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Ambient seismic vibrations in steep bedrock permafrost used to infer variations of ice-fill in fractures

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ABSTRACT

The behavior of ice in frozen rock masses is an important control on rock slope stability but the knowledge of the formation, extent and evolution of ice-filled fractures in steep bedrock permafrost is limited. Therefore, this study aims at characterizing the site specific ambient seismic vibration recorded at the Matterhorn Hörnligrat fieldsite over the course of more than three years. The observed normal mode resonance frequencies vary seasonally with four distinct phases: persistent decrease during summer (phase I), rapid increase during freezing (phase II), trough-shaped pattern in winter (phase III) and a sharp peak with a rapid decay during the melting/thawing season (phase IV). The relation between resonance frequency and rock temperature exhibits an annually repeated pattern with hysteretic behavior. The link between resonance frequency, fracture width and rock temperature indicates that irreversible fracture displacement is dominant in summer periods with low resonance frequency. These findings suggest that the temporal variations in resonance frequencies are linked to the formation and melt of ice-fill in bedrock fractures.

1. Introduction

Destabilization of steep bedrock permafrost is a natural hazard that potentially endangers populated mountain areas (Haeberli et al., 2010) as permafrost responds rapidly to climate change related warming (Deline et al., 2015), which leads to a change in the rock properties and in the processes controlling rock slope stability (Krautblatter et al., 2013). While the thawing of intact water-saturated rock results in a significant strength reduction (Mellor, 1973), the shear resistance of ice-filled discontinuities decreases with rising temperature and reaches a minimum just below 0 °C (Davies et al., 2001; Günzel, 2008). Rockfall events at several locations and with different volumes (from 10^3 to $>10^6$ m^3) have uncovered ice in the formerly buried detachment zone (e.g. Hasler et al., 2012). The formation of ice within rock often causes damage ranging from near-surface (Hallet et al., 1991) to the depth of several meters (Murton et al., 2006) and therefore may play a role in the destabilization of rock slopes and in preconditioning of rockfall (Gruber and Haeberli, 2007; Matsuoka and Murton, 2008). At the same time, the hydraulic permeability is much lower in rock masses with frozen and ice-filled fissures than in unfrozen fissures. This effect often leads to high hydrostatic stress due to perched water (Pogrebiskiy and Chernyshev, 1977). Further, no hydrostatic stress can develop in fractures completely filled with ice, but can change rapidly when the frozen fractures thaw.

There is only limited knowledge of the formation, extent and evolution of ice-filled fractures in steep bedrock permafrost. Characteristic patterns in relative surface displacement data have often been associated to cryogenic processes (e.g. Draebing et al., 2017), but no or only limited evidence was provided. A few studies measured electrical resistivity tomography (ERT) in solid rock faces (Sass, 2005) as well as in solid permafrost rock walls (Krautblatter and Hauck, 2007) and thereby observed temporal and spatial variations of moisture movement during freeze-thaw cycles. Further geophysical methods were semi-successfully applied directly in fractures to monitor changes in ice-infill of fractures, for example compression stress measurements (Hasler et al., 2012) or water pressure in fractures (Draebing et al., 2017).

Passive monitoring of elastic waves (either the detection of seismic events and/or the recording of ambient seismic vibrations) provides subsurface information within a delimited perimeter and can complement surface displacement measurements. In non-permafrost areas this method has been widely applied (i) to characterize the seismic response of unstable rock slopes

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(Moore et al., 2011; Bottelin et al., 2013a; Kleinbrod et al., 2017a; Burjánek et al., 2018), (ii) to study fracturing processes and factors influencing rock slope destabilization (e.g. Helmstetter and Garambois, 2010), (iii) to identify precursory behavior prior to slope failure (e.g. Amitrano et al., 2005; Lévy et al., 2010) or (iv) to detect small size rockfalls (e.g. Lacroix and Helmstetter, 2011).

Recordings of ambient seismic noise, which consists of ground vibrations that are not induced by seismic events, provide information about site specific resonance frequencies (Del Gaudio et al., 2014). Resonance describes an amplification of ground motion at a specific frequency, but often occurs manifold with different frequencies. These resonance frequencies are related to material properties and provide information on internal structure and geometry (e.g. depth and volume) of an unstable rock slope (Burjánek et al., 2012; Gischig et al., 2015). The characterization of variations in these resonance frequencies has been recognized as an important approach to identify permanent changes associated with internal rock mass damage (Burjánek et al., 2018). For example, seasonal variations of resonance frequencies in an unstable rock column were linked to the temperature dependent bulk elastic properties and related closure of fracture rock bridges due to the thermally induced expansion of rock or the formation of ice (Bottelin et al., 2013b).

Applications of passive monitoring of acoustic emissions and micro-seismic events in bedrock permafrost have gained in popularity in the last decade (e.g. Amitrano et al., 2010; Weber et al., 2018) but still experience difficulties in analysis and interpretation (Weber et al., 2018). And so far, the seismic response of bedrock permafrost based on ambient seismic vibration analysis is largely unexplored.

In this study, we aim to analyze ambient seismic noise recorded in steep, fractured bedrock permafrost at the Matterhorn Hörnligrat fieldsite over the course of more than three years. We critically interpret this dataset in relation to variations in external environmental forcing and investigate the working hypothesis that ambient seismic noise can provide evidence for the formation and melt out of ice-fill in fractures.

In the first part of this manuscript, we describe the measurement setup in the field, analysis methods and results derived from the recorded time series of ambient seismic noise, fracture displacement and temperature in the active layer of steep and fractured bedrock permafrost (Sections 2–4). We then elaborate on typical patterns observed, interpret relations found within these data and discuss the working hypothesis formulated above.

2. Matterhorn Hörnligrat fieldsite and instrumentation setup

The Matterhorn Hörnligrat fieldsite (see Fig. 1a) is located at an elevation of 3500 m a.s.l. on the North-East ridge of the Matterhorn in the Swiss Alps. This fieldsite is characterized by extensive structuring and the occurrence of ice-filled fractures (Hasler et al., 2012), a heterogeneous surface with debris-covered ledges and recurring patterns of snow cover (Weber et al., 2017). Geologically, this fieldsite is located above the Penninic Metasediments and Ophiolites (Combin Zone) and consists of gneiss and amphibolite of the Dent Blanche nappe (Bucher et al., 2004). There are many vertical rifts and the main fractures in the study area are oriented parallel to the ridge with a nearly vertical dip (Hasler et al., 2012). Local permafrost with an active layer of several meters is estimated on the south side while extensive permafrost with a thin active layer of few meters is observed on the north side (Weber et al., 2018). A detailed fieldsite description is given by Hasler et al. (2012) and Weber et al. (2017, 2018).

The instrumentation setup relevant for this study is shown in Fig. 1 and consists of (i) two three-component seismometers (Lennartz electronic low-noise seismometer LE-3Dlite MKIII with a

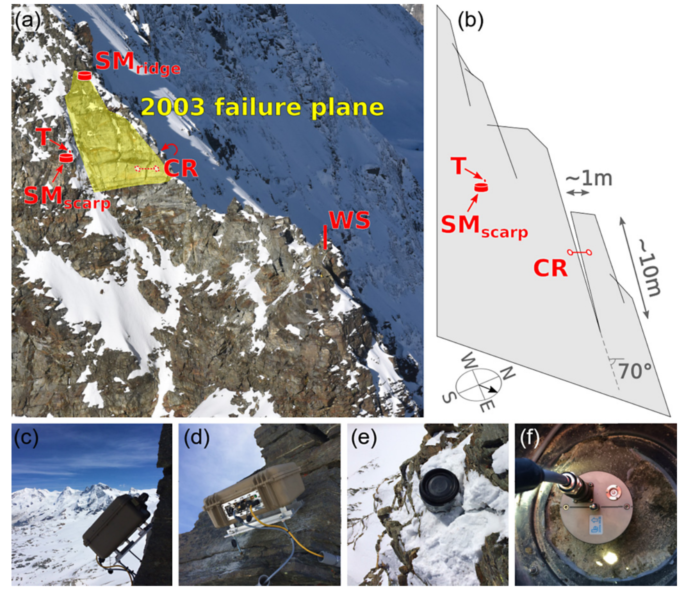

Fig. 1. Detailed view on the Hörnligrat fieldsite on the North-East ridge of the Matterhorn in the Swiss Alps at an elevation of 3500 m a.s.l. with an average slope >60°. The seismometers SM_{scarp} and SM_{ridge} are protected against mechanical damage with a bucket whereat the bucket of SM_{ridge} was filled with sand from 27 July 2015 until 18 July 2017 to reduce the signal noise (following the guidelines of Bard and SESAME Team, 2006). The temperature sensor rod T is mounted into a 1 m borehole next to the seismometer SM_{scarp}. The crackmeter CR is installed on the north-facing back site of the ridge (CR refers to the crackmeter *mh*03 in Weber et al., 2017) while the weather station WS is located on the ridge (WS refers to the location *mh*25 in Weber et al., 2017). (a) shows an aerial picture and (b) shows a schematic sketch while (c)–(f) show the seismometer setup. While the digitizer is deployed in a waterproof Peli case (c–d), the seismometer itself is mounted to the rock surface and protected with a bucket (e–f). (This figure is available in color in the web version of this article.)

1 Hz to 100 Hz passband and Nanometrics Centaur digital recorder, a 24-bit high-resolution seismic data acquisition system paced by GPS with a sampling rate of 1000 sps), (ii) one crackmeter (perpendicular to fracture, recorded at 2 min intervals with an accuracy of ±0.01 mm), (iii) one thermistor sensor rod measuring rock temperature at different depths (5, 10, 20, 30, 50 and 100 cm at 2 min intervals with an accuracy of ±0.2 °C) and (iv) a weather station (Vaisala WXT520 providing wind and air temperature data recorded at 2 min intervals). For precipitation, the MeteoSwiss SwissMetNet surface weather station Zermatt at an elevation of 1638 m a.s.l. was used. The recording at the Matterhorn Hörnligrat fieldsite started in June 2015. There are a few short gaps (few days) in all data and considerable gaps (several months) in the weather station data because of a system failure. Note, we do not aim to detect and localize micro-seismic events and thus two seismometer stations are sufficient.

3. Methods

3.1. Ambient seismic noise analysis

The Fourier amplitude spectrum was estimated for non-overlapping windows (10 min) of the recorded ambient seismic vibrations time series for each component of both seismometers. For this, first, the analysis toolbox provided by Prieto et al. (2009) was used to estimate the multitaper spectrum $\hat{S}(f)$:

$$\hat{S}(f) = \frac{\sum_{k=0}^{K-1} d_k^2 |Y_k(f)|^2}{\sum_{k=0}^{K-1} d_k^2}, \tag{1}$$