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Holocene ice-rafting and sediment transport from the glaciated margin of East Greenland (67–70°N) to the N Iceland shelves: detecting and modelling changing sediment sources[☆]

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ABSTRACT

We examine variations in the ice-rafted sources for sediments in the Iceland/East Greenland offshore marine archives by utilizing a sediment unmixing model and link the results to a coupled iceberg-ocean model. Surface samples from around Iceland and along the E/NE Greenland shelf are used to define potential sediment sources, and these are examined within the context of the down-core variations in mineralogy in the <2 mm sediment fraction from a transect of cores across Denmark Strait. A sediment unmixing model is used to estimate the fraction of sediment <2 mm off NW and N Iceland exported across Denmark Strait; this averaged between 10 and 20%. Both the sediment unmixing model and the coupled iceberg-ocean model are consistent in finding that the fraction of "far-travelled" sediments in the Denmark Strait environs is overwhelmingly of local, mid-East Greenland, provenance, and therefore with a significant cross-channel component to their travel. The Holocene record of ice-rafted sediments denotes a three-part division of the Holocene in terms of iceberg sediment transport with a notable increase in the process starting ca 4000 cal yr BP. This latter increase may represent the re-advance during the Neoglacial period of land-terminating glaciers on the Geikie Plateau to become marine-terminating. The contrast in spectral signals between these cores and the 1500-yr cycle at VM28-14, just south of the Denmark Strait, combined with the coupled iceberg-model results, leads us to speculate that the signal at VM28-14 reflects pulses in overflow waters, rather than an ice-rafted signal.

1. Introduction

Starting in 1988, research cruises have been undertaken by the Institute of Arctic and Alpine Research (INSTAAR) and international colleagues on both the Greenland and Iceland continental margins of the Denmark Strait (e.g. Mienert et al., 1992; Helgadóttir, 1997; Labeyrie et al., 2003) with a goal of establishing the late Quaternary history of this critical area. However, coring within Denmark Strait itself has not resulted in any cores being recovered that cover the last 7000 cal yr (Hagen and Hald, 2002; Andrews and Cartee-Schoofield, 2003) because of the erosive effect of Denmark Strait Overflow Water (Jochumsen et al., 2012). The only exception was the recovery of Holocene sediments in VM28-14 to the south of the sill (Fig. 1) (Kellogg, 1984; Bond et al., 1997, 2001), where variations in the percentage of sand-size haematite quartz sand grains (HSQ) has been used to infer a pervasive ice-rafted debris (IRD) 1500 yr cycle, although such an IRD cycle was not detected earlier on the adjacent East Greenland shelf (Andrews et al., 1997). Significant research in the region has been undertaken from the German research vessel Polarstern (Marienfeld, 1992; Hubberten et al., 1995; Ó Cofaigh et al., 2001; Evans et al., 2002; Stein, 2008) and the UK research ship Sir James Clark Ross (Dowdeswell et al., 2010) (Fig. 1).

One of the questions that arise from all this work is: what are the source(s) for the "foreign" minerals found in Holocene Icelandic marine sediments? In particular, previous attention focused on the variations in quartz (Eiriksson et al., 2000; Moros et al., 2006), which is essentially absent from the Iceland bedrock. Detailed

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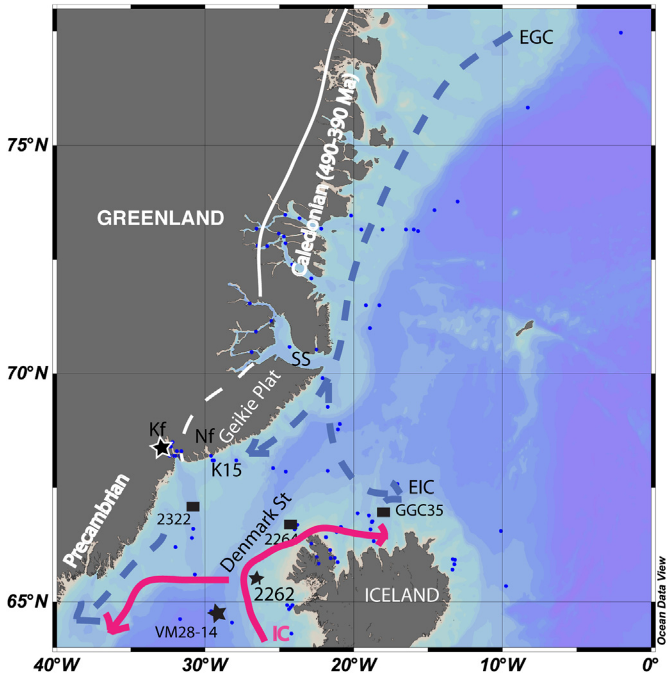

Fig. 1. Location of cores and surface samples (blue dots – Andrews and Eberl, 2007; Andrews et al., 2010; and new data) (see Table 1). Kf = Kangerlussuaq Fjord; Nf = Nansen Fjord; Is = Isarfjardjup. Djupall Trough is located at site 2264. The outcrop of early Cenozoic flood basalts is shown by the area within dashed white line and the massive Cenozoic felsic intrusion on the south side of Kangerlussuaq Fjord is shown by the white star. The simplified outcrop of Caledonian-aged sediments is shown by the solid white line (Higgins et al., 2008). The surface currents are labelled – EGC = East Greenland Current (dashed line), EIC = East Iceland Current (dashed line), and IC = Irminger Current. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

examination of many surface samples and cores by quantitative X-ray diffraction (qXRD) analysis (Andrews and Eberl, 2007; Andrews et al., 2009b) revealed a consistent pattern of quartz variations in cores from the NW-N Iceland shelf, but virtually no quartz was detected in cores from SW Iceland (Andrews, 2009). This pattern is attributed to the long-term patterns of drift ice coverage of the Iceland shelf, which in historic terms (Gray, 1881; Ogilvie, 1996; Ogilvie and Jonsdóttir, 2000; Divine and Dick, 2006) shows variable drift ice on the NW and N Iceland shelf, diminishing in severity clockwise around the Iceland coast. "Drift ice" is primarily sea ice, both first year and multi-year (Koch, 1945; Wallevik and Sigurjonsson, 1998), but records indicate that icebergs are also carried eastward from E and NE Greenland toward Iceland (Bigg et al., 1996). For example, in August 2004 a flotilla of icebergs (online map, Iceland Met. Office 2004, no longer available) invaded the NW Iceland shelf west of 16° W, and may have reflected the break-up of a sikussuak or floating ice tongue from N/NE Greenland. Parallel investigations of the mineralogy of marine sediments on the East Greenland shelf have been reported with particular attention paid to the abrupt transition in sediment mineral composition south of Scoresby Sund (Andrews et al., 2010; Andrews, 2011).

Icelandic tidewater glaciers ceased to deliver ice-rafted debris (IRD > 2 mm) to the shelf ca 10,000 cal yr BP (Castaneda et al., 2004), whereas there are numerous tidewater glaciers across Denmark Strait along the E/NE Greenland margin (Nuttall, 1993; Bigg, 1999; Seale et al., 2011). In our area of interest this includes the Kangerlussuaq ice stream (Dwyer, 1995; Joughin et al., 2008), 19 tidewater glaciers that debouche to sea level from the Geikie Plateau (Nuttall, 1993), and several large outlets in Scoresby Sund and fjords to the north (Reeh, 1994; Bigg, 1999; Reeh et al., 2001; Seale et al., 2011). The bedrock geology of Iceland (Kristjansson et al., 1979; Hardarson et al., 1997) is relative simple when compared with the situation across the Strait, where the East Greenland flood basalts of the Giekie Plateau (Blichert-Toft et al., 1992; Hansen and Nielsen, 1999) overlie Cenozoic/Paleogene sediments (Larsen et al., 1999), and also include complex felsic intrusions (Fig. 1). The bedrock geology north of Scoresby Sund consists of Precambrian igneous and metamorphic rocks outcropping at the margin of the Greenland Ice Sheet (GIS) but to the east succeeded by a 100 km wide outcrop of Caledonian sediments (including Devonian red beds), followed in turn by a restricted outcrop of Cenozoic volcanics along the coast (Henriksen, 2008; Higgins et al., 2008). Previous investigations between Scoresby Sund and Kangerlussuaq Fjord indicate that ice-rafted sediments from this northern region are overwhelmed by sediments derived from glacial erosion of the Geikie Plateau (Andrews, 2011).

The rationale for the use of variations in mineralogy as an index of glacier behaviour is that bedrock outcrop is rarely uniform over moderate distances, and thus as glaciers thicken and advance, or thin and retreat, then different mineral suites (both non-clay and clay minerals) would be subjected to glacier erosion and transport, in our case by calving and melting. The contributions from specific sediment sources (tidewater glaciers in fjords, or from sea ice from the Arctic Ocean) are expected to decrease in influence along the ice transport path.

1.1. *Research questions*

Sediments on the E Greenland and Iceland continental shelves receive contributions from a variety of sources, and the question is can these sources be identified on the basis of changes in mineralogy and can such changes be linked to reasonable variations in climatically-driven iceberg drift models. The questions that this

Table 1
Details of the cores used within this paper. All positions are shown in Fig. 1, except JM96-1232 that is very close to two other cores. The position, Sediment Accumulation Rate (m ka^{-1}), the existence of ^{210}Pb measurements, and the number of ^{14}C dates are shown where known for each core, as well as the prime reference.

Core	Latitude °N	Longitude °W	SAR[a]	^{210}Pb	Number ^{14}C dates	Reference
HU93030–019B	67.1	−30.8		Yes	1	Smith et al., 2002
MD99-2322	67.13	−30.82	2.12	No	21	Jennings et al., 2011 Stoner et al., 2007
MD99-2263	66.679	−24.197		Yes	7	Andrews et al., 2009
MD99-2264	66.679	−24.197	0.24	No	5	Olafsdottir et al., 2010
JR51GGC35	66.999	−17.961	0.42	No	10	Bendle and Rose-Mele, 2007
MD99-22262			NA	No		Andrews, unpubl.
B997–316PC3	66.746	−18.79	1.7	No	7	Jónsdóttir, 2001
BS1191–K15	68.1	−29.5	0.17	No	5	Andrews et al., 1997
JM96-1232	66.617	−24	0.43	No	4	Smith and Licht, 2000
V28-14	64.783	−29.57				Bond et al., 2008

[a] SAR, Sediment accumulation rate m/ka.