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REVIEW ARTICLE

Exploring the long-term Cenozoic Arctic Ocean climate history: a challenge within the International Ocean Discovery Program (IODP)

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Abstract The global climate evolution during Cenozoic times is characterized by the transformation from warm Paleogene oceans with low latitudinal and bathymetric thermal gradients into the more recent modes of circulation characterized by strong thermal gradients, oceanic fronts, cold deep oceans, and cold high-latitude surface waters. Our understanding of this long-term Cenozoic climate history is mainly based on the continuous and high-resolution records from the low and mid-latitudes, whereas records from the high latitudes, especially the high northern latitudes, are strongly limited. From the central Arctic Ocean, information is restricted to sedimentary sections recovered on Lomonosov Ridge during the single scientific drilling campaign of the Integrated Ocean Drilling Program (IODP) in 2004—the "Arctic Coring Expedition (ACEX)." By studying the unique ACEX sequence, a large number of scientific discoveries that describe previously unknown Arctic paleoenvironments have been obtained during the last decade. However, major key questions dealing with the Cenozoic climate history of the Arctic Ocean on its course from Greenhouse to Icehouse conditions remain unanswered. In this review paper, we present (1) the main highlights of the ACEX expedition and (2) why there is a need for further scientific Arctic drilling together with the plan, objectives and strategy for a drilling campaign on Lomonosov Ridge ("ACEX2"). ACEX2 is scheduled for 2018 as a mission-specific platform approach within the new International Ocean Discovery Program (IODP).

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Introduction and background

In comparison with the other world oceans, the Arctic Ocean is unique because it is surrounded by the world's largest shelf seas, it is seasonally to permanently covered by sea ice and is characterized by large, strongly enhanced seasonal river discharge (Fig. 1; [2, 50]; for review see Stein [125]). 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 Fram Strait into the North Atlantic, and changes in these export rates of freshwater would result in changes of North Atlantic as well as global oceanic circulation patterns. Climate change in the Arctic may cause major perturbations in the global environment because of changes in sea ice cover and Earth's albedo system, which are important factors with respect to the global thermohaline circulation. Due to complex feedback processes (collectively known as "polar amplification"), the Arctic is both a contributor of climate change and the region that will be most affected by global warming [3, 4, 133]. The Arctic Ocean and surrounding areas thus are and have been subject to rapid and dramatic change. Over the last decades, for example, the extent and thickness of Arctic sea ice has decreased dramatically, which appears to be much more rapid than predicted by climate models (Fig. 1; e.g., [3, 4, 59, 111, 134, 135]).

Despite the importance of the Arctic Ocean in the global climate/earth system, however, this region is one of the last major physiographic provinces on Earth where the short- and long-term geological history is still poorly known

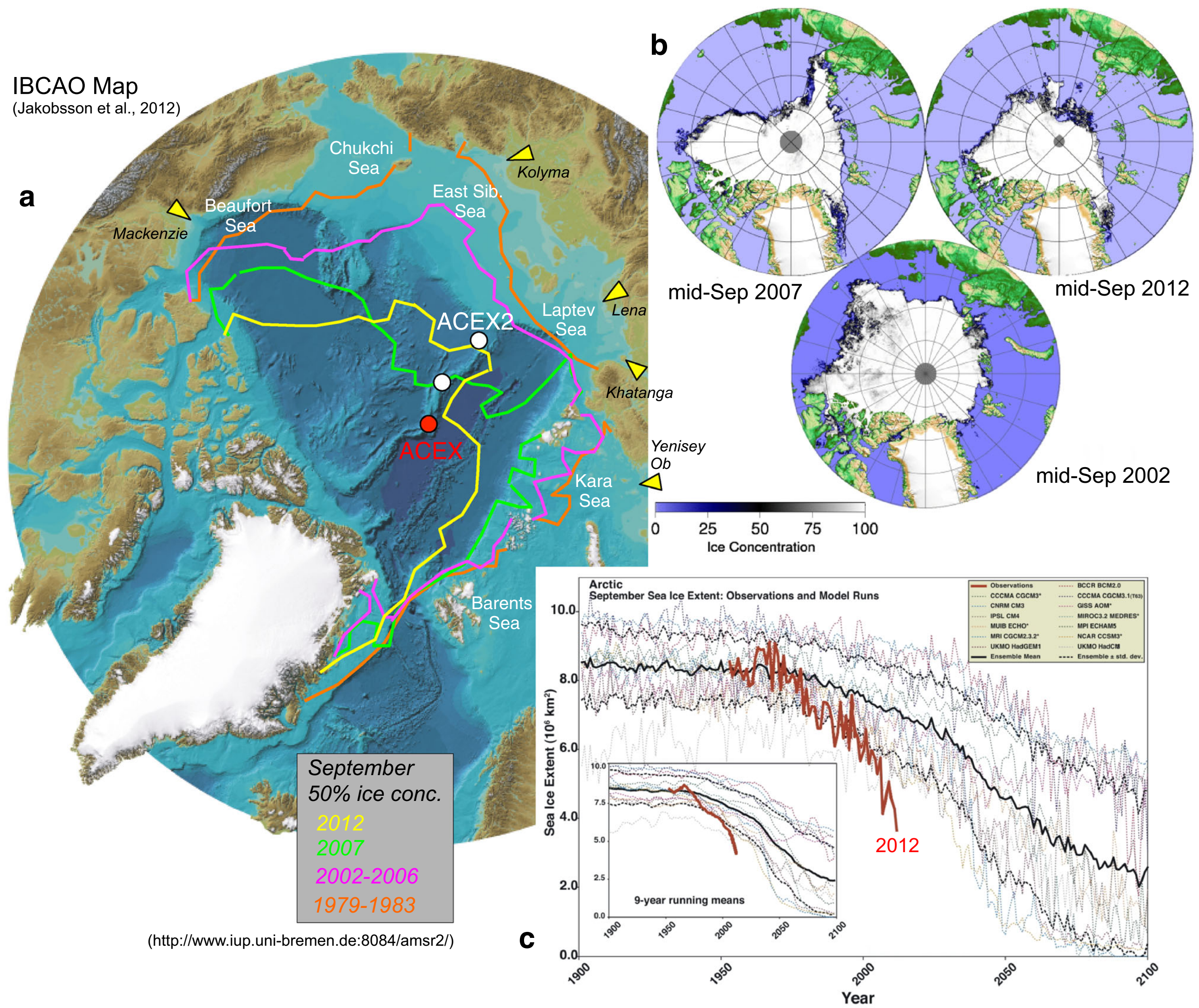


Fig. 1 **a** International bathymetric chart of the Arctic Ocean (IBCAO) [57] with limits of 50 % sea ice concentration in September (*orange*: mean for 1979–1983, *purple*: mean for 2002–2006, *green*: 2007, and *yellow*: 2012; *Source*: http://www.iup.uni-bremen.de:8084/amsr2/; cf., [119]. *Yellow triangles* mark discharge by the major Arctic rivers. ACEX and ACEX2 sites are indicated as *red* and *white circles*, respectively. **b** Maps showing the mid-September sea ice minimum concentrations for the years 2002, 2007, and 2012 (*Source*: http://www.iup.uni-bremen.de:8084/amsr2/; cf., [119]. **c** Arctic September sea ice extent (×106 km^2) from observations (*thick red line*) and 13 IPCC AR4 climate models together with the multimodel ensemble mean (*solid black line*) and standard deviation (*dotted black line*). The absolute minimum of 2012 is highlighted (Fig. from [134, 135], supplemented)

(Fig. 2). This lack in knowledge is mainly due to the major technological/logistical problems in operating within the permanently ice-covered Arctic region which makes it difficult to retrieve long and 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. [20] and CESAR [53]. During the last ~30 years, more than 30 expeditions with a geoscientific focus were carried out (Table 1), and numerous sediment cores were recovered from the main central Arctic Ocean ridges and basins (Fig. 3). Multidisciplinary studies of these sediment cores have greatly advanced our knowledge on central Arctic Ocean paleoenvironment and its variability through Quaternary times. Prior to 2004, however, piston and gravity coring was mainly restricted to the upper 15 m of the sedimentary column. Thus, all studies were restricted to the late Pliocene/Quaternary time interval, with a few exceptions (Fig. 2). In four short cores obtained by gravity coring from drifting ice floes over the Alpha Ridge (for location see Fig. 3), older pre-Neogene organic carbon-rich mud and laminated biosiliceous oozes were sampled. These were the only samples recording the Late Cretaceous/early Cenozoic climate history and depositional environment

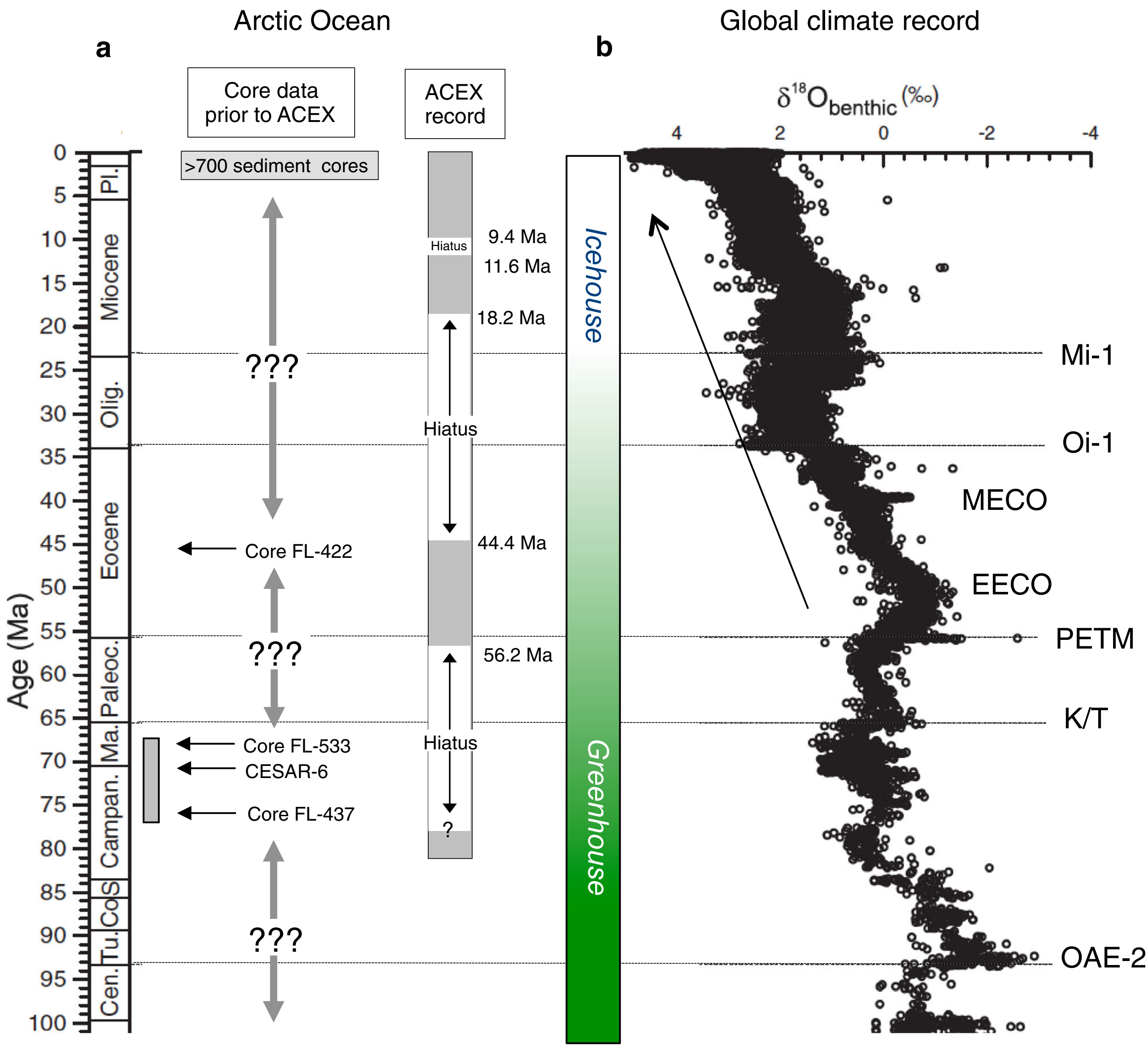


Fig. 2 **a** Stratigraphic coverage of existing sediment cores in the central Arctic Ocean prior to IODP-ACEX [140] and the section recovered during the ACEX drilling expedition [8, 13]. The middle Eocene sediments recovered at Core FL-422 are arbitrarily placed at 45 Ma, the three late Cretaceous (Maastrichtian/Campanian) cores are arbitrarily placed on the time axis as well. Each of these four cores all recovered on Alpha Ridge (Fig. 3) documents a time period of at the most a few hundred kyrs [8]. **b** Global d18O stack of benthic foraminifera for the past 100 million years representing the greenhouse–icehouse transition [39]. *OAE-2* Oceanic Anoxic Event 2, *C/P* Cretaceous/Paleogene Boundary, *PETM* Paleocene–Eocene Thermal Maximum, *EECO* Early Eocene Climate Optimum, *MECO* Middle Eocene Climate Optimum, *Mi-1* Major Miocene glaciation event, *Oi-1* Major Oligocene glaciation event. "?" indicates time intervals not represented in Arctic Ocean sediment cores prior to the ACEX coring campaign in 2004

[21, 28, 29, 37, 53, 58]. In general, these data suggest a warmer and ice-free Arctic Ocean with strong seasonality and high paleoproductivity. Continuous central Arctic Ocean sedimentary records, allowing a development of chronologic sequences of climate and environmental change through Cenozoic times and a comparison with global climate records (Fig. 2), were attempted to be acquired by the Integrated Ocean Drilling Program (IODP) Expedition 302, the so-called Arctic Ocean Coring Expedition—ACEX [13, 88].

With the successful completion of ACEX in 2004, the first mission-specific platform (MSP) expedition within IODP, a new era in Arctic geoscientific research began. For the first time, scientific drilling in the permanently ice-covered central Arctic Ocean was carried out, penetrating 428 m of Upper Cretaceous to Quaternary sediments on the

Table 1 List of selected geoscientific icebreaker cruises to the Central Arctic Ocean

Year of expedition and area	Ship and country	References (Cruise report or related paper)
1980 Nansen Basin, Yermak Plateau	*Ymer* (Sweden)	Schytt et al. [15], Boström and Thiede [110]
1987 Nansen Basin, Gakkel Ridge	*Polarstern* (Germany)	Thiede [137]
1991 Nansen/Amundsen Basin/Lomonosov Ridge	*Oden/Polarstern* (Sweden/Germany)	Andersen and Carlsson [5], Fütterer [41]
1993 Canada Basin/Chukchi Plateau	*Polar Sea* (USA)	Grantz et al. [43]
1993 Nansen Basin	*Polarstern* (Germany)	Fütterer [42]
1994 Transarctic (Canada Basin/Lomonosov Ridge)	*Polar Sea/Louis St. Laurent* (USA/Canada)	Aagaard et al. [1], Wheeler [151]
1995 Amundsen/Makarov Basin/Lomonosov Ridge	*Polarstern* (Germany)	Rachor [102]
1996 Lomonosov Ridge/Makarov Basin	*Oden* (Sweden)	Backman et al. [9]
1997 Fram Strait/Yermak Plateau	*Polarstern* (Germany)	Stein and Fahl [127]
1998 Alpha Ridge/Lomonosov Ridge	*Polarstern/Arktika* (Germany/Russia)	Jokat [63], Jokat et al. [63]
2000 Mendeleev Ridge	*Akademic Fedorov* (Russia)	Kabańkov et al. [66]
2001 Nansen Basin/Gakkel Ridge (AMORE)	*Healy/Polarstern* (USA/Germany)	Thiede [138]
2001 Nansen Basin/Lomonosov Ridge	*Oden* (Sweden)	Grönlund [44]
2004 Yermak Plateau	*Polarstern* (Germany)	Stein [122]
2004 Lomonosov Ridge (ACEX)	*Vidar Viking/Oden/Sovetskij Soyuz* (IODP)	Backman et al. [13]
2005 Transarctic (HOTRAX)	*Healy/Oden* (USA/Sweden)	Darby et al. [27]
2007 Eur. Cont. Marg/Nansen Basin/Lomo-, Alpha Ridge	*Polarstern* (Germany)	Schauer [108]
2007 Lomonosov Ridge off Greenland (LOMROG)	*Oden/50 Let Pobedy* (Sweden/Russia)	Jakobsson et al. [56]
2008 East Sib. Sea/Alpha-Mendeleev Ridge (AMEX)	*Polarstern* (Germany)	Jokat [61]
2011 Eur. Cont. Marg/Nansen Basin/Lomo-, Alpha Ridge	*Polarstern* (Germany)	Schauer [109]
2014 East Sib. Sea/Lomonosov Ridge (SWERUS)	*Oden* (Sweden)	Gustafsson and Jakobsson [45]
2014 Lomonosov Ridge (ALEX)	*Polarstern* (Germany)	Stein [123]

This list is certainly not complete. Several other Arctic expedition were carried out during the last one to two decades, e.g., the six Chinese National Arctic Research Expeditions with the icebreaker *XueLong* in 1999, 2003, 2008, 2010, 2012 and 2014 and the five Korean *Araon* expeditions between 2010 and 2015 into the Bering Strait, Chukchi Borderland, Alpha-Mendeleev Ridge and Canada Basin area. In addition, there were numerous national and international expeditions carried out in the circum-Arctic marginal seas as well as the Norwegian–Greenland Sea including Fram Strait, all not listed here

crest of Lomonosov Ridge between 87 and 88°N (Fig. 4; [8, 11–13, 88]). The Lomonosov Ridge, a 1800-km-long continental fragment broken off of the Eurasian continental margin near 56 Ma and separated by sea-floor spreading during the Cenozoic [60, 64, 65, 74], was identified as target area as the elevation of the ridge, ~3 km above the surrounding abyssal plains, indicates that sediments on top of the ridge have been isolated from turbidites and are likely of purely pelagic origin (mainly biogenic, eolian, and/or ice-rafted). The ACEX coring sites were carefully selected based on comprehensive geophysical data sets, including seismic reflection profiles [63–65, 75], high-resolution chirp profiles [55], and SCICEX swath bathymetry and sidescan sonar backscatter data [33]. Main objectives of the ACEX drilling campaign focused on the reconstruction of Cenozoic Arctic ice, temperatures, and climates. Some of the key questions to be answered from ACEX were framed around the evolution of sea ice and ice sheets, the past physical oceanographic structure, Arctic gateways, links between Arctic land and ocean climate, and major changes in depositional environments [8, 12, 13]. To date, the ACEX sites remain the only scientific deep sea drilling location in the central Arctic Ocean (Fig. 3).

This initial scientific drilling effort in the central Arctic Ocean was preceded by several workshops (Table 2) during which key scientific objectives as well as key areas for drilling were identified. Here, the science plan of NAD science committee [139] and the implementation plan of the Nansen Arctic drilling program [90] as well as the final report of the Ocean drilling program (ODP) "Arctic's role in GLOBAL climate change program planning group (APPG)" [51] deserve to be mentioned. This early phase of

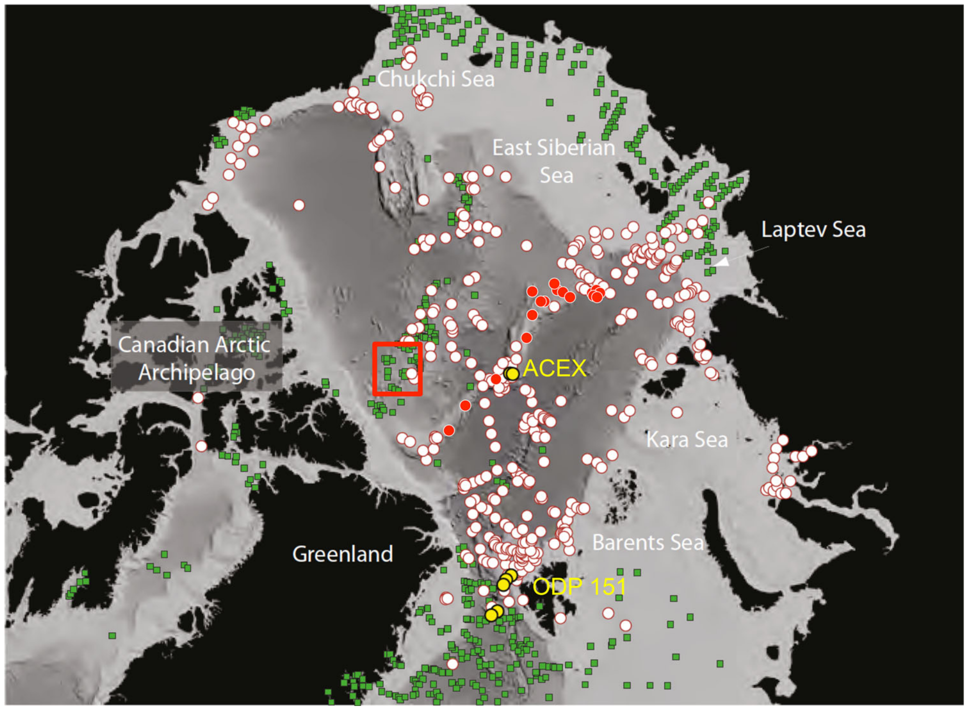


Fig. 3 Locations of gravity and piston cores from the Arctic Ocean [93], supplemented). *Green squares* = data downloaded from http://www.geomapapp.orgwww.geomapapp.org. *White circles* compiled data from ice-breaker led expeditions during the past 30 years, added by locations of gravity cores recovered during the 2014 *Polarstern* Expedition (*red circles*; [123]. *Yellow circles* ODP Leg 151 and IODP Exp 302/ACEX sites. *Large redlined square* indicates the area on the Alpha Ridge where short sediment cores with upper Cretaceous and Eocene sediments were recovered

planning subsequently resulted in ODP/IODP Proposal 533 [7]; http://www.eso.ecord.org/docs/533.pdf) that went through the ODP/IODP review system between 1998 and 2003 (Table 3) and finally was scheduled as IODP Expedition 302 in 2004.

The present publication is composed of two parts. In the first part, highlights of the first IODP drilling campaign ACEX are summarized, mainly extracted from a recent review by Stein et al. [131]. In the second part, the need for further scientific Arctic drilling and the plan, objectives, and strategy of a future IODP drilling on Lomonosov Ridge scheduled for 2018 are outlined. This second part is mainly based on the IODP Proposal 708—"ACEX2" (Table 3; [130]).

Highlights of the ACEX record

The ACEX Cenozoic record holds significant scientific discoveries that describe previously unknown paleoenvironments [11, 12]. Already the first results from some screening studies of the >400-m-thick sedimentary sequence, such as visual core description, smear-slide analyses, and total organic carbon (TOC) measurements [13, 124], suggest drastic paleoenvironmental changes through time. Whereas the upper half of the ACEX sequence (Subunits 1/1–1/4) is composed of silty clay with very low TOC contents of <0.5 %, i.e., values very similar to those known from upper Quaternary records determined in gravity cores from Lomonosov Ridge [125], the lower half of the ACEX sequence (Units 2–4) are characterized by high TOC values of 1 to >5 % (Fig. 5). In Subunit 1/5 (about 193–199 mcd) characterized by distinct gray/black color bandings ("Zebra Unit"), TOC maxima of 7–14.5 % were measured in samples from the black horizons [124].

By studying the unique sedimentary sequence recovered during ACEX in 2004, about 100 papers in highly ranked international peer-reviewed scientific journals have been published throughout the last decade. Key themes discussed in these papers are listed in Table 4. Some of the ACEX paleoceanographic themes and highlights with reference to the original literature are summarized here in some more detail (see also [11, 12, 125, 131]).

The ACEX age model: still an open question

A most important prerequisite of all types of paleoceanographic and paleoclimatic reconstructions is the development of precise chronologies. Backman's et al. [8] stratigraphic framework of the Cenozoic ACEX sequence, widely used in the scientific literature so far, is based on biostratigraphic, cosmogenic isotope, magneto- and cyclostratigraphic data. Based on age/depth control points, Neogene and Paleogene sedimentation rates reach values of about 1 and 2.4 cm ky^{-1}, respectively (Fig. 6). Although this ACEX age model may confirm that the average sedimentation rate mostly is >1 cm ky^{-1} (cf., [10]), a highly resolved and robust age model for the

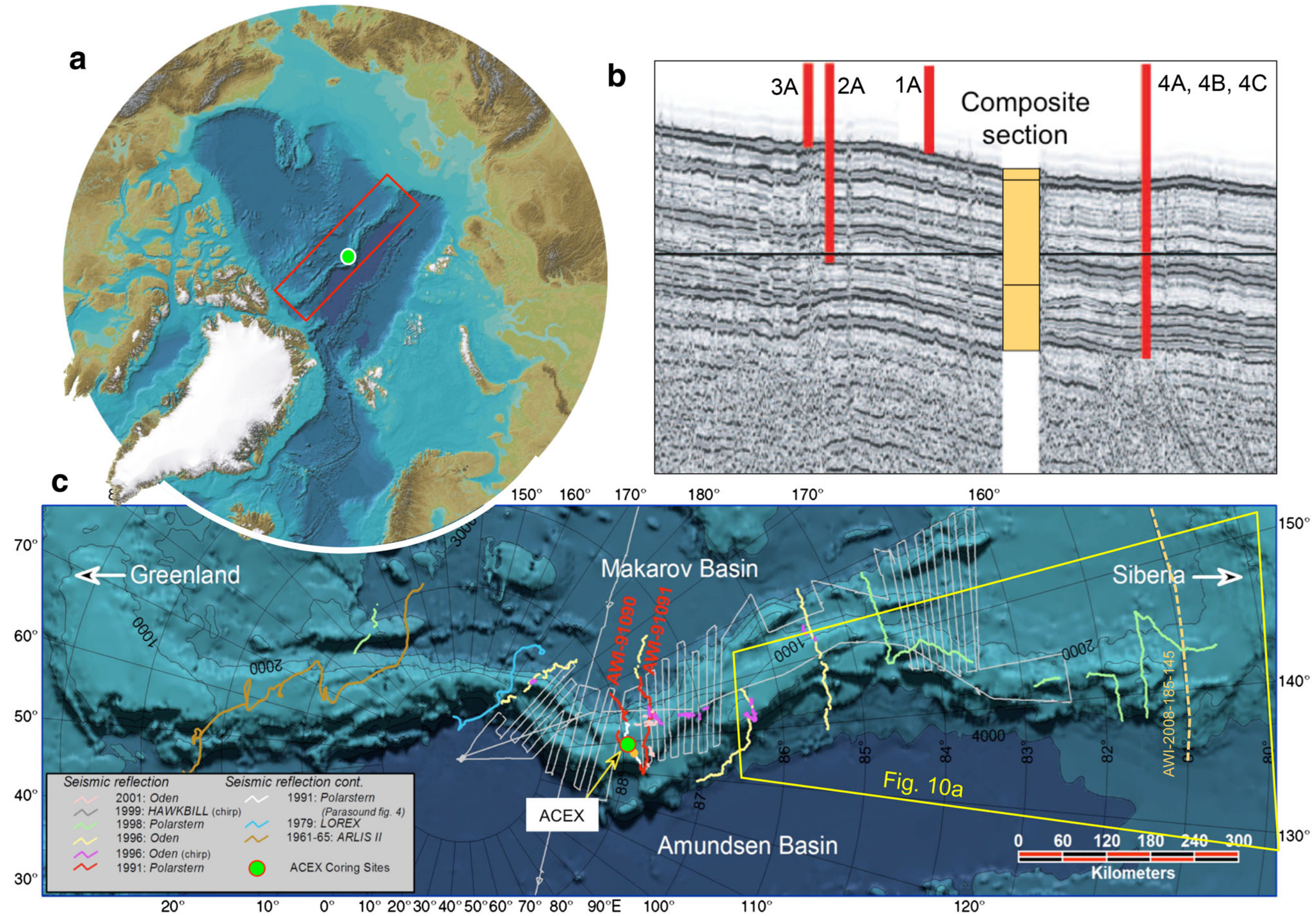


Fig. 4 **a** International bathymetric chart of the Arctic Ocean [57]. The ACEX site is shown as *green circle*, the *redlined rectangle* marks the area of Lomonosov Ridge shown in detailed in (**c**). **b** Seismic profile AWI 91090 across the Lomonosov Ridge, interpreted as continental crust truncated by a regional unconformity overlain by a continuous sediment sequence [64]. The four ACEX sites were positioned on this profile, shown as *solid vertical lines*. At each of the four sites (1–4), multiple holes (*A*, *B*, *C*) were drilled, and a composite section has been obtained [13]. **c** The ACEX coring sites have been carefully selected based on comprehensive geophysical data sets, including seismic reflection profiles [63–65, 75], high-resolution chirp profiles [55], and SCICEX swath bathymetry and sidescan sonar backscatter data [33]. The area of Lomonosov Ridge shown in Fig. 11a is marked

Table 2 International workshops carried out for planning Arctic Ocean drilling

Arctic drilling workshop Halifax December 1986
Arctic drilling workshop Ottawa June 1988
First Nansen arctic drilling (NAD) meeting Washington DC, 1989
NAD workshop Stockholm 1990 (Thiede et al. [139])
NAD workshop St. Petersburg 1996 [90]
ODP PPG "Arctic's role in global change" [51]
JEODI Arctic drilling workshop Copenhagen 2003 [76]
Arctic drilling workshop Bremerhaven November 2008 [22]
Arctic drilling workshop Copenhagen November 2011 (Lead PI: N. Mikkelsen)
Arctic drilling workshop San Francisco December 2011 (Lead PI: C. Ruppel)
Arctic drilling workshop Kananaskis February 2012 (Lead PI: M. O'Regan)
Arctic drilling workshop Columbus/Ohio March 2013 (Lead PI: L. Polyak)

References for workshop reports or name of lead PI are listed in brackets

Table 3 Steps of proposal submission and review of ACEX [7] and ACEX2 [130]

ACEX submissions		ACEX reviews		ACEX2 submissions		ACEX2 reviews	
533-Pre	1998–03	SSEP	1998-05	708-Pre1	2006-09	SSEP	2006-11
533-Full	1999-03	SSEP	1999-05			SSP	2007-02
533-Full2	1999-10	SSEP	1999-11	708-Pre2	2009-09	SSEP	2009-11
		SSP	2000-02	708-Full	2013-10	SEP	2014-01
		External	2000-02			External	2014-02
533-Add	2000-03	SSEP	2000-05	708-PRL	2014-02	SEP	2014-02
533-PRL	2000-04	SSP	2000-07			EFB	2014-03
		SCICOM	2000-08			SEP	2014-06
		SSP	2001-02	708-Add	2015-03	EFB	2015-04
533-PRL2	2001-07	SSP	2001-07				
		SCICOM	2001-09	Acronym	Name of panel	Acronym	Name of panel
533-Full3	2002-03	iSSEP	2002-06	SSEP	Science steering & evaluation panel	SEP	Science evaluation panel
		iSSP	2002-07	SSP	Site survey panel	EFB	ECORD facility board
		iPC	2002-08	SCICOM	Science committee	External	External review by experts outside ODP/IODP
		iSSP	2003-02	iSSEP	Interim science steering & evaluation panel		
		iPPSP	2003-06	iSSP	Interim site survey panel		
		iSSP	2003-07	iPC	Interim planning committee		
		SPC	2003-09	iPPSP	Interim pollution prevention & safety panel		

ACEX cores is still challenging due to the poor core recovery (about 1/3 of the penetrated section was not recovered), the occurrence of an unexpected major hiatus, the limited availability of biostratigraphic indicators, and the enigmatic preservation of the geomagnetic polarity record [8]. Recently, Poirier and Hillaire-Marcel [101] report rhenium–osmium (Re–Os) isochron ages and complementary Os—isotope measurements, together with new carbon and nitrogen data, that give information on the redox state of the sediment during deposition, and may allow a better assessment of the timing of events involved. Based on their new data, these authors also challenged the existing age model and the existence of a major hiatus between subunits 1/6 and 1/5. That means, they proposed an improved age model that closes the gap in the ACEX record, resulting in a continuous sedimentary section with three to five times lower sedimentation rates (0.2–0.8 cm ky^{-1}) between about 49 and 12 Ma (Fig. 6). The Os ages, of course, would significantly modify the reconstructions of the tectonic evolution of Lomonosov Ridge and the paleoceanographic history of the Arctic Ocean.

When using the Re–Os and organic carbon records, one should have in mind that these sediments contain significant amounts of reworked Eocene organic matter, on which the Re–Os records are measured. The palynology confirms the presence of late Eocene and even Oligocene elements in Subunit 1/5 ("Zebra") [8, 105, 106]. However, the presumed in situ aquatic palynomorphs are 99 % quasi-monotypic assemblages of previously unknown dinocysts that have morphologic similarity with early Miocene ones [107]. This points to a restricted marine, or perhaps even freshwater setting, extremely unlikely to have occurred during the Eocene or even Oligocene [105]. Furthermore, there are also massive geochemical breaks in this section that may point to discontinuous sedimentation [105, 106]. More long sedimentary records from the Arctic Ocean are needed to resolve these issues and related paleoenvironmental reconstructions.

Prominent paleogene events of anoxia: PETM event, elmo event, and azolla event

The Paleocene/Eocene Thermal Maximum (PETM) event, a relatively brief period of widespread, extreme climatic warming [71, 104, 144, 155, 156], and probably associated with massive atmospheric greenhouse gas input [31], was identified in the ACEX record by the occurrence of the dinocyst species *Apectodinium augustum*, which is diagnostic of the PETM [19], as well as a distinct negative anomaly in δ13Corg (Fig. 7) [98, 116, 117, 128]. During the PETM event, the Arctic Ocean surface water temperatures reached maximum values around 25 °C as reconstructed from TEX86 data [116, 117]. These are values

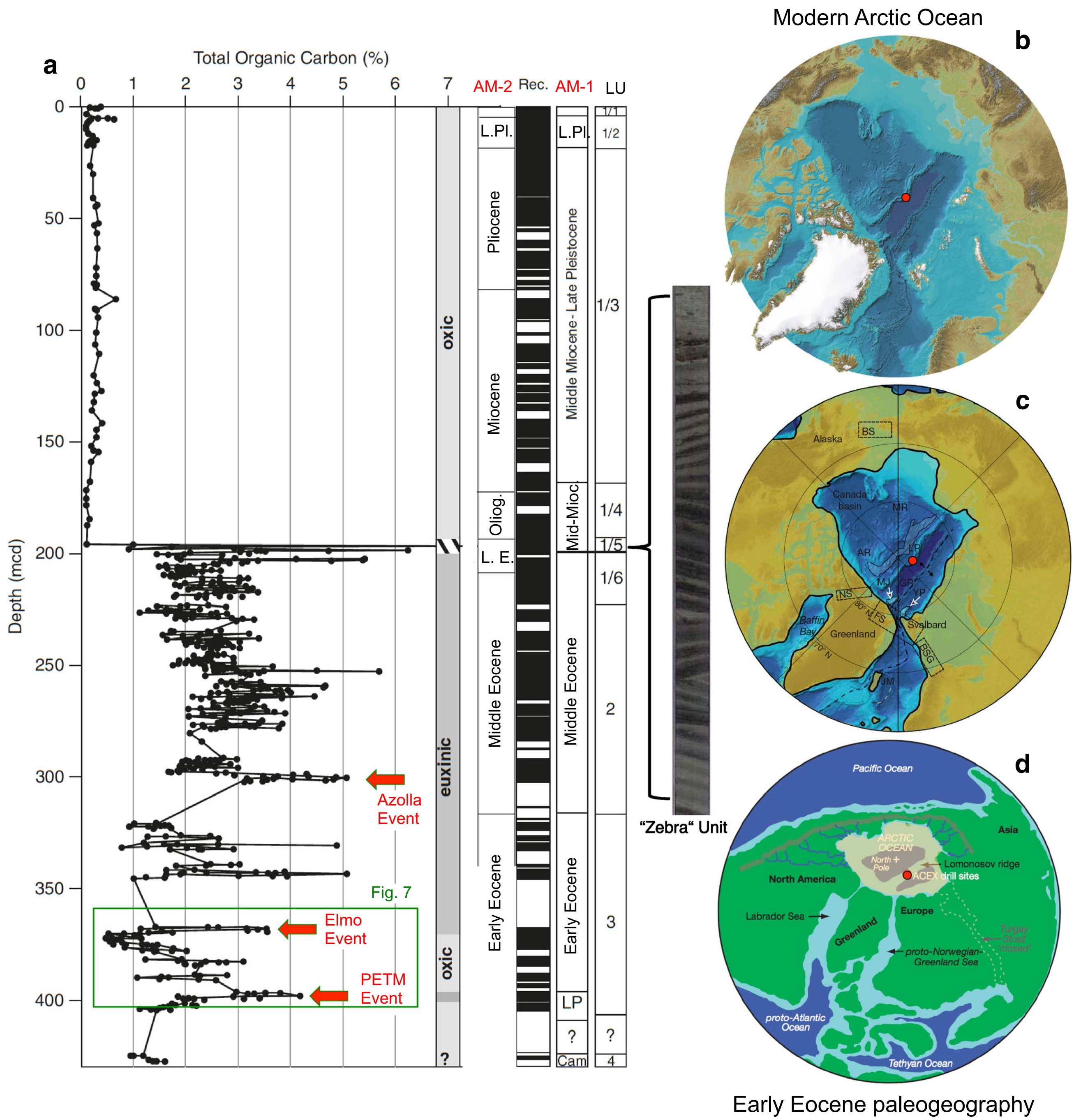


Fig. 5 **a** Record of total organic carbon (TOC) contents as determined in the composite ACEX sedimentary sequence [124]. Data on lithological units (LU) and core recovery (Rec.) from Backman et al. [13]. The "Zebra" Unit (Unit 1/5) marks the transition between an euxinic ocean and an oxygenated ocean that occurred when the formerly isolated Arctic Ocean became connected to the world ocean via Fram Strait (Fig. 5c). *Cam* Campanian, *LP* late Paleocene, *Mid Mioc*. middle Miocene, *L.Pl.* late Pleistocene. PETM, Elmo (ETM2), and *Azolla* events are indicated. Age models AM-1 [8] and AM-2 [101] are shown (cf., Fig. 6). For more details and data of the PETM-Elmo time intervals see Fig. 7. **b** International Bathymetric Chart of the Arctic Ocean [57] representing modern boundary conditions with connections to the world ocean. **c** Paleogeographic/paleobathymetric reconstruction for the late early Miocene. *BSG* Barents Sea Gateway, *JM* Jan Mayen Microcontinent, *KR* Knipovich Ridge, *MJ* Morris Jessup Rise, *NS* NaresStrait, *YP* Yermak Plateau [54], supplemented). **d** Paleogeography of the Arctic region for the early–middle Eocene during the phase of biosilica production and preservation and euxinic conditions (50–45 Ma) [18, 132]. The ACEX drill site is marked as *red circle*. "?" indicates uncertainties in the stratigraphy

Table 4 Main research themes and related papers of ACEX

ACEX objective/topic	References
Stratigraphy and chronology	Backman et al. [8], Frank et al. [38], O'Regan et al. [94], Matthiessen et al. [83], Kaminiski et al. [68], Onadera and Takahashi [95, 96], Poirier and Hillaire-Marcel [100, 101], Sangiorgi et al. [107], Setoyama et al. [112]
Description and analysis of microfossil assemblages	Eynaud et al. [36], Kaminiski et al. [68], Onadera et al. [97], Onadera and Takahashi [95, 96], Setoyama et al. [112], Suto et al. [136], Matthiessen et al. [83, 84], Sangiorgi et al. [107]
Subtropical warm conditions during PETM and the early–middle Eocene	Sluijs et al. [116, 117], Weijers et al. [149], Weller and Stein [150], Ogawa et al. [92], Stein et al. [131]
Arctic Ocean hydrological cycle during the Paleogene	Brinkhuis et al. [18], Pagani et al. [98], Waddell and Moore [147]
Black shales and euxinic conditions in the Eocene Arctic Ocean	Moran et al. [88], Stein et al. [128, 131], Stein [124], Knies et al. [72], Mann et al. [81]
Orbital forcing and environmental response during the Paleogene	Pälike et al. [99], Sangiorgi et al. [106], Spofforth et al. [120]
Early onset of Arctic sea ice and NHG in the middle Eocene	Moran et al. [88], St. John [121], Stickley et al. [132], Immonen [52]
Early (Miocene/Eocene) Arctic perennial versus seasonal sea ice	Darby [25, 26], Krylov et al. [77], Matthiessen et al. [83, 84], Kender and Kaminski [69], Stein et al. [131], Trembley et al. [143]
Arctic gateway evolution and circulation changes	Jakobsson et al. [54], Kaminski et al. [68]
Neogene paleoenvironmental changes	Cronin et al. [23], Haley et al. [46], Eynaud et al. [36], Matthiessen et al. [83, 84]
Tectonic/subsidence history of Lomonosov Ridge	Moore et al. [87], O'Regan et al. [94]

significantly higher than previous estimates of 10–15 °C [146] and model predictions [114, 142], indicating a distinctly lower equator-to-pole temperature gradient than previously believed [116].

With the PETM event, a drastic change in TOC content and composition of organic carbon (OC) is obvious, pointing to a prominent change in the environmental conditions (Fig. 7). Terrigenous OC is predominant in the late Paleocene, whereas the amount of labile OC significantly increased across the PETM as indicated by increased hydrogen index values as well as increased preservation of algae-type biomarkers [125, 131, 150]. The increased preservation of labile algae-type OC is related to a major change to euxinic conditions, as indicated by a drastic decrease in the C/S values, the occurrence of pyrite framboids [128], the absence of benthic foraminiferal linings [116], and the occurrence of fine lamination [13]. During the PETM, euxinic conditions expanded even into the photic zone as suggested from the occurrence of the biomarker isorenieratene related to photosynthetic green sulfur bacteria which requires euxinic conditions to thrive [115, 116, 150]. Toward the end of the PETM event in the earliest Eocene, a gradual return to a more terrestrial influence is obvious and oxic conditions reoccurred as clearly reflected in all geochemical proxies (Fig. 7).

Within the lower Eocene section of the ACEX sequence (at about 368 mcd), an event with similar characteristics as the PETM event was identified for the first time by Stein et al. [128] based on a prominent δ13Corg minimum (Fig. 7). This event may correlate with the global "Elmo (or ETM2) Event" representing a second (smaller) global thermal maximum [80]. In the ACEX record, this interval is characterized by significantly increased OC contents mainly composed of labile algae-type organic matter, as reflected in Rock–Eval data and biomarker composition. Furthermore, low C/S ratios (<1) point to an euxinic environment permitting the preservation of the labile OC (Fig. 7; [128, 150]).

The lowermost middle Eocene OC-rich section of the ACEX sequence (about 299–305 mcd; Fig. 5), representing the time interval between about 49 and 48.3 Ma, are composed of microlaminated sediments with extraordinary abundances of microspore clusters (massulae) of the free-floating freshwater fern *Azolla* [18]. *Azolla* is typically known from modern freshwater bodies, such as ponds, canals and flooded rice paddies in tropical, subtropical, and warm temperate regions, and cannot tolerate salinities higher than 1–1.6 ‰ [6, 103]. Based on (1) the presence of mature megaspores with and without attached massulae, (2) single, small groups, and large clusters of massulae and probable aborted megaspores of *Azolla*, and (3) support by

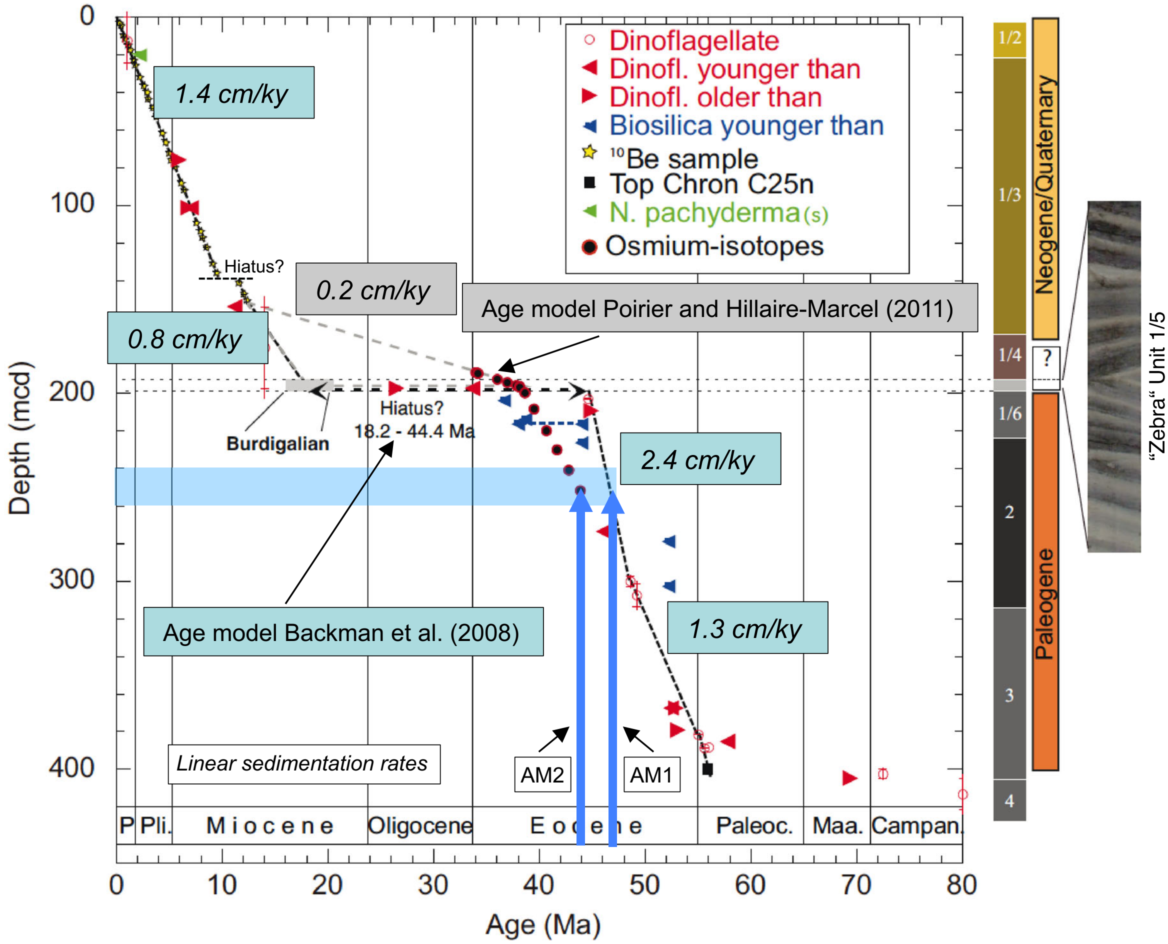


Fig. 6 Age/depth diagram and main lithological units of the ACEX section [93], supplemented, based on the biostratigraphically derived age model by Backman et al. [8]. The alternate chronology based on osmium isotopes [101] is also shown. Depth of first occurrence of IRD between 240 and 260 mcd are marked as *light blue horizontal bar*. The different ages of the first occurrence of IRD, obtained by the two age models—AM1 = Backman et al. [8], AM2 = Poirier and Hillaire-Marcel [101]—are indicated by the *blue arrows*. Mean sedimentation rates (cm/ky) are indicated. Figure from O'Regan [93], supplemented. "?" indicates uncertainties in the stratigraphy

the relative scarcity of terrestrially derived palynomorphs and extremely low BIT index values of <0.1 (indicating low river-derived terrestrial organic matter), Brinkhuis et al. [18] favor the idea that *Azolla* grew and reproduced in situ in the Arctic Ocean rather than being brought in by periodic mass transport from freshwater bodies on adjacent continents. That is to say, the *Azolla* event probably represents a distinct episodic freshening of Arctic surface waters lasting about 700–800 kyrs [14, 24, 118]. The freshening of surface waters supports stratification of water masses, causing the euxinic conditions reflected in the C/S diagram, with C/S ratios <1 [128, 131].

Early onset of Arctic sea ice formation and cooling of sea surface temperatures

From subarctic ice-rafted debris records in the Norwegian–Greenland Sea, Iceland Sea, and Irminger Sea and Fram Strait area, it has been indirectly inferred that the Northern Hemisphere Glaciation (NHG) began at about 14 Ma [40, 141, 152, 153]. Glaciation of Antarctica, on the other hand, began much earlier, with large ice sheets first appearing near the Eocene/Oligocene boundary at about 34 Ma [35, 70, 79, 85, 86, 113, 155, 156]. The ACEX results, however, push back the date of Northern Hemisphere cooling and onset of sea ice into the Eocene as well. The first occurrence of sea ice-related diatoms, contemporaneously with IRD, was at about 47–46 Ma (when using the ACEX age model of Backman et al. [8]; "Age Model 1") or ~43 Ma (when using the alternate chronology of Poirier and Hillaire-Marcel [101]; "Age Model 2") (Fig. 8). Iceberg transport was probably also present in the middle Eocene, as indicated by mechanical surface texture features on quartz grains from this interval [121, 132]. An early onset/intensification of NHGs during Eocene times is also supported by IRD records from the Greenland Basin ODP Site

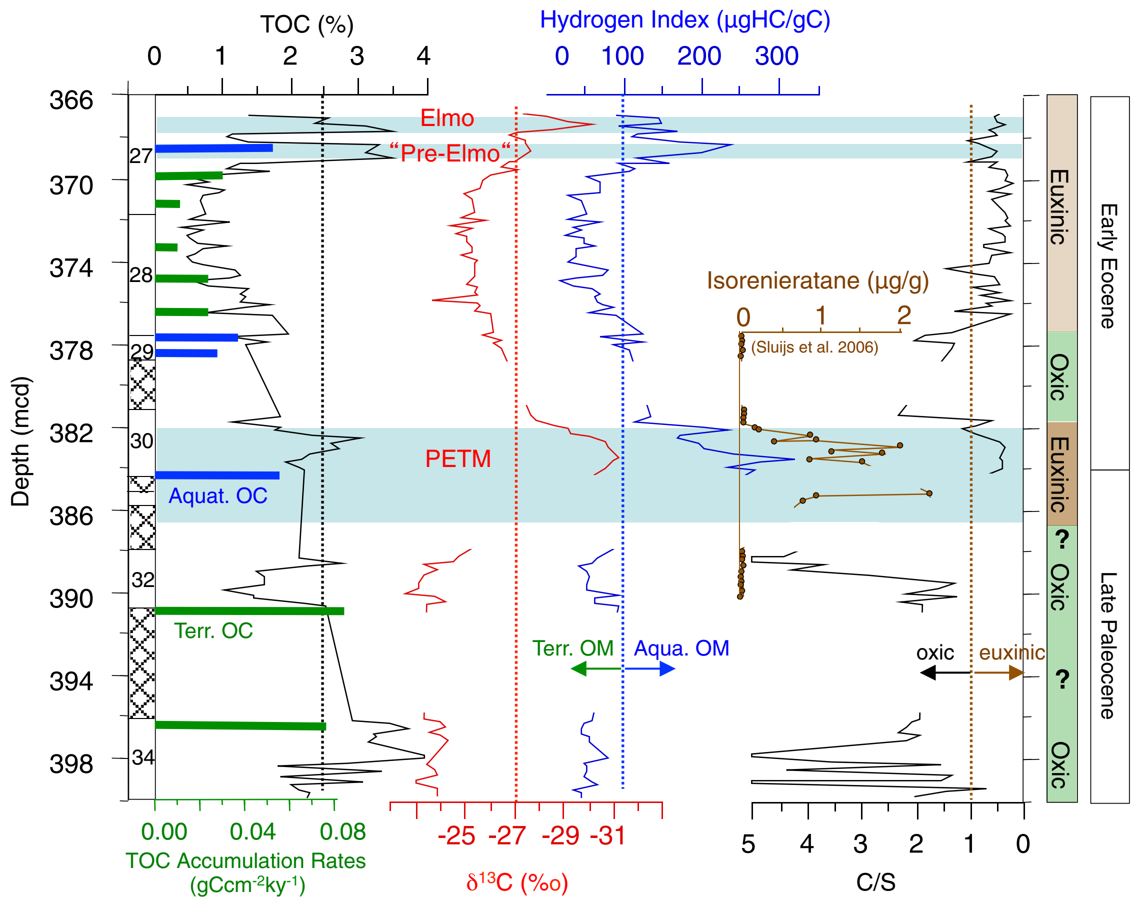


Fig. 7 TOC contents, TOC accumulation rates (*green bars*: terrigenous organic matter; *blue bars*: aquatic/marine organic matter), δ13C of the organic matter, hydrogen index values obtained by Rock–Eval pyrolysis, and C/S values with interpretation in terms of euxinic versus oxic conditions for the earliest Eocene/late Paleocene time interval of the ACEX reord, including the PETM and Elmo events [128, 129]. The δ13Corg Elmo Event is probably preceded by another distinct (euxinic) event of increased preservation of algae-type OC (or can be divided into two subevents). In addition, the occurrence of the biomarker isorenieratene across the PETM Event is shown [116]. The numbers 27–34 at the *left-hand side* are core numbers, crossed intervals are coring gaps. "?" indicates intervals where classification "oxic vs. euxinic" is not possible due to missing data/samples

913 [34, 145]. These findings suggest that Earth's transition from the Greenhouse to the Icehouse world was bipolar, which points to greater control of global cooling linked to changes in greenhouse gases in contrast to tectonic forcing [8, 13, 30, 88, 132].

The cooling trend and onset of sea ice formation recorded in the ACEX record, coinciding with the global post-EECO cooling trend [156], are also reflected in the ACEX sea surface temperature (SST) (Fig. 8; [131]. Prior to about 47 Ma (44 Ma* = "Age Model 2"), warm SST values between 18 and 26 °C were predominant, interrupted by a prominent, short-lived cooling to 5–10 °C event near 47.3 Ma (44.5 Ma*). At about 46.3 Ma (41.5 Ma*), summer SST dropped down to <17 °C (range 8–17 °C), coinciding with a significant increase in ice-rafted debris (IRD) [121, 132]. An absolute SST minimum of 6–8 °C was reached at about 44.8 Ma (37.8 Ma), followed by a short but prominent warm phase with a SST around 17 °C near 44.6 Ma (37.5 Ma*). This warming event is characterized by the absence of IRD (Fig. 8), interpreted to reflect lack of sea ice. Apart from this warm event, however, widespread sea ice seems to be the more typical phenomenon of the Arctic Ocean after about 45.5 Ma (40.5 Ma*) (Fig. 8).

Overall, the Arctic SST values remain surprisingly high, even in the upper part of our ACEX record. The apparent paradox of coincidence of such a warm SST and sea ice, however, can be explained. Assuming that the alkenone SST represents rather the summer SST and considering the strong seasonal temperature variability of >10 °C during the early–middle Eocene (see above), favorable conditions for sea ice formation may have occurred during winter time. That means, after about 46.3 Ma (41.5 Ma*) the environmental conditions in part of the Arctic Ocean might have been similar to that observed in the modern Baltic Sea where summer SSTs of >15 °C and winter SSTs <1 °C with sea ice formation are typical [73, 154].

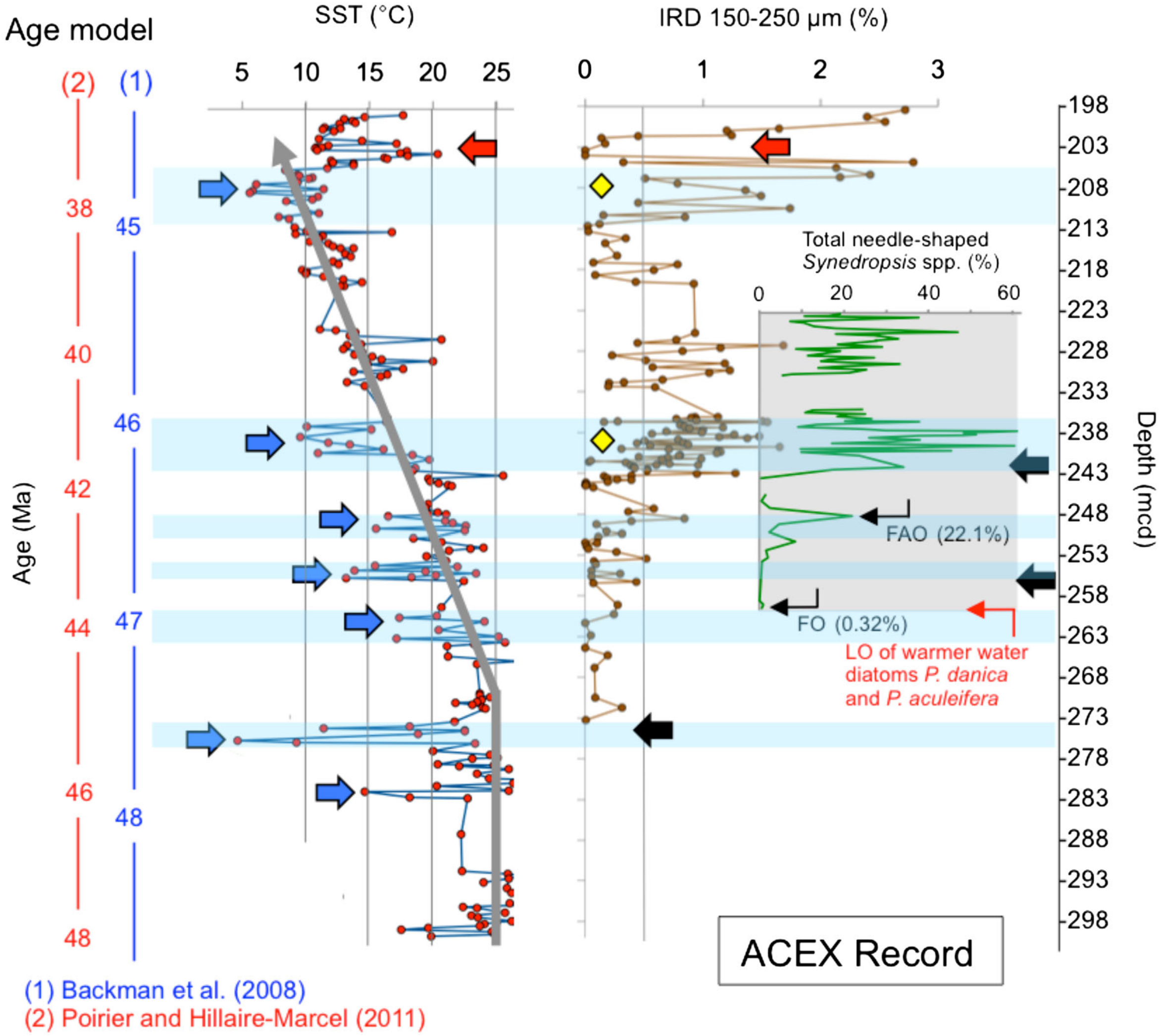
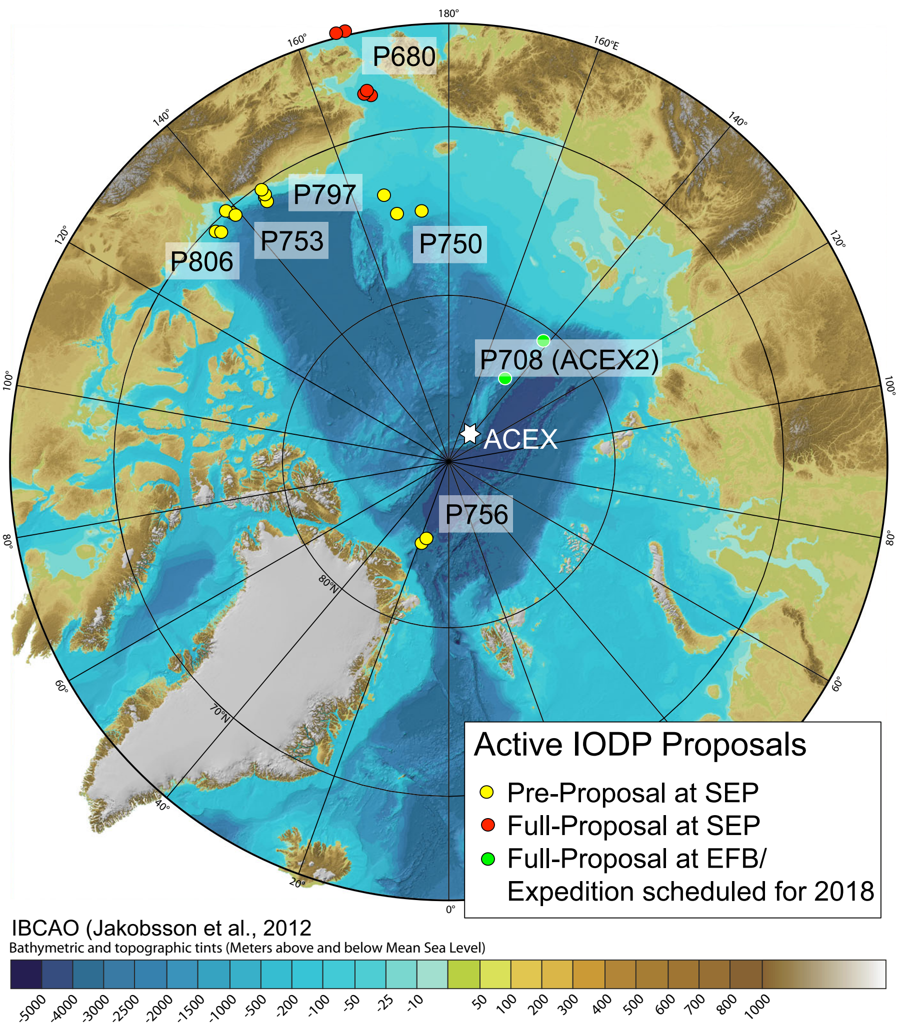


Fig. 8 Alkenone-based sea surface temperature (SST) [131] and abundance of ice-rafted debris (IRD) [121], determined in the ACEX sequence from 298 to 198 m below seafloor (mcd). For the ACEX interval 260–223 mcd, the abundance of sea ice diatom species *Synedropsis* spp. is also shown [132]. In the diatom record, the first occurrence (FO) and 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. The *two yellow* rhombs in the IRD record indicate occurrence of large-sized single dropstones [88]. *Large blue arrows* and *light blue horizontal bars* indicate major cooling events; the large *red arrows* highlight a major warming event near 44.6 Ma. Large *black arrows* indicate major steps/increases in sea ice cover. On the *left-hand side*, the two different age scales discussed in the text, are shown; Age Model 1 [8] and Age Model 2 [101]

In contrast to our interpretation, Darby [26] postulated ephemeral formation of even perennial sea ice in the Arctic Ocean during the middle Eocene. This statement is based on the occurrence of specific coarse Fe grains (IRD) with a distal source area that has a >1-year drift time to the ACEX core site. The onset of deposition of such Fe grains at the ACEX site is almost contemperaneous with the drop in SST as well as the onset of IRD, sea ice diatoms, and $C37_{:4}$ alkenones [131]. The latter data, however, are more indicative for a seasonal sea ice cover. Thus, if present, phases of perennial sea ice should have been more the exception in the middle Eocene, whereas seasonal sea ice should have been the rule. Based on the simulation of ice-drift pattern and velocities under permanent and seasonal ice conditions, Trembley et al. [143] challenged Darby's approach and also support a seasonal Arctic Ocean sea ice cover.

From an euxinic "lake stage" to a fully ventilated "ocean phase"

Black OC-rich, partly finely laminated, biosiliceous silty clays and clayey silts were found throughout the upper lower to middle Eocene of the ACEX record, indicating



Proposal	Main Theme/area	Lead PI
680-Full	Bering Strait Climate Change	S.J. Fowell (USA)
708-Full	Central Arctic Paleoceanography	R. Stein (Germany)
750-Pre	Bering Sea Sea Level	J. Brigham-Grette (USA)
753-Pre	Beaufort Sea Paleoceanography	M. O'Regan (Sweden)
756-Pre	Arctic Ocean Exit Gateway	M. Jakobsson (Sweden)
797-Pre	Alaska Beaufort Margin	**C.** Ruppel (USA)
806-Pre	Beaufort Gas Hydrate	C. Paull (USA)

Fig. 9 Active IODP proposals for drilling in the Arctic Ocean. From the seven proposals, only Proposal 708-Full is ready to go and scheduled for 2018. For each proposal, main area/key theme and lead PI are listed. *SEP* Science Evaluation Panel, *EFB* ECORD Facility Board

poorly ventilated bottom waters and variable primary production [16, 88, 124, 128]. One prerequisite of this extreme paleoenvironmental situation was the paleogeographic boundary setting, i.e., the early Arctic Ocean was isolated from the world ocean in terms of deep-water connections (Fig. 5; [13, 54, 89, 112]). Furthermore, the huge freshwater discharge has favored the development of widespread salinity stratification resulting in a poor ventilation of the subsurface, deeper water masses and causing the high OC preservation rate. A low surface water salinity (brackish) environment during middle Eocene times is also suggested from the rare and sporadic occurrence of radiolarians [13]. Runoff-related low salinity might be indicated as well by the abundance of terrestrial palynomorphs and green algae such as *Tasmanites* and *Botryococcus* [13].

The question how and when the transition from poorly oxygenated to ventilated conditions in the Arctic Ocean did occur, is still under discussion. Subunits 1/4–1/1 (middle Miocene to recent), characterized by very low OC values of <0.5 % (Fig. 5), already represent paleoenvironmental conditions similar to the modern ones, i.e., fully ventilated water masses preventing preservation of high amount of labile algae-type OC. Thus, the transition from euxinic to oxic conditions in the central Arctic Ocean should have occurred within/around "Zebra" Subunit 1/5 (Fig. 5).

Based on a paleogeographic and paleobathymetric reconstruction of the Arctic Ocean, together with a physical oceanographic modelling of the evolving strait and sill conditions in the Fram Strait, Jakobsson et al. [54] suggest that across Subunit 1/5 the Arctic Ocean went from an oxygen-poor "lake stage," to a transitional "estuarine sea" phase with variable ventilation, and finally to the fully ventilated "ocean" phase.

The key question when this change from euxinic to well-oxygenated open marine conditions in the Arctic occurred cannot be answered at present. As proposed by Jakobsson et al. [54], this change was correlated with the tectonically controlled widening of the Fram Strait in the late early Miocene ($\sim$17.5 Ma) if using the age model of Backman et al. [8]. A comparison of the deep-water agglutinated foraminifera assemblages from the Lomonosov Ridge with Miocene assemblages from ODP Hole 909C in the Fram Strait, Norwegian–Greenland Sea [67], suggests that the faunal exchange between the Arctic and the Norwegian Sea and by inference the inflow of Atlantic Intermediate Water into the Arctic probably began earlier, i.e., at least since the Early Miocene [68]. The recent Os–Re isotope dates from the cross-banded and underlying Eocene age biosiliceous-rich sediments of the ACEX sequence suggest that the transition from euxinic to well-oxygenated conditions may have occurred much earlier, i.e., already in the late Eocene (Figs. 5, 6; [100, 101]).

Need for future scientific drilling in the Arctic Ocean: "from ACEX to ACEX2"

While the Arctic paleoceanographic and paleoclimate results from ACEX were unprecedented, major questions related to the climate history development of the Arctic Ocean from Greenhouse to Icehouse conditions during early Cenozoic times remain unanswered, largely due to the major mid-Cenozoic hiatus and partly to the poor recovery of the ACEX record (Fig. 2). In addition to elevated atmospheric CO_2 concentrations in the early Cenozoic, other boundary conditions such as the freshwater budget, exchange between the Arctic and Pacific/Atlantic oceans as well as the advance and retreat of major circum-Arctic ice sheets have changed dramatically during the late Cenozoic. An understanding of how these boundary conditions have 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 global climate [93].

Following up ACEX and its cutting-edge science, several workshops for future Arctic scientific drilling have been carried out (Table 2), and further key areas and key research themes have been identified, resulting in several proposals submitted to IODP (Fig. 9; [22, 126]; http://www.iodp.org/active-proposals). One of these proposals is related to a second scientific drilling on the Lomonosov Ridge with a focus on the reconstruction of the continuous and complete Cenozoic climate history of the Arctic Ocean. A pre-proposal outlining the main objectives was submitted in 2006, followed by a full proposal in 2013 (Proposal Full-708/"ACEX2"; [130]; http://www.iodp.org/expeditions). The Proposal Full-708 (with the Proponent Response Letter/2014 and the Addendum/2015) is mainly based on new site survey data recovered during the *Polarstern* expeditions 2008 and 2014 [61, 123] and went through the IODP review system between 2013 and 2015 (Table 3). Finally, ACEX2 has been scheduled for drilling in 2018.

The primary objectives of ACEX2 share several of those in the original 533-Full3 (ACEX; [7] proposal and also build on what we learned from ACEX. Some of the key scientific themes and questions extracted from the Proposal Full-708 [130] are summarized as follows:

1. History of Arctic ice sheets, sea ice, and global climate Did the Arctic Ocean climate follow the global trend shown in Fig. 2? Are the Early Eocene Climate Optimum (poorly recovered in the ACEX record) and the Oligocene and middle Miocene warmings also reflected in Arctic Ocean records? Did extensive glaciations (such as the Oi-1 and Mi-1 glaciations) develop synchronously in both the Northern and Southern Hemispheres? (Fig. 2; [155, 156]). Did major East Siberian ice sheets occur during late Pliocene–Pleistocene as recently proposed by Niessen et al. [91]? What are the related scale and timing of short- and long-term sea level changes? What is the past variability of Cenozoic sea ice in terms of frequency, extent and magnitude, a pressing scientific question—even after the accomplishment of the first ACEX campaign.
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 (Figs. 5, 7), indicating poorly ventilated bottom waters and high but variable primary production [54, 128]. When and how did the change to oxygenated bottom waters typical for the Neogene and Quaternary Arctic Ocean occur? Was it in the early–middle Miocene as

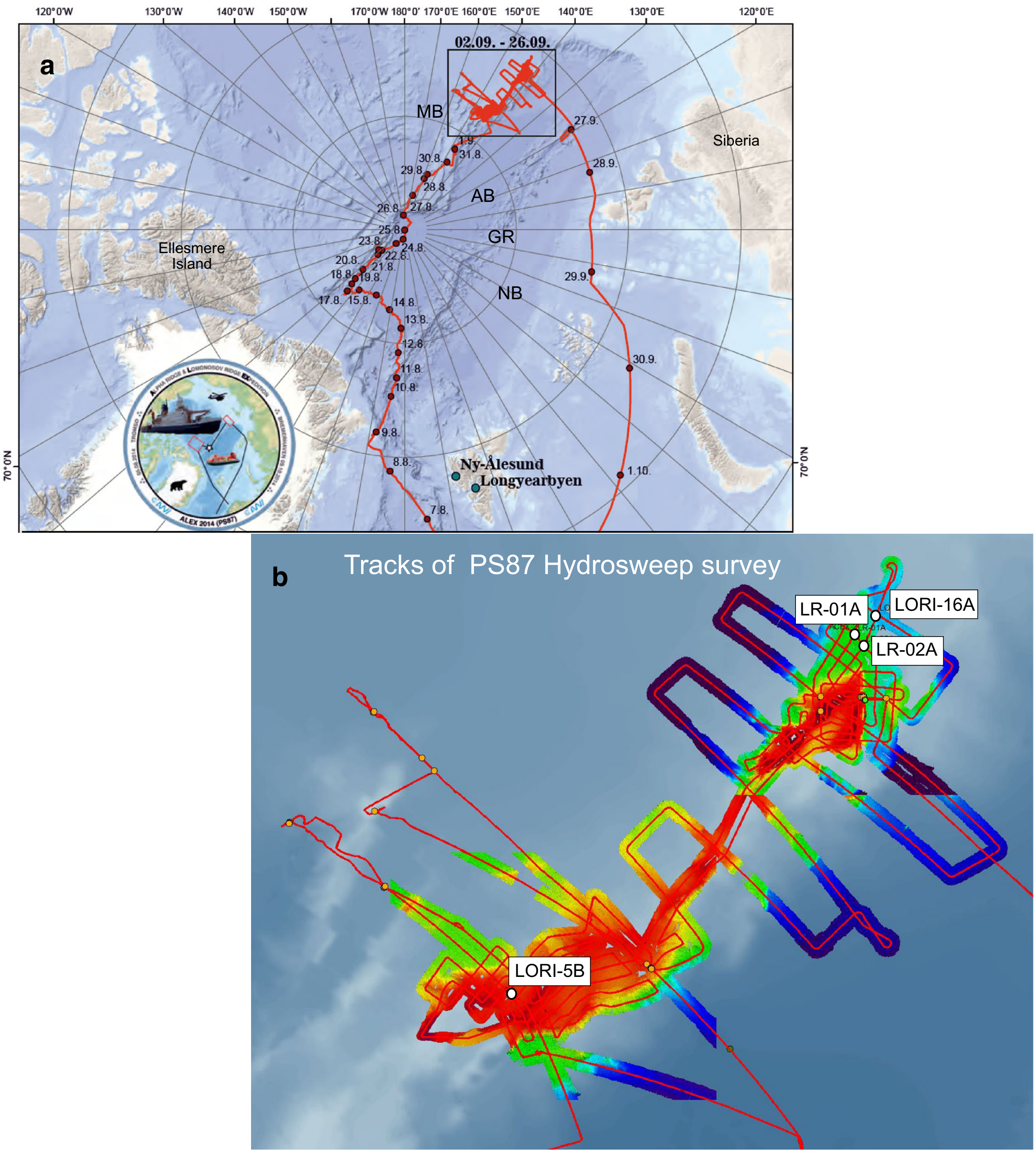


Fig. 10 **a** Cruise track of *Polarstern* Expedition PS87 from Aug 07 to Oct 01, 2014 [123]. *GR* Gakkel Ridge, *MB* Makarov Basin, *AB* Amundsen Basin, *NB* Nansen Basin. Box (Sep 02–26) indicates main PS87 working area with track lines of multibeam bathymetric survey shown in (**b**). **b** Track lines of PS 87 multibeam bathymetric and Parasound echosounding survey [123]. LR-01A, LR-02A, LORI-5B, and LORI-16A indicate locations of proposed IODP drill sites (IODP Proposal 708-Full; http://www.iodp.org/expeditions)

proposed by Jakobsson et al. [54] and Kaminski et al. [68] or the late Eocene as proposed by Poirier and Hillaire-Marcel [101]?

3. History of Arctic river discharge
The more proximal location relative to the Siberian margin of the proposed sites in ACEX2 allows a detailed study of the history of Arctic river discharge and its paleoenvironmental significance. In this context, the Miocene uplift of the Himalayan–Tibetan region is of particular interest as it may have triggered enhanced discharge rates of Siberian rivers and changed the freshwater balance of the Arctic's surface

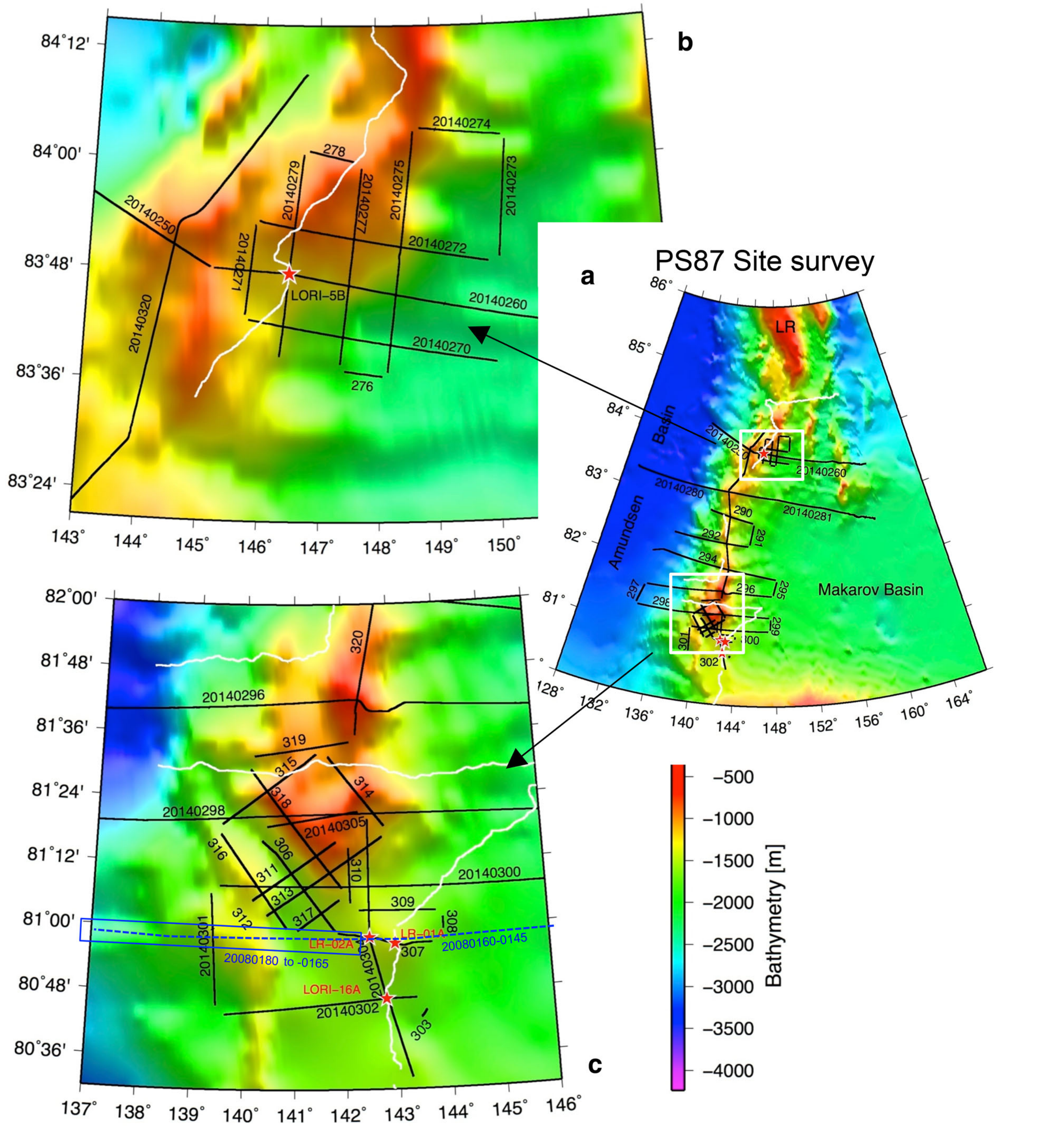


Fig. 11 **a** Overview map of main study of Polarstern Cruise PS87 in the Siberian part of the Lomonosov Ridge (cf. also Fig. 4). The *black lines* indicate the seismic reflection data gathered during the PS87 expedition. *Numbers* represent profile names. The *line numbers* are shortened in the very south to the last three digits. *White lines*: Seismic profiles acquired in 1998; *red stars*: proposed IODP drill sites, LR-Lomonosov Ridge. **b** Detailed survey in the area of a proposed alternate IODP drilling site LORI-5B. *White line*: seismic data gathered in 1998; *black lines*: seismic data gathered during this cruise. **c** Seismic profiles on the southernmost Siberian part of the Lomonosov Ridge, gathered to provide additional information around the primary drilling site LR-01A and the alternate sites LR-02A and LORI-16A. *White lines*: seismic data gathered in 1998; *black lines*: seismic data gathered during this cruise; stippled *blue line*: *seismic lines* AWI-20080145 to 20080180 [61]; red stars: proposed IODP drilling sites. (Fig. 10a–c from Jokat et al. in [123])

Table 5 Summary of ACEX2 site characteristics (based on multichannel seismic data)

Site	LR-01A	LR-02A	LORI-5B
Latitude	80.95°N	80.97°N	83.80°N
Longitude	142.97°E	142.47°E	146.475°E
Water depth	1405 m	1458 m	1334 m
Thickness Pliocene–Pleistocene[#]	170 m (3.2 cm/ky)	195 m (3.7 cm/ky)	303 m (5,7 cm/ky)
Top Miocene (yellow)	165–175 (170) mbsf	170-220 (195) mbsf	275–330 (303) mbsf
Thickness Miocene[#]	643 m (3.6 cm/ky)	705 m (4.0 cm/ky)	345 m (2.0 cm/ky)
Top Oligocene (pink)	790–835 (813) mbsf	880–920 (900) mbsf	635–660 (648) mbsf
Thickness Eocene–Oligocene[#]	312 m (1.0–1.3 cm/ky)	300 m (0.9–1.2 cm/ky)	477 m (1.4–1.9 cm/ky)
Lower Eocene (orange)	1105–1145 (1125) mbsf	1180-1220 (1200) mbsf	1100–1150 (1125) mbsf
Basement (purple)	1668–1681 (1675) mbsf*	1730-1820 (1775) mbsf	??
Penetration total	1225 m	1300 m	1300 m

?? The basement reflector (purple) and its depth cannot be identified for the location of Site LORI-5B

* At site LR-01A, an alternate interpretation of the seismic line is possible for the basement/purple reflector, resulting in a depth of 1777–1885 (1831) mbsf

[#] In brackets mean sedimentation rates are added

waters, considered to be an important factor for the formation of Arctic sea ice and onset of major glaciations [32], a hypothesis to be tested by ACEX2.

4. High-resolution characterization of the Pliocene warm period in the Arctic
   During the Pliocene warm period, sea surface temperature (SST) in several ocean basins was substantially warmer [48, 78, 82] and global mean surface temperature was estimated to be at least ~3 °C higher than today [47]. How did the Arctic Ocean evolve during the Pliocene warm period and subsequent cooling? How do the marine climate records correlate with terrestrial records obtained from the Siberian Lake Elgygytgyn [17]?
5. The "hiatus problem"
   What is the cause of the major hiatus spanning the late Eocene to early Miocene time interval in the ACEX record (based on the original age model of [8]? Does this hiatus in fact exist, or is it rather an interval of extremely reduced sedimentation rate as proposed by Poirier and Hillaire-Marcel ([100, 101]; Fig. 6)? If there is a major hiatus, is it related to the subsidence history of Lomonosov Ridge [94]? Was the hiatus a response to increased bottom water currents during the opening of surface and deep-water connections via the Fram Strait [87]? Additional long sedimentary records from the Arctic Ocean with good microfossil recovery are needed to solve these obvious problems in chronology and related paleoenvironmental and tectonic reconstructions.

Based on the *Polarstern* site survey in 2008 [61], primary and alternate ACEX2 sites were proposed [130]. The main factor for the site selection based on seismic data was 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, locations were selected indicating appropriate thicknesses and depths feasible for drilling into and through the Cenozoic strata of interest. Depth velocity information for estimating the thickness of the sedimentary units was derived from sonobuoys [62].

During the PS87 *Polarstern* Cruise, a new comprehensive site survey, including multibeam-bathymetry, Parasound and seismic profiling as well as sediment coring, was carried out in the area of the proposed four drill sites, i.e., the primary Site LR-01A and the alternate sites LR-02A, LORI-16A and LORI-5B [123]. Detailed bathymetric and high-resolution Parasound profiling (Fig. 10) and high-quality multichannel seismic profiles with crossing lines (Fig. 11) are available from all these four sites. Based on these data, the locations of all the originally proposed sites were approved and further alternate sites selected. During the *Oden* 2014 Expedition ("SWERUS"; [45]), additional multibeam-bathymetry and high-resolution Chirp data have been obtained for the alternate sites LR-02A, LORI-16A and LORI-5B. These *Oden* data perfectly support the PS87 *Polarstern* bathymetry and Parasound records.

Based on the PS87 data, seismic units were clearly identified by their reflection pattern and configuration on the new seismic lines. These data were recorded with a

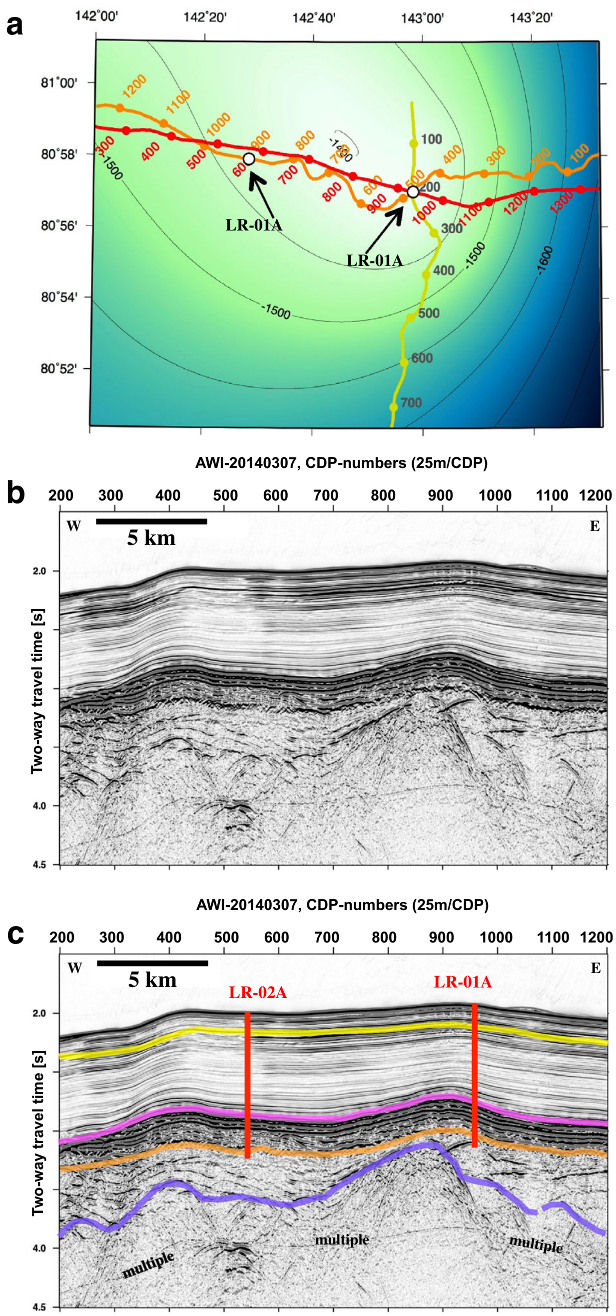


Fig. 12 **a** Map of the southern Lomonosov Ridge/Siberian continental margin area with location of seismic lines AWI-98597 (*yellow*), AWI-20080160 (*orange*), AWI-20140304 (*dark red*) and AWI-20140307 (*red*) annotated using CDP numbers (cf., Fig. 11). **b** Seismic profile of line AWI-20140307 between CDP 200 and 1200. **c** Seismic profile of line AWI-20140307 with interpretation of reflectors. *Top* of Miocene (*yellow reflector*), *top* of Oligocene (*pink reflector*) corresponding to top of the HARS (high-amplitude reflector sequence), and lower Eocene (*orange reflector*) (cf., Table 5). Location and stratigraphic range of drill sites LR-01A and LR-02A are shown

3000-m-long streamer, which enabled a detailed velocity analysis and that permitted a more accurate calculation of the depths of marker horizons and the thicknesses of these units (Table 5). The age control for the sedimentary units was estimated via links of seismic lines to drill site data of the Chukchi Shelf, ACEX drilling on central Lomonosov Ridge, and onshore geology from the New Siberian Islands [49, 148].

At the locations of southern sites LR-01A and LR-02A, the depths of the yellow (Top Miocene), pink (Top Oligocene), and orange reflectors (Lower Eocene) are at 170, 813, and 1125 m, and 195, 900, and 1200 m, respectively (Fig. 12; Table 5). That means, the Pleistocene–Pliocene, Miocene, and Oligogene–Eocene sections to be recovered at these two sites may reach thicknesses of 170 and 195 m, 643 and 705 m, and 312 and 300 m, respectively. At the more northern (more ice-covered) location of Site LORI-5B, the top of the Oligocene can be reached in even shallower depths of about 650 m (Fig. 13; Table 5). Furthermore, the Parasound profiles indicate totally undisturbed, continuous sedimentation in the upper part of the sedimentary sequences at all four site locations (Fig. 14). These carefully selected sites provide the chance to get a continuous Cenozoic sedimentary section that will allow to study the long-term climate change from Greenhouse to Icehouse conditions but also give the chance to study the Neogene–Pleistocene climate history in a higher time resolution than it was possible with ACEX sediments.

As the drill sites are located in the ice-covered Arctic Ocean, a mission-specific platform (MSP) is needed for the drilling operation. In comparison with the work area of the ACEX Expedition in 2004, however, ice conditions of ACEX2 are significantly less severe, especially when looking at the sea ice cover in recent years. In 2007 and 2012, the area of some of the proposed drilling operations was even completely ice-free or close to the ice edge during September (Fig. 1). Nevertheless, ice management operations by means of additional icebreaker support are needed to guarantee safe and successful drilling operations.

The ACEX2 MSP-type drilling campaign has been scheduled by the ECORD Facility Board for late summer/early autumn 2018, and detailed planning activities including selection of drilling platform, ice management etc. by the ECORD Science Operator and the 708 proponents have begun. As general drilling strategy, we propose one primary drill site on southern Lomonosov Ridge, Site LR-01A or in its neighborhood (Fig. 11c). At this site, we propose drilling three APC/XCB/RCB holes down to about 1300 m (Table 5). This is required to ensure recovery of a complete composite stratigraphic sediment record and to meet our highest priority paleoceanographic objective, the continuous long-term Cenozoic climate history of the central Arctic Ocean. Based on its protected location and the existing seismic profiles, a continuous record without a major hiatus is very probable. Logging should be carried out at one of the holes.

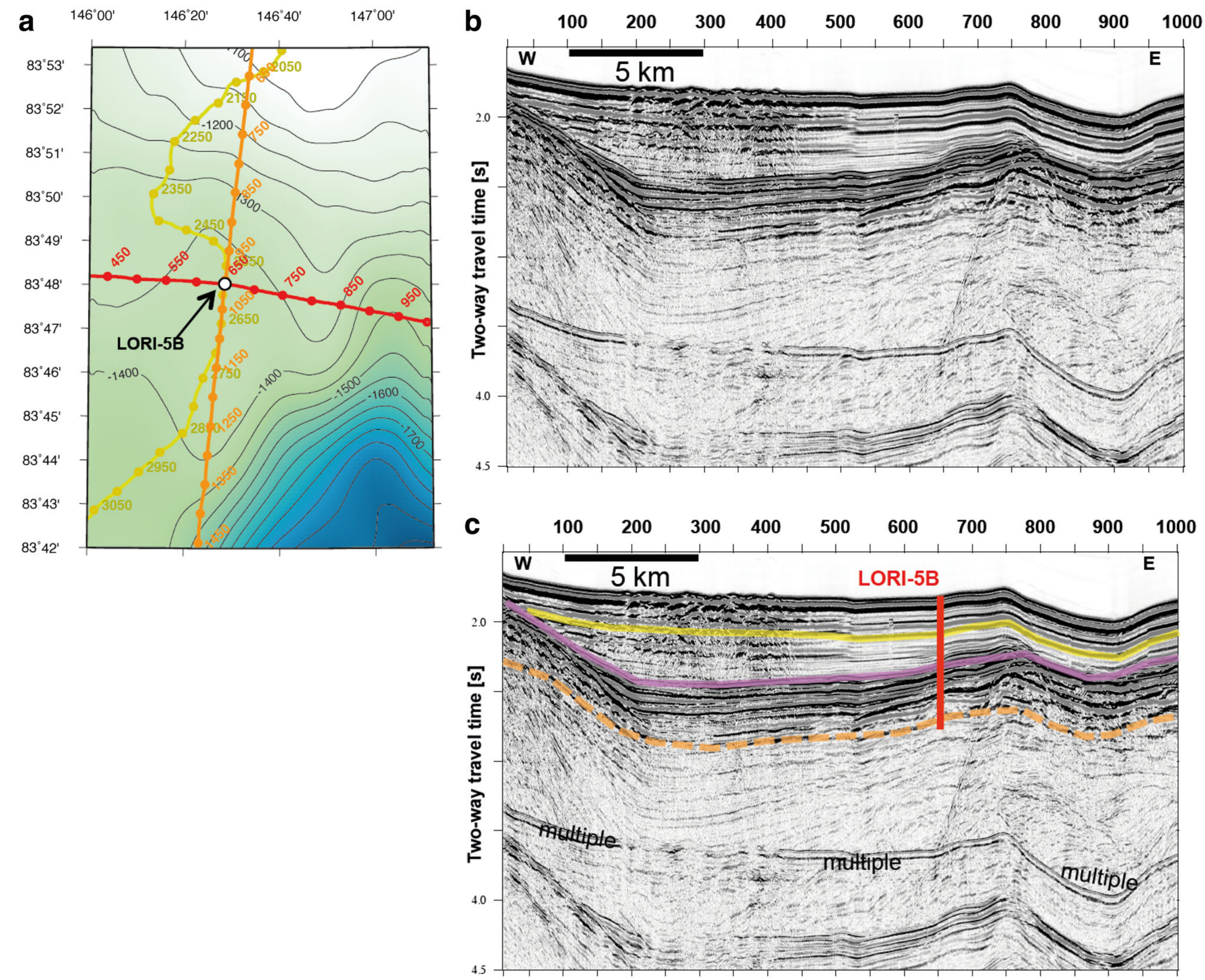


Fig. 13 **a** Detailed map of the area around Site LORI-5B with location of seismic lines AWI-98565 (*yellow*), AWI-20140260 (*red*), and AWI-20140279 (*orange*) annotated using CDP numbers (cf., Fig. 11). **b** Seismic profile of line AWI-20140260 between CDP 0 and 1000. **c** Seismic profile of line AWI-20140260 with interpretation of reflectors. *Top* of Miocene (*yellow reflector*), *top* of Oligocene (*pink reflector*) corresponding to top of the HARS (high-amplitude reflector sequence), and lower Eocene (*orange reflector*) (cf., Table 5). Location and stratigraphic range of drill site LORI-05B are shown

Finally, it must be emphasized that all questions dealing with the Arctic Ocean paleoclimatic (and tectonic) history cannot be answered by one additional expedition. Additional future drilling campaigns will be needed, some of which hopefully can be carried out within the current phase of IODP (Fig. 9; [125, 126]).

Conclusions

As the first scientific drilling in the permanently ice-covered central Arctic Ocean, IODP Expedition 302—the Arctic Coring Expedition (ACEX)—was certainly a benchmark in Arctic geoscientific research. By studying the unique about 400-m-thick ACEX sequence of Upper Cretaceous to Quaternary sediments recovered on Lomonosov Ridge close to the North Pole, a large number of scientific discoveries that describe previously unknown Arctic paleoenvironments, have been obtained during the last decade.

While highly successful, the ACEX record also has three important limitations:

1. Based on the different age models, the ACEX sequence either contains a large hiatus spanning the time interval from the late Eocene to the middle Miocene or a long-lasting time interval of strongly condensed sedimentation rates. In any case, this critical time interval, i.e., when prominent changes in

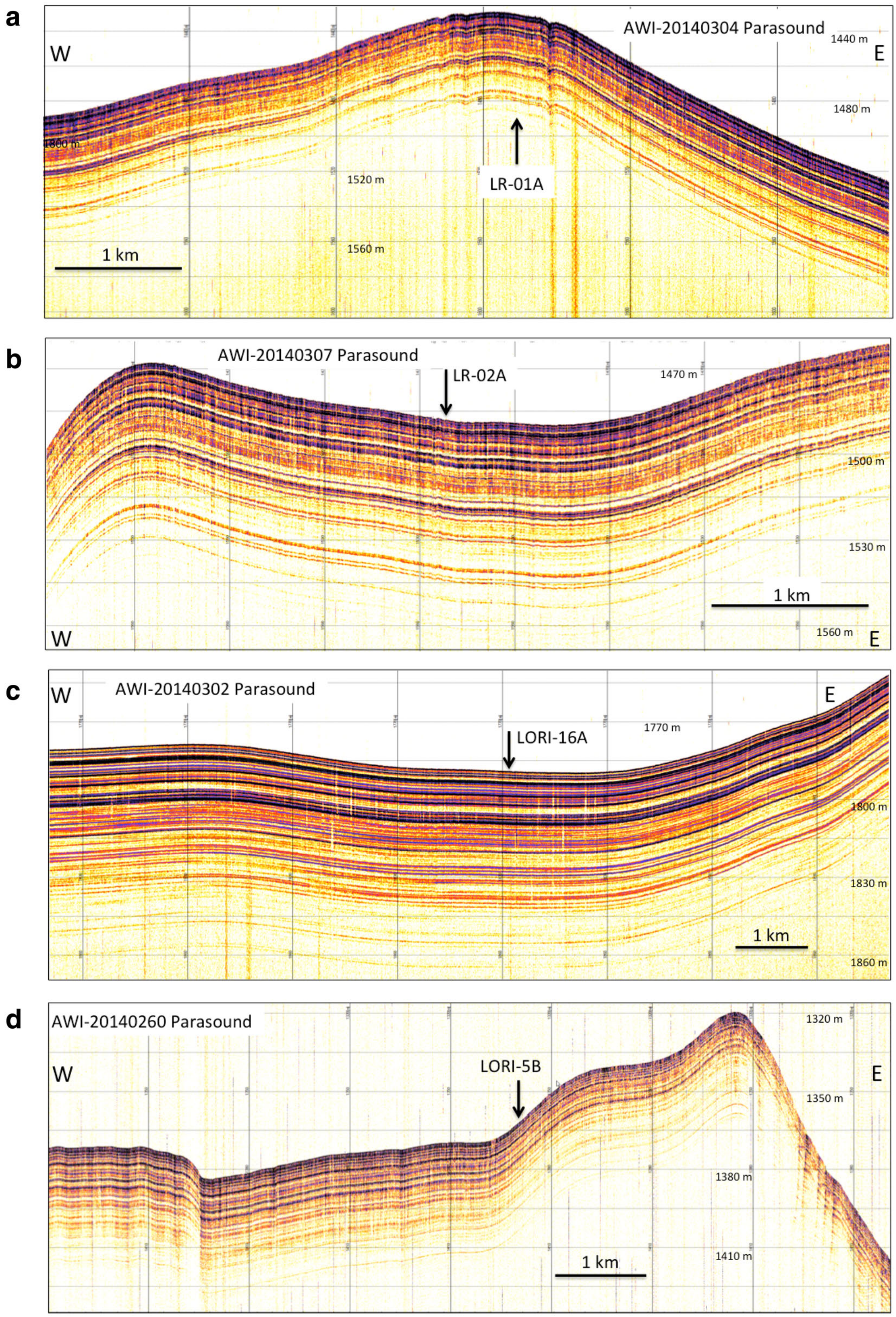


Fig. 14 Sediment echosounding (Parasound) profiles across locations of proposed drill sites **a** LR-01A, **b** LR-02A, **c** LORI-16A, and **d** LORI-05B

global climate took place during the transition from the early Cenozoic Greenhouse world to the late Cenozoic Icehouse world, is not at all or not well represented in the ACEX sequence.

2. The generally poor recovery as well as the partly poor preservation of microfossils prevented detailed and continuous reconstruction of Cenozoic climate history.
3. The second overall paleoceanographic objective of the original ACEX program, the high-resolution reconstruction of Arctic rapid climate change during Neogene to Pleistocene times, could not be accomplished because drilling on the southern Lomonosov Ridge was not carried out due to limitations with respect to operational constraints.

Having this in mind, we proposed a return to the Lomonosov Ridge for a second MSP drilling campaign within the framework of IODP (ACEX2) to fill these major gaps in our knowledge on Arctic Ocean paleoenvironmental history through Cenozoic times and its relationship to the global climate history. Based on the experience of ACEX and the comprehensive site survey expeditions in 2008 and 2014, we are convinced that our ACEX2 key goal, i.e., getting a complete record of Cenozoic climate history, can be achieved by careful site selection, appropriate drilling technology, and applying multiproxy approaches to paleoceanographic, paleoclimatic, and age model reconstructions. ACEX2 is scheduled for late summer/early autumn 2018, and a detailed planning by the ECORD Science Operator and the ACEX2 proponents is in progress.

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