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Subglacial permafrost evidencing re-advance of the Greenland Ice Sheet over frozen ground

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ABSTRACT

Greenland Ice Sheet (GrIS) covers an area of 1.7 km^2. It has been an important source of climate information and the air temperature history of Greenland is well known. However, the thermal history and temperature conditions of the Greenland bedrock are poorly known. There are only few records on the temperature of the proglacial bedrock and no records on bedrock temperature underneath the ice sheet. The Greenland Analogue Project (GAP) recently investigated hydrological, hydrogeological and geochemical processes in Kangerlussuaq, West Greenland. Because permafrost has a major hydrological impact in Arctic regions, the cryogenic structure of the bedrock was an important research topic. From previous studies it was already known that Kangerlussuaq is located within the zone of continuous permafrost. Temperature profiling in a new research borehole, extending horizontally 30 m underneath the ice sheet, revealed that permafrost is 350 m deep at the ice margin. This result raised the question how far the permafrost extends under the ice sheet? In order to investigate the thermal properties, we made a series of electromagnetic (EM) soundings at the ice margin area – on proglacial area and on the ice sheet – and detected, that subglacial permafrost extends at least 2 km from the ice margin to inland. We also observed a patchy unfrozen sediment layer between the ice and the frozen bedrock. Possible existence of subglacial sediments and their role in ice dynamics has been debated in many recent papers. Our successful campaign shows that geophysics can be used for bedrock investigations through thick ice, which is known to be challenging for electromagnetic methods. Our results provide the first direct evidence supporting the proposed Holocene ice re-advance over frozen ground, and contribute to the discussion on the rapid climate changes in past, to the future of the ice sheet under warming climate and hydrogeology at the ice margin.

1. Introduction

Permafrost covers about 25% of the Northern Hemisphere and the greatest depths, reported from Siberia, are more than 1400 m (e.g. Yershov, 1991). Among other effects, permafrost has a major hydrological impact in Arctic regions, both at the surface and in deep systems (e.g. White et al., 2007; Bosson et al., 2013; Kane et al., 2013). Permafrost is in a key role when surface hydrology or the ice sheet derived meltwaters are investigated. Potentially impermeable frozen bedrock and soil cover tend to restrain and redirect flow paths. Recharge of meteoric waters is limited to the active layer depth (formed during summer melting), thus surface run-off is the principle hydrological process, while mixing with bedrock groundwater is generally restricted. However, vertical unfrozen structures, through taliks, existing beneath lakes provide potential routs for vertical flow, allowing both recharge and discharge (e.g. Osterkamp and Burn, 2003; Kane et al., 2013). Very few studies of sub-permafrost groundwater flow have been performed and the conditions for groundwater flow are, consequently, poorly understood (Harper et al., 2016).

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Broadly speaking the distribution of permafrost in ice-free areas is known reasonably well. Instead, there is hardly any information about subglacial permafrost. Currently no observations from Greenland are known to us. In west Greenland this topic is particularly interesting and also potentially rather complex due to the Holocene deglaciation history (Ten Brink, 1975; van Tatenhove and van der Meer, 1995; Willemse et al., 2003; Forman et al., 2007; Rinterknecht et al., 2009; Funder et al., 2011; Storms et al., 2012; Carlson et al., 2014; Winsor et al., 2015; Young and Briner, 2015) and oscillation of the ice margin (Weidick, 1993, 1996; van Tatenhove et al., 1996; Wahr et al., 2001; Dietrich et al., 2005; Forman et al., 2007). It is well known that the Greenland Ice sheet (GrIS) is currently melting, resulting to negative mass balance (e.g. Helm et al., 2014). The ice sheet is warm-based with the basal ice temperature at the pressure melting point (0 °C or slightly below) for tens of kilometers inland from the margin (Harrington et al., 2014; Harper et al., 2016). These conditions do not, however, rule out the existence of relict permafrost in the subglacial bedrock.

The Greenland Analogue Project (GAP) investigated hydrological, hydrogeological and geochemical processes during glacial conditions at the ice sheet in West Greenland (Harper et al., 2016; Claesson Liljedahl et al., 2016). In this context, the vertical and lateral distribution of permafrost became an important issue, and various investigations were made to characterize the distribution of permafrost in the study area.

The GAP project drilled two bedrock holes close to the ice margin (Harper et al., 2016) and measured temperature profiles from the surface down to the depth of 550 m. The borehole DH-GAP04, extending (horizontally) approximately 30 m underneath the ice margin, showed permafrost down to the depth of 350 m. This raised an important question how far the permafrost extends under the ice? If it is only a narrow band, it may have recently grown laterally underneath the ice margin, but if it is extensive, it most likely predates the ice sheet.

Direct temperature measurements in the subglacial bedrock would reveal the distribution of the permafrost. However, it is practically impossible to drill into the bedrock through a moving ice sheet and monitor bedrock temperatures. Therefore, an indirect geophysical method, electromagnetic (EM) sounding, was chosen to address this question. The use of EM sounding is based on the phenomenon that the electrical resistivity of rock depends on its temperature so that freezing of the water in the rock pores and fractures increases the bulk electrical resistivity of the rock. The rate of increase in resistivity due to freezing depends on many factors, such as the rock type, fracturing, and chemistry of the pore water, but it is typically from a half to one-and-half orders of magnitude (Hoekstra and McNeill, 1973; Scott and Kay, 1988). The resistivity values for unfrozen saturated crystalline bedrock are typically between 5 000–10 000 Ohmm, while the frozen bedrock values are more than 30 000 Ohmm. Thus, our key hypothesis was that if subglacial permafrost exists, we will get an electrical resistivity image in which the layer below the ice sheet has the same order of resistivity that we measure for permafrost bedrock on the ice free areas.

A wide range of geophysical electrical methods exploit this cryogenic contrast and have been used in mapping the distribution of permafrost both laterally and vertically (e.g., see the review by Scott et al., 1990 and Hauck and Kneisel, 2008). The range of methods extends from direct current resistivity methods (e.g. Osterkamp et al., 1980; Hauck et al., 2000, Vanhala et al., 2009, 2012) to ground and airborne electromagnetic methods (Hauck et al., 2000; Vanhala et al., 2005; Auken et al., 2012; Minsley et al., 2012).

The geophysical investigations above are mainly concerned with the mapping of shallow permafrost. Because the aim was to investigate deep permafrost through ice, we applied a frequency-domain electromagnetic (FDEM) sounding method, which has earlier proved its potential for deep investigations of up to 1000 m in Antarctica (Ruotoistenmäki and Lehtimäki, 1997) and Arctic Canada (Paananen and Ruskeeniemi, 2003; Korhonen et al., 2009), on ice-covered (Antarctica) and ice-free (Canada) terrains. Prior to moving on ice we tested the method on ice-free areas in Kangerlussuaq in 2012 and 2013. The sounding results were consistent showing that the method is applicable in the local bedrock conditions (Harper et al., 2016). Moreover, we received valuable site-specific reference data about the regions cryogenic units and their electrical properties.

Here we present the results of the EM soundings, which are, to our knowledge, the first observations of subglacial permafrost in Greenland. Supporting, independent data acquisition on ice thickness was conducted by ice radar (for the method see Lindbäck et al., 2014). Since the findings have a strong connection to the late Holocene deglaciation/re-advance history of West Greenland, the results are discussed from this perspective.

2. Study area

The GAP research area is located close to the village of Kangerlussuaq, SW Greenland, just above the Arctic Circle (Fig. 1). The local bedrock is composed of reworked Archean to Paleoproterozoic metamorphic rock varieties, such as felsic banded gneisses and mafic orthogneisses (Garde and Marker, 2010; Engström and Klint, 2014). The nearest ice tongues of the GrIS are situated only 20 km east of the settlement. At this area the ice sheet terminates on land at a distance of 150 km from the sea coast. Kangerlussuaq is located at sea level at the end of a 170 km long fjord. The mean annual air temperature is -5.1 °C and the annual precipitation 173 mm for the period 1977–2011 (Cappelen, 2012). According to Christiansen and Humlum (2000), the Kangerlussuaq area is located within the zone of continuous permafrost, 50–60 km east of the boundary of the discontinuous permafrost zone.

van Tatenhove and Olesen (1994) reported mean annual ground temperature (MAGT) from shallow (<15 m) drill holes, which located close to the runway of Kangerlussuaq airport, to be −2.1 °C at 1.25 m depth and -1.6 °C at 15 m depth. Based on these values they calculated that the permafrost depth was 127 ± 31 m at that site.

The most recent information on the deep bedrock temperatures from the Kangerlussuaq region, and indeed the deepest from the whole of Greenland, was recorded in the GAP project. We drilled two subvertical bedrock holes (DH-GAP03: 340 m and DH-GAP04: 687 m long) in 2009 and in 2011, respectively, close to the ice margin (Harper et al., 2016) at an elevation of about 500 m a.s.l. The instrumentation in these holes provided continuous temperature profiles from the surface down to a depth of 550 m through optical fibers and the distributed temperature sensing (DTS) technique (Selker et al., 2006; Harper et al., 2016). Based on the 0 °C isotherm measured in the two boreholes, the thickness of permafrost is 315 m (DH-GAP03) and 350 m (DH-GAP04) (Harper et al., 2011, 2016; Claesson Liljedahl et al., 2016). The calculated non-corrected heat flows for the boreholes are 27 and 35 mW/m^2 (Harper et al., 2016), which are lower than earlier estimated values for this part of Greenland. For example, Shapiro and Ritzwoller (2004) reported c. 58 mW/m^2.

The only other deep bedrock temperature data from Greenland that are freely available are from Paakitsup, Ilulissat, 275 km north of Kangerlussuaq. At the Paakitsup site, temperature monitoring was carried out in a 250-m deep borehole between 1986 and 1992, and the depth of permafrost was observed to be 215 m (Kern-Hansen, 1990; van Tatenhove and Olesen, 1994).