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# A Robust, Multisite Holocene History of Drift Ice off Northern Iceland: Implications for North Atlantic Climate

John T. Andrews

Dennis A. Darby
*Old Dominion University*, ddarby@odu.edu

Dennis Eberle

Anne E. Jennings

Matthias Moros

***See next page for additional authors***



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# A robust, multisite Holocene history of drift ice off northern Iceland: implications for North Atlantic climate

John T. Andrews,[1]* Dennis Darby,[2] Dennis Eberle,[3] Anne E. Jennings,[1] Matthias Moros[4,5] and Astrid Ogilvie[6]

*([1]INSTAAR and Department of Geological Sciences, University of Colorado, Box 450, Boulder CO 80303, USA; [2]Department of Ocean, Earth and Atmospheric Sciences, Old Dominion University, Norfolk VA 23529, USA; [3]US Geological Survey, 3215 Marine Street, Suite E-127, Boulder CO 80303, USA; [4]Bjerknes Centre for Climate Research, Allegaten 55, 5007 Bergen, Norway; [5]Baltic Sea Research Institute, Seestrasse 15, 18119 Rostock, Germany; [6]INSTAAR and Department of Anthropology, University of Colorado, Box 450, Boulder CO 80303, USA)*

A HOLOCENE FAST-TRACK REPORT

**Abstract:** An important indicator of Holocene climate change is provided by evidence for variations in the extent of drift ice. A proxy for drift ice in Iceland waters is provided by the presence of quartz. Quantitative x-ray diffraction analysis of the < 2 mm sediment fraction was undertaken on 16 cores from around Iceland. The quartz weight (wt.)% estimates from each core were integrated into 250-yr intervals between –0.05 and 11.7 cal. ka BP. Median quartz wt.% varied between 0.2 and 3.4 and maximum values ranged between 2.8 and 11.8 wt.%. High values were attained in the early Holocene and minimum values were reached 6–7 cal. ka BP. Quartz wt.% then rose steadily during the late Holocene. Our data exhibit no correlation with counts on haematite-stained quartz (HSQ) grains from VM129-191 west of Ireland casting doubt on the ice-transport origin. A pilot study on the provenance of Fe oxide grains in two cores that cover the last 1.3 and 6.1 cal. ka BP indicated a large fraction of the grains between 1 and 6 cal. ka BP were from either Icelandic or presently unsampled sources. However, there was a dramatic increase in Canadian and Russian sources from the Arctic Ocean ~1 cal. ka BP. These data may indicate the beginning of an Arctic Oscillation-like climate mode.

**Key words:** Ice rafted debris, Iceland, quartz, drift ice, Holocene, Arctic basin.

## Introduction

We present a multisite proxy for drift-ice variations around Iceland (Figure 1) based on quantitative x-ray diffraction (XRD) analysis of the < 2 mm sediment fraction (usually > 99.9% of the total sediment) and thus expand on the results from MD99-2269 (Figure 2; Supplementary material available online) (Moros *et al*., 2006). As argued by Alley (2003) there is a need to replicate palaeoceanographic studies to test the robustness of conclusions reached from analysis of a single core. Drift ice is brought to Iceland in the East Iceland Current, an outer branch of the East Greenland Current, which exports sediment-laden sea ice from the Arctic Ocean through Fram Strait (Figure 1), or icebergs from the various east Greenland tidewater outlet glaciers. The bulk of the ice-transported sediment is in the silt and clay-size fractions (Hebbeln, 2000; Lisitzin, 2002), hence conventional protocols for defining ice-rafted debris (IRD), which are based on the sand fraction, will underestimate the total IRD contribution. The sea ice also carries driftwood from Russian and NW North American sources (Tremblay *et al*., 1997); abundant driftwood is stranded on Icelandic beaches and originates from areas inland from the Kara and Barents seas (Figure 1) (Eggertsson, 1993).

Climate modelling indicates that variations in the extent of Northern Hemisphere sea ice have a major impact on the climate system (Parkinson, 2000; Smith *et al*., 2003), especially on winter temperatures. Variations in drift-ice trajectories are associated with the atmospheric forcing associated with the North Atlantic or Arctic oscillations (NAO, AO) (Tremblay *et al*., 1997; Parkinson, 2000), hence variations in a drift-ice proxy have the potential to illuminate decadal- to millennium-scale shifts in oceanographic and atmospheric circulations. The indexes for the NAO and AO are linked but not identical. During a positive AO (warm) phase the atmospheric circulation is essentially zonal and although sea ice is exported through Fram Strait it tends to be re-circulated into the Greenland Sea. In the negative (cold) phase the circulation is more meridional (Lamb, 1979) with a blocking ridge over Greenland and a trough boundary along East Greenland. This configuration is ideal for the export of sea ice as far south as Iceland and the Faeroe Islands (Figure 1).

Periods of extensive drift ice around Iceland result from the export of fresh water from the Arctic Basin (as sea ice) and Greenland Ice Sheet (as icebergs). This was documented in AD

*Author for correspondence (e-mail: john.t.andrews@colorado.edu)

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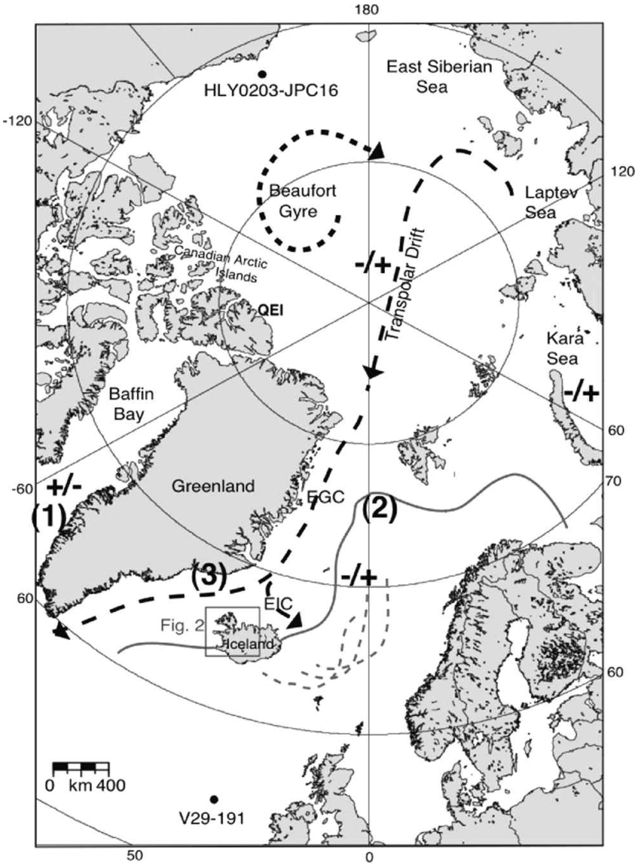


**Figure 1** Major surface currents exporting drift ice toward Iceland. Present-day extreme limit of the ice-edge (30% ice concentration) and historical ice limits (after Lamb, 1979; Parkinson, 2000). QEI, Queen Elizabeth Islands; EGC, East Greenland Current; EIC, East Iceland Current; Core V29-191 (see text). The + and – signs refer to the trend in sea ice extent for 1979–1990 versus 1990–1999 (Parkinson, 2000). Numbers (1), (2), and (3) refer to areas mentioned in the text

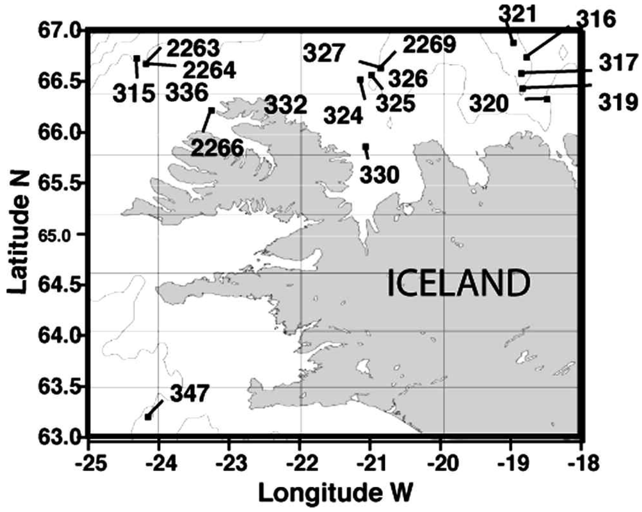


**Figure 2** Core sites for MD99-2263, -2264 and -2269; all the other sites are from cruise B997-. Fe-oxide data on seafloor samples were obtained from B997-326, -323, -336, -332, -321 and -316

1969 by the Great Salinity Anomaly (GSA) (Dickson *et al*., 1988), which led to the cessation of the formation of Labrador Sea deep water, a component of North Atlantic Deep Water. During the GSA the AO and the NAO achieved record negative values and ice invaded Iceland waters. When drift ice reaches the Iceland coast (usually in late winter/spring) it has a profound impact on both agriculture and fisheries (Ogilvie and Jonsdottir, 2000) because of the associated lowering of air and ocean temperatures (Jennings *et al*., 2001).

A major problem in palaeoclimate research is that of extending multiyear climate oscillations, detected from observational data, to the longer timescales that palaeostudies commonly deal with. By analogy we can imply positive or negative NAO- or AO-like conditions because of changes in our proxies, but how does the climate system maintain a multidecadal or century-long mode?

The ‘gold standard’ for Holocene drift-ice variations in the North Atlantic, and indeed for Holocene climatic variability, is the stacked haematite-stained quartz counts (HSQ) (Bond *et al*., 2001), which appear to show a pervasive signal. A key site, V29-191, lies well south of the historic ice edge limits (Figure 1) and well east of the present-day iceberg limit (Bigg *et al*., 1996), although the extreme historic limit of recorded growlers and bergy bits (International Ice Patrol) lies close to V29-191. However, other authors argued for significant regional variability in Holocene drift-ice histories (Moros *et al*., 2004; Andrews *et al*., 2006; Fisher *et al*., 2006).

## Methods and data

Our findings build on the results of quantitative XRD of the < 2 mm sediment fraction from core MD99-2269 (Table 1, Figure 2) (Moros *et al*., 2006), which has one of the best-dated Holocene records in the North Atlantic (Stoner *et al*., 2007). However, we agree with Alley (2003) that several cores from a region are required to fully substantiate a proxy record. The replication of results is especially important when there are reasons to expect that the proxy signal, in this case IRD, has the potential to be spatially and temporally variable (ie, noisy) because of changes in sediment entrainment, transport and melt (Warren, 1992; Bischof, 2000). It is also important to note that whereas the volume of ice calved per year from east Greenland tidewater outlet glaciers is of the order of tens of cubic kilometres per year, the flux of sea ice exiting the Arctic Ocean via the East Greenland Current (Figure 1) is two orders of magnitude more (~2000–5000 $km^3$/yr) (Foldvik *et al*., 1988).

The cored sediments on the Iceland shelf are principally clayey silts to sandy silts. Some 1665 samples from seafloor samples and from 15 cores (Table 1) were run on a D5000 Siemens x-ray diffraction (XRD) unit and processed through ‘RockJock’ (Eberl, 2003, 2004), identifying 18 non-clay and seven clay mineral species (see Andrews and Eberl, 2007 for additional information). This quantitative XRD method was placed third in the International Reynolds Cup competition (McCarty, 2002) for predicting a series of ‘unknown’ mineral mixtures; a third place finish was also awarded in 2008.

The clay minerals, volcanic glass, and calcite were excluded (this amounted to 56 ± 10 wt.%), and the data were then normalized to sum to 100%. In Iceland waters calcite is a measure of marine productivity (on average 13 wt.%), and volcanic glass (~30 wt.% of the sediment on average) is added mainly by air fall and reworking; the clay minerals are difficult to ascribe to a source(s). The identified non-clay minerals included quartz, k-feldspars, plagioclase, dolomite, amphibole, pyroxene, pyrite, haematite and magnetite. Principal Component Analysis of the surface samples indicated that quartz, k-feldspar and dolomite are strongly associated with the first PC axis whereas plagioclase and pyroxene are located at the opposite end of the axis (Andrews and Eberl, 2007: figure 7). Quartz and potassium feldspar are essentially absent in the native Icelandic bedrock and the presence of quartz is used as a proxy for IRD (Moros *et al*., 2006). Replicate analyses indicate that the fractional error (standard deviation/mean) for quartz is ±

**Table 1** Data on cores used in this study (see Figure 2)

| | Number dates | Core length (m) | Basal date | Top date | Number samples | Average/yr sample |
|---|---|---|---|---|---|---|
| *NW Iceland* | | | | | | |
| B997–315 [a] | 5 | 2.49 | 12 420 | 2760 | 92 | 105 |
| MD99–2264 | 6 | 11.45[b] | 11 850 | 1155 | 104 | 103 |
| MD99–2263 [a] | 5 | 0.46 | 1865 | −50 | 46 | 42 |
| *N Iceland* | | | | | | |
| B99–322 | 4 | 0.5 | 14 600 | 980 | 9 | |
| B997–323 | 3 | 1 | ~15 000 | 650 | 22 | |
| B997–324 | 17 | 2.89 | 12 300 | 150 | 107 | 114 |
| B997–325 | 10 | 2.71 | 11 610 | −50 | 85 | 137 |
| B997–327 | 5 | 3.29 | 4340 | 310 | 63 | 64 |
| MD99–2269 | 32 | 25.3 | 11 860 | −50 | 413 | 29 |
| B997–330 | 9 | 5.4 | 10 970 | −50 | 108 | 102 |
| B997–321 | 8 | 2.9 | 6160 | 355 | 62 | 94 |
| B997–316 | 3 | 2.81 | 1335 | −50 | 53 | 26 |
| B997–317 | 6 | 1.74 | 3930 | −50 | 32 | 124 |
| B997–319 | 13 | 2.27 | 8950 | 175 | 69 | 127 |
| B997–320 | 6 | 3.27 | 3400 | −50 | 59 | 58 |
| *SW Iceland* | | | | | | |
| B997–347 | 8 | 4.8 | 12 220 | 450 | 166 | 71 |
| MD99–2266 | 26 | 37.6 | 10 825 | 400 | 175 | 60 |

[a] Unpublished data

[b] Holocene length

0.08. Quartz and potassium feldspar are entrained into sea ice on the broad, shallow shelves of the Arctic Ocean (Lisitzin, 2002), or by glacial erosion and entrainment by calving outlet glaciers on East Greenland, the Queen Elizabeth Islands (QEI) (Figure 1), Svalbard and the Russian Arctic islands. Dolomite is principally contributed from the Palaeozoic outcrops in the southern QEI (Figure 1). For simplicity's sake we henceforth restrict our attention to variations in quartz wt.%, which is commonly accepted as an IRD proxy in Iceland marine sediments (Eiriksson *et al*., 2000).

As quartz is not a specific provenance indicator we sought information on source areas through a pilot programme that involved the analysis of Fe-oxides (Darby and Bischoff, 1996). Fe oxide mineral grains from cores B997-321 and -316 (Table 1, Figure 2) (12 and 19 samples, respectively) were separated using a Frantz magnetic separator and a hand magnet, analysed by a microprobe for 12 elements, and the elements matched to the circum-Arctic source data base (Darby, 2003). Surface samples from five nearshore Iceland sites (Figure 2) were analysed in order to characterize Fe grains from Iceland; there is however an absence of Fe oxide data from the NE Greenland shelf, upstream from our field area (Figure 1), a potential source area for IRD.

Age control is based on $^{14}C$ AMS dates calibrated using CALIB 5 with a $\Delta R$ of 0 (Stuiver *et al*., 1998). Age/depth relationships have been published for all the cores except B997-315PC and MD99-2263 (Table 1). Some loss of temporal resolution can be expected because of bioturbation, and there are errors inherent in deriving interpolated age estimates (Andrews *et al*., 1999; Telford *et al*., 2003). Because of the storminess in this area (Dawson *et al*., 2003), and the occurrence of shallow banks on the flanks of the troughs from where the cores were collected, some sediment redistribution is expected and may indeed have an important climate signal (Andresen *et al*., 2005). The sampling interval varied from ~20 to 100-yr/sample although coarser in two cores (−322 and −323), which were omitted.

A multisite study of any proxy is required to distinguish between regional long-term trends and the unique characteristics of any single site. In order to obtain an evenly dated, multisite record AnalySeries (Paillard *et al*., 1996) was used to integrate each record and derive quartz wt.% at 250-yr intervals, from −0.05 to 11.7 cal. ka BP (Figure 3A) (see Supplementary materal online). The correlation between the original quartz wt.% records and the 250-yr estimates was invariably $r > 0.9$ indicating little loss of information. We chose 250-yr as a somewhat conservative sample interval (Table 1) for the integration between AMS radiocarbon-dated levels. We hypothesize that if there were no coherent regional IRD signal then the resulting time series would have fluctuations no different than could arise by chance.

## Results

Sediments on the north Iceland shelf contain virtually no grains > 2 mm that can be attributed to the melting of icebergs. Thus they differ substantially from Holocene sediments on the East Greenland shelf, which are frequently stony diamictons with a large number of clasts > 2 mm (Andrews *et al*., 1997; Jennings *et al*., 2002). In seafloor samples, quartz is present on the outer to mid shelf in a band from NW Iceland to the limit of our sampling at 18°W (Moros *et al*., 2006; Andrews and Eberl, 2007: figure 4). Cores located close to land show zero or trace amounts of quartz whereas higher amounts of quartz wt.% are recorded in the more northern sites. B997-347 (Figure 2) from SW Iceland is at the extreme limit of drift ice during extremely severe ice years (Ogilvie, 2005) and showed only intermittent trace amounts of quartz.

Figure 3B shows the median quartz wt.% distribution – this record is similar ($r = 0.84$) to the high-resolution 30 yr/sample quartz wt.% data from MD99-2269 (Figures 2 and 4A) (Moros *et al*., 2006). The fact that our multicore record captures most of the lower frequency variations in MD99-2269 (Figure 4A) justifies the analysis of this core to provide a very high-resolution archive of Holocene environmental variability (eg, Andrews *et al*., 2003; Moros *et al*., 2006; Stoner *et al*., 2007) for an area affected by variations in the advection of Atlantic versus Arctic/Polar water masses (eg, Dickson *et al*., 1988). The time series of median quartz wt.% data is 'robust' in the sense that the estimate is not influenced by extreme values (Velleman and Hoaglin, 1981). We

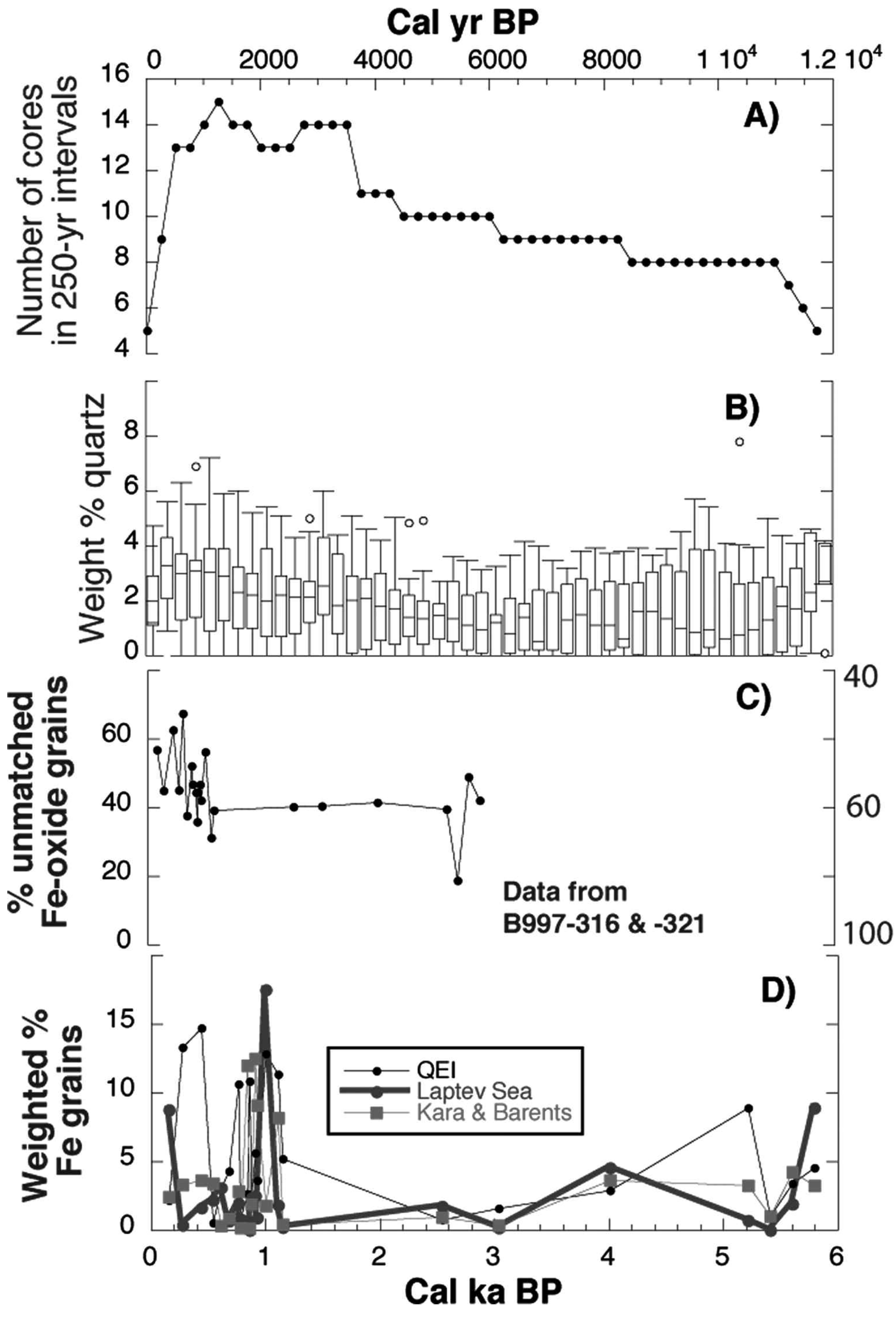


**Figure 3** (A) The number of cores whose records are included in (B) at 250-yr increments. (B) Box plot of quartz wt.% for nine non-clay minerals showing the inner 50% of the sample distribution for each 250-yr increment. The small circles represent statistical outliers. (C) Plot of the %unmatched Fe oxide data from B997-316 and -321. (D) Plot of the percent changes in Fe-oxides from cores B997-316 and -321 (Figure 2) in inputs from the Laptev, Kara and Barents seas, and the QEI (Figure 1)

tested the null hypothesis that the variations in the 250-yr median quartz wt.% are no different than might be expected by chance; the Runs Test rejected the null hypothesis ($z = -5.8$, $p > 0.000$) (Miller and Kahn, 1962). The null hypothesis was still rejected ($p \leq 0.04$) after removal of the low-frequency temporal trend by application of a second degree polynomial.

At the beginning of the Holocene, quartz was reaching Iceland in significant amounts; median values steadily declined between 11.7 and 10.95 cal. ka BP and then had two peaks in input prior to reaching a minimum at ~7 cal. ka BP. Marine temperature reconstructions (Smith *et al.*, 2005) indicated warmer conditions between 6 and 10 cal. ka BP. We attribute the early-Holocene high quartz wt.% in part to the delivery by icebergs from the northern margins of the Laurentide and Innuitian ice sheets (Dyke, 2004), via Fram Strait (Figure 1). This assertion is supported by the presence of dolomite in early-Holocene and late-Pleistocene sediments on the Iceland shelf and slope (Andrews, 2008). This period of high IRD occurred during an interval of warmer conditions (Smith *et al.*, 2005). Over the last 5–6 cal. ka BP, an interval when water temperatures were decreasing (Smith *et al.*, 2005), quartz wt.%

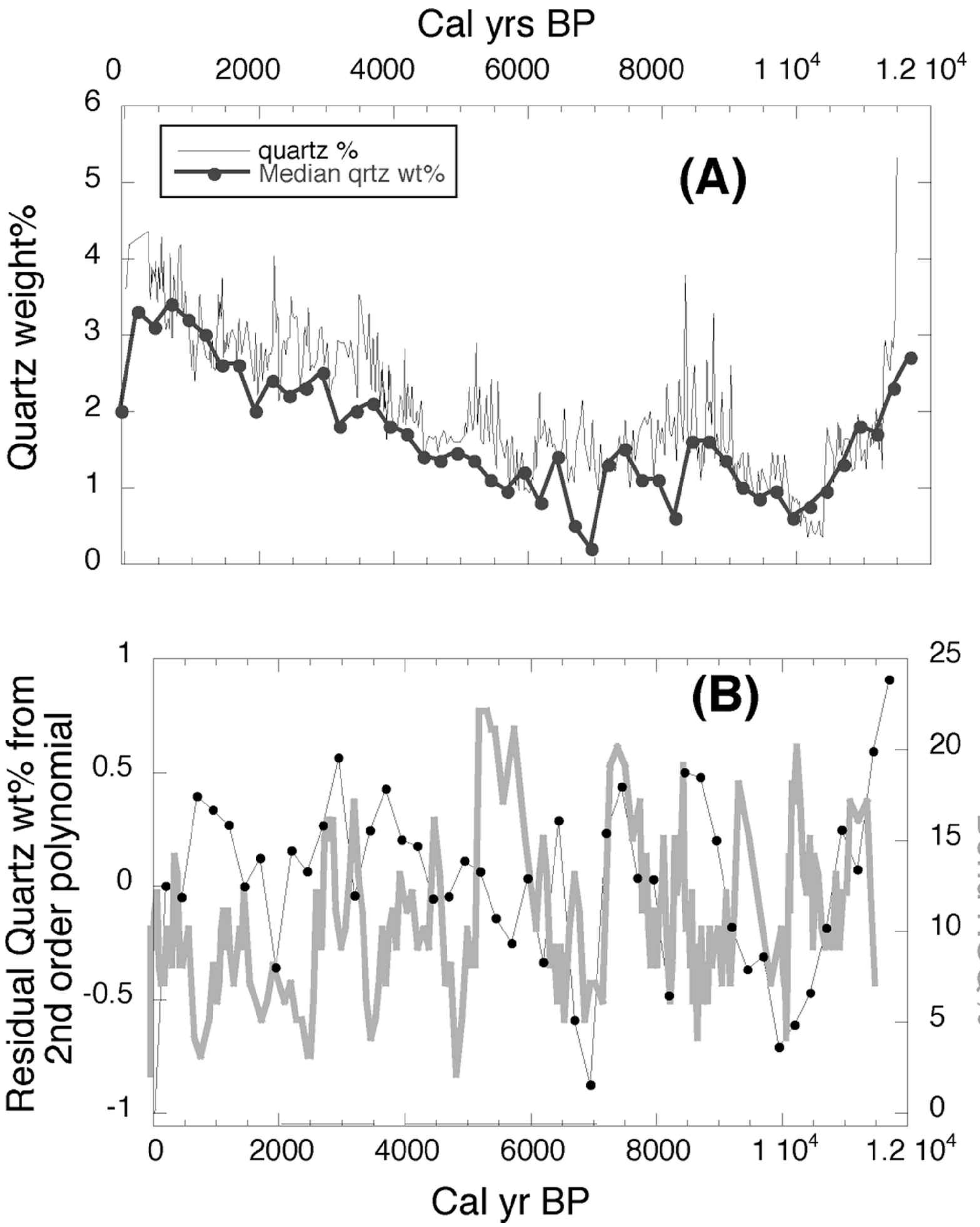


**Figure 4** (A) Comparison of the median quartz data from this paper and the MD99-2269 30 yr resolution data (Moros *et al*., 2006). (B) Comparison of the haematite-stained quartz data from VM29-191 (Figure 1) (Bond *et al*., 2001) with the residuals from a second order polynomial on the median quartz wt.% data (Figure 3B). The correlation between these two records is only 0.01

delivery to the Iceland margin increased, indicating an increase in sediment-laden ice. A jump in quartz wt.% at ~2 cal. ka BP (Figure 3B) correlates with the re-appearance of the 'glacial' benthic foraminifera *Elphidium excavatum* f *clavata* in north Iceland waters (Moros *et al*., 2006). Quartz wt.% reached a Holocene maximum *c*. AD 1800, about the time when the historical sea-ice index for Iceland reached its highest values (AD 1835) (Ogilvie, 1996). Multicentury- and millennial-scale oscillations are superimposed on this U-shaped record, which are more obvious if the overall trend is removed (Figure 4B). A single significant periodicity of ~670 yr was identified using the multiple taper method (MTM) (Weedon, 2005) on the residual data (Figure 4B).

An average of 65 Fe oxide grains (0–189) were obtained from the samples from cores 321 and 316 (Figure 2); on average 35 grains per sample were matched to a specific source region. The percentage of unmatched grains varied between ~15 and 70% (Figure 3C) and can be attributed in part to an absence in the data base of samples from the E and NE Greenland margins. Of the matched samples, most are from Iceland, however, two of the samples dated ~ 1 cal. ka BP from core 316 (Figure 3D) contained a majority of Fe grains from the QEI and the Laptev Sea (Figure 1). Both these sources are important elements in modern Arctic Ocean sea-ice (Darby, 2003). At *c*. 1 cal. ka BP, Fe grains from the Kara Sea (15%) and the East Siberian Sea (20%) further emphasize this interval of influx of sea ice from the Arctic Ocean. A smaller influx of Fe oxide grains from the QEI occurs at 270 cal. yr BP. Consideration of the atmospheric modes required to entrain IRD from the Laptev Sea and the QEI and deliver these through Fram Strait to Iceland suggests that a key element is a switch from a positive to a negative NAO/AO mode; in isolation, neither mode can explain the data (Figure 3D). The large peak of Fe grains at about 1 cal. ka BP, coincides with the a large peak in Fe grains from Russian sources in core P1/B3 northwest of Alaska at the edge of the Chukchi Shelf that is linked to a strong positive AO-like climate mode (Darby and Bischof, 2004).

## Conclusions

We present a quantitative, highly reproducible, stacked record from 16 cores around Iceland of the quartz wt.% in the < 2 mm sediment fraction. The presence of quartz throughout the Holocene demonstrates that on multicentury timescales, drift ice has rarely been absent from this region. Especially over the last 5 cal. ka BP, drift ice, most probably sea ice, has been pervasive. Thus on these timescales the North Atlantic circulation mode has probably been more meridional than zonal, implying a dominance of negative NAO-like conditions. IRD records from areas 1 and 2 in the North Atlantic (Figure 1) (Andrews *et al*., 2006) are distinctly different from the north Iceland record, which is however similar to area 3 (East Greenland) (Andrews *et al*., 1997; Jennings *et al*., 2002), hence Holocene drift-ice proxies show regional variability (Moros *et al*., 2004, 2006; Fisher *et al*., 2006) rather than a single pervasive pattern (Bond *et al*., 2001).

We do not detect a ~1500 yr periodicity in the quartz IRD, rather our multicentury-scale data show a ~670 yr periodicity. However, MTM analysis of the detrended high resolution data from MD99-2269 (Moros *et al*., 2006) (Figure 4A) indicates several significant periodicties ($p \geq 0.95$) between 87 and 61 yr, reminiscent of the multidecadal Atlantic oscillation (Kerr, 2005). Our data bear little similarity to the HSQ data at VM129-191 (Bond *et al*., 2001) (Figure 4B). Our sites are from a region that is clearly affected by drift ice (Figure 1) and lies at a boundary between Atlantic and Arctic/Polar water masses (Dickson *et al*., 1988). In contrast the HSQ data from VM29-191 is from an area within the regime of the North Atlantic Current (Moros *et al*., 2006), hence the delivery of a coherent IRD signal to the site is problematical and indeed unlikely.

We cannot as yet fully answer the question: what were the specific source areas for the drift ice that brought quartz to Iceland waters throughout the Holocene? The intermittent presence of dolomite throughout the Holocene (Andrews and Eberl, 2007) indicates the transport of sediment in drift ice, probably from Palaeozoic outcrops in the Canadian Arctic islands and channels. However, a major change occurred ~1 cal. ka BP when iron-oxide grains from a variety of sources around the Arctic Ocean reached Iceland. This may be associated with an intensification of a positive AO-like climate mode. An expansion of our pilot programme (Figure 3D), and an expansion of the Fe-oxide data base to NE and E Greenland sites is required to gain a better understanding of the sources of drift ice in Iceland waters on Holocene timescales.

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