

North Atlantic Paleoceanography: The Last Five Million Years

PAGES 129, 133

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.

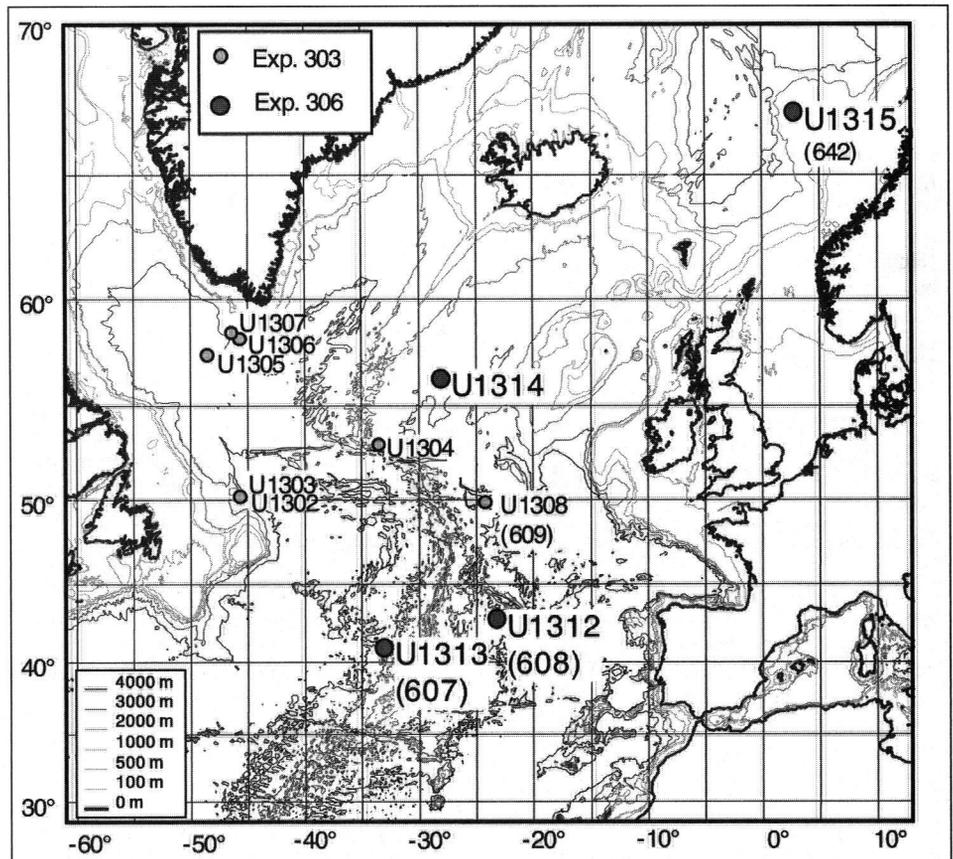


Fig. 1. Locations of sites drilled during expeditions 303 and 306. Cores that are reoccupied DSDP and ODP sites show the DSDP number (607, 608, and 609) and ODP number (642) in parentheses. Original color image appears at the back of this volume.

BY R. STEIN, T. KANAMATSU, C. ALVAREZ-ZARIKIAN, S.M. HIGGINS, J.E.T. CHANNELL, E. ABOUD, M. OHNO, G.D. ACTON, K. AKIMOTO, I. BAILEY, K.R. BJØRKLUND, H. EVANS, S.H.H. NIELSEN, N. FANG, P. FERRETTI, J. GRUETZNER, Y.J.B. GUYODO, K. HAGINO, R. HARRIS, K. HATAKEDA, J. HEFTER, S.A. JUDGE, D.K. KULHANEK, F. NANAYAMA, H. RASHID, F.J. SIERRA SANCHEZ, A. VOELKER, AND Q. ZHAI

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 (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.

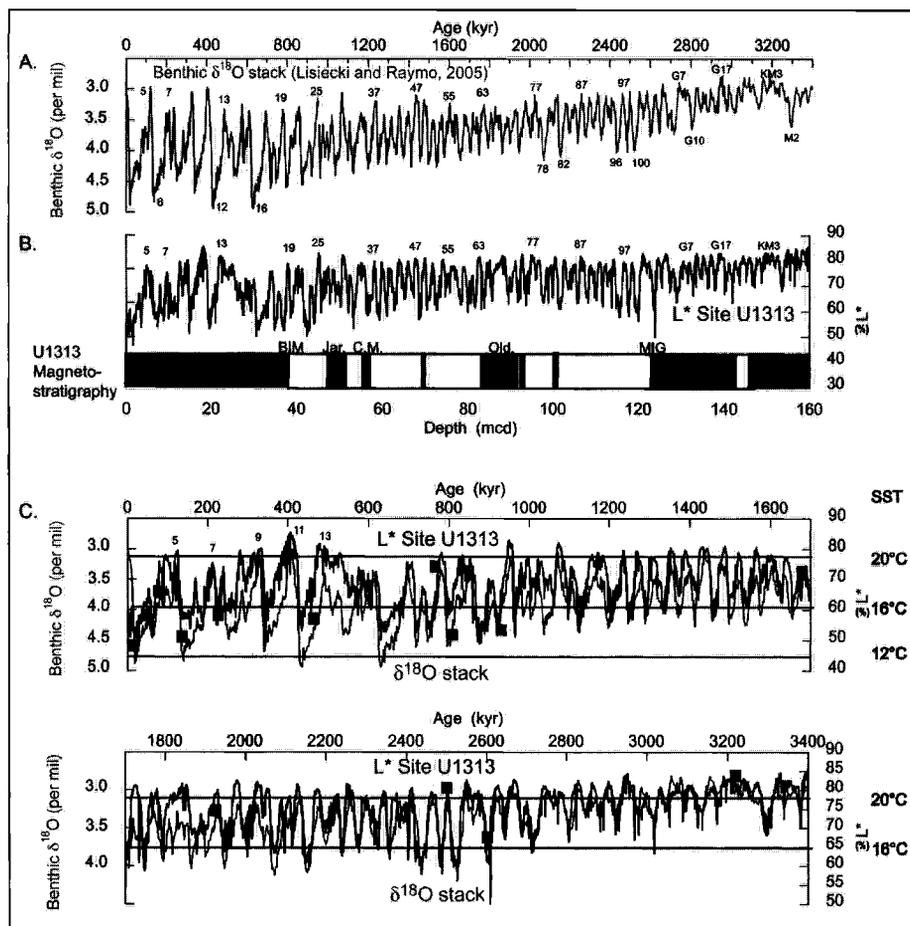
The detrital components become much more important and variable in the upper Pliocene-Pleistocene interval of the sequence, as indicated by the magnetic susceptibility record [Expedition Scientists, 2005] as well as the records of carbonate, natural gamma radiation (NGR), and lightness (L^*) from color 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 ~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 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].

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.



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.

References

- Bond, G. C., and R. Lotti (1995), Iceberg discharges into the North Atlantic on millennial time scales during the last glaciation, *Science*, **267**, 1005–1010.
- Channell, J. E. T., et al. (2004), North Atlantic climate, *Exped. 303/306 Sci. Prosp.*, Integrated Ocean Drill. Prog., Washington, D. C. (Available at <http://iodp.tamu.edu/publications/SP/303306SP/303306SP.PDF>)
- Dansgaard, W., et al. (1993), Evidence for general instability of past climate from a 250 kyr ice core record, *Nature*, **364**, 218–220.
- Expeditions Scientists (2005), North Atlantic climate 2, *Prel. Rep. 306*, doi:10.2204/iodp.pr.306.2005, Integrated Ocean Drill. Prog., Washington, D. C.
- Harris, R. N., et al. (2006), Borehole Observatory Installations on IODP Expedition 306 Reconstruct Bottom-Water Temperature Changes in the Norwegian Sea, *Scientific Drilling*, **2**, 28–31.
- Lisiecki, L. E., and M. E. Raymo (2005), A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}\text{O}$ records, *Paleoceanography*, **20**, PA1003, doi:10.1029/2004PA001071.
- Mudelsee, M., and M. Schulz (1997), The Mid-Pleistocene climate transition: Onset of 100 ka cycle lags ice-volume build-up by 280 ka, *Earth Planet. Sci. Lett.*, **151**, 117–123.
- Pflaumann, U., et al. (2003), Glacial North Atlantic: Sea surface conditions reconstructed by GLAMAP 2000, *Paleoceanography*, **18**(3), 1065, doi:10.1029/2002PA000774.
- Ruddiman, W. F., M. E. Raymo, D. G. Martinson, B. M. Clement, and J. Backman (1989), Pleistocene evolution: Northern Hemisphere ice sheets and North Atlantic Ocean, *Paleoceanography*, **4**(4), 353–412.
- Shipboard Scientific Party (2005), North Atlantic climate: Ice sheet–ocean atmosphere interactions on millennial timescales during the late Neogene-Quaternary using a paleointensity-assisted chronology for the North Atlantic, *Exped. 303 Prelim. Rep.*, Integrated Ocean Drill. Prog., Washington, D. C. (Available at <http://iodp.tamu.edu/publications/PR/303PR/303PR.PDF>)

Author Information

Ruediger Stein, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany,

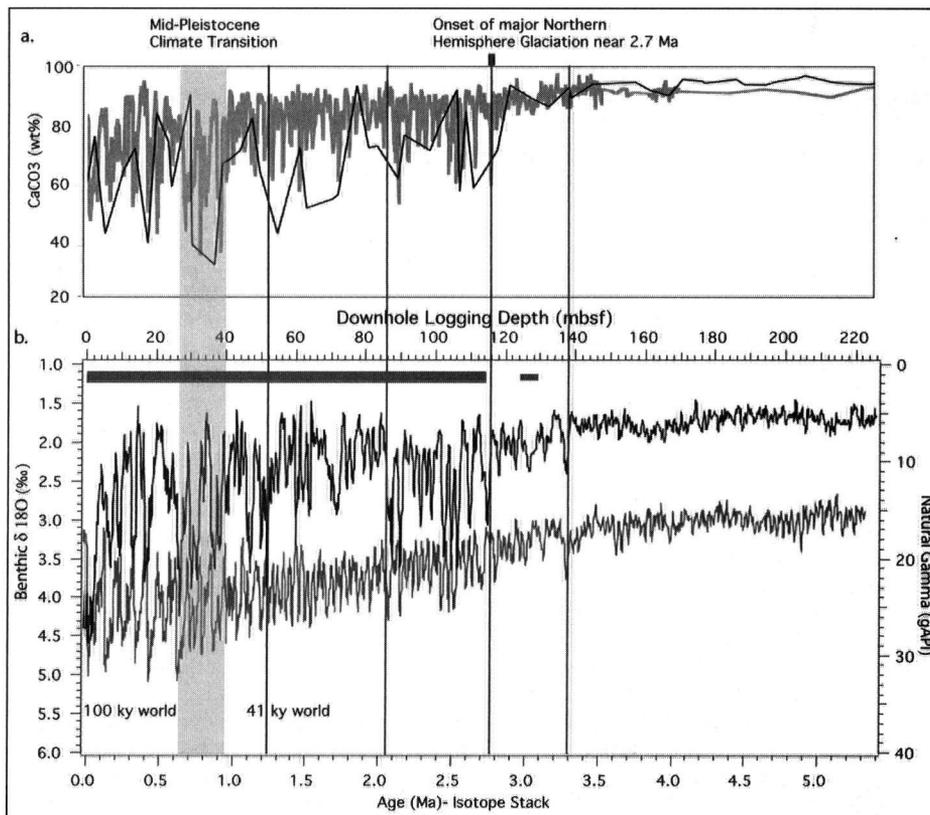


Fig. 3. (a) A preliminary low-resolution carbonate record of hole U1313A (black) and a high-resolution carbonate record of DSDP Site 607 (orange) [Ruddiman et al., 1989]. (b) Linear correlation of logging natural gamma radiation (using HSGR) (black) from hole U1313B and benthic oxygen isotope stack (red) 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. Original color image appears at the back of this volume.

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 Akiyama, Kumamoto University, Japan; Ian Bailey, University College, London, U.K.; Kjell R. Björklund, University of Oslo, Norway; Helen Evans and Simon H.H. Nielsen, University of Florida, Gainesville; Nianqiao Fang, China University of Geosciences, Beijing; Patrizia Ferretti, University of Cambridge, U.K.; Jens Gruetzner, University of Bremen, Germany; Yohan J.B. Guyodo, Laboratoire des Sciences du Climat et de l'Environnement, Gif-sur-Yvette, France; Kentaro Hagino, Hokkaido University, Sap-

poro, Japan; Robert Harris, Oregon State University, Corvallis; Kentaro Hatakeda, Tohoku University, Sendai, Japan; Jens Hefter, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany; Shelley A. Judge, Ohio State University, Columbus; Denise K. Kulhanek, Florida State University, Tallahassee; Futoshi Nanayama, Geological Survey of Japan, Ibaraki; Harunur Rashid, University of South Florida, St. Petersburg; Francisco J. Sierro Sanchez, Universidad de Salamanca, Spain; Antje Voelker, Instituto Nacional de Engenharia e Inovacao, Alfragide, Portugal; and Qiumin Zhai, University of Tokyo, Japan.

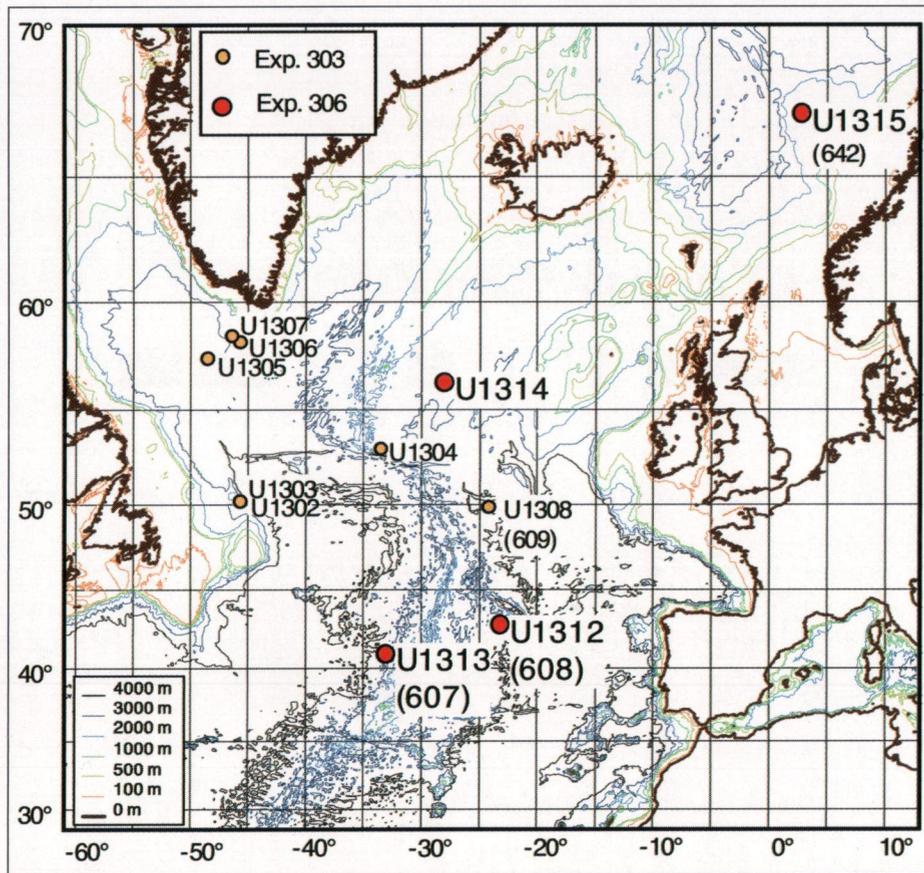


Fig. 1. Locations of sites drilled during expeditions 303 and 306. Cores that are reoccupied DSDP and ODP sites show the DSDP number (607, 608, and 609) and ODP number (642) in parentheses.

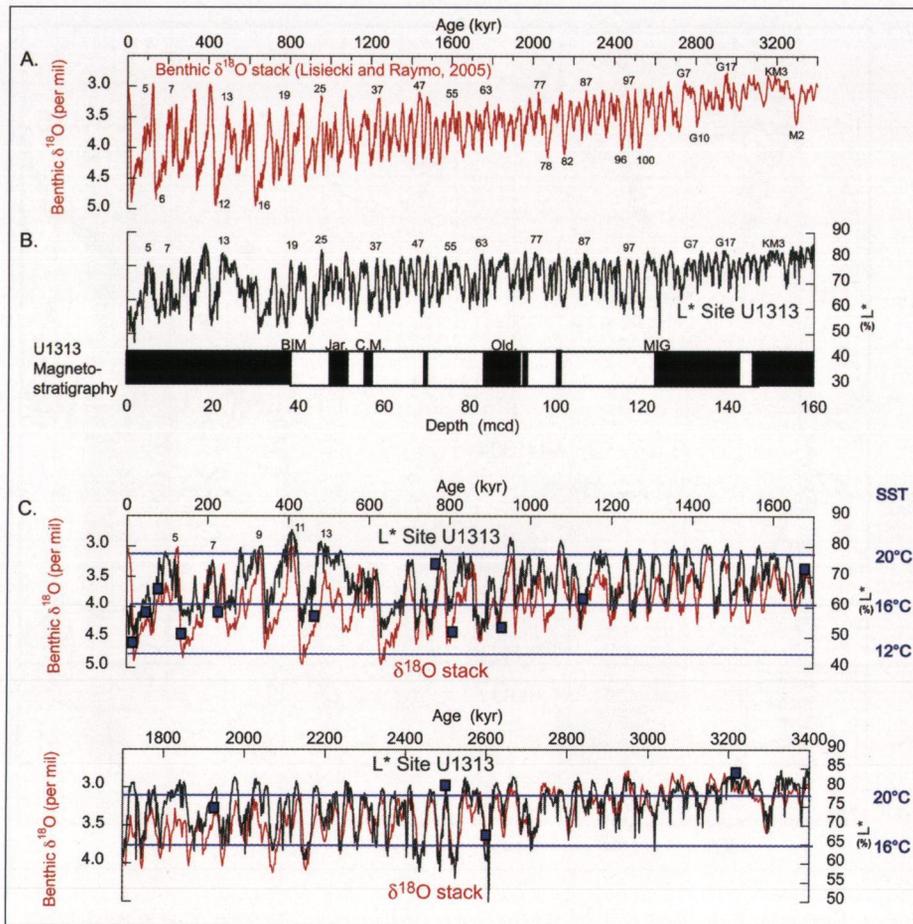


Fig. 2. Preliminary correlation between (a) the global benthic oxygen isotope stack of Lisiecki and Raymo [2005] and (b) the lightness (L^*) measured in the upper 160 meters of Site U1312. In addition, the magnetostratigraphy of Site U1313 is shown. Numbers indicate marine oxygen isotope stages according 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.

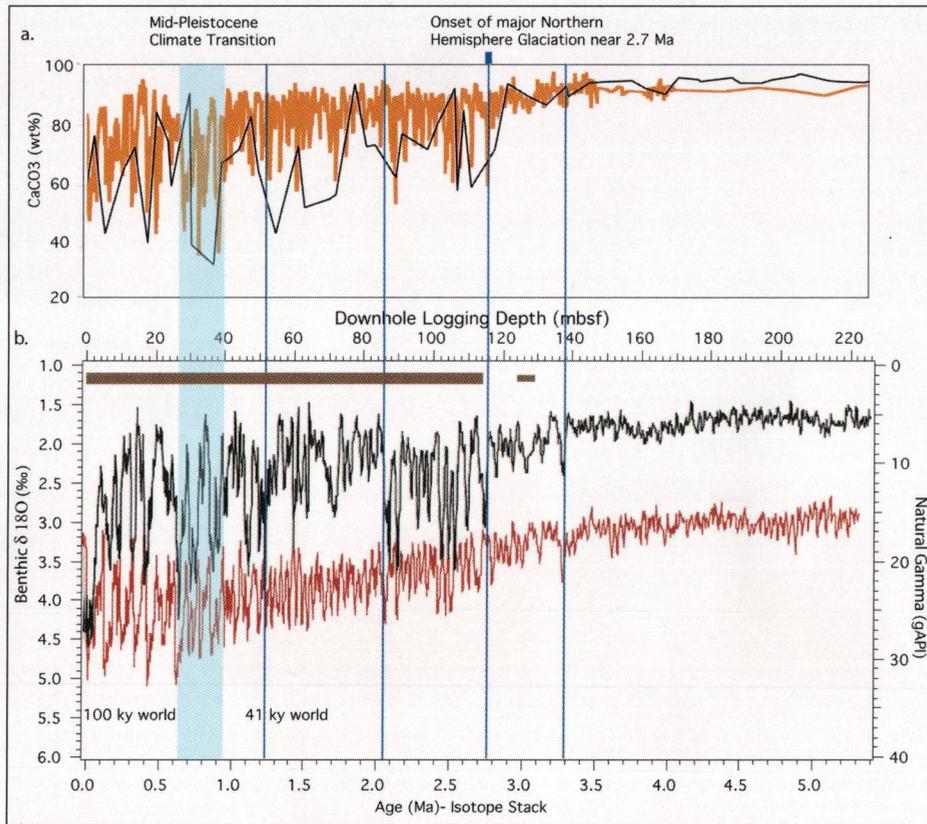


Fig. 3. (a) A preliminary low-resolution carbonate record of hole U1313A (black) and a high-resolution carbonate record of DSDP Site 607 (orange) [Ruddiman et al., 1989]. (b) Linear correlation of logging natural gamma radiation (using HSGR) (black) from hole U1313B and benthic oxygen isotope stack (red) 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.