
WP 6 – Action 6.2 – State of the art report

Hazards related to permafrost and to permafrost degradation

Citation reference of the report

Schoeneich P., Dall’Amico M., Deline P., Zischg A., eds (2011). *Hazards related to permafrost and to permafrost degradation*. PermaNET project, state-of-the-art report 6.2. On-line publication ISBN 978-2-903095-59-8.

Downloadable on: www.permanet-alpinespace.eu

Editors

Philippe Schoeneich, Institut de Géographie Alpine, Université de Grenoble, France

Matteo Dall’Amico, Geological service, Autonomous Province of Trento, Italy

Philip Deline, EDYTEM, Université de Savoie, France

Andreas Zischg, Abenis Alpinexpert GmbH/srl, Bozen/Bolzano, Italy

Project reference

European Territorial Cooperation, Alpine Space Programme

Project PermaNET – Long term monitoring network for permafrost, 2008-2011.

ADRA - Association pour la diffusion de la recherche alpine

14 bis av. Marie-Reynoard

F-38100 Grenoble

ISBN 978-2-903095-59-8

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Local ground movements and effects on infrastructures

Citation reference of the chapter

Dall'Amico M., Carton A., Cremonese E., Curtaz M., Morra di Cella U., Paro L., Phillips M., Pogliotti P., Schoeneich P., Seppi R., Zampedri, G., Zumiani M. (2011). Chapter 4: Local ground movements and effects on infrastructures. In Schoeneich P. et al. (eds): *Hazards related to permafrost and to permafrost degradation*. PermaNET project, state-of-the-art report 6.2. On-line publication ISBN 978-2-903095-59-8, p. 107-147.

Authors

Coordination : GST-PAT – Matteo Dall'Amico

Involved PPs and contributors :

- GST-PAT – Giorgio Zampedri, Roberto Seppi, Matteo Zumiani, Alberto Carton
- IGA-PACTE – Philippe Schoeneich
- RAVA and Fondazione Montagna Sicura (Valle d'Aosta – Italy) : Umberto Morra di Cella, Edoardo Cremonese, Paolo Pogliotti, Michèle Curtaz e Stefanie ...
- ARPA Piemonte : Luca Paro
- WSL-EISLF Davos : Marcia Phillips

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Summary fo decision makers

Local ground movements may be defined as phenomena of instability that affect slopes or flat ground in a surface of hundreds to thousands of square meters. Local ground movements are a common feature in permafrost areas, and include:

- Horizontal downslope movements, due to the creep of permafrost bodies.
- Vertical settling movements, due to the melting of ice bodies and/or interstitial ice.

These movements may cause damages to buildings and infrastructures or more rarely represent a hazard for persons:

- Damages to buildings are mainly due to differential settling of the ground. Some mountain huts are endangered by the collapse of the rock foundations.
- Cableways are the most common and sensible infrastructures in alpine permafrost areas. Movements of pylons and of start and end stations lead to problems of cable alignment. It induces increased maintenance costs, and reduces the lifetime of the investment.
- The stability of hazard protection infrastructures can be chngelled by premafrost degradation.
- Thermokarst phenomena due to the removal or compaction of the surface layer can cause substantial damage to planation works like ski tracks or roads.

In many cases, it must be emphasized that the infrastructure may induce itself the degradation of the undelying permafrost, through heat conduction by the infrastructure, or through the modification of the insulation capacity of the ground.

An adapted conception of the infrastructure can, in many cases, avoid both the influence on the permafrost state and damages due to movements.

When planning an infrastructure in a high mountain environement (e.g. above 2400 m), the possible presence of permafrost should always be investigated prior to the conception. The permafrost distribution map can give a first indication. Geophysical methods permit to detect the possible occurrence of frozen ground. But only a drilling can give reliable information on the presence and thickness of ground ice. Monitoring of temperature and movements during at least one year will give more informations on potential surface movements.

If permafrost is present, an adapted design should be developped, such as:

- A thermal insulation in order to avoid heat transmission from buildings into the frozen ground.
- Adapted foundations in order to accommodate movements.

Arctic countries have a long experience in adapted design of infrastructures. Guidelines for building on mountain permafrost were edited by Swiss authorities.

1. Introduction

Usually local ground movements are monitored and studied in low- and middle-range mountain environments, where the interaction and the hazard to human settlements are more elevated. In high mountain range these movements are rarely investigated, because of (1) logistical difficulties, (2) scarce interaction with infrastructures and villages and (3) the low level of knowledge on the phenomena related with the cryosphere.

Recent increase in global temperature and the ever more presence of human tourism and infrastructures in high mountains, has pointed out the importance of a more detailed study of these phenomena.

The presence of permafrost in high alpine environments increases the difficulty in dealing with the analysis of local ground movements. In fact, the current approach on analyzing slope deformations and landslides has often been hydro-mechanical, i.e. the tensions and deformations have normally been related to water pressure and mechanical stress-strain relationship. If this approach may be well suited for low range mountain elevations, this might be insufficient in high elevations, where the thermal effect could play an important role on the stability (Harris). For this reason it is important to start the monitoring of these phenomena in high alpine sites, and include to the current monitoring techniques the measurements of temperature. This will ultimately allow correlating the deformations of the slope to temperature variations. Furthermore, the presence of permafrost and its degradation could be taken into consideration in the analysis, in order to evaluate the hazard of high mountain environments to future climate change.

These movements have rarely been noticed and categorized in the past, due to the remoteness of the locations and the low interest. Nowadays more people are present at high elevations, thanks to winter and summer sports, and so various infrastructures (shelters, refuge, cable cars...) have been built. This has therefore increased the attention on this environment and also opened the path to a regular investigation and inventory of the occurrence of these phenomena. The frequency of occurrence is consequently hard to define because of the scarce database available.

Permafrost, infrastructures and local ground movements are sometimes linked together. Sometimes permafrost has been found while building an infrastructure, e.g. discovering ice cores in the rock. At the same time, local ground movements have been noticed by recording damages in the infrastructures, probably related to permafrost degradation. It is thus important to analyze the effects of local ground movement on infrastructures in an environment characterized by permafrost, in order to infer common problems and find possible correlations between slope movement and permafrost degradation.

2. Typology and involved processes

Local ground movements may be defined as phenomena of instability that affect slopes or flat ground in a surface of hundreds to thousands of square meters.

Local ground movements are a common feature in permafrost areas, and include:

- horizontal downslope movements, due to the creep of permafrost bodies;
- vertical settling movements, due to the melting of ice bodies and/or interstitial ice.

These movements may cause damages to buildings and infrastructures or more rarely represent a hazard for persons.

In the Alps, permafrost occurs only above 2400 to 2500 m asl. Damages to infrastructures and hazards due to direct effect of permafrost related ground movements are therefore usually limited to mountain huts, cable cars, foot paths and trails, ski tracks and access roads to these

infrastructures. In some cases, heavier infrastructures like mountain restaurants, hazard protection infrastructures or power production or transport installations may be affected too.

Damages to buildings

Damages to buildings are mainly due to differential settling of the ground, due to melting of ground ice. The movements can induce damages like fissuring, tilting, or even collapse.

Mountain huts, often built on narrow rock crests or at the edge of rock faces, can be affected by the collapse of the underlying bedrock.

Damages to cable cars

Cable cars are taken here in a generic sense and include: skilifts, chairlifts, cabins and heavy cable cars. These infrastructures are very sensitive to the alignment of the pylons supporting the cable, as a bad alignment may cause the cable to jump out and cause accidents. They are therefore very sensitive to local ground movements.

Many cable cars in high altitude ski resorts are located partially on permafrost bodies. Several cases can be distinguished :

- pylons on permafrost ;
- start or end station on permafrost;
- anchoring in permafrost.

Pylons

If one or more pylons are on a moving permafrost body, problems very similar to those known on slides will occur. The movements of the pylons will disturb the alignment of the cable, needing periodic (usually annual) control and corrections, increasing annual maintenance costs. If small movements can be accommodated by technical adjustments, larger cumulated movements can lead to the necessity of partial or total rebuilding, or even to the abandon of the cableway.

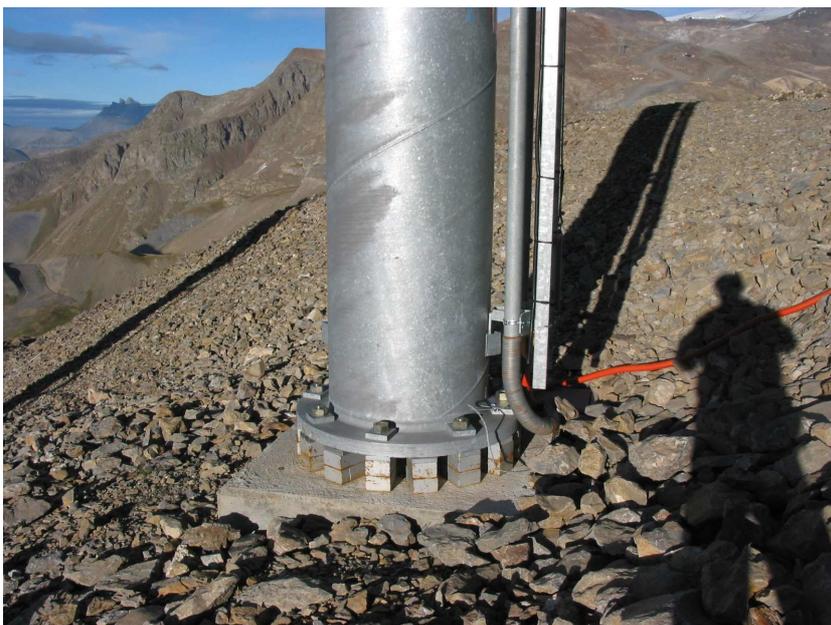


Fig. 4.1 – Chairlift pylon on a rockglacier. Subsidence due to movements and possibly ice melting necessitated adjustment of the pylon by intercalating metal pieces at the base. Adjustment capacity of the screws is exhausted, and any further vertical settling will need partial rebuilding of the pylon.

The problems should be smaller if movements occur in the direction of the cable. But it has to be noted that even small differential movements at the base of the pylon can be amplified on its top by tilting of the pylon in any direction, regardless to the direction of the ground movement.

Start or end station

The problems are almost the same as for pylons and can affect the alignment of the cable. In addition, stations are prone to settling of the ground, due to the thermal disturbance of the permafrost due to the station.

In case of important movements, they could affect the tension of the cable, or even the stability of the station.

Anchoring

Anchoring concerns only heavy cable cars, e.g. the different kinds of cabins. In most cases, anchoring and even pylons will be placed on bedrock, and for large installations, geotechnical investigations will be made before building. It has however to be mentioned, that even anchoring in frozen bedrock needs special measures, in order to avoid to enhance melting and weakening of the bedrock (e.g. case of Klein Matterhorn).

A weakening of the anchoring, due to melting of the permafrost or to local movements, can endanger the stability and the security of the whole installation.

As mentioned above, current problems are usually very moderate and can be solved by annual maintenance, inducing an additional maintenance cost. In some cases partial or total rebuilding or even abandonment of the infrastructure will be necessary. The hazard for persons is almost absent and no accident due to permafrost creep induced causes is reported yet. It has to be emphasized, however, that rock-glacier accelerations or even collapse, due to permafrost warming, could significantly increase the damages in the future, or even cause a threat to security (see chapter on rock-glaciers for more details on velocity variations).

Damages to hazard protections

Avalanche defense structures in permafrost

Avalanche defense structures are built to retain snow in steep avalanche starting zones. These are frequently located at high altitude sites, with unstable ice-bearing permafrost substrates. As costly damage induced by creep and rock fall has frequently been observed, special guidelines for the construction and maintenance of the structures in permafrost have been developed in Switzerland (Margreth 2007) with the aim of improving their performance and prolonging their service life. The guidelines include specifications on methods of permafrost detection, the type of structures and foundations to be used, suitable construction techniques and on various types of monitoring methods. In particular, the use of flexible snow nets is recommended, in combination with floating foundations and specifically developed grout for anchors at sub-zero ground temperatures. The contents of the guidelines are based on results obtained from long-term observations and measurements carried out at sites equipped with avalanche defense structures in the Swiss Alps (e.g. Phillips 2006; Phillips and Margreth 2008). The avalanche defense site *Wisse Schijen* has for example been investigated thoroughly since 1998 and the results are summarized in the case study section.

Earthwork induced « thermokarst »

In the Arctic, the permafrost is known to be very sensitive to any change in surface conditions. This is particularly true in the discontinuous permafrost belt, where the permafrost is covered by soil and vegetation and is in a very precarious equilibrium with climate. Any even small change in the thermal properties of the surface and of the active layer may have dramatic impacts on the thermal regime of the active layer and hence on the permafrost. The peaty soil of this zone is characterized by a very low thermal conductivity and provides a high insulation, so any disturbance of the soil layer will increase heat penetration. Changes in surface albedo are known too to have a high impact on radiation absorption and hence on the thermal regime of the underlying layers. The forest cover plays also a role in the regulation of surface temperatures, and extensive logging is known to be a potential trigger of extensive permafrost melting. These effects can have a very high spatial variability due to the uneven ground ice distribution (ice-wedges and lenses). All this is well known especially through numerous experiences with road constructions, railways, pipe-lines, but also forest logging, etc.



Fig. 4.2 – Road subsidence in the Seward Peninsula, Alaska. The road altered the thermal regime of the active layer and induced melting of the underlying permafrost. It lies now more than a meter below the initial ground surface. Ponds form where the road crosses ice-wedges (photo P. Schoeneich).

This problematic has been paid limited attention yet in the Alps, but could become an issue in the context of both climate warming and extension of ski resorts into high altitudes.

In high Alpine permafrost zones, there is neither vegetation nor soil cover, and one could think that these areas are less sensitive to perturbations of surface conditions. Actually, observations on earthworks made for ski tracks and on roads bulldozed through permafrost areas, show that even slight superficial modifications can induce thermokarst effects like differential settling of the surface, formation of furrows and depressions, needing annual reshaping of the surface.

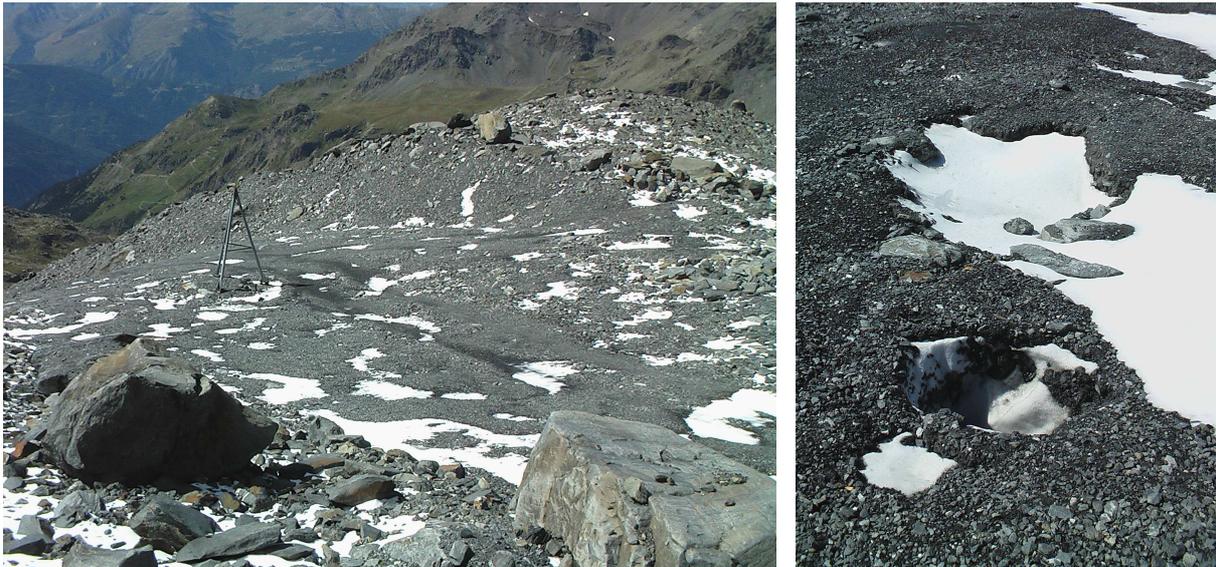


Fig. 4.3 – Ski track planated across the rockglacier complex Le Bouchet (ski resort Orelle, France). The track serves also as access road to the chairlift end station. The snow patches on the track reveal thermokarst features, induced by the removal of the coarse blocky surface layer. Right: detail of a thermokarst hollow. (photos P. Schoeneich, august 2010)

Almost no scientific studies exist on these phenomena, but the following processes can be assumed:

- if the active layer has been removed, a new active layer will form below, causing melting of the ice content. If the permafrost is supersaturated with ice, this will cause settling of the surface;
- earthworks generally induce a compaction of the material. Thermokarst effects can possibly be explained by changes (generally decrease) of the porosity of the surface layer, increasing the thermal conductivity. The high porosity of the coarse active layer is known to provide a thermal insulation and to induce a thermal offset between the ground surface and the permafrost table. The compaction will reduce this thermal offset ;
- if flat zones are created, the outflow of meltwater will be disturbed and it can even lead to stagnation of melt water. The high thermal capacity of water will then cause enhanced local melting ;
- the effect of embankments depends on the material: a porous material can have a positive impact on permafrost conservation as it provides an insulation layer. For this, the embankment must have a sufficient porosity and thickness to allow air circulation. A compact material will enhance thermal conductivity.

The importance of the vertical movements is highly variable. It can be locally limited or cause a general subsidence of the area. The movements can be uniform or highly spatially variable. It will depend on the ice content and on the type of ground ice. Maximal vertical settling is expected where massive ice layers are melting.

3. Case studies

3.1 France

The Bouchet chairlift

Latitude	45,25
Longitude	6,59
Elevation [m a.s.l.]	3000
Slope	moderate
Aspect	North
Type of soil	Rockglacier and fractured rock
Evidence of permafrost	Observation of ground ice, ground surface temperature, geo-electric
Presence of infrastructure	Yes
Type of infrastructure	Chairlift pylons
Evidence of movement	Geodetic survey of pylons, DGPS on blocks
Typology of movement	Rock-glacier creep
Area of phenomenon	mapped
Perimeter of phenomenon	mapped
Year of first data	2007: geophysics, ground surface temperature, BTS, DGPS

Within the Plan Bouchet ski resort (Orelle, Savoie), the Bouchet chairlift is partially built on a rock-glacier: start and end stations are on bedrock, but five pylons are on a moderately active rock-glacier in the middle part, and four pylons are on deeply frost shattered and creeping bedrock in the lower part.

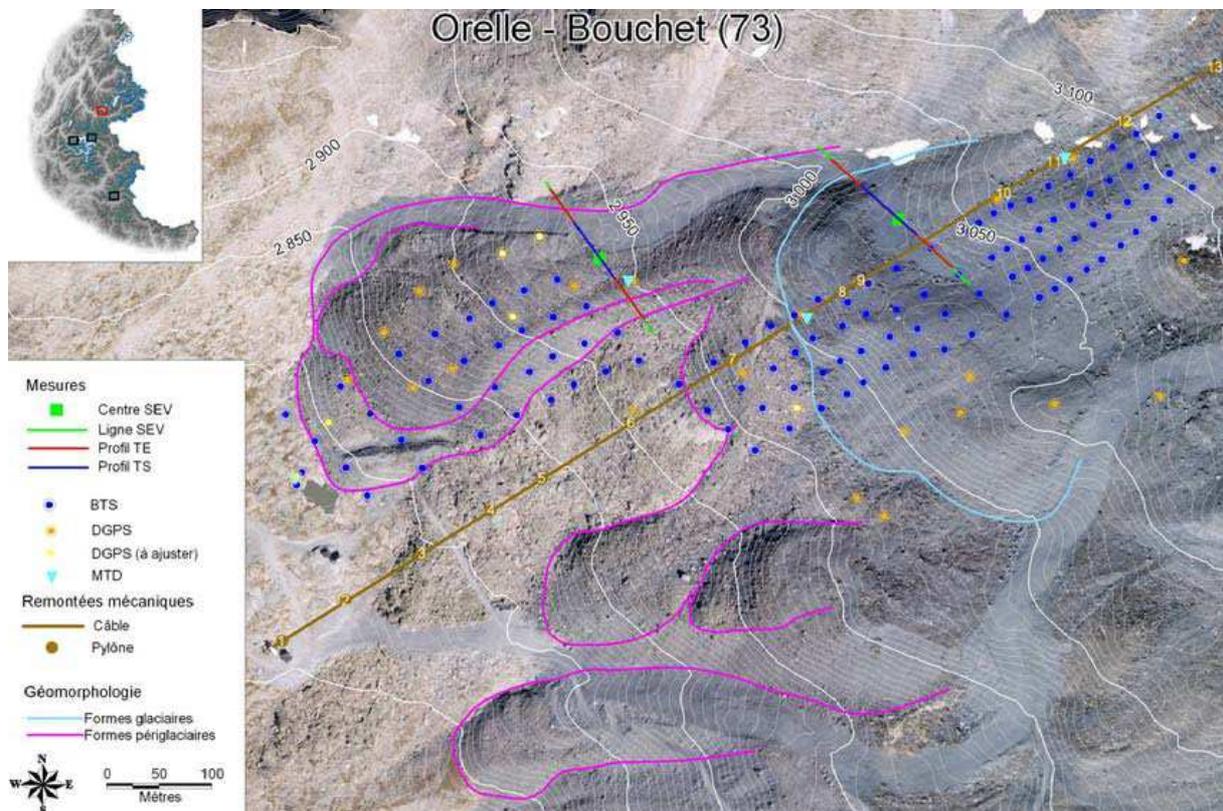


Fig. 4.4 – The Bouchet chairlift. Pylons 3 to 6 are on deeply shattered and creeping bedrock, pylons 6 to 11 are on a rock-glacier. Figure indicates the monitoring points and profiles.

Shortly after construction works the first movements and disturbances were noticed, and in 2005 a geotechnical investigation showed the occurrence of ground ice in trenches at 3.6 m below the surface. Movements of pylons are monitored annually and show ground displacements in the decimeter range, with a maximum of 16 cm y^{-1} . The ground movements occur almost in the direction of the cable, so that disturbances are limited. Alignment of cable has to be controlled and adjusted annually. The chairlift functions only in winter. Adjustment occurs at the end of summer/early winter.

Since 2007, the Bouchet rock-glacier has been monitored for ground surface temperature, surface displacements (in addition to the geodetic survey of the pylons) and two geophysical surveys have been performed in 2007 and 2009.

The presence of ground ice is confirmed by occurrence in exploration trenches in the vicinity of pylons, by frequent occurrences during planation works on neighbouring ski tracks, and is supported by high resistivity in geoelectrical tomographies. The thickness of the coarse blocky active layer can be placed by the seismic interface at 4 to 8 m.

Surface displacements measured by DGPS range from <3 to 20 cm.a^{-1} , in the same range as geodetic measurements on pylons, and vertical settling of a few cm y^{-1} .

On the ski tracks crossing the rockglacier area, extensive thermokarst features are observed. The surface of the ski tracks is regularly reshaped by bulldozers, in order to planate the thermokarst induced irregularities.

The Bellecombes chairlift

Latitude	44,99
Longitude	6,16
Elevation [m a.s.l.]	2710
Slope	moderate
Aspect	North
Type of soil	Rock-glacier and fractured rock
Evidence of permafrost	Observation of ground ice, ground surface temperature, geo-electric
Presence of infrastructure	Yes
Type of infrastructure	Chairlift pylons
Evidence of movement	Geodetic survey of pylons, DGPS on blocks
Typology of movement	Rock-glacier creep
Area of phenomenon	mapped
Perimeter of phenomenon	mapped
Year of first data	2007: geophysics, ground surface temperature, BTS, DGPS

Within the ski resort of Deux Alpes (Isère), the Bellecombes chairlift is partially built on a rockglacier : the start station and the lower and middle parts of the lift are on bedrock. The three last pylons and the end station are on a moderately active rockglacier.

The present chairlift replaces an older one that had to be replaced because of disturbances due to ground movements. Before building the new chairlift, geotechnical investigations have therefore been undertaken, and the location chosen in order to minimize disturbances. Most of the lift could be placed on bedrock, but the uppermost part with the end station had to be placed on a bi-lobate rock-glacier, on a flat area just above the separation of the two rock-glacier lobes.

A 2 to 4 m thick ice lens was encountered below a 4 m thick coarse blocky layer during foundation excavation of the end station, and totally removed.



Fig. 4.5 – Left : the top of the Bellecombes chairlift, with the last pylons and the end station on a rockglacier. Right : ice layer found at 4 m depth during construction of the end station.

Pylons show movements in the decimeter range, the end station slight settling in addition. Cable alignment is controlled and adjusted annually at the end of summer/early autumn. The chairlift functions in winter only.

The rock-glacier has been monitored since 2007 for ground surface temperatures, surface displacements (in addition to the geodetic survey of the pylons) and two geophysical surveys have been performed in 2007 and 2009.

Two boreholes have been drilled in 2009 in the vicinity of the end station, through the left lobe of the rock-glacier. They both show a 2 m thick coarse blocky and ice-free active layer, overlying 7-8 m of pure ice in the lower borehole and of an ice rich ice-rock mixture in the upper borehole, with bedrock at around 10 m. These boreholes show that the total ice thickness exceeds the observed thickness in the excavation, and that the ground ice underlying the end station has probably not been totally removed during construction.

The presence of ground ice was attested during the excavation, the two boreholes and thermokarst phenomena on the ski track just beneath the end station. The presence and extent of a pure ice or very ice-rich permafrost layer is supported by the very high resistivity encountered in all ERT profiles. The thickness of the active layer is consistent with the seismic interface and shows a nearly constant depth of ca 3 m.

Ground surface temperature monitoring indicates a high probability of permafrost, with strongly negative winter equilibrium temperatures. BTS mapping shows a clear ground surface temperature contrast between the cold rockglacier and the warmer surrounding bedrock and debris slope. The geomorphological and thermal limits are consistent with the limits of movements given by DGPS survey, with values in the cm to dm y^{-1} range.

The Bellecombes chairlift illustrates the problematic of foundation work on rock-glaciers and more generally on frozen debris. An ice layer was found during the excavation and removed before building, but in the absence of a drilling it remains unknown if there is more ice beneath. ERT or electrical soundings reveal the probable presence of ground ice, but the very high resistivity of the pure ice lens leads to overestimate its thickness. Finally, only a borehole can give a reliable knowledge on foundation conditions, like thickness of ice-rich layers and depth of bedrock.

3.2 Italy

Rifugio Ai Caduti dell'Adamello

Latitude	46,17
Longitude	11,57
Elevation [m a.s.l.]	3030
Slope	36.6
Aspect	South west
Type of soil	Debris and fractured rock
Evidence of permafrost	Ground temperature
Presence of infrastructure	Yes
Type of infrastructure	Alpine refuge
Evidence of movement	Inclinometric measurements
Typology of movement	Translational slide (in agree with Varnes landslide classification)
Area of phenomenon	Unknown
Perimeter of phenomenon	Unknown
Year of first data	2006: inclinometer, 2009: temperature

GST-PAT has started the monitoring of “Rifugio Ai Caduti dell'Adamello”, a high elevation alpine refuge in the Adamello-Presanella massif in the central Alps (see Fig. 4.6). The refuge is located on a slope and is affected by local ground movements and consequent instability of the building.

At the foot of the refuge three inclinometer boreholes were drilled in order to monitor the displacement of the slope (see Fig. 4.8). They have been equipped with a thermistor chain with data-logger for the monitoring of the temperature profile. After almost one year of measurements, it is possible to trace the thermal profile of the ground (see Fig. 4.9). The bottom of the active layer is located at 11.5m depth along the normal to the slope.

The next step is the evaluation of the correlation between the displacements and the thermal reaction due to permafrost degradation.



Fig. 4.6 – Alpine refuge "Ai Caduti dell'Adamello" 3030m lies on a slope subject to local ground movements.



Fig. 4.7 – Front view of the refuge



Fig. 4.8 – Inclinometer borehole is being equipped by a thermistor chain with data-logger.

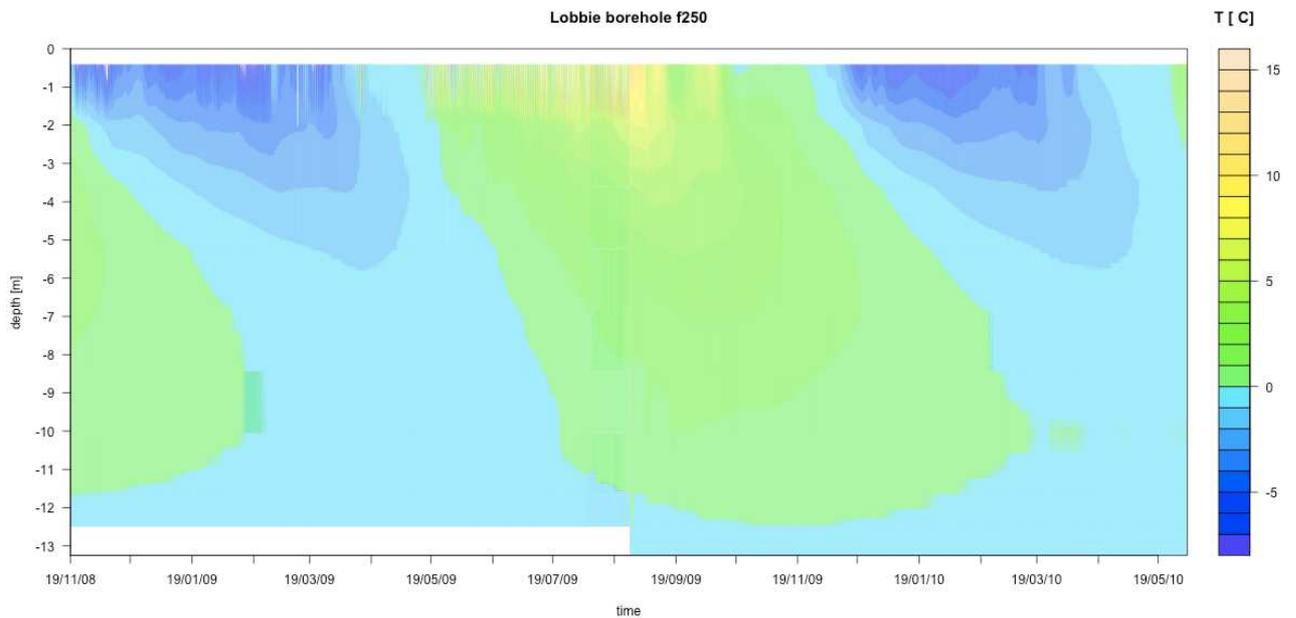


Fig. 4.9 – Thermal profile of the ground at the borehole. The colours indicate the temperature at a particular date and depth

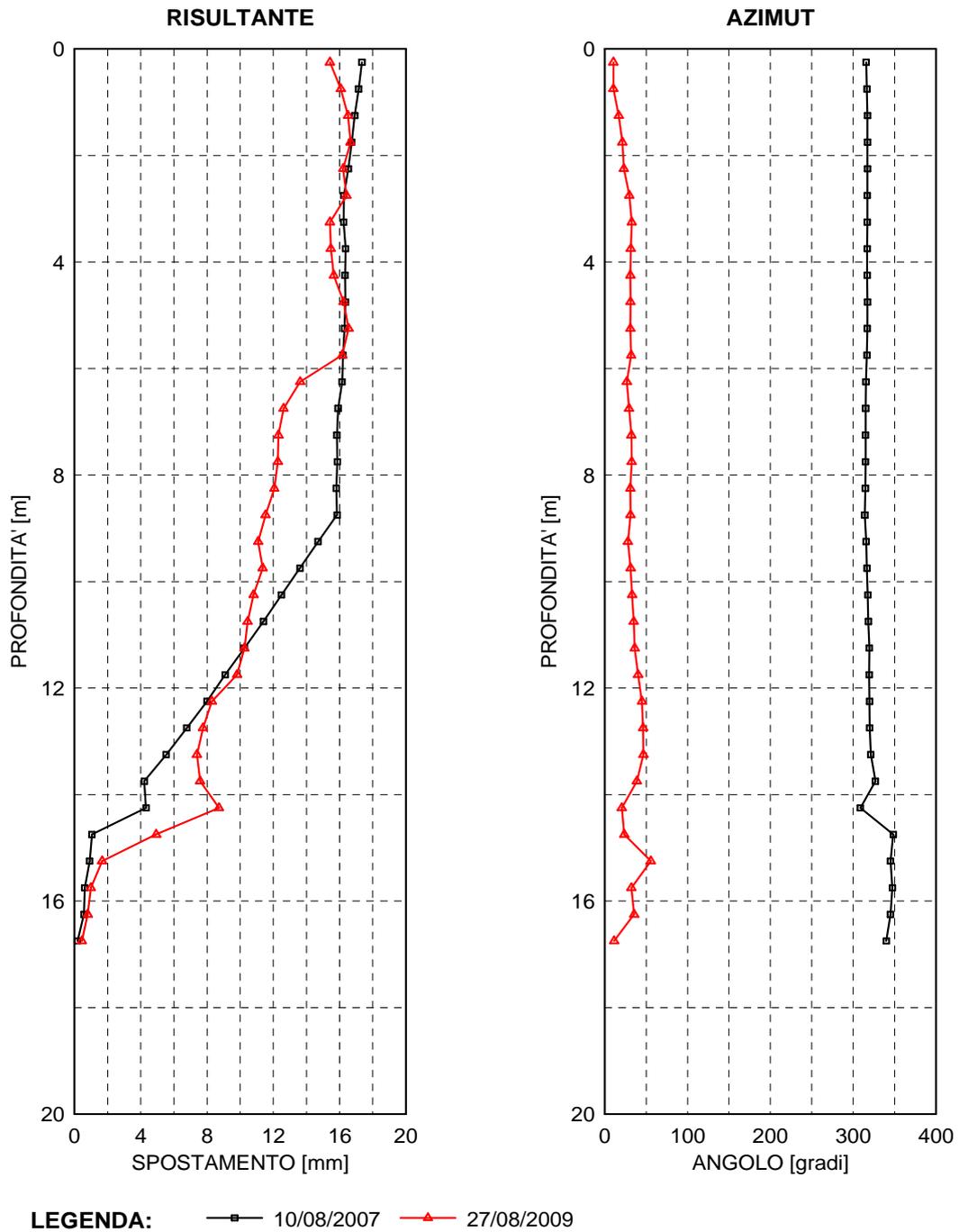


Fig.4.10 – Inclinometric surveys in one of the boreholes at “Ai Caduti dell’Adamello” site

Carrel Hut, Valtournenche (Aosta)

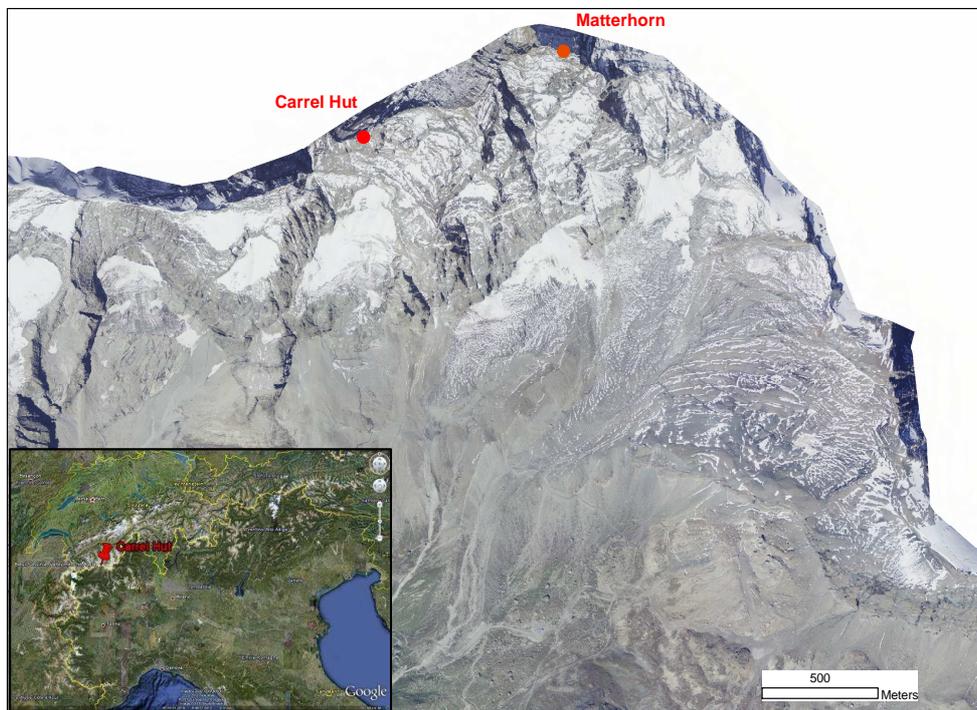


Fig. 4.11 – Carrel Huts on the West ridge of the Matterhorn along the Italian way going to the peak.

Latitude	45,97399
Longitude	7,649075
Elevation [m a.s.l.]	3830
Slope	35°
Aspect	SW
Type of soil	Fractured rock
Evidence of permafrost	Massive ice exposed in the scar of Cheminée rockfall (2003); Observed ice-filled discontinuities; Ground surface temperature (since 2005)
Presence of infrastructure	Yes
Type of infrastructure	Alpine refuge
Evidence of movement	Instability of the Carrel Hut basement.
Typology of movement	Differential movements
Area of phenomenon	Unknown
Perimeter of phenomenon	Unknown
Year of first data	2003: rockfall; 2005: temperature

The Carrel Hut is located on a very fractured rock spur on the SW ridge of Matterhorn. During the very hot summer 2003 the building basement underwent some deformations, and small rockfalls from the sectors above the Hut occurred. In particular after the Cheminée rockfall of 19th August 2003 (80 m below the building) the rock mass where the hut is based showed some joints widening causing the destabilization of the basement.



Fig. 4.12 – Left: The Cheminée after the rockfall of 19/08/2003. The water below the Cheminée comes from the melting of the ice lens uncovered by the rockfall.. Right: Rock mass under the hut basement after the Cheminée rockfall.

To guarantee the mountaineers security the authorities forbid the access at the Matterhorn in 2003 and in 2004 some consolidation works were done at Carrel Hut. The West and North faces of the rock spur have been strongly consolidated with restraint iron-rope netting and nails.

Furthermore, a metal structure based on the rocks beneath the spur was constructed: three lattices founded with anchor rods contrast the rock mass bound by the net.



Fig. 4.13 – Consolidation of the rock mass below the Carrel Hut basement.

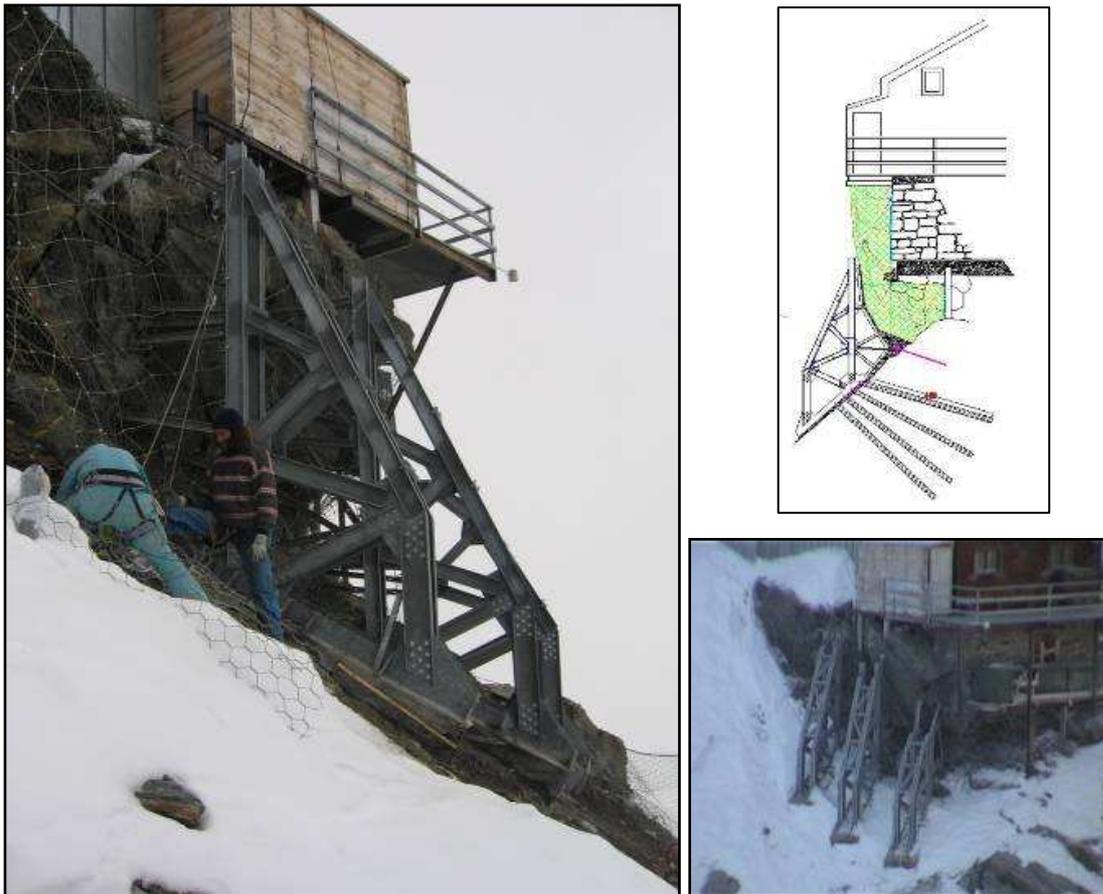


Fig. 4.14 – View of lattices contrasting the rock mass bound by nets beneath the hut basement (photos by Società Guide del Cervino – L. Trucco).

Other instabilities affected this sector in 2006 and 2009 as described in Chapter 2.

After the phenomena of 2003 this site started to be a case study where different monitoring techniques were applied. Started in the frame of the PERMAdataROC project (Alcotra project n° 196), from 2005 a continuous monitoring of surface rock temperature, air temperature and air humidity is performed by ARPA Valle d'Aosta. At the moment, three monitoring sites are active in the areas surrounding the Carrel Hut and the Cheminée. Experimental measures of incoming and outgoing solar radiation on near vertical rockwall have been performed during 2006 and 2007.

In the frame of the same project a geophone network has been installed by CNR-IRPI, with the support of Regione Valle d'Aosta and Solgeo. Data analysis, realised in cooperation with the Politecnico of Turin, was aimed to detect deforming areas and relations with temperature records.

In summer 2006 (25/07/2006) another rockfall occurred along the North West side of Matterhorn about 80-100 m below the Carrel Hut. The fall was heard by the people in the hut and made the hut shaking but no damages arrived at the structure. Rock temperature measurements recorded by ARPA Valle d'Aosta few tens meters above the rockfall scar showed that the event occurred during the hottest period of the summer 2006 (see plot), during which the minimum daily temperature (blue line) was above 0°C for several consecutive days.



Fig. 4.15 – Rockfall scar of 2006 event in the lower right corner, about one hundred meters below the Carrel hut. The yellow dot is the position of the rock temperature sensor (photo RAVA).

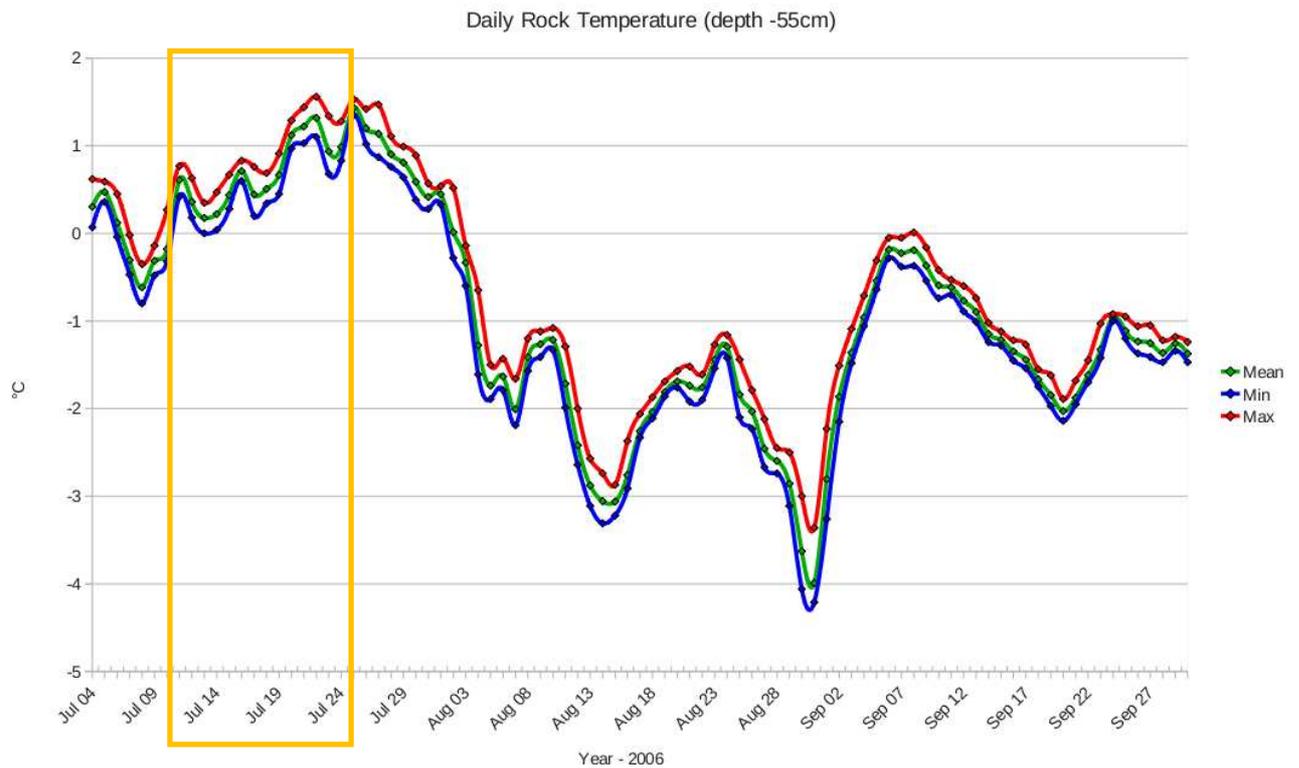


Fig. 4.16 – Daily rock temperature measured on the NW side of Matterhorn during summer 2006; the yellow box shows the temperatures above 0°C recorded before the rockfall of 25/07/2006. The measure is performed at 55 cm depth. Red line: maximum daily rock temperature; green line: mean daily rock temperature; blue line: minimum daily rock temperature.

Passo dei Salati – Indren cable way, Gressoney valley (Aosta)

Latitud	45.887244
Longitude	7.858783
Elevation [m a.s.l.]	3180
Slope	30°
Aspect	SE
Type of soil	Fractured rock and debris
Evidence of permafrost	Big ice lens (buried ice?) found during the excavation for the cableway construction
Presence of infrastructure	Yes
Type of infrastructure	Cableway (Funifor)
Evidence of movement	No
Typology of movement	-
Area of phenomenon	Unknown
Perimeter of phenomenon	Unknown
Year of first data	2006

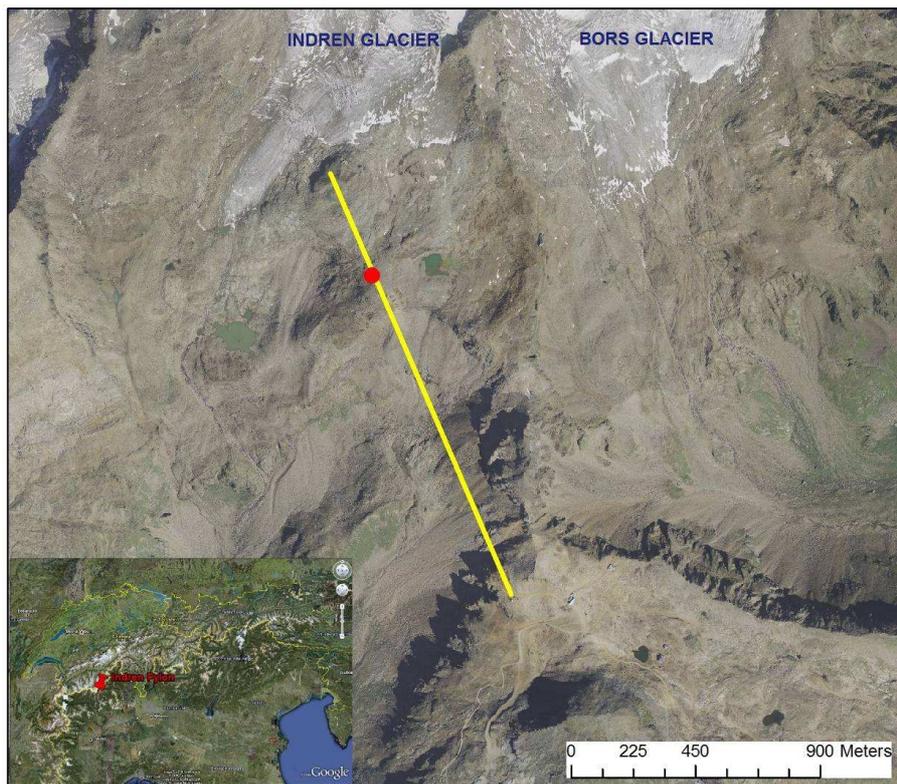


Fig. 4.17 – Location of the site: the yellow line indicates the cableway and the red dot its central pylon.

The cable way Passo dei Salati - Indren is a "Funifor" type cableway (a type of aerial lift with two guide ropes and a haul rope loop per cabin) which starts at 2960 m asl (Passo dei Salati) and ends at 3275 m asl with a central pylon at 3180 m asl (Fig. 4.19). The cableway is on the West side of the North-South ridge which separates Aosta Valley (West side, Indren glacier in the upper part) and

Piedmont (East side, Bors glacier in the upper part). The site is characterised by other rock spurs and ridges covered by coarse debris material (thickness up to 3 m) of both morainic and talus origin.

The original project of 2005 for the central pylon provided a foundation made by 4 plinths on the bedrock surface, which was thought to be shallow. In 2006 the works for the foundations began: instead of the bedrock, few meters below a big ice lens was found, and so the excavation had to be deepened and the ice removed, until the bedrock located about 20 m below (Fig. 4.18). The original project of the pylon had to be changed; the seismic surveys done in the area showed that the site was made of morainic deposits with ice lenses and rocks very loose in the surface layer. That's why the foundations adopted are micropiles which reach the bedrock and the pylon is 10 m higher than in the original design as the excavations deepened the surface where it's based.

The pylon works ended in Autumn 2008 and the cableway was opened in 2009 (Fig. 4.19).

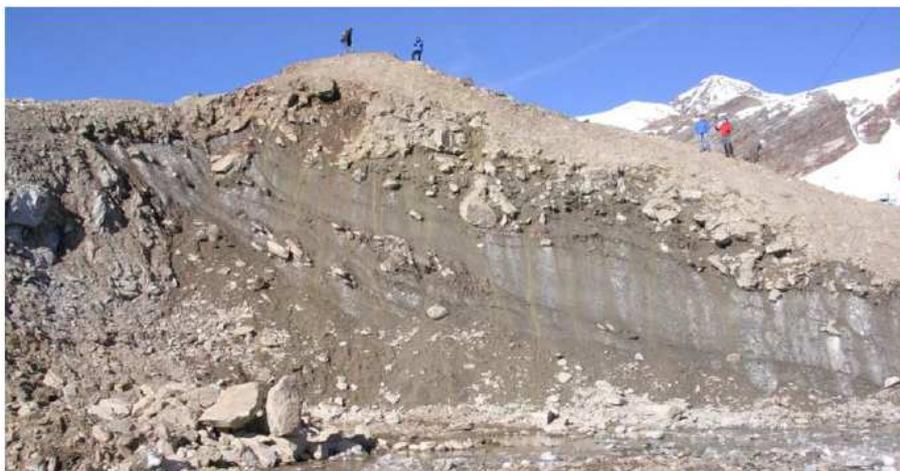


Fig. 4.18 - Ice lens found during the excavations for the foundation of the central pylon (Monterosa SpA).



Fig. 4.19 - View of the pylon (R. Pircher, www.funivie.org).

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Belvedere glacier and Monte Rosa east face (Piedmont, Italy)

Latitude	45.94
Longitude	8.01
Elevation [m a.s.l.]	2,063 ÷ 4,503
Slope	42° (about)
Aspect	E ÷ NE
Type of soil	Rocks and debris
Evidence of permafrost	Indirect
Presence of infrastructure	Yes
Type of infrastructure	Alpine shelters
Evidence of movement	Inclination of the structures
Typology of movement	Debris slide and flow and other complex phenomena
Area of phenomenon	Unknown
Perimeter of phenomenon	Unknown
Year of first data	1960's

The Monte Rosa east face is one of the highest flanks in the Alps (2,200 ÷ 4,500 m a.s.l.), situated in the upper Valle Anzasca above the village of Macugnaga, northern Italy (Fig. 4.20). Steep hanging glaciers and permafrost cover large parts of the wall. Since the end of the Little Ice Age (about 1850), the hanging glaciers and firn fields have retreated continuously. The Belvedere glacier is located at the foot of the Monte Rosa east face. It is a humid-temperate, heavily debris-covered glacier fed by hanging glaciers, ice and snow avalanches as well as rock falls from the Monte Rosa east face (Fig. 4.21).

During recent decades, the ice cover of the Monte Rosa east face experienced an accelerated and drastic loss in extension. Some glaciers have completely disappeared. New slope instabilities and detachment zones of gravitational mass movements developed and enhanced rock fall and debris flow activity was observed. Also the permafrost distribution, even though not directly visible, is believed to have experienced changes in extent and ground-temperatures, as in large parts of the European Alps (Harris et al., 2003).

Belvedere glacier also experienced a dramatic evolution in recent years. Between summer 2000 and summer 2001, it started a surge-type movement with ice velocities increasing by one order of magnitude and showed in parts a strongly uplifted glacier surface by 10 to 25 m. At the foot of the Monte Rosa east face, however, a large depression developed on the Belvedere glacier and the glacier surface was lowered by 15 to 35 m. Possibly, as a consequence of enhanced englacial water pressure or other processes related to the surge-type movement, the supraglacial lake Effimero formed in this depression on the glacier in September 2001 and in the following two summers with a maximum volume of $3 \times 10^6 \text{ m}^3$. Also the moraines are locally involved in landslide processes due to the underground ice melting and glacier mass modifications.

All these slope instability processes (linked to both glacial and periglacial environments) involved directly or indirectly some infrastructures. At the foot of the Mt. Rosa east face, close to the right moraine of Belvedere glacier, two alpine shelters are located: the "Rifugio Paradiso" (2,247 m a.s.l.) and the "Rifugio Zamboni-Zappa" (2,070 m a.s.l.). Actually, the Rifugio Paradiso is abandoned since 1975 due to moraine instability that compromised the infrastructure stability. This shelter was built in 1958 at the top of the moraine ridge of Locce glacier and during the following years the creep of the debris caused the slow inclination of the structure. Initially, some mitigation measures were

installed (guy ropes) but uselessly, and then the shelter was abandoned. The upper wood structure was dismantled and rebuilt in another place (close to the front of the Belvedere glacier tongue). Instead, the ruins of the lower concrete structure (platform and wall bases) with oxidised guy ropes are still visible on the Locce ridge moraine (Fig. 4.22).

Fischer et al. (2006) studied the relationships between geology, glacier and permafrost distributions and their recent-time evolution in order to analyse the triggering causes and to assess the potential hazards in the future. Results reveal that all analysed detachment zones of rock falls and debris flows are situated in the upper part of the rock wall, between 3,400 to 4,100 m a.s.l. Moreover, a concentration of detachment zones at transition zones between orthogneiss and paragneiss becomes apparent. This indicates that the transition zones between orthogneiss and paragneiss could favour or cause instabilities because of the different geotechnical properties of the two lithologies. The detachment zones of ice avalanches are also situated in the upper part of the flank, but most of them cannot directly be related to the geological setting. In some zones, though, where ice avalanches are influenced by rock fall and debris flows, lithological transition zones may have an indirect impact on the glaciers. The comparison of changes in glacier extent with current detachment zones shows that many rock fall and most debris flow events originate in recently deglaciated parts of the Monte Rosa east face. Today, Parete Innominata, channel Imseng and channel Marinelli represent the most active zones of both, glacial changes and mass movement activity.

In addition, modelling analyses suggest a probable linkage between permafrost degradation and the formation of detachment zones (Fig. 4.24). The Figure reveals that many detachment zones of the present rock fall and debris flow events and also some starting zones of ice avalanches are situated in areas of most probably warm permafrost at the lower boundary of permafrost occurrence. This fact confirms the assumption, that instabilities may be formed in part due to increased temperatures in warm permafrost occurrence, which in turn may lead to decreased shear strength in the rock wall and enhanced water pressure. However, some of the detachment zones of rock fall are situated at higher altitudes where occurrence of cold permafrost is predicted. This suggests that not all rock fall events are directly connected to changes in ground-thermal conditions. A rise in permafrost temperatures may also laterally influence the thermal regime of hanging glaciers and have a destabilizing effect on cold hanging glaciers. Rising temperatures can thereby induce higher ice temperatures and more percolating melt water at the glacier bed and thus increase the stresses at the front of steep glaciers (Fischer et al., 2006).

The influence of the ice presence is also recognizable in the case of structure instability of Rifugio Paradiso on the frontal moraine ridge of Locce glacier (Fig. 4.22). In order to advance the hypothesis of permafrost “degradation”, one should first of all verify the origin of the ice, i.e. derived from the glacier or self imposed (sedimentary or pore ice). Haeberli and Epifani (1986) suggest that the ice should derive from buried glacier ice. In any case, the ice melting in the till caused the slope instability and the abandon of the inclined alpine shelter. Probably the concrete platform of the shelter base increased the permafrost degradation velocity. The geo-electric analyses carried out in the 1980's (VAW-ETH of Zurich, Switzerland) and in 2007÷2008 (Insubria University, Italy) on the till of Locce moraine underline indirectly the trend to permafrost degradation, causing the melting of some meters of the frost layer (personal communication by M. Guglielmin). The NW side of the same moraine of the Locce glacier highlights a landslide process since 2005. The laser-scanner analyses carried out between 2005 and 2006 indicate velocity of debris slide and flow of about 36 m y^{-1} and the GPR analysis of summer 2007 evidence an “ice core” at $10 \div 20 \text{ m}$ deep in the moraine (Fig. 4.23, Mortara & Tamburini, 2009).

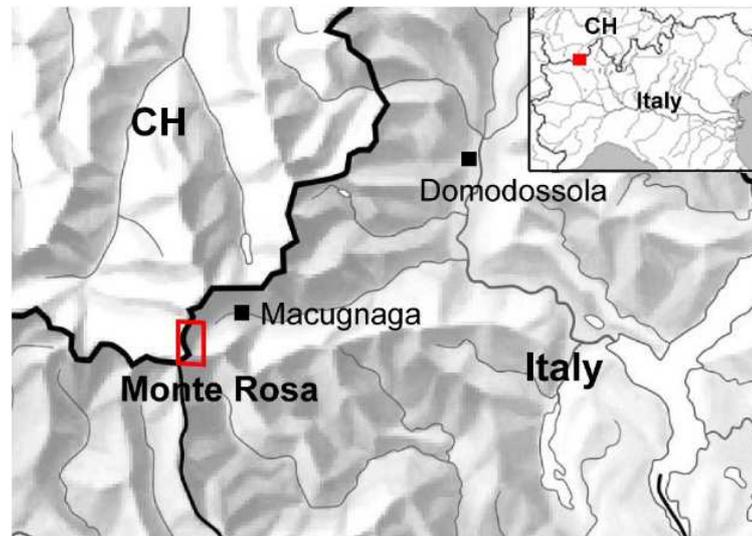


Fig. 4.20 – Sketch map of the investigated area (source: Fischer et al., 2006).

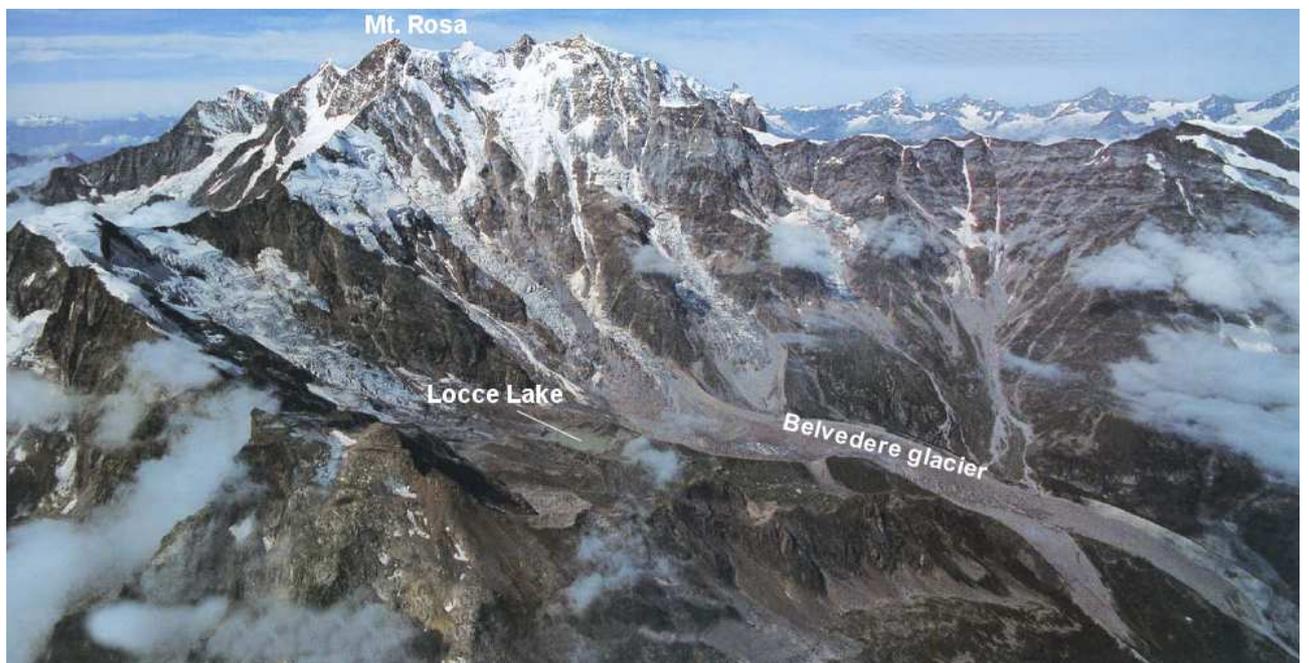


Fig. 4.21 – Mt. Rosa east face and the Belvedere glacier (source: G. Mortara, CNR-IRPI).



Fig. 4.22 – Rifugio Paradiso some days after its opening (1954, Mortara & Tamburini, 2009), in the middle 70's in which structure inclination is quite evident (1975, Mortara & Tamburini, 2009) and the ruins of the concrete platform with guy ropes as visible today (2007, photo by L. Paro, Arpa Piemonte)



Fig. 4.23 – Landslide evolution in the NW moraine of the Locce glacier (source: Mortara & Tamburini, 2009).

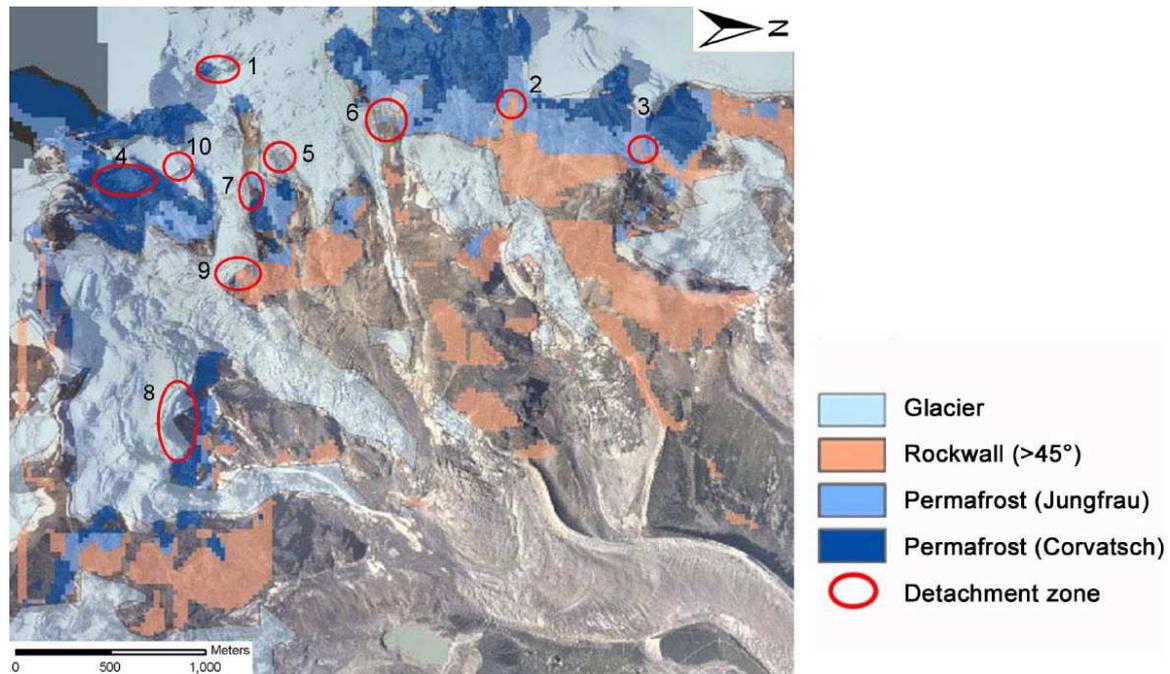


Fig. 4.24 – Permafrost distribution based on the ROCKFROST model (Gruber et al., 2004) with indicated active detachment zones (numbers) (source: Fischer et al., 2006).

3.3 Austria

Hoher Sonnblick (ZAMG, Salzburg, Austria)

Latitude	47° 03' 14''
Longitude	12° 57' 27''
Elevation [m a.s.l.]	3105
Slope	moderate
Aspect	S, SE
Type of soil	Biotit-Gneiss
Evidence of permafrost	direct (measurements)
Presence of infrastructure	Yes
Type of infrastructure	Cable car station
Year of first data	2007



Fig. 4.25 – The summit of Hoher Sonnblick with the exact location of the three boreholes. On the right you see the Zittelhaus, left the Observatorium and in the summit in the background is Hocharn.

Introduction

The crest of Hoher Sonnblick (3105 m asl) is located in the main chain of the Eastern Alps in the Region of Hohe Tauern, Austria. The neighbouring mountains of Hoher Sonnblick also reach heights about 3000 m a.msl. While the north site of Hoher Sonnblick is characterized by a very deep and steep north face, to the south moderate slope about 30° down to the top margin of the glacier Goldbergkees can be detected. A picture of Hoher Sonnblick can be seen in Figure 4.25. The Sonnblick observatory is on the right, the Zittelhaus on the left. The location of the three boreholes is also marked. In the vicinity of Hoher Sonnblick there are three glaciers. The largest glacier is the Goldbergkees. It is located to the southeast of the crest and its stream turns in the middle and lower margin and at last the tongue shows to the North. The second one is called Kleinfleißkees and it looks towards southwest and the aspect of the third glacier – Pilatuskees – is mainly North. Pilatuskees and Kleinfleißkees are small without a typical tongue, the Goldbergkees is a bit longer, but the ice break up one time in the upper section of the glacier and also in the lower part of the glacier. Glacier ice occurrence can be found below 2500 m. The rock in the region consists mainly of biotit-gneiss (Exner, 1964). The thickness of the debris layer around the summit, where the boreholes were drilled, is about 2 m and less.

The observatory was built in the end of 19th century and a mountain hut, the Zittelhaus, is also located on top of the summit. In a study in 2001, it was observed that fissuring of the crest demands for the necessity of a geological stabilization of the steep north face for the protection of the observatory. This redevelopment was done from 2003 to 2007. The main reason of the fissuring should be the change in meteorological conditions during the 20th century. Higher temperatures and more liquid precipitation advances the physical weathering process of the rock. Higher temperature contrasts causes frost shattering, which is more active than in past times. Climatological measurements especially of temperature started in 1886. Actually, each year counts 310 freezing days (daily minimum below 0 degree) and 239 ice days (daily maximum below 0 degree). All values refer to the period between 1971 and 2000. Up to now it exists an unbroken temperature row. Beneath the temperature measurements and measurements of other meteorological parameters, the Sonnblick observatory is a center of several scientific activities. For example measurements in atmospheric chemistry, snow chemical measurements, mass balance measurements of the surrounding glaciers, avalanche reports, of course permafrost long-term monitoring since 2007, and several more activities actually take place on Hoher Sonnblick.

Measurements and results

The relevance of Permafrost-long-term monitoring is widely spread. Climate change in the Alps is not only related to the retreat of glaciers, but rather to the existence of Permafrost. The temporal behaviour and other influences or interactions of Permafrost to several kinds of infrastructure, for example cable lifts, lift stations or mountain huts, signifies a very important knowledge. Furthermore drinking water reservoirs of Permafrost and their quality and usage for the future in the high mountain regions can also play an important role.

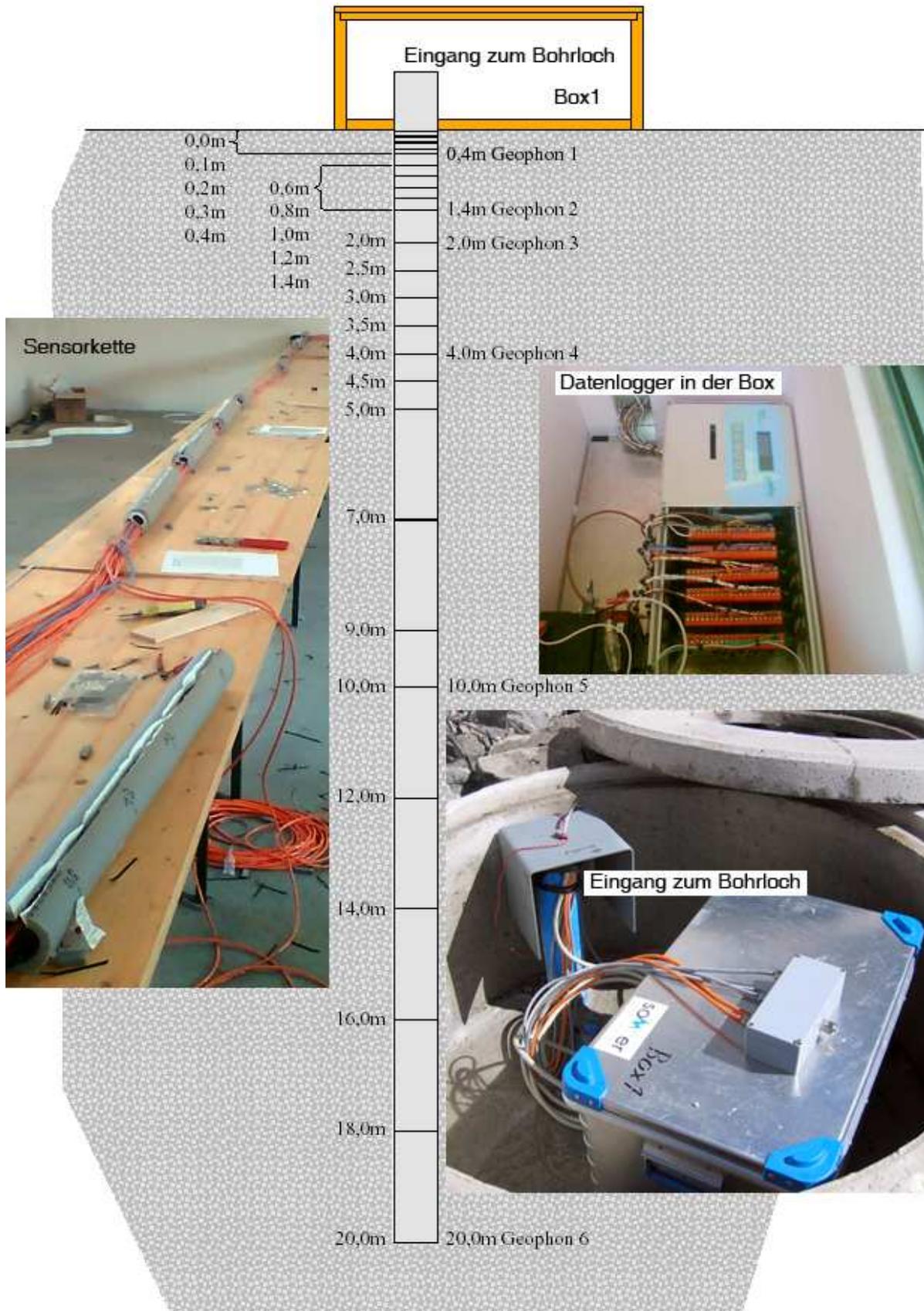


Fig. 4.26 – Construction of measurement chain in the boreholes with depths of the temperature sensors and geophones. Additionally you can see the entrance of the boreholes.

To measure these influences of Permafrost to climate change and the behaviour of Permafrost, on top of Hoher Sonnblick three 20 m deep boreholes were drilled on 14. and 15. September 2005 and were equipped with temperature sensors in different depths (see Figure 4.26) at the end of August 2006. Additionally, one 10 m deep borehole next to borehole 2 was drilled and equipped with extensometers. Daily actualized measurements of temperature data and extensometer data are online available and can be seen on www.sonnblick.net in the internet. All boreholes are located on the southern slope (see Figure 4.25). The mean gradient between borehole 1 and 3 is 27° and the total altitude difference counts 34 m. Borehole 1 is directly located to the Sonnblick observatory, borehole 3 is adjacent to an continuous snow field and borehole 2 is located between both of them.

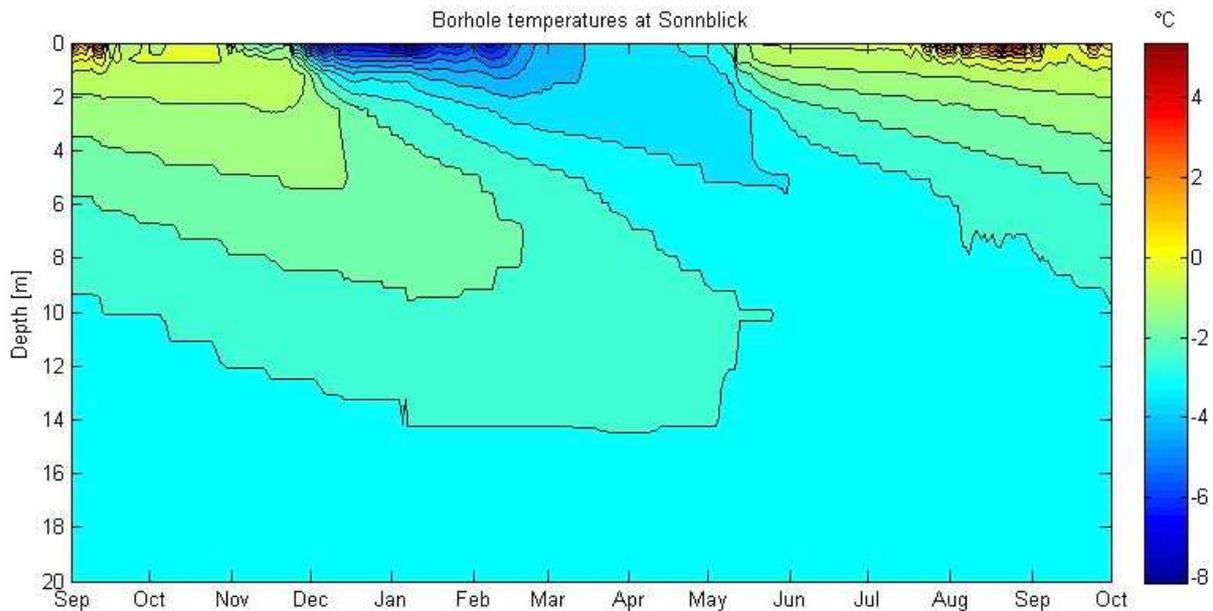


Fig. 4.27 – Temporal temperature variability with increasing depth for borehole 1 during the hydrological year 2007/2008.

But not only measurements in the boreholes are available. In October 2006 were installed 35 GTS (20 UTL-1 and 2 datalogger and 15 tidbits), which measure in wintertime the basis temperature of the snow cover and during summer season the surface rock temperatures. 20 logger of type UTL-1 and 2 were installed on moderate slope on the southern side of the summit. In the steep north face 15 tidbits were installed. Furthermore the temperature change in the past since 1886 is also available and useful. Figure 4.27 shows an example of temporal variability of the temperature with increasing depth for the hydrological year in 2008. Measurements of the boreholes show that the summer temperature amplitude is visible down to 15 m with a delay of about 6 to 7 months. The cooling from the winter season works down to 5 m with a delay of about 4 month. The thickness of the active layer in summer time is about 1 m in borehole 1 (2008) and 70 cm in 2009. In the boreholes 2 and 3 the active layer is less than 1 m. The frozen ground begins there in about 60 cm (2008). In 2009 there are no data available for borehole 2 and 3. In fact the thickness of the active layer is also dependent in the atmospheric conditions of the current year. Naturally, in the upper layers of the boreholes, the differences between summer and winter season are larger than in deeper levels. It is also interesting to compare yearly average temperatures as it is done in Figure 4.28. On the abscissa assigned is the temperature and on the ordinate you see the depth of the borehole. The curvature shows the temperature of borehole 1 in 2008 (blue line) and 2009 (red line). Down to about 9 m, in 2008 the temperature profile is much warmer than 2009. In 3 m there is a difference of 0.7 degree. The explanation of this difference is as follows: In autumn 2009 the summit region was for a long time snowless or with only slight snow cover. The loss of snow, which isolated the ground to the air,

makes it possible for the temperature to penetrate into the rock. Then it started to snow and the resulting snow cover isolated the rock temperature to the air temperature. In the beginning of the winter season of 2008, early in time snow cover was existent. The coldness could not penetrate in the ground. This fact causes the higher mean temperature in the upper layers in 2009. Another fact can be seen in this figure. Below 10 m nearly the same temperature occurs in these two years. One explanation could be that the penetration depth of seasonally temperature reaches only depth down to 15 m. This is why the differences are not as large as in the upper layers. This behaviour could also be seen in Figure 4.27. Below 15 m there are no temporal fluctuations and between 10 and 15 m the fluctuations are negligible small.

As it is mentioned, next to borehole 2 is another one, which was drilled down to 10 m and is equipped with extensometers. Measurements show that in autumn the extensometers measure negative values, which can be identified with compression. With warming during late spring and summer season no data available yet, but a first guess would be stretching with positive values. This thesis can be verified in spring or summer 2011.

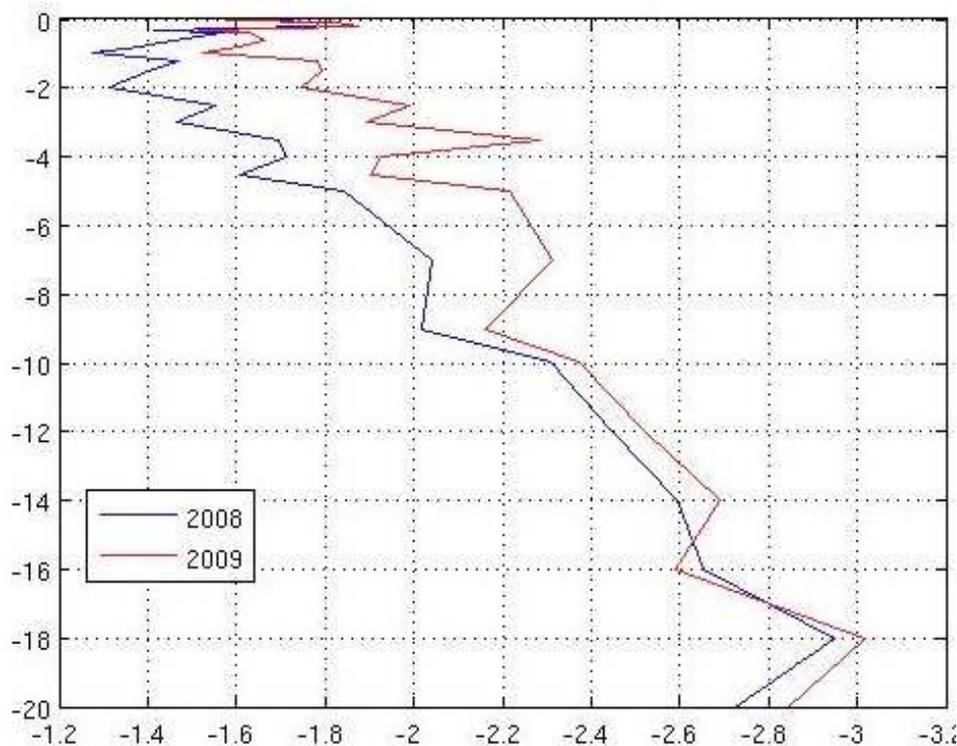


Fig. 4.28 – Mean temperature in 2008 (blue line) and 2009 (red line).

Horizontally oriented boreholes through the Grawand (Croda delle Cornacchie)-Peak (South Tyrol, Italy)

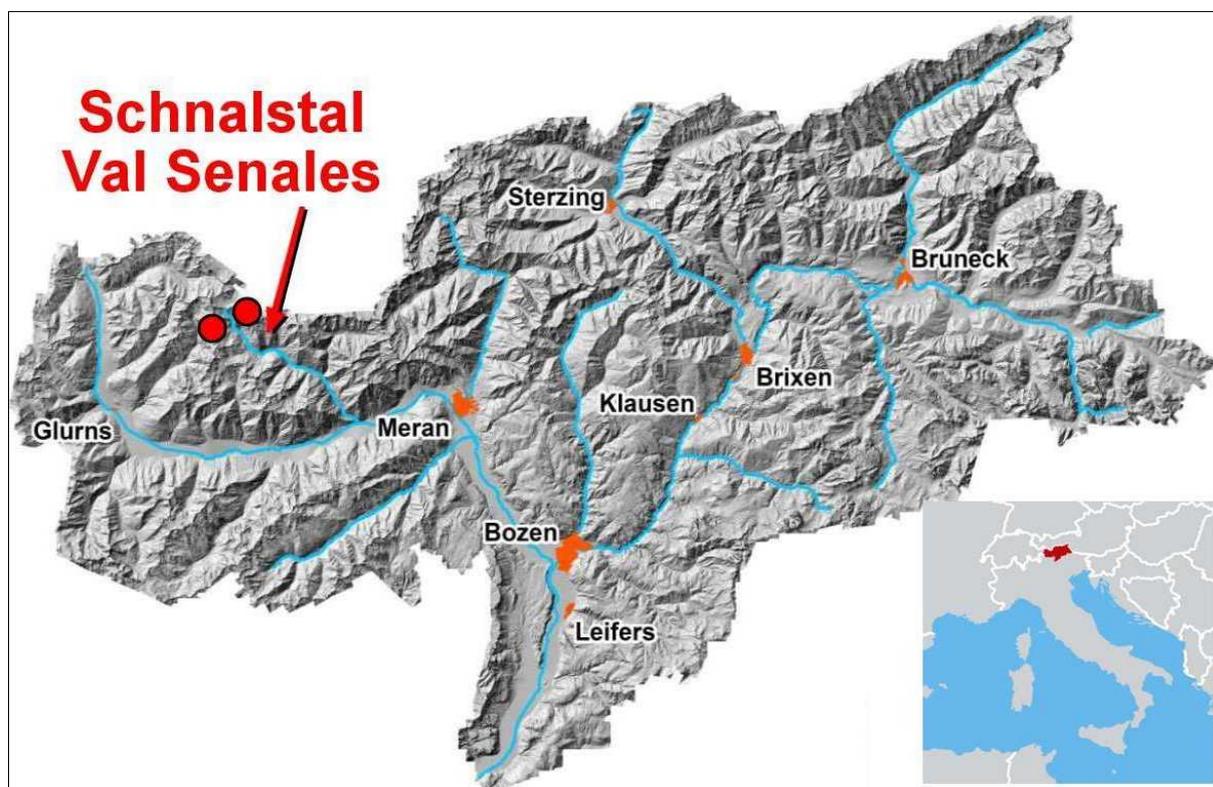


Fig. 4.29 – Location of the study area

Latitude	46.77
Longitude	10.80
Elevation [m a.s.l.]	3135
Slope	20.3
Aspect	North – South (horizontal)
Type of soil	fractured rock
Evidence of permafrost	Ground temperature
Presence of infrastructure	Yes
Type of infrastructure	Ski-trail, cable car
Evidence of movement	extensometers
Typology of movement	Creeping, rockfall
Area of phenomenon	Unknown
Perimeter of phenomenon	Unknown
Year of first data	December 2009



Fig. 4.30 – 3D- view of the Grawand ridge. The red arrow indicates the position of the mouth of boreholes

The ridge of the Grawand – Croda delle Cornacchie (3.251 m a.s.l.) is part of the main chain of the Alps and is located in Schnals valley in South Tyrol (Italy) as shown in Fig. 4.29. The goal of the drilling project, initiated in September 2009 (see Fig. 4.31), was to investigate the problems of rockfall on the glacier ski-trail and problems of stability of the ropeway- structures.



Fig. 4.31 – Drilling site, September 2009.

The first borehole, as shown in Fig. 30, is slightly inclined compared to the second one and is oriented perpendicular to the schistosity. It is 133 m long and instrumented with 5 extensometers in order to get information about the thermal dilatation of the bedrock.

The second borehole is oriented north-south and is 162 m long. It reaches the southern face of the Grawand ridge. The borehole is equipped with two thermistor chains in order to measure the temperature profile in the borehole.

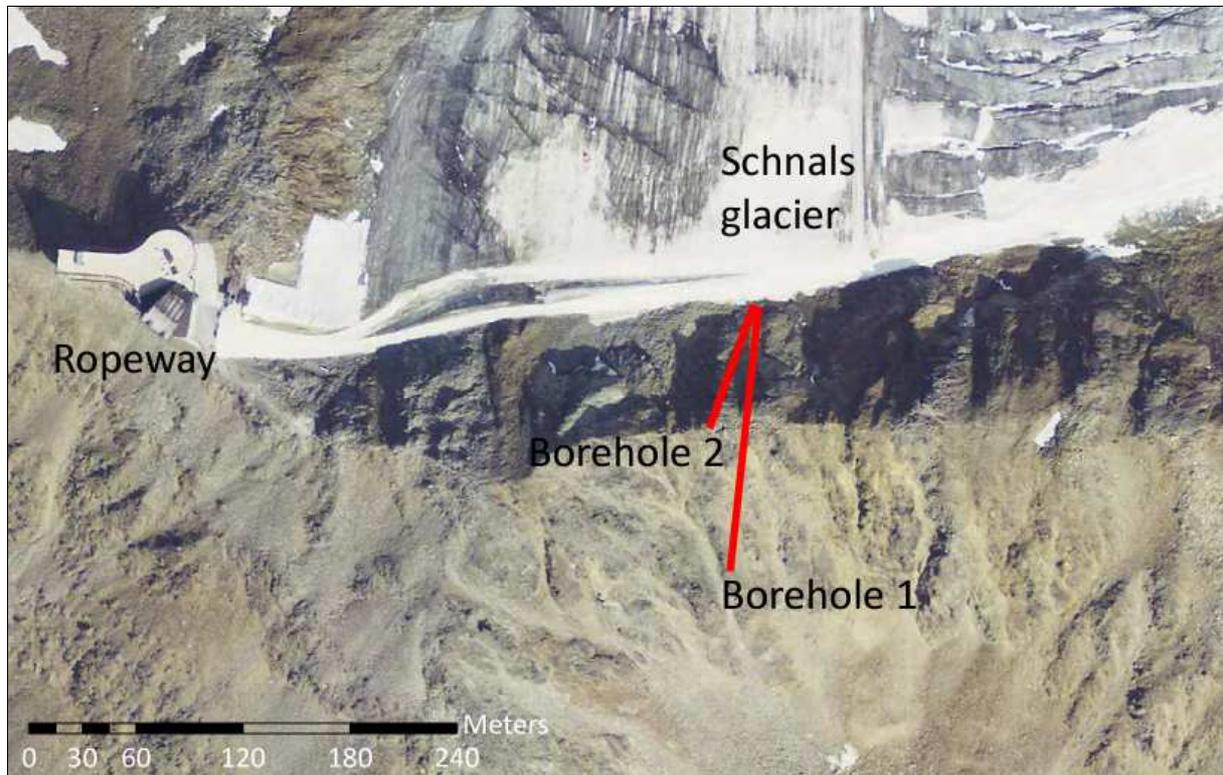


Fig. 4.32 – Location of the two boreholes

Movement and temperature data are available since December 2009 on an internet server. A first evaluation of the data shows that temperatures fluctuate extremely in the north-exposed slope until a depth of 4 m.

Furthermore it can be observed that on the northern flank from December 2009 to June 2010 the temperature in the borehole remains constantly below zero degrees (≈ -2.6 °C) with little fluctuation.

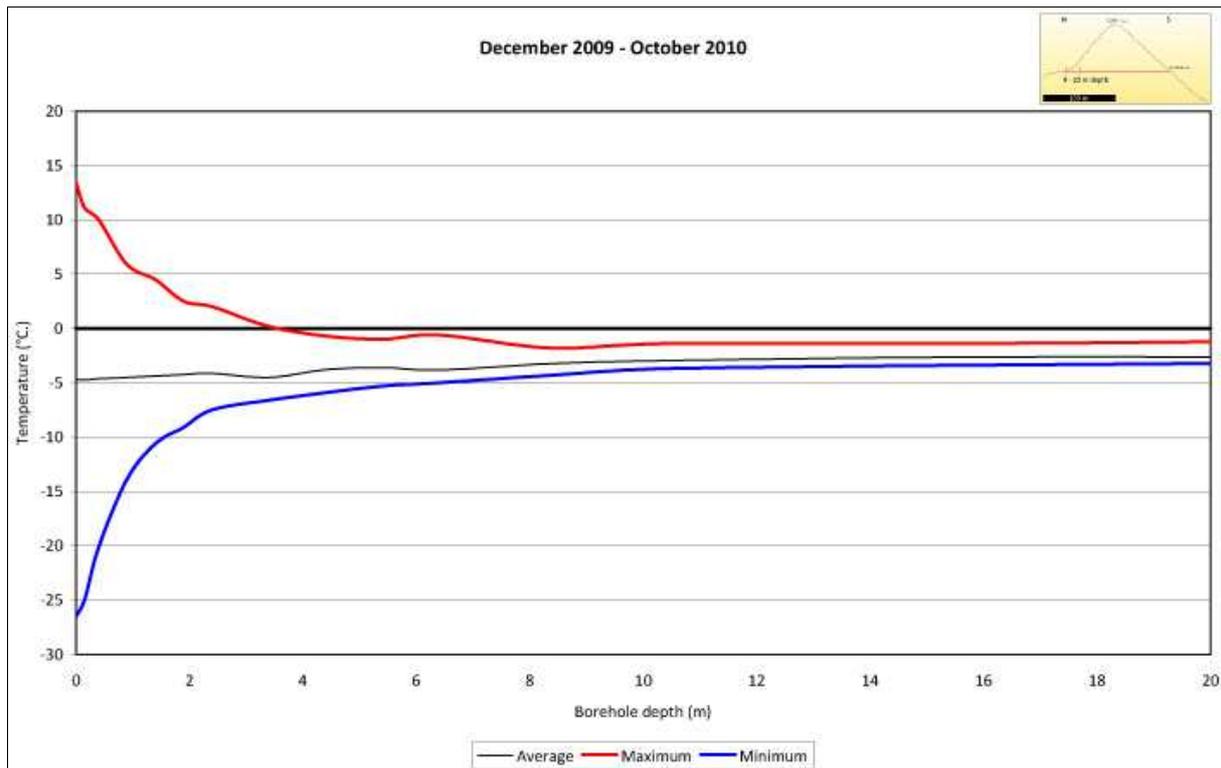


Fig. 4.33 – Minimum, maximum and average temperatures at different borehole depths in the time interval from December 2009 to October 2010. On the north side of Grawand until a depth of 4m the temperatures variate extremely. From 4m the temperatures are more or less constant.

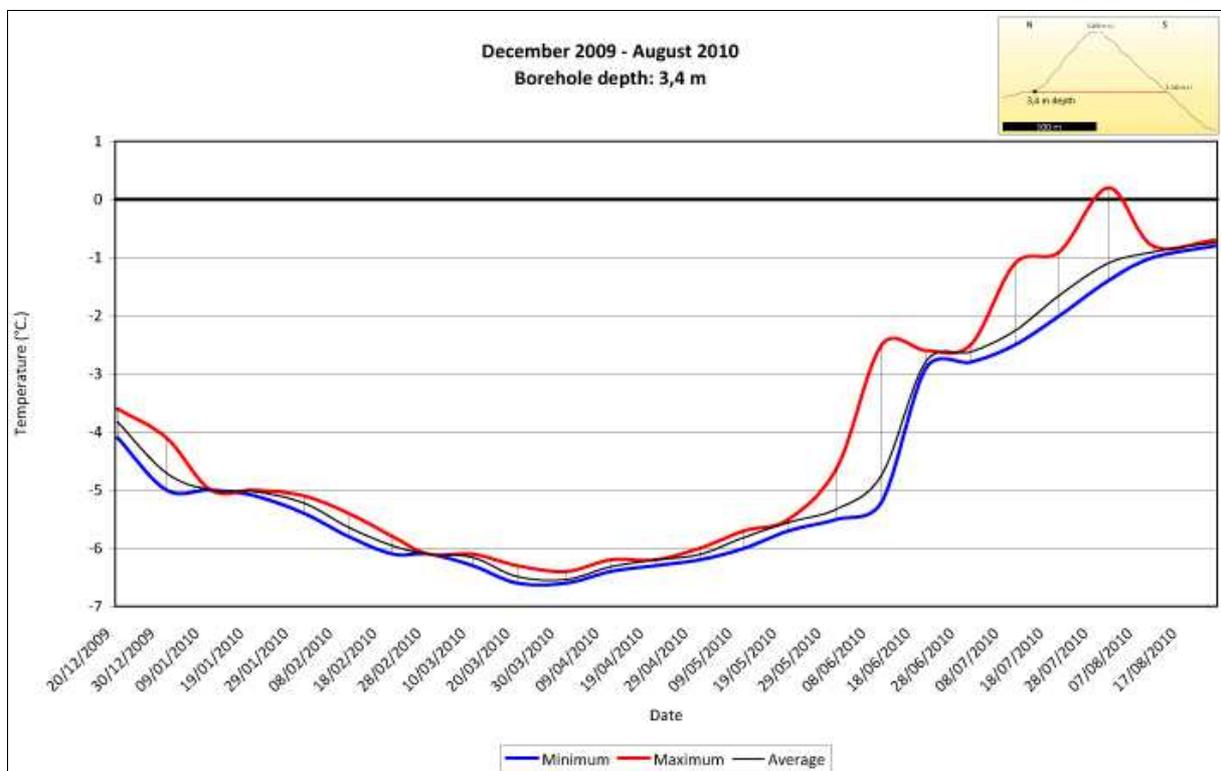


Fig. 4.34 – Minimum, maximum and average temperatures at 3.4m depth (north side) in the time interval from December 2009 to October 2010. In August the maximum temperature measured is slightly above zero degrees.

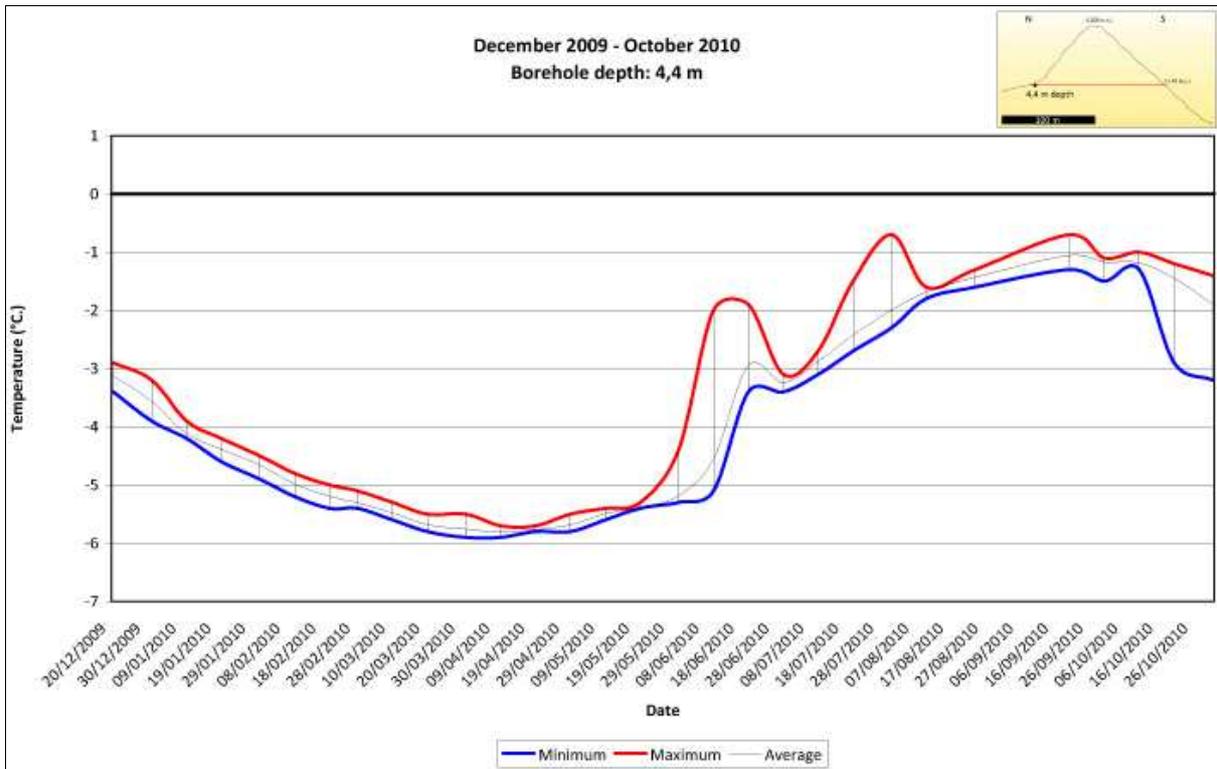


Fig. 4.35 – Minimum, maximum and average temperatures at 4.4m depth (north side) in the time interval from December 2009 to October 2010. From this depth the temperature remains constantly below zero degrees.

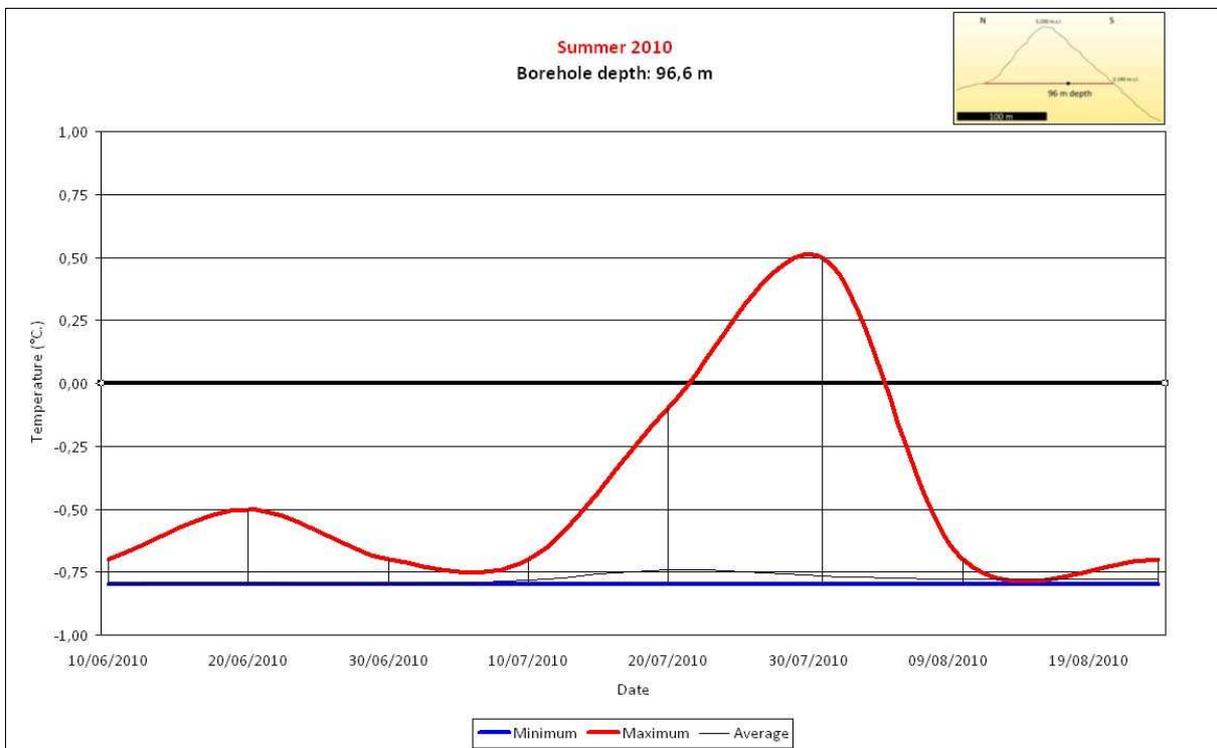


Fig. 4.36 – The temperature rise up to positive degrees during the summer months at a distance of 96m (from northern port) is probably caused by air circulation in rock fractures at this point.

At different distances from the northern port, especially at 42 m and 96 m, during the summer months the temperatures rise up to positive degrees. We speculate that in these zones warm air from the surface is circulating within an intensely fractured rock mass.

At the southern flank the permanent frozen part seems similar to the northern one. Unfortunately, the dataset of the southern flank is not complete, as the thermistor chain was temporarily out of service.

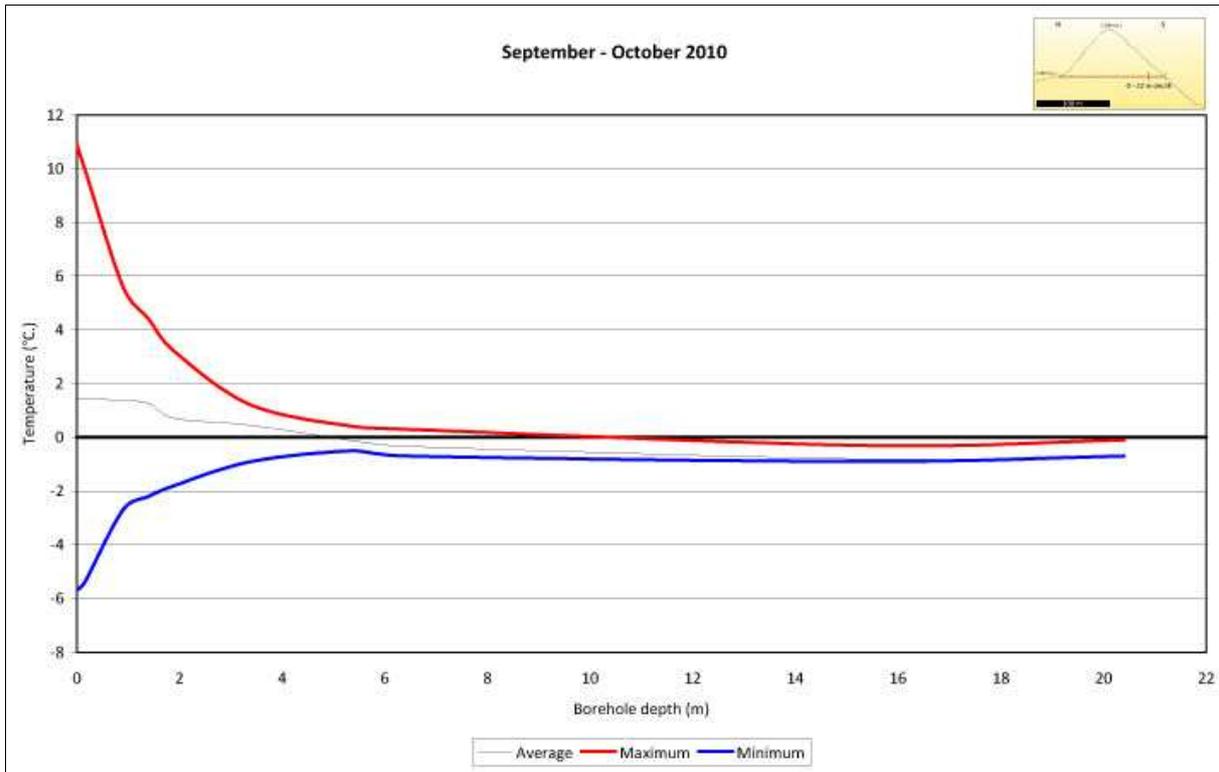


Fig. 4.37 – Minimum, maximum and average temperatures at different borehole distances at the southern side of Grawand ridge. In the time interval from September to October 2010 the temperatures fluctuate extremely until a distance of 5 m from the southern port.

The record of extensometer data from the second borehole is not complete, because the measuring instruments were damaged by a snow avalanche. The instruments were replaced in September and are fully working now. A first examination of data shows that the movements are in sub millimetre range (0.1 – 0.2 mm). The major movements are observed at a distance of 40 m (1.2mm) from northern port.

The preliminary data indicate that the active layer is restricted to the outermost rim of the ridge (4 – 6 m). The large fractures and fracture zones crosscutting the ridge destabilize the whole ridge but the movements are very small (max. 1.2 mm). Therefore we assume that at this time there is no danger for the infrastructures at the northern flank of the ridge.

3.4 Switzerland

Snow nets in permafrost at Wisse Schijen (Randa, Canton Valais, Switzerland)

Latitude	
Longitude	
Elevation [m a.s.l.]	3140
Slope	40°
Aspect	North
Type of soil	Blocky scree over ice-rich fine sediments and bedrock
Evidence of permafrost	Negative temperature, ground ice
Presence of infrastructure	Yes
Type of infrastructure	Snow nets
Evidence of movement	Deformation of net rows, dipping of base plates, etc.
Typology of movement	Scree creep
Area of phenomenon	
Perimeter of phenomenon	
Year of first data	1998: borehole temperature and inclinometer, geodesy

Wisse Schijen is a 40° steep avalanche slope located in the Mattertal at 3140 m ASL, above Randa. The slope is equipped with eight rows of flexible snow nets which are 24-45 m long and 4 m high. They were built in 1990-1991 to protect underlying snow bridges, the main road to Zermatt and the village Randa (Fig. 4.38). Ground cover consists of blocky scree, underlain by finer ice-rich sediments and bedrock in which the snow nets are anchored. Technical details on the snow nets can be found in Phillips & Margreth (2008).



Fig. 4.38 – Eight rows of avalanche defense snow nets at Wisse Schijen (3010-3140 m ASL) in steep permafrost terrain above Randa (Swiss Alps). The snow nets are located in the zone of lighter rock (see arrow, left). Ground cover consists of blocky scree (right) and the mean slope angle is 40°.

Originally, the snow nets were not built using specific methods for permafrost conditions and were therefore rapidly subject to the influences of creep, surface erosion, settlement and rock fall. These permafrost-related phenomena induced the disturbance of row geometry, elevated constraints in the superstructure, the dislocation of swivel supports, down-slope tipping of base plates and foundations and may even have led to the buckling or failure of anchors (Figs. 4.39 and 4.40). Major repairs had to be carried out in 2008, after a service life of only 17 years – whereas under normal circumstances the service life of snow nets is around 80 years.



Fig. 4.39 – Rock fall into snow nets at Wisse Schijen in summer 2008.



Fig. 4.40 – Dislocated swivel support and disturbed row geometry at Wisse Schijen (left). Tipped and undercut foundation (right).

In order to investigate the interactions between the snow nets and the unstable permafrost terrain, long-term monitoring was initiated at Wisse Schijen in 1998. Shallow boreholes were drilled for hourly automatic temperature readings and equipped with inclinometer tubing for annual deformation measurements - and the positions of 48 anchor heads were surveyed yearly using a theodolite. In addition, the snow nets were systematically inspected for damage visually every summer and photographed.

The results of these observations help to understand the particularly short service life of the snow nets at Wisse Schijen. Creep rates almost always exceed 5 cm/year, particularly in hot summers such as 2003, when horizontal displacements of over 10 cm were registered. Ground temperatures in the ice-bearing permafrost are fairly warm, between -0.5 and -1.5°C . Active layer depths vary between 1.6 and 2.0 m. Deformation occurs to a depth of 4-6 m within the bedrock (note that the structure anchors are 5 m long), with the highest deformation values registered within the active layer (Phillips & Margreth 2008). In addition, rock fall occurs regularly, damaging the superstructures.

The main improvements carried out during urgent repairs in 2008 involved the replacement of damaged fixed foundations with floating ones (steel bed plates) under the swivel posts of the snow nets (Fig. 4.41) and the use of specifically developed permafrost grout for anchors. In addition new boreholes were drilled to replace the strongly deformed initial ones. The future development of the snow nets and of the permafrost at this site continues to be monitored and the experience gleaned will be put to use at other avalanche defense sites in the Alps. Technical recommendations for all other types of typical mountain infrastructure in permafrost terrain have recently been published (Bommer et al. 2009, Bommer et al. 2010), as engineering projects in ice-bearing substrates are becoming increasingly challenging under the influence of climate change in the Alps (Phillips et al. 2008, Arenson et al. 2009).



Fig. 4.41 – Repaired snow nets with floating foundations (steel bed plates) in 2008.

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Version 5 – 23.12.2011 – GST-PAT + P. Schoeneich