

International Ocean Discovery Program Expedition 400 Preliminary Report

NW Greenland Glaciated Margin

Cenozoic evolution of the northern Greenland Ice Sheet exposed by transect drilling in northeast Baffin Bay

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Paul C. Knutz, Anne Jennings, Laurel B. Childress, and the Expedition 400 Scientists

Publisher's notes

Core samples and the wider set of data from the science program covered in this report are under moratorium and accessible only to Science Party members until 24 March 2025.

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Expedition 400 participants

Expedition 400 scientists

Paul C. Knutz

Co-Chief Scientist

Near Surface Land and Marine Geology Department
Geological Survey of Denmark and Greenland
Denmark

pkn@geus.dk

Anne Jennings

Co-Chief Scientist

Institute of Arctic and Alpine Research
University of Colorado Boulder
USA

anne.jennings@colorado.edu

Laurel B. Childress

Expedition Project Manager/Staff Scientist

International Ocean Discovery Program
Texas A&M University
USA

childress@iodp.tamu.edu

Raquel Bryant

Micropaleontologist (planktonic foraminifera)

Department of Earth and Environmental Sciences
Wesleyan University
USA

rbryant@wesleyan.edu

Sami K. Cargill

Paleomagnetist

College of Earth, Ocean, and Atmospheric Sciences
Oregon State University
USA

cargills@oregonstate.edu

Helen K. Coxall

Micropaleontologist (planktonic foraminifera)

Department of Geological Sciences
Stockholm University
Sweden

helen.coxall@geo.su.se

Tracy D. Frank

Sedimentologist

Department of Earth Sciences
University of Connecticut
USA

tracy.frank@uconn.edu

Georgia R. Grant

Sedimentologist

Surface Geoscience
GNS Science
New Zealand

g.grant@gns.cri.nz

Rachael E. Gray

Inorganic Geochemist

Department of Geology
Kent State University
USA

rgray30@kent.edu

Sandrine Le Houedec

Sedimentologist

University of Geneva
Switzerland

sandrine.lehouedec@unige.ch

Libby Ives

Sedimentologist

Jet Propulsion Laboratory
California Institute of Technology
USA

elizabeth.r.ives@jpl.nasa.gov

Vikash Kumar

Sedimentologist

National Centre for Polar and Ocean Research
Ministry of Earth Sciences
India

vikash@ncpor.res.in

Jannik Martens

Organic Geochemist

Lamont-Doherty Earth Observatory
Columbia University
USA

jmartens@ldeo.columbia.edu

Fawz Naim

Physical Properties Specialist

School of Earth Sciences
Ohio State University
USA

naim.9@buckeyemail.osu.edu

Mei Nelissen

Micropaleontologist (palynology)

Royal Netherlands Institute for Sea Research (NIOZ)
Netherlands

mei.nelissen@nioz.nl

Volkan Özen

Micropaleontologist (diatoms)

Museum für Naturkunde Berlin
Germany

volkan.oezen@mf.n.berlin

Sandra Passchier

Sedimentologist

Earth and Environmental Studies
Montclair State University
USA

passchiers@montclair.edu

Lara F. Pérez

Stratigraphic Correlator/Downhole Measurements

Near Surface Land and Marine Geology Department
Geological Survey of Denmark and Greenland
Denmark

lfp@geus.dk

Jian Ren**Micropaleontologist (diatoms)**

Key Laboratory of Marine Ecosystem Dynamics
Second Institute of Oceanography
Ministry of Natural Resources
China
jian.ren@sio.org.cn

Brian W. Romans**Sedimentologist**

Geosciences
Virginia Tech
USA
romans@vt.edu

Osamu Seki**Organic Geochemist**

Institute of Low Temperature Science
Hokkaido University
Japan
seki@lowtem.hokudai.ac.jp

Philip Staudigel**Inorganic Geochemist**

Institut für Geowissenschaften
Goethe Universität
Germany
staudigel@em.uni-frankfurt.de

Observers**Victor Gronmyr****Weather/Ice Observer**

Canada
gronmyrv@gmail.com

Outreach**Elizabeth Doyle****Outreach Officer**

Northern Virginia Community College
USA
edoyle@nvcc.edu

Lisa Tauxe**Paleomagnetist**

Scripps Institution of Oceanography
University of California, San Diego
USA
ltaxe@ucsd.edu

Emily J. Tibbett**Sedimentologist**

Department of Earth, Geographic, and Climate Sciences
University of Massachusetts-Amherst
USA
ejtibbett@gmail.com

Yuka Yokoyama**Physical Properties Specialist**

School of Marine Science and Technology
Tokai University
Japan
yyokoyama@tsc.u-tokai.ac.jp

Yancheng Zhang**Physical Properties Specialist/Stratigraphic Correlator**

School of Marine Sciences
Sun Yat-Sen University
China
zhangych99@mail.sysu.edu.cn

Heike Zimmermann**Microbiologist/Observer**

Department of Glaciology and Climate
Geological Survey of Denmark and Greenland
Denmark
hj@geus.dk

Paul Ruzyski**Weather/Ice Observer**

Canada
paul.ruzyski@gmail.com

Michelle Pratt**Outreach Officer**

Oregon State University
USA
mro8026@gmail.com

Operational and technical staff

Siem Offshore AS officials

Harm Nienhuis

Master of the Drilling Vessel

Wayne Lambert

Drilling Supervisor

JRSO shipboard personnel and technical representatives

Heather Barnes

Assistant Laboratory Officer

Timothy Blaisdell

Applications Developer

James Brattin

Applications Developer

Erick Bravo Jimenez

Marine Laboratory Specialist

Michael Cannon

Marine Computer Specialist

Oscar Cavazos

Marine Laboratory Specialist

Bridgette Cervera

Marine Laboratory Specialist

Etienne Claassen

Marine Instrumentation Specialist

Lisa Crowder

Laboratory Officer

Douglas Cummings

Publications Specialist

Kirby Garrett

Schlumberger Engineer

Myriam Kars

Marine Laboratory Specialist

Jan Kotze

Marine Instrumentation Specialist

Carel Lewis

Curatorial Specialist

Nicholas Logan

Marine Computer Specialist

Zenon Mateo

Marine Laboratory Specialist

Doris Lajas

Assistant Laboratory Officer

William Rhinehart

Operations Superintendent

Alexander Roth

Marine Laboratory Specialist

Johanna Suhonen

Marine Laboratory Specialist

Kara Vadman

Marine Laboratory Specialist

Maximilian Witek

Marine Laboratory Specialist

Abstract

Elucidating the geologic history of the Greenland Ice Sheet (GrIS) is essential for understanding glacial instability thresholds, identified as major climate system tipping points, and how the cryosphere will respond to anthropogenic greenhouse gas emissions. To address current knowledge gaps in the evolution and variability of the GrIS and its role in Earth's climate system, International Ocean Discovery Program (IODP) Expedition 400 obtained sedimentary records from Sites U1603–U1608 across the northwest Greenland margin into Baffin Bay where thick Cenozoic sedimentary successions can be directly linked to the evolution of the northern GrIS (NGrIS). The strategy of drilling along this transect was to retrieve a composite stratigraphic succession representing the late Cenozoic era from the Oligocene/early Miocene to Holocene.

The proposed sites targeted high-accumulation rate deposits associated with contourite drifts and potential interglacial deposits within a trough mouth fan system densely covered by seismic data. The principal objectives were to (1) test if the NGrIS underwent near-complete deglaciations in the Pleistocene and assess the ice sheet's response to changes in orbital cyclicities through the mid-Pleistocene transition; (2) ascertain the timing of the NGrIS expansion and examine a hypothesized linkage between marine heat transport through Baffin Bay and high Arctic warmth during the Pliocene; and (3) provide new understandings of climate-ecosystem conditions in Greenland during the geologic periods with increased atmospheric CO₂ compared to preindustrial values, encompassing the last 30 My. The deep time objective was attained by coring at Site U1607 on the inner shelf to 978 meters below seafloor, capturing a succession of mainly Miocene and Oligocene age. The six sites drilled during Expedition 400 resulted in 2299 m of recovered core material, and wireline downhole logging was completed at Sites U1603, U1604, U1607, and U1608. This unique archive will provide the basis for understanding the full range of forcings and feedbacks—oceanic, atmospheric, orbital, and tectonic—that influence the GrIS over a range of timescales, as well as conditions prevailing at the time of glacial inception and deglacial to interglacial periods. We anticipate that the shipboard data and further analytical work on Expedition 400 material can constrain predictive models addressing the GrIS response to global warming and its impending effects on global sea levels.

Plain language summary

Sea level consequences of anthropogenic climate forcing hinge on how the polar ice sheets respond to global warming. If fully melted, the Greenland Ice Sheet has the potential to raise sea level by >7 meters, yet we know very little about its long-term responses to past climate warming or its role in Earth's climate system. Expedition 400 seeks to address current knowledge gaps in the evolution and variability of the northern Greenland Ice Sheet by recovering sedimentary archives of warm and cold periods going millions of years back in time. This includes periods when the greenhouse gas content of the atmosphere was higher than it is today. By drilling at six sites to 978 meters below seafloor along a transect crossing the northwest Greenland margin into Baffin Bay, we obtained a total of 2299 meters of sediment. This extensive and unique sediment archive will be valuable for understanding the geologic history of the Greenland Ice Sheet and its response to past warming going back 30 million years before present. The sediment cores record climate conditions before Greenland became glaciated and indicate when the Greenland Ice Sheet first began to expand into the marine environment. We also see glacial and interglacial cycles when the ice sheet grew to its maximum position at the shelf edge and retreated toward land, possibly melting farther back than what is known from previous records.

1. Introduction

The Greenland Ice Sheet (GrIS) holds a large amount of freshwater, equivalent to ~7.4 m of global sea level (Bamber et al., 2013). Recent studies have highlighted the sensitivity of the GrIS to climate warming and the potential impact its meltwaters would have on sea level rise and the Atlantic Meridional Ocean Circulation (Alley et al., 2010; Khan et al., 2010; Hansen et al., 2016). With the prospect of irreversible ice sheet retreat as one of the major tipping points, documenting

the full range of forcings and feedbacks—oceanic, atmospheric, orbital, and tectonic—that influence the GrIS over a range of timescales is crucial for making robust predictions of future climate and sea level change (Intergovernmental Panel on Climate Change [IPCC] Sixth Assessment Report; <https://www.ipcc.ch/assessment-report/ar6>). To this end, high-resolution sedimentary archives proximal to Greenland that capture glacial discharges of meltwater and sediments under different ice sheet configurations as well as biogenic components reflecting marine and terrestrial climate conditions are needed. The objectives of Expedition 400 directly address the critical questions posed in the Climate and Ocean Change theme of the International Ocean Discovery Program (IODP) science plan: “How do ice sheets and sea level respond to a warming climate?” and “How does Earth’s climate system respond to elevated levels of atmospheric CO₂?”

The response of the GrIS to extreme interglacial warmth is a highly relevant and debated topic although it is poorly constrained by data. During the last interglacial period, Marine Isotope Stage (MIS) 5e, global sea level was likely in the range of 6–9 m higher than present (Dutton and Lambeck, 2012), of which the GrIS may have contributed between 10% and 40% (Neem Community Members, 2013; Dutton et al., 2015). During MIS 11c, described as a super-interglacial (Loutre, 2003; Melles et al., 2012), global sea levels 6–13 m higher than today have been estimated (Dutton et al., 2015). Several studies associate MIS 11c with a significant or near-complete loss of the GrIS (Willerslev et al., 2007; de Vernal and Hillaire-Marcel, 2008; Reyes et al., 2014; Christ et al., 2023). The MIS 11c ice sheet loss apparently occurred despite more moderate summer temperatures compared to MIS 5e (Cluett and Thomas, 2021). A compelling result by Schaefer et al. (2016), based on cosmogenic nuclides in subice bedrock, suggests that central Greenland became deglaciated during one or more periods over the last 2.5 My. This concept raises critical questions: (1) What forcings drove near-complete melting of the northern GrIS (NGrIS) during the Pleistocene? (2) How did the ice sheet reconfigure to a state of “normal” glacial–interglacial conditions? To answer these questions and test the temporal scenarios for ice sheet instabilities and extended deglaciation through the Pleistocene requires access to semicontinuous records from the continental margins around Greenland (Bierman et al., 2016).

The mid-Pleistocene transition (MPT) signifies a profound shift in glacial–interglacial cycles from 41 to 100 ky periodicities (Hodell and Channell, 2016). Although the 41 ky cycles are strongly linked to orbital forcing, the insolation changes associated with 100 ky cycles are weak and require a persistent amplification mechanism (Yin and Berger, 2010). Explanations for the MPT have focused on various aspects of CO₂ reservoir exchanges between ice, ocean, and atmosphere (Raymo et al., 1996; Paillard, 1998; Ruddiman, 2006; Yin and Berger, 2010; Rial et al., 2013; Lear et al., 2016) and changes in ice sheet dynamics controlled by bedrock/regolith cover of Northern Hemisphere terrains (Clark and Pollard, 1998; Clark et al., 2006; Abe-Ouchi et al., 2013; Willeit et al., 2019). All hypotheses implicate the GrIS, directly or indirectly, but its dynamic behavior across the MPT is scarcely known. A potential linkage between global climate cycles and GrIS dynamics is highlighted by a recent study denoting a major change in northwest GrIS configuration through the MPT (Knutz et al., 2019).

The current understanding of the Cenozoic evolution of the GrIS has been developed largely from North Atlantic deep-sea records. In northeast Greenland, marine-based glaciers appear to have been active since the Miocene (~18 Ma) (Thiede et al., 2011), but smaller outlets may have existed as early as the late Eocene (Eldrett et al., 2007; St. John, 2008; Tripathi et al., 2008). Deep drilling and seismic evidence indicate that glacially influenced sedimentation on the central–southern East Greenland margin began during the late Miocene (~7 Ma) (Larsen et al., 1994; Bierman et al., 2016; Pérez et al., 2018). Full-scale glaciation of Greenland is generally considered to be timed with intensification of the Northern Hemisphere glaciations interpreted from elevated ice rafting in the North Atlantic during the late Pliocene–Pleistocene (3.3–2.8 Ma) (Shackleton et al., 1984; Jansen et al., 2000; St. John and Krissek, 2002). This ice sheet growth phase is possibly linked with a westward expansion of the GrIS into Baffin Bay during the Pliocene (Nielsen and Kuijpers, 2013; Knutz et al., 2019; Aubry et al., 2021). However, the chronology is poorly constrained and lacks core stratigraphic information from the West Greenland margin.

A better knowledge of the inception of the GrIS and its sectorized expansion during the late Cenozoic is needed to support sensitivity studies and climate models (DeConto et al., 2008). In particular, there is a pressing need for understanding the GrIS behavior during the warm climates with elevated CO₂ of the Paleocene and Neogene. The Pliocene (5.3–2.6 Ma) is the most recent period when atmospheric CO₂ concentrations were similar to the modern levels of ~400 ppm. This geologic time period thus functions as a past analog interval for the ongoing and future response of the ice sheet under warming conditions. Notably, the mid-Pliocene warm period (3.3–3.0 Ma) has been a focal point for paleoclimate reconstruction and modeling (Haywood et al., 2010; Dowsett et al., 2013). To study analogs for future global warming scenarios (e.g., *p*CO₂ projections >600 ppm beyond 2050), it is necessary to access records going further back in time. Key stratigraphic intervals for gaining knowledge on elevated *p*CO₂ climate regimes include the middle Miocene (16–15 Ma) and most of the Oligocene (34–27 Ma) (Zhang et al., 2013; O'Brien et al., 2020; Guillermin et al., 2022). These pre-Quaternary intervals likely exist below the northwest Greenland margin (Knutz et al., 2015) but have yet to be explored by deep drilling.

The vulnerability of the GrIS to global climate change is a major concern, but it also highlights a knowledge gap that limits our ability to confidently project future cryospheric responses, including contributions to sea level rise (Dahl-Jensen et al., 2009; Briner et al., 2017). Cenozoic climate experienced significant changes in atmospheric greenhouse gas concentrations, notably linked to *p*CO₂ (Pearson and Palmer, 2000; Zachos et al., 2008; Pagani, 2014). Model studies suggest that even the modest atmospheric CO₂ changes (280–400 ppm) observed during the late Cenozoic exert a primary control on GrIS growth across the Pliocene–Pleistocene transition (Lunt et al., 2008; Tan et al., 2018). Other factors controlling ice sheet dynamics include changes in ocean currents (Nielsen et al., 2011; Knutz et al., 2015; Otto-Bliesner et al., 2017), tectonic base-level changes (Solgaard et al., 2013), and variations in geothermal heat flux (Fahnestock et al., 2001; Rogozhina et al., 2016), but these boundary conditions are poorly constrained by data and are not easily addressed by climate models. For the Oligocene and Miocene time periods, the linkage between global ice volume, surface temperatures, and atmospheric *p*CO₂ is enigmatic. The expansion and dynamic variability of ice sheets in Antarctica during periods of global warming and moderate *p*CO₂ levels imply a strong nonlinear behavior to climate forcing, with implications for ice sheet tipping points (Foster et al., 2012; Golledge et al., 2017; O'Brien et al., 2020; DeConto et al., 2021). The complex linkages or possible decoupling between *p*CO₂ and global ice volume (Raymo et al., 1996; Tripathi et al., 2009) underscore the importance of evaluating potential forcings in the earth system. Greenland is surrounded by narrow gateways that over millions of years may have changed configuration, potentially modulating ocean heat fluxes between the Arctic and North Atlantic regions (Thiede and Myhre, 1996). Unraveling the GrIS response to past global warming events will need to consider regional effects such as those related to ocean gateways, topography, and ecosystems (Otto-Bliesner et al., 2017; Hodson et al., 2010).

With a clear goal of addressing the multiple questions and hypotheses that concern the long-term evolution and stability of the NGrIS, Expedition 400 will obtain a composite sedimentary archive covering the last 25–30 My. The strategy was to drill seven sites along a transect across the northwest Greenland margin from the deep basin of Baffin Bay to the inner continental shelf (Figures F1, F2, F3). The transect is positioned between two major trough mouth fan (TMF) systems, the Melville Bugt and the Upernavik TMFs, which are the product of erosion and transport of sediments to the shelf edge by paleo-ice streams. The proposed sites primarily core high-accumulation rate deposits that include contourite, hemipelagic, and glacial-marine sediments of Quaternary, Pliocene, and Miocene–Oligocene age (Figure F4). With the data extracted from composite archives obtained in close vicinity to major glacial outlets, we aim to determine maximum and minimum NGrIS configurations throughout the middle to late Cenozoic, from shelf edge glaciation to hypothesized complete ice loss, such as during Pleistocene super-interglacials.

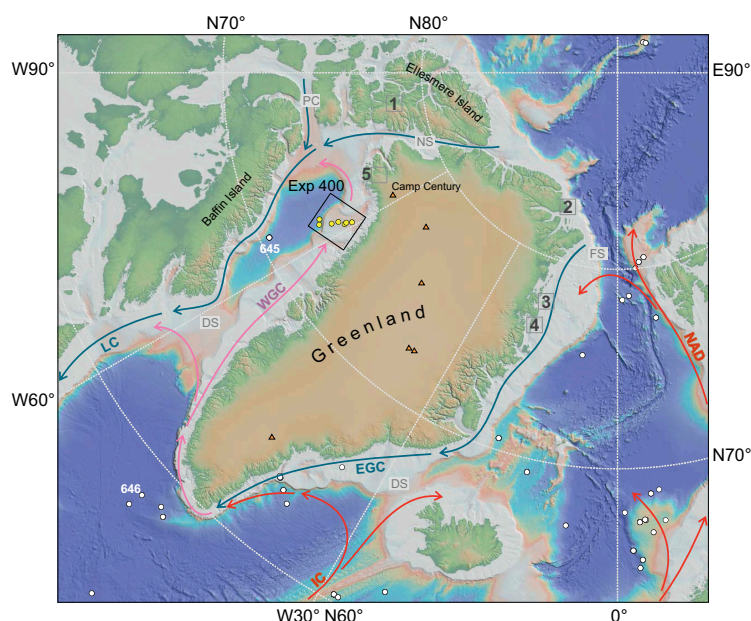


Figure F1. Topographic/bathymetric map showing Expedition 400 transect sites in relation to existing ODP/Integrated Ocean Drilling Program/IODP sites (white circles) and near-surface ocean currents. LC = Labrador Current, WGC = West Greenland Current, IC = Irminger Current, EGC = East Greenland Current, NAD = North Atlantic drift. Ocean gateways surrounding Greenland: DS = Davis Strait, PC = Parry Channel, NS = Nares Strait, FS = Fram Strait, DS = Denmark Strait. Locations of high Arctic Pliocene and early Pleistocene deposits: 1 = Beaufort Formation, high-level terrace locality on Ellesmere Island (Matthews and Ovenden, 1990; Rybczynski et al., 2013), 2 = Kap København Formation (Bennike and Böcher, 1990; Funder et al., 2001), 3 = Île de France Formation (Bennike et al., 2002), 4 = Store Koldewey Formation (Bennike et al., 2010), 5 = Pingorsuit early Pleistocene interglacial deposit (Bennike et al., 2023). Triangles = Greenland ice cores. Map was produced using GMRT v4.0 mapping tool.

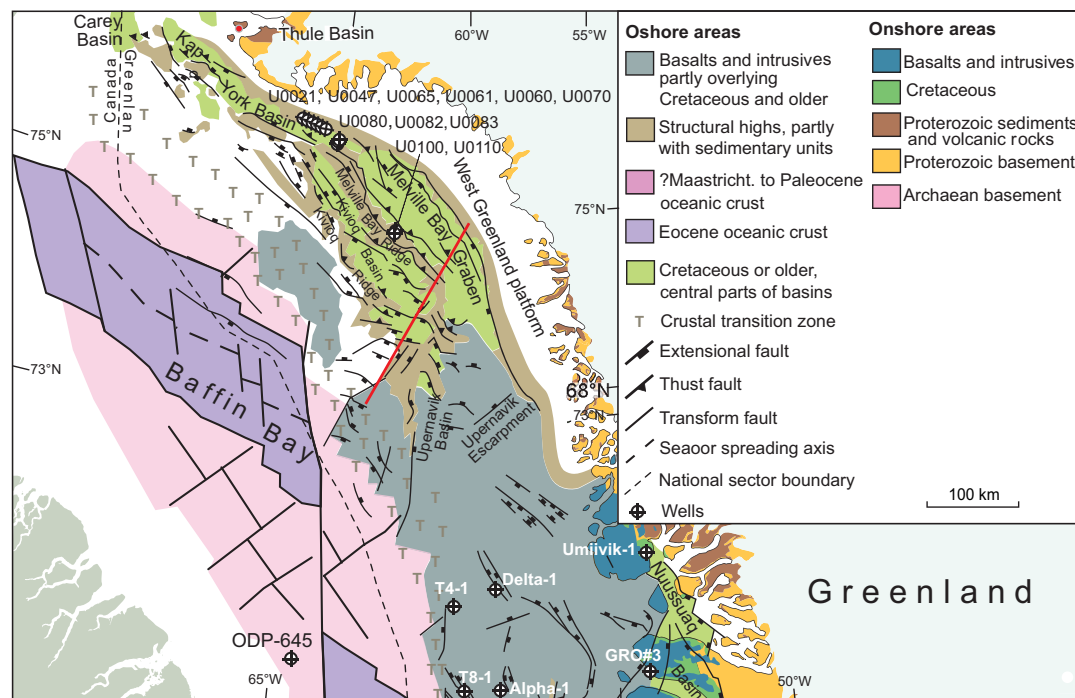


Figure F2. Tectonic elements map of northeast Baffin Bay showing position of Expedition 400 seismic transect (red line) (see Figure F4) and existing deep drilling sites (IODP, IODP, and exploration wells). Adapted from Gregersen et al. (2022).

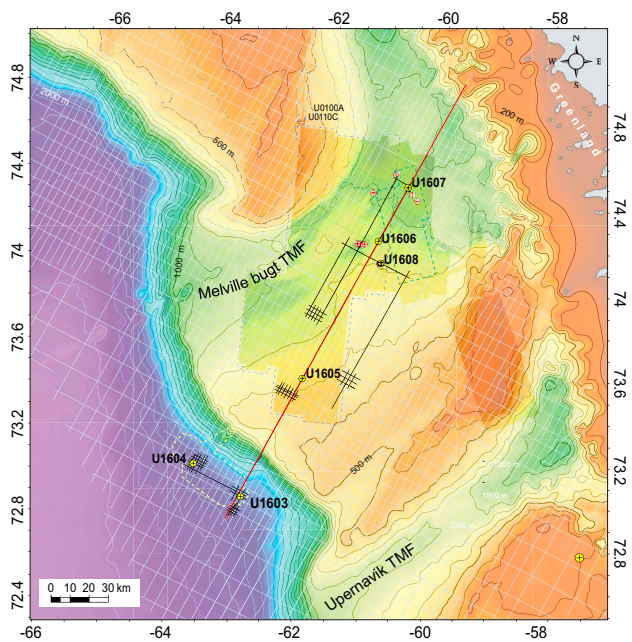


Figure F3. Map of site locations and site survey data for Expedition 400. Yellow dots = primary sites, red crosses = alternate sites. Regular 2-D seismic grid (blue-gray lines) = TGS Baffin Bay surveys 2007, 2008, 2009, and 2010 (minimum spacing = ~3.75 km). Broken line polygons = 3-D seismic surveys Shell-ANU-3D-2012 and Cairn-PITU-3D-2011 (dark and light blue, respectively). Thin black line grids = high-resolution survey LAKO 2019. Detailed bathymetry on shelf margin is based on industry multibeam data combined with first reflection extracted from 3-D seismic data (Newton et al., 2017). Regional bathymetry is based on IBCAO v3 (Jakobsson et al., 2012) shown with 100 m contours. Multibeam bathymetry data in deep-water basin (dashed line) was collected by Alfred Wegener Institute (Dorschel, 2017). Red line = position of key seismic transect (Figure F4).

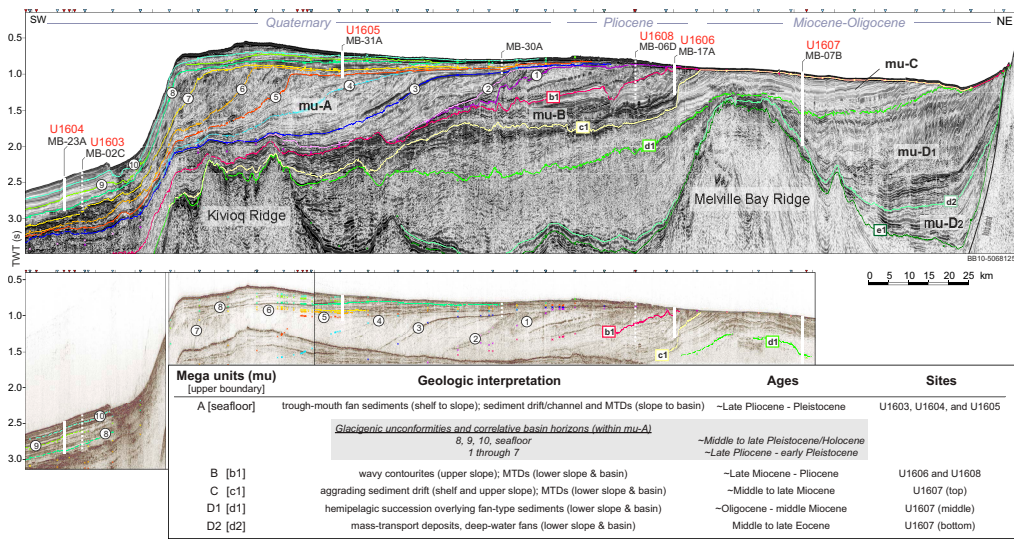


Figure F4. Key seismic transect for Expedition 400 coring sites (black = proposed, red = drilled) with seismic horizons and units. Top: deep seismic profile (BB10-5068125) courtesy of TGS (Knutz et al., 2019). Bottom: Stitched section of high-resolution seismic data from LAKO19 site survey. Small triangles over top axis = positions of crossing seismic profiles, blue = deep seismic lines, red = high-resolution seismic lines. Broken lines = sites projected onto transect from offset positions. The prograding sequence (Megaunit [mu] A) forming part of Melville Bugt/Upernavik TMF system is dissected by 10 horizons that, including the seabed horizon, correspond to 11 depositional units (Knutz et al., 2019). Horizons are defined by slightly dipping erosional surfaces (high-amplitude reflections in topset strata) with abrupt shelf breaks. Pre-TMF Horizons b1 (approximately late Pliocene) and c1 (approximately late Miocene) demarcate a package of wavy contourites formed within a major slide scar that truncates Horizon c1 (Knutz et al., 2015). Horizon d1, likely middle Miocene in age, defines the base of a late Neogene drift prism forming part of Megaunit C. Horizon d2 is not constrained by boreholes but is possibly late Oligocene in age. Melville Bay and Kivioq Ridge systems represent rift-tectonic elements modified by compression during late Paleogene (Gregersen et al., 2013, 2016). TWT = two-way traveltime. MTD = mass transport deposit.

2. Background

2.1. Baffin Bay hydrology

Baffin Bay is a semienclosed basin with predominantly cyclonic ocean circulation and a pronounced east–west hydrographic gradient (Figures F1, F2). The Baffin Island Current transports cold, low salinity Arctic waters along the Canadian margin and exits through western Davis Strait. In contrast, the West Greenland Current carries warmer (3°–5°C) waters derived from both the North Atlantic Irminger Current and the East Greenland Current. The West Greenland Current travels northward over the West Greenland shelf regions at water depths of 100–500 meters below sea level (mbsl) (Bourke et al., 1989; Hamilton and Wu, 2013). Observations of the deep to intermediate circulation of Baffin Bay and hydrographic modeling indicate a southward counter current along the West Greenland slope from 68° to 72°N at depths of 1000–1500 mbsl (Tang et al., 2004). Deepwater formation is possibly taking place in northern Baffin Bay, associated with brine formation during sea ice formation in the North Water Polynya, south of the Nares Strait (Yao and Tang, 2003). The rates and processes of water mass conversion in this area are not well understood (Bourke et al., 1989), but there is growing understanding of the role of the North Water Polynya and its influence on the interactions of northern and southern sourced water masses in the deep-water formation in Baffin Bay (Bâcle et al., 2002; Rysgaard et al., 2020).

2.2. Greenland Ice Sheet dynamics

The northwest Greenland shelf region was glaciated on multiple occasions, resulting in prominent TMFs that are the sedimentary expression of former glacial outlets of the NGrIS (Figure F3). Geophysical data and shallow core studies demonstrate the presence of fast-flowing ice streams that reached the outer shelf during the late Pleistocene (Ó Cofaigh et al., 2013; Dowdeswell et al., 2014; Slabon et al., 2016; Newton et al., 2017). The last glacial retreat from outer shelf grounding positions to fjord outlets in northwest Greenland probably occurred in discrete steps controlled by reverse bed gradients associated with shelf overdeepening (Patton et al., 2016; Newton et al., 2017) and enhanced marine ablation linked to the West Greenland Current (Jennings et al., 2017). Confluent Laurentide, Innuitian, and Greenland Ice Sheets blocked the Arctic–Atlantic gateways such as Parry Channel and Nares Strait during the Last Glacial Maximum, eliminating the inflow of Arctic waters into northern Baffin Bay and resulting in a circulation and sea ice regime much different from the modern one (Jennings et al., 2019; Jackson et al., 2021). Arctic–Atlantic gateway closures likely occurred during other glacial periods.

Ice sheet response to major climate transitions, such as the Pleistocene terminations, is poorly known. A recent study invokes a slow interglacial response to climate forcing, suggesting that the GrIS is in disequilibrium with global warming (Yang et al., 2022). Conversely, during glacial maxima ice shelves may have developed over Baffin Bay, buttressing the ice flow and possibly stabilizing the central ice domes in Greenland (Hulbe et al., 2004; Jennings et al., 2018; Couette et al., 2022). Thinning and breakup of stabilizing ice shelves can be triggered by ocean forcing at the grounding line amplified by drainage of surface meltwater to the bed (Holland et al., 2008; Straneo et al., 2012; Scambos et al., 2017; Catania et al., 2020; Jennings et al., 2022). Depending on physiographic factors such as bathymetry and lateral constraints, ice retreat can be catastrophic or episodic (Alley et al., 2007, 2015; Pollard et al., 2015; Scambos et al., 2017; Hogan et al., 2020). It is important to understand the complex forcings and conditions that initiate retreat and govern the rate of retreat of a previously stable marine-terminating ice sheet to better understand the impacts of ice sheet retreat on sea level, ocean circulation, nutrients, and ecosystems (Catania et al., 2020). Reconstructions of paleo–ice sheet behavior and mass balance change broaden the scope of our understanding of the potential outcomes of continued climate warming on the GrIS.

A better understanding of the boundary conditions and forcings determining long-term ice sheet evolution requires information only attainable by offshore drilling. However, long sedimentary records specifically illuminating NGrIS history are lacking. Previous drilled sites in the North Atlantic recovered sediment shed from elevated terrains in east Greenland (Thiede et al., 2011; Reyes et al., 2014) influenced by semipermanent alpine glaciers since the late Miocene (Bierman et al., 2016). The only deeply cored site in Baffin Bay (Site 645) was drilled during the early phase of

the Ocean Drilling Program (ODP), and its contribution to understanding GrIS history is limited because of its location on the Canadian margin, poor recovery, and age uncertainties (Baldauf et al., 1989). In 2012, shallow coring was carried out in northeast Baffin Bay targeting Mesozoic rift deposits in exhumed sedimentary basins north of the Melville Bugt trough (Expedition 344S; Acton and the Expedition 344S Scientists, 2012). However, two sites, U0100 and U0110, penetrated a 124 m thick interval of overcompacted, muddy diamicton. Cosmogenic nuclides and other proxy data extracted from these proximal glaciogenic sediments suggest that by the early Pleistocene, a persistent yet dynamic ice sheet existed in northwest Greenland (Christ et al., 2023).

The sensitivity of the GrIS to ocean warming (Holland et al., 2008; Yin et al., 2011) emphasizes the need for high-resolution records near the major glacial outlets of eastern Baffin Bay. Important advances in drilling techniques, dating methodologies, and proxy approaches make new drilling key for advancing understanding of past GrIS dynamics and ice-ocean-climate interactions, which so far have only been addressed by seabed mapping, shallow cores (Jennings et al., 2017, 2018), and seismic stratigraphy correlated to exploration wells (Hofmann et al., 2016).

2.3. Tectonostratigraphic development

The continental margin of northwest Greenland has a complex geologic and tectonic history that involves Cretaceous rift phases, extrusive volcanism, and tectonic inversion as seafloor spreading commenced in Baffin Bay. Rifting of the continental margins occurred during the Early and Late Cretaceous forming numerous sedimentary basins and elongate grabens that fringe the Baffin Bay margins (Whittaker et al., 1997; Gregersen et al., 2013; Nøhr-Hansen et al., 2021) (Figure F2). Opening of Baffin Bay ensued from the late Paleocene through the Eocene, likely in tandem with the opening of the Labrador Sea (Chalmers et al., 1993) (Figure F1). The separation of Greenland relative to the North American continent ceased during the early Oligocene (Chron C13) as seafloor spreading commenced along the Aegir Ridge system of the Icelandic plate boundary (Oakey and Chalmers, 2012; Gregersen et al., 2022). The geologic architecture and stratigraphic knowledge of this region is mainly based on seismic and borehole data collected between 2007 and 2012 (Gregersen et al., 2013, 2016, 2022; Knutz et al., 2015, 2019, 2022). Eight seismic megaunits have been described, of which Megaunits A–E are attributed to the Cenozoic interval deposited after continental rifting ceased. The drilling targets of Expedition 400 identified along the key seismic transect cover Megaunits A–D (Figure F4).

Oblique plate motions between Greenland and North America resulted in a transpressional tectonic regime (strike-slip) on the West Greenland margin, which gave rise to major basin infilling packages and deepwater fan systems guided by structural lineaments along inverted rift basins (Megaunit E). From the middle late Oligocene through the middle Miocene, a more passive sedimentation regime ensued with infilling of the remnant rift-basin topography (Megaunits D1 and D2) (Figures F1, F2, F4). In the Melville Bay Graben, juxtaposed to the Greenland craton, Megaunit D2 forms a several kilometer thick succession of continuously stratified deposits that are intensely faulted, primarily as a result of marine clay compaction (Berndt et al., 2003). This package of presumably clay-rich marine sediments overlies stacked fan-type packages that are lodged against the Greenland basement, separated by Megaunits D2 and C, and is described as the mid-Miocene Unconformity (d1) displaying erosion over structural highs and a conformable development within basin settings (e.g., Melville Bay Graben) (Figure F4). Megaunit C forms an asymmetric sediment prism covering wide parts of the inner shelf in northwest Greenland, with thicknesses up to 1200 m, that is variably modified by glacial erosion. The prism is interpreted to be a shelf-bound sediment drift that locally grades into clinoform features associated with prodeltaic environments (Knutz et al., 2015). The boundary between Megaunits C and B is an incised horizon (c1) that is correlated to extensive mass transport deposits on the lower slope and in the Baffin Bay basin, suggesting widespread submarine slope instability. The regional character of this erosion points to a phase of tectonic adjustment affecting the shelf margin, presumably during the late Miocene (Knutz et al., 2015). Megaunit B is characterized by distinct lenticular sediment bodies featuring asymmetric sediment waves that have accumulated into expanded sections over the Horizon c1 erosion scarp (Figure F4). The slope component of Megaunit B is interpreted to be a contourite drift with seismic ties to nearby drilled sections suggesting a Pliocene age (Knutz et al., 2015, 2019; Aubry et al., 2021).

2.4. Melville Bugt–Upernavik Trough Mouth Fan system

A prograded shelf package (Megaunit A) overlying the Neogene sediment drifts reflects deposition under the influence of major ice streams originating from the northwest GrIS sector (Figures F3, F4). Eleven prograding sedimentary units have been identified, each corresponding to bundles of glacial advance cycles within a major TMF system (Knutz et al., 2019; Newton et al., 2021). The TMF units are numbered according to their top bounding horizons, except for Unit 11, which is capped by the seabed. The units are separated by glacial unconformities defining paleotrajectories of shelf break grounding zones that prograded seaward with sediment supplied by successive advances of the NGrIS onto the outer shelf and slope. Between the two modern cross-shelf troughs (Melville Bugt and Upernavik TMFs), topset strata of prograding units and associated shelf breaks are extremely well preserved because of high sediment input from paleo-ice streams and basin subsidence over older rift structures. The Expedition 400 drilling transect was designed with the intention to extract paleoclimate information from this intertrough aggrading sediment wedge (Figure F4). Within the topset package, seismic reflections phase reversed from seabed onlap the glacial erosion surfaces or infill intrashelf depressions. These reflections, which have stratal thicknesses of >20–30 m, may represent marine muddy sediments deposited during periods of grounding line retreat and rising sea level, interrupting the glacial advance megacycles. An age model for the depositional evolution of the TMF was reconstructed by correlating the seismic horizons to nearby wells/boreholes (Knutz et al., 2019). It is hypothesized that the stratal onlaps, succeeding major shifts in ice stream configuration, may have formed during periods of extreme warmth, such as super-interglacials (Knutz et al., 2019).

Beyond the shelf break, the horizons of Megaunit A can be traced along clinoformal reflections to the basin strata, resulting in a complete pseudo-3-D mapping of the depositional units (Figure F4). The youngest depositional sequence, comprising Units 8–11, which are likely middle to late Pleistocene in age, form a series of contourites intersected by channel deposits on the lower slope. Thus, drilling these contourites will allow high-resolution paleoceanographic reconstructions back to, and potentially through, the MPT.

In summary, there are several reasons for choosing northeast Baffin Bay for documenting the Cenozoic evolution of the NGrIS:

- The area covers a large TMF system primarily constructed by glacial drainage over millions of years.
- It contains a succession of gently dipping strata where a composite sequence of Oligocene–Quaternary deposits may be drilled at relatively shallow depths.
- It has extensive coverage of high-quality 2-D and 3-D seismic data with outstanding imaging of glaciogenic sediment progradation, marine deposits formed by along-slope currents, and hemipelagic basin-infilling sediments.
- A detailed seismic stratigraphy tied to well/borehole information illuminates the sediment transport dynamics from the NGrIS (Knutz et al., 2019).
- The western Greenland margin is accessible due to amenable ocean temperatures and reduced sea ice associated with the northbound West Greenland Current (Tang et al., 2004; Holland et al., 2008).
- Expedition 344S demonstrated in 2012 that the R/V *JOIDES Resolution* can successfully operate in northeast Baffin Bay, a region that is crossed by icebergs but lacks pack ice (Acton and the Expedition 344S, 2012).

2.5. Geophysical data

The supporting site survey data for Expedition 400 are archived at the IODP Site Survey Data Bank (<https://ssdb.iodp.org/SSDBquery/SSDBquery.php>; select P909 for proposal number).

Development of the coring plan for Expedition 400 was facilitated by an extensive seismic database. The core sites initially submitted for IODP drilling Proposal 909-Full1 were located using 2-D seismic data, including four regional seismic surveys collected by TGS in 2007–2010. The final placement of sites (IODP drilling Proposals 909-Full2 and 909-Add) was accomplished based on (1) two 3-D data volumes, Cairn-PITU-3D-2011 and Shell-ANU-3D-2012, and (2) a dedicated

high-resolution seismic survey completed in 2019 as a collaboration between Geological Survey of Denmark and Greenland (GEUS) and Geoscience-Aarhus University using the Danish R/V *Lauge Koch* (LAKO) (Pearce and Knutz, 2019). Both 3-D surveys were utilized in a compilation of seabed geomorphology (Newton et al., 2017, 2021) and geohazard assessments for further refining drill site locations (Cox et al., 2020, 2021).

The LAKO 2019 survey data provide high-resolution coverage (vertical resolution = ~4–6 m) of all primary sites and several alternate sites. The multichannel reflection seismic acquisition (15–300 Hz) was optimized to gain enhanced resolution in the uppermost 500 m of the sedimentary section, complementary to the existing industry data. A 90 cubic inch generator-injector (GI) gun was used as a seismic source configured with a 45 inch³ main chamber and a 45 inch³ injection chamber. Shot time was 4.0 s for most of the data, and record length varied between 2.0 and 3.5 s. Shots were recorded on a Geometrics GeoEel streamer, which included five 25 m active sections of 8 channels each (40 channels total) with a group spacing of 3.125 m. A total of 861 line kilometers was collected. Initial processing producing a migrated data version was performed on the ship. Final processing on shore included confirmation of static and delay correction, deconvolution to zero-phase data, and fk filtering. The overall data quality was excellent, except some of the shelf sections marked by significant short wavelength variations due to a rough seabed (e.g., boulders, glacial scouring, and iceberg plough marks).

For converting seismic drilling targets into metric depths, the proposed sites were bundled into four groups based on similarities in the depositional setting, geologic context, and general target depths. To obtain the most realistic time-depth conversion, all available data from the region was reviewed. Velocity information was extracted from existing industry boreholes south of the transect (e.g., Gamma-1), data gained from Expedition 344S sites north of the transect, and an interval velocity cube derived from the Cairn-PITU-3D-2011 seismic volume. The average vertical profile velocities applied for each setting were 1800 m/s for the deepwater sites (U1603 and U1604; proposed Sites MB-23A and MB-02C), 2200 m/s for the glacial topset strata on the shelf (Site U1605; proposed Site MB-31A and not drilled Site MB-30A), 1900 m/s for the Pliocene contourite sediments (Sites U1608 and U1606; proposed Sites MB-06D and MB-17A), and 2050 m/s for the Miocene succession (Site U1607; proposed Site MB-07B).

3. Scientific objectives

The overall objective of Expedition 400 is to provide new insights into the long-term evolution of the NGrIS. To this end, seismic imaging from the deep basin to inner shelf has guided the selection of coring sites and stratigraphic correlation. A multiproxy diagnostic template has been developed, which in concert with a transect-drilling strategy can constrain different phases of ice extent and regional climate regimes (Figure F5). This template provides a methodological basis to test hypotheses that are crucial for understanding GrIS history, how the glacial margins will respond to continued warming in the near future, and how this may affect other components of the Earth system.

Expedition 400 objectives focus on answering three key questions.

3.1. How did the NGrIS respond to extreme interglacial warmth?

Cosmogenic nuclides in subice bedrock show that central Greenland was almost completely deglaciated during one or more intervals over the last 2.5 My (Schaefer et al., 2016). This study cannot determine a unique ice cover history, but three scenarios are proposed varying from ice-free interglacials to a single 280 ky deglacial event during the early Pleistocene, followed by ~1.1 Ma of uninterrupted ice sheet coverage. Cosmogenic exposure age dating of the basal sediments and sediment-rich ice at the base of the Camp Century ice core indicate that the northwest GrIS retreated significantly during MIS 11 (~400 ka before present [BP]) (Christ et al., 2023). The long-term depositional record on the margin of northeast Baffin Bay contains the glaciation history needed to infer when such extreme mass loss occurred. By drilling high-accumulation sites in the basin (Sites U1603 and U1604) and on the shelf margin (Site U1605) targeting potential interglacial deposits, we intend to test the hypothesis that the NGrIS underwent substantial deglaciation

on one or more occasions during the Pleistocene. Parameters for identifying warm interglacial periods will be derived from multiple qualitative and quantitative proxies that constrain ice sheet response and environmental conditions in both marine and terrestrial/atmospheric areas.

3.2. When did glacial inception occur in northwest Greenland, and how did the NGRIS dynamics evolve through Cenozoic climate transitions?

The relationship between long-term $p\text{CO}_2$ trends, temperature records, and global ice volume is poorly understood. A northwest Greenland perspective of this knowledge gap will be gained by retrieving a composite Oligocene, Miocene, and Pliocene interval covered by primary Sites U1606–U1608. These archives will provide information on timing, sedimentary processes, and changes in denudation rates of Greenland through periods of large atmospheric CO_2 variations. Organic components carried by these sediments in allochthonous or autochthonous fractions will provide insights into terrestrial and marine ecosystems and information on background climate states. We hypothesize that the decrease in $p\text{CO}_2$ from the early middle Oligocene (>600 ppm) to early Miocene (<300 ppm) coincides with cold and possibly glacial environments in northwest Greenland. This will be tested by recovering a 980 m long climate record from Oligocene–Miocene strata at Site U1607.

A complicating factor, disrupting or modulating a linear response between $p\text{CO}_2$ forcing and ice sheet growth/decay, may involve tectonic base-level adjustments causing snow line lowering (Foster et al., 2010) or changes in heat flux through oceanic gateways (Otto-Bliesner et al., 2017). Extensive submarine landslides into Baffin Bay associated with a late Miocene unconformity (c1) along the northwest Greenland margin may reflect a regional tectonic adjustment apparently pre-dating the first shelf edge advances (Knutz et al., 2015). This erosion event may be linked to hinterland uplift (Japsen et al., 2006), but a more concise understanding of its origin requires recovery of Neogene sediments. Following a full-scale glaciation, physical weathering would redistribute mass

Parameter	Proxy	Full Ice	Termination	Interglacial	Super-interglacial	Pre-GrIS
Sites		U1603, U1604, U1605, U1608	U1603, U1604, U1605, U1608	U1603, U1604, U1605, U1608	U1603, U1604, U1605, U1608	U1606, U1607, U1608
<i>Ice sheet configuration indicators</i>						
Iceberg production	IRD	0 to ++	++++	0 to +	0	0
Land exposure	^{10}Be	0	0	+	++	+++
Ice cover	$^{10}\text{Be}/^{26}\text{Al}$	<7 (burial)	<7 (burial)	7	7	7
Terrigenous flux	Volumetric sed. rate, sedimentary magnetism, NGR	+ to ++	++++	+	+	+ to ++
Terrestrial productivity	Pollen, leafwaxes, DNA, fossils	0	+	++	+++	++++
Sediment sourcing	Elemental, magnetic, mineral, and isotopic provenance	Glacial flowline, warm –polythermal bed	Glacial flowline, warm bed	Multiple ice-rafted sources, reworked glacial	Fluvial, reworked glacial, more local	Fluvial, basin only
Weathering intensity	Mineralogy, grain size and texture	0	0	+	++	++++
Glacial meltwater	Salinity reconstructions using $\delta^{18}\text{O}$ and trace elements in foraminifera, palmitic acid δD	0 to +	++++	++	0	0 to +
<i>Environmental indicators</i>						
Depositional processes (Shelf environment)	Lithofacies description	Tills	Glacial-marine, diamicton	Hemipelagic	Hemipelagic	Hemipelagic, contourite, deltaic
Depositional processes (Basin environment)	Lithofacies description	Glacial-marine, plumes/turbidites	Glacial-marine, plumes/turbidites	Hemipelagic, glacial-marine, contourite	Hemipelagic, contourite	Hemipelagic, contourite
Terrestrial climate	Pollen, brGDGT, leaf wax δD	Cold, dry	Transitional	Warm, wet	Warmer, wetter	Warmest, wettest
Ocean water conditions (surface/subsurface)	Dinoflagellate, diatom and foraminifera; isoGDGTs (e.g. TEX ₈₆), shell trace elements	Cold	Cool, strongly stratified	Warm, highly seasonal	Very warm	Very warm
Sea ice	IRD, Dinoflagellates and diatoms; biomarkers (HBIs, e.g. IP_{25})	+++	++ to +++	+	0-?	0-?

Figure F5. Diagnostic template for proxy interpretation. The combination of different proxy results will provide information on glacial response and paleoenvironmental settings associated with five overall stages of ice sheet configuration. Second row shows drill sites linked to each glaciation stage. Environmental parameters and proxies used to measure those parameters are shown in left columns. Hypothesized parameter response to each glaciation stage is shown in right columns. IRD = ice-rafted debris, brGDGT = branched glycerol dialkyl glycerol tetraethers, isoGDGTs = iso-glycerol dialkyl glycerol tetraethers, HBIs = highly branched isoprenoids. Descriptors for ice sheet configuration indicators: none (0), minor (+), moderate (++), high (+++), and very high (++++). $^{10}\text{Be}/^{26}\text{Al}$ values are based on Biermann et al. (2016).

from the Greenland craton to the continental slope and consequently accelerate hinterland uplift by isostatic compensation (Berger et al., 2008; Medvedev et al., 2013), prompting the question: did active tectonics play a role in the development of the GrIS (Solgaard et al., 2013), or are the late Neogene basin adjustments along the West Greenland margin a response to mass redistribution caused by glacial erosion (Ruddiman and Kutzbach, 1989; Molnar and England, 1990; Eyles, 1996)?

The timing of the advance of marine-based glaciers onto the northwest Greenland margin is presently ambiguous. Drilling through the initial clinoforms of the first prograding unit and farther into marine contourite sediments of probable Pliocene age (Sites U1608 and U1606) will test the hypothesis that glacial expansion of the NGrIS is linked with intensification of Northern Hemisphere glaciation (3.3–2.8 Ma).

Understanding the evolution of the NGrIS may hold the key to the origin of Northern Hemisphere glaciation, including the mechanisms of gradual amplification of glacial cycles since the late Pliocene and the shift from 40 to 100 ky cycles across the MPT (Raymo and Huybers, 2008). A major reorganization in the ice flow that drains the NGrIS apparently occurred across the MPT (Knutz et al., 2019). Hence, both local and regional evidence suggests that major changes in the size, erosivity, and responsiveness of the GrIS occurred throughout the Pleistocene (Bierman et al., 2016; Schaefer et al., 2016). By drilling Seismic Units 7–9 at the deepwater sites (U1603 and U1604) and on the shelf (Site U1605), we will examine changes in NGrIS dynamics through the MPT pertaining to recent models, in particular the regolith hypothesis (Clark and Pollard, 1998).

3.3. What is the paleoceanographic and cryospheric significance of Pliocene contourite drifts in northeast Baffin Bay?

The early mid-Pliocene was characterized by relatively warm and humid forest tundra conditions in the high Arctic of Canada (Matthews and Ovenden, 1990; Fyles et al., 1994; Csank et al., 2011; Rychczynski et al., 2013) and Greenland (Bennike et al., 2002). A similar environment was inferred from early Pleistocene interglacial deposits in northern Greenland (Funder et al., 2001), which is when southern Greenland appears to have been forested (de Vernal and Mudie, 1989). These warm Arctic conditions occurred under modest $p\text{CO}_2$ levels (~ 400 ppm), implying a high sensitivity of the Pliocene Arctic climate to $p\text{CO}_2$ or the influence of other forcing factors (Haywood et al., 2016, 2020; Feng et al., 2022). Pliocene glacial ice was likely limited to high-elevation terrains in eastern and southern Greenland, although climate models are limited by a dearth of proxy archives close to Greenland (Koenig et al., 2015). In the late Neogene, presumably the latest Miocene and Pliocene, the West Greenland/Baffin Bay margin was influenced by contour currents that deposited extensive sedimentary drifts (Knutz et al., 2015). The establishment of persistent oceanic gradients strong enough to maintain a geostrophic boundary current over millions of years is intriguing and may be linked with enhanced Pliocene Atlantic Meridional Ocean Circulation. Past configurations of Arctic gateways (e.g., Davis Strait, Nares Strait, Fram Strait, and Bering Strait) could have played a key role for poleward heat exchange during the Pliocene (Hu et al., 2015; Keisling et al., 2017); however, the tectonic history of these topographic thresholds is poorly known (Eyles, 1996; Knies et al., 2014). The contourite deposits of Megaunit B, presently exposed at shallow depths below the glacial trough, can illuminate the environmental conditions of this paleocurrent system that appear to have existed prior to the expansion of the NGrIS.

Sites U1608 and U1606 provide a composite succession that can constrain Pliocene climate variability and paleotemperatures and test whether or not the high Arctic warmth of the early mid-Pliocene is associated with enhanced heat advection through Baffin Bay.

3.4. Summary of scientific objectives

1. Test the hypothesis that the NGrIS underwent significant deglaciation at intervals within the frequency range of orbital eccentricity (~ 100 – 400 ky). Pleistocene sites on the slope (Sites U1603 and U1604) and the outer shelf (Sites U1605) are the key sites for attaining this objective.

2. Test the hypothesis that the general decrease in $p\text{CO}_2$ from the early middle Oligocene to the early Miocene resulted in cold and possibly glacially dominated environments in northwest Greenland. Site U1607 on the middle shelf addresses this objective.
3. Provide information on the timing, sedimentary processes, sediment sources, and Greenland exposure history in the context of late Neogene tectonic adjustments inferred from the seismic record. Pliocene drill sites on the middle shelf (Sites U1606 and U1608) and Oligocene to Miocene Site U1607 on the middle shelf will address this objective.
4. Test the hypothesis that major glacial expansion of the NGrIS is linked with widespread intensification of Northern Hemisphere glaciation (3.3–2.8 Ma). Pliocene drill sites on the middle shelf (Sites U1606 and U1608) will address this objective.
5. Assess recent models for the change in orbital cycles through the MPT by analyzing sediment maturity and regolith history. Pleistocene sites on the slope (Sites U1603 and U1604) and the outer shelf (Site U1605) are the key sites for attaining this objective.
6. Investigate whether high Arctic warmth of the early mid-Pliocene is related to heat advection through the western North Atlantic Ocean and Baffin Bay. Pliocene drill sites on the middle shelf (Sites U1606 and U1608) will address this objective.

3.5. Connections to the 2050 Science Framework

The scientific objectives of IODP Expedition 400 are relevant to Strategic Objectives 3 (Earth's Climate System), 4 (Feedbacks in the Earth System), and 5 (Tipping Points in Earth's History) of the 2050 Scientific Framework. Strategic Objective 3 Earth's Climate System recognizes the importance of understanding ice sheet history as a driver of sea level changes and ocean-atmosphere interactions, including understanding how the polar ice sheets will respond to increasing atmospheric CO_2 concentrations. During Expedition 400, a transect of sites were drilled that capture an extensive history of glaciation in northern Greenland over the last 25 My. This timescale includes past warm periods when atmospheric CO_2 was higher than today and interglacial periods when sea level exceeded today's, indicating significant ice sheet melting. The GrIS has been resilient in the face of modern warming but is showing signs of enhanced mass loss. The unique geologic archive recovered during Expedition 400 spans pre-Northern Hemisphere glaciation, early ephemeral glaciation on northern Greenland, and the expansion of Northern Hemisphere glaciation as recorded by the building of the Melville Bugt TMF. The information gained from Expedition 400 is societally relevant because it will contribute important data to computer models that aim to predict future rates and magnitudes of sea level rise from melting ice sheets. By sampling the natural range of sedimentary processes and responses to climate forcings involved in the change from Arctic warmth to extreme cooling and notably the onset of Northern Hemisphere glaciation, the Expedition 400 archive addresses Strategic Objectives 4 Feedbacks in the Earth System and 5 Tipping Points in Earth's History. A potential tipping point can result from Greenland Ice Sheet meltwaters entering the North Atlantic Subpolar Gyre, impacting areas of deepwater formation and leading to destabilization of the overturning circulation. Expedition 400 data provides high-resolution geologic records for evaluating such tipping points over multiple cycles in the past, which may help to predict how GrIS melt will influence, and be influenced by, today's changing climate.

4. Site summaries

4.1. Site U1603

4.1.1. Background and objectives

Site U1603 (proposed Site MB-23A) is located at 72°59.0386'N, 62°58.8333'W at a water depth of 1801 mbsl below a prominent crescent-shaped protrusion of the Melville Bugt TMF on the northwest Greenland shelf margin (Figures F1, F2). The site was aimed at retrieving a continuous high-resolution record of ice-ocean processes spanning the early late Pleistocene. The depth target was the base of an expanded drift-channel succession situated on the lower slope between the Melville Bugt and Upernavik TMFs that are the modern expression of major paleo-ice streams draining the NGrIS (Knutz et al., 2019; Newton et al., 2017, 2020, 2021). The sedimentary succession is covered

by regional 2-D as well as high-resolution multichannel seismic data providing a detailed seismic stratigraphy to guide the drilling objectives. The strategy at Site U1603 was to core through the youngest Seismic Units 9–11 and reach through a stratified interval within Seismic Unit 8, which appears to predate the channel formation. Site U1603 is paired with Site U1604 located ~35 km northwest, where a complementary stratigraphic coverage can be achieved by targeting an expanded section of Unit 8 and then continue drilling to just below Horizon 7 (Figure F6).

The drift-channel system cored at Site U1603 is influenced by the circulation of deep water masses in Baffin Bay, which is poorly constrained by synoptic data (Tang et al., 2004). Gyre pulses of the West Greenland Current overflow the site at intermediate depths around 300 mbsl (Münchow et al., 2015). The succession is considered to be a product of Pleistocene ice-ocean interactions that were particularly active during periods with ice was grounded on the outer shelf and phases of ice sheet retreat. The scientific objectives for drilling Sites U1603 and U1604 are to (1) test the hypothesis that the NGrIS underwent significant deglaciation at intervals within the frequency range of orbital eccentricity (~100–400 ky) (Schaefer et al., 2016; Knutz et al., 2019) potentially related to exceptionally strong super-interglacials (Melles et al., 2012) and (2) achieve a long-term

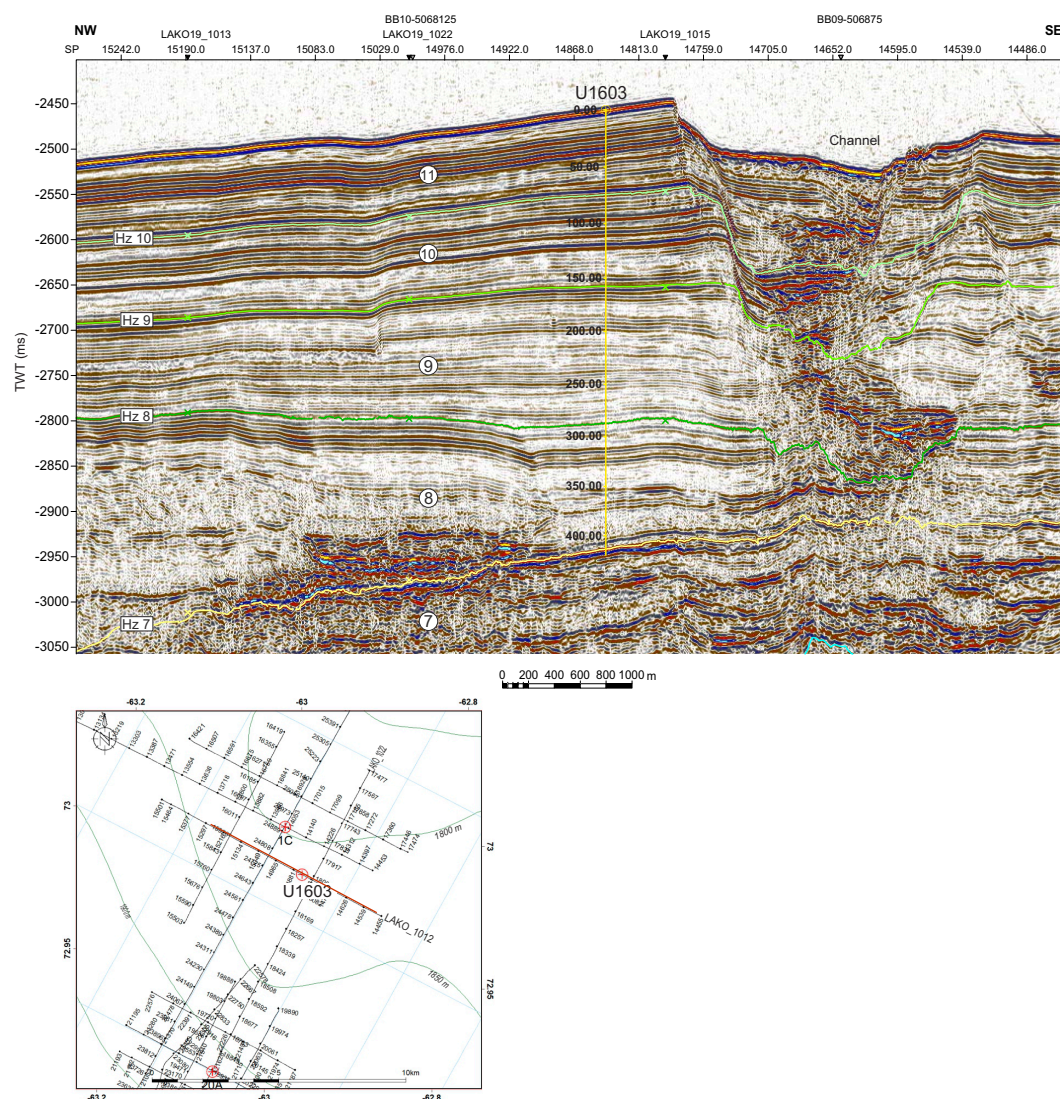


Figure F6. Top: seismic profile LAKO_1012 showing location of Site U1603 on lower slope of Melville Bugt TMF adjacent to a channel. Interpreted Horizons (Hz) 7–10 and associated units (Seismic Unit 11 being topmost) are shown. Vertical scale on Site U1603 line is meter depth based on preferred time–depth model. TWT = two-way travelttime. Bottom: close-up bathymetry map with seismic survey lines in vicinity of Site U1603. Gray line grid = regional 2-D seismic data (TGS), black line grid = high-resolution multichannel seismic data (LAKO19).

understanding (last 0.5 My or older) of marine-based ice sheet dynamics and phasing relations between ice streams draining different sectors of the North American and Greenland Ice Sheets. In particular, we hope that the records can provide insights to ocean conditions through glacial terminations and ice-ocean dynamics associated with the different stages of ice sheet configurations (Simon et al., 2014), which may implicate far-field effects such as opening/closing of the Canadian Arctic Straits (Lofverstrom et al., 2022). Finally, the multiproxy data collected at deep water Sites U1603 and U1604 will contribute to the objective of assessing the regolith hypothesis for the change in orbital insolation frequency across the MPT (Clark and Pollard, 1998; Willeit et al., 2019).

Coring was planned in three holes with a target depth of 250 m core depth below seafloor, Method A (CSF-A), using the advanced piston corer (APC) coring system in the first two holes and 422 m CSF-A in the third hole using the APC/extended core barrel (XCB) coring system. Downhole logging with triple combo tool string, Versatile Seismic Imager (VSI), and Formation MicroScanner (FMS) was planned for the third hole.

4.1.2. Operations

Expedition 400 began in Reykjavík, Iceland, at Skarfabakki Harbor at 0815 h on 12 August 2023. The IODP Expedition 395 science party departed the vessel on 12 August, and on 13 August the crew, staff, and science party of Expedition 400 boarded the vessel, with the oncoming *JOIDES Resolution* Science Operator (JRSO) technical staff arriving at 0900 h and the science party arriving at 1445 h. Immigration checks for those sailing were done dockside in the afternoon and completed by 1600 h. The science party began expedition preparation and received orientations including life at sea and safety training, along with introductions to the laboratories during the rest of the port call. The two ice navigators were set up with Internet access, and the ice analysis and reporting routine was initiated. Freight was completed throughout the port call and included off-going shipments of core and refrigerated and frozen samples as well as the loading of sepiolite (drilling mud), drilling equipment, and fresh and frozen foods. On 16 August, fuel was bunkered and a boat drill was conducted.

The vessel was readied for departure and the pilot came on board at 0745 h on 17 August. The tugs were secured shortly after, and the last line was released at 0806 h, marking the official start of the transit. By 0822 h, the tugboats were released, the pilot departed, and sea passage to Site U1603 began at 0824 h. The vessel remained underway until arriving at Site U1603 at 1355 h on 23 August. The thrusters were lowered and secured at 1412 h, and the vessel was fully in dynamic positioning (DP) mode at 1420 h, ending the transit. The journey covered 1721 nmi at an average speed of 11.3 kt (including pilotage).

The first attempt to spud Hole U1603A was an APC barrel shot from 1802.0 meters below rig floor (mbrf), resulting in a water core. The pipe was lowered 5 m, and a core barrel was shot from 1807 mbrf. Hole U1603A was spudded at 0425 h on 24 August with 4.65 m recovered. The seafloor was calculated at 1800.8 mbsl (1811.9 mbrf). Meters below rig floor depth is 11.1 m greater than meters below sea level. APC coring continued through Core 400-U1603A-13H at 118.6 m CSF-A. The advanced piston corer temperature (APCT-3) tool was run on Cores 4H, 7H, 10H, and 13H. The core liner shattered on Core 13H and had to be pumped out of the liner.

At 1515 h on 24 August, the bridge notified the drill floor that an iceberg had entered the Red Zone (i.e., will be within 3 nmi of the vessel in less than twice the time it will take to trip up to 50 m CSF-A). The drill string was tripped up with the top drive from 109.1 to 43.21 m CSF-A at 1600 h. From 1600 to 1715 h, the vessel tracked two icebergs. At 1715 h, with one of the icebergs entering the Termination Zone (within 1 nmi of the vessel) the order was given to pull the pipe clear of the seafloor. The drill string was again pulled up with the top drive, this time to 1778.3 mbrf, clearing the seafloor at 1742 h and ending Hole U1603A. The vessel was moved 500 m south in DP mode. The closest iceberg passed within ~0.6 nmi of the vessel. Once it was safe to do so, the vessel was moved back over location and offset 10 m northwest from Hole U1603A, coming into position at 2000 h on 24 August.

Hole U1603B was spudded at 2035 h on 24 August. Hole U1603B was washed down to 109.1 m CSF-A by 0100 h on 25 August. Coring began with Core 400-U1603B-2H from 109.1 m CSF-A and continued to Core 5H at 147.1 m CSF-A. After an overpull and drill over of Core 5H, we switched to the half-length APC (HLAPC) system. Coring with the HLAPC started with Core 6F and continued through Core 27F, shot from 243.9 m CSF-A at 0230 h on 26 August. The barrel pulled free from the formation with no overpull; however, the coring line could not pull the barrel up. The drill string was tripped back up to the vessel, with the bit clearing the rig floor at 1157 h, ending Hole U1603B. Once the bottom-hole assembly (BHA) was on board, the core barrel was recovered with 0.08 m of material, likely from the push down trying to free the barrel. The final depth for Hole U1603B was 244.0 m CSF-A.

The vessel was offset 10 m northwest, and Hole U1603C was spudded at 0105 h on 27 August. The hole was drilled down over the next 7.75 h. Cores 400-U1603C-2R through 9R advanced from 211.5 to 285.0 m CSF-A and recovered 22.78 m (33%). At 1945 h on 27 August, ice moved within 3 nmi of the vessel and we raised the drill string to 22.3 m CSF-A and began waiting on ice (WOI). At 0000 h on 28 August, ice entered the 1 nmi exclusion zone. We raised the drill string, clearing the seafloor at 0009 h, ending Hole U1603C and continued WOI. The vessel was moved 1200 m east-northeast and then 700 m east-southeast in DP mode to maintain a safe distance from the ice. By 0330 h, the ice had cleared the site and the vessel was positioned 10 m northwest from Hole U1603C.

Hole U1603D was spudded at 0455 h on 28 August and was drilled ahead with a wash barrel to 102.0 m CSF-A. Because ice once again neared the site, we decided to install a free-fall funnel (FFF) to allow us to reenter Hole U1603D. The FFF was deployed at 0950 h, and by 1030 h we resumed drilling ahead in Hole U1603D to 189.0 m CSF-A. At 1400 h, ice moved within 3 nmi of the vessel, and we raised the drill string to 22.3 m CSF-A by 1515 h and began WOI for the remainder of the day.

By 0015 h on 29 August, the ice had cleared the site. The drill string was lowered to 169.6 m CSF-A, and we washed back to 189.0 m CSF-A before drilling ahead to 269.4 m CSF-A. Cores 400-U1603D-2R through 8R advanced from 269.4 to 333.2 m CSF-A and recovered 14.62 m (24%). At 1400 h, ice moved within 3 nmi of the vessel, and we raised the drill string to 22.3 m CSF-A by 1545 h and began WOI. Once again ice entered the 1 nmi exclusion zone, and we raised the drill string, clearing the seafloor at 1930 h. The vessel was moved 1000 m north in DP mode to maintain a safe distance from the ice. By 2157 h, we began to move back toward the site, and the vessel was in position over Hole U1603D by 2348 h on 29 August.

At 0100 h on 30 August, we began preparing the subsea camera system to assist with reentering Hole U1603D. At 0320 h, we successfully reentered the hole and recovered the subsea camera system. The drill string was lowered to 294.4 m CSF-A, and we washed back to 318.5 m CSF-A before encountering material that had fallen into the bottom of the hole. A center bit was dropped, and we washed to 333.2 m CSF-A by 0800 h. Cores 400-U1603D-9R through 18R advanced from 333.2 to 422.0 m CSF-A and recovered 28.69 m (32%). Sepiolite (drilling mud) was swept in the hole, and the bit was released at 2315 h to prepare for logging Hole U1603D. We then tripped the drill string up with the bit positioned at 50.8 m CSF-A in preparation for logging.

The modified triple combo tool string, termed the “quad combo,” was rigged up and, following a repair to the logging winch, was deployed to the base of Hole U1603D (419.5 m CSF-A). The quad combo measures natural gamma ray, density, acoustic velocity, resistivity, magnetic susceptibility (MS), and density. Following a complete pass of the hole, the quad combo was pulled to the rig floor and broken down. The VSI was rigged up, and the protected species watch began at 1600 h on 31 August. The VSI was deployed but almost immediately experienced a communication issue. The tool was brought back on board and repaired. At 1800 h, the VSI was deployed to 413.1 m CSF-A, and stations were measured uphole until 2120 h when fog impacted visibility and the ability to monitor for protected species. After the VSI tool was brought back on board and broken down, the FMS-sonic tool string was assembled and deployed. The FMS-sonic tool string was run, and the tools were back on deck by 0345 h on 1 September. With logging completed, we tripped the pipe out of Hole U1603D, clearing the rig floor at 0900 h and ending Hole U1603D.

An APC/XCB BHA was made up, and we began tripping the drill pipe back to the seafloor at 1200 h. The vessel was offset 10 m northwest in DP mode, and the pipe was pumped with a cleanout tool while the tracer pumps were running. Hole U1603E was spudded at 1745 h on 1 September, and Core 400-U1603E-1H recovered 6.94 m. Core 2H advanced to 16.4 m and recovered 9.75 m (103%). Cores 3H through 6H each advanced 9.5 m but recovered almost no material (less than 20 cm each). The deplugger was run in the pipe. Core 7F advanced from 54.4 to 59.1 m CSF-A and recovered 0.31 m (7%). Following Core 7F we decided to abandon Hole U1603E because of lack of recovery, and the drill string was tripped out, clearing the seafloor at 0140 h on 2 September.

The vessel was offset 10 m southeast of Hole U1603A to hopefully improve recovery and allow for better correlation with other holes. Hole U1603F was spudded at 0235 h on 2 September. Cores 400-U1603F-1H through 5H advanced from 0 to 44.0 m CSF-A and recovered 45.49 m (103%). Core 6F (44.0–48.80 m CSF-A; 4.73 m recovered) was cored with the HLAPC system to help adjust core spacing to cover gaps in Hole U1603A. Cores 400-U1603F-7H through 15H advanced from 48.8 to 134.3 m CSF-A and recovered 66.71 m (78%). The APCT-3 tool was run on Cores 4H and 10H. We then began pulling the drill string out of the hole, clearing the seafloor at 1935 h. The drill string was tripped up, with the bit at the surface at 0030 h. The drill floor was secured for transit, and the thrusters were raised and secured for transit at 0145 h, ending Hole U1603F and Site U1603.

4.1.3. Principal results

4.1.3.1. Lithostratigraphy

Site U1603 consists of six overlapping holes (Holes U1603A–U1603F) cored to a total depth of 422 m CSF-A. Based on 243.6 m of recovered sediment, the 422 m thick section is divided into four lithostratigraphic units. Named lithofacies are sedimentary, are present in all four units with variable predominance, and include mud, calcareous mud, interlaminated to interbedded mud and sand, sandy mud with common clasts, and diamicton (Figure F7).

Sediments recovered are consistent with the site location at the base of the continental slope proximal to a glaciated margin and deposited during the early to late Pleistocene. The deposits from 0 to ~243 m CSF-A (Lithostratigraphic Units I and II) are consistent with downslope and along-slope sedimentation on a channel levee system with high sedimentation rates (~25 cm/ky). The upper ~42 m (Lithostratigraphic Unit I) consists of mud with irregular sand laminae and dispersed clasts. A thick sequence of interlaminated to interbedded mud and sand is predominant between ~42 and 243 m CSF-A (Lithostratigraphic Unit II) and is further divided into two subunits distinguished by laminae/bed thickness, proportion of mud versus sand, and clast occurrence. Lithostratigraphic Subunit IIA (42–145 m CSF-A) consists of finer laminae, thinner sand beds, and a lower proportion of sand, whereas Lithostratigraphic Subunit IIB (~145–243 m CSF-A) has thicker laminae and beds, a higher proportion of sand, and a relatively higher clast abundance. From 243 to 374 m CSF-A, weakly stratified mud lithologies were dominant, sand lithofacies were rare, and clast occurrence increases significantly (Lithostratigraphic Unit III). In the lower ~46 m of the Hole U1603D (Lithostratigraphic Unit IV; 374–422 m CSF-A), weakly stratified muds similar in character to Unit III are present, but this unit also contains an interval of calcareous mud and various types of soft-sediment deformation that is absent in overlying Unit III.

4.1.3.2. Micropaleontology

Core catcher samples from Holes U1603A–U1603D, together with additional samples from split sections, were examined for foraminifera, diatoms, dinocysts, and other palynomorphs. The additional samples examined for all microfossil groups were taken within cores where variations in lithology were observed. Sampling targets included intervals of massive muds, bioturbation, and muds with dispersed clasts that coincided with low natural gamma radiation (NGR) values, as well as carbonate-rich intervals. Mudline samples from Holes U1603A and U1603F were also examined. Cores from Holes U1603E and U1603F, which include a second copy of the upper ~130 m of the cored section, were not examined. Observations of foraminifera from palynomorph and diatom slide preparations were integrated in the overall foraminifera evaluations. Calcareous nannofossils were observed in smear slides by the sedimentology team in one core catcher sample and

two diatom slides. A cursory examination of these was attempted but requires further study by a nanofossil specialist.

The muds and interlaminated sands and muds typical of Site U1603 are generally barren of diatoms and foraminifera. Where foraminifera appear, including planktonic and benthic species, they remain as trace to rare occurrences, except for two distinct intervals in Cores 400-U1603A-8H and 400-U1603D-13R where the planktonic foraminifera species *Neogloboquadrina pachyderma* is common to abundant. Diatoms were found in about 6% of all samples examined with trace to rare amounts of specimens and species. Palynomorph preparations revealed persistent contributions of phytoclasts and reworked terrestrial pollen and spores. The observed microfossil specimens and assemblages for all groups are typical of cold-water polar environments and in situ dinocyst species are typical of coastal or neritic environments. Observed specimens and assemblages are broadly consistent with a Pleistocene and younger age. The observed planktonic and benthic foraminifera species have long stratigraphic ranges and provide limited age control; however, the observed dinocysts are of Pleistocene and younger age. More detailed analysis of calcareous nanofossils may provide future constraints and a test of the paleomagnetic reversal interpretations and provisional age model.

One mudline sample was collected for sedimentary ancient DNA (sedaDNA) in Hole U1603A. A total of 60 additional samples for sedaDNA analysis were collected: 9 samples from Hole U1603E

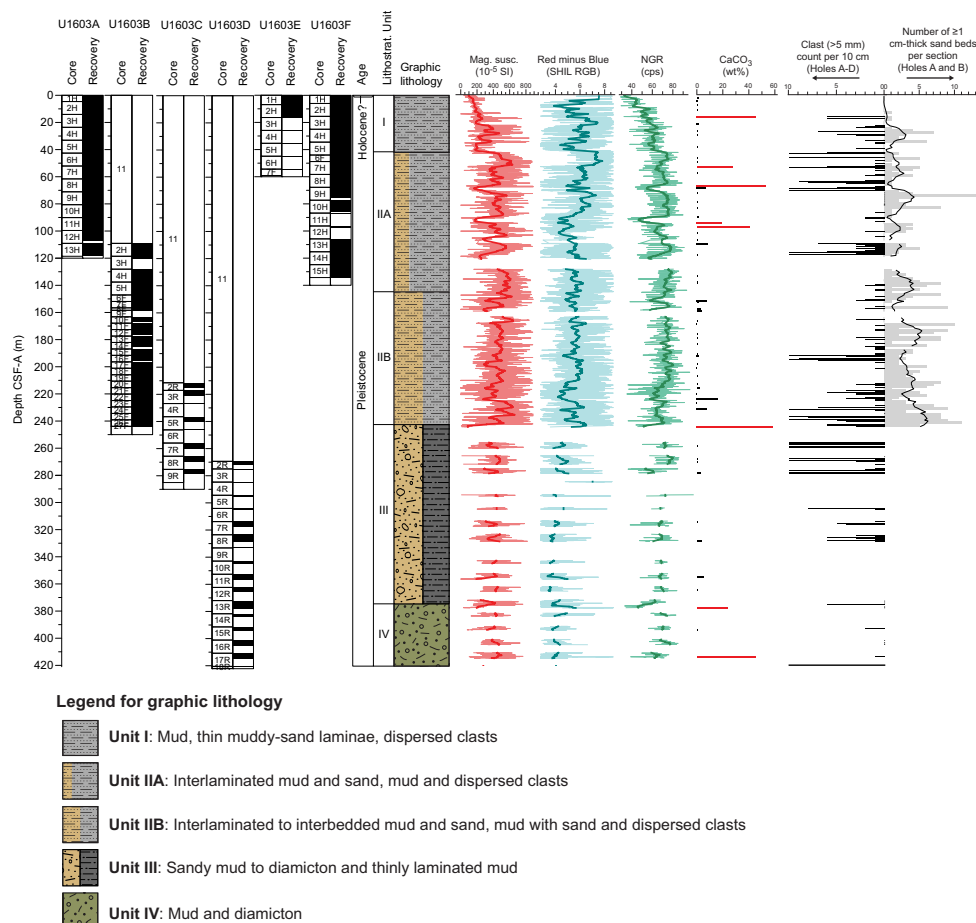


Figure F7. Lithostratigraphic summary, Site U1603. All Section Half Multisensor Logger (SHMSL) point MS measurements were filtered to exclude measurements greater than two standard deviations from mean (thin red line) and depth-based rolling average of filtered data using a 10 m window (thick red line). Same method was used to plot red minus blue Section Half Imaging Logger (SHIL) data and whole-round NGR measurements. Total weight percent calcium carbonate in measured samples are also shown (red lines = samples from intervals identified as calcareous mud [Lithofacies 2]). Clasts count per 10 cm data are centered on middle of 10 cm interval. Number of sand beds ≥ 1 cm thick per core section are centered on middle of core section (black line = depth-based rolling average of data using a 10 m window). cps = counts per second.

and 51 samples from Hole U1603F. Catwalk samples were generally taken at the bottom of Sections 1, 3, and 5 (if the section was available and the section bottom was undisturbed). Additional samples were collected in the working half of split sections targeting nonstratified mud layers characterized by low values of NGR and MS. All samples were immediately stored at -86°C . To assess the potential for contamination during coring and the sectioning of cores on the catwalk, a perfluorocarbon tracer was added to the drilling fluid and the majority of samples have a contamination level close to or below detection limit.

4.1.3.3. Paleomagnetism

Pass-through paleomagnetic measurements from Site U1603 were performed to investigate the natural remanent magnetization (NRM) in a total of 313 archive-half sections. Measurements were not made on 16 archive-half sections that had highly disturbed sediments, and no pass-through measurements were made on core catcher samples. All measurements on section halves were made at 2 cm intervals; we measured the initial magnetization and the magnetization following stepwise peak alternating field (AF) demagnetizations at 5, 10, 15, and 20 mT. Inclinations from filtered data imply that periods of both normal and reversed polarity were recovered at Site U1603. Most inclination magnitudes fall under expected values for the latitude of Site U1603 during normal (positive inclinations) and reversed (negative inclinations) polarities.

A total of 188 discrete cube samples were taken from the working-half sections from Holes U1603A–U1603D. Generally, we collected one sample per section, avoiding visually disturbed intervals. We measured 54 samples on the AGICO JR-6A spinner magnetometer, and 146 samples on the superconducting rock magnetometer (SRM). Some samples were measured on both instruments to ensure cross-calibration. Anhysteretic remanent magnetization (ARM) was also measured on a subset of 45 discrete samples from Holes U1603A and U1603B. These measurements were compared with bulk MS. The relationship between ARM and MS is quasilinear, which suggests that the concentration of magnetic minerals is the primary control on both measurements, and supports the use of normalized remanence for estimating relative paleointensity.

4.1.3.4. Physical properties

Physical property data were acquired on all cores of Holes U1603A, U1603B, U1603C, and U1603D using the Whole-Round Multisensor Logger (WRMSL) for wet bulk density from gamma ray attenuation (GRA), MS, and *P*-wave velocity (*P*-wave logger [PWL]). We also measured NGR in all sections longer than 50 cm. Thermal conductivity was measured in one whole-round section per core, when possible. However, it was measured on one working-half section per core if the sediment was too hard or the whole-round measurement readings were unreliable. For Holes U1603E and U1603F, only NGR and low-resolution MS were logged. These cores were sampled for pore water, thus equalization to room temperature was not possible, and therefore PWL measurements were not made. They were also sampled for sedaDNA, thus the GRA source was kept inactive during WRMSL logging to avoid possible effects on the DNA.

Once the whole rounds were split into two halves, we acquired X-ray imaging 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 (RGB) color of the sediments with digital color imaging. In addition, we determined *P*-wave velocities at discrete points on the working halves of almost all cores from Site U1603. In general, we measured discrete *P*-wave velocity in 3 sections per core for APC cores and 2 sections per core for HLAPC and rotary core barrel (RCB) cores. However, caliper *P*-wave velocity (PWC) was measured in all sections of Holes U1603E and U1603F to compensate the lack of PWL measurements. The measurement interval within each section was changed to accommodate lithologic variations. Two samples per core for moisture and density (MAD) were taken and processed from Holes U1603A–U1603D to obtain discrete wet bulk density, dry bulk density, grain density, and porosity.

Prominent variations in physical property values occur at similar depths in NGR, density, and MS and are associated with major lithologic changes in the cores. More uniform lithologies are reflected by more monotonous physical property signals. The correlation between these physical properties distinguishes four physical properties (PP) units (I–IV) for Site U1603. In PP Unit I (0–20 m CSF-A), NGR, density, and MS all increase gradually downhole through the unit, which

simultaneously transitions from mud to interlaminated mud with thin sandy beds. PP Unit II (20–160 m CSF-A) is characterized by high-amplitude variability in NGR, density, and MS. The lithology of PP Unit II is widely variable, and mud intervals correspond to low values of NGR, density, and MS whereas intervals of interbedded mud with abundant sand layers have high NGR, density, and MS values. In PP Unit III (160–215 m CSF-A), NGR is relatively constant whereas MS and density decrease slightly downhole in the unit. The low variability of these physical properties in PP Unit III occurs in a sand dominated lithology, and minimum MS values in the unit correlate to interbedded thin layers of mud. PP Unit IV (215–422 m CSF-A) is placed within a transition from primarily diamicton to primarily mud and sandy mud with small intervals of diamicton. High-amplitude variability of NGR, density, and MS is likely related to this lithologic transition.

4.1.3.5. Geochemistry

Samples for headspace gas, interstitial water (IW) chemistry, and bulk sediment geochemistry were analyzed at Site U1603. Headspace hydrocarbon gas measurements show low concentrations in the upper 150 m and higher concentrations of methane, with a low yet consistent presence of ethane, in sediments below 150 m CSF-A. A key observation from IW analysis is a decrease in lithium and potassium with depth, possibly suggesting clay formation. A monotonic decrease in sulfate with depth to a minimum at around 150 m CSF-A may provide evidence for a sulfate–methane transition zone. IW iron, manganese, and phosphate show elevated concentrations near the seafloor and sharp decreases to low concentrations with depth. Increases in IW calcium and alkalinity in the shallower depths 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 wt%.

4.1.3.6. Stratigraphic correlation

The physical property records for Site U1603 were compared and correlated where possible to establish a common depth scale. To minimize coring gap alignment, sequences from Holes U1603A–U1603D were examined using whole-round MS (2 cm resolution; WRMSL) and NGR (10 cm resolution; all holes) data. In addition, NGR and MS (5 cm resolution) data were measured on sections from Holes U1603E and U1603F and examined in near-real time to ensure adequate coring depths to fill the gaps in Hole U1603A. Because triple APC offset coring was abandoned in favor of reaching the total depth at Site U1603, the splice could only provide partial stratigraphic coverage. The difficulty was further magnified by low recovery rates below 105 m CSF-A. Thus, Holes U1603A, U1603B, U1603C, and U1603D are correlated to each other, but they were mostly aligned by the seafloor. Holes U1603E and U1603F were correlated to Hole U1603A, completing a splice of the upper 78 m core composite depth below seafloor, Method A (CCSF-A). Although it is still not possible to build a complete CCSF-A depth scale for Site U1603, the high recovery and core alignment between Holes U1603A, U1603E, and U1603F allows for the construction of a pseudo-splice to 98.5 m CCSF-A.

4.1.3.7. Age model

The age model for Site U1603 is largely based on magnetostratigraphic interpretations from Holes U1603A–U1603D. From the seafloor to ~194 m CSF-A, sediment is characterized by normal polarity and is interpreted to be the Brunhes Chron. At ~194 m CSF-A, there is a transition to reversed polarity, likely representing the Brunhes/Matuyama boundary. We also observe a shallowing in inclinations in the lower part of Core 400-U1603A-1H, likely representing the Laschamp excursion. Between the Laschamp excursion and the bottom of the Brunhes Chron, we estimate an average sediment accumulation rate of ~25 cm/ky. The normal polarity zone below ~327 m CSF-A in Hole U1603D is not well constrained because of gaps in recovery and drilling disturbance; however, it may be interpreted as the Jaramillo Subchron. The coarse biostratigraphic constraints provided by dinocysts and sporadic foraminifera and diatom occurrences are consistent with this interpretation of the magnetostratigraphy.

4.1.3.8. Downhole measurements

Downhole logging was carried out in Hole U1603D. A modified triple combo tool string, the quad combo, was deployed with Magnetic Susceptibility Sonde (MSS), natural gamma ray, electrical laterolog resistivity, acoustic velocity, and density tools. Upon completion of the downhole logging

with the quad combo, vertical seismic profiling was attempted with the VSI. The VSI aimed to obtain an accurate time-depth relationship to tie the logging and coring results with the seismic data. A total of 15 stations were planned for the geophones to record seismic images on the hole; however, a decrease in visibility due to fog resulted in terminating the VSI experiment after 10 stations were attempted. The coupling between the geophone and the hole failed at the bottom station. The FMS was run together with the Dipole Sonic Imager (DSI) to obtain formation resistivity and velocity data that were used in the core-log-seismic correlation of this site. The DSI was used for calibration/comparison with the velocities obtained using the quad combo. Logging measurements were crucial for covering recovery gaps during RCB coring. The downhole natural gamma ray and density logs have features in common with the equivalent laboratory data from Site U1603 with small offsets between log and core data because of the assignment of core depths when core recovery was not 100% and other effects. Additionally, the APCT-3 was deployed four times in Hole U1603A and two times in Hole U1603F, and formation measurements were used to derive a local geothermal gradient and heat flux.

4.2. Site U1604

4.2.1. Background and objectives

Site U1604 (proposed Site MB-02C) is located on the lower slope below the Melville Bugt TMF at a water depth of 1943.6 mbsl at 73°06.9077'N, 63°47.3996'W 16 km northwest of Site U1603 (Figure F8). The site targeted a high-resolution sediment drift sequence hypothesized to represent interactions between bottom contour currents and sediments supplied by NGrIS fluctuations from the early/middle Pleistocene age (up to 1 My) to present. The targeted sequence includes Seismic Units 8–11, especially focusing on an expanded interval of Seismic Unit 8, compared to Site U1603. Seismic Units 8–11 represent the most recent stages in the developmental history of the TMF. This site overlaps stratigraphically with the strata drilled at Site U1603. Accordingly, the two deepwater sites share similar objectives (see [Site U1603](#)). With a deeper stratigraphic target, Site U1604 is particularly relevant for testing the hypothesis that the NGrIS underwent significant deglaciation at intervals within the frequency range of orbital eccentricity (~100–400 ky) and assessing recent models for the change in orbital cycles through the MPT.

Coring was planned in two holes with a target depth to 432 m CSF-A in both holes using the APC/XCB coring system. Downhole logging with the triple combo tool string, VSI, and FMS was planned for the second hole.

4.2.2. Operations

The vessel transited 16 nmi from Site U1603 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 DP mode at 0337 h. The rig crew made up an APC/XCB BHA and began tripping the drill pipe. Hole U1604A was spudded at 1020 h, and Core 400-U1604A-1H recovered 2.04 m. The seafloor was calculated as 1942.2 mbsl. Cores 1H–26H advanced from 0 to 206.8 m CSF-A and recovered 195.34 m (96%). Temperature measurements were made on Cores 4H, 7H, 10H, and 13H.

We switched to the HLAPC coring system; however, Core 27F only recovered 2.85 m after a partial stroke. We then switched to the XCB coring system, and Cores 28X–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 WOI. By 2300 h, the ice had moved a sufficient distance away from the vessel and we began to lower the drill string back into Hole U1604A.

The drill string was lowered back into Hole U1604A and washed back to 233.0 m CSF-A by 0100 on 5 September. Cores 31X–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.

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 400-U1604B-1H through 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–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–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 31F–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 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 36X–55X advanced from 237.6 to 429.6 m CSF-A and recovered 88.25 m (46%).

Sepiolite (drilling mud) was swept in 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 was set at 58.7 m CSF-A.

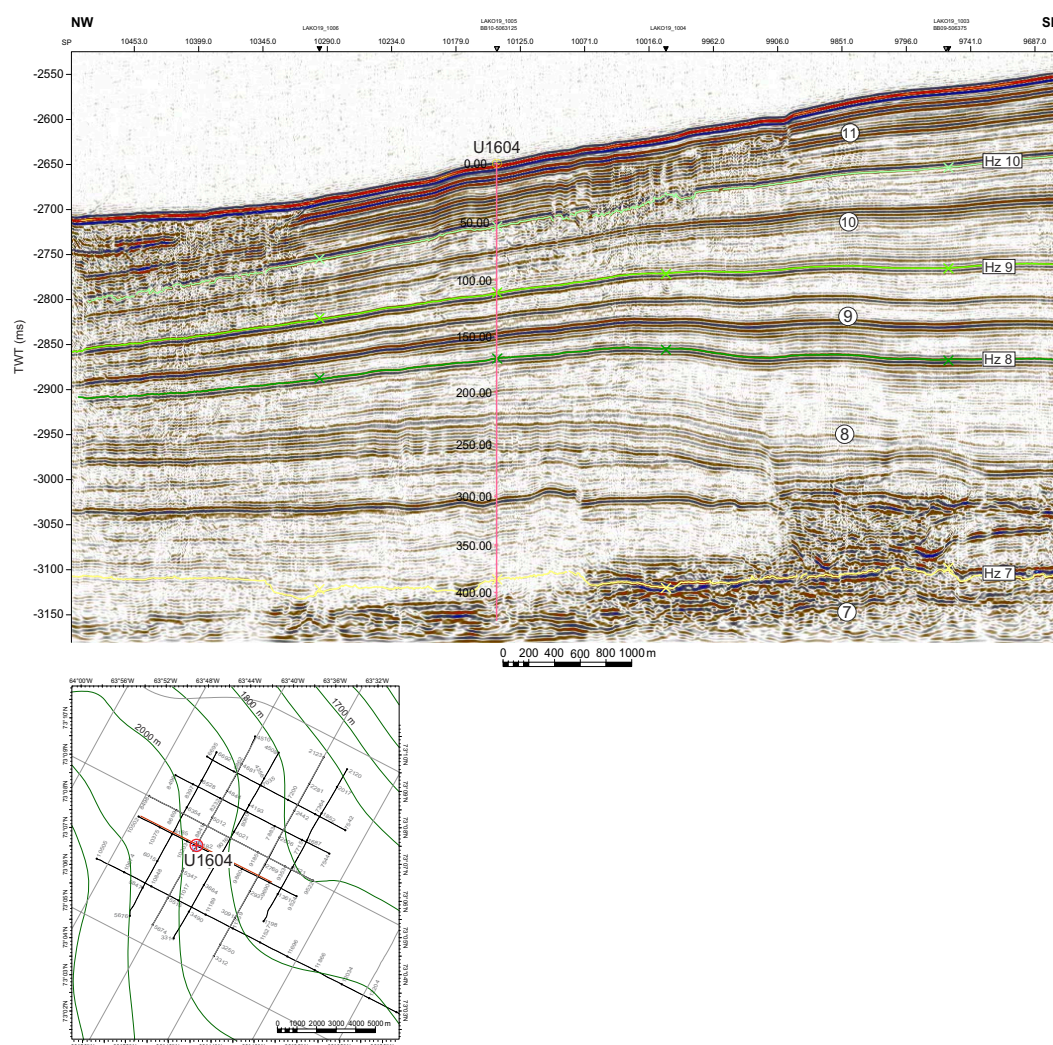


Figure F8. Top: seismic profile LAKO_1010 showing location of Site U1604 on lower slope of Melville Bugt TMF. Interpreted Horizons (Hz) 7–10 and associated units (Seismic Unit 11 being topmost) are shown. Vertical scale on Site U1604 line is meter depth based on preferred time-depth model. SP = shotpoint, TWT = two-way traveltime. Bottom: close-up bathymetry map with seismic survey lines in vicinity of Site U1604. Gray line grid = regional 2-D seismic data (TGS), black line grid = high-resolution multichannel seismic data (LAKO19).

The quad 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 was then assembled and deployed at 0640 h. The FMS was run, and the tools were back on deck by 1200 h. With logging completed 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, ending Hole U1604B and Site U1604.

4.2.3. Principal results

4.2.3.1. 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 (Figure F9). Lithostratigraphic Unit I comprises the upper ~210 m CSF-A of this site, and all lithofacies are present in various proportions. Lithostratigraphic Unit I is divided into Lithostratigraphic Subunits IA and

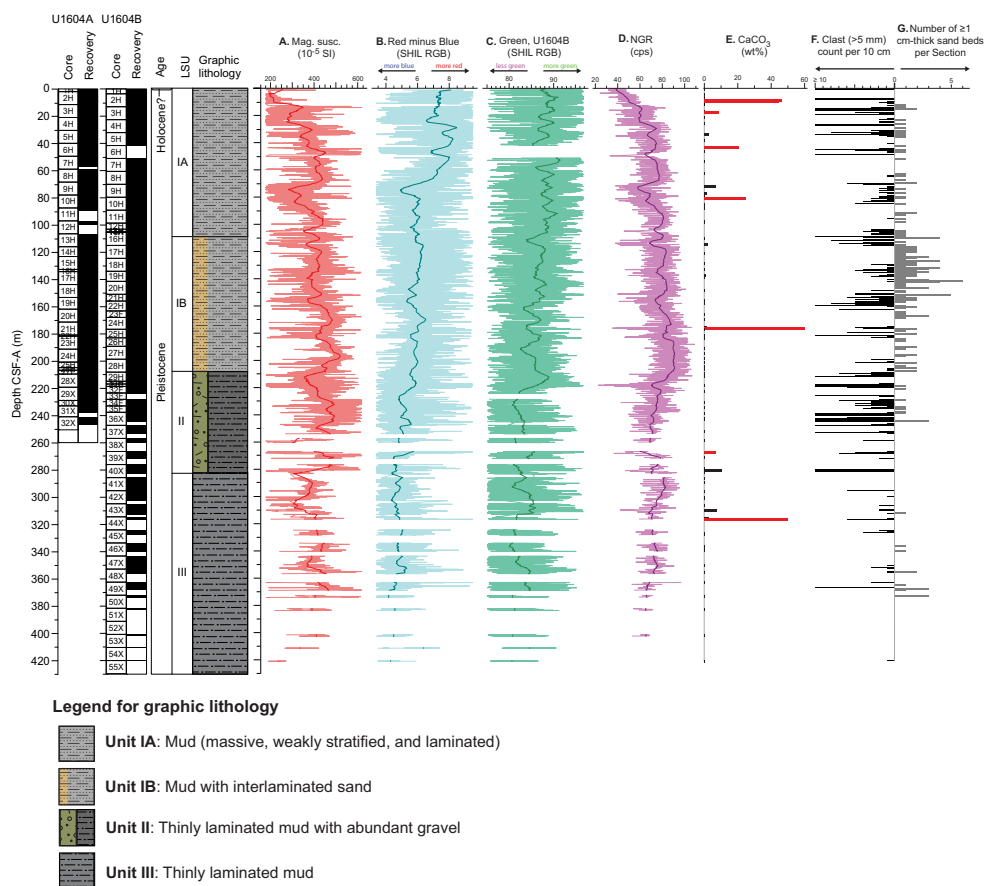


Figure F9. Lithostratigraphic summary, Site U1604. A. SHMSL point MS measurements filtered to exclude measurements greater than one standard deviation from mean of all values (thin red line) and depth-based rolling mean of these values with a 5 m window (thick red line). Higher MS values are typically associated with presence of silt, sand, and gravel. Lower MS values are typically associated with dominance of clay-sized particles and detrital carbonate layers. B. Section Half Imaging Logger (SHIL) RGB red minus blue values calculated by subtracting blue magnitude from red magnitude and subsequently filtered to exclude measurements greater than one standard deviation from mean of all values (thin blue line) and depth-based rolling mean of these values with a 5 m window (thick blue line). Abrupt increases in red minus blue values are typically associated with detrital carbonate intervals, especially when accompanied by dip in NGR and MS values. C. Hole U1604B SHIL RGB green values filtered to exclude measurements greater than one standard deviation from whole mean (thin green line) and depth-based rolling mean of these values with a 5 m window (thick green line). Fluctuations in this value are meant to highlight changes in prevalence of green-tinted muds. D. Whole-round NGR (thin purple line = unfiltered, thick purple line = depth-based rolling mean of these values with a 5 m window). cps = counts per second. E. Total weight percent calcium carbonate in measured samples (red lines = samples from intervals identified as calcareous mud or sand [Lithofacies 3]). F. Number of clasts >5 mm in diameter per 10 cm. Bars are centered on measured interval. G. Number of sand beds ≥ 1 cm thick per core section. Bars are centered on core section.

IB. Subunit 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 subunit, IB, has a larger proportion of interlaminated sand and mud and has relatively fewer outsized clasts (>2 mm diameter). Lithostratigraphic Unit II is dominated by laminated mud and diamicton, often occurring as decimeter-scale interbeds. The laminated mud lithofacies continues to be characteristic downhole into Lithostratigraphic Unit III, which is characterized by a significant reduction in sand laminae and gravel-bearing sediment compared to Unit 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 down-slope processes and likely ice rafting (providing granule- to boulder-sized clasts) and plumites.

4.2.3.2. 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 sedaDNA from the APC/HLAPC cores of Hole U1604B (through Core 400-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 dinocysts, which are present but scarce throughout the site, and 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 15 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 broadly 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.

4.2.3.3. Paleomagnetism

Pass-through paleomagnetic measurements from Site U1604 were performed using the SRM to investigate the NRM on a total of 389 archive-half sections (157 sections from Hole U1604A and 91 sections from Hole U1604B). Measurements were not made on archive-half sections 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 AF demagnetization of 20 mT. A total of 248 discrete cube samples were taken from the working-half sections. 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. 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 direct current (DC) field, and the remanence was measured. Comparison of the ARM with volume-normalized bulk MS shows a quasilinear relationship between ARM and MS, suggesting that the concentration of magnetic minerals is the primary control on both measurements and supporting the use of normalized remanence for estimating relative paleointensity.

4.2.3.4. Physical properties

Physical property data were acquired on all cores from Holes U1604A and U1604B using the WRMSL for wet bulk density from GRA, MS, and *P*-wave velocity (PWL). We also measured 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 400-U1604B-1H through 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 WRMSL logging.

Prominent variations in physical property values occur at similar depths in NGR, density, and MS and are associated with major lithologic changes in the cores. More uniform lithologies are reflected by more monotonous physical property signals. The correlation between these physical properties distinguishes the four PP units (I–IV) of Site U1604. PP Unit I (0–13 m CSF-A) is distinguished by increases in NGR, density, and MS that may be related to a decrease in water content below the mudline. Below, in PP Unit II (13–90 m CSF-A) high amplitude variability in NGR, density, and MS reflects broad variability in the lithology. Low values of NGR, density, and MS correlate with mud intervals, whereas intervals of interbedded mud and sand have higher NGR, density, and MS values. In PP Unit III (90–210 m CSF-A), NGR, MS, and density increase slightly downhole within the unit. The low variability of these physical properties in PP Unit III is within a sand dominated lithology, and minimum MS and NGR values in the unit correlate to intervals of mud. PP Unit IV (210–420 m CSF-A) is defined by low amplitude variability of NGR, MS, and density, which all slightly decrease downhole within the unit, which corresponds to a lithologic transition from mud to sand layers interbedded with diamicton.

4.2.3.5. Geochemistry

Samples for headspace gas, 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 CaCO_3 with contents of up to 60%.

4.2.3.6. 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. Because 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 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 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 400-U1604A-1H to 400-U1604B-2H, Cores 400-U1604A-3H to 400-U1604B-6H, and Cores 400-U1604A-7H to 400-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 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 was used to improve the depth accuracy of these cores.

4.2.3.7. 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 to be 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). DIPs are calculated from the normalized remanence ($\text{NRM}_{20\text{mT}}$) divided by MS. Seven well-defined DIPs in the Site U1604 relative paleointensity 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 MISs of the LR04 stack of Lisiecki and Raymo (2005) are at 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 because of 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 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. The coarse biostratigraphic constraints provided by dinocysts and sporadic foraminifera and diatom occurrences in Holes U1604A and U1604B are consistent with this interpretation of the magnetostratigraphy.

4.2.3.8. Downhole measurements

Downhole logging was carried out in Hole U1604B upon completion of the coring operations. A modified triple combo tool string was deployed with MSS, natural gamma ray, 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 below the pipe (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 that were used in the core-log-seismic correlation of this site.

Upon completion of 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 because 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 APCT-3 tool was deployed four times in Hole U1604A.

4.3. Site U1605

4.3.1. Background and objectives

Site U1605 (proposed Site MB-31A) is located at 73°33.6421'N, 62°09.0687'W at a water depth of 529 mbsl on the outer shelf of the northwest Greenland shelf margin (Figure F10). Constrained by high-quality seismic data, the objective was to recover potential marine intervals within packages of horizontal, semicontinuous reflections that aggrade over glacial unconformities within topset strata of the Melville Bugt TMF (Knutz et al., 2019). Site U1605 captures Seismic Units 7–10 with a target depth just below Seismic Horizon 6, corresponding to 282 m CSF-A (based on average *P*-wave velocity of 2200 m/s) (Figure F10). The sequence, considered to be mainly of early middle Pleistocene age, overlaps stratigraphically with deepwater Sites U1603 and U1604. The primary lithology was assumed to be compacted diamicton with intervals of sand and pebbly mud, representing marine to glaciomarine deposits, intersected by at least four glacial unconformities. The scientific objectives for drilling Site U1605 are complementary to deepwater Sites U1603 and U1604 but with an emphasis on testing the hypothesis that the NGrIS underwent significant deglaciation potentially related to exceptionally warm or prolonged super-interglacials (Schaefer

et al. 2016; Christ et al., 2023). Additionally, multiproxy data from Site U1605 can be used to assess the regolith hypothesis for the change in orbital insolation frequency across the MPT (Clark and Pollard, 1998).

Coring was planned in two holes with a target depth of 282 m CSF-A in the first hole using RCB coring and then logging with the triple combo and FMS-sonic. The plan for the second hole was to drill ahead to 70 m CSF-A followed by APC/HLAPC/XCB coring to 282 m CSF-A.

4.3.2. Operations

The vessel transited 39 nmi from Site U1604 to Site U1605, arriving on location at 2200 h on 9 September 2023. After we observed that ice was a sufficient distance away from the vessel, the thrusters were lowered and secured at 2224 h, and the ship was fully in DP mode at 2229 h. An RCB BHA was made up and tripped down. We initially attempted to spud Hole U1605A based on a water depth of 524.1 mbsl. Following a 3 m advance, the core barrel returned empty. The pipe was lowered, and Hole U1605A was spudded at 0340 h on 10 September and recovered 3.2 m from an 8.0 m advance. The seafloor was established as 528.66 mbsl. Cores 400-U1605A-1R through 47R advanced from 0 to 282 m CSF-A and recovered 38.45 m (13.6%). We then began pulling the drill string out of the hole, clearing the seafloor at 1535 h on 13 September. The drill string was tripped up, with the bit at the surface at 1720 h. The drill floor was secured for transit, and the

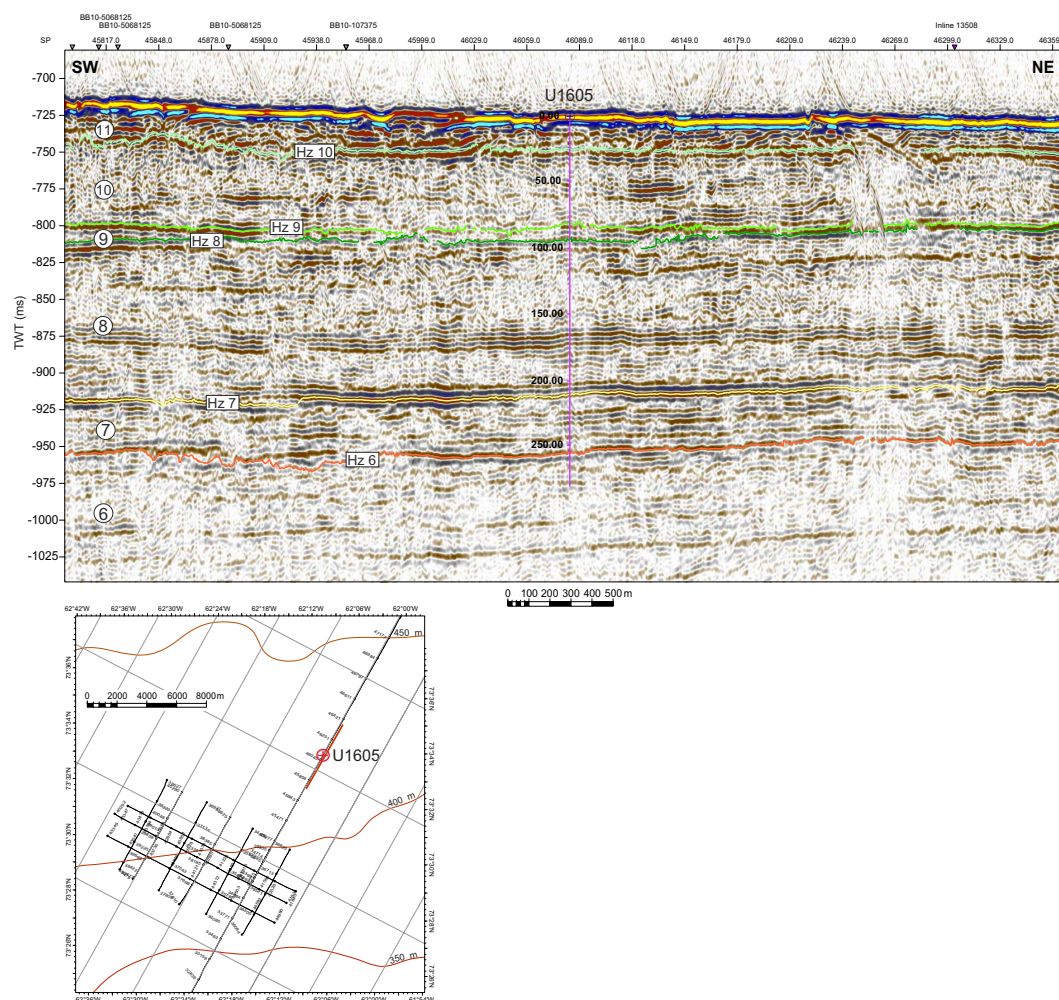


Figure F10. Top: seismic profile (LAKO_1033) showing location of Site U1605 on outer shelf of Melville Bugt, northwest Greenland. Interpreted Horizons (Hz) 6–10 and associated units are shown, with Seismic Unit 11 being topmost below a veneer of younger sediments. Vertical scale on Site U1605 line is meter depth based on preferred time–depth model. SP = shotpoint, TWT = two-way travelttime. Bottom: close-up bathymetry map with seismic survey lines in vicinity of Site U1605. Gray line grid = regional 2-D seismic data (TGS), black line grid = high-resolution multichannel seismic data (LAKO19).

thrusters were raised and secured for transit at 1748 h, ending Hole U1605A and Site U1605. The rate of penetration at Site U1605 was highly variable (0.16–28.8 m/h) and averaged 4.56 m/h.

4.3.3. Principal results

4.3.3.1. Lithostratigraphy

Because of low recovery, reporting of lithostratigraphy and depositional history is limited at Site U1605. Magnetostratigraphy and biostratigraphy were restricted by discontinuous sampling and require further interpretation. The recovered sediment is tentatively interpreted to be Pleistocene based on seismic stratigraphic constraints.

The stratigraphy of Site U1605 is summarized as one lithostratigraphic unit comprising two sub-units (Lithostratigraphic Subunits IA and IB; younger to older) (Figure F11). Named sedimentary lithofacies include massive diamicton and stratified diamicton. A significant proportion of core recovered contained “washed gravel” (a form of core disturbance) with lithologies consistent with clasts present in the diamicton. Of the ~13% recovered, ~8% (~23 m cumulative) is diamicton with the remaining ~5% made up of washed gravel. Subunit IA contains the upper ~83 m CSF-A and is composed of massive diamicton and gravel clasts (washed gravel) that are retained in the core barrel when finer unconsolidated sediment washed out during drilling. Subunit IB extends from 83 to 275.1 m CSF-A (deepest recovery) and consists of massive diamicton, stratified diamicton, and washed gravel.

4.3.3.2. Micropaleontology

Recovery was consistently poor, and many cores did not produce core catcher sediment samples. Where sediment was recovered, core catcher samples were composed of diamicton. Despite the

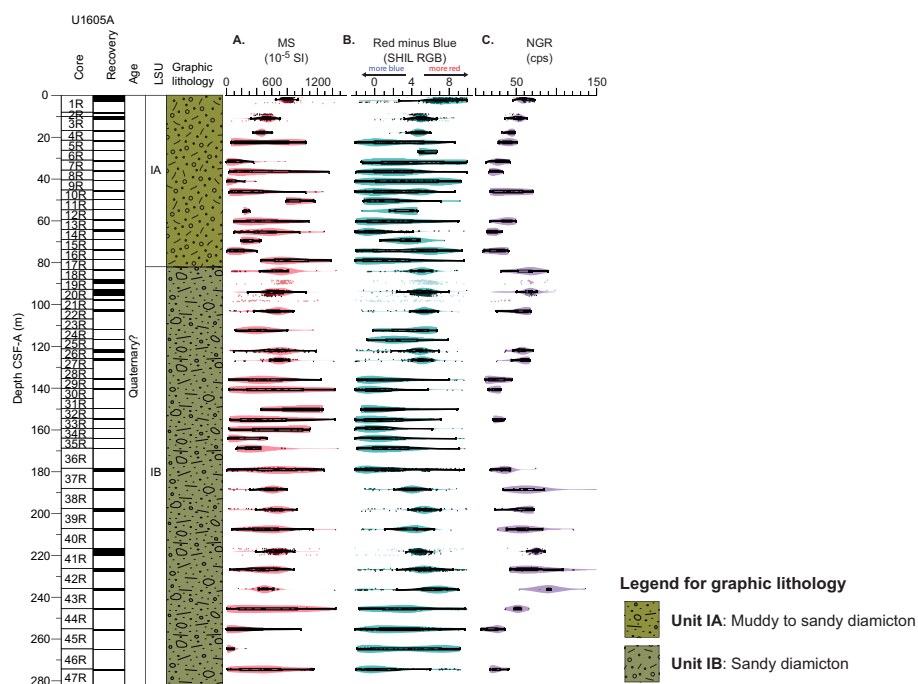


Figure F11. Lithostratigraphic summary, Site U1605. Because of discontinuous core recovery, this figure emphasizes measurements from discrete recovered intervals, instead of downcore trends emphasized for other sites. Changes in physical properties did not appear to correlate to lithologic changes. Prior to plotting, (A) SHMSL point MS and (B) Section Half Imaging Logger (SHIL) RGB data were filtered to exclude measurements greater than one standard deviation from whole mean with the intention of excluding most pebbles, cobbles, or boulders and making the plot more representative of recovered diamicton intervals; (C) NGR data were not filtered prior to plotting. Red minus blue values were calculated by subtracting blue magnitude from red magnitude. Light colored dots = individual filtered measurements. Box plots are at median depth of represented population, showing interquartile range (box), median (thick black line), and whiskers extend to 1.5 times interquartile values. Transparent, amorphous shapes around box plots are violin plots of the same data, whose relative thicknesses at any x value shows relatively likelihood (kernel density estimate) of a member of the population occurring at that value.

indurated nature of the diamicton, the material disaggregated relatively easily. A total of 12 core catcher samples from the 47 cores of Hole U1605A and 1 mudline sample were prepared and examined for foraminifera, diatoms, dinocysts, and other palynomorphs. The samples were largely barren of foraminifera and diatoms. Diatoms were visually barren in the majority of samples, except in the mudline sample, which contained rare, poorly preserved diatoms typical of modern Arctic marine environments. Dinocysts and other palynomorphs, including Leisospheres (a group of acritarchs), were observed in multiple samples. A mudline sample (~10 g) was collected as a modern DNA reference in Hole U1605A. No samples were collected for sedaDNA analysis.

4.3.3.3. Paleomagnetism

Recovery from Site U1605 was poor, containing many barrels of washed gravel. However, where cohesive diamicton was present, paleomagnetic measurements were made on the archive halves with the SRM and on discrete samples from the working halves, either cut using a parallel saw or collected using J-cubes. The 11 discrete samples were measured after stepwise demagnetization up to 80 mT peak AF demagnetization. Magnetic fabric assessed by anisotropic magnetic susceptibility indicated some potential disturbance of the sedimentary fabric. NRM and the remanence after 10 and 20 mT peak AF demagnetization were measured on 16 archive-half sections where diamicton was continuous for at least 40 cm. Careful filtering of the data for section end effects and/or other disturbances revealed an inclination change from steeply downward directions consistent with normal polarity at 217 m CSF-A to steeply upward directed below 217 m CSF-A, consistent with reversed polarity.

4.3.3.4. Physical properties

Standard physical property measurements were made on cores from Site U1605 using the WRMSL, SHMSL, and Natural Gamma Radiation Logger (NGRL) track instruments. Discrete measurements were also made for MAD analysis, thermal conductivity, and *P*-wave velocity on the PWC system. Because of the low recovery and highly disturbed cored material, PWC measurements were unreliable. PWC was limited to diamictic intervals because values of isolated clasts are not representative of the formation.

Prominent variations in physical property values occur at similar depths in NGR, density, and MS and are associated with major lithologic changes in the cores; however, the low recovery at this site prevents much interpretation of physical properties. Four PP units (I–IV) are identified at Site U1605. In PP Unit I (0–80 m CSF-A), NGR, density, and MS all decrease gradually downhole through the unit, which may be related to a transition from the mudline to clast-rich diamicton and gravel. PP Unit II (80–125 m CSF-A) is identified by a sharp increase in density values, combined with a more gradual increase in NGR and MS indicative of the intervals of diamict and gravel lithologies of the unit. Below, in PP Unit III (125–175 m CSF-A) NGR, MS, and density values are relatively low but have higher amplitude variability, likely due to the gravel present within this unit. PP Unit IV (175–282 m CSF-A) is composed of diamicton with some gravel and has relatively higher NGR, MS, and density values than PP Unit III. Core-log-seismic correlation was based on the average PWC obtained on the diamictic recovered intervals and weighted with gravel intervals based on the recovered lithologies.

4.3.3.5. Geochemistry

Whole-round core samples were processed for IW and headspace (HS) void gas samples were measured at Site U1605; however, the frequency of these samples was limited by the availability of sediment. HS measurements show low concentrations of hydrocarbons in the upper 130 m CSF-A and increasing concentrations at depth, with a low yet consistent presence of ethane below 180 m CSF-A. Although low recovery and sporadic sampling led to a discontinuous pore water record, the main findings from IW analysis include decreases in lithium and potassium with depth. A monotonic decrease in sulfate with depth to a minimum around 190 m CSF-A provides evidence for a sulfate–methane transition zone. IW iron, manganese, and phosphate show elevated concentrations near the seafloor and sharp decreases to low concentrations with depth. Increases in calcium and alkalinity in the upper ~100 m CSF-A are also observed. Elemental analysis of solid material revealed very low concentrations of carbon and nitrogen throughout the hole.

4.4. Site U1606

4.4.1. Background and objectives

Site U1606 (proposed Site MB-17A) is located at 74°13.9380'N, 61°2.2426'W at a water depth of 653 mbsl on the middle section of the northwest Greenland shelf (Figure F3). The site targets the transition from preglacial contourite drift sediments into glacial deposits of earliest TMF progradation (Seismic Unit 1), marking the first advance of the NGrIS onto the continental margin. The drilling target was at 411 m CSF-A near the base of Megaunit B above Horizon c1 (Figure F12), coring a succession that is complementary to Site U1608. The uppermost 180 m at Site U1606 aimed to capture a stratigraphic record of the preglacial to glacial transition that hypothetically corresponds to the Pleistocene/Pliocene boundary (Knutz et al., 2019). Below 150–180 m CSF-A, Site U1606 targeted a 200 m thick sedimentary unit characterized internally by a uniform bundle of tilting strata that converges updip against an erosional scarp defined by Horizon c1 (Figure F12). The seismic geometries imply accumulation of sedimentary drift deposits over a significantly truncated section of Megaunit C (Knutz et al., 2015).

The expected lithologies are gravel-sand, diamicton, and pebbly mud in the upper 40 m CSF-A and mudstone with silty-sandy intervals in the succession below. The seismic characteristics suggest a gradual transition from a deep marine (outer shelf) to a more nearshore environment, eventually replaced by a proglacial setting.

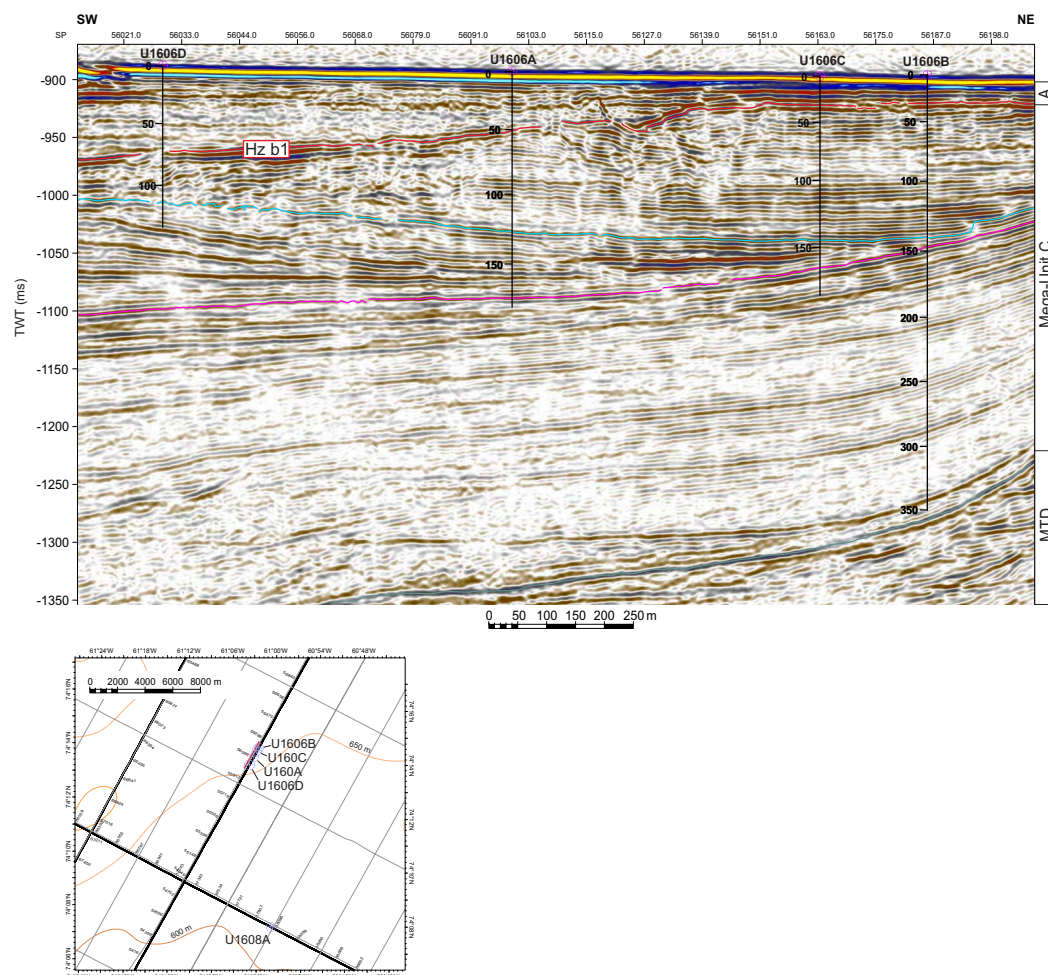


Figure F12. Top: seismic profile (LAKO19_1033) showing location of Site U1606 on outer shelf of Melville Bugt, northwest Greenland. Vertical scale on hole lines are meter depth based on preferred time-depth model. SP = shotpoint, TWT = two-way travelttime, MTD = mass transport deposit. Bottom: close-up bathymetry map with seismic survey lines in vicinity of Site U1606. Gray line grid = regional 2-D seismic data (TGS), black line grid = high-resolution multichannel seismic data (LAKO19).

There are two principal goals for this site: (1) capture deposits corresponding to the earliest shelf-based glaciations in northwest Greenland (earliest glacial clinoforms of Megaunit A) and (2) recover Neogene sediments of likely Pliocene age in Megaunit B that can elucidate paleoceanographic conditions prior to the major expansion of the GrIS (Knutz et al., 2015). Hypothetically, the contourite drift may provide a marine analog to terrestrial outcrops (e.g., Beaufort and Kap Kobenhavn formations), depicting warm climate conditions in the High Arctic during the late Pliocene to early Pleistocene (Gosse et al., 2017).

Planned drilling at Site U1606 included coring with the RCB system from the seafloor to 411 m CSF-A in the first hole. If intervals of special interest (e.g., marine mud) were encountered, a second hole would be attempted by washing down followed by coring using the APC system. Down-hole logging was planned for the first hole, including the triple combo tool string, FMS, and VSI check shots.

4.4.2. Operations

The vessel transited 44 nmi from Site U1605 to Site U1606. The thrusters were lowered and secured, and the ship was fully in DP mode at 2200 h on 13 September 2023. Ice monitoring began, and the vessel made the final approach to the site slowly as ice vacated the area. The rig crew made up an RCB BHA in preparation for Hole U1606A, and the drill string was partially lowered while we waited on ice to clear the site. By 0230 h on 14 September, we positioned the vessel over the site, and Hole U1606A was spudded at 0415 h. Cores 400-U1606A-1R through 20R advanced from 0 to 182.4 m CSF-A and recovered 30.14 m (16%). At 1030 h on 15 September, ice moved within 3 nmi of the vessel, and we raised the drill string to 24.6 m CSF-A by 1215 h. The ice was slow moving (nearly stationary) and was expected to linger over the site for more than a day while moving closer to the vessel. The decision was made to pull out of Hole U1606A and move to proposed Site MB-07B (Site U1607). The drill string was tripped up, with the bit at the surface at 1424 h. The drill floor was secured for transit, and the thrusters were raised and secured for transit at 1500 h.

The vessel transited the 6.6 nmi from Site U1608 back to Site U1606 on 30 September and arrived at 1715 h. The thrusters were lowered and secured, and the ship was fully in DP mode at 1738 h. The rig crew made up an RCB BHA, and the drill string was tripped to near the seafloor. Hole U1606B was spudded at 2125 h, tagging the seafloor at 656.4 mbsl. Cores 400-U1606B-1R through 39R advanced from 0.0 to 350.0 m CSF-A and recovered 164.44 m (47%). We tripped the pipe out of the hole, clearing the seafloor at 0110 h on 3 October, ending Hole U1606B.

The vessel was offset south-southwest of Hole U1606B, and Hole U1606C was spudded at 0245 h. The hole was drilled ahead to 25 m CSF-A before removing the center bit and dropping an RCB core barrel. Cores 400-U1606C-2R through 18R advanced from 25.0 to 186.7 m CSF-A and recovered 45.31 m (28%). We tripped the pipe out of the hole, clearing the seafloor at 0355 h on 4 October, ending Hole U1606C.

The vessel was offset south-southwest of Hole U1606A, and Hole U1606D was spudded at 0625 h on 4 October. The hole was drilled ahead to 13.6 m CSF-A before removing the center bit and dropping an RCB core barrel. Cores 400-U1606D-2R through 14R advanced from 13.6 to 132.1 m CSF-A and recovered 7.83 m (7%). We then tripped the pipe out of Hole U1606D, clearing the rig floor at 0815 h on 5 October. The drill floor was secured for transit, and the thrusters were raised and secured for transit at 1206 h, ending Hole U1606D and Site U1606.

4.4.3. Principal results

4.4.3.1. Lithostratigraphy

The stratigraphy of Site U1606 is divided into four lithostratigraphic units (Figure F13). Site U1606 was drilled along a ~1.3 km long southwest to northeast transect and targeted seismic stratigraphic packages with varying thicknesses in each hole; therefore, the lithostratigraphic units are not laterally continuous and at some sites are not present as a result of stratal pinch-out (Figure F12). Named sedimentary lithofacies include (1) laminated or bioturbated mud with or without dispersed sand; (2) calcareous mud and sand; (3) stratified or bioturbated sandy mud with and without dispersed clasts; (4) stratified or bioturbated muddy sand and sand, with and without

dispersed clasts; (5) interlaminated to interbedded sand and mud; and (6) muddy coarse sand, diamicton, and intraclast conglomerate.

Lithostratigraphic Unit I was recovered in Holes U1606A and U1606B and contains unlithified brown mud to sandy mud, overlying Lithostratigraphic Unit II of sandy diamicton ranging from clast poor to clast rich, also recovered only in Holes U1606A and U1606B. Lithostratigraphic Unit III is formed of sandy mud and muddy sand with dispersed clasts and has two subunits distinguished by the degree of bioturbation and stratification. Lithostratigraphic Subunit IIIA was recovered in all holes at Site U1606 and contains weakly to strongly stratified sandy mud and muddy sand with dispersed clasts. Lithostratigraphic Subunit IIIB is identified only in Holes U1606A and U1606C and is characterized as moderately bioturbated stratified sandy mud to muddy sand with dispersed clasts. Lithostratigraphic Unit IV is defined by alternating bioturbated mud and sandy mud (Lithostratigraphic Subunits IVA and IVC) with interbedded mud and sand (Lithostratigraphic Subunits IVB and IVD). Subunit IVA is present in both Holes U1606B and U1606C, whereas Subunits IVB–IVD are only present in Hole U1606B. Overall, the sedimentary succession collected at Site U1606 is consistent with an ice-proximal, subglacial or proglacial glaciomarine depositional environment with highly variable periods of potential bottom-current reworking.

4.4.3.2. Micropaleontology

Core catcher samples and additional split-core samples from Holes U1606A and U1606B were examined for foraminifera, diatoms, dinocysts, and other palynomorphs. Holes U1606C and U1606D were low recovery and considered duplicate copies and thus were not sampled routinely shipboard for biostratigraphic purposes, apart from two test samples for diatom analysis. Subsequent examination of the cores from all holes suggests considerable lithostratigraphic differences that might warrant full paleontological study in the future. The additional samples from working-half sections were taken in the upper 1.5 m CSF-A of soft, soupy muds of Core 400-U1606A-1R to provide Holocene reference assemblages. Mudline samples from Hole U1606A were also examined. Samples for sedaDNA were collected in Hole U1606B.

The sandy muds and muddy sands, with variable clast contributions, typical of Hole U1606A contain sparse but reasonably well-preserved calcareous microfossils. Where foraminifera appear, only benthic species occur and these remain as trace to rare occurrences, except for Sample 400-

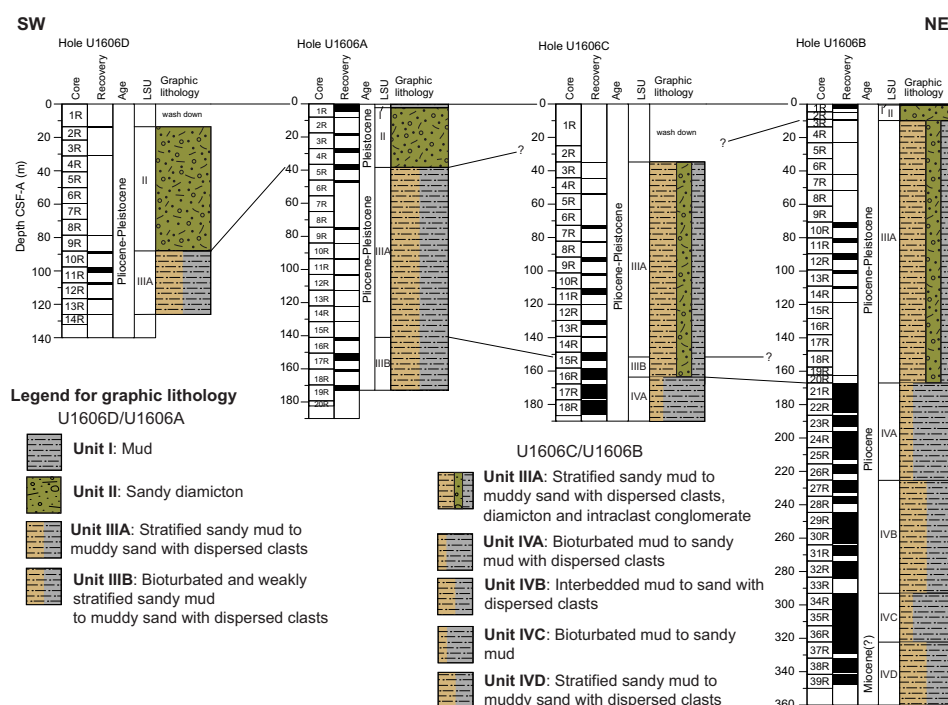


Figure F13. Lithostratigraphic summary, Site U1606.

U1606A-11R-CC-PAL (~94 m CSF-A) where benthic species are rare to common in the >63 μm residue. The benthic foraminifera containing interval from Cores 400-U1606A-10R to 13R (84.51–112.65 m CSF-A) is consistent with an age older than 700 ka. Diatoms were observed in ~52% of all samples examined with poor to moderate preservation. The diatom assemblages observed are consistent with a Pliocene age and signify Atlantic water influence at Site U1606. The dinocyst assemblages downhole to ~84 m CSF-A are indicative of a Pleistocene or younger age. In Holes U1606A and U1606B, reworked late Pliocene dinocysts are present. The assemblages of Hole U1606B are consistent with a Pleistocene to Pliocene age. Palynomorph preparations revealed varying abundances of in situ dinocysts and reworked terrestrial palynomorphs. The observed microfossil assemblages are typical of cold-water Arctic environments. Other fossil components observed include bivalve mollusk shell fragments, pieces of terrestrial wood and plants, and fragments of an encrusting bryozoan implying abundant marine life on the Greenland shelf.

4.4.3.3. Paleomagnetism

Pass-through paleomagnetic measurements from Site U1606 were performed using the SRM to investigate the remanent magnetization on a total of 182 archive-half sections. Measurements were not made on core catcher sections or those that were heavily disturbed. All measurements on archive-half sections were made at 2 cm intervals, up to a peak AF demagnetization of 20 mT. A total of 144 discrete cube samples were taken from working-half sections. Generally, we collected one sample per core section, avoiding visually disturbed intervals, using the parallel saw. Of the discrete samples, 123 were measured on the SRM and stepwise demagnetized up to 40 mT. The inclinations from the filtered 20 mT step archive half data are generally bimodal, with a much larger fraction of reversed polarity measurements. Magnetostratigraphy at Site U1606 is highly uncertain, and correlation between holes is complicated by prominent lateral changes in the sedimentary units, reflected in the seismic stratigraphy.

4.4.3.4. Physical properties

Standard physical property measurements were made on cores from Site U1606 using the WRMSL, SHMSL, and NGRL track instruments. Discrete measurements were also made for MAD analysis, thermal conductivity, and *P*-wave velocity on the PWC system. Because of the low recovery and highly disturbed cored material, PWC measurements were unreliable. PWC was limited to diamictic intervals because values of isolated clasts are not representative of the formation.

Prominent variations in physical property values occur at similar depths in NGR and MS and are associated with major lithologic changes in the cores; however, the abundant low recovery intervals of this site produce a highly fragmented record of physical properties. A positive correlation is found between NGR counts and MS at Site U1606, and the correlation between these physical properties distinguishes six PP units (I–VI) at Site U1606. In PP Unit I (0–170 m CSF-A), only scattered values related to low recovery were obtained and no trends are discernable. Below, in PP Unit II (170–197 m CSF-A) NGR increases downhole and MS values decrease, corresponding to the transition from mud to muddy sand within the unit. Density values remain relatively constant across PP Unit II. PP Unit III (197–250 m CSF-A) is characterized by a decrease in NGR downhole, an increase in MS values, and relatively constant density values. The upper half of PP Unit IV (250–290 m CSF-A) is dominated by interlaminated sand and mud that transitions to sandy mud in the lower half of the unit. NGR increases downhole in the upper part of PP Unit IV before a sharp decrease to minimum values in the lower part of the unit. Changes in MS and density in PP Unit IV are less pronounced, with MS gradually increasing and density gradually decreasing downhole within the unit. PP Unit V (290–335 m CSF-A) is defined by an increase downhole in MS throughout the unit, which is composed of mud and sandy mud. NGR and density remain relatively constant throughout the unit. PP Unit VI (335–350 m CSF-A) is composed primarily of muddy sand, with the percentage of sand increasing downhole within the unit. The top of PP Unit VI is marked by a sharp increase in NGR and density and a decrease in MS. Core-log-seismic correlation at Site U1606 was achieved through implementation of a synthetic seismogram from the WRMSL density values obtained in Hole U1606B. The obtained interval velocities were later applied to Holes U1606A, U1606C, and U1606D with local variations based on lithologic changes.

4.4.3.5. Geochemistry

Samples for headspace gas, IW chemistry, and bulk sediment geochemistry were analyzed at Site U1606, primarily in Holes U1606A and U1606B. Headspace hydrocarbon gas measurements showed low concentrations in the upper 10 m CSF-A of Holes U1606A and U1606B, and below this high concentrations of methane are present to the bottom of Holes U1606A, U1606B, and U1606D (up to 87,400 ppmv). The main findings from IW analysis include low salinity measurements (as low as 12) between approximately 20 and 140 m CSF-A. Gradual downhole increases in salinity, sodium, chloride, and bromide occur below approximately 150 m CSF-A. Elemental analysis of solid material revealed average concentrations of 0.36% organic carbon and 0.05% nitrogen throughout Holes U1606A and U1606B.

4.4.3.6. Stratigraphic correlation

Because of low recovery and the large distance between the holes at Site U1606, the standard procedure for stratigraphic correlation could not be implemented. Physical property data, including NGR and MS, from all holes at Site U1606 were imported and examined in Correlator v.4. All cores from Site U1606 were cored with the RCB system and thus gaps and missing intervals were expected. Core disturbances, cores pumped from the liners, and other issues impacting on core quality meant that the stratigraphic coherence of the recovered sequence was variable. Recovery gaps commonly overlap between all holes of Site U1606 in the upper 180 m CSF-A of the record, and only Hole U1606B significantly penetrates below this depth.

Further efforts were made to correlate the record of each hole with the seismic stratigraphy of the area. Physical properties and paleomagnetism, together with biostratigraphic and lithologic constraints were taken into consideration, and a core-log-seismic correlation was constructed. Despite the uncertainties on the absolute depths, this model provides a means for the further investigation of the Site U1606 record across all holes.

4.5. Site U1607

4.5.1. Background and objectives

Site U1607 (proposed Site MB-07B), the easternmost site in the Expedition 400 site transect, is located at 74°29.5499'N, 60°34.9900'W at a water depth of 739 mbsl on the middle shelf landward of the Melville Bay Ridge (Figure F14). Extensive seismic and limited borehole data indicate that this site captures Megaunits C, D1, and D2, interpreted to be a late–middle Miocene sediment drift that overlies a succession of mainly hemipelagic strata, possibly of early Miocene to Oligocene age (Knutz et al., 2022) (Figure F14). Accordingly, Site U1607 may capture the time period from 6 to 30 Ma.

The sediment sequence comprising seismic Megaunits D1 and D2 represents gradual infilling of the remnant rift basin topography, comprising the Melville Bay Graben (MBG) and adjacent ridge complex. The MBG was formed during an Early Cretaceous phase of continental rifting and ended during the early Paleocene as active seafloor spreading commenced in Baffin Bay (e.g., Gregersen et al., 2022). The overlying seismic Megaunit C is interpreted to be a shelf-based sediment drift receiving fine clastic input from nearby prodeltaic environments (Knutz et al., 2015). The boundary between Megaunits D2 and C is described as the mid-Miocene Unconformity (Hz d1). It occurs within a conformable sequence in the basin but is shown as an erosional feature on the adjacent structural highs. Two seismic unconformities, corresponding to regional horizons (Hz c1 and b1), are seen near to the top of the sequence. By correlating the seismic profile farther southward it becomes evident that part of Megaunit C has been removed by erosion (Knutz et al., 2015). Thus, apart from the seabed itself, some degree of hiatus development may be assigned to Hz c1 or d1. Based on the reflection strength, Hz b1 appears more prominently as an erosional unconformity.

The goal at Site U1607 is to reconstruct past ocean and terrestrial climates in northeastern Baffin Bay and on Greenland, including testing the hypothesis that decreasing atmospheric CO₂ from the middle Oligocene to early Miocene is linked to the onset of ephemeral glaciation in northwest Greenland (Scientific Objective 2). Additionally, the site may provide core data that can investigate the influence of Neogene tectonic adjustments on the sediment record (Scientific Objective 3).

The expected lithology is claystone with silty to sandy intervals and siliceous ooze, consistent with predicted hemipelagic marine environments.

4.5.2. Operations

The vessel transited 17 nmi from Site U1606 to Site U1607. The thrusters were lowered and secured, and the ship was fully in DP mode at 1707 h on 15 September 2023. The rig crew made up an RCB BHA, and the drill string was tripped to near the seafloor. Hole U1607A was spudded at 2225 h, tagging the seafloor at 738.6 mbsl.

Cores 400-U1607A-1R through 60R advanced from 0 to 566.3 m CSF-A and recovered 470.47 m (83%). On 20 September, we began a bit change (70 h on bit). The pipe was raised to 53.4 m CSF-A, and a FFF was deployed at 1542 h. The subsea camera system was then deployed at 1652 h to observe that the FFF had landed in position and ensure a clean exit from Hole U1607A. The bit cleared the seafloor at 1753 h, and the subsea camera system was back on board by 1834 h. The drill string was then tripped up, with the bit at the surface at 2037 h. An RCB BHA was made up

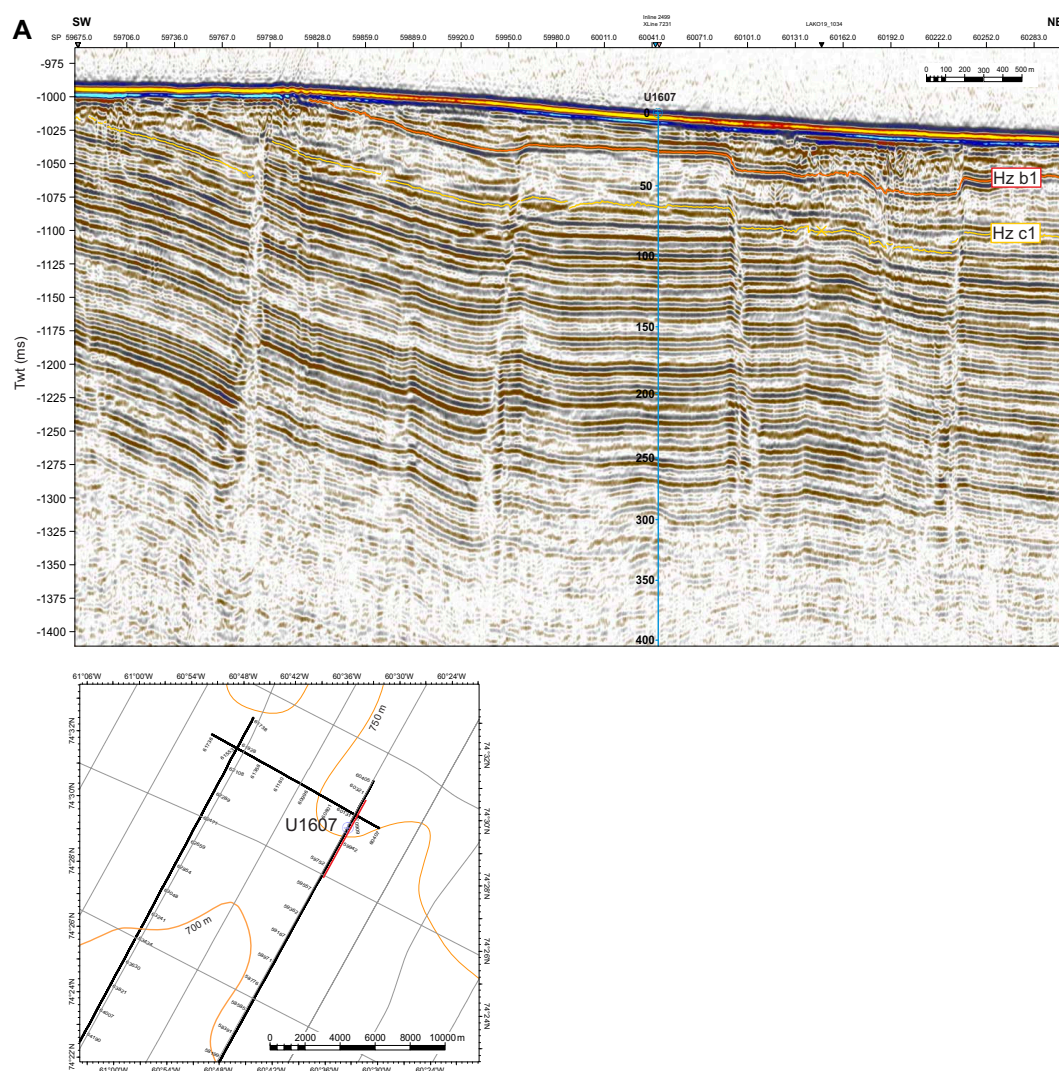


Figure F14. Top: seismic profiles (A) LAKO19_1034 and (B) LAKO19_1033 showing location of Site U1607 on inner shelf of Melville Bugt, northwest Greenland. Interpreted Horizons (Hz) b1, c1, d1, and d2, and corresponding megaunits, are shown. Hz b1 and c1 express unconformities where part of record may be missing. Vertical scale on Site U1607 line is meter depth based on preferred time-depth model supported by VSI and acoustic profiler. Note that from about 350 m CSF-A seismic energy is lost. SP = shotpoint, TWT = two-way traveltime. Bottom: close-up bathymetry maps with seismic survey lines in vicinity of Site U1607. Gray line grid = regional 2-D seismic data (TGS), black line grid = high-resolution multichannel seismic data (LAKO19). Position of profile in top panel marked in red. (Continued on next page.)

with a new C-4 bit, and the drill string was tripped back to the seafloor. The subsea camera system was deployed at 2245 h, and Hole U1607A was reentered at 0042 h on 21 September. The subsea camera was back on board at 0130 h. The drill string was lowered to 516.7 m CSF-A, and we washed back down to 566.3 m CSF-A. Cores 61R–103R advanced from 566.3 to 978.0 m CSF-A and recovered 282.38 m (68%).

Sepiolite (drilling mud) was swept in the hole, and the bit was released at 1940 h on 24 September to prepare for logging. The hole was displaced with heavy mud (barite), and the end of pipe was raised to 59.6 m CSF-A. The modified triple combo tool string was deployed to the base of Hole U1607A, and at 938 m CSF-A (40 m from the bottom of the hole) a hard contact was encountered. The drill pipe was raised to 42.1 m CSF-A for the main pass. Following a complete pass of the hole, the modified triple combo was pulled up to the rig floor and broken down. The VSI was rigged up, and the protected species watch began at 0930 h on 25 September. The VSI was deployed to 930 m CSF-A, and stations were measured every 30 m uphole until 1715 h, at which time the protected species watch also concluded. The VSI was brought back on board, and with logging completed we tripped the pipe out of Hole U1607A, clearing the rig floor at 2111 h. The drill floor was secured for transit, and the thrusters were raised and secured for transit at 2124 h, ending Hole U1607A and Site U1607.

4.5.3. Principal results

4.5.3.1. Lithostratigraphy

The stratigraphy of Site U1607 is divided into five lithostratigraphic units with subunits (Figure F15). Some of the named sedimentary lithofacies are present in all units with variable prominence,

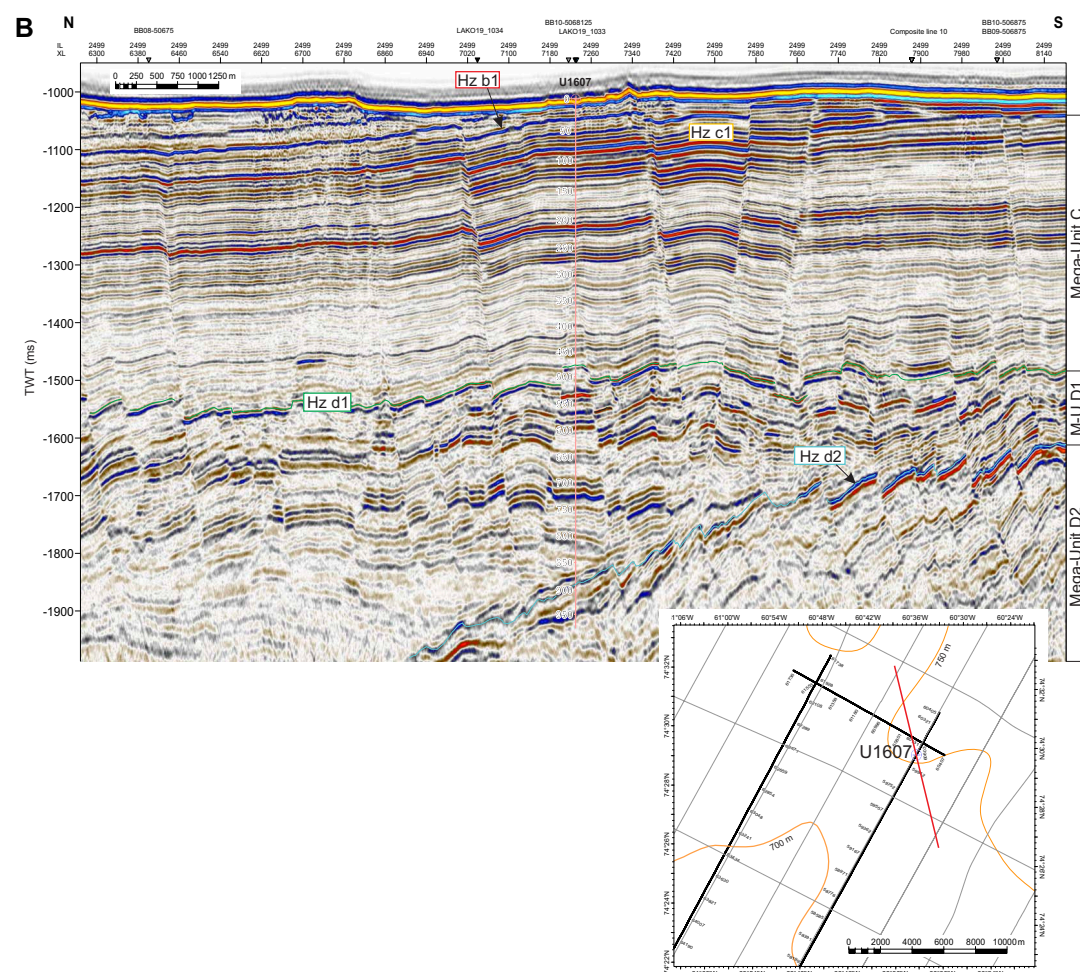


Figure F14 (continued).

whereas others are characteristic of a particular unit. The lithofacies include (1) mud, sandy mud, and muddy sand with dispersed clasts; (2) calcareous mud; (3) bioturbated sandy mud and muddy sand; and (4) glauconite-rich sandy mud, muddy sand, and sandy granule conglomerate.

Lithostratigraphic Unit I contains the upper 3.58 m CSF-A of the site and consists of unlithified, soupy mud that likely represents Holocene deposition. Lithostratigraphic Unit II, extending from 3.58 to 434.72 m CSF-A, contains bioturbated mud, sandy mud, muddy sand, calcareous mud, and dispersed clasts. This unit is divided into four subunits, IIA–IID, broadly following a downcore coarsening of sediment (mud to sand) and a decrease in dispersed clasts. Subunit IIA is 53.49 m

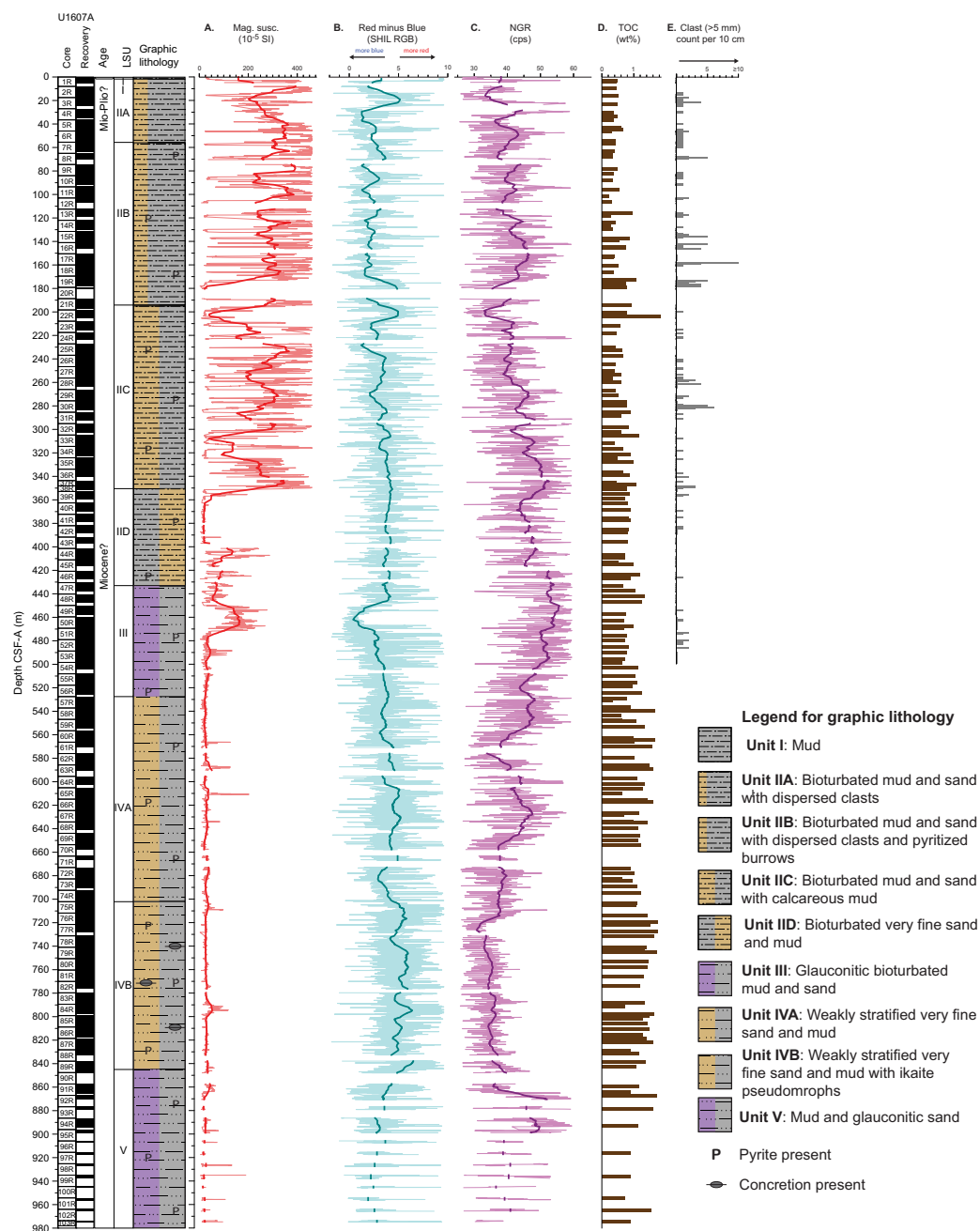


Figure F15. Lithostratigraphic summary, Site U1607. A. All SHMSL point MS measurements filtered to exclude measurements greater than two standard deviations from mean of entire data set (thin red line) and depth-based rolling average of this filtered data using a 10 m window (thick red line). Same method was used to plot (B) Section Half Imaging Logger (SHIL) RGB red minus blue data and (C) whole-round NGR measurements. D. Total weight percent organic carbon in measured samples. E. Clast counts per 10 cm are centered on middle of 10 cm interval. cps = counts per second, TOC = total organic carbon.

thick and contains meter-scale beds of bioturbated mud, sandy mud, and muddy sand with dispersed clasts and a few beds of cemented calcareous mud. The underlying Subunit IIB is 136.68 m thick, and it is lithologically similar to Subunit IIA, distinguished by a color change from greenish gray to grayish brown, the first appearance downhole of iron sulfide filled burrows, and common beds of cemented calcareous mud. Alternating mud and sandy mud to muddy sand lithologies on a decimeter scale is associated with Subunit IIC, which is 157.55 m thick, and represents an increase in the abundance of sand. Calcareous mud remains common, but a significant reduction in the occurrence of dark fine-grained iron sulfide-filled burrows and a decrease in dispersed clasts occurs within Subunit IIC. Subunit IID (83.42 m thick) is distinguished from overlying Subunit IIC by an increasing dominance of sand lithologies, a decrease in calcareous mud and carbonate cemented intervals, and rare occurrence of dispersed clasts. Lithostratigraphic Unit III, which extends from 434.72 to 530.47 m CSF-A, consists of bioturbated sand, muddy sand, and sandy mud. A distinguishing characteristic of Unit III is that it consists of glauconite-rich bioturbated sand, muddy sand, and sandy mud. Lithostratigraphic Unit IV is 315.08 m thick, shows a significant decrease in detrital glauconite, and is divided into two subunits. Subunit IVA is 171.63 m thick and has weakly stratified muddy sand and sandy mud as the dominant lithology. Although yellowish brown beds of calcareous mud occur in overlying units, they become more prominent in Subunit IVA, with beds ranging 3–77 cm in thickness. Subunit IVB is 143.45 m thick and has a similar lithology to overlying Subunit IVA. Marked differences include an increase in the dominance of sand over mud, the appearance of common pseudomorphs after ikaite and spherical calcareous concretions, and a decrease in calcareous mud. Lithostratigraphic Unit V, which is 132.45 m thick, continues to the bottom of Hole U1607A. This unit is distinguished by the abrupt reappearance of abundant glauconite as sand to granule grade intraclasts in sharp-based, graded, and stratified sandy lithologies, which is interbedded with and ultimately transitions downhole to brown and gray, sparsely bioturbated mud. Overall, the sedimentary succession recovered at Site U1607 is consistent with marine deposition within a subbasin situated inland of the Melville Bay Ridge.

4.5.3.2. Micropaleontology

Core catcher samples and additional split-core samples from the 103 cores of Hole U1607A were examined for foraminifera, diatoms, dinocysts, and other palynomorphs. The split-core samples targeted thin (typically centimeter scale) calcareous mud horizons and/or intervals close to mollusk shells, where carbonate/foraminifera preservation may have been enhanced, and intervals adjacent to where diatoms had been found in core catcher samples. Mudline samples were also examined for each group and collected for sedaDNA.

Microfossils generally occur only sporadically and discontinuously in the muddy sands, sandy muds and muds typical of Site U1607, apart from palynomorphs, which have more continuous occurrences. A combination of paleoenvironmental restrictions (i.e., shelf/neritic environments unfavorable to pelagic species) and diagenetic influences on pore water chemistry and preservation potential is likely responsible for the paucity of biomineralized skeletal remains in many intervals. Biostratigraphic results are therefore limited but provide some degrees of age control in different parts of the hole.

Foraminifera are mostly limited to benthic species, with agglutinated species being most common. Four samples from the weakly stratified very fine sands and muds of Lithostratigraphic Units IV and V (634–918 m CSF-A) contain scarce planktonic foraminifera species. Diatoms are observed in 12% of the samples examined. Dinocysts are present in the uppermost three core catcher samples and two additional samples that were taken from Core 400-U1607A-2R. No dinocysts were observed in core catcher samples from Cores 19R–74R, which is likely a result of dilution by terrigenous sediment input and a low concentration of dinocysts. Dinocyst abundances increase downhole from the core catcher sample of Core 74R. Postcruise palynological processing using hydrofluoric acid (HF) will provide more constraints on dinocyst abundances throughout this interval. Mollusk shells and their fragments are regular features of Site U1607 cores. Foraminifera shells, as well as mineralized burrow fills, are often pyritized.

The observed assemblages of all microfossil groups are generally composed of species with long geologic ranges. In terms of age control, all groups are consistent with Miocene ages, whereas

downhole some taxa are suggestive of Oligocene ages. The meager planktonic foraminifera assemblages are of low diversity and consist of few (5–20 specimens) small-sized individuals. The deepest occurrence of planktonic foraminifera, observed in the core catcher sample of Core 400-U1607A-88R, is consistent with an early Miocene to late Oligocene age. The diatom species observed suggest Miocene ages and downcore the dinocyst taxa reflect middle to late Miocene and older ages. In general, the microfossils from the upper 500 m CSF-A of Hole U1607A are characteristic of coastal or neritic environments with ample food/nutrient availability and below ~500 m CSF-A assemblages reflect more open marine environments that are at times favorable to planktonic foraminifera. The prominence of agglutinated benthic foraminifera, which are more environmentally tolerant than calcareous species, is also consistent with a food-rich inner shelf environment corrosive to small calcitic tests. All microfossil assemblages have environmental and climatic affinities comparable to assemblages observed in the Miocene of western Baffin Bay and the Labrador Sea (ODP Leg 105) and the North Sea (Kaminski et al., 1989; King, 1989).

4.5.3.3. Paleomagnetism

Pass-through paleomagnetic measurements from Site U1607 were performed using the SRM to investigate the remanent magnetization on a total of 491 archive-half sections. Measurements were not made on core catcher sections. All measurements on archive halves were made at 2 cm intervals up to a peak AF demagnetization of 20 mT.

A total of 525 discrete cube samples were taken from working halves. Generally, we collected one sample per core section, avoiding visually disturbed intervals. Of the 525 samples, 512 samples were taken using the parallel saw and the rest were sampled using J-cubes by inserting them into the working half. Of the discrete samples, 476 samples were measured on the SRM and stepwise demagnetized up to 50 mT. The remaining specimens were preserved for further study.

At Site U1607, we used a filtering method that assesses the magnetic stability of archive half and discrete sample data. Above ~375 m CSF-A, we defined 13 magnetic polarity zones. Below ~375 m CSF-A, magnetic data were unreliable because of a diagenetic loss of remanence-carrying material, and it was not possible to define polarity intervals. Further constraint awaits other chronological information, including confirmation of possible unconformities or hiatuses.

4.5.3.4. Physical properties

Standard physical property measurements were made on cores from Hole U1607A using the WRMSL, SHMSL, and NGRL track instruments. Discrete measurements were also made for MAD analysis, thermal conductivity, and *P*-wave velocity on the PWC system. Because of the low recovery and highly disturbed cored material, PWC measurements were unreliable. PWC was limited to diamictic intervals because values of isolated clasts are not representative of the formation.

Prominent variations in physical property values occur at similar depths in NGR and density and are associated with major lithologic changes in the cores. A positive correlation is found between density and NGR counts for Site U1607. The correlation between these physical properties distinguishes five PP units (I–V) at Site U1607. PP Unit I (0–180 m CSF-A) is distinguished by a sharp increase downhole in NGR, MS, and density in the upper 50 m of material, followed by relatively constant values to 180 m CSF-A. Below, in PP Unit II (180–350 m CSF-A) high-amplitude variability of NGR and MS reflects the broad variations in the lithology, which transition from more frequent intervals of mud to muddy sand and sandy mud moving downhole through the unit. PP Unit III (350–720 m CSF-A) is characterized by a decrease in NGR and density values compared to Unit II, which might reflect the transition from intervals of mud and sand to predominantly muddy sand toward the bottom of this unit. Muddy sand is also the primary lithology of PP Unit IV (720–825 m CSF-A), where NGR, MS, and density remain relatively constant relative to values observed in the lowermost interval of PP Unit III. PP Unit V (825–978 m CSF-A) is defined by a decrease in NGR and density to the bottom of the hole within a predominantly mud lithology.

4.5.3.5. Geochemistry

Samples for headspace gas, IW chemistry, and bulk sediment geochemistry were analyzed at Site U1607. Headspace hydrocarbon gas measurements reveal high concentrations below 5 m CSF-A with methane concentrations up to 113,700 ppm. Ethane is found at lower concentrations of up to 725 ppm, and longer chain hydrocarbon gases (propane, butane, and pentane) are detected at low

yet consistent levels below 500 m CSF-A. The main findings from IW analysis include low salinity values in the upper 200 m CSF-A of the site. IW iron, manganese, sulfate, and phosphate show elevated concentrations near the seafloor and sharp decreases to low concentrations with depth. Lithium and barium both increase significantly with depth. Elemental analysis of solid material reveal CaCO_3 contents of largely <1%, and some intervals contain greater amounts (up to 59%). The contents of total organic carbon and total nitrogen increase notably with increasing depth.

4.5.3.6. Age model

The initial age constraints of Site U1607 are based on magnetostratigraphic interpretations of inclination with two additional biostratigraphic considerations. The diatom *Proboscia barboi* is present at 198.7 m CSF-A and has an age range of 3.31–9.49 Ma in the North Atlantic (Koç and Scherer, 1996). The second possible constraint is from the co-occurrence of two diatoms (*Goniothecium rogersii* and *Goniothecium decoratum*) at 199.54 m CSF-A whose age ranges overlap between 16 and 23 Ma (Suto et al., 2008). These two observations are mutually inconsistent and lead to two possible age models. There are also unconformities recorded in the seismic profile reflecting potential hiatuses at about 26 and 73 m CSF-A, the latter of which may eliminate the highest normal polarity zone as a possible constraint.

The first age model is based on the occurrence of *P. barboi* at 198.7 m CSF-A, and in this model the transition from normal to reversed for the highest normal zone is correlated to Chron C4r.1r and the lowest reversed to normal transition is correlated to Chron C4Ar.2n. The average sediment accumulation rate for this age model is 19 cm/ky. The second age model is based on the co-occurrence of the *G. rogersii* and *G. decoratum* species, and in this model the transition from normal to reversed for the highest normal zone is correlated to Chron C5Cn.2r and the lowest reversed to normal transition is correlated to Chron C6n. The average sediment accumulation rate for this age model is 13 cm/ky. Further refinement of the age model for Site U1607 must await shore-based studies.

4.5.3.7. Downhole measurements

Downhole logging was carried out in Hole U1607A upon completion of the coring operations. A modified triple combo tool string was deployed with MSS, natural gamma ray, electrical laterolog resistivity, acoustic velocity, and density tools. Four runs (two down passes and two up passes) were carried out with the sensors recording on the way down and up. Two of the runs (initial down pass and final up pass) covered the full length of the hole to 40 m above the bottom. Two calibration runs (one up pass and one down pass) were logged on the deepest 100 m of the hole. The caliper showed a homogeneous and stable hole with minimum washouts to 880 m CSF-A.

Upon completion of the downhole logging with the modified triple combo, vertical seismic profiling was implemented with the VSI. The VSI aimed to obtain an accurate time-depth relationship to tie the logging and coring results with the seismic data. The geophones recorded the seismic signal at 33 stations located at an average spacing of 30 m and 3 good shots were recorded in most of the stations. Thus, VSI results were used in the core-log-seismic correlations at Site U1607. A protected species watch was in place before and during the use of the seismic source. Logging measurements were crucial for covering recovery gaps in RCB coring, especially near the bottom of Hole U1607A. Core logging and downhole logging results differ on absolute values, but the relative trends of the logs are comparable. Hence, logging data could be used to cover the formation recovery gaps with confidence.

4.6. Site U1608

4.6.1. Background and objectives

Site U1608 (proposed site MB-06D) is located at 74°7.6818'N and 60°58.3172'W at a water depth of 607 mbsl on the middle section of the northwest Greenland shelf west of the Melville Bay Ridge and graben structures formed during Cretaceous rifting (Figure F16). The main coring targets are mounded contourite drift deposits of expected Pliocene age associated with Megaunit B (Knutz et al., 2015, 2019; Aubry, 2021) and overlying sediments of Megaunit A, recording the transition into glacial deposits of earliest TMF progradation. The expanded interval of Megaunit B, captured at Site U1608 reflects deposition below a major incised escarpment that is at least 500 m tall and

extends into disturbed sediment packages interpreted to be mass transport deposits. The base of the contourite drift accumulation is defined by Horizon c1 of probable late Miocene age (Knutz et al., 2015). Site U1608 ends ~100 m above Horizon c1, which at this location is characterized by an erosional unconformity. In the overlying unit, Megaunit A, 10 horizons are mapped using high-resolution seismic data, and including the seabed they define 11 seismic units that each record progradation of the TMF system under the influence of grounded glacier ice (Knutz et al., 2019). TMF Seismic Unit 1 targeted at Site U1608 records the first advance of the northwest GrIS onto the continental shelf, hypothesized to correspond to the Pleistocene/Pliocene boundary (Knutz et al., 2019) (Figure F16).

The expected lithologies are gravel-sand, diamicton, and pebbly mud in the upper 40 m and mudstone with silty-sandy intervals in the succession below. The seismic characteristics suggest a gradual transition from a deep marine (outer shelf) to a more nearshore environment, eventually replaced by a proglacial setting. The expected lithologies are diamicton and mudstone with silty-sandy intervals such as would be expected in proglacial settings and from nearshore to deep marine environments. Drilling at Site U1608 includes RCB coring to 561 m drilling depth below seafloor (DSF) and logging.

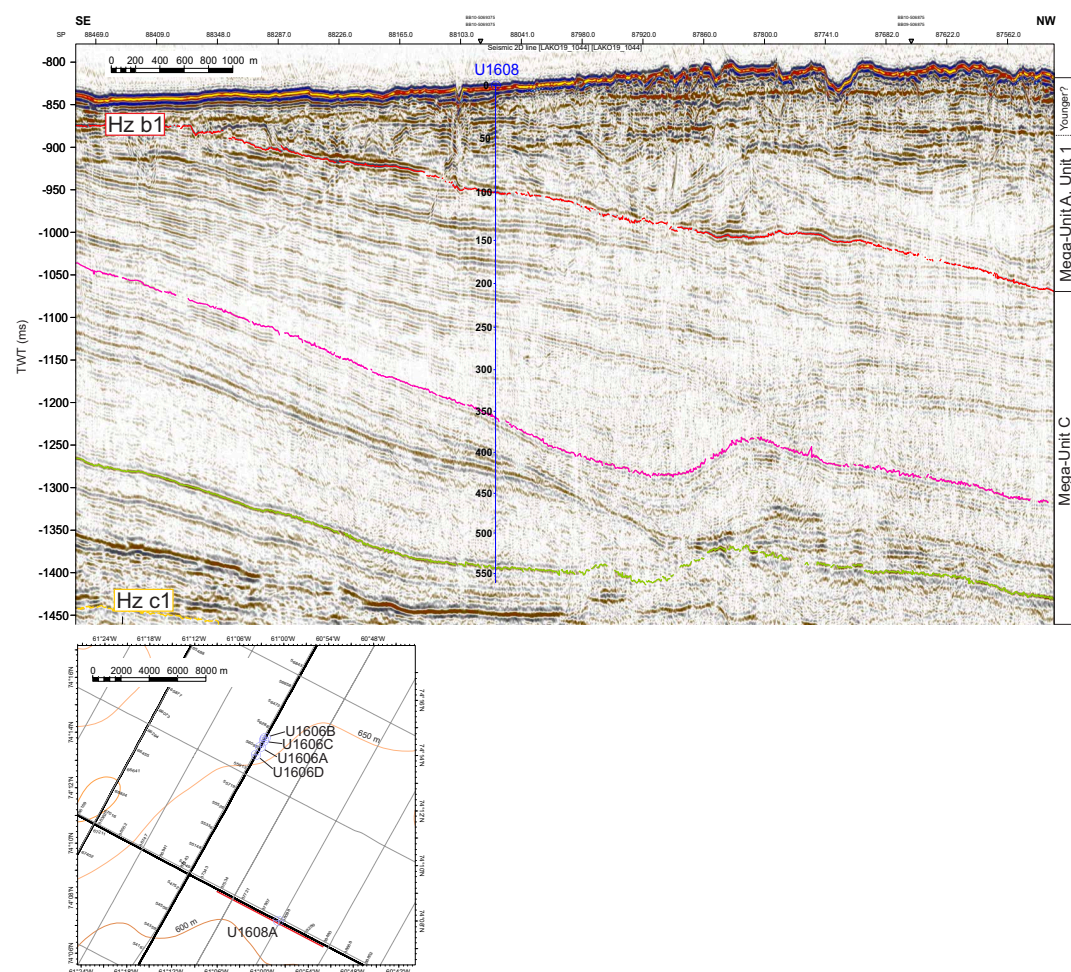


Figure F16. Top: seismic profile (LAKO19_1044) showing location of Site U1608 on outer shelf of Melville Bugt, northwest Greenland. Interpreted Horizons (Hz) b1 and c1 are indicated together with internal horizons (green, pink) that serve to connect Site U1608 with Site U1606. Vertical scale on Site U1605 line is meter depth based on preferred time-depth model. SP = shotpoint, TWT = two-way travelttime. Bottom: close-up bathymetry map with seismic survey lines in vicinity of Sites U1608 and U1606. Gray line grid = regional 2-D seismic data (TGS), black line grid = high-resolution multichannel seismic data (LAKO19).

There are two principal goals for this site: (1) capture deposits corresponding to the earliest shelf-based glaciations in northwest Greenland (earliest glacial clinoforms of Megaunit A) and (2) recover Neogene sediments of likely Pliocene age in Megaunit B that can elucidate paleoceanographic conditions prior to the major expansion of the GrIS (Knutz et al., 2015). Hypothetically, the contourite drift may provide a marine analog to terrestrial outcrops (e.g., Beaufort and Kap København formations), depicting warm climate conditions in the High Arctic during late Pliocene to early Pleistocene (Gosse et al., 2017).

Planned drilling at Site U1608 included coring with the RCB system from the seafloor to 561 m CSF-A in a single hole. Planned downhole logging included the triple combo tool string, FMS, and VSI check shots.

4.6.2. Operations

The vessel transited 23 nmi from Site U1607 to Site U1608. The thrusters were lowered and secured, and the ship was fully in DP mode at 0051 h on 26 September 2023. The rig crew made up an RCB BHA, and the drill string was tripped to near the seafloor. Hole U1608A was spudded at 0435 h, tagging the seafloor at 606.9 mbsl. Cores 400-U1608A-1R through 60R advanced from 0 to 561.0 m CSF-A and recovered 267.35 m (47%).

Sepiolite (drilling mud) was swept in the hole, and the bit was released in the hole at 1555 h on 29 September to prepare for logging Hole U1608A. The hole was displaced with heavy mud (barite), and the pipe was tripped up, with the end of the pipe ultimately placed at 103.9 m CSF-A because of concerns about the condition and stability of the hole. The modified triple combo tool string was deployed to the base of Hole U1608A and tagged the bottom at 558.6 m CSF-A. Following a complete pass of the hole, the modified triple combo was pulled to the rig floor and broken down. The FMS (without sonic) tool string was then assembled and deployed at 0235 h on 30 September. After two successful logs, the FMS tool was brought back on board and broken down. The VSI was rigged up and deployed, and the protected species watch began at 0730 h. Stations were measured uphole every 20 m, and the VSI was back on board by 1300 h. With logging completed, we tripped the pipe out of Hole U1608A, clearing the rig floor at 1555 h. The drill floor was secured for transit, and the thrusters were raised and secured for transit at 1630 h, ending Hole U1608A and Site U1608.

4.6.3. Principal results

4.6.3.1. Lithostratigraphy

The stratigraphy of Site U1608 is divided into four lithostratigraphic units (Figure F17). The lithofacies include (1) bioturbated mud with dispersed sand, (2) calcareous mud, (3) sandy mud/muddy sand with or without dispersed clasts, and (4) clast-poor sandy diamicton. Lithofacies 1 and 3 are present in all lithostratigraphic units, and Lithofacies 2 and 4 occur only in Lithostratigraphic Units II and IV.

Lithostratigraphic Unit I contains the upper 53.6 m CSF-A of the site and consists of washed gravel (a product of drilling disturbance) with diverse igneous, plutonic, and metamorphic clasts. Lithostratigraphic Unit II, extending from 53.6 to 293.5 m CSF-A, contains bioturbated sandy mud/muddy sand with or without dispersed clasts, calcareous mud, and occurrences of clast-poor sandy diamicton. Lithostratigraphic Unit III extends from 293.5 to 429.3 m CSF-A and contains meter- to decimeter-scale intervals of bioturbated mud with sand and sandy mud to muddy sand with or without dispersed clasts. Overall, Unit III is distinguished from Unit II by a decrease in the abundance of sand, a significant reduction in the occurrence of the calcareous mud lithofacies, and an increase in the abundance of bioturbated mud with dispersed sand. Underlying Unit III is the 135.8 m thick Lithostratigraphic Unit IV (429.3–561.46 m CSF-A), which consists of alternating meter- to decimeter-scale intervals of bioturbated mud with dispersed sand and decimeter-scale intervals of sandy mud/muddy sand. This unit marks a downhole increase in the sand proportion as well as an increase in the occurrence of yellowish calcareous mud. In this unit, the calcareous mud commonly occurs as centimeter-scale bioturbated patches. Overall, the sedimentary succession recovered at Site U1608 is consistent with deposition in a marine shelf setting with sedimentary contributions from glacial and minor hemipelagic biosiliceous sources.

4.6.3.2. Micropaleontology

Core catcher samples from the 60 cores of Hole U1608A were examined for foraminifera, diatoms, dinocysts, and other palynomorphs. Samples were also taken for sedaDNA analysis. The mudline was not recovered at Site U1608 and Cores 400-U1608A-1R through 3R contain washed gravel without fine-grained sediment suitable for microfossil analysis. All microfossil groups are present in Site U1608 cores and occur throughout much of the recovered sequence. Benthic foraminifera occur in 88% of the samples. Planktonic foraminifera are found in only 3 samples, represented in each case by a single specimen. Diatoms were observed in 70% of the samples, and dinocysts were observed in 84% of the samples.

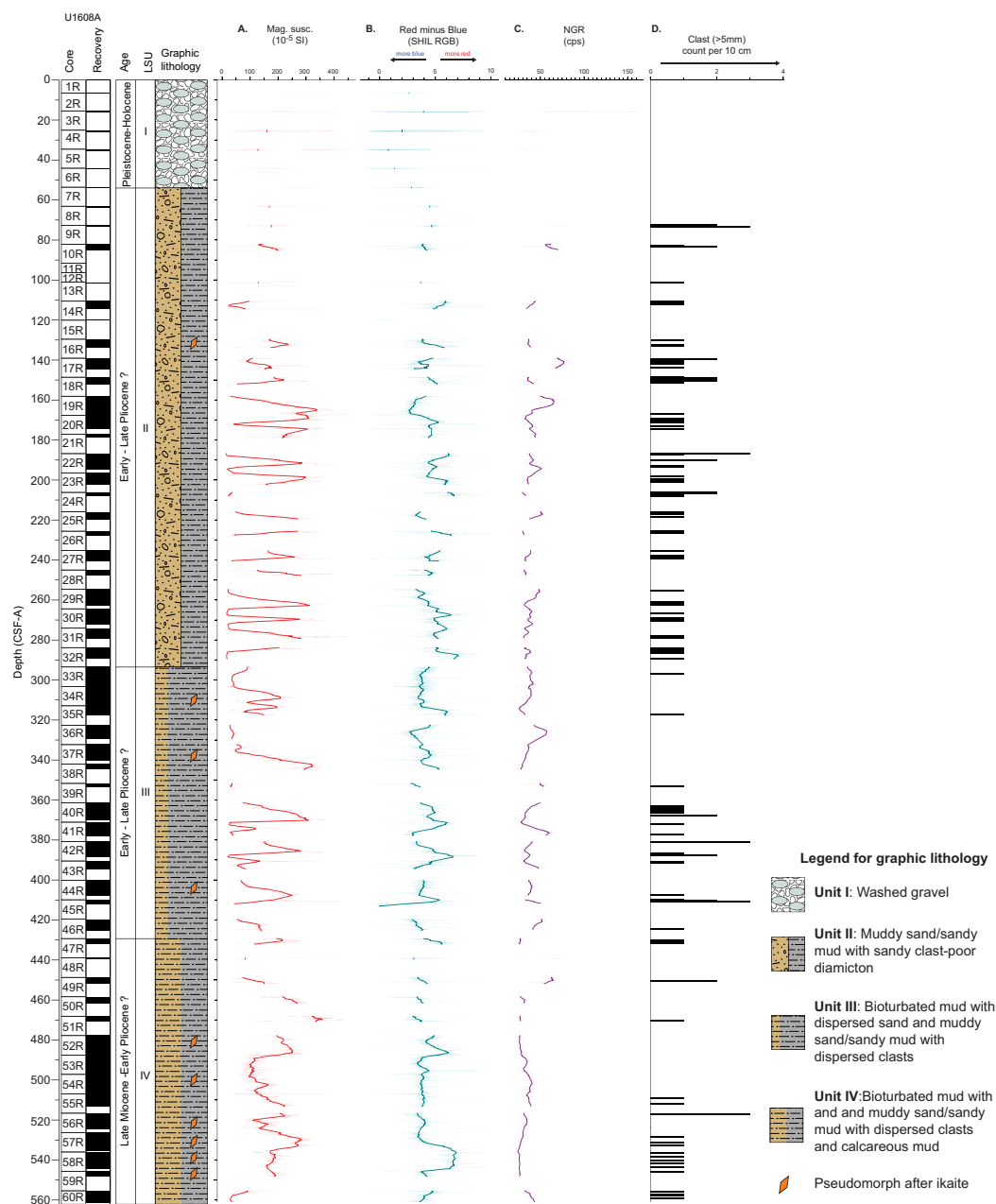


Figure F17. Lithostratigraphic summary, Site U1608. A. All SHMSL point MS measurements filtered to exclude measurements greater than two standard deviations from mean of entire data set (thin red line) and depth-based rolling average of this filtered data using a 10 m window (thick red line). Same method was used to plot (B) Section Half Imaging Logger (SHIL) RGB red minus blue data and (C) whole-round NGR measurements. D. Clast counts per 10 cm are centered on middle of 10 cm interval.

Foraminifera are absent until ~85 m CSF-A. Below this depth, they become rare to intermittently common to the base of the hole and consist of typical Arctic Neogene shelf-slope benthic species (Feyling-Hansen, 1976). The long-ranging benthic species offer little age control, although the presence of *Cassidulina teretis* implies that the foraminifera-bearing sediments between ~85 and 524 m CSF-A are older than 700 ky (early Pleistocene) but no older than middle Miocene (Seidenkrantz, 1995). Diatoms are barren until ~100 m CSF-A, below which they are present in most core catcher samples. The diatom assemblages are diverse and well preserved in some samples, providing both age and paleoenvironmental constraints. Palynomorphs occur in every sample in varying abundance, including the upper 100 m CSF-A where other microfossils are rare or absent. The dinocyst assemblages, which consist mostly of species associated with neritic, nutrient-rich environments, are also diverse in some intervals, providing additional chronostratigraphic and paleoenvironmental insights. Pulses of terrestrially derived organic material are a distinct feature of Site U1608. This is evidenced by occurrences of micro-/macrofossil wood and plant fragments in sieved foraminifera samples, as well as by smaller plant/wood fragments, pollen, spores, and fungal material in palynomorph preparations. These pulses of terrestrial material in the sieved (>63 μm) foraminifera samples occur intermittently and at times intensely from 85 to 488 m CSF-A.

4.6.3.3. Paleomagnetism

Pass-through paleomagnetic measurements from Site U1608 were performed using the SRM to investigate the magnetization of a total of 201 archive-half sections. Measurements were not made on core catcher sections. All measurements on section halves were made at 2 cm intervals up to a peak AF demagnetization of 20 mT. Inclinations from the filtered 20 mT step archive halves are generally bimodal at the estimates of inclinations for normal and reversed polarities at this latitude calculated from the geocentric axial dipole, and the bimodal inclination distribution suggests that intervals of both normal and reversed polarity were recovered at Site U1608. A total of 192 discrete cube samples were collected from the working-half sections; generally, we collected one sample per core section, avoiding visually disturbed intervals. Discrete specimens from Cores 400-U1608A-9R through 40R were measured on the SRM up to a peak AF demagnetization of 50 mT. Cores 41R–60R were only demagnetized to a peak field of 40 mT. We utilized a filtering method that assessed the magnetic stability of archive-half and discrete sample data and used the filtered data to define 11 polarity zones at Site U1608.

4.6.3.4. Physical properties

Standard physical property measurements were made on cores from Hole U1608A using the WRMSL, SHMSL, and NGRL track instruments. Discrete measurements were also made for MAD analysis, thermal conductivity, and *P*-wave velocity on the PWC system. Because of the low recovery and highly disturbed cored material, PWC measurements were unreliable. PWC was limited to diamictic intervals because values of isolated clasts are not representative of the formation.

Prominent variations in physical property values occur at similar depths in NGR and density and are associated with major lithologic changes in the cores. The correlation between these physical properties distinguishes five PP units (I–V) at Site U1608. PP Unit I (0–130 m CSF-A) includes mostly irregular values of NGR, MS, and density, which is largely due to poor recovery and partially due to the occurrence of washed gravel in the uppermost 50 m CSF-A at Site U1608. Thermal conductivity reaches a maximum value for Site U1608 in PP Unit I. Below, in PP Unit II (130–215 m CSF-A) high-amplitude variability of NGR and MS corresponds to lithologies of mud, sandy mud, and muddy sand. Throughout PP Unit II density decreases slightly downhole. PP Unit III (215–315 m CSF-A) is characterized by low-amplitude variability in NGR coupled with high-amplitude variability in MS in the upper half of the unit, followed by an increase in NGR and a decrease in MS intensity and variability in the lower half of PP Unit III. NGR and MS trends in PP Unit III reflect the transition from sandy mud to muddy sand as the dominant lithology throughout the unit. Muddy sand is also the primary lithology of PP Unit IV (315–450 m CSF-A), although it also contains intervals of calcareous mud in the lower half of the unit where density becomes more variable. NGR and MS in PP Unit IV are both highly variable. PP Unit V (450–561 m CSF-A) is defined by low NGR and MS values, which further decrease downhole throughout the unit.

4.6.3.5. Geochemistry

Samples for headspace gas, IW chemistry, and bulk sediment geochemistry were analyzed at Site U1608. Headspace hydrocarbon gas concentrations are low in the upper 50 m CSF-A. Below this depth, high concentrations of methane (average of 33,800 ppm) are found to the bottom of Hole U1608A. IW samples were not taken in the uppermost 9 cores of the hole because of low recovery. The main findings from IW analysis include downhole increases in alkalinity, potassium, magnesium, and phosphate to around 250 m CSF-A, and steadily decreasing values for these components below 300 m CSF-A. Elemental analysis of solid material revealed average concentrations of 0.5% organic carbon and 0.06% nitrogen throughout Hole U1608A.

4.6.3.6. Stratigraphic correlation

To analyze the extent of the core gaps and further improve the depth assessment of the recovered material, we correlate the physical properties measured on the cores to the downhole logs obtained from the borehole. Whole-round MS and NGR measured on the cores were imported in Correlator v.4 as well as downhole MS and NGR data, which were imported into the software as a single core table. Ties between downhole data and core data were assessed based on visual and statistical matches of the properties. This procedure has some significant uncertainties because of the presence of large-scale features in the downhole logging data that do not resemble the record measured on cores in the laboratory. However, the overall cyclicity of the records is well matched between the downhole logs and the cores, and the relative depth offset of each core provides information that can be used to confidently improve the depth constraints of the cores. The resulting depth scale is referred to as CCSF-A even though it is not a scale resulting from the alignment of two or more holes. The difference between the CSF-A and CCSF-A depths varies downhole from a few centimeters up to 10 m. The depth constraints provided by the downhole logging data allow an improved interpretation of the formation lithology, age, and physical properties.

4.6.3.7. Age model

The initial age constraints are based on magnetostratigraphic interpretations on inclination with two additional biostratigraphic constraints. The diatom *P. barboi* was identified in the interval between 180 and 507 m CSF-A and has an age range of 3.31–9.49 Ma (Koç and Scherer, 1996). The second potential constraint is from the occurrence of the diatom *Thalassiosira nidulus* throughout material recovered from Site U1608, whose first occurrence is at 4.57 Ma (Koç and Scherer, 1996) on the Iceland Basin Plateau. With these considerations, we have two possible age models. There are also possible hiatuses identified in the seismic data at 96 and 535 m CSF-A, the former of which eliminates the highest normal polarity zone as a possible constraint. Model 1 is inconsistent with the occurrence of *P. barboi* above 238 m CSF-A, and in this model the transition from normal (N2) to reversed (R1) is correlated to Chron C2An.1n. The average sediment accumulation rate for this age model is 18.5 cm/ky. In Model 2, the transition from normal (N2) to reversed (R1) is correlated to Chron C3n.1n and the N6–R5 reversal is correlated to Chron C3An.1n. The average sediment accumulation rate for this age model is 15.1 cm/ky.

4.6.3.8. Downhole measurements

Downhole logging was carried out in Hole U1608A upon completion of the coring operations. The modified triple combo tool string was deployed with MSS, natural gamma ray, electrical laterolog resistivity, acoustic velocity, and density tools. Two of the four runs (initial down pass and final up pass) covered the full length of the hole to 2 m above the bottom of the hole (561 m CSF-A). The caliper showed a stable hole, and the instruments yielded reliable measurements; however, large washouts were observed to 1020 mbrf, and the lower 157 m of the hole was homogeneous.

Upon completion of the modified triple combos runs, the FMS tool was lowered downhole. Three runs (a down pass and two up passes) were completed. Vertical seismic profiling was implemented with the VSI after the FMS run. The VSI aimed to obtain an accurate time-depth relationship to tie the logging and coring results with the seismic data, and the geophones recorded the seismic signal at 24 stations located at an average spacing of 20 m. Successful measurements were made at 20 of the 24 planned stations; however, stations between 970 and 1030 mbrf needed further processing. VSI results were used in the core-log-seismic correlation at Site U1608. A protected species watch was in place before and during the use of the seismic source.

Logging measurements were crucial for covering recovery gaps during RCB coring. 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 covering the formation recovery gaps with confidence.

5. Preliminary scientific assessment

Anthropogenic warming may be forcing the GrIS to respond in manners that are unpredictable, of which there are no comparisons in recent history (Siegert et al., 2020). For this reason, it is important to understand its past warm-phase behavior and provide a deep temporal baseline for GrIS variability. To address this need, the goal of Expedition 400 was to retrieve a GrIS proximal sedimentary archive, hitherto only imaged on seismic data (Knutz et al., 2015, 2019; Newton, 2021), that could provide new information and cover knowledge gaps pertaining to the evolution of the GrIS.

Expedition 400 recovered 2299 m of sediment core by drilling a composite succession of 3084 m, covered by six sites along the transect traversing the northwest Greenland continental margin (Figures F1, F2, F4, F18, F19; Table T1). In addition, wireline logging was completed at four sites with three of them including VSI data. The average recovery was 51%, which was unsurprising for a glaciated margin, but considerable variations were seen between sites and stratigraphic units. Sites U1603 and U1604 in the deep water produced recoveries of 90%–100% in the interval to 250 m CSF-A, whereas recoveries in the drilled succession below 250 m CSF-A were generally below 30%. Site U1605 on the outer shelf margin turned out to be less promising with only 13.6% recovery. For this reason and considering time constraints, we decided to omit proposed Site MB-30A. Site U1608 drilled to 561 m CSF-A with a recovery of 48%, which is partly due to poor core return in upper 100 m CSF-A. The pattern of increased recovery below Megaunit A was also manifested

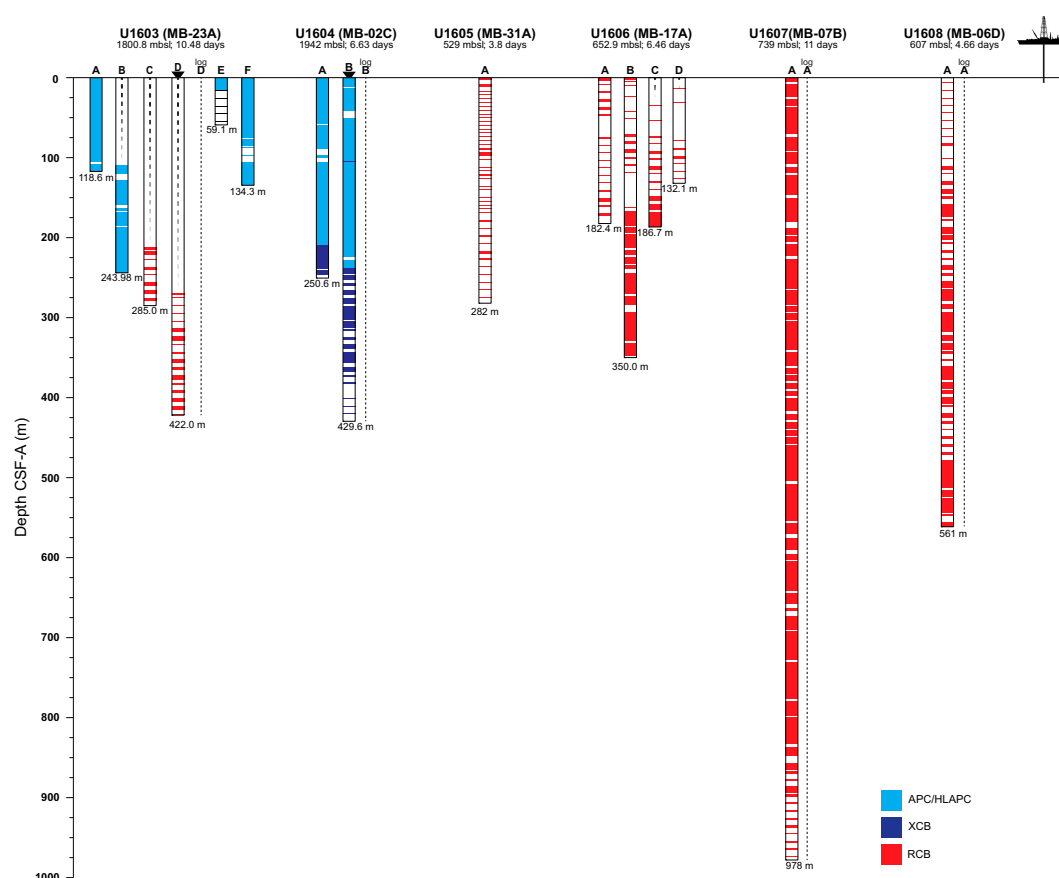


Figure F18. Coring systems used and core recovery during Expedition 400. Depths are bottom depth drilled (DSF).

by the four holes drilled at Sites U1606 and U1608. Most outstanding and somewhat surprising was Site U1607, which was cored to 978 m CSF-A and returned a recovery of 77%. Considering that we anticipated a total of 2000–3000 m of sediment at the outset, the actual amount of core gained meets our expectations. Four environmental and geologic settings were drilled as part of Expedition 400, and each of them aimed at meeting specific scientific objective.

5.1. Slope to deep-water basin of TMF—Sites U1603 and U1604

The aim of coring these sites within a drift-channel system was to obtain high-resolution records that could test the notion that the NGrIS has experienced significant episodes of glacial retreat associated warm interglacials, also referred to as super-interglacials, since the early Pleistocene. The age model for these sites was based on paleomagnetic reversals and relative paleomagnetic intensity stratigraphy. Sedimentation rates range 28–75 and 15–45 cm/ky for Sites U1603 and U1604, respectively, with the lowest values observed in the sections below 250 m CSF-A. This means that we can expect to gain continuous centennial-scale resolution records from these sites, which fulfills the requirement for identifying discrete pulses of sediment from Greenland. The lithology shows distinct changes in ice-rafted debris clasts, some of which fall within layers rich in detrital carbonate related to Baffin Bay Detrital Carbonate events (Andrews et al., 1998). The variation in clast composition throughout the lithologic sequence prescribe marked changes in the iceberg-emitting source regions. Further multiproxy studies will be needed to reach a detailed understanding of the evolution of the NGrIS and its interaction with ocean circulation as well as other glacial outlets (e.g., the Lancaster Sound and Nares Strait systems).

The content of microfossils in core catcher samples recovered at deepwater sites was generally sparse with only sporadic occurrences of assemblages. However, targeted sampling in core sections with low NGR improved the detection of microfossils, especially foraminifera, which is encouraging for further work.

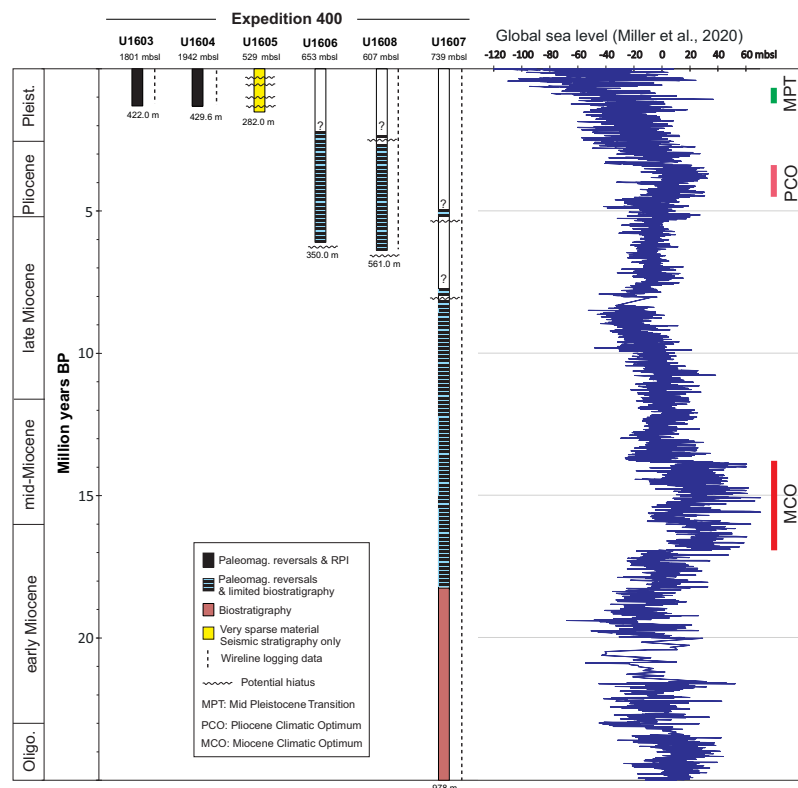


Figure F19. Age model overview. Chronological control is preliminary and age assignments may change with continued work. Present global sea level = 0. Sea level obtained using benthic (*Cibicidoides*) foraminifera $\delta^{18}\text{O}$ benthic splice and $\delta^{18}\text{O}_{\text{seawater}}$ using temperatures from Mg/Ca records (Miller et al., 2020). RPI = relative paleointensity.

The data produced from Sites U1603 and U1604 will allow us to test the potential Pleistocene scenarios for GrIS mass loss proposed by Schaefer et al. (2016): ice-free interglacials, ice-free super-interglacials, or one 280,000 y long ice-free period. An additional objective is to address the hypothesis originally proposed by Clark and Pollard (1998) suggesting that the transition from 40,000 to 100,000 y climate cyclicity across the MPT was related to continental ice sheets growing thicker once the regolith-soil on which they were grounded had been eroded away. Knutz et al. (2019) proposed a linkage between GrIS evolution and progressive regolith erosion based on seismic evidence indicating a pronounced shift in ice sheet configuration through the MPT. Bolstered

Table T1. Hole summary, Expedition 400. DSF = drilling depth below seafloor.

Hole	Latitude	Longitude	Water depth (m)	Penetration DSF (m)	Cored interval (m)	Recovered length (m)	Recovery (%)	Drilled interval (m)	Total cores (N)	APC cores (N)	HLAPC cores (N)	XCB cores (N)	RCB cores (N)
U1603A	72°59.0386'N	62°58.8333'W	1800.8	118.6	118.6	119.00	100	0.0	13	13	0	0	0
U1603B	72°59.0441'N	62°58.8431'W	1800.8	244.0	134.9	122.68	91	109.1	26	4	22	0	0
U1603C	72°59.0480'N	62°58.8542'W	1800.8	285.0	73.5	22.78	31	211.5	8	0	0	0	8
U1603D	72°59.0506'N	62°58.8735'W	1800.8	422.0	152.6	43.31	28	269.4	17	0	0	0	17
U1603E	72°59.0551'N	62°58.8829'W	1800.4	59.1	59.1	17.48	30	0.0	7	6	1	0	0
U1603F	72°59.0361'N	62°58.8180'W	1801.3	134.3	134.3	116.93	87	0.0	15	14	1	0	0
Site U1603 totals:				1263.0	673.0	442.18	61	590.0	86	37	24	0	25
U1604A	73°6.9002'N	63°47.4227'W	1942.2	250.6	250.6	232.91	92	0.0	32	26	1	5	0
U1604B	73°6.9077'N	63°47.3996'W	1943.6	429.6	429.6	317.85	74	0.0	55	28	6	21	0
Site U1604 totals:				680.2	680.2	550.76	84	0.0	87	54	7	26	0
U1605A	73°33.6421'N	62°9.0687'W	528.7	282.0	282.0	38.45	14	0.0	47	0	0	0	47
Site U1605 totals:				282.0	282.0	38.45	14	0.0	47	0	0	0	47
U1606A	74°13.9380'N	61°2.2426'W	652.7	182.4	182.4	30.14	17	0.0	20	0	0	0	20
U1606B	74°14.2845'N	61°1.6553'W	656.4	350.0	350.0	164.44	47	0.0	39	0	0	0	39
U1606C	74°14.1955'N	61°1.8156'W	654.1	186.7	161.7	45.31	28	25.0	17	0	0	0	17
U1606D	74°13.6459'N	61°2.7548'W	648.3	132.1	118.5	7.83	7	13.6	13	0	0	0	13
Site U1606 totals:				851.2	812.6	247.72	25	38.6	89	0	0	0	89
U1607A	74°29.5499'N	60°34.9900'W	738.6	978.0	978.0	752.64	77	0.0	103	0	0	0	103
Site U1607 totals:				978.0	978.0	752.64	77	0.0	103	0	0	0	103
U1608A	74°7.6818'N	60°58.3172'W	606.9	561.0	561.0	267.35	48	0.0	60	0	0	0	60
Site U1608 totals:				561.0	561.0	267.35	48	0.0	60	0	0	0	60
Expedition 400 totals:				4615.4	3986.8	2299.10	58	628.6	472	91	31	26	324

Hole	Date started (2023)	Time started UTC (h)	Date finished (2023)	Time finished UTC (h)	Time on hole (h)	Time on hole (days)	Time on site (days)
U1603A	23 Aug	1715	24 Aug	2045	27.60	1.15	
U1603B	24 Aug	2045	26 Aug	1500	42.24	1.76	
U1603C	26 Aug	1500	28 Aug	0315	36.24	1.51	
U1603D	28 Aug	0315	1 Sep	1200	104.64	4.36	
U1603E	1 Sep	1200	2 Sep	0445	16.80	0.70	
U1603F	2 Sep	0445	3 Sep	0445	24.00	1.00	
Site U1603 totals:						10.48	
U1604A	3 Sep	0630	5 Sep	1015	51.84	2.16	
U1604B	5 Sep	1015	9 Sep	2130	107.28	4.47	
Site U1604 totals:						6.63	
U1605A	10 Sep	0130	13 Sep	2045	91.20	3.80	
Site U1605 totals:						3.80	
U1606A	14 Sep	0100	15 Sep	1800	41.04	1.71	
U1606B	30 Sep	2045	3 Oct	0415	55.44	2.31	
U1606C	3 Oct	0415	4 Oct	0700	26.64	1.11	
U1606D	4 Oct	0700	5 Oct	1500	31.92	1.33	
Site U1606 totals:						6.46	
U1607A	15 Sep	2000	26 Sep	0030	244.56	10.19	
Site U1607 totals:						10.19	
U1608A	26 Sep	0345	30 Sep	1930	111.84	4.66	
Site U1608 totals:						4.66	
Expedition 400 totals:						42.22	

by the age model and sedimentation rates indicated by the shipboard results, sediments cored at Sites U1603, U1604, and U1605 provide a test for changes in basal ice-flow conditions related to progressive regolith-soil erosion since 1.2 Ma. Such changes might be revealed by the composition of detrital parent material or organic components reworked from land by successive glacial advances.

5.2. Outer shelf margin of TMF—Site U1605

Coring at Site U1605 was intended to capture interglacial muds potentially interbedded within the aggrading shelf wedge of the Melville Bugt TMF. It was also unique in being the only site coring into Seismic Unit 7 that unlike younger Seismic Units 8–11 displays an elongate slope front depocenter (Knutz et al., 2019). No muddy intervals were recovered at Site U1605. The material recovered at Site U1605, exclusive of drilled clasts, was mainly sandy to muddy diamicton. However, this lithology will be valuable for detrital archive analyses informing on weathering and landscape exposure (Christ et al., 2020) at the onset of the MPT.

5.3. Preglacial contourites—Sites U1606 and U1608

At Sites U1606 and U1608 the strategy was to core through the deposits of the first prograding unit, representing the onset of shelf based glacial expansion (Megaunit A), and then continue into marine contourite sediments of Megaunit B, as defined by the seismic geometries. The overall recoveries achieved were low (<50%) as a result of large variations (excluding washed gravel) in Megaunit A representing the uppermost 100–160 m at Sites U1606 and U1608, whereas recovery increases in underlying contourite drifts of Megaunit B. A 450 m thick contourite sequence was drilled at Site U1608 with recoveries generally increasing with depth. A highlight from Site U1608 was the discovery of species in the form of diatoms and foraminifera with affinity toward conditions significantly warmer than today. The paleomagnetic results from Sites U1606 and U1608 were of good quality through the lower part of the drilled succession where recovery was best. However, the interpretation of ages was not straightforward, resulting in two potential age models capturing different parts of the Pliocene. However, the micropaleontology results provide most support for the younger age model. Rare occurrences of foraminifera in glacial-marine sediments in Cores 400-U1606B-11R and 14R support an early Pleistocene age.

We have cored a prominent Pliocene archive and probably the late Pliocene–early Pleistocene transition, but elaboration on developing a multiproxy paleoclimate record from Sites U1606 and U1608 is needed. This work will establish the paleoceanography and tectonic framework responsible for maintaining a geostrophic boundary current over millions of years along the West Greenland margin during the Pliocene, potentially connected to Atlantic meridional circulation. Application of paleoceanographic tracers and sedimentologic work may provide information on current strength and potentially configuration of Arctic gateways, and coarse-grained detrital components can reveal presence and variability of the past GrIS. The marine sedimentary succession recovered at Sites U1606 and U1608 forms a unique empirical database for establishing Arctic climate development and ice-ocean interactions during the Pliocene warm analog.

5.4. Postrift basin—Site U1607

We cored Site U1607 to 978 m CSF-A with the aim of understanding early ice sheet evolution in northwest Greenland and its behavior in a past climate periods with stronger greenhouse forcing than the present. This was the primary site (formerly proposed Site MB-07B) for capturing a sequence that was characterized by seismic data as a hemipelagic basin infill (Figure F4). From regional seismic lines we also knew that there was a stratigraphic section, presumably over hundreds of meters, missing in the top of the section (~present seabed) because of tectonic uplift and/or glacial erosion (Knutz et al., 2015; Gregersen et al., 2022). The site was drilled on the outer rim of a sedimentary basin situated between a major boundary fault against Greenland (east) and the Melville Bay Ridge (west). These tectonic elements originated during the Cretaceous rift phase prior to Baffin Bay opening and were later modified by a late Eocene transpressional regime as spreading halted (Figure F2).

Expedition 400 achieved a nearly unbroken sedimentary record that according to biostratigraphic indexes goes back to the earliest Miocene–late Oligocene. Shipboard paleomagnetic stratigraphy was not affirmative and only possible to about 360 m CSF-A because of diagenetic influences on magnetic mineral components. With limited but important support from the shipboard micropaleontology team, two potential age models were presented, essentially capturing different parts of the Miocene. Onshore analyses, including further paleomagnetic work, micropaleontology based on comprehensive sampling and processing, as well as discrete radiogenic dating, will be necessary to produce a refined age model for Hole U1607A. With a better constrained age model it may be possible to extract climate rhythms from the continuous proxy data (e.g., NGR or other wireline logging data) that can be orbitally tuned to the global climate record (cf. Miller et al., 2020). With further elaboration on lithologic and organic matter proxies we hope to test the hypothesis that climate cooling in the late Miocene is associated with an ice sheet expansion in northwest Greenland from ephemeral glaciation to an ice dome drained by glacial-marine outlets. Site U1607 has provided us with an Oligocene–Miocene archive adjacent to west Greenland sedimentary sources that will be crucial for understanding the response of the cryosphere to greenhouse gas forcing and associated tipping points. This information will be valuable for validating paleoclimate ensemble models aimed at reconstructing warm analogs aimed at future warming scenarios.

Drilling Site U1607 to the planned target depth of nearly 980 m CSF-A was clearly a high-risk/high-gain operation, so we consider the results from Site U1607 to be an overachievement.

6. Outreach

Expedition 400 had two Education and Outreach officers on board. One outreach officer teaches and leads geology field trips at a community college and a university. The other outreach officer was a world geography educator and polar explorer and is currently a Program Manager for a National Science Foundation (NSF) funded outreach program.

6.1. Live broadcasts

Both outreach officers traveled to Denmark and Greenland prior to the expedition. The purpose was to meet with community and organization representatives who have relevant connections to the expedition's scientific objectives and who might be interested in ship-to-shore tours. During the expedition, the International School in Denmark scheduled tours for their 7th and 8th grade classes. Overall, Internet connectivity was excellent, with only a couple of tours experiencing significant connectivity problems.

Two open houses were hosted during the expedition; one open house was early during the expedition, and the other open house occurred later. The outreach officers facilitated a broadcasted presentation and tour led by Co-Chief Scientist Paul Knutz to the European Consortium for Ocean Research Drilling (ECORD) Summer School, as well as a tour led by Paul Knutz and GEUS colleague and shipboard scientist Lara Pérez to the GEUS community. The outreach officers facilitated a tour hosted by shipboard scientist Vikash Kumar's institution, the National Centre for Polar and Ocean Research (NCPOR), that was led by him and fellow shipboard scientist, Fawz Naim.

The outreach officers also facilitated two tours hosted by IODP China and led by shipboard scientists Jian Ren and Yancheng Zhang. In total, the outreach officers conducted 60 tours to approximately 2394 participants, plus approximately 2.5 million participants for the two IODP China events.

6.2. Expedition activities

The expedition was continuously documented by the two outreach officers using film, photographs, writing, and social media posts. A preexpedition blog about onshore outreach activities and an expedition video trailer were posted just prior to departure. A total of seven blog posts were posted on the *JOIDES Resolution* website along with three related Discovery on Deck videos posted on the *JOIDES Resolution* YouTube channel. The Reach The World collaboration, which

spanned the duration of the expedition, included three live broadcasts and four blog-style articles. A total of 28 classrooms registered for and several participated in live broadcasts.

6.3. Media

The outreach officers filmed language tours of *JOIDES Resolution* in French and Danish. The French tour was broadcast at a museum exhibition in Geneva, Switzerland, the home institution of shipboard scientist Sandrine Le Houedec. The Danish tour was filmed with Co-Chief Scientist Paul Knutz and will be used as a resource at his home institution, GEUS. They also facilitated several social media posts with GNS Science in New Zealand and shipboard scientist Georgia Grant. The outreach officers facilitated a media interview with Co-Chief Scientist Anne Jennings and assisted with edits on an article to be published at University of Colorado at Boulder.

6.4. Social media

Several posts were made each week on Facebook, Instagram, and X (formerly known as Twitter) during the expedition. Posts featured a variety of topics including cores recovered, life on board, advertising outreach events and resources, and expedition updates. Outreach officers each took the lead on platforms, dividing Facebook/Instagram and X/YouTube, to increase the variety of posts shared across all platforms. Social media statistics include 56 Facebook posts with 112,000 people reached and 56 new followers, 116 Tweets with 229,000 impressions and 146 new followers, and 112 Instagram posts with 65,000 people reached and 113 new followers. The scientists also made posts linked to the expedition and posted on LinkedIn.

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