitz glacier will probably not exist anymore too (Fig. 4.2).

Fig. 4.2 This diagram shows the change of the surface area of the different glaciers within the study area
4.2. Hydrology and Hydrochemistry of rock glaciers in the Oberberg Valley

In terms of geological mapping in the study area, samples of 14 springs and runoffs were taken in a time period between summer 2009 and summer 2011. In addition measurements of the water temperature and the electric conductivity were carried out several times with a conductivity meter (WTW). Furthermore a gouging system was installed in the apron of two rock glaciers to record data of water
temperature, electric conductivity and discharge of the runoff in a time period between autumn 2010 and fall 2011.

**Temperature**

The sense of measuring the temperature of rock glacier-springs is, that statements about the existence of permafrost, like an ice core or ice lenses, inside a rock glacier body can be made. According to Haeberli (1975), temperatures lower than 1°C are a reliable indicator for existing permafrost beneath the thick mantle of debris. The temperature of the spring water of an active rock glacier should remain constantly below 1°C during the whole melting period. Temperatures between 1 and 2°C indicate possible permafrost. Is the water temperature of the spring warmer than 2°C, it is unlikely that permafrost ice is present.

**Electric conductivity**

The electric conductivity of water is caused by the mineralization and increases proportionally to the amount of dissolved minerals. It can give statements for the length of stay inside the hydrologic system of a rock glacier. According to Krainer & Mostler (2000), the concentration of dissolved minerals in rock glacier spring water in regions of metamorphic basement rocks is small compared to the concentration in carbonate-dominating regions. Like the discharge the electric conductivity is characterized by seasonal variations, which are inversely related to the runoff. Usually the electric conductivity of the spring water of rock glaciers increases from the spring to the fall. Due to the snowmelt in spring and summer, which causes a higher discharge, the mineralization of the water is very low. Towards the end of the summer the runoff is usually very low and consists mainly of melted ice and groundwater, which causes a higher mineralization of the water.

**4.2.1. Hydrology**

To get information about the temperature and electric conductivity the spring water and runoff systems in the study area were measured by a conductivity meter, mostly during the high summer season until autumn, to avoid the possible influence of the thaw in spring. These measurements were carried out in the seasonal waters of rock glacier springs, which are located in the Stiergschwetz (BG-ST), Kuhgschwez (KU1,
KU2, KU3 and KU4) and Unnützes Grübl (UG-BG and UG-BG1) (see Fig. 4.6). Also waters in the apron of the rock glaciers were investigated (StQ2, StQ3, Q5, KU-BG, UG-BG and PL1).

Fig. 4.5 Measurement of the temperature and electric conductivity of rock glacier spring water; the measuring instrument LF323 by WTW was provided by Prof. Karl Krainer (University of Innsbruck, Institute for Geology and Paleontology)

Fig. 4.6 Map including the marked locations of hydrological measurements
Table 3 The measured water temperatures between summer 2009 and fall 2010. The values in blue represent the temperature of rock glacier springs and the values in red show the temperatures of the waters in the apron of the rock glaciers and glaciers.

Considering Table 3, the water temperatures were apparently increasing between July and August in 2010 and decreasing towards October 2010. In general, the temperatures of the measured spring waters remain constantly below 1°C, with an exception of the measuring point BG-ST in the Stiergschwetz. These springs seem to be supplied by the melt water of an ice core or melting ice lenses. The temperatures of 2.0°C in August and 1.4°C in September 2010 indicate that this water is derived from another source. It is likely, that it is originated from the Sommerwand glacier, which is located southwestwards behind the rock glacier (Fig. 4.7). The minimal temperatures of rock glacier spring water has the value of 0.1°C and it was measured in front of the rock glacier Kuhgschwetz 1, which is anyway expected to be of an active status. The temperatures in red are in a range between 0.2 and 10.9 °C, whilst the lowest temperatures are estimated to be measured in a small lake in front of the rock glacier Unnützes Grübl 3.
The following Table 4 includes the values of the electric conductivity:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>BG-ST</td>
<td>23</td>
<td>43</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KU1</td>
<td>20</td>
<td></td>
<td>54</td>
<td>34</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KU2</td>
<td>104</td>
<td></td>
<td></td>
<td></td>
<td>119</td>
<td></td>
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<td>KU3</td>
<td>93</td>
<td></td>
<td></td>
<td></td>
<td>172</td>
<td>144</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KU4</td>
<td>145</td>
<td></td>
<td></td>
<td></td>
<td>193</td>
<td>177</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>UG-BG</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
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<td>KU-BG</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gouge system (Pegel)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q5</td>
<td>27</td>
<td>29</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>StQ2</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>StQ3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UG-BG2</td>
<td>28</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4 The table shows the values of the electric conductivity between the 16.07.2009 and the 07.09.2011
The conductivity of the spring water varies in a range between a minimum of 20µS/cm in 2009 (KU1) and a maximum of 193µS/cm in October 2010 (KU4). Both springs probably drain the same rock glacier in the Kuhgschwetz. In general almost all springs and runoffs show an increasing electric conductivity from the early summer to the fall due to the high influence of low mineralized water of the snowmelt.

4.2.2. Hydrochemistry

To get information about the water chemistry, samples of 250ml were taken at the same places the previous measurements were made. The samples were transported in sterile PET-bottles and analyzed for the element concentration by Richard Tessadri at the Institute of Geology and Paleontology at the University of Innsbruck. The element concentration was measured by means of ICP-OLS. The water of two springs, one in the Kuhgschwetz and one in the Unnützes Grübl, was measured. One sample was taken in fall 2010 and the other one was taken in spring 2011.

<table>
<thead>
<tr>
<th>Element</th>
<th>08.10.2010</th>
<th>22.07.2011</th>
<th>08.10.2010</th>
<th>22.07.2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>As</td>
<td>0.041</td>
<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
</tr>
<tr>
<td>Ag</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Al</td>
<td>0.012</td>
<td>0.012</td>
<td>0.013</td>
<td>0.003</td>
</tr>
<tr>
<td>Ba</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>0.045</td>
<td>0.041</td>
</tr>
<tr>
<td>Be</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Ca</td>
<td>4.593</td>
<td>2.058</td>
<td>14.429</td>
<td>26.811</td>
</tr>
<tr>
<td>Cd</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Co</td>
<td>0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Cr</td>
<td>&lt; 0.002</td>
<td>&lt; 0.002</td>
<td>&lt; 0.002</td>
<td>&lt; 0.002</td>
</tr>
<tr>
<td>Cu</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Fe</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.002</td>
</tr>
<tr>
<td>K</td>
<td>0.152</td>
<td>0.239</td>
<td>4.734</td>
<td>6.195</td>
</tr>
<tr>
<td>Mg</td>
<td>0.070</td>
<td>0.056</td>
<td>2.027</td>
<td>1.506</td>
</tr>
<tr>
<td>Mn</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Na</td>
<td>0.167</td>
<td>0.204</td>
<td>0.330</td>
<td>0.374</td>
</tr>
<tr>
<td>Ni</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>P</td>
<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
</tr>
</tbody>
</table>
The results were compared and displayed in Table 5. At the sampling point in the Unnützes Grübl the concentration of the elements Ca, Mg, Si and Sr was decreasing, only the concentration of the elements K and Na was increasing. The amount of Al in the water remained constant. However, the samples from the Kuhgschwetz show a strong increase for the concentration of Ca. There was also a rise for K, Na and Si. The amount of dissolved Al, Mg and Sr decreased in 2011. These data were compared to the electric conductivity, which was also measured at the same sampling points on the same day. The conductivity of the measuring station UG-BG dropped between fall 2010 and summer 2011 from 60µS/cm to 40µS/cm. The decrease of the electric conductivity and the amount of dissolved minerals in the water is explainable with the snowmelt during the early summer, which brings a high amount of low-mineralized water into the system. In the Kuhgschwetz the conductivity of the water also fell from 193µS/cm to 177µS/cm, although a higher concentration of most elements was observed.
Table 6  Element concentration of the sampling points Q5 and St-BG in the Stiergschwetz; concentration of the elements, which appear in the samples are in bold type.

<table>
<thead>
<tr>
<th></th>
<th>ST-Q5</th>
<th>ST-BG</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>23.08.2010</td>
<td>11.09.2010</td>
</tr>
<tr>
<td>Cr</td>
<td>0,008</td>
<td>&lt; 0,002</td>
</tr>
<tr>
<td>Cu</td>
<td>0,001</td>
<td>0,011</td>
</tr>
<tr>
<td>Fe</td>
<td>17,761</td>
<td>0,237</td>
</tr>
<tr>
<td>K</td>
<td>4,180</td>
<td>1,011</td>
</tr>
<tr>
<td>Mg</td>
<td>4,132</td>
<td>0,925</td>
</tr>
<tr>
<td>Mn</td>
<td>0,177</td>
<td>0,004</td>
</tr>
<tr>
<td>Na</td>
<td>0,286</td>
<td>0,197</td>
</tr>
<tr>
<td>Ni</td>
<td>0,016</td>
<td>&lt; 0,001</td>
</tr>
<tr>
<td>P</td>
<td>0,021</td>
<td>&lt; 0,005</td>
</tr>
<tr>
<td>Pb</td>
<td>0,017</td>
<td>&lt; 0,005</td>
</tr>
<tr>
<td>Si</td>
<td>12,555</td>
<td>0,579</td>
</tr>
<tr>
<td>Sr</td>
<td>0,005</td>
<td>0,007</td>
</tr>
<tr>
<td>Ti</td>
<td>0,287</td>
<td>0,010</td>
</tr>
<tr>
<td>V</td>
<td>0,012</td>
<td>&lt; 0,001</td>
</tr>
<tr>
<td>Zn</td>
<td>0,024</td>
<td>&lt; 0,001</td>
</tr>
</tbody>
</table>

The samples taken in the Stiergschwetz (Table 6) generally show a higher concentration of various elements, than the samples of the Kuhgschwetz and the Unnützes Grübl. The concentration of most of the elements in both samples is decreasing between August 2010 and September 2010. However, the electric conductivity increased from 23µS/cm to 43µS/cm at the sampling point BG-ST and from 29µS/cm to 67µS/cm at the sampling point Q5. A reason for the high amount of different elements in the water could be the origin. The majority of the water is supposed to be molten water from the Summerwand glacier, which is lying in the cirque of the Stiergschwetz. The sampling point Q5 is located in the central part of the Stiergschwetz and this river probably drains the whole area of the Stiergschwetz, whereas the spring, where the sample BG-ST comes from, is located in front of the rock glacier Stiergschwetz, which is supposed to be fossil and without any storage of water. This water probably also comes from the glacier. The data of Q5 from August 23rd, 2010 are very interesting because they show higher concentrations of heavy metals, like for Pb and Ni. To make a statement about these concentrations more samples of this station have to be taken and analyzed all over the year.
4.2.3. Water gouge measurements: Unnützes Grübl

On September 7th, 2010 a gauge system was installed in the apron of the rock glaciers in Unnützes Grübl (Fig. 4.8 and Fig. 4.9) to measure the discharge during the winter and spring period until the fall in 2011. Water temperature, electric conductivity, turbidity and the water height are measured hourly. These data are saved on a data collector, which was placed next to the gouge. The data will be processed within the next months.

Fig. 4.8 Location of the installed water gouge system in the Unnützes Grübl in the apron of the rock glaciers UG3 and UG4. The water is estimated to be the discharge of both rock glaciers.

Fig. 4.9 Water gouge system in the Unnützes Grübl; the red arrow marks the position of the measuring instrument
4.3. Grain size analysis

4.3.1. Sieve analysis

The rock glaciers KU1 in the Kuhgschwetz and UG3 in the Unnützes Grübl were considered for sieve analysis of the grain size distribution. Thus, two sediment samples of each rock glacier were taken from the front and the side slopes of the front part (Fig. 4.10), where the material is much more fine-grained than on the rock glacier surface.

![Fig. 4.10 Western side slope of the rock glacier KU1; the picture shows the fine-grained layer beneath the blocky layer of the rock glacier mantle.](image)

The samples should weight more than 1.5 kg to be suitable for sieve analysis. From rock glacier Kuhgschwetz one sample (Sed1) was taken from the western sidewall near the front and another sample (Sed2) was taken from the eastern sidewall. Both sediment samples of this rock glacier contain mainly amphibolite rock fragments from the southern slopes in the cirque of the Kuhgschwetz and the western slopes of the Gschwetzgrat. The sediment samples of the rock glacier in the Unnützes Grübl were taken from the western side slope, on the border to the inactive rock glacier UG2 (Sed-UG1), and from the fine-grained front (Sed-UG2) (see Fig. 4.11). The rock fragments of these samples are mainly consisting of muscovite-granite gneiss.
The samples were dried and weighed in the laboratory and then analyzed by means of manual wet screening. The grain size categories of this analysis range from Pebble (64mm/ -6.0Φ) to very fine sand (0.0625mm/ 4.0Φ), whereas the lost material compiles the remaining material, less than 4.0Φ (Silt) (Fig. 4.12).

**Fig. 4.11** Aerial photograph of the Kuhgschwetz and the Unnützes Grübl with the marked locations of taken samples

**Fig. 4.12** Udden-Wentworth Classification after Wentworth (1922); for the analysis the range between the red lines was used
Then the data were processed with using Microsoft® EXCEL. With the help of the resulting diagram and the following formula sorting, skewness and kurtosis could be calculated after Folk and Ward (1957) (Fig. 4.13).

<table>
<thead>
<tr>
<th>Measure</th>
<th>Task†</th>
<th>Ivanov</th>
<th>Folk and Ward</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median</td>
<td>$Md = P_{10%}$</td>
<td>$Md = \phi_{10%}$</td>
<td>$Md = \phi_{50}$</td>
</tr>
<tr>
<td>Mean</td>
<td>$M = \frac{P_{35} + P_{55}}{2}$</td>
<td>$M = \frac{\phi_{36} + \phi_{54}}{2}$</td>
<td>$M = \frac{\phi_{36} + \phi_{54} + \phi_{72}}{3}$</td>
</tr>
<tr>
<td>Dispersion</td>
<td>$Sa = \frac{P_{25}}{P_{55}}$</td>
<td>$\sigma = \frac{\phi_{44} - \phi_{24}}{2}$</td>
<td>$\sigma = \frac{\phi_{44} - \phi_{14} + \phi_{24} - \phi_{54}}{2}$</td>
</tr>
<tr>
<td>Skewness</td>
<td>$Sk = \frac{P_{25}P_{75}}{Md^2}$</td>
<td>$\sigma_{Sk} = \frac{\phi_{32} - \phi_{14} - Md}{sa}$</td>
<td>$Sk = \frac{\phi_{14} + \phi_{44} - \phi_{52}}{2(\phi_{44} - \phi_{14})}$ $+$ $\frac{\phi_{24} - \phi_{52}}{2(\phi_{52} - \phi_{24})}$</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>$K = \frac{P_{75} - P_{25}}{2(Md - P_{10})}$</td>
<td>$\beta = \frac{\phi_{32} - \phi_{14} - \sigma_{2}}{\sigma_{a}}$</td>
<td>$K = \frac{\phi_{24} - \phi_{14}}{2.44(\phi_{32} - \phi_{25})}$</td>
</tr>
</tbody>
</table>

†The formula for kurtosis was proposed by Krumbein and Pettijohn. Many workers have used the square root of Sk rather than Sk itself as a measure of skewness.
- ‡P indicates a percentile measure, measured in millimeters.
- § indicates a φ percentile.

Fig. 4.13 Descriptive measures of sediment-size distributions according to several authors (taken from Blatt et al., 1980)

Results and interpretation

Rock glacier Kuhgschwetz 1

Two sediment samples were taken from the slopes of the front part of the rock glacier, Sed 1 and Sed 2. The grain size distribution curves of both samples show almost the same course.

The sample of Sed 1 contained 85% gravel, 10% sand and the silty amount is about 5%.

The result of Sed 2 contained 81% gravel, 13% sand and 6% silt.
Fig. 4.14 Grain size distribution for the samples Sed1 (blue) and Sed2 (pink). The x-axis represents the phi-values; the y-axis represents the percentage of the different grain size classes.

**Sorting (dispersion):**

\[
\sigma = \frac{[\Phi_{84} - \Phi_{16}]}{4} + \frac{[\Phi_{95} - \Phi_{5}]}{6.6}
\]

\[
\sigma_{\text{Sed1}} = 1.65
\]

\[
\sigma_{\text{Sed2}} = 2.03
\]

In consideration of the sorting of the grain sizes with this formula the value 1.65 (Sed1) and the value 2.03 (Sed2) was calculated. According to the classification of Compton (1957), this is a matter of poorly to very poorly sorted material, which is comparable to the grain size distribution of a lodgment till. This result is quite normal for the fine-grained slope of a rock glacier.

Fig. 4.15 Classification of degrees of sorting as seen through square hand lens; silt and clay size sediments are indicated by fine stipple. Values of standard deviation that divide each class of sorting are also shown [R. R. Compton, 1962, Manual of Field Geology (New York: Wiley)]

(Taken from Blatt, 1982)
Skewness:

\[ SK = \frac{[Φ_{16} + Φ_{84} - Φ_{50}] / 2(Φ_{84} - Φ_{16})} {[(Φ_{95} + 2Φ_{50}) / 2(Φ_{95} - Φ_{5})]} \]

\[
SK_{Sed1} = 16.74 \\
SK_{Sed2} = 14.85
\]

The skewness is the measure of the asymmetry of the distribution and it shows how well a sample is distributed. In this case both samples show invalid values of 16.74 (Sed1) and 14.85 (Sed2). Normally the values should range between -1 and +1.

Kurtosis:

\[ KG = \frac{[(Φ_{95} - Φ_{5}) / 2.44](Φ_{75} - Φ_{25})]} {[(Φ_{95} - Φ_{5}) / 2.44](Φ_{75} - Φ_{25})]} \]

\[
KG_{Sed1} = 3.32 \\
KG_{Sed2} = 4.46
\]

The kurtosis is a measure of the steepness of a distribution and shows, how heavy the distribution of the different grain sizes varies. The steep part between -5 and -2 Φ indicates a sharp increase from the coarse-grained material to the medium- to fine-grained material. The value for the kurtosis of the samples results 3.32 (Sed1) and 4.46 (Sed2), accordingly the diagram shows a distribution with positive excess.

Rock glacier Unnützes Grübl 3

The two samples, UG1 and UG2 also originate from the front part of the rock glacier and were analyzed with the manual sieve analysis. Like the sediment samples of rock glacier KU1, both grain size distributions show almost the same curve.

The sample UG1 is very coarse-grained and consists of 93% gravel, 4% sand and 3% silt. UG2 is also coarse-grained and is composed of 88% gravel, 8% sand and 4% silty material.
Fig. 4.16 Grain size distribution for the samples Sed-UG1 (blue) and Sed-UG2 (pink). The x-axis represents the phi-value. The y-axis represents the percentage of the different grain size classes.

**Sorting:**

\[ \sigma = \frac{1}{4}[\Phi_{84} - \Phi_{16}] + \frac{1}{6.6}[\Phi_{95} - \Phi_{5}] \]

\[ \sigma_{\text{UG1}} = 0.99 \]
\[ \sigma_{\text{UG2}} = 1.38 \]

The calculation of the sorting of UG1 shows a value of 0.99, which is (after R. R. Compton, 1962) in the range of poorly sorted material. The sample UG2 results a value of 1.38. This value also indicates poorly sorted sediments.

**Skewness:**

\[ Sk = \frac{1}{2}[\Phi_{16} + \Phi_{84} - \Phi_{50}] + \frac{1}{2}[\Phi_{5} + \Phi_{95} - 2\Phi_{50}] \]

\[ Sk_{\text{UG1}} = 3.65 \]
\[ Sk_{\text{UG2}} = 7.55 \]

Like the samples of the rock glacier KU1 the skewness of these samples show invalid values too and can not be used for further interpretation.

**Kurtosis:**

\[ KG = \frac{1}{2.44}[\Phi_{95} - \Phi_{5}] \]

\[ KG_{\text{UG1}} = 1.02 \]
\[ KG_{\text{UG2}} = 2.99 \]
The calculation of the kurtosis results a value of 1.02 (UG1) and 2.99 (UG2). The first value, which is smaller than the second one indicates, that there is a stronger variation within the grain-size distribution of UG1. The diagram shows, that there is a kind of a kink in the curve in the range between -5 and -1 $\Phi$, which indicates a sudden change between coarse-grained and finer grained material. This change is smoother in the curve of distribution of UG2.

### 4.3.1. Grain size measurements on the surface of rock glaciers

Every rock glacier owns a mantle of debris, which varies between usually 2 and 5 m in thickness. The sizes of the boulders, which build up the mantle, also vary within different areas on the rock glacier. In order to analyze the distribution of different grain size of these coarse-grained components on the surface of the rock glaciers, grain size measurements were carried out in summer and autumn 2010. Therefore, 200 components within selected areas of about 5 x 5 m were measured in their longest diameter. These measurements were carried out three times on two different rock glaciers each, on the rock glacier Kuhgschwetz KU1 and in the Unnützes Grübl, on the rock glacier UG3 (Fig. 4.17). Both are estimated to be active.

![Aerial photograph of the Kuhgschwetz on the right and the Unnützes Grübl on the left, with marked grain size measurement positions on the surface of the rock glaciers KU1 and UG3 (represented in Google Earth)](image)

**Fig. 4.17** Aerial photograph of the Kuhgschwetz on the right and the Unnützes Grübl on the left, with marked grain size measurement positions on the surface of the rock glaciers KU1 and UG3 (represented in Google Earth)
### Table 7
The table shows the percentage of different grain sizes of the boulder mantle of the rock glaciers KU1 and UG3

<table>
<thead>
<tr>
<th>Grain size</th>
<th>KU-KG1</th>
<th>KU-KG2</th>
<th>KU-KG3</th>
<th>UG-KG1</th>
<th>UG-KG2</th>
<th>UG-KG3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10 cm</td>
<td>16,5</td>
<td>6,5</td>
<td>24,5</td>
<td>26</td>
<td>19</td>
<td>46</td>
</tr>
<tr>
<td>11-20 cm</td>
<td>22</td>
<td>15,5</td>
<td>21</td>
<td>22,5</td>
<td>21</td>
<td>28</td>
</tr>
<tr>
<td>21-30 cm</td>
<td>11,5</td>
<td>20</td>
<td>11,5</td>
<td>12,5</td>
<td>9</td>
<td>6,5</td>
</tr>
<tr>
<td>31-40 cm</td>
<td>6,5</td>
<td>18</td>
<td>11</td>
<td>9</td>
<td>15</td>
<td>7,5</td>
</tr>
<tr>
<td>41-50 cm</td>
<td>7,5</td>
<td>13</td>
<td>7,5</td>
<td>6</td>
<td>7,5</td>
<td>4</td>
</tr>
<tr>
<td>51-60 cm</td>
<td>10</td>
<td>9,5</td>
<td>6,5</td>
<td>8</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>61-70 cm</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>3,5</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>71-80 cm</td>
<td>4,5</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>4,5</td>
<td>0,5</td>
</tr>
<tr>
<td>81-90 cm</td>
<td>3,5</td>
<td>3,5</td>
<td>3</td>
<td>1,5</td>
<td>3,5</td>
<td>1</td>
</tr>
<tr>
<td>91-100 cm</td>
<td>1,5</td>
<td>1,5</td>
<td>1,5</td>
<td>2</td>
<td>0,5</td>
<td>1</td>
</tr>
<tr>
<td>&gt;101 cm</td>
<td>10,5</td>
<td>4,5</td>
<td>6,5</td>
<td>4</td>
<td>7</td>
<td>1,5</td>
</tr>
</tbody>
</table>

Rock glacier Kuhgschwetz 1

On three different locations on KU1 grain size measurements of the coarse-grained mantle were carried out. Afterwards, the data were evaluated with Microsoft© EXCEL and represented in a diagram (Fig. 4.18).

**KU-KG1:** The first measurement was made on the lower part of the rock glacier, near the western slope at an altitude of 2560m. The debris in this area is mainly coarse-grained and the average grain size is 59cm. The majority of the clasts show a grain size between 1 and 30cm. There is a strong variation in the percentage, which reaches a second maximum with 11% for the amount of boulders bigger than 1m. The largest block measured a length of more than 2m.

**KU-KG2:** This measurement was carried out in the rear part of the rock glacier, near a depression at an altitude of about 2700m. The debris in this area turned out to be more fine-grained, compared to the debris of KU-KG1. The average grain size is 41cm and most of the clasts measured a length
between 11 and 40cm. Only 17.5% of the clasts display grain sizes above 60cm.

**KU-KG3:** This measurement was located near the front of the rock glacier a 2440m, near the eastern slope. 36cm is the average grain size and the maximum lies between 1 and 20cm. But the grain size increases in the range of more than 1m up to 13%. The largest blocks measure more than 1.80m in their longest axis.

![Grain size distribution KU1](image)

**Fig. 4.18** Grain size distribution on the surface of the active layer of the rock glacier KU1 in the Kuhgschwetz. This diagram shows mostly fine to medium grained areas.

**Rock glacier Unnützes Grübl 3**

Measurements of the grain size distribution were carried out on three locations on rock glacier UG3. The data were also evaluated and presented in a diagram (Fig. 4.19).

**UG-KG1:** This point was located near the front of the rock glacier, near the slope at an altitude of about 2650m. The distribution shows mainly fine-grained material, whereas 26% of all measured clasts are between 1 and 10cm
and 48.5% are between 1 and 20 cm. The average diameter of the boulders is 34 cm. Only 4% have diameters of more than 1 m, but some clasts even more than 3 m.

**UG-KG2:** This measurement was also carried out near the front of the rock glacier, near the eastern slope at an altitude of 2660 m. The clasts in this area are in average 40 cm large and the biggest clasts reach a length of more than 2 meters. About 7% of the clasts are bigger than 1 m.

**UG-KG3:** The grain-size distribution was also determined bear the central part of the rock glacier at 2660 m. This area showed a very fine-grained material, with an average diameter of the clasts of 21 cm. 74% of all measured clasts measure between 1 and 20 cm and boulders with diameters of more than 1 m are very rare. Clasts with diameters up to more than 2 m were observed.

![Grain size distribution UG3](image)

**Fig. 4.19** Grain size distribution on the surface of the active layer of the rock glacier UG3 in the Unnützes Grübl. This diagram shows mostly fine-grained areas.
4.4. Bottom temperature of the snow cover (BTS)

BTS measurements are a relatively cheap and an indirect method to establish the appearance of permafrost below a more or less thick layer of debris. The isolation of an 80 cm thick snow cover is sufficient to protect the ground-surface of radiation and air-temperature variations. According to Haeberli (1973) a BTS of less than -3°C is a reliable indicator for the existence of permafrost in the underground. If the measured temperatures are climbing over -2°C, permafrost is unsure.

The BTS loggers are usually installed in fall before the first snowfalls, and they get collected after the thawing period in early summer.

4.4.1. BTS of the winter period 2009-2010

Rock glacier Kuhgschwetz 1

On October 27th, 2009 six temperature loggers were installed in the blocky surface of the rock glacier KU1 to measure the temperature at the bottom of the snow cover during the winter season. They were placed on the rock glacier in a transect from the west to the east to get a profile of temperatures across the rock glacier. Two loggers were installed in front of the rock glacier to measure the BTS temperatures on permafrost-free ground. The measuring period started on November 1st, 2009 and ended on June 16th, 2010.

Fig. 4.20 Positioning of a data logger on the surface of the rock glacier Kuhgschwetz 1
The Temperature loggers were positioned and fixed on selected localities (Fig. 4.21), and these were marked with bright, pink marker spray. Furthermore GPS waypoints were taken, so that they could be found in the following spring.

**Fig. 4.21** Aerial photograph of the rock glacier Kuhgschwetz with the positions of the BTS loggers T1, T2, T3, T4, T5, T12, T14 and T17 (represented with Google Earth)

**Results of BTS measurements**

The diagram below (Fig. 4.21) shows, that the logger T1, which was installed in the front of the rock glacier on permafrost-free ground, continuously measured temperatures around 0°C, which is quite normal at the base of a snow cover. Logger T2, which was also positioned besides the rock glacier, shows very low temperatures during December. Probably there was no snow cover at this location and the logger was measuring the air temperature.

The loggers, which have been installed on the surface of the rock glacier, were measuring beneath a closed snow cover since the end of December and show minimum temperatures of about -12.5°C in January 2010. That minimum was measured in the central part of the rock glacier (logger T12). Loggers T3, T4, T5, T14 and T17 show similar temperatures during the whole winter and spring season. The values increased from the end of Mai 2010 until the end of the measuring period, with the thinning of the snow cover due to melting in spring.
Fig. 4.22 This diagram shows the variation of the temperature during November 2009 to June 2010 on the rock glacier Kuhgenschwetz at the base of the snow cover (BTS).

Interpretation

By measuring the BTS on permafrost-free ground outside the rock glacier (number T1 and T2) it was possible to find out, that there is a great difference of the temperatures on the rock glacier to the loggers that have been installed besides the rock glacier. The temperature at the base of the snow cover is around 0°C, which is not the case for the other 6 loggers. They show temperatures of approximately -5°C, what is significant for a cooling source beneath the layer of debris. Probably there are ice lenses, a massive body of ice or only ice cemented debris, which is isolated below the snow cover and cooling the surface of the rock glacier down.

In the central part of the rock glacier the BTS temperatures are lower than in the marginal parts. It is possible, that the thickness of ice increases towards the central part, where logger T12 was installed, or the cover of debris is not as thick as in the lateral areas, where the highest temperatures were measured.

The high temperature variations of the individual loggers may be caused by the thermal flow within the permafrost body or the penetration of cold air due to the variation of the thickness of the snow cover.
4.4.2. BTS of the winter period 2010-2011

Rock glacier Kuhgschwetz 1

In 2010 a total of 13 BTS loggers were installed to measure the temperatures at the base of the winter snow cover on three rock glaciers in the study area. Four loggers were positioned on rock glacier KU1 for a second time to compare these data to the temperatures, which were measured from 2009 to 2010. For this purpose the loggers T1, T4, T12 and T17 were selected to measure at the same location than the year before.

Results of BTS measurements
The diagram below (Fig. 4.23) shows that the reference logger T1, which was installed in the front of the rock glacier, recorded temperatures of 0°C. This value is corresponding to the temperature on the bottom of the snow cover. Temperature logger T4 measured almost the same temperatures, as during the previous winter season, but it never recorded data below -5°C. The temperature record of T4 is also much smoother than the other curves. This indicates that this logger was not completely under a closed snow cover. Probably it just measured the air temperature. T12, which reached the minimum in January 2010, shows two minima during the mid of December 2010 with -11°C and at the beginning of February 2011 with a value of -9°C. The lowest temperatures were measured by logger Tube T17 with -16°C during the mid of December 2010.
Fig. 4.23 This diagram shows the temperature variations between November 2010 and June 2011, measured by the loggers T1, T4, T12 and T17. T1 was located on permafrost-free ground.

Rock glacier Stiergschwetz

In fall 2010 4 BTS logger were installed on the rock glacier Stiergschwetz, in the southwestern part of the study area. This rock glacier is located in front of the Sommerwand glacier and it is supposed to be inactive or fossil. One logger (BTS-T2) was installed in front of the rock glacier to measure the reference temperature at the base of the snow cover on permafrost-free ground. Two loggers (BTS-T12 and BTS-T3) were installed near the front of the rock glacier and BTS-T5 near the rooting zone (Fig. 4.24).

Fig. 4.24 Overview of the rock glacier Stiergschwetz with the marked positions of the temperature loggers BTS-T2, BTS-T3, BTS-T5 and BTS-T12 (represented in Google Earth)
Results of BTS measurements
The temperatures measured on the rock glacier Stiergschwetz show completely different results (Fig. 4.25) compared to the temperatures recorded on Kuhgschwetz 1. The temperatures of the loggers BTS-T2, BTS-T5 and BTS-T12 show similar trends. They did not record temperatures below -2°C. However, logger BTS-T3, which was located near the front of the rock glacier, recorded temperatures of -8°C. The curve of this logger is also much smoother and does not show any short-time variations. An explanation would be the existence of an ice-lense in the frontal, thicker part of the rock glacier, because even the temperature loggers in the central part of the rock glacier do not show any influence by permafrost.

![BTS Stiergschwetz 2010-2011](image)

**Fig. 4.25** This diagram shows the temperature variations between November 2010 and June 2011, measured by the loggers BTS-T1, BTS-T3, BTS-T5 and BTS-T14

**Rock glacier Unnützes Grübl 3**

Four temperature loggers were installed in the Unnützes Grübl in front of the rock glacier (reference-logger BTS1), in a rock glacier spring (BTS-Pegel) and on the debris mantle of rock glacier UG3 (BTS2 and BTS4). BTS-Pegel will be collected in fall 2011 to get more information about the water temperature of rock glacier spring (Fig. 4.26).
Results of BTS measurements
The following diagram (Fig. 4.27) shows the temperatures, which were recorded during the winter period of 2010 to 2011 in the area of the Unnützes Grübl. Temperature logger BTS1 was installed in front of the rock glacier UG3 and measured the reference temperatures, where no permafrost was expected. The measured values showed temperatures slightly below 0°C between the November 1st, and the beginning of May, until the snow was completely melted. The temperatures of loggers BTS2 and BTS4 show a similar trend between the mid of December and the end of April. Both show a negative peak at the beginning of February, where the snow cover seemed to be the thickest. The temperatures were in a range between -6°C and -8°C. The minimum temperature of almost -11°C was recorded by logger BTS4, which was installed in the central part of the rock glacier.
Interpretation

Kuhgschwetz 1
The results of this measuring period confirm the existence of a cooling source beneath the debris mantle. Particularly loggers T12 and T17 measured very low temperatures, which are a reliable indicator for the existence of permafrost at the base of the isolating snow cover. Comparing these data with the temperatures of the previous year, a similar trend is visible, which supports the theory, that there is probably an ice core under the more or less thick debris cover.

Stiergschwetz ST
Due to the results of the BTS measurement on this rock glacier it is unlikely, that there is any permafrost or glacier ice below the debris layer. The temperatures on the bottom of the snow cover did not reach values below -2°C, except at one location. BTS-T3 measured temperatures, which indicate, that there is still ice beneath the surface. This rock glacier is expected to be inactive.
Unnützes Grübl 3

The low temperatures, which were recorded by logger BTS4 indicate, that there is permafrost beneath the surface, which is responsible for temperatures of almost -11°C. This rock glacier is located in a cirque, where until 40 years ago a glacier still existed. It is likely, that this rock glacier developed out of this glacier during its retreat. Thus it is very likely, that there is a massive ice core beneath the debris layer of rock glacier UG3.

Comparing the measurement results of the winter period 2010 to 2011, it is remarkable, that the deepest temperatures were always measured between the mid of November until the mid of December. Compared to the climate data measured at the Franz-Senn Hütte that the time of the first snow fall, was in the end of November. At this time it was also cold enough for a remaining, closed snow cover. This peak is the air temperature and signalizes, that the thermal regime on the surface of a rock glacier under the snow cover needs some time to find its equilibrium, where the temperature usually stays under -5°C.

4.5. The geology of the study area

4.5.1. Rock types

The rocks explored in the study area belong to the metamorphic basement of the Ötztal-Stubai Complex. These rocks are of sedimentary and magmatic origin and were mainly overprinted under amphibolite-facies conditions during the Variscan Orogeny. The rocks in the study area are mainly composed of amphibolite (Hornblende gneiss), different types of orthogneiss and subordinary mica-schist (Haimeyer, 1969). In his geological guidebook about the Ötztal and Stubai Alps, Purtscheller (1978) mentions the expression “Alpeinergranit” (after Hammer, 1929), which is granodiorite. Haimeyer (1969) describes rust-red weathering crusts on the surface of the “Alpeinergranit” due to its content of iron and manganese. He also comments the red-brown weathering-crusts of the biotite augen-gneiss on the basis of iron contained in biotite. Weathering-crusts of iron and manganese occur in the cold-arid
climate in the apron of glaciers. High surface temperatures of the rocks, due to the high radiation in high mountain areas, the low saturation level of the air and lower air pressure support the development of weathering crusts. Due to evaporation of water in the rocks, dissolved particles of iron and manganese remain on the surface as a crust. The duration of this process depends on the amount of iron and manganese and can last between 1 and 10 years. (Haimeyer, 1969)

Mica schist
This rock type was mainly found within the debris of talus slopes in the Stiergschwetz, where amphibolite crops out, and in the cirque of the Kuhgschwetz, also in association with amphibolite. This let us suspect that mica schist mainly appears intercalated in amphibolites, after Haimayer (1969) also intercalated in biotite granite-gneiss (“Alpeinergranit”). In the area of the Franz-Senn Hütte, next to amphibolite, mica-schist is cropping out too.

This rock type is mainly characterized by the high amount of muscovite. Garnet- and staurolite-crystals may reach centimeter-size and bulge between slightly weathering materials (Fig. 4.28). Biotite and feldspar may be present in small amounts.

Fig. 4.28 Mica schist boulder with bulging, red garnet crystals, which may reach more than a centimeter in size
Thin section photograph of mica-shist. The dark, big grain in the lower left represents a garnet-crystal. Clearly visible are also the layers of muscovite in the upper part of the picture;

**Amphibolite**

Another very common and important rock type in the study area is amphibolite, which appears in a dark green color, due to its high amount of hornblende. It occurs very often as banded amphibolite, as a result of the interlayering of hornblende, which gives it a dark color, and plagioclase, which is responsible for a lighter color. It also contains calcite, which appears as fillings of joints. Amphibolite is expected to be older than the adjacent “Alpeinergranit”, as there are xenoliths floating in the “Alpeinergranit” (Haimayer, 1969). Some boulders of amphibolite show a strong folding (Fig. 4.31 and 4.32) or boudinage (Fig. 4.33) due to the deformation during the Variscian event.

This rock type crops out at many places within the study area, as near the Franz-Senn Hütte and in the area of the Eastern Knotenspitze. Amphibolite also constitutes the majority of the debris cover of the rock glacier KU1.
Biotite granite-gneiss

This rock type is called “Alpeinergranit” in the study area and it is exposed in the cirque of the Sommerwand glacier from the Sommerwand to the Alpeiner Knotenspitze. This rock type is a coarse-grained orthogneiss with biotite as constituent mineral, which gives it the dark and spotty characteristics. Feldspar is mainly represented by plagioclase. Due to the difficult accessibility above the glacier it was not possible for me to map the Biotite-granite gneiss directly at the outcrop. However, it forms the majority of the debris in front of the glacier and the mantle of the rock glacier ST.
Biotite-granite gneiss with a big, biotite flake with fish-structure. The matrix is composed by mainly kalifeldspar, which saussurized by albite and zoisite with needle character.

**Two-mica augen- and flasergneiss**

Augen- and Flasergneiss is almost everywhere present in the study area and represents the main rock type. It is older than the biotite-granite gneiss and has changed more significantly. The appearance of two-mica (muscovite and biotite), is one of the key features. Due to tectonic stress muscovite has often transformed into sericite (Haimayer, 1969). The amount of biotite changes from the east, where muscovite is dominating, to the west. Feldspar is mainly represented by kalifeldspar, which is often modified by sericitization. Kalifeldspar appears very often as augen (Fig. 4.38) and shows twinning lamellae in the section.

**Fig. 4.36** Crossed nicols, width of photograph: 6.3mm  
Location: Stiergschwetz

**Fig. 4.37** Parallel nicols, width of photograph: 6.3mm  
Location: Stiergschwetz

**Fig. 4.38** Two-mica augen gneiss in the area of the Kuhgschwetz. Very conspicuous are the white feldspar crystals, which were deformed during metamorphism.
4.5.2. Tectonics

The study area is located within the austroalpine basement, which has a narrow and steep folding, traceable over long distances. There are only a few synclines and anticlines with very thick limbs.

The Alpeiner Valley (area of the Franz-Senn Hütte) is located in the south of an east-dipping synclinal axis, which runs from Östen to the Seejöchl. Thus, the foliations are dipping to the north or to the northeast. (Haimayer, 1969)

Within the study area, in the Stiergschwetz, the Kuhgschwetz and in the Unnützes Grübl measurements of the dipping and dip direction of the foliation planes and some faults were carried out. The measurements were processed with the program TectonicsFP and were plot in rose diagrams.

The first diagram (Fig. 4.41) shows a rose diagram of the direction and the dipping of the foliation plains of orthogneiss and amphibolite in the Stiergschwetz. The foliations of both rock types, two-mica augen gneiss and amphibolite, is dipping with an angle between 50° and 80° towards the west and northwest. This causes a high production of debris, especially at the north-exposed slopes in the southern part of the Stiergschwetz, which is required for the development of rock glaciers.
The following rose diagram (Fig. 4.42) shows the dip directions of the foliations within the area of the Kuhgschwetz of the same rock types, as in the Stiergschwitz. The dipping of the foliations show almost the same values, between 50° and 90°. However, the dip directions are mostly directed to the northeast, at the western slopes, and to the northwest, at the slopes of the cirque. This situation also causes a high production of debris in the cirque of Kuhgschwetz, that supplies the rock glaciers.
The rose diagram (Fig. 4.43) shows the measured values within the area of the Unnützes Grübl. The value for the dipping of the foliation of exclusively two-mica orthogneiss is always very high between 80° and 90°. The direction of dipping is mainly towards northwest and west.

In the field it is obvious, that the southern slopes of the cirque of the Unnützes Grübl deliver the highest amount of debris. Due to the inaccessibility of this part of the study area it was not possible to carry out more measurements. The high grade of decomposition and fracturing of the rock walls causes high rockfall activity (Fig. 4.44).

**Fig. 4.43** Rose diagram of the measured Dip/Dir values for the Unnützes Grübl; these values were measured on outcrops of orthogneiss
Fig. 4.44 Southern slope within the cirque of the Unnützes Grübl; decomposition of the rocks lead to a high entry of debris, and supplies the development of rock glaciers

4.6. Quaternary phenomena

Thufur
Besides rock glaciers there are other interesting periglacial phenomena present, like Thufur, which are also called “Bültenböden” in German. The term “Thufur” originates from the Icelandic term “Thufa”, which was defined by the Icelandic geologist Thoroddson in 1913. This periglacial phenomenon is typical for arctic and subarctic regions, but it is also common in alpine regions. Thufur are built up by mainly fine-grained material and a cover of vegetation, a core of permafrost ice is generally missing (Schunke, 1977). They usually appear extended as bump-shaped features with a height of 50cm and a diameter up to 1m (French, 1996), but they may also build up plateaus or walls. Thufur are observed in many parts of the study area (Fig. 45 and Fig. 4.46).
Solifluction

Another periglacial phenomenon is solifluction, which is found in the Stiergschwetz, near the Franz Senn Hütte, and in the Kuhgschwetz at the slopes below the Kuhspitz and the Platzenturm (Fig. 4.47). Solifluction is an extensive, downward directing, periglacial phenomenon, which occurs due to the thaw of the water saturated active layer above the permafrost body. The water reduces the friction of the soil, which is usually composed of fine-grained sand, silt or clay. The soil begins to creep with a velocity up to 30cm per month, depending on the angle of the slope (>2°), saturation of water and sediment type (Krainer, 2007).
Talus slopes
Talus slopes develop due to cliff sapping of the rock walls are found in every part of the study area. They deliver debris for the rock glaciers, mainly two mica augen-gneiss (Unnützes Grübl, Kuhgschwetz), Amphibolite (Kuhgschwetz) and biotite granite-gneiss (Stiergschwetz) (Fig. 4.48). The formation of detritus is the largest at the slopes exposed to the north within the study area, where frost weathering seems to be very high.

![Talus slopes in the southern part of the Stiergschwetz, near rock glacier ST](image)

Fig. 4.48 Talus slopes in the southern part of the Stiergschwetz, near rock glacier ST

Moraines and morainic ramparts
Within the entire study area morainic deposits can be found as lodgement till, which covers the apron of the rock glaciers and glaciers. A lodgement till is deposited at the base of a glacier and also gets highly compressed by the load of the glacier and gives the material a very high strength.

There are also moraine ramparts, which are observed especially in the apron of the Sommerwand glacier in form of lateral and terminal moraines (Fig. 4.49). But also in the apron of the Kuhgschwetz morainic ramparts are visible. Sometimes, when a glacier retreats, these walls can dam a lake of melt water and they can also be used to retrace the process of the glacial retreat.
Roche moutonnée
This phenomenon occurs due to the abrading strength of a glacier. It is also called “sheepback” in English or “Rundhöcker” in German. The most beautiful examples for a roche moutonnée can be found in front of the rock glaciers in the area of the Unnützes Grübl (Fig. 51). These are solid rocks with an asymmetric, convex shape, with a frontal, steep part and a longer, rear part. When a glacier flows over the surface of a solid rock, the surface, which faces the glacier gets into direct contact with the glacial ice. Due to the high pressure the ice on the basis melts and seeps into little cracks at the lee-side of the rock. The meltwater freezes again due to the movement of the glacier the process of plucking occurs, which means, that the surface at the lee-side splits into pieces and gets eroded by the glacier (Fig. 4.50). (Sugden, 1992)
Fig. 4.51 Roche moutonnée in front of the rock glaciers UG3 and UG4
5. **PERMANET**

5.1. **Description of the project**

PermaNET (Long Term Permafrost Monitoring Network) is a project of the European Union for acquisition and monitoring permafrost areas in the Alps. Under coordination of the Autonomic Province of Bozen there are overall 13 partners located in the affected areas from Switzerland, Austria, France and Italy, who are involved in permafrost registration and monitoring. PermaNET is founded by the INTERREG IIIB Alpine Space Program 2000-2006.

**Summary**

Permafrost areas are of high sensitivity to climate change. The degradation of permafrost is in close relation to natural hazards for traffic routes, tourism areas, settlements and infrastructures. A missing strategy for considering the consequences of climate change and hazards, developing under changing climate conditions, is the main problem. The main aim of this programme is an Alpine-wide permafrost-monitoring network for preventing natural hazards and contributing to sustainable development. The output should be a permafrost-map for the entire Alpine space and guidelines for the consideration of risk due to permafrost and water resources management. Citizens as governance and politics should get sensitized for the development and utilization of alpine mountain areas. ([www.alpine-space.eu](http://www.alpine-space.eu))

**Climate change in high mountain areas**

The denotation of the melting of mountain permafrost displays a hazard for present infrastructure like roads, skiing areas, railways or settlements. These hazards only become aware if infrastructures get damaged through rock falls or debris flows. However, scientific projects substantiate, that the impact of the melting of mountain permafrost is much bigger as suspected. For example one publication established, that permafrost melting could possibly also be responsible for an abnormal high amount of designated heavy metals in spring water (Bressan, 2007).
5.2. Rock glacier Inventory: Distribution of rock glaciers in the Stubai Alps

Rock glaciers are known from high mountain areas all over the world; in polar, subpolar or even equatorial regions, in alpine regions as well as in areas around sea level, like on Greenland. There are even similar surface structures observed on Mars (Colaprete and Jakosky, 1998).

In the Alps, referring to climatic terms from maritime to continental, the number of rock glaciers increases from the west to the east. The terms and conditions for rock glacier development in the central alpine areas are more ideal unlike the areas with high precipitation located at the margin. Höllermann (1983) defines this observation as peripherally-interior increase of rock glacier spreading. Keep in mind that rock type is also an important factor: in the Austrian Alps most rock glaciers occur in areas composed of metamorphic rocks such as mica schists, paragneisses, orthogneisses and amphibolites (“Altkristallin”)

In contrast to active and inactive rock glaciers, fossil rock glaciers, up to the timberline, have been active under cold and dry paleoclimatic conditions during late glacial times. The lower limit for the narrow belt of active and inactive rock glaciers is located approximately between 2250 and 2500m above sea level, the upper limit between 2800 and 3150m. Above this line only glaciers exist. Using a cross section through the Alps comparing the rock glacier line to the snow line, the snow line increases more towards the core of the central Alps than the lower limit of rock glaciers. Rock glaciers do not react as much on changing precipitation as normal glaciers do (Höllermann, 1983).

In context of the Interreg Project PermaNET (funded by the European Union) a data ascertainment sheet was established (Fig. 5.1) to document all rock glaciers of the Tyrolean Alps. This data sheet includes the following parameters of rock glaciers, which are taken from aerial photographs, laserscan images, field observations and laboratory data. These parameters are:
**Number** (depending on catchment area)

**Identification Number** (geographical ID)

**Basic Data**
- Easting
- Northing
- Mean Altitude
- Altitude of the Front
- Altitude of the Rooting Zone
- Maximum Length
- Maximum Width
- Area
- Exposition
- Surface Topography
- Shape
- Development
- Activity (active, inactive, fossil)

**Hydrology**
- River Catchment Area
- Local Catchment Area

**Geology**
- Mountain Range
- Type of Bedrock

**Hydrogeology**
- Springs
- Existing Water Analysis (yes/ no)
- Concentration of heavy metals (yes/ no)
- Data on water gouges (yes/ no)
- Literature (yes/ no)

---

**Fig. 5.1** Data ascertain sheet including important parameters for an inventory (in German)
Distinguishing active, inactive, and fossil rock glaciers by using aerial photographs (Fig. 5.2) or laserscan images is often difficult. The true status of a rock glacier can normally only be defined through geophysical measurements, core drillings, and measurements related to their movement. However, the ascertainment of rock glaciers in Tyrol delivers following data:

In the Austrian part of the Ötztal and Stubai Alps 1200 rock glaciers occur, 355 of them being classified as active, 350 as inactive and 495 as fossil. Most of these rock glaciers are exposed towards NNW to NNE. Rock glaciers, which are exposed to the south are very rare and occur at altitudes about 400m higher than those exposed towards a northern direction. The latter occurs in altitudes between 2600 and 2850m. The largest rock glaciers, like the Reichenkar rock glacier in the Stubai Alps, reach a maximum length of about 1650m and cover an area of almost 0.6km².

(Krainer, 2010)
Conclusions of the rock glacier inventory in the Stubai Alps

In the Stubai Alps 114 rock glaciers of different status were documented and their data collected. These data were summarized and illustrated in diagrams showing their altitude, their status, exposition and shape.

The Status

Fig. 5.3 shows the percentage of the different rock glacier status of the Stubai Alps. 53% of the rock glaciers in the Stubai Alps were classified as fossil, 29% as inactive and only 18% are still active.

![Pie chart of the percentage of active, inactive and fossil rock glaciers within the Stubai Alps](image)

Altitude and exposition

The diagram below (Fig.5.4) shows the distribution of active, inactive and fossil rock glaciers referring to their altitude and their exposition. It is obvious that most of the fossil rock glaciers occur at lower to medium altitudes between 2000 and 2400m and a high amount of them is exposed to the east. Inactive rock glaciers are mainly located at medium altitudes between 2400 and 2600m. They are dynamically inactive, but they still contain ice and may be reactivated again. At high altitudes between 2600 and 2800m most of the active rock glaciers are located.
One explanation for this distribution may be related to the climate warming, which could have been responsible for the inactivity of active rock glaciers. Due to decreasing temperatures through climate change new, active rock glacier may have developed. This would be an explanation for the lower position of inactive and relict rock glaciers. In the diagram it is visible, that rock glaciers are never exposed to the south, because they prefer regions of lower intensity of radiation and lower temperatures. Active rock glaciers of the Stubai Valley are mainly exposed towards E and NNW.

In addition to the diagram the map below (Fig.5.5) shows the location of active, inactive and fossil rock glaciers in the study area. Active rock glaciers are shown in light yellow, inactive rock glaciers in dark yellow and the fossil rock glaciers in an orange colour. When considering the position of the rock glaciers of different status it seems that fossil rock glaciers occur at lower altitudes. Fossil rock glaciers are normally older than active and inactive ones. They do not contain interstitial ice and after Barsch (1996) they might have been active in a period of 1000 to some thousand years. Therefore, they probably developed during the Pleistocene.
Shape of rock glaciers of different status

The pie chart (Fig. 5.6) shows the distribution of tongue-shaped, lobate and complex rock glaciers (combination of several tongue-shaped and/ or lobate rock glaciers) rock glaciers. It is obvious that tongue-shaped rock glaciers (Fig. 5.7) are the most common type in the Stubai Alps (86%). These rock glaciers may be of periglacial or glacial origin and probably occur mainly due to glacial retreat.

Fig. 5.5 Overview map on the distribution of rock glaciers of different status in the study area

Fig. 5.6 Percentage of different shape-types of rock glaciers
Lobate rock glaciers (Fig. 5.8) are mostly talus-derived and include 12% of all rock glaciers. These rock glaciers developed from talus slopes or moraine material. Only 2% of the rock glaciers display a complex shape.

Fig. 5.7 Tongue-shaped rock glacier in the study area (Kuhgschwetz)

Fig. 5.8 Lobate rock glacier southeast of the Franz-Senn Hütte
Size of rock glaciers

Fig. 5.9 shows the size of the rock glaciers in their maximum length and width. The longest rock glaciers in the Stubai Alps are active, these are up to 1300m long and up to 450m wide and are mostly tongue-shaped. The widest rock glaciers are fossil, lobate shaped with widths up to 500m. Inactive rock glaciers are commonly smaller than active and fossil rock glaciers. Dynamically inactive rock glaciers have no possibility to get larger because the topography allows no further movement.

**Fig. 5.9** Diagram showing length and width of rock glaciers in different status
Fig. 5.10 Rock glacier distribution map of the Stubai Valley
5.3. Core drilling on the rock glaciers “Lazaun” and “Rossbänk”

**Aim of the core-drilling program**

In context of the project PermaNET two core-drillings were carried out (under coordination of the geological survey of the Autonomous Province of Bozen in South Tyrol) in the area of Lazaun Alm in the Schnals Valley (South Tyrol) and in the area of the Ulten Valley (also South Tyrol). The drillings took place between the end of July and mid of October 2010. The aim of the drilling was, to get an insight into the internal structure of a rock glacier and to get information about age and composition of the frozen core through laboratory analysis.

In this paper the documentation and the results of the first core drilling on rock glacier Lazaun will be described in particular and an overview over the drilling on the rock glacier in the Ulten Valley will be given.

In addition, the results of 6 grain size analysis (2 sieve analysis and 4 grain size measurements on the surface of the rock glacier) will be presented and discussed.

5.3.1. Rock glacier Lazaun

This rock glacier was investigated in context of a Master thesis by David Bressan in 2007. The study area is located in the Schnals Valley (Ötztal Alps) in the area of the Lazaun Alm, at the border between Austria and Italy (Fig. 5.11).
Fig. 5.11 Frontal view from the apron to the rock glacier of Lazaun Alm

Fig. 5.12 Location of the core drillings in Schnals Valley (South Tyrol)
The rock glacier at the Lazaun Alm is morphologically characterized through its steep front and its tongue-shaped body. The debris of the rock glacier mainly consist of paragneiss and mica schist, which is delivered from the southern and the western slopes of the cirque. There are characteristic lobes, which are laterally developed towards the snout and longitudinal ridges and furrows are developed towards the rooting zone of the rock glacier. The lowest point at the front is positioned in an altitude of 2480m and the highest point is located at 2700m. The rock glacier is about 660m long and 200m wide. It covers an area of about 0.203km², which is an average size for rock glaciers. The thickness at the front measures about 30m and due to ground penetrating radar measurements it should be also not less than 30m in the upper part. The rock glacier is estimated to be still active. Rocks, which are falling down at the steep front are and indicator for the activity. (Summarized from Bressan, 2007)

There are high interests on this rock glacier because of the chemistry of its melt water. Analysis of water samples taken of all the springs on Lazaun Alm show, that there is an unusual high amount of Nickel in the water derived from rock glaciers and glaciers. It is still unclear, where the high concentration of this heavy metal is derived from.

**Location of drilling: Borehole 1**

The first core drilling was located in the central part of the rock glacier at an altitude of 2580m above sea level in between transversal running furrows and ridges (Fig. 5.12). Because of the difficulty of the topography on the rock glacier the drilling machine as well as the whole equipment was transported to the drilling site by a helicopter. The drilling team consisted of 2 to 3 people of the company LAND SERVICE from Bozen/ South Tyrol. The drilling of borehole 1 reached a depth of about 40 m.
Process of drilling
The beginning of the drilling was on the July 28th, 2010. Because of transport problems with the compressor by helicopter it was not possible to start at the intended date, which was originally set earlier in August.

The technique of drilling was carried out by rotary drilling with a diamond-coring bit. The diameter of the external tube, which was 3m in length, was 168mm, the diameter of the internal tube 131mm.

Originally the cooling inside the borehole was planned to be with air, because of contamination of a possible ice core with cooling water. Through the upper debris-rich, blocky layer of the rock glacier cooling with air was not possible, because the machine would have run hot. Therefore, cooling during the drilling process was consistently done with water. The cooling water was taken from a near located glacial melt water stream and was pumped to the rock glacier by a compressor. Power units ran freezers at the drilling station, which were used to cool the ice-core samples and prevent them from melting. The cores, which contained ice, were marked, isolated and subsequently stored in the freezers. Cores, which did not contain any ice, were marked and stored in wooden boxes.
On July 30th, as at the end of the drilling, the freezers with the ice cores were transported by helicopter to the next village, the ski resort Kurzras, where they were stored until the following transportation to Innsbruck.

Documentation of the drilling process
The drilling was started on July 28th at 2.00 PM. Just one hour later after drilling through the blocky mantle of the active layer the core bit had first contact to ice at a depth of 3m.
On July 29th the drilling was continued. The cores, which were drilled that day, mainly contained debris and smashed, blocky material. Between 5.00 and 12.50m ice was only present filling fractures or as lenses and not as a massive ice core.

On the 30th of July the drilled core contained mainly debris, fractured boulders and only little ice. A higher amount of ice appeared again between 16.50 and 18.00m depth. This day the first load of ice cores stored in the freezers was transported to the ski resort Kurzras, near the Lazaun Alm.
Fig. 5.21 and 5.22 Drilling core containing mainly debris and little ice between 15.20 and 16.50m

Fig. 5.23 and 5.24 Core between 16.50 and 18.00m, which contained mainly ice and subordinately debris and sand

The drilling was continued on August 2nd. On this day the team drilled a 6m long core, mainly consisting of ice with some fractured boulders and fine debris material (between 18.00 and 24.00m depth). However, the core down to 25.00m did not contain ice anymore.

Fig. 5.25 and 5.26 Ice-core associated with debris and smashed rock fragments
On August 3\textsuperscript{rd} only debris and fractured boulders, but no ice was drilled. Down from 28.00m the core also contained sandy and silty material. This day the team reached a depth of 30.50m, in which the material is expected to belong to a lodgment till. That kind of glacial deposit is composed by fractured debris and mainly by sand and silt, and it is highly compressed by the load of the glacier.

On August 4\textsuperscript{th} the drilling was continued without any ice contained in the core, like the material the day before. During the day the next load of cores was transported to Kurzras by helicopter. Because of the great depth, and following the decrease of power of the drilling machine, it was not possible for the team to lift up cores in meter-length. Therefore they had to shorten them to half-meter length. Between 31.50 and 40.00m the core contained only moraine material and some fractured boulders.
Fig. 5.32 Storage box containing the core of mainly moraine material between 31.50 and 34.50m depths.

In the afternoon the core pit broke because the stress between borehole and drilling tube became too high and therefore the drilling at borehole 1 had to be stopped.

Borehole 1: Description of the drilling profile

The drilling profile can be divided into 6 main sections:

1) The first section starts at the surface and reaches down to a depth of 3m. The machine had to drill through decimetre to meter large blocky material of mica schist, which represents the active layer of the rock glacier.

2) In the second section at a depth of 3 to 14m an alternating sequence of decimetre to meter large mica schist-blocks and a mixture of ice, gravel and sand got encountered.

3) From 14 to 16m the drilling went through blocks of mica schist and layers of gravel between them

Fig. 5.33: Simplified profile of the core of borehole 1 taken from Tonidandel et al. ((2010), Autonomous Province South Tyrol Bolzano - Geological Survey Italy, Italy)
4) The fourth layer reaches from 16 to 24 m and represents an alternating sequence of decimetre to meter large blocks of mica schist and a mixture of ice, gravel and sand again.

5) From 24 to 28 m depth the machine had to drill through decimetre to meter large pebbles of mica schist.

6) The sixth sequence also shows blocks of mica schist and intermediate layers of silty and sandy material between 28 and 40 m. This material could be the lodgement till of the rock glacier.

⇒ **Location of drilling: Borehole 2**

The second core drilling was located in the front part of the rock glacier at an altitude of 2538 m above sea level. The drilling team reached a depth of 32 m, until they came upon the lodgement till.

**Borehole 2: Description of the drilling profile**

The drilling profile of the second borehole looks similar to the first one and it can also be divided into 6 main sections:

1) From a depth of 1 to 4 m the active layer of the rock glacier shows very blocky material of decimeter to meter large mica schist rock fragments.

2) The second section represents an alternating sequence of decimetre to meter large mica schist rocks and a mixture of ice, gravel and sand.

**Fig. 5.34** Simplified profile of the core of borehole 2 taken from Tonidandel et al. (2010), Autonomous Province South Tyrol Bolzano - Geological Survey Italy, Italy)
3) In the third section mica schist and intermediate layers of gravel were drilled between a depth of 10 and 16 m.

4) An alternating sequence of decimeter to meter large blocky material of mica schist and a mixture of ice, gravel and sand characterizes the fourth section between 16 and 18 m.

5) The fifth sequence between 18 to 25 m consists of blocky mica schist and intermediate layered gravel.

6) The drilling through the sixth sequence between a depth of 25 to 32 m cropped out a mixture of mica schist with intermediated layers of silty sand and gravel, which is also supposed to be the lodgement till of the rock glacier.

These two drilling profiles were combined to get a profile of the internal structure of the rock glacier Lazaun Alm. In this longitudinal cross section it is possible to see, where layers or lenses of ice are located and how the build-up of a rock glacier may looks like. Based on this profile, also statements about the development and genesis can be made.

![Fig. 5.35 Overview of the drilling locations and the profile from A at borehole 1 to A’ at borehole 2](image)

The profile below was created by Tonidandel (2010) as a possible model of the internal structure of the Lazaun rock glacier. The layer on the top constitutes the active layer of the rock glacier with a more or less constant thickness of about 3m.
Below this layer two layers of ice, partly containing debris and blocky material, were established. These layers are interrupted by layers of debris and blocky, ice-free material. The deepest part is represented by the lodgement till, which underlies the rock glacier and consists of highly compressed silt, sand and fractured rocks.

**Fig. 5.36** Simplified longitudinal cross section of the rock glacier Lazaun Alm. (Profile taken from Tonidandel et al. (2010), Autonomous Province South Tyrol Bolzano - Geological Survey Italy, Italy)

Inclinometers and temperature loggers were installed inside the boreholes to establish the rates of movement and temperatures within the different parts the rock glacier. They are marked with red arrows in the profile above.

**Inclinometer measurements:**

**➔ Borehole 1**

Between August and mid September 2010 movements of 1.2cm have been measured at a depth of 24m. The highest rate, which was measured at the base of the first layer of ice, was about 1.8cm into the flow direction. Down from 24m only movements in a sub-millimeter range could be measured. Movements normal to the flow direction are very small.
Between mid September and mid October 2010 the rock glacier moved about 0.6 cm into flow direction down to a depth of 15m. The highest rates of almost 1cm have been measured at a depth of about 4m. Down from 15m there seems to be only very little movement. The rock glacier moved in average 5mm normal to the flow direction.

Sieve analysis

From two locations at the front slope of the rock glacier Lazaun sediment samples were taken for sieve analysis. The data were processed with Microsoft© EXCEL. The resulting grain-size distribution of these samples show the same trend, but they show a variation in the coarse-grained range between -6 and 0 Φ.

![Grain size distribution Lazaun](image.png)

**Fig. 5.37** Diagram of the grain size distribution of the sediment samples LZ3 and LZ4. The x-axis represents the Phi-values and the percentage is represented by the y-axis.

**Sorting (dispersion):**

\[
\sigma = \left( \frac{\Phi_{84} - \Phi_{16}}{4} \right) + \left( \frac{\Phi_{95} - \Phi_{5}}{6.6} \right)
\]

\[
\sigma_{LZ3} = 2.38
\]

\[
\sigma_{LZ4} = 2.88
\]
Comparing the results of the calculation of the sorting with the definition after Compton (1962), which is discussed in Chapter 4.3.2., the material of both samples is very poorly sorted.

**Skewness:**

\[
Sk = \frac{[\Phi_{16} + \Phi_{5}] + [\Phi_{5} + \Phi_{95} - 2*\Phi_{50}]}{2(\Phi_{95} - \Phi_{5})} \\
Sk_{LZ3} = 14.00 \\
Sk_{LZ4} = 11.50
\]

The value for the skewness is in both cases invalid, as it should range between -1 and +1.

**Kurtosis:**

\[
K_G = \frac{[\Phi_{95} - \Phi_{5}]}{2.44(\Phi_{75} - \Phi_{25})} \\
K_G_{LZ3} = 6.22 \\
K_G_{LZ4} = 15.16
\]

The kurtosis of both samples shows a positive excess, the sample LZ4 more than LZ3, which means, that the variation of the grain size in LZ4 is stronger than in LZ3.

**Grain size distribution on the surface of the rock glacier**

Besides the documentation of the core drilling measurements of the grain size distribution on the surface of the rock glacier Lazaun were carried out. Four locations on the rock glacier were selected, at which 200 clasts were measured in their longest axis within an area of 5 x 5m.
The data were processed in Microsoft© EXCEL to represent the results for the grain size distributions in a diagram.

**LZ-KG1**

On the western part of the rock glacier at the transition to the secondary tongue the debris in this area is relatively fine grained. 38% of the clasts range in diameter between 1 and 10 cm. 4% of the clasts measure more than 1 m in their longest axis. The grain size decreased gradually from 1 cm to 80 cm. The average clast diameter of the site KZ-KG1 was 27 cm.

**LZ-KG2**

The area of this measurement was located in the central part of the rock glacier. The fine fraction between 1 and 10 cm was dominating, but almost 15% of all measured boulders yielded lengths of more than one meter. The biggest clast was more than 3 m long. 37% of the clasts were in the range between 1 and 10 cm. The average length is 48 cm.

**LZ-KG3**

The grain size distribution of LZ-KG3 is similar to the distribution of LZ-KG2 and was carried out on the eastern part of the rock glacier, near the slope. It is mostly fine-
grained and 90% of the clasts showed a length between 1 and 50cm. The average length amounts 22cm.

**LZ-KG4**

The grain size distribution on site LZ-KG4 was calculated from an area near the rooting zone of the rock glacier and shows mostly values in the medium-sized range. The average of the measured boulders is 39cm.

![Grain size distribution Lazaun](image)

**Fig. 5.39** Diagram of the grain size distribution on the surface of the rock glacier Lazaun

**Conclusions and interpretation**

The core drilling on the rock glacier Lazaun provided a good insight into the internal structure of an active rock glacier. Both cores contained ice in form of massive ice, ice-cemented rocks and mixtures of ice and debris. Based on these two drilling cores, which are correlative, it was possible to create a longitudinal profile through the rock glacier with the result, that there are probably two layers of ice.

The upper layer is about 11m thick at the location of the borehole, the lower one is about 5m thick and is interrupted by several layers of debris. The lower, main layer of
Ice is located at a depth of 16.5m and is probably much thinner than the upper layer (7.5m at the borehole LZ1). The model, drawn by David Tonidandel (Geological Survey of the autonomous province Bozen in South Tyrol) is just one possibility to describe the internal structure of the rock glacier Lazaun and should be handled with care. After this model this rock glacier possibly consists of three rock glaciers. At the bottom a lodgement till is present. This means that the area was occupied by a glacier, which is confirmed in the diploma thesis of Bressan (2007). The existence of a former glacier at Lazaun Alm suggests, that these rock glaciers are of glacial origin and developed from a retreating glacier. The lowermost rock glacier, which is in direct contact to the lodgement till, is likely to be fossil and contains no ice anymore. The overlying rock glacier, still contains an ice core or ice lenses and could have developed from a retreating glacier too, like the uppermost part of the Lazaun rock glacier.

The ice cores were transported to the University of Innsbruck for further analysis, which should provide more information of genesis of the rock glacier and the age of the ice.

However, the rock glacier may developed out of a former glacier and contains several ice-saturated areas and possibly a main core.

Another unsolved question is the high amount of the heavy metal Nickel in the water of the rock glacier springs. Possibly the analysis of the ice-samples from the core will provide information about the origin of this unusual high amount of Nickel stored in the rock glacier. It would be interesting, to find out, when the Nickel was deposited in the glacial ice. In my opinion it is possible, that there is a connection between the Little Ice Age (15th to 19th century) and the industrial revolution during the 18th and 19th century, when the concentration of harmful substances in the atmosphere was very high. Due to the advanced glaciation a lot of harmful substances could have deposited on the glaciers through precipitation and could have been stored until today within the ice of rock glaciers, for example. But it would be still unclear, why the high concentration of heavy metals is only measured in the water of certain springs, like in the area of the Lazaun Alm.
5.3.2. Rock glacier “Rossbänk” in the Ulten Valley

The third core drilling in context of the project PermaNET was carried out in the Ulten Valley (South Tyrol) on the rock glacier “Rossbänk”. This rock glacier is located next to the reservoir Grünsee, near Weissbrunn. My fellow student Sabine Watzdorf, carried out the documentation.

This rock glacier is estimated to be in average 35m thick, 1.7 kilometers long, about 200m wide in the frontal part and 600m wide in the rooting zone. This rock glacier consists in total of 3 rock glaciers, which are characterized by all three status of activity: active on the top, inactive in between and fossil at the base. The average altitude of the active rock glacier is 2655m and it is exposed to the east. BTS and geo-electrical analysis were carried out in 2005/2006 in context of the diploma thesis of Patrick Ausserer with the result of the existence of an active permafrost-body beneath the surface.

The area of investigations is part of the Ortler-Campo Complex, thus the debris layer of the rock glacier consists of paragneiss, garnet mica schist and tonalite. About 60% of the clasts measure more than 1m in diameter.

Fig. 5.40 Rock glacier „Rossbänk“, the location of drilling site is marked with the red point, view towards southwest
**Documentation of the core drilling at the rock glacier “Rossbänk” in the Ulten valley**

According to the report of my fellow student Sabine Watzdorf many problems made the drilling very difficult. Due to the large size of the boulders on the surface of the rock glacier it was very hard to find a suitable place for the drilling. Another complication was the lack of a water source to deliver water for the cooling of the drilling machine. Therefore, water supply container and freezer for the cooling of the ice cores had to be delivered by helicopter. Because of other complications during the drilling the planned depth of 100 meters could not be reached by the drilling team. Instead, they had to stop the drilling at a depth of 30m. The program also got retarded because of the bad weather conditions at this time.

**Description of the drilling profile**

The drilling profile of the rock glaciers “Rossbänk” near Weissbrunn in the Ulten Valley contains only the part of the ice layer between 6 and 8m. During the drilling through the active layer and the other unconsolidated layers of fragmented rocks the borehole broke in several times, which caused a lot of problems and time delay. Following, due to the bad quality of the drilling core, only the ice core with a length of 2m was retrieved for further analyses.

The profile shows a core, which mainly consists of a mixture of ice and sand, gravel and blocky material.

![Fig. 5.41 Profile of the 2m long ice core of the rock glacier “Rossbänk” (drawn by Karl Krainer, University of Innsbruck, based on the documentation of David Tonidandel, Geological Survey of the Autonomous Province of Bozen, South Tyrol)]

**Conclusions and Interpretation**

Due to the problems before and during the drilling campaign, the result was just a 2m long drilling core, which consists mainly of ice. This confirms, that the rock glacier “Rossbänk” contains a permafrost body, which is located at a depth of 6m, below the active layer. On this rock glacier no second drilling was carried out. Therefore, it was not possible to get more information about the internal structure of this rock glacier.
3. Discussion and conclusions

3.1. Interpretation of conclusions

Summarizing there are 14 rock glaciers of different status mapped in the study area. Six of them, the largest rock glaciers, are estimated to be active and are probably glacier-derived. Four rock glaciers are probably inactive and four are classified as fossil. The tongue-shaped, active rock glaciers show a steep front slope and are not overgrown by vegetation, except different kinds of moss. They show a distinctive surface topography of longitudinal and transversal ridges. They are all located at altitudes between 2400m and 2800m and are more than 20m thick. The meltwater of these rock glaciers is released through one or more rock glacier springs at the front. The temperature of the spring water ranges between 0.1°C and 1.0°C indicating the presence of ice within these rock glaciers. The electric conductivity lies in a range between 20 µS/cm, and 193 µS/cm with the lowest values during snowmelt in spring and increasing values towards autumn.

The inactive rock glaciers in the study area were less well studied as they are considered to be less important compared to the active rock glaciers. Their front slope is less steep and except for rock glacier ST they do not show a distinctive surface topography. The inactive rock glaciers are located at altitudes between 2500m and 2800m.

The fossil rock glaciers are highly overgrown by vegetation. The front is very flat and they are thinner compared to active rock glaciers as the ice content is completely melted. They show an inarticulate surface topology and are located at lower altitudes between 2100m and 2400m.

The age of the rock glaciers is unsure, as no direct dating methods were carried out on them so far. But the moraines within the study area can help to reconstruct possible ages. The morainic ramparts within the Kuhgschwetz, which are located at lower altitudes, are supposed to be the oldest. They are possibly deposits from the “Egesen” stage, which is dated as 11.000 years before present. Thus the fossil rock glacier, which is partly framed by these morainic walls, is definitely younger than
11,000 years as are all the other rock glaciers within the study area. The active rock glaciers probably developed during the Little Ice Age. However, the morainic ramparts within the Stiergschwetz, which are located in front of the Sommerwand glacier, seem to be very young. Comparing the topographic maps of the Alpine Club they evolved during the retreat of the glacier after the Little Ice Age between 1896 and 1937.

Three rock glaciers were investigated in detail:

**Rock glacier Stiergschwetz**

This rock glacier is located in front of the Sommerwand glacier and supposed to be inactive. This rock glacier is probably less than 10m thick and the front slope has an angle of 35°C indicating that there is probably no activity anymore. Depressions on the surface of the rock glacier indicate that the major percentage of the ice contained inside is already melted. The temperatures of the spring water at the front of the rock glacier range between 1.4°C and 2.0°C. Haeberli (1975) claims that temperatures between 1°C and 2°C indicate that permafrost may be possible. In this case it is unsure if the spring water comes from the rock glacier itself or if it is just runoff from the glacier. The BTS-measurements on the surface of the rock glacier document that permafrost-ice may still be present, possibly in form of ice lenses. That would explain why one temperature logger recorded temperatures of constantly -5°C at the bottom of the closed snow cover.

I assume that this rock glacier is dynamically inactive, as the surrounding topography, which is very flat, does not allow further movement of the rock glacier. This rock glacier probably developed according to the model of a debris-rock glacier. The material of biotite-granite gneiss, which also builds up the rock walls in the rear part of the cirque, was transported and deposited from the Sommerwand glacier. The rock glacier Stiergschwetz probably developed during the end of the Little Ice Age out of an end moraine due to glacier retreat.

**Rock glacier Kuhgschwetz 1**

This rock glacier has a thickness of more than 20m and the gradient of the steep front is 42°. The rock glacier displays a very distinctive surface topology with many transversal ridges near the front and longitudinal ridges in the upper par, where a
depression is present too. A second front has developed at the eastern slope of the rock glacier at an altitude of about 2600m. The grain size distribution shows that the debris in the area of the depression in the upper part of the rock glacier is finer grained than the debris near the front and the side parts. The debris consists mainly of amphibolite, which is derived from the southern slopes of the cirque. There are three rock glacier springs at the front which are partly seasonal. The water temperatures of these springs are in a range between 0.1°C and 0.8°C, which is typical for a rock glacier containing permafrost ice. As well as the water temperatures, the BTS temperatures are indicating, that there is ice beneath the debris mantle. This rock glacier is estimated to be glacier-derived. The depression in the rooting zone is typical for this kind of rock glacier and it is very likely that it developed out of a former cirque glacier, which is shown on old topographic maps of the Austrian Alpine Club.

Rock glacier Unnützes Grübl 3
This rock glacier also has a very steep front with a gradient of 45° and a thickness of probably more than 20m. The surface shows a well developed topography with furrows and ridges, which display compressional flow near the front and extensional flow in the upper part, near the rooting zone. Grain size analysis show a distribution of finer grained material in the central part of the rock glacier and in the area of a furrow, and coarse-grained material near the slopes. There are two rock glacier springs at Unnützes Grübl, whereas one of them (UG-BG1) discharges into a small melt water lake, which is probably contaminated by rain water. The temperatures at the spring show values between 0.2 and 0.6°C, which are indicative for the presence of permafrost. The other spring seems to drain both rock glaciers of the Unnützes Grübl and the water temperature ranges between 0.2 and 0.8°C. The BTS temperature measurements also confirm that this rock glacier contains permafrost ice. A glacier-derived origin is very likely for this rock glacier, as older topographic maps show that there has been a cirque glacier in the Unnützes Grübl, which disappeared between 1970 and 2003.
3.2. Comparison to other rock glaciers in the Alps

As this master thesis mainly deals with the characteristics and genesis of active rock glaciers the results of the investigations in the study will be compared in the following paragraph to two other rock glacier in the Alps: the Reichenkar rock glacier and the Lazaun rock glacier, which was also discussed in chapter 5.

Comparison to the Reichenkar rock glacier
This tongue-shaped rock glacier is described by Krainer and Mostler (2000) and it is in my opinion the best example of an active, glacier derived rock glacier. It is also located within the Stubai Alps, in the Sulz Valley and it is about 1400m long and 160 to 240m wide, which makes it to one of the largest rock glaciers in Tyrol. It is located in a north-facing cirque, which is occupied by the Reichenkar glacier. Like the rock glacier in my study area the surface displays an obvious topography with transversal and longitudinal furrows and ridges and the debris of the mantle are also composed of metamorphic rocks, in this case eclogite and amphibolite. The Reichenkar rock glacier gets drained by a spring at the front, where the meltwater gets discharged. The grain size distributions on the surface of the debris mantle shows similar results to the distributions in the study area and varies depending on their location. The distribution of the fine grained material from the front slope of the snout also shows the same result of poorly sorted material, such as a lodgement till. The temperatures regime on the surface of the rock glacier during the winter season (BTS) is also comparable to the results in the Unnützes Grübl and the Kuhgschwetz. Furthermore, an outcrop of pure glacier ice of the Reichenkar rock glacier was found, which is the evidence, that this rock glacier developed out of a debris covered glacier. In this case, the rock glacier is even still connected to the glacier in the rooting zone. In the study area no outcrop of glacier ice was found, but many similarities to this perfect example of a glacier-derived rock glacier supports the theory, that the rock glaciers in my study area could have also developed out of old, debris covered glaciers.

Comparison to the Lazaun rock glacier
As I documented the core drilling on the Lazaun rock glacier, where I got an insight into the built up of an active rock glacier, I want to compare this rock glacier to the ones within my study area. As described in chapter 5, this rock glacier lies in a
cirque, where remnants of an ancient glacier are still existent. It is also tongue-shaped and shows an indicative furrow- and ridge topography on its surface. The grain size measurements on the surface, as the distributions of the fine-grained material of the snout, are also comparable to the results of the rock glaciers in my study area. The evidence of an ice content within the rock glacier was given by the drilling cores, which were taken in context of the project PermaNET in summer 2010. A possible profile was constructed on the base of these two cores, which illustrates, how the rock glacier could be built up, even though its correctness is unsure. It could be possible, that the active rock glaciers of my investigations look similar inside, but to find out, more geophysical methods or outcrops would be necessary.

The Lazaun rock glacier is also of a high ecologic importance, because of the unusual high concentration of the heavy metal Nickel in the meltwater of the rock glacier and the capture of a glacier spring. The concentration with 0.06-0.07 mg/l even exceeds the upper limit for drinking water quality almost three times, which is a serious problem (Bressan, 2007). The water sample of one the sampling points within my study area, Q5 in the Stiergschwetz, also showed a concentration of Nickel. However, it is with 0.016 mg/l still below the upper limit. It is not unlikely, that the heavy metals of the Lazaun rock glacier are stored within the glacier ice and the permafrost ice of the rock glacier but closer results will be delivered by chemical analysis of the ice core. The origin of the Nickel in the water in my study area is also unsure. It is possible, that it is also stored in the ice of the Sommerwand glacier. As it was just found in the sample, which was taken in fall 2010, it is possible, that it is just measurable in the pure runoff of the glacier after it got influenced by the snow melt. It is still unsure, where the concentration of heavy metals in the melt water has its origin.
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Acknowledgement

First of all I wish to thank the Marshall Plan Foundation in Vienna, which made it possible for me to write this thesis abroad, at the University of New Orleans (USA). During my 4-months stay I made great experiences with other students, the professors and geologists there. It was interesting and impressive to learn about the geology of Louisiana, as there are so many differences between the geology of Austria and the south of the United States. Besides, I learned a lot about the problems, the people in New Orleans have to come along with, and I evolved a lot of respect for how they manage to live with natural disasters like hurricanes or floods. I think this stay gave me besides a linguistic progress, a very special experience I will never forget.

I also wish to thank Prof. Karl Krainer (University of Innsbruck) for his support during my investigations in the field, as for his support and advice during my stay in New Orleans.

Thanks to Prof. Kraig Derstler (University of New Orleans), who was my advisor in New Orleans. He helped me to get along at UNO and paid a lot of attention for my thesis. He is a great teacher and brought me in contact with many geologists.

Prof. Günther Bischof and Gertraud Griessner, who are working at the Center Austria at the UNO helped me to get my J1-Visa for the stay in the USA and supported me with any kind of questions concerning studying at UNO. It was great to have Austrian company, you can always ask for help. Thanks a lot!
Furthermore I thank Mr. Reinhard Aichner and Mrs. Elisabeth Watzdorf, who helped me with my application for the Marshall Plan Scholarship, and also Mrs. Margareth Davidson, who was always ready to answer my questions regarding to the stay in the USA.

My special thanks go to my parents, who always supported me financially as mentally. Without their help it would not have been possible to manage the field work
and they always tried to help me with any problems I had during my stay in New Orleans.

I wish to thank my boyfriend, fellow student and best friend Mathias Egglseder, who supported me measurements in the field and helped me a lot with his geological advice.

I also wish to thank my student fellow and best friend Sabine Watzdorf, who also received the Marshall Plan Scholarship. Her motivation, life experience and her knowledge helped me a lot to get along in the United States and we had a great time together.

Richard Tessadri analyzed the water samples regarding to their element content and Prof. Peter Tropper helped me to characterize the thin sections of my rock samples.

Thanks to Mr. Peter Tumler and his family, who let me stay at their beautiful “Wieshof” during the documentation of the core drilling project in South Tyrol. They were also a great company and were very interested into my thesis.

Thanks to the geologists of the Geological Survey of the Autonomous Province of Bozen in South Tyrol, who supported me during the drilling documentation and provided me important information about the project.

Thanks to all the wonderful people who helped me with my thesis in Austria and in America!