Vol 441|1 June 2006|doi:10.1038/nature04800

nature

ARTICLES

The Cenozoic palaeoenvironment of the Arctic Ocean

Kathryn Moran[1], Jan Backman[2], Henk Brinkhuis[3], Steven C. Clemens[4], Thomas Cronin[5], Gerald R. Dickens[6], Frédérique Eynaud[7], Jérôme Gattacceca[8], Martin Jakobsson[2], Richard W. Jordan[9], Michael Kaminski[10], John King[11], Nalan Koc[12], Alexey Krylov[13], Nahysa Martinez[14], Jens Matthiessen[15], David McInroy[16], Theodore C. Moore[17], Jonaotaro Onodera[18], Matthew O'Regan[11], Heiko Pälike[19], Brice Rea[20], Domenico Rio[21], Tatsuhiko Sakamoto[22], David C. Smith[11], Ruediger Stein[15], Kristen St John[23], Itsuki Suto[24], Noritoshi Suzuki[25], Kozo Takahashi[18], Mahito Watanabe[26], Masanobu Yamamoto[27], John Farrell[11], Martin Frank[28], Peter Kubik[29], Wilfried Jokat[15] & Yngve Kristoffersen[30]

The history of the Arctic Ocean during the Cenozoic era (0–65 million years ago) is largely unknown from direct evidence. Here we present a Cenozoic palaeoceanographic record constructed from >400 m of sediment core from a recent drilling expedition to the Lomonosov ridge in the Arctic Ocean. Our record shows a palaeoenvironmental transition from a warm 'greenhouse' world, during the late Palaeocene and early Eocene epochs, to a colder 'icehouse' world influenced by sea ice and icebergs from the middle Eocene epoch to the present. For the most recent ~14 Myr, we find sedimentation rates of 1–2 cm per thousand years, in stark contrast to the substantially lower rates proposed in earlier studies; this record of the Neogene reveals cooling of the Arctic that was synchronous with the expansion of Greenland ice (~3.2 Myr ago) and East Antarctic ice (~14 Myr ago). We find evidence for the first occurrence of ice-rafted debris in the middle Eocene epoch (~45 Myr ago), some 35 Myr earlier than previously thought; fresh surface waters were present at ~49 Myr ago, before the onset of ice-rafted debris. Also, the temperatures of surface waters during the Palaeocene/Eocene thermal maximum (~55 Myr ago) appear to have been substantially warmer than previously estimated. The revised timing of the earliest Arctic cooling events coincides with those from Antarctica, supporting arguments for bipolar symmetry in climate change.

The significance of this palaeoenvironmental record is rooted in the Arctic Ocean's influence on global climate—specifically in terms of sea ice, which affects albedo, and the formation of cold, dense, bottom waters that drive global thermohaline circulation[1,2]. Recent studies have demonstrated the Arctic Ocean's role in freshening the upper ~1.5 km of the northern North Atlantic Ocean by increased export of sea ice, increased freshwater supply from the Nordic seas, and a deepening of Arctic Intermediate Waters[2,3]. So extracting a Cenozoic record that reveals the presence or absence of ice in the Arctic, its associated impact on the Earth's albedo, and the temporal variations of surface and deep ocean temperature and salinity, is of first-order importance. Here we present initial findings primarily focused on the occurrence and timing of Arctic Ocean ice in the form of the two primary cryosphere climate drivers, sea ice and icebergs—indicative of large continental ice sheets rimming and extending into the basin. Further, we interpret the sea ice record, a proxy for Earth's albedo, to discern seasonal from perennial periods.

In 1961, Heezen and Ewing[4] recognized that the Mid-Atlantic Ridge extends into the Arctic Ocean, where it becomes the Gakkel ridge. This led to the hypothesis that the Lomonosov ridge was a continental fragment that broke away from the Eurasian continental margin owing to spreading along the Gakkel ridge. Aeromagnetic surveys support this assumption, and suggest that initiation of Arctic seafloor spreading along the Gakkel ridge began during chron 24, ~57 Myr ago, the time of the Palaeocene/Eocene boundary[5,6]. As rifting progressed, the Lomonosov ridge moved away from the continent, towards the pole, and subsided ~1,200 m, initially at a slow rate in the Palaeogene, followed by more rapid subsidence later

[1]Graduate School of Oceanography & Department of Ocean Engineering, University of Rhode Island, Narragansett, Rhode Island 02882, USA. [2]Department of Geology & Geochemistry, Stockholm University, Stockholm SE-106 91, Sweden. [3]Laboratory of Palaeobotany & Palynology, Department of Biology, Utrecht University, 3584 DC Utrecht, The Netherlands. [4]Department of Geological Sciences, Brown University, Providence, Rhode Island 02912, USA. [5]US Geological Survey, Reston, Virginia 20192, USA. [6]Department of Earth Science, Rice University, Houston, Texas 77251, USA. [7]Département de Géologie et Océanographie, Université Bordeaux, 33405 Talence, France. [8]Department of Geophysics, CEREGE (CNRS), 13545 Aix-en-Provence, France. [9]Department of Earth & Environmental Sciences, Yamagata University, Yamagata 990-8560, Japan. [10]Department of Earth Sciences, University College London, London WC1E 6BT, UK. [11]Graduate School of Oceanography, University of Rhode Island, Narragansett, Rhode Island 02882, USA. [12]Norwegian Polar Institute, Polar Environmental Center, 9296 Tromsø, Norway. [13]Department of Lithology & Geochemistry, VNIIOkeangeologia, St Petersburg 190121, Russia. [14]Earth Sciences, Boston University, Boston, Massachusetts 02215, USA. [15]Alfred Wegener Institute Foundation for Polar and Marine Research, D-27515 Bremerhaven, Germany. [16]British Geological Survey, Murchison House, Edinburgh EH9 3LA, UK. [17]Geological Sciences, University of Michigan, Ann Arbor, Michigan 48109, USA. [18]Department of Earth and Planetary Sciences, Kyushu University, Fukuoka 812-8581, Japan. [19]National Oceanography Centre, University of Southampton, Southampton SO14 3ZH, UK. [20]Department of Geography & Environment, University of Aberdeen, Aberdeen AB24 3UF, UK. [21]Department of Geology, Paleontology & Geophysics, University of Padova, Padova 35137, Italy. [22]Institute for Research on Earth Evolution (IFREE), Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokosuka 237-0061, Japan. [23]Department of Geology & Environmental Science, James Madison University, Harrisonburg, Virginia 22807, USA. [24]Department of Earth & Planetary Sciences, Nagoya University, Chikusa, Nagoya 464-8602, Japan. [25]Institute of Geology & Paleontology, Tohoku University, Sendai City 980-8578, Japan. [26]Institute of Geoscience, Geological Survey of Japan, Ibaraki 305-8567, Japan. [27]Graduate School of Environmental Earth Science, Hokkaido University, Sapporo 060-0810, Japan. [28]Leibniz-Institute of Marine Sciences, IFM-GEOMAR, 24148 Kiel, Germany. [29]Paul Scherrer Institute, ETH-Hönggerberg, CH-8093 Zurich, Switzerland. [30]Department of Earth Science, University of Bergen, Allegaten 41, N-5007 Bergen, Norway.

in the Neogene. Hemipelagic and pelagic sediments accumulated atop the ridge during the Cenozoic. Seismic profiles across the ridge reveal a sediment sequence over 400 m thick on the ridge crest[7], suggesting the presence of a unique archive of Cenozoic sedimentation and palaeoclimate history.

A Cenozoic geologic record from the Arctic Ocean

Our present understanding of this ocean basin is limited by the logistical difficulties of working in harsh, ice-covered regions, and is commensurate with our knowledge of the other ocean basins 50 years ago. Before the Integrated Ocean Drilling Program Arctic Coring Expedition[8] (IODP ACEX), conducted in August 2004, the palaeoceanographic record of the central Arctic extended only to the mid-Pleistocene (~200–500 kyr ago), based on short piston cores, rarely longer than 10 m (ref. 9). Pre-Pleistocene material had rarely been recovered, and only piecemeal. The palaeoenvironmental record compiled from these short cores, although invaluable for reconstructions of relatively recent central Arctic glacial events, had not allowed the scientific community to address divergent hypotheses and a series of long-standing questions concerning the earlier Cenozoic evolution of the Arctic Ocean[10]. Closing this knowledge gap required a major technological advance, described elsewhere[11]. In short, ACEX used two large icebreakers to enable a third, outfitted as a drill ship, to maintain position over a site in heavy, moving sea ice (>9/10 sea surface cover) for extended periods.

ACEX drilled and cored four sites on the Lomonosov ridge (Fig. 1). The sites were positioned along a site survey seismic reflection profile line[7] (Fig. 2). This line was interpreted to represent a continuous Cenozoic sedimentary record atop rifted continental crust[7]. Although the sites are located up to ~15 km apart along the seismic line, the sediment cores from these sites could be correlated to each other on the basis of physical property data and on the continuity of seismic reflectors. This enabled us to create a composite sedimentary record that spans the Cenozoic. The recovered record comprises three distinct sediment types (in the upper ~200 m, 200–300 m and 300–420 m) and are described as separate units.

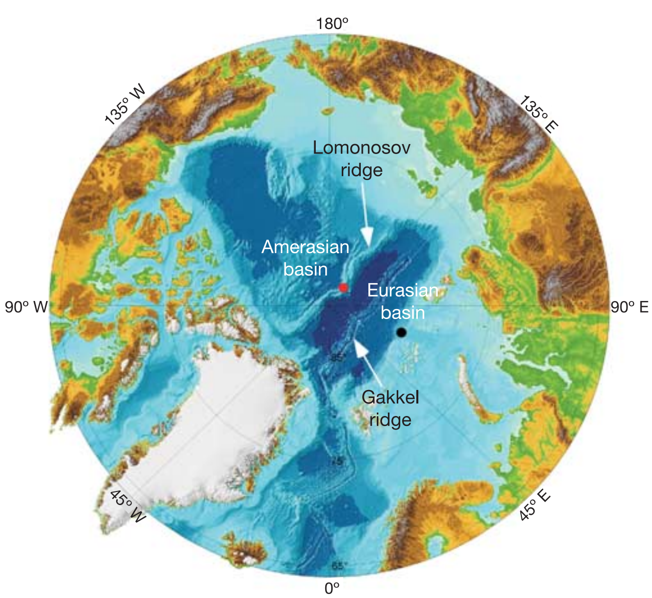

Figure 1 | Physiographic map of the Arctic Ocean. The location of the cores (red dot) is on the Lomonosov ridge, a continental sliver that broke away from the Eurasian continental margin ~57 Myr ago, owing to the spreading of the Gakkel ridge. Sediments atop the ridge record the palaeoenvironmental evolution of the Cenozoic Arctic Ocean. Colours are water depth; dark blue is ~4,000 m and the water depth over the ridge (light blue) varies from 800 m to 1,300 m. The black circle shows the approximate palaeoposition of the site. This map is from ref. 42.

The upper ~200 m (unit 1; Fig. 3a), which extends from the Miocene through to the present, consist of siliciclastic sediment, characterized by chemically controlled colour fluctuations, low organic carbon concentrations, and a biotic record dominated by organic walled microfossils (palynomorphs notably organic walled dinoflagellate cysts). Below 200 m, the early middle to early Eocene (44–50 Myr ago), sediments are microlaminated, organic carbon and biosiliceous rich, varying from silty clay to ooze (Fig. 3a; unit 2). Below 300 m, the early Eocene to late Palaeocene (50–56 Myr ago) sediment is predominantly siliciclastic and contains silica (only in the upper tens of metres) that has been altered to cristobalite. This interval (unit 3a; Fig. 3) unconformably overlies a Cretaceous unit composed of sand, sandstone and mudstone at about 400 m. The boundary is directly correlated to the seismically derived regional unconformity (Fig. 2) on the basis of conversion of the drilled depth to seismic time using core- and log-measured acoustic velocity.

The 'greenhouse' Arctic

The early Palaeogene marine environment can be characterized as warm, ice-free, brackish and biologically productive, resulting in the accumulation of siliciclastic sediments with high (up to 14%) organic carbon contents. The organic matter in the oldest part of the record (late Palaeocene) was mainly derived from algae, whereas that in the younger section (early middle Eocene) also includes higher plant material. This early middle Eocene section includes intervals of millimetre-scale laminated, pyritic black shale indicative of a quiet water anoxic basin[12], consistent with a shallow water environment.

In the oldest part of the sedimentary record, during the earliest Eocene, the typically warm water dinoflagellate genus *Apectodinium* dominated the fossil record in the pyrite-rich mudstone cores of unit 3. A global increase in *Apectodinium* occurred during the Palaeocene/Eocene thermal maximum (PETM)[13], the largest known climatic warming of the Cenozoic. In a companion paper[14], by TEX_{86} analysis, we show that even at extreme high latitudes in the Arctic Ocean, peak PETM sea surface temperatures soared to ~24 °C. Additional studies of this interval show major changes in the hydrology of the region during the PETM warming[15]. Within and below the PETM interval, dinoflagellate cysts and agglutinated benthic foraminifera assemblages typify a shallow (neritic) marine depositional environment during the latest Palaeocene through to the early Eocene (Fig. 3).

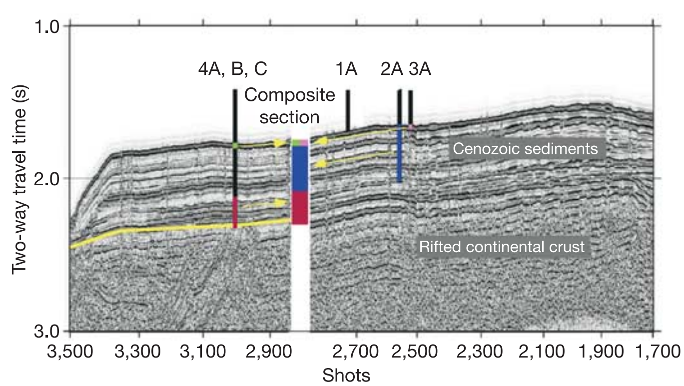

Figure 2 | Cross-section of the Lomonosov ridge. A seismic profile (AWI 91090) was interpreted as continental crust truncated by a regional unconformity overlain by a continuous sediment sequence[7]. The sites were positioned on this profile, shown as solid vertical lines. At each of the four sites (1–4), multiple holes (A, B, C…) were drilled and sampled to the depth of the solid vertical line. A 428-m-long composite sedimentary section was constructed by combining the holes, shown by different colours. The palaeoceanographic record overlies acoustic basement, a seismic unconformity (highlighted in yellow), that was confirmed to be Cretaceous continental crust.

A shift to an 'icehouse' Arctic

Later in the record, at ~49 Myr ago, a massive occurrence of glochidia (hair-like projections) and massulae of the fresh-water hydropterid fern *Azolla* confirms the presence of fresh surface water conditions[16] with cooler TEX_{86} temperatures of ~10 °C (ref. 17). A concomitant occurrence of ebridian and silicoflagellate and diatom assemblages, requiring marine to brackish salinities, points to seasonally changing stratification regimes (Fig. 3). If the *Azolla* originated from a seasonal bloom, the associated fresh and relatively cool surface waters may have enabled winter ice formation, marking the start of a middle Eocene transition to a bipolar 'icehouse' world. The occurrence of a gneiss dropstone, 1 cm in diameter, at ~45 Myr ago is interpreted as ice-rafted debris (IRD), present much earlier than previously thought in the Northern Hemisphere. This dropstone was recovered from an undisturbed section of core, and could not have been reworked or moved downward from higher in the sedimentary section. The location of the ACEX site during this time period, although probably in shallow water (~200 m), was distal from the Siberian continental coast, and isolated from it by the Gakkel ridge, making improbable the delivery of pebbles to the site by any mechanism other than ice.

The sediment interval from ~44 to 16 Myr ago is characterized by slow to non-deposition and erosion that left a condensed and partially missing section. This interval marks a distinct change from organic-rich Palaeogene sediments with intervals of abundant microfossils, to the sparsely fossiliferous silty muds of the overlying Neogene. The marked contrast represents a striking shift in the physical, chemical and ecological environment of the Arctic Ocean. This interval overlaps with the timing of a global shift from a largely ice-free, warm, 'greenhouse' world with high relative sea level to a world characterized by the climate-modulated waxing and waning of ice sheets.

The condensed interval ends in the early Miocene when sedimentation rates once again increased, and the unfossiliferous sediment was dominated by IRD, in the form of dropstones and the initial occurrence of sand (Fig. 3). The abundance of dropstones and sand suggests that sea ice and icebergs, calved from glaciers, were present in the Arctic Ocean. At ~14 Myr ago, the abundance of ice-derived sand increases significantly, with sedimentation rates reaching 1–2 cm kyr^{-1} and the intermittent appearance of cold- to cool-water dinoflagellates suggesting seasonal ice conditions.

At ~3.2 Myr ago, sediment physical properties show a large influx of coarse-grained sediment that is reflected in the consolidation index and acoustic velocity[16] (Fig. 3c), suggesting increased sea ice and icebergs. This timing coincides with the start of large, Northern Hemisphere continental ice sheet expansion[18], particularly in Greenland (Fig. 3b).

The youngest part of the ACEX record shows a change to slightly higher sedimentation rates at ~1 Myr ago (Fig. 3b), coincident with an intensification of the 100-kyr Milankovitch climate cycle. The

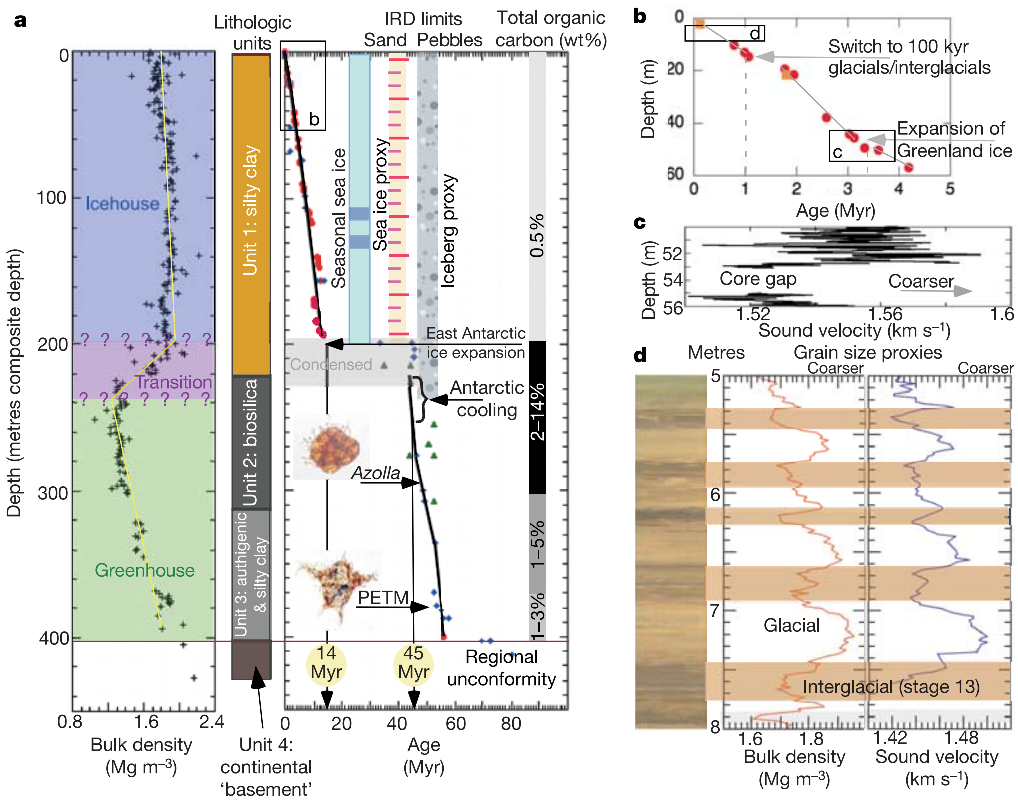

Figure 3 | Synthesis of the ACEX coring results. a, Right panel. Age is based on: palaeomagnetic stratigraphy shown as red circles; biostratigraphic data (dinocysts, blue diamonds; silicoflagellates, green triangles; and a few calcareous microfossils, squares, which only occur in the upper 25 m and can best be seen in **b**). Box shows position of panel **b**. Two micrographs are shown in their stratigraphic positions; the upper is *Azolla* and the lower is *Apectodinium*. Middle panel, lithologies are labelled with separate colours. Left panel, the Eocene 'greenhouse' world is separated from the Miocene 'icehouse' world by a transition period whose timing is not well constrained. Bulk density shows a normal increase in depth during both 'greenhouse' and 'icehouse' times; yellow solid lines are consolidation trends, suggesting uninterrupted sedimentation. Ice-rafted debris (IRD) in the form of pebbles begins in the 'greenhouse', and IRD (sand) starts at ~14 Myr ago (as noted by the black, labelled arrow, bottom of right panel, consistent with the timing of the East Antarctic ice expansion). Interpreted seasonal ice occurrences are noted as darker blue bars within lighter blue shading. The arrow labelled 45 Myr, bottom of right panel, indicates concurrence with the Antarctic cooling time span shown by the bracket above. PETM, Palaeocene/Eocene thermal maximum. See text for information on *Azolla*. **b**, The age model from 0 to 5 Myr ago, showing changes in sedimentation rates concurrent with global climate events. Symbols denote different age control markers and are the same as in **a**. Boxes show positions of panels **c** and **d**. **c**, An example of increased sediment coarsening at 3.2 Myr ago. **d**, An expansion of the youngest part of the record, showing a core photograph (left) with proxies (right); glacials in the photograph are lighter, coarser and thicker in comparison to interglacials.

cause of this change remains unknown, but is presumed to be a nonlinear response to glacial ice expansion. ACEX results show a change in sediment composition across this major climate switch, and glacial and interglacial cycles are clearly resolvable (Fig. 3d). Further analyses of this interval may shed light on the contributing mechanisms for this increase in strength in the 100-kyr cycle.

Palaeoenvironmental implications

Origin of the Lomonosov ridge. ACEX 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 (Fig. 2). Below the late Palaeocene mudstone, ACEX recovered Upper Cretaceous (Campanian age; ~80 Myr) sands, sandstone and mudstone that are interpreted to have been of shallow marine origin because of the presence of agglutinated foraminifera. This palaeoenvironment is consistent with the theorized origin of the ridge as part of the shallow Barents continental margin. The confirmation of continental rifting also validates the ridge as a palaeoenvironment that captured a long sediment record over a time period of ~57 Myr.

Timing of palaeoenvironmental changes. ACEX results reveal changes during the PETM (~55 Myr ago). Our results show an early Cenozoic basin that was dominated by shallow water in the early Eocene and warm surface water conditions during the PETM[14]. These conditions have ramifications for explaining the causes of global warmth during this important time interval. A leading hypothesis for PETM warming is elevated atmospheric CO_2 (ref. 19) that probably briefly exacerbated the release of seabed methane hydrates, caused by a switch of deep water formation from high-latitude Southern Hemisphere regions to intermediate depth waters in the mid-latitudes of the North Pacific Ocean[20]. ACEX results show that the Arctic Ocean experienced persistent surface water temperatures of 18 °C immediately before and after the PETM, but during this event temperatures peaked near 24 °C (ref. 14), which is notably higher than previous estimates of 10–15 °C (ref. 21) and indicates an even lower equator-to-pole temperature gradient than previously believed.

As important as extreme warmth is our evidence for a geographically isolated basin with a relatively wet climatic regime in the Arctic, as shown from palaeoplate reconstructions for this time[22] and supported by the occurrence in ACEX cores of dark organic-rich sediment with sub-millimetre scale laminations, abundant fish teeth and bone fragments, the ecology of dinoflagellate and siliceous microfossil assemblages, and the lack of burrows and benthic microfauna. This evidence reveals a semi-enclosed basin environment with estuarine circulation and short-term (perhaps seasonal) oscillations in fresh to brackish conditions that reflect an absence of hyper-saline or evaporative conditions. At least at times, there was strong salinity stratification leading to seasonal or even perennial bottom-water hypoxia and anoxia. These indicators signify strong seasonality or inter-annual variability in runoff from adjacent continents, rather than forcing by tectonic processes or sea level oscillations. Two aspects of the globally warm PETM puzzle are clarified by these results and should be integrated into future models. First, wetter conditions and strong rainfall seasonality suggest an enhanced hydrological cycle in high latitudes of the Northern Hemisphere. Second, a PETM-isolated Arctic limits oceanic interchange between the Arctic and the North Atlantic[23] and decreases the likelihood that oceanic heat transport was directly responsible for warmth near the pole[24].

The increased occurrence of IRD at ~14 Myr ago in the ACEX cores suggests greater Arctic cooling and sea ice growth, which in turn, increases albedo and serves as a positive feedback for additional cooling. This timing is generally synchronous with the end of the middle Miocene climatic optimum and with East Antarctic ice sheet growth at 14.5 Myr ago[25], suggesting a second major, bipolar ice-growth event. The presence of Arctic Ocean sea ice may have enhanced the albedo affect, contributing to low temperatures for subsequent Northern Hemisphere glacial ice expansion during the Pliocene. Mechanisms that had previously been proposed as responsible for glacial onset at 6–10 Myr ago (for example, enhanced run-off from Siberian rivers due to Tibetan uplift and an associated change in the freshwater budget of the Arctic's surface water)[26] may have contributed to glaciation, but post-date the initiation observed here.

Palaeoenvironmental evidence for sea ice and icebergs. Prior studies of Northern Hemisphere glaciation are based primarily on IRD in basins that are marginal to the Arctic Ocean, and thus can only indicate times when ice sheets were sufficiently large to shed icebergs into the neighbouring oceans and seas. The type of ice in the Arctic Ocean extends beyond icebergs to include sea ice, and possibly ice shelves. For example, recent sonar images show evidence of ice scouring of the sea floor on Lomonosov ridge, suggesting the presence of ice sheets up to 1 km thick[27] or similarly sized icebergs embedded in sea ice[28] in the central Arctic Ocean as recently as the early Pleistocene. ACEX results now provide direct evidence of icebergs (indicating the presence of proximal glaciers) and sea ice in the Arctic from the Eocene to the present.

A change from lower to higher organic carbon sediment is found at ~49 Myr ago, when the environment is interpreted to have been characterized by fresh, relatively cool (~10–14 °C) surface waters. Although a deep-water connection did not exist between the Arctic Ocean basin and the other oceans at this time, the presence of fresh water in the Arctic may have enhanced the initiation of sea ice that increased albedo and contributed to global cooling. This time interval is also characterized by a preservation of organic carbon in a shallow setting, in contrast to the modern Arctic Ocean continental shelves where organic carbon content deposition is relatively low, despite spring blooms.

In the Neogene record, the absence of dinoflagellate cysts (specifically intervals where the abundance is described as 'rare to absent') and the presence of IRD suggests perennial sea ice (Fig. 3a). Although the Arctic Ocean appears to have been ice covered during much of the Neogene, this was not always the case. Two intervals where dinoflagellate cyst abundance increases to 'common' occur at ~8 and ~9.2 Myr ago and could have been times of seasonal, rather than perennial, ice. This suggests that seasonal sea ice was present in the Arctic basin during the time when Greenland glacial ice began to grow. Continuing efforts to establish the geographic source of the IRD will allow verification, and improved differentiation between seasonal and perennial ice.

In the youngest portion of the record, during the late Quaternary the resolution is high enough to reveal late Pleistocene glacial–interglacial cycles (Fig. 3d). During glacial periods, larger grain size and concomitant increases in bulk density and sound velocity are attributable to intensified sea ice and iceberg activity.

Early onset of Northern Hemisphere ice. One striking feature of the overall sediment record is the average sedimentation rate ranging from 1 to 2 cm kyr^{-1} (Fig. 3), which is an order of magnitude higher than estimates made by previous investigators who interpreted the Arctic as 'sediment-starved'[9,29]. The higher sedimentation rates observed in the ACEX cores enable the reconstruction of palaeoceanographic records in sufficient detail to not only resolve glacial and interglacial cycles (Fig. 3d), but also to identify the timing of major climate events. The difficulty in developing a reliable chronostratigraphy formed the basis of a long-standing debate over sedimentation rates in this basin, with arguments made for both low (mm kyr^{-1})[29,30] and high (cm kyr^{-1})[9,31] rates. These disparate interpretations profoundly inhibited reconstructions of Arctic glacial history and are now resolved with the ACEX record, allowing for interpretations of the timing of northern high-latitude cooling events.

Investigators have long debated the timing, extent and nature of the onset of Northern Hemisphere glaciation[32–38]. Previous studies suggest that such glaciation began between 10 and 6 Myr ago, whereas glaciation of Antarctica began much earlier, as early as ~43 Myr ago[39]. Our results push back the date of Northern Hemisphere cooling to ~45 Myr ago, and suggest contemporaneous co-evolution of ice on the poles, and thus symmetry in cooling and a bipolar transition from the 'greenhouse' to 'icehouse' world. Indirect evidence supporting 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[40] and synchronous changes in calcium carbonate compensation depth[41].

Arctic palaeoenvironmental significance

ACEX results suggest that the Earth's transition from the 'greenhouse' to the 'icehouse' world was bipolar, which points to greater control of global cooling linked to changes in greenhouse gases in contrast to tectonic forcing. Tectonic changes, such as the opening of the Drake Passage, may modify portions of the planet's ocean circulation systems but initiate climate changes that progress too slowly to induce synchronous global cooling patterns. Initial interpretations of the early presence of Arctic sea ice suggests that this mechanism may have led cooling in the Northern Hemisphere as early as ~45 Myr ago and is implicated as a participant in other cooling events, such as expansion of East Antarctic (~14.5 Myr ago) and Greenland (~3.2 Myr ago) ice. Further delineation of sea ice and its role in climatic cooling through enhanced albedo is warranted.

Received 4 August 2005; accepted 13 April 2006.

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Acknowledgements We thank the IODP European Science Operator (ESO), led by the British Geological Survey; the Swedish Polar Research Secretariat, who provided shiptime for *Oden* as well as the ice and fleet management; icebreaker Captains Årnell, Backman, Davidjan, Haave, Shirley, Smith and Vikström, and the crews of *Oden*, *Vidar Viking* and *Sovetskiy Soyuz*; and Seacore Ltd, who provided the drilling services. This research used samples and data provided by the Integrated Ocean Drilling Program.

Author Contributions J.B. was the lead investigator on the ACEX proposal to IODP. K.M. and J.B. conducted much of the project planning with support from J.F. J.B. and K.M. led the expedition. Ship- and shore-based core analyses were conducted by the IODP 302 science party (H.B., S.C.C., T.C., G.R.D., F.E., J.G., M.J., R.W.J., M.K., J.K., N.K., A.K., N.M., J.M., T.C.M., D.M., J.O., M.O., H.P., B.R., D.R., T.S., D.C.S., R.S., K.S., I.S., N.S., K.T., M.W. and M.Y.). Additional sediment analyses were conducted by M.F. and P.K. Geophysical data were collected and analysed by W.J. and Y.K.

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