Ice Dynamic Investigations with Seismological Components

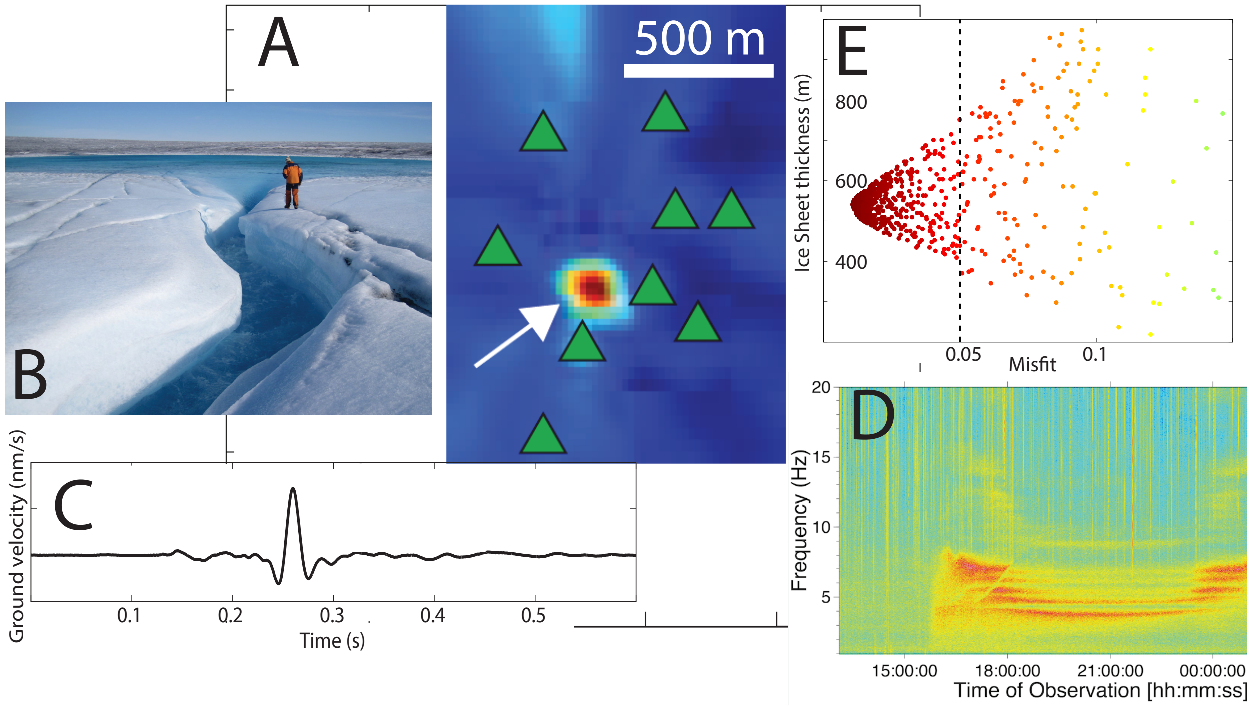

Figure 1: Illustration of selected project highlights. (A) Results of grid search to determine epicenter (white arrow) of a water-tremor source near the western margin of the Greenland ice sheet (green triangles denote seismometer locations). (B) Melt water channel on the surface of the Greenland ice sheet (photo: C. Ryser). (C) Surface icequake seismogram. (D) Spectrogram of water tremor with warm (red) colors indicating tremor excitation over several hours. (E) Estimation of ice sheet thickness from inversion of noise-derived seismic velocity dispersion (for clarity, misfit is color-coded). In the shown case, the best inversion fit (smallest misfit) was obtained for an ice sheet thickness between 500 and 600 m.

INTRODUCTION

The goal of this project was to investigate and monitor natural seismicity in glacial ice. Harnessing the host institution's world-leading expertise in seismic noise analysis, the project emphasized analysis of sustained ambient noise signals. The conducted investigation can be divided into two fields: First, I studied various glacier-related seismic sources. Second, by focusing on the seismic waves emitted by these sources, I was able to derive glacial ice properties, such as ice sheet thickness, basal structure and englacial seismic velocities. The study was fully based on already existing data from the western margin of the Greenland ice sheet, a Swiss glacier and other publically available data sets from Arctic and Antarctic glaciers.

SEISMIC SOURCES ON GLACIERS AND ICE SHEETS

A central result of the source study was that water plays a pivotal role in the occurrence and frequency signature of seismogenic processes of glaciers and ice sheets. Spectral analysis of continuous seismic records from the Greenland ice sheet revealed that water flow within englacial channels ("glacier moulins") is a dominant noise source (Figures 1A and 1D; Walter et al., submitted). In contrast to our expectations, moulin water pressure, rather than available surface melt (Figure 1B), determines frequency content and strength of the water-generated seismic noise (Figure 1B; Röösli et al., 2014). Similarly, subglacial water flow generates seismic tremor, whose frequency content depends on the water channel morphology (Heeszel et al., in press).

The presence of water also has a profound effect on seismic sources near the bed of Alpine glaciers. Reviewing the polarity of seismic phases from basal "icequakes", I found compelling evidence for hydro fracturing in response to changes in subglacial water pressures (Walter et al., 2013a). Moreover, the frequency content of these events exhibits spectral peaks characteristic for hydro fracture geometry (Heeszel et al., in press). In contrast, basal stick-slip motion is the dominant seismicity from the base of the Greenland ice sheet. An automated waveform search revealed thousands of these events beneath a seismic network operational during summer 2011 (Figure 1A). Importantly, the magnitudes of these events exhibit clear diurnal fluctuations, which can again best be explained with changing subglacial water pressures. I am currently further pursuing this matter with scientists at the former host institute (ISTerre) in Grenoble, France, and the Swiss Federal Institute of Technology in Zurich, Switzerland.

SEISMIC WAVE PROPAGATION THROUGH GLACIAL ICE

Investigation of the signal coherence of surface icequakes (Figure 1C) and water tremor showed that high-frequency (> 1Hz) seismicity consists mainly of direct waves (Walter et al., submitted). As a result, seismic waves scattering from crevasses, micro fissures or ice impurities is negligible. This is in stark contrast to seismicity in the Earth's crust. Here, geologic heterogeneity gives rise to a highly scattered wave field. Many noise interferometry techniques developed for crustal applications therefore cannot be directly applied to glacial settings. On the other hand, I was able to exploit the coherence of direct waves of the ambient seismicity, such as water tremor and icequakes, to measure seismic velocities at frequencies between 1 Hz and 20 Hz. The resulting dispersion relationship was then inverted for ice sheet thickness (Figure 1E). This demonstrates that ice sheet properties can be measured and potentially monitored using purely passive seismic measurements without the need for man-made sources, such as explosions, air guns or hammer blows.

In a parallel study I analyzed another type of seismic signal recorded on the Greenland ice sheet: Applying the "receiver function" analysis to seismograms of far away earthquakes revealed the existence of a thick (at least 80 m) subglacial sediment layer beneath the network shown in Figure 1A (Walter et al., 2014). This finding is in line with recent numerical modeling exercises and observations suggesting the presence of a "soft" bed (Bougamont et al., 2014), which may have a profound impact on ice sheet flow, in particular during a changing climate.

OTHER ACTIVITIES

In collaboration with research partners in the US I investigated the seismic background noise on the Amery Ice Shelf, Antarctica, which provided insights into the propagation of large rifts prior to major iceberg calving episodes (Heeszel et al., 2014). Moreover, I directed the instrument deployment and data analysis of an unprecedented full-year monitoring of basal seismicity beneath an Alpine glacier. This study revealed for the first time a multi-year lifetime of hydro fracturing clusters at the glacier base. At the beginning of the project I furthermore finished an investigation of iceberg calving events in Greenland using calving-generated standing waves in proglacial fjords (Walter et al., 2013b; Clinton et al., 2014). Finally, I participated in a source study of induced seismicity during geothermal drilling (Guilhelm and Walter, submitted). Facilitating outreach, I have created a webpage that presents various aspects of the relatively young discipline of glacier seismology (https://sites.google.com/site/icyquakes/home).

IMPACT

The results of this project have offered new insights into glacier dynamics and hydraulics. In particular, the discovery of a thick subglacial sediment layer has to be considered in theoretical considerations of ice sheet flow. Perhaps most importantly, this project has shown that ice sheet and glacier properties can be derived from purely passive seismic recordings. This has important implications for monitoring capabilities: As seismic wave propagation depends to some degree on the englacial damage state, noise-derived seismic velocities can be used in future stability monitoring of steep glaciers. Such monitoring approaches are desperately needed wherever human settlements and infrastructure locate within high-altitude terrain where glacial hazards exist. In the historic past, glacial lake outburst floods and collapses of steep glaciers have claimed up to thousands of lives within a single event (e. g. Lliboutry, 1975). Thus, passive measurements of englacial seismic velocities such as developed in this project provide new tools to improve natural hazard management. Villages and tourist resorts locating in the European Alps and other mountain regions will thus benefit from implementation of seismic monitoring tools in the context of unstable glaciers.

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