One decade of permafrost monitoring at the Zugspitze (Germany/Austria)

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Abstract

Mechanical and thermal properties of frozen rock slopes hence permafrost degradation determine its stability and impose an increasing risk on people and infrastructure in high mountain regions. Electrical resistivity tomography (ERT) became the dominating tool for temporal and spatial permafrost monitoring. Here we present results from one decade of ERT-based permafrost monitoring at the Zugspitze. We hypothesize a link between seasonal and long-term climate variability and permafrost temperature development and its spatial variability. External climate forcings affect permafrost rock temperatures with a signal propagation time of ca. 2 - 6 months. Short term influences through cleft and pore water via convective heat transport cause abrupt local changes of the temperature regime.

Keywords: Permafrost rock walls; geophysical monitoring; electrical resistivity tomography (ERT); rock slope failure.

Introduction

Degradation of alpine permafrost due to changed thermal and mechanical properties of rock and ice are key process trigger for rock slope instabilities in high mountain areas (Krautblatter *et al.*, 2013), imposing a significant risk on people and infrastructure instalments.

Geoelectric measurements, such as electrical resistivity tomography (ERT) provide a simple and detailed inside into the spatial - temporal variability of permafrost occurrence in high mountain regions. Electric resistivity of frozen rock is highly temperature sensitive and can differentiate between frozen and unfrozen conditions (Krautblatter *et al.*, 2013; Keuschnig *et al.*, 2017). Here we present results from one decade of ERT-based permafrost monitoring at the Zugspitze, assessing monthly spatial variations of permafrost distribution and quantitative information on frozen rock temperature.

Study Area

The Zugspitze, Germany's highest mountain (summit: 2962 m asl.) is located at the German-Austrian border. Geologically it is part of the Northern Calcareous Alps, built up by 800 m of decameter bedded Triassic limestone, dipping NW-ENE at the north face (Miller, 1961; Krautblatter *et al.*, 2010; Ulrich & King, 1993). According to Ulrich & King (1993) permafrost is present above 2500 m asl. Borehole temperature data below the Zugspitze summit indicate permafrost temperatures between -2 °C and -4 °C (LfU 2017). Meteorological data recorded at the summit DWD station monitor a warming trend of MAAT (mean annual air temperature) since the late 1980s (Krautblatter *et al.*, 2010).

Methods

ERT-measurement are conducted in the Kammstollen along the north face. Three electrode arrays are used for optimal spatial resolution: Wenner configuration with 61 electrodes ($a = 4.6$ m) along the main gallery, two Wenner-Schlummberger arrays with 41 electrodes each ($a = 1.53$ m) perpendicular thereto in the side gallery, resulting in ~1100 data points (Krautblatter *et al.*, 2010). First measurements were carried out from February to September 2007, since 2014 a continuous monthly monitoring is executed. Data acquisition is conducted using the ABEM Terrameter SAS1000 or LS device. ERT-inversion is accomplished using the 2-D smoothness-constraint inversion algorithm CRTomo by Kemna (2000) (Krautblatter *et al.*, 2010). ERT-temperatures are based on laboratory calibration of electric resistivities to rock temperature for Wetterstein limestone by Krautblatter *et al.* (2010).

First results & interpretation

Along the side gallery a high-resistivity body appears between 50 – 150 m and from 240 – 276 m, reaching resistivity values $\geq 10^{4.5}\ \Omega\text{m}$ ($\cong -0.5$ °C), indicating frozen rock displaying a core section with resistivities $\geq 10^{4.7}\ \Omega\text{m}$ ($\cong -2$ °C) (Fig. 1) (Krautblatter *et al.*, 2010). Seasonal variability is seen by laterally aggrading and degrading marginal sections (Krautblatter *et al.*, 2010). The "permafrost lens", defined as the perennial $>10^{4.5}$ Ωm rock body, shows an areal alternation between ~1,500 to >3,000 m^2. Highly fractured zones allow the breakthrough of water passage in the core section from summer forward accounting for warming of the adjacent rock mass.

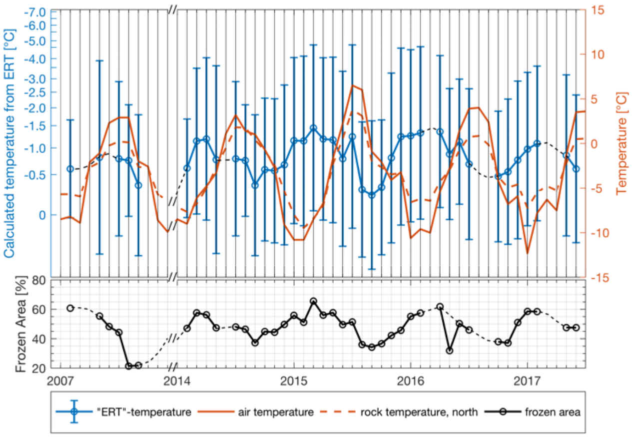

Figure 2: Calculated temperatures from ERT-measurements (mean value, standard deviation), combined with air temperature and north face rock temperatures, as well as relative frozen area. Missing values due to data acquisition errors. Dashed lines are interpolated values.

Calculated temperatures from ERT-data show a phase shift of ~2 (past T_{max}) to ~6 month (past $T_{0°C}$) in comparison to measured air temperatures (Fig. 2). This time span equates the time needed by the climate signal to propagate through the rock wall via convective energy transport resulting in recession and readvance of the zero-curtain in rock (Krautblatter *et al.*, 2010). Further quantitative analysis linking ERT and climate parameters to be executed.

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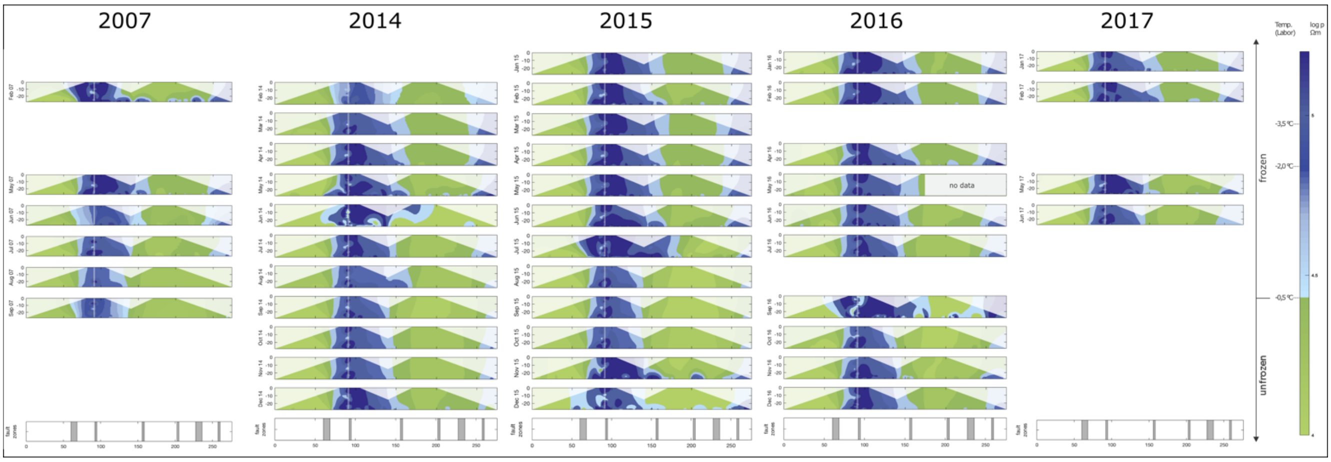

Figure 1: Monthly ERT-results from 2007 & 2014 - 2017. Shaded areas indicate extrapolated values. Last bar shows fracture zones with joint apertures > 2 mm (ref.: Krautblatter *et al.* 2010)