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Expedition 303/306 synthesis: North Atlantic climate[1]

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Chapter contents

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Abstract

The sites occupied during Integrated Ocean Drilling Program Expedition 303/306 were chosen to recover late Miocene to Quaternary records of North Atlantic environmental variability at elevated mean sedimentation rates from locations appropriate for oxygen isotope ($\delta^{18}O$) and relative paleointensity (RPI) stratigraphies. The overall objective is to correlate these climate/paleoceanographic records to two (ostensibly) independent global stratigraphic signals ($\delta^{18}O$ and RPI), thereby enhancing stratigraphic resolution. One site at Orphan Knoll (Site U1302/U1303) provided a proximal record of Laurentide Ice Sheet instability for the Brunhes Chron. Three sites from the Eirik Drift (Sites U1305, U1306, and U1307) provided records of the strength and location of the Western Boundary Undercurrents well as monitors of Greenland Ice Sheet instability back into the Pliocene. Poor weather over the Erik Drift during the second phase of drilling (Expedition 306) precluded the planned return that would have further enhanced knowledge of the history of the drift. Three sites (U1308, U1312, and U1313) constituted reoccupations of classic paleoceanographic sites drilled in 1983 during Deep Sea Drilling Project Leg 94. Although poor weather compromised the record at Site U1312, the new drilling at Sites U1308 and U1313 provided complete sections to the Pliocene and late Miocene, respectively, that were not available from Leg 94. Site U1308 provided evidence for "Hudson Strait" Heinrich Events in the eastern North Atlantic from the end of the middle Pleistocene transition (~640 ka). One site on the central part of the Gardar Drift (Site U1314) and one site at the southern tip of the Gardar Drift (Site U1304) provided high-resolution deepwater paleoceanographic records that can be linked with shallower water drift sites in the Iceland Basin, drilled during Ocean Drilling Program Leg 162. Site U1315, located on the Vøring Plateau, was drilled to 179 meters below seafloor. Instruments to monitor seafloor temperature variations resulting from bottom current changes were installed with a circulation obviation retrofit kit to seal the borehole.

Introduction

The sites occupied during Integrated Ocean Drilling Program (IODP) Expedition 303/306 (Fig. F1; Table T1) were chosen to recover Miocene to Quaternary records of North Atlantic 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 high-resolution stratigraphies through geomagnetic relative paleointensity (RPI), oxygen isotopes, and regional environmental patterns (see the "Expedition 303 summary" and "Expedition 306 summary" chapters; Channell et al., 2006).

The timing of the two drilling expeditions, separated by an interval of 5 months, allowed experience from the first expedition (Expedition 303: September–November 2004) to be incorporated in the plan for the second expedition (Expedition 306: March–May 2005). Results of the first expedition did indeed lead to a revised drilling plan for the second expedition, particularly for the Eirik Drift off southeast Greenland. In this region, cores recovered during Expedition 303, combined with the multichannel seismic data acquired in 2002, allowed a refined choice of sites. Unfortunately, poor weather conditions during Expedition 306 precluded the ship reaching the Eirik Drift.

Nonetheless, the sites occupied during Expeditions 303 and 306 provided a rich archive of Miocene to Quaternary environmental conditions from the North Atlantic. At the outset, the decision was made to limit drilling to depths achievable using the advanced piston corer (APC), the rationale being that the extended core barrel (XCB) does not provide adequate core quality for planned high-resolution studies. Recovery of complete composite sections through shipboard control of hole-to-hole offsets was given high priority.

The North Atlantic has been the focus of some of the most intriguing advances in paleoceanography in the last 20 y, including the recognition of Heinrich layers and Bond cycles and the proposed ~1500 y pacing in ice-rafted debris (IRD) proxies such as hematite-stained grains and Icelandic glass (Broecker et al., 1992; Bond et al., 1992, 1999, 2001). These observations have been largely restricted to the last glacial cycle because of the lack of high sedimentation–rate records with known continuity that extend beyond the last glacial cycle. A principal objective of Expedition 303/306 was to obtain sedimentary records that would extend our knowledge of millennial-scale paleoceanographic change beyond the last glacial cycle, through the so-called "100 k.y. world" and into the "41 k.y. world." The critical role of age control in interpreting these paleoceanographic phenomena, particularly beyond the range of radiocarbon dating and the Greenland ice core record, requires that sites be appropriate not only for oxygen isotope stratigraphy but also for more recently developed stratigraphies based on RPI studies.

A summary of the polarity stratigraphies and biostratigraphies obtained from sites occupied during Expedition 303/306 are given in Figure F2. Sites from Orphan Knoll (Site U1302/U1303), Eirik Drift (Site U1305/U1306), and Gardar Drift (Site U1314) yielded records covering the last ~1–2 m.y., at mean sedimentation rates of 10–20 cm/k.y. Shipboard hole-to-hole correlations indicate that complete composite sections can be constructed for large parts of the sedimentary records recovered at these sites (Table T1). At Sites U1308 and U1313, two previously drilled North Atlantic sites (Deep Sea Drilling Project [DSDP] Sites 609 and 607, respectively) were reoccupied to obtain composite sections for sites that lie in the heart of the North Atlantic "Ruddiman" (1977) IRD belt (Site U1308) and at the southern edge of the belt (Site U1313). Sites 607 and 609 have provided key records of Pliocene to Quaternary North Atlantic paleoceanography (Ruddiman et al., 1986, 1989; Raymo et al., 1989), and the objective of reoccupation of these sites was to obtain demonstrably complete sections that would lend themselves to analytical methods developed since the sites were drilled over 25 y ago. At these two sites (U1308 and U1313), mean sedimentation rates are 4–10 cm/k.y., and the recovered sections extend back to 3.2 and 5 Ma, respectively. Site U1312 on the southern flank of the King's Trough constituted a redrill of DSDP Site 608 with the principal target being the classic upper Miocene section (e.g., Miller et al., 1991). Unfortunately, severe weather conditions resulted in a high degree of drilling disturbance in the recovered cores that precluded the construction of a composite section at this site and resulted in its premature abandonment. Site U1315 was drilled at the site of Ocean Drilling Program (ODP) Site 642 to 179 meters below seafloor (mbsf) and cased to receive a 150 m thermistor string for monitoring bottom water temperatures and seafloor diffusion over a multiyear period.

Site U1302/U1303

The overall objective at Site U1302/U1303 is to explore the record of Laurentide Ice Sheet (LIS) instability at this location close to Orphan Knoll (Fig. F1). Piston cores collected nearby (Cores 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; Hiscott et al., 2001). The correlation of these detrital layers to the classic Heinrich layer stratigraphy and to other central Atlantic detrital layers (e.g., Bond and Lotti, 1995) remains problematic. Oxygen isotope data from planktonic foraminifers imply that these detrital layers are often associated with low-productivity meltwater pulses (Hillaire-Marcel et al., 1994). The Heinrich-type detrital layers usually appear as lighter colored intervals, particularly where they are rich in detrital carbonate. The detrital layers are often evident in magnetic susceptibility and gamma ray attenuation (GRA) density data measured on the shipboard multisensor track (MST). The objective at Sites U1302 and U1303 is to document this manifestation of LIS instability both during and prior to the last glacial cycle, beyond the reach of previously existing piston cores.

Sites U1302 and U1303 are separated by 5.68 km. The move to a different location from Site U1302 was an effort to avoid a debris flow at ~110 mbsf that halted drilling at both sites. An almost complete composite section was constructed at Site U1302 spanning 0–107 meters composite depth (mcd). Although it was not possible to construct a complete composite record at Site U1303, the density and magnetic susceptibility records from Sites U1302 and U1303 are remarkably similar and can be easily correlated. A short segment from one core of Site U1303, together with the record from Site U1302, provides a continuous composite stratigraphic sequence to ~107 mcd.

Sediments at Sites U1302 and U1303 are dominated by varying mixtures of terrigenous components and biogenic debris (primarily quartz, detrital carbonate, and nannofossils); the most common lithologies are clay and nannofossil ooze with silty clay. Dropstones are present throughout the cores. Calcium carbonate content ranges from 1 to 47 wt%. At the base of the sediment sequence, debris flow deposits (106–132 mcd) contain abundant intraclasts in a matrix of sand-silt-clay.

Samples from Site U1302 contain 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. 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 allows identification of glacial and interglacial conditions. The diatom assemblage in the upper 48 m at this site has been studied by **Romero.**

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 concentration decreases from seawater value to 5.9 mM close to the base of the recovered section, indicating that sulfate reduction is almost complete by 109 mcd.

Benthic foraminifers are rare at this site, although a continuous planktonic oxygen isotope record for the Brunhes Chron has been acquired using *N. pachyderma* (sinistral) (Hillaire-Marcel et al., pers comm., 2009). Shore-based U-channel paleomagnetic data have shown that the Matuyama/Brunhes boundary is recorded just above the debris flow at ~105 mcd, yielding a mean Brunhes sedimentation rate of 13.5 cm/k.y. (Channell et al., 2009a). Several magnetic excursions are recorded within the Brunhes Chron, including the Iceland Basin excursion at 188 ka, providing further stratigraphic markers and extending the inventory of magnetic excursions in the North Atlantic. The RPI record (Channell et al., 2009a) can be correlated to the oxygen isotope record to provide high-resolution age control throughout the record.

The detrital layer stratigraphy, recognized for the last glacial cycle in conventional piston cores from close to the site (e.g., Cores HU91-045-094P, MD99-2237, and MD95-2024), can be recognized using a variety of parameters including GRA density measurements, Ca/Sr ratios from X-ray fluorescence (XRF) core scanning, and magnetic hysteresis properties. The Ca/Sr ratio derived from XRF core scanning provides an efficient means of recognizing detrital carbonate associated with Heinrich-type detrital layers derived from Hudson Strait (Hodell et al., 2008). Comparison of the Ca/Sr ratio with GRA density and magnetic hysteresis and susceptibility data allows detrital carbonate events to be differentiated from low detrital carbonate events.

The acquisition of oxygen isotope and RPI data from Site U1302/U1303 provides a stratigraphic resolution that permits the proximal record of detrital layers obtained from Orphan Knoll to be correlated to the distal record at Site U1308 (Fig. **F1**). The correlation of detrital layers across the North Atlantic, particularly beyond the last glacial cycle, has been stymied by the lack of stratigraphic precision that has not allowed unequivocal correlation of detrital layers and hampered the understanding of distribution and provenance of detrital layers in the North Atlantic (e.g., van Kreveld et al., 1996).

Site U1304

The objective at Site U1304 was to obtain a deep water record from the southern edge of the Gardar Drift (Fig. **F1;** Table **T1**) to compare with the intermediate depth site on the northern part of the Gardar Drift sampled during ODP Leg 162 at Site 983. Site U1304 is north of the Charlie Gibbs Fracture Zone, 217 km west-northwest of DSDP Site 611. The mean sedimentation rate at Site U1304 (15 cm/k.y.) is about six times that in the same stratigraphic interval at DSDP Site 611.

Four holes were cored with the APC coring system to a maximum depth of 243.8 mbsf at Site U1304. Correlation of cores among holes at Site U1304, utilizing mainly magnetic susceptibility and natural gamma radiation, provides a continuous stratigraphic sequence to ~258 mcd with a single potential break within an 8 m thick diatom mat at ~199 mcd. The spliced composite section relies on sections from Holes U1304A and U1304B 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 that 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 conditions.

Recurring laminated diatom sequences are the most prominent feature at Site U1304 (Shimada et al., 2008). The thicker diatom mats are clearly distinguished by very low magnetic susceptibility values. Diatom assemblages are dominated by needle-shaped species of the *Thalassiothrix/Lioloma* complex. All other fossil groups investigated, coccoliths, planktonic and benthic foraminifers, radiolarians, and palynomorphs, are present in high to moderate abundance and are well preserved (see **Liu;** Yamasaki et al., 2008). Biostratigraphic datums were mainly derived from coccoliths and are consistent with datums provided by diatoms, planktonic foraminifers, dinoflagellate cysts, and magnetostratigraphy. The composite sequence covers the uppermost Pliocene and the entire Quaternary. The microfossil assemblage indicates only minor redeposition. Excellent preservation of benthic and planktonic microfossils enhances the potential for a high-resolution environmental record. The site monitors North Atlantic Deep Water (NADW) and sea-surface temperatures and may provide a record of central Atlantic detrital-layer stratigraphy. Oxygen isotope stratigraphies based on both planktonic and benthic foraminifers are presently in development for this site. Published stable isotope data at Site U1304 has demonstrated that the site provides a particularly high resolution record of the last interglacial, where sedimentation rates were ~40 cm/k.y., where frequent thin diatom-rich layers inhibit bioturbation (Hodell et al., 2009). Planktonic oxygen isotope data from a number of planktonic foraminifer species are compared with benthic oxygen and carbon isotope data, yielding a unique picture of surface and deep water evolution during marine isotope stage (MIS) 5 (Hodell et al., 2009). The results from this study of MIS 5 at Site U1304 illustrate the potential of the site for detailed studies of Quaternary paleoceanography.

Preliminary paleoceanographic 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 interpretation of diatom and planktonic foraminifer assemblages (Shimada et al., 2008). 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 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 a magnetostratigraphic sequence that includes the Brunhes Chron and part of the Matuyama Chron, the Jaramillo and Cobb Mountain Subchrons, and the top of the Olduvai 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. The shore-based magnetic stratigraphy has resolved two magnetic excursions at this site and has refined the position of the major reversals (C. Xuan and J.E.T. Channell, unpubl. data). The RPI record at this site is in the process of being developed and awaits correlation to the oxygen isotope records.

Site U1304 pore water profiles indicate active sulfate reduction (minimum value of 2.8 mM reached at 214 mbsf) with corresponding increases in alkalinity and ammonium, although 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 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 sub-Arctic convergence between the surface Labrador Current and the North Atlantic Current (see Bodén and Backman, 1996). Good preservation of both calcareous and siliceous microfossils, abundant benthic foraminifers, and a high-fidelity magnetostratigraphic record indicate that the environmental record, including monitoring of NADW, can be placed in a tight chronological framework based on oxygen isotope and RPI data.

Site U1305

Site U1305 is located close to the southwest extremity of the Eirik Drift, 82.2 km south of ODP Site 646 (Fig. **F1**; Table **T1**). The thickness of the sediments above the mid-upper Pliocene seismic Reflector R1 (~540 m) is almost twice that at Site 646. The water depth (3518 m) 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 mean Quaternary sedimentation rate (>17 cm/k.y.) provides a high-resolution record of ice sheet instability, and changes in surface and deep water masses.

Three holes were cored at Site U1305 with the APC system to a maximum depth of 287 mbsf. 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 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. 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. 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 bimodal 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. An oxygen isotope stratigraphy based on *N. pachyderma* (sinistral) is presently in development (C. Hillaire-Marcel, pers. comm., 2009).

Sediments at Site U1305 carry well-defined magnetization components and appear to provide useful records of polarity transitions. Natural remanent magnetization (NRM) intensities decrease by about one-half below 166 mcd. Directional magnetization data allow identification of the Brunhes Chron and part of the Matuyama Chron, including the Jaramillo, Cobb, and Olduvai Subchrons. 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 relative paleointensity record is presently being developed for this site (A. Mazaud, pers. comm., 2009).

A continuous stratigraphic composite section was constructed to ~295 mcd with a single problematic interval between 197.2 and 206 mcd. The mean sedimentation rate calculated using biostratigraphic and magnetostatigraphic datums is 17.5 cm/k.y. for the entire section. Using only paleomagnetic datums, sedimentation rates are relatively uniform with the exception of a higher 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 (see **Ennyu and Malone**). 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 other Expedition 303 sites, 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 magnetic susceptibility and density, are highly variable, recording lithologic and mineralogic changes. Low magnetic susceptibility and density values usually coincide with the presence of silt-sized detrital carbonate. The detrital carbonate (Heinrich-type) layers are characterized by a very specific biomarker association, pointing to an Ordovician oil shale close to Hudson Strait as the source of these layers (Hefter et al., 2007). Natural gamma radiation (NGR) increases at the transition between detrital carbonate- and siliciclastic-dominated background sediments, 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/cm³), decreasing porosity (from 80% to 62%), and low *P*-wave velocities (1500–1600 m/s).

Data from wireline logs in Hole U1305C span the interval from 95.3 to 265.9 mbsf. The triple combination (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, with density increasing and porosity decreasing downhole. Density and gamma ray logging data show similar downhole trends to those observed in core data.

The analysis of MST, biostratigraphic, and paleomagnetic data indicates that a complete and continuous high-resolution record (mean sedimentation rate = 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 documents episodes of instability in the surrounding (Laurentide, Greenland, and Inuitian) ice sheets, the history of surface currents and deep water 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 can be integrated into a high-resolution stratigraphy.

Site U1306

At Site U1306, late Pliocene and Quaternary mean 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 Site 646. The placement of the site was designed to yield a high-resolution (high sedimentation rate) Quaternary environmental record from a water depth 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. Hole U1306D was cored to 180.0 mbsf to provide necessary stratigraphic overlap for the upper portion of the sediment sequence. Five cores were obtained by drillover, and the 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 that 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 a high detrital carbonate content are present in all holes at Site U1306, but they are thinner and less common than at Site U1305.

Rich assemblages of calcareous, siliceous, and organic-walled microfossils are present at Site U1306, although benthic foraminifers are barren in many samples below 175 mcd. An oxygen isotope record based on *N. pachyderma* (sinistral) is presently in development (J.D. Wright, pers. comm., 2010). 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 sea-surface temperatures (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. Within the Brunhes Chron, the Iceland Basin magnetic excursion (~188 ka) was observed in three of the holes.

A continuous stratigraphic composite section was constructed to ~337 mcd. 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. 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 (see **Ennyu and Malone**). 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 slightly again (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. The higher carbonate content in the upper ~100 mcd results in lower NGR and magnetic susceptibility values than in the sediments below. Site U1306 sediments are characterized by an overall downcore increase in density (1.5 to ~1.8 g/cm^3) and decreasing porosity (~70% to 50%).

Based on nearby piston cores, Site U1306 is expected to exhibit expanded glacial intervals, complementary to 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 the instability of surrounding ice sheets. The site monitors the activity of the WBUC, which supplies a component of NADW to the Labrador Sea, and appears to have the attributes required for the generation of a well-constrained age model based on oxygen isotopes, micropaleontology, and RPI.

Site U1307

The location of Site U1307 was chosen for access to Pliocene sediments below the Quaternary sequence drilled at Site U1306. A thinner Quaternary sedimentary sequence at Site U1307 allows the Pliocene sequence to be sampled using the APC system.

Two holes were cored at Site U1307, reaching a maximum depth of 162.6 mbsf. Two partial strokes of the APC required RCB drilling of two intervals in Hole U1307A that were difficult to penetrate using APC (50.5–52.5 and 73.7–77.7 mbsf). Average recovery was 102% for the cored intervals at Site U1307. Coring was terminated because of excessive heave when a passing storm system affected drilling operations.

The lower Pliocene to Pleistocene sedimentary succession at Site U1307, which is divided 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 Quaternary 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 a minor biogenic component. Unit III (133.86–173.6 mcd) comprises 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%).

Calcareous, siliceous, and organic-walled microfossils are common to rare with moderate to poor preservation. A possible hiatus (~0.25 m.y. in duration) or condensed interval (~1.21–1.45 Ma) is indicated by nannofossil biostratigraphy at ~56–61 mcd. 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. Sarnthein et al. (2009) measured oxygen isotope data and SST proxies in the 2.7–3.5 Ma interval at Site U1307 and interpreted the results in terms of a cooling by ~6°C and freshening by ~2 psu from 3.2 to 3.0 Ma, attributable to changes in the East Greenland Current, that they associate with a phase of closure of the Central American Seaway, thereby implicating this tectonic event in the onset of Northern Hemisphere Glaciation.

Paleomagnetic directional data yield an almost continuous sequence and permit unambiguous identification of the Brunhes, Matuyama, and Gauss Chrons. Within the Matuyama Chron, the Jaramillo, Olduvai, and Reunion Subchrons are clearly recognized. Within the Gauss, 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, 76.4–104.7, and 104.7–146.2 mcd), which were then appended in the record. The mean sedimentation rate calculated using biostratigraphic and magnetostatigraphic datums is 4.8 cm/k.y. 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 (see **Ennyu and Malone**). Pore water sulfate decreases linearly from seawater values to ~1 mM at 79 mbsf. The methane profile is atypical, decreasing from 200 ppmv near the sediment/water interface to a low of ~30 ppmv at 54 mbsf and 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. The variability in sediment composition recorded in magnetic susceptibility, 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 (~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 (at 1.2–1.4 Ma) the sedimentary record at Site U1307 is apparently continuous with a mean sedimentation rate of ~5 cm/k.y. The base of the recovered section correlates to the uppermost Gilbert Chron, indicating that the record extends to ~3.6 Ma. The sediments from Site U1307 will provide information on the history of bottom and surface currents and of the Laurentide and Greenland ice sheets. Age control for seismic reflectors, provided by Site U1307 stratigraphy, will provide important constraints on the sedimentary architecture of the Eirik Drift.

Site U1308

Site U1308 is a reoccupation of Site 609, located in the core of the Ruddiman (1977) IRD belt (Fig. **F1**; Table **T1**). During DSDP Leg 94 (June–August, 1983), two principal holes (Hole 609A and Hole 609B) were drilled with the variable length piston coring (VLHPC) system and XCB. During that leg, 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 Site 609 have played a major role is driving some of the most exciting developments in paleoceanographic research during the last 20 y, 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 (Broecker et al., 1992; Bond et al., 1992, 1999, 2001). 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, the reoccupation of Site 609, was to recover a demonstrably complete composite record and hence considerably enhance the potential for Pliocene–Quaternary climatic records from this site.

The upper Miocene through Quaternary sedimentary succession at Site U1308, which is divided into two units, records variations in the input of terrigenous and biogenic sediments, primarily nannofossil ooze, nannofossil silty clay, and silty clay. Unit I (0–196.85 mcd) comprises a Holocene to upper Pliocene sequence of interbedded biogenic and terrigenous sediments with dropstones. Subunit IIA (196.85–262.14 mcd) is 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. Calcareous microfossils are abundant with good preservation in the upper ~200 mcd, grading to moderate preservation below this depth (**Sato et al.**; **Chiyonobu et al.**). 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 absent below 255 mcd. The concentration of terrestrial palynomorphs is low. Dinocysts are common to abundant in the upper 200 mcd. Microfossil floral changes observed at Site U1308 document the onset of Northern Hemisphere glaciation, as well as seasonal changes in bioproductivity and the location of hydrographic fronts.

Paleomagnetic directional data document an apparently continuous sequence of polarity transitions. Identification of the Brunhes, Matuyama, and Gauss Chrons are unambiguous (see Channell et al., 2008). 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 complete recovery of the stratigraphic section to 247 mcd. The unusually large number of holes was required because of poor recovery and core disturbance caused by excessive heave and crushed core liners. One problematic interval between ~186 and ~196 mcd contains inclined bedding and sharp lithologic contacts that 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. Prior to that time the mean sedimentation rate was ~3.3 cm/k.y. based on biostratigraphic markers.

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 indicates that recrystallization (not dissolution) of biogenic carbonate is occurring. 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. In Subunit IIA (197–262 mcd), magnetic susceptibility and NGR values decrease both in absolute value and variability and L* increases. 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), magnetic susceptibility and NGR values are significantly lower and less variable than in 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 of white upper Miocene nannofossil ooze was recovered below this level down to 356 mcd. The upper Pliocene to Quaternary composite section provides 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.

At Site U1308, a detailed benthic oxygen isotope record has been resolved for the upper 110 mcd, equivalent to the last 1.5 m.y. (Hodell et al., 2008). The age model was based on the optimal fit of the benthic oxygen isotope record to the oxygen isotope stack of Lisiecki and Raymo (2005), augmented by correlations to Core MD952042 (Shackleton et al., 2004) for the 35–60 ka interval, and by ^{14}C ages in the 14–35 ka interval that were transferred from Site 609 using reflectance records (Hodell et al., 2008). The resulting sedimentation rate map indicates interval sedimentation rates in the range of 3.8–16.0 cm/k.y., with minima in glacial MIS 10, 12, and 48 and the maximum in interglacial MIS 31. Although other interglacial stages, such as MIS 13 and 17, have relatively high sedimentation rates, other prominent interglacial stages such as MIS 11 do not have particularly elevated sedimentation rates relative to neighboring glacial intervals.

Heinrich-type detrital layers at Site U1308 can be detected using magnetic susceptibility, GRA density measurements, $\delta^{18}O$ of bulk carbonate, and Ca/Sr ratios derived from XRF core scanning (Figs. **F3, F4**) (Hodell et al., 2008). The Ca/Sr ratio provides a means of distinguishing detrital carbonate from biogenic carbonate (and hence detecting Heinrich-type detrital layers) because of the relatively high concentration of Sr in biogenic carbonate relative to detrital carbonate dominated by inorganic carbonate and dolomite. The $\delta^{18}O$ of bulk carbonate is also a useful proxy for Heinrich-type detrital layers because of the different values of $\delta^{18}O$ for (inorganic) detrital carbonate and foraminifer calcite (Hodell and Curtis, 2008). The Si/Sr ratio from XRF scanning was used to detect layers that are poor in biogenic carbonate (low Sr and Ca) but relatively rich in detrital silicate minerals (Hodell et al., 2008). The Si/Sr ratio mimics counts of the ratio of lithics to foraminifers from Site 609 (Bond et al., 1992) (Fig. **F3**).

The record of "Hudson Strait" Heinrich-type detrital layers, based on the Ca/Sr ratio, has been placed in a precise chronostratigraphic framework based on benthic oxygen isotope data, indicating the existence of detrital carbonate-rich layers during glacial stages to MIS 16 (Hodell et al., 2008). Hudson-Strait–derived Heinrich-type events, characterized by detrital carbonate, appear in MIS 8, 10, 12, and 16 but not apparently in MIS 6 or 14 (Fig. **F4**). At Site U1313 (see below), located at the southern edge of Ruddiman's IRD belt, Heinrich-type layers characterized by lithics with detrital carbonate (dolomite) appear in glacial MIS 10, 12, and 16 as well as at Terminations V and VII (Stein et al., 2009; Voelker et al., 2010).

The lead (Pb) isochron method applied to detrital carbonate grains extracted from Heinrich-type detrital layers detected through the Ca/Sr ratio yields Ordovician depositional/diagenetic ages consistent with a Hudson Strait (Laurentide) source (Nielsen and Hodell, submitted). Furthermore, the Heinrich-type detrital layers were clearly identified by a unique biomarker association of "petrogenic" compounds such as benzohopanes, D-ring monoaromatic 8,14-secohopanes, rearranged diasterenes, mono- and triaromatic steranes, and isorenieratene derivatives, as well as characteristic pristane/n-C_{17} and pristane/phytane ratios (Hefter et al., 2007). This biomarker association provides circumstantial evidence for derivation from a relatively immature Paleozoic marine rock deposited under occasional photic zone anoxic conditions, which is today located on the Laurentide/Canadian shield (Rashid and Grosjean, 2006). Reinvestigation of available geologic and organic geochemical data narrowed this assumed source to an Ordovician oil shale close to Hudson Strait, which bears a striking resemblance in terms of biomarker distributions when compared to the specific association of compounds in Heinrich-type detrital events (Hefter et al., 2007).

Interestingly, MIS 6 (and MIS 14) differs from other glacial stages in the MIS 2–16 interval as being apparently devoid of Heinrich-type detrital layers. This observation is consistent with the rarity or absence of the radiolarian species *Amphimelissa setosa* during MIS 6, indicating relatively warm sea-surface conditions relative to other Brunhes-aged glacial stages (see K.R. Bjørklund et al., unpubl. data). In addition to the Ca/Sr ratio, Heinrich-type detrital layers rich in dolomite can be effectively detected using a Fourier transform infrared spectrophotometer (Balsam et al., 2007), and this method has been put to use in the uppermost 29 m of the sediment recovered at Site U1308 (Ji et al., 2009).

Oxygen isotope ($\delta^{18}O$) values from detrital carbonate associated with Heinrich-type layers are ~9‰ lower than coexisting foraminifer calcite. Hodell and Curtis (2008) have shown that the $\delta^{18}O$ of bulk carbonate at Sites U1308 and U1302/U1303 provides a means of detecting detrital carbonate associated with Heinrich-type layers. The $\delta^{18}O$ of bulk carbonate can therefore be used to recognize Heinrich-type layers rich in detrital carbonate, and hence provide a clue to provenance. This observation has implications for oxygen isotope data from (planktonic) foraminifers within carbonate-rich detrital layers that may be "contaminated" by adhered detrital carbonate resulting in spuriously low $\delta^{18}O$ values, previously interpreted as meltwater pulses (e.g., Hillaire-Marcel et al., 1994).

Benthic stable isotope data and lithic grain counts in the MIS G4 and 100 (2.5–2.6 Ma) interval at Site U1308, close to the Gauss/Matuyama boundary, indicate large amplitude suborbital variations in ice rafting at the onset of Northern Hemisphere Glaciation (NHG) (Bailey et al., 2010). As benthic $\delta^{18}O$ maxima were ~0.45‰ lower in this interval than for the late Pleistocene, it was supposed that the benthic oxygen isotope "ice-volume threshold" at the onset of NHG, required to trigger ice sheet instability, was lower than for the late Pleistocene, implying differences in ice sheet dynamics and morphology at the onset of NHG (Bailey et al., 2010).

Stratigraphic control at Site U1308 has been enhanced by a RPI record that has been calibrated using benthic oxygen isotope data for the last 1.5 m.y. (Fig. F5) (Channell et al., 2008). The Site U1308 RPI and $\delta^{18}O$ records have higher resolution and fidelity than most coupled RPI/$\delta^{18}O$ records. They are therefore used as the templates for RPI and $\delta^{18}O$ stacks for the last 1.5 m.y., through correlation to Site U1308 of 12 globally distributed (but mainly North Atlantic) sites that have yielded both RPI and $\delta^{18}O$ data (Channell et al., 2009b). The coupled correlations of isotope and RPI data are accomplished using the Match algorithm (Lisiecki and Lisiecki, 2002). The simultaneous match reduces the degree of freedom associated with correlations using RPI or oxygen isotope records alone. The overall compatibility of RPI and oxygen isotopes indicates a dominant global component in both signals. The so-called PISO-1500 stacks represent a powerful new stratigraphic tool that can be used to correlate among marine sediment records and link them to polar ice cores through variations in cosmogenic nuclide production. Scaling the RPI stack to values for virtual axial dipole moment (VADM) indicate maxima at ~15 × 10^{22} Am^2 and minima that imply a threshold of ~2.5 × 10^{22} Am^2, below which values are associated with either polarity reversals or magnetic excursions. The resulting RPI/isotope templates are part of an overall goal of enhancing stratigraphic resolution by combined use of oxygen isotope and RPI.

Site U1312

Site U1312 is a reoccupation of Site 608 drilled in 1983 with a total penetration of 530 mbsf and reaching basaltic basement (capped by middle Eocene sediments) at 515 mbsf. The principal objective at Site U1312 was to recover a complete composite section of a classic upper Miocene section that became a reference section for Miocene stratigraphy through stable isotope, magnetic, and paleontological studies (Clement and Robinson, 1987; Miller et al., 1991; Gartner, 1992). Recently acquired paleomagnetic data derived from a resampling of Site 608 cores (Krijgsman and Kent, 2004) attests to the fidelity of the paleomagnetic record at this site, even after 25 y of core storage. This new sampling extended from polarity Chron 3Br to 5An and indicated a mean sedimentation rate in this part of the late Miocene of 2.5 cm/k.y. The reoccupation of Site 608 held the promise of recovery of a complete composite section, particularly for the upper Miocene and lower Pliocene. At the time of original drilling (1983) during

Leg 94, composite section construction during drilling was not a viable option.

Two holes were drilled at Site U1312, however, the quality of the recovered core was very poor compared to that recovered 25 y earlier during Leg 94. Both Holes U1312A and U1312B were affected by drilling disturbance and "flow-in" such that a composite record could not be constructed for this site. The high level of drilling disturbance was attributed to excessive ship heave (>5 m), and the site was finally abandoned as weather conditions worsened. The shipboard magnetic stratigraphy was only interpretable in one hole (U1312B), and in this hole only back into the Matuyama Chron, to ~2 Ma. Shore-based magnetic studies have improved the fidelity of the magnetic record over the last ~2 m.y., and RPI proxies in this interval have been correlated to other records from the North Atlantic (**Kanamatsu et al.**).

In view of the high-quality magnetic data acquired from Site 608 (Clement and Robinson, 1987; Krijgsman and Kent, 2004), the lack of interpretable magnetic stratigraphy prior to ~2 Ma for the section recovered during Expedition 303/306 must be attributable to core quality, although this disturbance is not always visually apparent according to shipboard core descriptions. The lack of a complete composite section and magnetic stratigraphy beyond the last ~2 m.y. will inhibit further work on cores recovered from Site U1312.

Site U1313

Site U1313 is a reoccupation of Site 607, drilled in 1983 during Leg 94. The rationale for reoccupying this site is essentially the same as that for Site 609 (Site U1308). Together, Sites 609 and 607 constitute benchmark sites for the long-term (millions of years) surface and deep ocean climate records from the subpolar North Atlantic (Ruddiman et al., 1986, 1989; Raymo et al., 1989). Leg 94 drilling of this site preceded the shipboard capability for construction of composite sections and pass-through magnetometers for continuous measurement of magnetic parameters, and the objective was to recover a complete composite section and generate a high-resolution stratigraphic record.

Four holes were drilled at Site U1313, reaching a maximum depth of 308 mbsf and providing the means of constructing an apparently complete composite section back into the late Miocene (~6 Ma) at mean sedimentation rates of ~5 cm/k.y. for the Pliocene–Quaternary and perhaps as high as ~13–14 cm/k.y. for the upper Miocene. The Holocene to upper Pliocene sediments are composed of nannofossil ooze and silty clay nannofossil ooze. Below these sediments, the Pliocene to upper Miocene sediments are homogeneous nannofossil oozes with high (>90 wt%) carbonate values.

Shipboard correlation among holes was unambiguous in the upper 168 m, based largely on sediment color/reflectance data that mimic the marine oxygen isotope curve (Stein et al., 2006). The homogeneity of the nannofossil oozes below this level resulted in less secure hole-to-hole correlations. The shipboard magnetic stratigraphy is interpretable through most of the Gauss Chron to ~150 mbsf. Below this depth, the magnetic stratigraphy is hampered by low magnetization intensities, although postcruise U-channel studies have helped to resolve the magnetic stratigraphy through the Gilbert Chron and into the late Miocene (Evans et al., 2006).

Diatom flora are present within the upper ~70 mbsf (Pliocene–Pleistocene interval). Calcareous nannofossils are abundant and moderately well preserved to well preserved, and a complete succession of nannofossil datums has been determined for the upper 158 mbsf, to ~3 Ma (**Hagino and Kulhanek**). **Sierro et al.** studied Pliocene–Pleistocene planktonic foraminifer events at this site and assigned ages using the correlation of sediment color/reflectance data to an oxygen isotope reference curve. These ages have been compared with the same datums in the Mediterranean where calibration was previously achieved through astrochronology. An oxygen isotope stratigraphy has been generated from planktonic and benthic foraminifers for part of the record, specifically the MIS 10–16 interval (Voelker et al., 2009, 2010), providing both chronological control and information about surface and deep water conditions. Planktonic and benthic oxygen isotope data, lithic fragment, and physical grain size data at Site U1313 indicate that major Heinrich-type ice-rafting events were associated with Terminations V and VII and with MIS 10 and 12 (Voelker et al., 2010). Lower benthic $\delta^{13}C$ values indicate weakened meridonial overturning circulation (MOC) and the presence of Antarctic Bottom Water during all glacial periods in this interval (MIS 10–16) with strong MOC during all interglacials.

First results from biomarker analyses, performed shipboard, indicate that alkenone-derived SSTs show variability from ~13° to 19°C during the Pleistocene (Stein et al., 2006). A few data points from the late Pliocene interval display SST values of ~17° to 22°C. With new shore-based data representing the 320–640 ka (MIS 9–16) interval, Stein et al. (2009) are able to compare SST variability, surface water productivity, and IRD deposition during the more severe glacials (MIS 16, 12, 10) with the weaker glacial MIS 14, and, on the other hand, the extreme interglacials

MIS 11 and the less extreme interglacial MIS 15 and 13. Alkenone-based SST reached an absolute maximum of ~19°C during MIS 11.3 and absolute minima of <10°C during MIS 12 and 10. Within MIS 11, prominent cooling events (MIS 11.22 and 11.24) occurred. The absolute SST minima, recorded directly before and after the glacial maxima MIS 12.2 and 10.2, are related to Heinrich-like meltwater pulses, as supported by the coincidence of SST minima with maxima in $C_{37:4}$ alkenones and dolomite (Fig. **F6**). Based on these data, ice sheet disintegration and subsequent surges and outbursts of icebergs and meltwater discharge appear to have been triggered by increased insolation forcing at high northern latitudes (Stein et al., 2009).

Ferretti et al. (2010) documented the MIS 20–23 interval at Site U1313 using $\delta^{18}O$ from both benthic and planktonic foraminifers. MIS 21 can be broken into four interstadial periods that can be correlated to other North Atlantic isotopic records from Site U1308 (Hodell et al., 2008), Site 983 (Channell and Kleiven, 2000), and ODP Site 1063 (Ferretti et al., 2005). These variations in MIS 21 are evident in both the planktonic and benthic isotope records, although they are more muted in the benthic records. Ferretti et al. (2010) matched these variations to insolation variations at the Equator and suggested a forcing mechanism related to low-latitude precession variations and advection to high latitudes by tropical convective processes.

Site U1314

The objective of drilling Site U1314 was to obtain a deepwater record of past oceanographic conditions to compare to deepwater Site U1304 from the southern Gardar Drift and the intermediate depth site on the northern part of the Gardar Drift sampled during Leg 162 at Site 983. Site U1314 is located north of Site U1304 in the southern Gardar Drift (Fig. **F1**), at a water depth of 2820 meters below sea level (mbsl), and just north of the Ruddiman (1977) IRD belt. As at Site U1304, the stratigraphic record at Site U1314 will allow high-resolution monitoring of NADW variability and ice sheet instability over the last ~3 m.y.

Three holes were drilled at Site U1314 using the APC system to a maximum depth of 280 mbsf. Hole-to-hole stratigraphic correlation was straightforward to 281 mcd (mid-Gauss Chron; ~3 Ma) using magnetic susceptibility and NGR, apart from one tenuous tie between Holes U1314B and U1314C at 25.90 mcd. The sedimentary sequence is composed of mainly greenish gray nannofossil oozes with clays, with abundant siliceous and calcareous microfossils. Calcium carbonate content ranges from <10 to >70 wt%, with an average of 34 wt%, and the variations are in step with nannofossil abundance. A variability of 20–30 wt% in $CaCO_3$ around the mean persists throughout the entire section. Variations in sediment color/reflectance follow $CaCO_3$ variations but do not mimic an oxygen isotope record. Biogenic silica abundances, dominated by diatoms, reach 25% of visible grains in shipboard smear slides. Diatom-rich laminae, dominated by *Thalassiothrix*, recur periodically throughout the stratigraphic sequence. J. Grützner and S.M. Higgins (unpubl. data) have derived an orbital age model for Site U1314 by correlating sediment physical properties from this site with equivalent data from Site 983. Mean sedimentation rates are estimated at ~7–8 cm/k.y. in the Pleistocene and 11–12 cm/k.y. in the late Pliocene. The magnetic polarity stratigraphy is unambiguous to the Gauss Chron at ~3 Ma, and the fidelity of the magnetic record is exemplified by detailed study of the Gauss–Matuyama polarity transition (Ohno et al., 2008). The longer polarity subchrons (Jaramillo and Olduvai) and brief subchrons such as the Cobb Mountain and Réunion are recorded.

Rich nannofossil (**Hagino and Kulhanek**), radiolarian, and planktonic foraminifer and diatom (see the **"Site U1314"** chapter) assemblages occur throughout the sedimentary sequence and are suitable for reconstruction of SSTs for the late Pliocene–Pleistocene interval. Benthic foraminifers (see the **"Site U1314"** chapter) and ostracodes (**Alvarez Zarikian**) are diverse and generally well preserved. The good preservation of benthic microfossils makes this site suitable for developing a benthic isotopic record and reconstructing deep-sea environmental conditions. Alvarez Zarikian et al. (2009) studied the ostracode assemblage at this site over the past 170 k.y. and showed that changes in ostracode abundance, diversity, and assemblage composition are apparently linked to changes in deep sea water masses and glacial–interglacial cyclicity. The ostracod assemblage found during glacial stages comprises shelf and intermediate water Arctic/subarctic species, and abyssal North Atlantic species, which possibly reflect temporal shifts in the influence of high-nutrient southern source waters (e.g., Antarctic Bottom Water) and low-nutrient waters (e.g., Glacial North Atlantic Intermediate Water) at these times. In contrast, interglacial ostracode assemblages are characterized by deep cosmopolitan species that are known to be associated with NADW and increased food supply to the sediments (Dingle and Lord, 1990; Cronin et al., 1999; Didié and Bauch, 2000). Glacial and interglacial ostracode assemblages found at Site U1314 show a strong affinity to those found on the Rockall Plateau (Didié and Bauch, 2000) and the mid-ocean ridge in the North Atlantic

(Cronin et al., 1999), but species diversity is higher during the last two glacial intervals at Site U1314. Initial results by Sorrell and Judge (2007) and Alvarez Zarikian et al. (2009) have shown that sediments at Site U1314 contain a record of ice-rafted debris that can be used for monitoring ice sheet instability and reconstructing the glacial climate history of the North Atlantic Ocean.

Site U1315

ODP Site 642 (Site U1315) is located on the Vøring Plateau in a water depth of ~1280 mbsl. The primary objective at this site is to document the bottom water temperature and salinity variations with instrumentation that sits in the water column attached to an elevated reentry cone. Hole U1315A was drilled to 179 mbsf and cased. The installed borehole observatory consists of a circulation obviation retrofit kit (CORK) to seal the borehole from the overlying ocean and instruments to monitor and document subbottom temperature variations. The instrumentation in Hole U1315A includes two pressure cases and a thermistor string. This configuration allows high-precision temperature measurements as a function of both depth and time. By analyzing subbottom temperature perturbations we expect to reconstruct, for the first time, a temperature record of bottom water during at least the last 100 y (i.e., going back in time far beyond the directly measured temperature records available up to now). This record will contribute significantly to the ongoing discussion about causes and consequences of oceanographic and climatic changes observed in the North Atlantic over the last few decades. After setting the CORK in the newly drilled Hole U1315A (Harris et al., 2006), temperature measurements were made in Hole 642E to compare with those acquired 20 y ago when the hole was drilled (see Eldholm et al., 1987). The comparison indicates fluid flowing from the basement, up the hole, and into the ocean at an estimated rate of 6–11 m/h and yields an estimated permeability of 10^{-13} m^2, reflecting relatively impermeable sediments overlying a relatively permeable basement (Harris and Higgins, 2008).

Conclusions

The overall objective of Expedition 303/306 is to generate high-resolution records of late Miocene-Quaternary North Atlantic environmental change that can be placed in a high-resolution stratigraphic framework based on oxygen isotope and RPI data.

Apart from Site U1312, where coring disturbance attributed to severe weather conditions contributed to poor preservation of the record, paleomagnetic records from Expedition 303/306 sites are of high fidelity. In general, polarity chrons are well defined in shipboard data. Two postcruise studies of the details of polarity transitions attest to the quality of the magnetic records (Ohno et al., 2008; Mazaud et al., 2009). Isotope records are still in development at most Expedition 303/306 sites, although a coupled isotope/RPI record has been published for Site U1308 for the last 1.5 m.y. (Hodell et al., 2008; Channell et al., 2008) and this stratigraphy has been augmented by detailed nannofossil stratigraphy at this site (**Sato et al.; Chiyonobu et al.**). The benthic isotope and RPI records at Site U1308 over the last 1.5 m.y. have high resolution and fidelity and provide the reference records for coupled RPI/isotope stacks generated by tandem correlation of isotope and RPI data from 13 globally distributed records (Channell et al., 2009b). The tandem correlations use the Match protocol (Lisiecki and Lisiecki, 2002) that allows repeatable correlations using penalty functions that can be set to inhibit abrupt sedimentation rate changes within the records. This is a first step toward generating a template for stratigraphic correlation at a resolution not obtainable from oxygen isotopes alone. This development is important for the study of millennial-scale environmental change because the lack of tools for stratigraphic correlation, at an appropriate resolution, is presently a severe impediment to the study of phenomena associated with short-term "abrupt" climate change.

The detrital layer stratigraphy at Site U1308 has been resolved using density, magnetic susceptibility and XRF scanning, specifically the Ca/Sr ratio, which is a valuable proxy for Hudson Strait–derived (Heinrich-type) detrital layers because of the low Sr content of inorganic (detrital) versus biogenic carbonate (Hodell et al., 2008). In addition, the distinctively lower $\delta^{18}O$ values for detrital carbonate, relative to foraminifer calcite, means that bulk carbonate $\delta^{18}O$ provides an additional means of recognizing detrital events (Hodell and Curtis, 2008). Low $\delta^{18}O$ values from planktonic foraminifer tests contaminated by adhered detrital carbonate may mimic meltwater events. Hudson Strait–derived Heinrich events, characterized by detrital carbonate, appear in MIS 8, 10, 12, and 16 but not, apparently, in MIS 6 or 14 (Hodell et al., 2008).

At Site U1313, Heinrich-type layers characterized by lithics with detrital carbonate occurred in glacial MIS 10, 12, and 16 as well as at Terminations V and VII (Stein et al., 2009; Voelker et al., 2010). High-resolution isotopic, alkenone, and XRD studies at Site U1313 in the 320–640 ka (MIS 9–16) interval have allowed detailed comparison of SST variability, surface water productivity, and IRD deposition in the central mid-latitude North Atlantic (Stein et al., 2009; Voelker et al., 2010). Peaks in dolomite and feldspars and associated maxima in land-plant derived *n*-alkanes are interpreted as indicators of Heinrich-like events related to instability of the LIS, especially during early and late stages of glacial intervals (Stein et al., 2009).

Hudson Strait–derived Heinrich-type detrital layers first appear in the sedimentary records at Sites U1308 and U1313 in MIS 16, approximately coincident with the end of the mid-Pleistocene climate transition between the so-called 41 and 100 k.y. worlds. Although iceberg survivability may play a role in the apparent onset of this IRD record, it is more likely that ice volume and glacial stage duration surpassed critical thresholds at that time that activated LIS instability (Hodell et al., 2008). Benthic $\delta^{13}C$ variations at Site U1308 support a link between iceberg discharge and weakening of thermohaline circulation.

Planktonic and benthic microfossils at Site U1314 have yielded valuable proxies for surface (radiolarian and calcareous nannofossils) and deep (ostracodes) water conditions in the North Atlantic. Radiolarian assemblages indicate warm SSTs during MIS 6 relative to other Brunhes glacial stages (K.R. Bjørklund et al., unpubl. data), whereas ostracode assemblages and species diversity can be associated with changes in deep ocean circulation and climate variability (Alvarez Zarikian et al., 2009).

The results from Sites U1308, U1313, and U1314 are a foretaste of what will be forthcoming from the group of sites occupied during Expedition 303/306. The preliminary data indicate that all sites have the attributes to provide records of North Atlantic environmental change that can be placed in a chronological framework based on oxygen isotope data and RPI.

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Figure F1. Location of sites occupied during IODP Expedition 303/306.

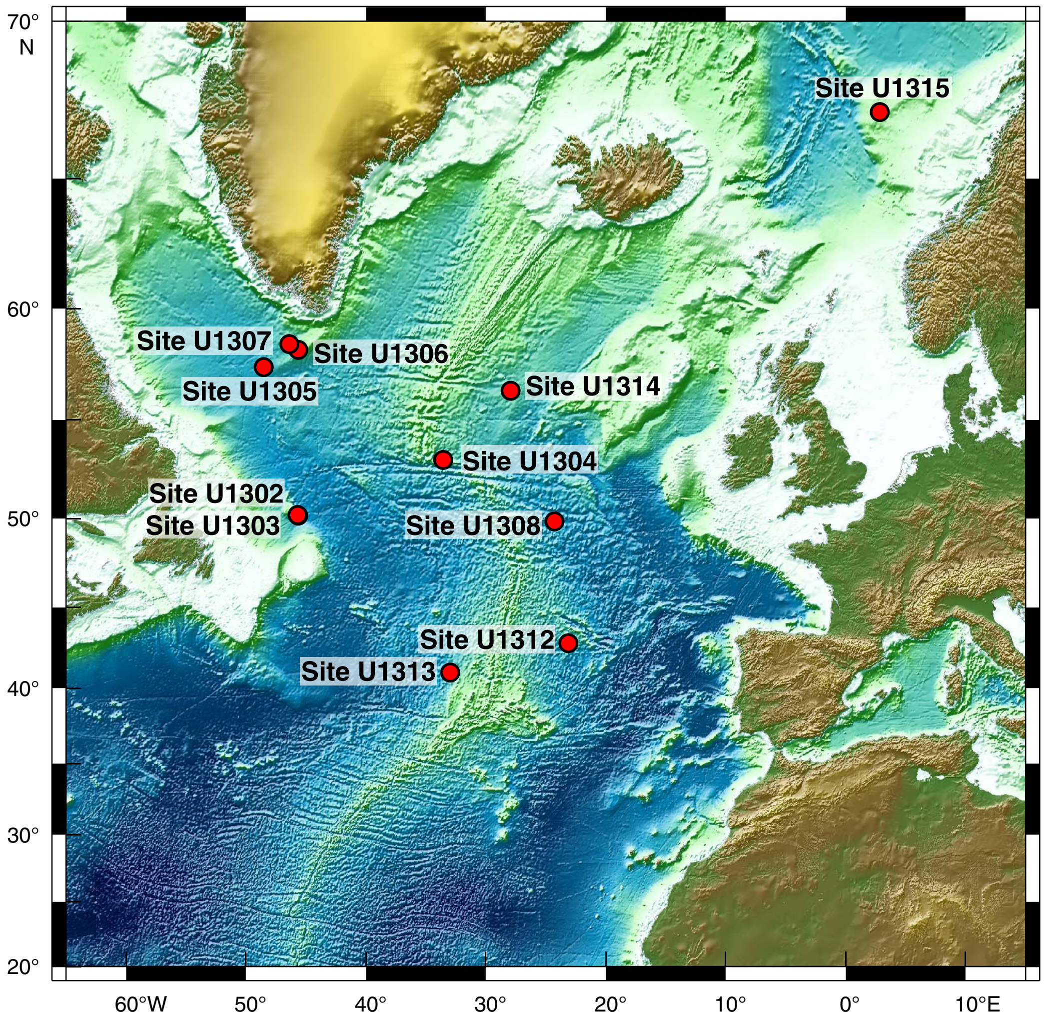

Figure F2. Summary of stratigraphies at sites occupied during IODP Expeditions (**A**) 303 and (**B**) 306, excluding Site U1315. IRD = ice-rafted debris. Blue = nannofossil-based tie lines, red = magnetostratigraphic tie lines. In polarity columns, black = normal polarity, white = reversed polarity, hatched or gray = indeterminate polarity. TD = total depth. (**Continued on next page.**)

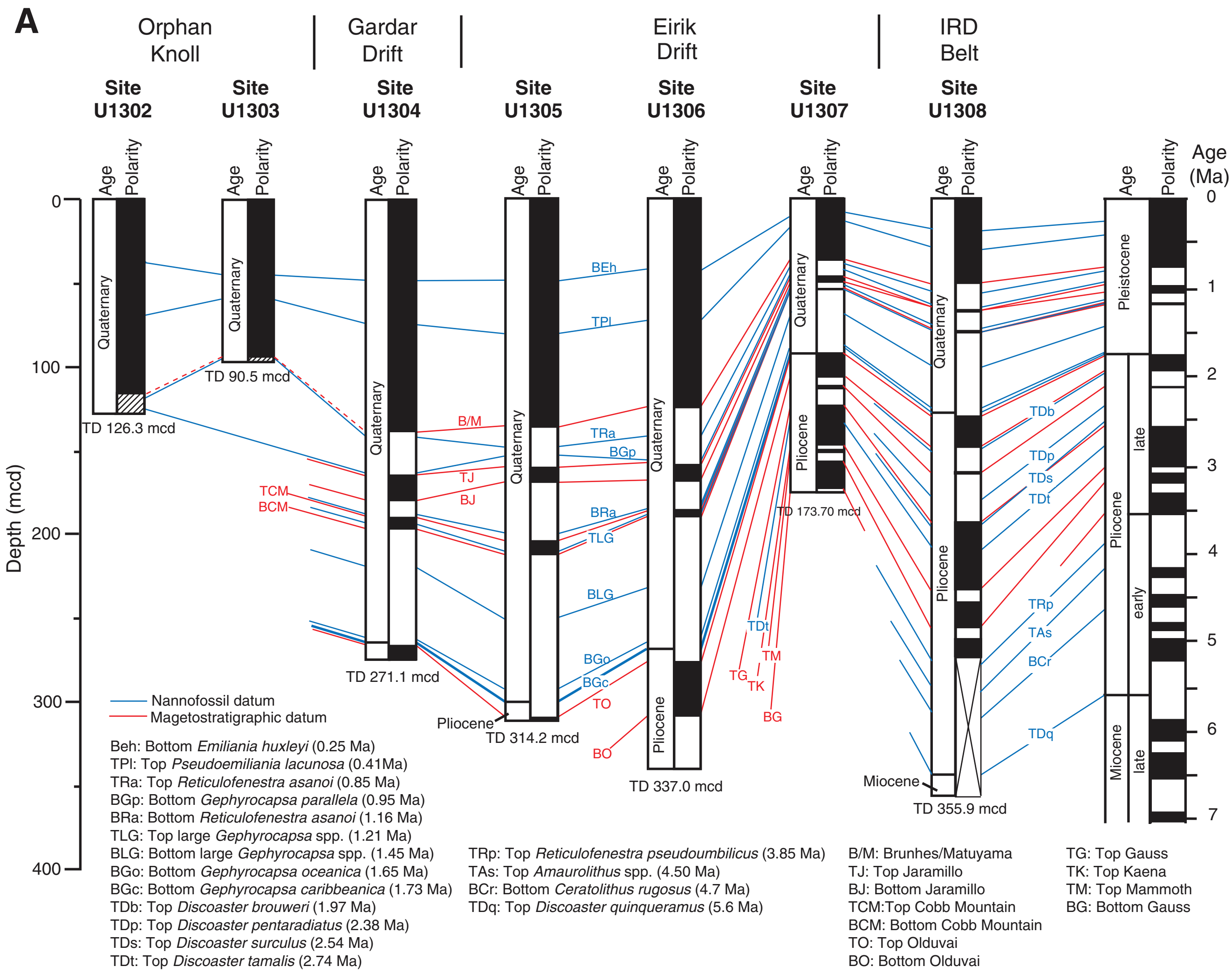

Figure F2 (continued).

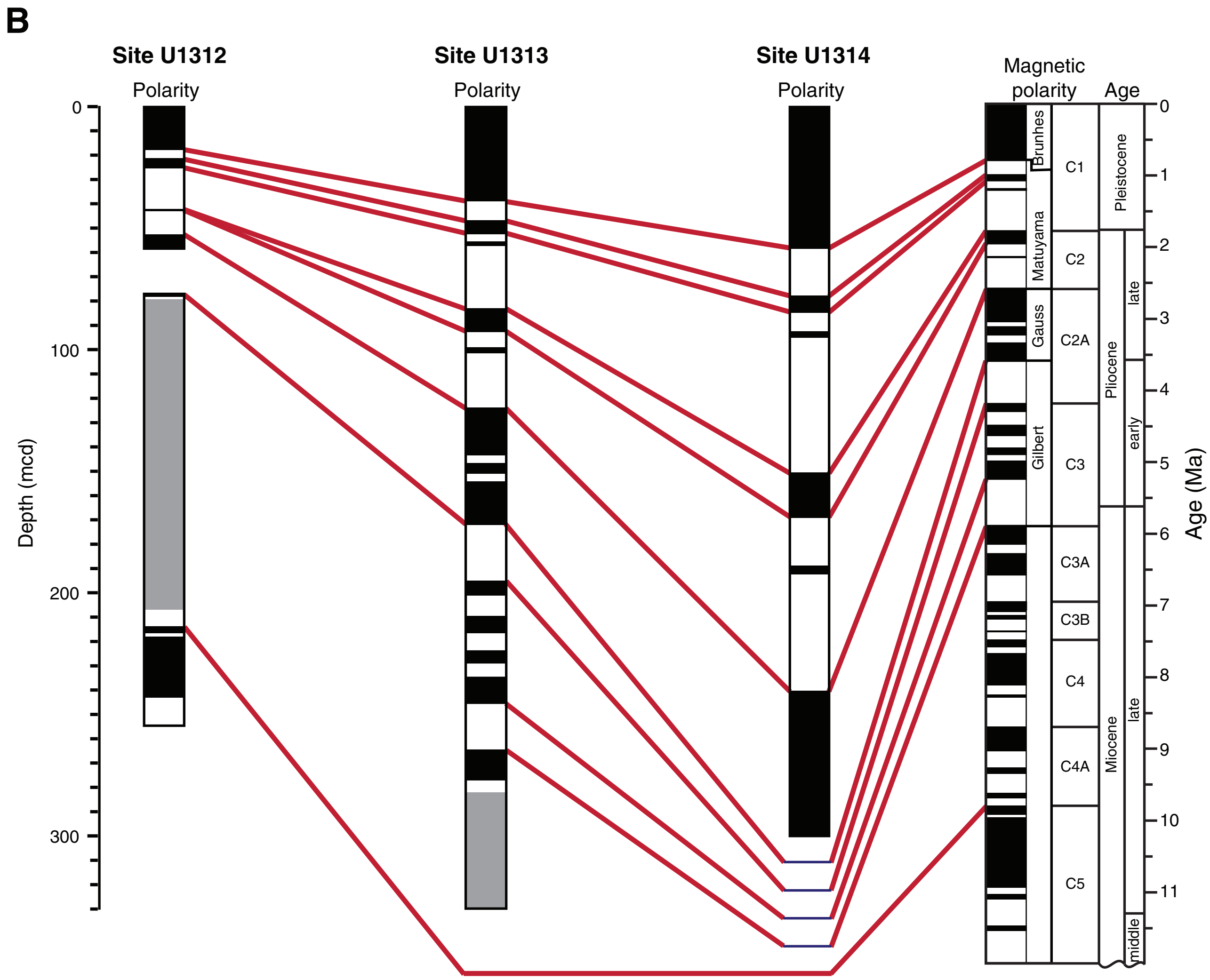

Figure F3. Comparison of percent detrital carbonate (red) and ratio of lithics to foraminifers (light green) at DSDP Site 609 (Bond et al., 1992) with XRF scanning Ca/Sr (blue) and Si/Sr (black), magnetic susceptibility (dark green), and bulk carbonate $\delta^{18}O$ (gray) at Site U1308. Figure from Hodell et al. (2008). H1–H6 = Heinrich Events.

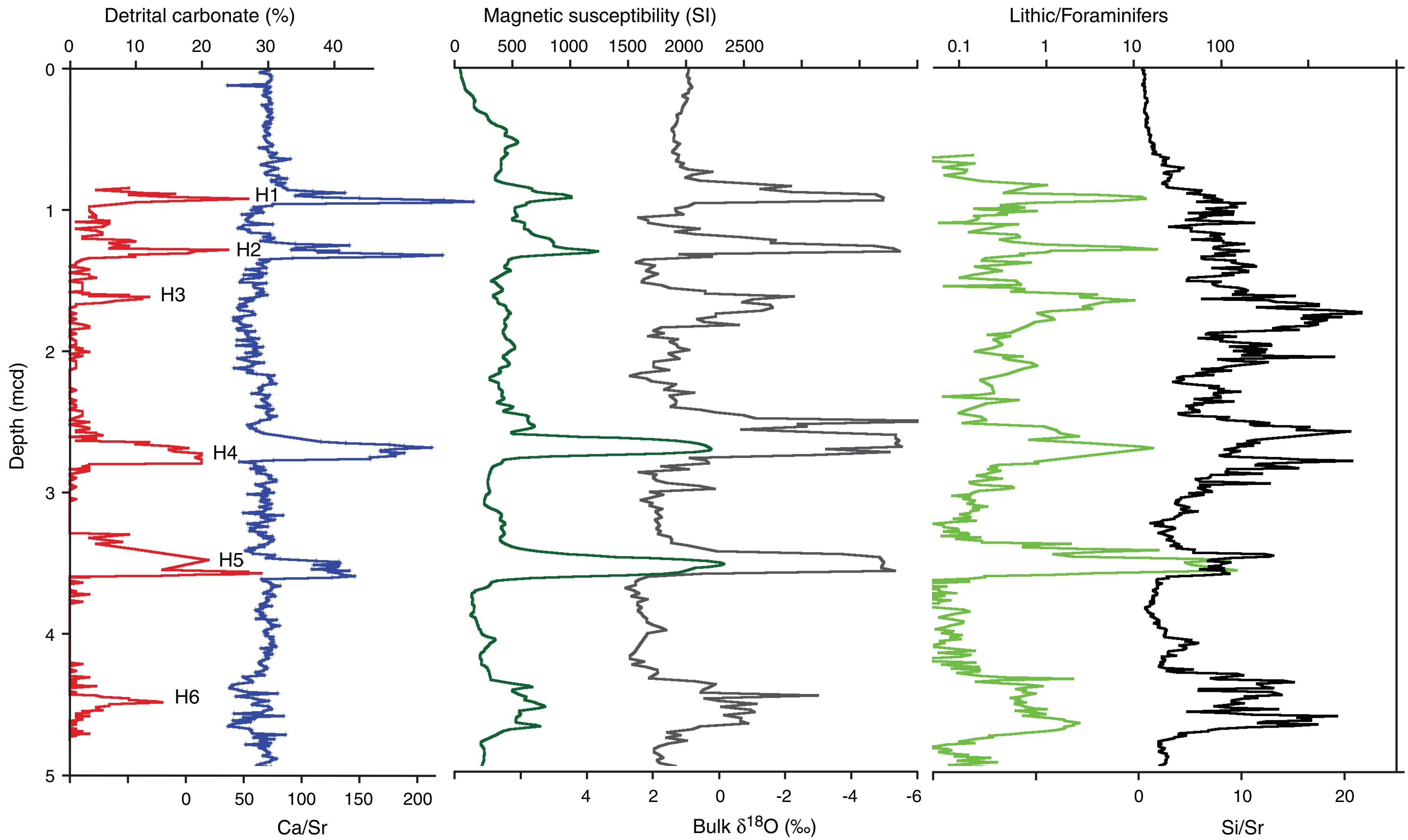

Figure F4. Magnetic susceptibility (gray), gamma ray attenuation (GRA) density (dark green), Ca/Sr (red) and Si/Sr (blue) from XRF scanning, and bulk carbonate δ^{18}O (black) and benthic δ^{18}O (light green, with glacial MIS labeled) for the last 1.4 m.y. Detrital carbonate layers, marked by peaks in Ca/Sr, first occurred in MIS 16 at ~640 ka. Figure from Hodell et al. (2008).

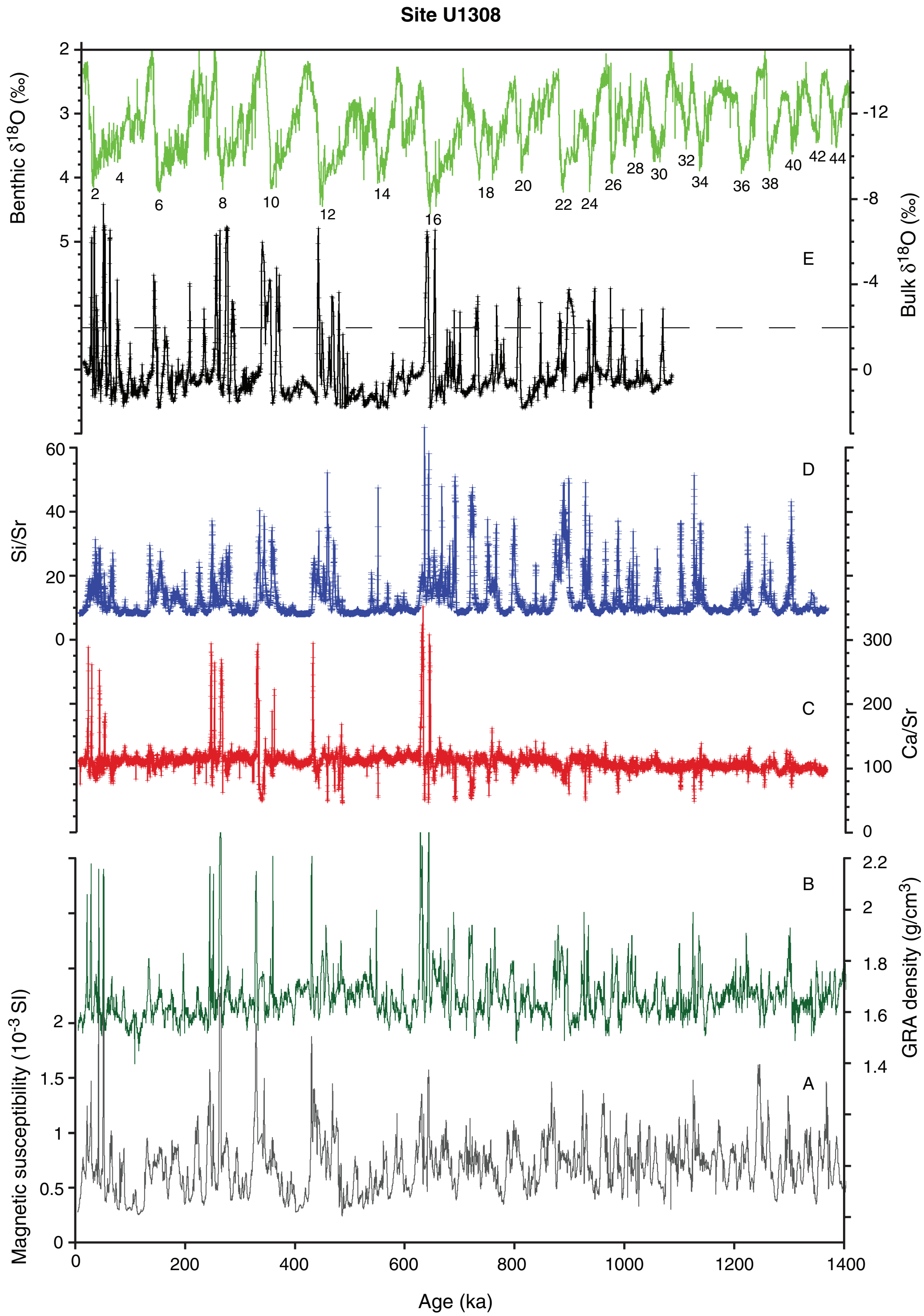

Figure F5. A. Linear correlation coefficients for slopes of natural remanent magnetization (NRM) versus anhysteretic remanent magnetization (ARM) during alternating-field demagnetization (red) and NRM demagnetization versus ARM acquisition (ARMAQ) (blue) that constitute the RPI proxies. **B.** Component inclination of NRM. **C.** Benthic $\delta^{18}O$ record (red) correlated to the Lisiecki and Raymo (2005) stack (blue) by Hodell et al. (2008). Glacial MIS are labeled. **D.** Slopes of NRM/ARM (red) and NRM/ARMAQ (blue) for the 20–60 mT demagnetization and acquisition interval that constitute RPI proxies. Figure from Channell et al. (2008).

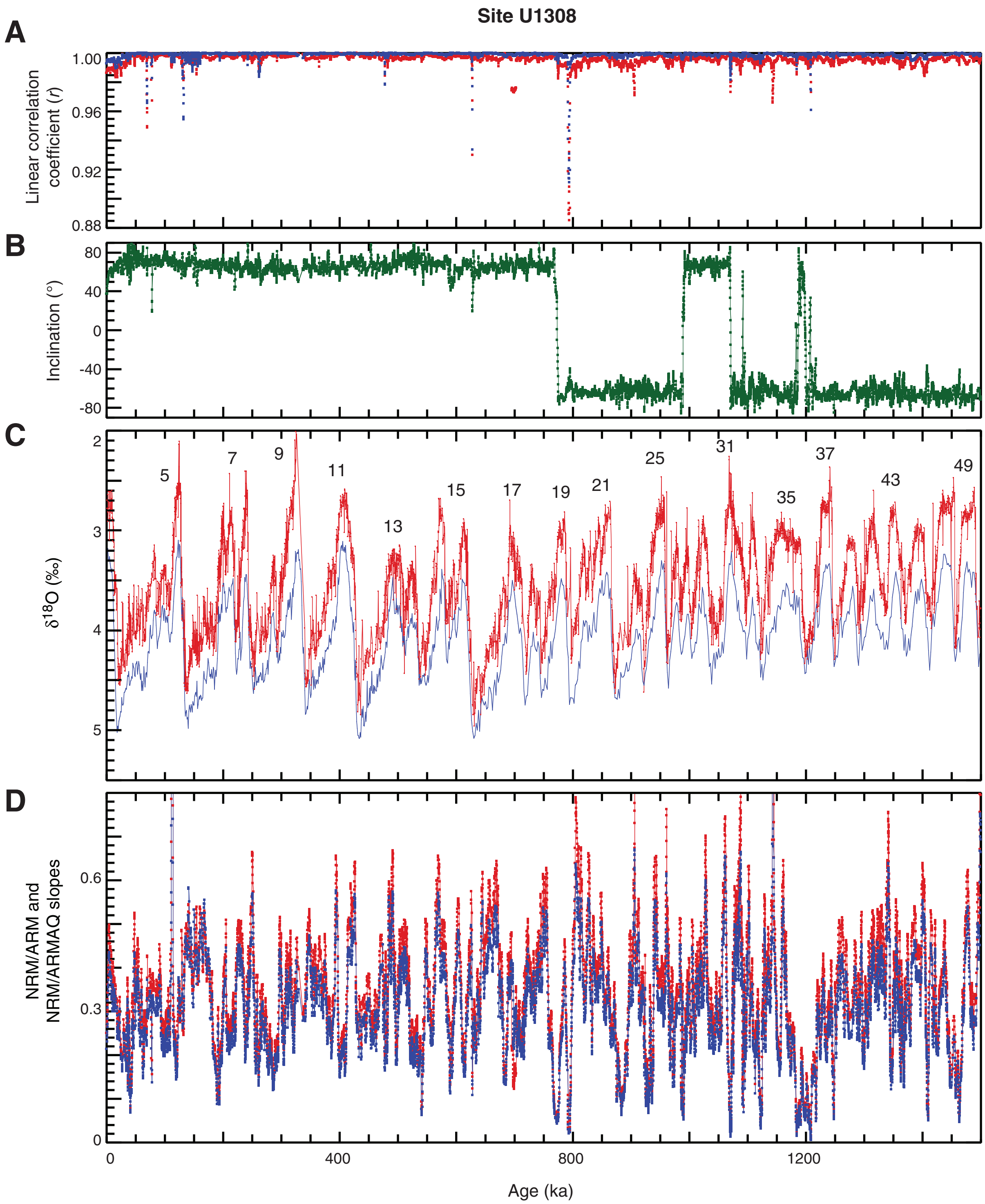

Figure F6. Three-point moving averages of total organic carbon (TOC), calcium carbonate ($CaCO_3$), relative (rel.) XRD intensities for dolomite, and alkenone-based sea-surface temperatures (SST). Global benthic isotope stack from Lisiecki and Raymo (2005). Marine isotope stage (MIS) and substage numbering from Bassinot et al. (1994). T = Termination. Orange rhombs indicate occurrence of Heinrich-like events (HE) at Site U1308 (from Hodell et al., 2008). Modern SST (from Locarnini et al., 2006) and estimated SSTs for MIS 2 and 6 are indicated. Figure from Stein et al. (2009).

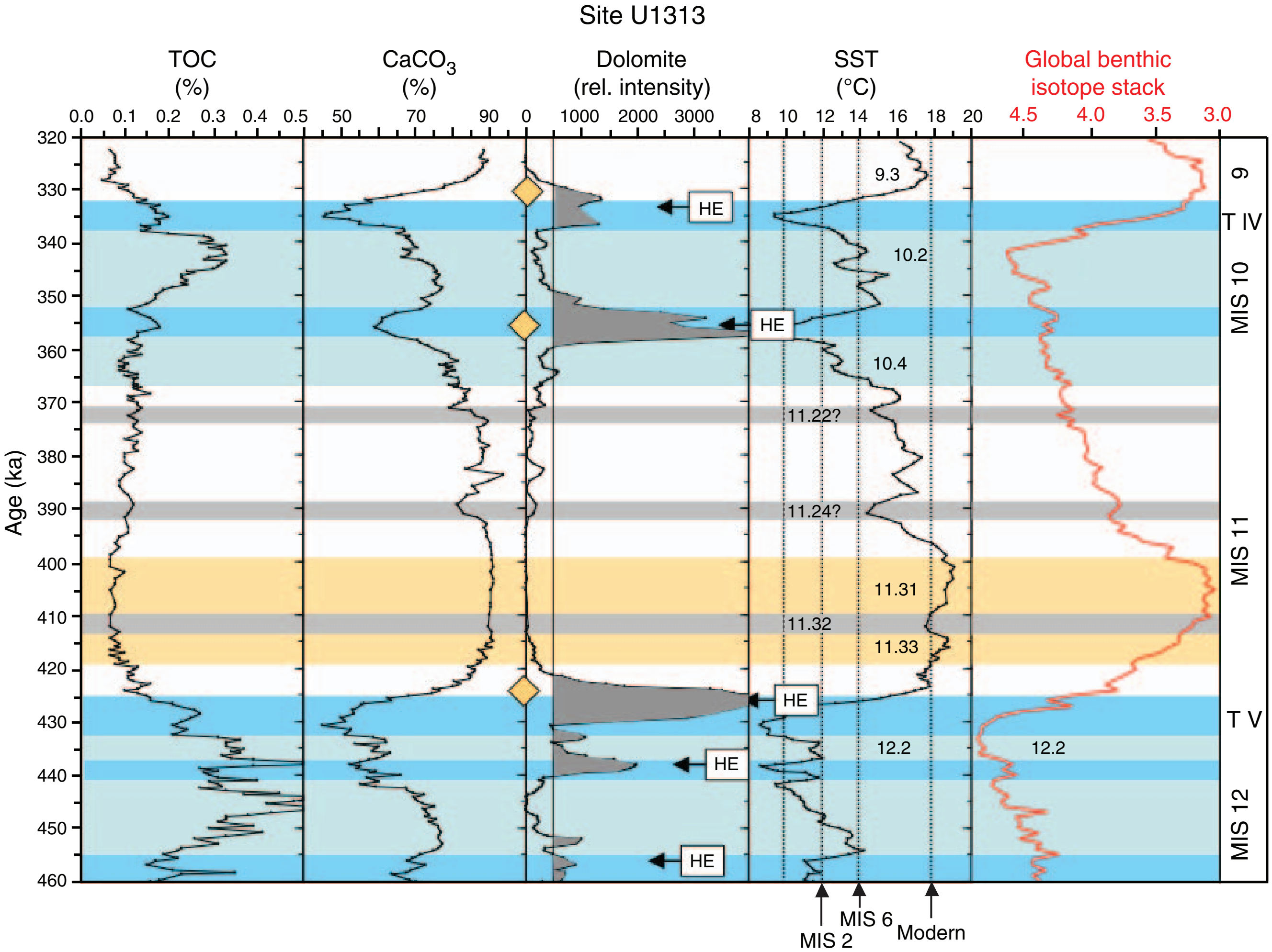

Table T1. Composite section depths and ages. (See table note.)

Site	Location		Water depth (mbsl)	Total depth (mbsf)	Composite depth (mcd)	Maximum composite age (ka)
	Latitude	Longitude				
U1302/U1303	50°10′N	45°38′W	3555	107	104	~750
U1304	53°3.4′N	33°31.7′W	3065	243	199	~1300
U1305	57°28.5′N	48°31.8′W	3518	287	303	~1600
U1306	58°14.2′N	45°38.5′W	2273	309	337	~2100
U1307	58°30.3′N	46°24′W	2575	162	56	~1200
U1308	49°52.7′N	24°14.3′W	3871	341	247	~3400
U1312	42°50.2′N	23°5.2′W	3554	248	0	NA
U1313	41°0.1′N	32°57.4′W	3426	308	301	~6700
U1314	56°21.9′N	27°53.3′W	2820	280	281	~2800
U1315	67°12.7′N	2°56.2′E	1280	179	NA	NA

Note: NA = not applicable.