2004) of opal and of organic carbon were positively correlated with the high organic carbon content of sediments deposited during warm periods (Bølling and Holocene; Fig. 1). We find elevated $^{231}$Pa/$_{230}$Th and $^{10}$Be/$^{230}$Th ratios during warm periods as well (Fig. 1), indicating that increased productivity must have contributed to the higher preserved fluxes of opal and carbon at those times.

### Conclusions

While these results do not rule out changes in the ventilation of intermediate waters, they do provide clear evidence for changes in biological productivity and the export flux of biogenic particles. Enhanced productivity during warm events reflects a shoaling of the nutricline, an increase in upwelling-favorable winds, or some combination thereof.

### NOTE

Data used in this study will be available in the NOAA Paleoclimatology data base at: www.ncdc.noaa.gov/paleo/paleo.html

### REFERENCES

Altabet, M.A., Higginson, M.J., and Murray, D.W., 2002: The effect of millennial-scale changes in Arabian Sea denitrification on atmospheric $CO_2$. *Nature*, **415**(6868): 159-162.

Chase, Z., Anderson, R.F., Fleisher, M.Q., and Kubik, P., 2002: The influence of particle composition on scavenging of Th, Pa and Be in the ocean. *Earth and Planetary Science Letters*, **204**: 215-229.

Francois, R., Frank, M., Rutgers Van Der Loeff, M.M., and Bacon, M.P., 2004: Th-230 normalization: An essential tool for interpreting sedimentary fluxes during the late Quaternary. *Paleoceanography*, **19**(1): PA1018, doi:10.1029/2003PA000939.

Kumar, N., Anderson, R.F., Mortlock, R.A., Froelich, P.N., Kubik, P., Dittrich-Hannen, B., and Suter, M., 1995: Increased biological productivity and export production in the glacial Southern Ocean. *Nature*, **378**(6558): 675-680.

Ortiz, J.D., O'Connell, S.B., Delviscio, J., Dean, W., Carriquiry, J.D., Marchitto, T., Zheng Y., and Van Geen, A., 2004: Enhanced marine productivity off western North America during warm climate intervals of the past 52 ky. *Geology*, **32**(6): 521-524.

# Is there a pervasive Holocene ice-rafted debris (IRD) signal in the northern North Atlantic? The answer appears to be either no, or it depends on the proxy!

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### Introduction

One of the most cited papers (271 citations by June 2006) on Holocene climate change is the 2001 paper by Bond and colleagues (2001), which argued for a pervasive ~1500 yr signal in the delivery of hematite-stained quartz (HSQ) sands to sites at or beyond the historic limits of observed drift ice (Fig. 1) (we use the term "drift ice" to denote any mixture of glacier icebergs or various forms of sea ice). To critically examine the hypotheses set forth in Bond et al. (2001), we selected a series of cores for analysis of ice-rafted debris (IRD). These cores were collected from sites that are much more within the historically known limits of drift ice (Fig. 1), hence lie to the north of the sites examined for HSQ. Two of the cores are exceptionally well dated (Moros et al., 2006) and the other two have sufficient age control to examine the Holocene trends in IRD.

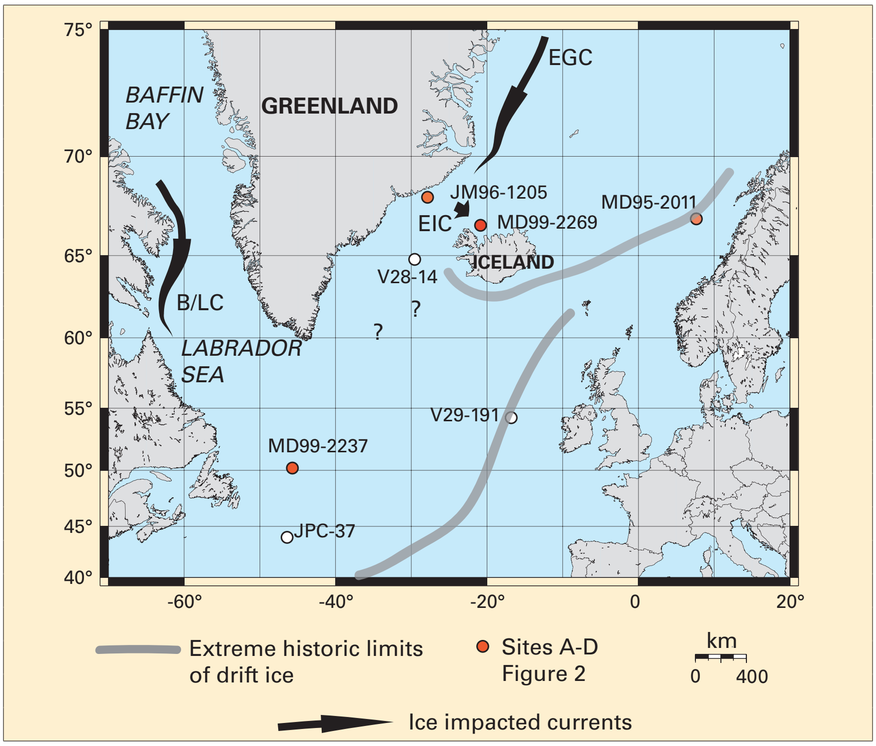

*Figure 1: Location of cores used in this study (red circles) and cores reported by Bond et al. (2001). Historic maximum limits of drift ice are shown based on data from the International Ice Patrol (www.uscg.mil/LANTAREA/IIP/home.html) and the Norsk Polar Institute (acsys.npolar.no/ahica/quicklooks/looks.htm). Arrow labels: EGC = East Greenland Current; B/LC = Baffinland and Labrador Current; EIC = East Iceland Current.*

### Methods

There is no single working definition of IRD (Andrews, 2000); the variations in sediment carried by drift ice are often defined on the basis of grain-size or on some aspects of provenance (i.e. mineralogy) (Ruddiman, 1977; Andrews et al., 1989; Andrews et al., 1997; Bischof, 2000). Icebergs and sea ice carry sediments that vary in size from pebbles to fine clay and the largest contribution by weight is generally in the silt fraction. We use quantitative X-ray diffraction identification on the <2000 µm size fraction (Eberl, 2004; Moros et al., 2006), i.e. the sand plus silt plus clay, to identify minerals that are exotic to particular sites, and which can be associated with the transport and delivery of sediments in drift ice (Moros et al., 2006). Between 1-3 g of sediment is milled and spiked with a known weight of corundum or zincite. X-ray scanning is conducted between 5 and 65° two-theta (Eberl, 2004) and the weight% of non-clay and clay minerals is carried out automatically on the digital output files. Results are reported as weight% of the non-clay and clay minerals. Replication experiments indicate that standard errors on the major minerals of interest are of the order of ± 0.5 weight%. We typically identify 15-18 non-clay and 7 clay minerals.

The total volume of icebergs calved into Baffin Bay is of the order of 200 km$^3$/yr. Some 40,000 icebergs a year are estimated to calve into Baffin Bay from the large outlet glaciers of W/NW Greenland and the Canadian High Arctic; these icebergs are carried southward in the Baffinland and Labrador currents. The primary sediment signature for glacial erosion and transport in icebergs from NW Greenland is dolomite (Marlowe, 1966). We hypothesize that the major agent of transport in the western North Atlantic, including Baffin Bay and the Labrador Sea, is in icebergs, as the only major source for sediment loading of sea ice is the western area of Hudson Bay.

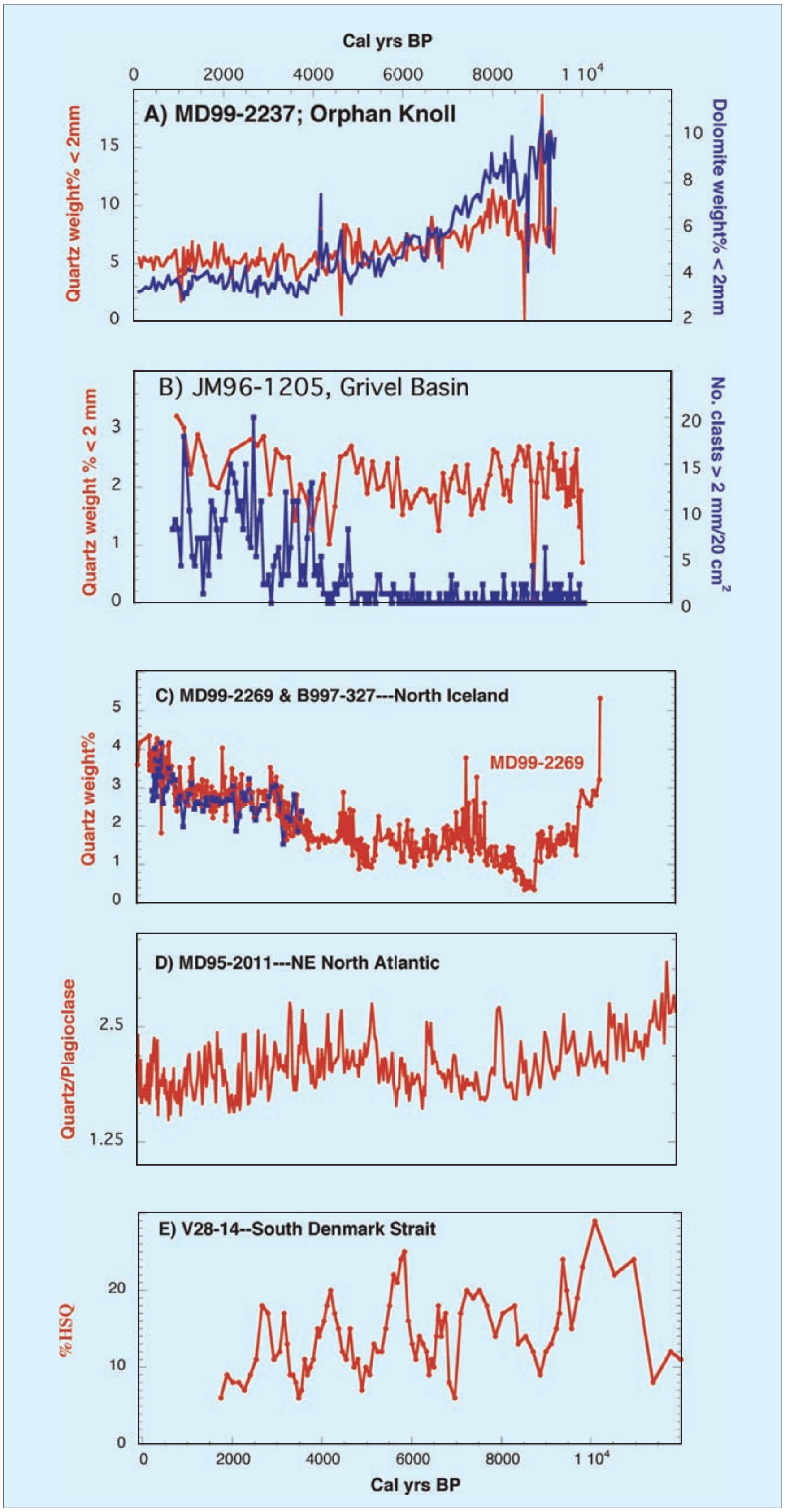

*Figure 2: Data from northern North Atlantic cores (Fig. 1) compared with hematite-stained quartz data from V28-14 (Bond et al., 2001). Data in plots A-D are based on weight% of minerals in the <2000 µm size fraction.* ***A)*** *MD99-2237—Orphan Knoll;* ***B)*** *JM96-1205—Grivel Basin;* ***C)*** *MD99-2269 and B997-327—North Iceland;* ***D)*** *MD95-2011—Vorring Plateau;* ***E)*** *V28-14—South Denmark Strait.*

The bedrock geology of Iceland and the East Greenland area in the vicinity of JM96-1205 is composed of Cenozoic flood basalts—hence there is virtually no normative quartz in the bedrock. However, on East Greenland, the basalts lie on Precambrian granites and gneisses, and large outlet glaciers extend seaward along several fjords. Early Tertiary and older sedimentary rocks lie to the north of Kangerlussuaq Fjord and Scorsby Sund, respectively (Jennings et al., 2002). The sediment transport by drift ice in the eastern North Atlantic (through Fram Strait) is dominated by finegrained silt and clay incorporated into the sea ice on the extensive shelves fronting the Arctic Ocean (Hebbeln, 2000).

## Results

We discuss the cores along a west to east transect (Fig. 1 & 2A-D) and compare these results with the HSQ data from V28-14 just south of the Denmark Strait. (Bond et al., 2001) (Fig. 2E). MD99-2237 (Fig. 1) was sampled at ~100 yr intervals. On the East Greenland shelf we use the results from JM96-1205, which we also sampled at 100 yr/sample intervals. MD99-2269 from the North Iceland shelf is from an area where drift ice from the East Iceland Current frequently traverses the site. The core was sampled at ~30 yr/sample and covers the last 12 cal ka BP (Moros et al., 2006). The easternmost core is MD95-2011, located on the Vorring Plateau, and has an average sampling interval of 20 yrs/sample.

The Orphan Knoll data (Fig. 2A) presently covers the last 10 cal ka BP. Quartz and dolomite track each other over this interval. Both minerals show a progressive decrease in their weight% toward the present. There are no large-scale changes in either species and, surprisingly, there is no clear indication of an increase in delivery associated with the neoglacial readvance of the Greenland Ice Sheet.

The quartz weight% data from the East Greenland margin, south of Scorsby Sund, (Figs. 1 & 2B) shows a very slight trend to increase over the last 4 cal ka BP but the average input of quartz has remained relatively constant over the last 10 cal ka BP. The counts of clasts >2 mm on X-radiographs shows variable IRD inputs between 10 and 8 cal ka BP followed by a period with virtually no IRD and then a marked increase in IRD ca. 4 cal ka BP, consistent with previous data from the East Greenland shelf (Jennings et al., 2002).

Drift ice entrained in the East Iceland Current historically impacts the North Iceland shelf where MD99-2269 was retrieved (Moros et al., 2006). The quartz weight% data shows a decrease from high values in the early Holocene to the mid Holocene, and then a sharp and pronounced increase in quartz over the last 5-6 cal ka BP. Quartz data from core B997-327PC, which was taken within a few 100 m of MD99-2269, are nearly identical.

The most easterly core, MD99-2011, was taken from the Vorring Plateau (Fig. 1). Here, the Quartz/Plagioclase (Q/P) ratio is used as a measure of ice rafting. The long-term trend in these data (Fig. 2E) is for the Q/P ratio to decrease toward the present. Hence, it does not show the late Holocene increase in IRD proxies that characterize the sites on either side of the Denmark Strait (Figs. 2B & C).

## Discussion and conclusions

Our four records (Fig. 2A-D) bear little resemblance to the %HSQ from south of Denmark Strait or from the other sites (Fig. 1 & Fig. 2E), although our data are from sites where the deposition of ice-rafted sediments should be much more obvious because of their more ice-proximal locations. Our data do not posses the amplitude of variation noted in the HSQ data (although this is partly a function of the plotting scale and whether the data are detrended or not) and they do not show a clear ~1.5 ka periodicity. Indeed, the sites differ significantly in their long-term trends (compare Figs. 2A & 2C). In each area, we have results from other cores (e.g. Fig. 2C) that we are using to develop robust regional IRD signals. Of special interest on the Labrador and East Greenland margins is whether or not there is a coupling between the IRD proxies associated with grain-size and mineralogy (e.g. Fig. 2B). This begs the question as to whether we can construct a proxy for Holocene IRD that incorporates all the necessary elements of both grain-size and provenance. Given that the bulk of glacial and sea ice transported sediments is much finer than 63 µm, then the XRD method offers significant advantages, especially if we can distinguish mixtures of minerals that define source areas (Darby, 2003).

Our results should make researchers question the underlying forcing behind the HSQ data (Fig. 2E). The cycles in this and the other records may be linked to solar forcing but the specific link to ice rafting appears ambiguous. The varying trends in our data suggest we need to consider the Holocene oceanographic/climate evolution of each region individually (de Vernal and Hillaire-Marcel, in press).

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### NOTE

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For detailed information, contact the authors.

### REFERENCES

Andrews, J. T., 2000: Icebergs and Iceberg Rafted Detritus (IRD) in the North Atlantic: Facts and Assumptions. *Oceanography*, **13**: 100-108.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffman, S., Lotti-Bond, R., Hajdas, I., and Bonani, G., 2001: Persistent solar influence on North Atlantic climate during the Holocene. *Science*, **294**: 2130-2136.

Darby, D. A., 2003: Sources of sediment found in the sea ice from the western Arctic Ocean, new insights into processes of entrainment and drift patterns. *Journal of Geophysical Research*, **108**: 13-11 to 13-10. doi: 10, 1111029/1112002JC1001 350, 1112003.

De Vernal, A., and Hillaire-Marcel, C., in press: Provincialism in trends and high frequency changes in the northwest North Atlantic during the Holocene: *Global Planetary Change*.

Eberl, D. D., 2004: Quantitative mineralogy of the Yukon River system: Variations with reach and season, and sediment source unmixing. *American Mineralogist*, **89**: 1784-1794.

Jennings, A. E., Knudsen, K. L., Hald, M., Hansen, C. V., and Andrews, J. T., 2002: A mid-Holocene shift in Arctic sea ice variability on the East Greenland shelf. *The Holocene*, **12**: 49-58.

Moros, M., Andrews, J. T., Eberl, D. D., and Jansen, E., 2006: Holocene history of drift ice in the northern North Atlantic: Evidence for different spatial and temporal modes, *Paleoceanography*, **21**, PA2017, doi:10.1029/2005PA001214.

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