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Expanding the Cenozoic paleoceanographic record in the Central Arctic Ocean: IODP Expedition 302 Synthesis

Research Article

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Abstract: The Arctic Coring Expedition (ACEX) proved to be one of the most transformational missions in almost 40 year of scientific ocean drilling. ACEX recovered the first Cenozoic sedimentary sequence from the Arctic Ocean and extended earlier piston core records from ∼1.5 Ma back to ∼56 Ma. The results have had a major impact in paleoceanography even though the recovered sediments represents only 29% of Cenozoic time. The missing time intervals were primarily the result of two unexpected hiatuses. This important Cenozoic paleoceanographic record was reconstructed from a total of 339 m sediments. The wide range of analyses conducted on the recovered material, along with studies that integrated regional tectonics and geophysical data, produced surprising results including high Arctic Ocean surface water temperatures and a hydrologically active climate during the Paleocene Eocene Thermal Maximum (PETM), the occurrence of a fresher water Arctic in the Eocene, ice-rafted debris as old as middle Eocene, a middle Eocene environment rife with organic carbon, and ventilation of the Arctic Ocean to the North Atlantic through the Fram Strait near the early-middle Miocene boundary. Taken together, these results have transformed our view of the Cenozoic Arctic Ocean and its role in the Earth climate system.

Keywords: ocean drilling • Lomonosov Ridge • Cenozoic paleoceanography • Arctic tectonics

1. Introduction

The modern Arctic Ocean, the smallest ocean basin, occupies about 2.6% of the modern global ocean surface area and 1.0% of its volume [1]. Despite its small size, this ocean has exerted a large influence on the global Cenozoic paleoclimate because of its long-lasting polar position [2, 3], being a locus for: sea-ice formation affecting Earth's albedo, the production of deep-water masses, and global thermohaline circulation [4–6]. The Arctic Ocean is an integral part of the global ocean-climate system, yet due to the logistical difficulties of working in this ice-covered region, it remains virtually unsampled. Improving our knowledge of the evolution, variability, and key drivers of this system requires us to understand the history of this polar basin and its changing environmental conditions over geological timescales. The Arctic Coring Expedition (ACEX) was conducted by the Integrated Ocean Drilling Program (IODP Expedition 302) and was conceived to directly address these challenges and thus

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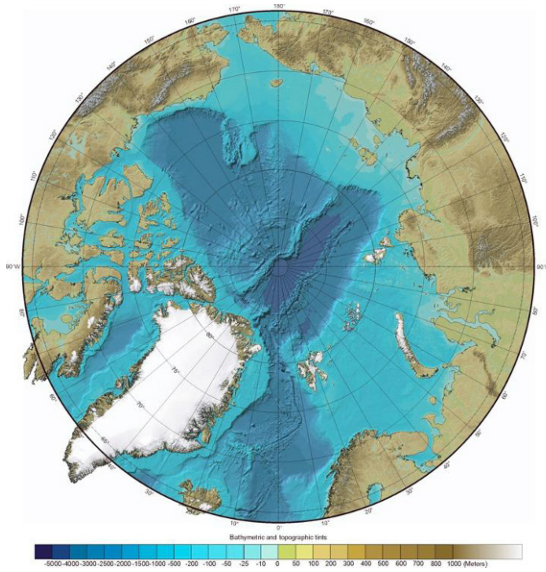

Figure 1. IBCAO 3D grid model of Arctic Ocean with place names of key features. The location of the ACEX drill sites are: Site 2A – 87°55.271'N, 139°21.901'E; Site 3 – 87°56.000'N, 139°32.100'E; Site 4 – 87°51.995'N, 136°10.475'E. Sites are marked by a red star on the Lomonosov Ridge. The Amerasian and Eurasian basins are located west and east, respectively, of the Lomonosov Ridge. This 3D grid was generated by Jakobsson et al. [112]. Download available from: www.ngdc.noaa.gov/mgg/bathymetry/arctic/downloads.html

include the Arctic Ocean in our evolving understanding of global paleoceanography.

The continuously land-locked Arctic Ocean began to develop during Late Jurassic or Early Cretaceous time [7, 8], at about 140-150 Ma according to the 2004 timescale [9]. The Amerasian Basin was the only deep basin in the Arctic Ocean for about 80-90 Myr. The Lomonosov Ridge separates the older Amerasian Basin from the younger Eurasian Basin (Figure 1). This ridge was rifted from the Eurasian margin as a continental margin fragment during the late Paleocene, initiating the formation of the Eurasian Basin [10–14]. The deep basins of the Arctic Ocean are blanketed with thick sediment sequences, 6-10 km in the older Amerasian Basin and 2-3 km in the younger Eurasian Basin [15]. In contrast, submarine ridges in the Arctic Ocean are generally covered by a much thinner sediment drape, suggesting that the deep basins are largely filled with mass wasting products from surrounding margins. This makes the thinner and shallower ridge crest sediments more suitable for paleoceanographic study.

One such ridge sequence was mapped on the Lomonosov Ridge in 1991 between 87°30'N and 88°N [16], showing "undisturbed flay-lying strata... deposited on top of the peneplaned ridge since it rifted from the Barents–Kara Sea margin" [13]. Seismic reflection and refraction data from this part of the ridge indicate a thickness varying from 430 m to 520 m for the sediment drape resting on the regional unconformity [17]. Their stratigraphic model includes four Cenozoic seismic units: LR-3 through LR-6. These units were interpreted to represent continuous deposition beginning at the base of the middle Eocene, at about 49-50 Ma (Chron C22n), when the Lomonosov Ridge was assumed to subside below sea-level, marking the onset of Cenozoic marine sediment accumulation on the ridge crest [17].

Based on these interpretations, the ACEX aim was to continuously recover the 430-520 m thick Eocene-Recent sediment sequence on the Lomonosov Ridge between 87°30'N and 88°N. The ACEX name was coined during discussions in early 2004 with Dr. Kenneth Hunkins, a pioneer of geoscientific research in the Arctic Ocean. The planning and execution of this transformational drilling expedition to the ice-covered central Arctic Ocean involved many new challenges in terms of station keeping of the drill ship, which were solved well beyond expectations with the aid of two support ice-breakers [18].

ACEX relied on a set of clearly defined scientific objectives [19], but to a large extent had the character of true exploration, similar to the excitement of the early days of the Deep Sea Drilling Project [20], which was driven by the expectation that the recovery of ocean-floor sediments and rocks would lead to new perspectives on the geological history of the planet [21, 22].

The Pliocene through Oligocene paleoenvironmental evolution in the central Arctic Ocean was virtually unknown before ACEX because of a complete lack of samples [23]. A one-meter long core section from the Alpha Ridge had provided a glimpse of, and the sole evidence for, marine Eocene conditions from diatom, ebridian and silicoflagellate assemblages [24–26]. Paleocene samples did not exist and were not expected to be retrievable from the Lomonosov Ridge sediments [17]. Thus, prior to ACEX, about 98% of the Cenozoic stratigraphy from the central Arctic Ocean was unsampled and unknown.

2. Objectives

Arctic paleoceanography was so poorly known, before ACEX, that the recovery of any material would be viewed as 'true exploration' that would increase our knowledge and understanding of this critical region. Additionally, there were a number of specific paleoceanographic objectives framed from lower latitude results for which testable hypotheses were developed that were consistent with the scientific objectives outlined in the IODP Initial Science Plan. The overall objectives focused on recovering records to reconstruct past Arctic ice, sea-ice and glacial ice, temperatures and climates. Some of the key questions which we hoped to answer from ACEX were framed around the evolution of sea-ice and ice sheets, the past physical oceanographic structure, Arctic gateways, links between Arctic land and ocean climate, and major changes in depositional environments.

Sea-ice and ice sheet evolution - Ocean drilling in the Norwegian, Iceland, Irminger, and Greenland Seas has shown that the first, coarse, ice-rafted material appeared earlier off southern Greenland than in the Fram Strait - Yermak Plateau region [27]. Drilling results from the Fram Strait and Yermak Plateau regions have shown a series of middle and late Miocene pulses of ice rafting (14 Ma, 10.8-8.6 Ma, 7.2-6.8 Ma, 6.3-5.5 Ma, and continued in sediments younger than 5 Ma) [27]. The resolution of the temporal and spatial distribution of sea-ice had important ramifications on the climatic history of the Arctic. Questions that stemmed from these studies were:

- Did Miocene and Pliocene sea-ice exist in the central Arctic Ocean?
- Did the cooling and glacial inception occur earlier in the sub-arctic than in the central Arctic or vice versa?
- When did the first seasonal sea-ice occur?
- When did a permanent sea-ice cover occur?
- Was Svalbard ice expansion local or can the events also be observed in the central Arctic?

ACEX goals were structured to answer these questions by analyzing the presence or absence of ice-rafted material within a constrained stratigraphic context.

Past Arctic oceanographic structure – The influence of the fresh water supply to the Arctic Ocean has since long been considered as a prerequisite for sea-ice formation [28]. Aargard and Carmack [5] also envisaged a scenario in which fresh water modifies the extent of sea-ice in the Arctic Ocean. Driscoll and Haug [6] called upon changes in fresh water input, from Siberian rivers, to facilitate ice formation and contribute to the onset of Northern Hemisphere glaciation. A decrease in fresh water supply would move the present site of deep water North Atlantic convection from the Greenland Sea into the central Arctic basins and implies a virtually ice-free Arctic Ocean. ACEX sought to determine this important history of fresh water supply to in the Arctic ocean. The contrast from ice-covered, well-stratified and oxygen poor Arctic Ocean waters to ice-free waters with free air-sea exchange (well-oxygenated) would be seen as a recognizable signal in the sediments accumulating on the seafloor, for example in terms of sediment color or degree of bioturbation. A major change in river input should yield a strong sedimentological signal and deposit pollen and spores.

Arctic Ocean gateways – Today, the Fram Strait represents the only deep-water connection between the Arctic and the world ocean. The timing of the formation of this passage is critical to the development of global circulation models. Several reconstructions exist, based mostly on tectonic arguments [11, 29, 30], that place the opening from early Oligocene to late Miocene. A major question that ACEX targeted for answering was: what would the effect of the outflow of Arctic bottom waters have on the environment within the Arctic Basin? The replacement of oxygen-poor Arctic waters with more oxic waters should be discernable using various sedimentological and geochemical proxies.

Consistent with the modern Arctic model, a decrease in fresh water supply combined with a shut-off of the Bering Strait inflow would result in the virtual loss of sea-ice [5, 28]. Classically, the opening of the Bering Strait had been recognized by a dramatic change in the composition of shallow water marine faunas [31] and in particular the influx of Pacific boreal mollusks to Iceland [32]. ACEX hoped to shed light on the timing of the opening of the Bering Strait by studying the ice-rafted debris in the sediment record. Ice-rafted debris would reveal when sea-ice first formed in the Arctic Basin and could answer whether or not the timing of this first permanent sea-ice cover was coincident with the arrival of the Pacific boreal mollusks to Iceland.

Land-sea links – Funder et al. [33] demonstrated that northern-most Greenland was forested in the late Pliocene. ACEX goals included the study of the sediment to extract fossil evidence of temperature change to determine if this warming was local or regional, whether sea-ice was present during these warm Greenland times, and if biogenic carbonate was preserved in the Arctic Basin at this time.

History of biogenic sedimentation – Drilling prior to ACEX raised only four cores that contained pre- Pleistocene sediment from the Alpha Ridge. These predominantly consisted of black biosiliceous muds suggesting poorly ventilated waters. Three of the cores were Late Cretaceous in age, and one was from to the "upper middle Eocene or upper Eocene" [25]. Plio-Pleistocene cores from Fram Strait and Yermak Plateau all contained some biogenic carbonate and were barren of biosilica. These results raised important questions about the Arctic that ACEX included in its goals. For example, ACEX sought to determine if Eocene time was characterized by a poorly stratified ocean. It also sought to determine when this transition, from biosiliceous to carbonate sedimentation, occurred and its relationship to North Atlantic high latitude advection.

Tectonic – The Lomonosov Ridge is a seafloor feature more than 1500 km long and 30-80 km wide which rises 3 km above the adjacent abyssal plains. If proven to be a continental fragment, it would provide unique global information on the relative strength of continental and oceanic lithosphere. The olivine rheology of the oceanic lithosphere is estimated to be three times stronger than typical continental lithosphere [34]. Juxtaposed oceanic and continental lithosphere in a tensional stress field would be weakest landward of the continental shelf edge [35] and the Lomonosov Ridge may have formed as a result of this mechanism. The tectonic objectives for ACEX were 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 to study the history of rifting and the timing of tectonic events that affected the ridge.

3. Overview of ACEX publications

Immediately following the expedition and core processing during late 2004, the operational success and early scientific results gained high profiles in science news articles [36–39] and in the popular press (e.g., New York Times, Der Spiegel, The Guardian, Independent, Globe & Mail, Times of India, Le Monde, Frankfurter Allgemeine Zeitung, Boston Globe, Svenska Dagbladet, among many others). The focus of these popular and science news articles was the success of the first central Arctic drilling operation and the unusually warm past climates uncovered by ACEX. The popular interest in ACEX speaks volumes about the increasing public interest and awareness of the Arctic Ocean and related climate issues. It is also clear that articles regarding polar adventure and information about the inaccessable world of the North Pole are of broad popular interest.

A first glimpse of the ACEX scientific results was presented by Backman et al. (2005) [40] in the inaugural issue of *Scientific Drilling*, which was followed by a first publication peak in 2006, with the release of the IODP Expedition Results volume [19] and four *Nature* papers [41–44]. ACEX was featured on the cover of *Nature* in its June 1st (2006) issue, showing the IBCAO bathymetric map of the Lomonosov Ridge and adjacent basins [45]. A fifth Nature paper was subsequently published [46] in addition to three peer-reviewed ACEX related publications which focus on the geochemistry were presented [47–49]. A second wave of ACEX publications appeared in 2008 and started with an article in *Nature Geoscience* on the influence of brine formation on Arctic Ocean Intermediate Water circulation during the past 15 million years [50]. This was followed by a special issue in *Paleoceanography* containing 20 ACEX articles. Furthermore, several articles will be published in *Micropaleontology*.

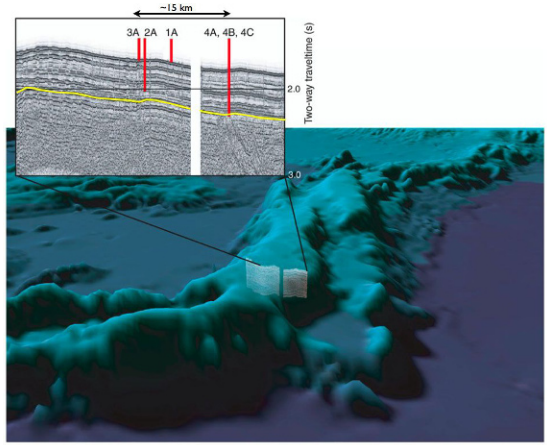

Figure 2. Seismic reflection profile AWI-91091 [13] showing locations of ACEX drill sits (red bars) and their penetration depths [113]. Yellow line marks the position of the 26 Myr long mid-Cenozoic hiatus. Reproduced by permission from the Integrated Ocean Drilling Program.

Here we aim to amalgamate this wealth of new information acquired from the Cenozoic sediment sequence recovered during the ACEX. After a brief synopsis of the IODP ACEX drilling operations, we describe the development of depth scales, age/depth relationships and sedimentation rates. This is followed by a presentation of the key results in relation to the original scientific objectives and a summary.

4. Operations

Four sites were drilled during ACEX between 87°52'N and 87°55'N [19] (Table T1), which were located <16 km of each other on seismic line AWI-91090 on the crest of the Lomonosov Ridge [13, 17] (Figure 2). Local ice conditions determined where sites were positioned along the seismic line. Targeted sites on a neighbouring seismic line (AWI-91091), also crossing the Lomonosov Ridge south of AWI-91090, were not approached because of more severe local ice conditions.

Site M0001 (Figure 2, where the drilled Holes are referred to as 1A, 2A, 3A, 4A-C) was abandoned after no recovery because of the loss of the bottom hole assembly. Deeper penetration was achieved at sites M0002 and

M0004, which are interpreted as a single site because of the internally consistent seismic stratigraphy along the short distance separating them on line AWI- 91090 [19] (Figure F2). The drilling of Site M0002 was interrupted at 270 meter below seafloor (mbsf) because ice conditions deteriorated, reducing the drill ship's ability to maintain position over the drill site. Ice conditions not only prevented deeper penetration at this site, but also logging of the hole. As conditions improved, Site M0003 was cored about 1 km away from Site M0002. Drilling equipment problems stopped operations after the recovery of only three cores at Site M0003 at 15 mbsf. During repairs, ice conditions deteriorated further. While equipment was being repaired, an ice reconnaissance study was undertaken using a helicopter and one of the two support ice-breakers. Based on their observations, a decision was made to move 15.5 km towards the Eurasian margin of the ridge crest, along line AWI-91090, to drill Site M0004 under better ice conditions.

Time limitations forced us to wash down to 265 mbsf at Site M0004 in an attempt to recover the older part of the Cenozoic stratigraphy and a few tens of meters of the underlying sedimentary bedrock. This strategy was aimed to establish a short overlap with the deepest portion of Site M0002. Hole M0004A was deepened to 427.9 mbsf, the deepest 22.2 m in slow advance and with poor core recovery (6.3%). The overall core recovery for Hole M0004A was 49.8%, two short wash-down intervals not included. Logging was attempted for 26 hours at Hole M0004A but was unsuccessful, most likely because of a plugged drill bit that prevented the logging tools from entering the open borehole.

Initial analyses of Hole M0004A core catcher samples by shipboard scientists immediately revealed intriguing and highly interesting Paleogene paleoceanographic conditions, including the surprising partial recovery of the PETM interval, which, according to the seismostratigraphic model of [17], should not have been present in the cored Lomonosov Ridge sediment sequence. It was therefore decided to use most of the remaining time (the final 24 hours were reserved for APC coring of the upper sediment column) to wash down in a new hole in order to improve the completeness of the poorly recovered Paleogene section, and to log the hole. Over the following 26-27 hours penetration advanced to 219 mbsf in Hole M0004B. Three cores were retrieved from Hole M0004B before air temperatures dropped to between -10°C and -12°C causing drilling operations to be aborted due to freezing of equipment. This hole was successfully logged. Nine additional cores (4 APC, 5 XCB) were retrieved in the upper 37.3 mbsf from Hole M0004C before ACEX coring operations ended on September 5th, 2004, after 22.5 days over

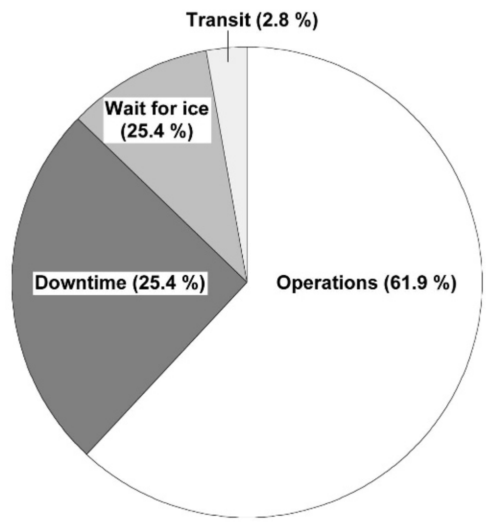

Figure 3. Breakdown of time during ACEX drilling operations on the Lomonosov Ridge, about 225 km away from the North Pole. Calculated percentages are based on a total of 541 hours (22.5 days) on the ridge crest.

the Lomonosov Ridge. The allocation of time for operations, transit, breakdown time, and waiting on ice over the 22.5 days is presented in Figure 3.

A total of 495.47 m was cored, of which 339.06 m were recovered, resulting in a total recovery rate of 68.4% [19] (Figure F1, Table T1). Ice rafted drop stones did not hinder the drilling, although a fair number of centimetre-sized pebbles were recovered. Rather, the lithologies encountered on this first IODP Mission-Specific Platform operation were similar to those predicted, representing fairly standard paleoceanographic drilling conditions in a 428 m thick unlithified section which was dominated by finer-grained siliciclastic sediments containing thin sand lenses, and a ca. 93 m thick section composed of biosiliceous ooze and mud. The total thickness of the ACEX section is close to the calculated minimum estimate determined from seismic data of the sediment drape [17].

5. The recovered sediment record

Lithostratigraphy – The recovered sediments were subdivided into four lithologic units (Figure 4) on the basis of color, texture, compositional variations, x-ray diffraction data, and total organic carbon contents (TOC). Units 1, 3, 4 are dominated by siliciclastic sediments, whereas Unit 2 is dominated by a biogenic component. Here we summarize the key characteristics of the four lithological units. Backman, Moran et al. [19] provide full descriptions, which can be downloaded at http://publications.iodp.org/proceedings/302/104/104%5F2.htm

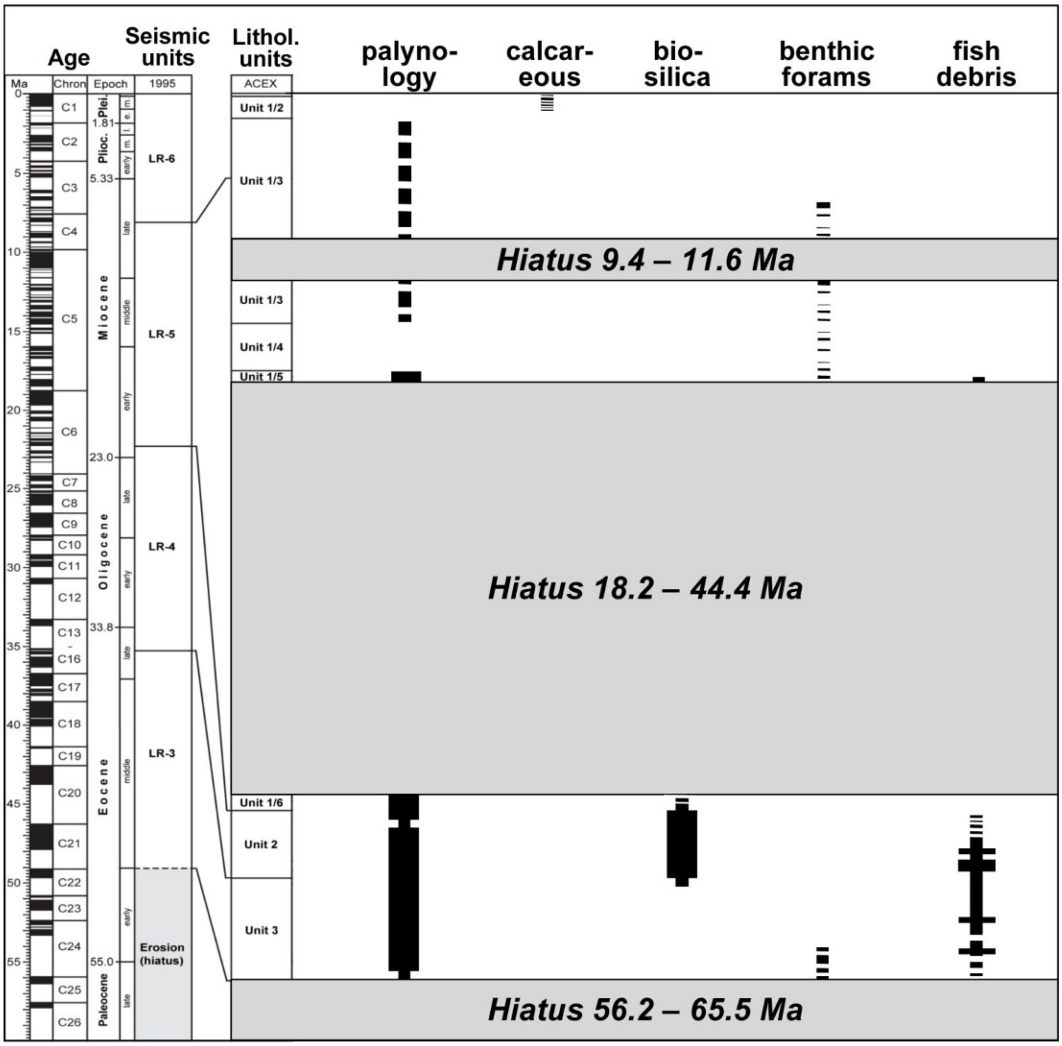

Figure 4. Chronostratigraphic distribution of the Cenozoic ACEX sediments. Age column shows the geomagnetic polarity timescale chosen for ACEX together with Chron assignments (C1- C26) [65], and Cenozoic epochs (Pleistocene-Paleocene). Numbers at far left show age in Ma. The seismic unit column shows Jokat's et al. [13, 17] chronostratigraphic interpretations of reflection seismic data at the ACEX drill sites. Cenozoic lithologic units are from Backman, Moran et al. [19] and correlation lines between seismic and lithologic units are from Backman et al. [65]. The Upper Cretaceous Unit 4 is not shown. Columns showing distribution of microfossil groups represent our interpretation of range chart tables presented by Backman, Moran et al. [19]. Two key early Paleogene biostratigraphic age indicators are shown (Azolla, Apectodinium augustum) [42, 43]. Narrow, interrupted bars imply discontinuous occurrences and low abundances. Wide, continuous bars imply continuous occurrences and high abundances.

(1) Unit 1 is characterized by siliciclastic sediments, color banding, sandy lenses and isolated pebbles, from the sediment-water interface to 220.24 mbsf. This unit is subdivided into six sub-units, distinguished from each other mainly by changes in color, texture, and composition, including contents of TOC and micro-concretions. Age range is Holocene to middle Eocene. Sediments in Subunits 1/1 through 1/4 (0-192.94 mcd), and part of Subunit 1/5 (192.94-198.70 mcd) show low TOC contents and represent

deposition under oxic conditions.

(2) Unit 2 is characterized by mud-bearing biosiliceous oozes, and represents a sharp transition from the overlying siliciclastic-dominated sediments of Unit 1. Unit 2 belongs to the middle Eocene. Hole M0002A reaches 47.5 m into Unit 2 on the mbsf scale. The lower half of Unit 2 was retrieved from Hole M0004A. The lowermost occurrences of isolated pebbles and sand horizons are observed in the upper part of Unit 2. Lower Unit 2 contains high abundances of remains of the fresh-water fern Azolla. Unfortunately, the paleoenvironmental development leading up to this event is lost in a non-recovery interval stretching over 12.2 m. Parts of Subunit 1/5 and the whole of Unit 2 represent deposition under poorly oxygenated conditions and show elevated TOC concentrations.

(3) Unit 3 is characterized by a return to siliciclastic-dominated clayey sediments at 313.61 mbsf, lasting down to 404.8 mbsf, with pyrite concretions and submillimeter-scale laminations. Age range is late Paleocene to early Eocene.

(4) Unit 4 (located below the regional unconformity and not shown in Figure 4) consists of dark, clayey mud, with silty sand at its bottom. Only 1.39 m was recovered. The highly disturbed Unit 4, of Campanian age, is separated from Unit 3 by a non-recovered interval of 19.7 m.

Biostratigraphy and taxonomy – The stratigraphic distribution of the key microfossil groups is summarized in Figure 4, together with the chrono- and seismo-stratigraphy of the ACEX sediments. Biogenic carbonate is restricted to sporadic occurrences in the upper ca. 20 m of the sediment column [51, 52], that is, in Pleistocene sediments younger than ca. 1.3-1.7 Ma [53, 54]. Calcareous plankton groups may very well have been intermittently productive in Arctic waters during Neogene and/or Paleogene times. If so, their general absence in the ACEX sediments may reflect a preservation bias. Alternatively, it is possible that the calcareous plankton groups were excluded from the central Arctic because of unfavorable paleoecological conditions. The first option appears more reasonable, however, considering the relatively low pH and alkalinity values below ca. 20 mbsf [19]. Moreover, the fact that North Atlantic surface waters have continuously entered the Arctic since earliest middle Miocene times [46], and at least sporadically also during middle Eocene times [55], suggests that these advances of North Atlantic waters into the Arctic Ocean likely carried calcareous plankton communities. Again, this supports the interpretation that the absence of calcareous plankton groups below 20 mbsf reflects preservation rather than productivity.

Rare to few dinoflagellate cysts occur in the oxic sediments represented by Subunits 1/1 through 1/3 (0-168.53 mbsf), whereas Subunit 1/4 (168.53-192.94 mbsf) is barren. Biostratigraphic resolution in these middle Miocene to Recent sediments is, therefore, at a minimum, especially when the lack of calcarous plankton below 20 mbsf and the total absence of biosilica are considered (Figure 4). An acritarch species (Decahedrella martinheadii) of late Miocene age, however, provides an important chronologic control point at 74 mbsf [56]. Furthermore, palynomorphs provide the only available biostratigraphic age constraint in the important Subunit 1/5 (192.94-198.13 mbsf). An early Miocene age (Burdigalian) has been suggested for Subunit 1/5 [57]. The biostratigraphic resolution improves below Subunit 1/5 (below 198.13 mbsf). Continuous, diverse and moderately well preserved dinoflagellate cyst assemblages occur in Subunit 1/6 through Unit 4 (198.13-427.63 mbsf). Unit 2 contains an accurately dated palynological event, namely an "acme" interval of the remains of the hydrophterid fern Azolla which encompassed an 0.8 Myr long interval centered on 48.7 ($\pm$0.4) Ma [42]. Another well dated "acme" interval is comprised of Apectodinium augustum, having a short range within the Carbon Isotope Excursion of the PETM, dated to ca. 55 Ma [43]. Subsequently, the presence of a younger Eocene hyperthermal, the Eocene Thermal Maximum 2 (ETM2) at ca. 53 Ma, was confirmed by [58] the presence of the dinoflagellate cyst species Cerodinium wardenense. In the ACEX record, the ETM2 event was first proposed by [47] based on a carbon isotope study on bulk organic material. Finally, the oldest sediments recovered were formed during Late Cretaceous (Campanian) times according to dinoflagellate cyst assemblages. This makes the palynomorphs the most consistently present, and hence biostratigraphically most useful, microfossil group in the ACEX sediments. A new dinoflagellate cyst genus, containing two new species, is described by Sangiorgi et al. [57].

Biosiliceous microfossils are represented by abundant chrysophyte cysts, diatoms, diatom resting spores, ebridans, and silicoflagellates. These are restricted to a ca. 5 Myr long interval in the early half of the middle Eocene (44.6-49.7 Ma). Radiolaria are present only in rare numbers in a few samples in this biosilica-rich interval. Despite the relatively short duration of this interval, it represents the only phase of biosilica production and preservation for the entire Cenozoic from the Arctic Ocean. The assemblages are diverse, well-preserved and represent shallow marine taxa. Many new diatom resting spore taxa are described by [59–61]. New ebridian and silicoflagellate taxa are described by [62, 63]. Stickley et al. [64] note that "the recent discovery of ∼100 m of early middle Eocene, biosiliceous sediments from the Lomonosov Ridge... represents perhaps the most significant discovery of Paleogene diatoms in nearly two decades". The taxonomy of the ACEX diatom flora awaits description. Over 30 different morphotypes of chrysophyte cysts have been observed in the ACEX sediments, which represent "the most diverse, abundant and sustained levels of fossil chrysophytes ever discovered in a Paleogene setting" [64]. Many of these taxa are new and remain to be described. Thus, the rapid evolution among the biosiliceous groups provides many potentially useful Paleogene biostratigraphic events in the Arctic Ocean. Many of these taxa are endemic to the Arctic Ocean, however, and in the absence of magnetostratigraphy or any other independent age control in the Eocene ACEX sediments, the biostratigraphic properties of the biosiliceous assemblages are still uncertain. The Cenozoic biostratigraphy was briefly discussed by Backman et al. [65], including the nearly 9 Myr difference in age estimate of the Eocene sediments just below the major hiatus. The young estimate was generated from diatom indicators whereas the older (used) estimate was derived from dinoflagellate cysts.

Age models – Multiple recovery of the same cored intervals exist for the upper 30 m of the sediment column. The remainder of the 428 m long ACEX section was cored in two holes (M0002A, M00004A) with a short overlap, according to driller's depths, at about 268 mbsf. This overlap could not be confidently confirmed with geophysical data. Nevertheless, based on splicing of overlapping cores in the uppermost 30 m of the sediment column, a corrected depth scale (meters corrected depth: mcd) was developed for the entire ACEX section [19] (Tables T24- T26). A continuous sedimentary section was subsequently pieced together from all five ACEX holes in the upper 27 m of the sediment column [53], which prompted [66] to refine the mcdscale and re-assess the depth offsets for cores in the upper 55 mbsf, resulting in a revised mcd (rmcd) scale.

A preliminary plot of age/depth relationships relied on the use of a combination of biostratigraphy and magnetostratigraphy [19] (Figure F19). The ACEX results clarify the debate about average sedimentation rates in the Arctic Basin [23, 67] and give average Cenozoic sedimentation rates ranging between 1 and 2 cm/ka, approximately one order of magnitude higher than estimates for the central Arctic Ocean [68–70].

Two different interpretations of the geomagnetic inclination record in the 0-190 mcd interval were presented by [19] (Figure F46). These interpretations were unconstrained by biostratigraphy. The ACEX Neogene inclination record is complicated for two reasons. First, its large number of polarity intervals are not compatible with the established number of geomagnetic polarity zones and subzones across the pertinent time interval [71]. Second, numerous coring gaps amplify the problem of interpreting this complex inclination pattern in terms of magnetostratigraphy. For these reasons, Backman et al. [65] excluded the Neogene magnetostratigraphic data in their revised age model. In terms of magnetostratigraphy, their age model is restricted to the use of a single reversal boundary, namely the top of Chron C25n. In this revised age model, Neogene age control between 0 Ma and 12.3 Ma is chiefly constrained by 10Be data [54]. This cosmogenic isotope has a half-life of 1.51 million years and provides age estimates well back into the middle Miocene. The few biostratigraphic indicators available are consistent with the 10Be stratigraphy. Natural remanent magnetization values are too low in the 193–388 mcd interval to permit recognition of any geomagnetic polarity zones.

The current ACEX age model [65] represents a compilation of biostratigraphy, a singleb magnetostratigraphic control point, cosmogenic isotope stratigraphy and, to some extent, cyclostratigraphy [72]. The details of this model are bound to change once additional data are generated or new Cenozoic sediment sections from the central Arctic Ocean are recovered and investigated. For example, a study of helium isotopes, conducted by ACEX scientist Jérôme Gattacecca, found elevated concentrations of 3He in three samples taken from Subunit 1/4, which are interpreted as indicating strongly reduced sedimentation rates, much lower than the 0.8 cm/ka suggested by [65] (J. Gattacecca, personal communication, 28 May 2008). Nevertheless, the age model is considered robust and will likely remain intact where Paleogene biogenic productivity and, to some extent the input of ice-rafted debris (IRD), has maintained sedimentation rates on the order of one to two cm/ka. In the Neogene, input of biogenic material to the sediments was negligible, rather, siliciclastic IRD is the main sediment source. The Neogene IRD-dominated sediments accumulated at an average rate of 1.2 cm/ka.

6. Tectonic results and the 26 Myr long mid-Cenozoic hiatus

Due to poor core recovery, the depth where the ACEX drilling ended cannot be precisely determined or correlated to the seismic reflection profile [13, 17]. There is an unconformity representing a time interval on the order of 27 Myr between the oldest recovered Cenozoic sediment at 404.8 mbsf, of late Paleocene age, and the next recovered sediment at 424.5 mbsf, of Mesozoic (Campanian) age. It is reasonable to interpret this hiatus as the regional unconformity (Figure 2) described by Jokat et al. [13, 17], which separates the overlying sedimentary drape from the underlying sedimentary bedrock.

Benthic foraminiferal and palynological data indicate a shallow-marine, neritic, setting for the disturbed 1.4 m thick Mesozoic sediments below the unconformity [19]. Volcanogenic sedimentary products are rare or absent in both the overlying Paleocene and the underlying Campanian strata, presumably indicating a virtual lack of magma upwelling and extrusive volcanism during the rifting process [73], assuming that volcanogenics are not concentrated to the non-recovered interval between 404.8 and 424.5 mbsf. Furthermore, it is difficult to correlate the recovered 1.4 m thick Mesozoic sediment slurry to any known geological formation on the Eurasian margin, and particularly to the geology of the Franz Josef Land [74–76].

Thus, there are few key conclusions that can be drawn to address the original tectonic objectives. We cannot firmly establish that the regional unconformity was penetrated between the Cenozoic sediment drape and the underlying sedimentary bedrock. In addition, the lack of recovery of the underlying sedimentary bedrock prevents us from linking the ridge to a specific stratigraphic interval of the Eurasian margin and eliminates our ability to extract details about the initial rifting history. However, the results do suggest that rifting occurred in a magma-poor setting and the continuous early Paleogene sediment drape, above the regional unconformity, started during early Chron C25n time, consistent with the most recent interpretation of the Eurasian Basin seafloor geomagnetic anomaly data [14].

Although the pre-cruise tectonic objectives to investigate the nature and origin of the Lomonosov Ridge remain unanswered, the surprising ca. 26 million year hiatus near 200 mbsf brought the tectonics back into focus and suggests an unusual subsidence history. This major mid-Cenozoic hiatus in the ACEX stratigraphy encompasses 40% of the Cenozoic and contrasts with the seismostratigraphy interpreted as a continuous depositional sequence from the base of the middle Eocene [17] (Figure 12). The hiatus occurs at the bottom of the 5.2 m thick lithologic Subunit 1/5, referred to as the "zebra" interval because of its alternating cm-thick light and dark coloured layers.

Initial analyses of micropaleontological properties of the ACEX sediments indicated that the mid-Cenozoic hiatus (18.2-44.4 Ma) was bounded by "a coastal, restricted marine, brackish setting", that the composition of the middle Eocene diatom rich assemblages is "especially common in neritic environments", and that the early Eocene – latest Paleocene interval held "inner neritic" benthic foraminiferal assemblages [19]. These diverse micropaleontological data are consistent and indicate a depositional setting in epipelagic depths (0-200 m) throughout the Paleogene interval (44-56 Ma) and, importantly, across the hiatus into the oldest recovered sediments of late early Miocene age.

The details of these preliminary observations have been subsequently addressed, and confirmed, through studies involving diatoms, chrysophyte cysts [64], diatom resting spores [59, 60], ebridians and silicoflagellates [55], and palynology [77].

Present water depths of the ACEX drill sites range from 1206 m to 1288 m [19]. An intergrated seismo-stratigraphic interpretation of the sediment sequences in the Amundsen Basin and on the crest of the Lomonosov Ridge were considered to mark the onset of Cenozoic sedimentation at the base of seismic unit LR-3 at 49-50 Ma, and that the ridge had "subsided to greater depths" during the formation of seismic unit AB-4 (46–39 Ma) in the Amundsen Basin [17]. Shipboard results revealed, however, that early Paleogene sediments were continuously deposited from the late Paleocene (56.2 Ma) and included the partial recovery of the PETM [43]. Using that information, Moore et al. [78] modeled subsidence of the Lomonosov Ridge assuming post-rifting thermal subsidence to modern water depths. This model indicates water depths for the drilling sites of about 500 m at 46 Ma, and about 700 m at 39 Ma, which are inconsistent with the depositional environments interpreted from microfossil assemblages.

O'Regan et al. [79] suggest that the 26 Myr long hiatus results from unroofing and erosion of the ridge crest. This view is consistent with consolidation trends in the ACEX section, implying that, during the time span of the hiatus, only minor amounts of sediments accumulated on the ridge crest at the drill site, if at all [41].

The mechanism(s) that kept the ridge crest at epipelagic depths, and rising even perhaps subaerially at times, for well over 30 Myr after rifting and moving away from the Eurasian continental margin, rather than following a subsidence driven by lithospheric thermal cooling [80], are addressed by O'Regan et al. [79]. They also address the question about the trigger mechanisms for the rapid early Miocene onset of subsidence. In short, they combine the present knowledge of the structure and sedimentary cover of the Lomonosov Ridge with ACEX drilling results and theoretical subsidence models, in order to provide a plausible explanation for the stalled subsidence history of the Lomonosov Ridge. O'Regan et al. [79] show that basin-wide compression occurred in two stages: the first phase was caused by a northward movement of the Greenland micro-plate during Eocene times and terminated when Greenland joined the North American plate during Chron C13 [14, 81]; The second phase occurred along the Laptev Sea margin and was initiated by plate re-organization during Chron C13. This lasted until Chron C6 at about

19 Ma and resulted in the structural evidence observed on the New Siberian Islands and the northern Verkhoyansk Range, as well as the prominent hiatuses on the Laptev and Siberian shelves [82–84]. O'Regan et al. [79] argue that the end of the long lasting (56–19 Ma) basin-wide compression occurred shortly prior to, or in conjunction with, the observed onset of early Miocene subsidence of the Lomonosov Ridge, thus permitting post-rifting lithospheric thermal cooling to begin.

The key geodynamic implication of the study of ref. [79] is that the crest of the Lomonosov Ridge, at the ACEX drill site, remained at epipelagic depths, from the time of the late Paleocene rifting from the Eurasian margin to the late early Miocene when the basin wide compression ended.

7. Paleoceanographic results

Early Paleogene environments – The recovery of late Paleocene and early Eocene sediments, previously not considered to be preserved on the ridge crest [17], enabled the study of the PETM interval (~55 Ma) near the North Pole [43]. Despite poor core recovery in this interval, dinocyst assemblages and inorganic geochemistry point to subtropical conditions during the PETM, when sea surface temperatures warmed 5-6°C from 18°C to over 23°C. These high temperatures are likely representative of summer conditions because the Paleocene ACEX sites were at a polar position, similar to today, that prevented photosynthesis during the dark winter months. A three- to five-fold increase in sedimentation rates occurred during the PETM, probably caused by enhanced river input of siliciclastic material [56] driven by an intensified hydrological cycle [44].

The depositional setting of the ACEX sites represents a near-shore environment during the Paleocene/Eocene transition [58]. These authors suggest that neighbouring parts of the ridge were subaerial, judging from the occurrence of large fern spores (Osmundaceae), abundant amorphous organic matter of predominantly terrestrial origin and organic geochemistry indicators (high BIT index values). They also combine variations among dinocyst assemblages and organic geochemistry parameters to demonstrate variability in salinity and water column oxygenation during and after the PETM. These findings should be viewed in the context of the tectonic history of the ridge. Rifting began shortly prior to the PETM event, as seen in the seafloor geomagnetic anomaly record in the Amundsen Basin adjacent to the Lomonosov Ridge [14] (Figure 3), but had not yet progressed to open the Amundsen Basin, south of the ACEX drill sites, until well after the PETM. Thus, areas to the south of the ACEX drill sites were still connected to the Eurasian margin during earliest Eocene times, a picture consistent with many of the detailed observations made by ref. [58] about the changing depositional environments across the Paleocene/Eocene boundary and early Eocene interval.

Dinocyst assemblages confirm the presence of a second early Eocene hyperthermal, the Eocene Thermal Maximum 2 (ETM2, or Elmo) near 53 Ma [58]. Previously, this event had been suggested by [47] based on δ13C data generated from organic matter. Sluijs et al. [58] employed XRF scans to demonstrate cyclic variations in element concentrations in sediments older than ETM2. These variations are attributed to precession cycles modulated by eccentricity, which helped constrain the late Paleocene and early Eocene sedimentation rates.

Later, during the early Eocene, fresh to brackish water conditions prevailed in the shallow water environment at the ACEX drill site location, as indicated by the composition of the dinocyst assemblages [58]. As salinity further decreased, these conditions culminated in the wide spread but relatively short (0.8 Myr) Azolla event [42] which straddles the early/middle Eocene boundary and indicates a surface layer of virtually fresh water. As marine diatoms also occur in the Azolla bearing samples, the upper water column must have been strongly stratified, creating a fresh water lid and Azolla growth for nearly a million years.

In a Sr-Nd radiogenic isotope study of well-preserved early and middle Eocene ichthyoliths (fish debris) from the ACEX sites, Gleason et al. [85] record isotope values that are consistent with a brackish to fresh surface water environment. These data set suggest even lower salinities (5- 20≤) than those indicated by oxygen isotope records from fish bone apatite (21-25≤) [85]. Gleason et al. [85] emphasize that the Eocene Arctic Ocean was poorly mixed and characterized by a highly stratified water column with a pervasive "fresh" upper layer and limited, periodic, shallow connections to other oceans.

The middle Eocene ACEX sediments have dark grey to black colour because of elevated concentrations (1–5%) of organic carbon [47]. The highest concentrations (up to 14%) occur in the lower part of the short, lower Miocene "zebra" subunit (1/5), a few meters below the abrupt change into ventilated conditions, which was initiated by a critical tectonic threshold during the early Miocene – the opening of the Fram Strait [46]. Judging from ratios of carbon and sulfur concentrations, Stein et al. [47] concluded that euxinic conditions began shortly after the PETM event and lasted Throughout the, ca. 10 Myr long early to middle Eocene interval. Samples analyzed from a few black layers in the early Miocene "zebra" subunit are also characterized by euxinic conditions [47] (Figure S3). Because euxinic conditions characterize the sediments on each side of the mid-Cenozoic hiatus, it is reasonable to assume that these conditions existed during the time interval represented by the hiatus, thus extending the duration from 10 Myr to 37 Myr.

The organic carbon rich middle Eocene sediments have good source-rock potential. However *in situ* generation of oil and gas has not occurred as demonstrated by the immaturity of the ACEX sediments based on Tmax and vitrinite reflectance values [48]. The depositional environment, interpreted from fish remains, suggests low surface water salinities (21-25 $\leq$) throughout the Eocene [86]. The composition of the biosilica groups, containing largely endemic assemblages of marine diatoms, ebridians, and chrysophyte cysts, is consistent with a strong halocline separating the uppermost near-fresh and/or brackish waters from the underlying waters containing assemblages that require more saline conditions [64] (Figure 9). However, the variation in dominance among the middle Eocene biosilica groups suggests variable surface water salinities, water column stratification and productivity. The endemic composition of the silicoflagellate and ebridian assemblages suggests that the Arctic Ocean was isolated from the Pacific and Atlantic Oceans during the early part of the middle Eocene [55]. This isolation ended ~45 Ma when shallow connection(s) to the Atlantic (Nordic Seas) became established, as reflected in the occurrence of high abundances of the silicoflagelle genus *Corbisema*. These observations are consistent with a study of paleoproductivity using nitrogen isotopes and bulk nitrogen measurements [87].

The early and middle Eocene sediments exhibit clear variations in physical properties and XRF-derived element concentrations that reflect environmental changes driven by orbital forcing [57, 72, 88, 89]. Astronomically based age models are, therefore, potentially feasible for early Paleogene sediment sequences in the central Arctic Ocean, although the poor core recovery (50%) inhibited their application in the ACEX material. However, the above-cited authors demonstrated that both physical and geochemical properties oscillate at Milankovitch frequencies enabling sedimentation rates to be constrained in various parts of these early Paleogene sequences. These studies suggest euxinic conditions prevailed, although Spofforth et al. [89] noticed that the biosiliceous Unit 2 exhibits periodic oxygenation.

It is far from clear which environmental factor or combination of factors caused the transition from the underlying dominance of biosiliceous ooze and muds to the overlying dominance of siliciclastic sedimentation, that is, the transition from lithologic Unit 2 (below) to Unit 1 (above) at 223.56 mcd (45.4 Ma). Backman et al. [65] discuss the problems associated with the adopted age model in this critical transition. An unresolved hiatus may be present, which may help explain the abruptness of the transition from biogenic to siliciclastic sedimentation.

Taking a closer look at lower lithologic Unit 1 using both geochemical and micropaleontological proxies, Sangiorgi et al. [77] demonstrated a cooling trend throughout Subunit 1/6 shortly prior to the 26 Myr long hiatus, together with shoaling and progressively fresher conditions. This interpretation is consistent with the diatom assemblages present [64]. Early Paleogene sedimentation ends in the uppermost Subunit 1/6 at 198.70 mcd. The best age estimate of 44.4 Ma is from palynomorph based biostratigraphy, although diatom biostratigraphy suggests a younger age, later in the Eocene for the youngest Paleogene sediments.

Early Arctic ice and Northern Hemisphere glaciation – The ACEX terrigenous sediments provide the first long Cenozoic record of Arctic ice (sea-ice and/or iceberg) history. One of the major results during ACEX was the presence of IRD in the middle Eocene, indicating that seasonal sea-ice was present from ca. 46 Ma [19, 41]. Previous evidence of Northern Hemisphere cooling has been dated to ca. 12 Ma, based on evidence from the Norwegian Sea [90], and to 2.7 Ma in the Atlantic where DSDP cores document the intensification of Northern Hemisphere glaciation (NHG) with the occurrence of IRD [91].

Several mechanisms have been proposed as triggers for this intensification. Driscoll and Haug [6] propose that the closing of the Panama isthmus enhanced thermohaline circulation resulting in increased precipitation and river runoff in the northern high latitudes and freshening of Arctic Ocean waters to such an extent that sea-ice could form. The formation of sea-ice would have caused a step-function increase in albedo that enhanced cooling and growth of NH ice-sheets. One of the ACEX goals was to test this concept. However, later studies have suggested that the onset of NHG did not coincide with this oceanographic reorganization [92]. Rather, they suggest moisture was not a major contributor and that cooling was gradual. In an analysis of 2.7 Ma old cores from the subarctic Pacific Ocean Haug et al. [93] showed that summer sea surface temperatures increased, providing water vapor that fell as snowfall thus initiating NHG while winter temperatures fell enough to form sea-ice.

The question about the timing of Northern Hemisphere cooling and bipolar ice sheet formation has been much debated in recent years [94–98]. In a study of the ACEX coarse fraction, St. John [100] confirmed the initial interpretation of early occurrence of IRD in the ACEX record [19, 41] (Figure 5). This study cleary demonstrated that the coarse fraction is IRD and not other types of primary sedimentation, e.g. fluvially deposited. Moreover,

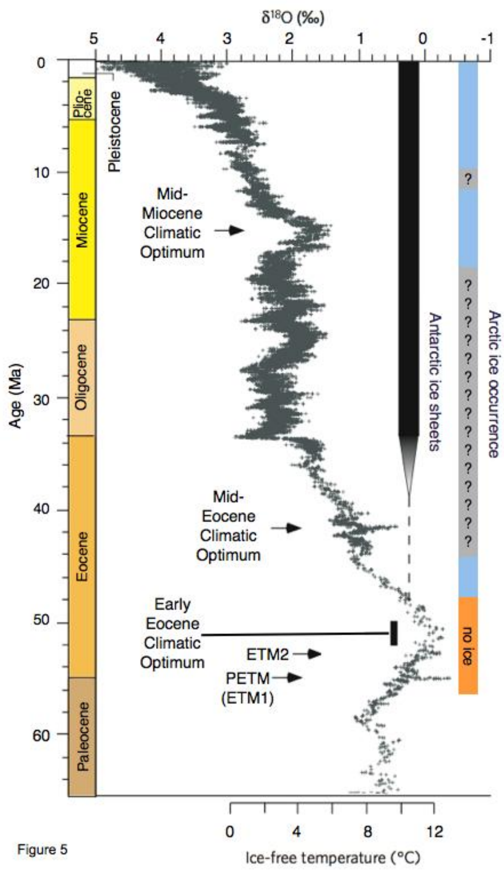

Figure 5. The stacked curve (left plot on the diagram) of deep-sea benthic foraminiferal oxygenisotope based on records from Deep Sea Drilling Project and Ocean Drilling Program sites for the Cenozoic is derived from Zachos et al. [114] showing the long-term cooling trend. These data are shown with their interpreted timing of the Southern Hemisphere cooling (black/gray bar and dashed line), labeled "Antarctic ice sheets" and the ACEX results showing early seasonal cooling, labeled "Arctic ice occurrence", which is based on the presence of ice rafted debris (light blue) bars. The gray bars labeled with "?" are intervals that were not recovered by ACEX or are part of hiatuses.

the timing of the IRD event at 46 Ma implies 10 Myr of seafloor spreading that had moved the Lomonosov Ridge away from the Eurasian margin, making fluvial influence from this margin unlikely. Thus, even if the ACEX age model uncertainties are taken into account, a middle Eocene timing for initial sea-ice formation, leading to IRD deposition on the tectonically isolated Lomonosov Ridge, and Arctic winter cooling appears robust.

A recent global climate/ice-sheet model [101] has shown that the first step in the development towards an "ice-house" world is the occurrence of seasonal sea-ice in the Arctic Ocean. DeConto's et al. [101] model suggest that the carbon dixoide threshold for build-up of an Antarctic ice sheet is nearly three times higher (750 ppmv) compared to the corresponding threshold for the build-up of Northern Hemisphere ice sheets (280 ppmv). Thus, major ice sheets developed much later in the Northern Hemisphere than in the Southern Hemisphere [101] despite the fact that initial sea-ice formation in the Arctic Ocean began earlier than the first Cenozoic ice sheet build-up on Antarctica. It therefore follows that Eocene and Oligocene IRD in the Greenland Sea having sources from Greenland and/or Svalbard [94, 98] represent ephemeral glaciers rather than major ice sheets.

In terms of sea-ice circulation conditions, the ACEX provenance results show a dominant Russian source for the IRD that extends from the present back to the middle Eocene [100], suggesting that the modern two-component sea-ice circulation system (Transpolar Drift and Beaufort Gyre) has been a persistent feature since this time.

In the Neogene, the onset of a perennial sea-ice pack in the Arctic Ocean has been suggested, using different analytical approaches, to have occurred sometime between 15 Ma and 13 Ma [100, 102–104]. This spans the time of major growth of the East Antarctic ice sheet [105] and may point to a paleoclimatic teleconnection between the two poles during the middle Miocene [105, 106].

The sparse foraminiferal record from one hole (M0004C) has been interpreted in terms of ice environments based on a faunal change from calcareous to agglutinated foraminifers at the MIS 6/7 boundary [51]. The lack of calcareous taxa prior to this boundary is likely an effect of carbonate dissolution.

Arctic gateway evolution and circulation changes – Arctic environmental interpretations for the time intervals immediately before and after the long 26 Myr hiatus document a low oxygen, euxinic setting [47, 64, 77, 87]. This environment was maintained partially through tectonic isolation of the basin from the intermediate and deep waters of the global ocean. These isolated conditions began to change post-hiatus when subsidence of the Lomonosov Ridge accelerated [79] and which coincides with a more open ocean, oxygenated environment.

Jakobsson et al. [46] conducted a detailed study of this post-hiatus period and integrated the depositional environments interpreted from the ACEX cores, with seismic reflection data, basin reconstructions, and regional tectonics, all constrained by hindcasted physical oceanographic conditions. They attributed these depositional environmental changes to Arctic Ocean ventilation associated with the opening and deepening of the Fram Strait and demonstrated that the Arctic Ocean moved from an oxygen-poor isolated basin to a ventilated ocean at ca. 17.5 Ma. The paleoceanographic development proposed by Jakobsson et al. [46] implies that the oxygenation of the ridge crest sediments was caused by enhanced Atlantic influence rather than reflecting a subsidence of the ridge below an (hypothetical) oxygen minimum zone.

Ventilation of the Arctic Ocean may have impacted the chemistry and circulation of the North Atlantic and perhaps the global ocean. The previously isolated Arctic Ocean basin was likely rich in dissolved organic carbon (DOC), analogous to the modern Black Sea. Today the Arctic Ocean and adjacent Northern Seas represent the largest pool of DOC in the global ocean [107] and prior to the opening of the Fram Strait, its concentration would have been significantly higher. Mechanisms for the distribution of DOC in the world's oceans are not understood, but it is clear that changes to the size of the reservoir would significantly impact the concentration of atmospheric CO2 [108]. A modeled DOC during the "snowball" earth showed that remineralization and burial of a massive pool of dissolved organic carbon led directly to an atmospheric CO2 increase and subsequent warming [109]. Release of Arctic Ocean water rich in DOC to the North Atlantic after 17 Ma could have had a similar impact as "snowball Earth" model suggests. This is an, as yet, untested, but possible causal mechanism for the initiation of the middle Miocene climate optimum.

In terms of circulation, the ventilation of the Arctic Ocean through the Fram Strait may have inhibited the Atlantic Meridional Overturning Current (MOC) by influx of fresher Arctic Ocean water to the North Atlantic. A similar physical occurrence, the fresh water input through the influx of melting icebergs during Heinrich event 1, has been shown in model studies to have impeded the MOC [110]. However, if the inflow of Arctic fresher water was hyperpycnal due to a particulate laden water mass, the impact on the MOC would have been negligible [111].

In a study of oceanographic conditions, using neodymium isotopes, two different modes of operation over the past 15 Ma are presented. Between 15 Ma and 2 Ma, Arctic Intermediate Water was primarily produced from brine formation in the Eurasian shelf regions. However, from 2 Ma to the present, the modern circulation pattern was switched on with North Atlantic Intermediate Water as the major contributor to the Arctic Intermediate Water. The results from Cronin et al. [50] support the opening scenario suggested by Jakobsson et al. [46] because the results of the former authors infer an open Fram Strait. The identification of two different modes of deep water formation suggests another link with the Antarctic. Brine rejection, which dominates deep water formation in the Antarctic today, is the proposed mechanism for deeper water formation until ~2 Ma.

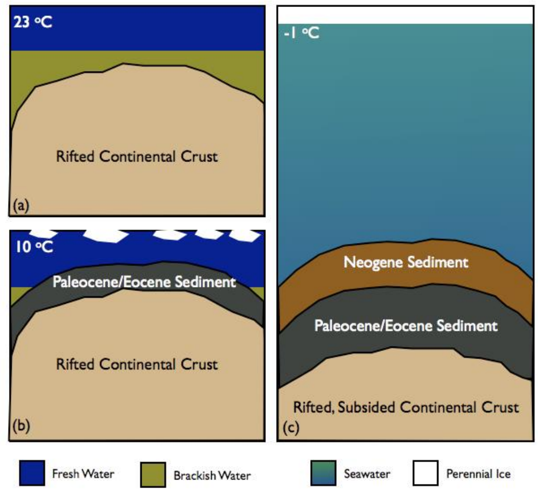

Figure 6. Cartoons showing the interpreted paleoenvironments of the Lomonosov Ridge interpreted from the ACEX Cenozoic record. The oldest interval (a) began during the early Eocene at a time of basin-wide isolation from the world ocean immediately after initial rifting, includes two hyperthermal events, and is characterized as a shallow warm fresh surface water setting that is strongly stratified with deeper brackish water. This is followed by a time during the middle Eocene (b) of continued basin isolation but an even stronger stratification with a thicker fresh surface water lid and euxinic conditions that allowed the deposition of organic rich sediment with slightly cooler temperatures that promoted the early formation of seasonal sea ice. After a 26 Myr long hiatus, the environment of (b) continued briefly, but then flipped into the environment shown in c) with oxygenated, deep marine waters, and a perennially ice covered Arctic Ocean.

8. Summary and conclusions

The ACEX Cenozoic record holds a significant number of scientific discoveries that describe previously unknown paleoenvironments. Some of these paleoenvironmental characteristics are local to the Lomonosov Ridge, for example, shallow water sediments containing terrestrial palynomorphs, while others are likely representative of the entire basin (e.g. salinity and temperature). Generally, these environments can be described in terms of three different settings which are: a) a period after rifting in the early Eocene that included two hyperthermals and warm fresh surface water; b) a period of fresh surface water and early cooling; and c) a period with oxygenated, ice covered Arctic Ocean.
The PETM hyperthermal in the Arctic Ocean was characterized by high surface water temperatures and an enhanced hydrological cycle resulting from the extremely wet climate [43, 44, 58], the exact opposite of the Arctic's cold and dry present-day climate (Figure 6a). Because rifting of the Lomonosov Ridge was in its early stages the shallow water, nearshore setting revealed by the micro-

fossil record is not surprising. Warm and wet conditions prevailed after the second hyperthermal. The ETM2 was also a transient period of warm climate but with slightly lower surface water temperatures [58].

As rifting progressed, the ridge remained in a nearshore and shallow water setting. This shifted from a marine environment to one that was dominated by a thick layer of fresh surface water and highly stratified subsurface waters at ca. 49 Ma. This environment was perfect for sequestering organic carbon on the basin's ridges and floors because of the lack of oxygen available for decomposing organic matter. It could be argued that this oceanographic setting is generally analogous to today's Black Sea.

Over the time interval spanning the hyperthermals and the Azolla event, the Arctic basin was tectonically isolated from the world's oceans. This isolation provided the conditions for the development of a brackish water body with a stable fresh water lid. Because the basin served as a fresh water reservoir for the surrounding continental river flow and runoff, it also primed as a "tipping point" to begin freezing of winter sea-ice and increasing albedo as the Earth continued on its long-term cooling trend in the Eocene (Figure 6b). In the middle Eocene, the ridge remained in shallow and near shore waters. Although the major Eocene/Oligocene hiatus does not allow for interpretation of climate environments over a 26 Myr interval, when deposition resumed at ~18 Ma, an almost identical environment to the pre-hiatus time prevailed.

After 18 Ma, tectonic events drove the climate changes on two fronts: the Lomonosov Ridge began a rapid phase of subsidence and the period of basin isolation ended when deep connection with the North Atlantic was established through the Fram Strait. This resulted in a dramatic shift from the previous stable, long-lasting, and isolated basin conditions. The environment made a step change to a new steady-state condition, characterized by its oxygenated, marine, and ice covered waters (Figure 6c) that continue to the present-day. A shorter duration hiatus occurred during this time period in the Neogene, but no change in depositional environments occurred across it. This major shift from an isolated basin to one fully connected to the world ocean may have had an impact on the global climate because the deepening of the Fram Strait enabled the exchange of Arctic with the North Atlantic. This could have resulted in a release of a large, built-up reservoir of DOC-rich water into the North Atlantic. The ACEX expedition was one of the most technically challenging among the over two hundred Legs completed in scientific ocean drilling. Nonetheless, the paleoceanographic record from the Lomonosov Ridge not only described much of the Arctic over Cenozoic time (Figure 7), but has also enhanced our understanding of the Arctic's role in the global climate system – knowledge that is of considerable significance today. Clearly, the missing climate record spanning ~26 Ma, including the entire Oligocene when major cooling of the planet occurred, is a high priority for future research. Recovering this record and others of higher time resolution from this basin will likely deliver rich paleoclimate reconstructions for further advancing our understanding of the complex global climate system.

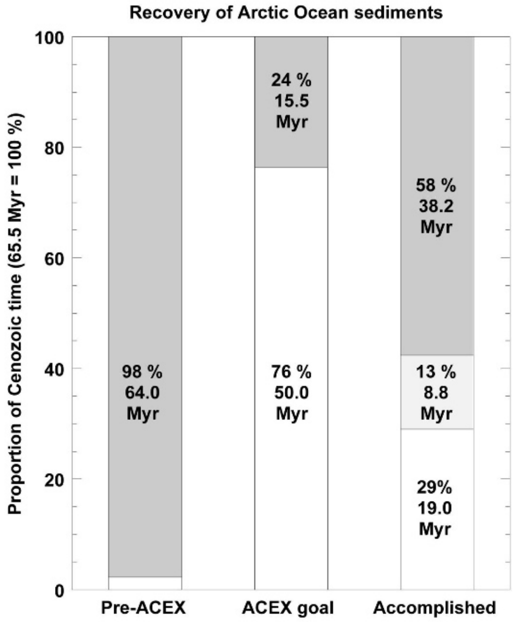

Figure 7. Columns showing cored and available Cenozoic sediments from the Arctic Ocean before ACEX (left column), with 2% of Cenozoic time represented in piston- and gravity cores. ACEX aimed (middle column) to recover 76% (50 Myr) of Cenozoic time. The presence of a regional unconformity below the sediment drape on the ridge crest was assumed to encompass the oldest 15.5 Myr (24.0%) of the Cenozoic Era [13, 17]. Right column shows the proportion of Cenozoic time represented in recovered ACEX sediments (29% or 19.0 Myr), the proportion of Cenozoic time lost (13% or 8.8 Myr) due to the fact that only 68% of the penetrated sediments were recovered, and the proportion of Cenozoic time lost (58% or 38.2 Myr) due to one expected and two unexpected hiatuses. The geological history of the Arctic Ocean hence remains unknown for over 2/3 of Cenozoic time.

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