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Evidence for the asynchronous retreat of large outlet glaciers in southeast Greenland at the end of the last glaciation

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ABSTRACT

Recent rapid changes in the marine-terminating sectors of the Greenland Ice Sheet (GrIS) have prompted concerns about the future stability of the ice sheet. Long-term records of ice sheet behaviour provide valuable context to assess the magnitude of current change and may help resolve the mechanisms driving deglaciation. We report 23 new ^{10}Be exposure ages which constrain the deglacial history of two large fjord systems in southeast (SE) Greenland. We compare our chronologies with existing data from the centre of the sector to examine the timing and style of deglaciation at a regional-scale. Glacial erratic ^{10}Be exposure ages demonstrate that Kangerdlugssuaq Fjord deglaciated at ~11.8 ka at the end of the Younger Dryas (YD – 12.8–11.6 ka). Retreat at Kangerdlugssuaq Fjord coincided with known incursion of the warm Irminger Current (IC) onto the continental shelf; this is inferred to have initiated retreat. Comparison with recently published results from Sermilik Fjord and new ^{10}Be ages from Bernstorffs Fjord indicates deglaciation occurred ~1 ka later in the south of the SE region. Sermilik Fjord (~10.9 ka) and Bernstorffs Fjord (~10.4 ka) deglaciated later; retreat likely occurred in response to dramatic climatic amelioration at the termination of the YD stadial. We suggest that the disparate timing of deglaciation across the SE region may be primarily explained by the varying influence of the warm IC; glaciers in southern SE Greenland were isolated from warm Atlantic waters during the YD by complex shelf bathymetry. In all fjord settings ice retreat was rapid and persistent, consistent with the absence of geomorphological evidence for stillstand or readvance events. Ice retreat was accompanied by rapid thinning and likely continued to well within present-day ice sheet margins. Glacial erratic ^{10}Be age determinations and geomorphological observations show no evidence for Holocene readvance events prior to the Little Ice Age (LIA).

1. Introduction

Recent glaciological changes in southeast (SE) Greenland (Fig. 1) highlight the importance of the sector to the overall mass balance of the Greenland Ice Sheet (GrIS). In the first decade of the 21st century marine-terminating outlet glaciers across the region accelerated, thinned and then retreated simultaneously, apparently in response to regional-scale forcing(s) (Krabill et al., 1999; Howat et al., 2008; Thomas et al., 2009; Murray et al., 2010; Moon et al., 2012; Straneo and Heimbach, 2013). Dynamic thinning has been shown to penetrate far inland, resulting in enhanced regional mass loss which now dominates the mass balance of the wider GrIS (Rignot and Kanagaratnam, 2006; Pritchard et al., 2009; Sasgen et al., 2012). Assessing the magnitude of current glaciological changes requires a well-defined 'baseline' beyond the record of historical observations and measurements. Techniques such as cosmogenic isotope dating enable reconstruction of glacier behaviour over long timescales and are valuable for understanding the response of the GrIS to external forcings. Detailed regional chronologies may also allow the identification of the individual driving mechanism(s) of deglaciation (e.g. Roberts et al., 2010, 2013; Larsen et al., 2013). Furthermore, records of palaeo-ice sheet behaviour are important for testing numerical ice sheet

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models which attempt to predict the future behaviour of the GrIS (Simpson et al., 2009; Vinther et al., 2009). Despite its current significance to the overall mass balance of the GrIS, relatively little is known about the glacial history of the SE coast and it remains one of the least investigated regions of Greenland. Recently published results from the centre of the sector demonstrate that the area around Sermilik Fjord deglaciated at ~10.9 ka and that retreat was both rapid and sustained (Jakobsen et al., 2008; Long et al., 2008; Roberts et al., 2008; Hughes et al., 2012).

The deglacial history of the rest of the region is largely unknown. Terrestrial areas are particularly poorly represented; this reflects the predominantly erosional landscape which offers few opportunities for ^{14}C dating. Understanding the behaviour of large, high-discharge outlet glaciers is important as their history is intrinsically linked to the fate of the wider GrIS. Simple questions remain unanswered; it is not known when glaciers across the region retreated, how rapidly they deglaciated or which driver(s) paced retreat. We present new ^{10}Be exposure ages from Kangerdlugssuaq Fjord and Bernstorffs Fjord, the drainage portals for two of the largest glaciers in SE Greenland (Fig. 1). This enables investigation of the timing and style of deglaciation across the sector.

2. Study area – Southeast Greenland

The SE region covers 1500 km of coastline from Kap Farvel in the south to Kap Brewster at the entrance to Scoresby Sund (Fig. 1). The region is heavily glaciated; large tidewater outlet glaciers drain ~173,000 km^2 of the GrIS through long fjord systems incised into the coastline (Rignot and Kanagaratnam, 2006). Numerous independent mountain glaciers exist in the narrow, alpine coastal belt and in many locations the ice sheet margin sits directly at the modern coastline (Dwyer, 1995; Kelly and Long, 2009). Unglaciated terrain is predominantly characterised by ice-scoured bedrock; vegetation is sparse and limited to favourable locations (Humlum and Christiansen, 2008). The continental shelf is 60–200 km wide and typically a few hundred metres deep (Murray et al., 2010). Terrestrial fjord systems continue onto the continental shelf as transverse troughs up to 900 m deep; these generally shallow towards the shelf-break (Andrews et al., 1996; Kuijpers et al., 2003).

The modern SE region spans sub-Arctic to Arctic climate zones. Stable high-pressure conditions prevail during spring and summer, while low-pressure cells track the SE coast delivering heavy precipitation during autumn and winter (Hastings, 1960; Ohmura and Reeh, 1991). The SE region records the highest accumulation of the GrIS (Bales et al., 2009); this is offset by an ablation rate of ~6 m a^{-1} at sea-level between 60 and 68°N (Reeh et al., 1999). The climate of the SE region is regulated by the GrIS and by cold southerly flowing ocean currents (Fig. 1). The coastal currents of SE Greenland form the north-eastern limb of the Subpolar Gyre: a broad anticlockwise circulation feature which partly regulates heat and salinity delivery in the North Atlantic (Aagaard and Coachman, 1968a, b; Hátún et al., 2005; Thornalley et al., 2009). The East Greenland Current (EGC) and its inner-shelf extension, the East Greenland Coastal Current (EGCC), are cool, low-salinity, high-velocity surface currents (Sutherland and Pickart, 2008). These currents are augmented by glacial ice and meltwater from the GrIS (Bacon et al., 2002; Sutherland and Pickart, 2008). The Irminger Current (IC) flows at depth beneath a 'cap' of Arctic water and delivers warm, saline water from the subtropics (Straneo et al., 2010; Brearley et al., 2012; Sutherland et al., 2013). The IC penetrates the deepest troughs and fjords, reaching at least some outlet glacier termini (Murray et al., 2010; Straneo et al., 2010; Christoffersen et al., 2012).

2.1. Sampling sites – Kangerdlugssuaq Fjord and Bernstorffs Fjord

This study focusses on two large fjord systems in the SE region (Figs. 1 and 3). The fjords are situated 750 km apart; approximately equal distances north and south of Sermilik Fjord, the subject of similar investigation (Hughes et al., 2012).

Kangerdlugssuaq Fjord, in the north of the sector, is ~70 km long, up to 12 km wide and headed by the marine-terminating Kangerdlugssuaq Glacier. The glacier is the largest of the sector, draining ~30% of the SE GrIS and discharging ~28 km^3 of ice annually (Rignot and Kanagaratnam, 2006). Kangerdlugssuaq is one of the fastest outlet glaciers of the GrIS; velocities near the calving front can exceed 30 m day^{-1} (Luckman et al., 2006; Murray et al., 2010). The glacier drains through a deep bedrock trough which extends ~40 km inland below sea-level (Bamber et al., 2013). Several smaller outlet glaciers drain into the main fjord through tributary fjords and numerous cirque glaciers and glacierets occupy favourable locations on the fjord walls which rise to >2000 m above sea-level (asl) (Schjøtt, 2007a). The bathymetry of the fjord is characterised by a featureless, steep-walled basin which deepens to a maximum of 870 m near the mouth (Dowdeswell et al., 2010). The surface bedrock of Kangerdlugssuaq Fjord is very diverse and is underpinned by reworked Archaean gneiss of the Nagssugtoqidian mobile belt (Nutman et al., 2008 – Fig. 1). Palaeogene flood basalts lie to the north and east (Nielsen et al., 1981) and several significant gabbro intrusions border the fjord. Additionally, an intense swarm of coast-parallel mafic dykes dissect the area; these were emplaced during the opening of the North Atlantic (Wager and Deer, 1938; Myers, 1980). The landscape is predominantly erosional and is characterised by ice-scoured, striated bedrock. Minor 'fresh' moraines are associated with cirque and valley glaciers and are assumed to delineate Little Ice Age (LIA) extent, as elsewhere in the region (Fristrup, 1970; Hasholt, 2000; Kelly and Lowell, 2009).

Bernstorffs Fjord, in the south of the sector, is part of a complex of geometrically similar east-west trending fjords which drain ice from a large plateau beneath the southern dome of the GrIS (Bamber et al., 2013). Bernstorffs Glacier drains a smaller catchment than Kangerdlugssuaq Glacier, yet high accumulation rates (~80 g cm^{-2} a^{-1}) sustain velocities of up to 13 m day^{-1} near the calving front (Bales et al., 2009; Murray et al., 2010). The fjord is ~50 km long and up to 7 km wide; steep mountains rise to >1500 m asl forming the fjord walls (Schjøtt, 2007b). A complex of three glaciers discharge into the head of the fjord. These directly drain the GrIS and are thought to have coalesced during the last glaciation to form an ice stream in the fjord. Detailed bathymetry is not available for the fjord; limited echo-sounding data show areas >800 m below sea-level (bsl) in the main fjord and no significant shoaling to at least Ensomheden Island (Fig. 3; unpublished GLIMPSE cruise data, 2011). The bathymetric data also show a prominent sill (~250 m bsl) at the mouth of Bernstorffs Fjord. Numerous grounded icebergs prevented bathymetric surveying here but we consider it likely that the sill runs the full width of the fjord mouth (unpublished GLIMPSE cruise data, 2011). Ensomheden Island lies in the middle of the fjord 35 km from the mouth and is ~250 m asl at its highest point (Schjøtt, 2007b). A well-defined line of grounded icebergs (observed in 2011) and a partly visible submerged moraine indicate that the northern passage around Ensomheden Island is very shallow (Fig. 2C). High-resolution aerial photos reveal this is the extension of a 'fresh' cirque glacier moraine, exhibiting a well-defined ridge line and a lack of vegetation (A. Bjørk, personal communication). Cirque and valley glaciers through the fjord are associated with similar moraines. These are assumed to have formed during the LIA. Bernstorffs Fjord lies