Evidence That's an Ocean Apart:

Co-Varying Records of Ice-Rafted Debris Flux and Plio-Pleistocene Bipolar Ice Sheet Disintegration

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ABSTRACT

The ice-rated debris (IRD) records from Ocean Drilling Program (ODP) sites 918 (St. John and Krissek, 2002) and 1101 (Cowan, 2001) provide evidence for bipolar climate connections during the Plio-Pleistocene. These IRD records were derived from distant but similarly situated glaciomarine settings, the SE Greenland and the Antarctic Peninsula continental rises. Similar methods of sediment analysis were used in developing the temporal records of ice-rafted debris accumulation; at both sites IRD mass accumulation rates were used to represent the histories of IRD supply through time. Age-depth models were also similarly constructed, relying upon magnetostratigraphic and biostratigraphic age-depth data. Comparison of IRD records from these two sites reveals a shared pattern of long-term IRD flux, which is dominated by IRD abundance maxima in both records at 0.9, 1.9, 2.7-2.9 Ma. These three episodes of high IRD flux are at least twice as large as the average IRD peaks in the respective records.

The cause of these repeated, and perhaps cyclic (~ 1 Myr), episodes of high IRD accumulation is uncertain; however, their presence in both Southern and Northern Hemisphere high latitude sites suggests that large-scale oceanographic and climatic controls were involved. That each episode occurred during eustatic highstands and during suppressed North Atlantic Deep Water formation favors repeated massive calving events related to ice sheet disintegration as a possible cause.

INTRODUCTION

In science, it is sometimes the curious observation that leads a researcher to think outside the "box". The box being defined, perhaps, by the boundaries of a carefully constructed research program, or more globally, a paradigm of thought. Deciding not to ignore, or perpetually put aside, the curious observations may divert one from an established path of research, but may also lead to new ideas and scientific insight. It can also be an exercise in creative thinking. Described here is an argument for a Plio-Pleistocene bipolar climate connection that is rooted in a curious observation: two similar 3-Myr ice-rafted debris (IRD) records from opposite polar regions, the Irminger Basin off SE Greenland and the marine basin west of the Antarctic Peninsula. A preliminary argument for a Plio-Pleistocene bipolar relationship was made by St. John and Cowan (2000); here it is developed further and is based on a comparison of the IRD records published by St. John and Krissek (2002) and Cowan (2001).

The study of north-south linkages is not new to the field of paleoclimatology. However, most studies of this type focus on identifying high-resolution bipolar connections, including lead-lag relationships, over millennial time scales for the late Pleistocene (e.g., Blunier and Brook, 2001; Kanfoush et al., 2002; Stocker, 2002). Long-term bipolar comparisons are less common (e.g., Schnitker, 1980), and by their very nature (i.e., lower temporal resolution) less robust, but valuable just the same. Climate change records over several thousand to millions of years provide a context for the late Pleistocene millennial-scale climate studies in much the same way that an understanding of U.S. history provides a context for understanding modern U.S. political science issues. In addition, given the controversy that exists over the proper interpretation of the Pliocene glacial history of Antarctica (e.g., Miller and Mabin, 1998, and related articles), and the limited understanding of the long-term history of the Greenland Ice Sheet (St. John and Krissek, 2002), continued long-term paleoclimatic study of Antarctic and Greenland records is warranted.

IRD records reflecting provenances of SE Greenland and the Antarctic Peninsula, as described here, are particularly well suited for examining possible bipolar climate relationships over the long-term because both the SE Greenland Ice Sheet and the Antarctic Peninsula Ice Cap are established as dynamic regions of climate change compared with the remainder of their respective continental cryospheres (Krabill et al., 1999; Bart and Anderson, 2000). The primary objective of this paper is to propose a hypothesis for a bipolar, subArctic-Antarctic climate connection from the late Pliocene through the mid-Pleistocene. This is based on broadly co-varying IRD records, which are dominated by three shared episodes of high IRD flux (Cowan, 2001; St. John and Krissek, 2002), and on a synthesis of concurring oceanography and climatic changes described in the literature.

LOCATIONS AND LITHOLOGIES

Detailed setting and lithological descriptions of sites 918 and 1101 are given in the respective Ocean Drilling Program Initial Reports volumes (Shipboard Scientific Party, 1994, 1999), in St. John and Krissek (2002) and in Cowan (2001). Both sites were drilled in continental rise sediment accumulations proximal to glaciated mountainous coastlines at latitudes poleward of 63° (Fig. 1). Site 918 is located ~65 km from the SE Greenland shelf edge in 1869 m of water in the Irminger Basin. Site 1101 is located ~94 km from the Antarctic Peninsula's western shelf edge in 3280 m of water. Both sites lie within the present limit of iceberg transport. Plio-Pleistocene ice-rafted debris accumulations at these sites were used to interpret temporal and spatial variations in iceberg release and transport from the adjacent coasts (Cowan 2001; St. John and Krissek, 2002). In addition, the extensive site 918 IRD record was used to argue that glacial expansion to sea level in SE Greenland preceded the general Northern Hemisphere glaciation by several million years; IRD evidence suggests it was glaciated as early as 7.3 Ma (Larsen et al., 1994; St. John and Krissek, 2002).

Largely due to the commonalities in the site

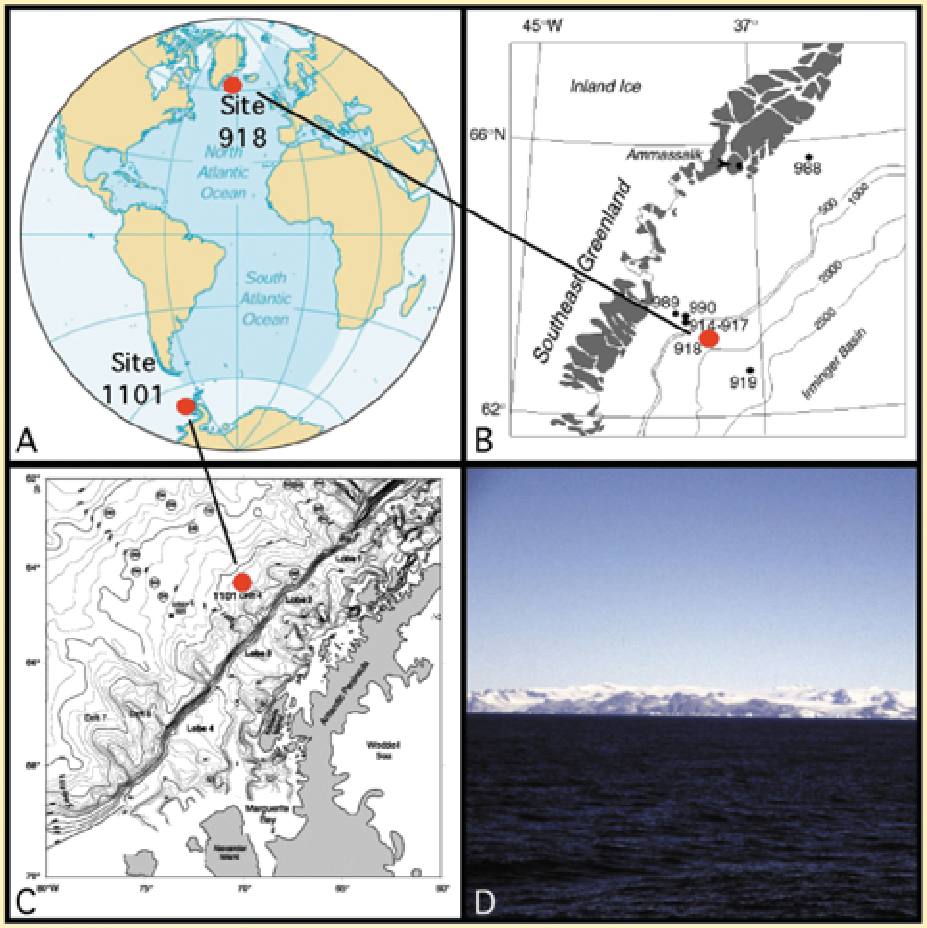

Figure 1. A. Map showing the general locations of Ocean Drilling Program Sites 918 and 1101 (modified from http://geography.about.com/library/cia/blcatlantic.htm); B. Map of Site 918 located on the upper continental rise ~65 km from SE Greenland's shelf edge in 1869 m of water in the western Irminger Basin. Shaded areas indicate outcrop regions (from Teagle and Alt, 1999); C. Map of Site 1101 located on a sediment drift on the continental rise ~94 km from Antarctic Peninsula's western shelf edge in 3280 m of water (from Cowan, 2001, and after Rebesco et al., 1998); D. Glaciated SE Greenland coast with calved icebergs (photo by St. John, 1995).

characteristics, site 918 and site 1101 sediment lithologies are also similar, although their thickness differ. The 600 m Miocene to Pleistocene sediment section upper at site 918 and the Plio-Pleistocene 218 m sediment section at site 1101 are dominated by biogenic-bearing marine muds and silts, with dropstones. These are interpreted as hemipelagic sediments and fine-grained distal turbidites with discrete occurrences of IRD. In addition, intervals of poorly sorted, ungraded sand, silt and pebbles also occur and are interpreted as glaciomarine diamictons.

COMPARABLE AGE-MODELS AND METHODS

Bulk sediment samples for IRD analysis were taken approximately every 50-75 cm from the sedimentary sections of site 918 (St. John and Krissek, 2002) and every 75 cm from the sedimentary sections of site 1101 (Cowan, 2001). In both studies, the medium to coarse sand fractions (250 mm to 2 mm) were isolated from the rest of the bulk sample and weight percentages were calculated. The proportion of terrigenous grains in this grain size fraction was then either estimated visually (site 1101) or physically isolated (Site 918). It was this terrigenous (non-volcanic) medium-coarse sand that was used as the indicator of ice-rafted debris accumulation in both studies (Fig. 2).

As described in St. John and Krissek (2002) and Cowan (2001), age models for the sedimentary sections of sites 918 and 1101 were based on shipboard (site 1101) and post-cruise (site 918) magnetostratigraphic and biostratigraphic age-depth markers. The resultant age models were used to calculate the linear sedimentation rates and sample ages. Linear sedimentation rates were high at both sites (averaging 11 cm/kyr at site 918 and 6 cm/kyr at site 1101), but were more variable at site 918. A summary of the depth ranges, calculated ages, and linear sedimentation rates for both sites is provided in Table 1 for the overlapping time span of interest (0-3 Ma).

Because IRD accumulation in a core results from a different set of processes than exist for other sediment components, it is necessary to examine the variable input of IRD in isolation (Fig. 3). This can be achieved by calculating the mass flux of IRD to the sea floor, or in other words, the IRD mass accumulation rate (MAR; Rea and Leinin, 1989). The IRD MAR is independent of the supply rates of other coarse sand-size components, such as volcanic ash and biogenic material, and therefore yield a more unequivocal record of IRD supply than would be provided by the weight percentages of the medium-coarse sand fraction alone. IRD MAR was the method used in both studies to quantify IRD flux (Cowan, 2001; St. John and Krissek, 2002). The MAR of the terrigenous medium-coarse sand (i.e., IRD) was calculated for each sample from sites 918 and 1101 as follows:

$$\text{IRD MAR } [g/cm^2/kyr] = \text{LSR } [cm/kyr] \times \text{DBD } [g/cm^3] \times \%MCS \times \%IRD$$

where the dry bulk density (DBD) value was obtained from the stratigraphically closest discrete shipboard physical property measurement, %MCS reflects the medium-coarse sand weight percent multiplied as a decimal fraction, and %IRD reflects the weight percent (site 918) or volume percent (site 1101) of terrigenous material in the medium-coarse sand fraction multiplied as a decimal fraction. This method assumes a constant linear sedimentation rate (LSR) between age-depth markers.

DATA AND DISCUSSION

IRD MARs at sites 918 and 1101 are shown in Figure 4. Generally the IRD MAR at site 918 was ten times greater than that to site 1101 since at least 3.0 Ma. Assuming the most important factors influencing IRD flux were

Figure 2. Terrigenous medium to coarse sand (250mm - 2mm) mineral grains and rock fragments interpreted as ice-rafted debris (IRD) from ODP Site 918A 6H5, 132-136 cm (~0.9 Ma).

Table 1: Summary of the depth ranges, calculated ages, and linear sedimentation rates for sites 918 (from St. John and Krissek, 2002) and 1101 (from Cowan, 2001), 0 to ~3 Ma.

	Depth (mbsf)	Calculated Age (Ma)	Linear Sedimentation Rate (cm/kyr)
Site 918	0-21.45	0-0.26	8.3
	21.45-49.00	0.26-0.99	3.8
	49.00-52.90	0.99-1.07	4.9
	52.90-71.10	1.07-1.39	5.7
	71.10 erosional unconformity	hiatus	—
	71.10-81.00	1.71-1.77	16.5
	81.00-115.10	1.77-1.95	18.9
	115.10-146.80	1.95-2.14	16.7
	146.80-413.89	2.14-3.65	17.7
Site 1101	0-55.08	0-0.78	7.06
	55.08-71.2	0.78-0.99	7.68
	71.2-76.15	0.99-1.07	6.19
	76.15-121.12	1.07-1.77	6.42
	121.42-126.98	1.77-1.86	3.25
	126.98-165.98	1.86-2.49	6.18
	165.98-209.4	2.49-2.95	9.46

source-related, this implies that there was either greater iceberg discharge from east Greenland than from the Antarctic Peninsula and/or greater debris content in the Greenland ice compared with ice calved from the Antarctic Peninsula during this time.

When comparing the timing and relative magnitude of IRD flux from these two source regions, a broadly similar pattern can be recognized; both records are dominated by IRD MAR maxima at 0.9, 1.9, 2.7-2.9 Ma. These three episodes of high IRD flux are at least twice as large as the average IRD MAR peaks in the respective records. On a finer scale differences in the two IRD MAR records are evident; there are times when IRD flux is high in one region but not the other (e.g., at 0.5 Ma). These differences are completely expected given the various local conditions that can influence the accumulation of IRD on the sea floor at any particular site, including the climatic conditions on land (e.g., debris content of the ice, iceberg calving rate and provenance) and the oceanographic conditions in the surface water environment (e.g., temperature, presence of sea ice, current strength and direction). What is not expected, is to see repeated coincident high magnitude IRD MAR peaks (i.e., at 0.9, 1.9, 2.7-2.9 Ma) in records from two regions so far apart. It is this broad pattern of high IRD flux episodes that is the focus of the discussion.

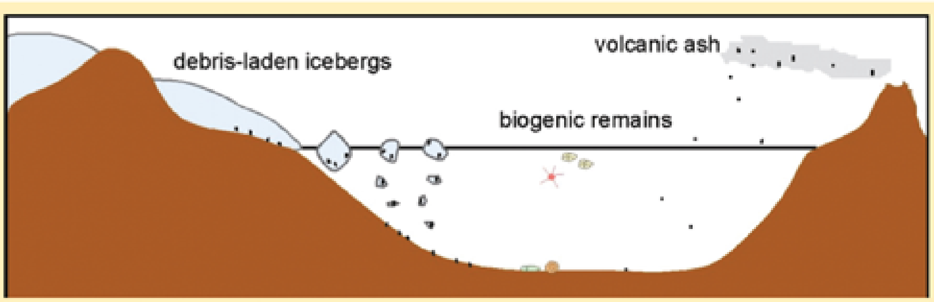

Figure 3. Sketch illustrating the primary sediment components contributing to the sediment accumulation in glaciomarine settings such as site 918. In addition to the input of terrigenous sediment from the rainout of debris laden icebergs, planktonic and benthic biogenic material is deposited. Ash from nearby volcanic eruptions may also be transported and deposited in this setting. Each sediment component can be considered a paleoenvironmental archive.

TEMPORAL PATTERNS

Both the overall co-varying pattern and the specific timing of each of the high IRD flux episodes are intriguing. That a similar pattern of high IRD flux exists for sites so distant from each other, must either be explained by global-scale oceanographic and climate connections, or be written off as pure coincidence. The question then becomes, what oceanographic and climatic conditions existed during these times of high IRD flux that could possibly increase iceberg discharge and/or the debris content of east Greenland and Antarctic Peninsula glaciers, or otherwise focus iceberg melt at these two sites?

A summary of potentially relevant conditions that existed at the times of the three high IRD flux episodes is provided in Table 2. Also included in Table 2 is reference to two other high IRD flux episodes (at ~3.5 and ~4.5 Ma; St. John and Krissek, 2002) recorded in the longer sedimentary section at site 918. The timing of these older high IRD flux episodes is poorly constrained given increased uncertainties in the site 918 age-model down core. However, it appears that similar oceanographic conditions existed at these times as existed during the influx of IRD at 0.9, 1.9 and at 2.7 Ma.

An oceanographic condition that appears to be common to all of the high IRD flux episodes was high eustatic sea level (Table 2; see references therein). One way to explain

Table 2. Comparison of the timing of high IRD flux to sites 918 and 1101 with potentially relevant oceanographic and climatic conditions.

High IRD Flux		Potentially Relevant Concurrent Oceanographic & Climatic Conditions				
Site 918, SE Greenland (St. John & Krissek, 2001)	Site 1101, Antarctic Peninsula (Cowan, 2001)					
0.9 Ma	0.9 Ma	NADW Suppressed (0.9 Ma)[1,2,3]	Low-Salinity Surface Water, Irminger Basin (0.6-0.9 Ma)[6]	Mid-Pleistocene Climate Transition (0.88-0.92 Ma)[7,8,9]	Subantarctic high IRD flux (0.65-0.9 Ma) 11, 14 & extreme deglaciation of the Antarctic Peninsula (0.88 Ma)[10]	Eustatic Highstand (1.0-0.9 Ma)[12]
1.9 Ma	1.9 Ma	NADW Suppressed (1.75-1.8 Ma)[4,5]				Eustatic Highstand (1.8-1.9 Ma)[12]
2.7 Ma	2.8 Ma	NADW Suppressed (2.5-2.7 Ma)[3,4,5]		Warm Southern Ocean (2.48-2.9 Ma)[11]	Subantarctic High IRD flux (2.8 Ma)[13]	Eustatic Highstand (2.6-2.7 Ma)[12]
3.5 Ma (?)	(below base of record)	NADW Suppressed (3.5 Ma)[3,5]				Eustatic Highstand (3.2-3.4 Ma)[12]
4.5 Ma (?)		NADW Suppressed (4.5-5.0 Ma)[3,5]				Eustatic Highstand (4.2-5.0 Ma)[12]

[1]Raymo et al., 1990; [2]Raymo et al., 1997; [3]King et al., 1997; [4]Raymo et al., 1989; [5]Haug & Tiedemann, 1998; [6]Flower, 1998; [7]Berger & Jansen, 1994; [8]Mudelsee & Schulz, 1997; [9]Clark & Pollard, 1998; [10]Anderson & Andrews, 1999; [11]Ciesiklski et al., 1982; [12]Haq et al., 1987; [13]Murphy et al., 2002;

this association is that coastal portions of the east Greenland Ice Sheet and the Antarctic Ice Cap were repeatedly susceptible to destabilization by rising sea levels and increases in the volume of iceberg discharge, and presumably increases in IRD rainout, ensued. This is essentially the scenario proposed by Bornhold (1983) for an increase in IRD flux to the SE Argentine Basin at 0.90-0.65 Ma and by Murphy et al. (2002) for an increase in IRD flux to Meteor Rise in the South Atlantic at 2.8 Ma. Alternatively or additionally, an increase in debris content of the ice would likely have occurred if the glacial ice became increasingly warm-based, as Anderson and Andrews (1999) suggested to explain an increase in Antarctic Peninsula IRD in the Weddell Sea at 0.88 Ma.

A second oceanographic condition that appears to be concurrent with each of the high IRD flux episodes at sites 918 and 1101 was suppressed North Atlantic Deep Water (NADW) formation (Table 2, and references therein). An associated increase in meltwater (i.e., iceberg melt) to the northern North Atlantic during these times of high IRD flux may account for this. A freshwater cap in the northern North Atlantic could interfere with deepwater production as surface water salinities decreased causing the water column to become more stratified (Broecker, 1991). There is oxygen-isotope evidence for such a meltwater pool in the Irminger Sea at 0.9 Ma (Flower, 1998).

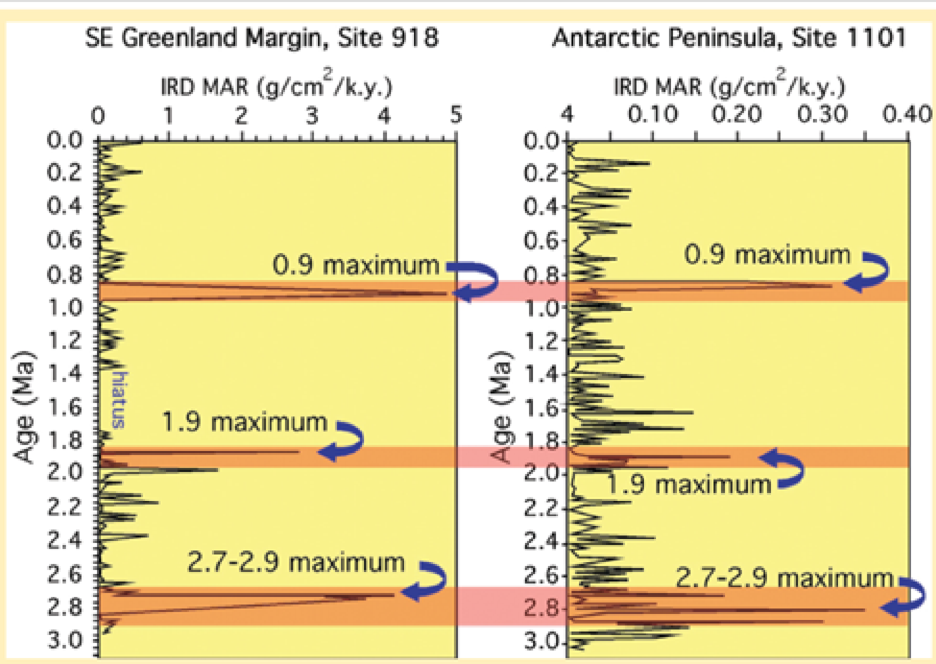

Figure 4. Ice-rafted debris mass accumulation rate (IRD MAR) records plotted against calculated ages for sites 918 (St. John and Krissek, 2002) and 1101 (Cowan, 2001). A hiatus exists in the site 918 record at 71 meters below sea floor, which is interpreted to represents duration of 320 kyr, from 1.71 to 1.39 Ma (St. John and Krissek, 2002).

The approximate 1-Myr time span between each of the high IRD flux episodes identified at both sites 918 and 1101 does not go without notice. However, because the age-models for these sites were based on a limited number of age-depth markers, chronological uncertainties in the timing of IRD flux to the two sites exist, disallowing any rigorous statistical investigation of the timing of these events or of lead-lag relationships. Speculatively, the timing of major IRD flux may reflect a 1-Myr cyclicity in global climate. Crowley and North (1991) noted that other late Cenozoic records, including those of sea level (Moore et al., 1987) and of temperature sensitive marine biofacies (Poore, 1981), display a characteristic 1-Myr fluctuation as well. A common origin for this possible cyclicity is not known (Schlanger, 1986).

TEMPORAL EVENTS

Two of the high IRD flux episodes common to sites 918 and 1101, are interesting for an additional reason: their timing with respect to global climate reorganization. Within the bounds of the age-models, the increased IRD flux to sites 918 and 1101 at 2.7-2.9 Ma may slightly precede the general onset of Northern Hemisphere glaciation at 2.65 Ma. This is consistent with the view that the SE Greenland Ice Sheet (Krabill et al., 1999; Jansen et al., 2000; St. John and Krissek, 2002) and the Antarctic Peninsula Ice Cap (Bart and Anderson, 2000; Cowan, 2001) are dynamic regions of climate change, and were specifically more sensitive to global climate forcing than was the Laurentide ice sheet in North America.

The increased IRD fluxes to sites 918 and 1101 at 0.9 Ma can also be linked to a major global climate reorganization that is well recognized but poorly understood: the mid-Pleistocene climate transition (MPT; Table 2). The MPT is marked by a period of increased ice-rafting from climatically sensitive regions around the global, such as Scandinavia (Fronval and Jansen, 1996; Jansen et al., 2000) and SE Alaska (St. John and Krissek, 1999), in addition to SE Greenland (St. John and Krissek, 2002) and the Antarctic Peninsula (Cowan, 2001). The MPT is also marked by a shift to more extreme global glacial-interglacial cycles (Berger and Jansen, 1994; Muldeless and Schultz, 1997; Clark and Pollard, 1998).

CONCLUSION

Records of IRD flux derived from similarly situated but distant glacimarine settings, the continental margins of SE Greenland (ODP site 918) and the Antarctic Peninsula (ODP site 1101), co-varied during the Plio-Pleistocene. These records are dominated by high IRD flux episodes at 0.9, 1.9, 2.7-2.9 Ma, which appear to fit in a global, and perhaps cyclic (~1-Myr), pattern of oceanographic changes in sea level and thermohaline circulation. Evidence points to repeated bipolar destabilizations of coastal ice bodies in these climatically-sensitive regions as sea levels achieved highstand positions. Subsequent increases in the calving of debris-laden icebergs would explain the episodes of high IRD flux to sites 918 an 1101. An increase in freshwater input from melting icebergs in the northern North Atlantic may also explain the concurring pattern of suppressed NADW formation.

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