Permafrost in Austria:

Impact of climate change on alpine permafrost and related hydrological effects

Final Report

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Cover: Krummgampen Valley, Ötztal Alps, Austria

Contents

1 Introduction

The aim of this project is the quantitative assessment of alpine permafrost in a well-defined catchment area, the impact of permafrost on climate warming and the establishment of a hydrological model to understand the associated changes. The multi-disciplinary project combines methods from geology, hydrology, meteorology, geodesy and geophysics to investigate permafrost in unconsolidated sediments and their consequences on the hydrological regime. The appearance of permafrost is indicated by active rock glacier, patterned ground, sorted stripes, outcrops of frozen ground and the high frequency of rock falls.

Beside of the previous investigated rock glaciers Reichenkar (Stubai Alps, Tyrol), Kaiserbergtal and Ölgrube (Ötztal Alps, Tyrol) we selected a study area in the Krummgampen valley (Glockturm-Weißseespitze, Ötztal Alps) to investigate the impact of permafrost on the hydrological regime. First we use existing models and geomorphologic mapping to estimate the local permafrost distribution. On this basis we select areas for the seismic mapping and the measurements of ground temperature (BTS). Afterwards we use these field observations to model the lateral and vertical permafrost distribution. To assess the sediment volume and hydrologic relevant parameters we use further geophysical methods. The major aims for the hydrological investigations are as following: (a) Establishment of a numerical stream flow model using the permafrost and sediment distribution maps, (b) Monitoring of relevant meteorological, hydrologic parameters such as discharge, precipitation and temperature, (c) Calibration of the numerical model by the field data.

The final report on the project Permafrost in Austria – Part I consists of:

a) Manuscript in preparation:

Hausmann, H., Krainer, K. and Brückl, E.: Mapping and modeling of permafrost using seismic refraction and ground surface temperatures, Krummgampen Valley, Ötztal Alps, Austria. Permafrost and Periglacial Processes.

Hausmann, H., Krainer, K. and Brückl, E.:, Rogger, M., Chirico, G.B., and Blöschl, G. Sediment and water storage in an Alpine permafrost catchment area, Krummgampen Valley, Ötztal Alps, Austria. Ground Water Research.

b) Submitted manuscript:

Rogger, M., Chirico, G.B., Hausmann, H., Krainer, K., Brückl, E. and Blöschl, G. (2013): Impact of mountain permafrost on flow paths and runoff response in a high alpine catchment. Water Resources Research (submitted).

c) Published papers:

Krainer, K., Kellerer-Pirklbauer, A., Kaufmann, V., Lieb, G.K., Schrott, L. and Hausmann, H., 2012: Permafrost Research in Austria: History and recent advances. Austrian Journal of Earth Sciences, 105/2, 2-11.

Hausmann, H., Krainer, K., Brückl, E. and Ullrich, C., 2012. Internal structure, ice content and dynamics of Ölgrube and Kaiserberg rock glaciers (Ötztal Alps, Austria) determined from geophysical surveys. Austrian Journal of Earth Sciences, 105/2, 12-31.

d) Abstracts in Conference Proceedings:

Hausmann H, Krainer K, Staudinger M, Brückl E. 2009. Continuous recording of seismic signals in Alpine permafrost. Oral Presentation at EGU, General Assembly, Vienna, Austria, 19-24 April 2009. Geophysical Research Abstracts, Vol. 11, EGU2009-10330, 2009.

Hausmann H, Krainer K, Brückl E, Blöschl G, Chirico GB, Komma J, Illnar R, Eipeldauer S. 2010. Sediment quantification and ground water storage in an alpine permafrost catchment: Krummgampen Valley, Ötztal Alps, Austria. 3rd European Conference on Permafrost (EUCOP III), June 13-17, 2010, Svalbard, Norway. 56.

Rogger, M., Blöschl, G., Hausmann, H., Krainer, K. and Brückl, E., 2012. On the use of geophysical information for distributed hydrological modeling in a mountain catchment. Geophysical Research Abstracts, Vol. 14, EGU General Assembly, Vienna, p.5671

We also edited a special volume of the Austrian Journal of Earth Sciences (vol. 105/2, Permafrost in Austria: http://www.univie.ac.at/ajes/archive/volume_105_2/) which contains a number of contributions on permafrost in the Austrian Alps, many of them funded by the Austrian Academy of Sciences.

2 Permafrost Research in Austria: History and recent advances

Krainer, K., Kellerer-Pirklbauer, A., Kaufmann, V., Lieb, G.K., Schrott, L. and Hausmann, H.

Published in: *Austrian Journal of Earth Sciences, 105/2, 2-11.*

2.1 Abstract

This article provides a historical overview on Permafrost research in Austria which started with the study of rock glaciers in the Ötztal Alps in 1928 when Finsterwalder (1928) first described the active rock glacier at Innere Ölgrube, Kaunertal and Pillewizer measured the flow velocity of this rock glacier (Pillewizer, 1938; 1957) and in 1938 started to measure flow velocities at Hochebenkar Rock Glacier near Obergurgl which is one of the largest and most active rock glaciers in the Austrian Alps. However, until the 1980s little has been published and only since then the number of publications related to permafrost in national and international journals increased substantially.

Since the end of the 20th century permafrost activities in Austria increased substantially as the Universities of Innsbruck, Vienna and Salzburg as well as the Central Institute for Meteorology and Geodynamics (ZAMG) started or intensified their permafrost research in Western and Central Austria (Ötztal Alps, Stubai Alps and Hohe Tauern Range): In Western Austria several rock glaciers (Ölgrube, Kaiserberg, Reichenkar) have been studied in detail and co-workers and included geomorphologic mapping, sediment analyses, hydrologic and geodetic monitoring, GPS measurements and GPR surveys. The hazard potential of degrading permafrost was first assessed for debris flows in the Hohe Tauern Range. Recent advances in remote sensing came with terrestrial and airborne laser scanning (TLS and ALS) as well as synthetic aperture radar (SAR) interferometry and were applied to monitor rock glaciers and periglacial permafrost areas. The spatial distribution of permafrost in Styrian part of the Niedere Tauern Range was modelled at a regional scale and monitored at a local scale. In the same regional study area the relevance of geological conditions on rock glacier distribution was studied. Another study was focussed on the effect of a warming climate on alpine rockwalls and its effects on mountain permafrost in central Austria and on the relationship between glacier retreat and formation of permafrost-related landforms in the Schober Mountains.
The Schmidt-hammer exposure-age dating (SHD) method was applied at nine rock glaciers for age determinations. Macrofabric analyses at several rock glaciers were carried out in the the Niedere Tauern Range pointing out the importance of flow dynamics, the influence of topography, the size of the studied rock glaciers as well as the movement of blocks during permafrost thawing for clast orientation.

The chemical composition (ion and metal concentration) of high mountain lakes and creeks which are situated in the catchment area of active rock glaciers were investigated. Combinations of several geophysical methods (GPR, seismic refraction, gravimetry) provided improved models of rock glaciers and facilitated to investigate their rheological behaviour using the derived ice content and permafrost thickness. A first estimation of permafrost distribution in Austria has been published using the lower limit of active rock glaciers in Central and Eastern Austria. A first approach to model the permafrost distribution of Austria has recently been performed. Permafrost in ice caves was also studied and included the link between (speleo-) meteorology and ice formation, determination of the age of the ice as well as local quantification of ice volumes Recently slopes were investigated by using a combination of ground temperature measurements, TLS and geophysical methods to detect permafrost. The authors describe the occurrence of sporadic and discontinuous permafrost in the

Glatzbach catchment (Hohe Tauern Range) with strong lateral variations controlled by regolith grain size and solar radiation. Recently research activities were reactivated on the hydrogeological role of rock glaciers in the Styrian part of the Niedere Tauern Range thereby focussing on the hydraulic properties of relict rock glaciers applying hydrograph analyses and the analyses of natural and artificial tracer breakthrough curves.
In a separate chapter current permafrost research activities in Austria are briefly listed which are described in detail in the special issue including the following topics:
(a) Modeling of mountain permafrost distribution and distribution of rock glaciers and permafrost in the past and at present, (b) Internal structure and dynamics of rock glaciers (c) Permafrost monitoring (d) Climate Change and Natural Hazards.

Finally organization and networkings are documented and open questions briefly discussed.

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3 Mapping and modelling of permafrost using seismic refraction and ground surface temperatures, Krummgampen Valley, Ötztal Alps, Austria

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In preparation for: *Permafrost and Periglacial Processes*

3.1 Abstract

The main objective of this study is to map and model the local permafrost distribution of unconsolidated sediments in a well defined Alpine catchment area. In our approach we use the results of seismic refraction and ground surface temperature (GST) measurements to discriminate field locations underlain by sporadic- and discontinuous permafrost, or no permafrost. We show that an efficient and reliable interpretation of the present permafrost condition is provided by comparing tomographic inversions, offset bin stacks, and velocity depth functions combined with GST values. The spatial permafrost distribution modeling is based on an empirical-statistic model where field observations with geophysical characteristics are related to the most important topoclimatic variables. The study area includes the Krummgampen Valley which is located in the vicinity of the Kauner Valley (Ötztal Alps, Austria). The altitudes vary between 2400 and 3300 m.a.s.l and the area is 5.76 km². The mean annual precipitation is ~1500 mm and the mean annual air temperature at a nearby meteorological station (Weißsee, 2540 m a.s.l) is -0.7°C. Active rock glaciers, fissure ice in bedrock and patterned ground indicate the presence of extensive alpine permafrost. Prevailing subsurface classes are talus slopes (17%), pre-LIA lodgement and meltout till (18%), LIA lodgement and meltout till (27%), rock glacier (5%), and bedrock (33%).

To discriminate field locations underlain with sporadic- and discontinuous permafrost, or no permafrost we analyzed the seismic data by applying the following methods: (i) an offset bin stack of the wave field to identify different phases or ice-rich permafrost and to provide information on the homogeneity of a profile, (ii) a 1-D ray tracing and inversion in combination with GST values to give a fast indication of the presence of permafrost, (iii) a 3-D first arrival tomographic inversion of travel times to provide tomographic sections which image the heterogeneity of a profile. The spatial permafrost distribution model consists of a bedrock- and a sediment model. The sediment model is applied for each landform class separately and delineates the local permafrost distribution as a function of direct solar radiation and altitude. Areas with sporadic- and discontinuous permafrost, or no permafrost were delineated by using the interpreted seismic profile locations. The applied rock model uses a topoclimatic key with different aspects classes and differentiate between three slope angles classified as rock slopes/walls, steep slopes and slope foot-positions (Schrott et al., 2012).

The investigated rock glaciers show ice along the whole profile, ice near to the front wall or no ice. In talus slopes ground ice was identified in a similar way, whereas the occurrence of ice in the foot slopes clearly prevails. Noteworthy is the occurrence of permafrost in talus slopes with expostion to South at an altitude of 2750 m. The formation of ground ice in such locations can be explained by the distribution of ground surface temperatures which show the coldest temperatures (about -6°C) on coarse-grained sediments at foot slopes. No permafrost was detected on the pre-LIA till which is sparsely vegetated and covered by a very thin layer of soil. The locations of patterned ground and solifluction lobes in Krummgampen Valley do not indicate permafrost, but rather seasonal frost. In total 71% of the area is classified to be underlain by permafrost, whereas 20% are attributed to discontinuous permafrost and 51% to sporadic permafrost.

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4 Sediment and water storage in an Alpine permafrost catchment area, Krummgampen Valley, Ötztal Alps, Austria

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4.1 Abstract

The aim of this work is the quantitative assessment of the sediment- and water storage in a well-defined catchment area. Ground water storage is estimated from the available pore space and compared to that from hydrological analysis. On the basis of three scenarios the impact of permafrost on the ground water storage is evaluated. As scenarios we use the investigated actual distribution of sporadic- and discontinuous permafrost assessed in Hausmann et al., (in prep.) and an additional one representing the absence of permafrost. The defined catchment are is the Krummgampen Valley located in the vicinity of the Kauner Valley (Ötztal Alps, Austria). It covers an area of 5.5 km². Predominant subsurface classes are talus slopes (17%), pre-LIA lodgment and meltout till (18%), LIA lodgment and meltout till (27%), rock glacier (5%), and bedrock (33%). In total 71% of the area is classified to be underlain by permafrost, whereas 20% are attributed to discontinuous permafrost and 51% to sporadic permafrost.

In our approach the sediment thicknesses are derived on the basis of comprehensive geophysical methods. The depth to the bedrock was calculated from prominent Ground-penetrating radar (GPR) reflectors and seismic data using a horizontal layered model for the moraines and from the tomographic inversions for the talus slopes. For ice-rich rock glaciers the combination of GPR and seismic refraction was applied, whereas for degrading rock glaciers the tomographic approach was chosen. The depth to the permafrost table (active layer thickness) was analyzed from the critically refracted head wave together with a horizontal layered model. A correlation between the depth and the altitude was then used to interpolate for the entire area. Statistic correlations between the subsurface class's thickness and their geomorphometric surface characteristics were used in combination with Kriging to extrapolate the obtained sediment thicknesses for the entire valley. Subsequently the pore space was estimated from the porosity of the surface debris using the compressional wave velocity. Base flow recession analyses were applied to derive the ground water storage for the years 2009, 2010, and 2011.

Ground water storage as result from base flow recession showed variations between 1.2 and 1.5 Mio. m³. A rough comparison of the ground water storage from base flow and from the pore space (assuming that ground water is retained at a slope of up to 13°) result in a well agreement with the estimate of the sporadic- and discontinuous permafrost distribution. In relation to the total pore space (5.9 Mio. m³) the sporadic- and discontinuous permafrost has a potential water storage of 25%, and the discontinuous permafrost a storage of 31%. The largest potential ground water storage is found in the LIA till (19%) and the pre-LIA till (12%). The two other landforms talus and rock glacier exhibit only small values each about 3%. For a permafrost-free scenario the changes in ground water storage is about 10% of the available pore space or about 600.000 m³. The largest changes occur in the LIA till (8%). Rock glacier and talus slopes show only small changes of about 1%. This effect can be explained by the steep bedrock topography for this landform classes.

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5 Impact of mountain permafrost on flow path and runoff response in a high alpine catchment

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5.1 Abstract

The degradation of alpine permafrost in a warmer climate may change the runoff regime of high mountain catchments. While previous studies provide interesting insight into local permafrost environments and their runoff characteristics, very little is known about subsurface flow path and permafrost occurrence for an entire catchment and its influence on runoff response. The aim of this study is to understand subsurface flow path in a permafrost influenced catchment and to assess the effect of permafrost degradation on the hydrological response. Detailed field investigations were conducted in a 5.5 km² catchment to assess its main hydrogeological settings. The well defined catchment is the Krummgampen Valley located in the vicinity of the Kauner Valley (Ötztal Alps, Austria. Predominant subsurface classes are talus slopes (17%), pre-LIA lodgment and meltout till (18%), LIA lodgment and meltout till (27%), rock glacier (5%), and bedrock (33%).

Ground-penetrating radar data, seismic refraction measurements and ground surface temperature data were employed to map the spatial permafrost distribution and depth of the permafrost table and the bedrock interface. The results for different types of unconsolidated sediments were then translated into five sets of flow path concepts in the presence and absence of permafrost. A distributed hydrological model (NetThales) was applied to simulate the catchment discharge in the actual condition and in a future scenario when permafrost has completely disappeared. The flow path concepts and other information from field surveys proved to be extremely useful for selecting the subsurface model parameters. Only small changes in the parameters were necessary to represent the observed runoff hydrographs well.

It was found that typical flow path for different types of mountain sediments in the Krummgampen catchment exists which may be applicable to similar environments exhibiting mountain permafrost. Geophysical data on the subsurface and other information from the field surveys were extremely helpful in selecting the runoff model parameters. But also less quantitative information such as observations of the presence of surface saturation was also very useful. The simulations indicate that the complete thawing of permafrost will increase the catchment storage capacity which will reduce the flood peaks by up to 20% and increase runoff during recession by about 15%. It is anticipated that the type of combined process and modeling studies presented in this paper will gain more momentum in the future as the focus in hydrology shifts towards exploring the effects of environmental change.

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6 Internal structure, ice content and dynamics of Ölgrube and Kaiserberg rock glaciers (Ötztal Alps, Austria) determined from geophysical surveys.

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6.1 Abstract

In this study we use a concept based on three geophysical methods (Ground-penetrating radar / GPR, seismic refraction, gravimetry) to provide new insight into the internal structure, ice content and dynamics of the two active rock glaciers Ölgrube and Kaiserberg. Both investigated rock glaciers are located in the catchment area of the Kauner Valley in the western Ötztal Alps, Tyrol, Austria and represent two of the largest rock glaciers in this area. They were chosen because of their large size, their impressive high front lobes, their high surface velocities and their expected high ice volume. Additionally, many previous studies exist on this rock glacier. Recent work on a regional rock glacier inventory exhibited 123 rock glaciers (7.3 km²) in the catchment of the Kauner Valley which include 39 (32 %) active, 42 (34 %) inactive and 42 (34 %) relict rock glaciers. Both rock glaciers consist of debris derived from orthogneiss, paragneiss and mica schist.

We used the concept introduced by Hausmann et al. (2007) to investigate the internal structure of ice-rich rock glaciers by applying the following methods: (1) GPR measurements , (2) Seismic refraction (3) The results from GPR and seismic refraction are combined to establish a density model. (4) In a next step the density of the ice-rich permafrost is determined by the gravimetric data. Based on the derived structure and densities, the relative ice content is calculated.
We additionally used the resulting structural and physical parameters to better understand the dynamic behaviour of the rock glacier. To quantify the stress regime which drives the movement of the rock glaciers, we compute a parameter related to the shear stress at the base (Paterson, 1994) of the ice-rich permafrost layer. In a next step we compare this parameter with the observed parameters (P-wave velocities, bulk densities, thicknesses) from the two rock glaciers and one rock glacier that was investigated by applying the same methods (Hausmann et al., 2007). To describe the movement of the three rock glaciers we use the power law. Finally, the GPR-reflections of the permafrost layer are displayed together with the P-wave velocities, the densities (ice contents) and the surface velocities along the profiles of the main flow direction.

The geophysical concept introduced by Hausmann et al. (2007) was applied successfully to establish 4-layer models for the two investigated rock glaciers Ölgrube and Kaiserberg. For both rock glaciers an ice-free sediment layer had to be introduced below the ice-rich permafrost body. A confirmation of the 4 layers was found in areas where the bedrock surface was resolved by GPR and seismic refraction. The geophysical models provided relevant information on structural and physical parameters and helped to understand dynamic processes of the rock glacier.
For both rock glaciers we found 4 layers to be composed of (a) 4 - 6 m surface debris (“active layer”), (b) 20 - 30 m ice-rich permafrost, and (c) 10 - 15 m ice-free sediments overlying the (d) bedrock. The average depth to the bedrock surface is 35 - 50 m. The geophysical model of the Ölgrube rock glacier exhibits large changes in thickness of the ice-rich permafrost, density and P-wave velocity of the permafrost in flow direction. We estimated a volumetric ice content of 43 % in the frontal part and 61 % in the root zone. For Kaiserberg rock glacier the geophysical model detected only slight structural changes of the thickness of the ice-rich permafrost along both profiles. The ice content varies laterally between about 40 and 50 %.

The recent flow fields clearly show an extensional flow field for both rock glaciers near their frontal parts. The geophysical model combined with the flow field further provides details on the movement of the rock glacier. Structural and physical parameters assessed by surface based geophysical methods are used to explain the dynamics of the rock glacier. From the two studied active rock glaciers and an additional rock glacier (Reichenkar rock glacier), which was investigated by applying the same methods (Hausmann et al., 2007), we found a parameter that describes their creep behaviour and shows that the three geophysical models are conclusive. Concerning the dynamics of these active rock glaciers, the data indicate that a reduction of the ice content causes an increase of internal friction, lower seismic P-wave velocities, and higher bulk densities. In order to keep a degrading rock glacier in motion a thickening is required. The GPR-reflection patterns of the permafrost layer and their relation to the structural and physical parameters primarily reveal that long reflectors parallel to the surface are found in regions with high P-wave velocity and low density, indicating zones with high ice content.

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7 Abstracts

7.1 Continuous recording of seismic signals in Alpine permafrost

Hausmann H, Krainer K, Staudinger M, Brückl E

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Over the past years various geophysical methods were applied to study the internal structure and the temporal variation of permafrost whereof seismic is of importance. For most seismic investigations in Alpine permafrost 24-channel equipment in combination with long data and trigger cables is used. Due to the harsh environment source and geophone layouts are often limited to 2D profiles. With prospect for future 3D-layouts we introduce an alternative of seismic equipment that can be used for several applications in Alpine permafrost.
This study is focussed on controlled and natural source seismic experiments in Alpine permafrost using continuous data recording. With recent data from an ongoing project ("Permafrost in Austria") we will highlight the potential of the used seismic equipment for three applications: (a) seismic permafrost mapping of unconsolidated sediments, (b) seismic tomography in rock mass, and (c) passive seismic monitoring of rock falls. Single recording units (REFTEK 130, 6 channels) are used to continuously record the waveforms of both the seismic signals and a trigger signal. The combination of a small number of recording units with different types of geophones or a trigger allow numerous applications in Alpine permafrost with regard to a high efficiency and flexible seismic layouts (2D, 3D, 4D). The efficiency of the light and robust seismic equipment is achieved by the simple acquisition and the flexible and fast deployment of the (omni-directional) geophones. Further advantages are short (data and trigger) cables and the prevention of trigger errors. The processing of the data is aided by 'Seismon' which is an open source software project based on Matlab® and MySQL (see SM1.0). For active-source experiments automatic stacking of the seismic signals is implemented. For passive data a program for automatic detection of events (e.g. rock falls) is available which allows event localization.
In summer 2008 the seismic equipment was used for the three different types of applications. It enabled fast and efficient field work and provided excellent seismic data at two permafrost sites.

7.2 *Sediment quantification and ground water storage in an alpine permafrost catchment*

Hausmann H, Krainer K, Brückl E, Blöschl G, Chirico GB, Komma J, Illnar R, Eipeldauer S.

Published in: *3rd European Conference on Permafrost (EUCOP III), June 13-17, 2010, Svalbard, Norway. 56.*

Changing permafrost may have significant consequences on the hydrological regime of an alpine catchment. For an area abundant in unconsolidated sediments model parameters such as the spatial distribution of the effective storage volume, the permafrost distribution and the hydraulic conductivity are essential. In this work the first steps such as the quantification of the effective storage volume, the detection of permafrost, and the estimation of ground water storage are presented.

The study area (Krummgampen Valley, Ötztal Alps, Austria) is located at altitudes between 2400 and 3300 m.a.s.l and covers an area of 5.5 km². The mean annual precipitation is ~1500 mm and the mean annual air temperature at a nearby meteorological station (2500 m.a.s.l) is ~ -0.7 °C. Active rock glaciers, fissure ice in bedrock and patterned ground indicate the presence of extensive alpine permafrost. Predominant subsurface classes are talus slopes (17%), pre-LIA lodgement and meltout till (18%), LIA lodgement and meltout till (27%), rock glacier (5%), and bedrock (33%). Geophysical methods (seismic refraction, georadar) along numerous profiles are applied to estimate the sediment volume. Statistic correlations between the subsurface class's thickness and their geomorphometric surface characteristics were used to extrapolate for the entire valley. The permafrost distribution was assessed by seismic methods and evaluated by continuously recorded BTS-temperatures. Discharge data is available for 2008 and 2009 for the main catchment and for 2009 for three sub-catchments. Base flow recession analysis was applied to separate the ground water flow from surface and subsurface runoff.

Permafrost with active layer depths of up to ~ 3 m was detected above 2500 m.a.s.l (north facing). Estimated mean sediment thicknesses (disregarding the impermeable permafrost) are 8 m (talus slopes), 6 m (pre-LIA till), 5 m (LIA till), and 20 m (rock glacier). The flow data recorded by the hydrograph at the main outlet is characterized by processes such as snow melt, ground water flow, subsurface and surface run off with peak flows of up to 2000 l/s. The hydrologic data from 2009 show a recharge of ground water lasting from late April to early August. According to recession analysis the ground water system has a response time larger than 30 days. The ground water storage computed from recession analysis and the effective water storage estimated from the sediment volume by geophysical investigations show similar values. Finally we discuss how permafrost degradation could affect the hydrological regime.

7.3 Wie beeinflußt Permafrost den Abfluß? - Erste Ergebnisse des Einzugsgebietes Krummgampental, Ötztaler Alpen

Hausmann H, Krainer K, Brückl E, Chirico GB, Blöschl G, Eipeldauer S, Illnar R, Komma J.

Publiziert in: *Geo.Alp 7: 93-108, 2010*

Wie beeinflußt Permafrost im Lockergestein das hydrologische Regime? Diese Arbeit zeigt wie im Rahmen des Projekts 'Permafrost in Austria' diese Fragestellung untersucht wird und präsentiert erste Ergebnisse des Einzugsgebietes Krumgampental (Ötztaler Alpen, Tirol). Mit Erfassung von Permafrostverbreitung, Quantifzierung der Sedimentspeicher und hydrologischer Parameter liefert diese Studie die Grundlagen für die Erstellung eines nachfolgenden hydrologischen Modells. Für die Erfassung der Permafrostverbreitung wurde eine Kombination aus einer seismischen Methode mit kontinuierlichen Aufzeichnungen von BTS-Loggern verwendet. Mit einem empirisch-statistischen Modell (Höhe, Strahlung) wurden diese Daten dann flächenhaft extrapoliert. Zur Quantifizierung der Sedimentspeicher wurden die geophysikalische Methoden Georadar und Seismik in Kombination mit geomorphometrischen Analysen verwendet. Für die hydrologische Untersuchung stehen Feldbeobachtungen, Wasserproben, Sedimentproben, und Abflußmessungen an vier Pegel zur Verfügung. Zur Trennung des Grundwasseranteils von Oberflächen- und Zwischenabfluß wurde eine Rezessionsanalyse des Basisabflusses angewandt. Das Krummgampental (2400-3300 m) hat eine Fläche von 5.5 km2, einen mittleren Jahresniederschlag von 1500 mm, die mittlere Jahrestemperatur an der nähesten meteorologischen Station (2500 m) beträgt -0.7°C. Die vorherschenden Untergründe bestehen aus Moränenablagerungen (27% LIA, 18% prä-LIA), Schutthalden (17%), Blockgletscher (5%), und Fels (33%). Permafrost mit aktiven Schichtdicken von 5 m wurden in Höhenlagen von 2500 (nordseitig) bis 2850 m detektiert. Die Mittelwerte für die Sedimentspeicher betragen 8 m (Schutthalden), 6 m (prä-LIA Moränenablagerung), 5 m (LIA Moränenablagerung), und 20 m (Blockgletscher). Die aufgezeichneten Abflußdaten sind durch die Prozesse der Schneeschmelze, Grundwasserabfluß sowie Oberflächen- und Zwischenabfluß mit Spitzenwerten von 2000 l/s charakterisiert. Die Abflußdaten vom Jahr 2009 zeigen eine Anreicherung von Grundwasser von Ende April bis Anfang August. Die Rezessionsanalyse ergab eine Reaktionszeit von über 30 Tagen für das Grundwassersystem. Der Vergleich zwischen Grundwasserspeicher aus der Rezessionsanalyse und dem Sedimentspeicher aus den geophysikalischen Untersuchungen zeigen ähnliche Werte.

7.4 On the use of geophysical information for distributed hydrological modelling in a mountain catchment

M. Rogger, H. Hausmann, K. Krainer, E. Brückl, and G. Blöschl

Published in: *Geophysical Research Abstracts, Vol. 14, EGU2012-5671, 2012, EGU General Assembly 2012*

For most hydrological model applications only very little information on the properties of the subsurface is available. Soil storage parameters are hence most often back-calculated from observed runoff. There is, however, the possibility to use geophysical investigations to get a better insight in the subsurface and gain valuable information for hydrological models. In case such investigations are available, they can be used as input information and one would expect that they facilitate the models parameter choice. In the presented case study a spatially distributed hydrological model was used to simulate runoff generation and routing in a 5 km² alpine permafrost catchment in the Ötztal Alps, Tyrol, Austria. Detailed seismic refraction and ground penetrating radar investigations were performed to identify the spatial patterns of unconsolidated sediments where groundwater flow can take place. Seismic refraction and diving wave tomography together with temperature measurements were used to identify permafrost occurrence which influences the subsurface storage capacities. The first results of the study indicate that geophysical information vastly facilitates the identification of model parameters. Subsurface parameters are much better constrained and require little calibration compared to the use of observed runoff alone. While the effort for hydrogeophysical investigations is substantial, it does reduce the parameter identifiably problem of spatially distributed hydrologic models and helps to improve the understanding of subsurface processes.

7.5 Distributed hydrological modelling in a permafrost catchment - on the value of geophysical information

M. Rogger, H. Hausmann, K. Krainer, E. Brückl, and G. Blöschl

Published in: *Geophysical Research Abstracts, Vol. 15, EGU2013-PREVIEW, 2013, EGU General Assembly 2013*

Alpine permafrost is prone to decrease in a warmer climate as a consequence of climate change which in turn may affect the runoff regime of high alpine catchments. In the presented case study detailed geophysical field investigations were performed in a 5 km² large catchment in Western Austria to gain information about subsurface properties and permafrost occurrence. Ground penetrating radar, seismic refraction and ground-surface-temperature measurements were applied to map the spatial permafrost distribution, depths to the permafrost table and bedrock interface. This information was used to infer subsurface flow paths concepts for different geologic formations in the presence and absence of permafrost. The concepts were then used to set up a rainfall-runoff model and simulate the runoff response of the catchment for scenarios with and without permafrost. The results of the study show that geophysical information helps to improve the understanding of subsurface processes and to reduce the parameter identifiably problem. Subsurface model parameters are well constrained by the available field information and require little calibration. Furthermore, the simulations indicate that the melting of permafrost increases the available catchment storage which causes a reduction of flood peaks and an increase of runoff during recession. A reduction of extreme events is important since it may also affect flood events in downstream catchments.

8 Conclusion

The seismic refraction method in combination with the ground surface temperature (GST) measurements allow for discrimination of sporadic and discontinuous permafrost. Ice-rich rock glaciers differ from ice-poor permafrost locations identified at the foot of talus slopes. The investigated rock glaciers show ice along the whole profile, ice near to the front wall or no ice. In talus slopes ground ice was identified in a similar way, whereas the occurrence of ice in the foot slopes clearly prevails. Remarkable is the occurrence of permafrost in talus slopes with aspect to South at an altitude of 2750 m. The formation of ground ice in such locations can be explained by the distribution of ground surface temperatures which show the coldest temperatures (about -6°C) on coarse-grained sediments at foot slopes. No permafrost was detected on the pre-LIA till which is sparsely vegetated and covered by a very thin layer of soil. The locations of patterned ground and solifluction lobes in Krummgampen Valley do not indicate permafrost, but rather seasonal frost. A empirical-statistic permafrost distribution model was established for the sediment areas using the field data as a function of direct solar radiation and altitude. In total 71% of the area is classified to be underlain by permafrost, whereas 20% are attributed to discontinuous permafrost and 51% to sporadic permafrost.
The largest thicknesses with regard to the actual permafrost distribution is found in the pre-LIA till and in the LIA till. In a scenario where permafrost is absence the largest thicknesses are found for talus slopes and rock glaciers. There the depths reach values of up to about 25 m. In such a case the mean thickness increase from 4.6 m to 10.6 m for rock glaciers. The depth to the permafrost table correlates well with the altitude and facilitates to interpolate for the entire area. About 20% of the total sediment storage is occupied by discontinuous permafrost. Large fractions are found in rock glaciers (12%) and smaller fractions occur in talus slopes (4%) and in LIA till (4%). If we add the occurrences of sporadic permafrost (assuming that the sporadic permafrost is found from the active layer down to the bedrock interface) the total value increases to 37%. The absolute value for the sediment storage is 5.9 Mio. m³ for ice-free sediments. Thereof 2.2 Mio. m³ are occupied with sporadic- and discontinuous permafrost and 1.2 Mio. m³ with discontinuous permafrost.
To select runoff model parameters or flow path concepts geophysical surveys and other information from the field surveys were extremely helpful. There exist typical flow path for different types of mountain sediments in the Krummgampen catchment which may be applicable to similar environments exhibiting mountain permafrost. These flow path are likely to change with the melting of permafrost and will increase the storage capacity of the catchment. If permafrost is present, water can only infiltrate up to the permafrost table which forms the lower boundary for groundwater flow. Without permafrost this boundary will be deeper, i.e. at the sediment - bedrock interface. The simulations indicate that the disappearance of permafrost in the Krummgampen catchment may lead to a decrease in flood peak discharge of up to 20% and an increase of runoff during recession periods of up to 15%. Both changes are due to an increase in the storage capacity of the catchment.
Ground water storage as result from base flow recession varied between 1.2 and 1.5 Mio. m³ during the years 2009-2011. A rough comparison of the ground water storage from base flow and from the pore space (assuming that ground water is retained at a slope of up to 13°) result in a well agreement with the estimate of the sporadic- and discontinuous permafrost distribution. In relation to the total pore space (5.9 Mio. m³) the sporadic- and discontinuous permafrost has a potential water storage of 25%, and the discontinuous permafrost a storage of 31%. The largest potential ground water storage is found in the LIA till (19%) and the pre-LIA till (12%). The two other landforms talus and rock glacier exhibit only small values each about 3%. For a permafrost-free scenario the changes in ground water storage is about 10% of the available pore space or about 600.000 m³. The largest changes occur in the LIA till (8%). Rock glacier and talus slopes show only small changes of about 1%. This effect can be explained by the steep bedrock topography for this landform classes.

9 Results

Deliverables

- A geologic/geomorphologic map of the Krummgampen catchment and adjacent areas
- Results from the seismic mapping and the structural explorations in the Krummgampen catchment and at Ölgrube and Kaiserberg rock glaciers.
- Documentation of ground surface temperatures (GST, MAGST) and run off flow at four gauges in the Krummgampen catchment
- Sediment thickness maps for the actual and a future scenario (including a map of the active layer depths)
- A permafrost distribution map for the occurrences of sporadic- and discontinues permafrost
- A hydrological model and the modelling of the actual run off and a future scenario
- Results on the impact of permafrost on the hydrological regime in unconsolidated sediments

1st Austrian Permafrost Workshop

Alpine permafrost (rock glacier, permafrost in unconsolidated sediments, permafrost in fissures) is widely distributed in the Eastern- and Southern Alps. The importance of alpine permafrost was underestimated for a long time and became of (public) interest with the climate warming (since the 1990's). Since that time various working groups has been formed which address the topic "alpine permafrost". The aim of the first Austrian Permafrost Workshop (Organisation: K. Krainer, H. Hausmann) was to invite all interested permafrost working groups of Austria and South Tyrol. This workshop should provide new results and data on the permafrost in the Eastern- and Southern Alps and to present and discuss ideas on this topic. With more than 40 participants the workshop was of success. The discussion on the future of the Austrian permafrost research (October, 14th, 2010) was attended by all working groups which concluded to establish an "Austrian permafrost working group". This group should be used to improve the coordination for a long term monitoring of alpine permafrost and to select therefore suitable „key sites" which have to be supervised. On October, 15th we could made an excursion to the active rock glacier "Äußeren Hochebenkar". The Abstracts of the oral and poster presentations were published in Geo.Alp (Volume 7, December 2010).

Special Issue "Permafrost in Austria"

We edited a special volume of the Austrian Journal of Earth Sciences (vol. 105/2, Permafrost in Austria: http://www.univie.ac.at/ajes/archive/volume_105_2/) which contains a number of contributions on permafrost in the Austrian Alps, many of them funded by the Austrian Academy of Sciences.

10 Publications

Peer reviewed publications

Hausmann H, Krainer K, Brückl E, Ullrich C. 2012. Internal structure, ice content and dynamics of Ölgrube and Kaiserberg rock glaciers (Ötztal Alps, Austria) determined from geophysical surveys. Austrian Journal of Earth Sciences 105(2): 12-31.

Hausmann, H., Krainer, K. and Brückl, E.: (in prep.)Mapping and modeling of permafrost using seismic refraction and ground surface temperatures, Krummgampen Valley, Ötztal Alps, Austria, Permafrost and Periglacial Processes.

Krainer K, Kellerer-Pirklbauer A, Kaufmann V, Lieb G, Schrott L, Hausmann H. 2012. Permafrost Research in Austria: History and recent advances. Austrian Journal of Earth Sciences 105(2): 2-11.

Krainer K., Ribis M. 2012. A Rock Glacier Inventory of the Tyrolean Alps (Austria). Austrian Journal of Earth Sciences. 105(2): 32-47.

Rogger, M., Chirico, G.B., Hausmann, H., Krainer, K., Brückl, E. and Blöschl, G. (submitted): Impact of mountain permafrost on flow paths and runoff response in a high alpine catchment. Water Resources Research.

Talks and Poster Presentations (with Proceedings-Entry)

Hausmann H, Krainer K, Brückl E, Mostler W. 2007. Creep of Two Alpine Rock Glaciers - Observation and Modelling (Ötztal- and Stubai Alps, Austria). In: Grazer Schriften der Geographie und Raumforschung, Band 43:145-150; Institute for Geography and Regional Science, Karl Franzens University Graz, Austria Available from http://www.uni-graz.at/geowww/hmrsc/proceedings9.htm [accessed November 2006.

Hausmann H, Krainer K, Brückl E, Mostler W, Ullrich C. 2007. Internal structure, ice content, and dynamic behaviour of three Eastern Alpine rock glaciers. Poster Presentation at EGU, General Assembly, Vienna, Austria, 15-20 April 2007. Geophysical Research Abstracts, Vol. 9, A-04164, 2007. SRef-ID: xxx/gra/xx.

Hausmann H, Krainer K, Brückl E, Blöschl G. 2008. Geophysical investigations of alpine permafrost in the Ötztal Alps of Austria. Poster Presentation at EGU, General Assembly, Vienna, Austria, 13-18 April 2008. Geophysical Research Abstracts, Vol. 10, EGU2008-A-02814, 2008, SRef-ID: 1607-7962/gra/EGU2008-A-0281.

Hausmann H, Krainer K, Staudinger M, Brückl E. 2009. Continuous recording of seismic signals in Alpine permafrost. Oral Presentation at EGU, General Assembly, Vienna, Austria, 19-24 April 2009. Geophysical Research Abstracts, Vol. 11, EGU2009-10330, 200.

Mertl S, Hausmann H. 2009. Seismon - a flexible seismic processing software. Poster Presentation at EGU, General Assembly, Vienna, Austria, 19-24 April 2009. Poster Presentation at EGU, General Assembly, Vienna, Austria, 19-24 April 2009. Geophysical Research Abstracts, Vol. 11, EGU2009-4266, 200.

Hausmann H, Krainer K, Brückl E, Blöschl G, Chirico GB, Komma J, Illnar R, Eipeldauer S. 2010. Sediment quantification and ground water storage in an alpine permafrost catchment: Krummgampen Valley, Ötztal Alps, Austria. 3rd European Conference on Permafrost (EUCOP III), June 13-17, 2010, Svalbard, Norway. 56.

Hausmann H, Krainer K, Brückl E, Chirico GB, Blöschl G, Eipeldauer S, Illnar R, Komma J. 2010. Wie beeinflußt Permafrost den Abfluß? - Erste Ergebnisse des Einzugsgebietes Krumgampental, Ötztaler Alpen. Geo.Alp 7: 93-108.

Krainer, K. und Ribas, M. (2010). Blockgletscherinventar Ötztaler - Stubaier Alpen. Kurzfassungen der Beiträge des Permafrost Workshop Obergurgl, 14-15. Oktober 2010, Geo.Alp, 7, 93-108.

Krainer, K. und Mussner, L. (2010). Blockgletscher und Naturgefahren: Der aktive Blockgletscher "Murfreit" in der nördlichen Sellagruppe, Dolomiten. Kurzfassungen der Beiträge des Permafrost Workshop Obergurgl, 14-15. Oktober 2010, Geo.Alp, 7, 93-108.

Rogger, M., Chirico, G.B., Hausmann, H., Krainer, K., Brückl, E. and Blöschl, G.: Distributed hydrological modeling in a permafrost catchment - on the value of geophysical information. EGU General Assembly, Vienna (abstract).

Talks and Poster Presentations (without Proceedings-Entry)

Hausmann H, Krainer K, Brückl E. 2009. Geophysikalische Methoden zur Kartierung und Strukturerkundung von Permafrost (Ötztaler Alpen). Oral Presentation at Gletscherworkshop, Obergurgl, Austria, 3.-4. August 2009.

Hausmann H, Krainer K, Brückl ,E. 2012. Detektion, Struktur und Dynamik von Permafrost in den Tiroler Alpen. Oral presentation at PANGEO AUSTRIA 2012, 15-20. September 2012,Salzburg.

Preceding publications or unpublished reports supportive for this work

Gabrielli P, Carturan L, Gabrieli J, Dinale R, Krainer K, Hausmann H, Davis M, Zagorodnov VS, Seppi R, Barbante C, Dalla-Fontana G, Thompson LG. 2010. Atmospheric warming threatens the untapped glacial archive of Ortles mountain, South Tyrol. Journal of Glaciology 56 (199): 843-853.

Hausmann H, Behm M. 2011. Imaging the structure of cave ice by ground-penetrating radar. The Cryosphere 5: 329-340. doi:10.5194/tc-5-329-201.

Hausmann H, Krainer K, Brückl E, Mostler W. 2007. Internal Structure and Ice Content of Reichenkar Rock Glacier (Stubai Alps, Austria) Assessed by Geophysical Investigations. Permafrost and Periglacial Processes 18: 351-367. DOI: 10.1002/ppp.60.

Hausmann H. 2009. Ground Ice Detection in a glacier forefield using Georadar and Seismics (Pasterze, Hohe Tauern, Austria). unpublished report, Institute of Geodesy and Geophysics, Vienna University of Technology, 7pp.

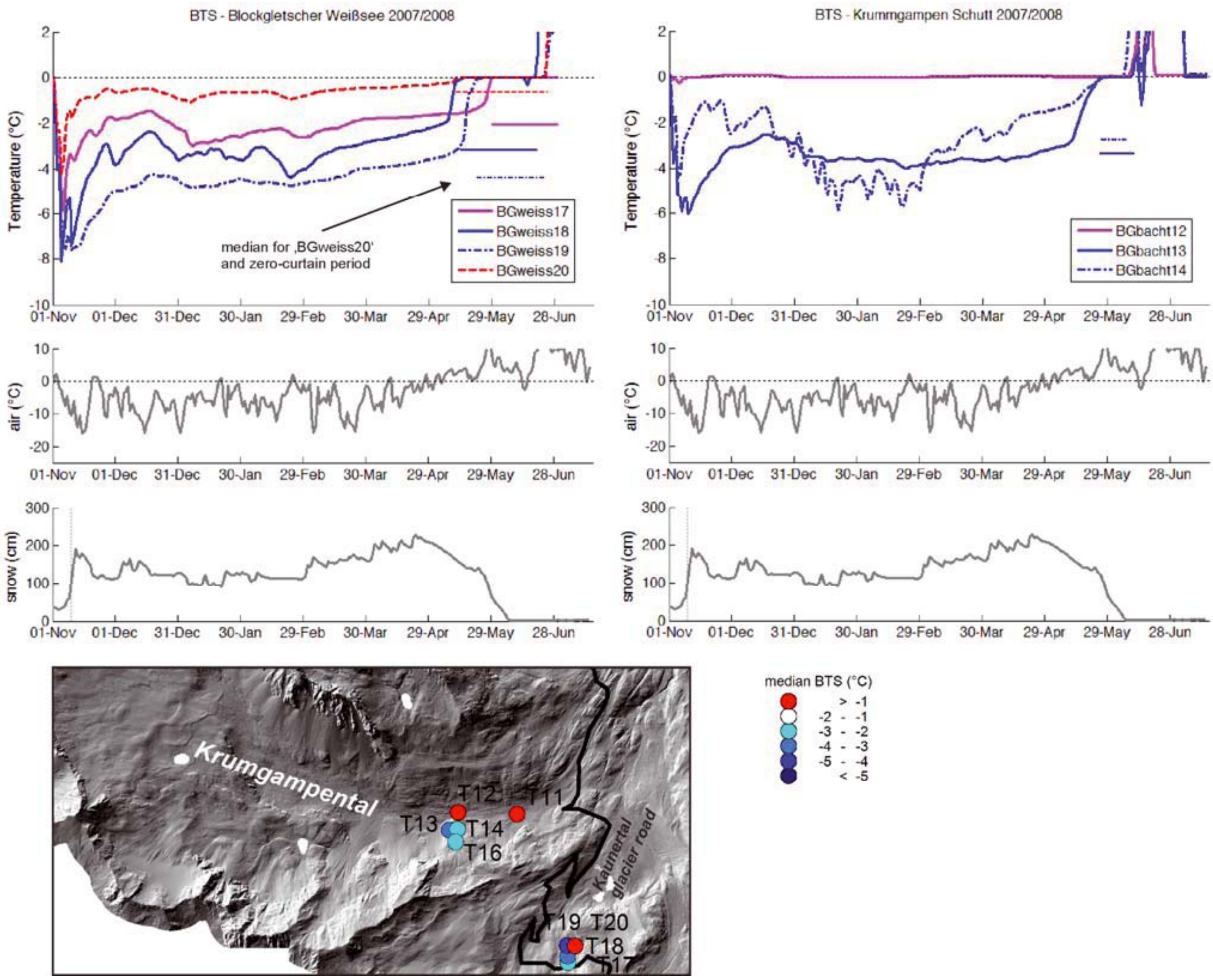
Hausmann H. 2010. Hammerschlagseismik an der unterkühlten Schutthalde bei Puchenstuben (Bezirk Scheibbs, Niederösterreich). unpublished report, Institute of Geodesy and Geophysics, Vienna University of Technology, 6pp.

Krainer K, Lang K, Hausmann H. 2010. Active Rock Glaciers at Croda Rossa/Hohe Gaisl, Eastern Dolomites (Alto Adige/South Tyrol, Northern Italy). Geografia Fisica e Dinamica Quaternaria 33.

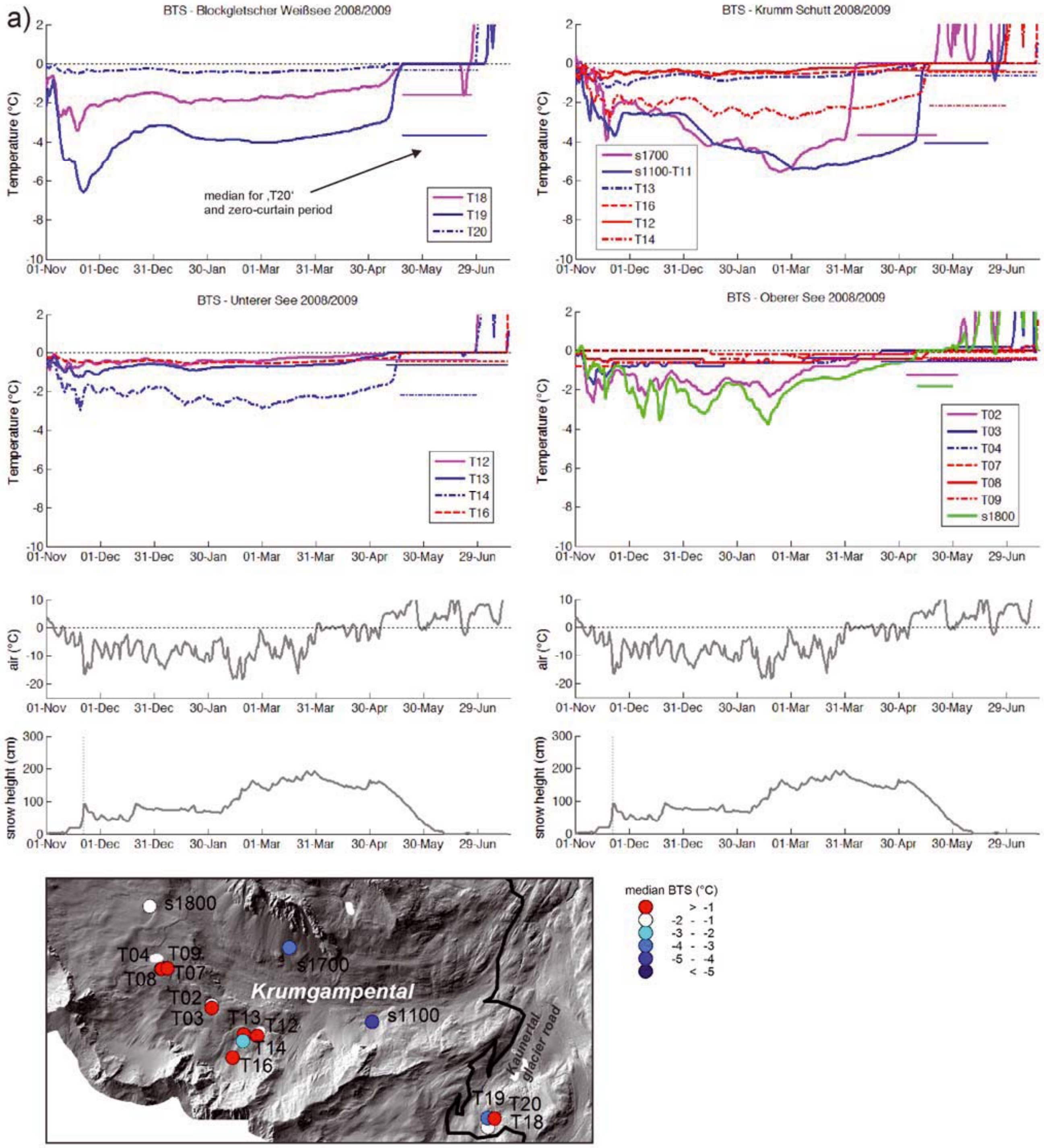
Schöner W, Boeckli L, Hausmann H, Otto JC, Reisenhofer S, Riedl C, Seren S. 2012. Spatial Patterns of Permafrost at Hoher Sonnblick (Austrian Alps) - Extensive Field-measurements and Modelling Approaches. Austrian Journal of Earth Sciences 105(2): 154-168.

11 Appendix

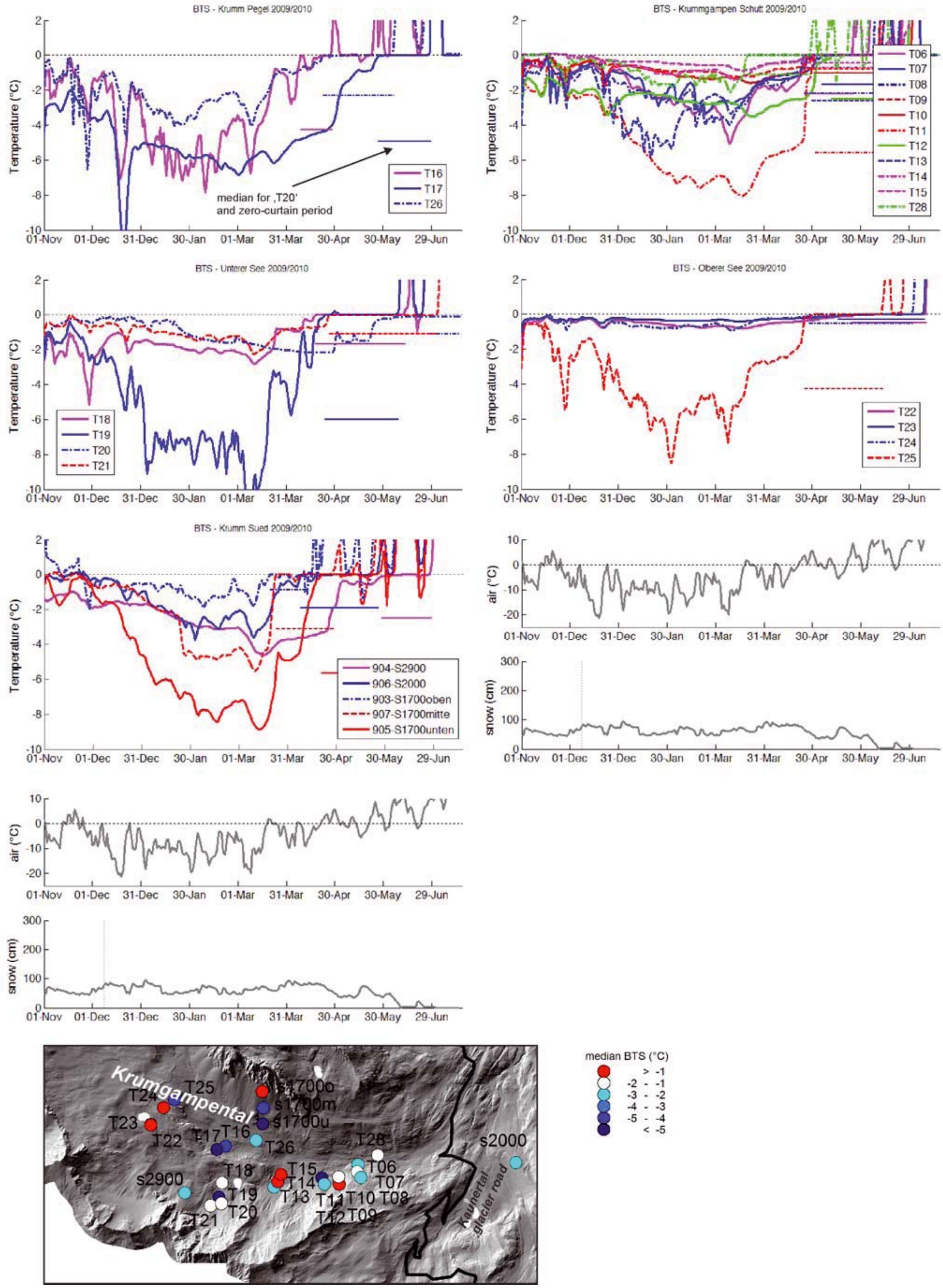
11.1 Ground surface temperatures



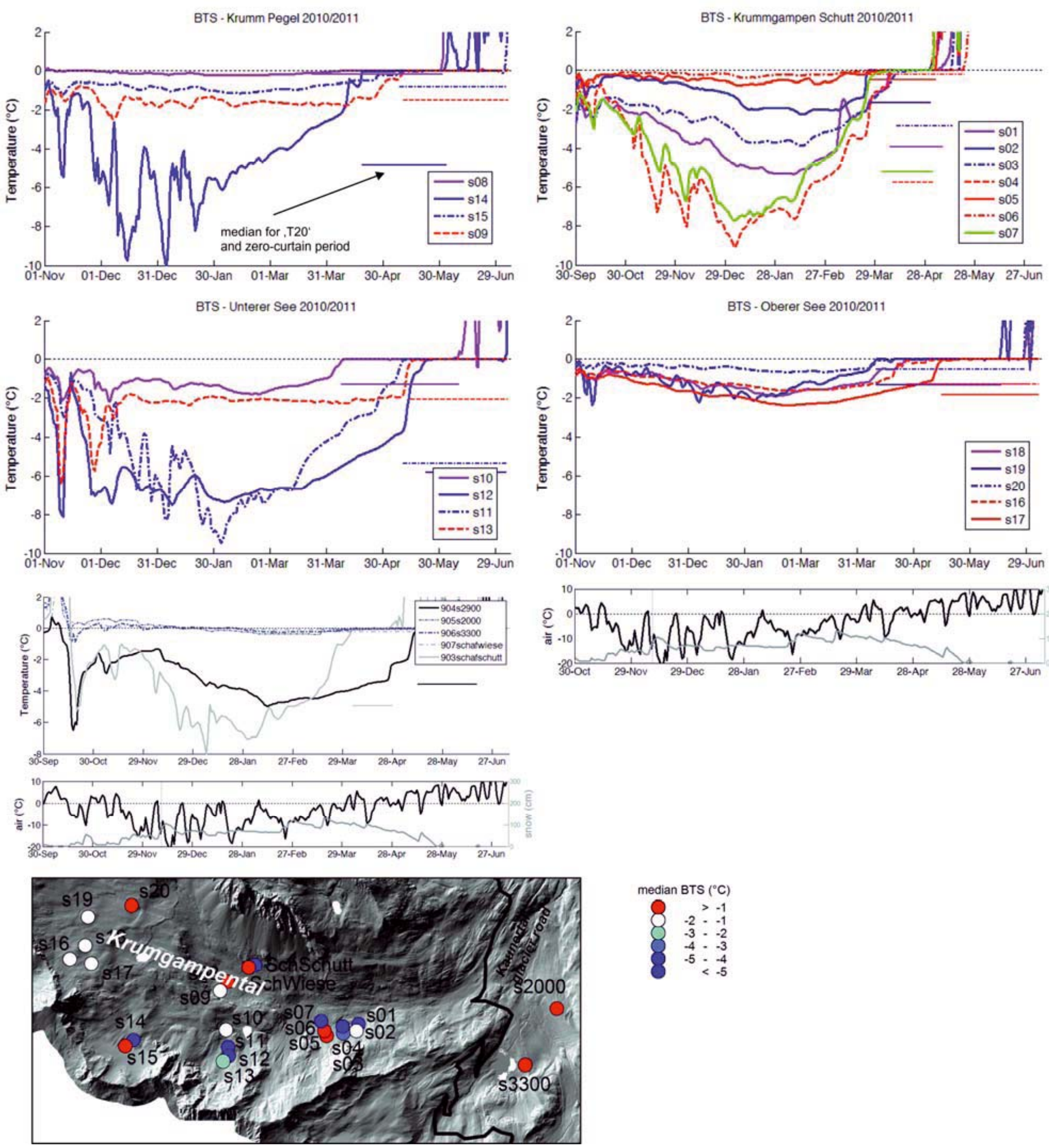
Ground surface temperatures for the winters 07/08. Median values of the temperature and duration of the zero-curtain effect are displayed as horizontal lines at the end of spring. Snow height and air temperatures measured at a close meteorological station (Weißsee, 2540 m.a.s.l.) are displayed in the bottom of each figure.



Ground surface temperatures for the winters 08/09. Median values of the temperature and duration of the zero-curtain effect are displayed as horizontal lines at the end of spring. Snow height and air temperatures measured at a close meteorological station (Weißsee, 2540 m.a.s.l.) are displayed in the bottom of each figure.

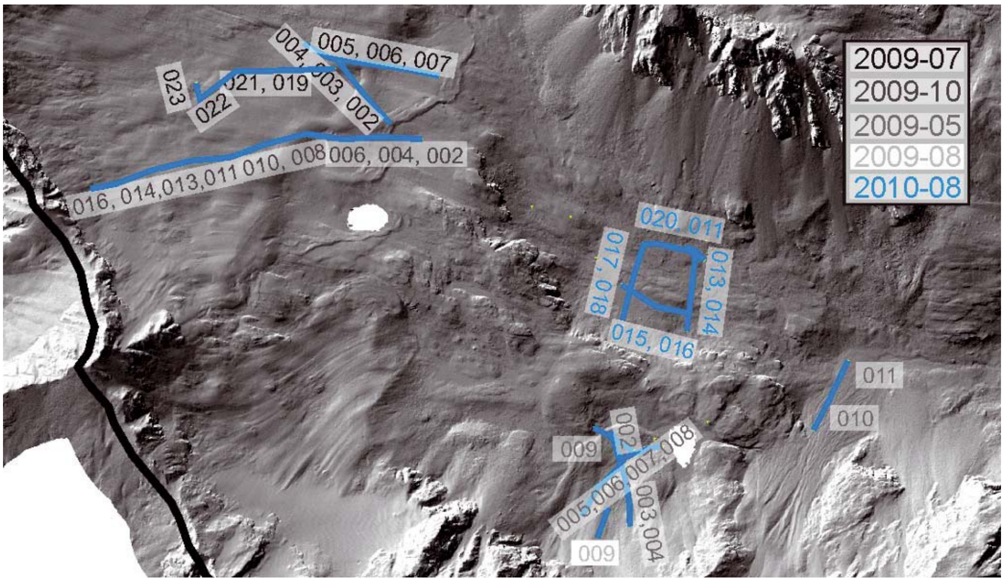


Ground surface temperatures for the winters 09/10. Median values of the temperature and duration of the zero-curtain effect are displayed as horizontal lines at the end of spring. Snow height and air temperatures measured at a close meteorological station (Weißsee, 2540 m.a.s.l.) are displayed in the bottom of each figure.



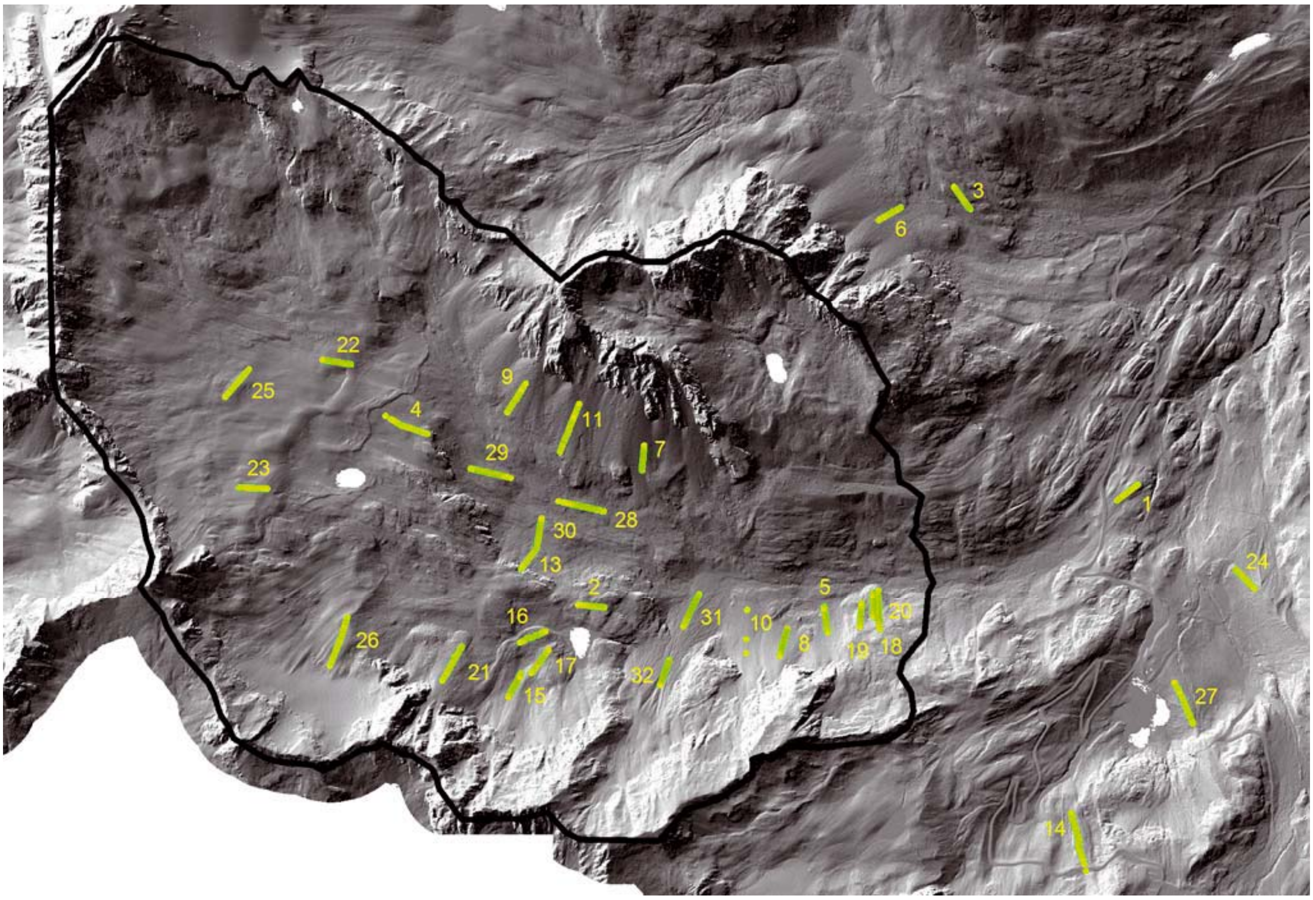
Ground surface temperatures for the winters 10/11. Median values of the temperature and duration of the zero-curtain effect are displayed as horizontal lines at the end of spring. Snow height and air temperatures measured at a close meteorological station (Weißsee, 2540 m.a.s.l.) are displayed in the bottom of each figure.

11.2 Ground-penetrating radar

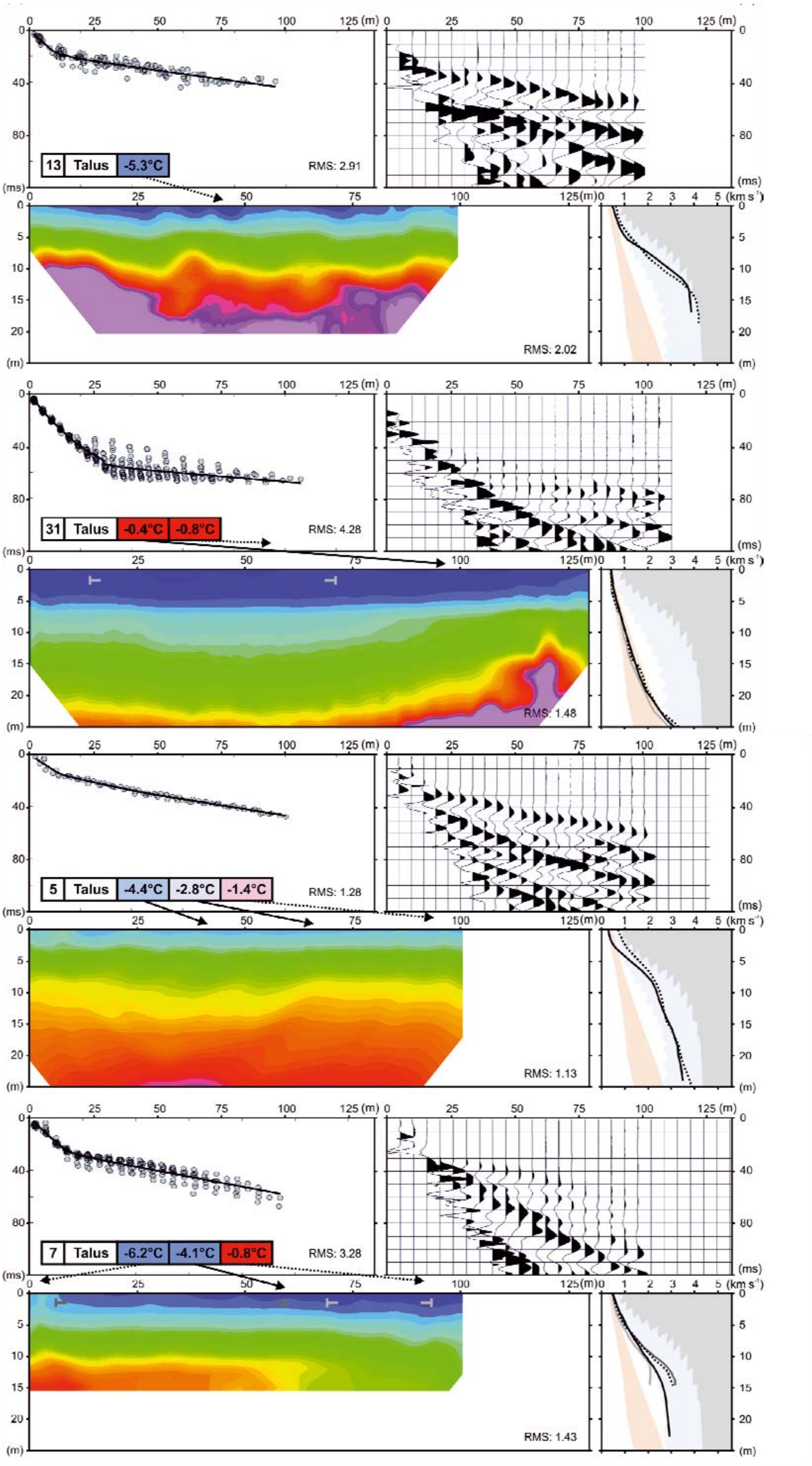


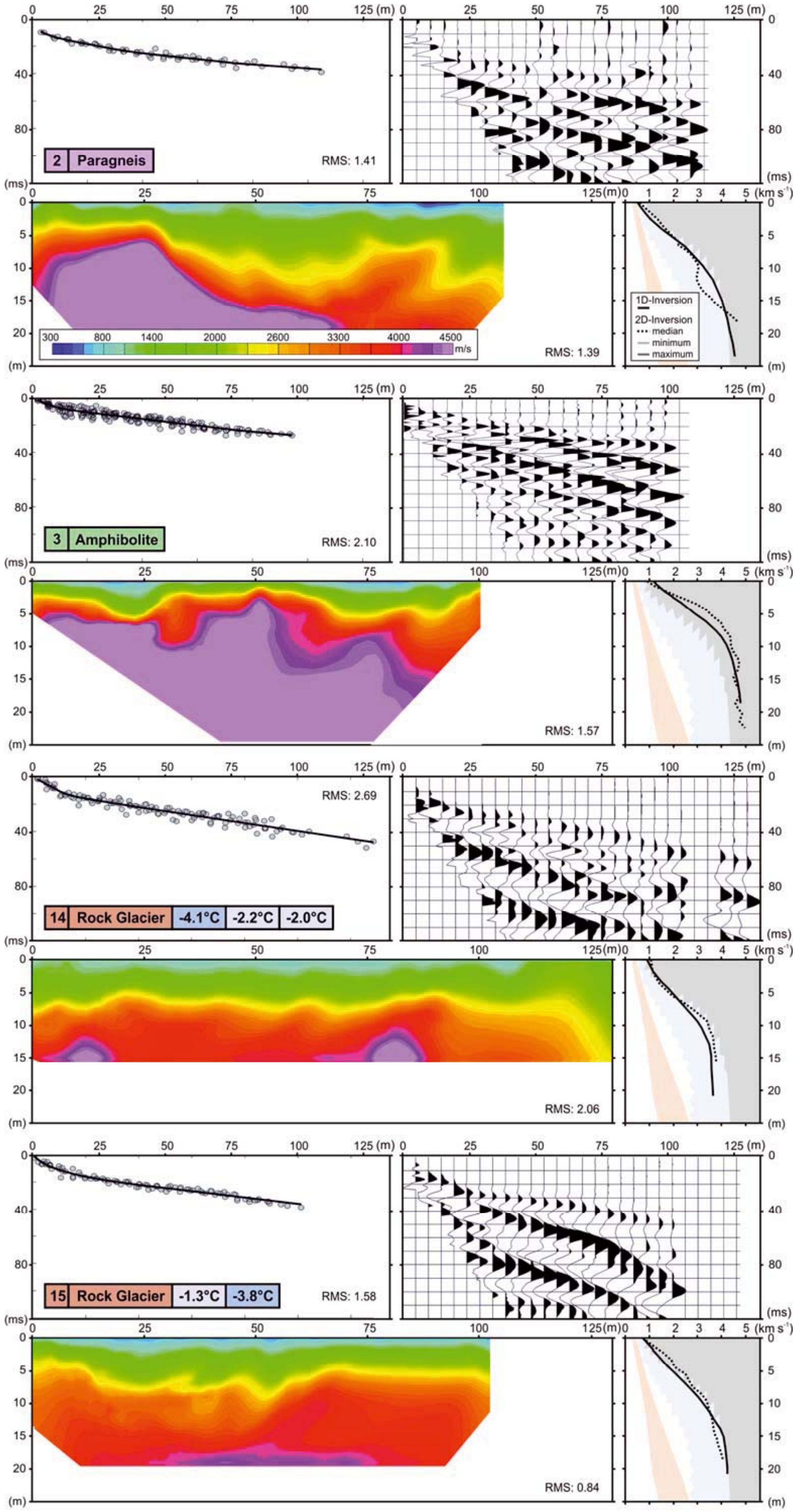
Locations of the GPR profiles for the survey in 2009 and 2010. The applied frequency ranged between 35 and 80 MHz for the structural exploration.

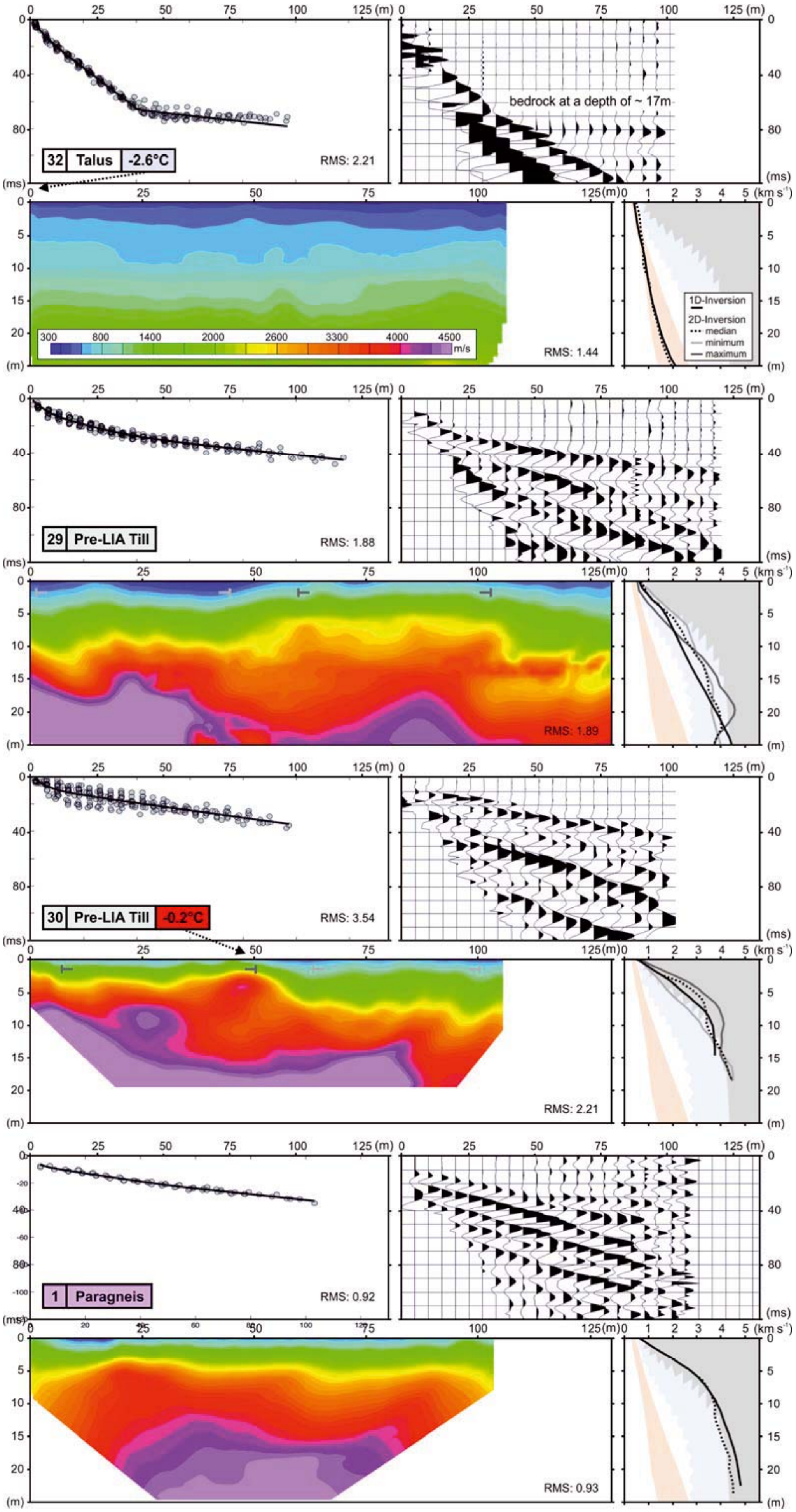
11.3 Seismic refraction

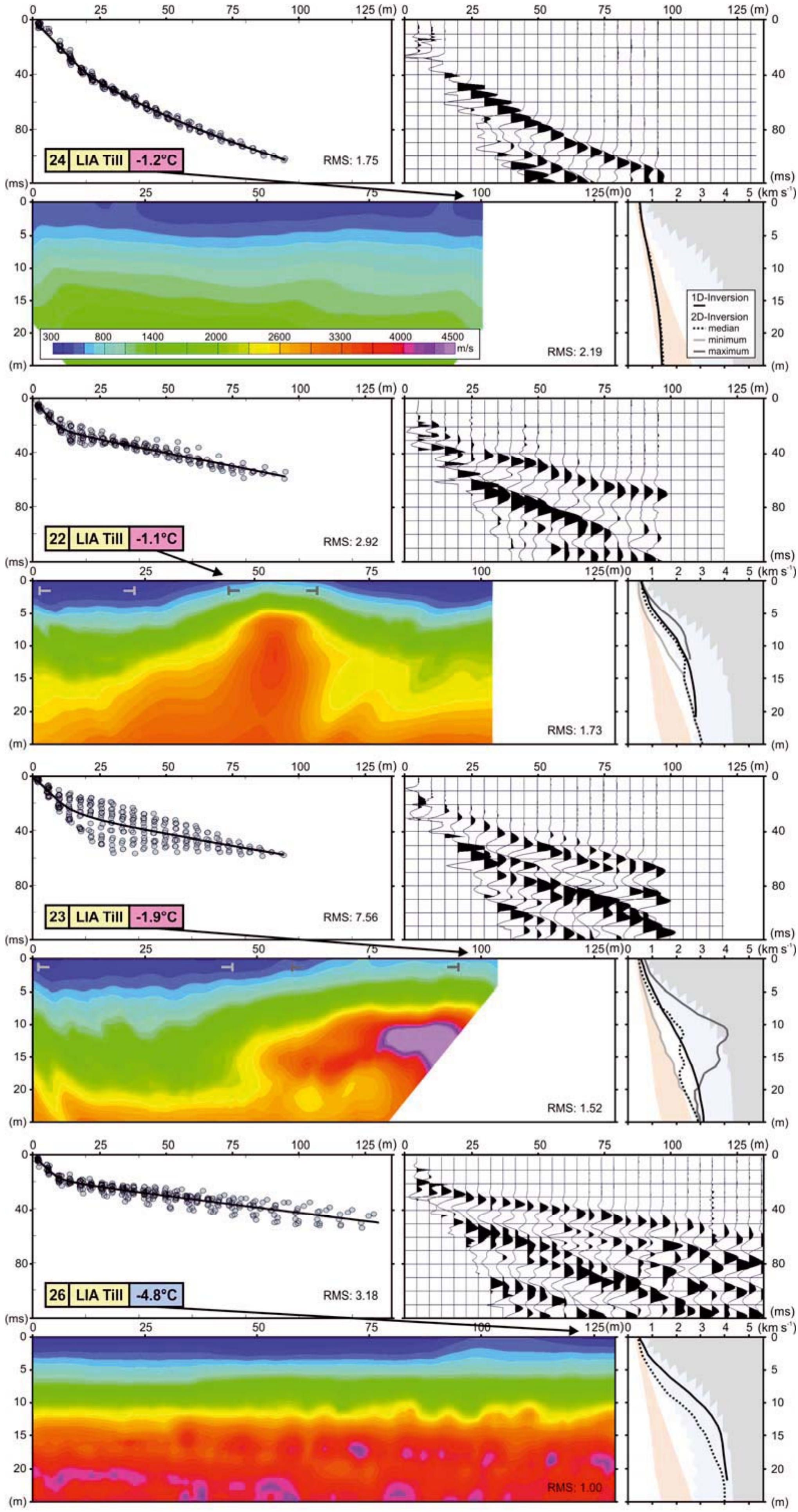


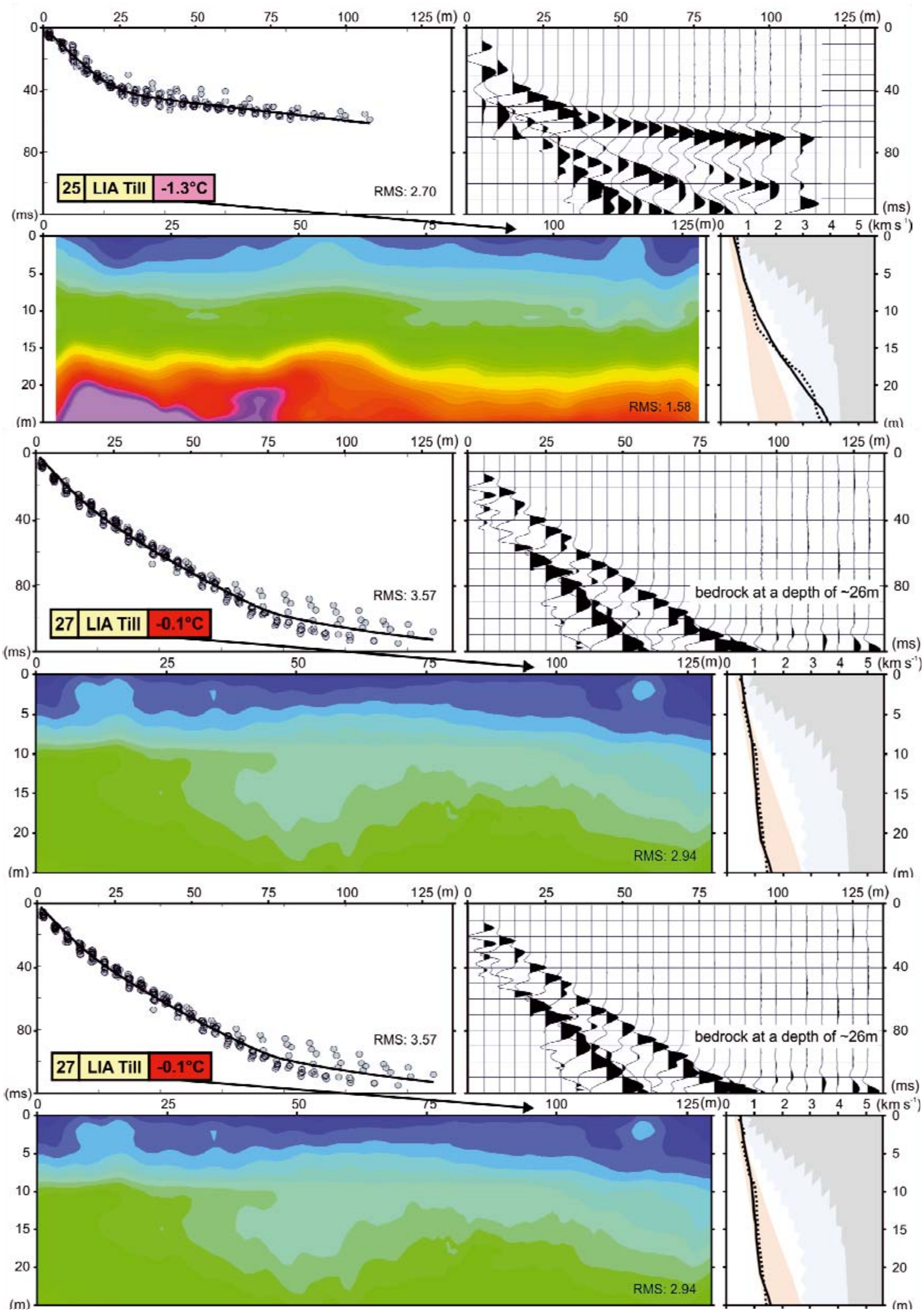
Location of the seismic profiles and delineation of the Krummgampen catchment.

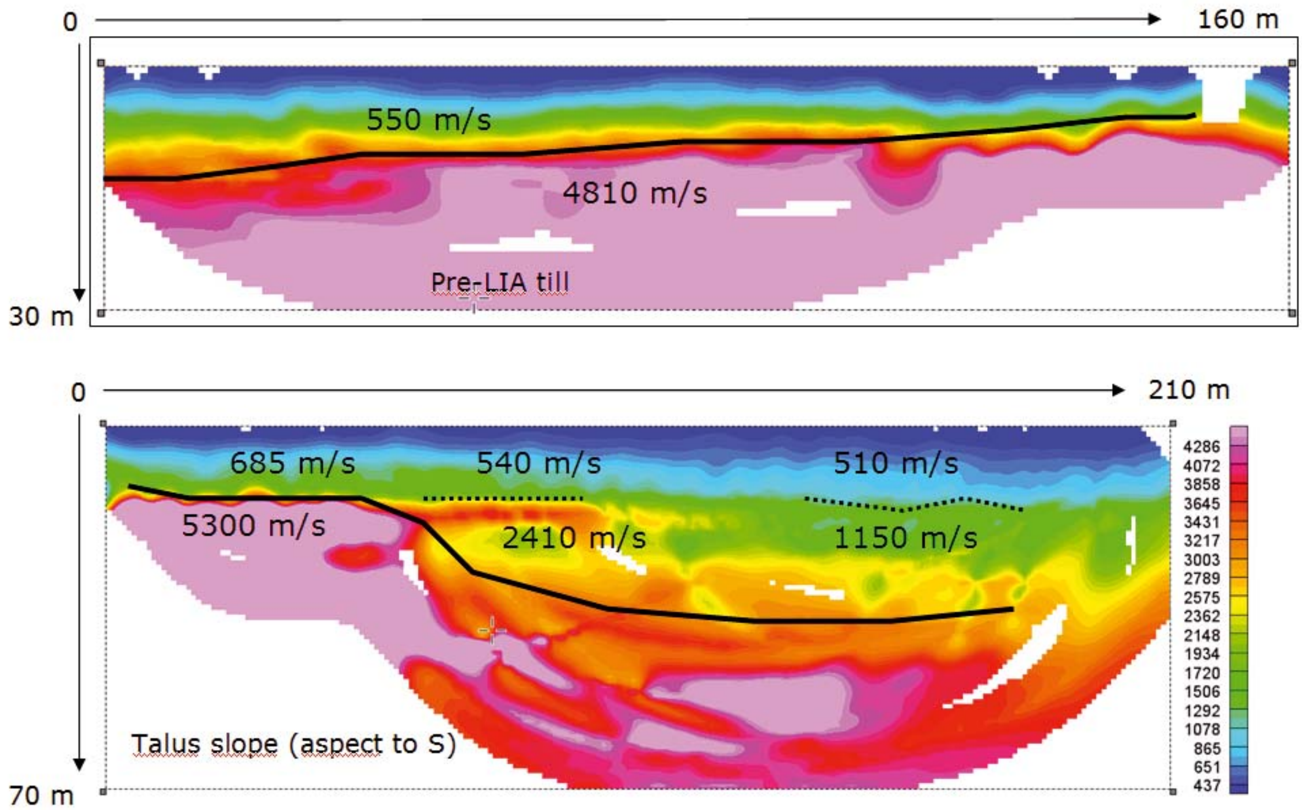

13 Talus -5.3°C
RMS: 2.91
RMS: 2.02
31 Talus -0.4°C -0.8°C
RMS: 4.28
RMS: 1.48
5 Talus -4.4°C -2.8°C -1.4°C
RMS: 1.28
RMS: 1.13
7 Talus -6.2°C -4.1°C -0.8°C
RMS: 3.28
RMS: 1.43


2 Paragneis
RMS: 1.41
RMS: 1.39
300 800 1400 2000 2600 3300 4000 4500 m/s
1D-Inversion
2D-Inversion
median
minimum
maximum
3 Amphibolite
RMS: 2.10
RMS: 1.57
14 Rock Glacier -4.1°C -2.2°C -2.0°C
RMS: 2.69
RMS: 2.06
15 Rock Glacier -1.3°C -3.8°C
RMS: 1.58
RMS: 0.84
(m)
(ms)
(km s-1)


32 Talus -2.6°C
RMS: 2.21
bedrock at a depth of ~ 17m
RMS: 1.44
1D-Inversion
2D-Inversion
median
minimum
maximum
300 800 1400 2000 2600 3300 4000 4500 m/s
29 Pre-LIA Till
RMS: 1.88
RMS: 1.89
30 Pre-LIA Till -0.2°C
RMS: 3.54
RMS: 2.21
1 Paragneis
RMS: 0.92
RMS: 0.93
(m)
(ms)
(km s⁻¹)

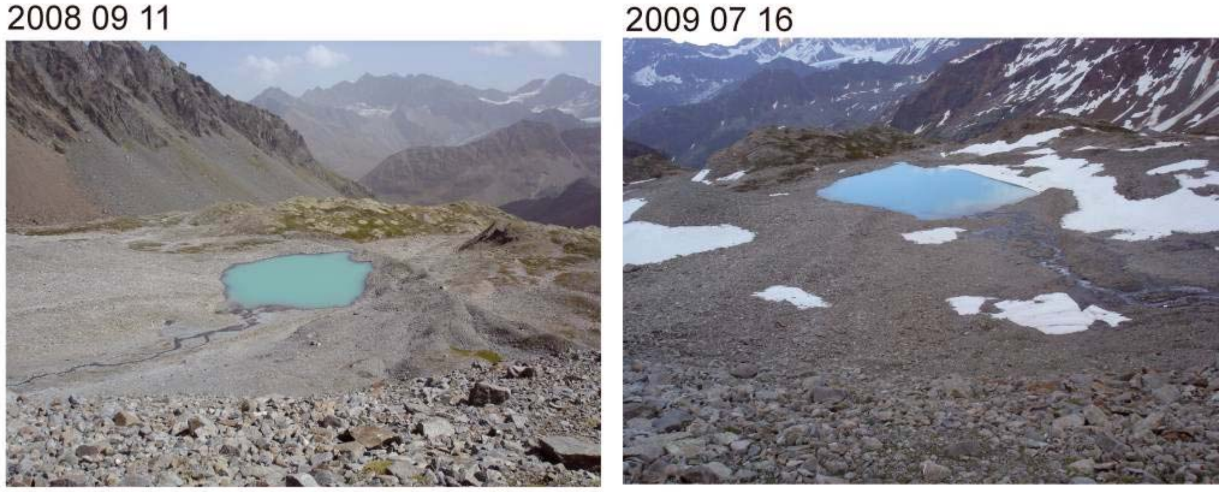

24 LIA Till -1.2°C
RMS: 1.75
RMS: 2.19
1D-Inversion
2D-Inversion
median
minimum
maximum
300 800 1400 2000 2600 3300 4000 4500 m/s
22 LIA Till -1.1°C
RMS: 2.92
RMS: 1.73
23 LIA Till -1.9°C
RMS: 7.56
RMS: 1.52
26 LIA Till -4.8°C
RMS: 3.18
RMS: 1.00
(ms)
(m)
(km s⁻¹)


25 LIA Till -1.3°C
RMS: 2.70
RMS: 1.58
(km s⁻¹)
27 LIA Till -0.1°C
RMS: 3.57
bedrock at a depth of ~26m
RMS: 2.94
27 LIA Till -0.1°C
RMS: 3.57
bedrock at a depth of ~26m
RMS: 2.94

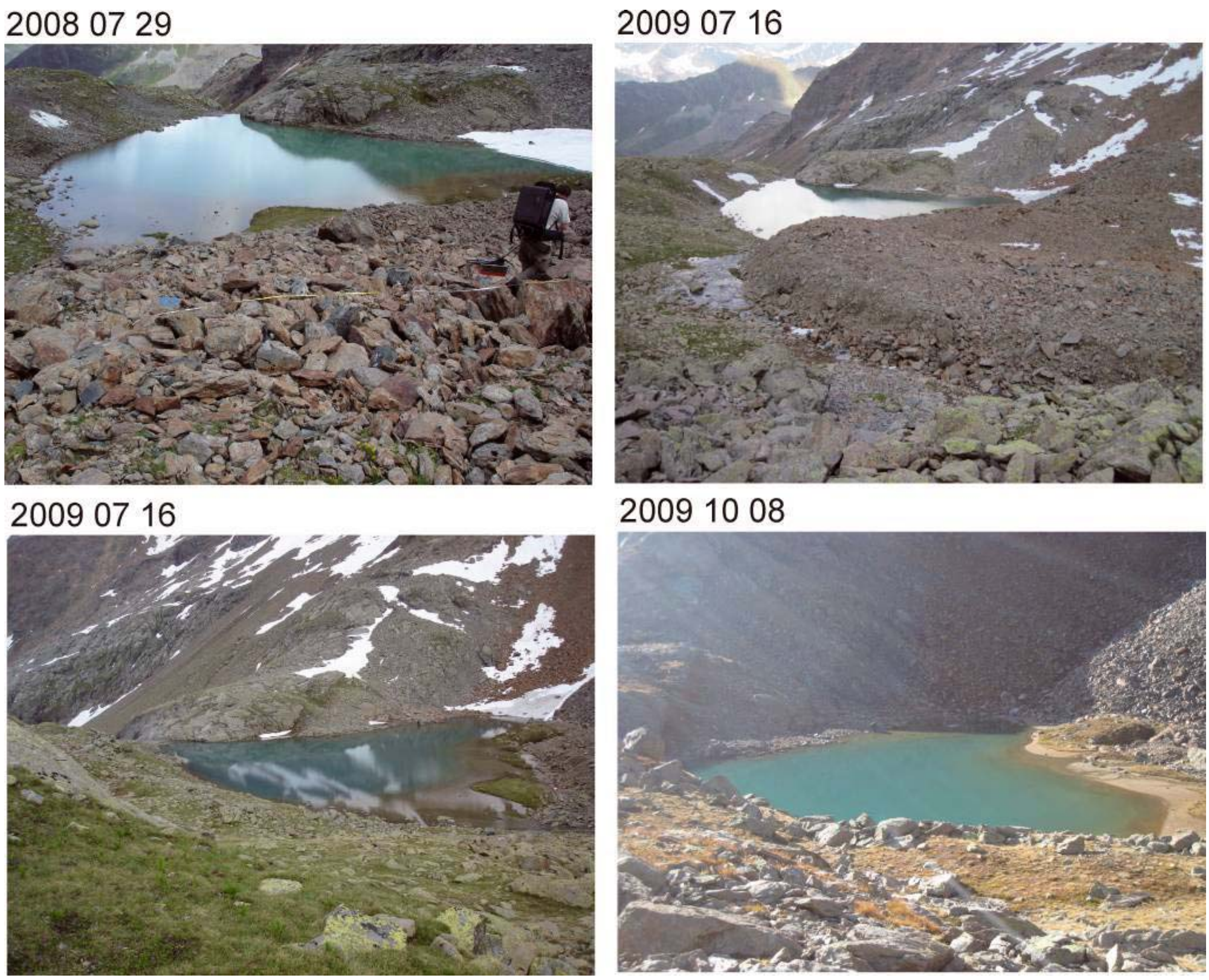


Example of seismic data with the interpreted trend of the bedrock interface. (top) Profile 28 on the pre-LIA till, (bottom) Profile 11 on a talus slope with aspect to South. The presence of sporadic permafrost is delineated by a dashed line and a refractor velocity higher than 2400 m/s.

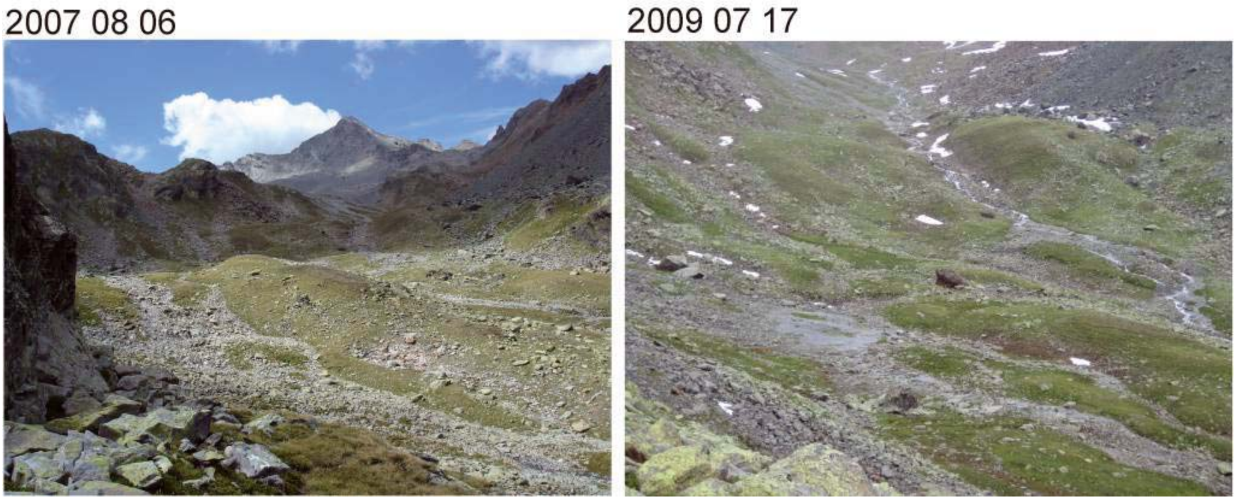
11.4 Hydrologic Data



Runoff formation on the landform LIA till (~ 2900 m).

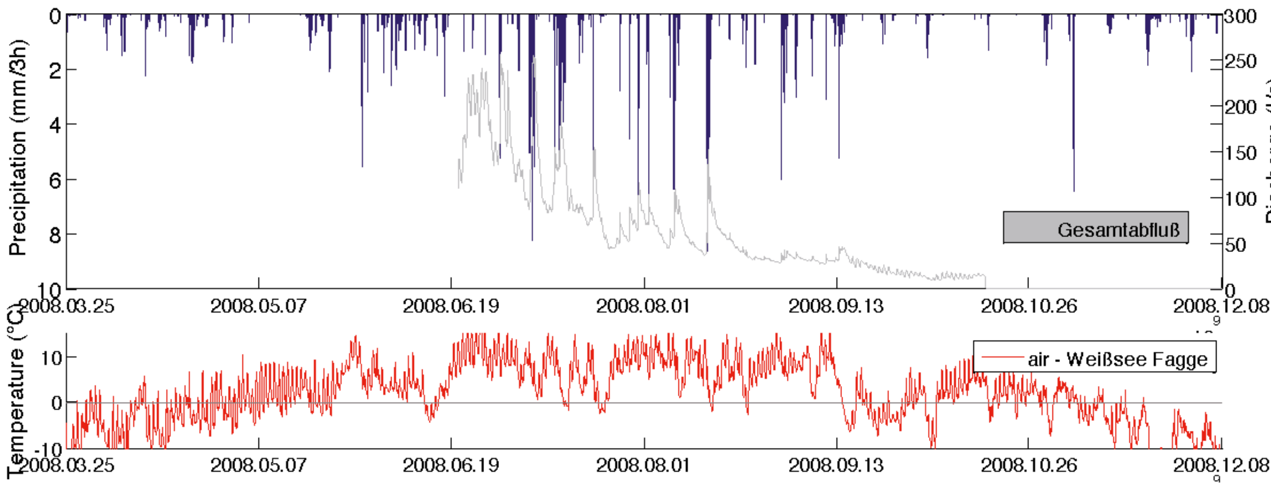


Runoff formation in the region of ‚verborgenen See' (~ 2700 m).

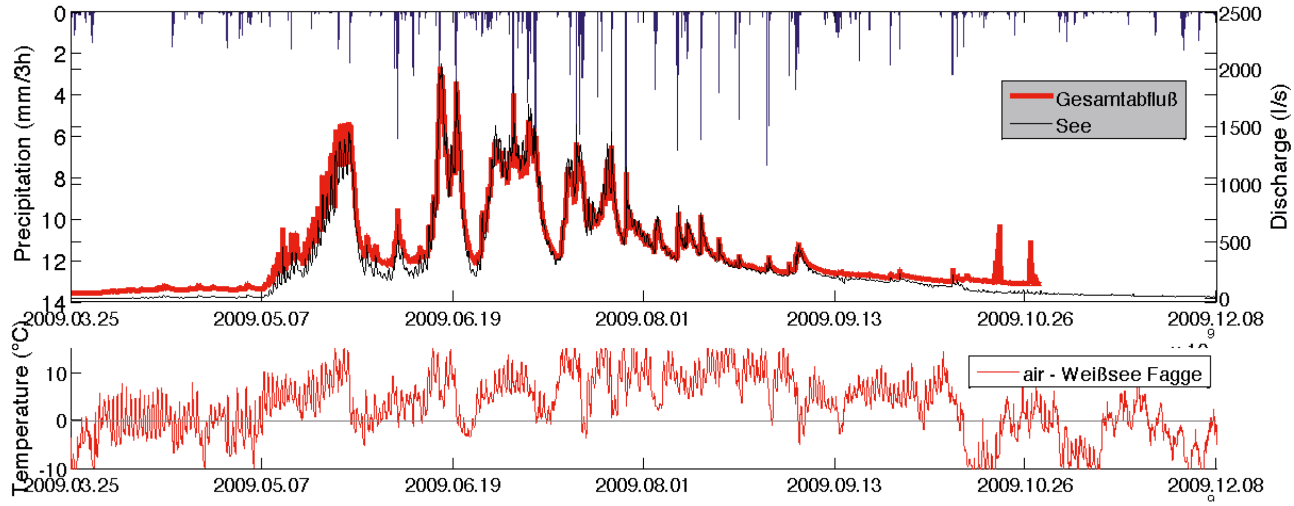


Runoff formation on the landform pre-LIA till (~ 2600 m). The right picture was take during a heavy rainfall event and show clear areas of saturation.

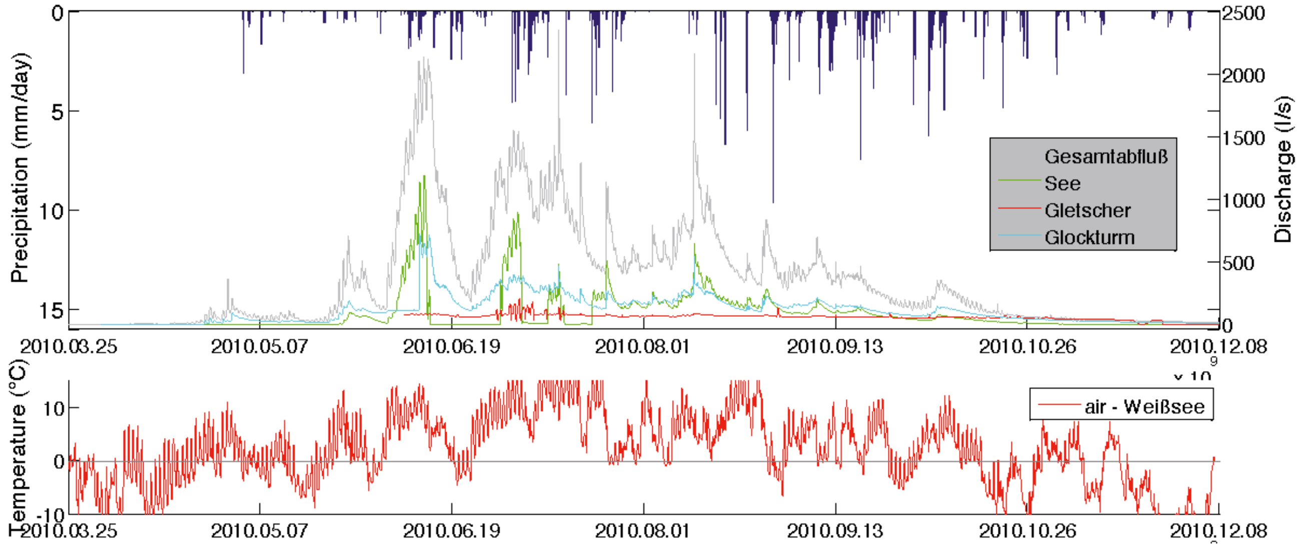
Saturation- and Surface runoff on the landform pre-LIA till (~ 2550 m) during the snow melt.



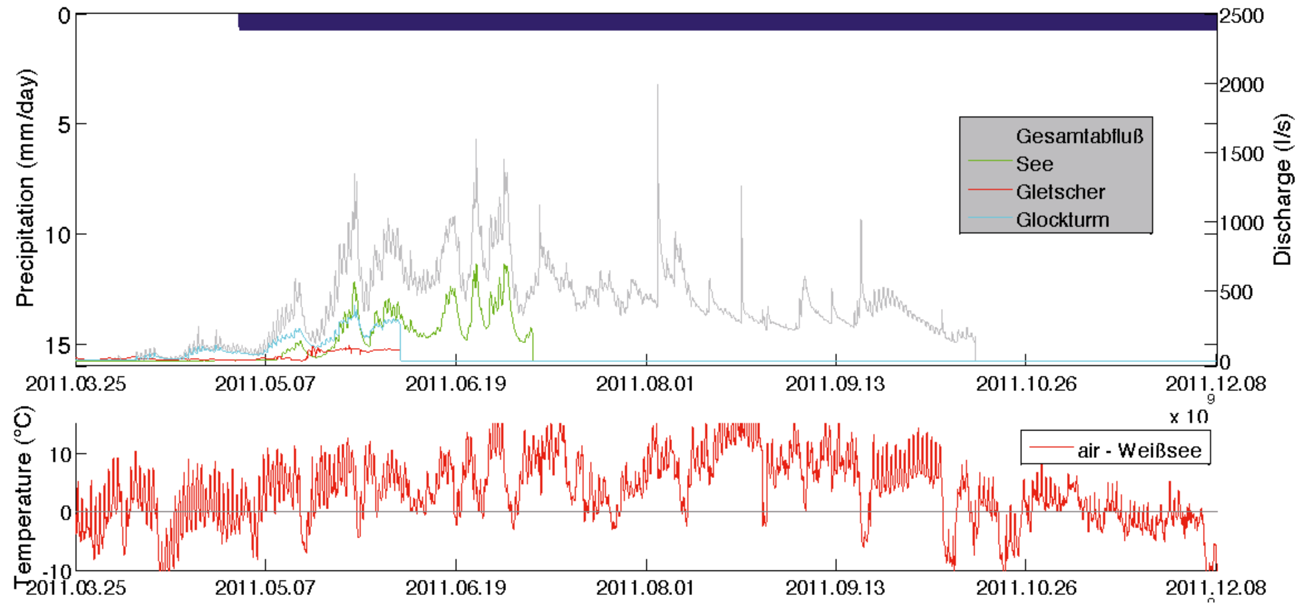
Discharge of the main catchment area with air temperature and precipitation for 2008.



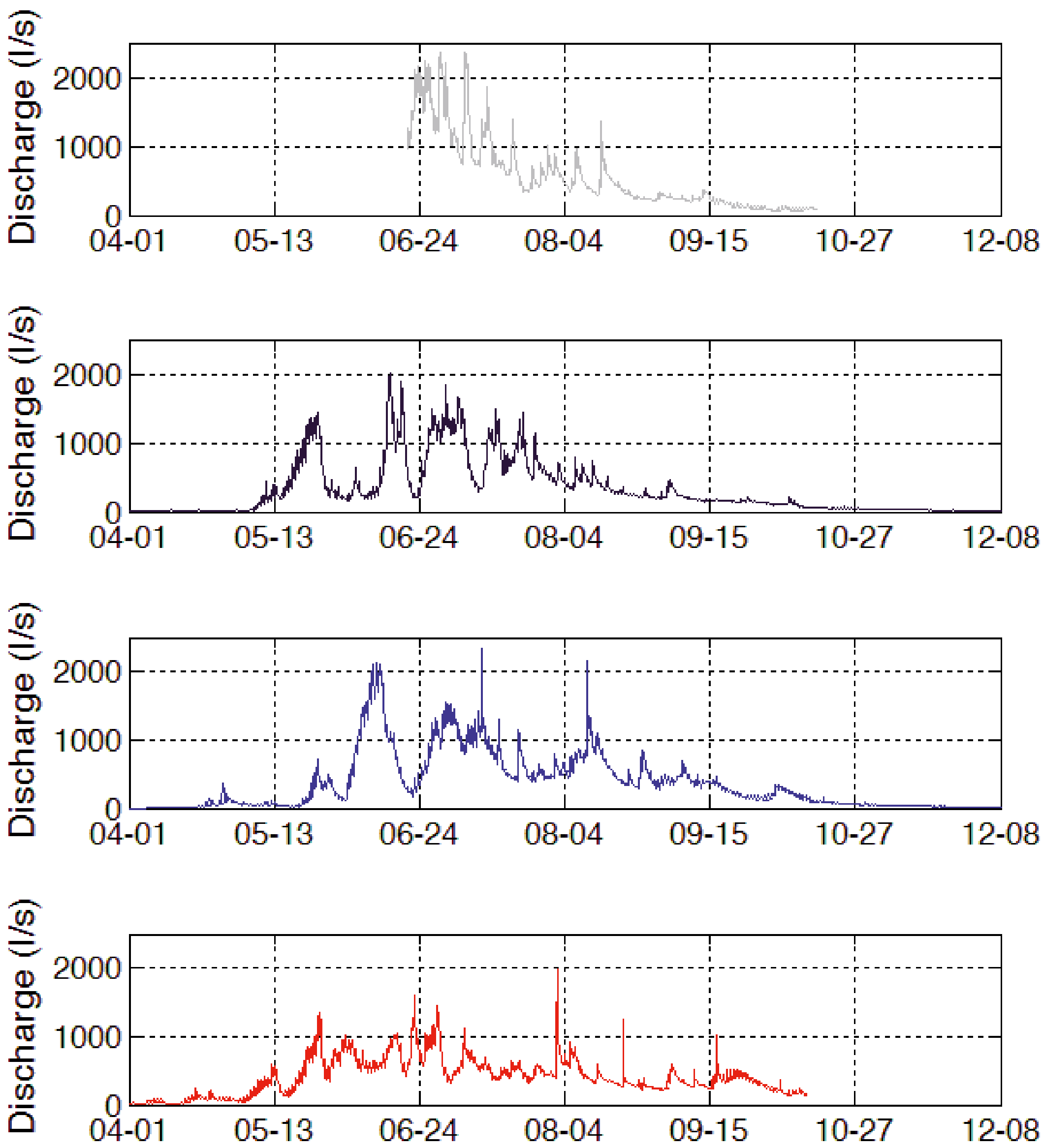
Discharge of the four catchment areas with air temperature and precipitation for 2009.



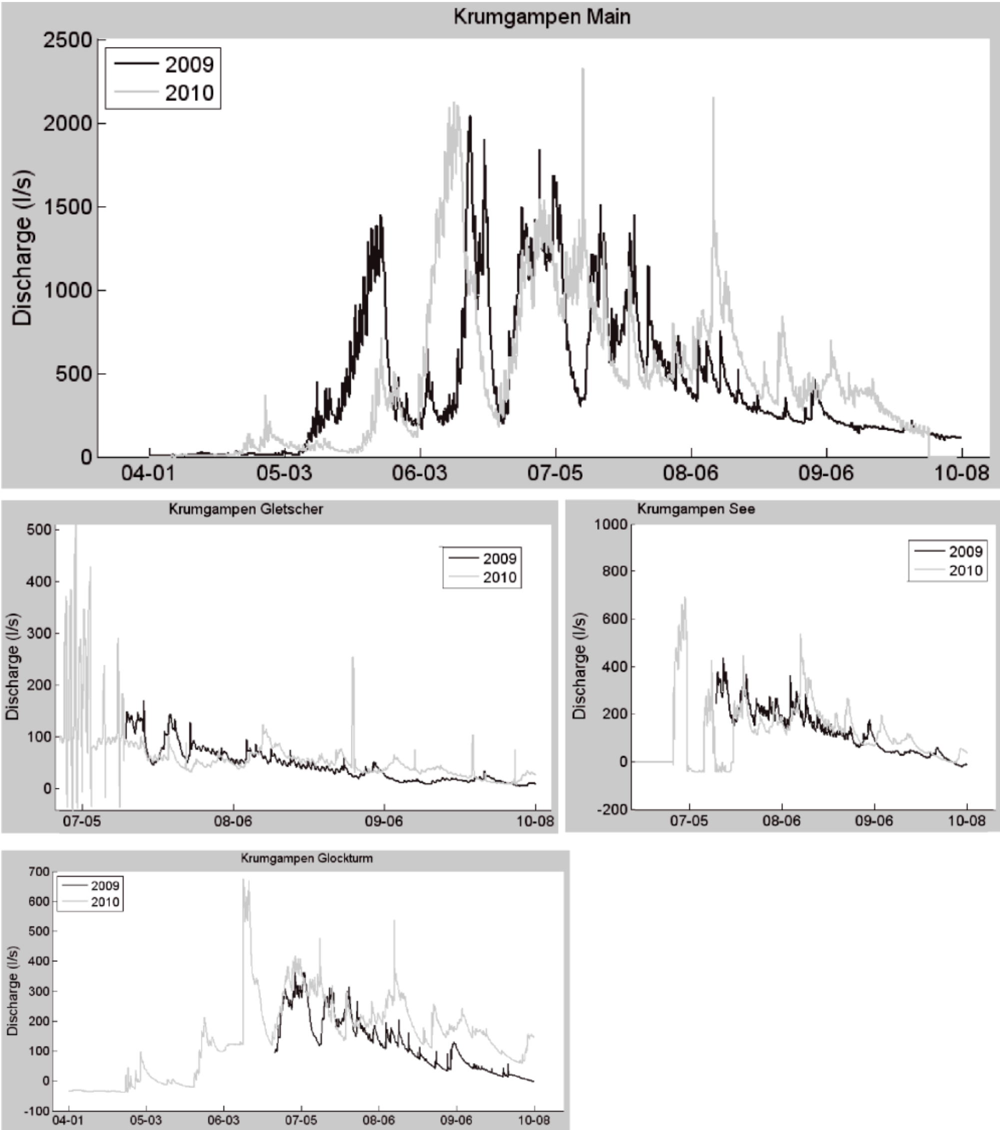
Discharge of the four catchment areas with air temperature and precipitation for 2010.



Discharge of the four catchment areas with air temperature for 2011.



Discharge at the main gauge of Krummgampen Valley for the years 2007-2011.



Comparison of the four gauges for the years 2009 and 2010. Notable is the change in the flow rates for the catchment „Glockturm“ in the period August- September.