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The Geoscience of Climate and Energy 3. The Cenozoic Arctic Ocean Climate

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INTRODUCTION

Throughout the Cenozoic, over the past 65 million years, Earth's climate system has experienced sometimes rapid and sometimes gradual change. This long-term climate change has induced a transition from a planet with no ice caps, glaciers or sea-ice, dubbed the 'greenhouse world' to today's 'icehouse world' of glacial and interglacial cycles.

It is well known that the climate is primarily forced by regular and predictable changes in Earth's orbital geometry and secondarily by long-term tectonic rearrangements of the continents, yet an explanation for the shift from the warm to the cold world is not yet known. What is clear is that the polar regions are critical cogs in the climate wheel, so they must have played a role in the switch from the 'greenhouse' to 'icehouse' world. For example, Earth's albedo (the percent of reflected solar radiation) can be classified as a major climate feedback mechanism, and polar ice has the highest albedo of any part of the planet. So, the establishment or destruction of ice at the poles can 'tip' the planet to a cooler or hotter place. Today, we are witnessing such a shift – the Arctic's permanent sea-ice rapidly melting.

The greenhouse/icehouse transition took millions of years, but a prominent overprint on the long-term cooling trend are extreme climate events, called hyperthermals, e.g. the Paleocene–Eocene Thermal Maximum (PETM) at ~55 Ma. Hyperthermals have been identified and studied with the purpose of advancing our knowledge of how the Earth system responds to large atmospheric, oceanographic, and/or external perturbations. Both the gradual paleoclimate evolution and the extreme events are captured in various archives located around the globe in ocean and lake sediments, ice sheets, caves, and reefs. The Earth is currently undergoing a climatic warming of unprecedented rapidity, and the understanding of the Earth's long-term climate trends and its response to past climatic extreme events has become increasingly important.

Zachos et al. (2001) reviewed the current state of knowledge of Cenozoic climate in a landmark paper that assembled the known (at that time) extreme events and integrated them with a robust compilation of proxy data from equatorial and mid-latitudes that describe the long-term changes throughout this era. This review has formed the framework upon which much of the recent Cenozoic paleoceanographic research has been based.

THE ARCTIC CORING EXPEDITION (ACEX)

Since 2001, much more has been added to the knowledge bank of Cenozoic climate. New extreme events have been discovered (e.g. Lourens et al. 2005), additional records were collected permitting some other extreme events to be better constrained in terms of amplitude and timing (Coxall et al. 2005), new techniques have been developed and employed for paleoclimate reconstructions (Jenkyns et al. 2004), much more has been learned about the little known Oligocene (Pälike et al. 2006), and significantly, the first Cenozoic-long climate record was recovered from the Arctic Ocean (Backman et al. 2006; Moran et al. 2006) during the Arctic Coring Expedition (ACEX).

In late summer 2004, the Integrated Ocean Drilling Program (IODP) initiated the ACEX (IODP Expedition 302; Backman et al. 2006; Moran et al. 2006), which recovered the first Cenozoic sediment record from the Lomonosov Ridge, Arctic Ocean (Figs. 1, 2). Previous Arctic paleoclimate records had been limited to the past ~1.5 Ma, but ACEX was able to extend this to ~57 Ma. The ACEX was one of the most transformational missions in the almost 40-year history of scientific ocean drilling. This technically challenging expedition recovered a unique, and somewhat surprising record, and the results have dramatically advanced our understanding of the Arctic's past climate, which has major implications for our ability to predict future climate.

The ACEX was accomplished by implementing a fundamentally new, multiple-vessel approach developed

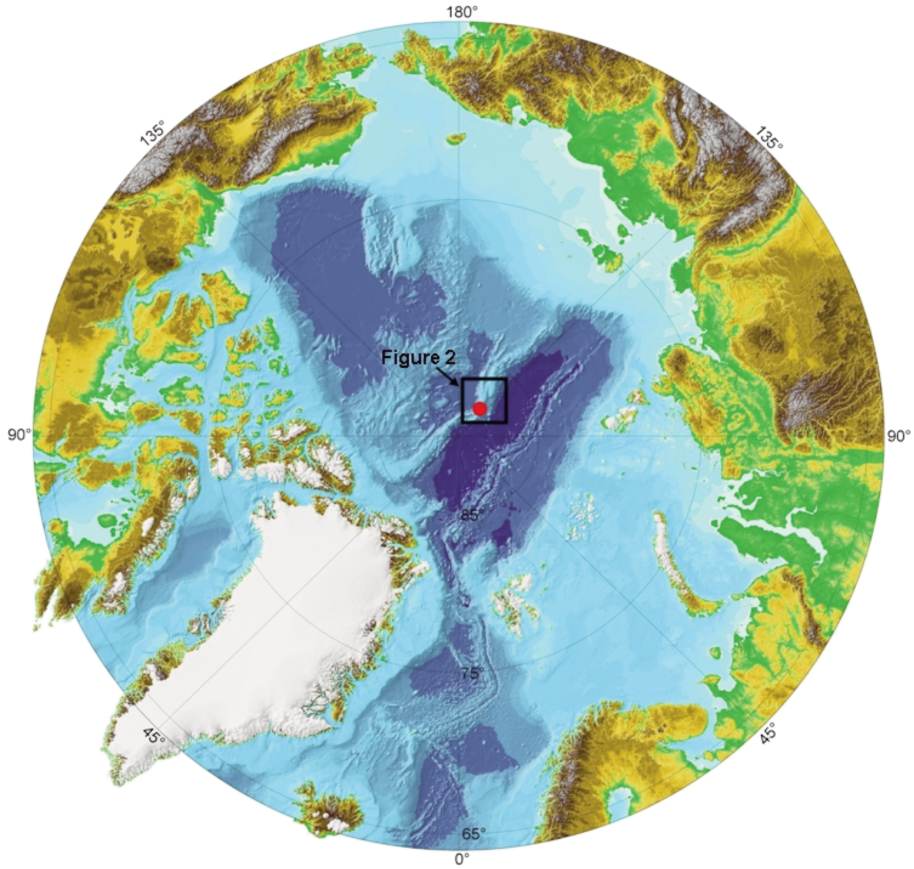

Figure 1. Map of the Arctic Ocean (International Bathymetric Chart of the Arctic Ocean – IBCAO) showing the location of the ACEX drill sites (red dot).

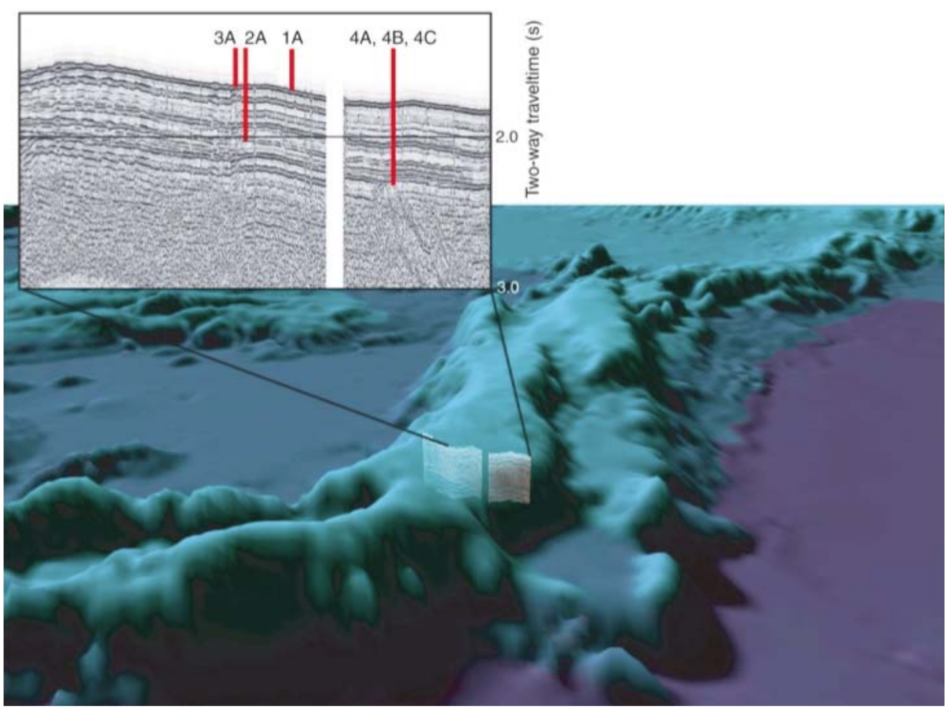

Figure 2. The Lomonosov Ridge shown as a three-dimensional seafloor surface generated from IBCAO data, with an overlay of the seismic reflection data used to select the sites. The seismic line is expanded in the upper left corner and the locations of the completed boreholes are shown.

under the auspices of the Ocean Drilling Program and the Integrated Ocean Drilling Program. This approach overcame the difficulty of maintaining position over a drill site and recovering sediments in waters that are blanketed in moving ice floes. The ACEX involved over 200 people, including scientists, technical staff, ice-breaker experts, ice-management experts, ships' crews, and educators.

Three icebreakers were used to complete ACEX (Fig. 3). The Swedish diesel-electric icebreaker *Vidar Viking* was converted into a drillship for this expedition by adding a geotechnical drilling system that was capable of suspending over 2000 m of drill pipe through the water column into the underlying sediments, and by creating a hole in the hull (moonpool) capable of accommodating the drilling system. The two other icebreakers, a Russian nuclear vessel, *Sovetskiy Soyuz*, and the Swedish diesel-electric *Oden*, protected Viking by circling 'upstream' in the flowing sea-ice, breaking the floes into smaller pieces that would not dislodge the drilling vessel more than a 75 m radius from its fixed position. Despite thick and pervasive ice cover, the fleet and ice management teams successfully enabled the drilling team to recover cores from four sites selected along the Lomonosov Ridge, in water depths ranging between 1100 to 1300 m. The ACEX recovered almost complete sediment cores from depths greater than 400 m below the seafloor.

The ACEX record held many scientific discoveries about the previously unknown past Arctic Ocean and its environments. Some discoveries are interpreted to be local to the Lomonosov Ridge, and others represent the broader Arctic Ocean. During the expedition, an initial scientific party of 19 grew to over 40; this group conducted analyses on the recovered core, carried out geophysical borehole logging, and collected seismic data (Fig. 4). These analyses are reported in six *Nature* papers and a special volume of *Paleoceanography* (Brinkhuis et al. 2006; Pagani et al. 2006; Sluijs et al. 2006; Jakobsson et al. 2007; Moran et al. 2006; Haley et al. 2008; Backman and Moran 2008).

The ACEX results describe three broadly defined past environmental settings (Backman and Moran 2009; Figs. 5, 6). These environmental settings do not include the entire Oligocene because of a long hiatus in the record. From oldest to youngest, these settings are: an Early Eocene warm environment that was overprinted by at least two hyperthermals; a mid-late Eocene fresh surface-water environment that culminated in surprising early cooling and carbon sequestration; and a well-oxygenated, sea-ice-covered Neogene environment.

EARLY EOCENE ARCTIC WARM ENVIRONMENT

Like other areas of the world's oceans, the Early Eocene Arctic Ocean was warm and the Lomonosov Ridge was a shallow-water environment. The ACEX identified the well-known PETM hyperthermal, analysis of which revealed high surface water temperatures (~24^{O}C) and an extremely wet climate, in contrast to the Arctic of today, which has a cold desert climate (Sluijs et al. 2006; Pagani et al. 2006). A second, younger, hyperthermal, the Eocene Thermal Maximum 2 (ETM2), was characterized by slightly lower surface water temperatures compared to the PETM (Sluijs et al. 2008).

These inferred high temperatures at a location close to the North Pole were surprising because modelled data suggest that temperatures should have been more than 10^{O}C cooler (Moran et al. 2006). The implication of this for the Anthropocene of today is that these results can be used to calibrate our models, which may then show that warming in the Arctic regions could be higher than previously predicted.

A MID-LATE EOCENE FRESH ENVIRONMENT

During the mid to Late Eocene, the Lomonosov Ridge remained in a shallow-water setting (O'Regan et al. 2008), but recorded salinities reflect a change from predominantly marine to predominantly fresh (surface water). This was documented by the abundant occurrence of the freshwater fern, *Azolla* (Brinkhuis et al. 2006), suggesting the former presence of a very large body of fresh water. Because the water column was highly stratified and therefore poorly oxygenated, the environment also fostered the sequestration of organic carbon and accumulation of carbon-rich sediment on the seafloor; these conditions are analogous to today's Black Sea. The source-rock potential (Stein et al. 2007) of the Eocene sediment is fair to good, but no *in situ* hydrocarbons were present because the ACEX sediments are immature.

Figure 3. Photograph of the ACEX ships taken from a helicopter. Ice is moving from top to bottom. The three ships from top are: *Sovetskiy Soyuz, Oden,* and *Vidar Viking*. Photo by M. Jakobsson.

At ~46 Ma, the sediment record surprisingly included ice-rafted debris, showing that sea-ice was present more than 30 Ma earlier than previously thought (Moran et al. 2006; St. John 2008). This timing also suggests that northern high-latitude cooling was synchronous with that in southern high latitudes. In turn, bi-polar cooling suggests that the mechanism for this shift is atmospheric, caused by reduced concentrations of greenhouse gases.

THE SEA-ICE-COVERED NEOGENE

During the Miocene, after 18 Ma, the Lomonosov Ridge began to rapidly subside (O'Regan et al. 2008). This occurred almost concurrently with the ventilation of the Arctic Ocean by the establishment of a deep-water connection to the North Atlantic through the Fram Strait (Jakobsson et al. 2007; Fig. 6). These tectonic events transformed the earlier, isolated Arctic Ocean into the Arctic Ocean of today, a well-oxygenated ocean covered in sea-ice. Several studies, using independent techniques, have shown that the Arctic Ocean's perennial sea-ice cover has been in existence since at least 13 Ma (St. John 2008; Krylov et al. 2008; Darby 2008). The longevity of this important polar feature, which contributes to keeping the climate cool by

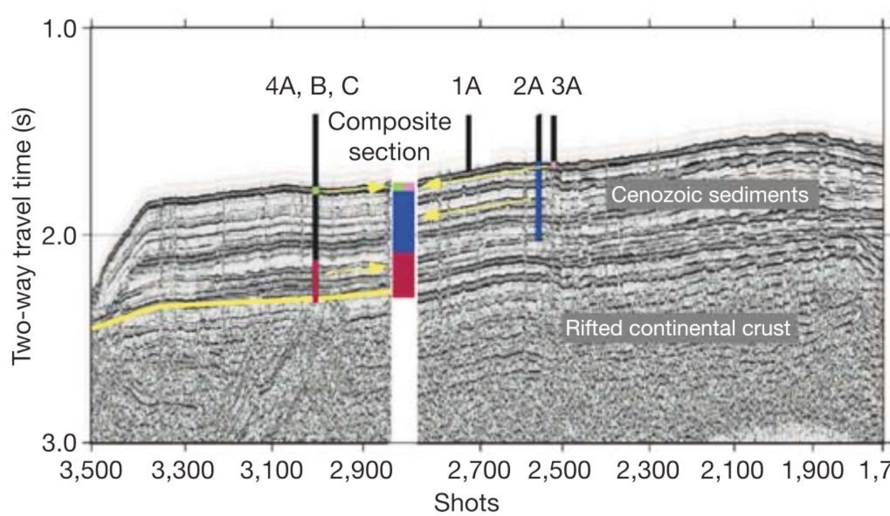

Figure 4. Seismic reflection line showing the ACEX drill sites and the composite section. Figure from Moran et al. (2006); seismic data from Jokat et al. (1992).

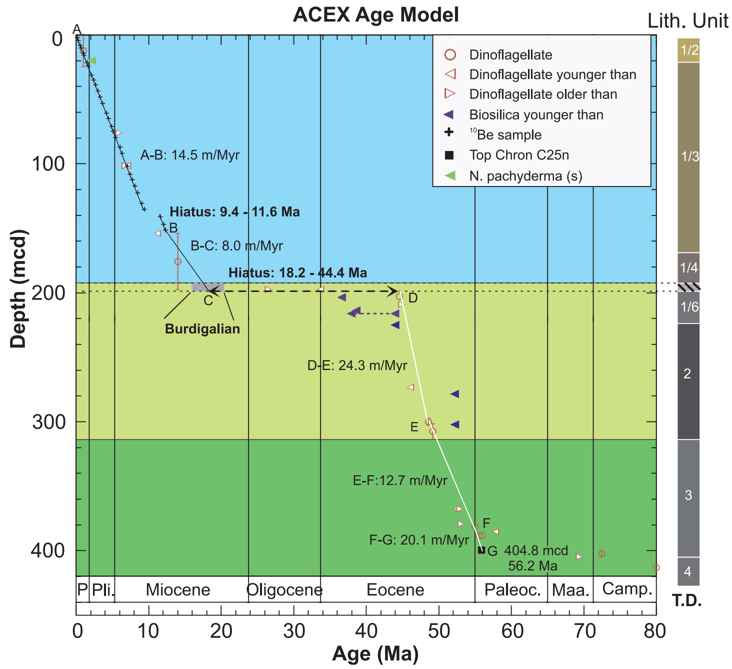

Figure 5. The ACEX age model, modified from Backman et al. (2008) Background colours depict 'greenhouse' and 'icehouse' worlds: the deeper green denotes the warm Arctic in the Early Eocene; the lighter green is the younger Eocene freshwater Arctic; and the blue represents the sea-ice-covered, cold Arctic. Lithologic units 1-4 are from Backman et al. (2006). mcd is metres composite depth. P: Pleistocene; Pli.: Pliocene; Paleoc.: Paleocene; Maa.: Maastrichtian; Camp.: Campanian.

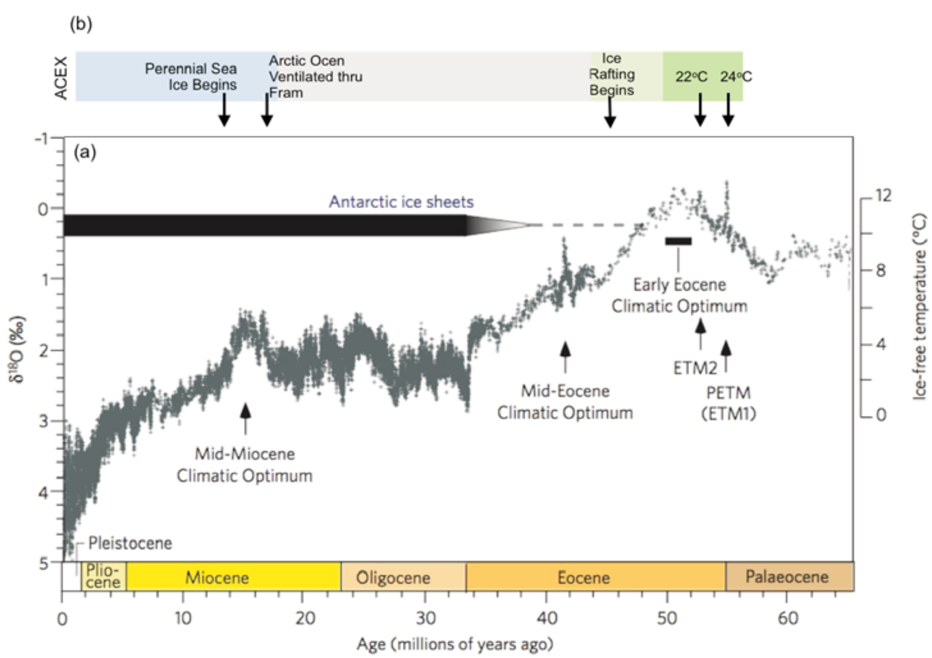

Figure 6. a) Oxygen isotope ratio global compilation (modified from Zachos et al. 2008) shown, with b) a summary of the ACEX results. In (b), light blue depicts the ventilated, sea-ice covered Arctic Ocean, grey depicts the long hiatus that occurred due to a prolonged stalling of Ridge subsidence (O'Regan et al. 2008), light green depicts a warm, freshwater Arctic, and the deeper green represents a warmer Eocene Arctic Ocean.

means of its high albedo, is in stark contrast to current predictions of the loss of summer sea-ice as early as ten years from now.

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