IOP Conf. Series: Earth and Environmental Science **14** (2011) 012001 doi:10.1088/1755-1315/14/1/012001

# The great challenges in Arctic Ocean paleoceanography

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**Abstract**. Despite the importance of the Arctic in the climate system, the data base we have from this area is still very weak, and large parts of the climate history have not been recovered at all in sedimentary sections. In order to fill this gap in knowledge, international, multidisciplinary expeditions and projects for scientific drilling/coring in the Arctic Ocean are needed. Key areas and approaches for drilling and recovering undisturbed and complete sedimentary sequences are depth transects across the major ocean ridge systems, i.e., the Lomonosov Ridge, the Alpha-Mendeleev Ridge, and the Chukchi Plateau/Northwind Ridge, the Beaufort, Kara and Laptev sea continental margins, as well as the major Arctic gateways towards the Atlantic and Pacific oceans. The new detailed climate records from the Arctic Ocean spanning time intervals from the Late Cretaceous/Paleogene Greenhouse world to the Neogene-Quaternary Icehouse world and representing short- and long-term climate variability on scales from 10 to $10^6$ years, will give new insights into our understanding of the Arctic Ocean within the global climate system and provide an opportunity to test the performance of climate models used to predict future climate change. With this, studying the Arctic Ocean is certainly one of the major challenges in climate research for the coming decades.

## 1. Introduction and background

Although major progress in Arctic Ocean research has been made during the last decades, the knowledge of its short- and long-term paleoceanographic and paleoclimatic history as well as its plate-tectonic evolution is much behind that from the other world's oceans. That means - despite the importance of the Arctic in the climate system (see [1] for recent review and references) - the data base we have from this area is still very weak, and large parts of the climate history have not been recovered at all in sedimentary sections (figure 1). This lack of knowledge is mainly caused by the major technological/logistic problems in reaching this permanently ice-covered region with normal research vessels and in retrieving long and undisturbed sediment cores.

Concerning future Arctic geoscientific research, the climate history must be studied at different temporal scales from 10 to $10^6$ years, as paleoclimate research and climate models demonstrate that processes and varying conditions in polar regions play a key role in driving and amplifying global climate variability and sea-level change on time scales of decades to millions of years. For example, the Arctic sea ice, a key indicator and agent of climate change, affecting surface reflectivity, cloudiness, humidity, exchanges of heat and moisture at the ocean surface, and ocean currents, had been undergoing retreat over the past three decades, as recognized by the science community with some alarm [2]. In order to contextualize recent dramatic reductions in sea ice cover in the polar regions, it is essential to determine spatial and temporal changes in sea ice occurrence and its natural variability in the past [3, 4]. To reconstruct past climate (including sea ice) variability and the interrelation of different processes for times prior to direct measurements, one has to rely on indirect evidence, i.e., on information provided by "proxies" determined in sediment (and ice) cores. These proxies may be used for reconstruction of past temperature, salinity, sea ice cover, global ice volume, nutrients, marine biological productivity, etc. [1, 5]. Whereas a large number of these proxies are routinely used, others are new and still have to be fully established in Arctic Ocean environmental research. In this context, one key issue of overall importance in Arctic research is the establishment of a stratigraphic/chronological framework at highest accuracy possible, to be achieved with a combined effort of different stratigraphic methods including radiometric dating, microfossils, stable isotopes, cosmogenic isotopes, and geomagnetic records. Such a framework is the prerequisite for all paleoenvironmental studies and for the correlation of Arctic sedimentary records with other sedimentary records from the low, mid, and southern high latitudes, as well as climate records from land and ice cores ([1] and references therein).

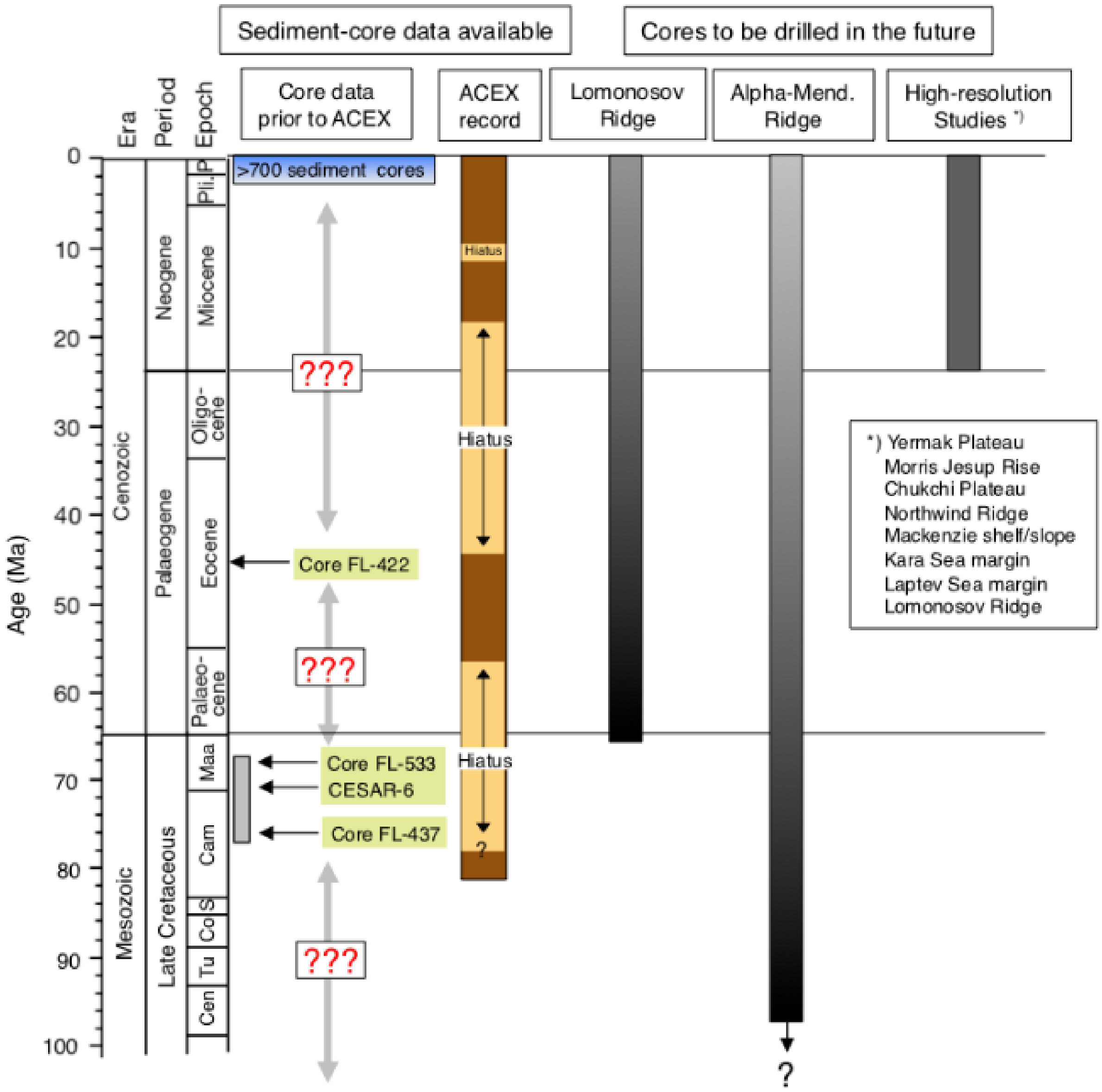


**Figure 1.** Stratigraphic coverage of existing cores in the central Arctic Ocean prior to ACEX (based on [6]) and the section recovered during the ACEX drilling expedition [7, 8], and stratigraphic coverage and key locations of sites to be drilled in the future [1].

## 2. Future major research themes in Arctic Ocean paleoceanography

Some of the key topics of future research are presented here. These topics are certainly not complete and have to be seen as examples.

### 2.1. Quaternary and Neogene climate variability on sub-millenial to Milankovich time scales

Arctic high-resolution (sub-millenial) climate records are still rare and known from only a few locations in the Nordic Seas and the Eurasian shelf seas. Some of these high-resolution records, for example, indicate short-term centennial- to millennial-scale variability in Arctic climate and river discharge correlating with the Greenland ice core record, changes in sea-ice cover in the North Atlantic and advance/retreat of Norwegian glaciers, and may reflect natural cyclic climate variations related to changes of the North Atlantic Oscillation/Arctic Oscillation (NAO/AO) pattern as described for the last decades [1, 9]. Considering the importance of the Arctic Ocean for the global ocean circulation and the climate system, more high-resolution paleoceanographic data sets from key areas are needed to reconstruct the climatically important parameters (e.g., sea-surface temperature and salinity, inflow of Atlantic Water, sea-ice cover, river discharge). This kind of data sets going back beyond the time scale of direct discharge measurements, can be used to determine the natural variability of these parameters as a background for an assessment of anthropogenically influenced changes in the last 100-150 years.

In this context, the strategic approach is to merge atmosphere and ocean signals from ice, marine and land (lake/permafrost) climate records at orbital, millennial, and up to decadal time scales to decipher their complex inter-relationship and impact, their relation with processes in low and middle latitudes, and the effect of external forcing. Of overall interest is the understanding of the polar mechanisms and thresholds in triggering rapid ($10^2$-$10^3$ yr) climate changes during warm and cold climate conditions (ice-permafrost-ocean-atmosphere mechanisms) and the comparison of the spatial and temporal evolution of such changes in Northern and Southern High Latitudes.

High-resolution records are needed from the Fram Strait/Yermak Plateau area (sites to study the variability of North Atlantic water inflow, sea-ice cover, primary production, etc.), the continental margins surrounding the Arctic Ocean (sites to study the variability of circum-Arctic river discharge, marginal-ice-zone processes, Atlantic- and Pacific-water influence, etc.), and the central Arctic Ocean (sites to study the variability of sea-ice cover and drift, water-mass characteristics, primary production, etc.). Coring sites characterized by high sedimentation rates, have to be carefully selected by bathymetric (Hydrosweep) and acoustic/seismic (PARASOUND and multi-channel seismic) surveys. For studying the Holocene climate variability, cores may be retrieved by conventional piston and kastenlot coring. For studying the (sub-) millennial climate variability on longer time scales, i.e., under different boundary conditions during Quaternary/Neogene times, however, drill cores are needed.

### 2.2. Long-term Mesozoic-Cenozoic climate history of the Arctic Ocean

Despite the success of Integrated Ocean Drilling Program (IODP) Expedition 302 -ACEX- [7, 10], major key questions related to the climate history of the Arctic Ocean and its long- and short-term variability during Mesozoic-Cenozoic times, cannot be answered from the ACEX record due to the poor core recovery and, especially, a major mid-Cenozoic hiatus (figure 1). This hiatus just spans the critical time when prominent changes in global climate took place during the transition from the early Cenozoic Greenhouse world to the late Cenozoic Icehouse world (figure 2; [11] and references therein). The success of ACEX has certainly opened the door for further scientific drilling in the Arctic Ocean. The ACEX results will frame the next round of questions to be answered from new drill holes to be taken during a series of drilling legs. Some of the main scientific topics are listed in the following (from [1] and references therein):

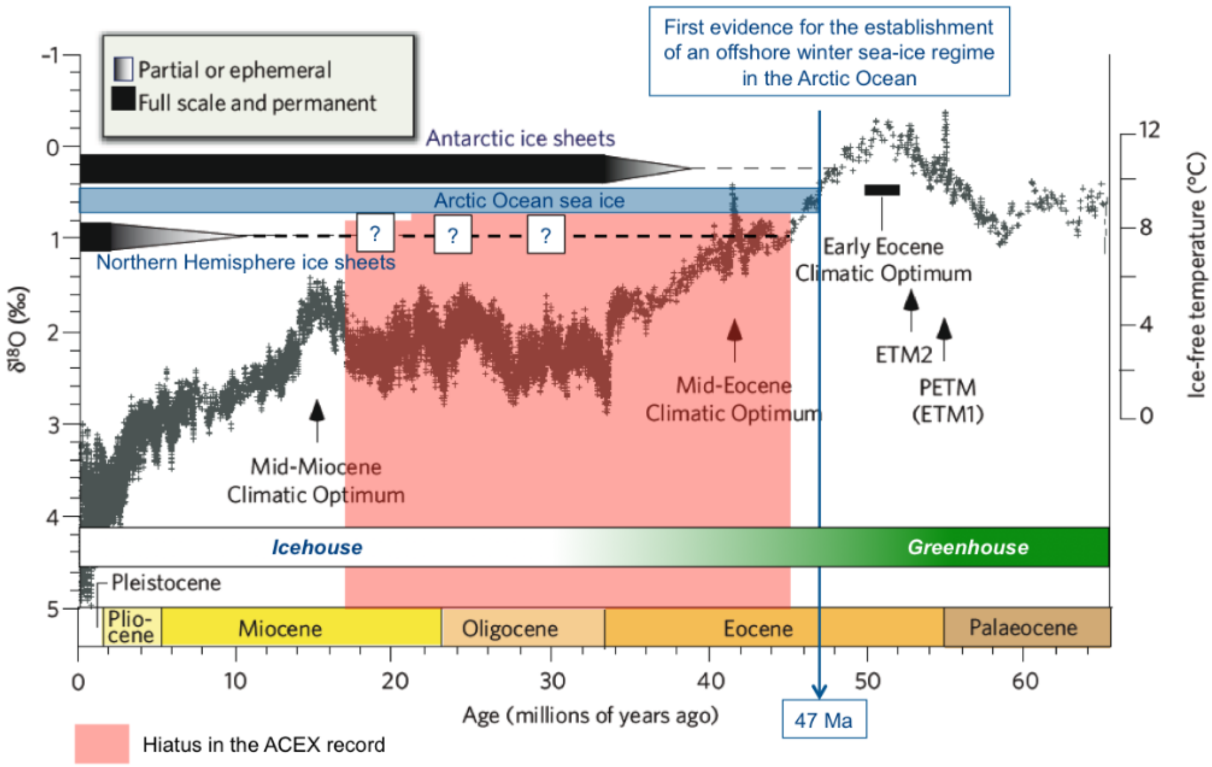


**Figure 2.** A smoothed global benthic foraminifer $\delta^{18}O$ time series showing the long-term cooling and the Greenhouse/Icehouse transition through Cenozoic times ([11], supplemented). The occurrence of Cenozoic glaciations on the Northern and Southern Hemisphere and Arctic sea ice are shown [11, 12]. The hiatus in the ACEX record is indicated.

(1) 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 as well as short-term extreme cooling transients [11]. Some of the related key questions are: Did the Arctic Ocean climate follow the global trend shown in figure 2? Are the Early Eocene Climate Optimum (poor recovery in the ACEX record) and the Oligocene and Mid-Miocene warmings also reflected in Arctic Ocean records? Were extensive glaciations developed synchronously in both the Northern and Southern Hemispheres? What was the variability of sea ice in terms of frequency, extent and magnitude?

(2) Black biosiliceous silty clays and clayey silts rich in organic carbon were found throughout the upper early to middle Eocene of the ACEX record [7, 10, 13], but also in a short sediment core from the Alpha Ridge, representing the late Cretaceous [14]. These data indicate a paleoenvironment characterized by poorly ventilated bottom waters and high but variable primary production. When and how did these extreme conditions develop during Mesozoic and Cenozoic times? When and how did the change to oxygenated bottom waters typical for the Neogene and Quaternary Arctic Ocean occur? Did anoxia occur down to the deep basins?

(3) Drill sites more proximal to the Siberian margin allows a detailed study of the history of 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 flow of Siberian rivers and changed the fresh-water balance of the Arctic's surface waters, considered to be a key factor for the formation of Arctic sea-ice and onset of major glaciations [15], a hypothesis to be tested by drilling along the Kara and Laptev Sea continental margin influenced by discharge of the large rivers Lena, Ob, and Yenisei.

(4) 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?

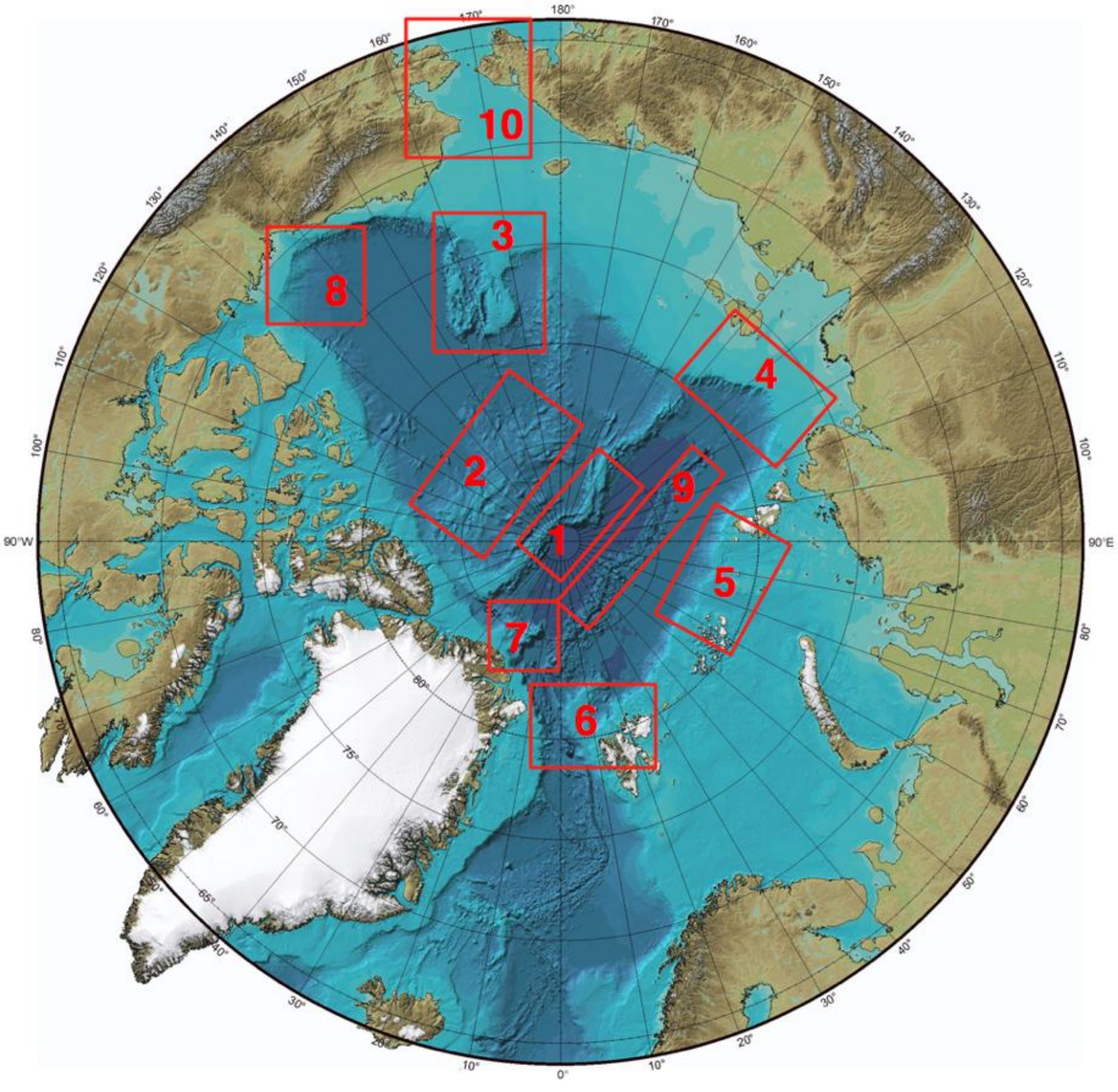


**Figure 3.** Key areas for future drilling areas in the Arctic Ocean (based on [16, 17]; bathymetric map according to [18]). 1 = Lomonosov Ridge; 2 = Alpha-Mendeleev Ridge; 3 = Chukchi Plateau/Northwind Ridge; 4 = Laptev Sea continental margin; 5= Kara Sea continental margin; 6 = Fram Strait/Yermak Plateau; 7 = Morris Jesup Rise; 8 = Mackenzie shelf/slope; 9 = Gakkel Ridge; 10 = Northern Bering Sea/Bering Strait area.

## 3. Key areas for future Arctic Ocean drilling

In order to study the long-term Mesozoic-Cenozoic climate evolution, we need to obtain undisturbed and complete sedimentary sequences to be drilled on depth transects across the major ocean ridge systems, i.e., the Lomonosov Ridge, the Alpha-Mendeleev Ridge, and the Chukchi Plateau/Northwind Ridge (figure 3, key areas 1 to 3). High-resolution records allowing to study climate variability on Milankovich and millennial to sub-millennial time scales, can be drilled along the continental margins characterized by high sedimentation rates. Here, key areas are the Kara, Laptev and Beaufort seas characterized by their large river discharge (figure 3, key areas 4, 5 and 8). Key location for studying the history of exchange of the Arctic Ocean with the world's oceans are the Fram Strait/Yermak Plateau, Morris Jesup Rise and Chukchi Plateau/Northwind Ridge and Bering Sea areas (figure 3, areas 3, 6, 7, and 10).

## 4. Concluding remarks and outlook

Concerning the short- and long-term evolution of the Arctic Ocean and its importance for the understanding of the global climate history, most of the key questions mentioned above as well as the key areas for scientific drillling in the Arctic Ocean needed to answer these questions, were already identified on several workshops during the last two decades and published in workshop reports [16, 17, 19, 20, 21]. Over the years, however, scientific drilling in the ice-covered Arctic Ocean remained a dream. The ACEX drilling in 2004 [7, 10] was the first major step that part of this dream became reality. Now, further drilling campaigns including the use of new technologies, are needed to follow-up in the future. In this context, for example, the "MeBo", a remotely controlled drill rig that is deployed on the sea bed, and developed at the Center for Marine Environmental Sciences (MARUM), Bremen University, Germany, might be an option for future Arctic drilling (for technical details see http://www.marum.de/en/Sea_floor_drill_rig_MeBo.html). MeBo has been successfully used in a recent drilling campaign at the continental slope off Chile where more than 70 m long continuous sediment records with an average core recovery of close to 90% were obtained, and it is planned to further develop MeBo to be suitable even for drilling longer cores up to 200 m [22]. MeBo-type drilling could be carried out from existing ice-strengthend research vessels (such as the German *Polarstern,* a double-hulled icebreaker that can break through ice 1.5 metres thick at a speed of approx. 5 knots). That means, this type of Arctic drilling which is certainly sufficient for reaching numerous major goals in Arctic Ocean paleoceanographic research, could even start almost now and allow an IODP-type drilling program. In order to obtain long (>500 m) drill cores from the oceanic ridges as well as the deep basins, however, the construction of a new large icebreaker with deep-water drilling capability - such as the *Aurora borealis* – might be the optimum, but also very expensive solution that may open another new dimension in multidisciplinary Arctic Ocean research [23].

Finally, it should be clearly emphasized that for the precise planning of any future Arctic Ocean drilling campaigns including site selection, evaluation of proposed drill sites for safety and environmental protection aspects, etc., comprehensive site survey data are needed first. That means, the development of detailed site survey strategy is a major challenge for the coming years.

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