Permafrost in Switzerland

2006/2007 and 2007/2008

Glaciological Report (Permafrost) No. 8/9

2010

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Permafrost Monitoring Switzerland

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Cover Page

Meteo station at the PERMOS temperature site Schilthorn in the Bernese Alps at 2970 m asl, and the mountains Eiger, Mönch, and Jungfrau in the background. Photo: J. Noetzli.

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Published Reports

The PERMOS concept and annex were approved by the permafrost coordination group on November 18, 1999 and by the Cryospheric Commission (Expertenkommission Kryosphäre EKK; former Glaciological Commission) on January 14, 2000 and were published in 2000. Annual reports on «Permafrost in Switzerland» started in 1999. The reports listed below are available and can be downloaded from the PERMOS web site at http://www.permos.ch.

Reporting Period	*Report No.*	*Published*
1999/2000	1	2001
2000/2001 and 2001/2002	2/3	2004
2002/2003 and 2003/2004	4/5	2007
2004/2005 and 2005/2006	6/7	2009
2006/2007 and 2007/2008	8/9	2010

Preface

The past two winter seasons will remain in our memories as snowy and cold. There are many who might think of this like «Oh, that's fine for the glaciers and permafrost areas in the Alps (and anyway, climate warming probably is not as bad as generally pretended)». Although this is a misinterpretation, obvious for every scientist, there are still many open research questions about the processes forcing the distribution and dynamics of alpine permafrost. It is one of the objectives of the Swiss Permafrost Monitoring Network (PERMOS) to provide a decent base to address these questions. It aims at a long-term database for sound science, which is available throughout the research community. Another important duty of PERMOS is to provide appropriate information to the public, for example, in order to clarify that the relation between permafrost and snow is much more complex than mentioned above.

The bi-annual report in hand is just one result of this information effort. Another element is the synoptical cryosphere report, which is published annually in the journal of the Swiss Alpine Club. And a further, valuable source of information are the numerous public talks given by members of the Swiss permafrost community. I would like to seize the opportunity to thank them explicitly for their service, which is often performed in free time. Both tasks – providing instruments and support in a long-term perspective to the benefit of the research community and the dialogue between science and society – are part of the mission of the Swiss Academy of Science (SCNAT). PERMOS fits perfectly well to our portfolio.

We all know, and often complain about it: public memory is short-lived. But pictures of valleys devastated by periglacial debris flows, the alarming headlines of crumbling mountains, menacing important infrastructure and even eternal landmarks like the Matterhorn, brought topics like permafrost and glacier retreat to an unusual public awareness. Facing these facts, the claim of Goethe's Faust – «Dass ich erkenne, was die Welt im Innersten zusammen hält» («So that I may perceive whatever holds / The world together in its inmost folds») – becomes, literally, a societal obligation. And beyond pure scientific knowledge, public and local authorities expect a clear assessment and precise forecasts concerning permafrost-related dangers and the evolution of the cryosphere – a claim which hardly can be fullfilled, of course. That's why two Swiss federal authorities – the Federal Office for the Environment (FOEN) by its Hazard Prevention Division and the Federal Office of Meteorology and Climatology MeteoSwiss by its Swiss GCOS Office – are engaged in PERMOS, together with SCNAT, the umbrella organisation of the Swiss natural sciences community. A fruitful collaboration so far, as it allowed to supply PERMOS with a professional office since 2007, which was an important step to strengthen the network at the point of transition from the pilot phase to the implementation phase. This, in turn, is substantially helpful to secure long-term oriented data handling and archiving and to reach a standardised configuration and support of the monitoring sites.

But the real strength of the PERMOS network is its combination of a slim, commonly funded structure with a bottom-up organized, research driven network of academic partners spread among the whole country, and highly committed people in all involved institutions.

I hope that PERMOS will provide a contribution to reduce Dr. Faust's scepticism about the value of scientific knowledge, and that it will provide solid data that – judiciously assessed – help to answer long-term questions.

May 2010, Christian Preiswerk, member of the PERMOS Steering Committee

Summary

The present report on permafrost in the Swiss Alps covers the two hydrological years 2006/2007 and 2007/2008. It is the first report of the four year implementation phase (2007–2010) of the Swiss Permafrost Monitoring Network (PERMOS). During this phase all monitoring elements and sites were evaluated, resulting in a slightly changed structure of the PERMOS network. It is now based on three types of observations: (1) ground temperatures measured at and below the surface at 14 borehole sites, (2) changes in subsurface ice and unfrozen water content at five of these sites inferred by geoelectrical surveys (ERT), and (3) kinematics of permafrost determined at 13 rock glaciers by geodetic surveys and/or photogrammetry. In addition, standardized documentation of fast mass movements (rock falls) from permafrost areas is being established.

The meteorological conditions in 2006/2007 were characterized by above average temperatures from October 2006 through to August 2007, low snow fall amounts, and a record breaking hot April. The period 2007/2008 was mild with intense snow fall in winter, and in spring and summer weather conditions were variable.

Near-surface temperatures of the year 2006/2007 were characterized by comparably warm conditions, but without reaching extreme values. In the following year 2007/2008 values were slightly lower. The mean annual ground surface temperature of the two years reported was slightly higher than the decadal mean. Active layer thicknesses determined from borehole measurements were rather stable for the five summer seasons that followed the extreme conditions of 2003. The 10-m temperatures were relatively high in 2007 as a result of the extremely warm autumn 2006 and lower in 2008 following the long lasting snow cover in winter 2007/2008. In the ERT results, no strong and sustained influence on the observed resistivity distribution and no large-scale impact was observed for all sites. After the extraordinary high horizontal velocities in 2003 and 2004, the velocities measured at several rock glaciers dropped until 2006 and since 2007 most of the sites show a small increase. While the relative changes in horizontal velocities show large variations between 2001 and 2005, the changes are much smaller in recent years.

In summary, the permafrost conditions at the measurement sites remained more or less stable with average conditions for this warm decade and without showing any extreme variations since the extreme conditions observed in the year 2002/2003.

Zusammenfassung

Der vorliegende Bericht zum Permafrost in den Schweizer Alpen dokumentiert die beiden hydrologischen Jahre 2006/2007 und 2007/2008. Es ist der erste Bericht der vierjährigen Implementierungsphase (2007–2010) des Schweizer Permafrost Monitoring Netzwerks (PERMOS). In dieser Zeit wurden alle Beobachtungselemente und -standorte evaluiert und die Struktur von PERMOS etwas angepasst. Das Netzwerk basiert heute auf drei Arten von Beobachtungen: (1) Temperaturen an der Oberfläche und im Untergund, gemessen an 14 Bohrlochstandorten, (2) Veränderungen des Untergrundeises und ungefrorenen Wassergehalts an fünf der Bohrlochstandorte, abgeleitet aus geo-elektrischen Messungen (ERT), und (3) Bewegungen im Permafrost gemessen an 13 Blockgletschern mittels geodätischer Vermessung und/oder Photogrammetrie. Zusätzlich wurde die standardisierte Dokumentation schneller Massenbewegungen (Felsstürze) aus Permafrostgebieten eingeführt.

Die meteorologischen Bedingungen im Jahr 2006/2007 waren geprägt durch überdurchschnittliche Temperaturen von Oktober 2006 bis August 2007, geringe Schneemengen und einen rekordmässig heissen April. Der Zeitraum 2007/2008 war mild mit intensivem Schneefall im Winter und variablen Wetterverhältnissen im Frühjahr und Sommer.

Oberflächennahe Temperaturmessungen zeigten für das Jahr 2006/2007 vergleichsweise warme Bedingungen, aber ohne Extremwerte. Im folgenden Jahr 2007/2008 waren die Werte etwas tiefer. Die mittlere jährliche Oberflächentemperatur der beiden Berichtsjahre war leicht höher als das Mittelwert der letzten Dekade. Die Tiefe der Auftauschicht, die aus Bohrlochmessungen abgeleitet wird, war in den letzten fünf Sommern nach 2003 relativ stabil. Die Temperaturen in 10 m Tiefe waren in 2007 als Folge des extrem warmen Herbst 2006 relativ hoch und im Sommer 2008 etwas tiefer wegen der lange anhaltenden Schneedecke im Winter 2007/2008. In den ERT Ergebnissen wurde für keinen der Standorte ein signifikanter Einfluss auf die Verteilung der Widerstände oder ein grösser-skaliger Effekt beobachtet. Nach den überdurchschnittlich hohen horizontalen Geschwindigkeiten in 2003 und 2004 fiel die Geschwindigkeit bei den meisten Blockgletschern bis 2006. Seit 2007 zeigen die meisten der Standorte wieder einen geringen Anstieg. Die relativen Veränderungen der horizontalen Geschwindigkeiten zeigten zwischen 2001 und 2005 grosse Variationen, diese sind aber in den letzten Jahren deutlich kleiner geworden.

Zusammenfassend waren die Permafrostverhältnisse an den Messstandorten mehr oder weniger stabil mit durchschnittlichen Bedingungen für diese warme Dekade und ohne extreme Variationen seit den Rekordwerten im Jahr 2002/2003.

Résumé

Ce rapport documente les variations du pergélisol observées dans les Alpes Suisses durant les deux années hydrologiques 2006/2007 et 2007/2008. Il s'agit du premier rapport couvrant la phase d'implémentation (2007–2010) du Réseau Suisse de Monitoring du Pergélisol (PERMOS). Durant cette phase, tous les éléments et sites de monitoring ont été soumis à évaluation. Il en a résulté une structure de PERMOS partiellement modifiée: PERMOS est désormais basé sur trois types d'observations : (1) températures du sol en surface et en profondeur sur 14 sites de forage, (2) variations des teneurs en glace et en eau non-gelée du sous-sol sur cinq de ces sites, valeurs basées sur les résultats de mesures géoélectriques (ERT), et (3) cinématique du pergélisol (déplacements) sur 13 glaciers rocheux par relevés géodésiques et/ou photogrammétrie. De plus, une documentation standardisée des mouvements de masse rapides (éboulements) se décrochant à partir de zones de permafrost est en cours d'élaboration.

Les conditions météorologiques de 2006/2007 ont été caractérisées par des températures supérieures à la normale depuis octobre 2006 jusqu’en août 2007, par de faibles cumuls d'enneigement et par un mois d'avril exceptionnellement chaud. La période 2007/2008 fut douce et marquée d'intenses chutes de neige en hiver, alors que le printemps et l’été connurent des conditions météorologiques variables.

Durant l'année 2006/2007, les températures du sol en sub-surface furent relativement élevées, sans toutefois atteindre des valeurs extrêmes. En 2007/2008, les valeurs furent légèrement plus basses. La température moyenne annuelle du sol sur l’ensemble des deux années fut légèrement supérieure à la moyenne décennale. La profondeur de la couche active, déterminée à partir des mesures de température en forage, fut plutôt stable au cours des cinq saisons estivales qui suivirent les conditions extrêmes de 2003. A 10 m de profondeur, les températures furent relativement élevées en 2007 par suite de l'automne 2006 extrêmement chaud. Elles s’abaissèrent quelque peu en 2008 en raison notamment de la fonte relativement tardive du manteau neigeux de l'hiver 2007/2008. Le monitoring géoélectrique (ERT) n’a montré aucune influence notoire et durable des conditions météorologiques sur la distribution des résistivités et aucun impact à large échelle n’a été observé sur aucun site. Après les valeurs extraordinairement élevées mesurées en 2003 et 2004, les vitesses de déplacement mesurées sur les glaciers rocheux chutèrent jusqu'en 2006, puis, en 2007, recommencèrent à légèrement accélérer sur la plupart des sites. Alors que les changements relatifs de vitesse horizontale connurent de grandes variations entre 2001 et 2005, les fluctuations ont été beaucoup plus faibles lors des dernières années.

En résumé, les conditions du pergélisol aux sites d'études sont restées plus ou moins stables et proches des conditions moyennes de la décennie écoulée – une décennie qui fut toutefois chaude. Il n’y a plus eu non plus de variations aussi extrêmes que celles observées en 2002/2003.

Riassunto

Questo rapporto sullo stato del permafrost nelle Alpi svizzere copre i due anni idrologici 2006/2007 e 2007/2008. Si tratta del primo rapporto della fase di implementazione, intercorsa tra il 2007 e il 2010, della Rete Svizzera per il Monitoraggio del Permafrost (PERMOS). Durante questa fase, l'insieme degli elementi di monitoraggio e tutti i siti monitorati sono stati valutati da un punto di vista scientifico; i risultati presentati nel rapporto riflettono quindi questa importante fase di valutazione. Attualmente, PERMOS è basata su tre tipi di osservazioni: (1) misure delle temperature al suolo e nel sottosuolo in 14 siti di perforazioni profonde, (2) misure dei cambiamenti del tenore in ghiaccio e acqua del sottosuolo mediante tomografia delle resistività elettriche (ERT) in cinque di questi siti, e (3) misure della cinematica del permafrost con sorveglianza geodetica e/o fotogrammetrica di 13 rock glaciers. Oltre a ciò, una documentazione standardizzata sui movimenti di massa rapidi (caduta roccia) in aree di permafrost è stata stabilita.

Le condizioni meteorologiche durante l'anno idrologico 2006/2007 sono state caratterizzate da temperature sopra la media stagionale da ottobre 2006 fino ad agosto 2007, da deboli quantitativi di precipitazioni nevose e da un mese di aprile particolarmente caldo. Il periodo 2007/2008 è stato relativamente mite con nevicate intense durante l'inverno e condizioni meteorologiche molto variabili durante la primavera e l'estate.

Le temperature della superficie del suolo per l'anno idrologico 2006/2007 sono state particolarmente calde, sebbene non siano stati raggiunti dei valori estremamente alti. Nell'anno seguente (2007/2008), le temperature sono state leggermente inferiori. La temperatura media annua del suolo per i due anni compresi nel presente rapporto è stata leggermente più calda rispetto alla media decennale. Lo spessore dello strato attivo, determinato grazie alle misure di temperatura in perforazioni profonde, è rimasto assai stabile durante le ultime cinque stagioni estive che hanno seguito le condizioni di temperatura estreme dell'estate 2003. Le temperature del sottosuolo a 10 m di profondità sono state relativamente alte durante il 2007, come conseguenza dell'autunno 2006 eccezionalmente caldo, e relativamente basse nel 2008, a seguito dell'importante e persistente copertura nevosa dell'inverno 2007/2008. Per i risultati delle tomografie delle resistività elettriche (ERT), nessuna influenza particolare sulla distribuzione delle resistività osservate e nessun effetto importante delle condizioni climatiche sono stati osservati nelle misure effettuate a ogni sito. Per quel che concerne lo spostamento dei rock glaciers, dopo le straordinarie velocità orizzontali misurate durante il 2003 e il 2004, i valori sono molto diminuiti fino al 2006 e molti siti mostrano un leggero aumento a partire dal 2007. Mentre le variazioni relative delle velocità orizzontali dei rock glaciers hanno presentato delle grandi variazioni tra il 2001 e il 2005, queste variazioni sono state molto più contenute negli anni più recenti.

In riassunto, negli anni idrologici 2006/2007 e 2007/2008 lo stato del permafrost nei siti monitorati è rimasto più o meno stabile e in condizioni di temperatura medie nonostante la decade assai calda, e dopo l'anno idrologico 2002/2003 caratterizzato da condizioni meteorologiche estreme non si sono più verificate delle variazioni eccezionalmente importanti.

Resumaziun

Quest rapport pertucont la schelira permanenta en las Alps svizras cuviera ils dus onns hidrologics 2006/2007 e 2007/2008. Igl ei igl emprem rapport dalla fasa da implementaziun (2007–2010) dalla reit svizra per survigilonza della schelira permanenta (PERMOS). Duront quella fasa ein tut ils elements da surveglianza e tuttas zonas d'operaziun vegnidas evaluadas ed ils resutads vegnan ussa communicai en quest rapport: (1) da 14 foras da sondagi ein las temperaturas da terren vegnidas mesiradas sin e sut la surfatscha, (2) differenzas da glatsch sutterren e dil cuntegn dad aua per tschun zonas d'operaziun ein vegnidas derivadas entras mesiraziuns geoelectricas (ERT), e finalmein (3) da 13 glatschers da schelira permanenta ei il moviment dalla schelira permanenta vegnius determinaus entras mesiraziuns geodeticas e/ni mieds fotogrammetrics. Plinavant ei in standardisau system da documentaziun per rapids moviments da massa (bovas) en loghens da schelira permanenta vegnius mess en funcziun.

Las condiziuns meteorologicas digl onn 2006/2007 ein caracterisadas da temperaturas sur la media duront il meins d'october 2006 entochen igl uost 2007, sco era da pauca neiv ed in cauld meins d'avrel cun temperaturas da record. La perioda 2007/2008 ei stada migeivla cun in unviern da bia neiv e condiziuns variablas per primavera e stad.

Las temparaturas datier dalla surfatscha digl on 2006/2007 ein caracterisadas da relativamein cauldas condiziuns, denton senza cuntonscher valetas extremas. Il suandont onn 2007/2008 ha purtau temperaturas levamein pli bassas. La media annuala dalla temperatura dil terren per ils dus onns da survigilonza ei stada levamein pli aulta che la media per la decada. La grossezza dil plaun activ determinda dallas mesiraziuns ellas foras da sondagi ein stadas plitost stablas duront las tschun sesiuns da stads dapi las cundizuns extremas duront la stad 2003. Sco consequenza directa digl extem cauld atun 2006 ein las temperaturas da 10 m stadas relativamein aultas el 2007 e plitost bassas el 2008, suenter che la cuverta da neiv digl unviern 2007/2008 ha giu teniu ualti ditg. Els resultads da ERT sesanflan negins mussaments per ina influenza ferma ni permanenta sin la distribuziun da resistenza observada. Plinavon ein neginas observaziuns dad effects da gronda surfatscha vengidas fatgas. Suenter che ils onns 2003 e 2004 vevan mussau ora ina spertadad horizontala extraordinaria ein tenor las mesiraziuns las spertadads da certs glatschers da schelira permanenta idas anavos entochen igl onn 2006 e carschidas mo levamein naven digl onn 2007. Malgrad che las midadas relativas en spertadad horizontala han giu ina gronda variaziun duront ils onns 2001 tochen 2005 ein las midadas stadas bia pli pintgas ils davos onns.

En resumaziun san ins dir che las condiziuns da schelira permanenta en las zonas d'operaziun ein stadas pli u meins stablas cun condiziuns medias per questa decada caulda e senza grondas variaziuns dapi las condiziuns extremas digl onn 2002/2003.

Contents

1 Introduction

The present report on permafrost in the Swiss Alps covers the two hydrological years 2006/2007 and 2007/2008. It is the first report of the four-year implementation phase of the Swiss Permafrost Monitoring Network (PERMOS), which started in 2007 (Vonder Muehll et al. 2008). During this period PERMOS developed from being a mainly research-based network towards a more operational monitoring network. For this, all PERMOS monitoring elements and sites were evaluated considering the monitoring strategy, site characteristics and instrumentation, new research results, and experience from six year Pilot Phase 2000–2006. Approved elements and sites shall be maintained for the next decade(s). Accordingly, the structure of the bi-annual permafrost report has been reworked and adapted for the present issue in order to reflect the results of the evaluation.

Today, PERMOS is based on three types of observation: (1) temperatures measured in boreholes and near the surface around the boreholes at locations with different topographic setting and surface type, (2) changes in subsurface ice and unfrozen water content at borehole sites inferred by geoelectrical surveys, and (3) permafrost kinematics determined by geodetic surveys and/or photogrammetry. The elements newly introduced in the last report (Glaciological Report Permafrost No. 6/7, PERMOS 2009) have become an inherent part of the PERMOS network: Rock surface temperature (RST) measurements are integrated into the temperature observations. The latter are complemented by geoelectrical surveys based on electrical resistivity tomography (ERT), which provide information on changes in subsurface conditions. Terrestrial surveys to determine surface displacement and permafrost creep have been introduced to the network as a pilot study in 2007 and complement the photogrammetric analyses based on air photos. In addition, standardized documentation of fast mass movements from permafrost areas (e.g., rock fall) is being established and for the first time reported in the present report.

Two main types of PERMOS sites are presently distinguished (Tab. 1.1, Figs. 1.1 and 1.2): temperature sites (which include near-surface temperatures, borehole temperatures, and ERT) and kinematics sites (which include terrestrial surveys and photogrammetric analyses). In the evaluation, a number of sites have additionally been designated as PERMOS Reference Site: These sites are the ones where long-term monitoring is reasonable and feasible, and they build the corner stones of the network. The PERMOS network includes 14 temperature sites (with 7 PERMOS Reference Sites) with 27 boreholes. ERT monitoring is performed at fixed installed profiles at five of the temperature sites. Terrestrial surveys are carried out on 13 rock glaciers (with 4 PERMOS Reference Sites). Air photos have been taken at seven sites during the reporting period.

The chapter dedicated to selected aspects of permafrost monitoring or PERMOS presents the temperature site Dreveneuse in the Chablais area in more detail. The Dreveneuse is the PERMOS site with the lowest elevation (around 1600 m asl) and permafrost developed due to special thermal conditions in the talus slope.

Table 1.1: *Overview of the PERMOS sites and the types of measurement carried out. Sites are sorted alphabetically and PERMOS Reference Sites are marked in bold. T stands for temperature site, K for kinematics site, K(AP) for sites where only air photos are taken (listed at the bottom). BH=borehole, GST=ground surface temperature, RST=rock surface temperature, ERT=electrical resistivity tomography, AP=air photos, TS=terrestrial survey.*

Site name	Type	Region	BH	GST	RST-Region	ERT	AP	TS
Alpage de Mille/Aget	K	Central Valais		x				x
Les Attelas	T	Central Valais	x	x	Lapires	x		
Dreveneuse	T	Chablais	x	x		x		
Flüela	T	Engadine	x	x		x		
Gemmi/Furggentälti	K	Berner Oberland		x			x	x
Gemsstock	T	Central CH	x			x		
Gentianes	T	Central Valais	x		Lapires	x		
Gianda Grischa	K	Engadine		x		x	x	
Grosses Gufer	K	Berner Oberland					x	x
Lapires	T K	Central Valais	x	x	Lapires	x		x
Largario/Valle di Sceru	K	Tessin		x				x
Matterhorn	T	Mattertal	x					
Monte Prosa	K	Central CH		x				x
M.d.Barba Peider/Schafberg	T	Engadine	x	x	Corvatsch		x	
Muragl	T	Engadine	x		Corvatsch		x	x
Murtèl-Corvatsch	T K	Engadine	x	x	Corvatsch	x	x	x
Réchy	K	Central Valais		x			x	x
Ritigraben	T	Mattertal	x	x				
Schilthorn	T	Berner Oberland	x	x	Schilthorn	x		
Stockhorn	T	Mattertal	x	x		x		
Tsarmine	K	Central Valais		x				x
Tsaté	T	Central Valais	x	x	Réchy			
Turtmanntal/Hungerlitälli	K	Mattertal		x			x	x
Yettes Condjà	K	Central Valais		x				x
Gruben	K(AP)	Mattertal					x	
Suvretta	K(AP)	Engadine					x	

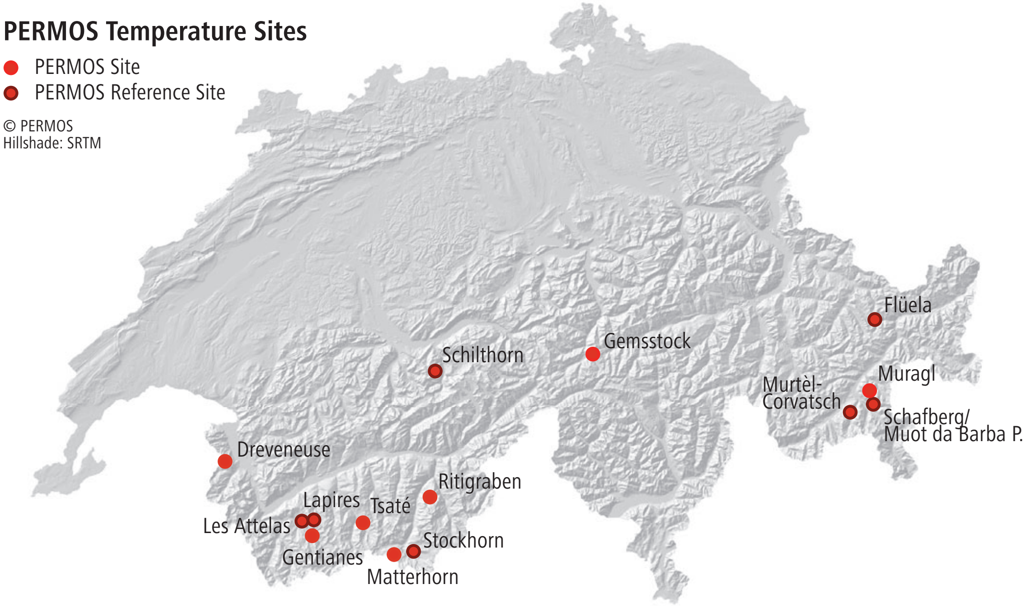


Figure 1.1: *PERMOS temperature sites.*

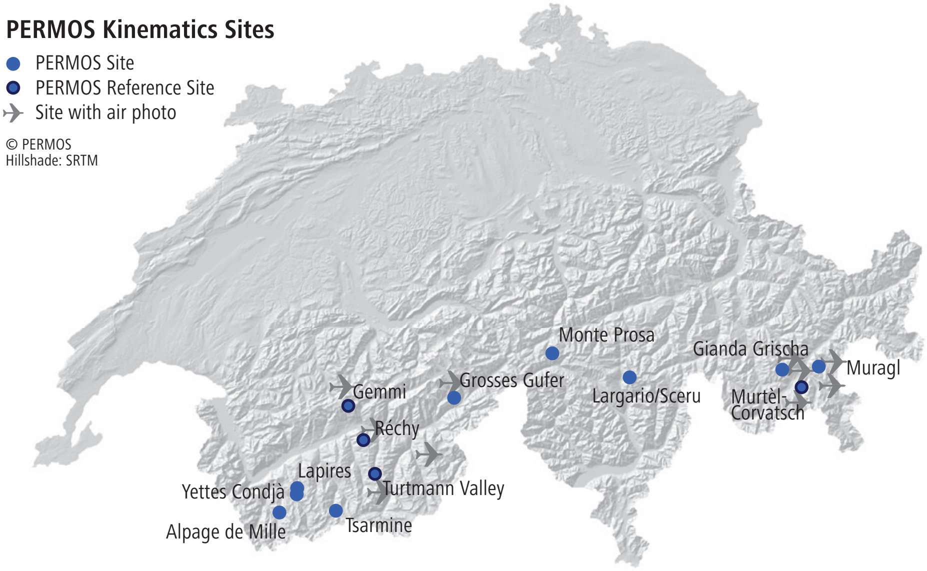


Figure 1.2: *PERMOS kinematics sites.*

The field work and site maintenance of the PERMOS network have been carried out by the PERMOS partner institutes. The PERMOS partners also carry the main work load of data acquisition and processing:

- University of Zurich: Department of Geography, Glaciology, Geomorphodynamics & Geochronology (UZH, host of the PERMOS Office)
- ETH Zurich: Institute for Geotechnical Engineering (IGT-ETH)
- University of Berne: Department of Geography (UniBE)
- University of Fribourg: Department of Geosciences, Alpine Cryosphere and Geomorphology (UniFR)
- University of Lausanne: Faculty of Geosciences and Environment, Geography Institute (UniL)
- WSL Institute for Snow and Avalanche Research Davos (SLF)

Photo 1: Panorama with Eiger, Mönch, and Jungfrau and the temperature site Schilthorn in the front left. Photo: I. Gärtner-Roer.

2 Weather and Climate

In this section, the weather and climate conditions that have the most important influence on permafrost and the subsurface thermal regime are described: air temperatures in summer and timing and thickness of the snow cover in winter. Because the snow cover thermally insulates the ground from the conditions in the atmosphere, the time of the first snow fall, the duration and thickness of the snow cover, and the time when the ground surface becomes snow free in spring play decisive roles for the thermal conditions of the subsurface. The continuous recording of ground surface temperature (GST; cf. Section 3.1) allows to determine the phase of snow melt: When the snow cover is wet down to its base, the percolation of melt water provokes a sudden increase of GST to 0 °C (zero curtain start) and GST remains almost stable until the snow cover completely disappears (snow free date). During the time when the terrain is snow free, air temperature is the most important factor influencing ground temperatures that has significant interannual variability. In steep bedrock with little or now snow, air temperature is the most important factor during the entire year. The weather and climate information is taken from the reports by MeteoSwiss (MeteoSwiss 2006, 2007, 2008), the snow information originates from SLF.

2.1 Snow Cover and Air Temperatures in 2006/2007

The meteorological conditions during the period 2006/2007 were characterized by above average (1961–1990) temperatures from October 2006 through to August 2007, low snow fall amounts, a record breaking hot April (5.8 °C above the long-term climatic mean), and frequent thunderstorms with above average precipitation during summer. The year 2007 is the fourth warmest year since the beginning of the measurements in 1864 (MeteoSwiss 2006, 2007).

Winter 2006/07 was characterized by several extremes: a late arrival of the snow cover, high air temperatures and small quantities of snow. After a record heat wave in autumn, the winter was the second warmest in the mountains since 1864. In the period between October 2006 and April 2007 there was less precipitation than normal and the winter was particularly snow-deficient at altitudes below 2000 m asl. The snow arrived much later than normal for the third consecutive year. Winter snow depths were mostly lower than the long-term average (1971–2000), with new minimum values recorded at some sites. Snow melt started in April and finished two to four weeks earlier than normal (Figs. 2.1–2.3).

In the GST time series the zero curtain phase began 10 to 30 days earlier than in the preceding years, but it was as long as for snowy years at many sites. At some sites, the snow cover disappeared at the earliest date since the beginning of the GST-series, whereas on other sites the date was close to the decadal mean. Three consecutive weeks of colder weather at the end of June and the beginning of July allowed the snow cover to persist where it had not completely melted, that is, at higher elevations and/or sites with a thicker winter snow pack (Fig. 2.3).

Summer temperatures during the months May to August 2007 were 1–3 °C above the long-term climatic mean, followed by lower values in September. In total, mean summer temperatures 2007 were 1–2.5 °C above average all over Switzerland (Figs. 2.4 and 2.5).

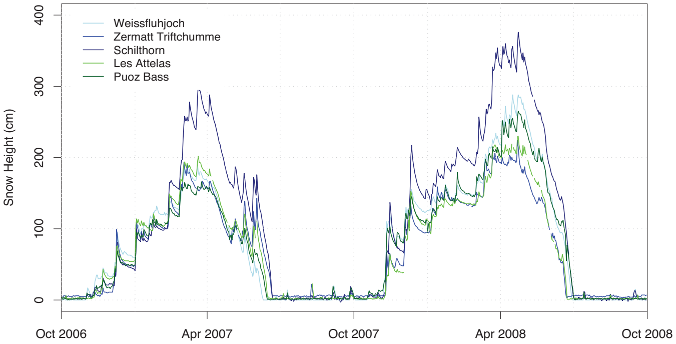
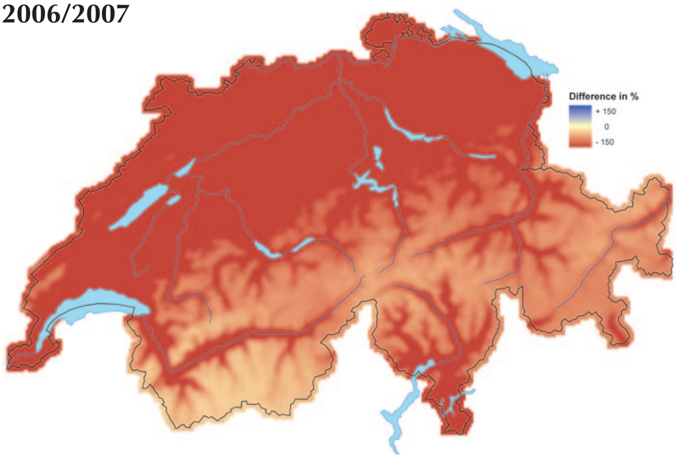


Figure 2.1:
Snow depths during the observation period 2006/2007 and 2007/2008 at five measurement stations in the Swiss Alps. Data provided by SLF.

2006/2007



2007/2008

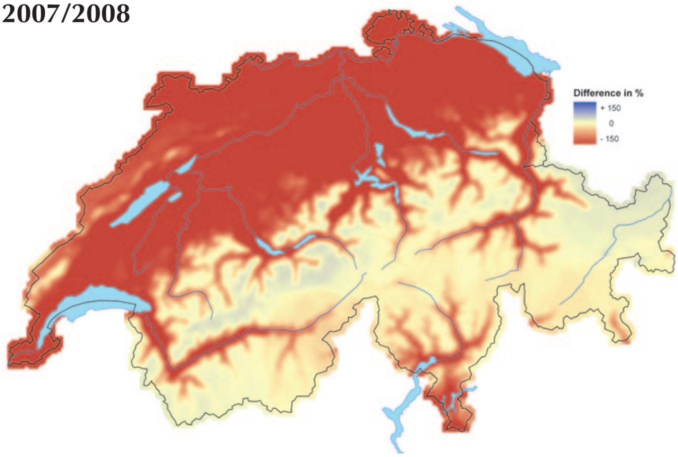


Figure 2.2:
Regional variability of deviations of winter snow amounts for the years 2007 (top) and 2008 (bottom), deviation from the mean value 1971–2000 in percent. Figures provided by C. Marty, SLF.

2.2 Snow Cover and Air Temperatures in 2007/2008

The meteorological period 2007/2008 started with a mild autumn and an early winter with intense snow fall, which was very mild and sunny at the end of the season. Spring and summer 2008 were characterized by stormy and variable weather conditions and can be described as normal. After two cold weeks, autumn was again mild and sunny (MeteoSwiss 2007, 2008).

Winter 2007/2008 started early with intense snowfall, both North and South of the Alps, resulting in the second highest snow depths ever measured in mid-November (Figs. 2.1 and 2.2). In mid-December the snow depths in all regions North of the Alps were higher than average. In particular in the lower Valais, the Northern flank of the Alps and in Northern Grisons, snow depths were two to three times the long-term average. In January several southerly weather situations led to intense snowfalls down to low altitudes on the southern flank of the Alps. At the end of April most areas above 2000 m asl still registered over 2 m of snow.

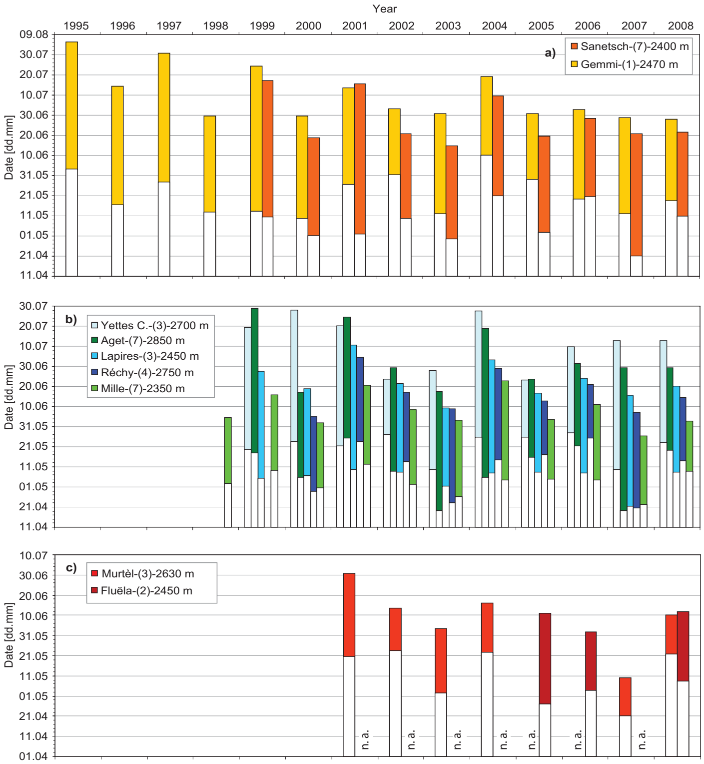


Figure 2.3: *Dates of snow melt (1995–2008) at PERMOS GST-sites: a) Bernese Alps, b) Valais Alps, and c) Engadine. The bottom and the top of the coloured bars indicate the starting and the ending dates of the zero curtain period. If several series are available on a site, the mean value is calculated. Legend: site-(number of measurement locations)-mean elevation.*

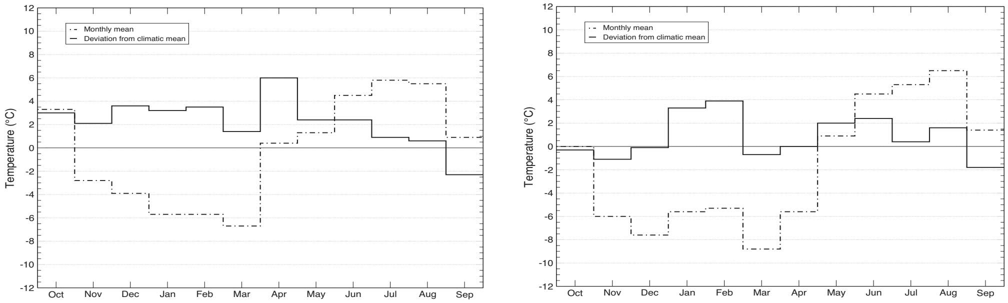
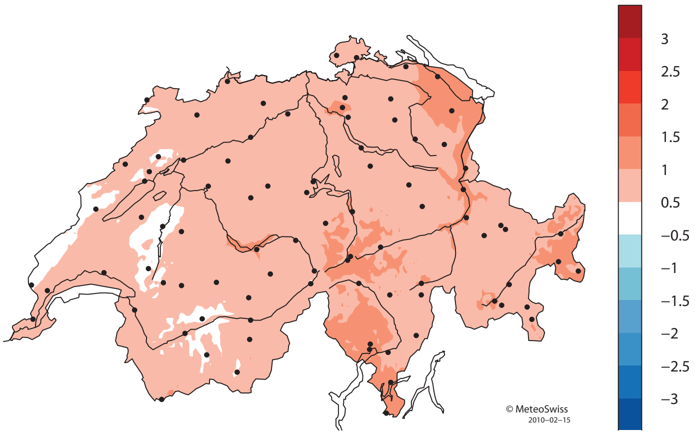


Figure 2.4: *Mean monthly air temperatures along with the deviations from the long-term climatic mean (period 1961–1990) for the climate station at Weissfluhjoch. Left: reporting period 2006/2007, right: reporting period 2007/2008. Data provided by MeteoSwiss.*

Temperature Anomaly (deg) 2007.05–2007.09



Temperature Anomaly (deg) 2008.05–2008.09

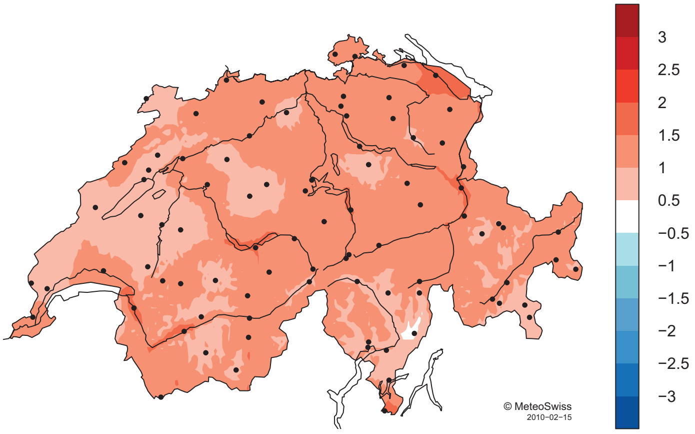


Figure 2.5:
Regional variability of mean summer air temperatures for the year 2007 (top) and 2008 (bottom), deviation from the mean value 1961–1990 in degrees Celsius. Figures provided by MeteoSwiss.

The phase of snow melt 2008 deduced from GST-series show average conditions of the last decade. Compared to the previous year, the zero curtain period started 1 to 3 weeks later. The phase of snow melt was intense, particularly during the second half of June. Despite a thicker snow pack than in 2006/2007, the zero curtain phase was much shorter and the snow cover disappeared only a few days later (Fig. 2.3).

In May and June 2008 air temperatures were considerably above average, and May 2008 was the second warmest on record. July and August were changeable but still slightly above average warm. September started very mild but changed to late autumn conditions in the second half. In mid June and August, short cold periods induced snow fall in regions above 1800 m asl. In summary, summer 2008 was warmer than average, in the mountain areas between 1 and 1.5 °C (Figs. 2.4 and 2.5).

Photo 2: PERMOS site Réchy/Bec de Bosson in the Val de Réchy (VS). Photo: R. Delaloye.

3 Ground Temperatures

The basis of the permafrost monitoring is the observation of the thermal conditions of the subsurface in permafrost areas. Ground temperatures are measured in and around boreholes at 14 sites (see Tab. 1.1), in rock glaciers, scree slopes, and ridges.

Near-surface temperatures are measured to characterize the spatial variability of ground temperatures, and because their changes are the main driving factor of changes in permafrost conditions. Near-surface temperatures are predominantly influenced by ground and snow cover as well as by mountain topography (such as slope and aspect) and their variations mainly reflect the short term variations in atmospheric and snow conditions. In addition, distributed measurements of near-surface temperatures in the vicinity of the drill sites help to asses the representativeness of the boreholes. Measurement devices are installed at three main types of locations: steep bedrock maximizes the influence of topography on ground temperatures but has little snow or debris cover, gently sloping bedrock additionally includes the effect of snow cover, and debris mantled slopes display further complicated effects of thermal offset. In addition, the bottom temperature of the snow cover (BTS) is measured at three sites.

Photo 3:
Boreholes on the Matterhorn Hörnligrat at 3500 m asl. Photo: M. Phillips.

Active layer thickness (ALT) is defined by the maximum depth of the 0 °C isotherm in the ground during one year. It is a reflection of the local snow and atmospheric conditions reigning during the current and previous year, as well as of the local ground characteristics. Here, we use linear interpolation to determine ALT from temperature data obtained from multiple thermistors in boreholes. Temperatures at greater depths are used for comparison between sites and allow the observation of seasonal and interannual temperature variations. At ca. 10 m depth short term external noise factors can more or less be disregarded, due to the damping effect of the ground, which causes a time lag of around six months here.

3.1 Near-surface Temperatures

3.1.1 Rock

Measurement activities of near-surface rock temperatures at 35 sites yielded 29 complete temperature time series of hourly resolution during the hydrological year 2006/2007 and 23 during 2007/2008 (Tab. 3.1). Incomplete series resulted from broken equipment or interrupted service visits during the summer 2009. Subsequent fieldwork may further increase the number of complete series for 2007/2008. A synopsis of mean annual temperatures is provided in Figure 3.1. The left part of the illustration shows that mean annual rock temperatures (MART) are generally warmer than mean annual air temperatures (MAAT) and that in shaded locations, the mean rock surface temperature is approximately equal to that of the air. Due to the much larger spread in exposition to solar radiation, the range of relative rock temperatures in steep terrain is about 10 °C whereas it is about 5 °C underneath a seasonal snow cover. The right part of the illustration shows that inter-annual fluctuations of temperatures in steep rock correlate closely with air temperature changes whereas rock subject to seasonal snow cover exhibits much larger variability. For both, 2006/2007 was about 1 °C warmer than 2005/2006. The year 2007/2008 was about 1 °C colder than 2006/2007.

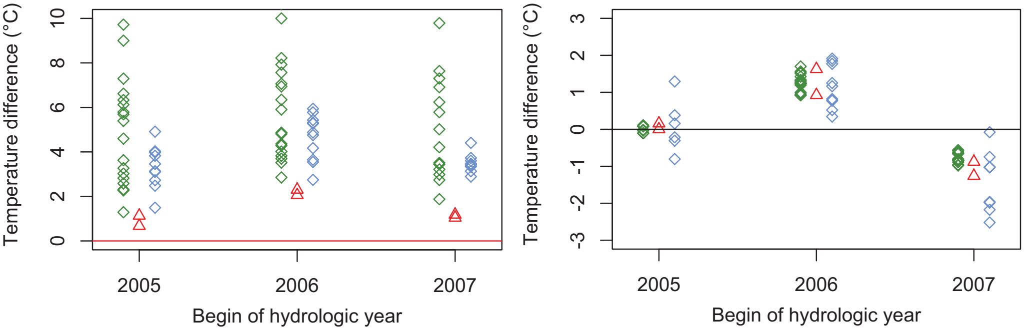


Figure 3.1: *Relative mean annual rock temperatures (MART) plotted for the reporting period and the preceding hydrological year, relative to the mean air temperature 1961–1990 (left) and relative to the previous year (right). Green: steep bedrock without the influence of snow, blue: gently inclined rock with seasonal snow cover, red: air temperature at Jungfraujoch and Corvatsch (Data: MeteoSwiss).*

Table 3.1: RST sites and mean annual rock temperatures (MART) for the reporting period.

Name	Region	Elevation (m asl)	Slope (°)	Aspect (°)	MART 2006/2007	MART 2007/2008
BB-v01	Réchy	3100	90	75	2.28	1.46
BB-v02	Réchy	3120	75	308	–0.04	–0.70
BB-v03	Réchy	3140	95	198	2.53	1.87
BB-v04	Réchy	2590	85	278	4.44	3.55
BB-v05	Réchy	2590	90	50	2.05	n.a.
BB-h01	Réchy	2600	0	0	2.12	n.a.
La-v01	Lapires	2380	95	325	3.92	3.11
La-v02	Lapires	2730	95	39	3.97	3.41
La-v03	Lapires	2720	90	140	5.91	5.33
La-v04	Lapires	2700	80	225	5.75	5.12
La-v05	Lapires	2770	10	341	1.72	0.87
La-h01	Lapires	2735	0	0	1.14	1.06
Murtèl Front	Corvatsch	2630	15	20	2.44	1.70
Mandra South	Corvatsch	2830	98	185	6.98	n.a.
Mandra East	Corvatsch	2805	90	88	4.08	n.a.
Fuorcla	Corvatsch	2740	11	344	2.32	1.29
Corvatsch Top Gate	Corvatsch	3285	72	333	–2.16	–3.00
Corvatsch Hubbel	Corvatsch	2545	0	0	4.11	n.a.
Corvatsch Middle Flat	Corvatsch	2690	8	320	3.19	1.23
Corvatsch Snow Canon	Corvatsch	2649	0	0	3.03	1.04
Corvatsch Middle Ridge	Corvatsch	2784	85	278	2.08	n.a.
Corvatsch Top Flat	Corvatsch	3300	0	0	–0.30	–2.48
Corvatsch Top Ridge	Corvatsch	3300	58	181	n.a.	n.a.
Fuorcla North	Corvatsch	2765	23	11	3.34	0.82
Eigerfenster	Schilthorn	2860	90	325	0.48	–0.48
Birg East 2	Schilthorn	2620	0	0	n.a.	1.47
Schwarzgrat	Schilthorn	2800	0	0	n.a.	n.a.
Engital	Schilthorn	2410	10	130	2.45	n.a.
Schilthornhuette	Schilthorn	2450	0	0	n.a.	n.a.
Birg West 2	Schilthorn	2680	22	130	3.38	2.36
Birg vertical	Schilthorn	2670	85	205	n.a.	n.a.
Jungfrau East Ridge South	Schilthorn	3750	70	145	1.64	0.78
Jungfrau East Ridge North	Schilthorn	3750	55	344	–6.15	–7.13
Eismeer	Schilthorn	3150	87	100	n.a.	n.a.
Moench West Ridge	Schilthorn	3550	72	288	–3.42	–4.26

3.1.2 Debris Slopes

The recording of ground surface temperature (GST) in loose debris material has been carried out at 12 sites in 2006/2007 and 2007/2008 instrumented with 3 to 21 single-channel temperature data loggers (Tab. 3.2). The parameters observed are (a) the duration of the snow cover (see Chapter 2), (b) the Ground Freezing Index (GFI), which is the sum of all daily negative ground temperatures measured during the winter and indicates how cold a winter is at the ground surface, and (c) the Mean Annual Ground Surface Temperature (MAGST), which mainly results from (a), (b), and summer temperatures.

Ground Freezing Index

The GFI values were low in 2006/2007, however, without reaching the minima of winter 2000/2001 or 2002/2003 (Fig. 3.3). This has also been observed by BTS measurements. Despite exceptionally high air temperatures in fall and winter 2006/2007, a relatively thin snow cover in early winter led to a colder ground surface. In 2007/2008 the GFI values were lower with values at or below the mean of the past decade. Since the start of measurements within PERMOS in 1999/2000, the GFI values of the four past winters (2004/2005–2007/2008) were on average significantly lower (25–150%) than the six preceeding winters.

Table 3.2: GST-sites and available data. GST-measurements: c/n + (i), n=total number of measurement places; c=complete series; i=incomplete series; BH=borehole linkage; KN=rock glacier kinematics site.

Site	Region	Available data	GST 2006/2007	GST 2007/2008	BTS	BH	KN
Aget	Central Valais	since 1998	7/7	7/7			x
Alpage de Mille	Central Valais	since 1997	16/18	16/18	x		x
C. de la Lé-Sanetsch	Berner Oberland	since 1998	6/7+(1)	5/7+(2)			
Dreveneuse	Chablais	since 2004	6/6	6/6		x	
Flüela	Engadine	since 2004	0/2	6/6		x	
Gemmi	Berner Oberland	since 1994	13/18+(2)	13/18+(4)			x
Lapires	Central Valais	since 1998	15/15	15/15	x	x	x
Murtèl-Corvatsch	Engadine	since 2000	4/4	4/4		x	x
Réchy	Central Valais	since 1997	9/10+(1)	9/10+(1)	x		x
Schafberg	Engadine	since 2000	4/9	3/9		x	
Schilthorn	Berner Oberland	since 1999	being processed			x	
Yettes Condjà	Central Valais	1998–2005	8/21(+1)	18/21(+2)	x		x

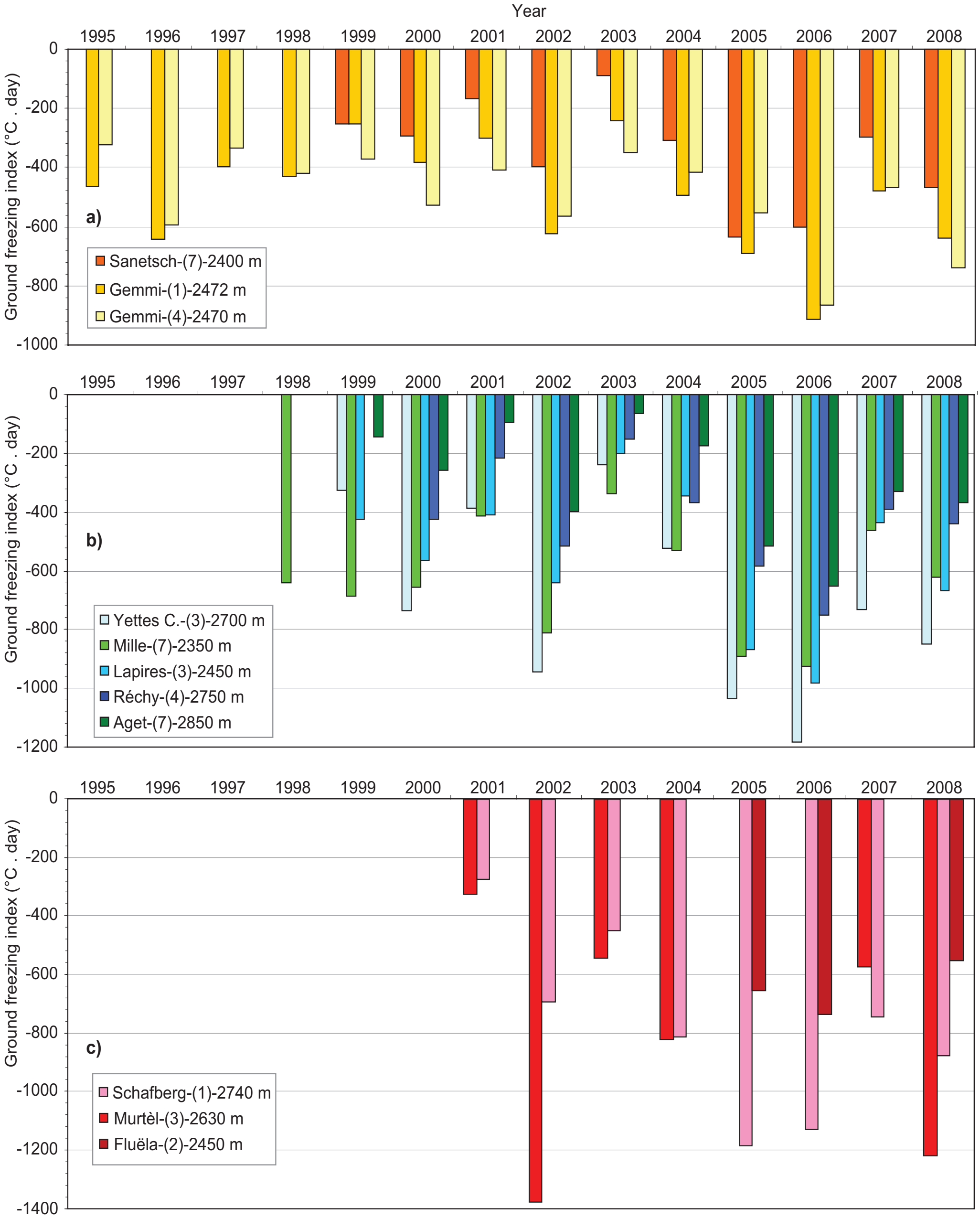


Figure 3.2: Ground freezing index (GFI) at PERMOS GST-sites; a) Bernese Alps; b) Valais Alps; c) Engadine. Legend: site-(total number of sensors)-mean elevation.

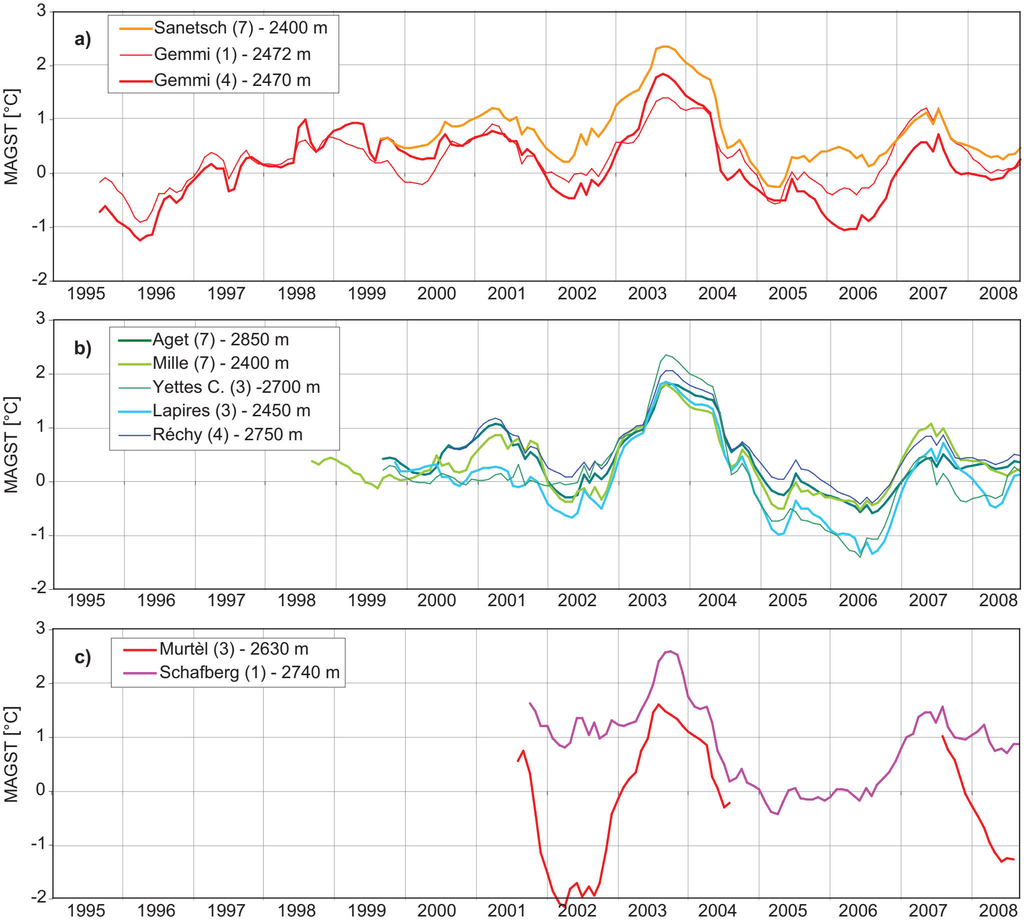


Figure 3.3: Evolution of the mean annual ground surface temperature (MAGST) on PERMOS GST-sites: a) Bernese Alps, b) Valais Alps, c) Engadine. MAGST is computed as a monthly running mean. The date on the time axis corresponds to the end of the annual period used for the calculation of the mean. Legend: site-(total number of sensors)-mean elevation.

Mean Annual Ground Surface Temperature

As a result of the exceptionally warm fall 2006 and the reduced cooling of the ground in winter 2006/2007, mean annual surface temperatures (MAGST) rose by about 1 to 1.5 °C until mid-2007 (Fig. 3.3). The thin early winter snow cover prevented the MAGST from increasing as strongly as the MAAT. Even if MAAT in 2006/2007 exceeded the 2003 value by about 1 °C, MAGST remained about 1 °C lower. Lower ground surface temperatures during winter 2007/08 made the MAGST values decrease about 0.5 to 1 °C until early summer 2008. By the end of September 2008, MAGST values were close to the mean of the last decade.

3.1.3 BTS

BTS measurements were performed at two sites in spring 2007 and 2008 in the western Valais Alps (Lapires, Mille, Tab. 3.3). Annual mean values for BTS and snow depth at the time of the measurement campaign are depicted in Figure 3.3. At Mille, the mean BTS value in March 2007 was about 1 °C higher than the long-term mean, and the snow depth was slightly above average. The warmer conditions were primarily a result of the extremely mild weather during most of the wintertime. The snow depth in March 2008 was the lowest since the beginning of the measurements in 1996. The thermal insulation was reduced during the winter 2007/2008 and favored the cooling of the ground surface. Accordingly, BTS values reflect relatively cold conditions.

Table 3.3: BTS measurements in 2007 and 2008.

Site	Region	Available BTS	BTS 2007	BTS 2008	Mean 2000	BH
Alpage de Mille	Central Valais	since 1996	09.03	08.03	x	
Lapires	Central Valais	since 2001	14.03	18.03	x	x
Réchy	Central Valais	2000–2004	n.a.	n.a.	x	
Yettes Condjà	Central Valais	2002–2004	n.a.	n.a.	x	

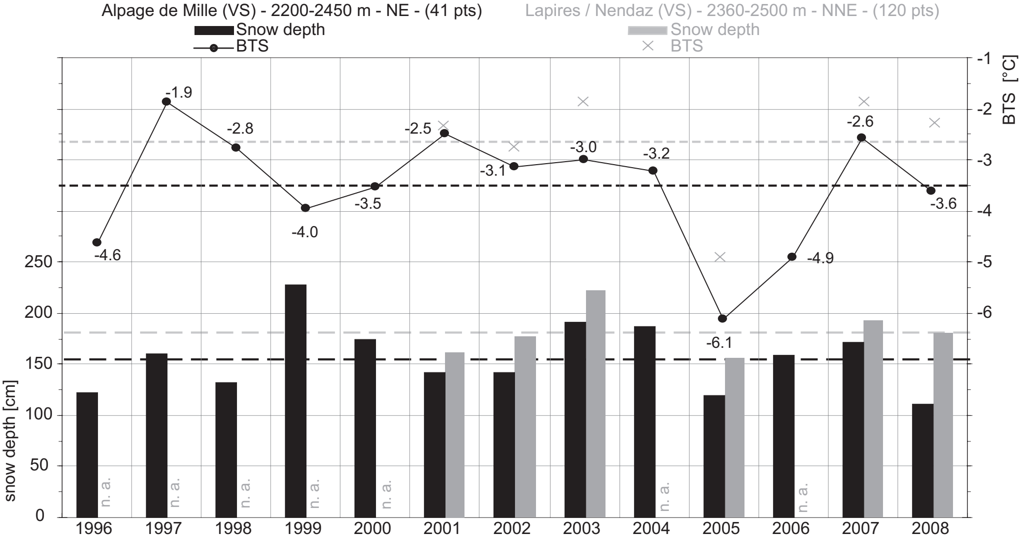


Figure 3.4: Mean BTS and snow depth values since 1996 on two sites in the western Valais Alps, and in brackets the number of BTS measurements. Dotted lines are the mean values for available BTS and snow depth time series at Mille (1996–2008, black) and Lapires (2001–2008; grey).

3.2 Borehole Measurements

The PERMOS Network currently includes 27 boreholes at 14 sites. Five borehole sites are newly included in this report: Les Attelas, Dreveneuse, Matterhorn, and Ritigraben in the western part of Switzerland, and Gemsstock in Central Switzerland. The borehole at Ritigraben existed for several years, and data are currently being processed and the installation renovated. The boreholes at Les Attelas and three new boreholes at Lapires have been drilled during the reporting period and data will be included in the coming reports. The instrumentation on the Stockhorn (VS) was completely destroyed by a storm in 2008 and the station needed to be repaired and newly set up. Therefore a larger data gap exists and data from only one of the two boreholes are reported here.

Table 3.4: Active layer thickness (ALT) and corresponding date for the years 2007 and 2008. No AL means that no active layer could be recorded because only seasonal freezing occured at the borehole site; n.a. means that no data is available for this period.

Borehole	Region	Elev. (m asl)	ALT 2007 (m)	Date	ALT 2008 (m)	Date
Attelas 0108	Central Valais	2657	–	n.a.	–	n.a.
Attelas 0208	Central Valais	2689	–	n.a.	–	n.a.
Attelas 0308	Central Valais	2741	–	n.a.	–	n.a.
Dreveneuse 0104	Chablais	1580	–	no AL	–	no AL
Flüela 0102	Engadine	2394	2.98	31.08.2007	2.98	14.09.2008
Gemsstock 0106	Central CH	2910	–	no AL	–	no AL
Gentianes 0102	Central Valais	2895	1.47	26.09.2007	–	n.a.
Lapires 0198	Central Valais	2500	4.65	01.10.2007	4.75	01.10.2008
Lapires 1108	Central Valais	2500	–	n.a.	–	n.a.
Lapires 1208	Central Valais	2500	–	n.a.	–	n.a.
Lapires 1308	Central Valais	2500	–	n.a.	–	n.a.
Matterhorn 0205	Mattertal	3270	3.31	25.08.2007	2.88	11.09.2008
M. da Barba Peider 0196	Engadine	2946	1.00	01.09.2007	1.00	15.09.2008
M. da Barba Peider 0296	Engadine	2941	1.97	05.09.2007	2.05	22.09.2008
Muragl 0199	Engadine	2536	–	no AL	–	no AL
Muragl 0499	Engadine	2549	4.48	16.09.2007	–	n.a.
Murtèl-Corvatsch 0287	Engadine	2670	3.51	03.09.2007	3.51	04.09.2008
Murtèl-Corvatsch 0200	Engadine	2670	2.47	16.08.2007	2.48	06.09.2008
Ritigraben 0102	Mattertal	2600	–	n.a.	–	n.a.
Schafberg 0190	Engadine	2755	3.96	20.08.2007	3.97	07.09.2008
Schafberg 0290	Engadine	2735	5.03	24.08.2007	5.03	16.09.2008
Schilthorn 5198	Jungfrau	2910	4.66	09.10.2007	4.97	25.09.2008
Schilthorn 5000	Berner Oberland	2910	3.14	04.10.2007	3.89	13.09.2008
Schilthorn 5200	Berner Oberland	2910	1.16	09.10.2007	1.89	17.09.2008
Stockhorn 6000	Mattertal	3410	–	n.a.	–	n.a.
Stockhorn 6100	Mattertal	3410	–	n.a.	3.42	17.09.2008
Tsaté 0104	Central Valais	3040	6.39	21.07.2007	6.43	06.10.2008

3.2.1 Active Layer Thickness

In both summer seasons reported, 2007 and 2008, the ALT remained stable at all sites and were similar to those registered in 2006 (Tab. 3.4). For 2007, ALT was determined for 15 boreholes, and for 2008 for 14 boreholes. The differences measured were of the order of a few centimeters, as can be seen in Figure 3.5. This is of particular interest, as the two preceding winters had very different temporal and spatial snow distribution characteristics.

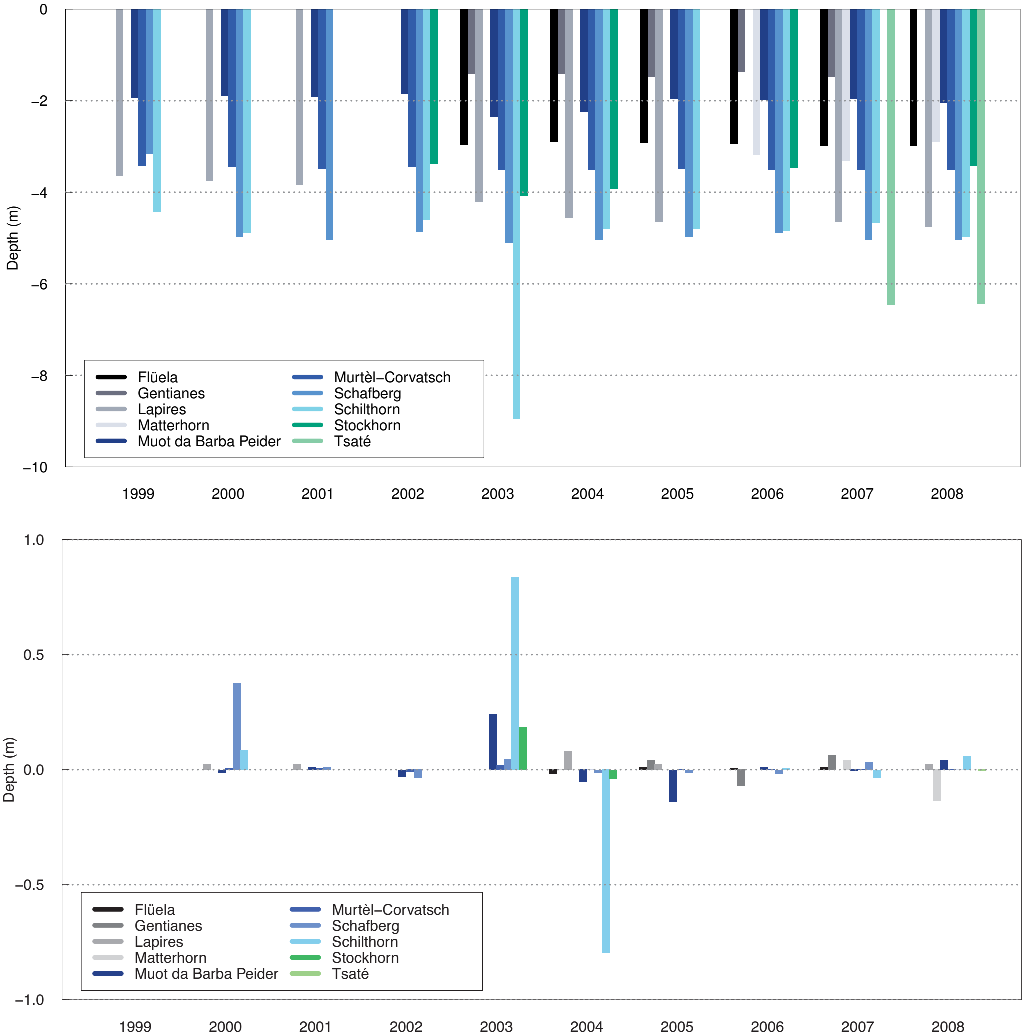


Figure 3.5: *Active layer thickness (ALT) of the past decade measured in ten PERMOS boreholes until 2008 (top), and relative differences in ALT (in comparison with the previous year and relative to the mean ALT measured in the borehole).*

ALT ranged between 1.5 and 6.5 m at the different sites during the reporting period. At three boreholes (Dreveuneuse 0104, Gemsstock 0106, and Muragl 0199) no AL was recorded because the entire profile thawed in the course of the summer.

3.2.2 Borehole Temperatures

Temperatures measured during the reporting period in several PERMOS boreholes are depicted in Figures 3.6 and 3.7. The temperatures at ca. 10 m depth particularly reveal the importance of both air temperatures and snow depth as regulators of ground temperatures at the regional to national scale. The record heat wave in autumn 2006 is reflected by relatively high minimum ground temperatures in 2007 (in comparison with the previous and following years). In contrast, the minimum ground temperatures at 10 m depth were lower again in 2008, following a very snow-rich spring, which helped to prevent the ground from being warmed by solar radiation and high air temperatures.

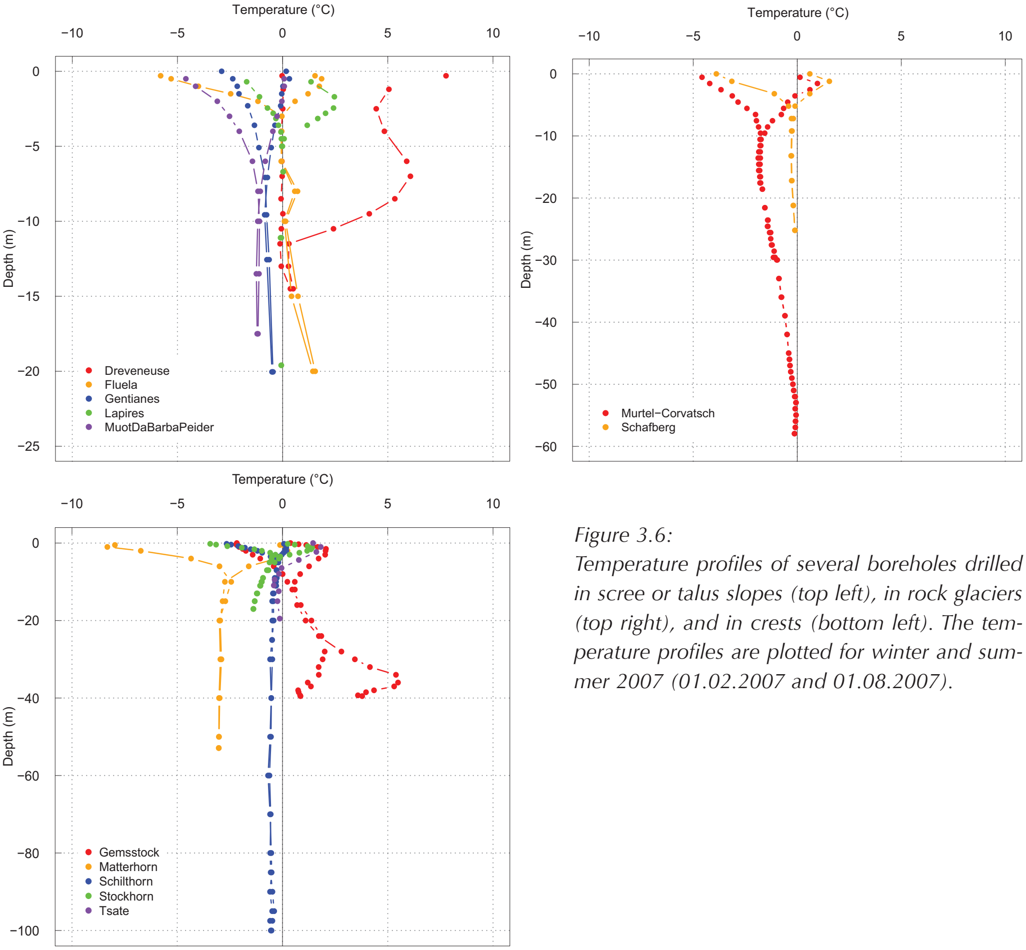


Figure 3.6:
Temperature profiles of several boreholes drilled in scree or talus slopes (top left), in rock glaciers (top right), and in crests (bottom left). The temperature profiles are plotted for winter and summer 2007 (01.02.2007 and 01.08.2007).

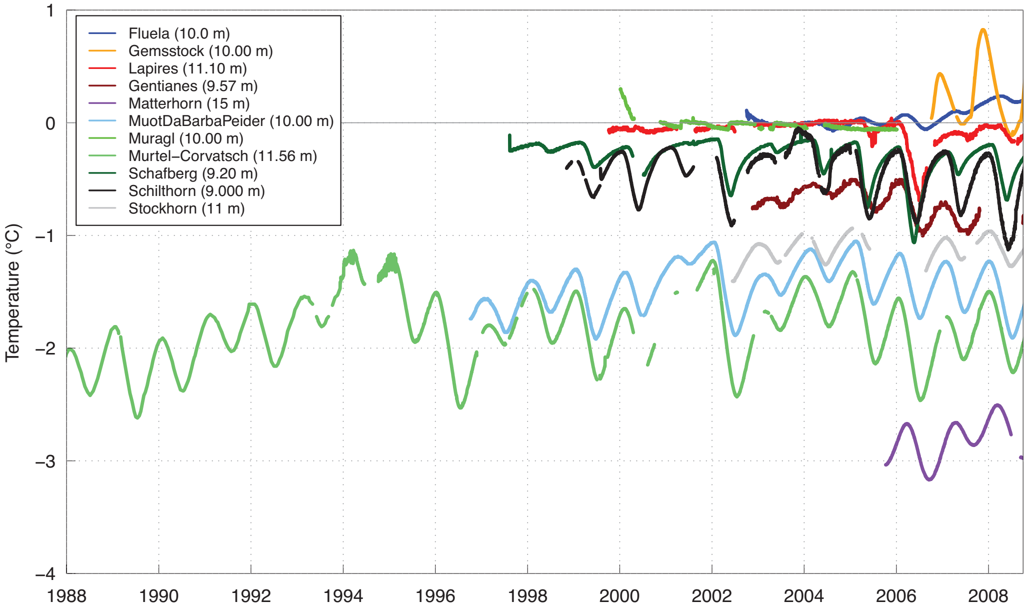


Figure 3.7: *Temperatures at ca. 10 m depth measured in PERMOS boreholes in the past decade.*

3.3 Summary

Near-surface temperatures measured during the reporting period reflect the differing athmospheric conditions during the two years. The year 2006/2007 can be characterized by warm surface conditions with higher values for RST, GST, GFI, and BTS, however, without reaching extreme values. The near-surface thermal conditions of the following year 2007/2008 were colder again. MAGST increased consecutively in 2006/2007 without reaching the extreme values of 2003, and slightly decreased in 2007/2008. For the two reported years MAGST was almost higher than the decadal mean.

Active layer thicknesses were similiar to 2006 for both reporting years despite the different spatial and temporal distribution of the snow cover. They can be described as more or less stable for the past five summer seasons that followed the extreme conditions of 2003. The 10-m temperatures measured in the borehole also showed the influence of differing winter and summer conditions, but with a time lag of about half a year, and were relatively high in 2007 as a result of the extremely warm autumn 2006 and lower in 2008 following the long lasting snow cover in winter 2007/2008.

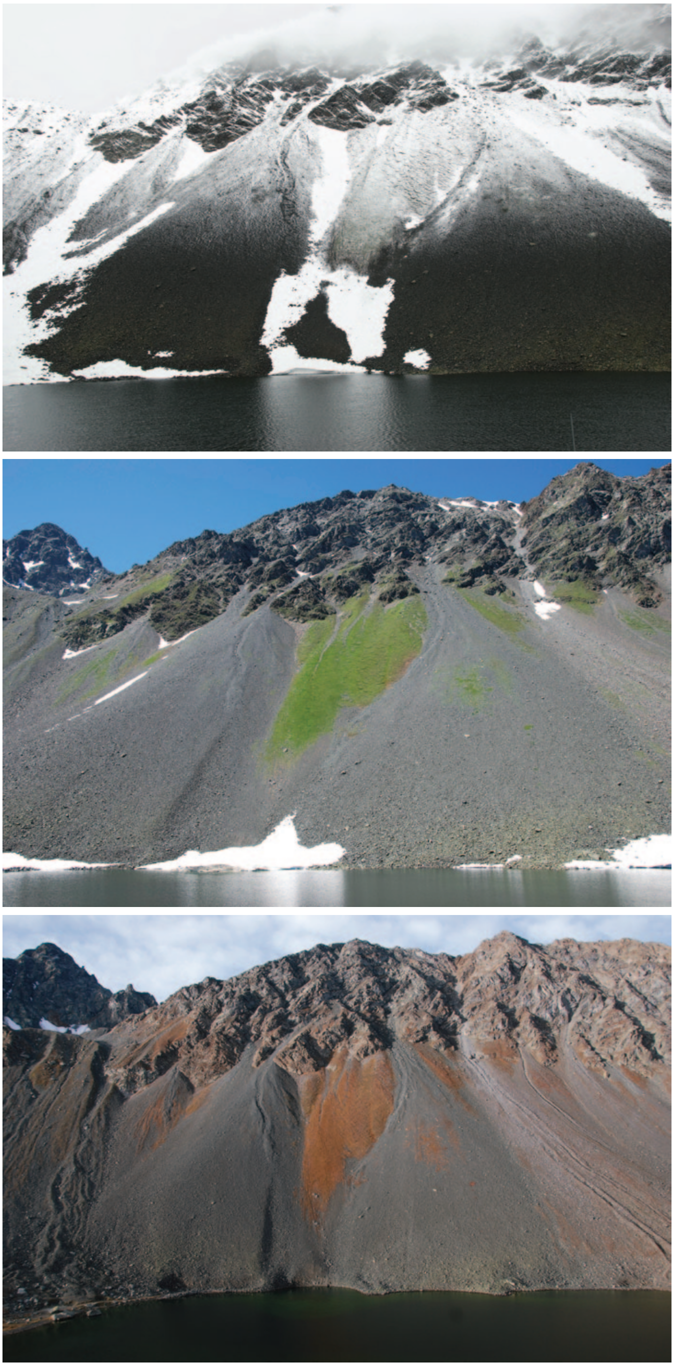


Photo 4:
The PERMOS Reference Site Flüela in Grisons in spring, summer, and autumn. Photos: M. Phillips.

4 Electrical Resistivities

At present, five permanent ERT profiles located close to the boreholes are part of the network. This allows a joint analysis of the borehole temperatures with the temporal changes in resistivities, the latter being indicative for changes in water and ice contents. For long-term inter-annual comparisons at least one measurement each August/September is necessary.

4.1 ERT Results for 2006/2007 and 2007/2008

The Figures 4.1 to 4.4 (left panels) show selected tomograms for all sites, comparing the ERT results for measurements from August/September 2006–2008. Strong variations of the mean electrical resistivity ranges are observed between the different sites, which is mainly due to differences in substrate and different ice and unfrozen water contents. Since air and ice are electrical isolators, dry and coarse blocky substrates (e.g., Murtèl, Lapires) generally have much higher resistivities than fine-grained material (e.g., Schilthorn, Stockhorn), and ice-poor materials have much lower resistivities than ice-rich materials. The very low resistivity values at Schilthorn, for example, are a result of both fine-grained substrate and very low ice contents, while the extraordinarily high values of the Murtèl rock glacier are caused by its high ice content. Unfrozen water is electrically conductive and causes decreasing resistivities in case of infiltration and/or melting of ice. The right panels of Figures 4.1 to 4.4 show the inter-annual changes in electric resistivity between the years indicated. Blue colours denote a resistivity increase, and red colours a decrease.

Table 4.1: Overview of all ERT sites.

	Schilthorn (SCH)	Schilthorn (SCV)	Stockhorn (ST)	Lapires (LAH)	Murtèl (MT)
location along the crest	cross profile in N-slope	longitudinal profile (N-S)	N-S-profile across plateau	cross profile in N-slope	longitudinal profile along rock glacier
# of electrodes	30	47	55*	43	48
spacing	2 m	4 m	2 m	4 m	5 m
profile length	58 m	184 m	108 m*	168 m	235 m
investigation depth (app.)	10 m	30 m	15 m	25 m	40 m
borehole position (horiz. dist.)	51/98: 11 m 50/00: 26 m	51/98	60/00: 28 m* 62/00: 57 m*	01/98: 112 m	02/87: 55 m
ERT since	8/1999	8/2006	9/2005	8/2006	8/2005

* The Stockhorn profile initially consisted of 48 electrodes, and was extended by 7 electrodes in July 2007, increasing the total length by 14 m. The new electrodes were placed in the northern rock face of the plateau and shifted the starting point of the profile to the north and hence the relative position of the boreholes within the profile. The table describes the new profile.

The northern slope of the Schilthorn crest shows only minor resistivity changes between 2006 and 2008 (Fig. 4.2). Compared to 2006, the Lapires talus slope exhibits a strong decrease in 2007 in the central high resistive ice body beneath the cable car pylon (Fig. 4.1), and similarly, a confined anomaly is visible in the central part of the Murtèl rock glacier with significantly lower resistivities at the top of permafrost in 2007 (Figure 4.3). Both anomalies occurred after the warm winter 2006/2007, and show a heterogeneous impact of the high air temperatures on the permafrost conditions. In both cases the strong resistivity changes occur in the form of relatively small anomalies close to the borehole positions, the latter showing only relatively small changes. In contrast, increasing resistivity values are observed within the active layer and top of permafrost at Stockhorn in 2007 and 2008 (Fig. 4.4). Increasing values in the active layer can be attributed to drier conditions, which may correspond to the rather warm summer 2007. Higher values below the permafrost table indicate colder conditions with less amounts of unfrozen water within the frozen zone. Unfortunately, data gaps of the Stockhorn boreholes prohibit a validation of this observation with borehole temperatures. Similarly to the increase in 2008, the Schilthorn crest also shows significantly higher resistivities at the surface in 2008 (Fig. 4.2).

Figure 4.5 shows the long-term mean apparent resistivity evolution at Schilthorn (horizontal profile). The different colours each stand for one of the past ten years. Even though the cold autumn 2007 led to the currently highest observed resistivities in late winter 2007/2008, the high spring and early summer temperatures led to an early snow melt and a corresponding high energy input during summer 2008. The mean apparent resistivity values at the end of summer 2008 therefore indicate medium to slightly below-average ice content conditions.

To allow a comparison of the observed resistivities with the borehole temperatures, specific resistivities were extracted from the tomograms at the position of the boreholes and illustrated in terms of «virtual boreholes» (Fig. 4.6). This illustration confirms that no important anomalies were observed around the boreholes between 2006 and 2008.

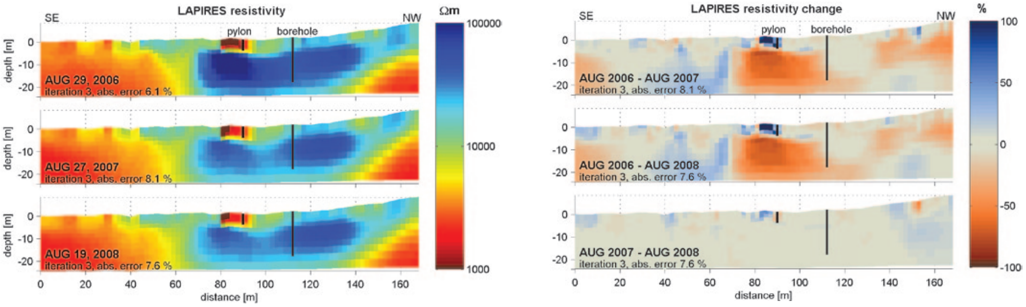


Figure 4.1: Tomograms with the resistivity distribution (left) and time-lapse tomograms with the temporal resistivity change (right) for the years 2006–2008 of the horizontal ERT profile in the Lapires talus slope (LAH).

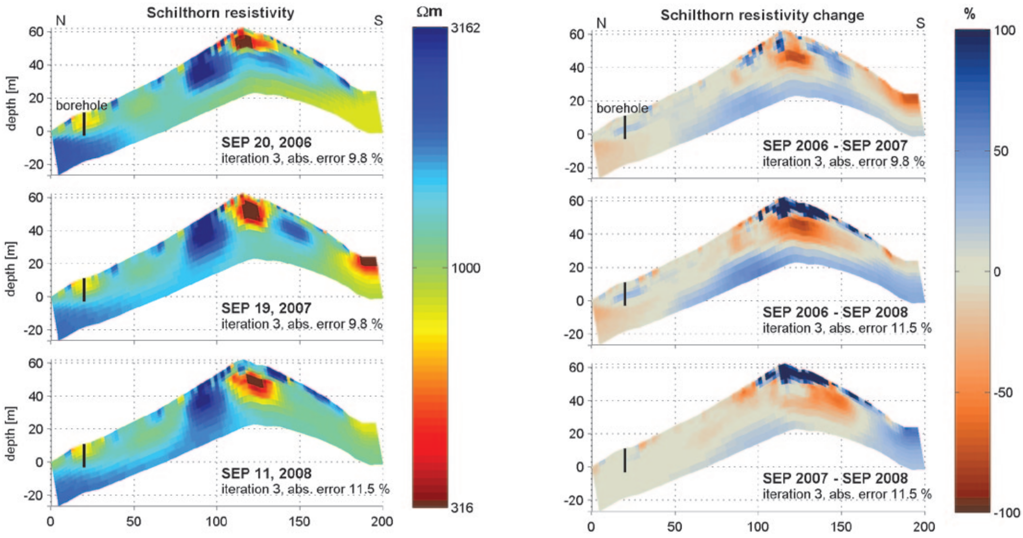


Figure 4.2: *Tomograms with the resistivity distribution (left) and time-lapse tomograms with the temporal resistivity change (right) for the years 2006–2008 of the longitudinal ERT profile across the Schilthorn crest (SCV).*

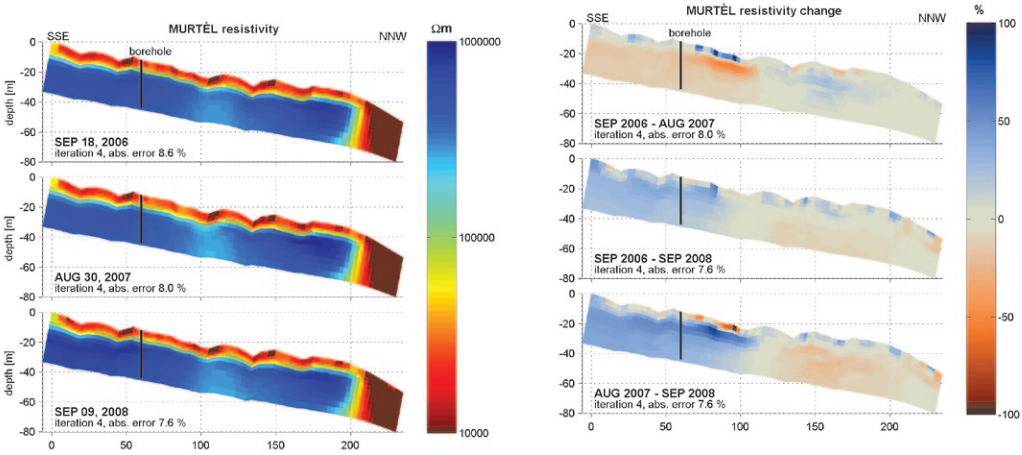


Figure 4.3: *Tomograms with the resistivity distribution (left) and time-lapse tomograms with the temporal resistivity change (right) for the years 2006–2008 of the longitudinal ERT profile across the frontal part of the Murtèl rock glacier (MT).*

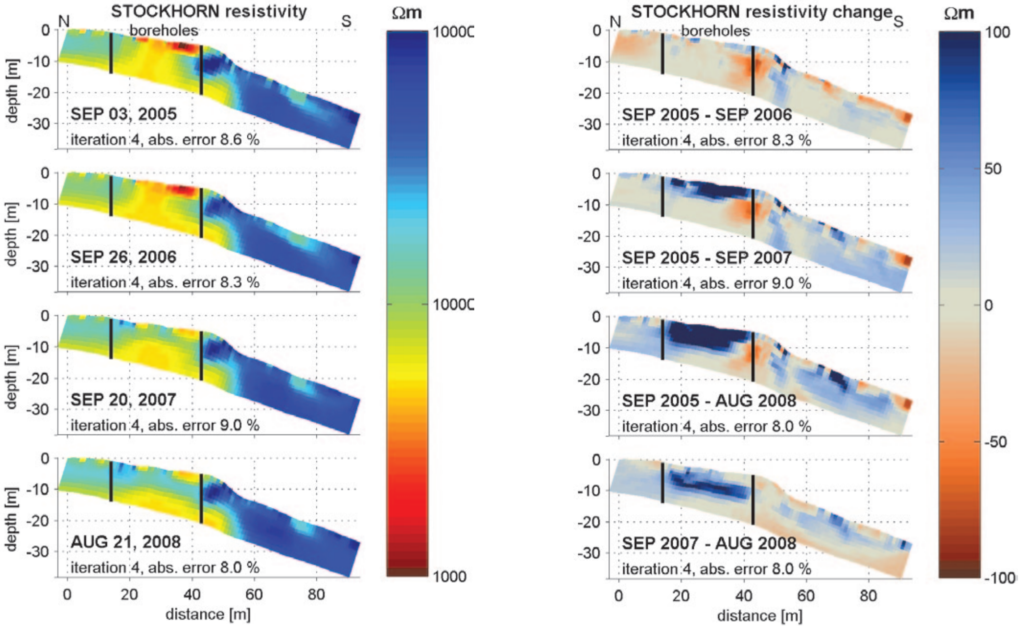


Figure 4.2: *Tomograms with the resistivity distribution (left) and time-lapse tomograms with the temporal resistivity change (right) for the years 2005–2008 of the ERT profile across the Stockhorn plateau (ST).*

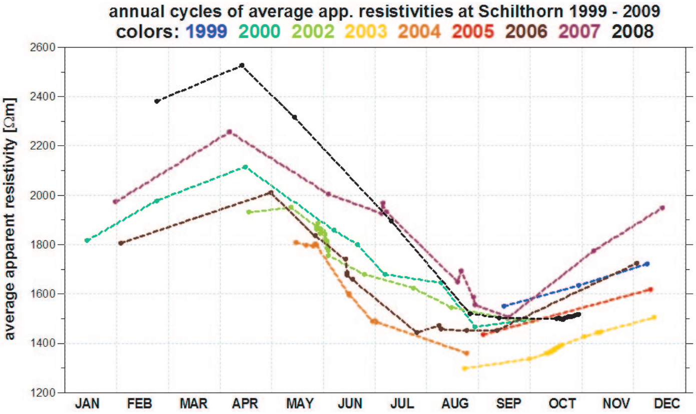


Figure 4.5: *Annual cycles of average apparent resistivities per measurement 1999–2008 for the horizontal ERT profile in the northern slope of the Schilthorn (SCH).*

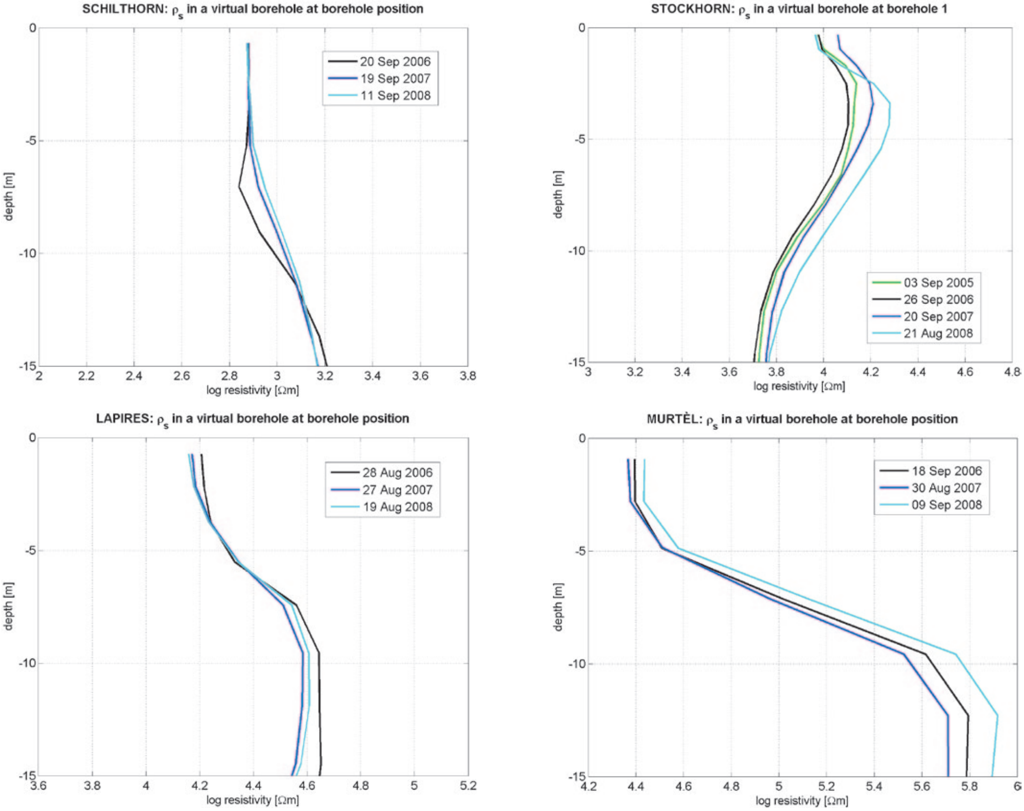


Figure 4.6: *Depth profiles of the specific electrical resistivity (ρ_S) shown as virtual boreholes through the ERT tomograms at the position of the (true) boreholes.*

4.2 Summary

In general, the period between 2006 and 2008 had no strong and sustained influence on the observed resistivity distribution. Due to the mostly effectively insulating snow cover, the warm winter 2006/2007 had only limited impact on the permafrost at the ERT sites. For example, at Schilthorn, the snow cover was too thick to allow a significant influence of high air temperatures on the ground. At Lapires and on Murtèl rock glacier, confined anomalies with a significant resistivity decrease could be observed as a consequence of the warm winter, which indicate an increase in the unfrozen water content. This impact was already compensated in the following year at Murtèl but was more sustained at Lapires. However, no large-scale impact was observed for all sites.

5 Kinematics

Kinematics [greek:kínema = movement] is defined as the quantification of movement (velocity) without considering the forcing factors. The velocity is generally described as a vector in a four-dimensional field v(x, y, z, t), where x and y represent the coordinates, z depicts the elevation, and t the time. The horizontal components at the surface are determined by $\Delta x/\Delta t = v_x$ and $\Delta y/\Delta t = v_y$. Thus, the velocity includes temporal (velocity between the times of the measurements) as well as spatial aspects (velocity between the corresponding points) (Kääb 1996, Roer 2007). In geomorphology, kinematics are described for several gravitational processes; for slow processes such as rock glaciers, but also for fast processes such as debris flows. Within PERMOS, rock fall events related to permafrost areas are newly documented systematically with date, location of the starting zone, volume, and geological characteristics.

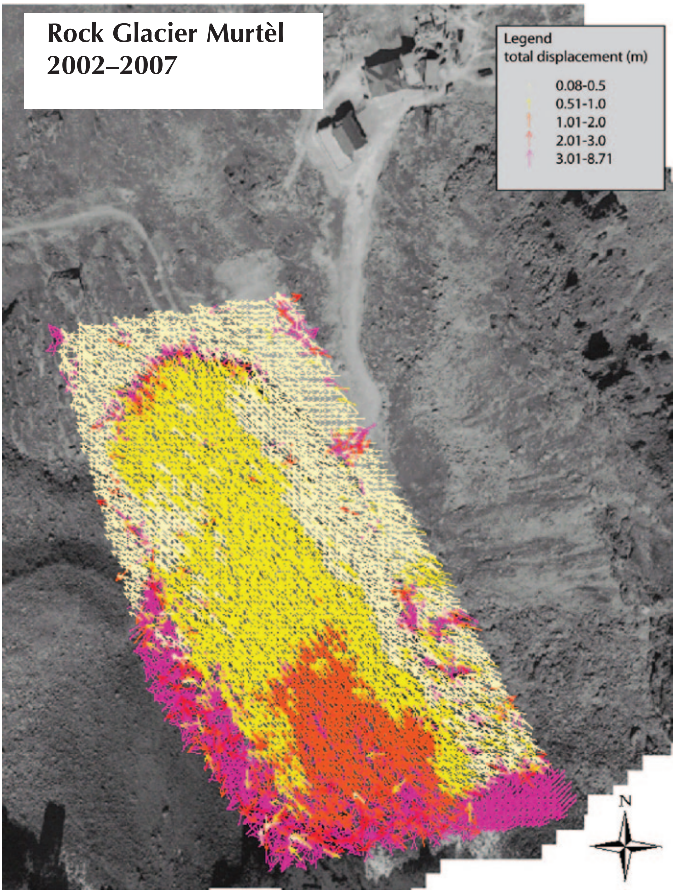


Figure 5.1:
PERMOS kinematics site Murtèl (Engadine): horizontal velocities between 2002 and 2007 derived from digital photogrammetry. Underlying orthophoto from 1996 (© Swisstopo).

For creeping permafrost landforms, changes in geometry are analyzed to describe horizontal velocities and vertical changes. Using photogrammetry, these parameters are derived for the entire landform. Vertical changes quantified from DTM comparison are thus determined independently of the horizontal movement. In contrast, geometry changes derived from terrestrial surveys are related to single points (blocks) at the surface and vertical changes are related to the horizontal component, due to downslope movement of the block.

If a certain number of point measurements exist for a landform (about 20 points per hectare), mean, median, and maximum values can be calculated and compared. Reference values, defined by the responsible investigator, can be given depending on morphology, flow pattern, and specific characteristics of the landform.

5.1 Permafrost Creep

Within PERMOS, a combination of remote sensing and in-situ measurements have turned out to be best suited for monitoring of permafrost creep by quantifying decadal, annual as well as seasonal movements.

5.1.1 Aerial Photographs/Photogrammetry

Within PERMOS, special aerial photographs taken from low flying altitude (scale about 1:6000) are used to monitor different rock glacier sites (Tab. 1.1, Fig. 1.2). These aerial surveys are conducted every 5–7 years. The orthophotos are used for the quantification of horizontal velocities by application of the image matching program CIAS (Kääb and Vollmer 2000). The DTMs are used for the quantification of thickness changes. An accuracy assessment was performed by Kääb and Vollmer (2000). Horizontal velocities as well as vertical changes are derived for entire landforms and spatial patterns can be described for the different parameters. During the reported period 2006/2007 and 2007/2008, both methods were applied at the PERMOS sites.

Aerial photographs were taken at Gruben (2006, 2007), Muragl (2007), Murtèl (2007), Schafberg (2007), Suvretta (2007), Gross Gufer (2008) and Rechy (2008) (cf. Appendix).

Table 5.1: PERMOS sites with terrestrial survey for the period 2000–2008 (dGPS=differential Global Positioning System, TSt=Total Station).

Site	Method	2000	2001	2002	2003	2004	2005	2006	2007	2008
Aget	dGPS		x		x	x	x	x	x	x
Becs/Bosson	dGPS		x		x	x	x	x	x	x
Gemmi	various	x	x	x	x	x	x	x	x	x
Gross Gufer	dGPS								x	x
HuHH1	TSt		x	x	x	x	x			
HuHH3	TSt			x	x	x	x	x	x	x
Muragl	TSt	x	x	x	x	x				
Yettes Condjà	dGPS	x	x		x	x	x	x	x	x

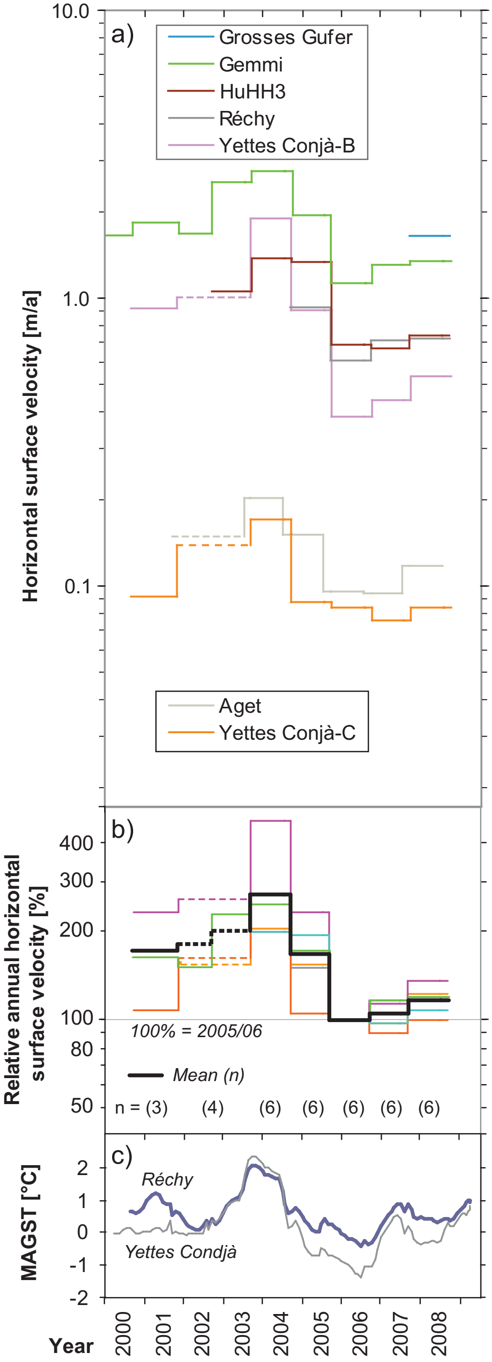


Figure 5.2:
Horizontal velocities (reference values) of six Valaisian sites between 2000 and 2008, as derived from terrestrial surveys. a) Horizontal velocities (m/a) and b) relative annual horizontal velocities (%) are linked to c) MAGST.

Table 5.2: *Relative change of the mean horizontal surface velocity (reference values) of PERMOS rock glaciers (comparison to the respective previous year).*

Site	2004/2005	2005/2006	2006/2007	2007/2008	2008/2009	num
Aget	–25%	–36%	–2%	24%	9%	27
Gemmi	–30%	–31%	4%	2%	2%	21
Gross Gufer					67%	15
HuHH3	–3%	–49%	–3%	11%	63%	22
Réchy		–34%	18%	2%	19%	6
Yettes Condjà-B	–52%	–57%	14%	21%	44%	12
Yettes Condjà-C	–48%	–4%	–11%	12%	62%	19
Average	–32%	–35%	3%	14%	44%	

5.1.2 Terrestrial Survey

With the detection of strong temporal variations in rock glacier kinematics (Roer et al. 2005, Kääb et al. 2007, Delaloye et al. 2008, PERMOS 2009), an additional focus was made on the realization of repeated annual and seasonal measurements. Therefore, terrestrial geodetic surveys using total station or differential GPS have been carried out at several PERMOS sites for a few years (PERMOS 2009), and are officially implemented in PERMOS for a pilot phase starting in 2008. These surveys have to be repeated at least once a year at approximately the same date (in late summer) and an approximate number of 20 points (blocks) per hectare.

5.2 Rock Fall from Permafrost Areas

The stability of high mountain rock walls is influenced by factors such as geology, topography, and hydrology but also by the occurrence of permafrost and changes to it. Even though knowledge of the relation between the occurrence of rock fall events and the presence of permafrost is limited, there are several indications which point to a relation between rock fall events in high mountain areas and the degradation of permafrost. For instance, the observation of large numbers of rock falls in the extremely hot and dry summer 2003, or the presence of massive ice in detachment zones right after the event (cf. Gruber and Haeberli 2007).

In the scope of a Masters thesis at the UZH in collaboration with SLF, the Federal Office for the Environment (FOEN), MeteoSwiss, and the Swiss Mountain Guide Association (SBV) an inventory was established for PERMOS to document rock fall events with their starting zones in permafrost areas. The data compiled therein was used for a statistical analysis of the topographic and geological characteristics of the detachment zones which was followed by the investigation of the permafrost conditions at the detachment zones (Naegeli 2010). Results indicated that a large part of the rock fall events above the tree line started from permafrost areas, and many of them originated from areas with potentially warm permafrost. About one third of the events started from locations with convex topography such as ridges or peaks. However, no clear concentration of starting zones could be shown.

Table 5.3: *Summary of the rock fall events documented in the reporting period. Ice indicates whether ice was visible in the starting zone after the event.*

Location	Date	Ice	Elevation (m asl)	Aspect	Volume (m^3)
Mauvoisin	10.10.2006		2092	W	
Dents du Midi Haute Cime	29.10.2006		3080	W	1'000'000
Dents Blanches	08.11.2006	yes	2508	NW	1'000'000
Mutthorn	10.2006				
Monte Rosa Ostwand	04.2007				300'000
Säntis	22.05.2007				10'000
Jägerhorn	05.08.2007		3587	NE	1000
Gross Chärpf	28.09.2007	yes	2600		30'000
Einserkofel	12.10.2007				60'000
Kleines Tschingelhorn	08.07.2008	yes	3275	S	
Piz Jenatsch	03.08.2008		3184	NE	
Clariden Bocktschingel	24.08.2008		2907	N	1000
Grünhorn	Summer 2008		2592	SE	1500
Grand Combin	29.09.2008				

Photo 5: *Rock fall from the Gross Chärpf in the Glarus area on September 28, 2007. Photos: O. Adolph.*

14 rock fall events have been reported and documented for the observation period from October 2006 to September 2008. They were located at an elevation between 2000 and 3500 m asl and in three of the detachment zones the presence of ice could be observed (Tab. 5.3). The events occured in the months between April and November.

5.3 Summary

The combination of remote sensing and in-situ measurements allows for the quantification of permafrost creep parameters on various temporal scales. The benefit of the analysis of repeated aerial images is the availability of data for the entire landform, including movement patterns. In addition, vertical changes are quantified independently of the downslope movement and changes related to ice melt or aggradation can be observed. In contrast, by the application of terrestrial methods, annual and seasonal changes can be described and interpreted.

Most of the aerial data have been processed and analyzed. The terrestrial survey was extended during the reporting period and longterm data (five years in series) is now available for six PERMOS sites. After the extraordinary high horizontal velocities in 2003 and 2004, the velocities dropped until 2006 and starting in 2007, most of the sites show a small increase. While the relative changes in horizontal velocities show large variations between 2001 and 2005, the changes have been much smaller in recent years.

An inventory of rock fall events originating from permafrost areas has been newly established, together with a questionnaire available on the PERMOS web site to report additional or future events.

Photo 6:
GPS reference station at Réchy, Valais Alps. Photo: R. Delaloye.

6 Selected Focus Topic

6.1 Extrazonal Permafrost in a Low Elevation Talus Slope (Dreveneuse d’en Bas, Swiss Prealps)

Discontinuous mountain permafrost is currently encountered above ca. 2400 m asl in the Alps, depending on orientation and type of terrain. Exceptionally cold ground conditions point out the possible occurrence of isolated permafrost have also been reported at much lower elevation in debris accumulations like talus slopes and sometimes relict rock glaciers (e.g., Wakonigg 1996, Morard et al. 2008). At these particular sites, which can be located more than 1000 m below the regional lower limit of discontinuous permafrost, occurrences of cold airflows (<5 °C) blowing out between the blocks and ground ice in summer have often been reported at locations with a MAAT clearly above 0 °C (e.g., Wakonigg 1996, Delaloye et al. 2003, Zacharda et al. 2007). The most typical evidence for cold ground temperatures during summer is the development of dwarf forests, the so-called «Hexenwäldi» (Bächler 1930), with the two most famous places in Switzerland located in the Brüeltobel (Alpstein) and the Creux-du-Van (Jura mountains, Fig. 6.1). The occurrence of boreo-alpine vegetation species and relict ecosystems from the Last Ice Age have also been described (e.g., Bertinelli et al. 1993, Ruzicka 1999, Zacharda et al. 2005, Körner and Hoch 2006). In some cases geophysical surveys or trenches have indicated

Figure 6.1: Evidence of cold ground conditions in summertime in the lower part of the Dreveneuse d’en Bas talus slope: dwarf adult trees, cold air outflow and ground ice. Photos: R. Delaloye and S. Morard.

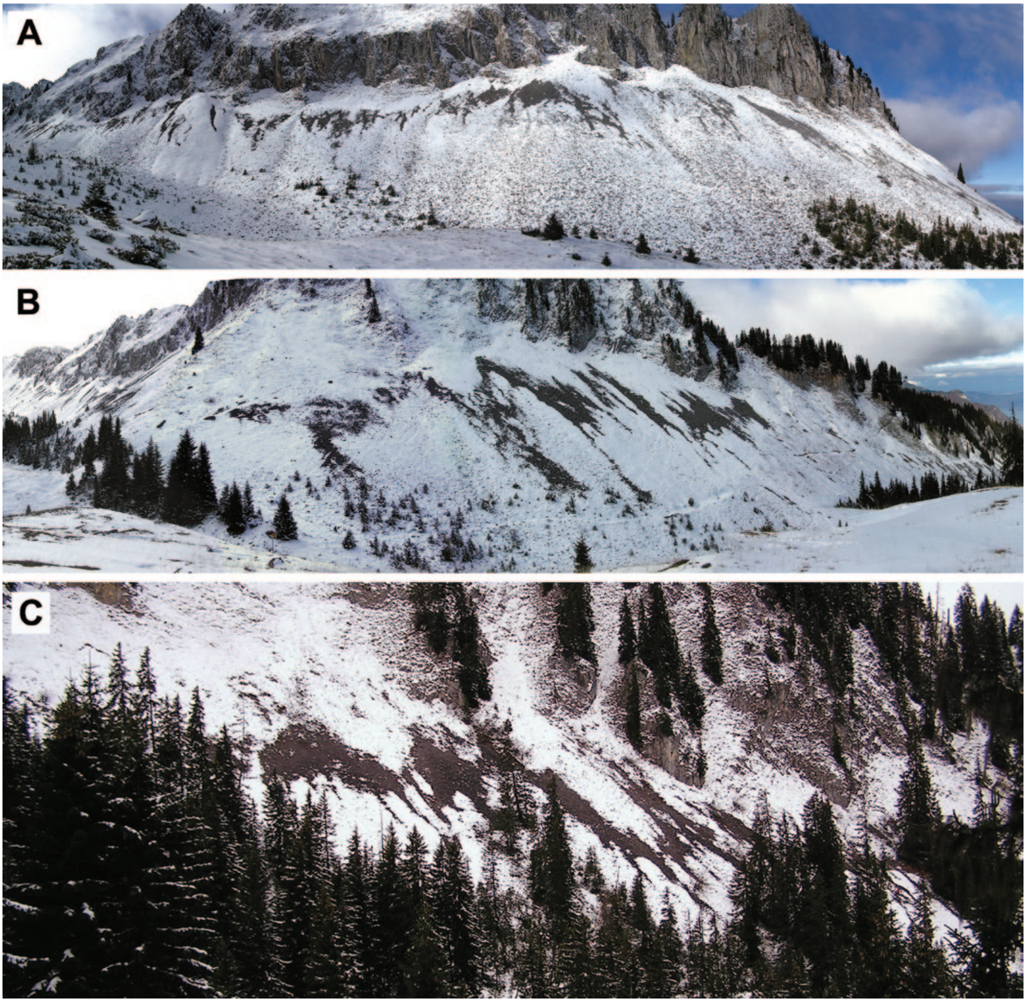


Figure 6.2: *Snow melt windows (evidences of warmer air outflows) in the upper part of the talus slopes of the Combe de Dreveneuse. A: Dreveneuse d'en Haut, B: Dreveneuse du Milieu, C: Dreveneuse d'en Bas. Photos: R. Delaloye (November 2004).*

the occurrence of summer ice or extrazonal permafrost in the porous debris accumulation (Gude et al. 2003, Hauck and Kneisel 2008, Sawada 2008).

A reversible air circulation process (the chimney effect) is likely the main factor for the exceptionally cold conditions at these sites (Wakonigg 1996, Delaloye et al. 2003, Morard et al. 2008). This cooling effect of air circulation through porous media has been used during centuries as natural refrigerators («Milkhouses») to preserve food (DeSaussure 1796), or in embankments to preserve permafrost conditions under transportation infrastructure at high latitudes or high altitudes (Arenson and Sego, 2006).

Variations of direction and velocity of the airflow through an accumulation of loose sediments are primarily controlled by the thermal contrast between the outside and inside (ground) air (Delaloye et al. 2003). The airflow direction reverses seasonally: during winter an ascent of relatively warm light air typically occurs in the upper part of the debris accumulation (Fig. 6.2) and causes a forced aspiration of cold external air in the lower part of the slope, even through a thick but porous snowpack (Fig. 6.3). A cold reservoir is thus built in the ground. During summer a gravitationally driven flow of relatively cold dense air occurs in the lowermost part of the debris accumulation and prevents the ground temperature to rise significantly above 0 °C.

The present report focuses on the thermal monitoring near the ground surface and in boreholes in the low elevation talus slope of Dreveneuse d'en Bas, a temperature site of the PERMOS network (cf. Tab. 1.1).

6.2 Dreveneuse d'en Bas Talus Slope

The cold talus slope at Dreveneuse d'en Bas is located between 1590 and1670 m asl in the Valais Prealps (Fig. 6.1). The site is exposed to the east and the MAAT is ca. 4 °C. The talus slope consists of limestone blocky and pebbly clasts, is about 150 m long, inclined 25–35°, and is in its lowermost third covered by a singular forest of dwarf spruces. The lower part of the talus slope is located on a late-glacial moraine of a local glacier (Fig. 6.4).

Five UTL-loggers were placed along a longitudinal profile to characterize the GST regime. Additionally, two boreholes were drilled and instrumented in November 2004 to investigate the ventilation process that causes the strong cooling of the lower part of the slope. The borehole BH1 is located a few meters above the dwarf trees, where air is supposed to flow between the lower and the upper part of the slope (Figs. 6.3 and 6.4). Here, the blocky layer is 11 m thick and covers at least 5 m of fine sediments. The second borehole BH2 is 5 m deep and was drilled in the lower half of the dwarf trees area. Here, the blocky layer is only about 4 m thick.

6.3 The Chimney Effect

A very heterogeneous and seasonally contrasted GST regime is observed in Dreveneuse d'en Bas (Fig. 6.5): During winter ascending air circulation prevails. In the upper part of the slope (DrB-15) the GST remains positive with a decreasing trend, illustrating the evacuation of the heat of the talus slope. Visual evidence is provided by snow melt windows and funnels in the snow pack (Figs. 6.2 and 6.4). As a consequence, cold air is aspirated in the lower (and sometimes in the middle) part of the slope. Here, the ground surface reached subzero tem-

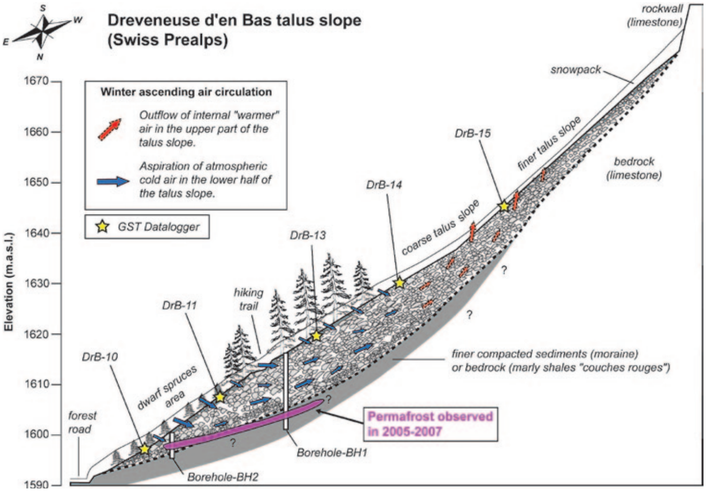


Figure 6.3: *Main characteristics of the Dreveneuse d'en Bas talus slope for the winter ascending air circulation phase. The limit between the porous blocky material and the substratum is based on borehole data and geophysical measurements*

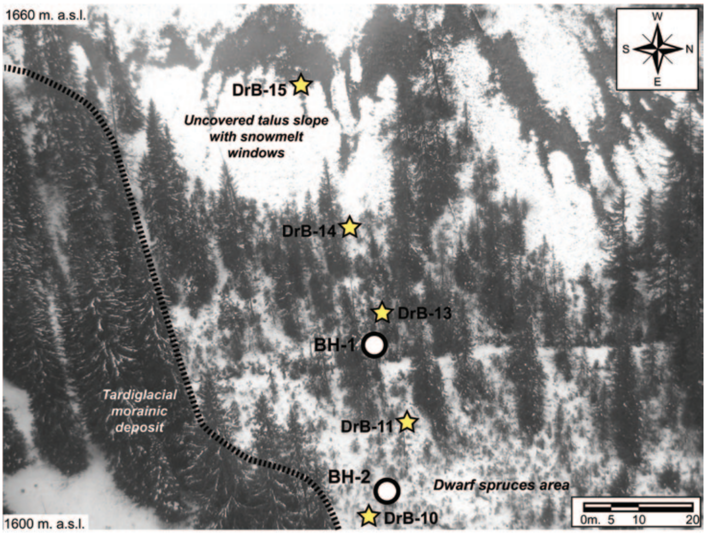


Figure 6.4: *Aerial view of the Dreveneuse d'en Bas talus slope in November 2004. Photo: C. Lambiel.*

peratures despite a thick snow cover (>2 m in 2005/2006). The temperature difference between DrB-11 (lower part) and DrB-15 (upper part) is 18 °C in late November and late December 2005. The distance between the sensors is only 80 m.

Due to the aspiration of cold air, the entire talus slope cooled strongly and rapidly, especially at BH1, during the cold winters 2004/2005, 2005/2006 and 2009/2010 (Fig. 6.6). At depth, short-term temperature changes are recorded during the entire winter, and a minimal value of –8 to –9 °C was recorded at a depth of 8.5 m. In contrast, during the mild winter 2006/2007, no intense freezing was observed in the porous blocky layer and the ground temperatures remained at about 0 °C. The temperatures in BH1 show intermediate values in 2007/2008 and 2008/2009. The shape of the temperature profiles in borehole BH1 (with mean, minimal and maximal values) differs significantly from classical permafrost profiles (cf. Section 3.2, Fig. 6.7): The minimal temperature is recorded at 8.5 m depth and not at the surface. In addition, no active layer is observed.

In late winter and spring when melt water percolates, ground ice forms at the beginning of a zero-curtain period. At the surface, the ground remains frozen until June in the lower part. In BH1, the temperature remains stable and below zero at 8.5 m depth until September 6 in 2005, July 16 in 2008, and July 27 in 2009. After the mild winter 2006/2007 it was already above 0 °C on April 27.

In summer, in BH1, the blocky talus slope gradually warms from the surface (Fig. 6.4). At 8.5 m the ground temperature never exceeds 5 °C. The flow of cold, dense air maintains stable cool conditions in the lower part of the slope. The coldest place is located in the lowermost part (DrB-10), where GST remains below 3 °C during the entire summer (Fig. 6.5). Here, cold air outflows between blocks are perceptible and a more or less well-established inverse relationship between the GST and the external air temperature is observed. During summer 2005, a wind sensor in the lower part of the slope recorded a velocity of the air discharge of 0.2–0.4 m/s, with increasing velocity during the hotter days (Delaloye and Lambiel 2007). The middle and upper part of the slope are not affected by the cold air outflows.

6.4 Advection-induced Extrazonal Permafrost

The rapid temperature changes in the blocky material illustrate the effect of convective/advective energy fluxes due to internal air circulation. The borehole data showed temporary permafrost aggradation as a consequence of the cold winters 2004/2005 and 2005/2006, its temperate state of 0 °C (except between February and April 2006) and its particular geometry in the talus slope between 2004 and 2006 (Fig. 6.6 and 6.7) inside the blocky material in the lower half of the dwarf trees areas (at 3 m depth in BH2), where cold air outflow occurred in summertime. It seems to extend to greater depth at least up to the middle of the slope (at 11.5 m depth in BH1) in the finer sediments below the talus slope (Fig. 6.3). After the exceptionally mild winter 2006/2007 seasonal freezing was observed during the following three winters. Because of the fast formation and disappearance, the frozen ground in Dreveneuse d’en Bas could be regarded as short-term permafrost, called «pereletok» by Gorbunov et al. (2004).

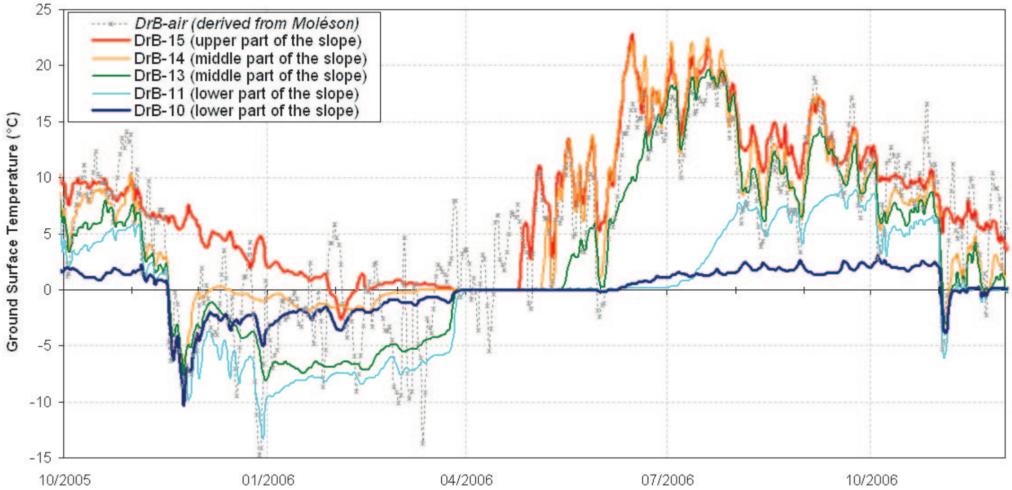


Figure 6.5: *Heterogeneous ground surface thermal regime between October 2005 and September 2006. Note the asymmetry between the coldest places in winter and in summer. The sensor positions are shown in Figure 6.4.*

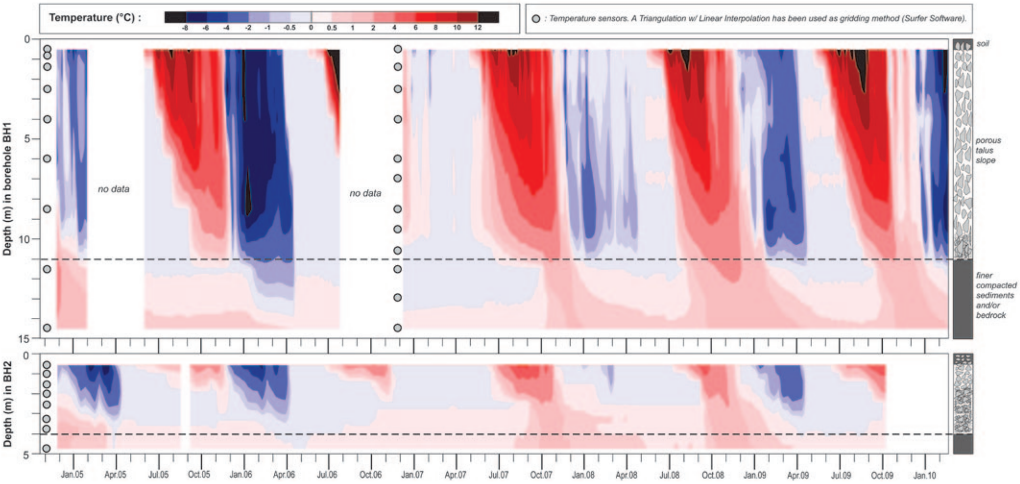


Figure 6.6: *Boreholes temperature evolution in BH1 (middle part of the slope) and BH2 (lower part of the slope) between November 2004 and February 2010. The sensor positions were changed in December 2006. A triangulation w/linear interpolation has been used as gridding method.*

6.5 Conclusion

Data acquired in Dreveneuse d'en Bas illustrate the role of convective/advective heat fluxes in the thermal regime of the talus slope. The airflow acts as an efficient vector of heat in the porous debris and its effect is not strongly reduced by a thick snow cover. The key-variable of the thermal conditions of a low elevation talus slope is the intensity of winter cooling and the recharge of the cold reservoir. Snow cover and summer temperatures play only a minor role. This is in contrast with the factors classically controlling permafrost terrain.

The GST regime in ventilated debris accumulation is characterized by a continuous succession of negative thermal anomalies in the lower part of a ventilated area and constantly positive anomalies in the upper part. The low level and stability of the GST during summer in the lower part provides favorable conditions for extrazonal boreo-alpine ecosystems.

At depth, thin (sub-)talus permafrost can occur just a few meters below the surface in the lower part of the slope and extend to greater depth until the middle part of the slope. This extrazonal permafrost is mainly temperate and its geometry and occurrence can change quickly.

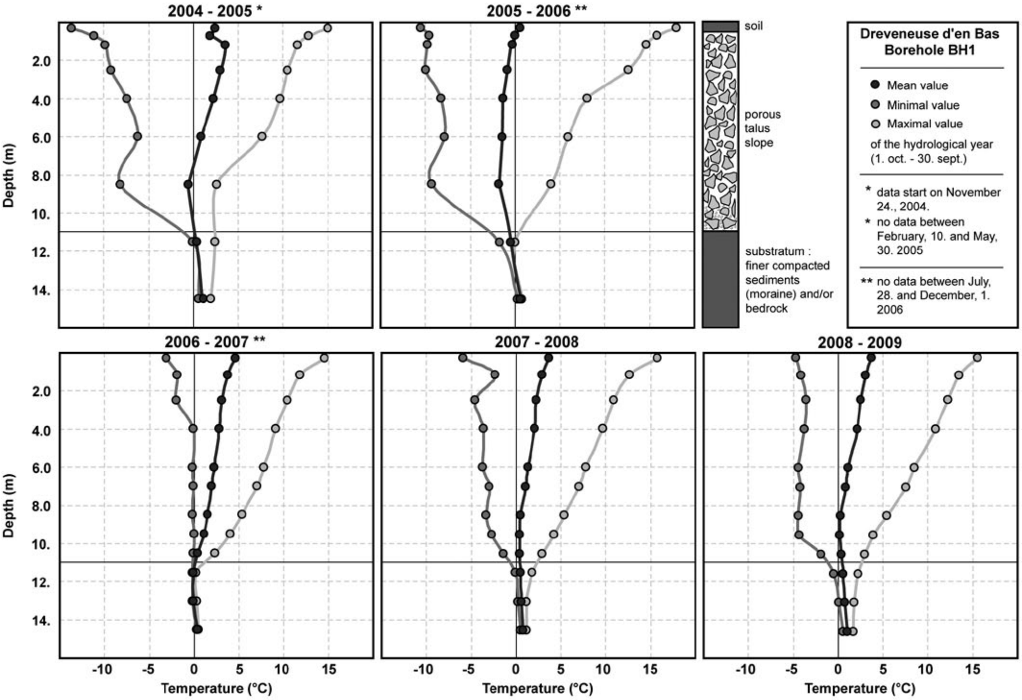


Figure 6.7: Temperature profile in borehole BH1. Note that the ground remained permanently frozen at 11.5 m in 2005/06 and 2006/07.

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Appendix

PERMOS Boreholes

Table A.1: Location and characteristics of the PERMOS borehole sites.

Borehole	Region	Morphology	Lat CH	Lon CH	Elev. (m asl)	Slope (°)	Aspect	Surface mat.
Les Attelas 0108	Central Valais	Talus slope	587196	105043	2661	30	W	Debris
Les Attelas 0208	Central Valais	Talus slope	587243	105040	2689	30	W	Debris
Les Attelas 0308	Central Valais	Talus slope	587339	105023	2741	30	W	Debris
Dreveneuse 0104	Chablais	Talus slope	557670	124805	1580	30	E	Coarse blocks
Flüela 0102	Engadine	Talus slope	791375	180575	2394	26	NE	Debris
Gemsstock 0106	Central CH	Crest	689781	161780	2940	50	NW	Bedrock
Gentianes 0102	Central Valais	Moraine	589467	103586	2888	20	E	Debris
Lapires 0198	Central Valais	Talus slope	588070	106080	2500	25	NE	Debris
Lapires 1108	Central Valais	Talus slope	588070	106080	2500	25	NE	Debris
Lapires 1208	Central Valais	Talus slope	588070	106080	2500	25	NE	Debris
Lapires 1308	Central Valais	Talus slope	588070	106080	2500	25	NE	Debris
Matterhorn 0205	Mattertal	Crest	618399	92334	3295	0	–	Debris
M. da Barba Peider 0196	Engadine	Talus slope	791300	152500	2946	38	NW	Debris
M. da Barba Peider 0296	Engadine	Talus slope	791300	152500	2941	38	NW	Debris
Muragl 0199	Engadine	Rock glacier	791025	153726	2536	15	W	Coarse blocks
Muragl 0499	Engadine	Rock glacier	791017	153688	2549	15	SW	Coarse blocks
Murtèl-Corvatsch 0287	Engadine	Rock glacier	783158	144720	2670	10	NW	Coarse blocks
Murtèl-Corvatsch 0200	Engadine	Rock glacier	783158	144720	2670	10	NW	Coarse blocks
Ritigraben 0102	Mattertal	Rock glacier	631755	113775	2690	0	–	Coarse blocks
Schafberg 0190	Engadine	Rock glacier	791000	152500	2755	0	–	Coarse blocks
Schafberg 0290	Engadine	Rock glacier	790750	152775	2735	0	–	Coarse blocks
Schilthorn 5198	Berner Oberland	Crest	630365	156410	2909	30	NE	Debris
Schilthorn 5000	Berner Oberland	Crest	630350	156410	2910	30	NE	Debris
Schilthorn 5200	Berner Oberland	Crest	630350	156410	2910	30	NE	Debris
Stockhorn 6000	Mattertal	Crest	629878	92876	3410	8	S	Debris
Stockhorn 6100	Mattertal	Crest	629867	92850	3410	8	S	Debris
Tsaté 0104	Central Valais	Crest	608490	106400	3040	30	W	Bedrock

Table A.2: Instrumentation of the PERMOS boreholes.

Borehole	Since	Depth (m)	Lowest S. (m)	#Therm.	Sensors	Data Access	Calib.	Institution
Les Attelas 0108	2008	26.00	24.00	12	MAAD	On site	2008	UNIL
Les Attelas 0208	2008	21.00	20.00	11	MAAD	On site	2008	UNIL
Les Attelas 0308	2008	15.00	15.00	12	MAAD	On site	2008	UNIL
Dreveneuse 0104	2004	15.00	14.50	12	MAAD	On site	2006	UNIFR
Flüela 0102	2002	23.00	20.00	12	YSI 46006	On site	2002	SLF
Gemsstock 0106	2006	40.00	39.50	27	YSI 44008	On site	2005	SLF
Gentianes 0102	2002	20.00	20.00	11	MAAD	On site	2002	UNIL
Lapires 0198	1998	19.60	19.60	12		GSM	1998	UNIFR
Lapires 1108	2008	40.00	39.00	28		GSM	2008	UNIFR
Lapires 1208	2008	35.00	34.00	18		GSM	2008	UNIFR
Lapires 1308	2008					GSM	2008	UNIFR
Matterhorn 0205	2005	53.00	53.00	12	YSI 44008	On site	2005	SLF
M. da Barba Peider 0196	1996	18.00	17.50	10	YSI 44008	On site	1996	SLF
M. da Barba Peider 0296	1996	18.00	17.50	10	YSI 44008	On site	1996	SLF
Muragl 0199	1999	70.20	69.00	18	YSI 44006		1999	ETH-IGT
Muragl 0499	1999	71.00	69.60	22	YSI 44006		1999	ETH-IGT
Murtèl-Corvatsch 0287	1987	62.00	58.00	46	YSI 44006	GSM	1997	UZH
Murtèl-Corvatsch 0200	2000	62.00	62.00	30				ETH-IGT
Ritigraben 0102	2002	30.00	18.00	25	YSI 44006	GSM		SLF
Schafberg 0190	1990	67.00	15.90	15	YSI 46006	On site		SLF
Schafberg 0290	1990	37.00	25.20	10	YSI 46006	On site	1997	SLF
Schilthorn 5198	1998	14.00	13.70	14	YSI 44006	GSM	1998	UZH
Schilthorn 5000	2000	101.00	100.00	30	YSI 44006	GSM	1999	UZH
Schilthorn 5200	2000	100.00	92.00	19	YSI 44006	GSM	1999	UZH
Stockhorn 6000	2000	100.00	98.30	30	YSI 44006	GSM	2000	UNIFR
Stockhorn 6100	2000	31.00	17.00	18	YSI 44006	GSM	2000	UNIFR
Tsaté 0104	2004	20.00	19.50	11	MAAD	On site	2006	UNIL

Dreveneuse 0104

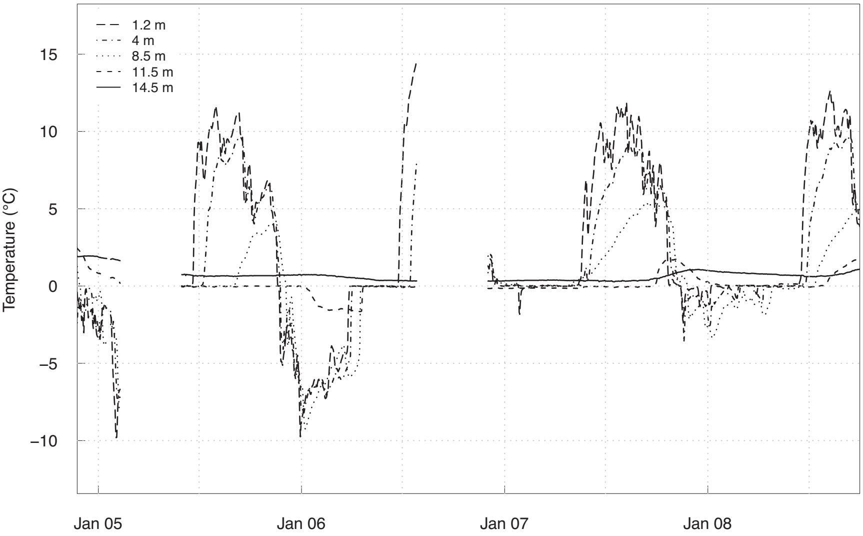

Figure A.3: *Temperature-time plot of the borehole Dreveneuse 0104.*

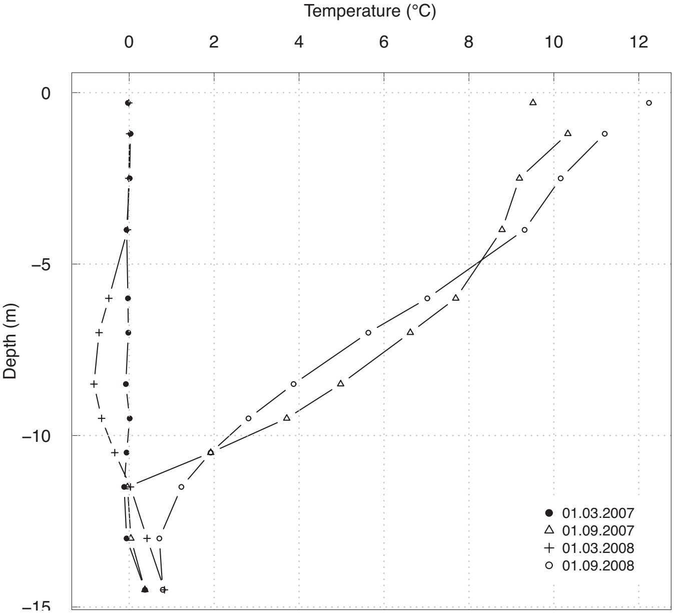

Figure A.4: *Temperature profiles of the borehole Dreveneuse 0104.*

Flüela 0102

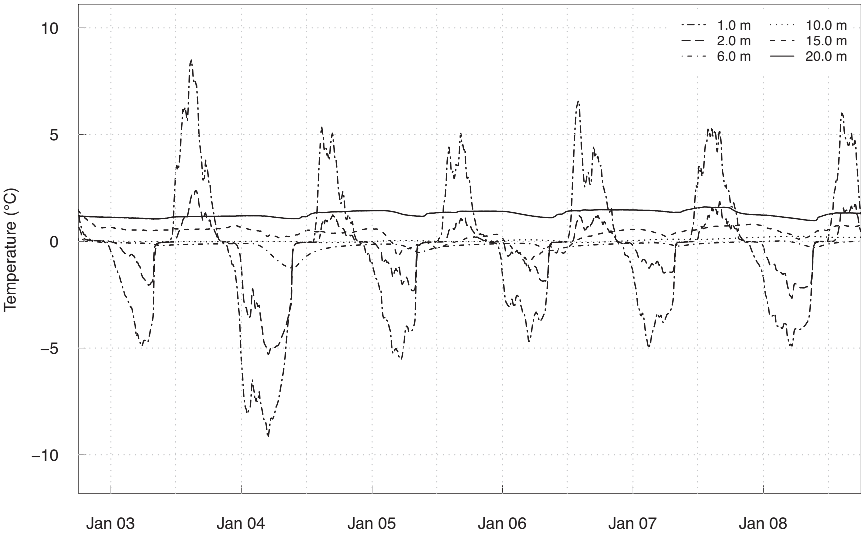

Figure A.3: *Temperature-time plot of the borehole Flüela 0102.*

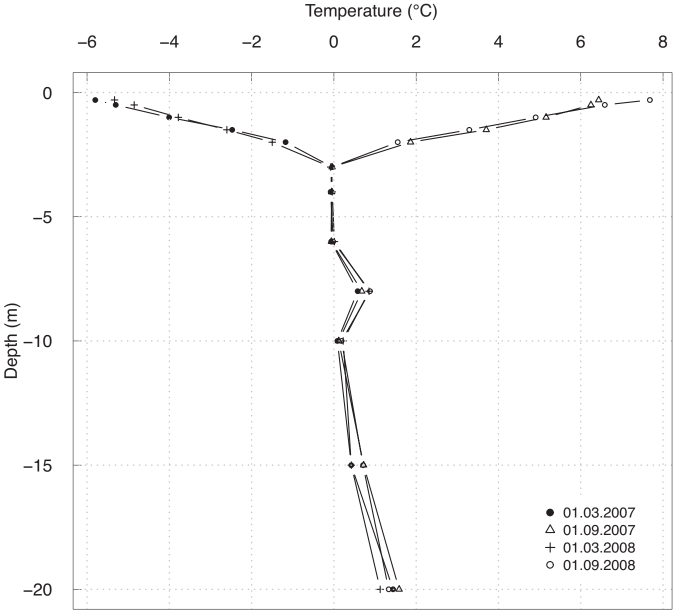

Figure A.4: *Temperature profiles of the borehole Flüela 0102.*

Gemsstock 0106

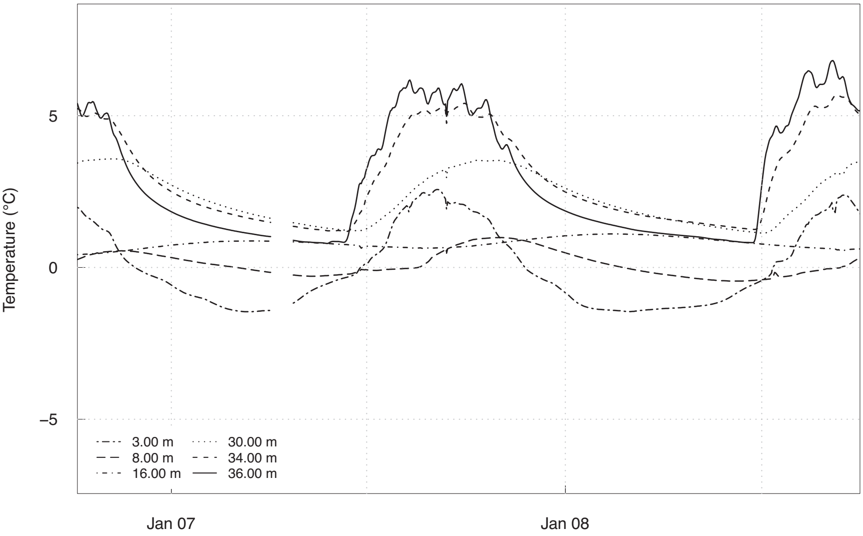

Figure A.5: *Temperature-time plot of the borehole Gemsstock 0106.*

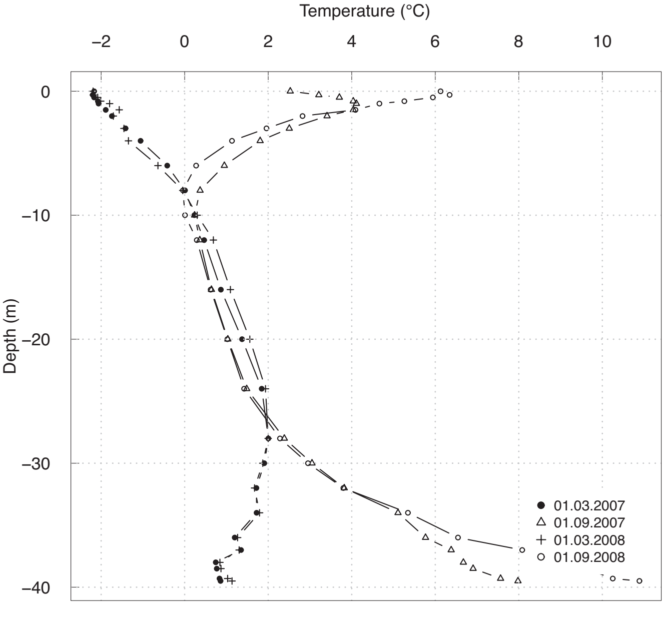

Figure A.6: *Temperature profiles of the borehole Gemsstock 0106.*

Gentianes 0102

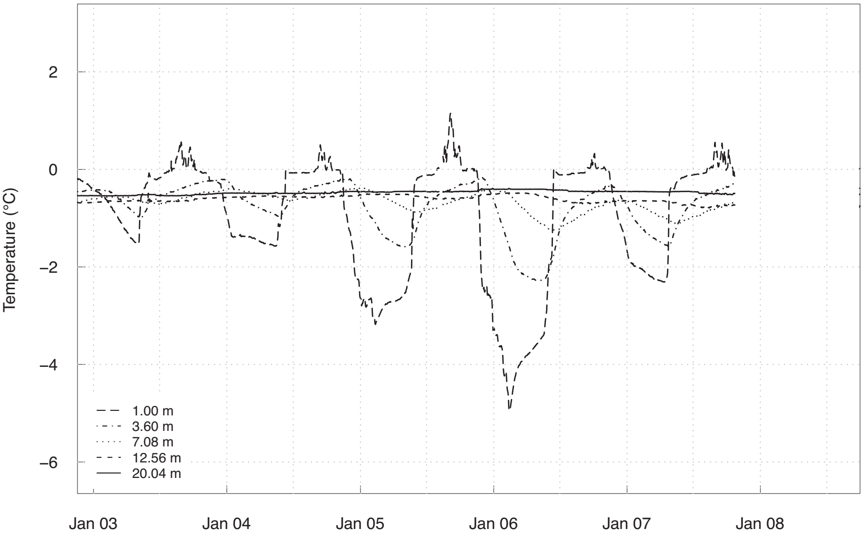

Figure A.7: Temperature-time plot of the borehole Gentianes 0102.

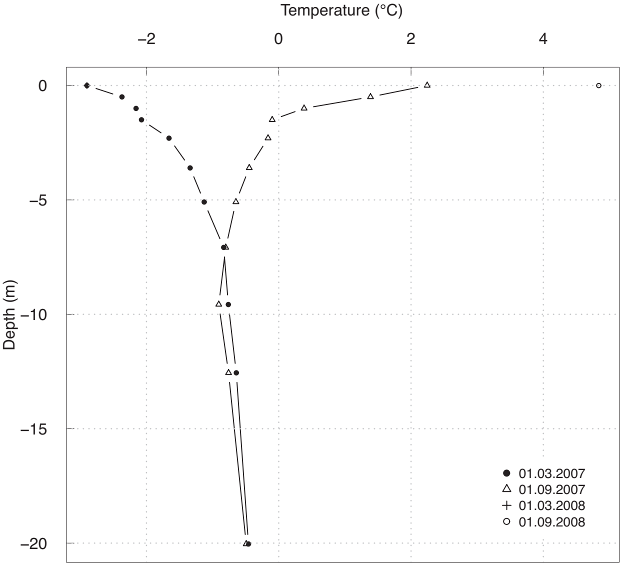

Figure A.8: Temperature profiles of the borehole Gentianes 0102.

Lapires 0198

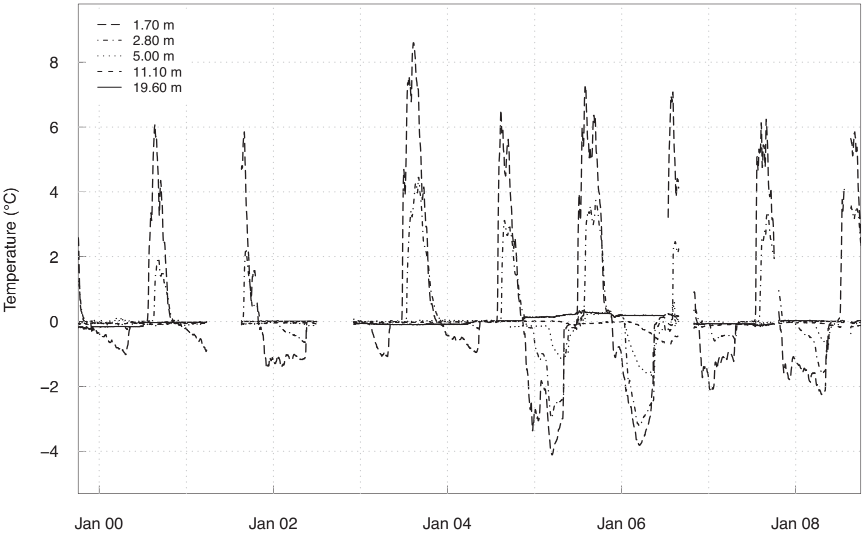

Figure A.9: *Temperature-time plot of the borehole Lapires 0198.*

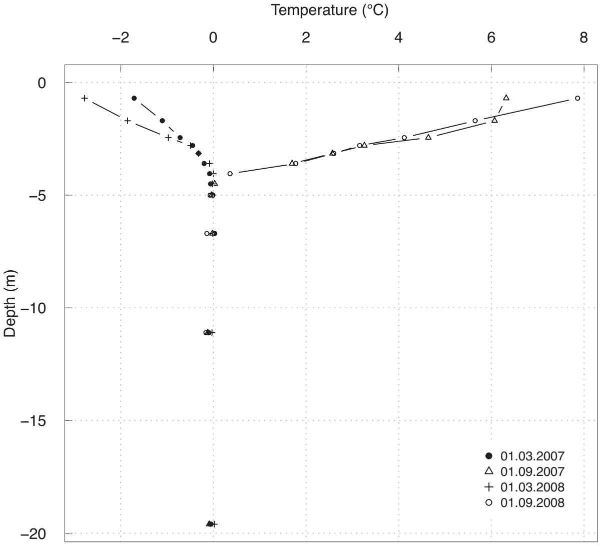

Figure A.10: *Temperature profiles of the borehole Lapires 0198.*

Matterhorn 0205

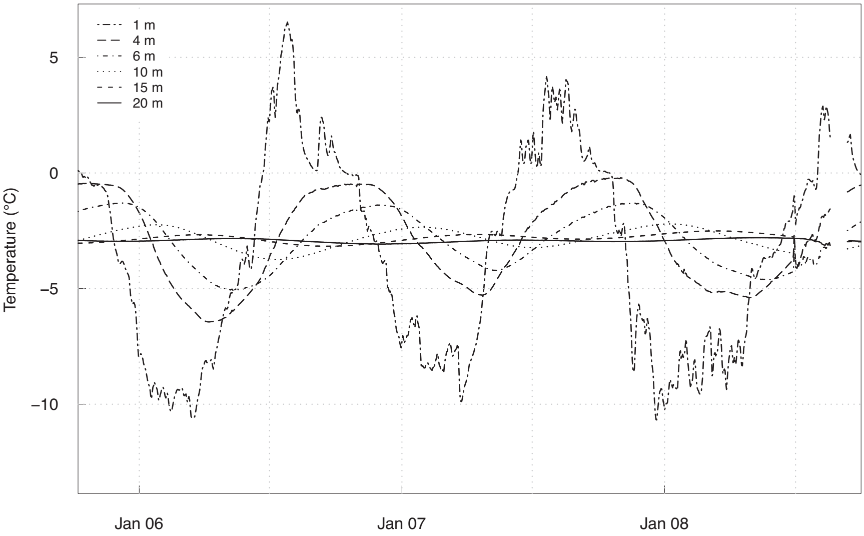

Figure A.11: Temperature-time plot of the borehole Matterhorn 0205.

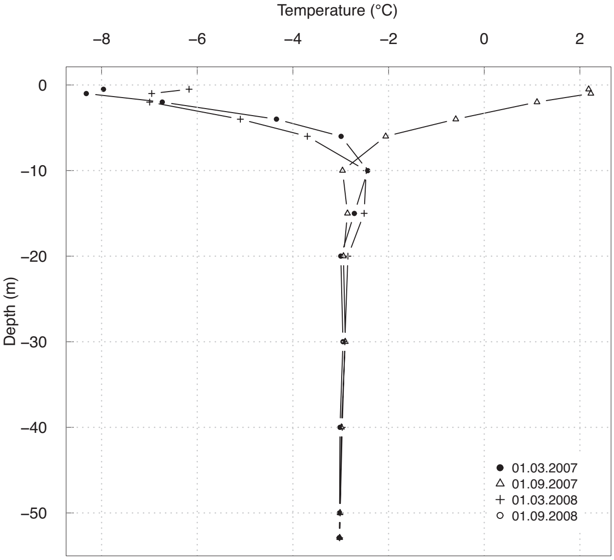

Figure A.12: Temperature profiles of the borehole Matterhorn 0205.

Muot da Barba Peider 0196

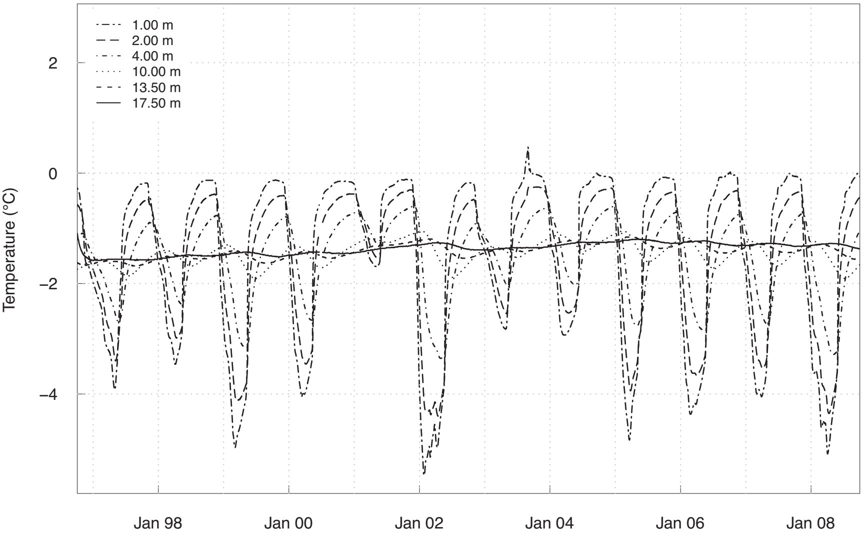

Figure A.13: Temperature-time plot of the borehole Muot da Barba Peider 0196.

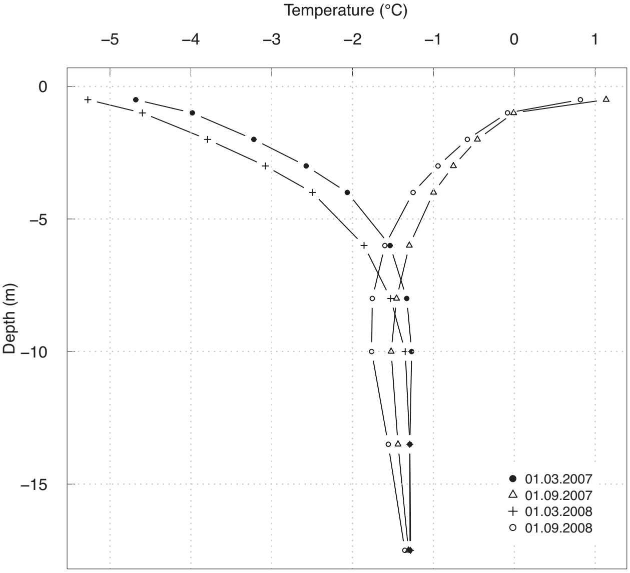

Figure A.14: Temperature profiles of the borehole Muot da Barba Peider 0196.

Muot da Barba Peider 0296

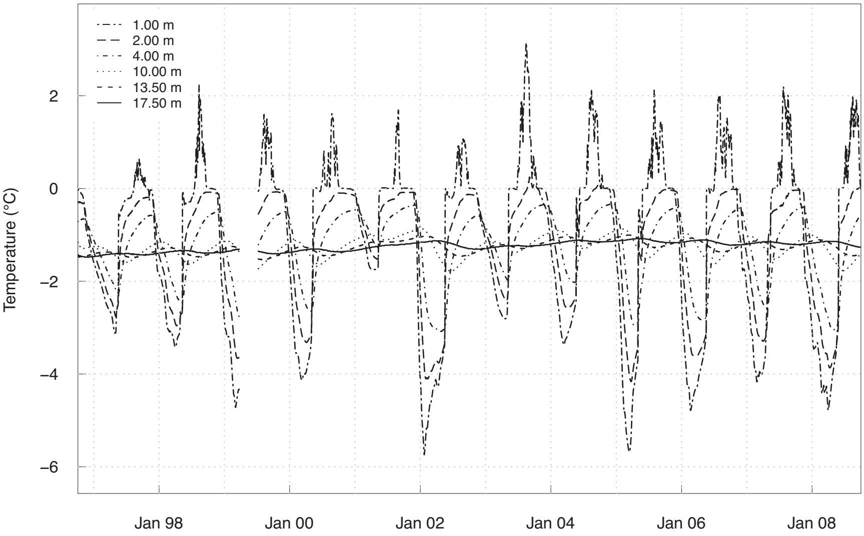

Figure A.15: *Temperature-time plot of the borehole Muot da Barba Peider 0296.*

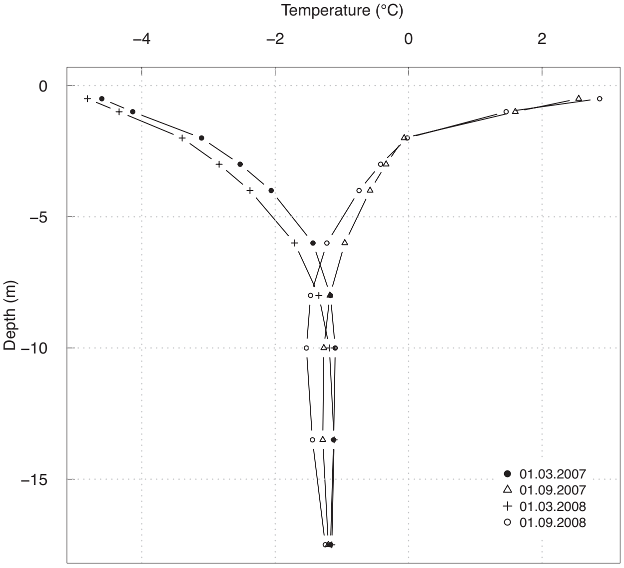

Figure A.16: *Temperature profiles of the borehole Muot da Barba Peider 0296.*

Muragl 0199

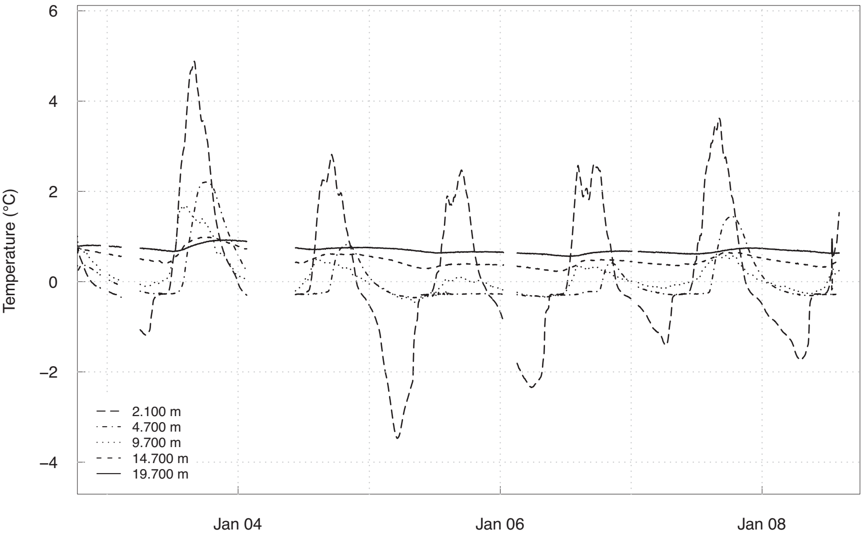

Figure A.17: Temperature-time plot of the borehole Muragl 0199.

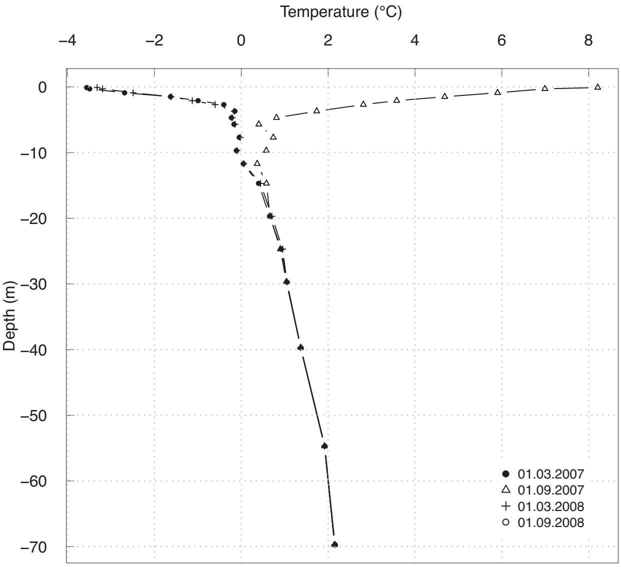

Figure A.18: Temperature profiles of the borehole Muragl 0199.

Muragl 0499

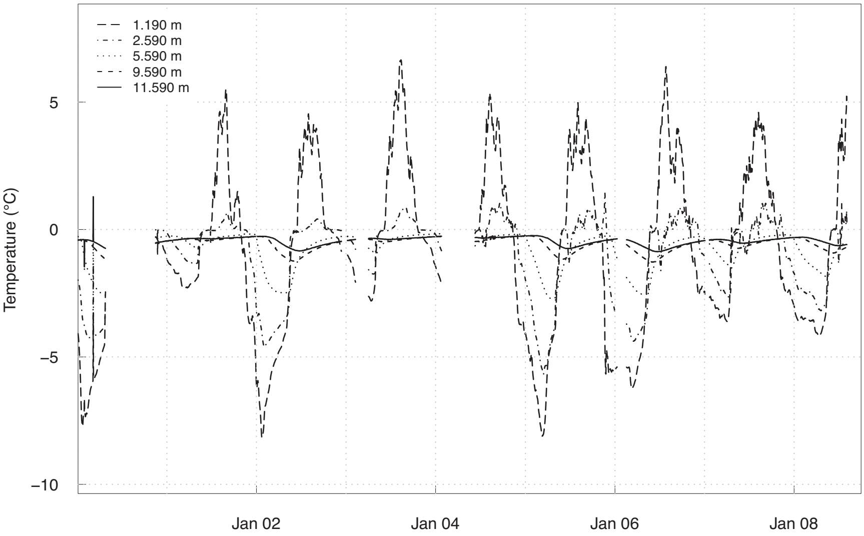

Figure A.19: *Temperature-time plot of the borehole Muragl 0499.*

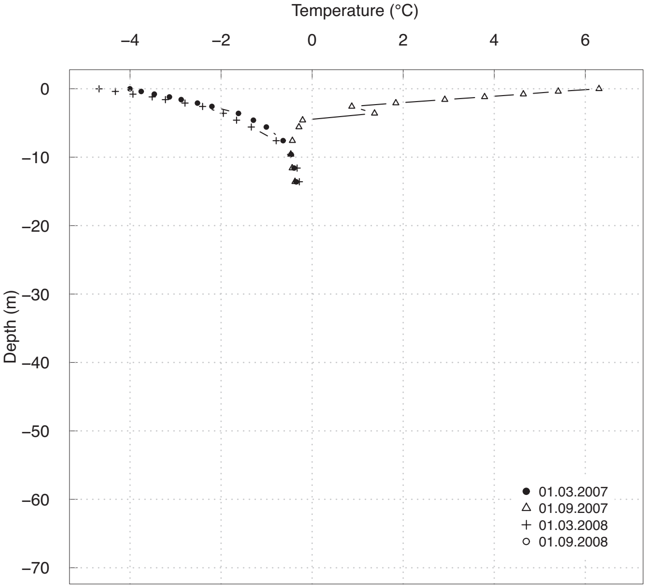

Figure A.20: *Temperature profiles of the borehole Muragl 0499.*

Murtèl-Corvatsch 0287

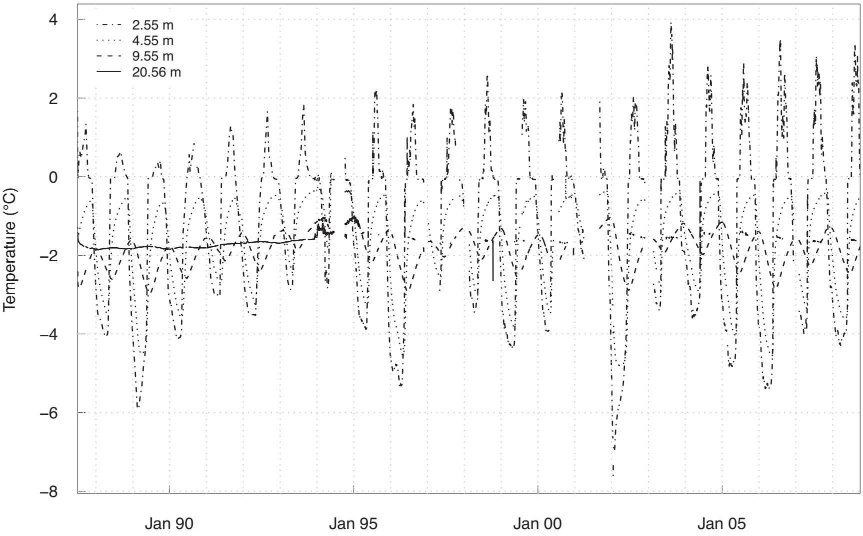

Figure A.21: *Temperature-time plot of the borehole Murtèl-Corvatsch 0287.*

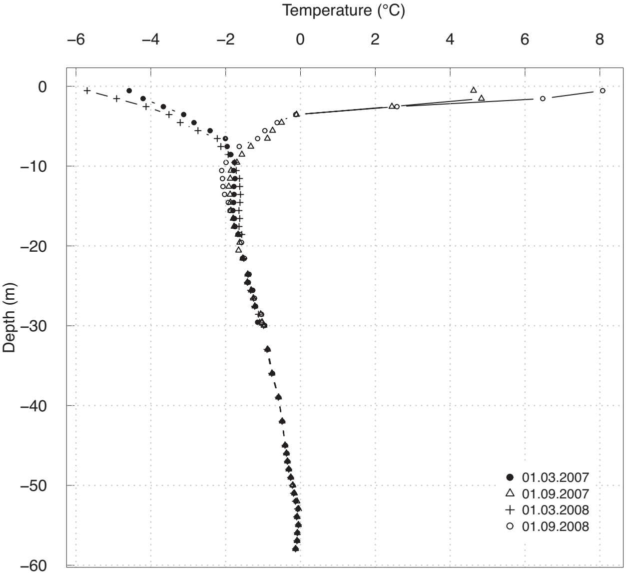

Figure A.22: *Temperature profiles of the borehole Murtèl-Corvatsch 0287.*

Murtèl-Corvatsch 0200

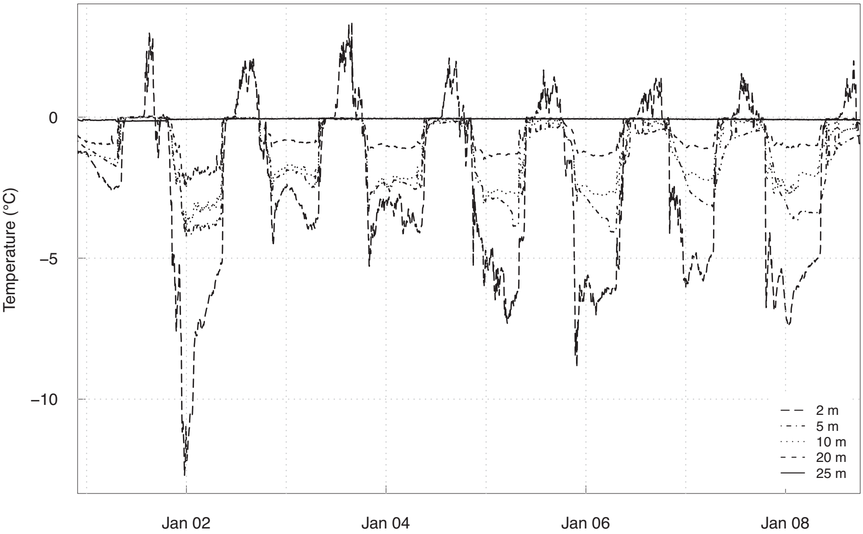

Figure A.23: Temperature-time plot of the borehole Murtèl-Corvatsch 0200.

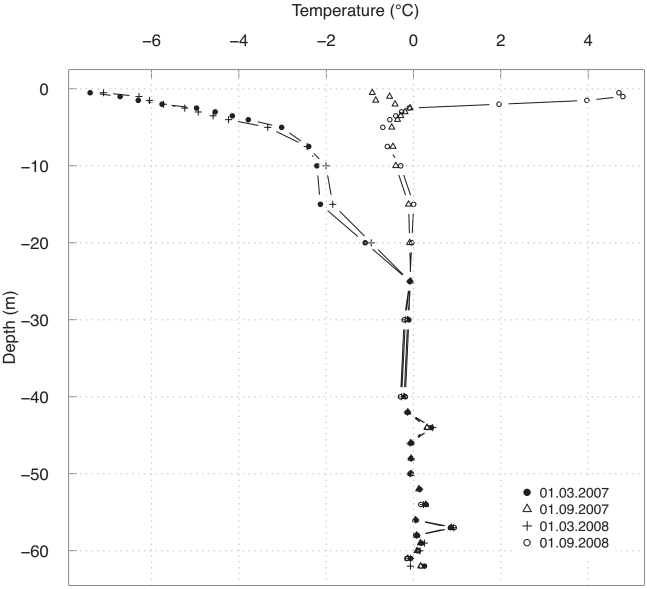

Figure A.24: Temperature profiles of the borehole Murtèl-Corvatsch 0200.

Schafberg 0190

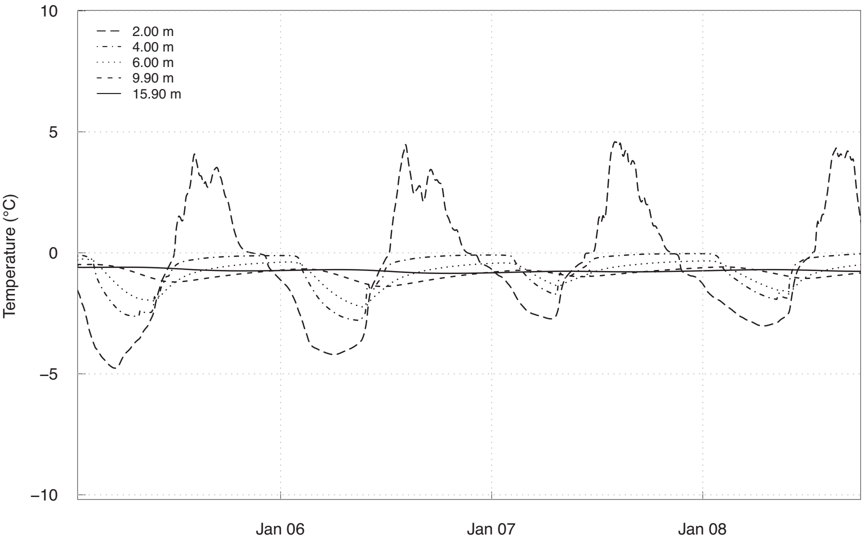

Figure A.25: Temperature-time plot of the borehole Schafberg 0190.

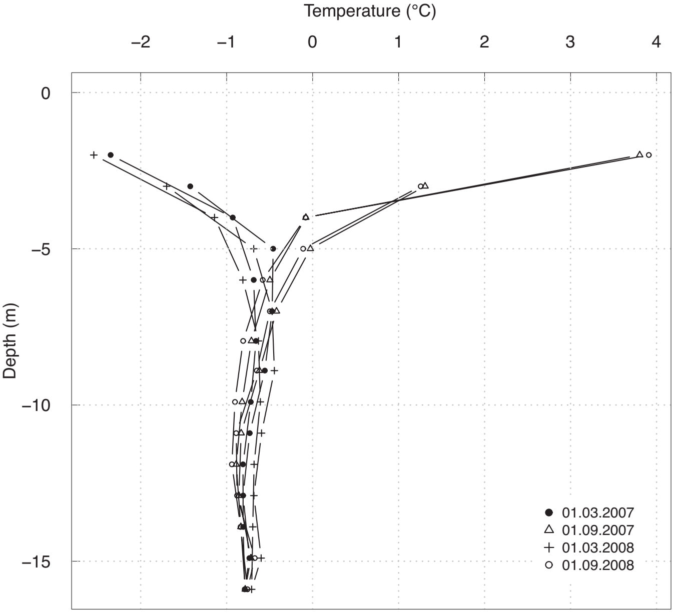

Figure A.26: Temperature profiles of the borehole Schafberg 0190.

Schafberg 0290

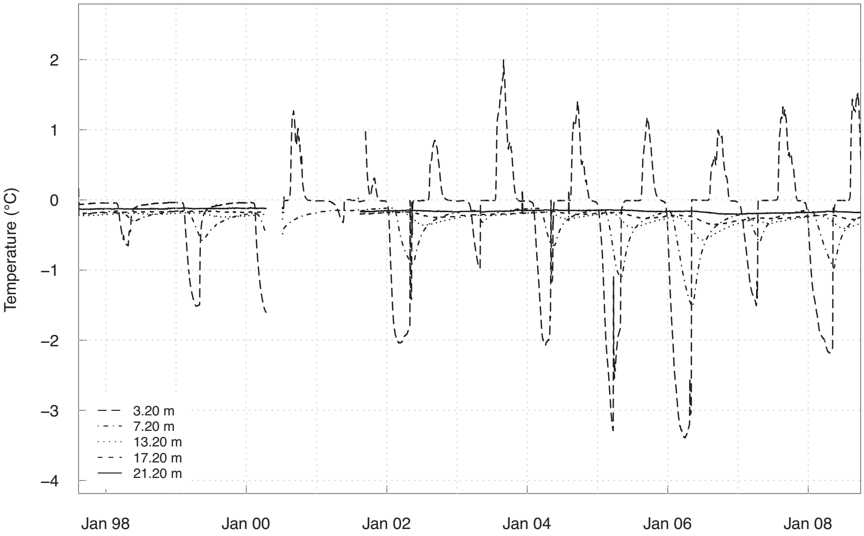

Figure A.27: *Temperature-time plot of the borehole Schafberg 0290.*

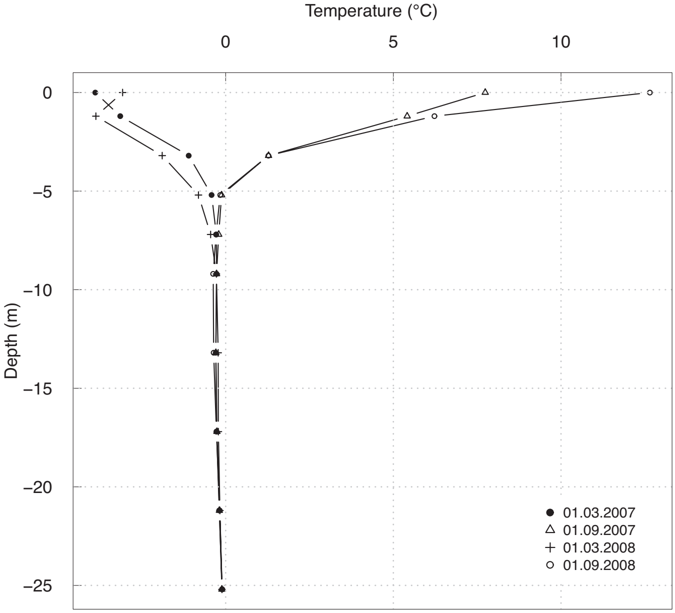

Figure A.28: *Temperature profiles of the borehole Schafberg 0290.*

Schilthorn 5198

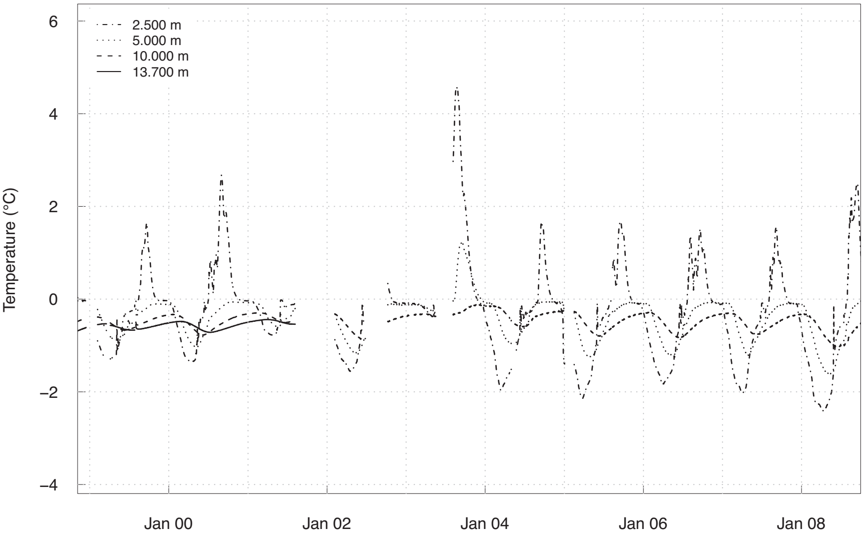

Figure A.29: *Temperature-time plot of the borehole Schilthorn 5198.*

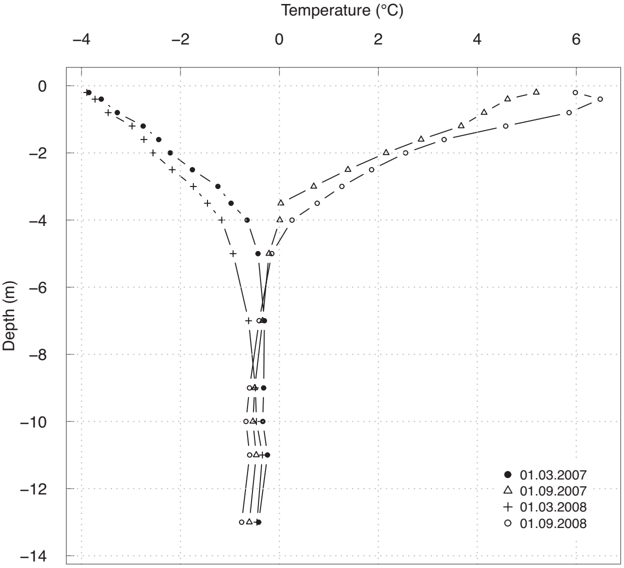

Figure A.30: *Temperature profiles of the borehole Schilthorn 5198.*

Schilthorn 5000

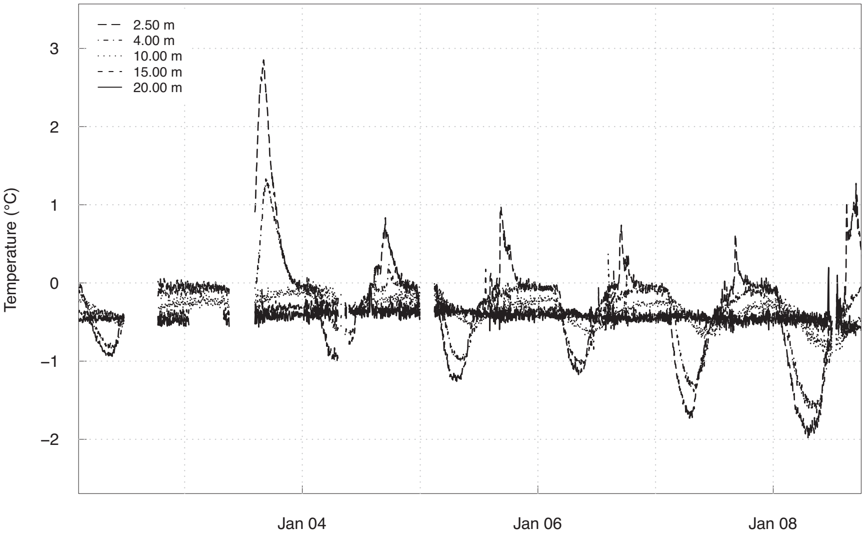

Figure A.31: Temperature-time plot of the borehole Schilthorn 5000.

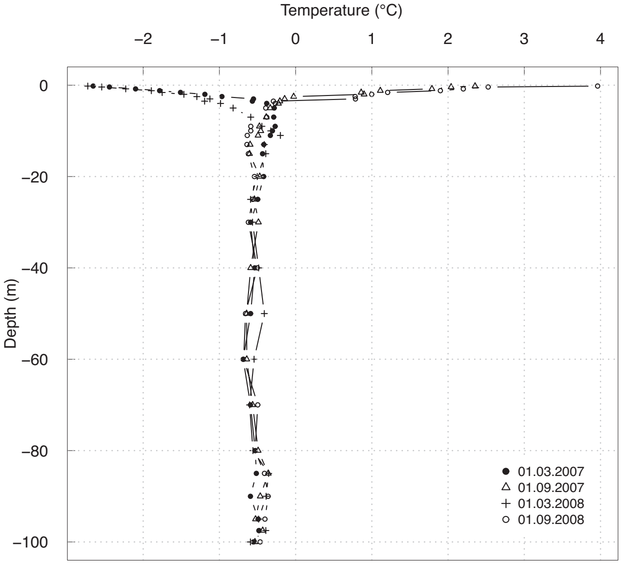

Figure A.32: Temperature profiles of the borehole Schilthorn 5000.

Schilthorn 5200

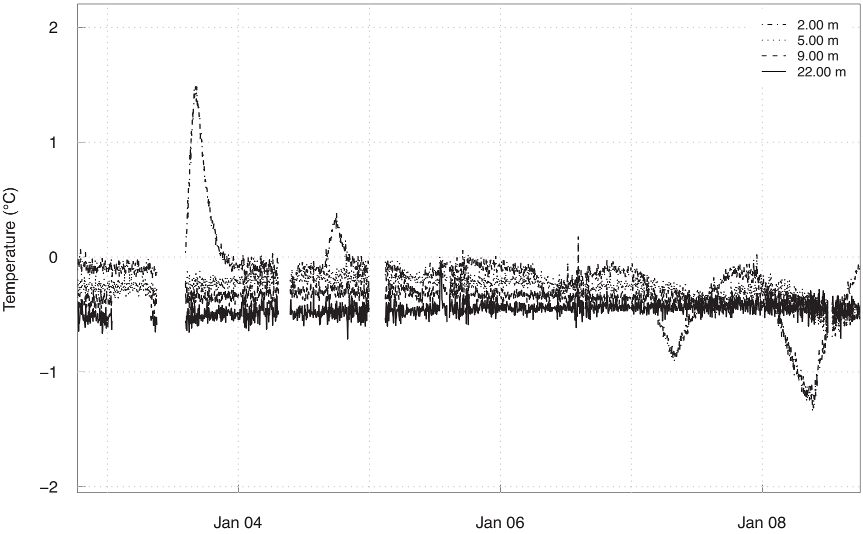

Figure A.33: *Temperature-time plot of the borehole Schilthorn 5200.*

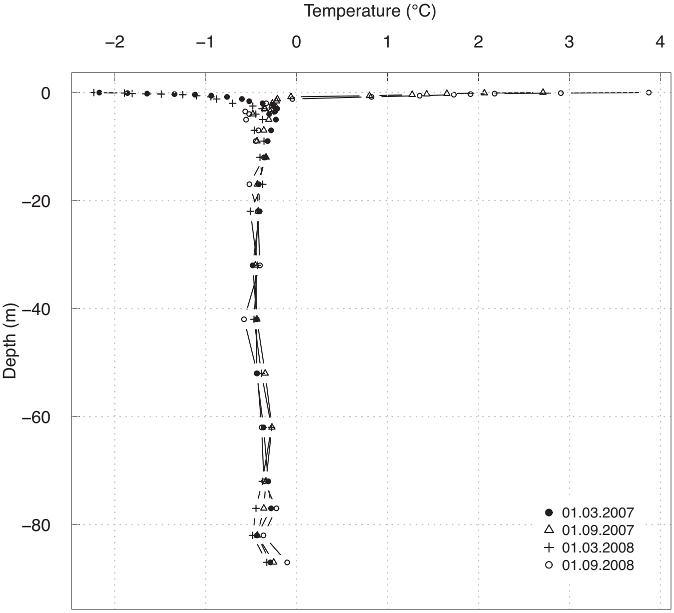

Figure A.34: *Temperature profiles of the borehole Schilthorn 5200.*

Stockhorn 6100

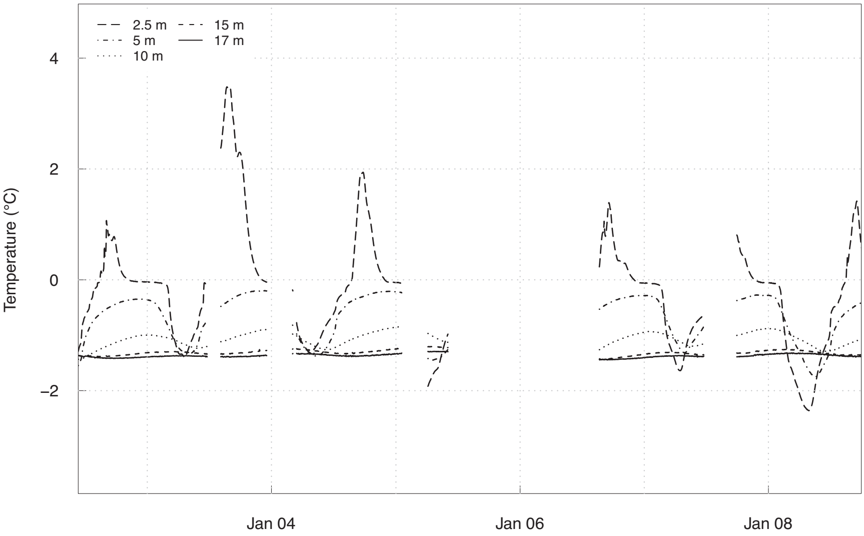

Figure A.35: Temperature-time plot of the borehole Stockhorn 6100.

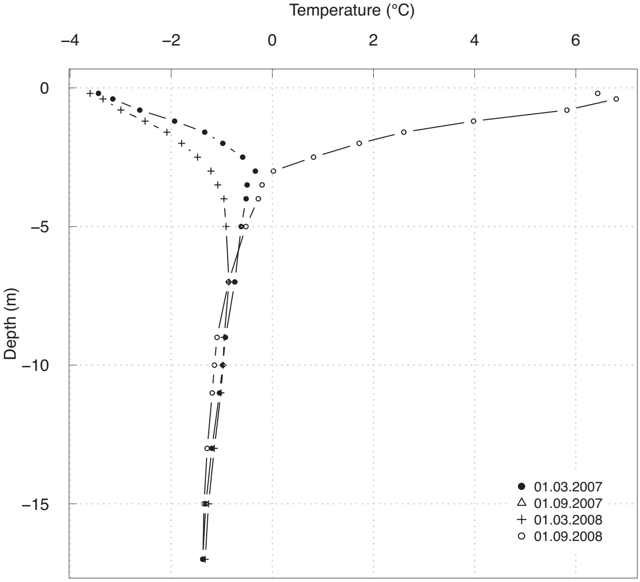

Figure A.36: Temperature profiles of the borehole Stockhorn 6100.

Tsaté 0104

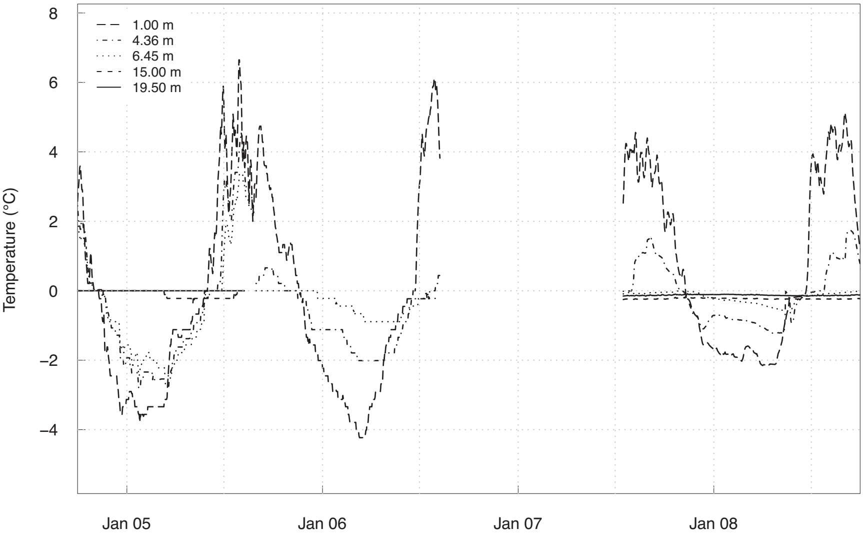

Figure A.37: *Temperature-time plot of the borehole Tsaté 0104.*

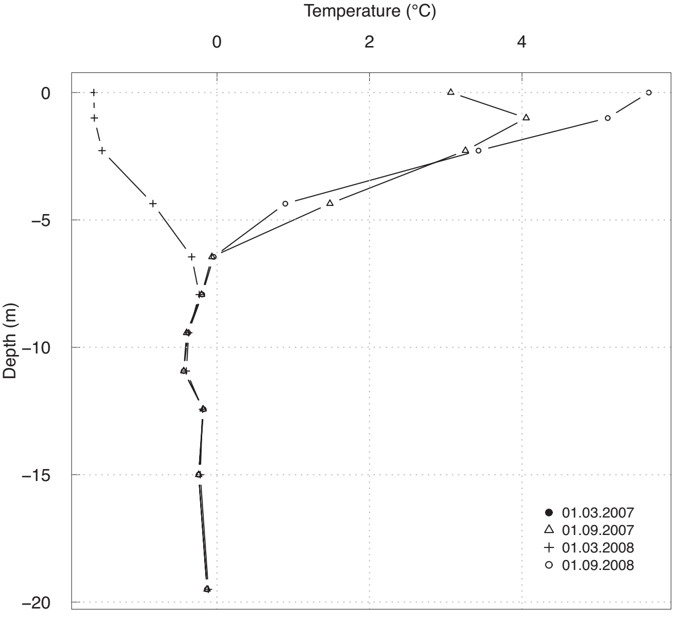

Figure A.38: *Temperature profiles of the borehole Tsaté 0104.*

PERMOS Rock Temperature Loggers

Table A.3: Locations of rock temperature loggers.

Code	Name	Region	Responsible	Coordinates	Elevation (m asl)	Slope (°)	Aspect (°)	Skyview
CH_0001	Eigerfenster	Schilthorn	UZH	643307/159034	2860	90	325	0.48
CH_0002	BB-v01	Réchy	UniFR	606217/112954	3100	90	75	0.46
CH_0003	BB-v02	Réchy	UniFR	606193/112951	3120	75	308	0.57
CH_0004	BB-v03	Réchy	UniFR	606137/112930	3140	95	198	0.45
CH_0005	BB-v04	Réchy	UniFR	605052/113919	2590	85	278	0.48
CH_0006	BB-v05	Réchy	UniFR	605091/113946	2590	90	50	0.41
CH_0007	BB-h01	Réchy	UniFR	605150/113933	2600	0	0	0.99
CH_0008	La-v01	Lapires	UniFR	588670/106300	2380	95	325	0.38
CH_0009	La-v02	Lapires	UniFR	587740/106089	2730	95	39	0.39
CH_0010	La-v03	Lapires	UniFR	587767/106142	2720	90	140	0.43
CH_0011	La-v04	Lapires	UniFR	587558/105773	2700	80	225	0.55
CH_0012	La-v05	Lapires	UniFR	587693/105622	2770	10	341	0.36
CH_0013	La-h01	Lapires	UniFR	587650/105875	2735	0	0	0.99
CH_0014	Murtel Front	Corvatsch	UZH	783028/144838	2630	15	20	0.93
CH_0015	Mandra South	Corvatsch	UZH	784607/145527	2830	98	185	0.39
CH_0016	Mandra East	Corvatsch	UZH	784665/145584	2805	90	88	0.47
CH_0017	Fuorcla	Corvatsch	UZH	784587/144561	2740	11	344	0.97
CH_0018	Corv. Top Gate	Corvatsch	UZH	783150/143538	3285	72	333	0.65
CH_0019	Corv. Hubbel	Corvatsch	UZH	783822/145760	2545	0	0	0.96
CH_0020	Corv. Middle Flat	Corvatsch	UZH	783182/145226	2690	8	320	0.99
CH_0021	Corv. Snow Canon	Corvatsch	UZH	783463/145390	2649	0	0	0.99
CH_0022	Corv. Middle Ridge	Corvatsch	UZH	783370/144916	2784	85	278	0.49
CH_0023	Corv. Top Flat	Corvatsch	UZH	783100/143413	3300	0	0	0.92
CH_0024	Corv. Top Ridge	Corvatsch	UZH	783103/143427	3300	58	181	0.73
CH_0025	Fuorcla North	Corvatsch	UZH	784615/145365	2765	23	11	0.9
CH_0026	Birg East 2	Schilthorn	UZH	632285/156996	2620	0	0	0.99
CH_0027	Schwarzgrat	Schilthorn	UZH	630492/156597	2800	0	0	0.96
CH_0028	Engital	Schilthorn	UZH	632167/157427	2410	10	130	0.88
CH_0029	Schilthornhuette	Schilthorn	UZH	632622/157941	2450	0	0	0.93
CH_0030	Birg West 2	Schilthorn	UZH	630834/156689	2680	22	130	0.92
CH_0031	Birg vertical	Schilthorn	UZH	631995/156799	2670	85	205	0.48
CH_0032	Jungfrau E-Ridge S	Schilthorn	UZH	640816/155013	3750	70	145	0.57
CH_0033	Jungfrau E-Ridge N	Schilthorn	UZH	640816/155025	3750	55	344	0.77
CH_0034	Eismeer	Schilthorn	UZH	643830/158049	3150	87	100	0.51
CH_0035	Moench W-Ridge	Schilthorn	UZH	642189/155603	3550	72	288	0.65

PERMOS Kinematics Sites

Table A.4: Rock glaciers where terrestrial surveys are conducted in the scope of PERMOS.

Site	Region	Aspect	Elevation (m asl)	Start	Institution
Aget	Central Valais	SE	2810–2890	2001	UniFR
Furggentälti	Berner Oberland	N	2450–2650	1994	UniBE
Grosses Gufer	Berner Oberland	NW	2360–2600	2007	UniFR
HuHH1	Central Valais	NNW	2630–2780	2001	UZH
HuHH3	Central Valais	NW	2515–2650	2002	UZH
Lapires	Central Valais	NNE	2640–2610	2007	UniFR
Yettes Condjà B	Central Valais	NE	2600–2740	2000	UniL
Yettes Condjà C	Central Valais	NE	2620–2820	2000	UniL
Monte Prosa A	Gotthard	N	2430–2600	2009	UniFR
Monte Prosa B	Gotthard	WNW	2450–2520	2009	UniFR
Murtèl	Engadine	NW	2630–2800	2009	UZH
Muragl	Engadine	NW	2490–2750	2009	UZH
Piancabella	Tessin	NE	2450–2550	2009	UniL
Réchy	Central Valais	NW	2610–2850	2001	UniFR
Tsarmine	Central Valais	W	2460–2640	2004	UniFR/UniL

Air Photos

Table A.5: Rock glacier areas where air photos are acquired regularly since 1980 for systematic monitoring of creep (low flying height (low f. h.), black and white (b-w)).

Site	Type	Available years
Furggentälti	low f. h., b-w	1990, 1995, 1999, 2000
Gross Gufer	low f. h., b-w	1987, 1994, 2000, 2008
Gruben	low f. h., b-w	1967, 1975, 1983, 1985, 1988, 1989, 1990, 1991, 1992, 1994, 1995, 1996, 1997, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, ,… is monitored annually (with gaps) in the scope of the glacier monitoring
Murtèl	low f. h., b-w	1987, 1988, 1991, 1995, 1996, 2002, 2007
Muragl	low f. h., b-w	1981, 1985, 1990, 1994, 1998, 1999, 2000, 2002, 2007
Réchy	low f. h., b-w	1986, 1991, 1995, 1999, 2004, 2008
Schafberg	low f. h., b-w	1991, 1994, 1998, 1999, 2000, 2007
Suvretta	low f. h., b-w	1992, 1997, 2002, 2007