North Atlantic Paleoceanography: The Last Five Million Years

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In the North Atlantic, cold, relatively salty water sinks in the icy Labrador and Greenland seas, forming North Atlantic Deep Water (NADW). This circulates through the global ocean, driving ocean overturning and global heat transport and, thus, impacting global climate. As one of the most climatically sensitive regions on Earth, the North Atlantic has experienced abrupt changes to its ocean-atmosphere-cryosphere system, triggered by fluctuations in meltwater delivery to source areas of NADW formation.

For about the past 100 thousand years, these abrupt jumps in climate state have manifested as 'Dansgaard/Oeschger' (D/O) oscillations (millennial-scale warm-cold oscillations) and 'Heinrich' events in ice and marine sediment cores, respectively [e.g., *Dansgaard et al.*, 1993; *Bond and Lotti,* 1995]. These Heinrich events are characterized as huge input of ice-rafted debris (IRD) and meltwater pulses, documenting episodes of sudden instability and collapse of the current Greenland ice sheets and the Laurentide ice sheet, the latter of which covered northern North America several times during the Pleistocene Epoch.

Understanding the mechanisms and causes of the abrupt climate change is one of the major challenges in global climate change research today. In this context, the determination of the long-term evolution of millennial-scale variability in surface temperature, ice sheet stability as a source for meltwater discharge, and thermohaline circulation can provide clues to the mechanisms responsible for abrupt climate change, which are still poorly understood in detail.

To shed more light on these topics, the North Atlantic Ocean was visited by scientific drilling ship *JOIDES Resolution* during Integrated Ocean Drilling Program (IODP) Expedition 306 in March–April 2005. The main goal of Expedition 306—as was the main goal of Expedition 303—was to generate a continuous high-resolution chronology spanning the last ~5 million years (late Neogene-Quaternary), using North Atlantic climate proxies collected from layers of ocean sediments.

Using a range of stratigraphic tools, including stable isotopes and relative (geomagnetic) paleointensity [e.g., *Channell et al.*, 2004; *Shipboard Scientific Party,* 2005; *Expedition Scientists,* 2005], these records will be correlated at scales much smaller than the Milankovitch cycles of eccentricity (100,000 years), obliquity (41,000 years), and precession (23,000 years), which are known to externally govern climate changes. For this specific research program, nine holes were drilled to a depth of several hundred meters below the seafloor at three sites in the central North Atlantic between 40° and 56°N in water depth between 2800 and 3400 meters, using the advanced piston coring (APC) system (see Figure 1: Sites U1312, U1313, and U1314).

As a second important objective of Expedition 306, a borehole observatory for measurements of sub-bottom temperatures for long-term reconstruction of bottom-water temperatures was installed successfully in a newly drilled 180-meter-deep hole close to the Ocean Drilling Program's Site 642 (see Figure 1: Site U1315). By analyzing sub-bottom temperature perturbations, a temperature record may be able to be reconstructed for the first time of bottom water during at least the past 100 years, i.e., going back in time far beyond the directly measured temperature records available up to now [*Harris et al.*, 2006].

Preliminary Results From Site U1313

For this North Atlantic paleoceanographic study, more than 2.3 kilometers of sediment cores were recovered at the three sites. The preliminary shipboard data indicate that glacial/interglacial as well as (sub)millennial cycles of excellent quality are preserved in these sediments. As an example, some initial results from Site U1313 are presented here in more detail (Figures 2 and 3).

Site U1313 is a reoccupation of Deep Sea Drilling Project (DSDP) Site 607, located at the base of the upper western flank of the Mid-Atlantic Ridge in a water depth of 3426 meters, approximately 390 kilometers northwest of the Azores (Figure 1). Site 607 has been very important for generating a stable isotope stratigraphy for the last ~3 million years and for interpreting this stratigraphy in terms of ice sheet variability and changes in NADW circulation [e.g., *Ruddiman et al.*, 1989]. DSDP Leg 94 drilling of this site, however, preceded the advent of the shipboard capability for construction of composite sections and pass-through magnetometers for continuous measurement of magnetic parameters. Furthermore, the present condition of existing DSDP cores collected in 1983 does not permit the high-resolution studies proposed here.

At Site U1313, four holes with a maximum penetration down to 308.6 meters below seafloor (mbsf) were drilled. The sedimentary succession of the last six million years

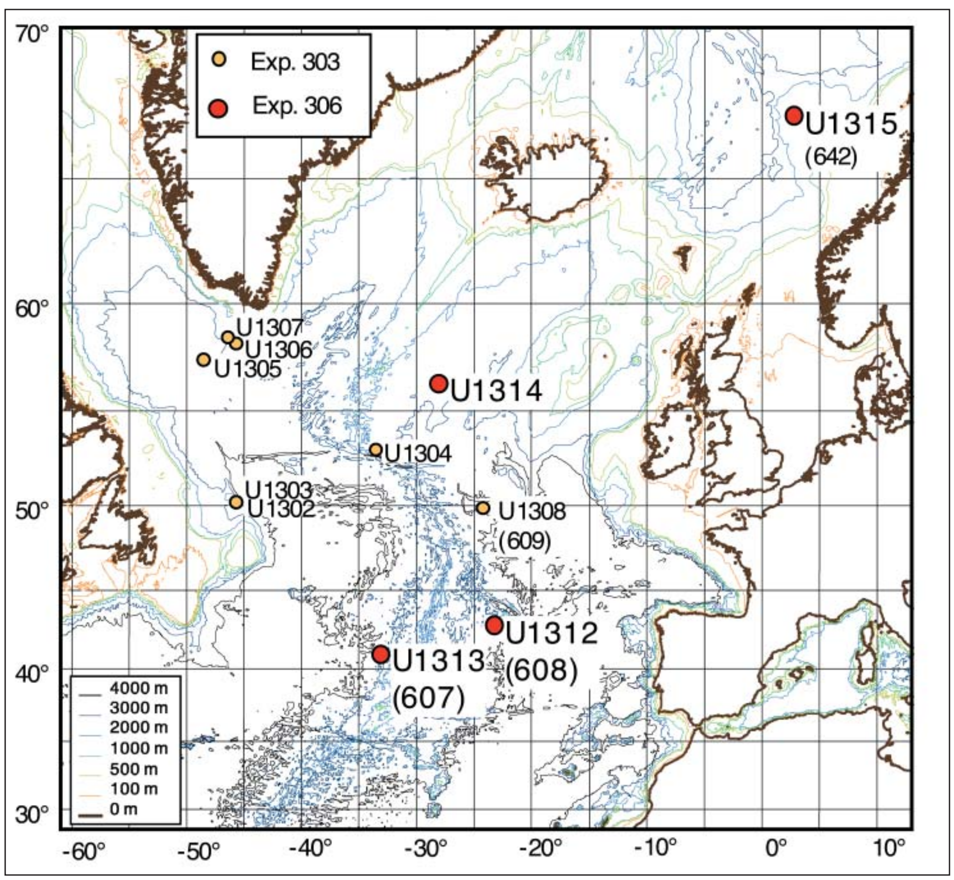

Fig. 1. Locations of sites drilled during expeditions 303 and 306. Cores that are reoccupied DSDP and ODP sites show the DSDP number (607, 608, and 609) and ODP number (642) in parentheses.

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(Holocene to latest Miocene) at Site U1313 consists primarily of nannofossil ooze with varying amounts of foraminifers and clay- to gravel-sized terrigenous components. Biostratigraphy and magnetostratigraphy indicate uniform average sedimentation rates of about five centimeters per thousand years throughout the Pliocene to Holocene time interval [0 to 5 million years ago (Ma)], whereas in the late Messinian (5 to 6 Ma) sedimentation rates are increased to ~13–14 centimeters per thousand years.

The detrital components become much more important and variable in the upper Pliocene-Pleistocene interval of the sequence, as indicated by the magnetic susceptibility record [*Expedition Scientists,* 2005] as well as the records of carbonate, natural gamma radiation (NGR), and lightness (L*) from color reflectance measurements (Figures 2 and 3), probably reflecting increased Northern Hemisphere ice sheet instability.

In particular, the L* record, controlled mainly by the variability of carbonate content [*Expedition Scientists,* 2005], mimics glacial/interglacial variations in the global benthic oxygen isotope stack of *Lisiecki and Raymo* [2005] in detail. The peaks and troughs of the oxygen record through time, labeled as marine isotope stages (MIS), show that when compared to the L* record, MIS 11 was the most prominent Pleistocene interglacial interval (Figure 2). A preliminary age model was constructed by matching sharp L* variations with glacial and interglacial terminations (Figure 2).

First results from biomarker analysis already performed onboard the *JOIDES Resolution* indicate that alkenone-derived sea surface temperatures (SST) show a variability from ~13º to 19°C in the Pleistocene (Figure 2), although interglacial maxima have probably not yet been sampled. A few data points from the upper Pliocene interval (1.9 to 3.2 Ma) display SST values of about 17º–22°C. The Pleistocene SST variability of about 6°C agrees with the last glacial maximum (about 20,000 years ago) to modern temperature difference estimated for the same area [*Pflaumann et al.,* 2003].

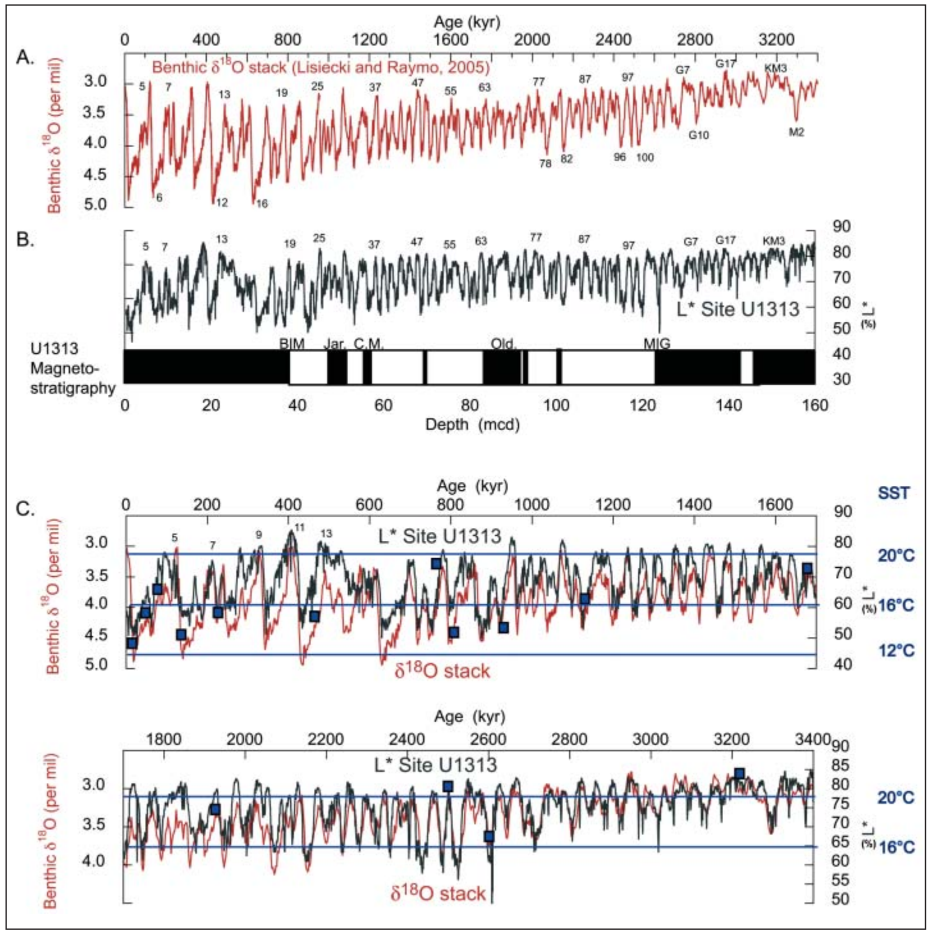

Fig. 2. Preliminary correlation between (a) the global benthic oxygen isotope stack of Lisiecki and Raymo *[2005] and (b) the lightness (L*) measured in the upper 160 meters of Site U1312. In addition, the magnetostratigraphy of Site U1313 is shown. Numbers indicate marine oxygen isotope stages according to* Lisiecki and Raymo *[2005]. (c) By matching sharp L* variations with glacial and interglacial terminations, the Site U1313 depth scale was transferred into an age scale. In addition, sea surface temperatures (SST) as obtained from alkenone data of Site U1313 samples are shown as blue squares.*

Implications of NGR Studies at Site U1313

At Site U1313, in situ downhole logging was successfully carried out using a triple combo tool string. The records provided density, porosity, NGR, resistivity, and photoelectric-effect data throughout the 300-meter sedimentary sequence. Corresponding core physical property measurements could be correlated with in situ downhole data. The consistency of downhole logging data with core data will allow mapping of the spliced core record to actual depth, resulting in more accurate sedimentation and mass accumulation rate calculations, as well as more detailed age-depth models.

The NGR was measured with the Hostile Environment Gamma Ray Sonde in American Petroleum Institute gamma ray units (gAPI). In the upper 65 meters, the values were measured through the drill pipe and are attenuated by a factor of about four to five. For this part of the record, the original values were multiplied by a factor of five. Further information on the procedures and wireline tools used during Expedition 306 can be found at http://iodp.ldeo.columbia.edu/TOOLS_LABS/index.html

Of special note is the consistent linear correlation of downhole NGR (upper 225 mbsf) with the recent *Lisiecki and Raymo* [2005] benthic oxygen isotope stack of the past 5.3 million years (Figure 3). The NGR value is mainly driven by the radiogenic thorium concentrations derived from clay content. By interpreting the NGR signal as a record for detrital clay input, the following still preliminary statements can be made:

- Very low and almost constant NGR values, paralleled by very high carbonate contents of more than 90 percent, are typical for the lower part of the record, indicating low detrital input prior to about 3.3 Ma.
- At about 140 mbsf, correlating with MIS M2 at 3.3 Ma (see Figure 2), a first increase in NGR values suggests slightly increased detrital input.
- At 115 mbsf (near 2.75 Ma, MIS G6–G10, and contemporaneous with the onset of major Northern Hemisphere glaciation), NGR values significantly increased, carbonate contents decreased and gravel-sized dropstones frequently occurred (Figure 3), indicating extended glaciation. Distinct NGR maxima occurred between 106 and 86 mbsf, correlating with the prominent glacial stages 100, 98, 96, 82, and 78 (see Figure 2).
- Between 86 and 52 mbsf (between about 2.05 and 1.25 Ma), maximum NGR values are lower than in the previous interval (except one peak at about 60 mbsf or 1.4 Ma), suggesting reduced detrital input.
- The upper 52 meters (the past 1.25 million years) display high-amplitude variations in NGR (detrital input) related to a pronounced glacial/interglacial instability of major Northern Hemisphere ice sheets. A shift toward higher amplitude and more glacial conditions occurred between 0.95 and 0.65 Ma, during the Mid-Pleistocene climate transition (Figure 3) [*Ruddiman et al.,* 1989; *Mudelsee and Schulz,* 1997].

From the multidisciplinary studies to be performed on these new IODP cores (together with the sites from IODP Expedition 303) during the coming years, new milestones in the understanding of mechanisms and causes of abrupt climate change, one of the major challenges in global climate change research today, are expected to be reached.

Acknowledgments

This success of Expedition 306 was the result of excellent cooperation between the IODP staff, the Transocean employees, and the Shipboard Science Party.

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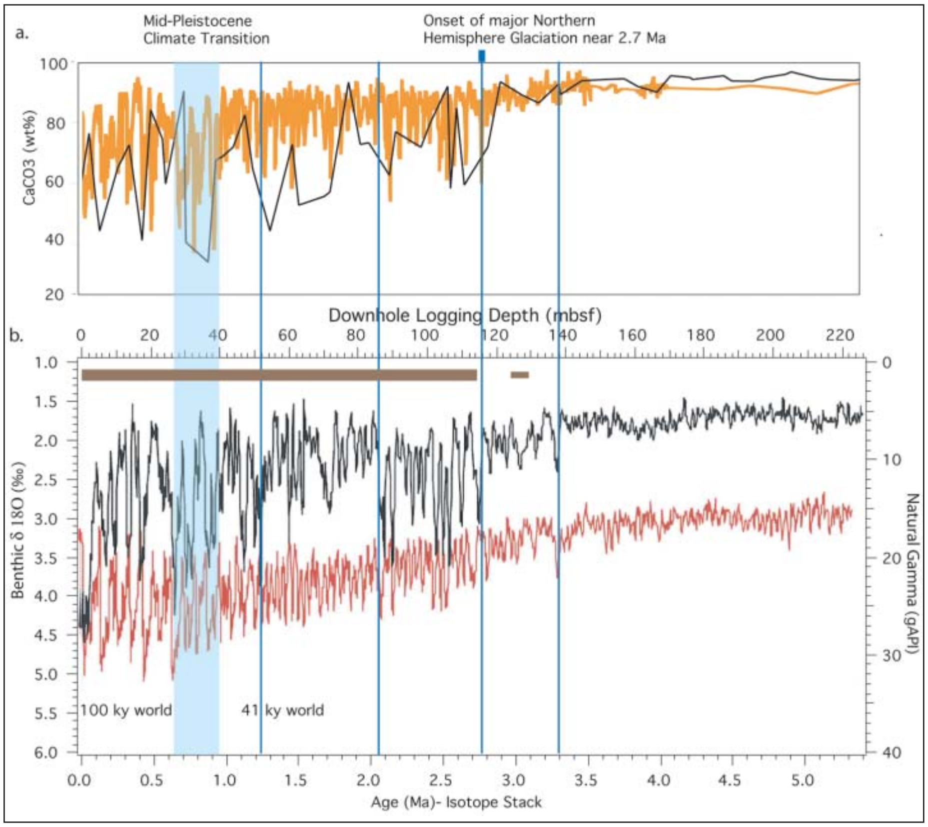

*Fig. 3. (a) A preliminary low-resolution carbonate record of hole U1313A (black) and a high-resolution carbonate record of DSDP Site 607 (orange) [*Ruddiman et al., *1989]. (b) Linear correlation of logging natural gamma radiation (using HSGR) (black) from hole U1313B and benthic oxygen isotope stack (red) over the past 5.3 million years [*Lisiecki and Raymo, *2005]. The correlation has only two tie points at 0 and 5.2 Ma with no stretching or squeezing of logging data depths. Vertical blue lines indicate major changes in the NGR record. The blue-shaded interval between 0.6 and 0.9 Ma marks the Mid-Pleistocene climate shift, where obliquity periodicity transitions from a dominant 41,000-year cycle to a dominant 100,000-year cycle [e.g.,* Mudelsee and Schulz, *1997]. The brown bar marks the occurrence of gravel-sized dropstones.*