SPECIAL ISSUE FEATURE

The Arctic Coring Expedition (ACEX) Recovers A Cenozoic History of the Arctic Ocean

BY KATHRYN MORAN, JAN BACKMAN,
AND THE IODP EXPEDITION 302 SCIENCE PARTY

The Arctic Ocean is a small, nearly landlocked ocean basin that is the shallowest in the world (Figure 1). It has maintained a polar location since forming in Early Cretaceous times (Grantz et al., 1990). The ocean's two central deep basins (Amerasian and Eurasian) and its shelf seas occupy 2.6 percent of the global ocean area and less than 1 percent of the global ocean volume (Menard and Smith, 1966; Jakobsson, 2002). The mean water depth is ~ 1400 m, which is ~ 2.5-km shallower than the global ocean mean depth (Jakobsson, 2002). The Arctic Ocean is further distinguished from the other oceans by its large shelf areas (53 percent in Arctic vs. 13 percent of total average area in all other oceans), small basins (17 percent vs. 42 percent), and large ridge areas (16 percent vs. 3 percent) (Jakobsson, 2002).

During much of the Cenozoic, the shallow Arctic shelves and basins accumulated massive amounts of sediment from some of Earth's largest rivers (Peterson et al., 2002). More than 6 km of sediment accumulated in the Amerasian Basin since seafloor spreading began opening this basin, ca. 120–130 million yeas ago (Ma) (Jackson and Oakey, 1990; Grantz et al., 1990), while the younger (~ 56 Ma) Eurasian Basin accumulated sediment thicknesses of 2–3 km (Jackson and Oakey, 1990). Ridges, such as the Lomonosov, were capped with thinner sediment sequences that were ca. 0.5–2 km thickness (Jackson and Oakey, 1990; Hall, 1979; Kristoffersen, 1990; Fütterer, 1992).

In 1961, Heezen and Ewing (1961) recognized that the Mid-Atlantic Ridge extended into the Arctic Ocean, this segment now known as the Gakkel Ridge. This realization led to the hypothesis that the Lomonosov Ridge was a continental fragment that broke from the Eurasian continental margin during spreading along the Gakkel Ridge. Aeromagnetic surveys supported this assumption and suggested that Arctic seafloor spreading initiated along the Gakkel Ridge during Chron24 near the Paleocene-Eocene boundary (Wilson, 1963; Vogt et al., 1979). Reconstruction of the rift motion puts the Lomonosov Ridge at the Barents/Kara Sea margin in the early Cenozoic. The *Arctic '91* expedition, the first non-nuclear icebreaker effort to reach the North Pole (Fütterer, 1992), shot two seismic reflection profiles across the 40-km wide Lomonosov Ridge. These profiles revealed a sediment

Kathryn Moran *(kate.moran@uri.edu) is Professor, Graduate School of Oceanography and Department of Ocean Engineering, University of Rhode Island, Narragansett, RI, USA.* **Jan Backman** *is Professor, Department of Geology and Geochemistry, Stockholm University, Stockholm, Sweden.* **The IODP Expedition 302 Science Party**: *David McInroy, Henk Brinkhuis, Steve Clemens, Thomas Cronin, Gerald Roy Dickens, Frédérique Eynaud, Jérôme Gattacceca, Martin Jakobsson, Richard W. Jordan, Michael Kaminski, John King, Nalân Koc, Nahysa C. Martinez, Jens Matthiessen, Theodore C. Moore Jr., Matthew O'Regan, Jonaotaro Onodera, Heiko Pälike, Brice Rea, Domenico Rio, Tatsuhiko Sakamoto, David C. Smith, Ruediger Stein, Kristen E.K. St. John, Itsuki Suto, Noritoshi Suzuki, Kozo Takahashi, Mahito Watanabe, and Masanobu Yamamoto.*

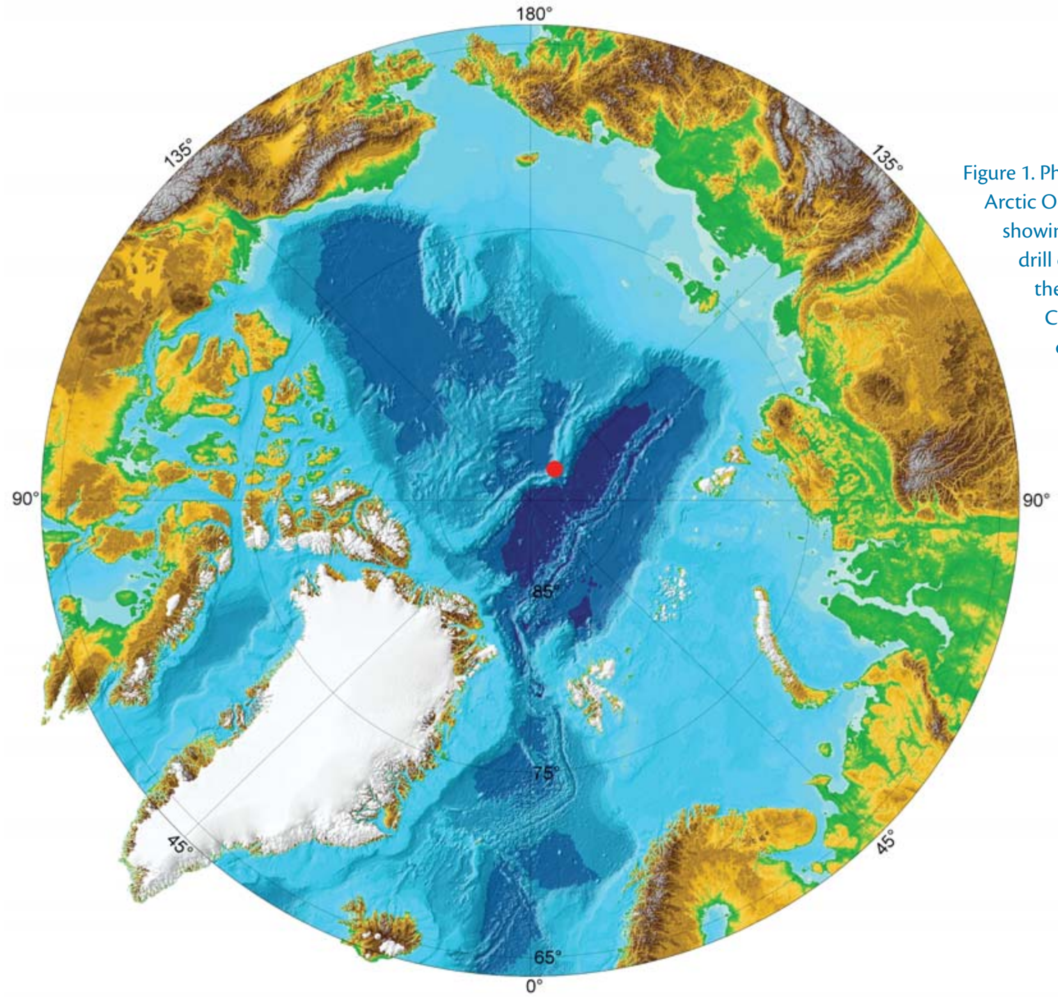

Figure 1. Physiographic map of the Arctic Ocean (IBCAO, 2003), showing the location of the drill core sites (red dot) on the Lomonosov Ridge. Colors represent water depth where dark blue is ~ 4000 m and the Lomonosov Ridge (light blue) varies from 800 m to 1300 m.

sequence over 400-m thick on the ridge crest (Holland et al., 2001), indicating the presence of a unique archive of the past 56 million years of sedimentation and paleoclimate history in the central Arctic Ocean.

The significance of this paleoenvironmental record is rooted in the Arctic Ocean's influence on global climate, specifically in terms of sea ice and the formation of cold, dense, bottom waters that drive global thermohaline circulation (Broecker, 1997; Holland et al., 2001). Recent studies have demonstrated the Arctic Ocean's critical role in freshening the upper ~1.5 km of the northern North Atlantic due to an increase in the export of sea ice, increased freshwater supply from the Nordic Seas, and a deepening of Arctic Intermediate Waters (Holland et al., 2001; Curry and Mauritzen, 2005). As such, extracting a Cenozoic record that describes the presence or absence of ice in the Arctic, its associated impact on Earth's albedo, and the temporal variations of surface and deep-ocean temperature and salinity is of first-order importance.

THE ARCTIC CORING EXPEDITION (ACEX)

Our knowledge of the Arctic Ocean basin, limited by the logistical difficulties of working in harsh, ice-covered regions, is commensurate with our knowledge of the other ocean basins 50 years ago. Prior to the Integrated Ocean Drilling Program's Arctic Coring Expedition (IODP ACEX) conducted in August 2004, the paleoceanographic record of the central Arctic extended only to the mid-Pleistocene (~ 200–500 thousand years ago), where analyses were based on short piston cores, rarely longer than 10 meters (Backman et al., 2004). Pre-Pleistocene material had rarely been recovered, and when it was, only piecemeal. The paleoenvironmental record compiled from these short cores, although invaluable for recent reconstructions of central Arctic glacial events, neither allowed the scientific community to address divergent hypotheses, nor address a series of longstanding questions concerning the earlier

Figure 2. Aerial photograph of the three icebreakers during drilling operations. The *Sovetskiy Soyuz* (top) breaks the large, unbroken floes; *Oden* (middle) breaks these pieces into smaller ice to allow the *Vidar Viking* (lower) to maintain station over the drill site.

Cenozoic evolution of the Arctic Ocean (Houghton et al., 2001). Closing this knowledge gap required a new technological approach.

To attack these important scientific questions, the Ocean Drilling Program (ODP) and the IODP developed a fundamentally new approach to Arctic Ocean studies, using multiple vessels to drill in deep water of the central Arctic Ocean near the North Pole. ACEX used two large icebreakers to enable a third, outfitted as a drillship, to maintain position over a site in heavy, moving sea ice (greater than 90 percent sea surface cover) for extended periods (Figure 2). This approach overcame the difficulty of maintaining position over a drill site in waters that are blanketed in moving ice floes. In August 2004, the three icebreakers met at the ice edge, northwest of Franz Josef Land, and headed north, as a convoy, to begin ACEX, IODP Expedition 302. This expedition successfully recovered core in water depths between 1100 and 1300 m. ACEX involved over 200 people, including scientists, technical staff, icebreaker experts, ice management experts, ship's crew, and educators.

At the drill sites, temperatures hovered near 0°C and occasionally dropped to -12°C. Ice floes 1 to 3 meters thick blanketed more than 90 percent of the ocean surface, and ice ridges, several meters high, were encountered where floes converged. The ice drifted at speeds of up to 0.3 knots and changed direction over short time periods, sometimes within an hour.

The Swedish diesel-electric icebreaker *Vidar Viking* was converted into a drillship for this expedition by adding a geotechnical drilling system that was capable of suspending greater than 2000 m of drill pipe through the water column and into the underlying sediments and by creating a hole in the hull (moonpool) capable of accommodating the drilling system (see Evans et al., this issue). The two other icebreakers, a Russian nuclear vessel, *Sovetskiy Soyuz*, and the Swedish diesel-electric vessel, *Oden*, protected the *Vidar Viking* by circling upstream in the flowing sea ice, breaking the floes into smaller pieces that would not dislodge the drilling vessel from within a 75-m radius from a fixed position.

Despite thick and pervasive ice cover, the fleet and ice-management teams successfully enabled the drilling team to recover cores from three sites. Ice conditions became unmanageable only twice, forcing the fleet to retrieve the pipe and move away until conditions improved. From the technological standpoint, ACEX was the first expedition to drill in the central Arctic Ocean where heavy sea ice prevails year-round. The approach used proved successful and is applicable for future scientific and exploration drilling in this challenging environment.

A 56 MA SEDIMENT RECORD

ACEX drilled and cored three sites on the Lomonosov Ridge within 20 km of each other (Figure 1). The sites were positioned along a site survey seismic reflection profile collected in 1991. This profile was interpreted to represent a continuous Cenozoic sedimentary record atop rifted continental crust (Jokat et al., 1992). Although the sites are located up to ~ 15-km apart along the seismic line, continuity of the seismic reflectors among the sites and physical property data allow sediment cores recovered from each site to be correlated to each other; they are interpreted together as a single depth time series spanning the Cenozoic (Moran et al., 2006).

Glimpses of pre-Miocene climatic conditions in the central Arctic were meager prior to ACEX because they were based on only four short cores (< 10-m long) from the western Arctic

Ocean basin on the Alpha-Mendeleyev Ridge. These cores consisted of black biosiliceous material, suggesting poorly ventilated bottom waters at ~ 70 Ma (million years ago) and ~ 35 Ma, and an estimate for Cretaceous sea surface temperatures of 15°C (Jenkyns et al., 2004).

In the youngest part of the ACEX record, the Plio-Pleistocene, a change to higher sedimentation rates at 1.9 Ma occurs at a time when Northern Hemisphere glaciation intensified and global cooling accelerated. Immediately prior to this switch to higher rates, over the time interval ~ 3 Ma to 2.5 Ma, sediment physical properties show a large influx of coarser-grained sediment that is reflected in the consolidation index, acoustic velocity, and bulk density (Figure 3), potentially reflecting increased sea ice and icebergs roughly coincident with the large expansion of continental ice sheets (Shackleton et al., 1984).

ACEX initial results show that ice-rafted debris (IRD), in the form of fine to coarse sand and dropstones, was present as early as 45 Ma (Figure 3). Further analyses of the IRD will help to discern sea-ice versus iceberg delivery and perennial versus seasonal sea-ice regimes. For example, if the source of sea-ice IRD is from a location that is far from the Lomonosov Ridge where multiple ice years are required to transport it, then we can discriminate seasonal versus perennial sea ice (Darby, 2003). These occurrences of IRD in ACEX cores suggest that sea ice and/or icebergs were present in the central Arctic earlier than the late Tibetan Plateau tectonic uplift event, as far back as the Eocene. With an earlier inception of Northern Hemisphere glaciation, the lag between the onset of major Southern and Northern Hemisphere glaciations is reduced or even eliminated. Recent support for the synchroneity of these events comes from detailed oxygen isotope records that document a sharp increase in $\delta^{18}O$ values across the Eocene-Oligocene boundary (Coxall et al., 2005) and synchronous changes in calcium carbonate compensation depth (Tripati et al., 2005).

Among our results, the best age control spans the middle Miocene (Figure 3). Paleoenvironmental analyses

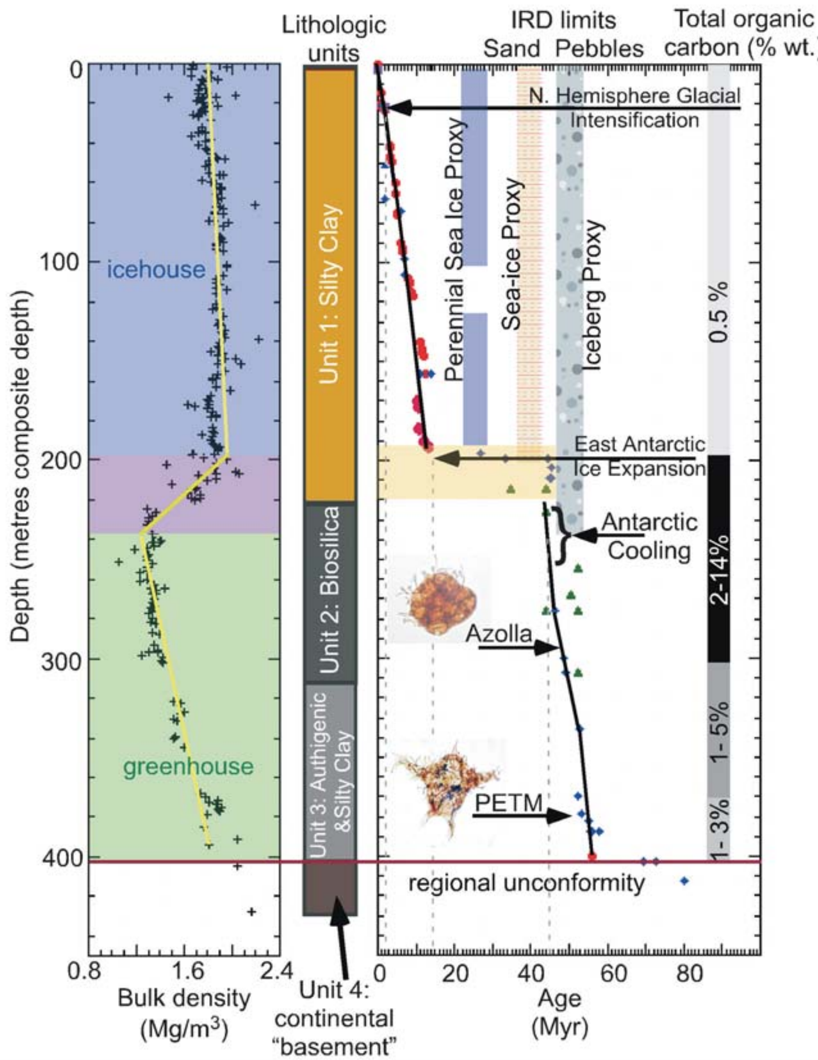

Figure 3. Synthesis of the ACEX coring results showing the age model. Lithologic units are identified as separate colors. The "greenhouse" world of the Eocene is distinctly different in sediment characteristics from the "icehouse" world of the Miocene. A long hiatus (located in the upper orange shaded zone of the age model) separates sharp changes in the sediment properties above and below (bulk density, organic carbon content, occurrence of pyrite). The bulk density shows a normal increase in depth during both the greenhouse and icehouse times; the yellow solid lines are consolidation trends for each unit and show a reverse density trend within the transition zone.

indicate major changes in the Arctic basin environment since that time. Earlier, during the Eocene, the Lomonosov Ridge was shallow and supported an upper water column dominated by freshwater conditions near the surface and deeper conditions that preserved organic matter. Sometime after the middle Eocene, a major change in the Arctic environment occurred, which is represented in our sediment record as a long hiatus. Sedimentation, at a slow rate, was probably re-established by the Miocene (Figure 3), but, with the exception of the one interval, was devoid of benthic or planktonic remains until ~ 14 Ma when sedimentation rates increased.

The Paleogene ACEX sedimentary record differs significantly from the overlying sediments in terms of physical properties and an increase in organic carbon (Figure 3) (Moran et al., 2006). Below the hiatus, in the middle Eocene, dinoflagellate cysts, diatoms, ebridians, and silicoflagellates are common to abundant and typify an ice-free, brackish to sometimes fresh, productive, and warm environment. Collectively, these assemblages represent a highly productive neritic (shallow water) environment. Black firm clay in this interval is characterized by high organic content, fine laminations, and pyrite similar to other black shale deposits, suggesting shallow-water deposition (Figure 3) (Wignall, 1994). A shallow-water setting is consistent with the physiography of the Arctic Ocean basin where, for example, over 40 percent of the modern seafloor is shallower than 200 m. This percentage was probably greater in Eocene times when higher sea level flooded much of what is now dry land. Thus, results from the ACEX site, although distal from the coastline, suggest a relatively fresh Eocene basin, strongly influenced by high productivity and the mixing and recycling of nutrients.

At the base of the middle Eocene, a massive occurrence of the freshwater hydropterid fern *Azolla* suggests greatly reduced surface-water salinity or perhaps even fresh surface-water conditions at this time (49.5 Ma) (Brinkhaus et al., 2006). A concomitant occurrence of marine ebridian and diatom assemblages points to a warm and highly stratified shallow upper water column occurring at the end of the early Eocene (Figure 3).

During the earliest Eocene, the (sub-) tropical dinoflagellate species *Apectodinium augustum* dominated the fossil record in the pyrite-rich mudstone cores of Unit 3. A global increase in *A. augustum* occurred during the Paleocene Eocene Thermal Maximum (PETM) (Crouch et al., 2001), the largest known climatic warming of the Cenozoic. Records from mid-latitude oxygen isotopes ($\delta^{18}O$) of biogenic carbonate suggest a sea-surface warming of 4–5°C. This warming perturbed the hydrologic cycle, resulting in a surface-water salinity increase at low latitudes (Zachos et al., 2003) that was probably matched by a salinity decrease at high latitudes. ACEX analyses of the *A. augustum* using TEX_{86} (Sluijs et al., 2006) show that even at extreme high latitudes in the Arctic Ocean, sea-surface temperatures were on the order of 20°C. The geographic location of the ACEX sediment record was close to its current position during the time of the PETM, which suggests that this temperature probably represents a seasonal summer high. Additional studies of this interval show that major changes occurred to the hydrology of the region during the PETM warming (Pagani et al., in review). Within and below the PETM interval, agglutinated benthic foraminifers occur, typifying a shallow marine depositional environment during the latest Paleocene through early Eocene (Figure 3) (Moran et al., 2006).

SUMMARY

The ACEX successfully recovered the first major paleoceanographic record from the central Arctic using IODP's new Mission-Specific Platform operational approach. The results are exciting and reveal a constricted Arctic Ocean basin during the early Cenozoic, dominated by shallow water in the early Eocene and warm surface water conditions during the PETM. A change from low to high organic carbon sediment occurs later at ~ 49.5 Ma during a time of fresh, warm surface water. The initiation of Northern Hemisphere cooling began much earlier than previously estimated and may have been synchronous with the onset of Antarctic glaciation. ACEX also confirmed the previously hypothesized continental origin of the Lomonosov Ridge by recovering core material deeper than the Cenozoic sedimentary sequence across the regional seismic unconformity.

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