International Ocean Discovery Program
Expedition 377 Scientific Prospectus

Arctic Ocean Paleoceanography (ArcOP)

Toward a Continuous Cenozoic Record
from a Greenhouse to an Icehouse Earth

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DISCOVERY PROGRAM

Publisher's notes

This publication was prepared by the European Consortium for Ocean Research Drilling (ECORD) Science Operator (ESO) and Texas A&M University (TAMU) as an account of work performed under the International Ocean Discovery Program. Funding for IODP is provided by the following agencies:

National Science Foundation (NSF), United States
Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan
European Consortium for Ocean Research Drilling (ECORD)
Ministry of Science and Technology (MOST), People's Republic of China
Korea Institute of Geoscience and Mineral Resources (KIGAM)
Australia-Research Council (ARC) and New Zealand Institute for Geological and Nuclear Sciences (GNS), Australian/New Zealand Consortium
Ministry of Earth Sciences (MoES), India

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Citation

Stein, R., St. John, K., and Everest, J., 2021. *Expedition 377 Scientific Prospectus: Arctic Ocean Paleoceanography (ArcOP).* International Ocean Discovery Program. https://doi.org/10.14379/iodp.sp.377.2021

ISSN

World Wide Web: 2332-1385

Abstract

Prior to 2004, geological sampling in the Arctic Ocean was mainly restricted to near-surface Quaternary sediments. Thus, the long-term pre-Quaternary geological history is still poorly known. With the successful completion of the Arctic Coring Expedition (ACEX) (Integrated Ocean Drilling Program Expedition 302) in 2004, a new era in Arctic research began. Employing a novel multivessel approach, the first mission-specific platform (MSP) expedition of the Integrated Ocean Drilling Program proved that drilling in permanently ice-covered regions is possible. During ACEX, 428 m of Quaternary, Neogene, Paleogene, and Campanian sediment on Lomonosov Ridge were penetrated, providing new and unique insights into Cenozoic Arctic paleoceanographic and climate history. Although it was highly successful, ACEX also had three important limitations. The ACEX sequence contains either a large hiatus spanning the time interval from late Eocene to middle Miocene (based on the original biostratigraphic age model) or an interval of strongly reduced sedimentation rates (based on a more recent Os-Re-isotope-based age model). This is a critical time interval, spanning the time when prominent changes in global climate took place during the transition from the early Cenozoic Greenhouse Earth to the late Cenozoic Icehouse Earth. Furthermore, generally poor recovery during ACEX prevented detailed and continuous reconstruction of Cenozoic climate history. Finally, a higher-resolution reconstruction of Arctic rapid climate change during Neogene and Pleistocene times could not be achieved during ACEX. Therefore, Expedition 377 (Arctic Ocean Paleoceanography [ArcOP]) will return to the Lomonosov Ridge for a second MSP-type drilling campaign with the International Ocean Discovery Program to fill these major gaps in our knowledge on Arctic Ocean paleoenvironmental history through Cenozoic times and its relationship to global climate history.

The overall goal of this drilling campaign is to recover a complete stratigraphic sedimentary record of the southern Lomonosov Ridge to meet our highest priority paleoceanographic objective, the continuous long-term Cenozoic climate history of the central Arctic Ocean. Furthermore, sedimentation rates two to four times higher than those of ACEX permit higher-resolution studies of Arctic climate change. The expedition goal can be achieved through careful site selection, the use of appropriate drilling technology and ice management, and by applying multiproxy approaches to paleoceanographic, paleoclimatic, and age-model reconstructions. The expedition will complete one primary deep drill hole (proposed Site LR-11B) to 900 meters below seafloor (mbsf), supplemented by a short drill site (LR-10B) to 50 mbsf, to recover an undisturbed uppermost (Quaternary) sedimentary section. This plan should ensure complete recovery so scientists can construct a composite section that spans the full age range through the Cenozoic.

Schedule for Expedition 377

Expedition 377 is based on International Ocean Discovery Program (IODP) drilling Proposal 708-Full and Addenda 708-Add, 708-Add2, 708-Add3, and 708-Add4. Following ranking by the IODP Science Advisory Structure, the expedition was scheduled by the European Consortium for Ocean Research Drilling (ECORD) Facility Board as a mission-specific platform expedition, to be jointly implemented by the ECORD Science Operator (ESO), the Swedish Polar Research Secretariat, and Arctic Marine Solutions. The expedition is scheduled for August–October 2022, with an estimated 50 days available for the drilling, coring, and downhole measurements described in this report and on the ESO Expedition 377 web page. The onshore science party (OSP) in Bremen, Germany, is provisionally scheduled for either November–December 2022 or January–February 2023 (exact dates to be confirmed) and lasts for a maximum of 4 weeks (dependent on core recovery).

The following links should be used in conjunction with this *Scientific Prospectus*:

- The Expedition 377 web page will be periodically updated with expedition-specific information on the platform, facilities, coring strategy, measurements plan, and schedule. The full proposal and addenda can be accessed via this page: **http://www.ecord.org/expedition377**.
- General details about the offshore facilities provided by ESO are provided on the ESO-specific web pages on the MARUM Center for Marine Environmental Sciences website: **http://www.marum.de/en/Offshore_core_curation_and_measurements.html**.
- General details about the onshore facilities provided by ESO are provided on the ESO-specific web pages on the MARUM website: **https://www.marum.de/en/Research/Onshore-Science-Party-OSP.html**.
- The supporting site survey data for Expedition 377 are archived in the IODP Site Survey Data Bank. Please note that not all site survey data associated with this expedition are publicly available: **http://ssdb.iodp.org**.

Introduction

A major element in the global climate evolution during Cenozoic times was the transformation from warm Paleogene oceans with low latitudinal and bathymetric thermal gradients to the more recent modes of circulation characterized by strong thermal gradients, oceanic fronts, cold deep oceans, and cold high-latitude surface waters (e.g., Miller et al., 1987; Zachos et al., 2001, 2008; McKay et al., 2019). Throughout the Cenozoic, the climate on Earth changed from one extreme (Paleogene Greenhouse lacking major ice sheets) to another (Neogene Icehouse with bipolar glaciation).

A strong greenhouse effect probably contributed to global warmth during the early Cenozoic. CO_2 concentrations of up to around 2000 ppm have been estimated for the late Paleocene and earliest Eocene periods (Figure **F1**) (Pearson and Palmer, 2000; Pagani et al., 2005; Lowenstein and Demicco, 2006; Royer, 2006; Zachos et al., 2008; Kent and Muttoni, 2013; Masson-Delmotte et al., 2013). Bottom temperatures in the early Eocene, the time of maximum Cenozoic warmth that peaked at the Paleocene/Eocene Thermal Maximum (about 55.8 Ma) and the Early Eocene Climatic Optimum (about 52–50 Ma), were of the order of 12°–14°C, and large-scale continental ice sheets were probably absent (Figure **F1**) (Miller et al., 1987; Lear et al., 2000; Pearson and Palmer, 2000; Zachos et al., 2008; Expedition 318 Scientists, 2010; McKay et al., 2019). The climate in lowland settings along the Wilkes Land coast of Antarctica, for example, supported the growth of highly diverse, near-tropical forests characterized by mesothermal to megathermal floral elements (Pross et al., 2012). Based on stable isotope data of fossil mollusk shells from Ellesmere Island and Alaska, Paleocene temperatures of Arctic (80°N) coastal waters of about 10° to 22°C were reconstructed (Bice et al., 1996; Tripati et al., 2001).

The long-term history of Cenozoic high-latitude cooling starting at about 48 Ma is characterized by four major steps: in the early mid-Eocene (about 48–45 Ma), at the Eocene/Oligocene boundary (near 34 Ma), in the mid-Miocene (at about 15 Ma), and in the late Pliocene (at about 3.5–2.6 Ma) (Figure **F1**) (Miller et al., 1987; Zachos et al., 1994, 2001; Lear et al., 2000; McKay et al., 2019). Reconstructions of past atmospheric CO_2 concentrations show—although with obvious differences in absolute values—distinct drops in atmospheric CO_2 between about 50 and 25 Ma (Kent and Muttoni, 2013; Masson-Delmotte et al., 2013; Zhang et al., 2013) that generally correspond to the global cooling trend and development of major polar ice sheets except for the interval around the early mid-Eocene cooling (Figure **F1**).

On Antarctica, large ice sheets likely first appeared near the Eocene/Oligocene boundary at about 34 Ma ("Oi-1 glaciation;" e.g., Shackleton and Kennett, 1975; Kennett and Shackleton, 1976; Miller et al., 1987, 1991; Lear et al., 2000; Zachos et al., 2008), coincident with decreasing atmospheric CO_2 concentrations and deepening of the calcite compensation depth in the world's oceans (van Andel, 1975; Pearson and Palmer, 2000; Coxall et al., 2005; Tripati et al., 2005). For the Northern Hemisphere, on the other hand, it was indirectly inferred from sub-Arctic ice-rafted debris (IRD) records in the Norwegian-Greenland, Iceland, and Irminger Seas and Fram Strait area that glaciations began much later (i.e., in the middle Miocene as early as about 14 Ma; e.g., Fronval and Jansen, 1996; Wright and Miller, 1996; Thiede et al., 1998, 2011; St. John and Krissek, 2002). Based on more recent modeling results as well as new IODP sediment core data, however, this general picture needs to be revised significantly (see below).

Although it is generally accepted that the Arctic Ocean is a very sensitive and important region for global climate change (Houghton et al., 1996; Solomon et al., 2007; Serreze et al., 2000; ACIA, 2004, 2005), this region is the last major physiographic province on Earth where the short- and long-term geological history is still poorly known (Figure **F2**). Our ignorance is due to the major technological/logistical problems in operating in the permanently ice-covered Arctic region, which makes it difficult to retrieve long, undisturbed sediment cores. Prior to 1990, the available samples and geological data from the central Arctic Basins were derived mainly from drifting ice islands such as T-3 (e.g., Clark et al., 1980) and CESAR (Jackson et al., 1985). During the last ~30 years, several international expeditions, including Polarstern/Oden 1991 (Fütterer, 1992), Louis St. Laurent/Polar Sea 1994 (Wheeler, 1997), Healy/Polarstern 2001 (Thiede, 2002), Healy/Oden 2005 ("HOTRAX;" Darby et al., 2005), Oden 2007 ("LOMROG" 2007; Jakobsson et al., 2008b), Polarstern 2008 (Jokat, 2009), Oden 2014 (The SWERUS Scientific Party, 2016), and Polarstern 2014 and 2018 (Stein, 2015, 2019a), have greatly advanced our knowledge of the central Arctic Ocean paleoenvironment and its variability through Quaternary times. Prior to 2004, however, in the central Arctic Ocean, piston and gravity coring was mainly restricted to obtaining near-surface sediments, (i.e., only the upper 15 m could be sampled). Thus, all studies were restricted to the late Pliocene/Quaternary time interval, with a few exceptions. These exceptions include the four short cores obtained by gravity coring from drifting ice floes over Alpha Ridge, where older pre-Neogene organic carbon–rich muds and laminated biosiliceous oozes were sampled. These were the only samples recording the Late Cretaceous/early Cenozoic climate history and depositional environment (e.g., Jackson et al., 1985; Clark et al., 1986; Firth and Clark, 1998; Jenkyns et al., 2004; Davies et al., 2009, 2011). In general, these data suggested a warmer (ice-free) Arctic Ocean with strong seasonality and high paleoproductivity, most likely associated with upwelling conditions.

With the successful completion of the Arctic Coring Expedition (ACEX) (International Ocean Drilling Program Expedition 302, the program's first mission-specific platform [MSP] expedition) in 2004, a new era in Arctic research began. For the first time, scientific drilling in the permanently ice-covered central Arctic Ocean was carried out, penetrating 428 m of Quaternary, Neogene, Paleogene, and Campanian sediment (Figure **F3**) on the crest of Lomonosov Ridge between 87° and 88°N (Expedition 302 Scientists, 2006; Backman et al., 2008; Moran et al., 2006; Backman and Moran, 2008, 2009). This record provided a unique glimpse of the early Arctic Ocean history and its long-term change through Cenozoic time. To date, the ACEX sites remain the only drill holes in the central Arctic Ocean (Figure **F2**).

Although the expedition was highly successful, the ACEX record also has three important limitations. Based on the original age model (Backman et al., 2008), the ACEX sequence contains a large hiatus spanning the time interval from late Eocene to middle Miocene (44.4–18.2 Ma) and encompassing nearly 45% of the Cenozoic history of Lomonosov Ridge (Figure **F3**). This is a critical time interval because it spans the time when prominent changes in global climate took place during the transition from the early Cenozoic Greenhouse Earth to the late Cenozoic Icehouse Earth (Figure **F1**). Furthermore, generally poor recovery prevented detailed and continuous reconstruction of Cenozoic climate history. Finally, the second overall paleoceanographic objective of the original ACEX program, the high-resolution reconstruction of Arctic rapid climate change during Neogene to Pleistocene time, could not be reached because drilling on the southern Lomonosov Ridge was not carried out due to limited drilling time. A return to Lomonosov Ridge for a second MSP-type drilling campaign during IODP to fill these major gaps in our knowledge on Arctic Ocean paleoenvironmental history through Cenozoic times and its relationship to the global climate history is therefore timely.

The scientific value of ArcOP is expected to be significant. The polar regions are changing rapidly in response to global warming, and calibration of global climate models requires data on past conditions (Figures **F1**, **F4**). Currently, the understanding of deep time climate evolution in the central Arctic Ocean is based only on cores collected during ACEX in 2004, and the record they provide is not complete. Expedition 377 aims to fill this gap with a more continuous and higher resolution (two to four times the sedimentation rate of ACEX) record. Obtaining a geologic record of a 50–60 million year time span will provide opportunities to examine trends, patterns, rates, causes, and consequences of climate change that are important and relevant to our future.

Background

Modern environment and geological setting of the Arctic Ocean

The Arctic Ocean is unique in comparison to the other world oceans. It is surrounded by the world's largest shelf seas, is seasonally to permanently covered by sea ice, and is characterized by large, very seasonal river discharge equivalent to 10% of global runoff (Aagaard and Carmack, 1989; Holmes et al., 2002; Jakobsson, 2002; for review, see Stein, 2008). The freshwater supply is essential for the maintenance of the ~200 m thick low-salinity layer of the central Arctic Ocean and thus contributes significantly to the strong stratification of the near-surface water masses, encouraging sea ice formation. The melting and freezing of sea ice result in distinct changes in surface albedo, energy balance, and biological processes.

Freshwater and sea ice are exported from the Arctic Ocean through the Fram Strait into the North Atlantic Ocean. Changes in these export rates of freshwater would result in changes of North Atlantic and global oceanic circulation patterns. Because factors such as the global thermohaline circulation, sea ice cover, and Earth's albedo have a strong influence on the earth's climate system, climate change in the Arctic could cause major perturbations in the global environment.

As a result of complex feedback processes (collectively known as "polar amplification"), the Arctic is both the harbinger of change and the region that will be most affected by global warming. The need for further scientific drilling in the Arctic is motivated in part by climate change models predicting the greatest future temperature changes in polar regions and because polar systems may be particularly sensitive to change now and in the past (e.g., Houghton et al., 1996; Solomon et al., 2007; Intergovernmental Panel on Climate Change, 2014; Meredith et al., in press). There is a general consensus that the polar regions—and especially the Arctic Ocean and surrounding areas—are (in real time) and were (over historic and geologic time scales) subject to rapid and dramatic change. Over the last decades, for example, the extent and thickness of Arctic sea ice has decreased dramatically, and this decrease seems to be much more rapid than predicted by climate models (Figure **F4**) (e.g., Johannessen et al., 2004; ACIA, 2004, 2005; Francis et al., 2005; Serreze et al., 2007; Stroeve et al., 2007, 2011; Notz and Stroeve, 2018). On geological time scales, on the other hand, the Arctic Ocean has undergone profound long-term paleoclimatic changes over millions of years and evolved from a warm and ice-free epicontinental sea in the Cretaceous and early Cenozoic to its late Neogene–Quaternary state as a cold, isolated ocean with extensive seasonal to perennial sea ice cover (see syntheses by O'Regan et al., 2011 and Stein, 2019b).

To study Cenozoic climate evolution, we need to obtain undisturbed and complete sedimentary sequences. Scientific reasoning and seismic evidence indicate that such sequences in the Arctic Ocean occur on isolated ridges such as the Lomonosov Ridge. The elevation of the ridge, ~3 km above the surrounding abyssal plains, indicates that the sediments it supports are isolated from turbidites and are likely of purely pelagic origin (i.e., mainly biogenic, eolian, and/or ice-rafted), an observation borne out by countless shorter cores collected from icebreakers in the past decades and by previous drilling during ACEX. After Heezen and Ewing (1961) recognized that the mid-ocean rift system extended from the North Atlantic into the Arctic Ocean, it was realized that the 1800 km long Lomonosov Ridge was originally a continental fragment that had broken from the Eurasian continental margin and subsequently separated from it by seafloor spreading. Regional aeromagnetic data indicated the presence of seafloor spreading anomalies in the basins north and south of Gakkel Ridge, the active spreading center located in the middle of the Eurasian Basin (Kristoffersen, 1990, and references therein). The interpretation of the magnetic anomalies in terms of seafloor spreading and their correlation with the geomagnetic time scale allowed linking the evolution of the Eurasian Basin to the opening of the Norwegian-Greenland Sea. According to this correlation, seafloor spreading was probably initiated in the Eurasian Basin between Chron 24 and Chron 25 in the late Paleocene near 56 Ma (e.g., Kristoffersen, 1990). As the Lomonosov Ridge moved away from the Eurasian plate and subsided, pelagic sedimentation on top of this continental sliver began.

Scientific objectives

Primary objectives

Although the Arctic paleoceanographic and paleoclimatic results from ACEX were unprecedented, key questions related to the climate history of the Arctic Ocean on its course from Greenhouse to Icehouse conditions during early Cenozoic times remain, due largely to the major mid-Cenozoic hiatus and partly to low recovery of the ACEX record. In addition to elevated atmospheric CO_2 concentrations in the Cenozoic, other boundary conditions such as the freshwater budget, exchange between the Arctic and Pacific/Atlantic Oceans, and the advance and retreat of major circum-Arctic ice sheets changed dramatically during the late Cenozoic. An understanding of how these boundary conditions influenced the form, intensity, and permanence of the Arctic sea ice cover can help improve our understanding of the complex modern ocean-atmosphere-ice system and how it has evolved with the global climate (Polyak et al., 2010; O'Regan et al., 2011; Stein, 2019b). Therefore, the primary objectives of ArcOP share several of those in the original 533-Full3 (ACEX) proposal and also build on what we learned from ACEX.

1. *Scientific (Key) Objective 1: A complete characterization of the Cenozoic transition from Greenhouse to Icehouse in the Arctic.*

The Cenozoic transition of the Earth's climate from one extreme (Paleogene Greenhouse lacking ice) to another (Neogene Icehouse with bipolar glaciation characterized by an Antarctic continental ice cap and seasonally variable but persistent sea ice cover in the Arctic) is linked to increased latitudinal gradients and oceanographic changes that connected surface and deep-sea circulation between high- and low-latitude oceans. The general Cenozoic cooling trend, however, is interrupted by warming intervals, such as the late Oligocene warming and the Mid-Miocene Climatic Optimum, and short-term extreme cooling transients, such as the Oi-1 glaciation and the Mi-1 glaciation (Figure **F1**) (Zachos et al., 2001, 2008; Coxall et al., 2005; Tripati et al., 2005).

Some of the related key questions for this objective are the following: Did the Arctic Ocean climate follow the global trend shown in Figure **F1**? Are the Early Eocene Climatic Optimum (poorly recovered in the ACEX record) and the Oligocene and mid-Miocene warming periods also reflected in Arctic Ocean records? Did extensive glaciations develop synchronously in both the Northern and Southern Hemispheres? Are the Oi-1 and Mi-1 glaciations bipolar (Figure **F1**) (Zachos et al., 2001, 2008) (i.e., are there indications for major Northern Hemisphere glaciations [NHGs] at that time)? The proposed sites for this expedition are much closer than the ACEX sites to the Siberian shelf and thus should contain clearer signals of past (Siberian) ice sheets if such sheets existed (Figure **F5**). What are the related scale and timing of short- and long-term sea level changes? Does the mineralogical signature of sediments reveal changing source areas for Cenozoic glaciations as was demonstrated in existing late Pliocene/Pleistocene records from Ocean Drilling Program (ODP) Leg 151 (Matthiessen et al., 2006)?

In addition, based on records of sediment and foraminiferal geochemistry, Tripati et al. (2005) report evidence of synchronous deepening and subsequent oscillations in the calcite compensation depth in the tropical Pacific and South Atlantic Oceans from 42 Ma, with a permanent deepening at 34 Ma, coinciding with changes in seawater oxygen isotope ratios. They suggest lowering of global sea level through significant storage of ice in both hemispheres by at least 100 to 125 m. This hypothesis (not proved yet; cf., Edgar et al., 2007) (i.e., the occurrence and variability of NHGs during this time span) will be tested by this expedition. It is generally accepted that during the major Pleistocene glaciations huge ice sheets occupied western Eurasia, Greenland, and North America and terminated at their continental margins (e.g., Svendsen et al., 2004; Ehlers and Gibbard, 2007; Jakobsson et al., 2014; Batchelor et al., 2019). The exposed continental shelves in the Beringian region of Siberia, on the other hand, are thought to have been covered by a tundra landscape; large ice sheets did not exist at that time (Alekseev, 1997; Gualtieri et al., 2005). Based on detailed multibeam swath sonar system data, sediment echosounding, and multichannel seismic reflection profiling along the East Siberian continental margin, Niessen et al. (2013) postulated that huge, kilometer-thick marine ice sheets occurred repeatedly off the coast of Siberia during Pleistocene glacial intervals (Figure **F5**) and possibly since the Pliocene (Hegewald and Jokat, 2013). Based on new evidence of ice-shelf groundings on bathymetric highs in the central Arctic Ocean, Jakobsson et al. (2016) proposed that an extended thick ice shelf covered the entire central Arctic Ocean (Figure **F5**) and dated it to Marine Isotope Stage (MIS) 6 (~140 ka). The existence of such huge ice sheets and ice shelves must have significantly influenced Earth albedo and oceanic and atmospheric circulation patterns, which is not considered in climate models to date (Niessen et al., 2013). To test this hypothesis, however, long, complete, undisturbed, and well-dated sedimentary sections are needed. These sequences are planned to be recovered from the southern Lomonosov Ridge during the ArcOP drilling campaign (Figure **F5**).

Even after several studies on ACEX material, the variability of sea ice in terms of frequency, extent, and magnitude remains a pressing scientific question. Specifically, there remains considerable debate concerning the onset and subsequent persistence of perennial sea ice cover. Based on Fe oxide and heavy-mineral data, Darby (2008) and Krylov et al. (2008) proposed that a perennial sea ice cover was predominant in the central Arctic Ocean since the middle Miocene. Matthiessen et al. (2009), on the other hand, stated that the co-occurrence of *Nematosphaeropsis* spp. and *Impagidinium* spp. found in the Neogene part of the ACEX sequence points to seasonally open waters. Open-water conditions during Arctic summers in late Miocene times is also supported by biomarker records obtained from a *Polarstern* sediment core recovered close to the ArcOP area on the southern Lomonosov Ridge (Stein et al., 2016). How can these discrepancies be explained? New complete sedimentary sections from Lomonosov Ridge may support or disprove the different hypotheses of onset, extent, and variability of Arctic sea ice cover.

2. *Scientific Objective 2: History of Arctic bottom and surface water circulation.*

Black biosiliceous silty clays and clayey silts rich in organic carbon were found throughout the upper lower to middle Eocene section of the ACEX record, indicating poorly ventilated bottom waters and high but variable primary production (Stein et al., 2006; Jakobsson et al., 2007a). Important questions to address include the following: When and how did the change to oxygenated bottom waters typical for the Neogene and Quaternary Arctic Ocean occur? Was it in the early mid-Miocene as proposed by Jakobsson et al. (2007a) or the late Eocene as proposed by Poirier and Hillaire-Marcel (2011)? What are the implications for the gateway configurations of the Arctic and its connection to the Earth's oceans? How critical is the exchange of water masses between the Arctic Ocean and the Atlantic and Pacific Oceans for the long-term climate evolution as well as rapid climate change? High-resolution records of Neogene/Quaternary Arctic climate in comparison with similar records from the North Atlantic (ODP Leg 151 and Integrated Ocean Drilling Program Expeditions 303/306) and the Bering Sea (Integrated Ocean Drilling Program Expedition 323) may help to answer this question.

3. *Scientific Objective 3: History of Arctic (Lena) river discharge.*

The more proximal location of the proposed sites in ArcOP to the Siberian margin allows a detailed study of the history of Arctic river discharge and its paleoenvironmental significance. In this context, the Pliocene closure of the Isthmus of Panama and/or the Neogene uplift of the Tibetan and Mongolian Plateaus are of particular interest. These plate tectonic processes might have triggered enhanced discharge rates of Siberian rivers and changed the freshwater balance of the Arctic's surface waters. This balance was a key factor in the formation of Arctic sea ice and onset of major glaciations (Figure **F6**) (Driscoll and Haug, 1998; Wang, 2004), a hypothesis to be tested by drilling.

Furthermore, a record of the Siberian river discharge might give important insight into the evolution of continental climate in the hinterland through Miocene/Pliocene times. Key questions to be addressed include the following: What is the history of Siberian river discharge and how critical is it for sea ice formation, water mass circulation, and climate change? What does the mineralogical signature of river-transported sediments reveal about past changes in continental climate and weathering conditions?

4. *Scientific Objective 4: High-resolution characterization of the Pliocene warm period in the Arctic.*

During the Pliocene warm period, sea surface temperature in several ocean basins was substantially warmer (Marlow et al., 2000; Haywood et al., 2005; Lawrence et al., 2006) and global mean surface temperature was estimated to be at least ~3°C higher than today (Haywood and Valdes, 2004). Furthermore, cooling in the surface ocean seems to have started at least 1 My before intensification of NHG as shown, for example, in the eastern equatorial Pacific (EEP), implying that while the growth of Northern Hemisphere ice sheets undoubtedly played a major role as climatic feedback during the Pliocene–Pleistocene Transition, it did not force or initiate EEP cooling (Lawrence et al., 2006). Key questions still to be answered include the following: How did the Arctic Ocean evolve during the Pliocene warm period and succeeding cooling? How do the marine climate records correlate with terrestrial records obtained from Siberian Lake Elgygytgyn, which contains a continuous sedimentary sequence of Arctic continental climate since the mid-Pliocene (Melles et al., 2012; Brigham-Grette et al., 2013)?

5. *Scientific Objective 5: Resolution of the "hiatus problem."*

One of the unexpected discoveries of ACEX was a major hiatus spanning the late Eocene to early Miocene in the ACEX record (based on the original age model of Backman et al., 2008). Unresolved questions include the following: What is the cause of the major hiatus? Does this hiatus in fact exist or is it rather an interval of extremely reduced sedimentation rate as proposed by Poirier and Hillaire-Marcel (2009, 2011)? If there is a major hiatus, is it related to the subsidence history of Lomonosov Ridge? Was there a phase of uplift and exposure of the ridge in the Oligocene, tentatively linked to a transpressional/compressional episode in the formation of the Amundsen Basin caused in part by the northward motion of Greenland in the Paleogene (Brozena et al., 2003; O'Regan et al., 2008)? Was the hiatus a response to increased bottom water currents during the opening of surface and deepwater connections via the Fram Strait (Moore et al., 2006)? Recovery of the complete mid-Cenozoic interval can be used to test these hypotheses.

Previous drilling

Prior to ACEX, information on the long-term evolution of the paleoenvironmental Arctic Ocean history, especially the onset and variability of NHGs, was restricted to the sub-Arctic region. For example, ODP Legs 151 (see Figure **F2** for site locations) and 152 recovered a series of Neogene pulses of ice rafting (14 Ma, 10.8–8.6 Ma, 7.2–6.8 Ma, 6.3–5.5 Ma, and in sediments younger than 5 Ma) in the North Atlantic and Yermak Plateau regions (Larsen et al., 1994; Thiede et al., 2011). However, it is not clear whether these reflect local Svalbard and Greenland ice expansion or whether the events can be correlated with processes in the central Arctic Ocean.

ACEX was an outstanding success for two reasons. First, the biggest technical challenge was to maintain the drillship's location while drilling and coring in heavy sea ice over Lomonosov Ridge. ACEX proved that with an intensive ice management strategy—(i.e., a three-ship approach with two powerful icebreakers [*Sovetskiy Soyuz* and *Oden*] protecting the drillship [*Vidar Viking*] by breaking upstream ice floes into small pieces) successful scientific drilling in the permanently ice-covered central Arctic Ocean is possible. The icebreakers kept the drillship on location in 90% cover of multiyear ice for up to nine consecutive days, a benchmark feat for future drilling in this harsh environment. Second, the first scientific results comprise a milestone in Arctic Ocean research, and future results of ongoing studies on ACEX material will certainly bring new insights into the Arctic Ocean climate history and its global significance (for review and a comprehensive list of references for ACEX studies, see Stein et al., 2014). Some of these highlights follow.

- The Arctic Ocean surface water temperatures reached peak values around 25°C during the Paleocene/Eocene Thermal Maximum event (Sluijs et al., 2006, 2008) and at the end of the Early Eocene Climatic Optimum (EECO) (Weller and Stein, 2008; Stein et al., 2014). This temperature is notably higher than previous estimates of 10°–15°C (Tripati et al., 2001) and indicates an even lower Equator-to-pole temperature gradient than previously believed (Sluijs et al., 2006). In the middle Eocene, following the EECO, a strong stepwise drop in Arctic sea surface temperature by about 15°C occurred (Figure **F7**) contemporaneously with the onset/increase of Arctic sea ice as reflected in sea ice diatoms and IRD (St. John, 2008; Stickley et al., 2009, 2012; Stein et al., 2014).
- Near 49 Ma, a major occurrence of the freshwater fern *Azolla* and accompanying abundant freshwater organic-walled and siliceous microfossils indicate episodic freshening of Arctic surface waters with cooler temperatures of about 10°C during an 800,000-year interval. Although a deepwater connection did not exist between the Arctic Ocean Basin and the other oceans at this time, the presence of freshwater in the Arctic may have triggered the initiation of sea ice formation that increased albedo and contributed to global cooling (Brinkhuis et al., 2006; Moran et al., 2006).
- Previous studies suggest that NHG began no earlier than about 14 Ma (e.g., Thiede et al., 1998; Winkler et al., 2002), whereas glaciation of Antarctica began much earlier, as early as about 43 Ma (Lear et al., 2000). ACEX results from sea ice diatom and IRD data push back the date of Northern Hemisphere cooling and the onset of sea ice into the Eocene as well (Stickley et al., 2009). The first occurrence of sea ice–related diatoms, which happened contemporaneously with IRD, was at about 47–46 Ma (using the original ACEX age model of Backman et al., 2008) or ~43 Ma (using the alternate chronology of Poirier and Hillaire-Marcel, 2011) (Figures **F3**, **F8**). Iceberg transport, however, was probably also present in the middle Eocene, as indicated by mechanical surface texture features on quartz grains from this interval (St. John, 2008). An early onset/intensification of NHGs during Eocene times is also supported by IRD records from the Greenland Basin ODP Site 913 (Eldrett et al., 2007; Tripati et al., 2008; Tripati and Darby, 2018). These findings suggest that the Earth's transition from the Greenhouse to the Icehouse Earth was bipolar, which points to greater control of global cooling linked to changes in greenhouse gases in contrast to tectonic forcing (Backman et al., 2008; Expedition 302 Scientists, 2006; Moran et al., 2006; Stickley et al., 2009).
- One of the most profound changes in the character of sedimentation in the ACEX record was the mid-Cenozoic shift from freshwater-influenced biosilica- and organic carbon–rich deposits of a poorly ventilated and isolated Eocene ocean to fossil- and organic carbon–poor glaciomarine silty clays of a well-ventilated Miocene ocean (Figure **F9**) (Moran et al., 2006; Stein et al., 2006; Stein, 2007). Based on the original ACEX age model (Backman et al., 2008), the transition between these two modes of sedimentation is obscured by a large hiatus spanning the time interval from late Eocene to middle Miocene (44.4–18.2 Ma) (Figure **F3**). This change from euxinic to well-oxygenated open marine conditions was correlated to the tectonically controlled widening of the Fram Strait in the late early Miocene (~17.5 Ma), which allowed a critical two-way surface exchange between the Arctic Ocean and Norwegian Greenland Seas to commence (Jakobsson et al., 2007a). The recent Os-Re isotope dates from the cross-banded and underlying Eocene-age biosiliceous-rich sediments, however, suggest that the transition from euxinic to well-oxygenated conditions may have occurred much earlier, already in the late Eocene/early Oligocene (Poirier and Hillaire-Marcel, 2009, 2011).
- Dating Arctic Ocean sediments is a classic problem in stratigraphy. However, ACEX proved that with a combination of existing techniques such as micropaleontology, Be isotopes, cyclostratigraphy, and magnetostratigraphy, a stratigraphic framework adequate to answer the key scientific questions could be established for the Cenozoic time interval (Backman et al., 2008; Frank et al., 2008) (Figure **F3**). ACEX results did also once and for all confirm that there are, at least in this part of the Arctic, centimeter-scale rather than millimeter-scale sedimentation rates, which has implications for all paleoceanographic reconstructions based on sediment cores. A large mid-Cenozoic hiatus recognized in the original ACEX age model, however, was recently challenged by osmium isotope dates that suggest very low sedimentation rates (Poirier and Hillaire-Marcel, 2009, 2011) (Figure **F3**). The development of a multiproxy-based age model across a more expanded/continuous Eocene through Miocene section will be a major outcome of the proposed ArcOP program. Furthermore, dating of Pliocene and Quaternary age sediments was also problematic in ACEX because of poor overlapping recovery. In ArcOP, the selection of sites in areas with higher surface water productivity (i.e., in the marginal ice zone), higher-resolution records, and complete and overlapping recov-

ery in multiple holes will provide a more robust framework for developing a Quaternary–Pliocene age model.

During the research vessel *Polarstern* Expedition ARK-XI/1 in 1995 (Rachor, 1997), 10 gravity cores were recovered on a transect across Lomonosov Ridge very close to the proposed ArcOP primary sites (Figure **F10**). Main lithologies of these <8 m long sediment cores are brown, beige, gray to dark gray, and olive-green partly bioturbated or laminated silty clays probably representing MISs 6 to 1 (Figure **F10**) (Stein et al., 1997, 2001). Several sediment cores representing very similar lithologies that can be correlated by color scanning, and physical property records were recovered during *Polarstern* expeditions in 2014 and 2019 (Stein, 2015, 2019a). The dark gray lithologies in the lower part of the more eastern cores (MIS 6) are characterized by increased organic carbon contents of >1% (Stein et al., 2001; Stein, 2008). Sand-sized material is more or less absent in these sequences. For Cores PS2757 and PS2761, a huge amount of sedimentological, geochemical, and mineralogical data (e.g., grain-size distributions; heavy, bulk, and clay mineralogy; organic carbon composition; biomarker data including IP25 as sea ice proxy; multisensor core logging (MSCL) data; paleomagnetism) are available and are successfully used for reconstruction of past glaciations, oceanic circulation patterns, and depositional environments during the late Quaternary time interval (e.g., Behrends, 1999; Müller, 1999; Stein et al., 2001, 2012; Stein., 2008). Mean sedimentation rates vary between 3.5 and 6 cm/ky. Therefore, these are values very similar to those estimated for the proposed ArcOP drill sites.

Proposed drilling

Because the drill sites are located in the ice-covered Arctic Ocean, an MSP is needed for the drilling operation. Ice conditions of ArcOP are expected to be significantly less severe but potentially more variable than those of the ACEX work area of 2004, given records of sea ice cover in recent years. The ArcOP primary site was on average more than 70 km from the ice edge in September 2007, 2014, 2019, and 2020 (Fetterer et al., 2017, updated daily) (Figure **F4C**).

Some general predictions about the types of sediments that will be recovered at the proposed ArcOP sites can be obtained from the ACEX sequence and a small number of gravity cores taken in the vicinity of the ArcOP drill sites. The ACEX sequence was divided into four main lithologic units (Figure **F9**):

- Unit 1 (Quaternary to middle Eocene) is dominated by silty clay ranging from light olive-brown at the top through olive and gray to very dark gray at the bottom. Color banding is strong. Millimeter-to-centimeter-scale sandy lenses and isolated pebbles are present.
- Unit 2 (middle Eocene) is dominated by very dark gray mud-bearing biosiliceous ooze with submillimeter-scale laminations as well as isolated pebbles.
- Unit 3 (late Paleocene to early Eocene) is dominated by very dark gray clay with submillimeter-scale laminations.
- Unit 4 (Campanian) is dominated by very dark gray clayey mud and silty sands.

Whereas the upper (middle Miocene to Quaternary) part of the ACEX sequence is composed of silty clay with very low organic content (total organic carbon [TOC] < 0.5%), the Campanian and Paleogene sediments are characterized by high TOC values of 1 to >5% (Figure **F9**). Within some distinct late early Miocene gray/black color band, even TOC contents as high as 14.5% were measured. Hence, organic-rich sedimentation with good potential for the preservation of organic and siliceous walled microoragnisms can be expected for Eocene-age sediments. They may also characterize Oligocene–Miocene sediments if the early mid-Miocene opening of the Fram Strait was the major factor in driving the ventilation of the Arctic (Jakobsson et al., 2007a).

Proposed drill sites

Site locations

One primary deep drill site (LR-11B) in 794 m water depth with 900 mbsf proposed drill depth has been selected, to be supplemented by one short drill site (LR-10B) in 890 m water depth with 50 mbsf drill depth (Figure **F11**). In addition, 10 alternate sites are included, located in water depths ranging from ~764–1458 m with total penetration depths between 740 and 1300 mbsf (Table **T1**). Due to the rating of the drill rig being deployed, recovery of sections deeper than 2000 m below sea level will not be attempted.

Sediments at both sites are expected to be silty clays, biogenic ooze, and silty sands; the overall goal of the proposed drilling campaign is the recovery of a complete stratigraphic sedimentary record on the southern Lomonosov Ridge. This will meet our highest priority paleoceanographic objective, the reconstruction of the continuous long-term Cenozoic climate history of the central Arctic Ocean. Sedimentation rates two to four times higher than those of ACEX permit higher-resolution studies of Arctic climate change. As demonstrated in the proposal, this goal can be achieved by careful site selection, appropriate drilling technology and ice management, and applying multiproxy approaches to paleoceanographic, paleoclimate, and age-model reconstructions. The combination of a deep drill core recovered from the primary site (LR-11B) supplemented by a short drill site (LR-10B) will recover multiple sections of the sediment sequence to ensure complete recovery for construction of a composite section.

Site survey data

Deep-penetration reflection seismic profiles were acquired from Lomonosov Ridge on icebreaker-based expeditions between 1991 and 2018 (Jokat et al., 1992, 1995, 1999; Jokat, 2005, 2009; Kristoffersen et al., 1997; Darby et al., 2005; Jakobsson, 2007b; Stein, 2015, 2019a). The first high-resolution chirp profiles were collected in 1996 (Jakobsson, 1999). In 1999, the Submarine Arctic Science Program (SCICEX) collected high-resolution chirp subbottom profiler data, swath bathymetry, and sidescan sonar backscatter data from a US Navy nuclear submarine (Edwards and Coakley, 2003) and contributed significantly to the much improved bathymetric chart of the Arctic Ocean (Jakobsson et al., 2008a, 2012). In 1995, 1998, 2014, and 2019, an intensive Parasound survey in conjunction with a coring program of near-surface (Quaternary) sediments was carried out in the area of the proposed sites (Stein et al., 1997, 2001; Jokat et al., 1999; Stein, 2015, 2019a). The relevant site survey data from this area are included in the IODP Site Survey Data Bank.

The primary and alternate ArcOP sites were selected based on the more recent *Polarstern* site surveys in 2008 (Jokat, 2009), 2014 (Stein, 2015), and 2018 (Stein, 2019a) (Figure **F11**). The main factor for site selection based on seismic data is the mapping of continuous and laterally conformable reflectors indicating continuous sedimentary sequences. Locations with any indications of faults, slumps, or hiatuses were avoided to ensure flat-lying, unfaulted, undeformed, and well-stratified deposits. Furthermore, selected locations indicated appropriate thicknesses and depths feasible for drilling into and through the strata of interest. Depth-velocity information for estimating the thickness of the sedimentary units was derived from sonobuoys (Ickrath and Jokat, 2009), and interval velocities were calculated from stacking velocities of selected common depth point gathers (Weigelt et al., 2014).

The age control for the sedimentary units (Figure **F11**) was estimated via links of seismic lines to drill site data of the Chukchi shelf, ACEX drilling on the central Lomonosov Ridge, and onshore geology from the New Siberian Islands (Figure **F12**) (Weigelt et al., 2014). Referring to basin-wide similarities of reflection pattern and configuration of strata, two distinguished seismic units were mapped throughout the area and are the constraints for dating the remaining units.

Operational strategy

Drilling platform

This proposal calls for an ice-capable drilling platform that can conduct deep penetration coring in deep water. A high-end geotechnical drilling vessel, the *Dina Polaris,* operated by Geoquip Marine, has been contracted to undertake the drilling and coring.

Built in 2017, the *Dina Polaris* is a Class 2 dynamic positioning (DP2) vessel specially designed for offshore installation services in harsh weather conditions. This ice class vessel (ICE 1A) is designed to operate in Arctic conditions. The *Dina Polaris* is 99 m long and 21 m wide and is one of the largest geotechnical vessels currently available in the industry, creating an extremely stable platform.

The *Dina Polaris* accommodates Geoquip Marine's twin derrick GMTR120 drilling rig, a fully heave-compensated (6 m stroke) rig positioned over the 7.2 m × 7.2 m midship moonpool. Pipe handling is semiautomated, and a drilling monitoring system includes sensors and gauges to record various drilling parameters. The drilling system includes a seabed frame, which will allow borehole reentry if required. The seabed frame utilizes electrically operated pipe clamps for coring operations, is acoustically operated from the surface, and provides video monitoring of borehole entry.

Coring will be performed using wireline coring equipment through the moonpool using a top drive power swivel. A borehole mud program will utilize a variety of environmentally friendly products to stabilize the upper layers and provide bit cooling, lubricity, and hole cleaning.

Coring methodology

ArcOP will draw on the experiences of IODP Expedition 302 in 2004, an expedition where much was learned about continuous coring operations, deck processes, and equipment reliability in a remote, Arctic region. Those experiences are well-documented, and staff with direct ACEX experience are taking part in ArcOP both from the coring side and the ice management side.

The drill string will consist of a 5.5 inch drill pipe (internal diameter 4.5 inches), 7 inch drill collars, and a 7 inch bottom hole assembly into which a series of coring tools can be latched and interchanged without tripping the drill string. Utilization of the available tools will be dependent on the ground conditions to ensure maximum core recovery on every run. Key coring tools include the following:

- Advanced piston corer (APC) (for soft to firm sediments),
- Leading shoe assembly (retractable inner tube cutting shoe for variable, soft, interbedded formations),
- Marine core barrel (rotary coring driven by the drill string for harder formations), and
- Noncoring plug bit.

Depending on the coring method used and lithology being cored, core runs will vary between 1.5 m and 9 m, and core diameter will be either 68 mm (leading shoe core barrel) or 80 mm (triple-tube core barrel). A variety of drill bits will be provided to cope with formations of varying hardness, including drag bits, polycrystalline diamond (PDC) bits, rock roller bits, thermally stable polycrystalline (TSP) "Geocube" bits, and diamond impregnated bits.

Coring will commence using the APC, which will continue to be used until the penetration rate or core quality consistently drops. From that point, the leading shoe corer will be used until the limitation of the corer is reached. The borehole will then be progressed using rotary coring and more aggressive drill bits. Open-hole drilling remains an option; however, the operational objective is to continuously core the primary site.

Downhole logging

In all MSP expeditions, the downhole logging program is an integral part of the offshore operation and is designed to help meet the expedition-specific scientific objectives and maximize scientific output in general.

The various coring strategies and resulting logging conditions (e.g., water depth, pipe and borehole diameter) on MSPs require an appropriate set of logging tools. The type of logging tools used, including super-slimline tools, memory-mode tools, and standard oilfield tools, varies from expedition to expedition.

The suite of super-slimline tools can be used alone or stacked in a tool string, offering the possibility to collect multiple measurements in a single tool string run. At various stages in the project, the Petrophysics Staff Scientists liaise with the Co-Chief Scientists, Expedition Project Manager (EPM), ESO Operations Manager and operational team (Geoquip), logging engineers, and the science party. These exchanges, before and during the expedition, are crucial to ensure that the best decisions are made to address the scientific objectives, taking into consideration time and operational constraints as well as borehole conditions.

The tool suite available for ArcOP includes spectral and total gamma ray, *P*-wave sonic velocity, *S*-wave sonic velocity, electrical conductivity, and magnetic susceptibility (MS).

For Expedition 377, the plan is to acquire downhole logging data at the completion of coring and drilling operations at the primary site (LR-11B). To address the scientific objectives, spectral gamma ray, *P*-wave sonic, and MS have been identified as highest priority measurements because they allow core-to-hole correlation and hole-to-seismic correlation. These tools will be combined in one tool string in order to acquire the data in one run. Preexpedition scientific and operational discussions will consider whether the hole should be logged in depth stages to maximize the ability to acquire data where the borehole may be unstable. The logging plan might be modified during the expedition depending on hole conditions. The provisional downhole logging program is detailed below (but may be subject to change):

- Through-pipe: spectral gamma ray (standalone);
- Open hole: gamma ray + electrical conductivity; sonic + MS (stacked).

The Petrophysics Staff Scientists will be responsible for data processing, QA/QC of data, and ongoing scientific support for data interpretation and research. The final set of downhole data (following the full QA/QC process) will be made available to the science party at the commencement of the OSP.

Site priorities and contingency considerations

In this section, we briefly describe overarching priorities for sites, coring, and logging given the science goals of the expedition as well as examples of possible contingency strategies.

The planned order of sites is LR-11B (or one of its alternatives) and then LR-10B (or one of its alternatives). Proposed Site LR-11B was chosen as the first site because it will sample the longest time record on the Lomonosov Ridge. Proposed Site LR-10B will provide a more expanded section of upper Quaternary sequence than the deep drill core. This latter is essential for reconstructing a high-resolution record of the later Quaternary sedimentary history.

The coring strategy is relatively simple: to continuously core deep Site LR-11B from seabed to target depth (900 mbsf). Ice, weather, and technical and geological factors may disrupt this strategy, and they may lead to the borehole being terminated and restarted.

The main decision-making group for science issues will be the Co-Chief Scientists and the EPM, who will be advised by the various operational teams (ice, weather, drilling, vessels, and ESO Operations Manager) on what can be achieved operationally. Decisions on how to proceed, for example, with a new borehole, will take into account lessons learned during previous operations. Those experiences will inform the Co-Chief Scientists and EPM on where to start a new borehole (same site or alternative site), what depth to begin coring, and what interval(s) to open hole. If necessary, priority will be given to complete coring at deep Site LR-11B over coring at shallow Site LR-10B because Site LR-10B can potentially be targeted by a national-scale research cruise utilizing piston coring or seafloor drilling. In the event that coring goes better than anticipated, extra holes may be cored at either the primary site (duplicate recovery) or alternative sites. Under all circumstances, the coring time will be limited by the expedition budget, and the fleet will depart the ArcOP site when the operational budget is exhausted.

Core on deck

As cores are recovered to deck, they will undergo initial labeling and sampling on a core bench prior to processing through the on-deck curation and laboratory containers. The operation will proceed using changeover of inner core barrels to ensure continuity of the coring operation in as timely a fashion as possible. The deck operators will deploy an empty core barrel immediately after the previous one has been retrieved, then address the core removal and subsequent readying of that core barrel for reuse. The cores will be collected in a plastic liner, and the usual IODP curation procedures will be followed and documented in the ESO Expedition 377 Core Curation, Initial Sampling and Analyses Handbook. After curation (and temperature equilibration), unsplit core sections and core catcher (CC) materials will be passed to the science party members for onboard description, physical properties measurements, analysis, and sampling, as described below.

Science operations

A sampling and measurements plan (SMP) for Expedition 377 will be developed by ESO and the Co-Chief Scientists to meet the scientific objectives of IODP Proposal 708-Full and Addenda 708-Add, 708-Add2, 708-Add3, and 708-Add4.

Offshore science activities

Compared to the larger and specifically designed research drilling vessels *JOIDES Resolution* and *Chikyu,* it is the nature of MSP expeditions that laboratory space is limited or lacking as part of the platform infrastructure and accommodation. As a consequence, cores are not split at sea, and only a few selected scientific analyses are carried out on board by a subset of the science team (in this case, between 10 and 14 members, to be confirmed). Science activities on the platform are confined to those essential for decision-making at sea (e.g., physical core logging on a MSCL, core curation, securing samples for pore water chemistry and microbiology, measurement of ephemeral properties, and downhole logging). Cores will typically be cut into 1.5 m lengths for curation. Most of the scientific analyses, including visual core description, are carried out during the OSP in Bremen,Germany, when the cores are split.

The following is a summary of the offshore scientific activities (please refer to the online tutorial **http://www.marum.de/en/Offshore_core_curation_and_measurements.html**):

- Basic curation and labeling of cores.
- All cores >15 cm will be measured on the MSCL for gamma density, *P*-wave velocity, electrical resistivity, MS, and natural gamma radiation.
- CC description and sampling, if available, for initial sedimentological, micropaleontological, petrophysical, and/or structural characterization, including taking a CC image.
- Taking and properly storing samples for gas analyses, and acquiring and splitting pore water samples.
- Pore water geochemistry analysis, microbiological sampling and analysis, and any other ephemeral properties agreed in the SMP.
- Temperature-controlled core storage.
- Downhole logging.
- Preliminary core-log-seismic integration using available downhole logging data and/or core physical properties data.
- Associated data management of all activities (see below).

In order to deliver the scientific requirements on the platform with a subset of the science party, a staffing plan has been devised. The plan requires flexibility of approach from all participants, with priority given to safety, core recovery, curation, and procedures for the measurement of ephemeral properties.

Report preparation will take place on board as required; the reports to be compiled include the following:

- Daily and weekly operational reports will be compiled by ESO and provided to the management and panels of ECORD and IODP, science party members, and any other relevant parties that choose to register with the ESO Public Announcement mailing list at **https://www.jiscmail.ac.uk/cgi-bin/webadmin?SUBED1=ECORDSO&A=1**. Scientific reports are provided by the Co-Chief Scientists. Summarized daily reports will be publicly available on the ESO website for any interested parties.
- Completion of the offshore sections of the expedition reports (primarily the Methods chapter but also recording of initial results from offshore observations, measurements, and analyses) will be undertaken by offshore science party members and ESO staff.

Onshore science activities

The OSP will be held at the IODP Bremen Core Repository (BCR), MARUM-Center for Marine Environmental Sciences, University of Bremen, Germany. The scientific work will follow the SMP to be developed with the Co-Chief Scientists. The majority of the scientific reporting for the expedition is also undertaken during the OSP by science party members.

Details of the facilities that will be available for the OSP at the BCR and MARUM laboratories can be found in the Expedition 377 SMP link at **https://www.marum.de/en/Research/Partner-to-the-ECORD-Science-Operator.html**. The measurements plan will take account of MSP specifications for QA/QC procedures. Additional facilities can be made available through continuing close cooperation with additional laboratories at the MARUM-Center for Marine Environmental Sciences and the Department of Geosciences at the University of Bremen, all of which are situated nearby on campus.

The following list briefly summarizes the OSP scientific activities:

- Prior to the OSP, thermal conductivity measurements will be taken on all cores (as appropriate) using a needle probe. These measurements will be undertaken by ESO personnel.
- After core splitting, an archive half will be set aside per IODP procedure.
- For core description, ESO will provide a data entry system that is IODP standard. For data entry ESO will employ the ESO expedition database (see **Data management** below).
- High-resolution digital imaging using a digital linescan camera system.
- Color reflectance spectrophotometry using an MSCL-mounted spectrophotometer.
- *P*-wave velocities measured on discrete samples using an MSCL discrete *P*-wave system;
- Moisture and density (MAD) on discrete samples using a pycnometer.
- Core sampling for expedition ("shipboard") samples to produce IODP measurements data for program legacy and publish through the Expedition report (e.g., petrophysical properties, *P*-wave, MAD analyses, geochemistry).
- Smear slide preparation and investigation (undertaken by sedimentologists and/or micropaleontologists at regular intervals as required).
- Thin section preparation (as requested) and description by the science team.
- Biostratigraphy.
- Inorganic geochemistry (bulk sediment and pore fluid chemistry) and organic geochemistry (TOC; carbonate).
- Bulk mineralogy, including X-ray diffraction (XRD) analysis on discrete samples.
- Paleomagnetic measurements.
- For core sampling for individual postexpedition research, a detailed sampling plan will be devised after the scientists have submitted their revised sample requests following completion of the offshore phase (see **Research planning: sampling and data sharing strategy** below).
- Sample allocation will be evaluated and approved by the Sample Allocation Committee (SAC) (see below for further details).

In view of the existing geographical distribution of all Deep Sea Drilling Project/ODP/IODP cores, the BCR will be the long-term location for the Expedition 377 cores.

Report preparation will take place during the OSP as required by ECORD. The reports to be compiled include the following:

- Weekly progress reports to ECORD and relevant parties. Scientific reports are provided by the Co-Chief Scientists.
- Preliminary Report compiled by the science party (submission to IODP Publication Services at the end of the OSP).
- The expedition report compiled by the science party (submission to IODP Publication Services as soon as practically possible after the OSP).

For more information, refer to SMP link and the online tutorial at **http://www.marum.de/Onshore_Science_Party_OSP.html**).

Staffing

Scientific staffing is determined on the basis of task requirements and nominations from the IODP Program Member Offices (**http://www.iodp.org/program-member-offices**). ESO staffing is based on the need to carry out the drilling and scientific operations safely and efficiently (Table **T2**).

Data management

A data management plan for the expedition will be developed once the data requirements and operational logistics are finalized. The outline plan is as follows:

- The primary data capture and management system will be the ESO expedition database. This is a relational database and will capture drilling, curation, and geoscience metadata and data during the offshore and onshore phases of the expedition.
- This database system includes tools for data input, visualization, report generation, and data export.
- A file server will be used for the storage of data not captured in the database (e.g., documents and image files) and for the inputs/outputs of any data processing, interpretation, and visualization applications used during the expedition.
- On completion of the offshore phase of the expedition, the ESO expedition database and file system will be transferred to MARUM/BCR to continue data capture during the OSP.
- Between the end of the offshore phase and the start of the OSP, the expedition scientists will have access to the data by using a password-protected website.
- On completion of the OSP, expedition scientists will continue to have access to all data through a password-protected website throughout the moratorium period.
- During the moratorium, all metadata and data, apart from downhole logging data, will be transferred to the Publishing Network for Geoscientific and Environmental Data (PANGAEA) for long-term archiving.
- The Petrophysics Staff Scientists will manage the downhole logging data (including formation temperature measurements), MSCL data, and other physical properties data.
- Downhole logging data will be stored separately for processing and compositing and will be made available to the science party via the log database hosted by the Lamont-Doherty Earth Observatory. These data will be archived at the Lamont-Doherty Earth Observatory.
- Cores and samples will be archived at the BCR.

- After the moratorium, all the expedition material and data will be made accessible to the scientific community.

Outreach

ECORD aims to interact positively with the media, nongovernmental organizations, governments, the scientific community, and the general public to demonstrate the work and beneficial outcomes of IODP-MSP expeditions and of IODP in general.

ECORD recognizes the unique outreach opportunity that ArcOP presents. The ECORD Outreach Task Force, in collaboration with the Co-Chief Scientists, has been working on a number of outreach initiatives for ArcOP, and these will be followed up in months before and after the expedition. All outreach activities and protocols will be documented in an ArcOP Communications Plan to be distributed to the science party in the lead-up to the expedition.

Outreach activities before the start of the expedition include but may not be limited to the following:

- Develop a detailed Communications Plan in close cooperation with Co-Chief Scientists. This plan will provide guidance to the science party and will explain their responsibilities.
- Produce and distribute an expedition flyer.
- Produce a media pack on the ESO website, including the expedition's web page and biographies of the Co-Chief Scientists.
- Organize expedition kickoff media briefings in appropriate locations.
- Distribute an international media release in parallel with the expedition kickoff media briefing.
- Organize ship visits for the media during or after mobilization, if possible.
- Produce a "Frequently asked questions" document to distribute to the science party and to be made public.
- Produce a guide to social media to distribute to the science party.
- Network with participants' university media offices, particularly the Co-Chief Scientists' host organizations.
- Produce an official expedition logo for use on all promotional materials.

Outreach activities during the offshore phase of the expedition include but may not be limited to the following:

- Participation of a contracted film crew to gather material for an ArcOP documentary. Video footage and individual interviews will be collected.
- An offshore outreach program to be led by a contracted science communicator.
- Blog entries by expedition participants (all roles: science, operations, support, logistics, domestics) to be posted on ECORD blog site and shared by individual/institutional blog sites.
- Social media posts by expedition participants posted through ECORD accounts and then shared by individual/institutional accounts.
- Collection of photos and videos taken by expedition participants for various purposes.
- Publication of media releases (in the case of special events/findings and, if appropriate, at the end of the expedition).
- Promotion of the expedition through national and international media and organize interviews with Co-Chief Scientists and other science party members as necessary/requested.
- Collation of photographs that document the entire expedition with the view to putting together a touring photographic exhibition.
- Facilitation of Ask Me Anything (AMA) Reddit sessions off shore and on shore.

Outreach activities during the OSP may include the following:

- Contracted film crew to continue to gather material for an ArcOP documentary.
- Facilitated involvement of science communicator(s) for a portion of the OSP.
- Blog entries by expedition participants (all roles: science, operations, support, logistics, domestics) to be posted on ECORD blog site and shared by individual/institutional blog sites.
- Social media posts by expedition participants posted through ECORD accounts and than shared by individual/institutional accounts.
- Collection of photos and videos taken by expedition participants for various purposes.
- Preparation of background material to provide to the media.
- Hold a media day toward the end of the OSP and invite key journalists and TV teams.
- Publish an international media release (tentative results).

Outreach activities after the expedition may include the following:

- Support the contracted film crew to gather postexpedition material and edit material for the ArcOP documentary.
- Promotion at international conferences (booths, talks) (e.g., EGU, AGU Fall, and Ocean Sciences Meetings).
- Promote the science through development of education resources in collaboration with teachers, science communicators, and national organizations, including visitor attractions and museums.
- General outreach to the media as scientific results of the expedition become available.
- Continued logging of any outreach activities undertaken by any of the science party members, including interviews, blog entries, and abstracts submitted. The ESO outreach team will depend on science party members to alert ESO to their activities. In addition, ESO will set up an Agility Alert for the expedition to scan all printed media globally.

Research planning: sampling and data sharing strategy

All researchers requesting samples should refer to the IODP Sample, Data, and Obligations Policy & Implementation Guidelines posted on the web under "IODP-wide Policies and Procedures" through **http://www.iodp.org/program-documents**. This document outlines the policy for distributing IODP samples and data to research scientists, curators, and educators. The document also defines the obligations that sample and data recipients incur. The SAC, composed of Co-Chief Scientists, EPM, and the IODP Curator for Europe (BCR and MSPs) or offshore curatorial representative, will work with the entire science party to formulate an expedition-specific sampling plan for shipboard (expedition, including offshore and OSP) and postcruise (individual postexpedition research) sampling.

Members of the science party are expected to carry out and publish scientific research for the expedition. Before the expedition, all members of the science party are required to submit research plans and associated sample/data requests via the IODP Sample and Data Request (SaDR) system at **http://web.iodp.tamu.edu/sdrm/** or a successor system (tba) before the deadline specified in their invitation letters. Based on sample requests submitted by this deadline, the SAC will prepare a tentative offshore sampling plan. The sample requests can be revised any time but definitely after the offshore phase dictated by recovery and cruise objectives. Cores will be split during the onshore phase of the expedition (OSP) in Bremen.

All postcruise research projects should provide scientific justification for desired sample size/volume, frequency, and scientific analytical method. The sampling plan will be subject to modification depending on the material recovered and collaborations that may evolve between scientists during the expedition. This planning process is necessary to coordinate the research to be conducted and to ensure that the scientific objectives are achieved. Modifications to the sampling plan and access to samples and data during the expedition and the 1-year postexpedition moratorium period require the approval of the SAC.

Offshore sampling will be restricted to that necessary for acquiring ephemeral data types that are critical to the overall objectives of the expedition and to preliminary lithologic and biostratigraphic sampling to aid decision-making at sea and planning for the OSP.

The permanent archive halves are officially designated by the IODP curator for BCR and MSPs. All sample frequencies and volumes must be justified on a scientific basis and will depend on core recovery, the full spectrum of other requests, and the expedition objectives. Some redundancy of measurement is unavoidable, but minimizing the duplication of measurements among the shipboard party and identified shore-based collaborators will be a factor in evaluating sample requests.

If critical intervals are recovered, there may be considerable demand for samples from a limited amount of cored material. A sampling plan coordinated by the SAC will be required before critical intervals are sampled.

The SAC strongly encourages, and may require, collaboration and/or sharing among the shipboard and shore-based scientists so that the best use is made of the recovered core. Coordination of postcruise analytical programs is anticipated to ensure that the full range of geochemical, isotopic, and physical property studies are undertaken on a representative sample suite. The majority of sampling will take place at the OSP in Bremen, and the SAC encourages scientists to start developing collaborations before and during the expedition.

Acknowledgments

This publication was prepared by the authors using contributions provided by the proponents of IODP Proposal P708, staff members of the ECORD Science Operator (ESO), and expedition contractors.

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Table T1. ArcOP proposed sites. Depths are expected drilling depths of the main horizons at the proposed sites. * = primary sites. Depth differences result from inaccuracies of velocity models or ambiguous marker reflectors. Bold = most likely depths. Colors refer to colored lines marking the horizons of interest in the seismic sections (Figure F11). † = target depth is total drill pipe length < 2000 m. CDP = common depth point, HARS = high-amplitude reflector sequence. mbsf = meters below seafloor, mbsl = meters below sea level.

Site:	LR-01A	LR-02A	LR-03A	LR-04C†	LR-05B†	LR-06A†	LR-11B*†	LR-10B*†	LR-07A†	LR-08A	LR-09A†	LORI-5B
Latitude: Longitude:	80.9502°N 142.9717°E	80.965°N 142.4717°E	81.1825°N 142.0918°E	81.3531°N 141.2484°E	81.3256°N 141.4248°E	81.4568°N 140.7299°E	81.4365°N 140.8405°E	81.48363°N 140.5855°E	81.6851°N 142.3074°E	82.4215°N 142.1678°E	82.8274°N 142.4677°E	83.8005°N 146.475°E
Line(s):	20080160	20140304 20140307	20140310	20140298	20180310	20140315	20180310	20180310	20140321	20140292	20140324 20140290	20140565 20140260 20140279
CDP(s):	475	2147 567	600	5230	1600	725	970	700	220	1720	135 1615	2582 650 1004
Depth (m) Seafloor (bathymetry)	1402	1458	1013	875	906	779	794	890	764	1450	1251	1333
Seafloor seismic	1405	1460	1013–1022	860–880	910–917	776–782	795–810	890–910	760–765	1435–1450	1244–1251	1334
Top Miocene (yellow)	1570–1580	1600–1650 (1670)	1219–1225 **1220**	1090–1110 **1100**	1120–1180 **1180**	975–1000 **980**	1045		950–960	1570	1375	1610–1670
Thin reflector band	2080	2190–2200	1620–1650 **1630**	1490–1510 **1500**	1530–1555 **1550**	1280–1300 **1300**	1420		1015–1030	1920–1935	1700–1715	
Top Oligocene HARS (pink)	**2170**–2240	2300–2330	1705–1730 **1725**	1580–1600 **1590**	1635–1660 **1655**	1375–1390 **1375**	1480		1040–1060	1990–2020	1750–1755	1970–1995
Lower Eocene (orange)	**2450**–2550	2610–2650	2150–2195 **2180**	1780–1800 **1790**	1920–1985 **1930**	1563–1700 **1565**	1680		1480–1490	2290–2325	1940–**1945** (2045–2055)	2490–2600
Basement (purple)	3070–3090 (3180–3290)	3160–3270	2590–3340 (3000)						1800–2000	2600–2620	2750–2770	3100–3200
Proposed penetration (mbsf)	1225	1300	1185	930	1050	800	900	Short log 50	740	865	750	1250
Proposed total (mbsl)	2630	2750	2200	1800	1960	1600	1750	Short log 940	1500	2315	2000	2580
Ranking	Alternate	Alternate	Alternate	Alternate	Alternate	Alternate	Primary	Primary	Alternate	Alternate	Alternate	Alternate

Table T2. Provisional summary of science party and operator (ESO) personnel, Expedition 377.

Offshore team total (30)		
ESO (16)	Offshore science party (14)	Science party (36)
2 ESO Expedition Project Managers (EPM) 1 ESO Trainee EPM 1 ESO Operations Manager 2 ESO Curators 1 ESO Geochemist 2 ESO Petrophysics Staff Scientists 1 ESO Petrophysicist 2 ESO Data Managers 2 ESO Drilling Coordinators 2 ESO Logging Engineers 2–4 Filmmakers (contracted) 1 Science Communicator (contracted)	2 Co-Chief Scientists 1 Petrophysicist 3 Geochemists/Microbiologists 2 Sedimentologists 2 Dinoflagellate specialists 1 Radiolarian specialist 1 Diatom specialist 1 Foraminifer specialist 1 Nannofossil specialist	All invited scientists (spread of disciplines to be decided)

Figure F1. Cenozoic Greenhouse to Icehouse climate records. A. Left: compilation of atmospheric CO_2 proxies through the Cenozoic (Masson-Delmotte et al. 2013). Right: Best and worst case representative concentration pathways (RCPs) for historic and future atmospheric CO_2 emissions (Meinshausen et al., 2011). PD = present day. B. Composite deep-ocean benthic $\delta^{18}O$ record for the last 65 Ma (Zachos et al., 2001, 2008). Proposed Northern Hemisphere ice sheets and Arctic Ocean sea ice according to Moran et al., 2006; Eldrett et al., 2007; St. John, 2008; Tripati et al., 2008; and Tripati and Darby, 2018. C. Long-term trend in deep-sea temperature through the Cenozoic based on removal of the ice volume component of the benthic $\delta^{18}O$ record (black line with gray uncertainty band) and Mg/Ca ratio estimates of deep-sea temperatures (Cramer et al., 2009) and scaled $\delta^{18}O$ for the past 10 My (Miller et al., 2011). D. Reconstruction of sea-level lowstands (black lines) with minimum uncertainty ranges (gray shading) and smoothed highstand trend (black dotted line) using sequence stratigraphy for the New Jersey (Kominz et al., 2008). Red arrow = interval of the hiatus in the ACEX sequence according to the original age model of Backman et al., 2008. Figure modified from McKay et al., 2019, supplemented.

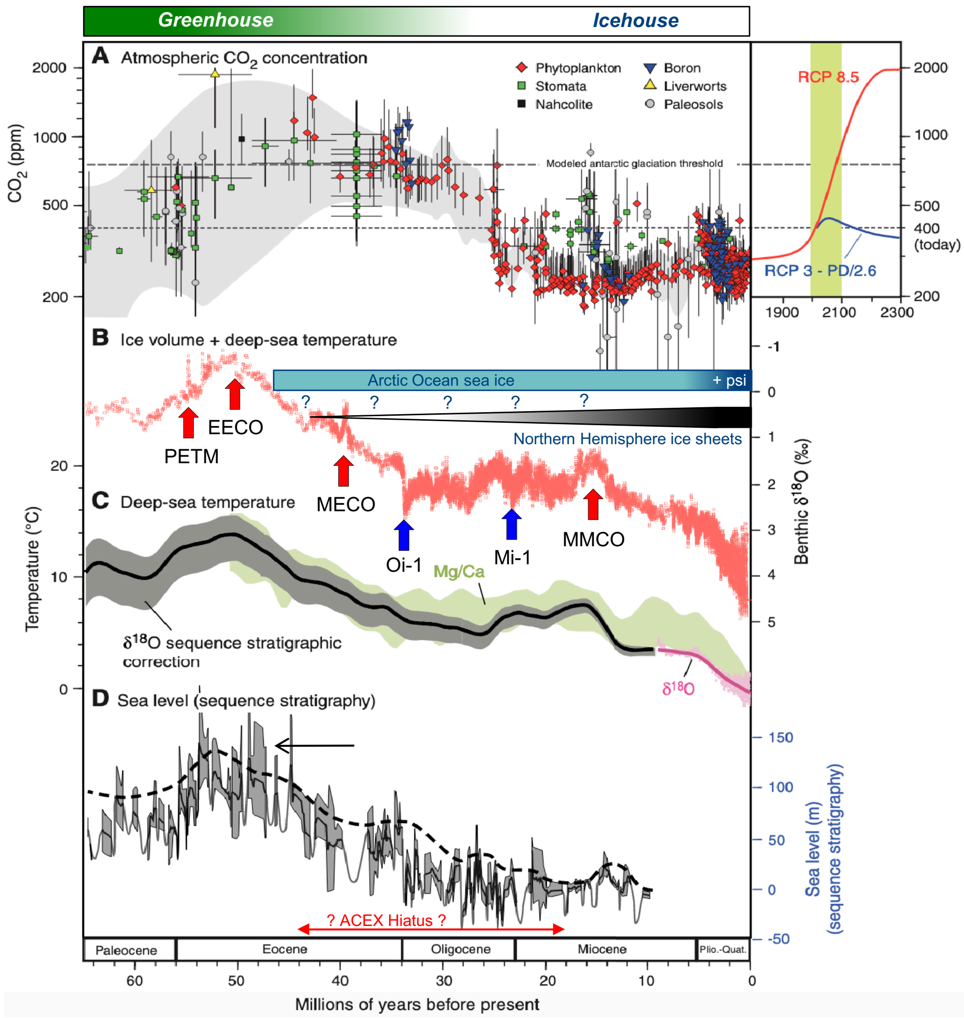

Figure F2. Google map of Northern Hemisphere with DSDP, ODP, and IODP sites (Figure from Stein, 2019b). White arrows = major rivers discharging into the Arctic Ocean are indicated. Marginal seas are: BS = Beaufort Sea, CS = Chukchi Sea, ESS = East Siberian Sea, LS = Laptev Sea, KS = Kara Sea, BaS = Barents Sea. Open white circles = Arctic to Atlantic Ocean connection via the Fram Strait and Arctic to Pacific Ocean connection via the Bering Strait.

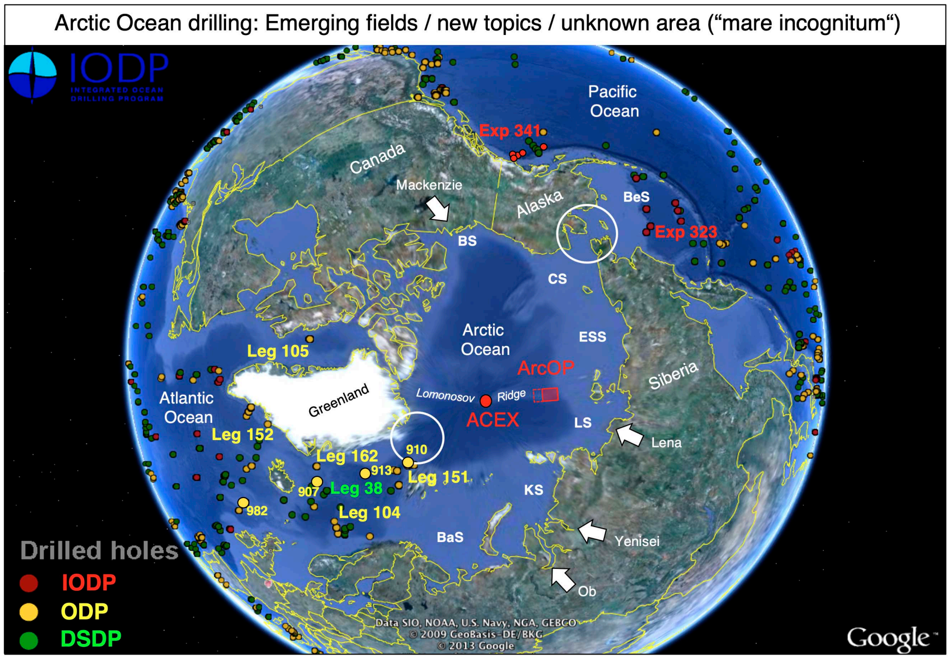

Figure F3. Age-depth diagram and main lithologic units of the ACEX section based on the biostratigraphically derived age model by Backman et al. (2008) and alternate chronology based on osmium isotopes (Poirier and Hillaire-Marcel, 2011). Blue bar = depth of first occurrence of ice-raft debris between 240 and 260 meters composite depth. Blue arrows = ages of the first occurrence of ice-rafted debris, obtained by the two age models: AM1 = Backman et al., 2008, AM2 = Poirier and Hillaire-Marcel, 2011. Mean sedimentation rates (cm/ky) are indicated. Figure from O'Regan (2011), supplemented.

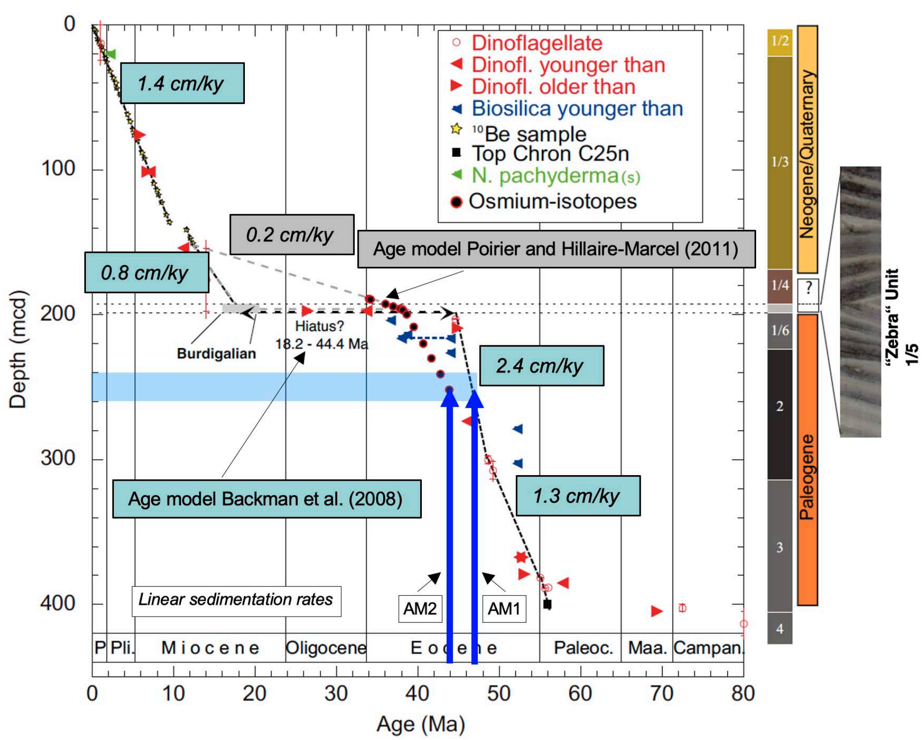

Figure F4. A. Distribution of ice sheets and sea ice (courtesy of Martin Jakobsson, Stockholm University, 2012). B. The extent of Arctic sea ice in 2017 with maximum in March and minimum in September. During recent years, the sea ice extent has reduced significantly compared to the long-term median of the years 1981 to 2010 shown as yellow line (Spreen et al., 2008; https://seaice.uni-bremen.de/arctic-sea-ice-minima/). BG = Beaufort Gyre, TPD = Transpolar Drift, WSC = West Spitsbergen Current (WSC), EGC = East Greenland Current. The location of the ACEX drill site and the working area of the IODP Expedition 377 (ArcOP) are shown in green. C. September sea ice extent in the Arctic Ocean (1890–2090) based on historical data, direct observations/measurements, and projected by different climate models and different IPCC scenarios toward 2090 (Intergovernmental Panel on Climate Change, 2014; Stroeve et al., 2007, 2012). D. September sea ice extent in 1980, 2007, and 2012 (source: National Snow and Ice Data Center; https://nsidc.org/).

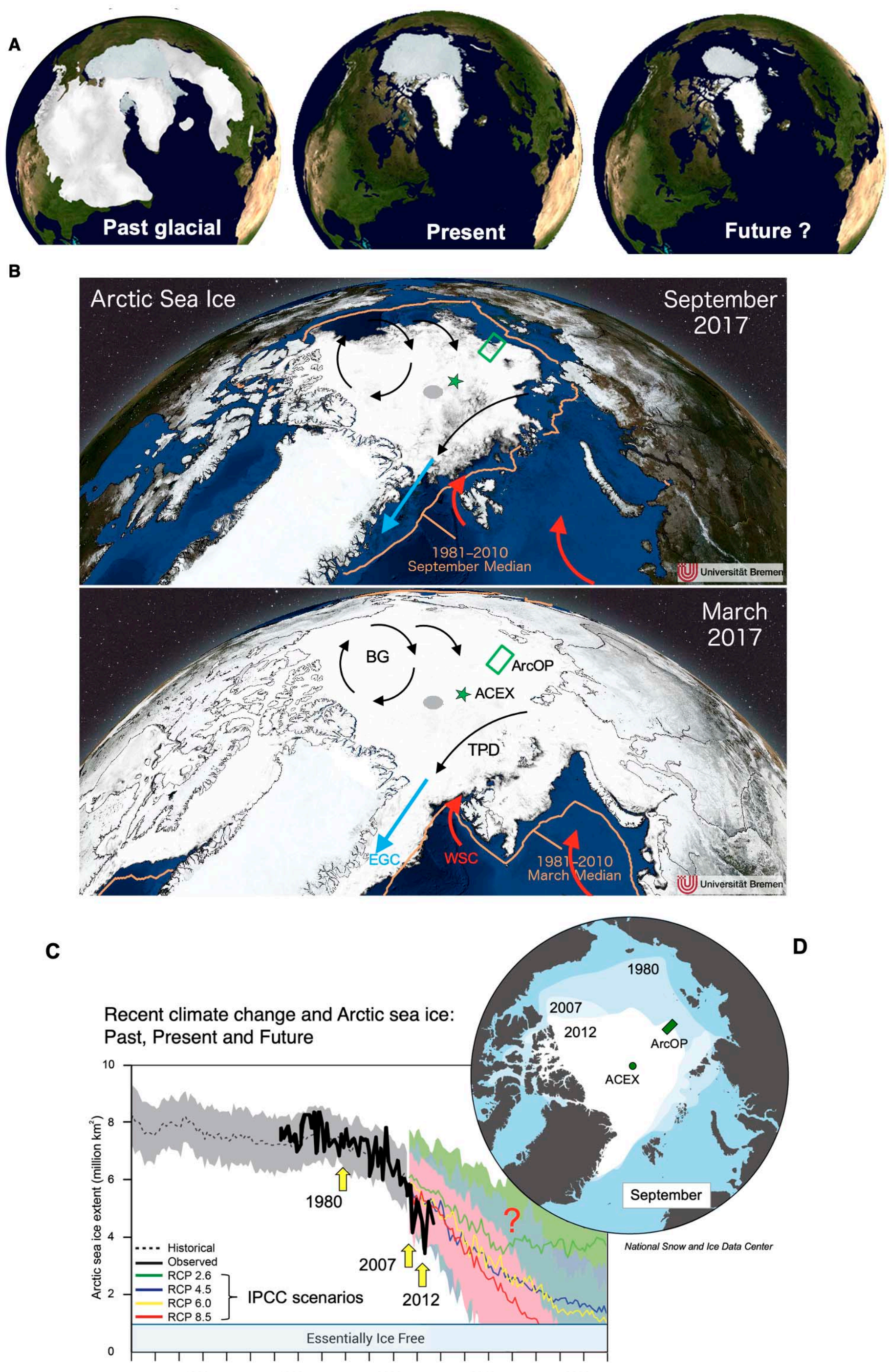

Figure F5. A. Tentative reconstruction of Marine Isotope Stage 6 ice shelves and ice sheets. Orange arrows = ice flow inferred from geophysical mapping. White arrows = hypothesized ice flow. B. Ice shelf covering the entire central Arctic Ocean with flow lines generalized from mapped glacial landforms (Jakobsson et al., 2016). AP = Arlis Plateau, CB = Chukchi Borderland, LR = Lomonosov Ridge, MJ = Morris Jesup Rise, YP = Yermak Plateau; x–x? highlights the crest of the Lomonosov Ridge. C. Proposed maximum extent of an ice sheet on the East Siberian Continental Margin and compiled Pleistocene circum-Arctic ice sheets. Red arrows = major ice streams. White arrows = propagation of proposed ice shelves.

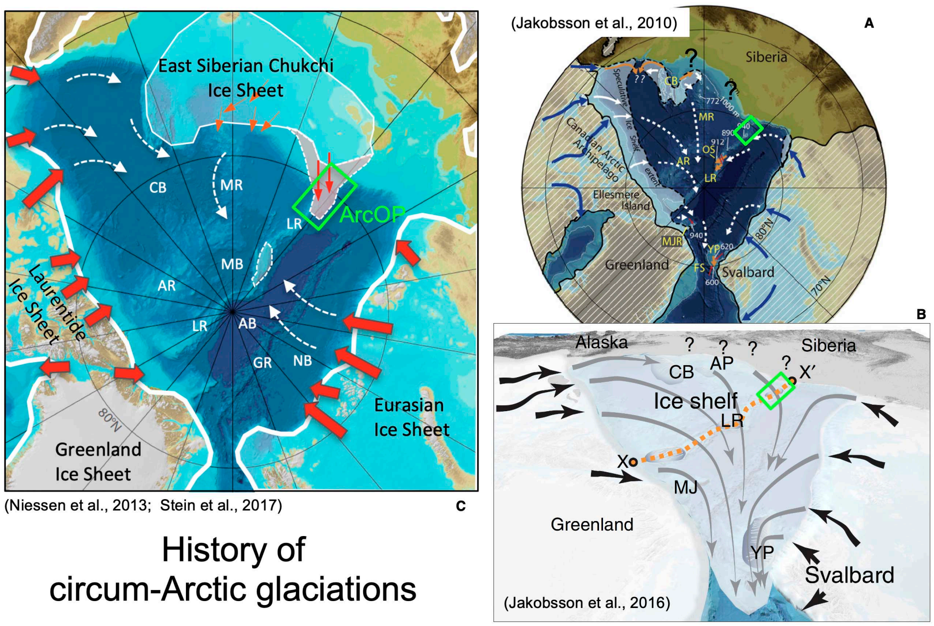

Figure F6. The ocean's thermohaline circulation in the North Atlantic and the proposed short circuit of the system through freshening of the Arctic Ocean. Hypothesis 1 (Driscoll and Haug, 1998) and Hypothesis 2 (Wang, 2004) as trigger mechanisms for increased Arctic river discharge are shown. TP = Tibetan Plateau, MP = Mongolian Plateau.

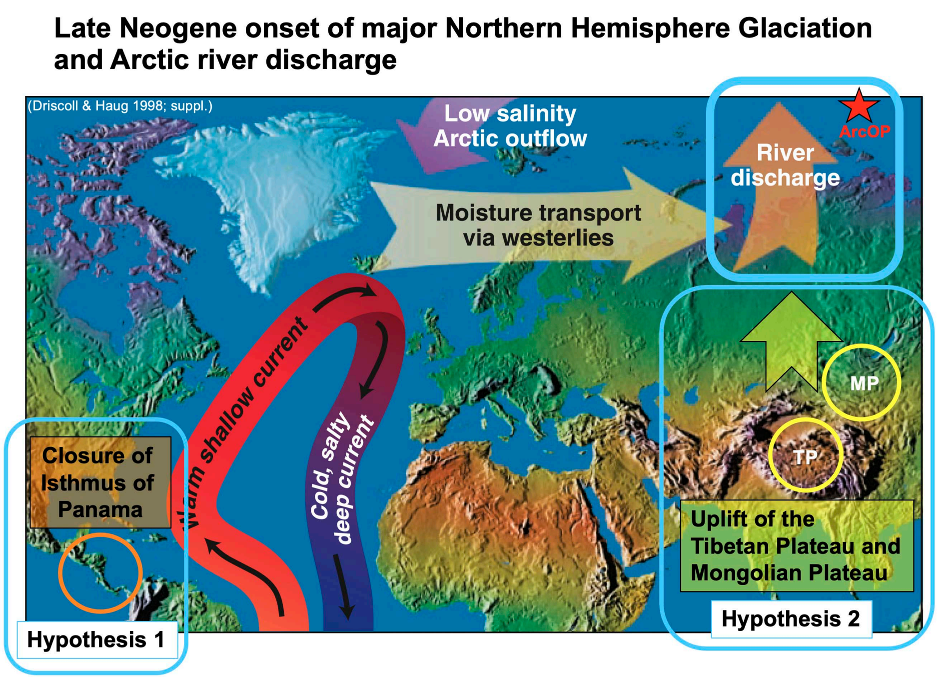

Figure F7. Alkenone-based sea-surface temperature (SST) (red circles) (Weller and Stein, 2008; Stein et al., 2014). Abundance of ice-rafted debris (brown circles; yellow diamonds = large dropstones; Record d) (St. John, 2008) determined in the ACEX sequence from 298 to 198 mbsf, representing the time interval from the end of the Early Eocene Climate Optimum (EECO) near 48.6–44.4 Ma or near 48–37 Ma. For the ACEX interval 260–223 mbsf, the abundance of sea-ice diatom species *Synedropsis* spp. is also shown (Record e) (Stickley et al., 2009). In the diatom record, the first occurrence (FO) and the first abundant occurrence (FAO) of the sea-ice species and the last occurrence (LO) of warmer water diatoms *Porotheca danica* and *Pterotheca aculeifera* are also shown. Blue arrows = major cooling events. Red arrows = major warming events. Stars= modern pole–equator temperature gradient. (a) = global benthic $\delta^{18}O$ stack (Zachos et al., 2008); (b) = TEX_{86} SST record of ODP Site 1172 at latitude 65°S (Bijl et al., 2009); (c) = TEX_{86} SST range recorded at the Tanzania site at 20°S (Pearson et al., 2007) (figure from Stein et al., 2014).

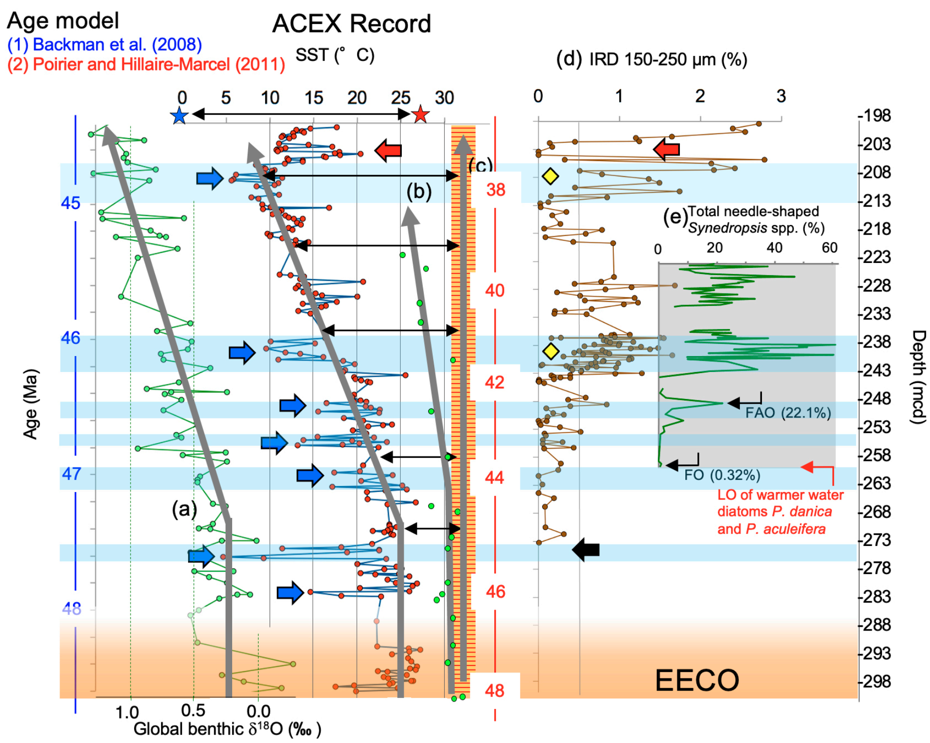

Figure F8. Ice-raft debris (IRD) mass accumulation rates (g cm^{-2} ky^{-1}) in the >250 µm (dotted line and open circles) and 150-250 µm (black line and solid circles) size fractions of the Eocene to Pleistocene (270 to 0 meters composite depth [mcd]) section of the ACEX record (St. John, 2008, supplemented), along with isolated granules and pebbles (large gray circles) (from Expedition 302 Scientists, 2006) vs. age (Ma). Green line with red arrow = onset of ice rafting. Open arrows = major pulses of IRD input. The Mid-Miocene Climate Optimum (e.g., Flower and Kennett, 1995 ; Zachos et al., 2001) is marked. Red numbers are in mcd. On the right, an enlargement of the middle Eocene interval (44.5–47.5 Ma) of this dataset and the concentrations of needle-shaped sea-ice diatom *Synedropsis* spp. (Stickley et al., 2009) are shown.

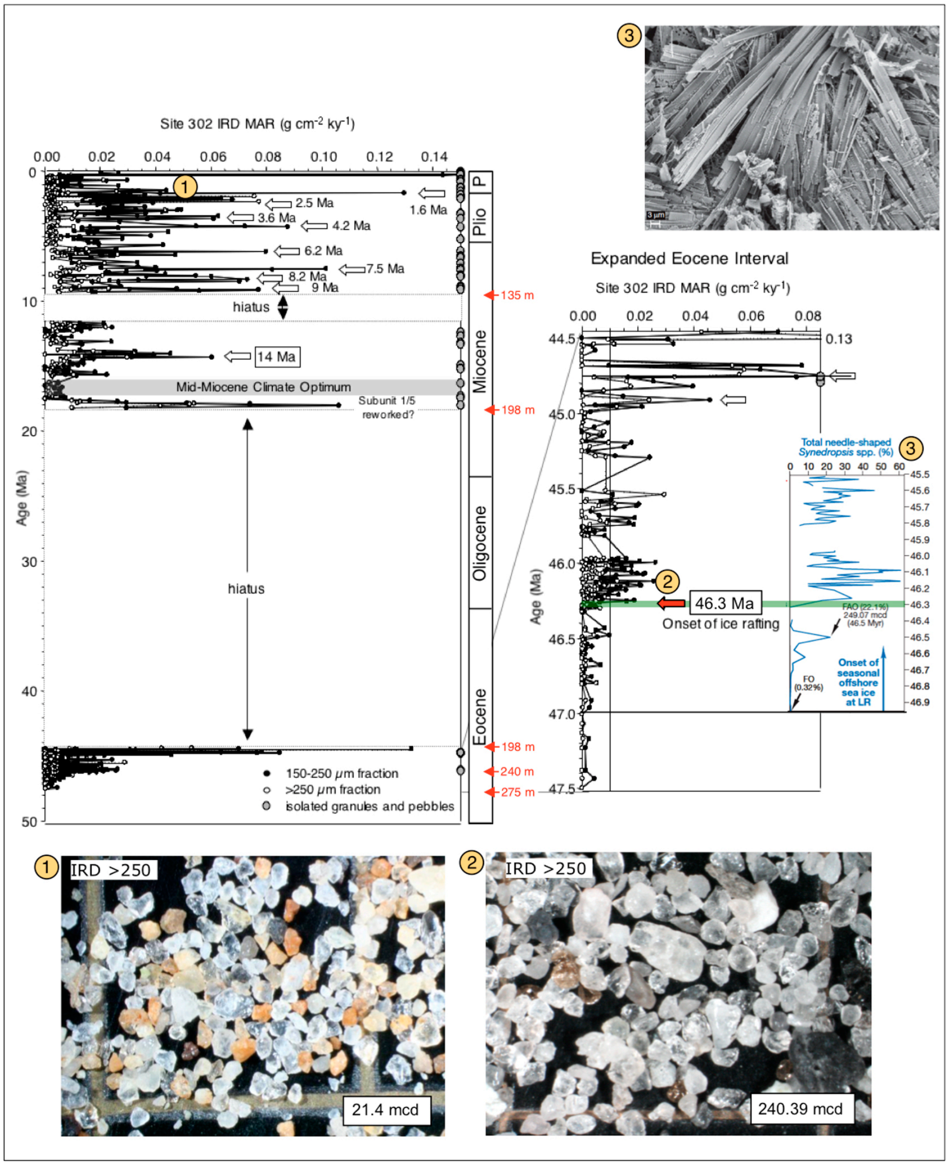

Figure F9. Total organic carbon contents as determined in the composite ACEX sedimentary sequence (Stein, 2007). Data on recovery, stratigraphy, and lithologic units (1–4) and subunits (1/1 to 1/6) from Backman et al., 2006. Cam = Campanian, LP = late Paleocene, L.Pl. = late Pleistocene. Map with Eocene paleogeography from Stickley et al., 2009.

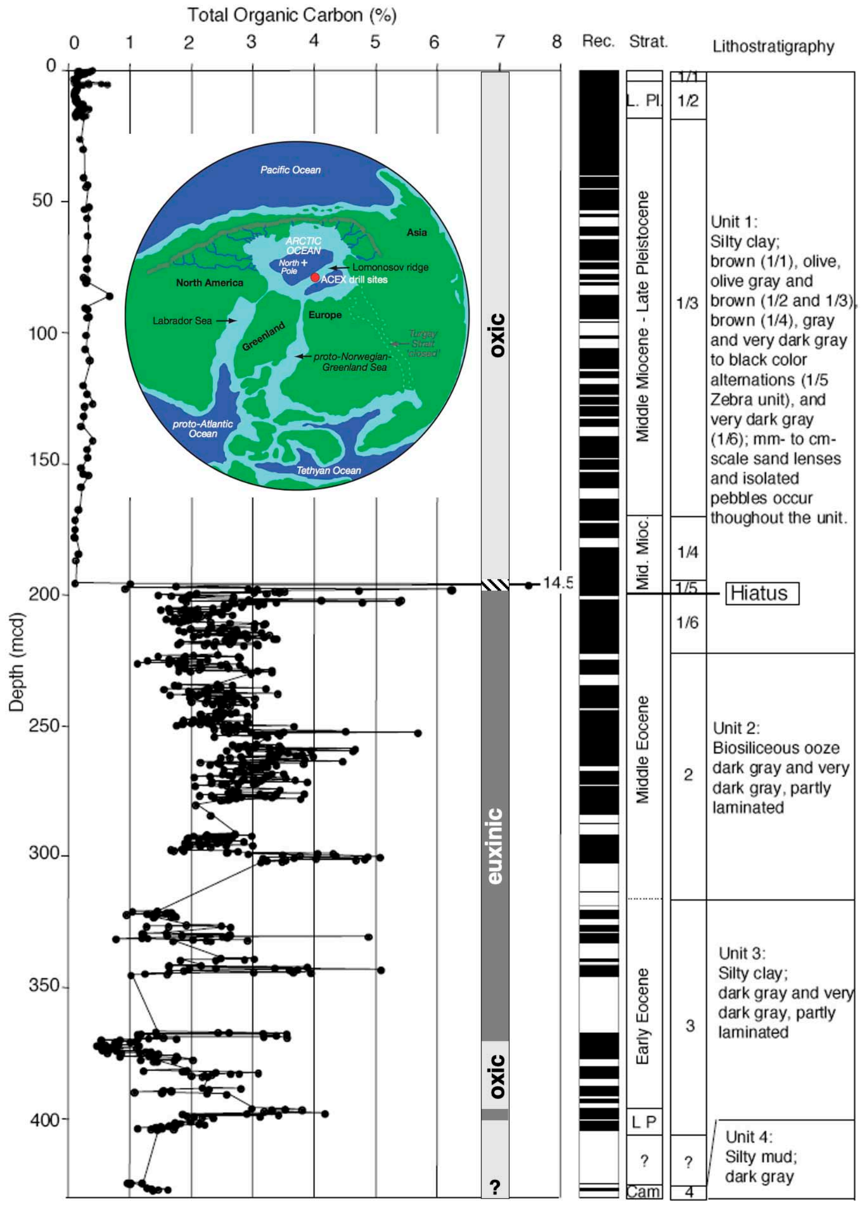

Figure F10. Transect of selected sediment cores recovered across the southern Lomonosov Ridge during *Polarstern* expeditions in 1995, 2014, and 2018 showing main lithologies, lithostratigraphy, and still tentative age model (MIS 6 to 1) based on shipboard data and core correlation (Stein et al., 1997; Stein, 2015, 2019a). Core PS115/2-14-3 was recovered at the location of proposed IODP Site LR-06A. Map shows locations of Polarstern cores (white circles: 1995; blue circles: 2014; black circles: 2018) and eight of the proposed ArcOP sites (large yellow circles).

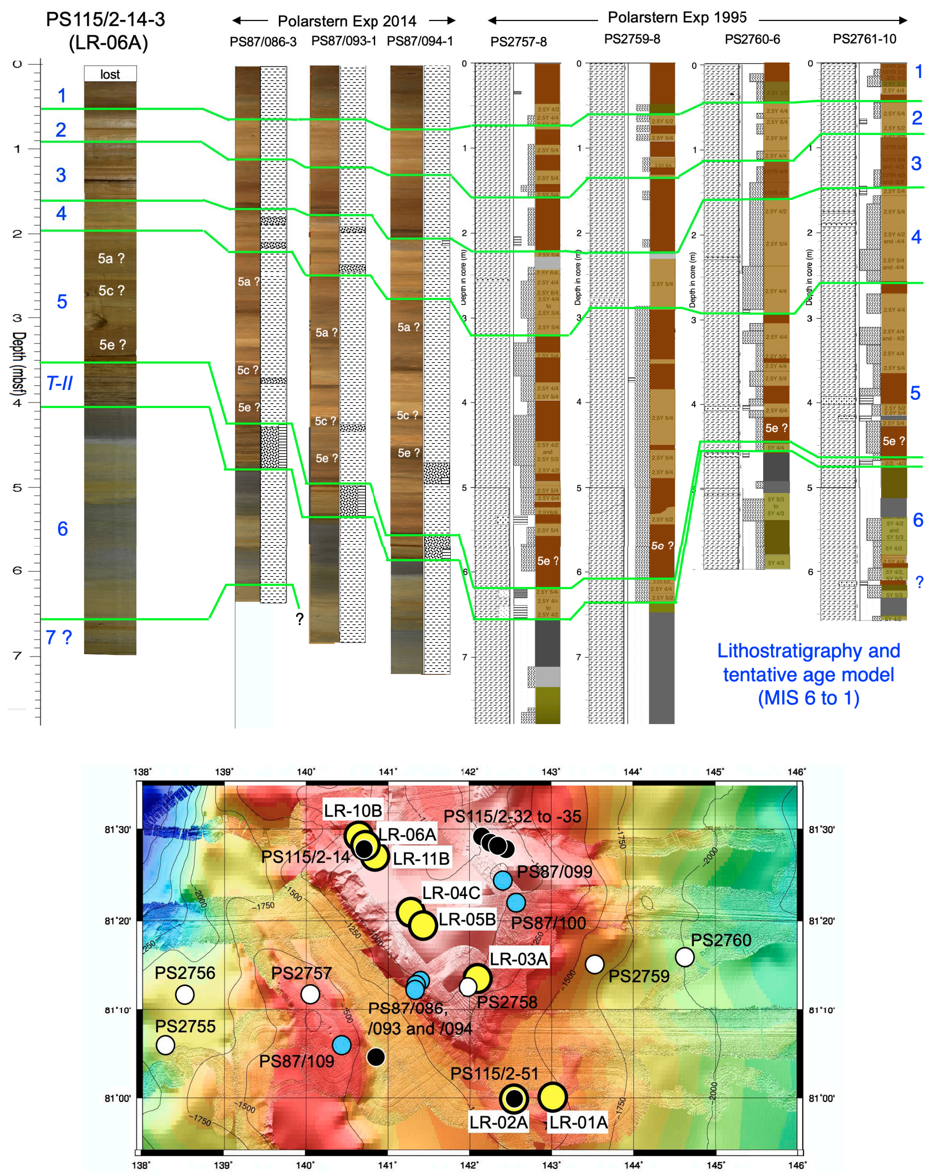

Figure F11. Left: map of southern Lomonosov Ridge with locations of ArcOP primary sites LR-11B and LR-10B and some of the ArcOP alternate sites. Black lines = seismic profiles.Right: seismic profile across sites LR-11B and LR-10B with main seismic units and depths of prominent reflectors separating the Eocene–Oligocene, Miocene, and Pliocene–Quaternary (Stein, 2019b).

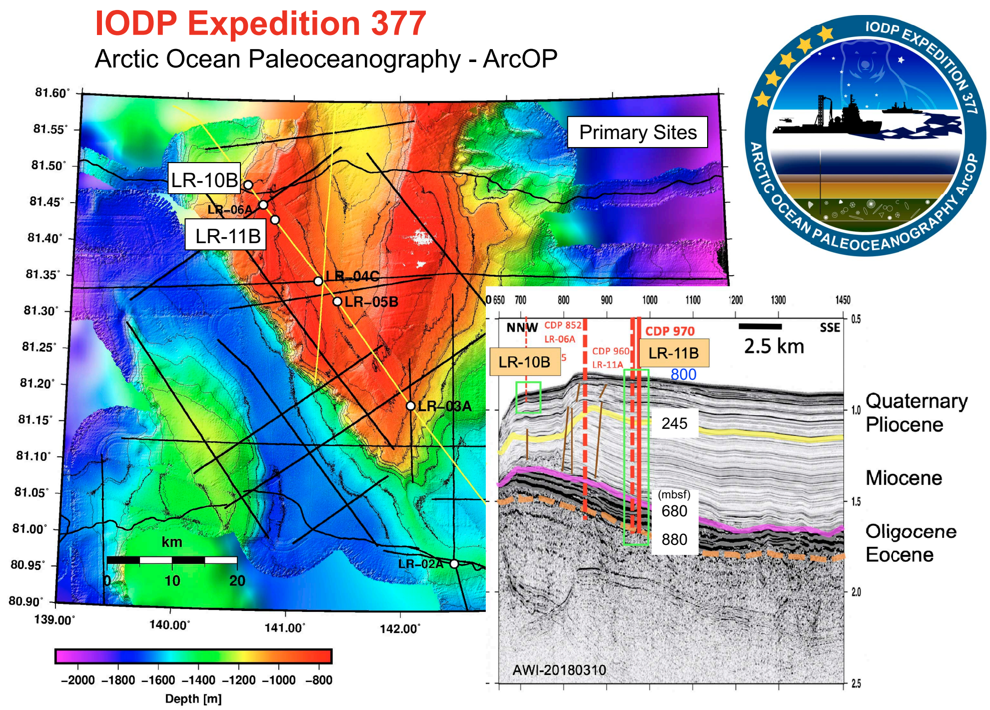

Figure F12. Example of seismic sections (locations on map: red lines) demonstrating conformities in reflection pattern, marker horizons, and reflector configurations across large parts of the Siberian part of the Arctic Ocean. These similarities enable a data transfer from remote drill sites (map: blue circles) onto seismic profiles (map: yellow lines) (Weigelt et al., 2014). Age information was extrapolated from drill sites on the Chuckchi shelf (Sherwood et al., 2002), ACEX drilling on the central Lomonosov Ridge (Moran et al., 2006), and onshore geology from the New Siberian Islands (Franke et al., 2004; Kos'ko and Korago, 2009). In these examples, marker horizons defined and inferred via the drill sites on the Chukchi shelf after Hegewald and Jokat (2013) are shown.