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Research paper

A geophone wireless sensor network for investigating glacier stick-slip motion

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ABSTRACT

We have developed an innovative passive borehole geophone system, as part of a wireless environmental sensor network to investigate glacier stick-slip motion. The new geophone nodes use an ARM Cortex-M3 processor with a low power design capable of running on battery power while embedded in the ice. Only data from seismic events was stored, held temporarily on a micro-SD card until they were retrieved by systems on the glacier surface which are connected to the internet. The sampling rates, detection and filtering levels were determined from a field trial using a standard commercial passive seismic system. The new system was installed on the Skalafellsjökull glacier in Iceland and provided encouraging results. The results showed that there was a relationship between surface melt water production and seismic event (ice quakes), and these occurred on a pattern related to the glacier surface melt-water controlled velocity changes (stick-slip motion). Three types of seismic events were identified, which were interpreted to reflect a pattern of till deformation (Type A), basal sliding (Type B) and hydraulic transience (Type C) associated with stick-slip motion.

1. Introduction

The motion of glaciers is highly dependent on the behaviour of meltwater (generated at the glacier surface by atmospheric melting) which can influence the rate at which glaciers move by creep (Duval, 1977), reduce friction to allow basal sliding (Weertman, 1957; Iken et al., 1983), and deform underlying sediments (Boulton and Jones, 1979). Recent studies of continuous measurements of glacier velocities by GPS have indicated that ice motion is commonly episodic and it has been proposed that this reflects stick-slip motion (Bahr and Rundle, 1996; Fischer and Clarke, 1997; Tsai and Ekstrom, 2007; Wiens et al., 2008). Such a process would generate microseismic events (ice quakes) at the glacier bed, which could be measured by seismometers (Weaver and Malone, 1979; Anandakrishnan and Bentley, 1993; Metaxian et al., 2003; Smith, 2006). However, other sources of ice quakes within the glacial environment include ice calving (Qamar, 1988; O'Neel and Pfeffer, 2007), crevassing (Neave and Savage, 1970; Deichmann et al., 2000) and basal fracture (Walter et al., 2008).

Wireless sensor networks which are designed to be deployed for earth-science research have brought low power networking to remote areas (Chong and Kumar, 2003; Martinez et al., 2004; Hart and Martinez, 2006; Gehrke and Liu, 2006; Oliveira and Rodrigues, 2011; Huang et al., 2015). These environmental sensor networks have enabled a wider range of areas to be monitored for fundamental science and hazard warnings (Szewczyk et al., 2004; Delin et al., 2005; Werner-Allen et al., 2005; Hasler et al., 2008; Xu et al., 2014).

Most current commercial passive seismic systems require large power supplies and do not provide "live" data. Surface based deployments also require regular manual re-levelling, due to surface melt. In contrast, we required a long-term, low power automatic system housed in a borehole in order to avoid re-levelling, lessen the effects of noise from the glacier surface and insure a direct contact with the ice. We have developed a low power borehole geophone as part of a wireless sensor network, which can be used alongside GPS, subglacial wireless probes (Martinez et al., 2004), temperature and time lapse camera data (Young et al., 2015) to monitor a range of glacial processes. One advantage of the sensor network is its ability to send data back to a server in the UK daily, which provides researchers with a "live" feed via an internet connection. Due to the potentially high levels of data produced from continuous recording, we used an event detection system, so that the system only stored and communicated data related to the ice quakes (events). This new system, which is the first of its kind, consists of a small, borehole based, low power, event detection system providing a "live" data stream. The design has the potential to

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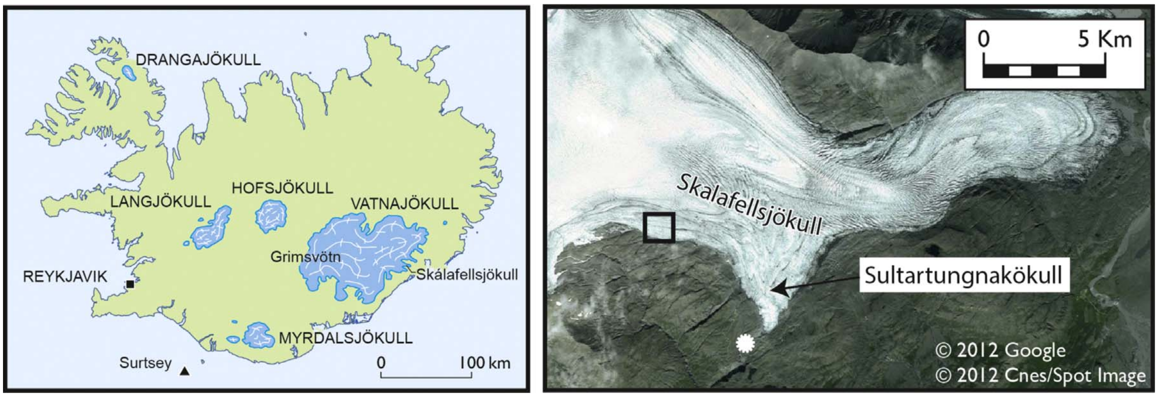

Fig. 1. Location of study area at Skálafellsjökull, b) Image of study area, square indicates main Glacsweb study site, star indicates camera location.

allow geophone sensing over longer time periods while providing researchers with frequent updates and an understanding of the state of the hardware. It could be used in other seismic deployments where long-term monitoring of short-term events is required.

The aims of this paper are:

- To discuss the design and development of the geophone system and its integration into a heterogeneous environmental sensor network.
- To report the findings from a field trial using a commercial passive seismic recording device on the glacier surface. This was undertaken to detect basal ice quakes and also investigate the required sampling rates, detection and filtering for our custom system.
- To present analysis of data generated from the new system to study the timing and nature of microseismicity associated with daily stick-slip motion at an Icelandic glacier.

2. The field site

Skalafellsjökull, Iceland (Fig. 1a) is an outlet glacier of the Vatnajökull icecap which rests on Upper Tertiary grey basalts. This glacier has an area of approximately 100 km^2 and is 25 km in length (Sigurðsson, 1998). The study site was located on the glacier at an elevation of 792 m a.s.l., where the ice was flat and crevasse free. The subglacial meltwater in this area emerged 3 km away at the southern part of the glacier (known as the Sultartungnajökull tongue, Fig. 1b).

The Glacsweb sensor network was deployed at Skalafellsjökull, Iceland (Fig. 1a) (2008–2013) and provided the ideal infrastructure for this research. This consisted of multiple heterogeneous nodes which have been developed during several years of continuous deployments (Martinez et al., 2009, 2012; Hart et al., 2006). Fig. 2 illustrates the design of the wireless sensor network system in 2012/3. A set of sensor nodes on/in the glacier used appropriate radio frequencies (868 MHz surface, 173 MHz ice) to communicate to a base station that uses either Wi-Fi or GPRS to send the data to a server hosted in the Amazon Web Services cloud (Martinez and Basford, 2011). As well as acting as routing nodes the gateways include a meteorological station, GPS, cameras and other diagnostic sensors. There were also four standalone dGPS units recording ice velocity 2012/3 and a time-lapse camera monitoring river discharge (Young et al., 2015).

Ground penetrating radar (GPR) surveys and borehole measurements have shown that the glacier at the study site ranges from 0 to 200 m in thickness. The glacier rests on a fine grained till, with a series of active till thrust sheets approximately 5 m thick, moving at 3 m per year throughout the year. The water content (calculated from GPR) of the glacier is very low (0.5%), but surface meltwater moves rapidly though englacial crevasses and moulins to the glacier bed (Hart et al., 2015). Data from the wireless Glacsweb probes show the water pressure in the till is high during the summer, but fluctuates during the winter depending on meltwater inputs.

Weather data were obtained from the base station and, during periods of mechanical failure, from a transfer function applied to data from the neighbouring Icelandic meteorological station at Höfn. Daily surface melt was calculated by the degree day algorithm (PDD) (Braithwaite, 1985; Hock, 2003), using degree day factors for Satujökull, Iceland (Johannesson et al., 1995), 5.6 mm d^{-1} °C^{-1} for snow and 7.7 mm d^{-1} °C^{-1} for ice. Albedo was calculated from the MODIS data, using the threshold between ice and snow to be 0.45, on a 30×30 m grid ASTER DEM.

3. Field trial using a commercial system in 2011

Six commercial geophones were installed on the glacier surface. Each station consisted of a 4.5 Hz 3-component geophone with pre-amplifier, powered by lead-acid battery and two 20 W solar panels. Data were recorded by ISSI (Integrated Seismic Systems International) SAQS (Stand Alone Quake Systems) systems units capable of sampling at up to 24 kHz. The units recorded 24 bit data per channel at a sample rate of 1 kHz. The systems were placed 90 m apart from so the spacing

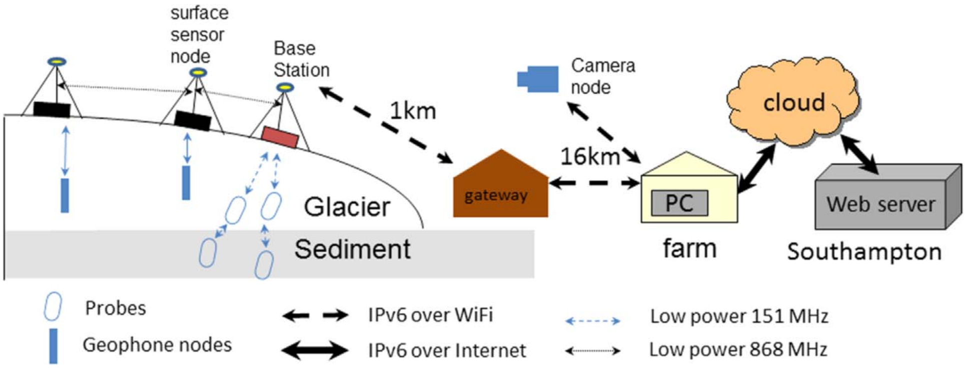

Fig. 2. Sensor network deployed in Iceland. Showing the geophone nodes integrated into the radio network.

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