Electrical resistivity monitoring for the detection of changes in mountain permafrost at different time scales

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Introduction

Permafrost is thermally defined as subsurface material that remains below the freezing point for at least two consecutive years. The presence of moisture in the subsurface of alpine environments thereby leads to permafrost consisting of a variable content of ice, liquid water, air and subsurface material. Geophysical methods have been widely used to characterise areas of perennially frozen ground and locate massive ice. Permafrost problems resolvable by geophysical techniques include the assessment of spatio-temporal changes in subsurface geophysical properties due to permafrost cooling, warming, aggradation or degradation through geophysical monitoring (KNEISEL et al., 2008). Due to the great sensitivity of electrical resistivity to the transition from unfrozen to frozen materials, electrical resistivity measurements constitute one of the standard geophysical methods in permafrost investigation (KNEISEL and HAUCK, 2008). With a repetition of electrical resistivity measurements along the same profile temporal changes within the subsurface can be investigated. Degradation or aggradation of ground ice in areas with permafrost takes place at different time scales and includes short-term (daily to weekly), medium-term (seasonal) and long-term (annual to decadal) changes. In recent years, electrical resistivity monitoring approaches have been able to detect temporal variations in frozen ground (KNEISEL, 2006, 2010; HILBICH et al., 2008, 2011; ROTH, 2011) and frozen rock walls (KRAUTBLATTER, 2010), respectively. In this contribution we present data and results from three alpine sites with different permafrost characteristics. Changes in frozen ground conditions are derived from electrical resistivity monitoring data with different temporal resolution and thus enable the investigation of time-dependent processes.

Study areas

All three investigation sites are located in the Upper Engadin, an inner-alpine dry valley in the south-eastern Swiss Alps. Comparatively low precipitation and high incoming radiation do not allow for a pronounced glaciation, but enable permafrost to exist at higher altitudes (>2500 m a.s.l.) and sporadically even below the timberline. Within the north-west exposed glacier forefield at Val Muragl (2700 m a.s.l.) electrical resistivity measurements have been conducted annually during snow free months to assess the year-to-year variability in active layer thickness and permafrost conditions. A fixed electrode array was installed at a supercooled scree slope at Val Susauna (1665 m a.s.l.) to detect changes in resistivity pattern with higher temporal resolution. Between 2008 and 2011 measurements have been conducted in a 6-8 week interval.

In March 2011 an automated monitoring system with daily resolution was installed at a small rock glacier (2680 m a.s.l.) in the Murtèl/Corvatsch area to increase the process understanding within the active layer during snowmelt.

Technical details and data acquisition

Basic information on array type, instrumentation, period of data acquisition and the total length of the data record is summarized in Table 1. Three different array types are used depending on the intended horizontal/vertical resolution and the surface conditions.

Some data sets had to be omitted due to erroneous values, which were in most cases caused by difficult contact resistance during winter. Problems with the communication between the automated monitoring system and the computer at Murtèl hindered the data transfer for several days.

	Val Muragl	**Val Susauna**	**Murtèl/Corvatsch**
Altitude [m a.s.l.]	2700	1665	2680
Morphology/Substrate	glacier forefield, medium to fine grained till	talus slope, wooded, thick moss/humus cover	small rock glacier, coarse debris
Instrumentation	Syscal Junior Switch, Iris Instruments	Syscal Junior Switch, Iris Instruments	Geotom-Res-IP, Geolog
Array length [m]	35, 70	105	70
No. of electrodes	36	36	36
Electrode spacing [m]	1, 2	3	2
Array types measured	Wenner/Wenner-Schlumberger	Wenner/Dipole-Dipole	Wenner/Wenner-Schlumberger
No. of measurements	25	26	59/46
Period of data acquisition	snow-free months	year-around, 6-8 week interval	March-June 2011, almost daily
Data record	2005-2010	2008-2011	2011

Tab. 1: Key information on electrical resistivity monitoring setups and measurements.

Results

The multiannual development of frozen ground with electrical resistivity tomograms of a 35 m profile in the Val Muragl is shown in Figure 1. There is a clear trend towards absolute resistivity changes in the center of the high-resistivity anomaly (Fig. 1a). The 4-years period shows a decrease of resistivity in the order of 15-20 % within the permafrost body (Fig. 1b). Much more variation, however, can be observed in the resistivity distribution within the uppermost 5 m (active layer). In this zone, the impact of the existent moisture conditions during the time of data acquisition is evident. Time-lapse inversion shows variations in ground resistivity, reaching relative changes as high as +/- 45 %. However, the yellowish colors of the active layer (<5 kΩm) indicate non-frozen conditions and the absolute changes in resistivity values are rather small (1-2 kΩm). So far, no deepening of the active layer has been observed, while absolute values within the permafrost body dropped from 24 kΩm to 19 kΩm.

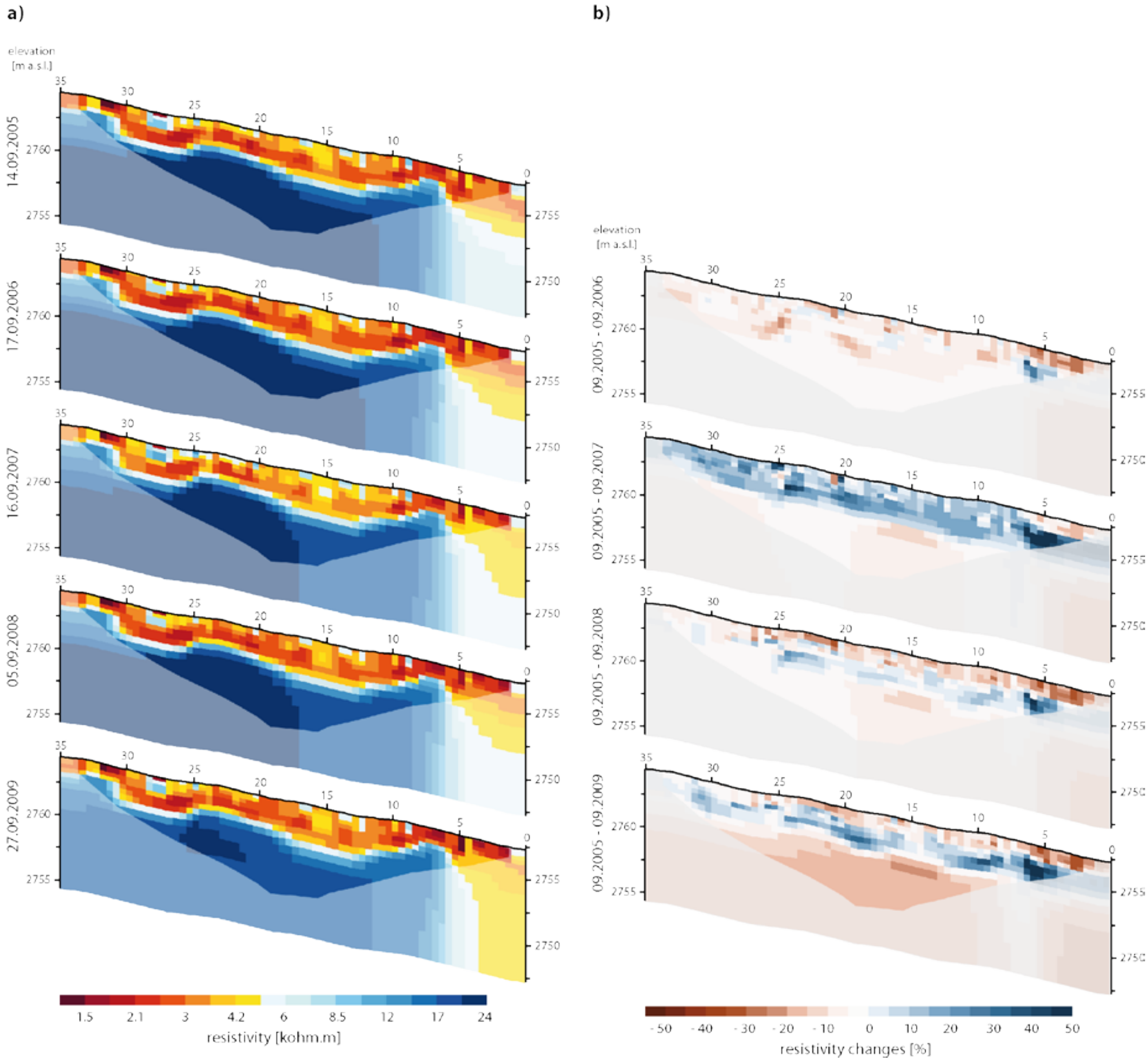

Fig. 1: a) Multiannual resistivity distribution (2005-2009) within the glacier forefield Muragl measured at the end of the thawing period. b) Time-lapse tomograms showing changes in resistivity related to the initial conditions in 2005. Parts of the geological model that are not constrained by data are faded, as done for the following figures.

Figure 2a shows the development of resistivity values within a talus slope with permafrost (Val Susauna) throughout the seasons. In summer and autumn 2009, an anomaly is visible in the bottom half of the slope with highest resistivity values of 100 kΩm in August, which are decreasing towards 80 kΩm in October. Resistivity values in the surrounding material increase between the two measurements. A marked increase – as seen in the central time-lapse tomogram (Fig. 2b) – occurred during winter leading to resistivity values as high as 900 kΩm in March 2010, which is attributed to a drastic reduction in liquid water content. In July 2010 the resistivity distribution resembles the initial situation the year before. The uppermost 2-3 m, representing the active layer, are well below 15 kΩm. However, values within the active layer as well as inside the anomaly at the foot of the slope are still higher compared to the autumn measurement.

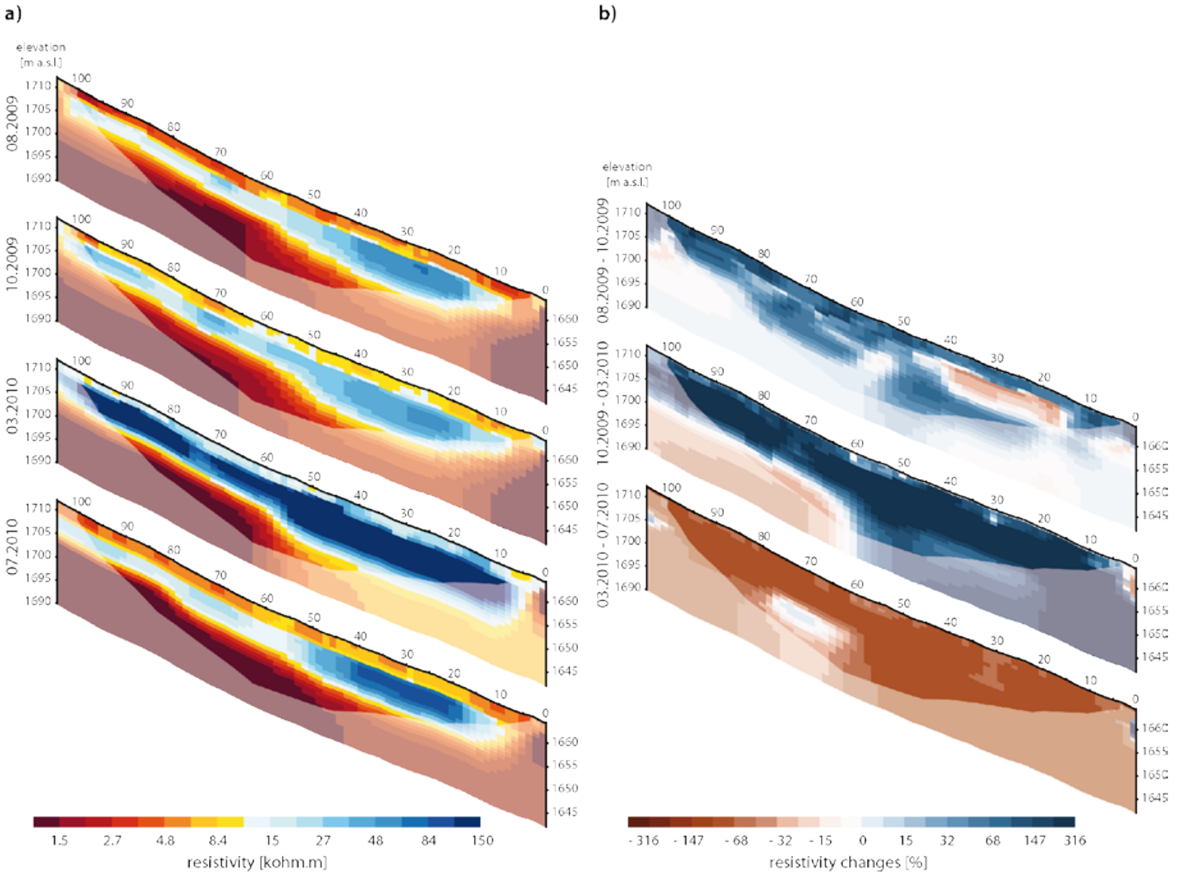

Fig. 2: a) Subsurface resistivity distribution within the talus slope in Val Susauna between August 2009 and July 2010. Color transition from yellow to blue refers to the presence of frozen ground with increasing resistivity values. b) Resistivity changes (time-lapse) between two succeeding measurements.

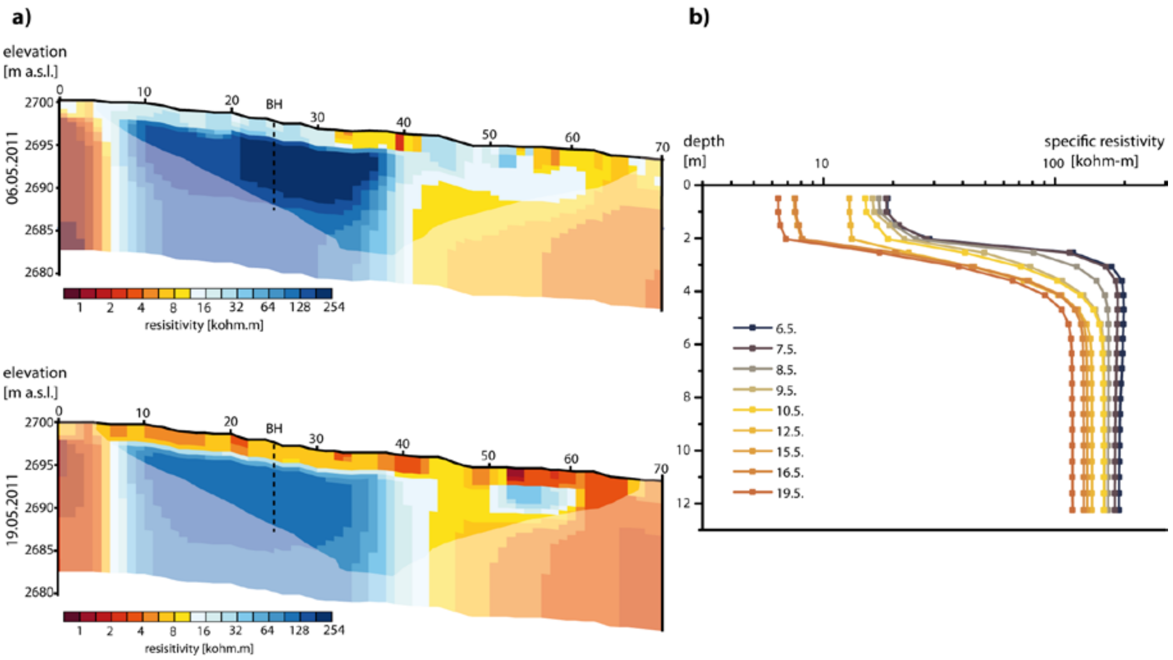

Fig. 3: a) Resistivity values on 06.05. and 19.05.2011 at monitoring Murtèl. b) Virtual borehole at horizontal distance 25 m indicating resistivity distribution with depth for nine consecutive measurements.

Resistivity changes on shorter time scales are resolved with the automated monitoring at the Murtèl site. The two tomograms in figure 3 highlight the resistivity distribution at the beginning and the end of a two week period, respectively. On the right hand side (Fig. 3b), resistivity values of each single data set obtained within this period is plotted as virtual borehole at horizontal position 25 m, i.e. in the centre of the high-resistivity anomaly. The largest absolute reduction of ground resistivity with up to 100 kΩm is observed below a depth of 3 m. However, values around 100 kΩm are still indicative for permafrost conditions. In contrast, the uppermost layer shows the largest relative decrease in resistivity. The lowering near the surface down to 2 m depth – from about 20 kΩm to 3 kΩm – coincides with the onset of the snowmelt and percolating melt water at that site.

Discussion and Conclusion

The use of geoelectrical monitoring systems allows for the investigation of changes and processes that occur within mountain permafrost environments over different time scales. Varying the frequency of measurements, enhances the interpretability of permafrost-related problems such as seasonal and long-term permafrost evolution but also the effect of percolating water. The operation of automated monitoring systems marks a further step towards a very efficient observation of short-time processes within the active layer and the frozen ground below. Nevertheless, repeated measurements with a larger interval are necessary and useful for the investigation of seasonal and annual changes of permafrost conditions in terms of degradation and aggradation processes and resultant consequences for sediment storage/supply as well as environmental changes. It has to be noted, that the resistivity distribution, especially near the surface and within the active layer, depends on a large extent on the meteorological conditions prior to the measurement and prevailing moisture conditions (e.g. HILBICH et al., 2011). Using a fixed monitoring setup simplifies a regular implementation of the measurement, even though it has to be done manually. However, the installation allows for a perennial accessibility of the investigated site.

The example from Val Susauna with maximum resistivity values, ranging between 80 kΩm in autumn and >900 kΩm in March, shows the high temporal variability in subsurface conditions during a year of measurements. Extremely increasing subsurface resistivities during winter mark an immense cooling with a decrease in the liquid water content. In spring, percolating melt water refreezes on the supercooled talus material, leading to an increase in ice volume accompanied by rising temperatures due to the release of latent heat during the freezing process. As a consequence, the liquid water content is increased leading to a distinct decrease in resistivity values of the permafrost body between March and July. The large range in resistivity values is caused by a thermal-driven circulation within the talus slope (Chimney-effect, e.g. HARRIS and PEDERSEN, 1998) which is responsible for the seasonal cycle of massive ice growth and degradation throughout the year.

A more detailed understanding of the processes that occur at short time scales within permafrost-affected landforms was gained with an automated monitoring system. It is shown from the Murtèl data that the onset of snowmelt and subsequent infiltration of water coincides with a reduction of active layer resistivity of about 700% within two weeks. Inside the permafrost body, absolute values also decrease (around 100 kΩm). However, they are still indicative for frozen ground conditions.

The application of ERT monitoring systems on different time scales has significantly enhanced the understanding of permafrost related problems. Especially the introduction of automatic monitoring systems, allowing for data acquisition with a high temporal resolution, marks a further step in permafrost research. Problems that arise with the use of the fixed and automated monitoring system are related to damage of the electrode array (broken contacts to the electrodes over time), moisture within the plug and interrupted power supply (data gaps due to power failure at the remote laptop).

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