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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[☆]

John T. Andrews [a], [b], [*], Grant R. Bigg [c], [1], David J. Wilton [c]

[a] INSTAAR, University of Colorado, Boulder, CO 80309, USA
[b] Department of Geological Sciences, University of Colorado, Boulder, CO 80309, USA
[c] Department of Geography, University of Sheffield, Sheffield S10 2TN, UK

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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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[*] Corresponding author. INSTAAR, University of Colorado, Boulder, CO 80309, USA. Tel.: +1 303 492 5183.

E-mail address: andrewsj@colorado.edu (J.T. Andrews).

[1] grant.bigg@sheffield.ac.uk.

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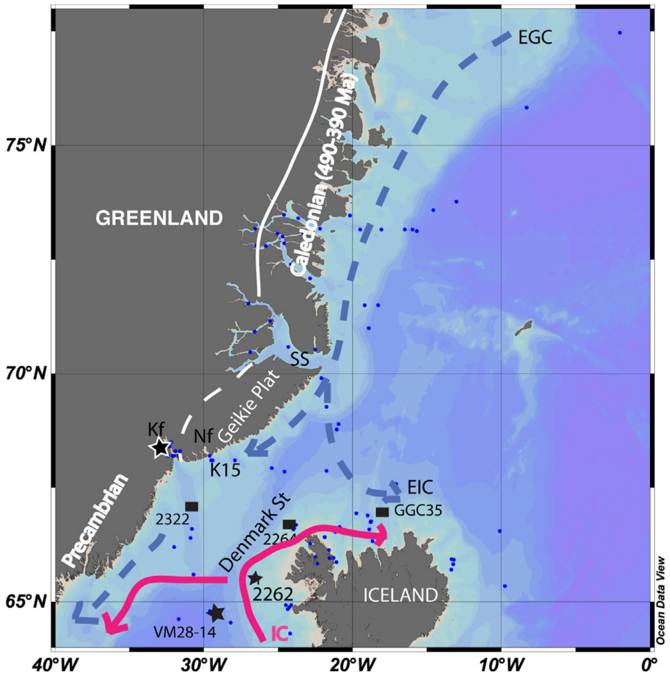

Fig. 1. Location of cores and surface samples (blue dots – Andrews and Eberl, 2007; Andrews et al., 2010; and new data) (see Table 1). Kf = Kangerlussuaq Fjord; Nf = Nansen Fjord; Is = Isarfjardjup. Djupall Trough is located at site 2264. The outcrop of early Cenozoic flood basalts is shown by the area 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.

paper therefore address are: 1) what are the present-day non-clay and clay mineral distributions across the Denmark Strait and northward along the Greenland shelf; 2) what fraction of the sediment on the North Iceland shelf is derived from E/NE Greenland; 3) can we target source areas for “foreign” material; 4) do these sources vary in importance across the N Iceland shelf; and 5) have they varied during the Holocene? This paper thus integrates the previous analyses of sediment mineral composition, which had been undertaken separately for the Iceland and East Greenland areas, with an iceberg drift model with the goal of deriving a better understanding of the processes underlying the distribution of ice rafted sediments in the western Nordic Seas.

2. Research strategy and methodology

In answering the questions in Section 1.1 we use sediment data and compare that to results from an iceberg-ocean coupled model (Levine and Bigg, 2008). We examine the data along a West to East transect across Denmark Strait, focussing on three sites. In the Kangerlussuaq Trough we merge data from the giant piston core MD99-2322 with a box core HU93030-019B; in the Djupall Trough, NW Iceland, we use the giant piston core MD99-2264 and merge data with the box core MD99-2263 from the same location; finally off North Iceland we use the giant gravity core JR51GGC35 (Fig. 1, Table 1). Henceforth we refer to the cores simply as 2322, 2264, GGC35. It is important to note that repeated coring on the seafloor of Denmark Strait itself indicates that mid- and late Holocene sediments are not present (Andrews and Cartee-Schoofield, 2003) because of the high current velocities in the Denmark Strait Overflow Water (Jochumsen et al., 2012).

2.1. Chronology and lithofacies

The detailed radiocarbon-based chronologies for these three well-dated sites have been presented elsewhere (Bendle and Rosell-Mele, 2007; Stoner et al., 2007; Ólafsdóttir et al., 2010; Jennings et al., 2011) and are summarized here (Fig. 2). The dates were obtained on a variety of marine carbonates as detailed in these papers. The calibrations are all based on an ocean reservoir correction of 400 yr ($\Delta R = 0$; Eiriksson et al., 2004). 210Pb and 137Cs data show that the box cores retained sediment younger than AD 1960, and are used to derive the sediment accumulation rate (SAR) for the first 100 yr (Smith et al., 2002; Andrews et al., 2009a) – the SAR for sites 2322 and 2263 are 20 and 8 cm/100 yr respectively. The date from 0.5 cm in GGC35, however, is 476 ± 36 BP (calibrated age range AD 1950 to 1829, median age AD 1862 ± 62) indicating the possible loss of some near-surface sediment. The chronologies for the sites 2322 and 2264 are controlled by 20 and 12 radiocarbon dates, plus key Icelandic tephras (Jennings et al., 2002a, 2013; Ólafsdóttir et al., 2010); GGC35 has 10 radiocarbon dates (Bendle and Rosell-Mele, 2007). The “Chron-Rater” scores (Kaufman et al., 2013) for the three sites are 3.08, −0.47 and 0.96 respectively, which compare to a mean score on 106 Arctic terrestrial and marine sites of 0.68 ± 2.38 (range 7.05 to −4.08). Thus, as is evident on Fig. 2, the most securely dated core is 2264 followed by GGC35 and then 2264.

Calibration of basal radiocarbon dates (Oxcal 4.2) from the two box cores and core-top dates from the companion giant piston cores, 2322 and 2264, indicate an overlap in the median cal ages of 151 and 925 yr respectively. For these two sites the qXRD data are

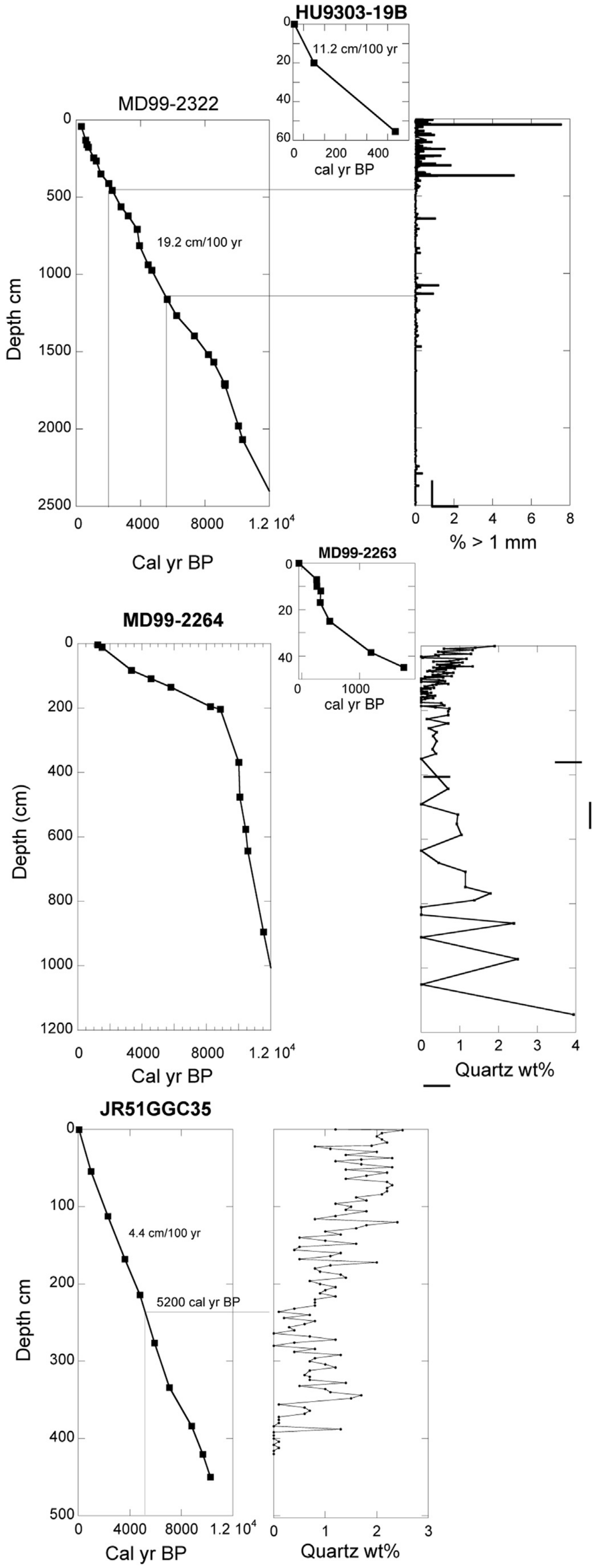

Fig. 2. Depth/age models for the three sites. A) MD99-2322 and HU93030-19B, and the wt% of IRD >0.5 mm. B) MD99-2264 and MD99-2263 and quartz wt% for MD99-2264. C) JR51GGC35 and quartz wt%.

merged based on their interpolated ages from each depth/age model. At our three sites the average Holocene SARs are (west to east) 212, 24, and 42 cm/ka. SARs are essentially monotonic at all sites for the last 8000 cal yr BP (Fig. 2) but with faster rates in the early Holocene. Thus, as sediment densities do not vary greatly across the region (Andrews et al., 2002) IRD sediment flux will be closely associated with the wt% of that sediment fraction. Sampling at 100-yr intervals was undertaken on the basis of the depth/age data (Fig. 2), thus allowing for the recovery of century-scale proxy records.

The lithofacies at the three sites have been presented in previous publications (Geirsdóttir et al., 2002; Bendle and Rosell-Mele, 2007; Jennings et al., 2011). They consist of relatively massive, very poorly sorted, bioturbated muds with varying amounts of sand. Only site 2322 has scattered IRD clasts (see later). The coarsest sediments are found at site 2264 on the Djupall Drift and reflect strong current activity, whereas the most glacial proximal site, 2322 (Fig. 1), is dominated by fine silt-size sediments.

2.2. *Ice-rafted sediments*

An implicit assumption in many IRD studies is that the IRD proxy is proportional to the iceberg flux, however, other factors may have an effect, such as changes in sediment entrainment or ocean climate (Warren, 1992; Clark and Pisias, 2000; Death et al., 2006). Previous studies of the presence and variations in IRD in the Denmark Strait area have focussed on two approaches. The first has been counts of clasts >2 mm on core X-radiographs (Grobe, 1987). Counts are undertaken in 2-cm wide intervals down-core and are a standard method employed on Polarstern cores (Evans et al., 2002; Stein, 2008). A modification of this approach was to obtain the weight % of very coarse sand (≥0.5 mm) from sieved sediment samples (Jennings et al., 2011) (Fig. 2A). On X-radiographs >2 mm clasts are a persistent feature in East Greenland shelf sediments between 69° and 66°N with a simple three-part division during the Holocene, with an early Holocene interval of pervasive IRD, followed by an interval of ~3000 yr with virtually no IRD, and then an increase in IRD during the last 4000 cal yr BP (Andrews et al., 1997; Jennings et al., 2002b). A regional study of variations in the count of IRD clasts >2 mm (Pirrung et al., 2002) shows a swath of high IRD values extending along the inner NE Greenland shelf. The IRD counts decline across the shelf, and in a study of IRD counts on the Greenland side of Denmark Strait, Andrews et al. (1997) showed that IRD declined away from the coast as a power function of distance. Pirrung et al. (2002)'s data suggests that the IRD from E/NE Greenland sources does not have a strong SE component toward Iceland. Large (>2 mm) size clasts are a relatively small fraction of most glacial diamictons, which tend to have a bimodal wt% grain-size distribution (Dreimanis, 1982; Drewry, 1986; Andrews and Principato, 2002). Thus the probability of encountering IRD clasts >2 mm decreases along the transport path (Death et al., 2006), because of preferential gravitational settling of the larger clasts, and the IRD signal has to be searched for in the <2 mm fractions. Thus, for example, this approach to IRD identification does not work on the Iceland shelf where visible coarse IRD is very rare or absent over the last 10,000 cal yr BP.

The second approach to IRD identification has focussed on sediments from the Iceland shelf, where the identification of quartz in sediment is used to argue for an ice-rafting signal (Eiriksson et al., 2000; Moros et al., 2006; Andrews et al., 2009b) (Fig. 2B & C). This is because Icelandic basalt lacks quartz (Fig. 3D). However, neither the IRD counts nor the identification of quartz carries any specific information on the probable source region(s). Bond et al. (1997) counted sand grains, which were stained red by haematite (HSQ grains), including sediments from VM28-14 (Fig. 1) at the mouth of Denmark Strait. A possible source for these grains was the outcrop of Devonian red sandstone in NE Greenland (Reeh et al., 1999; Alonso-Garcia et al., 2013), which lies within the Caledonian basin (Fig. 1). However, this is not a unique tracer of a source as red beds outcrop over a wide area of the Arctic (Bond et al., 1997).

However, neither IRD counts nor data on quartz occurrence define the IRD source(s); thus, in order to define source areas for East Greenland and Iceland IRD we have successfully used qXRD on the <2 mm fraction of seafloor surface sediments to define regional mineral compositions (Andrews and Eberl, 2007; Andrews et al., 2010) (Suppl. Table 1A). The data were obtained on samples carefully retrieved from the upper centimetres of grab samples. Given the SARs on the Iceland and East Greenland continental shelves (e.g. Smith et al., 2002; Alonso-Garcia et al., 2013) such sediments usually represent late to mid- 20th Century deposition. Downcore samples from the three sites (Table 1) were also processed in the same way (see below). The qXRD approach uses the methods detailed in Eberl (2003) and previously presented for the areas on either side of Denmark Strait (Andrews et al., 2009b, 2010). The samples are run on a Siemens D5000 X-ray diffractometer using Cu- radiation between 5° and 65° 2Θ, scanning every 0.02° 2Θ at 2 s. We process the qXRD output data in Rockjock v.6 (Eberl, 2003) and obtain weight% data for 23 non-clay and 10 clay minerals, including nine varieties of feldspar (Suppl. Table 1A). Feldspars are notoriously difficult to identify because of solid solution substitutions and our identifications are based solely on mineral standards embedded within Rockjock v.6 (Eberl, 2003). A goodness-of-fit statistic is calculated based on comparison of all the HKL indices from XRD runs of standard minerals.

To avoid bias in down-core trends the data are not processed in any specific sequence. Reproducibility is ±1.0% and the average bias (absolute difference between measured and calculated (from qXRD)/number minerals) is generally ≤ 3% wt. The qXRD data will be deposited in the NOAA Paleoclimate data base (www.ncdc.noaa.gov/paleo/data.html).

We demonstrate the contrasts in the average surface mineralogy wt% along the E/NE Greenland shelf and around Iceland in Fig. 3A–D. For illustrative purposes we have simplified the mineralogy by excluding many species with values <2% and grouping other minerals, such as the plagioclase feldspars, smectites, and illites (Fig. 3) (Suppl. Table 1A and B). On the regional scale the data indicate that quartz diminishes drastically south of Scoresby Sund where values of >20 wt% are replaced by values <10 wt% in sediments shed from the Geikie Plateau (Fig. 3A, B and G), although these increase at the mouth of Kangerlussuaq Fjord (Andrews et al., 2010) (Fig. 3C). Along the inner N Iceland shelf and off SW Iceland, quartz is not detectable (<1 wt%). In contrast, pyroxene reaches maximum values around the coast of the Geikie Plateau, with this maximum extending across Denmark Strait and around Iceland (Fig. 3B & D). Dark mafic IRD clasts were retrieved from cores off W Iceland (MD99-2262) and within Nansen Fjord (Nf) (Fig. 1) – they were crushed, milled, and processed (Fig. 3E and F). The Iceland basalt has large differences from the Iceland surface sediments, which can largely be attributed to the extensive accumulation of volcanic glass (amorphous silica) on the Iceland shelf (Andrews et al., 2013). Amorphous silica also includes the contribution from diatoms, fine-grained chert, and finely ground quartz (Andrews et al., 2013).

In order to derive a quantitative estimate of the fraction of sediments that can be attributed to specific source areas (i.e. Fig. 3) we use the non-linear unmixing program SedUnMix (Eberl, 2004; Andrews and Eberl, 2012) (Suppl. Table 1C). This allows up to six sources, each represented by up to 5 samples. Random variations in the contributions of each of the 5 samples per source allows an

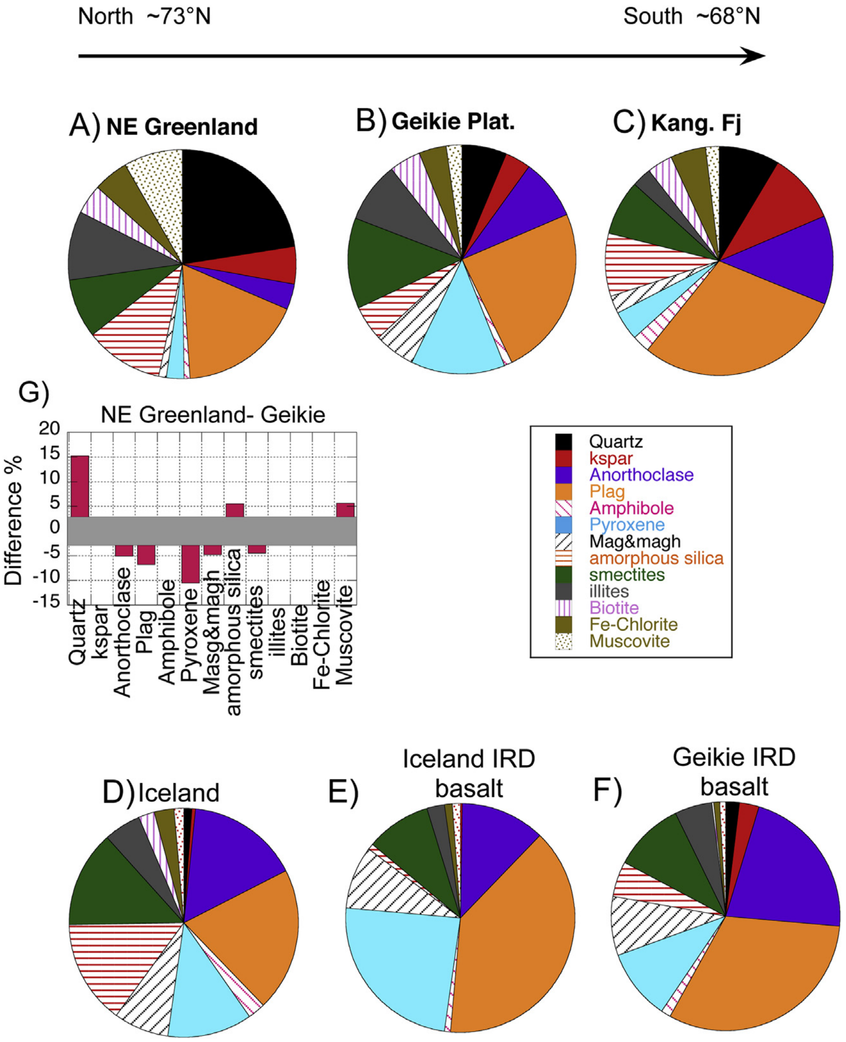

Fig. 3. Pie diagrams of average surface mineral wt% compositions for A) NE Greenland, B) areas off Geikie Plat, C) Kangerlussuaq Fjord, D) Iceland shelf, and E) and F) mineral composition of mafic IRD clasts from Iceland (MD99-2262, West Iceland) and JM96-1210 Nansen Fjord (Fig. 1). G) Shows the difference in wt% between surface NE Greenland samples and from the seafloor off from the Geikie Plateau. The shaded grey area blocks differences of ±2%.

error estimate to be made on the final fraction attributed to a specific source.

2.3. Coupled ocean-iceberg modelling

The ocean component of the coupled model is a curvilinear general circulation ocean model, with its North Pole displaced to central Greenland to increase horizontal resolution in the North Atlantic and Arctic (Wadley and Bigg, 2002; Bigg et al., 2005), in this case to <0.5° locally but ~1–2° in the Southern Hemisphere. The sea ice component is a thermodynamic model with simple advection (Wadley and Bigg, 2002). The coupled iceberg component (Levine and Bigg, 2008) is a dynamical and thermodynamical iceberg trajectory model (Bigg et al., 1996, 1997), with a range of iceberg sizes released from the main Northern Hemisphere calving sites, carrying a weighting scaled by an estimated iceberg flux from each site (Levine and Bigg, 2008). Each model iceberg carries a flag denoting the site of its calving. Following a 300 year spinup, the coupled model is run for over a century (1890–2008), forced by daily varying momentum, heat and freshwater fluxes from the Twentieth Century Reanalysis (Compo et al., 2011). This simulation is a measure of recent, interannual to century scale variability in iceberg numbers and mass near the Denmark Strait. A 100-yr data set of monthly iceberg numbers crossing 48° N, off the Newfoundland coast (Murphy, 2011; Bigg and Wilton, 2013) was used to scale the interannual variability of the Greenland iceberg release flux so as to match the model's iceberg flux at this latitude to that observed (Bigg and Wilton, 2013).

3. Down core variations across Denmark Strait

Based on present day surface currents and winds, two potential source areas can be distinguished for the ice-rafted debris on the Icelandic shelf, both of which contribute both sea ice and icebergs. Both the East Greenland Current (EGC) and the East Iceland Current (EIC) transport drift ice from the immediately adjacent area of E Greenland, as well as from further north along the Greenland coast, onto the N Iceland shelf (Fig. 1). It is also plausible that ice transported in the EGC and EIC has source areas in the Arctic Ocean – sea ice formed on the shallow Arctic Ocean shelves entrains sediment, generally in the silt and clay size (Dethleff, 2005; Darby et al., 2009, 2011) and icebergs from the European Arctic can exit the Arctic through Fram Strait (Bigg et al., 1996; Werner et al., 2011). Contributions from such distant sources have been detected on both the Iceland and E Greenland shelves using Fe-oxide geochemistry as a tracer (Andrews et al., 2009b; Darby et al., 2011; Alonso-Garcia et al., 2013), but it was hardly detectable in qXRD mineralogy (Andrews, 2011). On the East Greenland shelf sediment is also carried out onto the shelf in meltwater plumes (Andrews and Syvistki, 1994; Syvitski et al., 1996; Dowdeswell et al., 2010). Sediment transport by meltwater plumes typically has an e-folding metric of tens of kilometres, but these plumes would be deflected southward in the EGC. In addition, the grounding of icebergs remobilizes sediment (Dowdeswell et al., 1993, 1994; Syvitski et al., 2001), and finer fractions can be re-transported by bottom currents. Thus, the identification of ice rafted sediments by grain size or mineralogy rarely results in a 1:1 mapping.

Potential sources for sediment in 2322 (Fig. 1) are therefore estimated to be from: Kangerlussuaq Fjord and the Geikie Plateau, with possible contributions from Scoresby Sund and sources to the north (Fig. 3). We expect the sediments in 2264, 294 km east of 2322, off NW Iceland to be predominantly sourced from local Icelandic basalt, but with contributions from across Denmark Strait and sources to the north. For example, 40Ar/39Ar dates indicate that early Cenozoic basaltic clasts from East Greenland were transported into the Djupall Trough (Principato et al., 2005, 2006). Site GGC35 (Bendle, 2003; Bendle and Rosell-Mele, 2007) lies 274 km east of 2264 (Fig. 1) and is in a position where Iceland-derived sediments could be mixed with IRD from E/NE Greenland and the Arctic Ocean (Andrews, 2011). Investigation by Darby of the Fe-oxide grains in B997-316PC (48 km west of GGC35, Fig. 1) showed a contribution from several sources around the Arctic Ocean (Andrews et al., 2009b). Core 2322 lies ~270 km northwest of VM28-14 (Fig. 1), hence we would expect some similarities in their Holocene IRD.

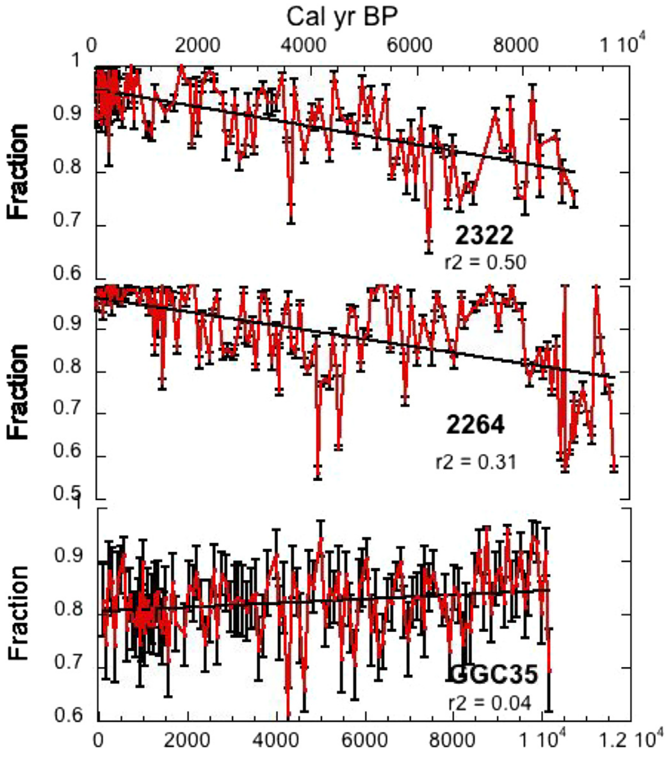

Fig. 4. Fraction of sediment with a similar composition to the uppermost 5 samples from the three cores (2322, 2264 and GGC35) in the West to East transect (A, B and C) (Fig. 1). The line in each graph is the best-fit linear trend and the fraction of the explained variance, r^2 is shown. The vertical black bars are the ± standard errors about the mean.

3.1. Changes from "recent" mineral composition

Our first objective is to document the degree of difference between "recent" sediments and the remainder of the Holocene. To quantify this we have used SedUnMix on each core with one source, that is the top 5 samples from each site – we present all results in the West to East sequence: 2322, 2264, GGC35 (Fig. 4). We reduced the non-clay and clay mineral species by eliminating the wt% of calcite, because it can be either an in situ marine productivity indicator (Andrews et al., 2001) or reflect erosion of limestone outcrops on NE/NW Greenland or from the Canadian margins of the Arctic Ocean (Stokes et al., 2005). We also eliminated other species that were minor contributors – the data (Suppl. Table 1C) were then normalized to sum to100%. Samples from 2322 to 2264 were taken from their respective box cores (Fig. 2A and B) with a 1-cm sampling interval and represent the last 100 yr; the GC35 samples represent the last 300 yr. Although not identical in age range, the comparisons (Fig. 4) reflect long-term changes in mineral composition. The results show the estimated fractional similarity of each down-core sample with the upper 5 samples (Fig. 4); they portray a series of marked oscillatory records indicating changes in the relative importance of source(s) at each site. In all three cases there is a trend toward values becoming increasingly similar to present-day values, although the trend is very weak at GGC35 (Fig. 4).

3.2. Changes in sediment sources across Denmark Strait

In this section we present the results of using SedUnMix on our West to East transect of cores (Fig. 1); an earlier version of SedUnMix was used to unmix down-core changes at site 2322 (Andrews et al., 2010). Site 2322 lies in a position to receive glacially derived sediment from the main Kangerlussuaq ice stream (Syvitski et al., 1996), as well as from a variety of other tidewater glaciers within that fjord and along the Geikie Plateau (Smith and Andrews, 2000; Seale et al., 2011). There are also numerous sources for icebergs within Scoresby Sund and the fjords to the north (Bigg, 1999; Reeh et al., 2001; Seale et al., 2011). Sediment can also be carried in Arctic Ocean sea ice (Darby et al., 2011) and deposited on the E Greenland and Iceland shelves (Alonso-Garcia et al., 2013). However, this appears to be a very small fraction of the total sediment inputs (Andrews, 2011).

We have presented the results of a mixing experiment on samples from Kangerlussuaq and Nansen fjords (Alonso-Garcia et al., 2013), which showed that SedUnMix provides a close match to the known sample mixes from these fjords. Given the bedrock variations within the area, it is probable that even 5 subsamples per source will not capture the mineralogical range of possible sources. To circumvent this problem we ran SedUnMix on the down-core mineralogy of 2322 with 4 sources, two sets from sediments within Kangerlussuaq Fjord, and two sets from different fjords (Mikkis and Nansen) within the early Cenozoic outcrop. The fractions and errors were summed for the two primary sources (Taylor, 1997). SedUnMix indicated that the sediments in Kangerlussuaq Trough have a larger fraction attributable to sediments from the Geikie Plateau rather than Kangerlussuaq Fjord. Excluding two outliers there is an inverse relationship between the fractions of sediment ($r^2 = 0.8$). However, the attribution to the latter source has a much more distinctive signal (Fig. 5A), which is similar to that presented previously from earlier versions of SedUnMix (Andrews, 2011). Further investigation revealed that 60% of the variance in the Kangerlussuaq Trough fraction was positively associated with changes in quartz wt%. The records show a rapid increase in sediments associated with Kangerlussuaq Fjord, hence an increase in quartz wt%, with a regime shift shortly after 4000 cal yr BP.

Site 2264 lies close to Denmark Strait and some 55 km from the mouth of Isarfjardjup (Andrews et al., 2009a; Ólafsdóttir et al., 2010) and essentially at the same location as KN 158-4-72GGC (Andresen et al., 2005). qXRD and SedUnMix have also been obtained from another nearby core JM96-1232 (Table 1) and these data are used later in this paper to gain an insight into source variability. Potential sediment sources at 2264 include the local NW Iceland bedrock, and far-travelled (exotic) sources associated with drift ice (Koch, 1945). IRD basaltic clasts from a site off W Iceland (MD99-2262, Fig. 1) were used as a source (no quartz), as were quartz-free sediments from inner NW Iceland shelf sites (Andrews and Eberl, 2007). The result of comparing sediments from 2264 with samples from Iceland sources, plus three sources from across Denmark Strait (Kangerlussuaq Fjord and two sources from the Geikie Plateau), (Fig. 5B) indicate the combined exotic inputs have a similar pattern to those noted at 2322 (Fig. 5A), especially with the increase after 4000 cal yr BP (Fig. 5C). However, this increase is associated with inputs that are dominated by sources from the Geikie Plateau. Andresen et al. (2005) stressed the variability in a nearby core, and the importance of storms in contributing to millennial and century-scale changes in grain-size and petrology of sand in the Djupall Trough, where 2264 is located.

GGC35 lies well east of Denmark Strait (Fig. 1) in a location more closely linked to the East Iceland Current and the North Iceland marine front, which lies between the EIC and the North Iceland Irminger Current (NIIC) (Belkin et al., 2009). The mineral data were processed using the same 4 sources as for NW Iceland, although this site is better placed to receive IRD inputs from NE Greenland and the Arctic Ocean (Andrews, 2011). The results (Fig. 5D) mirror to a reasonable degree those from NW Iceland (Fig. 5B) with a marked rise in far-travelled contributions to the sediment archives starting about 4000 cal yr BP ago. However, as with 2264, this contribution was most closely associated with sources linked to the Geikie Plateau. The trend in the overall increase in far-travelled minerals is matched by a parallel, but negative, trend in the SST record from this site (Bendle and Rosell-Mele, 2007).

An issue we briefly examine here is which mineral species most closely associated our estimates of the fraction of ice-rafted sources

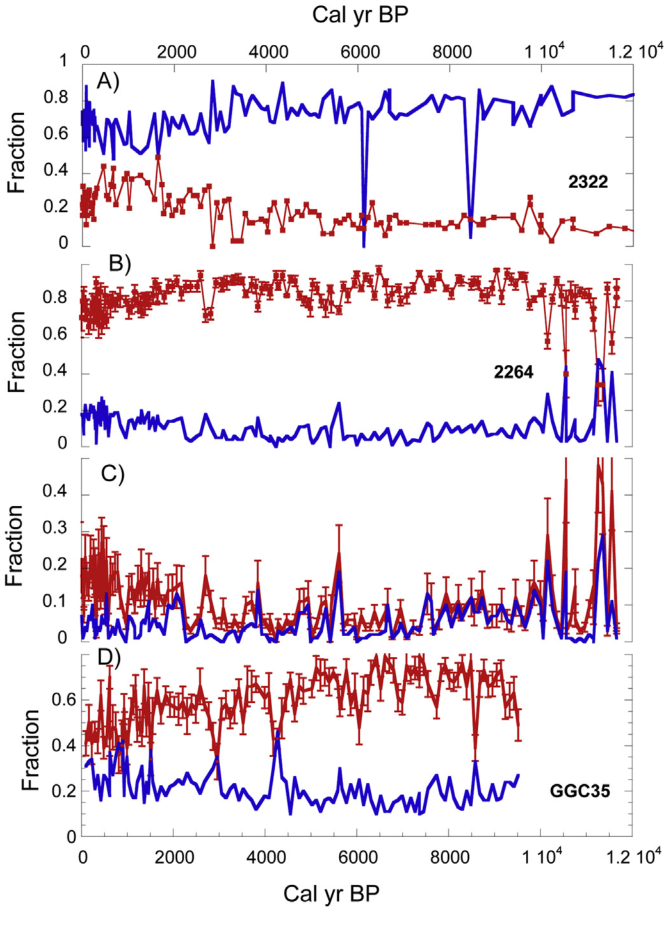

Fig. 5. A) Fraction of sediment in 2322 attributed to Kangerlussuaq Fjord (red) versus the Geikie Plateau (blue, upper curve). ±1 Standard error bars on the mean are shown. B) Fraction of sediment in 2264 from local (NW Iceland) sources (red, upper line) versus from Kangerlussuaq Fj. and Geikie Plateau (blue, lower curve). C) Comparison of the estimated fractions from Kangerlussuaq Fjord (red) and Total non-Icelandic (blue) in 2264. D) Fraction of Icelandic (red, upper) versus foreign (East Greenland) (blue, lower) sediment in GGC35. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

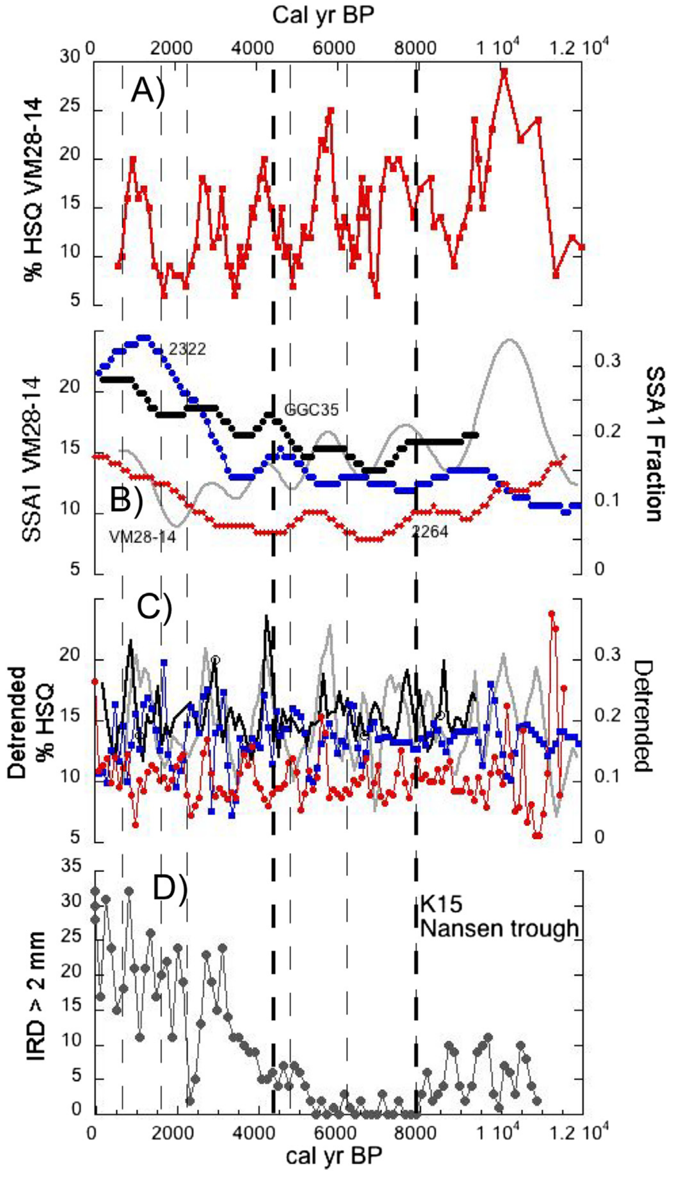

Fig. 6. A) Percent of haematite stained quartz grains (HSQ) in VM28-14 (see Fig. 1). B) Singular spectrum analysis trends on the haematite stained quartz from VM28-14 (Fig. 1) (grey line) (Bond et al., 2008) versus the "foreign" mineral data from 2322, 2264, and GGC35 – data sampled at 100-yr intervals; C) Residuals from the trends (Fig. 6B) D) Counts of IRD >2 mm in 2-cm thick slices in core BS1191-K15 from Nansen Trough (Fig. 1) (Andrews et al., 1997). The thick dashed lines represent proposed divisions of the Holocene (Walker et al., 2012) and the thin grey dashed lines are "cold events" from Wanner et al. (2011).

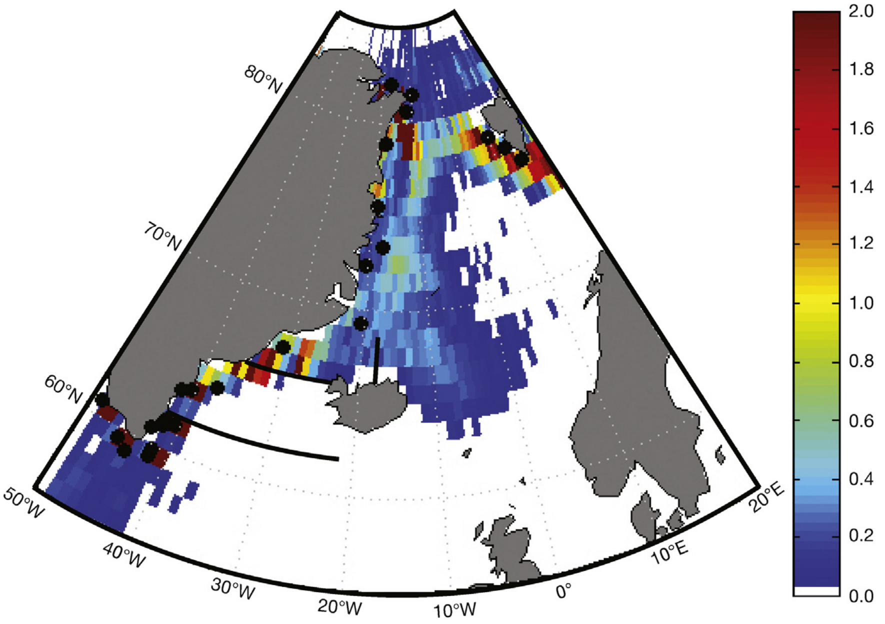

Fig. 7. Average modelled iceberg density map for the NE Atlantic, showing the release sites (solid black circles) and the three lines (in bold) where iceberg numbers were counted. The density scale is number of icebergs per 1° × 1°; for display purposes it is capped at 2, but locally, near calving sites, is much higher. The coastlines show the model grid, interpolated to a Lambert conical projection. Note that the release sites are off-shore of the Greenland coast, to remove numerical issues with model bergs escaping from fjords.

off Iceland (Fig. 6B–D). We investigate this by employing multiple stepwise regression, using the fraction of far-travelled sediment as the dependent variable and the wt% of the minerals (Suppl. Table 1C) as the independent variables. Rigorous interpretation of the results are complicated by the closed array problem (Chayes, 1971). At GGC35 quartz, microcline, and oligoclase are positive coefficients and pyroxene in negative and 53% of the variance in the far-travelled fraction (Fig. 6D) is associated with these 4 species. The explained variance at site 2264 is much lower (20%) but quartz (+) and pyroxene (−) were the primary selected minerals. These analyses confirm the importance of quartz as an index of IRD off Iceland (Moros et al., 2006) but the SedUnMix compositional approach used here better indicates source(s) of the IRD (Fig. 6).

3.3. Time-series analyses

Each record on Fig. 5 was integrated in AnalySeries (Paillard et al., 1996) to produce 100-yr step time series; these data were analysed for significant periodicities using kspectaTM (Ghil et al., 2002). We also compared these data with the HSQ data from VM28-14 (Bond et al., 1997, 2008) as, given the proximity to our sites (Fig. 1), we might expect common IRD signal(s), however, this is not the case (Fig. 6).

The records of the IRD contributions (Fig. 5) and HSQ grains from VM28-14 show little correspondence. In contrast to the records from 2322 to 2264, where IRD has an increase toward the present-day, the HSQ data (Fig. 6A) show a persistent decrease in this inferred IRD component; this trend accounts for 60% of the variance (Fig. 6B). After this trend is removed, Multi-Taper Method (MTM) analyses show three strong (99% confidence) periodicities of 1390, 820, and 470 yr. The 1st component of the Singular Spectrum Analysis (SSA) for 2322 accounts for 71% of the variance and, when removed, MTM analyses indicate significant periodicities (95% CI) of 670 and 480 yr. The 1st SSA explains 38% and 42% respectively for the two Iceland sites (Fig. 6B); MTM was performed on the two detrended series although the "trend test" in kspectra only indicated it was significant for GGC35. The analysis resulted in significant periodicities of 1040, 660, and 370 yr in 2264, compared to a single significant periodicity (99%CI) of 650 yr in GGC35. In a study of 18O records from the Hulu Cave, GRIP and GISP2 Clemens (2005) noted widespread evidence in Holocene records for ~500, 350, and 286-yr periodicities and suggested a link with solar variability.

In all regards, the HSQ data from VM28-14 (Fig. 6A–C) has little similarity with our IRD data (Fig. 5) that are only ~300 km away (Fig. 1). We return to this conundrum in the Discussion. We also briefly note a calculation of the sediment fluxes (M L2 T-1) associated with iceberg rafting across our section. As noted earlier, sediment densities are similar in the region (Andrews et al., 2002), hence the key variable is the sediment accumulation rate (SAR, L T-1) and thus the flux of IRD material will decrease, on average, by an order of magnitude across Denmark Strait (Fig. 2).

4. Application of the iceberg model

Our three core sites have the main contribution of their "foreign" material stemming from the region of the Geikie Plateau, both down-core (Fig. 5) and at core top (Fig. 4). Given that the two principal currents in the area, the EGC and EIC, transport sea ice from further north along the NE Greenland coast (Kwok, 2000; Bigg and Wilton, 2013), this was unexpected. One way to confirm this finding is to use the iceberg trajectories from the coupled iceberg-ocean model for the twentieth century (Bigg and Wilton, 2013). The model has approximately 100 calving sites globally, with 70 in the Northern Hemisphere, and about a dozen along the East Greenland coast (Fig. 7). To quantify the iceberg flux through the Denmark Strait and off N Iceland three lines were used (Fig. 7) where icebergs crossing the lines were counted, and their origin noted. The variation in the iceberg number crossing the Denmark Strait and NE Iceland lines shows considerable interannual variability (Fig. 8), as is also the case for the observed 48°N section, off Newfoundland (Bigg and Wilton, 2013). South and east of the Denmark Strait the numbers of modelled icebergs are very much less, with declines of over 80% in the mean over 400 km (Fig. 8). This rapid decline with distance suggests that the modelled Denmark Strait icebergs are largely locally derived, as is indeed the case (cf. Fig. 9A, C). This is true throughout the twentieth century (Fig. 10A). Note, however,

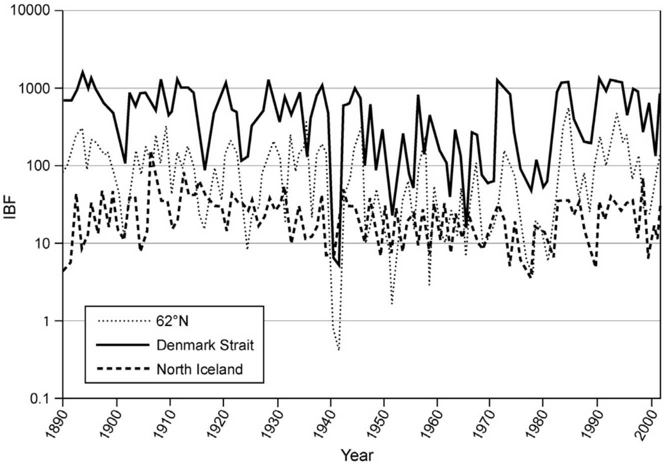

Fig. 8. Annual modelled iceberg flux (IBF), in numbers, during 1890–2008 crossing the Denmark Strait (bold), the N Iceland section (line) and 62° N off East Greenland (dashed). All lines are shown in Fig. 7. Note the use of a log scale, to make comparison between the different sections easier. The 62° N line is at about the same distance south of 2322 as GGC35 is east of it.

that for the NE Iceland line the iceberg model suggests the EIC carries a greater proportion of icebergs from further north, even from the Arctic (Fig. 9B), although the total number of icebergs modelled to reach the vicinity of GGC35 is an order of magnitude smaller than the Denmark Strait flux (Fig. 8), with approximately a sixth of the number of more northerly-origin icebergs reaching GGC35 than passing through the Denmark Strait (Fig. 10B).

The iceberg-ocean model results agree with the core data in suggesting IRD in the Denmark Strait and environs has a local origin: the Geikie Plateau. However, does the model adequately represent the real world, and, particularly, is its variability through the twentieth century consistent with down-core variation? The core data shown here were converted to 100-year timeseries for much of the analysis. However, some cores in the Denmark Strait off NW Iceland have higher temporal resolution than this within the twentieth century (MD99-2263 & JM96-1232). The combined core record has 7 data points stretching across the twentieth century and a SedUnMix calculation has been carried out on this combined core. Most of the material is of local, Icelandic, origin, but 7–25% is attributable to East Greenland sources, mostly from Nansen Fjord off Geikie Plateau. We hypothesize here that the variation in this percentage through the twentieth century is related to the iceberg number in the Denmark Strait. While core dates are notionally given to 1-yr accuracy the samples will actually represent a time period inversely proportional to the SAR (Table 1). Correlations of the percentage variation with modelled Denmark Strait iceberg number (and mass) were performed over a range of timescales. The best relationship was found with 20-yr smoothing of the iceberg number (Fig. 11). This period relates well to the mean temporal spacing of core dates. The linear correlation was $r = 0.66$; this is only statistically significant at the 10% level but, given the nature of the processes required to produce the two sets of data, this is a satisfactory level at which to claim that the model iceberg flux and down-core East Greenland fraction are related.

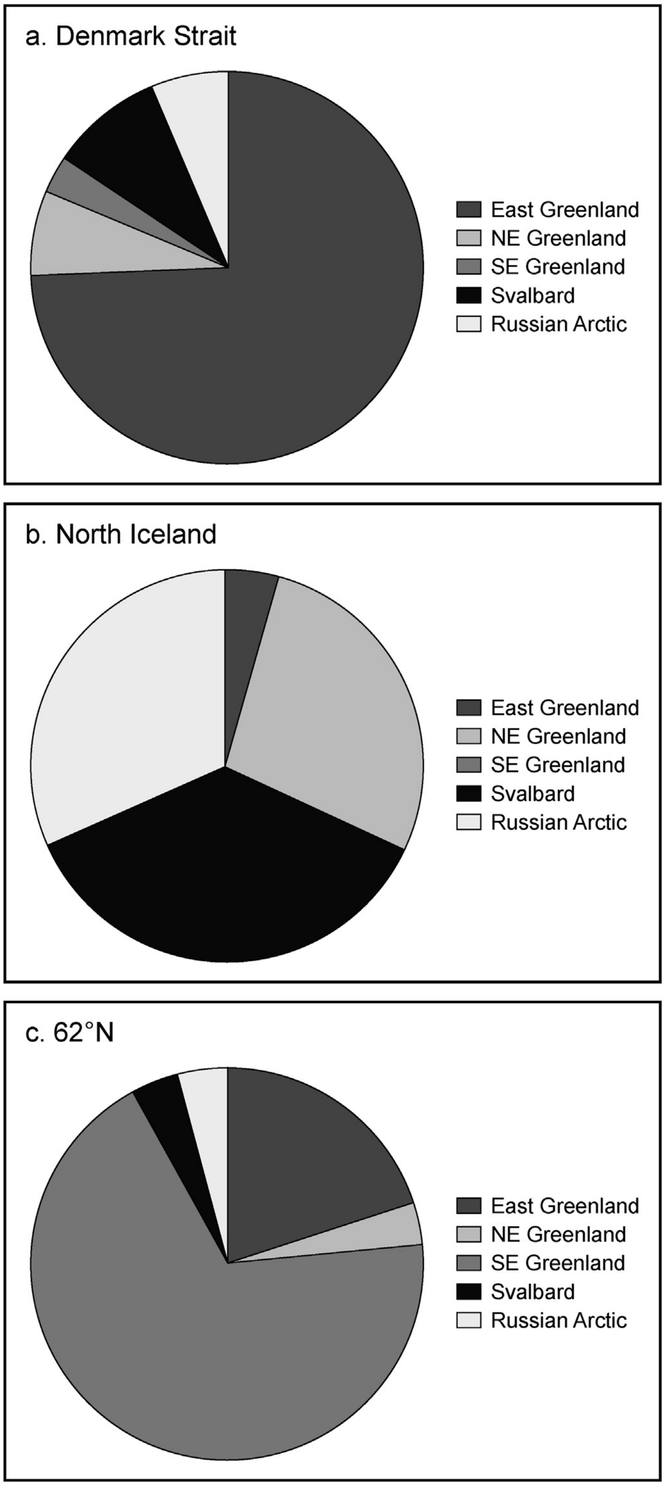

Fig. 9. Origin of twentieth century modelled A) Denmark Strait, B) NE Iceland and C) 62° N icebergs. “East Greenland” largely refers to the Geikie Plateau sources, while SE Greenland icebergs are from Kangerlussuaq Fjord south and NE Greenland icebergs are from north of Scoresby Sound. “Arctic” refers to all iceberg sources bordering the Arctic Ocean, including Svalbard.

5. Discussion

We can now answer the questions posed in the Introduction.

1) What are the present-day non-clay and clay mineral distributions across the Denmark Strait and northward along the Greenland shelf? This question has been answered and partly illustrated in Figs. 3–5. The changes in the bedrock geology of NE Greenland (Fig. 1) are reflected in the dramatic changes in the mineralogy of surface sediments (Fig. 3A–C), especially in the decrease of quartz off-shore from the Geikie Plateau and the concomitant increase is species such as maghemite, pyroxene

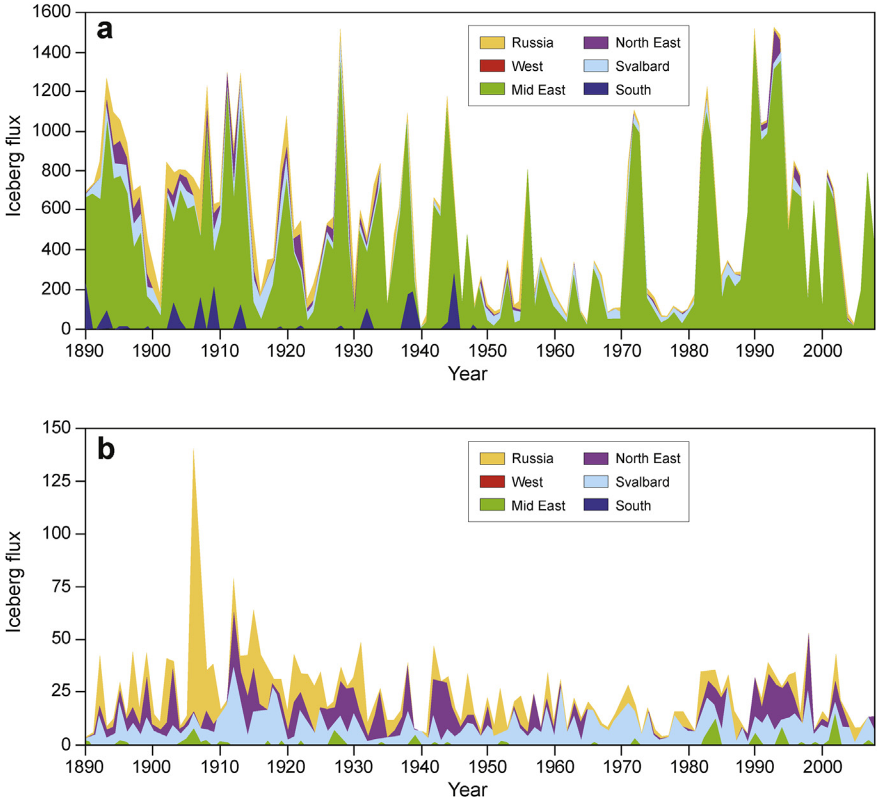

Fig. 10. A) Variation in sources of Denmark Strait iceberg number in the iceberg-ocean model, over 1890–2008. "Mid-East" here largely corresponds to the Geikie Plateau sources of Greenland. B) Variation in sources of NE Icelandic shelf icebergs in the iceberg-ocean model, over 1890–2008.

and smecite. The eastward transport of sediment from glaciated Greenland is illustrated by the contrast in mineralogy between IRD Icelandic basalt and Icelandic seafloor sediments (Fig. 3E and D).

2) What fraction of the sediment on the North Iceland shelf is derived from E/NE Greenland? The SedUnMix modelling indicates that downcore variations in mineral composition are well explained by local sources plus a combination of sediments derived from the "felsic" Kangerlussuaq Fjord and the more mafic outcrops of the Geikie Plateau. The fraction of sediment transported from East Greenland to Iceland varies (Fig. 5), averaging 0.1 and 0.2 for 2264 and GGC35 respectively but with considerable variations.

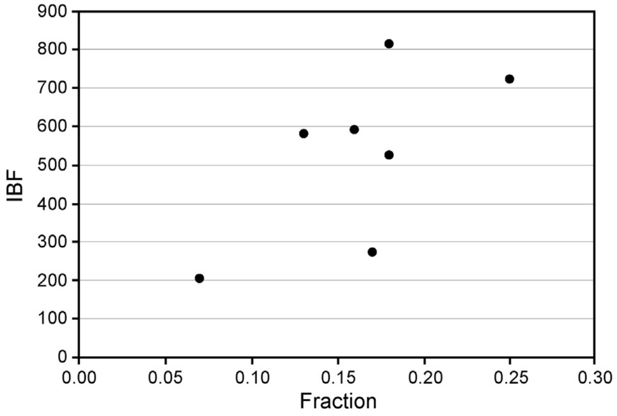

Fig. 11. Correlation plot of East Greenland fraction from the twentieth century samples from the combined cores JM96-1232 & MD99-2263 with the 20-yr smoothed Denmark Strait IBF. See legend for Fig. 8 for definition of IBF.

3) Can we target source areas for "foreign" material? Both the downcore data (Figs. 4 and 5) and the iceberg-ocean model (Fig. 9) suggest that much of the "foreign" material in the Denmark Strait cores derives from the Greenland coast along the Geikie Plateau (Fig. 1). They also suggest similar proportions of Geikie Plateau material compared to "foreign" sources further afield: an average of 68% for the downcore material (today-9700 cal yr BP, combined core JM96-1232 & MD99-2263) and 74% from the iceberg-ocean model (1890–2008 across Denmark Strait). The remaining "foreign" material comes from a range of other drift ice sources along the E Greenland coast and elsewhere in the European Arctic. These, and their variation in importance during the twentieth century, are shown for the iceberg-ocean model in Fig. 10A. This shows a more complex picture than our simple averages suggest, as there are minor variations in the contributions from sources on sub-decadal to sub-centennial scale.

At the easternmost site of GGC35 there is more difference between the data and model analyses. While both show that East Greenland sources are important constituents of "foreign" material and both suggest an order of magnitude decline in the SAR, the model results suggest that icebergs of European Arctic origin should provide the majority of this material (Fig. 9B). There is also paleoceanographic evidence for more severe conditions near the largest Svalbard ice mass of Nordaustlandet in the last few millennia (Kubischta et al., 2011) that is consistent with a higher European Arctic iceberg flux.

However, the model source region varies dramatically with time, partly because so few icebergs make up the signal (Fig. 10B). Thus, over the whole period of 1890–2008 32% of model icebergs are locally derived, but this rises to 45% during 1981–2008. With so few icebergs contributing to the core signal compared with the Denmark Strait, and the inherent large interannual variability in both number and source, it is not surprising that there is some discrepancy between core and model analyses at this location. The iceberg model is also known to not melt its icebergs as quickly as observed (Gladstone et al., 2001) and this means that the Arctic signal off N Iceland may be artificially high.

4) Do these sources vary in importance across the N Iceland shelf? As both a percentage and absolute flux, the model suggests that there is a decrease in E Greenland material from west to east (Fig. 9). However, while the core SARs agree with the model's reduced flux, the SedUnMix analyses suggest relatively similar proportions of E Greenland material across the section, with the least at the central site of 2264 (Fig. 5). It is worth noting, however, that the stations are varying distances from shore, with the lowest "foreign" fraction at the most inshore station (2264), The pyroxene field (Fig. 3D) is consistent with a west to east decrease.
5) Have they varied during the Holocene? The evidence for ice-rafted transport in the west to east transect (Fig. 1) across Denmark Strait in the <2 mm sediment (Fig. 5) mirrors the coarse IRD fraction from sites on the inner East Greenland shelf (Andrews et al., 1997) (Fig. 6D) and confirms a broad 3-part division of the Holocene in terms of the importance of IRD, the timings of which conform to the suggestions of a formal tripartite division of the Holocene (Walker et al., 2012), with transitions at 4200 and 8200 cal yr BP (Fig. 6). These boundaries are similar in age to two of the six Holocene cold events defined by Wanner et al. (2011) (Fig. 6D). One possible reason for this variation is that the sources of icebergs varied through the Holocene, with more from further north before 4000 cal yr BP (e.g. Fig. 10A). This could have come about because of climate change affecting ocean circulation, and hence the relative survivability of icebergs from different sources on their journey to the Denmark Strait. Distinct climate change is seen in the local SST trend at site GGC35 (Bendle and Rosell-Mele, 2007). However, another possibility is that climate change led to sufficient alteration in the Greenland Ice Sheet margins that the available calving sources have shifted over time. Peltier's (1994) ice sheet reconstructions have the Greenland Ice Sheet at a minimum fairly early in the Holocene, but growing again in East Greenland 3–5000 cal yr BP. Qualitatively, this potential for marginal change is also seen from the geographical distribution of those marine-terminating glaciers in Greenland that appear to have relatively recently retreated onto land, from inspection of Landsat images. The Geikie Plateau has a noticeable concentration of these.

We also return here to the discrepancy in periodicity between the weakly, sub-millennial, oscillatory behaviour of the three cores studied here along the Denmark Strait and N Iceland axis and the strongly 1500-yr periodicity in IRD of nearby VM28-14 (Fig. 1). There clearly is a ~1500 year periodicity in a range of Holocene climate variables (Bond et al., 1997; Bianchi and McCave, 1999; Thornalley et al., 2009; Giradeau et al., 2010; Darby et al., 2012). However, we have seen here that the origin of icebergs in the Denmark Strait is very local (Figs. 5 and 9). Given the absence of a strong 1500-yr periodicity in the drift ice provenance in Denmark Strait it is likely that an alternative explanation is required for VM28-14. We suggest that the answer is found in variation in the strength of the Denmark Strait overflow through the Holocene, leading to preferential erosion of bottom sediment at VM28-14, downstream of the sill of the main overflow, but to the east of its core (Hunter et al., 2007), leaving larger particles (and thus a higher %HSQ) during faster flow. It is known that Holocene erosion of sediment is a severe problem in the Denmark Strait (Andrews and Cartee-Schoofield, 2003). The Iceland–Scotland Overflow water shows similar variation south of Iceland (Bianchi and McCave, 1999), in response to a ~1500 year cycle in the properties of the inflow into the Nordic Seas (Thornalley et al., 2009; Giraudeau et al., 2010) which would affect the properties of both principal deep southward exits from the area. Further support for a localization of this strong periodicity is found in a study lacking significant evidence for the signal in the mid-Atlantic (Obrachta et al., 2012), and in evidence for an eastern bias for such a signal in the NW Atlantic (Solignac et al., 2004).

6. Conclusions

The mineralogy of sediments in glacial marine environments potentially reflects contributions from a number of tidewater ice streams and glaciers. Counts of IRD clasts do not delimit source areas, but we show the qXRD analyses can be used to characterize the fraction of sediment contributed from specific areas (Fig. 6) and to document long-term changes in these sources (Fig. 5).

The ice-rafted sediments across the Denmark Strait have been shown to vary in origin from west to east, but with a very clear local contribution. Over 90% of these sediments at the most western site 2322 derive from local, East Greenland sources (Figs. 3B and C, 5A), as is also true for the east Denmark Strait site of 2264, although here "local" is ~80% NW Iceland and 10% East Greenland (Fig. 7B). Further east, on the N Iceland shelf (GC35), the ice-rafted sediment is sometimes a similar percentage, but this varies through the Holocene and more recently, during the period of increasing "foreign" ice-rafted sedimentation. The results of the coupled iceberg-ocean model agree with these general conclusions about the dominance of local sources for the far-travelled sediment, and provide a possible source for the additional non-local sediment in recent millennia, namely, the European or Canadian Arctic (see Fe oxide data in Andrews et al., 2009b; Alonso-Garcia et al., 2013). Future iceberg modelling work dedicated to determining the provenance and magnitude of the Greenland Holocene IRD intends to adapt the sediment entrainment approach of Death et al. (2006) to model the IRD process itself. Furthermore, significant improvement in characterizing sediment provenances can result by combing qXRD mineralogy with X-ray fluorescence chemistry (Eberl, 2008).

The Denmark Strait records also do not show the 1500-yr oscillations found in the nearby core VM28-14 (Bond et al., 2001). As discussed, there are clear climate signals in the Holocene with this periodicity, but the results presented in this paper do not show evidence that this signal is containing directly in IRD derived from Greenland. This, combined with evidence of hiatuses from other cores in the centre of the overflow zone in the Denmark Strait, suggests that the periodicity seen in VM28-14 is erosional in origin rather than depositional.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2013.08.019.

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