North Atlantic Paleoceanography: The Last Five Million Years

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 fluctuations in meltwater delivery to source areas of NADW formation). 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—was as was the main goal of Expedition 303—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 at 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].

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 north-west 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 (mbf) 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.
(Holocene to latest Miocene) at Site U1313 consists primarily of nanofossil ooze with varying amounts of foraminifers and clay-
to-gravel-sized terrigenous components. Bio-
stratigraphy and magnetostratigraphy indi-
cate uniform average sedimentation rates of
about five centimeters per thousand years through-
out 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 vari-
ability from ~13° 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
17°–22°C. The Pleistocene SST variability of
(1.9 to 3.2 Ma) display SST values of about
17°–22°C. The Pleistocene SST variability of
modern (about 6°C) agrees with the last glacial maxi-
mum (about 20,000 years ago) to modern
temperature difference estimated for the
same area [Pflaumann et al., 2003].

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 photo-
electric-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 spiked
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 Ameri-
can 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 thor-
ium concentrations derived from clay con-
tent. By interpreting the NGR signal as a
record for detrital clay input, the following
still preliminary statements can be made:

- At 115 mbsf (near 2.75 Ma, MIS G6–G10,
  and contemporaneous with the onset
  of major Northern Hemisphere glaciation),
  NGR values significantly increased, carbon-
  ate 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), sug-
  gesting reduced detrital input.

- The upper 52 meters (the past 1.25 mil-
  lion years) display high-amplitude variations
  in NGR (detrital input) related to a pro-
  nounced glacial/interglacial instability of
  major Northern Hemisphere ice sheets. A
  shift toward higher amplitude and more gla-
  cial 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 per-
fomed on these new IODP cores (together

![Fig. 2. Preliminary correlation between (a) the global benthic oxygen isotope stack of Lisiecki and Raymo [2005] and (b) the tightness (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.](http://www.earth-space.org/edp/2006/0029/fig2.jpg)
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.

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References


Author Information

Ruediger Stein, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany; E-mail: rstein@awi-bremerhaven.de; Toshiya Kanamatsu, Institute for Research on Earth Evolution, Kanagawa, Japan; Carlos Alvarez-Zarikian, Texas A&M University, College Station; Sean M. Higgins, Lamont-Doherty Earth Observatory of Columbia University, Palisades, N.Y.; Jim E.T. Channell, Department of Geological Sciences, University of Florida, Gainesville; Essam Aboud and Masao Ohno, Kyushu University, Fukuoka, Japan; Gary D. Acton, University of California, Davis; Kazumi Akimoto, Kumamoto University, Japan; Ian Bailey, University College, London, U.K.; Kjell R. Bjorklund, University of Oslo, Norway; Helen Evans and Simon H.H. Nielsen, University of Florida, Gainesville; Qiumin Zhai, University of South Florida, St. Petersburg; Francisco J. Siervo Sanchez, Universidad de Salamanca, Spain; Antje Voelker, Instituto Nacional de Engenharia Tecnologia e Inovacao, Alfagide, Portugal; and Qumin Zhai, University of Tokyo, Japan.