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Deglaciation of Fennoscandia

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A R T I C L E I N F O

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A B S T R A C T

To provide a new reconstruction of the deglaciation of the Fennoscandian Ice Sheet, in the form of calendar-year time-slices, which are particularly useful for ice sheet modelling, we have compiled and synthesized published geomorphological data for eskers, ice-marginal formations, lineations, marginal meltwater channels, striae, ice-dammed lakes, and geochronological data from radiocarbon, varve, optically-stimulated luminescence, and cosmogenic nuclide dating. This is summarized as a deglaciation map of the Fennoscandian Ice Sheet with isochrons marking every 1000 years between 22 and 13 cal kyr BP and every hundred years between 11.6 and final ice decay after 9.7 cal kyr BP.

Deglaciation patterns vary across the Fennoscandian Ice Sheet domain, reflecting differences in climatic and geomorphic settings as well as ice sheet basal thermal conditions and terrestrial versus marine margins. For example, the ice sheet margin in the high-precipitation coastal setting of the western sector responded sensitively to climatic variations leaving a detailed record of prominent moraines and other ice-marginal deposits in many fjords and coastal valleys. Retreat rates across the southern sector differed between slow retreat of the terrestrial margin in western and southern Sweden and rapid retreat of the calving ice margin in the Baltic Basin. Our reconstruction is consistent with much of the published research. However, the synthesis of a large amount of existing and new data support refined reconstructions in some areas. For example, the LGM extent of the ice sheet in northwestern Russia was located far east and it occurred at a later time than the rest of the ice sheet, at around 17–15 cal kyr BP. We also propose a slightly different chronology of moraine formation over southern Sweden based on improved correlations of moraine segments using new LiDAR data and tying the timing of moraine formation to Greenland ice core cold stages.

Retreat rates vary by as much as an order of magnitude in different sectors of the ice sheet, with the lowest rates on the high-elevation and maritime Norwegian margin. Retreat rates compared to the climatic information provided by the Greenland ice core record show a general correspondence between retreat rate and climatic forcing, although a close match between retreat rate and climate is unlikely because of other controls, such as topography and marine versus terrestrial margins. Overall, the time slice reconstructions of Fennoscandian Ice Sheet deglaciation from 22 to 9.7 cal kyr BP provide an

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important dataset for understanding the contexts that underpin spatial and temporal patterns in retreat of the Fennoscandian Ice Sheet, and are an important resource for testing and refining ice sheet models.

1. Introduction

Melting of the Greenland and Antarctic ice sheets, and the threat of accelerated melt in response to future climate warming, has firmly positioned ice sheet deglaciation processes and rates on the global research agenda (Warrick and Oerlemans, 1990; Briner et al., 2009; Church et al., 2013; Stokes et al., 2014). This is because an important implication of accelerated ice sheet melt, in addition to ice sheet mass loss through calving, is an expected rise in global mean sea level, with spatial variations around that mean (Milne et al., 2009; Kopp et al., 2010; Slangen et al., 2014) and resulting challenges for coastal land use. The current condition of the Greenland and Antarctic ice sheets, grown out of highlands but also covering extensive lowlands and subglacial basins below sea level, is similar to the situation of the former Laurentide and Fennoscandian ice sheets at their last maximum positions, and implies ice sheet retreat with margins extending offshore. Future retreat patterns, if recent trends persist, will likely differ starkly for margins that are predominantly terrestrial and those that are terminating in a marine environment. The latter are prone to destabilization and run-away effects through sea level rise and margin thinning (Hughes, 1975; Favier et al., 2014). This insight has been gained from the dynamics and deglaciation histories of the former Northern Hemisphere ice sheets (Kleman and Applegate, 2014) and from measurements and modelling pertaining to the Greenland and Antarctic ice sheets (Joughin et al., 2014; Rignot et al., 2014).

At the height of glaciation, during the global Last Glacial Maximum (LGM, 26.5-20 thousand years ago [cal kyr BP]; Clark et al., 2009b), a considerable portion of the Northern Hemisphere landmass above 60 °N was ice-covered (Denton and Hughes, 1981). Reconstructions of the maximum extent and the timing of initial retreat of these Northern Hemisphere ice sheets has been a research focus for the last 175 years (Agassiz, 1840; Torell, 1872, 1873; Jackson and Clague, 1991). The first deglaciation reconstructions were entirely based on geomorphological and sedimentological/stratigraphical evidence for glaciation. In the absence of a reliable dating technique, the pace of deglaciation was initially inferred from the correlation between sequences of silty light- and clayey dark-coloured sediment couplets. These 'varves' formed during summer and winter seasons, respectively, through ice sheet melt, runoff, and proglacial sedimentation. Extensive varve deposits are typically exposed between highest shore lines and the present coasts, and can be used for dating of the ice recession. This is because the age of the first varve overlying the formerly subglacial terrain (typically bedrock or till), denotes the age of deglaciation and therefore the former position of the ice sheet margin (De Geer, 1884, 1912, 1940; Sauramo, 1918, 1923). In a series of seminal studies on the deglaciation of the Fennoscandian Ice Sheet, De Geer (1884, 1896, 1912, 1940) developed the Swedish Time Scale (STS) varve chronology (Lidén, 1938; Wohlfarth et al., 1995). In the past three decades many studies have refined the STS (Strömberg, 1985a, b, 1989, 1990; 1994; Kristiansson, 1986; Cato, 1987; Andrén, 1990; Brunnberg, 1995; Wohlfarth et al., 1995, 1998; Hang, 1997; Lindeberg, 2002), eventually resulting in a correlation of the STS with the Greenland GRIP and NGRIP ice core record layer-counting chronology (Andrén et al., 1999, 2002; Stroeven et al., 2015). These attempts to correlate varve- and ice core chronologies have, however, revealed that hundreds of varves are missing in the STS, thus exposing a key shortcoming of this indirect dating technique (Andrén et al., 2002).

With the advent of radiometric dating techniques (Bard and Broecker, 1992), in particular radiocarbon (Anderson et al., 1947; Arnold and Libby, 1949), the timing of maximum glacier extent, has typically been constrained by the first occurrence of living matter in proglacial lakes dammed by the ice margin (yielding ages older than the maximum ice extent) and in lakes dammed by the end moraine once the ice margin had retreated from its maximum extent (yielding ages younger than the maximum ice extent). Dating the initiation of ice-free conditions using radiocarbon has been the dominant dating-driven ice sheet reconstruction method, and an abundance of minimum age constraints has permitted detailed ice-sheet wide retreat reconstructions (e.g., Dyke et al., 2003; Gyllencreutz et al., 2007).

There are a number of limitations associated with radiocarbon dating in formerly glaciated regions (Hajdas, 2008). Critically, there is dearth of datable organic material in many locations because deglaciation occurred in polar deserts. Given the inevitable delay in organic growth following deglaciation, ^{14}C dates provide minimum limiting ages on deglaciation. In addition, the precision of radiocarbon dating is compromised by the potential incorporation of young carbon contaminants, incorporation of old carbon in the depositional environment (marine reservoir or hard water effects; Snyder et al., 1994), and variations in the atmospheric radiocarbon concentration over time. These combined effects produce similar radiocarbon ages for samples that were deposited hundreds of years apart (radiocarbon dating plateaux). Because of these potential pitfalls, considerable effort has been devoted to the improvement of sample preparation methods and calibration of the radiocarbon chronology (Bard et al., 1990, 1997; Wohlfarth et al., 1995; Reimer et al., 2009, 2013). The best radiocarbon age determinations come from environments where terrestrial macrofossils have been used to constrain the age model (Barnekow et al., 1998).

During recent decades two new dating techniques have emerged, based on the burial of sand through optically-stimulated luminescence (OSL) and the exposure of quartz-bearing clasts and bedrock through measuring concentrations of cosmogenic nuclides. In each case, datable material is abundant in pro-glacial and glacial environments.

The OSL method is based on the build-up of a luminescence signal in quartz grains that are shielded from sunlight through burial (Rhodes, 2011). Exposure to sunlight deletes any previous luminescence dose (bleaches the quartz grain). Hence, OSL can be applied to date the burial of quartz grains (feldspar is also routinely measured) given that two crucial conditions are met: 1) during transport the grains are exposed to sunlight for a duration sufficient to become bleached and; 2) the sample has not been re-exposed (Huntley et al., 1985; Aitken, 1998). Whereas the latter condition can usually be verified in stratified sediments, partial-bleaching is a major obstacle when dating glacial sediments, commonly resulting in an over-estimation of the depositional age of the landform (Fuchs and Owen, 2008; Alexanderson and Murray, 2012b). OSL is therefore typically applied in settings where these conditions are more easily met, such as where aeolian, fluvial, or lacustrine