Integrated Ocean Drilling Program
Expedition 302 Preliminary Report

Arctic Coring Expedition (ACEX)

Paleoceanographic and tectonic evolution of the central Arctic Ocean

7 August–13 September 2004

Expedition 302 Scientists

PUBLISHER'S NOTES

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ABSTRACT

The first scientific drilling expedition to the central Arctic Ocean was completed in late summer 2004. Integrated Ocean Drilling Program Expedition 302, Arctic Coring Expedition (ACEX), recovered sediment cores deeper than 400 meters below seafloor (mbsf) in water depths of ~1300 m at the top of the world, only 250 km from the North Pole.

ACEX's destination was the Lomonosov Ridge, hypothesized to be a sliver of continental crust that broke away from the Eurasian plate at ~56 Ma. As the ridge moved northward and subsided, marine sedimentation occurred and continued to the present, resulting in what was anticipated (from seismic data) to be a continuous paleoceanographic record. The elevation of the ridge above the surrounding abyssal plains (~3 km) ensures that sediments atop the ridge are free of turbidites. The primary scientific objective of ACEX was to continuously recover this sediment record and to sample the underlying sedimentary bedrock by drilling and coring from a stationary drillship.

The biggest challenge facing ACEX was maintaining the drillship's location while drilling and coring 2–4 m thick sea ice that moved at speeds approaching half a knot. Sea-ice cover over the Lomonosov Ridge moves with the Transpolar Drift and responds locally to wind, tides, and currents. Until now, the high Arctic Ocean Basin, known as "mare incognitum" within the scientific community, had never before been deeply cored because of these challenging sea-ice conditions.

Initial offshore results, based on analysis of core catcher sediments, demonstrate that biogenic carbonate only occurs in the Holocene–Pleistocene interval. The upper ~170 m represents a record of the past ~15 m.y. composed of sediment with ice-rafted sediment and occasional small pebbles, suggesting that ice-covered conditions extended at least this far back in time. Details of the ice cover, timing, and characteristics (e.g., perennial vs. seasonal) await further study. Earlier in the record, spanning a major portion of the Oligocene to late Eocene, an interruption in continuous sedimentation occurred. This may represent a hiatus encompassing a time interval of nondeposition or an erosional episode that removed sediment of this age from the ridge. The sediment record during the middle Eocene is of dark, organic-rich siliceous composition. Isolated pebbles, interpreted as ice-rafted dropstones, are present down to 239 mbsf, well into the middle Eocene section. An interval recovered around the lower/middle Eocene boundary contains an abundance of *Azolla* spp., suggesting that a fresh/low

salinity surface water setting dominated the region during this time period. Although predictions based on geophysical data had placed the base of the sediment column at 50 Ma, drilling revealed that the latest Paleocene to earliest Eocene boundary interval, well known as the early Eocene Thermal Maximum (EETM), was recovered. During the EETM, the Arctic Ocean was subtropical with warm surface ocean temperatures. ACEX penetrated into the underlying sedimentary bedrock, revealing a shallow-water depositional environment of Late Cretaceous age.

INTRODUCTION

Geological Setting

Ever since Bruce Heezen and Maurice Ewing recognized, in their 1961 paper, that the mid-ocean rift system extended from the North Atlantic into the Arctic Ocean, it has been assumed that the Lomonosov Ridge (Fig. **F1**) was originally a continental fragment broken off of the Eurasian continental margin. Aeromagnetic surveys of the Eurasian Basin have since mapped a remarkably clear pattern of magnetic lineations which can be interpreted in terms of seafloor spreading along the Gakkel Ridge since Chron C24 at ~53 Ma (Wilson, 1963; Vogt et al., 1979; Kristoffersen, 1990). If we compensate for that motion of the seafloor, the Lomonosov Ridge is brought into juxtaposition with the Barents/Kara Sea margin in early Cenozoic reconstructions. Zircon-bearing bedrock samples from the Lomonosov Ridge at 88.9°N yield a latest Permian (~250 Ma) age (Grantz et al., 2001). The only known source for zircons aged ca. 250 Ma in the circum-Arctic is in the post-tectonic syenites of northern Taymyr Peninsula and nearby islands in the Kara Sea, lending support to the tectonic model in which the ridge is interpreted to be a continental sliver that separated from the Eurasian plate.

As the Lomonosov Ridge moved away from the Eurasian plate and subsided, sedimentation on top of this continental sliver began and continued to the present, providing a >400 m thick stratigraphic sequence. The elevation of the ridge above the surrounding abyssal plains (~3 km) indicates that sediments on top of the ridge have been isolated from turbidites and originate from hemipelagic, biogenic, eolian, and/or ice-rafted input.

Two key seismic profiles (AWI-91090 and AWI-91091) were acquired across the Lomonosov Ridge in about 8/10 sea-ice cover in 1991 (Jokat et al., 1992). At 88°N in ~1 km of water, the ridge is 80 km wide with a 410 m thick section of acoustically stratified sediments that cap the ridge above an unconformity (Fig. F2). Below this unconformity, sediments are present in down-faulted asymmetric half-grabens.

Several dozen short cores (<10 m) of Pleistocene and Holocene age exist from the central parts of the Lomonosov Ridge, indicating average sedimentation rates of ~10 m/m.y. (e.g., Gard, 1993; Jakobsson et al., 2000, 2001; Backman et al., 2004).

Prior to the Arctic Coring Expedition (ACEX), little information was available about pre-Pleistocene paleoenvironments in the central Arctic Ocean. Temperate marine conditions existed during the Late Cretaceous (Campanian–Maastrichtian) based on evidence provided by silicoflagellates and diatoms from three short T-3 and CESAR cores, all retrieved from the Alpha Ridge in the Amerasian Basin (Clark et al., 1980; Bukry, 1981; Thiede et al., 1990). One 3.64 m long core (F1-422) containing a 1.65 m section with middle Eocene diatoms and silicoflagellates provided the sole evidence for early Cenozoic marine conditions in the Arctic (Bukry, 1984; Ling, 1985).

Scientific Objectives

The history of Arctic paleoceanography is so poorly known that we can look at the recovery of any material as a true exploration that will, by definition, increase our knowledge and understanding of this critical region. The key objective of ACEX was to recover a continuous ~450 m thick sediment sequence including the upper part of the underlying acoustic basement (bedrock) from the crest of the Lomonosov Ridge. The overall, primary scientific goal was to determine the paleoenvironmental development in the central Arctic Ocean during post-Paleocene times and to decipher its role in the global climate evolution. A secondary scientific goal was to acquire information about the early tectonic evolution of the Eurasian Basin.

Specific paleoceanographic objectives are to:

- Determine the history of ice rafting and sea ice;
- Study local versus regional ice sheet development;
- Determine the density structure of Arctic Ocean surface waters, the nature of North Atlantic, and the conveyor and onset of Northern Hemisphere glaciation;
- Determine the timing and consequences of the opening of the Bering Strait;
- Study the land-sea links and the response of the Arctic to Pliocene warm events;
- Investigate the development of the Fram Strait and deepwater exchange between the Arctic Ocean and Greenland/Iceland/Norwegian Sea; and

- Determine the history of biogenic sedimentation.

The tectonic objectives are focused on ridge evolution. Specific tectonic objectives for drilling on the Lomonosov Ridge are to:

- Investigate the nature and origin of the Lomonosov Ridge by sampling the oldest rocks below the regional unconformity in order to establish the pre-Cenozoic environmental setting of the ridge and
- Study the history of rifting and the timing of tectonic events that affected the ridge.

Strategy

The biggest challenge facing ACEX was maintaining the drillship's location during drilling and coring in moving, heavy sea ice. Sea-ice cover over the Lomonosov Ridge moves with the Transpolar Drift and is affected by local responses to wind, tides, and currents. Until now, the high Arctic Ocean Basin, known as "mare incognitum" to the scientific community, had never been deeply cored before because of these challenging sea-ice conditions.

Plans for this first-ever event were carefully crafted over several years and included a fleet of three icebreaker-class ships: a drilling vessel, the *Vidar Viking*, which remained at a fixed location and suspended over 1600 m of drill pipe through the water column and into the underlying sediments; a Russian nuclear icebreaker, *Sovetskiy Soyuz;* and the diesel-electric icebreaker *Oden*. The *Sovetskiy Soyuz* and *Oden* protected the *Vidar Viking* by breaking "upstream" floes into small bergy bits to allow the *Vidar Viking* to stay positioned to drill and recover the sediment cores.

This strategy was successful. Planners had predicted that the fleet could maintain the drillship's station for up to 2 full days, yet the stationkeeping ability was stretched to more than 9 consecutive days. The three ships coordinated their efforts through a central Fleet Manager, at times on a minute-to-minute basis. The fleet kept the *Vidar Viking* on location in 9/10, multiyear ice for up to 9 days—a landmark feat that has empowered scientists to continue to explore this least known of our oceans through scientific ocean drilling for many years to come.

The *Sovetskiy Soyuz* conducted the first attack on oncoming heavy floes, whereas *Oden* was the last defense in protecting the drilling operation against the oncoming ice (Fig. F3). During these defensive operations, the officers on the *Vidar Viking* kept station by manually driving the powerful thrusters with the bow continuously maneuvered to head into the direction of the oncoming ice. The ice management defense strategies were continuously updated with information from a full-time ice and weather forecast team onboard the *Oden* and *Sovetskiy Soyuz*.

Coring operations were conducted by Seacore, Ltd., using a specially built drill rig for the *Vidar Viking*. Coring tools were provided by the British Geological Survey. Cores were collected on the *Vidar Viking* from five boreholes drilled to a maximum depth of 428 meters below seafloor (mbsf). A ~160 m record of wireline geophysical logs was collected in one borehole.

The cores, collected in plastic liners, were sealed for postexpedition analyses onshore at the Integrated Ocean Drilling Program repository in Bremen, Germany. Before they were stored, cores were analyzed for physical properties using Geotek's nondestructive multisensor track. Selected intervals were sampled to extract pore water and microbiology samples. During the expedition, core catcher samples were routinely transferred to the *Oden* twice a day for analyses that included micropaleontology, stratigraphy, petrophysics, chemistry, and sedimentology.

SYNTHESIS

Site Overview

Cores were recovered in five holes across three sites (Holes M0002A, M0003A, M0004A, M0004B, and M0004C) (Tables **T1, T2, T3**), with a total recovery of 68.4%, which precluded the complete recovery of the entire sediment drape, a key objective (Fig. **F4**). The first hole at Site M0001 was abandoned because a bottom-hole assembly (BHA) was lost (see **"Site Operations"** in "Operations"). Logging was attempted in two holes and data were collected over a 160 m interval in Hole M0004B.

The ACEX sites are situated within 15.7 km of each other on seismic Line AWI-91090 and have been treated as a single site because of the internally consistent seismic stratigraphy across that distance (Fig. **F2**). A limited amount of site-to-site correlation was conducted, based primarily on physical property data (gamma ray attenuation bulk density, magnetic susceptibility, *P*-wave velocity, and electrical resistivity) generated using a multisensor core logging system. Site correlation was also aided by lithologic descriptions and high-resolution geochemical pore water measurements of chiefly ammonia concentrations and alkalinity. In terms of recovered stratigraphy, the bulk of material was provided by Hole M0002A for the upper half of the 428 m long stratigraphic record and Hole M0004A for the lower half, with correlation made possible by a short overlap between the two holes. The other holes recovered multiple portions of the upper ~30 m and allowed construction of a composite depth scale and spliced record for this short interval.

Preliminary Scientific Assessment

The overall goal of ACEX was to study Arctic paleoceanography in order to understand this region's past climate and its impact on Earth's climate over the Cenozoic, with particular emphasis on the change from the "greenhouse" world of the Eocene to the "icehouse" world of today.

The prospectus outlined the methods to achieve this goal. The primary method was to apply a well-known and effective technique for complete core recovery: continuous piston core and extended core barrel sampling in multiple holes at one site. This technique results in a continuous stratigraphic record. ACEX was not able to apply this method during Expedition 302, as no sites in ACEX were multiply cored (Table **T1;** Fig. **F4**). In addition, single hole penetrations suffered from relatively low recovery. The average core recovery for all holes was 68.4%; below 270 m (~47 Ma) to total depth at 428 mbsf, the recovery dropped to 43.1%. This lower recovery interval spanned two of the most important ACEX events: the *Azolla* and the early Eocene Thermal Maximum (EETM), resulting in incomplete records for both.

The early results of ACEX show that further analyses of the sediment and basement cores will contribute to five of the seven major paleoceanographic objectives and both of the tectonic objectives. The degree to which advances are made depends on the level of detail that can be extracted from the sediment record. Because of the low core recovery, an average of one-third of this detailed record is missing, thus reducing the chances for fully meeting each objective.

The predicted lithologies were encountered. Stratigraphically, the ACEX sites show a major hiatus spanning the transition from the Neogene to the Paleogene. The overall age span of the sediment section was greater than predicted by a few million years. The overall impact of these two factors is limited. The hiatus means that paleoceanographic analyses over this missing interval cannot occur, but interpretation of the overall time and causal mechanisms will contribute to furthering our understanding of the tectonic evolution. The longer age interval will allow us to interpret the paleoclimate conditions during the EETM at a position close to the North Pole.

Among the seven specific paleoceanographic objectives, results from ACEX will be used to determine the history of ice rafting and sea ice; study local (e.g., Svalbard) versus regional ice sheet development; reconstruct the density structure of surface waters, the nature of North Atlantic conveyor, and the onset of Northern Hemisphere glaciation; make contributions to the investigation of the development of the Fram Strait and deepwater exchange between the Arctic and the world ocean; and determine the history of biogenic sedimentation. Because one of the hiatuses in the sediment record may span the Pliocene, it is possible that ACEX results may not be useful in the study the land-sea links and the response of the Arctic to Pliocene warm events. Also, the lack of a carbonate stratigraphic record precludes study of the timing and consequences of the opening of the Bering Strait. Biogenic carbonate occurs only rarely and occasionally in the upper 18 m of the sediment column. The disappearance of carbonate occurs together with a decrease in pH and alkalinity, suggesting that the lack of cocolithophorids, calcareous foraminifers, and ostracodes in deeper sediments is caused by dissolution.

ACEX results partially addressed the two tectonic objectives. The regional unconformity was penetrated but not sampled except for a small bag sample. Fossils from this sample constrain timing of the initiation of rifting to between 80 Ma and the oldest age of the sediment overlying the unconformity at 58 Ma.

Early results reveal that the upper sediments hold a record of sea-ice distribution in the Arctic Ocean well into the middle Miocene. The situation is different in older, underlying cores where dark, organic-rich sediments contain abundant diatoms, ebridians, silicoflagellates, and dinoflagellate cysts, indicating a middle Eocene age and an environment partly characterized by ice-free, warmer surface ocean waters. Isolated pebbles, interpreted as dropstones, were observed downhole to ~239 mbsf, suggesting the presence of at least seasonal ice throughout most of the middle Eocene.

Abundant megaspores of the hydropterid fern *Azolla* occur at the early/middle Eocene boundary, suggesting strongly reduced surface water salinity or perhaps even a brief episode of freshwater conditions at the surface. It is yet not known if the *Azolla* spores represent an indigenous signal, indicating fresh to nearly fresh surface waters, or if they have been transported into a marine Arctic basin from neighboring freshwater systems. However, the sporadic and rare presence of radiolarians suggests that the Arctic's surface water salinities indeed were reduced throughout the Eocene interval containing biosilica. Biosilica is not preserved before the late early Eocene. The dinoflagellate species *Apectodinium augustum* is abundantly present at ~380 m in pyrite-rich mudstones, indicating that the EETM interval was partly recovered. During this thermal maximum, the Arctic Ocean experienced surface temperatures on the order of 20°C.

Lithostratigraphy

The lithostratigraphy of the Lomonosov Ridge sites is described in terms of four units (Fig. F5). Recovered sediments, ranging in age from Holocene to Late Cretaceous (0–428 mbsf), are dominated by lithogenic material. With the exception of sandy lenses, the dominant terrigenous component of all lithologic units is fine grained, ranging from clays to silty muds indicative of predominantly low energy marine environments. The upper ~220 mbsf comprises soft to hard silty clay with colors varying from light brown to olive green to gray (Unit 1). Isolated pebbles are present throughout Unit 1, with the deepest pebble observed in Unit 2 (239.34 mbsf). This may indicate the presence of at least seasonal sea ice as early as the middle Eocene. Lithologic unit changes do not coincide with hiatuses interpreted on the basis of biostratigraphy. However, a major hiatus is likely within Core 302-M0002A-46X near the boundary of Subunits 1/5 and 1/6.

Below ~220 mbsf, the sediments change from biosiliceous silty clay to biosiliceous ooze encompassing an interval of ~93 m (Unit 2). The biosiliceous sediments overlie an interval of hard silty clay to mudstone (Unit 3), which, at ~410 mbsf, rests unconformably on Campanian marine sands, sandstone, and mudstone (Unit 4).

Micropaleontology

Prior to ACEX, information about microfossil contents in central Arctic Ocean cores was limited to observations made in short piston and gravity cores. These cores held records of variable and discontinuous abundances of calcareous nannofossils, planktonic and benthic foraminifers, ostracodes, and dinoflagellate cysts (e.g., Aksu et al., 1988; Scott et al., 1989; Gard, 1993; Cronin et al., 1994; Ishman et al., 1996; Matthiessen et al., 2001). A single core from the Alpha Ridge contained middle Eocene diatoms and silicoflagellates (Bukry, 1984; Ling, 1985). Before ACEX, no accurate knowledge existed about which biostratigraphically useful microfossil groups may be encountered at depth. Therefore, expertise representing all above microfossil groups participated during the offshore phase. ACEX core catcher samples were also systematically searched for radiolarians and fish debris.

Biogenic carbonate is missing with the exception of the upper 18 m. Dinoflagellate cysts provide the bulk of available biostratigraphic information in the upper ~170 m.

A 23 m thick interval below ~170 mbsf appears to be completely devoid of microfossils, referred to as the "spooky" interval by the offshore micropaleontologists. The spooky interval separates the overlying middle Miocene from the underlying middle Eocene and presumably preserves some of the lower Neogene and upper Paleogene sections. Dinoflagellate cysts, diatoms, ebridians, and silicoflagellates are common to abundant in the middle Eocene section, which ends in an interval with megaspores of the freshwater hydropterid fern *Azolla* at the lower/middle Eocene boundary (~306 m). Biosilica is not preserved prior to the late early Eocene (~320 m).

The (sub)tropical dinoflagellate species *A. augustum* occurs abundantly at ~380 m, indicating that the Paleocene/Eocene boundary and the associated carbon isotope excursion interval was at least partly recovered.

Benthic foraminifers indicate that the lower Eocene through upper Paleocene sediments were deposited in shallow-marine, neritic to inner-neritic environments.

Sedimentation Rates

Biostratigraphy provided age/depth information that will be useful when developing the age model for the ACEX sites. Paleomagnetic data are being acquired postcruise, which will be amalgamated with the biostratigraphic data to provide an age model. These data will be presented in the Expedition 302 Results volume. Among the biostratigraphy, dinocysts provide the bulk of the Neogene biostratigraphic data. In the Eocene, diatoms and silicoflagellates were added to the dinocyst data set. The general structure of the biostratigraphic age/depth point distribution shows two distinct intervals, both having rates on the order of 1–3 cm/k.y. (10–30 m/m.y.), namely a Pleistocene to middle Miocene interval and a middle Eocene to uppermost Paleocene interval. Presently we lack age information for a ~23 m thick interval separating the two intervals. However, the distribution of presently available biostratigraphic age/depth points clearly suggests the presence of a major hiatus separating the Neogene and Paleogene intervals. The precise extent of this hiatus and its precise location in the stratigraphic column is presently unknown. Another major hiatus appears to separate upper Paleocene from the underlying Campanian sediments.

Petrophysics

Petrophysical measurements performed during the offshore component of ACEX included downhole wireline logging; nondestructive whole-core measurements of bulk density, compressional *P*-wave velocity, resistivity, and magnetic susceptibility; and discrete measurements of shear strength and moisture and density.

Downhole Wireline Logging

Downhole logging was attempted in both Holes M0004A and M0004B. A 160 m interval was successfully logged in Hole M0004B with two upward passes, with the second pass crossing the seafloor (see **"Site M0004 (Shotpoints 3006 [A, B] and 3004 [C] on Line AWI-91090)"** in "Operations"). The tool string comprised the Natural Gamma Ray Spectrometry Tool (NGT), Formation MicroScanner (FMS), Borehole Compensated Sonic (BHC) tool, and Scintillation Gamma Ray Tool (SGT).

The calliper logs from the FMS (two per pass) provided a method for assessing the borehole condition (diameter and rugosity). The bit outer diameter is 9 inches and it was observed that, for much of the formation, the hole diameter was under gauge and narrowed significantly between 75 and 90 mbsf, at 155 mbsf, and again between 180 and 184 mbsf. Given the narrow borehole diameter, the FMS pads should have made contact with the borehole wall for the entire length of the logged section. The caliper logs indicated that the borehole conditions for the complete logged section were good and nowhere did the borehole appear washed out to the degree that it would adversely affect the tool response. This judgement is supported by a favorable comparison of parameter magnitudes between passes. The depth match between the logging passes is good (being for the most part less than ±1 m) but becomes offset by as much as 2.6 m at ~155 meters below rig floor (mbrf) and improves again in the bottom of the hole. This offset was removed by depth matching the passes.

Multisensor Core Logger and Discrete Physical Property Measurements

Downhole variations in density, *P*-wave velocity, and magnetic susceptibility highlight a number of prominent stratigraphic changes that exist at all sites and correlate well with observed seismic reflectors. The stratigraphic similarities among the sites allowed a single composite section to be constructed (Fig. **F6A, F6B**).

Compositionally, the upper 220 m of sediment recovered from Lomonosov Ridge is predominantly silty clay (lithologic Unit 1). In contrast to deep marine sediment sequences, this interval does not exhibit a single, clearly defined consolidation pattern with depth. The upper ~20 mbsf shows first order increases in both density and velocity that appear to arise from normal consolidation processes (Fig. **F7A, F7B**). Throughout this upper unit, well-defined decimeter-scale variations in density, velocity, and susceptibility occur in phase.

Between 70 and 100 mbsf, there is a shift away from the high-amplitude variation in magnetic susceptibility that is a characteristic feature of the sediments below ~20 mbsf. A subtle first-order reduction in the magnetic susceptibility of the sediments begins at 100 mbsf and continues to ~160 mbsf. This reduction may result from gradual compositional changes occurring through this interval.

A noticeable decrease in all petrophysical properties measured on the multisensor core logger (MSCL) occurs at ~166 mbsf and accompanies the transition from predominantly olive-green sediments into those characterized by a more yellowish to brown hue at the Unit 2/3 boundary. One of the most prominent changes is a large decrease in *P*-wave velocity at ~198 mbsf, marking the transition into a biosiliceous unit. The upper part of this biosiliceous unit is largely composed of pyritized diatoms and is reflected in the petrophysical data as a low-velocity, high-density interval. At ~220 mbsf, density decreases sharply from 1.7 to 1.3 g/cm^3 without a noticeable change in the *P*-wave velocity and is associated with the transition from a biosiliceous silty clay unit into a biosiliceous ooze (Unit 2).

Large gaps in core recovery occur from ~220 to ~350 mbsf. An increase in density through this interval could be the result of normal consolidation or a reduction in the biosiliceous contribution to the matrix material. Below ~370 mbsf and the end of the petrophysical record at ~410 mbsf, bulk density fluctuates between 1.6 and 2.1 g/cm^3. Throughout this interval, large amounts of pyrite are found in the core catcher samples. Peaks in susceptibility (>5 × 10^{-3} SI) and density (>3 g/cm^3) indicate the presence of dense material that is probably of diagenetic origin. The deepest cores recovered from Hole M0004A, documenting the transition through sandstone and mudstones and into basement, were too short and disturbed to be run on the MSCL.

Based on undrained shear strength measurements made on the ends of recovered core sections, the Lomonosov Ridge sediments have a low consolidation index (~0.1) (Fig. **F8**), suggesting underconsolidation with the exception of specific intervals. At ~55 mbsf, a single measurement indicates a highly overconsolidated zone that overlies seemingly normally consolidated material. Below 155 mbsf, the consolidation ratio becomes slightly elevated and remains high until 193 mbsf where the resolution of the measurement device was suddenly exceeded.

In Situ Temperature Measurements

In situ temperature was measured during coring operations using the British Geological Survey (BGS) and Adara temperature tools (Fig. **F9**). The mudline temperature was recorded on all runs and varied between tools. An attempt to normalize the in situ measurements was made by using the average Adara determined mudline temperature and adjusting all in situ measurements to this baseline value. The average gradient calculated using all available data points is 43.2°C/km.

Chemistry

Significant features in the shipboard pore water chemistry profiles describe three geochemical environments: shallow carbonate dissolution, deep sulfate reduction, and shallow ammonium oxidation (Fig. **F10**).

Lithologic and micropaleontogical descriptions of sediment note a general absence of primary carbonate below ~16 mbsf, where pH and alkalinity drop below 7.4 and 2.5, respectively. This means that pore waters near this depth are more corrosive to carbonate tests than the overlying sediment or water column. Carbonate tests may have dissolved when they were buried to the depth of these corrosive pore waters.

High alkalinity below 200 mbsf suggests that chemical reactions are adding substantial amounts of HCO_3^- at depth without accompanying H^+. The likely candidate is sulfate reduction of organic carbon:

$$2CH_2O(s) + SO_4^{2-}(aq) \rightarrow 2HCO_3^-(aq) + H_2S(aq).$$

Black sediments (Unit 5) were rapidly deposited below 200 mbsf. These sediments host abundant pyrite and lie beneath dark banded intervals that may be composed of other iron sulfide minerals. Organic matter in the black sediment probably reacted with dissolved SO_4^{2-} since the time of burial, producing abundant H_2S and, ultimately, iron sulfide minerals.

A peak in alkalinity (at ~6 meters composite depth [mcd]) coincides with a sharp steady rise in NH_4^+. The peak in alkalinity supports the interpretation that some chemical reaction is producing HCO_3^- without accompanying H^+. The NH_4^+ profile further suggests that upward diffusing NH_4^+ drives this reaction.

Microbiology

Sampling for microbiological analyses was conducted at fairly regular depth intervals from the surface (7 mbsf) to near basement (398 mbsf) with a notable gap between 169 and 241 mbsf. A total of 21 samples were preserved for enumeration of microorganisms to provide estimates of subsurface biomass. Nineteen samples were stored anaerobically for the purpose of shore-based cultivation studies. A subset of samples (18) was stored at –51°C for DNA extraction and subsequent microbial community characterization. Finally, 10 samples were stored at –51°C for lipid biomarker analysis.

OPERATIONS

Mobilization of the *Vidar Viking*, Aberdeen, Scotland

The *Vidar Viking* came under contract on Thursday, 22 July 2004, when mobilization began in Aberdeen. By 26 July, all equipment for the *Vidar Viking* had arrived, including information technology equipment bound for the *Oden*, and the derrick was load tested and certified. The *Vidar Viking* took on a full complement of fuel at Aberdeen.

Test Coring Site: Witch Ground, North Sea

The *Vidar Viking* set sail for Landskrona, Sweden, on 28 July. While the ship was en route, a first test of the drilling equipment was conducted in the Witch Ground area of the North Sea, ~8 h steam from Aberdeen. A test borehole was drilled in 152 m water depth to a depth of 37 m using both the advanced piston corer (APC) and the extended core barrel (XCB). Cores were obtained with both systems. The APC recovered >4 m in all runs (maximum = 4.5 m). The *Vidar Viking* left the test coring site at 1900 h on 30 July and proceeded to Landskrona.

Meanwhile, the mobilization of the *Oden* proceeded at Gothenburg, which included loading the laboratory equipment. On the evening of 31 July, the *Oden* set sail for Tromsø, Norway.

Mobilization of the *Vidar Viking*, Landskrona, Sweden

The *Vidar Viking* reached Landskrona on the morning of 1 August. The stern notch, a 100 ton section required by the *Vidar Viking* when working in ice, and the helideck were installed. The remaining containers were loaded onto the deck, including the core curation container sent from Bremen, Germany. Other mobilization work continued until the morning of 3 August, when the *Vidar Viking* departed for Tromsø.

Mobilization of the *Vidar Viking* and *Oden*, Tromsø, Norway

The *Oden* arrived in Tromsø on the evening of 5 August. The *Vidar Viking* arrived on the morning of 7 August. Two helicopters, required for ice reconnaissance missions, landed on the *Oden* and were secured.

Rendezvous of the Three ACEX Ships

Expedition 302 officially began when the *Oden* left Tromsø, Norway, at 2350 h on 7 August 2004. The *Vidar Viking* remained in Tromsø for the next 12 h to wait for dynamic positioning (Konsberg) spare parts to arrive.

Oden transited to 81°56′N, 44°59′E to meet the other two ships in the ACEX fleet, the *Sovetskiy Soyuz* and *Vidar Viking*, at the edge of the polar ice pack on 10 August. The fleet entered the ice together with the *Sovetskiy Soyuz* leading, the *Oden* following, and the *Vidar Viking* bringing up the rear.

Transit to the First Site

During the transit to the operational area, ice reconnaissance and personnel transfer flights began on 12 August. The fleet made an unprecedented headway of 8–10 kt in sea ice.

The fleet arrived on site at 2350 h on 13 August and began preparations for drilling and operations for maintaining position in the sea ice.

Preparations for drilling began with clearing ice from the moonpool. Once this was done, a steel skirt was deployed through and below the moonpool to protect the drill string from ice impact. Once the ice protection skirt was in place, the drill floor and iron roughneck were installed. The drill floor was ready for operations by 0900 h on 15 August.

During this time, the fleet's ability to maintain station was tested by positioning the *Sovetskiy Soyuz* and the *Oden* upstream of the *Vidar Viking*. The initial stationkeeping tests were successful, and the Fleet Manager gave approval to start drilling operations at 1100 h on 15 August.

Site Operations

Cores were recovered in five holes (M0002A, M0003A, M0004A, M0004B, and M0004C) (Tables **T1, T2, T3**). Hole M0001A was abandoned after a BHA was lost. Logging was attempted in two holes and data were collected over a 160 m interval in Hole M0004B.

Table **T4** documents the allocation of time, broken down into (1) waiting for better ice conditions, (2) operational breakdown, and (3) drilling operations.

"Breakdown time" is defined as operational time consumed as a result of equipment or mechanical failure. The loss of a BHA, for example, regardless if caused by human error or mechanical failure, necessitated a drill string trip. If the trip time is caused by equipment failures, it was considered as breakdown time "B." Waiting for better ice conditions was labeled "W." Similarly, if waiting on ice conditions required pulling pipe and subsequent preparations to begin drilling operations, these times were included in the "W" category because that time delay was caused by the "waiting for ice" situation.

Site M0001 (Shotpoint 2720 on Line AWI 91090)

We reached Site M0001 at 1100 h on 15 August. Later that day during drill string deployment, the high-pressure mud valve was damaged. The valve was removed, the rest of the drill string was run, and then the broken valve was replaced. Pipe trips were slowed or stopped intermittently to allow overheated hydraulic fluid in the new drill rig to cool.

By 16 August, the drill string was deployed to the seafloor and the first piston corer was deployed at 0600 h. After pumping for 30 min, pressure was not obtained and the piston corer was retrieved without having fired. Damaged seals on the piston corer were replaced. Ice conditions were marginal, and at 0900 h operations were stopped and the drill string was lifted from the seabed. Ice conditions improved by 1400 h, and operations continued. The piston corer was deployed again, and no pressure developed in the drill string. Upon retrieval, the piston corer had not fired. It was suspected that the piston corer had not latched into the BHA. The XCB was then deployed but was not recovered, which indicated that the BHA was lost. At 2000 h, the drill string was tripped and the BHA and XCB losses were confirmed.

Beginning early on 17 August, a new BHA was assembled and we began to lower the drill string. When >800 m was deployed, the high-pressure mud valve on the swivel was damaged again during pipe handling; we decided to trip the drill string because the operator did not want to risk leaving the drill string hanging in the water column for an unspecified period of time. After tripping pipe, the damage was assessed and *Oden's* chief engineer was tasked with manufacturing a new valve using materials from a spare pup joint. As an interim solution, a conventional valve assembly was installed.

Ice conditions deteriorated between 0900 and 2200 h, and the time was utilized to move the *Vidar Viking* to a new position (Hole M0002A). Because there were no mud valve spares, the Swedish Polar Research Secretariat (SPRS) began making arrangements for a Swedish Air Force C-130 airdrop of two new valve parts and one conventional valve assembly.

Site M0002 (Shotpoint 2560 on Line AWI-91090)

Based on a strategy developed by the ice management team, the drill string was lowered while drifting onto location. By 2200 h on 18 August, this strategy put the *Vidar Viking* within 190 m of the proposed site. The final positioning was done by icebreaking this short distance to Hole M0002A. Once on location at 0820 h, three more drill pipes were added and coring started. Because the mud valve was not yet repaired, the XCB was deployed instead of the APC. A first attempt at coring was unsuccessful, but after adding more pipe and drilling another core run, some core was retrieved. The first core on deck arrived at 1335 h at a water depth of 1209 m. Drilling operations continued throughout the afternoon. The newly fabricated mud valve from the *Oden* arrived late in the afternoon, and preparations were made for its installation during a wireline trip. The temporary valve was replaced before more drill pipe was added for the next core run. By midnight on 19 August, a depth of 31 mbsf had been reached.

Drilling and XCB coring continued until 23 August when the Fleet Manager ordered the drill pipe to be pulled to 40 mbsf because ice conditions were deteriorating. Permission to continue drilling operations was given midday, and operations continued until 2100 h when the ice conditions forced the termination of Hole M0002A at a depth of 271.69 m.

The drill string was tripped to the drill deck during the morning of 24 August. After waiting for ice conditions to change in the afternoon, a transit began at 1930 h to a position from which the *Vidar Viking* could drift onto location while tripping in drill string.

While we waited on ice conditions and set up for the next site, an air gun seismic survey was run from the *Oden* to tie Site M0002 to the next site (M0003).

Site M0003 (Shotpoint 2521 on Line AWI-91090)

The *Vidar Viking* reached the ice-drift position at 2100 h and awaited ice reconnaissance results. The iron roughneck, which had been removed to repair oil leaks, was installed after repairs; the ice protector tube was lowered; and the drill floor was prepared. At 2300 h, the BHA and drill collars were run. At 0240 h on 25 August after 400 m of pipe had been deployed, the housing of the iron roughneck cracked and had to be removed for major repairs. Operations resumed at 1400 h using power tongs. The seafloor was reached at ~2300 h, and at 0110 h on 26 August, the first APC core was recovered from Hole M0003A (Table T2).

A second APC core with a shattered liner was recovered. The third APC core became stuck in the BHA. While trying to release the corer, the wireline parted at the mechanical termination, and it was necessary to pull the string. Hole M0003A was terminated at 0440 h.

The ice management team conducted ice reconnaissance surveys, reviewed options, and recommended that the fleet move to a location farther west, where a longer-term prediction of relatively good ice could be made. Once the site was selected, the ice team predicted an upstream ice position for the *Vidar Viking* to start to drift onto the new location. The fleet steamed to the updrift ice position, arriving at 0630 h on 27 August. During this time, wireline termination repair, APC service, and iron roughneck the testing/refitting took place.

Site M0004 (Shotpoints 3006 [A, B] and 3004 [C] on Line AWI-91090)

At 0755 h during pipe tripping, the high-pressure mud valve was damaged again. The valve was removed, and the remaining string was run to 1150 m depth while the valve was repaired. At 1800 h, the *Vidar Viking* was on location (Hole M0004A). Once on station, the repaired mud valve was installed and the drill string was run to the seabed. At 2230 h, drilling operations in Hole M0004A commenced and the hole was advanced by washing ahead 17 mbsf (Table T3) before a piston corer was deployed.

Shortly after midnight on 28 August, the APC became stuck in the BHA but was freed after ~1 h. Once on deck, the plastic liner in the core barrel was found to be shattered and 3.5 m of the core was stuck in the barrel. In light of these problems with the APC, in particular the risk of junking the hole again, it was decided to switch to XCB coring. Two XCB cores were recovered to a depth of 30.5 mbsf followed by washing down to 265 mbsf using the insert bit. This decision to wash ahead was made in order to recover sediment deeper than that recovered in Hole M0002A. By 2240 h, a depth of 265 mbsf was reached.

XCB coring operations continued for the next 3 days (29–31 August), where the hole was advanced at varying rates with good to poor recovery. During this time, the drilling was very slow (e.g., 1 m/h) and recovery in many cores was zero (Cores 302-M0004A-13X through 18X). Different strategies were tried to improve the advance rate. At times, the hole was advanced by washing ahead in an attempt to make faster progress but was ultimately abandoned after it was found that the washing rate was almost the same as the coring rate. On 31 August from 0200 to 0500 h, for two coring runs in a row, no core was recovered. The XCB shoe was switched to a coring shoe for a third attempt at recovery. This coring run cleared a blockage in the bit as the pump pressure dropped significantly. Following this core (with good recovery) and after clearing the blocked bit, core recovery and advancement improved over the next 12 h until basement was reached in Core 302-M0004A-35X. Basement penetration was difficult (8 m penetration in 12 h with low core recovery), and a decision was made at 0900 on 1 September to stop coring at total depth of 428 mbsf and conduct logging in Hole M0004A.

The logging tools were moved to the rig floor and the tool string (FMS-APS-NGT-SGT) and wireline rig-up proceeded simultaneously. The run into hole commenced at 2130 h. This was done at low speed in order to allow the tools to warm up. Communication with the tool was established, and it was lowered to the end of the drill pipe. A computer malfunction caused a communication loss to the tools. The problem was corrected by 0200 h. The tool was powered up, and attempts were made to get the tool to pass through the BHA into the open hole. All efforts failed at the same depth (~1366 mbrf); so, while at rest at this depth, the calipers were opened on the FMS to check whether it was free or lodged. The calipers had some movement, which indicated that the tool string was free.

The landing ring for the core barrel is the narrowest section of the whole pipe string (95 mm) and lies ~6 m above the bit. All the logging tools had been checked through a landing ring dockside in Aberdeen, but there was no hole calibration ring onboard that could be used as a second check. Sequentially, four more logging attempts were made. Each time, it was assumed that the logging tools were too large in diameter and the string diameter was further reduced by removing the larger diameter components. The APS bowspring was removed first, followed by the knuckle joint. Finally, only the narrowest velocity-density string was deployed, which failed to clear the bit at the same depth as the previous runs. After the fifth attempt failed, the logging time allocated had been used up and attempts to log Hole M0004A ended at 1045 h on 2 September.

After the logging gear was cleared away and the drill string was lifted out of the seabed, preparations were made to start a second hole (M0004B) at the site. During preparations, the inner barrel was deployed but did not latch. After an improvised downhole hammer was deployed and worked for 2 h, a short length of core (~10 cm of mudstone), which had been partially blocking the BHA, was recovered.

By 2030 h on 2 September, the *Vidar Viking* was at the new position for the next hole (M0004B). Coring in Hole M0004B started at a depth of 10 mbsf using the XCB because the APC was deemed too risky. After retrieving the first sample, the hole was washed to 20 mbsf for an in situ temperature measurement. The BGS temperature probe was lowered to the base of the hole, pushed into the sediment, and programmed to record the temperature every 5 s. The probe was left to record temperature for 40 min, after which it was retrieved. Plans to wash to a depth of 215 mbsf, core to 230 mbsf, and then wash to 250 mbsf and log were stymied by problems with drilling pressure lines/gauges freezing at –10°C. Because of these problems and the limited time left, the hole was only advanced to a depth of 220 mbsf. Temperature measurements were made at 60 and 100 mbsf.

At 0000 h on 4 September, the pipe was pulled to 65 mbsf to prepare for logging. Rigging of the wireline and tool string occurred concurrently, and rig-up of both was completed by 0415 h. The tool string comprised the FMS-BHC-NGT-SGT; the choice of tools was such that it could be run as a straight-through tool string without the need for articulation and eccentralization subs. The logging string was run slowly to the bit to warm the tools before powering them up. The logging string passed through the bit at 0530 h, and the first pass was completed at 0610 h. Logging operations were completed at 0710 h. Rig-down of the logging tool and wireline was completed by 0905 h, and preparations began for a third hole (M0004C). Hole M0004C was spudded at 1200 h on 4 September, and the first APC core was recovered at 1420 h. Two more APC cores were recovered during the next 10 h. An attempt to make a temperature measurement at 9 mbsf using the Adara tool on the APC failed because of a dead battery. At a depth of 14 mbsf, the APC core barrel became stuck after being fired. The period from midnight to 0530 h on 5 September was spent trying to retrieve the piston tool. Various attempts to recover the tool included flush only, hoist only, mixture of flush and hoist, and hoist and leave at top of hoist for some time. The APC was freed and recovered by 0530 h, and the barrel was slightly bent (the liner was easily removed). Because of the risk of getting stuck again, coring continued using the XCB with a modified Adara shoe to complete two more temperature measurements to a depth of 37 mbsf. Drilling operations ended at 1500 h. The drill string was retrieved by 0500 h on 6 September.

The *Oden* came alongside the *Vidar Viking* to transfer 400 T of fuel, and all three ships of the fleet carried out required maintenance before the return transit. A seismic survey was attempted from the *Oden* but was abandoned because of difficult ice conditions. The operational phase of the expedition ended, and the return transit began.

Transit from the ACEX Coring Sites to Tromsø, Norway

The convoy left the study area at 1930 h on 6 September and headed toward the North Pole. Progress was slow in the first half of the day but improved later, and the fleet arrived at the pole at ~2230 h. The convoy departed at 0100 h on 7 September and made good progress toward Tromsø in almost continuous open water. The *Oden* arrived in Tromsø at 2300 h on Tuesday 13 September.

The *Vidar Viking* parted company with the *Oden* at the ice edge in the early hours of Saturday, 11 September and headed due south. A crew change and demobilization were effected in Tanager, Norway, on 16 and 17 September. The *Vidar Viking* then sailed for Landskrona in Sweden, where the helideck was removed together with the European Science Operator core and curation containers and the deep freeze samples. BGS/Seacore personnel continued the reconstruction of the deck, while vessel and shipyard personnel removed the moonpool and other expedition-linked items.

On 22 September, the *Vidar Viking* sailed for Aberdeen, Scotland, to complete the demobilization. Upon arrival in Aberdeen at 0800 h on 24 September, the remainder of the expedition equipment was demobilized and the vessel was cleared for her next charter by 2200 h that day. Formal end of charter, following tank cleaning and reinstatement and off-hire recertification, was completed on 25 September.

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We thank the Captains (Jørgen E Haave, Tomas Årnell, and Stanislav Smith) and the crews of the *Vidar Viking, Oden,* and *Sovetskiy Soyuz* for skillfully helping us to accomplish the first deep-sea drilling and coring in the central Arctic Ocean.

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Table T1. Summary of core recovery.

Hole	Cored length (m)	Core recovered (m)	Core recovery (%)
M0002A	271.69	213.15	78.5
M0003A	15.00	14.85	99.0
M0004A	157.59	78.41	49.8
M0004B	11.00	7.31	66.5
M0004C	40.19	25.34	63.1
Totals:	495.47	339.06	68.4

Table T2. Type and number of cores recovered.

Hole	APC	XCB	Wash
M0002A	0	62	
M0003A	3	0	
M0004A	1	41	
M0004B	0	2	1
M0004C	4	5	
Total number of cores:	8	110	1
Cored length (m):	37.07	455.40	3
Core recovered (m):	36.86	301.2	1
Core recovery (%):	99.4	66.1	33.3

Note: APC = advanced piston corer, XCB = extended core barrel.

Table T3. Washed interval details.

Hole	Depth (mbsf) Top	Depth (mbsf) Base	Washed interval (m)
M0004A	0.00	17.00	17.00
M0004A	30.50	265.00	234.50
M0004A	330.18	339.00	8.82
M0004A	345.60	355.60	10.00
		Total:	270.32
M0004B	0	10	10
M0004B	15	212	197
		Total:	207

Table T4. Breakdown of operational time while on site during Expedition 302 (ACEX).

Date (2004)	Time (h) T	P	D	W	B	TR	Total	Comments
15 Aug	8.50	2.50			2.00		13	Chicksan valve broken
16 Aug	6.00			5.00	13.00		24	XCB lost
17 Aug					24.00		24	BHA lost; chicksan valve broken
18 Aug				13.00	11.00		24	Repair of chicksan valve
19 Aug			9.58		14.42		24	
20 Aug			22.83	1.17			24	
21 Aug			15.83	8.17			24	
22 Aug			24.00				24	
23 Aug			10.00	14.00			24	
24 Aug	9.50	1.00		10.00		3.50	24	
25 Aug	10.67	1.00	1.00		11.33		24	Iron roughneck failed; reflective seismics (D)
26 Aug		3.50	4.25		16.25		24	Wireline termination failed
27 Aug	13.50		1.50		1.75	7.25	24	Chicksan valve broken third time
28 Aug			21.33		2.67		24	APC stuck
29 Aug			24.00				24	
30 Aug			24.00				24	
31 Aug			24.00				24	
1 Sept	4.75	5.42	11.67	1.00	1.17		24	
2 Sept	1.83		2.92		19.25		24	Logging failed, plugged bit
3 Sept			23.08	0.92			24	
4 Sept		5.50	12.67		5.83		24	Equipment frozen
5 Sept	8.33		8.75		6.92		24	APC stuck in BHA
6 Sept	5.00		6.50		8.00	4.50	24	Maintenance of ships; reflective seismics (D)
Totals:	68.1	18.9	247.9	53.3	137.6	15.3	541	
Percent.	12.6	3.5	45.8	9.8	25.4	2.8		

Notes: XCB = extended core barrel, BHA = bottom-hole assembly, APC = advanced piston corer. Approval was given to start running pipe on Site M0001 at 1100 h on 15 August.

Figure F1. Map of the Arctic Ocean showing the location of the Arctic Coring Expedition (ACEX) study area on the Lomonosov Ridge. The insert is a small scale map showing the locations of ACEX 302 sites.

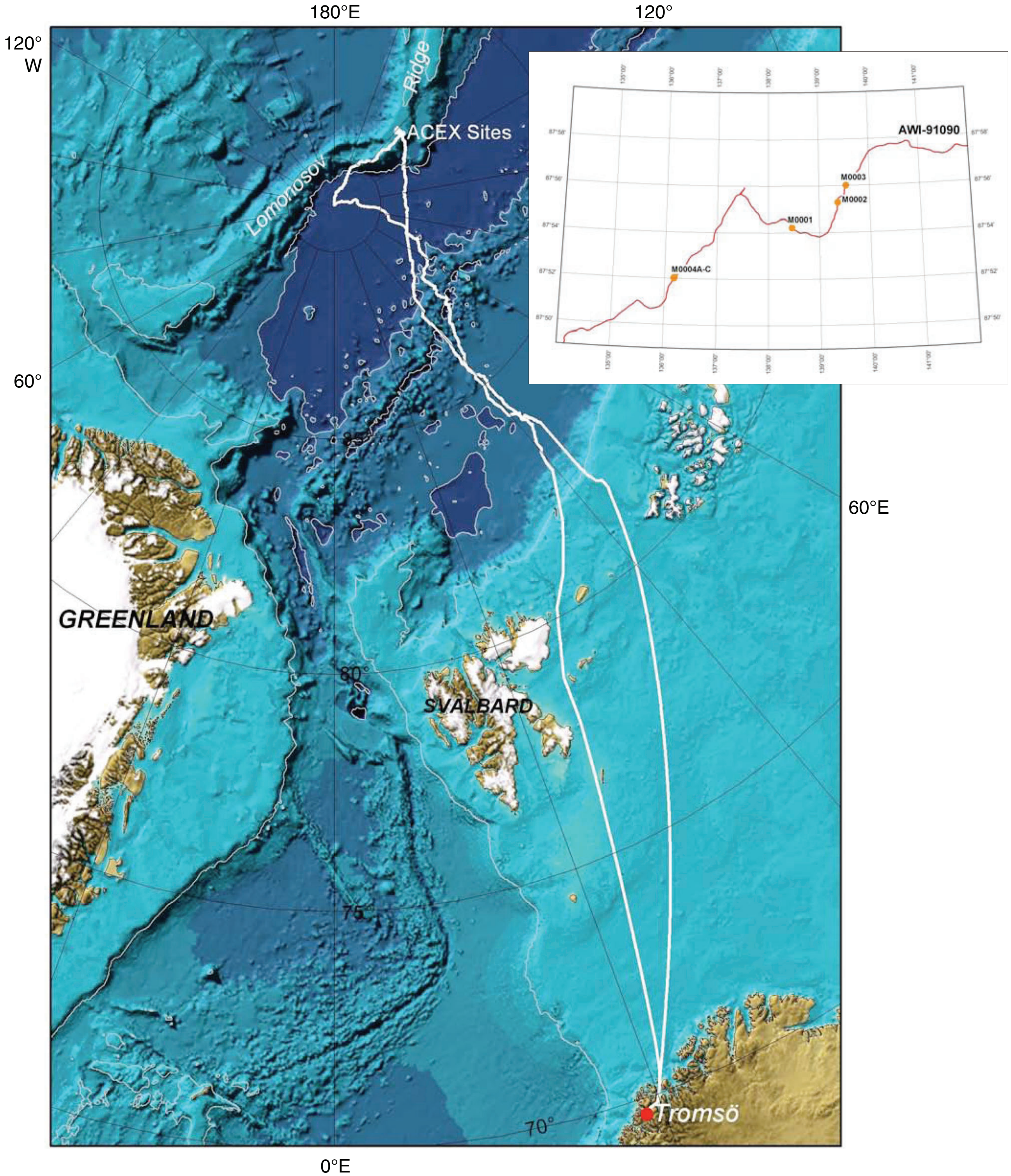

Figure F2. Reflection seismic profile of Lomonosov Ridge (AWI-91090) with locations of ACEX 302 coring sites. Multichannel seismic data are from Jokat et al., 1992. Cores were not retrieved from Hole M0001A because the BHA (gray on figure) was lost. Hole M0004B is located ~60 m away from Hole M0004A; Hole M0004C is located ~60 m away from Hole M0004B. SP = shotpoint.

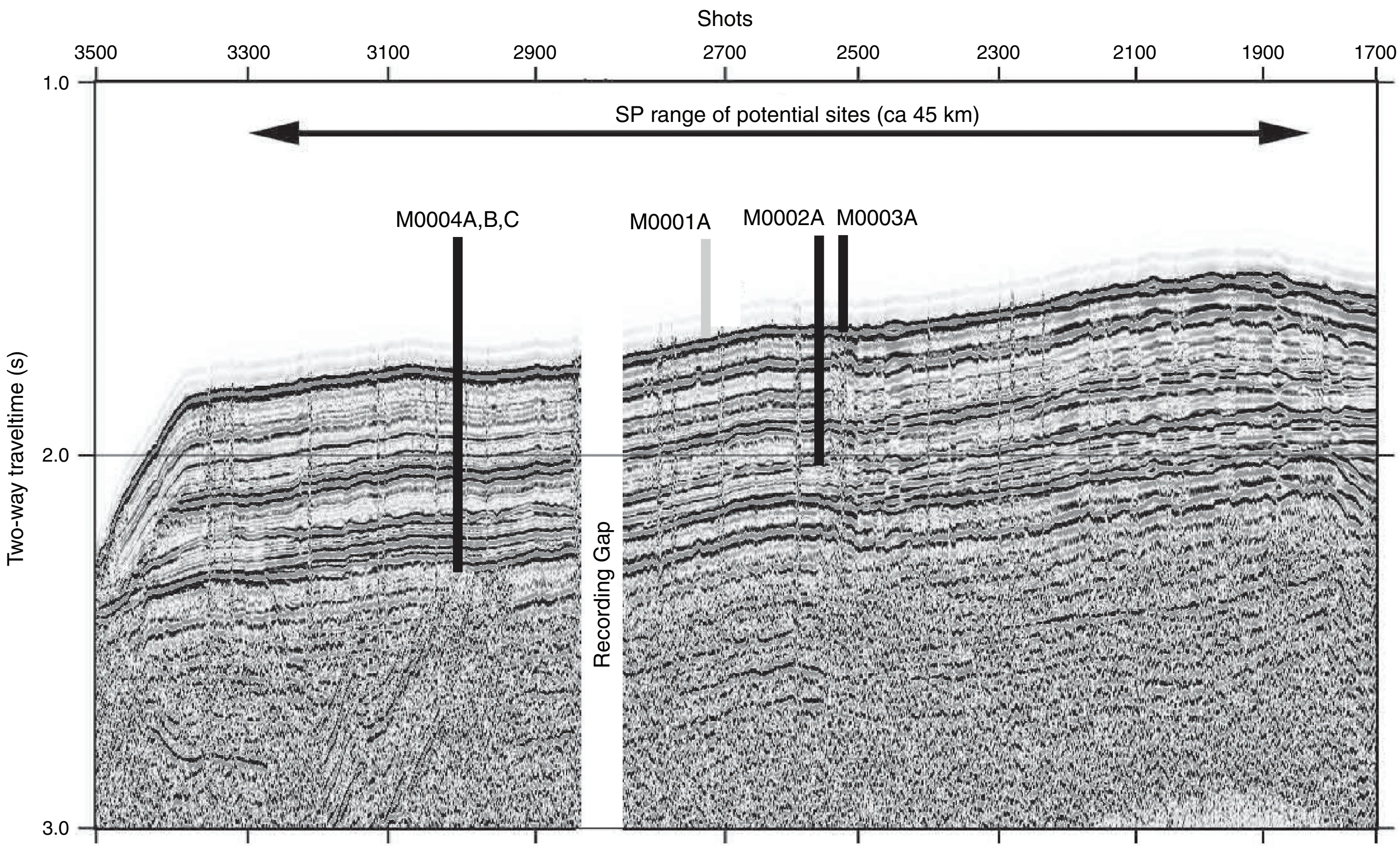

Figure F3. Photograph taken from one of the ACEX helicopters of station-keeping operations. *Sovetskiy Soyuz* is shown at the top of the image breaking large ice floes, *Oden* is in the middle of the image crushing mid-sized ice floes, and *Vidar Viking* is in the lower section of the image maintaining station over the drill site.

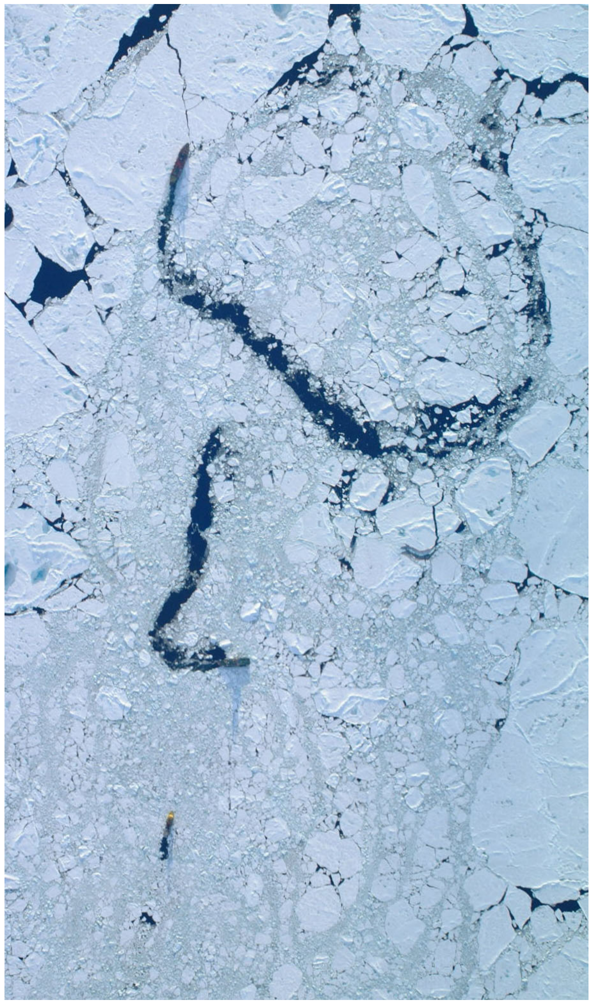

Figure F4. Core recovery summary diagram for all ACEX holes. Black = recovered core, white = no recovery, and gray = washed intervals. Total recovery was 68.4%. Hole M0004B was logged.

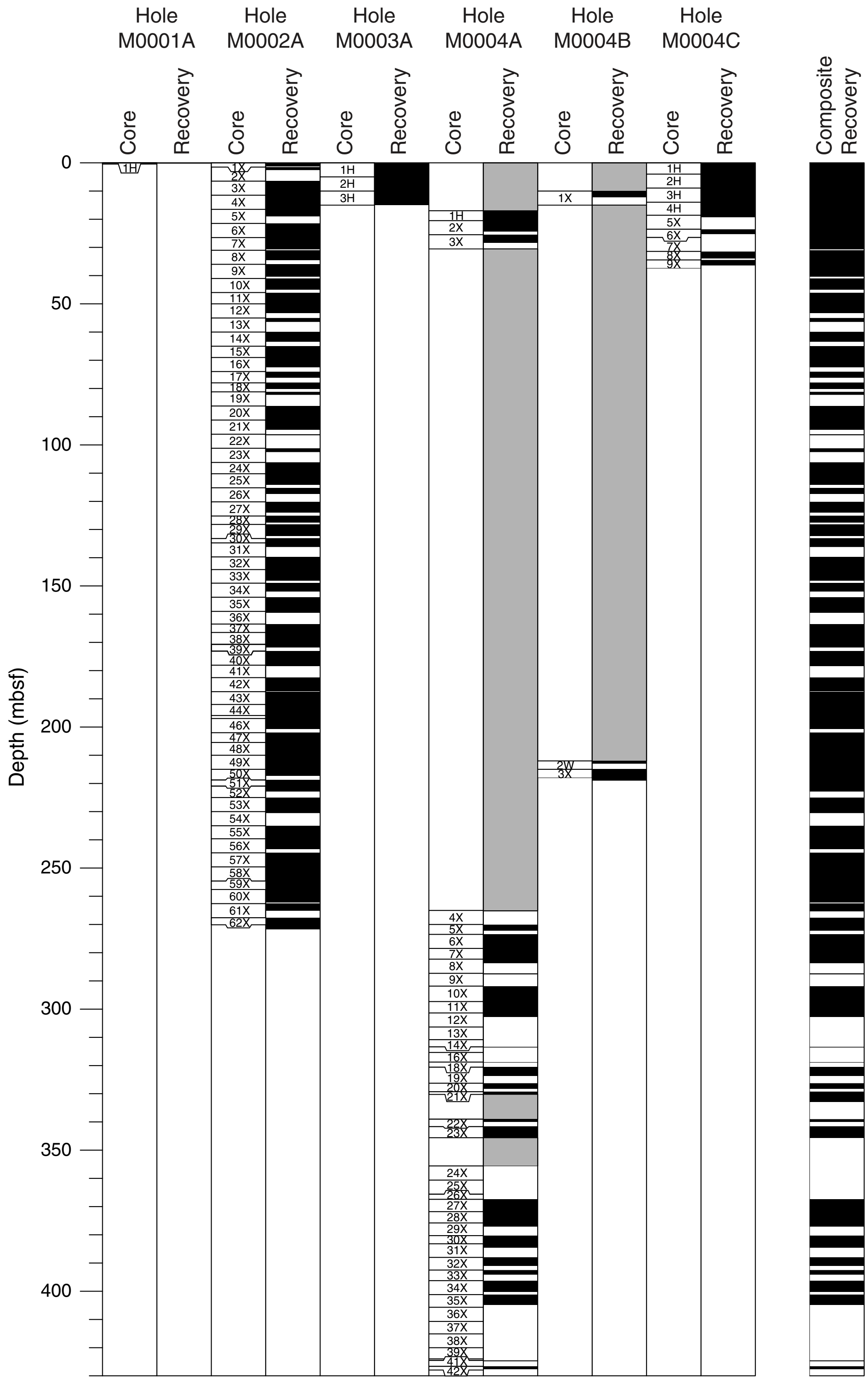

Figure F5. Lithostratigraphic column with age estimates of the Lomonosov Ridge sediments and basement. This is a compilation from all five boreholes. (Continued on next page.)

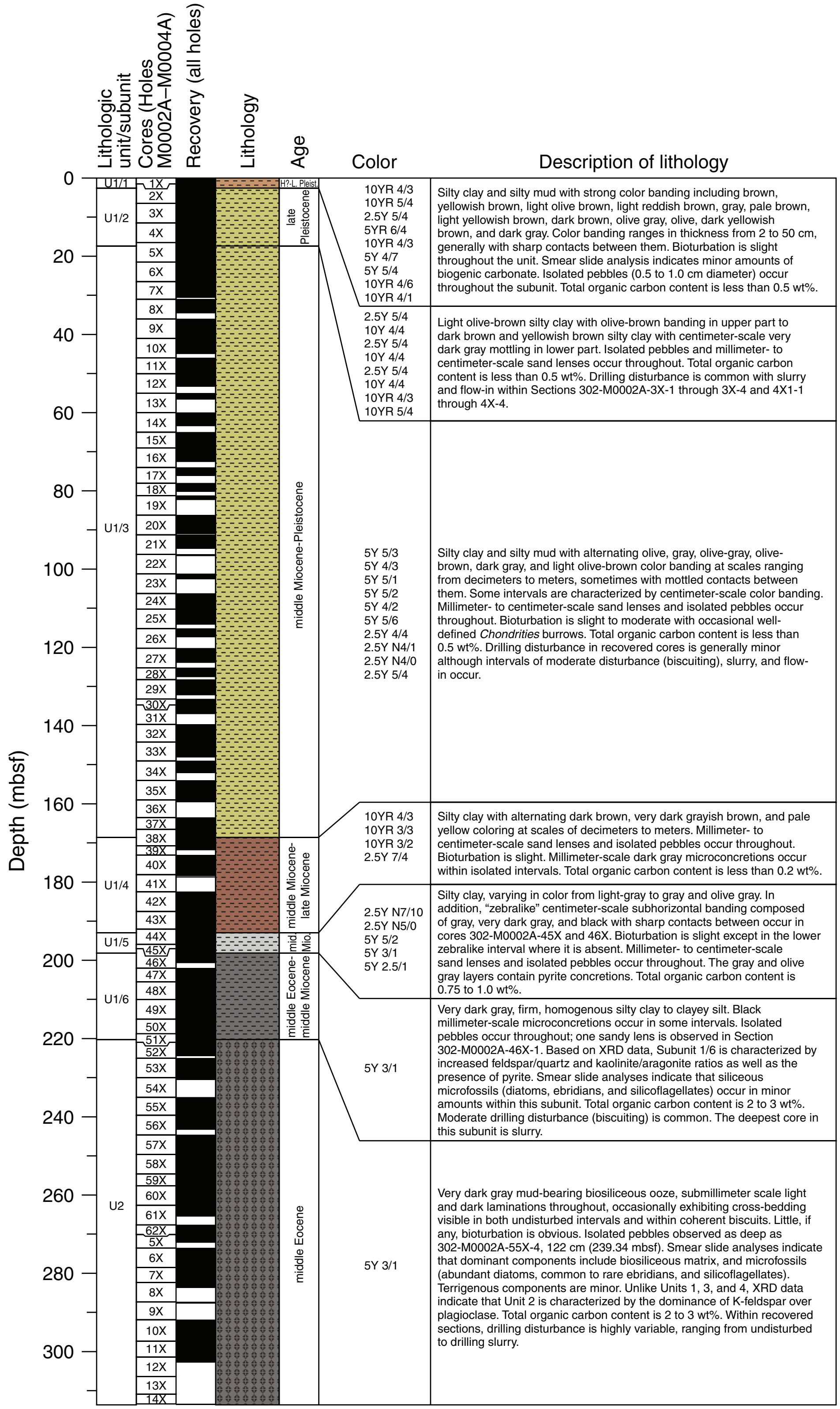

Figure F5 (continued).

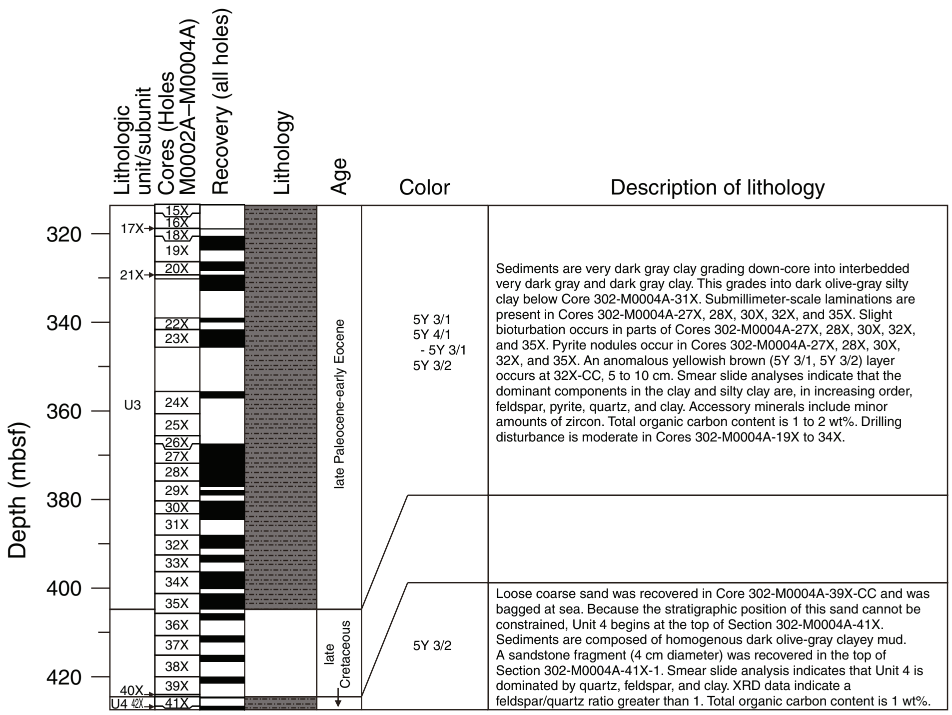

Figure F6. Multi Sensor Core Logger data plotted on a meters composite depth (mcd) scale and spliced together across all sites. GRA = gamma ray attenuation, NGR = natural gamma radiation. cps = counts per second. (Continued on next page.)

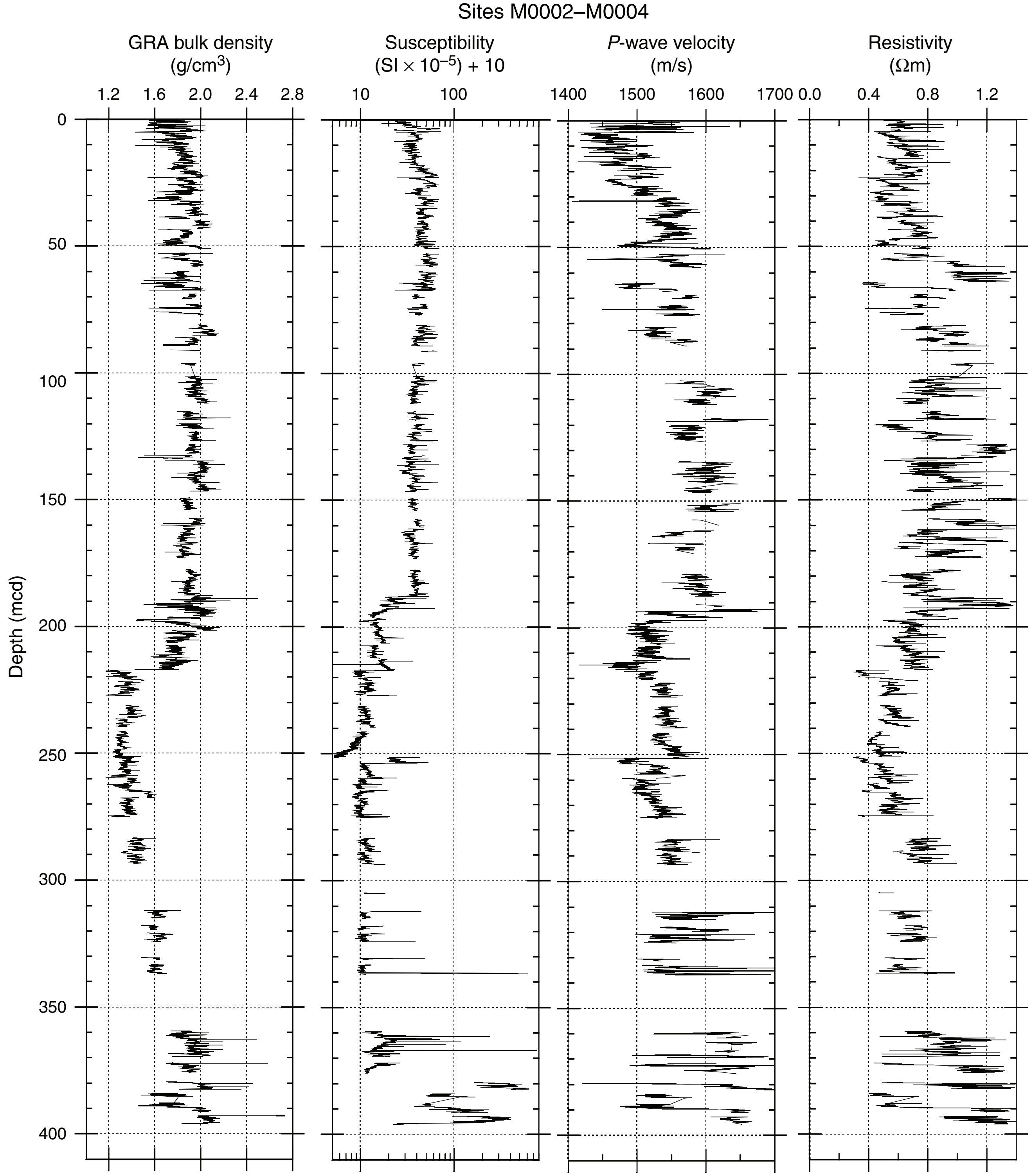

Figure F6 (continued).

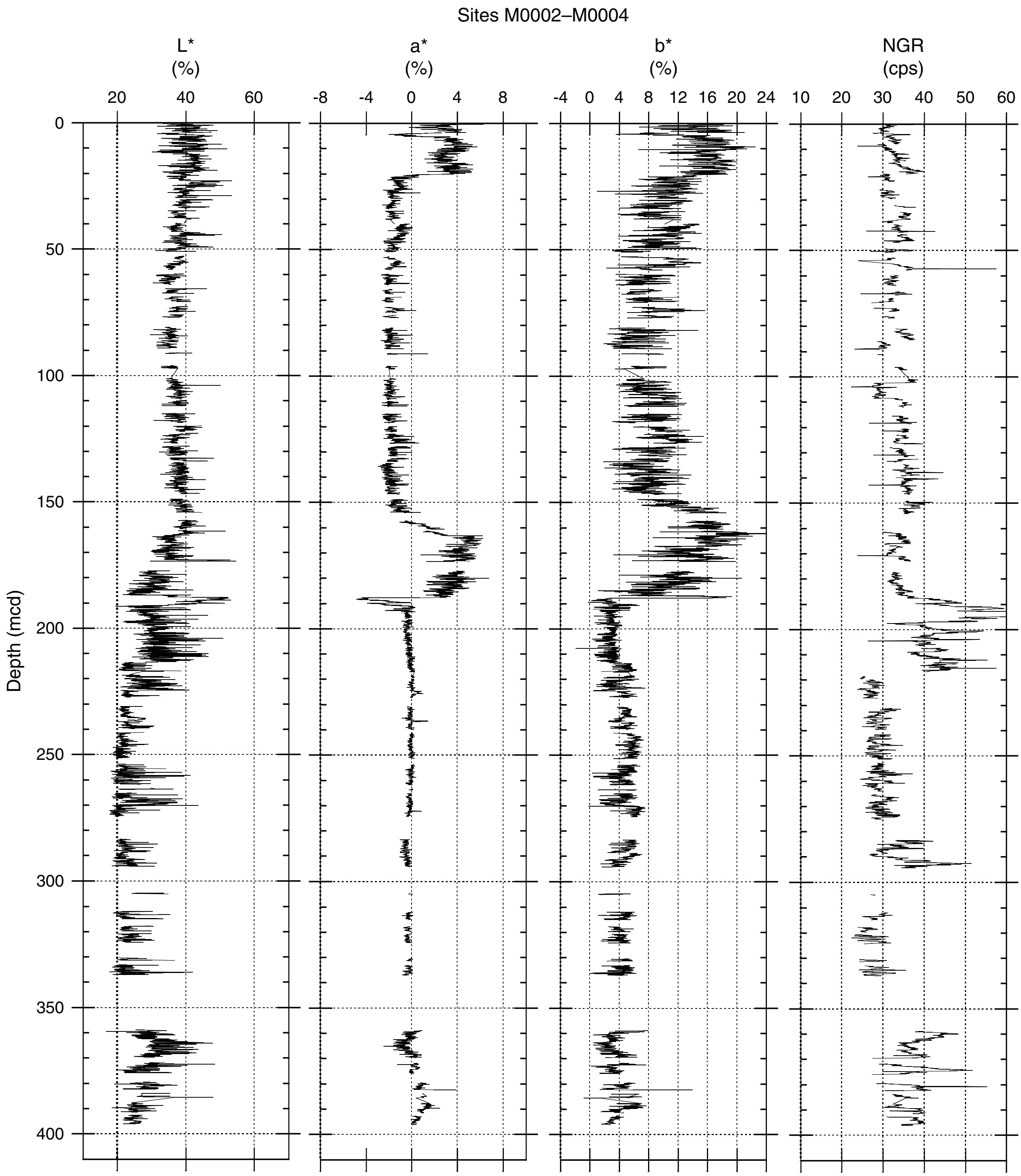

Figure F7. Multi Sensor Core Logger data for the upper 20 mcd showing all holes and the overlap achieved among them. (Continued on next page.)

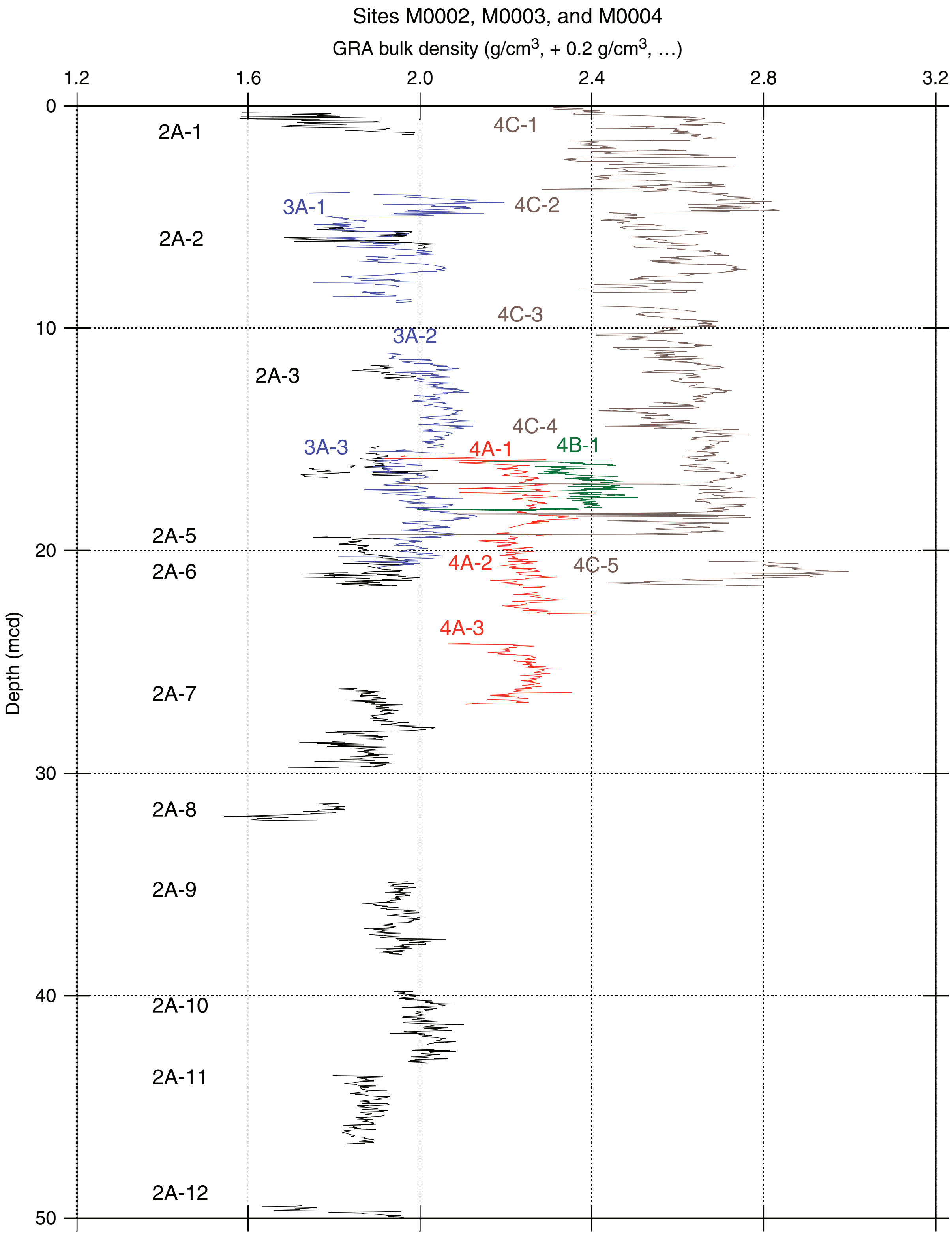

Figure F7 (continued).

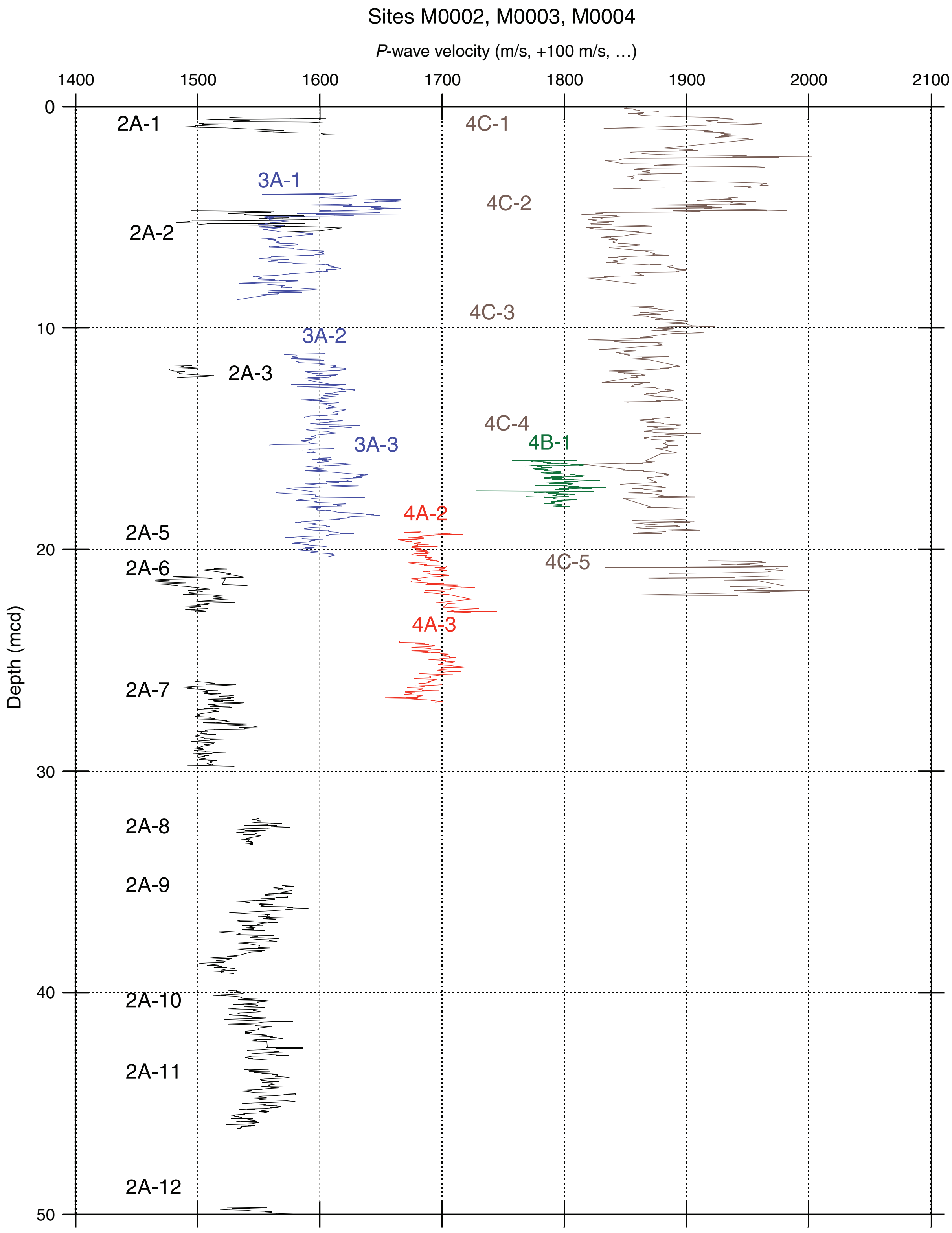

Figure F8. Consolidation index (S_u/P_c') plotted as a function of depth. This index describes the consolidation and/or diagenetic characteristics of the sediment column.

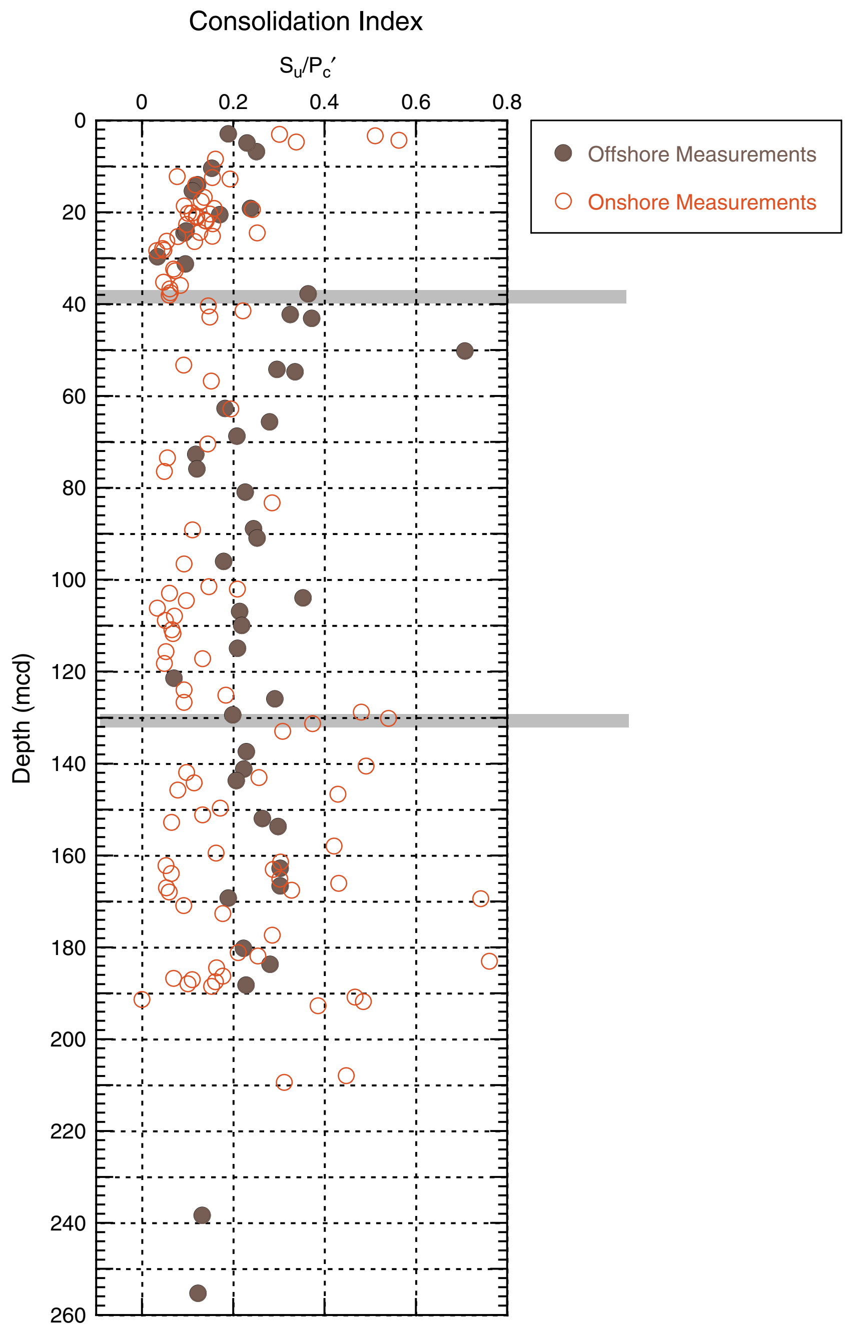

Figure F9. In situ temperature as a function of depth at Site M0004.

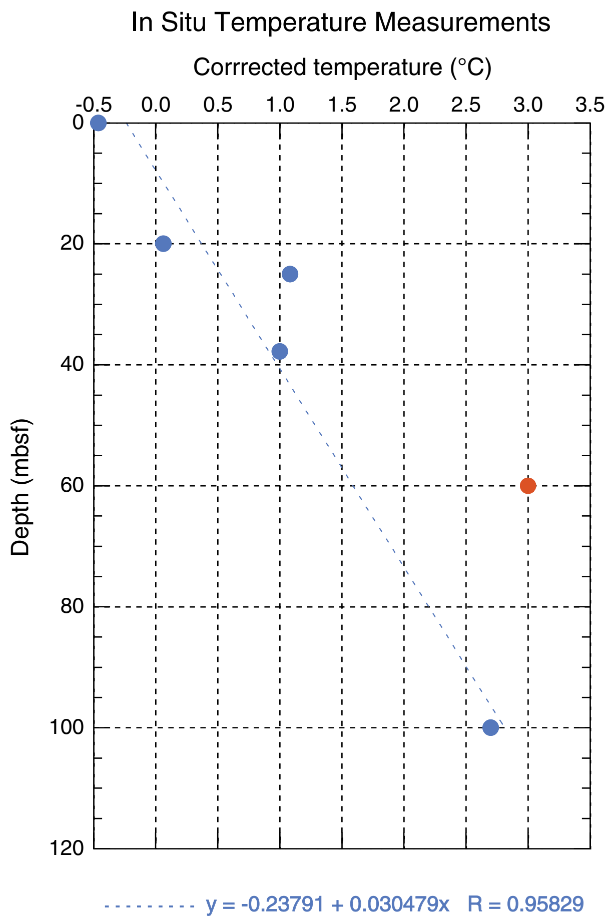

Figure F10. Geochemical profiles measured in pore waters extracted from cores during the offshore phase of ACEX 302.