IODP Expedition 400: NW Greenland Glaciated Margin

Site U1604 Summary

Background and Objectives

Site U1604 (proposed Site MB-02C) was cored on the lower slope below the Melville Bugt trough mouth fan (TMF) at a water depth of 1943 m at 73°6.9077′N, 63°47.3996′W, 16 nmi northwest of Site U1603. The site targeted a high-resolution sediment drift sequence hypothesized to represent interactions between bottom contour currents and sediments supplied by northern Greenland Ice Sheet (NGrIS) fluctuations from the Early/Middle Pleistocene (up to 1 Ma) to present. Selection of Site U1604 was guided by regional 2D and high-resolution seismic data from where 10 horizons have been mapped that, with the inclusion of the seabed, define 11 seismic units of the prograded TMF system (Knutz et al., 2019). The strategy was to core through the youngest Seismic Units 9, 10, and 11, to capture the expanded depositional sequence within Seismic Unit 8 which shows stratified intervals with asymmetric geometries resembling contourite drifts. Site U1604 cores overlap stratigraphically with Site U1603. The main scientific objective is to test the hypothesis that the NGrIS underwent significant deglaciation at intervals within the frequency range of orbital eccentricity (~100–400 ky) and to assess recent models for the change in orbital cycles through the mid-Pleistocene transition (Clark and Pollard, 1998; Schaefer et al., 2016).

Coring was planned in two holes with a target depth to 432 m core depth below seafloor, Method A (CSF-A) in both holes using the advanced piston corer/half-length advanced piston corer (APC/HLAPC) and extended core barrel (XCB) coring systems. Downhole logging with the triple combo, Versatile Seismic Imager (VSI), and Formation MicroScanner (FMS) with sonic was planned for Hole U1604B.

Operations

Hole U1604A

The vessel transited 16 nmi to Site U1604, arriving on location at 0306 h on 3 September 2023. The thrusters were lowered and secured at 0324 h and the ship was fully in dynamic positioning (DP) mode at 0337 h. The rig crew made up an APC/XCB bottom-hole assembly (BHA) and began tripping the drill pipe. Hole U1604A was spudded at 1020 h and Core U1604A-1H recovered 2.04 m. The seafloor was calculated as 1942.2 meters below sea level (mbsl). Cores U1604A-1H to 26H advanced from 0 to 206.8 m CSF-A and recovered 195.34 m (96%). Formation temperature measurements were made on Cores 4H, 7H, 10H, and 13H.

We switched to the HLAPC coring system; however, Core U1604A-27F only recovered 2.85 m after a partial stroke. We then switched to the XCB coring system and Cores U1604-28X to 30X advanced from 209.6 to 233.0 m CSF-A and recovered 23.71 m (103%). At 1930 h on 4 September, ice moved within 3 nmi of the vessel and we raised the drill string to 16.2 m CSF-A by 2045 h and began waiting on ice (WOI). By 2300 h the ice had moved a sufficient distance away from the vessel.

The drill string was lowered back into Hole U1604A and washed back to 233.0 m CSF-A by 0100 on 5 September. Cores U1604A-31X to 32X advanced from 233.0 to 250.6 m CSF-A and recovered 11.05 m (63%). At 0430 h ice moved within 3 nmi of the vessel and we raised the drill string to 16.7 m CSF-A by 0545 h and began WOI. Ice then entered the 1 nmi exclusion zone and we raised the drill string, clearing the seafloor at 0715 h, ending Hole U1604A. The vessel was moved 700 m north and then 700 m west to maintain a safe distance from the ice.

Hole U1604B

By 1600 h, on 5 September we began to move back toward the site and the vessel was in position over Hole U1604B (20 m northeast of Hole U1604A) by 1630 h. Hole U1604B was spudded at 1755 h and the seafloor established as 1943.6 mbsl. Cores U1604B-1H to 14H advanced from 0 to 105.3 m CSF-A and recovered 98.14 m (93%). However, Core 14H only recovered 0.2 m of material. An XCB core barrel was dropped and Core 15X advanced from 105.3 to 105.5 m CSF-A and recovered 0.22 m of hard material. We then switched back to APC coring and Cores 16H to 22H advanced from 105.5 to 163.1 m CSF-A and recovered 59.68 m (103%). Cores 21H and 22H were only partial strokes, so we switched to the HLAPC system for Core 23F which advanced from 163.1 to 167.9 m CSF-A and recovered 4.78 m (100%). We switched back to APC coring and Cores 24H to 30H advanced from 167.9 to 216.8 m CSF-A and recovered 49.87 m (102%). We then switched to the HLAPC coring system and Cores U1604B-31F to 35F advanced from 216.8 to 237.6 m CSF-A and recovered 16.89 m (83%). With ice still in the general area we decided to install a free-fall funnel (FFF) to allow us to complete coring and logging of the site in Hole U1604B. The FFF was deployed at 1530 h on 7 September, and by 1630 h we resumed coring Hole U1604B. Cores U1604B-36X to 55X advanced from 237.6 to 429.6 m CSF-A and recovered 88.25 m (46%).

Sepiolite (drilling mud) was swept into the hole and heavy barite mud was added in preparation for logging Hole U1604B. The drill string was tripped up and the end of pipe set at 58.7 m CSF-A. The modified triple combo tool string was rigged up by 0100 h on 9 September and deployed to the base of Hole U1604B. Following a complete pass of the hole the quad combo was pulled to the rig floor and broken down. The FMS (without sonic) was then assembled and deployed at 0640 h. The FMS was run and the tools were back on deck by 1200 h. The planned VSI logging run was abandoned due to time constraints and difficulties experienced at Site U1603 with the tool in a similar lithology. With logging complete we tripped the pipe out of Hole U1604B, clearing the rig floor at 1720 h. The drill floor was secured for transit and the thrusters were raised and secured for transit at 1824 h on 9 September, ending Hole U1604B and Site U1604.

Principal Results

Lithostratigraphy

The sediments recovered at Site U1604 are divided into three lithostratigraphic units with named sedimentary lithofacies including massive mud, weakly stratified mud, calcareous mud, thinly laminated mud, interlaminated sand and mud, and gravel-bearing sediment. Lithostratigraphic Unit I (LSU I) comprises the upper ~210 m CSF-A of this site, and all lithofacies are present in various proportions. LSU I is subdivided in LSU IA and LSU IB. LSU IA is ~110 m thick and contains the massive mud, weakly stratified mud, and laminated mud lithofacies with interbeds of calcareous mud and gravel-bearing sediment. The underlying unit, LSU IB, has a larger proportion of interlaminated sand and mud and has relatively fewer outsized clasts (>2 mm diameter). LSU II is dominated by laminated mud and diamicton, often occurring as decimeter-scale interbeds. The laminated mud lithofacies continues to be characteristic downhole into LSU III, which is characterized by a significant reduction in sand laminae and gravel-bearing sediment compared to LSU II. Overall, the sedimentary succession recovered at Site U1604 is consistent with a glaciated continental slope environment with inputs from a combination of hemipelagic, contour current, and rare downslope processes, and likely ice rafting (providing granule- to boulder-sized clasts) and plumites.

Micropaleontology

Core catcher samples and additional split-core samples from the 32 cores of Hole U1604A and 21 of the cores from Hole U1604B were examined for foraminifera, diatoms, dinocysts, and other palynomorphs. A special sampling scheme involving catwalk samples from section ends and freshly split cores was adopted to provide uncontaminated samples for sedimentary ancient DNA (sedaDNA) from the APC/HLAPC cores of Hole U1604B (through Core U1604B-35F). Core catcher samples were not collected from the upper 35 cores of Hole U1604B because they represent a copy of the first ~240 m CSF-A of material cored in Hole U1604A. The additional samples were taken within intervals of muds and muds with dispersed clasts, avoiding interlaminated mud and sand lithologies. Mudline samples from Hole U1604A were also examined for microfossils. Observations of foraminifera from palynomorph and diatom slide preparations were integrated in the overall foraminifera evaluations. The muds and interlaminated sands and muds typical of Site U1604 are generally barren of microfossils, apart from occasional horizons where rare to few microfossils are found among the clast-rich lithologies. Where foraminifera appear, they remain as trace to rare occurrences, except for a few discrete intervals where they are rare to common in >63 µm residues. Juvenile foraminifera were observed in palynomorph 10 µm-sieved preparations. Diatoms were found in ~5% of all samples examined with specimens presenting as fragments or few individuals. Palynomorph preparations revealed generally low abundances of in situ dinocysts and varying abundances of reworked terrestrial and marine palynomorphs. The observed microfossil specimens and assemblages for all groups are consistent with a Pleistocene age. The observed taxa have long stratigraphic ranges and thus provide limited age control. Specimens and assemblages of all groups are typical of cold-water, polar environments.

Paleomagnetism

Pass-through paleomagnetic measurements from Site U1604 were performed using the superconducting rock magnetometer (SRM) to investigate the natural remanent magnetization (NRM) on a total of 389 archive section halves (157 from Hole U1604A and 91 from Hole U1604B). Measurements were not made on archive section halves that had highly disturbed sediments or on core catcher sections. All measurements on section halves were made at 2 cm intervals, up to a peak alternating field (AF) demagnetization of 20 mT. A total of 248 discrete cube samples were taken from the working section halves. Discrete samples were measured on the SRM or the JR-6A spinner magnetometer. Generally, one sample per core section was collected, avoiding visually disturbed intervals, and filling in gaps where the other hole did not have recovery. Anhysteretic remanent magnetization (ARM) was measured on a subset of 29 discrete samples from Hole U1604A. This subset of samples was demagnetized to 100 mT on all three axes prior to measuring the remanence. An ARM was imparted with a peak 100 mT AF and 50 μT DC (direct current) field and the remanence was measured. Comparison of the ARM with volume-normalized bulk magnetic susceptibility (MS) shows a quasilinear relationship between ARM and MS, suggesting that the concentration of magnetic minerals is the primary control on both measurements and supports the use of normalized remanence for estimating relative paleointensity.

Physical Properties

Physical property data were acquired on all cores of Holes U1604A and U1604B using the Whole-Round Multisensor Logger (WRMSL) for wet-bulk density from gamma ray attenuation (GRA), MS, and *P*-wave velocity (PWL). We also measured natural gamma radiation (NGR) in all sections longer than 50 cm. Thermal conductivity was measured in one whole-round section per core, when possible, from Hole U1604A and below 250 m CSF-A in Hole U1604B. Thermal conductivity was measured on the working-half sections if the sediment was too hard or the whole-round measurement readings were unreliable. In the upper 250 m CSF-A of Hole U1604B, only NGR and low-resolution MS were logged. Cores U1604B-1H to 35F constitute a replica of Hole U1604A so equilibration to room temperature and GRA measurements were avoided in the interest of stratigraphic correlation and sedaDNA sampling. Thus, PWL measurements were not made and the GRA source was kept inactive during the WRMSL logging.

X-ray imaging was acquired on the archive halves of every core. The Section Half Multisensor Logger (SHMSL) was used to measure point MS and color reflectance using the L*, a*, b* color system as well as red-green-blue color space (RGB) of the sediments with the Section Half Imaging Logger (SHIL). In addition, we determined *P*-wave velocities at discrete points on the working section halves for almost all cores at Site U1604. *P*-wave velocities were measured in variable intervals to accommodate lithological variations, but in general were measured on three sections per APC core and two sections per core on HLAPC and XCB cores. To compensate for gaps in PWL measurements, caliper measurements of *P*-wave velocity (PWC) were measured in all the sections of Cores U1604B-1H to 35F. Two samples per core for moisture and density (MAD) were taken and processed for Hole U1604A, and from Core U1604B-36X to the bottom of the hole to obtain discrete wet-bulk density, dry-bulk density, grain density, and porosity. No MAD samples were taken on Cores U1604B-1H to 35F.

Prominent variations in physical property values occur at similar depths in NGR, density and MS signals, and are associated with major lithological changes in the cores. NGR values oscillate between 32 and 100 counts/s with a mean of 75 counts/s. *P*-wave velocities range from 1455 to 1829 m/s and gradually increase downhole. MAD density values range from 1.4 to 2.1 g/cm^3, with a mean of 1.9 g/cm^3 and with an overall downhole increase, and the average porosity of Site U1604 is 48%.

Geochemistry

Samples for headspace gas, interstitial water (IW) chemistry, and bulk sediment geochemistry were analyzed at Site U1604. Headspace hydrocarbon gas concentrations are low in the upper 200 m CSF-A and higher concentrations of methane, with a low yet consistent presence of ethane, are present in sediment below 200 m CSF-A. The main findings from IW analysis include decreases in lithium and potassium with depth. A monotonic decrease in sulfate with depth to a minimum at ~200 m CSF-A provides evidence for a sulfate–methane transition zone. IW iron, manganese, and phosphate concentrations are elevated near the seafloor and sharply decrease to low concentrations with depth (below ~20 m CSF-A). Increases in IW calcium and alkalinity in the upper ~25 m CSF-A may indicate dissolution of calcium carbonate minerals. Elemental analysis of solid material revealed overall low concentrations of carbon and nitrogen across most intervals, albeit individual layers were rich in calcium carbonate ($CaCO_3$) with contents of up to 60%.

Stratigraphic Correlation

Sequences from Hole U1604A were examined using NGR data measured on 10 cm intervals and whole-round MS measured at 2 cm resolution with the WRMSL. In addition, 10 cm interval NGR data and 5 cm resolution MS data were measured on sections from Hole U1604B and examined in near real time to ensure adequate coring depths to fill the gaps in Hole U1604A. Since triple APC offset coring was not planned at Site U1604, a splice for this site was not completed. Recovery gaps commonly overlap between Holes U1604A and U1604B. The difficulty was further magnified by the deformation related to XCB coring. Thus, Holes U1604A and U1604B were correlated to the extent possible, but they were mostly aligned based on the mudline.

The top of Hole U1604A (which preserved a mudline) served as the anchor (zero depth point) for the generation of the core composite depth below seafloor (CCSF-A) depth scale at this site. From this reference, the relative core depths were determined by establishing depth offsets, or affine ties, between cores from the two holes based on optimized correlation of WRMSL-derived MS and NGR data. The upper part of the sequence is tied through Cores U1604A-1H to U1604B-2H, Cores U1604A-3H to U1604A-6H, and Cores U1604A-7H to U1604B-10H. Below, the cores are placed on a relative depth to each other. Core disturbances, shattered core liners, and other issues impacting core quality meant that the stratigraphic coherence of the recovered sequence recovered was variable. Below 223 m CSF-A in Hole U1604A, NGR and MS are less coherent, which makes the stratigraphic correlation of the lowermost overlapping section dubious. In summary, it is not possible to build a complete CCSF-A depth scale for Site U1604. The high recovery and core alignment between Holes U1604A and U1604B allows for the construction of a preliminary CCSF-A depth scale, but the gaps between cores are unknown. Downhole logging data may potentially be used to improve the depth accuracy of these cores.

Age Model

The age model for Site U1604 is based on magnetostratigraphic interpretations of Holes U1604A and U1604B. The upper ~138 m CSF-A of sediment is characterized by normal polarity (Zone N1), and is interpreted as the Brunhes Chron (C1n; 0–0.773 Ma, Ogg, 2020). From this identification, we estimate an average sediment accumulation rate of ~17 cm/ky during the Brunhes Chron. In addition, within the Brunhes Chron there are a number of decreases in relative paleointensity (DIPs). The DIPs are calculated from the normalized remanence (NRM_{20mT}) divided by MS. Seven well-defined DIPs in the Site U1604 relative paleointensity (RPI) record correlate well with the Paleomagnetic Dipole Moment for the last 2 My (PADM2M) constructed by Ziegler et al. (2011). Using the PADM2M tie points, it is possible to predict where the marine isotopic stages of the LR04 stack of Lisiecki and Raymo (2005) are in Site U1604.

The age model below ~138 m CSF-A is based on the inclinations. The normal polarity zone below 245 m CSF-A in Hole U1604B (Zone N2) is not well constrained due to gaps in recovery and drilling disturbance. However, the best supported identification of this reversal is with the Jaramillo subchron (C1r.1n at 0.99 Ma, Ogg, 2020). If this scenario is correct, the average sediment accumulation rate from the base of the Brunhes/Matuyama boundary to the top of the Jaramillo subchron is 34 cm/ky. From the paleomagnetic constraints described above, a preliminary age-depth model is constructed where the sediment accumulation rates are 17 cm/ky for the Brunhes Chron interval and 34 cm/ky below.

Downhole Measurements

Downhole logging was carried out in Hole U1604B upon completion of the coring operations. A modified triple combo tool string was deployed recording MS, NGR, electrical laterolog resistivity, acoustic velocity, and density tools. Three runs (a down pass, repeat, and a main pass) were carried out covering almost the full length of the open hole (427.6 m CSF-A; 2 m above the bottom of the hole). The repeat (or calibration run) logged the deepest 100 m of the hole. The caliper showed a relatively stable hole with frequent washouts and the instruments yielded reliable measurements.

Upon completion of the downhole logging with the modified triple combo, the FMS (without sonic) was lowered downhole. Three runs (a down pass plus two up passes) were completed. On the down passes, only the gamma ray was measured as the caliper of the FMS was closed. The FMS resulted in a high-quality resistivity image of Hole U1604B.

Logging measurements were crucial for covering recovery gaps. Core logging and downhole logging results differ in absolute values, but the relative trends of the logs are comparable. Hence, logging data could be used for correlation purposes and for covering the formation recovery gaps with confidence. Additionally, the advanced piston corer temperature (APCT-3) tool was deployed four times in Hole U1604A.

References

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