Integrated Ocean Drilling Program
Expedition 303 Preliminary Report

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

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DISCLAIMER

The following scientists and personnel were aboard the *JOIDES Resolution* for Expedition 303 of the Integrated Ocean Drilling Program.

Shipboard Scientific Party

James E.T. Channell
Co-Chief Scientist
Department of Geological Sciences
University of Florida
241 Williamson Hall
Gainesville FL 32611-7340
USA
jetc@nersp.nerdc.ufl.edu
Work: (352) 392-3658
Fax: (352) 392-9294

Tokiyuki Sato
Co-Chief Scientist
Institute of Applied Sciences, Mining College
Akita University
Tegata-Gakuencho 1-1
Akita 010-8502
Japan
toki@quartet.ipc.akita-u.ac.jp
Work: (81) 18-833-5261
Fax: (81) 18-837-0401

Mitchell J. Malone
Expedition Project Manager/Staff Scientist
Integrated Ocean Drilling Program
Texas A&M University
1000 Discovery Drive
College Station TX 77845-9547
USA
malone@iodp.tamu.edu
Work: (979) 845-5218
Fax: (979) 845-0876

Stuart Robinson
Logging Staff Scientist
Borehole Research Group
Lamont-Doherty Earth Observatory
of Columbia University
PO Box 1000, 61 Route 9W
Palisades NY 10964
USA
stuartr@ldeo.columbia.edu
Work (845) 365 8695
Fax: (845) 365 3182

Gretta Linda Bartoli
Sedimentologist
Institute for Geosciences
Christian-Albrechts-Universität zu Kiel
Olshausenstrasse 40
24118 Kiel
Germany
gb@gpi.uni-kiel.de
Work: (49) 431-880-2884
Fax: (49) 431-880-4376

Shun Chiyonobu
Paleontologist (nannofossils)
Institute of Geology and Paleontology
Tohoku University
Graduate School of Science
Aramaki-aza-Aoba
Aoba-ku, Sendai 980-8587
Japan
chiyonobu@dges.tohoku.ac.jp
Work: (81) 18-889-2371

John (Jed) E. Damuth
Sedimentologist
Department of Geology
University of Texas at Arlington
PO Box 19049
500 Yates Street, Room 107
Arlington TX 76019-0049
USA
damuth@uta.edu
Work: (303) 471-2090
Fax: (817) 272-2628

Lucia de Abreu
Physical Properties Specialist
Department of Earth Sciences
University of Cambridge
The Godwin Laboratory
Pembroke Street - New Museums Site
Cambridge CB2 3SA
United Kingdom
ld206@cus.cam.ac.uk
Work: (44) 1223-334870
Fax: (44) 1223-334871

Anne De Vernal
Palynologist
GEOTOP
Université du Québec à Montréal
CP 8888, Succursale Centre Ville
Montréal Québec H3C 3P8
Canada
deverna.anne@uqam.ca
Work: (514) 987-3000, ext 8599
Fax: (514) 987-3635

Atsuhito Ennyu
Inorganic/Organic Geochemist
Department of Earth and Planetary Sciences
Hokkaido University
N 10 W 8
Sapporo 060-0810
Japan
aennyu@nature.sci.hokudai.ac.jp
Work: (81) 11 706 4498
Fax: (81) 11 706 2986

Estela Vazquez Esmerode
Sedimentologist
University of Copenhagen
Geologisk Institut
Oster Voldgade 10
1350 Copenhagen
Denmark
estelav@geol.ku.dk
Work: (45) 264-34987

Satoshi Funakawa
Paleontologist (radiolarians)
Department of Geology, Faculty of Agriculture
Utsunomiya University
Utsunomiya, Tochigi 321-8505
Japan
funakawa@msg.biglobe.ne.jp
Work: (81) 28-649-5426
Fax: (81) 28-655-4802

Samuel S. Henderson
Physical Properties Specialist
Department of Geological Sciences
Rutgers, The State University of New Jersey
610 Taylor Road
Piscataway NJ 08854-8066
USA
samhend@rci.rutgers.edu
Work: (732) 445-3507
Fax: (732) 445-3374

David A. Hodell
Stratigraphic Correlator
Department of Geological Sciences
University of Florida
214 Williamson Hall
PO Box 112120
Gainesville FL 32611
USA
dhodell@geology.ufl.edu
Work: (352) 392-6137
Fax: (352) 392-9294

Masashi Ito
Inorganic Geochemist
Institute for Frontier Research
on Earth Evolution (IFREE)
Japan Marine Science and Technology Center
2-15 Natsushimacho
Yokosuka 237-0061
Japan
masasitou@jamstec.go.jp
Work: (81) 468-67-9793
Fax: (81) 468-67-9775

Kiichiro Kawamura
Sedimentologist
Research Group 3
Fukada Geological Institute
2-13-12 Honkomagome
Bunkyo-ku 113-0021
Japan
kichiro@fgi.or.jp
Work: (81) 3-3944-8010
Fax: (81) 3-3944-5404

Noriko Kawamura
Sedimentologist
Graduate School of Human and
Environmental Studies
Kyoto University
Yoshida-Nihonmatsu-cho
Sakyo-ku, Kyoto 606-8501
Japan
kwmr@gaia.h.kyoto-u.ac.jp
Work: (81) 75-753-6891
Fax: (81) 75-753-2972

Lawrence A. Krissek
Sedimentologist
Department of Geological Sciences
Ohio State University
130 Orton Hall
155 South Oval Mall
Columbus OH 43210-1308
USA
krissek@mps.ohio-state.edu
Work: (614) 292-1924
Fax: (614) 292-1496

Sasha N.B. Leigh
Sedimentologist
School of Geography and Geosciences
St. Andrews University
Irvine Building, North Street
St. Andrews, Fife
Scotland KY16 9AL
United Kingdom
snbl@st-andrews.ac.uk
Work: (44) 07929 714 848

Chuanlian Liu
Paleontologist (nannofossils)
School of Ocean and Earth Science
Tongji University
1239 Siping Road
Shanghai 200092
People's Republic of China
clliu@online.sh.cn
Work: (86) 21-65984876
Fax: (86) 21-65988808

Alain Mazaud
Paleomagnetist
Laboratoire des Sciences du Climat
et de l'Environnement (LSCE)
CNRS
Domaine du CNRS, Avenue de la Terrasse
Gif-sur-Yvette
91198 France
mazaud@lsce.cnrs-gif.fr
Work: (33) 1 69 82 3527
Fax: (33) 1 69 82 3568

Stephen Obrochta
Sedimentologist
Division of Earth and Ocean Sciences
Duke University
Durham NC 27708
USA
spo@duke.edu
Fax: (919) 684-5833

Oscar E. Romero
Paleontologist (diatoms)
Department of Geosciences
Universität Bremen
PO Box 33 04 40
28334 Bremen
Germany
oromero@uni-bremen.de
Work: (49) 421 218 7759
Fax: (49) 421 218 8916

Ralf Schiebel
Paleontologist (foraminifers)
Earth Science
Eidgenössische Technische Hochschule—Zentrum
Sonneggstrasse 5
8092 Zürich
Switzerland
schiebel@erdw.ethz.ch
Work: (41) 1 6323676
Fax: (41) 1 6321080

Chieko Shimada
Paleontologist (diatoms)
Graduate School of Life and Environmental
Sciences
University of Tsukuba
1-1-1 Tennodai
Tsukuba 305-8572
Japan
cshim@arsia.geo.tsukua.ac.jp
Work: (81) 29-853-4465
Fax: (81) 29-851-9764

Joseph S. Stoner
Paleomagnetist
Institute of Arctic and Alpine Research
University of Colorado at Boulder
1560 30th Street
Campus Box 450
Boulder CO 80309-0450
USA
joseph.stoner@colorado.edu
Work: (303) 492-7641
Fax: (303) 492-6388

Roy H. Wilkens
Stratigraphic Correlator
Hawaii Institute of Geophysics and Planetology
University of Hawaii at Manoa
1680 East West Road
Honolulu HI 96822
USA
rwilkens@hawaii.edu
Work: (808) 956-5228
Fax: (808) 956-3188

James D. Wright
Sedimentologist
Department of Geological Sciences
Rutgers, The State University of New Jersey
Room 238 Wright Geological Laboratory
610 Taylor Road
Piscataway NJ 08854-8066
USA
jdwright@rci.rutgers.edu
Work: (732) 445-5722
Fax: (732) 445 3374

Makoto Yamasaki
Paleontologist (foraminifers)
Institute of Applied Earth Sciences
Faculty of Engineering and Resource Science
Akita University
1-1 Tegata-Gakuencho
Akita 010-8502
Japan
yamasaki@keigo.mine.akita-u.ac.jp
Work: (81) 18-889-2383
Fax: (81) 18-837-0401

Transocean Officials

Alexander Simpson
Master of the Drilling Vessel
Overseas Drilling Ltd.
707 Texas Avenue South, Suite 213D
College Station TX 77840-1917
USA

Wayne Malone
Drilling Superintendent
Overseas Drilling Ltd.
707 Texas Avenue South, Suite 213D
College Station TX 77840-1917
USA

IODP Shipboard Personnel and Technical Representatives

Ronald M. Grout
Operations Superintendent

Roy Davis
Laboratory Officer

Paula Clark
Marine Computer Specialist

Trevor J. Cobine
Marine Laboratory Specialist: Paleomagnetism

Lisa K. Crowder
Marine Laboratory Specialist: Underway Geophysics

John Michael Davis
Marine Computer Specialist

John Eastlund
Programmer Specialist

Dennis Graham
Marine Laboratory Specialist: Chemistry

Michiko Hitchcox
Yeoperson

Ted Gustafson
Marine Laboratory Specialist: Downhole Tools/ Thin Sections

Leah Shannon Housley
Imaging Specialist

Eric Jackson
Marine Laboratory Specialist: X-Ray

Jan Jurie Kotze
Marine Instrumentation Specialist

Chieh Peng
Assistant Laboratory Officer

Steve Prinz
Marine Laboratory Specialist: Physical Properties

Pieter Pretorius
Marine Instrumentation Specialist

Paula Weiss
Marine Curatorial Specialist

Robert M. Wheatley
Marine Laboratory Specialist: Chemistry

Javier Espinosa
Schlumberger Engineer

ABSTRACT

Integrated Ocean Drilling Program (IODP) Expedition 303 was designed to sample and study climate records, including the composition and structure of surface or bottom waters and detrital layer stratigraphy indicative of ice sheet instability, at strategic sites that record North Atlantic Pliocene–Quaternary climate. The sites are distributed from the mouth of the Labrador Sea (Eirik Drift and Orphan Knoll) to the central Atlantic in the region of the Charlie Gibbs Fracture Zone. The sites were chosen on the basis of the importance of the climate or paleoceanographic record, adequate sedimentation rates in the 5–20 cm/k.y. range, and the attributes for a stratigraphic template based on relative geomagnetic paleointensity and oxygen isotope data.

INTRODUCTION

The focus of Integrated Ocean Drilling Program (IODP) Expedition 303 was to place late Neogene–Quaternary North Atlantic climate history into a paleointensity-assisted chronology (PAC) based on oxygen isotopes and geomagnetic paleointensity. The nine primary drilling locations (Fig. **F1**) are known, either from previous Ocean Drilling Program (ODP)/Deep Sea Drilling Project (DSDP) drilling or from conventional piston cores, to have the following attributes:

- They contain distinct records of millennial-scale environmental variability (in terms of ice sheet–ocean interactions, deep circulation changes, or sea-surface conditions);
- They provide the requirements for developing a millennial-scale stratigraphy (through geomagnetic paleointensity, oxygen isotopes, microfossils, and regional environmental patterns); and
- They document the details of geomagnetic field behavior.

The ultimate objective is to generate a chronostratigraphic template for North Atlantic climate proxies to allow their correlation at a sub-Milankovitch scale and their export to other parts of the globe.

BACKGROUND

Geological Setting

The North Atlantic Ocean is undoubtedly one of the most climatically sensitive regions on Earth because the ocean-atmosphere-cryosphere system is prone to mode jumps that are triggered by changes in freshwater delivery to source areas of deepwater formation. During the last glaciation, these abrupt jumps in climate state are manifest by Dansgaard/Oeschger (D/O) cycles and Heinrich events in ice and marine sediment cores. Given the paramount importance of the North Atlantic as a driver of global climate change, we drilled at nine key locations to extend the study of millennial-scale climate variability over the last few million years. What is the rationale for studying millennial-scale variability in the North Atlantic over the last few million years rather than just the last glacial cycle (recoverable by conventional piston cores)? Determining the long-term evolution of millennial-scale variability in surface temperature, ice sheet dynamics, and thermohaline circulation can provide clues to the mechanisms responsible for abrupt climate change. For example, the average climate state evolved toward generally colder conditions with larger ice sheets during the Pliocene–Pleistocene. This shift was accompanied by a change in the spectral character of climate proxies from dominantly 41 k.y. to 100 k.y. periods between ~920 and 640 ka (Schmieder et al., 2000). Among the numerous questions to be answered are the following:

- When did “Heinrich events” first appear in the sedimentary record of the North Atlantic?
- Are they restricted to the “100 k.y. world” when ice volume increased substantially?
- Is the quasi-periodic 1500 y cycle documented for the last climate cycle a stable feature of the North Atlantic throughout the Pleistocene?
- How has millennial-scale variability evolved during the Pleistocene as orbital and glacial boundary conditions changed?

SCIENTIFIC AND OPERATIONAL OBJECTIVES OF EXPEDITION 303

Climate-Related Objectives

Stratigraphy is the fundamental backbone of our understanding of Earth’s history, and stratigraphic resolution is the main factor that limits the timescale of processes that can be studied in the past. Sub-Milankovitch-scale climate studies face the challenge of finding a stratigraphic method suitable for correlation at this scale (see Crowley, 1999). Even under optimal conditions, chronologies based on $\delta^{18}O$ are unable to provide sufficient stratigraphic resolution. Within the North Atlantic region, recent improvements in stratigraphic resolution have resulted in a new understanding of the dynamics of millennial-scale climate variability over the last ~100 k.y. (e.g., Bond et al., 1993; McManus et al., 1994; van Kreveld et al., 2000; Sarnthein et al., 2001). These stratigraphies have utilized chronologies from the Greenland Summit ice cores (GRIP/GISP2) and the recognition of regional lithostratigraphic linkages such as Heinrich events and higher-frequency ice-rafted debris (IRD) layers, ash layers, and susceptibility cycles combined with planktonic/benthic $\delta^{18}O$, acceleration mass spectrometry (AMS)^{14}C dates, and geomagnetic paleointensity data (e.g., Bond et al., 1992, 1993, 1999; McManus et al., 1994; Stoner et al., 1998, 2002; Voelker et al., 1998; Kissel et al., 1999; Laj et al., 2000).

The objective of the expedition is to integrate stable isotope and relative geomagnetic paleointensity data with paleoceanographic proxies and, in so doing, generate integrated North Atlantic millennial-scale stratigraphies for the last few million years.

Understanding the mechanisms and causes of abrupt climate change is one of the major challenges in global climate change research today (see Clark et al., 1999, p. vii) and constitutes a vital initiative of the Initial Science Plan of IODP. Ideally, the best approach to this problem would be to collect records of climate variability from a dense geographic network of sites, but this is impractical in paleoceanographic research. In the absence of dense coverage, the most viable approach is to obtain long, continuous time series from key regions and compare the response and timing of climate change among sensitive regions. We intend to develop PACs to establish the phase relationships among globally distributed millennial-scale records. Building global correlations on millennial timescales is an essential step to understanding the underlying mechanisms of abrupt climate change.

A persistent quasi-periodic ~1500 y cycle that is apparently independent of glacial or interglacial climate state has been observed for the past 80 k.y. (Bond et al., 1997, 1999). The millennial-scale cyclicity in the Holocene appears to be mirrored in the last interglacial (marine isotope Stage [MIS] 5e) and is defined by the same petrologic proxies in both interglacials. The presence of this cyclicity in interglacials and the IRD petrology that defines it indicate that the cyclicity does not reflect ice sheet instability or changes in calving of coastal glaciers, but rather changes in sources or survivability of drifting ice, driven by changes in the size and intensity of the subpolar cyclonic gyre (Bond et al., 1999). The Holocene cycles reflect a mechanism operating on at least hemispheric scale (Sirocko et al., 1996; Campbell et al., 1998; De Menocal et al., 2000), indicating that the MIS 5e and Holocene cyclicities have a common origin possibly related to solar forcing (Bond et al., 2001). The implication is that the 1500 y cycle may have been a dominant feature of the Earth's ocean-atmosphere climate over a very long time, which leads to the following questions:

- How far back in time does the ~1500 y cycle extend?
- Do D/O cycles simply represent an amplification of this?
- Do distinct modes of variability persist through other glacial and interglacial intervals?
- If so, is the pacing always the same or does millennial-scale variability evolve during the late Pleistocene?

Recently published evidence from earlier interglacials (MIS 11 and 13) in both the subpolar and subtropical North Atlantic suggests that interglacial cyclicity at those times may have had a significantly longer pacing, on the order of 5000 y or more. The interglacial records from MIS 11 and 13 in Oppo et al. (1998) and McManus et al. (1999), for example, show rather sporadic events that, regardless of age model, cannot occur every 1500 y. Similarly, an MIS 11 record from ODP Site U1063 off Bermuda indicates large shifts in benthic $\delta^{13}C$ on the order of 5–6 k.y. (Poli et al., 2000). In contrast, data from MIS 11 at ODP Site 980 implies the presence of 1–2 k.y. pacing (McManus et al., 1999), suggesting that the 1500 y cycle may be operating in MIS 11 and in other pre-MIS 5e interglacials. If this is true, then the interglacial climate variability may reflect a persistent, perhaps periodic, process operating continuously within the Earth's climate (rather than red noise resulting from a highly nonlinear climate system).

The best evidence for the 1500 y cycle during interglacials seems to be coming from IRD proxies that monitor changes in the subpolar gyre in the North Atlantic. Our drilling sites are positioned to monitor such changes. In contrast to ODP Site 980 (Feni Drift), our sites are located well within the main present-day routes of iceberg transport into the North Atlantic and are therefore well suited to capture faint interglacial signals that respond to shifting ocean surface circulation. If we can connect the 1500 y cycle to paleointensity records, we will have a means of directly comparing both signals with climate records from well outside the North Atlantic region.

Geomagnetic-Related Objectives

Understanding the changes in the ice sheet-ocean-atmosphere system that gave rise to millennial-scale climate changes requires the precise long-distance correlation of ice cores and marine sediment cores. Geomagnetic paleointensity records from marine sediment cores have been shown to contain a global signal suitable for fine-scale correlation (see Meynadier et al., 1992; Guyodo and Valet, 1996; Channell et al., 2000; Stoner et al., 1995, 2000, 2002; Laj et al., 2000), at least for the last glacial cycle.

Beyond the range of AMS ^{14}C dating, geomagnetic paleointensity data may provide the only viable means of sub-Milankovitch-scale long-distance correlation. Paleointensity records have been applied to stratigraphic correlation in the Labrador Sea for the last 200 k.y. (Stoner et al., 1998), throughout the North Atlantic for the last 75 k.y. (Laj et al., 2000), and for the Atlantic realm for the last 110 k.y. (Stoner et al., 2000). As variations in geomagnetic paleointensity control atmospheric production of ^{10}Be

and ^{36}Cl isotopes and the flux of these isotopes is readily measurable in ice cores, paleointensity records in marine cores provide an independent link between marine sediment and ice core records (e.g., Mazaud et al., 1994). The lows in paleointensity at ~40 and ~65 ka are readily identifiable as highs in ^{10}Be and ^{36}Cl fluxes (Baumgartner et al., 1998; Raisbeck et al., 1987) in the Vostok and GRIP ice cores, respectively. Frank et al. (1997) showed that 10^4–10^5 y variability in ^{10}Be production rate, as determined from globally distributed deep-sea cores over the last 200 k.y., can be matched to sediment paleointensity data. This observation and the similarity of globally distributed paleointensity records indicate that much of the variability in paleointensity records is globally correlative. The few high-resolution paleointensity records available beyond 200 ka also indicate that fine-scale features are correlative. For example, the paleointensity record for the MIS 9–11 interval (300–400 ka) from the Iceland Basin (ODP Sites 983 and 984) can be correlated to the sub-Antarctic South Atlantic (ODP Site U1089) at suborbital (millennial) scale (Stoner et al., 2003).

In addition to the practical use of magnetic field records for correlation of climate records, further drilling of high-sedimentation-rate drift sites will impact the “solid Earth” theme of IODP by documenting the spatial and temporal behavior of the geomagnetic field at unprecedented resolution. Such data are required to elucidate processes in the geodynamo-controlling secular variation and polarity reversal of the geomagnetic field. Recently derived records of directional secular variation and paleointensity from drift sites (e.g., ODP Legs 162 and 172) have substantially advanced our knowledge of magnetic secular variation, magnetic excursions, and directional/intensity changes at polarity reversal boundaries (see Channell and Lehman, 1997; Channell et al., 1998, 2002; Lund et al., 1998, 2001a, 2001b). Numerous directional magnetic excursions have been observed within the Brunhes Chron at ODP Leg 172 drift sites (Lund et al., 1998, 2001a, 2001b) and in the Matuyama Chron at ODP Leg 162 sites (Channel et al., 2002). These excursions (or brief subchronozones) correspond to paleointensity minima and have estimated durations of a few thousand years. From ODP Leg 162 records and records from the Pacific Ocean, it has been suggested that spectral power at orbital frequencies in paleointensity records may reflect a fundamental property of the geodynamo (Channell et al., 1998; Yamazaki, 1999; Yamazaki and Oda, 2002) rather than climate-related influences on paleointensity records (Guyodo et al., 2000).

There is no doubt that North Atlantic drift sites have revolutionized our understanding of the behavior of the geomagnetic field by providing Brunhes Chron paleomagnetic records at unprecedented resolution. The records can now provide useful constraints for numerical simulations of the geodynamo (e.g., Glatzmaier and Roberts, 1995; Gubbins, 1999; Coe et al., 2000). As a result of these parallel advances, our understanding of the geomagnetic field is on the threshold of substantial progress.

The Expedition 303 sites will provide high-resolution paleomagnetic records extending through the Matuyama Chron (to ~3 Ma). They will allow us to assess the temporal and spatial variability of the geomagnetic field in the Brunhes Chron and compare these records with reversed polarity records from the Matuyama Chron, and to address the following questions:

- Are the characteristics of secular variation different for the two polarity states?
- Are polarity transition fields comparable for sequential polarity reversals?
- Does the geomagnetic field exhibit a complete spectrum of behavior from high-amplitude secular variation to polarity reversals that has not hitherto been documented for lack of high-resolution records?

The nonaxial-dipole (NAD) components in the historical field vary on a centennial scale, and this has been interpreted to indicate similar repeat times in the past (Hulot and Le Mouël, 1994; Hongre et al., 1998). If this is correct, paleointensity records from cores with sedimentation rates less than ~10 cm/k.y. are unlikely to record anything but the axial dipole field. On the other hand, standing NAD components have been detected in the 5 m.y. time-averaged field, although the distribution of these NAD features remains controversial (Kelley and Gubbins, 1997; Johnson and Constable, 1997; Carlut and Courtillot, 1998). Refinement of time-averaged field models as the paleomagnetic database is augmented will lead to a better grasp of how the nonzonal terms in the time-averaged field may influence paleointensity records.

RELATIONSHIP TO PREVIOUS NORTH ATLANTIC DRILLING

Two previous ODP legs to the North Atlantic recovered sequences that are continuous and have sedimentation rates high enough to study oceanic variability on sub-Milankovitch timescales. During Leg 162, four sites were drilled on sediment drifts south of Iceland. These sequences are yielding invaluable insight into the nature of millennial-scale climate variability in the North Atlantic (Raymo et al., 1998, 2004; McManus et al., 1999; Raymo, 1999; Flower et al., 2000; Kleiven et al., 2003). Similarly, during Leg 172 in the northwest Atlantic between ~30° and 35°N, sequences were recovered with high deposition rates that are suitable for millennial- and perhaps centennial-scale studies (Keigwin, Rio, Acton, et al., 1998). Given the successes of Legs 162 and 172, why are additional sites needed in the North Atlantic? The sites drilled during Expedition 303 will augment those of Legs 162 and 172 in two fundamental ways. First, most of our sites are located in the North Atlantic "IRD belt" where massive iceberg discharges are recorded by coarse layers of ice-rafted detritus that are depleted in planktonic foraminifers and have oxygen isotopic values indicative of reduced sea-surface salinities. Site 980 (from ODP Leg 162) does lie within the IRD belt, but it is located on its distal northeastern edge and, consequently, lacks the strong sea-surface response to millennial-scale IRD events that is so well displayed to the south and west. Second, the depth distribution of the Expedition 303 sites (2273–3884 meters below sea level [mbsl]) is ideal for monitoring millennial-scale changes in the production of North Atlantic Deep Water (NADW). Leg 162 sites span 1650–2170 mbsl and provide the intermediate-depth end-member for studies of the formation of Glacial North Atlantic Intermediate Water (GNAIW). Leg 172 drift sites provide a relatively complete depth transect spanning 1291–4595 mbsl. The Expedition 303 sites unify the record of millennial-scale variability in the North Atlantic by bridging the "gap" between Legs 162 and 172. The sites will also expand the geographic range of sites needed to distinguish between latitudinal changes in the mixing zone between southern and northern source waters and changes due to vertical migration of water mass boundaries (Flower et al., 2000).

Data and modeling studies point to changes in the modes of NADW formation as one of the principal factors driving millennial-scale climate change in the high-latitude North Atlantic and Europe (for review, see Alley et al., 1999). Expedition 303 sites (Fig. **F1**) are distributed so that they monitor the major deepwater end-members of NADW: Norwegian-Greenland Seawater (Site U1304) and Labrador Seawater (Sites U1305–U1307) as well as the final NADW mixture (Sites U1302 and U1303). Alley et al. (1999) discussed three distinct modes of thermohaline circulation in the North Atlantic: modern (M), glacial (G), and Heinrich (H). The modern mode is marked by deepwater formation in the Nordic Seas and North Atlantic where the three end-members mix to form NADW. In the glacial mode, deepwater formation is suppressed in the Nordic Seas and GNAIW forms farther south in the North Atlantic. In the Heinrich mode, both deep- and intermediate-water formation is greatly reduced. The modern mode may be a relatively rare feature of the Pleistocene (Raymo et al., 2004). Together with the depth transects drilled during Legs 162 and 172, the Expedition 303 sites will permit monitoring deep- and intermediate-water formation during all three modes of formation.

OPERATIONAL STRATEGY

The (high-resolution) stratigraphic goals require high sedimentation rates (>5 cm/k.y.) at the chosen sites, as well as complete and undisturbed recovery of the stratigraphic sequence. The drilling strategy consisted of advanced piston coring (APC) in three or more holes at each site to ensure complete and undisturbed recovery of the stratigraphic section. The "fast track" magnetic susceptibility core logger (MSCL) allowed near real-time drilling decisions to aid complete recovery of the stratigraphic section. We used the "drillover" strategy employed during ODP Leg 202 to maximize APC recovery and penetration. The depth limit of APC coring is traditionally controlled by the overpull required to retrieve the core barrel. In cases where the full APC stroke was achieved but excessive force was required to retrieve the core barrel (often the limit of APC penetration), the drillover strategy entailed advance of the rotary bit to free the APC barrel. APC coring was generally terminated when the full APC stroke could no longer be achieved. Because of the pivotal role of magnetic studies in the objectives of the proposal, nonmagnetic core barrels were generally used. However, due to the relative fragility and high cost of nonmagnetic core barrels, the normal steel magnetic barrels were used after the initiation of drillover. This proved to be a prudent policy, as four steel core barrels were bent during drillover at Site U1308.

Two factors influenced the decision to terminate holes at the limit of the APC and therefore *not* to utilize extended core barrel (XCB) technique:

- The increase in drilling disturbance associated with the XCB, particularly in the upper part of the XCB section, has not been conducive to the generation of high-resolution PAC chronologies. Poor recovery and "biscuiting" are common in poorly consolidated lithologies recovered by XCB.
- At all locations other than Site U1304 the deeper stratigraphic section has been sampled in the region (although not at any individual site other than Site U1308) during previous DSDP or ODP drilling legs.

SITE RESULTS

Sites U1302 and U1303

The overall objective at Sites U1302 and U1303 was to explore the record of Laurentide Ice Sheet (LIS) instability at this location close to Orphan Knoll (Fig. F1). Piston cores collected at Site U1303 (HU91-045-094P, MD99-2237, and MD95-2024) show the presence of numerous detrital layers within the last glacial cycle, some of which are rich in detrital carbonate (Hillaire-Marcel et al., 1994; Stoner et al., 1995, 1996). The digital image of Core 303-1303B-1H is shown in Figure F2, illustrating that these detrital layers are recognizable visually and in magnetic susceptibility (MS) and gamma ray attenuation (GRA) density measured on the shipboard multisensor track (MST). Isotopic data from planktonic foraminifers indicate that these detrital layers are associated with low-productivity meltwater pulses (Hillaire-Marcel et al., 1994). The objective at Sites U1302 and U1303 is to document this manifestation of LIS instability both during and prior to the last glacial cycle. The two sites are separated by 5.68 km. Drilling revealed a very similar stratigraphic sequence at the two sites. The MST data could be correlated from site to site at fine scale. The rationale for drilling Site U1302 was that the single-channel air gun seismic data (Toews and Piper, 2002) indicated a thicker section above mud waves at Site U1302 than at Site U1303 (the site of the piston cores mentioned above). We moved to Site U1303 after encountering a coarse-grained debris flow at ~105 meters composite depth (mcd) at Site U1302 that caused the cessation of APC penetration. The same debris flow, however, was encountered at Site U1303. The top of the debris flow coincides with a strong reflector in the air-gun seismic data, at ~100 ms two-way traveltime, which can be traced between the two sites.

Five holes, offset from each other by 30 m, were cored with the APC system at Site U1302 with an average recovery of 90.3%. Three holes (Holes 1302A–1302C) were cored to total depth (maximum of 107.1 meters below seafloor [mbsf]) (Table T1), which was limited by the presence of a debris flow. Holes U1302D and U1302E consisted only of two cores each to capture the intervals at the top of the succession and provide overlap with coring gaps from the previous holes. Water depth was estimated to be 3555 mbsl based on recovery of the mudline core in Hole U1302D. We cored two APC holes 30 m apart at Site U1303. Penetration depth was limited by the debris interval to 93.9 mbsf in Hole U1303A (73.6% recovery) and 85.7 mbsf in Hole U1303B (83.5% recovery). Water depth at Site U1303 was estimated to be 3518 mbsl based on recovery of the mudline core in Hole U1303B.

An almost complete composite section was constructed at Site U1302 spanning the interval 0–107 mcd. It was not possible to construct a complete composite record at Site U1303. However, the density and MS records from Sites U1302 and U1303 are remarkably similar and can be easily correlated. Using a short segment of one core from Site U1303 and the composite record from Site U1302 provides a continuous stratigraphic sequence to ~107 mcd (Fig. F3).

The sediments at Sites U1302 and U1303 are dominated by varying mixtures of terrigenous components and biogenic debris (primarily quartz, detrital carbonate, and nannofossils), so that the most common lithologies are clay, silty clay, silty clay with nannofossils, nannofossil silty clay, silty clay nannofossil ooze, and nannofossil ooze with silty clay. Dropstones are present throughout the cores. Calcium carbonate content ranges from 1 to 47 wt%. The sediments at Sites U1302 and U1303 have been designated as a single unit due to the gradational interbedding of these lithologies at scales of a few meters or less. This unit has been subdivided into two subunits, however, based on evidence for downslope mass flows at the base of the section. Subunit IA (0–~106 mcd) is composed of undisturbed sediments, whereas Subunit IB (106–132 mcd) contains abundant intraclasts in a matrix of sand-silt-clay and is interpreted to be debris flow deposits.

Samples from Site U1302 reveal rich assemblages of calcareous, siliceous, and organic-walled microfossils. Coccoliths are abundant and well preserved in most samples and permit establishment of biostratigraphic schemes that are complemented by a few datums from diatoms and palynological data. According to these schemes, the composite sequence of Site U1302 covers an interval spanning <1.16 m.y. and approximately the last 0.95 m.y., whereas the composite sequence of Site U1303 probably corresponds to an interval spanning approximately the last 0.85 m.y. (Fig. **F4**). The mean sedimentation rate at these sites is 13.4 cm/k.y. (Fig. **F5**). Beyond the biostratigraphic schemes, the micropaleontologic assemblages provide insight into paleoclimatologic and paleoceanographic conditions. In particular, the relative abundance of the planktonic foraminifer *Neogloboquadrina pachyderma* (sinistral) and some dinocyst assemblages allow identification of glacial and interglacial conditions from some core catcher samples.

The pore water chemistry from Sites U1302 and U1303 is dominated by reactions associated with organic matter degradation, despite the relatively low organic matter content of the sediments (~0.5 wt%). Sulfate concentrations decrease from seawater values to 5.9 mM close to the base of the recovered section indicating that sulfate reduction is almost complete by 109 mcd. Corresponding increases in alkalinity and ammonium downcore are byproducts of organic matter reactions. Alkalinity does not reach concentrations expected for the degree of sulfate reduction indicating alkalinity is being consumed within the cored interval. The decrease in calcium (to a minimum of 5.5 mM, a 52% decrease from seawater values) suggests precipitation of carbonate minerals as one possible explanation for the alkalinity profiles. Strontium concentrations remain at seawater values or lower throughout the cored interval indicating that carbonate dissolution and recrystallization are not important processes at these sites.

Overall, sediments of lithologic Subunit IA from Sites U1302 and U1303 are excellent geomagnetic field recorders as indicated by the fidelity of the shipboard paleomagnetic record. Inclinations vary coherently around those expected for the site latitudes. Declinations show consistent behavior within cores and, when Tensor corrected, between cores. Directional geomagnetic excursions are observed in three replicate sections from Holes 1302C, 1303A, and 1303B at ~31.40 mcd and are interpreted to represent the Iceland Basin Event at ~187 ka. Magnetization intensities are strong and magnetic properties look favorable for shore-based paleointensity studies. Within the debris flow (lithologic Subunit IB), the paleomagnetic record is not of the same quality. There is some evidence for reversed magnetizations within apparently undisturbed sediment within or below the debris flow, possibly denoting the uppermost Matuyama Chron, but the scattered magnetization directions in Subunit IB do not allow further interpretation (Fig. **F4**). In addition, it appears that the removal of the drill string magnetic overprint is greatly facilitated by the utilization of nonmagnetic core barrels.

The MS records obtained at these sites are strongly influenced by the detrital layer stratigraphy (Fig. **F2**) superimposed on a pattern of glacial–interglacial variability (Fig. **F3**). At both sites, natural gamma ray (NGR) variation is consistent with both MS and density measurements (i.e., low MS and density values correspond to low NGR counts: 20–22 cps), which suggests these intervals were characterized by carbonate-dominated sedimentation. The downcore MST records not only provide a guide to the glacial-interglacial cycles, possibly back to MIS 17 but also provide a millennial-scale record of LIS instability through recognition of Heinrich-like detrital events. Detrital events in the Heinrich layer 1–6 (H1–H6) interval are easily recognized in the MST data at Sites U1302 and U1303 and can be unambiguously correlated to similar records in neighboring piston cores such as MD95-2024 and MD99-2237 that record the last glacial cycle. The sedimentary succession at Sites U1302 and U1303 provides a record of LIS instability back to at least MIS 17. This record is a proximal analog to the classic Heinrich-layer stratigraphy of the central Atlantic.

Site U1304

The objective at Site U1304 was to obtain a deepwater record from the southern edge of the Gardar Drift to compare with the intermediate depth site on the northern part of the Gardar Drift sampled during ODP Leg 162 (Site 983). Site U1304 lies in a partially enclosed basin north of the Charlie Gibbs Fracture Zone (GFZ), 217 km west-northwest of DSDP Site 611. The mean sedimentation rate at Site U1304 (14.9 cm/k.y.) (Fig. **F5**) is about six times that in the same interval at DSDP Site 611. Excellent preservation of benthic and planktonic microfossils enhances the potential for a high-resolution environmental record. The site will provide a monitor of NADW and sea-surface temperatures (SSTs) and a record of central Atlantic detrital layer stratigraphy.

Four holes were cored with the APC coring system to a maximum depth of 243.8 mbsf at Site U1304 (Fig. **F6;** Table **T1**). Overall recovery was 102.6%. Hole U1304C was limited to 69.6 m penetration when operations had to be terminated because of deteriorating weather conditions (heave in excess of 4 m at the rig floor). After waiting more than 3 h for the weather to abate, Hole U1304D was spudded and the interval 0–52 mbsf drilled before APC coring continued to total depth. The interval from 180.3–181.3 mbsf was also drilled in Hole U1304D (i.e., not cored) due to an apparent hard interval impeding APC penetration. Water depth was estimated to be 3065 mbsl based on recovery of the mudline cores in Holes 1304C and 1304D. The drillover technique was utilized in Holes 1304A, 1304B, and 1304D to extend APC coring past initial refusal depth.

Correlation of cores among holes at Site U1304, utilizing mainly MS and NGR (Fig. **F6**), provides a continuous stratigraphic sequence to ~258.1 mcd with a single potential break within an 8 m thick diatom mat at ~199.3 mcd. The spliced composite section relies on sections from Holes 1304A and 1304B because good weather conditions during the early occupation of Site U1304 led to excellent recovery and good core quality.

The sediments at Site U1304 are predominantly interbedded diatom oozes and nannofossil oozes with less common intervals of clay and silty clay, which also contain abundant nannofossils and/or diatoms. Calcium carbonate content ranges from 5 to 70 wt% and organic carbon content is low (generally <0.5 wt%). This sedimentary succession has been designated as a single unit because the various lithologies are generally interbedded on a scale of only centimeters to decimeters. Most contacts between nannofossil ooze and clay intervals are gradational, although sharp contacts are also observed. The contacts between diatom ooze beds and the other lithologies are generally sharp. Redeposited beds of silt and sand-sized particles are rare, as are disturbed units related to mass-transport processes (e.g., slumps and debris flows).

Thus, the section cored at Site U1304 apparently represents a relatively continuous pelagic section where the sediments record changes in productivity in response to oceanographic and climatic fluctuations.

Recurring laminated diatom sequences are the most prominent feature at Site U1304. The thicker diatom mats are clearly distinguished by very low MS values (Fig. **F6**). Diatom assemblages are dominated by needle-shaped species of the *Thalassiothrix/Lioloma* complex. All other groups investigated (coccoliths, planktonic and benthic foraminifers, radiolarians, and palynomorphs) are present in high-to-moderate abundance and are well preserved. Biostratigraphic datums mainly derive from coccoliths and are consistent with datums provided by diatoms, planktonic foraminifers, dinoflagellate cysts, and magnetostratigraphy (Fig. **F4**). The composite sequence covers the uppermost Pliocene and the entire Quaternary. The microfossil assemblage indicates only minor redeposition.

Preliminary paleoceanographic and paleoclimatologic interpretation of the microflora and microfauna reveals large-amplitude changes in surface water temperature and trophic conditions. Diatom layers were formed during both cold and warm phases, according to the diatom and planktonic foraminiferal assemblages. The presence of the benthic foraminifer *Epistominella exigua* documents recurring flux pulses of fresh organic matter to the seafloor. A shift from dominance of autotrophic to dominance of heterotrophic dinocyst assemblages is recorded after 1.2 Ma, which may suggest a general change in trophic conditions of the surface ocean.

Site U1304 sediments document an almost continuous sequence including the Brunhes Chron and part of the Matuyama Chron including the Jaramillo Subchron, the Cobb Mountain Subchron, and the top of the Olduvai Subchron (Fig. **F4**). Short intervals of apparent normal polarity were recognized in the Matuyama Chron below the Cobb Mountain Subchron. Mean sedimentation rates of 17.8 cm/k.y. are estimated for the last 0.78 m.y. and 12.2 cm/k.y. for the interval from 0.78 to 1.77 Ma, with an overall mean sedimentation rate of 14.9 cm/k.y. (Fig. **F5**).

Site U1304 pore water profiles indicate active sulfate reduction (minimum value of 2.8 mM at 214 mbsf) with corresponding increases in alkalinity and ammonium. Alkalinity values do not reach concentrations expected for the degree of sulfate reduction. Calcium concentrations decrease downcore to 2.7 mM, a ~75% reduction from standard seawater values. The decrease in calcium and consumption of alkalinity suggests active carbonate mineral precipitation. However, Sr concentrations remain at seawater values or lower, indicating that carbonate dissolution and recrystallization reactions are not important processes in the cored interval.

The Quaternary sequence recovered at Site U1304 provides a high-resolution, high-sedimentation-rate (average ~15 cm/k.y.) record of environmental change at a sensitive location close to the subarctic convergence between the surface Labrador Current and the North Atlantic Current. Good preservation of both calcareous and siliceous microfossils, abundant benthic foraminifers, and a high-fidelity magnetostratigraphic record indicate that the environmental record, including the monitoring of NADW, can be placed in a tight chronological framework.

Site U1305

Site U1305 is located close to the southwest extremity of the Eirik Drift, 82.2 km south of ODP Site 646. The thickness of the sediments above the mid–Upper Pliocene seismic reflector R1 (~540 m) is almost twice that at ODP Site 646. The water depth (3459 mbsl) means that the seafloor at Site U1305 lies below the main axis of the Western Boundary Undercurrent (WBUC) and hence preserves expanded interglacial intervals and relatively condensed glacial intervals. The high mean sedimentation rate (>17 cm/k.y. for the Quaternary) promises a high-resolution record of ice sheet instability and changes in surface and deepwater masses.

Three holes were cored at Site U1305 with the APC system to a maximum depth of 287.1 mbsf (Fig. F7; Table T1) with an average recovery of 104%. Six cores had to be obtained by drillover in Hole U1305A, two in Hole U1305B, and none in Hole U1305C. After completing coring operations, Hole U1305C was prepared for logging and the triple combination (triple combo) tool string was deployed to ~258 mbsf (~29 m from the bottom of the hole). The hole was logged successfully on the first pass, but the tool became stuck when attempting to retrieve it into the drill pipe after a short second pass. The tool was eventually freed, and upon retrieval we discovered that one of the caliper arms had broken off and the logging line had been damaged. Because of heave state (up to 4 m), the hole condition, tool safety, and operational constraints, we decided to forego the deployment of the Formation MicroScanner (FMS)-sonic tool string, concluding operations at Site U1305.

The sediments at Site U1305 are designated as a single unit dominated by varying mixtures of terrigenous components and biogenic material, primarily clay minerals, quartz, detrital carbonate, and nannofossils. Calcium carbonate content ranges from

1 to 49 wt%. The most common lithologies are dark gray to very dark gray silty clay, silty clay with nannofossils, nannofossil silty clay, silty clay nannofossil ooze, and nannofossil ooze with silty clay. In addition, olive-gray sandy silt laminae and centimeter- to decimeter-scale intervals of silty clay with detrital carbonate are present at Site U1305. The sediments are gradationally interbedded at scales of a few meters or less.

Calcareous, siliceous, and organic-walled microfossils show generally good preservation and abundance in the upper ~200 mcd (Fig. **F4**). However, the abundance of microfossil assemblages is variable below this depth with generally poorer preservation. All microfossil groups investigated are dominated by subpolar to polar assemblages. Planktonic foraminifers show a biomodal test-size distribution. The small test-sized planktonic foraminifers, which are cold-water species, coexist with increased abundance of benthic foraminifers, possibly indicating transport by bottom currents.

The sediments at Site U1305 carry well-defined magnetization components and appear to provide useful records of geomagnetic transitions. Natural remanent magnetization (NRM) intensities are strong both before and after demagnetization and show variability at both the meter scale and throughout the sequence. NRM intensities decrease by ~50% below 166 mcd. Directional magnetization data allow identification of the Brunhes and part of the Matuyama Chron, including the Jaramillo, Cobb, and Olduvai Subchrons (Fig. **F4**). The Cobb Mountain Subchron and the top of the Olduvai Subchron are less clearly identified because of the incomplete removal of the normal polarity drill string magnetic overprint.

A continuous stratigraphic composite section was constructed to ~295 mcd with a single problematic interval between 197.2 and 206 mcd (Fig. **F7**). The mean sedimentation rate calculated using biostratigraphic and magnetostatigraphic datums is 17.5 cm/k.y. for the entire section cored at Site U1305 (Fig. **F5**). Using only paleomagnetic datums results in sedimentation rates that are still relatively uniform with the exception of a greater mean sedimentation rate between 1.07 and 1.19 Ma (from the base of the Jaramillo to the top of the Cobb Mountain Subchrons) that averages 29.3 cm/k.y.

Despite the low organic carbon content (mean = <0.4 wt%), organic matter diagenesis dominates the pore water chemistry. Sulfate decreases linearly downcore and is completely reduced by 58 mbsf. Methane increases immediately below the sulfate reduction zone, reaching a maximum of 46,000 ppmv at 228 mbsf. Ethane fluctuates between 2 and 14 ppmv within the methanogenic zone, but no higher hydrocarbons were detected. Alkalinity increases downcore reaching a maximum of 18.9 mM at the sulfate/methane interface (SMI). Calcium reaches a minimum of 2.58 mM at the same depth, suggesting carbonate precipitation associated with anaerobic methane oxidation at the SMI. Similar to previous Expedition 303 locations, dissolved strontium at Site U1305 is at or below seawater values indicating little or no carbonate dissolution or recrystallization.

Physical property records at Site U1305, in particular MS and density, are highly variable, recording lithologic and mineralogic changes (Fig. **F7**). Low MS and density values usually coincide with the presence of silt-sized detrital carbonate. Natural gamma radiation increases toward the transition between detrital carbonate and terrigenous-dominated layers, suggesting a relative increase in the clay component. Site U1305 sediments are also characterized by an overall downcore increase in density (from 1.3 to ~1.9 g/cm^3), decreasing porosity (from 80% to 62%) and low velocities (1500–1600 m/s).

Data from wireline logging in Hole U1305C span the 95.3–265.9 mbsf interval. The triple combo tool string was successfully deployed, yielding downhole records of density, porosity, NGR, electrical resistivity, and photoelectric factor. Density and porosity are generally inversely related to each other, with density increasing downhole and porosity decreasing. Density and porosity data are in some places affected by the large diameter of the hole (up to ~18 in), although these intervals most likely correspond to softer sediments that are more easily washed away. Density and gamma ray logging data show similar downhole trends to those observed in core data, suggesting that it will be possible to correlate core and logging data. The logging data also exhibit stratigraphic trends that appear to be cyclic, possibly caused by temporal changes in lithology. Successful core-log integration will permit an assessment of the origin and significance of the trends in the logging data.

The initial analysis of MST, archive multisensor track (AMST), biostratigraphic, and paleomagnetic data indicates that a complete and continuous high-resolution record (mean sedimentation rate of 17.3 cm/k.y.) covering the uppermost Pliocene and Quaternary has been recovered at Site U1305. The record represents a rich archive of environmental change that will document episodes of instability in the surrounding (Laurentide, Greenland, and Inuitian) ice sheets, the history of surface currents and deepwater currents, and, hence, the strength of the WBUC that contributes to NADW. Good preservation of both planktonic and benthic foraminifers for isotopic analysis and a high-fidelity paleomagnetic record indicate that the environmental record has the necessary attributes for construction of a paleointensity-assisted chronostratigraphy.

Site U1306

Site U1306 was placed at the crossing of two seismic lines (Lines 19 and 24) in the multichannel seismic (MCS) network obtained over the Eirik Drift during Cruise KN-166 (*Knorr,* Principal Investigator [PI]: Greg Mountain) in summer 2002. At this location, mean Upper Pliocene and Quaternary sedimentation rates were estimated to be ~18 cm/k.y. based on identification of seismic reflector R1, which can be correlated to the mid–Upper Pliocene at ODP Site 646. The placement of the site was designed to yield a high-resolution, high-sedimentation-rate Quaternary environmental record from a water depth (2273 mbsl) within the main axis of the WBUC. Based on a nearby conventional piston core from a similar water depth (Core HU90-013-012) (Hillaire-Marcel et al., 1994), we expect glacial intervals to be expanded relative to interglacial intervals.

Four holes were cored with the APC system at Site U1306 reaching a maximum depth of 309.3 mbsf (Fig. **F8;** Table **T1**). Hole U1306D was cored to 180.0 mbsf to provide necessary stratigraphic overlap for the upper portion of the succession. Five intervals totaling 13 m were drilled without coring to adjust the stratigraphic offset between holes or to get through difficult-to-core intervals. Five cores were obtained by drill-over. Average recovery was 102.5% for the cored interval.

The sediments at Site U1306 are designated as a single lithostratigraphic unit, composed of Holocene to uppermost Pliocene terrigenous and biogenic sediments, which are gradationally interbedded at scales of a few meters or less. Calcium carbonate content is low ranging from 0.3 to 12.3 wt% (mean = 3.2 wt%). The most common lithologies are silty clay, silty clay with diatoms, nannofossil silty clay, and silty clay nannofossil ooze. Dropstones are present throughout the cored interval, and large dropstones (~4 cm) are common to abundant. Centimeter- to decimeter-scale beds of olive-gray or greenish gray silty clay or clay with high detrital carbonate content are present in all holes at Site U1306, but are thinner and less common than at Site U1305.

Rich assemblages of calcareous, siliceous, and organic-walled microfossils are present at Site U1306 (Fig. **F4**), although benthic foraminifers are barren in many samples below 175 mcd. Large variations in abundance of microfossils occur downcore. Although preservation is moderate to good in the upper part of the succession, preservation generally decreases below ~170 mcd for calcareous and siliceous microfossils. All samples contain moderately well to well-preserved palynomorphs, but variable numbers of dinocysts, which are abundant only in a few samples. Some redeposition is indicated by the presence of reworked nannofossils and palynomorphs of Cretaceous to Miocene age through the cored interval. The dominant components of each microfossil group reflect cold SSTs for most of the time represented by the sedimentary sequence.

The sediments at Site U1306 carry well-defined magnetization components and document an apparently continuous sequence including the Brunhes Chron and much of the Matuyama Chron. The Jaramillo, Cobb Mountain, and Olduvai Subchrons are clearly identified (Fig. **F4**). Within the Brunhes Chron, the Iceland Basin Event (~187 ka) was observed in three of the holes.

A continuous stratigraphic composite section was constructed to ~337 mcd (Fig. **F8**). Below 287 mcd, cores were recovered in two holes only, but the section is complete with only a single tenuous tie near the base of the record. The mean sedimentation rate calculated using biostratigraphic and magnetostatigraphic datums is 15.6 cm/k.y. for the entire section cored at Site U1306 (Fig. **F5**). Using only paleomagnetic datums, interval sedimentation rates vary between 12.4 and 19.3 cm/k.y.

Pore water chemical profiles at Site U1306 document very similar reactions to nearby Site U1305. Complete sulfate reduction is achieved at shallow depths at Site U1306 (85 mbsf) despite the low organic carbon content (mean = 0.3 wt%). Methane increases below 85 mbsf, reaching a maximum of 46,000 ppmv. Alkalinity reaches a maximum of 18.7 mM at the SMI, whereas calcium concentration attains a minimum value (3.7 mM), indicating carbonate mineral precipitation associated with methane oxidation. From 114 to 258 mbsf, sulfate increases again slightly (1.5 mM). This interval corresponds to pH and iron fluctuations, which are antithetic to each other, and may indicate zones of anaerobic pyrite oxidation. Dissolved strontium remains at or below seawater values, suggesting little or no carbonate dissolution or recrystallization.

Physical property records at Site U1306 are highly variable, recording lithologic and mineralogic changes (Fig. **F8**). The higher carbonate content in the upper ~100 mcd results in average lower NGR and MS values than in the sediments below. Site U1306 sediments are characterized by an overall downcore increase in density (1.5–~1.8 g/cm^3) and decreasing porosity (~70%–50%).

Based on current knowledge from nearby piston cores, Site U1306 has expanded glacial intervals. This sedimentary pattern is complementary to that at Site U1305 where interglacials are likely to be relatively expanded. The apparently complete Quaternary record recovered at Site U1306 provides a high-resolution, high-sedimentation-rate record of detrital events derived from instability of surrounding ice sheets, and provides a monitor of the activity of the WBUC that supplies a component of NADW to the Labrador Sea. The site appears to have the attributes required for the generation of a well-constrained age model based on oxygen isotopes, micropaleontology, and geomagnetic paleointensity.

Site U1307

Site U1307 is positioned in 2575 m of water at common depth point (CDP) 14375 on seismic Line 25a in the MCS network obtained over the Eirik Drift during Cruise KN-166 (*Knorr,* PI: Greg Mountain) in summer 2002. The location was chosen because of potential access to Pliocene sediments below the Quaternary sequence drilled at Site U1306. A thinner Quaternary sedimentary sequence at Site U1307 allowed the Pliocene sequence to be sampled using the APC.

Two holes were cored with the APC system at Site U1307, reaching a maximum depth of 162.6 mbsf (Fig. **F9;** Table **T1**). Two partial strokes of the APC required drilling two intervals in Hole U1307A that were difficult to APC core (50.5–52.5 mbsf and 73.7–77.7 mbsf). Five cores were advanced by recovery. Only one core was a partial stroke in Hole U1307B, and no intervals required drillover. Average recovery was 102% for the cored intervals at Site U1307. Coring was terminated due to excessive heave when a passing storm system began to affect drilling operations.

The Lower Pliocene to Pleistocene sedimentary succession at Site U1307 (Fig. **F4**), which is subdivided into three units, records variations in the input of terrigenous and biogenic components (mostly quartz, detrital carbonate, nannofossils, and foraminifers). Unit I (0–49.55 mcd) is composed of Holocene and Pleistocene mixtures of foraminifers, silty clay, and nannofossils (silty clay with foraminifers, foraminifer silty clay, and nannofossil silty clay). Minor lithologies include eight discrete foraminifer silty sand and sandy foraminifer ooze beds. Unit II (49.55–133.86 mcd) is composed mainly of Pleistocene to Upper Pliocene silty clay with little biogenic component.

Unit III (133.86–173.6 mcd) is composed of Upper to Lower Pliocene silty clay, silty clay with nannofossils, and nannofossil silty clay. With the exception of the foraminifer sand beds, calcium carbonate content is low (mean = 3.8 wt%).

The abundances of calcareous, siliceous, and organic-walled microfossils at Site U1307 are common to rare with moderate to poor preservation. A possible hiatus (duration ~0.25 m.y.) or a condensed interval (~1.21–1.45 Ma) is indicated between ~56 and 61 mcd (Figs. F4, F9). The dominant components of each microfossil group reflect subpolar to polar conditions during the Pleistocene. In the lower Upper Pliocene (before 2.74 Ma), the nannofossil assemblage suggests warmer surface water conditions.

Paleomagnetic directional data yield an almost continuous sequence and permit unambiguous identification of the Brunhes, Matuyama, and Gauss Chrons (Fig. F4). Within the Matuyama Chron, the Jaramillo, Olduvai, and Reunion Subchrons are clearly recognized. Within the Gauss Chron, the Kaena and Mammoth Subchrons are also recognized, with the base of the section corresponding to the top of the Gilbert Chron.

With only two holes drilled, it was impossible to construct a complete spliced record for Site U1307. However, several long intervals of overlap between holes allowed segments to be correlated between holes (0–56.5 mcd, 76.4–104.7 mcd, and 104.7–146.2 mcd), which were then appended in the record (Fig. F9). The mean linear sedimentation rate calculated using biostratigraphic and magnetostatigraphic datums is 4.8 cm/k.y. (Fig. F5). Using only magnetostratigraphic datums, interval sedimentation rates vary between 2.7 and 7.6 cm/k.y.

As for the other Eirik Drift sites, pore water geochemical profiles reflect the influence of organic matter remineralization reactions. Sulfate decreases linearly from the uppermost sample to 79 mbsf, where it remains at or below ~1 mM. The methane profile is atypical, decreasing from 200 ppmv in the uppermost sample near the sediment/water interface to a low of ~30 ppmv at 54 mbsf and then increasing again below the sulfate reduction zone to a high of 26,000 ppmv. Calcium and strontium attain minimum values (5.5 mM and 76 µM, respectively) at the base of the sulfate reduction zone where alkalinity reaches a maximum (10 mM), suggesting carbonate mineral precipitation.

Physical property records at Site U1307 document high-frequency changes in sediment composition (Fig. F9). The variability in sediment composition recorded in MS, NGR, and density likely reflect changes in paleoceanographic conditions in the overlying and surrounding water masses and ice sheets at a range of timescales. Site U1307 sediments are also characterized by an overall downcore increase in density (from 1.55 to ~1.76 g/cm^3) and variable but generally decreasing porosity (from ~70% to 40%).

Site U1307 demonstrates that the Pliocene sediments of the Eirik Drift are located at penetration depths achievable with the APC. Apart from one possible hiatus (in the 1.2–1.4 Ma interval), the sedimentary record at Site U1307 is apparently continuous (Fig. F4) with a mean sedimentation rate of ~5 cm/k.y. (Fig. F5). The base of the recovered section correlates to the uppermost Gilbert Chron, indicating that the record extends back to ~3.6 Ma (Fig. F4). The sediments from Site U1307 will provide information on the history of bottom and surface currents, the Laurentide and Greenland ice sheets, and age control for seismic reflectors that will provide constraints on the sedimentary architecture of the Eirik Drift. The Pliocene–Quaternary history at this site can be placed into a tight age model, as the sediments have the attributes required for high-resolution chronostratigraphy based on paleontologic, isotopic, and magnetic methods.

Site U1308

Site U1308 constitutes a reoccupation of DSDP Site 609 (Fig. F1). During DSDP Leg 94 (June–August 1983), two principal holes (Holes 609 and 609B) were drilled with the variable-length hydraulic piston corer (VLHPC) and XCB. Two cores were collected from Hole 609A to recover the mudline, and seven XCB cores were collected from Hole 609C to recover the 123–190 mbsf interval. Samples from DSDP Site 609 have played a major role in driving some of the most exciting developments in paleoceanographic research during the last 10–15 years, such as the recognition and understanding of Heinrich layers, the recognition of the 1500 y pacing in hematite-stained grains and Icelandic glass, and the correlation of ice core $\delta^{18}O$ to SST proxies. The majority of the analyses from Site 609 have dealt with the record younger than MIS 6, partly because of the lack of a continuous pristine composite record. A primary objective at Site U1308 was to recover a demonstrably complete composite record, hence, considerably enhance the potential for Pliocene–Quaternary climatic records from this site.

Six holes were cored with the APC system at Site U1308: (1) Hole U1308A to 341.mbsf, (2) Hole U1308B to 198.3 mbsf, (3) Hole U1308C to 279.9 mbsf, (4) Hole

U1308D to 6.7 mbsf, (5) Hole U1304E to 193.0 mbsf, and (6) Hole U1308F to 227.0 mbsf (Fig. F10; Table T1). Water depth was estimated to be 3871 mbsl. Average recovery was 95.4% for the cored intervals. Sea swell up to 6 m affected Hole U1308A core quality below ~170 mbsf. We therefore waited ~16 h for the swell to abate before coring Hole U1308B. Coring in Hole U1308B was terminated after three successive poor-recovery cores suggested accumulation of debris either in the hole or in the bottom hole assembly (BHA). However, we could not spud Hole U1308C because of incomplete firing of the APC indicating the problem was bit obstruction. Holes U1308C, U1308D, and U1308E were cored after clearing the bit, but core recovery was not optimal (<100%) due to loss of core from the base of core liners and (possibly related) crushed core liners. The bit was cleared again before coring Hole U1308F with an average recovery of 100.7%, although crushed liners were still commonplace.

The upper Miocene through Quaternary sedimentary succession at Site U1308 (Fig. F4), which is subdivided into two units, records variations in the input of terrigenous and biogenic sediments (primarily nannofossil ooze, nannofossil silty, and silty clay). Unit I (0–196.85 mcd) is composed of a Holocene–Upper Pliocene sequence of interbedded biogenic and terrigenous sediments with dropstones. Subunit IIA (196.85–262.14 mcd) is composed of Upper Pliocene nannofossil ooze interbedded with terrigenous sediment-rich layers but at a lower frequency than Unit I. Subunit IIB (262.14–355.89 mcd) is entirely composed of lowermost Upper Pliocene to uppermost Miocene nannofossil ooze.

Diverse assemblages of calcareous, siliceous, and organic-walled microfossils were recovered at Site U1308 (Fig. F4). Calcareous microfossils are abundant with good preservation in the upper ~200 mcd grading to moderate preservation below this depth. Siliceous microfossils are rare to common and moderately preserved above ~255 mcd (Upper Pliocene–Pleistocene) with radiolarians locally abundant only in the middle part of the cored sequence. Siliceous microfossils are barren below 255 mcd. The concentration of terrestrial palynomorphs is low. Dinocysts are common to abundant in the upper 200 mcd but less common below. Microfossil assemblage changes observed at Site U1308 document the onset of Northern Hemisphere glaciation, as well as seasonal changes in bioproductivity and hydrographic fronts.

Paleomagnetic directional data document an apparently continuous sequence of polarity transitions. Identification of the Brunhes, Matuyama, and Gauss Chrons are unambiguous (Fig. F4). The Gilbert Chron is tentatively recognized in the lower part of Hole U1308A. The Jaramillo, Cobb Mountain, Olduvai, Reunion, Kaena, and Mammoth Subchrons are also clearly identified.

Six holes were cored at Site U1308 to ensure the complete recovery of the stratigraphic section to 247 mcd (Fig. F10). The unusually large number of holes was required because of poor recovery and core disturbance due to excessive heave and crushed core liners. There is one problematic interval between ~186 and ~196 mcd where inclined bedding and sharp lithologic contacts suggest a possible break in continuity of sedimentation. The mean linear sedimentation rate calculated using magnetostatigraphic datums is ~8.3 cm/k.y. for the last ~3.5 m.y. (Fig. F5). Prior to that time, the mean sedimentation rate was ~3.3 cm/k.y. based on biostratigraphic markers (Fig. F5).

Interstitial water sulfate decreases downhole to 9 mM, but complete sulfate reduction is not achieved within the cored interval. Unlike all other Expedition 303 sites, strontium increases with depth to a maximum of 1592 µM at Site U1308. The nearly linear strontium increase and the corresponding increase in Sr/Ca ratios indicate that recrystallization (not dissolution) of biogenic carbonate is occurring. The approximately linear downhole decreases in magnesium and potassium and increase in calcium below ~100 mbsf are consistent with the alteration of volcanic material and/or basement below the cored interval.

Physical property records at Site U1308 document long-term changes in sediment composition, which likely reflect fundamental changes in North Atlantic climate. The NGR and lightness (L*) records from lithologic Unit I (0–197 mcd) show a strong glacial–interglacial variability (Fig. F10). In Subunit IIA (197–262 mcd), MS and NGR values decrease both in absolute value and variability and L* increases (Fig. F10). NGR shows a fairly abrupt change in absolute values and variability at the Unit II/I boundary at ~197 mcd (~2.74 Ma). In the white nannofossil ooze of lithologic Subunit IIB (262–356 mcd), MS and NGR values are significantly lower and less variable than in Subunit IIA. Data for Subunit IIB (262–356 mcd) are not shown in Figure F10, as the composite record does not extend below Subunit IIA.

The six holes at Site U1308 have been pieced together to produce a complete composite section to ~247 mcd. The base of the composite section correlates to the middle part of the Gauss Chron at ~3.2 Ma. A discontinuous record was recovered below this level to 356 mcd in upper Miocene white nannofossil ooze. The Upper Pliocene to Quaternary composite section will provide a means of studying the evolution of NADW, the extension of the central Atlantic detrital layer (Heinrich-type) stratigraphy beyond the last glacial cycle, and the 1500 y cycle in the petrologic characteristics of IRD. The mean sedimentation rate for the composite section (7.6 cm/k.y.) indicates that these studies can be carried out at moderately high resolution. Good preservation of benthic and planktonic calcareous and siliceous microfossils indicates that the site will yield high-quality environmental and isotopic records. The pristine magnetostratigraphic record indicates that the site has good potential for the generation of a PAC that will place the environmental record into a global millennial-scale stratigraphic framework.

OVERVIEW OF EXPEDITION ACHIEVEMENTS

The overall objectives of Expedition 303 were stated as follows: "*To establish late Neogene–Quaternary intercalibration of geomagnetic paleointensity, isotope stratigraphies and regional environmental stratigraphies and, in so doing, develop a millennial-scale stratigraphic template. Such a template is required for understanding the relative phasing of atmospheric, cryospheric, and oceanic changes that are central to our understanding of the mechanisms of global climate change on orbital to millennial timescales.*"

The site locations for Expedition 303 are known from previous ODP/DSDP drilling or from conventional piston cores to (1) contain distinct records of millennial-scale environmental variability (in terms of ice sheet–ocean interactions, deep circulation changes or sea-surface conditions), and (2) provide the requirements, including adequate sedimentation rates, for developing millennial-scale stratigraphies (through geomagnetic paleointensity, oxygen isotopes, and regional environmental patterns).

The drilling and core recovery phase of the expedition was a success because of the quality and nature of the cores recovered and the potential of the cores to meet the scientific objectives of the expedition. The common overall objective of Expeditions 303 and 306 (scheduled for March–April 2005) provided more flexibility to occupy sites as weather conditions allowed than is usual for an individual expedition. The October–November window in the North Atlantic ensured that this flexibility would be utilized.

It was decided in the early planning stages that the expedition would utilize the APC only. Cores acquired using the XCB, particularly in the interval immediately below the limit of APC drilling, are usually disturbed by the drilling process and do not meet the standards of core quality required for high-resolution stratigraphic studies.

Emphasis was placed on the recovery of complete, undisturbed composite sections utilizing multiple APC holes with drillover to increase the depth of APC recovery.

The overall objective at Sites U1302 and U1303 is to explore the record of LIS instability at this location close to Orphan Knoll (Fig. **F1**). Piston cores collected previously at or near Sites U1302 and U1303 (HU91-045-094P, MD99-2237, MD95-2024, and MD95-2025) show the presence of numerous detrital layers, some of which are rich in detrital carbonate (Hillaire-Marcel et al., 1994; Stoner et al., 1996, 2000; Hiscott et al., 2001). Isotopic data from planktonic foraminifers indicate that these detrital layers are associated with low-productivity meltwater pulses. The objective at Sites U1302 and U1303 is to document this manifestation of LIS instability further back in time to the base of the recovered section (~MIS 17). The mean sedimentation rates at Sites U1302 and U1303 are estimated to be ~13 cm/k.y. (Fig. **F5**), ensuring a high-resolution record.

At Site U1302, the first site to be drilled off Orphan Knoll (Fig. **F1**), we encountered a debris flow at ~105 mcd that was not recognized in seismic data (Toews and Piper, 2002). The top of the debris flow appears to be within the Brunhes Chron at ~700 ka, and the base of the section is estimated from nannofosssil stratigraphy to be at ~950 ka (Fig. **F4**). To avoid the debris flow, we traversed in dynamic positioning (DP) mode (with the base of the drill string lifted a few hundred meters above the seafloor) to Site U1303, located 5.68 km northwest of Site U1302. The debris flow was again encountered at Site U1303 at approximately the same depth, and drilling was again discontinued. The presence of a debris flow at shallow depths (~105 mcd) also precluded downhole logging operations as planned in the prospectus, which was then deferred to the next planned site on Eirik Drift. Sites U1302 and U1303 can be easily correlated using a range of MST data, and it is clear that essentially the same section was recovered at the two sites. We generated a complete and continuous composite section by combining the five holes from Site U1302 and the two holes from Site U1303. Short segments of three cores from Site U1303 and the composite record from Site U1302 provide a continuous stratigraphic sequence to ~107 mcd.

- *Sites U1302 and U1303 near Orphan Knoll have a detrital layer stratigraphy that is a proximal analog to the detrital stratigraphy of the central Atlantic and provides a detailed record of the instability of the Laurentide Ice Sheet since 700 ka.*

While en route to prospective sites on the Eirik Drift (Sites U1305–U1307), the unfavorable weather forecast for this area forced the ship to be diverted to Site U1304 at the southern edge of the Gardar Drift (Fig. **F1**). The sediments at Site U1304 comprise interbedded diatom and nannofossil oozes with clay and silty clay. The lithologies are generally interbedded on a centimeter or decimeter scale. Diatom assemblages are dominated by needle-shaped species of the *Thalassiothrix/Lioloma* complex. The site is located within the central Atlantic IRD belt and therefore provides a distal record (relative to that at Sites U1302 and U1303) of the ice sheet instability. Site U1304 provides a high-resolution, high-sedimentation-rate record at a water depth (3065 mbsl) sufficient to determine the millennial-scale changes in the influence of NADW at the site. The diatom-rich sedimentary section extends back into the uppermost Pliocene at 258 mcd. Mean sedimentation rates of 17.8 cm/k.y. are estimated for the last 0.78 m.y. and 12.2 cm/k.y. for the interval from 0.78 to 1.77 Ma. The diatom-rich stratigraphy implies that the site has been located at the subarctic convergence between the surface Labrador Current and the North Atlantic Current (see Bodén and Backman, 1996). The good preservation of benthic and planktonic foraminifers, the pristine magnetic properties, and the construction of a complete composite section from four holes indicate that the environmental record can be placed into a reliable and precise age model. With the clearing weather over Eirik Drift coinciding with completion of coring at Site 1304 and the scientific preference for obtaining logs at one of the Eirik Drift sites, logging was not conducted at Site 1304 in favor of Site 1305.

- *Site U1304 provides a high-sedimentation-rate, high-resolution pelagic record at the southern edge of the Gardar Drift suitable for monitoring NADW and recording the detrital layer stratigraphy of the central Atlantic IRD belt since latest Pliocene time.*

Three sites (Sites U1305, U1306, and U1307) were drilled on the Eirik Drift (Fig. **F1**). The first of these was the designated the “deepwater” site (Site U1305) in 3459 meters water depth at the western extremity of the Eirik Drift. The primary “shallow-water” site (Site U1306) in 2273 meters water depth is located 191 km northeast of Site U1305. The two sites were chosen by maximizing the thickness of the Quaternary sedimentary section in the MCS network obtained over the Eirik Drift during Cruise KN-166 (*Knorr,* PI: Greg Mountain) in summer 2002.

Conventional piston cores have shown that the sedimentation history on the Eirik Drift during the last glacial cycle is strongly affected by the WBUC, which sweeps along east Greenland and into the Labrador Sea (Hillaire-Marcel et al., 1994; Stoner et al., 1998). Based on two conventional piston cores (HU90-013-013P and HU90-013-012) from the Eirik Drift at similar water depths, the deepwater site (Site U1305) is expected to display relatively expanded interglacials and relatively condensed glacial intervals and the converse is true for the shallow-water site (Site U1306). The base of the section at both sites lies within the Olduvai Subchron at ~300 mcd, and the mean sedimentation rates are 17–18 cm/k.y. Sites U1305 and U1306 will provide complementary high-resolution records of the history of the WBUC, detrital layer stratigraphy signifying instability of the surrounding ice sheets, and the attributes for well-constrained age models using stable isotopes, biostratigraphy, and geomagnetic paleointensity.

- *Sites U1305 and U1306 provide complementary records of Quaternary sedimentation on the Eirik Drift. The mean sedimentation rate (~17 cm/k.y.) is similar for both sites, but the patterns of sedimentation are expected to be different due to the contrasting water depths of the sites and the influence of the WBUC. The sites not only record the activity of the WBUC, and hence this component of NADW, but also monitor the detrital layer stratigraphy associated with instability of surrounding ice sheets, particularly the Greenland Ice Sheet.*

Site U1307 was not in the initial plan for Expedition 303, but was occupied when a storm moving northeastward across the North Atlantic blocked our passage to our intended next site (Site U1308). Site U1307 was placed at a location on the Eirik Drift (Fig. **F1**) where the Quaternary sedimentary section appears to be thinned relative to its thickness at Site U1306, providing APC access to the underlying Pliocene section. Two holes were drilled at Site U1307 reaching a maximum depth of 162 mcd in the uppermost Gilbert Chron (~3.6 Ma). The mean sedimentation rate for the recovered section was 4.9 cm/k.y. Interval sedimentation rates between polarity reversals ranged from 2.7 to 7.6 cm/k.y. Poor weather and excessive ship heave curtailed drilling at this site and the two holes were insufficient to generate a complete composite section. The site did, however, establish the feasibility of recovering the Pliocene sedimentary section on the Eirik Drift using the APC. The site extends the environmental record back to ~3.6 Ma and will provide invaluable age control throughout the MCS network established on the Eirik Drift by the KN-166 cruise in 2002.

- *Site U1307 provides a record of sedimentation on the Eirik Drift since ~3.6 Ma. The tight age control on the sedimentary record will be used to provide age control for seismic reflectors that can be traced through the KN-166 seismic network, thereby contributing to the understanding of the sedimentary architecture of the Eirik Drift.*

The final site of Expedition 303 was Site U1308, a reoccupation of DSDP Site 609. Shipboard and shore-based analytical techniques have changed considerably in the 21 y since this site was originally drilled (in 1983). For example, the shipboard facilities for the construction of composite section were introduced eight y later (1991).

DSDP Site 609 has been the focus of some of the most important developments in paleoclimate research in the last 15 y. Layers of IRD containing detrital carbonate (Heinrich events) were recognized at this site in the early stages of their correlation to the Greenland ice core record (e.g., Bond et al., 1993). The 1500 y cycle in petrologic characteristics such as hematite-stained grains and Icelandic glass has also been recognized at this site (Bond et al., 1999). Most of the recent work on DSDP Site 609 sediments has been conducted on the last glacial cycle due in part to uncertainties in the continuity of the section at greater depth. The objective of the reoccupation of DSDP Site 609 was to recover a demonstrably complete sedimentary section that could be used to establish the isotopic characteristics of NADW, monitor the detrital layer stratigraphy of the central Atlantic IRD belt, and place this record into a well-constrained chronostratigraphy. Several factors affected core quality at Site 1308. Sea swells reaching 6 m during drilling in Hole 1308A affected this hole as well as other holes at this site. In addition, sticky clay and other debris caught around the bit and in the BHA were believed to be the cause of loss of core from the base of core liners, and crushed liners in intervals from all holes. To obtain a complete, undisturbed stratigraphic record at Site 1308 required six holes consuming all the remaining operational time. The maximum penetration at Site U1308 was 341 mbsf to the upper Miocene at ~6 Ma (Fig. **F4**). However, the complete composite section is limited to the uppermost 247 mcd, extending well within the Gauss Chron at ~3.1 Ma, with the mean sedimentation rate since that time being ~8.3 cm/k.y (Fig. **F5**).

- *Site U1308 is a reoccupation of a classic site (DSDP Site 609) in the central Atlantic that has driven many of the most important advances in paleoceanography during the last 10–15 y. A demonstrably complete section was recovered back to 3.1 Ma, with almost continuous recovery back to about 3.5 Ma. The site will provide a record of central Atlantic detrital layer stratigraphy, as well as a means of monitoring NADW, within a well-constrained chronostratigraphy.*

The drilling and recovery phase of Expediton 303 has been an unqualified success due to the dedication of IODP staff, the Transocean employees, and members of the science party. The weather also played an important role in permitting the recovery of high-quality cores at all sites. A total of 4656 m of high-quality core was recovered from sites with mean sedimentation rates in the 5–18 cm/k.y. range. The sites were chosen to recover Pliocene and Quaternary records of millennial-scale environmental variability in terms of ice sheet–ocean interactions, deep circulation changes, or sea-surface conditions. The sites provide the requirements, including adequate sedimentation rates, for developing millennial-scale stratigraphies (through geomagnetic paleointensity, oxygen isotopes, and regional environmental patterns). We expect research on these cores in the coming years to break new ground in the fields of paleoclimatology and paleoceanography.

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Table T1. Expedition 303 operations summary.

Hole	Latitude	Longitude	Water depth (mbsl)	Number of cores	Interval cored (m)	Core recovered (m)	Recovery (%)	Drilled interval (m)	Penetration (m)	Time on hole (h)	Time on site (days)
U1302A	50°9.985′N	45°38.271′W	3568.6	13	107.1	91.7	85.6	0.0	107.1	30.50	1.3
U1302B	50°9.995′N	45°38.290′W	3563.4	11	104.7	102.8	98.2	0.0	104.7	13.25	0.6
U1302C	50°10.007′N	45°38.309′W	3559.2	11	104.5	97.1	92.9	0.0	104.5	13.67	0.6
U1302D	50°10.019′N	45°38.324′W	3555.7	2	13.0	4.9	37.5	0.0	13.0	2.58	0.1
U1302E	50°10.030′N	45°38.343′W	3558.1	2	15.1	14.6	96.6	0.0	15.1	4.00	0.2
		Site 1302 totals:		39	344.4	311.0	90.3	0.0	344.4	64.00	2.7
U1303A	50°12.401′N	45°41.220′W	3524.2	10	93.9	69.1	73.6	0.0	93.9	14.83	0.6
U1303B	50°12.383′N	45°41.197′W	3517.9	9	85.7	71.5	83.5	0.0	85.7	20.42	0.9
		Site 1303 totals:		19	179.6	140.6	78.3	0.0	179.6	35.25	1.5
U1304A	53°3.401′N	33°31.781′W	3069.1	26	239.0	251.4	105.2	0.0	239.0	35.75	1.5
U1304B	53°3.393′N	33°31.768′W	3065.4	26	242.4	252.1	104.0	0.0	242.4	30.50	1.3
U1304C	53°3.384′N	33°31.751′W	3064.5	8	69.6	71.8	103.2	0.0	69.6	12.17	0.5
U1304D	53°3.378′N	33°31.741′W	3064.5	21	190.9	185.7	97.3	53.0	243.9	46.08	1.9
		Site 1304 totals:		81	741.9	761.0	102.6	53.0	794.9	124.50	5.2
U1305A	57°28.507′N	48°31.842′W	3463.0	30	280.0	294.6	105.2	0.0	280.0	44.00	1.8
U1305B	57°28.507′N	48°31.813′W	3459.2	28	264.8	274.3	103.6	0.0	264.8	33.50	1.4
U1305C	57°28.509′N	48°31.783′W	3458.8	31	287.1	298.2	103.9	0.0	287.1	59.75	2.5
		Site 1305 totals:		89	831.9	867.1	104.2	0.0	831.9	137.25	5.7
U1306A	58°14.228′N	45°38.588′W	2270.5	33	303.3	307.0	101.2	1.0	304.3	38.33	1.6
U1306B	58°14.227′N	45°38.557′W	2273.0	33	305.3	315.9	103.5	4.0	309.3	35.67	1.5
U1306C	58°14.228′N	45°38.527′W	2274.8	28	257.5	267.6	103.9	8.0	265.5	28.50	1.2
U1306D	58°14.227′N	45°38.500′W	2271.8	19	178.0	179.5	100.9	2.0	180.0	21.50	0.9
		Site 1306 totals:		113	1044.1	1069.9	102.5	15.0	1059.1	124.00	5.2
U1307A	58°30.347′N	46°24.033′W	2575.1	19	156.6	160.5	102.5	6.0	162.6	27.42	1.1
U1307B	58°30.358′N	46°24.054′W	2575.3	17	154.6	157.0	101.5	0.0	154.6	25.08	1.0
		Site 1307 totals:		36	311.2	317.4	102.0	6.0	317.2	52.50	2.2
U1308A	49°52.666′N	24°14.287′W	3871.0	36	341.1	323.8	94.9	0.0	341.1	67.92	2.8
U1308B	49°52.667′N	24°14.313′W	3871.1	22	198.3	186.2	93.9	0.0	198.3	52.83	2.2
U1308C	49°52.684′N	24°14.287′W	3872.7	30	279.9	271.1	96.9	0.0	279.9	49.50	2.1
U1308D	49°52.700′N	24°14.287′W	3873.8	1	6.7	6.7	100.3	0.0	6.7	1.83	0.1
U1308E	49°52.700′N	24°14.287′W	3871.0	21	193.0	172.5	89.4	7.5	200.5	28.92	1.2
U1308F	49°52.700′N	24°14.312′W	3872.1	24	227.0	228.6	100.7	0.0	227.0	41.00	1.7
		Site 1308 totals:		134	1246.0	1188.9	95.4	7.5	1253.5	242.00	10.1
		Expediton 303 totals:		511	4699.1	4656.1	99.1	81.5	4780.6	779.50	32.5

Figure F1 Location of IODP Expedition 303 sites (red), and other DSDP and ODP sites mentioned in the text. Figure modified after Raymo et al. (2004). Arrows indicate major deepwater flows. DSOW = Denmark Strait Overflow Water; NGS = Norwegian Greenland Sea; ISOW = Iceland Sea Overflow Water; WTRO = Wyville Thomson Ridge Overflow; GFZ = Charlie Gibbs Fracture Zone; LSW = Labrador Sea Water; LDW = Lower Deep Water.

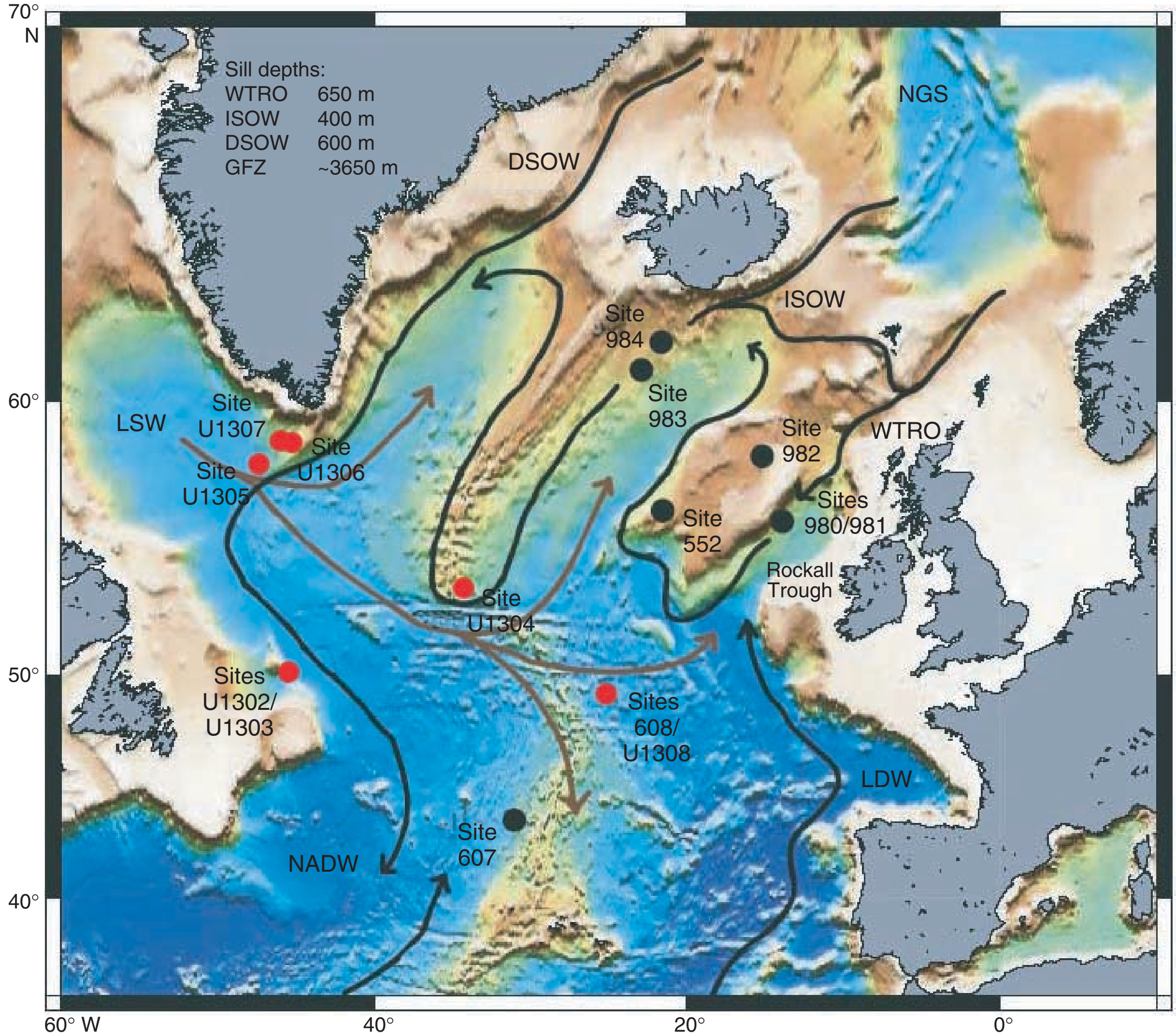

Figure F2. Composite digital image scan of Core 303-U1303B-1H indicating detrital layers delineated by magnetic susceptibility (MS) (red line) and gamma ray attenuation (GRA) density (yellow line). Detrital layer labels follow Stoner et al. (2000) for Core MD95-2024 collected at the same location. The detrital layer H6 (Heinrich Layer 6) has an age of ~60 ka, indicating a mean sedimentation rate in this core of 15 cm/k.y.

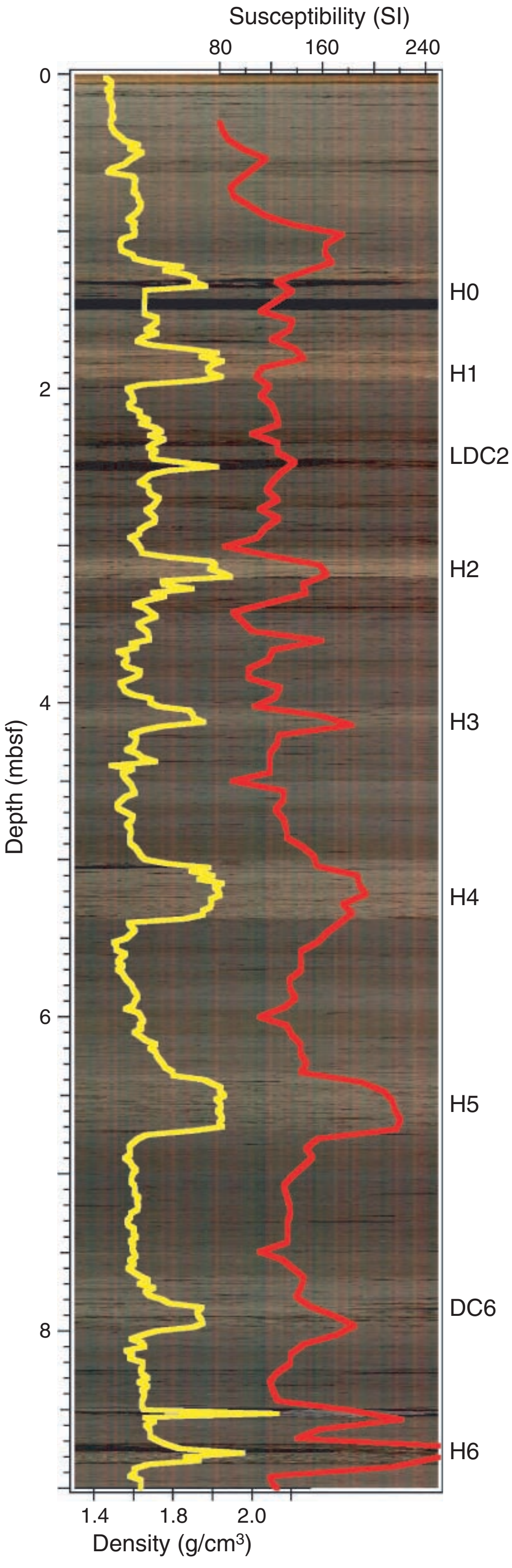

Figure F3. Recovery record at Sites U1302 and U1303 with natural gamma ray (NGR), magnetic susceptibility (MS), gamma ray attenuation (GRA) density, and lightness (L*) for the composite section (mcd).

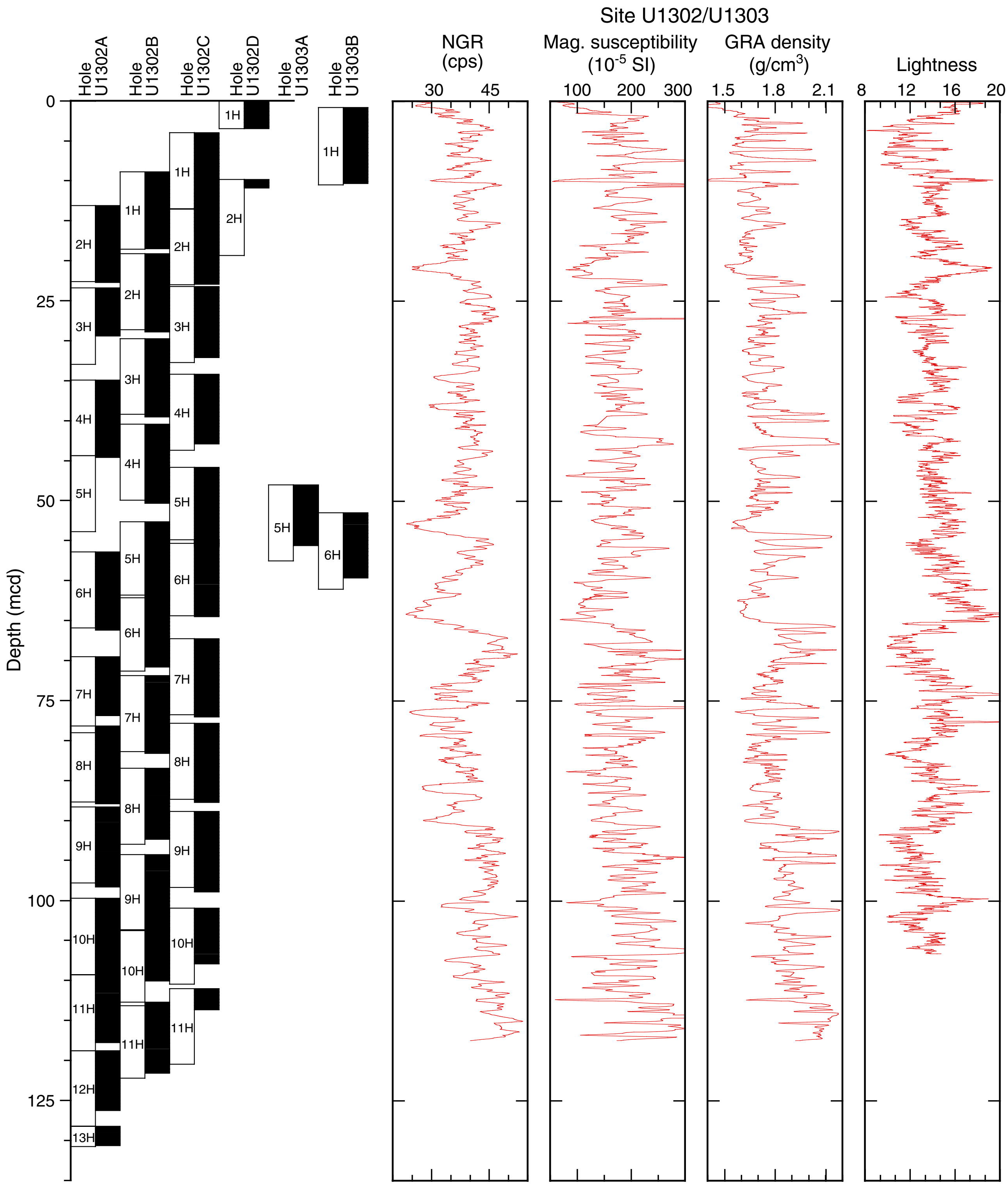

Figure F4. Schematic stratigraphy at the seven sites drilled during Expedition 303. The geomagnetic polarity timescale is shown on the right. The normal and reversed polarity zones are indicated in black and white, respectively. Hatched intervals indicate uncertain polarity in the debris flow of Sites U1302 and U1303. Blue tie lines indicate biostratigraphic datums and correlations. Red tie lines indicate magnetostratigraphic correlations.

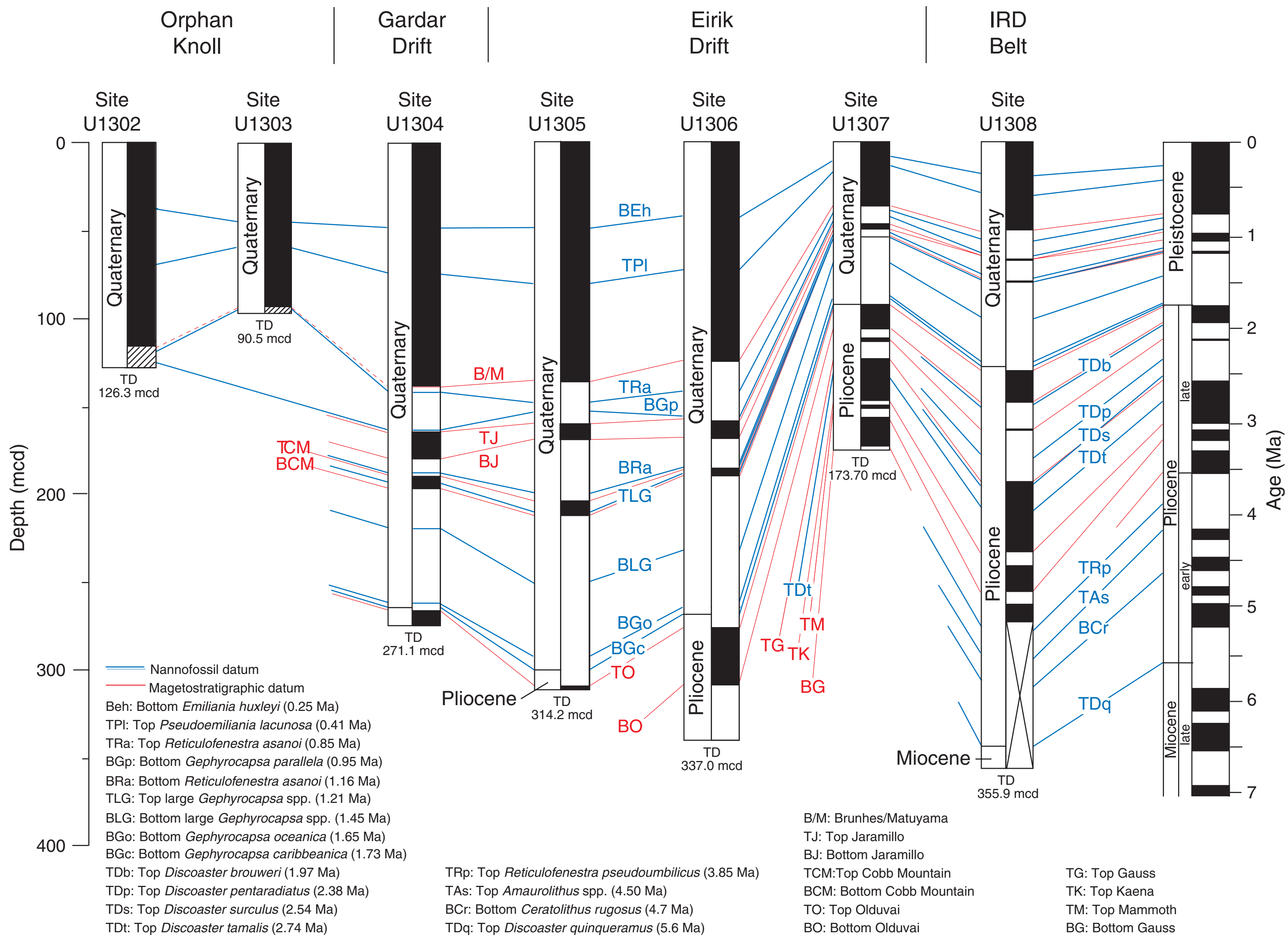

Figure F5. Sedimentation rates at the sites drilled during Expedition 303. Solid circles = magnetostratigraphy-based ages, open circles = nannofossil-based ages, open squares = diatom-based ages, open triangles = foraminiferal-based ages. Mean sedimentation rates are calculated from straight-line segments.

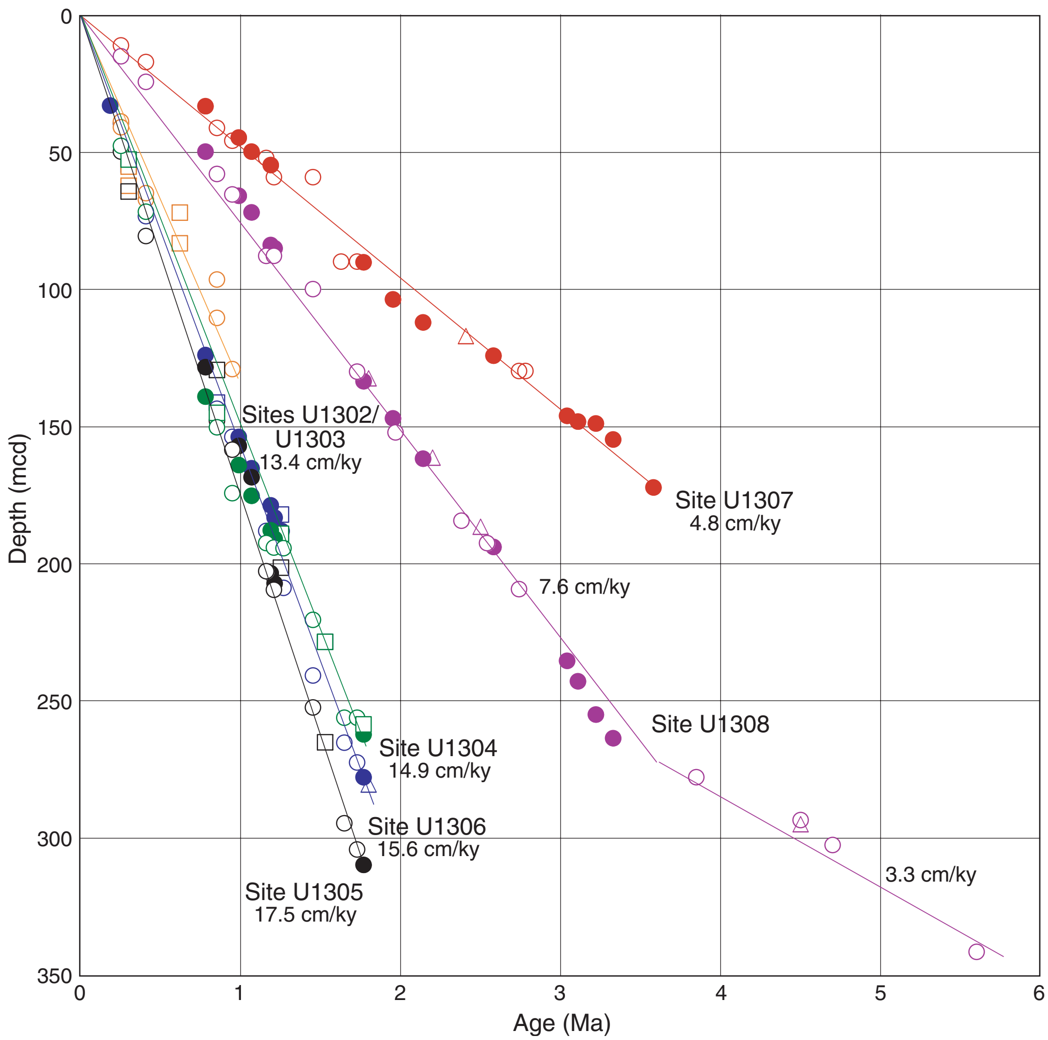

Figure F6. Recovery record at Site U1304 with natural gamma ray (NGR), magnetic susceptibility (MS), gamma ray attenuation (GRA) density, and lightness for the composite section (mcd).

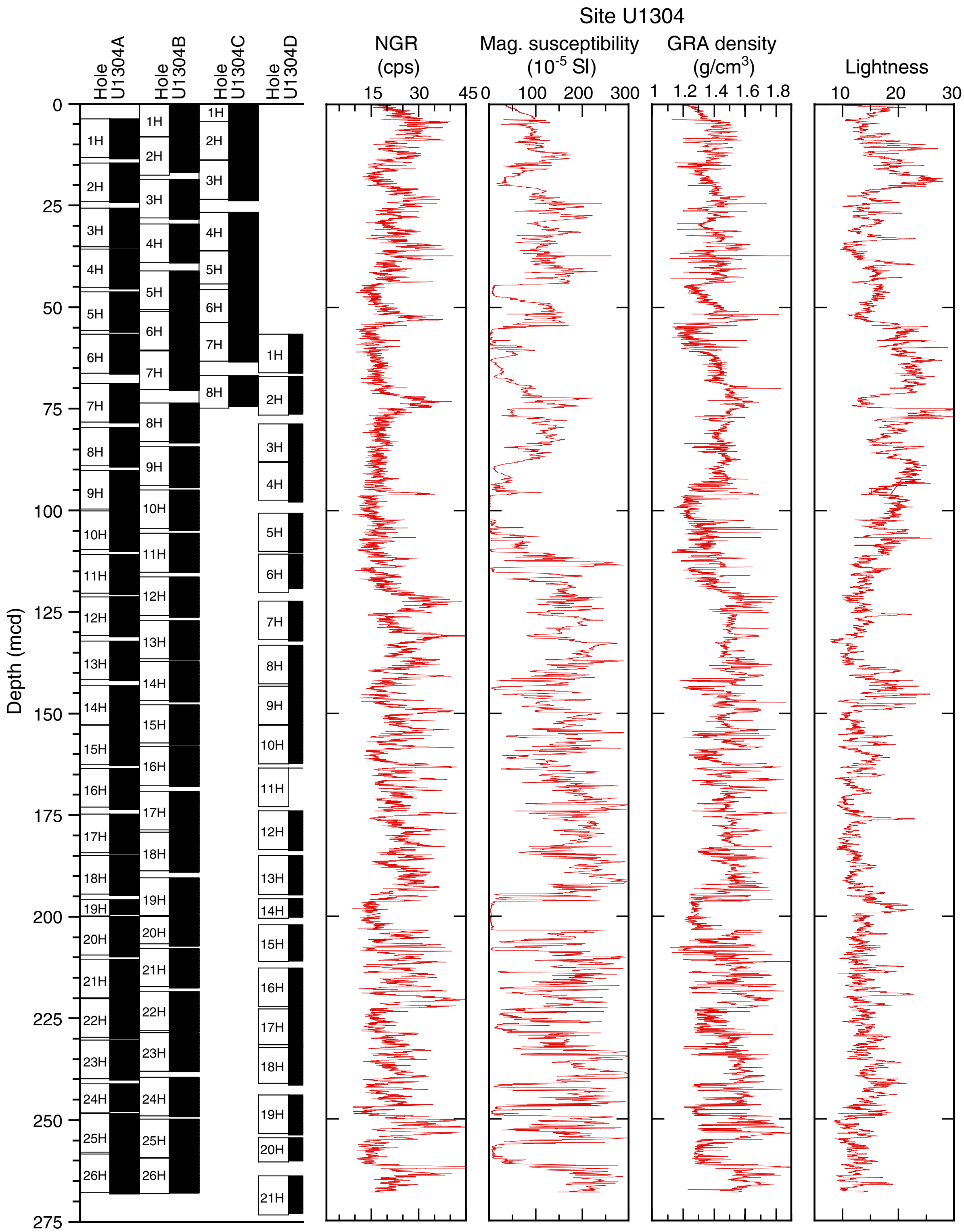

Figure F7. Recovery record at Site U1305 with natural gamma ray (NGR), magnetic susceptibility (MS), gamma ray attenuation (GRA) density, and lightness for the composite section (mcd).

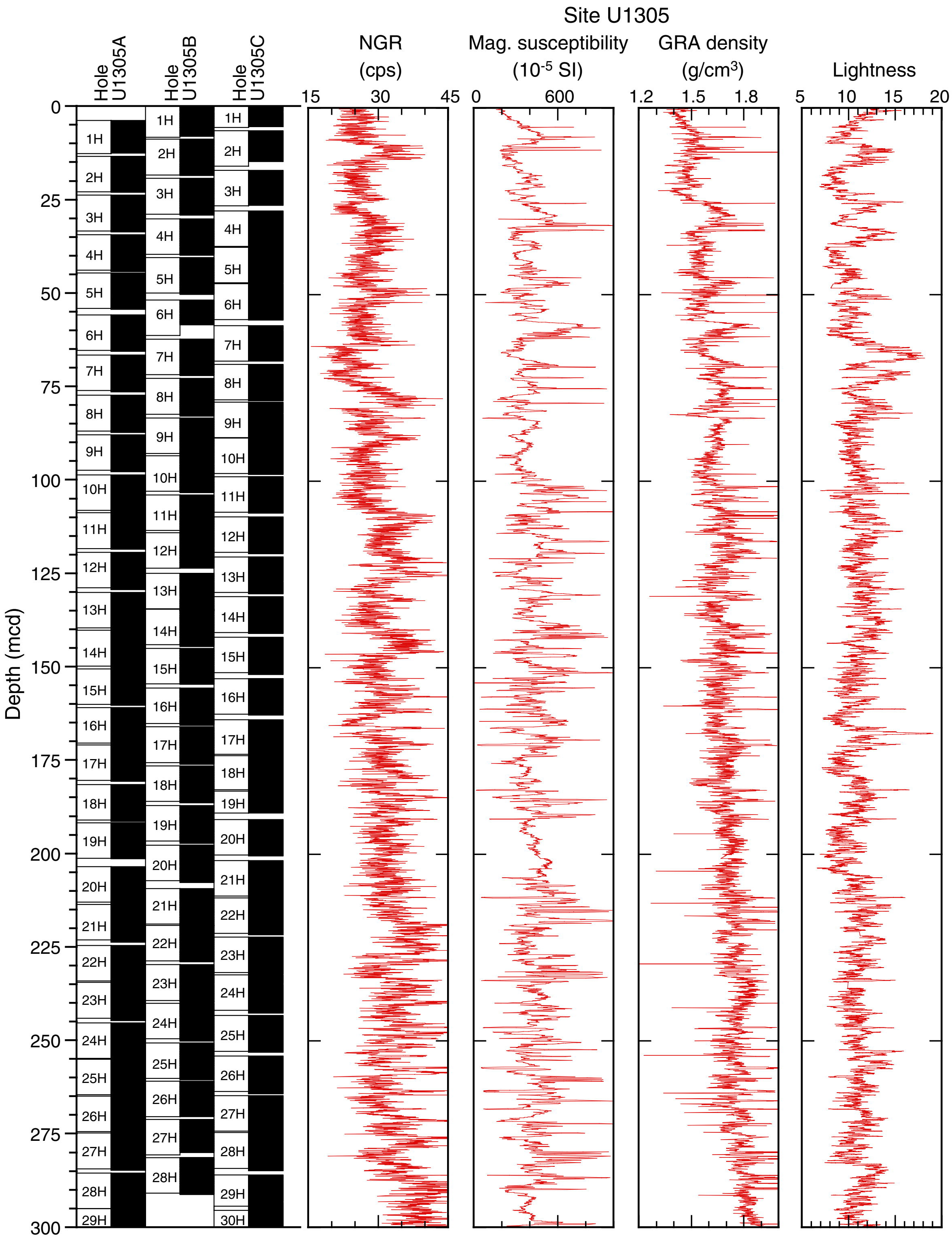

Figure F8. Recovery record at Site U1306 with natural gamma ray (NGR), magnetic susceptibility (MS), gamma ray attenuation (GRA) density, and lightness for the composite section (mcd).

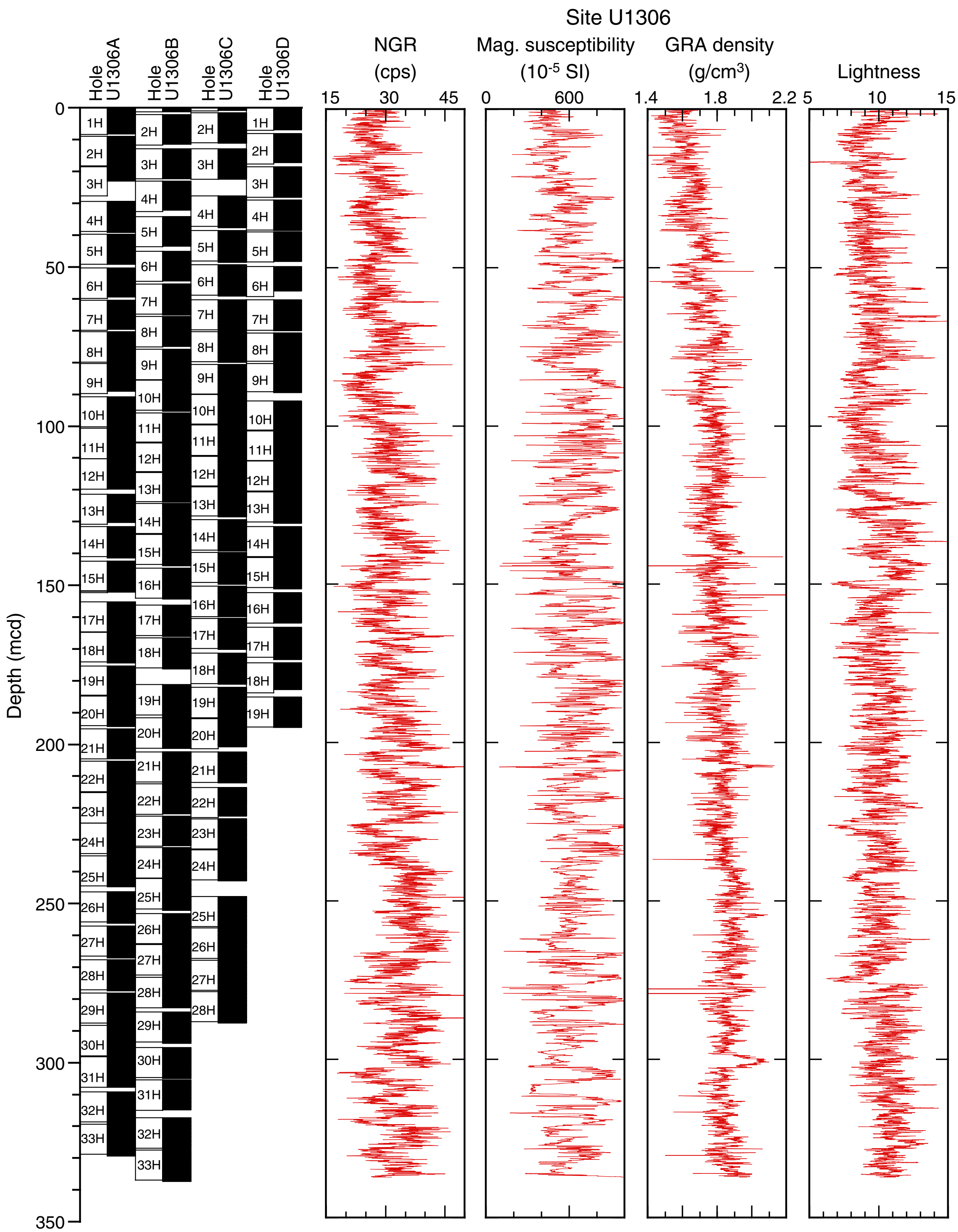

Figure F9. Recovery record at Site U1307 with natural gamma ray (NGR), magnetic susceptibility (MS), gamma ray attenuation (GRA) density, and lightness for the composite section (mcd).

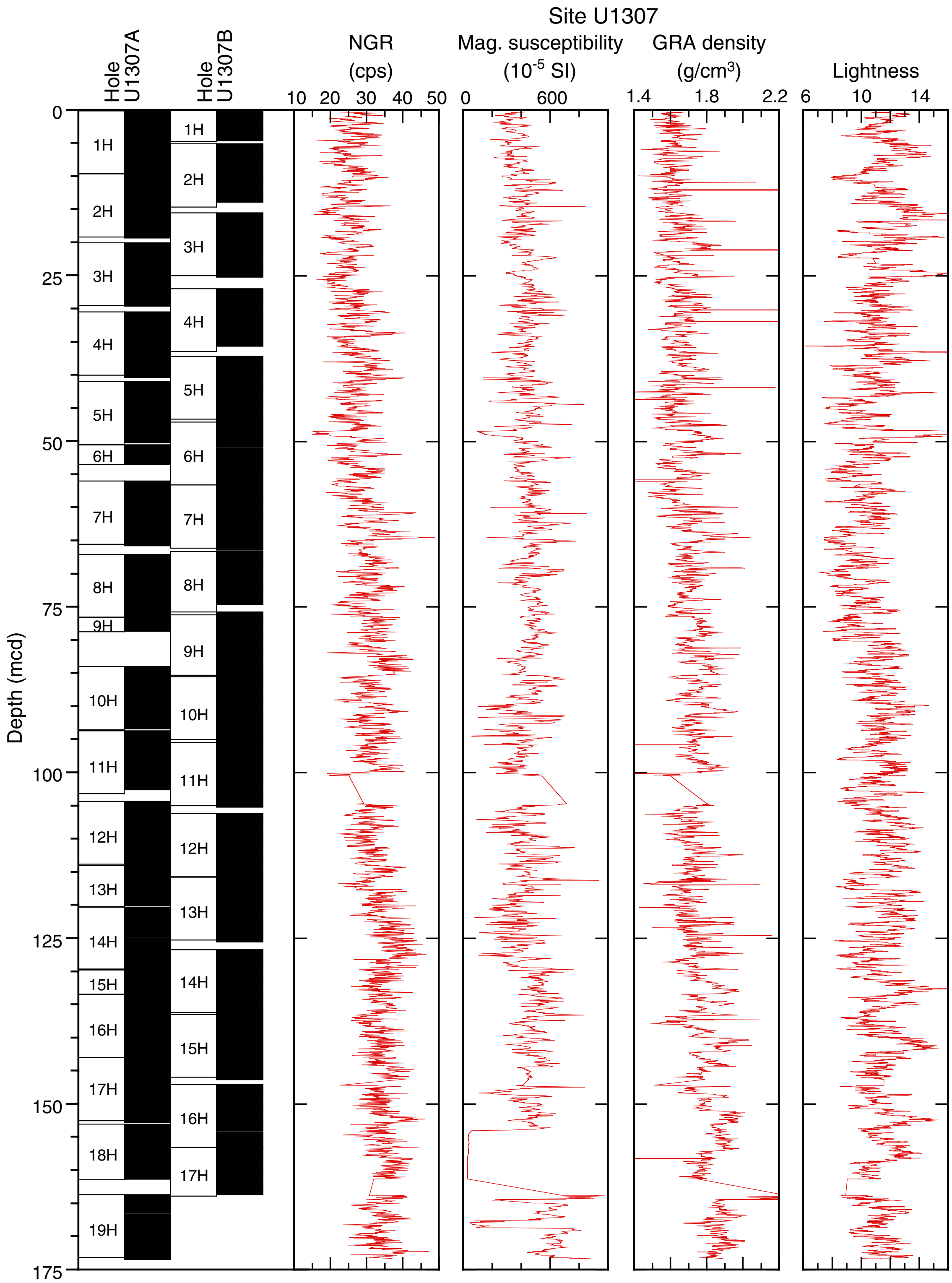

Figure F10. Recovery record at Site U1308 with natural gamma ray (NGR), magnetic susceptibility (MS), gamma ray attenuation (GRA) density, and lightness for the composite section (mcd).