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Scientific Deep Drilling in the Arctic Ocean: Status of the Seismic Site Survey Data Base*

by Wilfried Jokat

Abstract: In the last decades, several geophysical research expeditions have led to a significant growth of the seismic database in the central Arctic Ocean. In particular, the combination of seismic data with results of scientific deep drilling in 2004 have dramatically changed the view on the Arctic climate evolution. Since then, several proposals have been submitted to the Integrated Ocean Drilling Program (IODP) to solve certain scientific problems through deep drilling. Seismic data are crucial to foster any progress regarding these proposals in the Arctic, in order to justify the selection of the drill sites. This contribution reviews the current distribution of seismic reflection data, especially in the High Arctic. This study will focus on various areas of the High Arctic and briefly address the scientific questions for these specific regions.

Zusammenfassung: In den letzten zwei Dekaden führten mehrere wissenschaftliche Expeditionen in die Hocharktis dazu, dass die geowissenschaftliche Datenbasis kontinuierlich wuchs. Insbesondere die Kombination einer wissenschaftlichen Tiefbohrung aus dem Jahr 2004 mit seismischen Daten veränderte die Sicht auf die Klimaentwicklung der Arktis dramatisch. Als Folge dieser ersten erfolgreichen Tiefbohrung im zentralen arktischen Ozean wurden mehrere Bohrvorschläge beim "Integrated Ocean Drilling Program" (IODP) eingereicht, um auch andere Fragestellungen mit entsprechenden Tiefbohrungen zu beantworten. Kritisch für jeglichen Fortschritt zur Verwirklichung dieser Bohrvorschläge sind seismische Daten mit denen die Auswahl der Bohrpositionen gerechtfertigt werden kann. In diesem Beitrag soll die momentane Verfügbarkeit der seismischen Daten insbesondere im zentralen arktischen Ozean zusammengefasst und vorgestellt werden. Die Beschreibung wird sich auf einige Regionen konzentrieren und die speziellen Fragestellungen kurz anreißen.

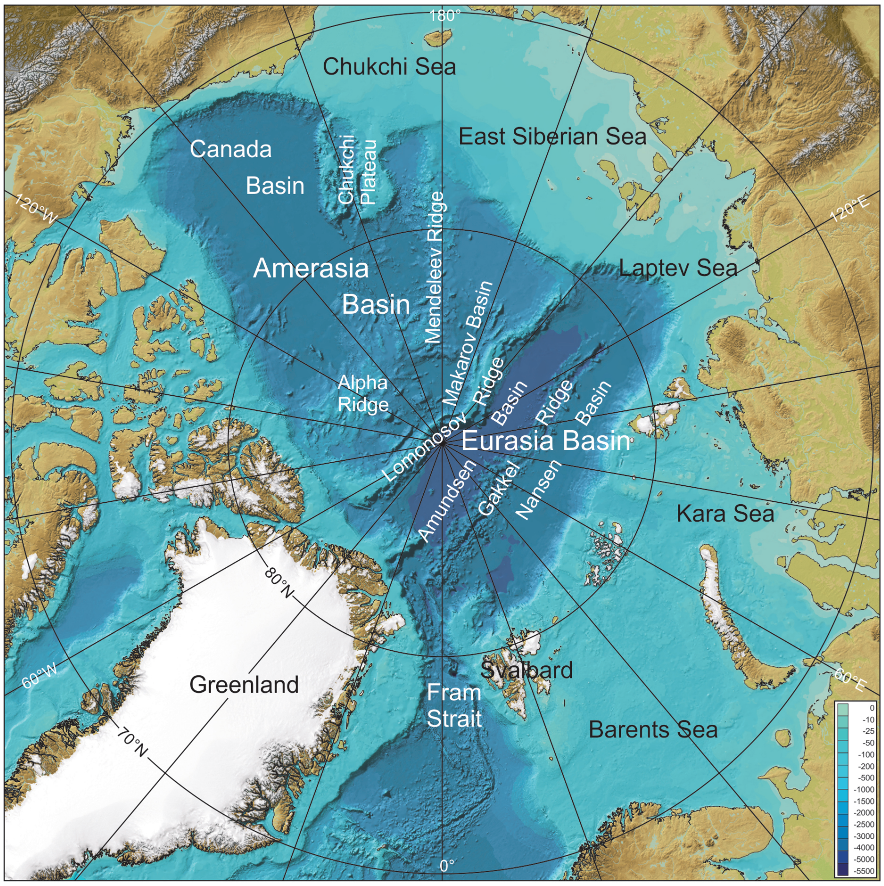

Fig.1: Physiography of the Arctic Ocean showing major structural tectonic units discussed in this study.

Abb.1: Physiographie des arktischen Ozean mit den wichtigsten tektonischen Strukturelementen, die in diesem Beitrag diskutiert werden.

INTRODUCTION

Compared to most of the global oceans the Arctic underwent quite a complex tectonic history, which created several ridges and basins (Fig. 1). These structures were created during a two-phase tectonic evolution of the central Arctic Ocean: the Eurasia Basin formed during the Cenozoic, and the Amerasia Basin during the Mesozoic. The seafloor spreading in the Eurasia Basin along the ultraslow spreading Gakkel Ridge is still going on, and well documented by Cenozoic magnetic seafloor spreading anomalies (KARASIK 1968, VOGT et al. 1979). Interestingly, the Gakkel Ridge terminates in the East towards the Siberian shelf, namely the Laptev Sea. In contrast to other continental rift systems, the stretching of the continental crust in the Laptev Sea and southwards, is not accompanied by massive volcanism. The Eurasia Basin is bounded to the south by the Siberian and Svalbard shelves, while in the north the Lomonosov Ridge, almost 1800 km long, forms the boundary to the Mesozoic part of the Arctic Ocean. Around 56 Myr ago the Lomonosov Ridge was part of the Siberian shelves and rifted apart when the formation of the Eurasia Basin started (JOKAT et al. 1992). Thus, it is in general agreed that the Lomonosov Ridge is a continental sliver.

Explaining the tectonic history is more difficult, since no extinct spreading centre is to be identified, which helps to constrain the tectonic history of the Amerasia Basin (VOGT et al. 1982). A few weak magnetic stripes are to be observed in

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[1] Alfred Wegener Institute for Polar and Marine Research, Am Alten Hafen 26, D-27568 Bremerhaven, Germany; <wilfried.jokat@awi.de>

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the Canada Basin. However, they cannot be dated, because the basement is covered by several kilometres of sediments. The most intriguing structure in the Amerasia Basin is the Alpha-Mendeleev Ridge striking almost parallel to the Lomonosov Ridge (Fig. 1). All existing geophysical data point towards a volcanic origin of this ridge complex (Hunkins 1961, Vogt et al. 1982, Forsyth et al. 1986, Jackson et al. 1986). The magnetic field shows highly irregular anomalies with no evidences for any magnetic seafloor spreading anomalies. The Russian deep seismic experiment revealed crustal thickness below the ridge of 32 km (Lebedeva-Ivanova et al. 2006) with a velocity-depth distribution similar to those of submarine Large Igneous Provinces (LIP) elsewhere. However, problematic for any conclusive understanding of this complex are samples from the basement, which can be analysed and dated.

For constraining the long-term climate history of the Arctic Ocean, the Lomonosov and Alpha Mendeleev ridges are important to investigate. Since the water depths of both ridges are well above the adjacent basins, they are less influenced by mass wasting events from the surrounding margins. Therefore, the sediments on top of both structures should hold a more or less complete, but undisturbed sediment package for the Cenozoic (Lomonosov Ridge; Jokat et al. 1992, Jokat 2005) and the Mesozoic/Cenozoic (Alpha – Mendeleev Ridge; Jokat 2003, Dove et al. 2010) respectively. Though, for all relevant geological structures of the global oceans the general bathymetry is fairly well known, still most of the central Arctic Ocean has never been visited by any scientific expedition. The sea-ice cover is the most important limiting factor. It allows ship-based expeditions only in August/September, and because of the highly variable sea-ice cover, there is no guarantee that the proposed research area can be reached.

For seismic investigations in the central Arctic Ocean a second icebreaking ship is essential to allow the acquisition of any high quality data, which can be used e.g. for any site selection to retrieve long sediment cores (Jokat et al. 1995). The selection of sites for scientific drilling requires an even greater effort. Normally, several expeditions are necessary to find appropriate locations and to fulfil the safety requirements for the later drilling campaign. Since only few icebreakers are available for such an effort it simply takes time to coordinate the scientific icebreakers from different countries, and to convince funding agencies to support such efforts.

An important issue in the last century was to develop a technology setup to conduct geophysical surveys in ice covered areas. The first natural approach was to use the ice floes themselves as carrier. Russian, American, Canadian institutions equipped large and thick ice floes with ice camps, which were regularly supplied by aircrafts. The natural drift of the ice floes allowed the acquisition of seismic data but also of geological samples. Such drift camps allowed to investigate areas, which could not be reached by any conventional research vessel in the 1950's and 1960's of the last century. In any case these ice islands were the first break through for geoscience in the Arctic by gathering first order information on bathymetry, sediment thickness and geology (shallow cores, dredges; Hall 1973, Hunkins 1961). The critical factor of these ice-island geophysical experiments was the limited energy for the seismic sources. It simply constrained the vertical penetration of the sound energy into the sediments. Thus, a mix of weak seismic sources (sparker, small airguns) and strong dynamite blasts were used to investigate the sedimentary and crustal structure of various Arctic ridges and basins (Hunkins 1961, Hall 1973, Jackson et al. 1990). Another constraint was that the drift direction of the ice floe could not be predicted. It was a drift into the "unkown", which was to some extend successful since some ice islands carried an ice camp for several years (T3 1967-1970; Hall 1973).

The situation changed in 1980's, when icebreaking research vessels such as RV "Polarstern" became available for research also in the central Arctic Ocean. The use of the icebreakers should allow within the summer season to approach any specific location in the Arctic Ocean. A first and successful attempt to gather seismic data from a single icebreaker operation was made by North American scientists on the Chukchi Plateau and Canada Basin (Grantz et al. 2004). However, several meter thick ice floes made seismic profiling during ice breaking extremely difficult.

In 1991, a different approach was initiated. During the joint multi-disciplinary Arctic Ocean expedition – the ARCTIC'91 – of the ice-breaking research vessels "Oden" and "Polarstern" it was planned to work in a tandem. Norwegian and German geophysicists used this tandem setup trying to obtain multichannel seismic data. The plan was that "Oden" as leading vessel did the icebreaking, while the seismic gear – airguns and streamer – was towed in a more or less standard configuration behind "Polarstern's" stern in a passage through the ice more or less open (Jokat et al. 1995). This approach proved to be the next break-through for seismic data acquisition in the ice-covered areas of the central Arctic Ocean. For the first time long seismic profiles were acquired within a few days showing the deeper sedimentary structure of the Amundsen Basin and the Lomonosov Ridge (Jokat et al. 1992, Jokat et al. 1995a, 1995b). The quality of the records after some data processing was comparable to open water data quality. This international Arctic expedition in 1991 with the overwhelming amount of new high quality seismic data from the central Arctic Ocean demonstrated the efficient setup of two icebreakers working in tandem for geophysics.

Since then numerous High Arctic expeditions were conducted with ice breaking vessels from several countries to retrieve seismic information. In most cases the setup of "Oden" and "Polarstern" was adapted to ensure and optimize the data acquisition. The tremendous amount of new seismic data of >10,000 km gathered in the Canada Basin, a formerly almost un-surveyed area, was investigated by a combined effort of Canadian and US icebreakers. Even industry has adapted and modified this setup for gathering seismic data along the ice rim of East Greenland but with streamer lengths up to 8000 m. Again, the leading icebreaking vessel to some extend guarantees an efficient and predictable seismic data acquisition by the following seismic vessel. Finally, though this tandem set-up was extremely successful in the Arctic, it turned out that the major difficulty for geophysics, at least, in the past was to organize two ice breaking research vessels for a joint scientific expedition.

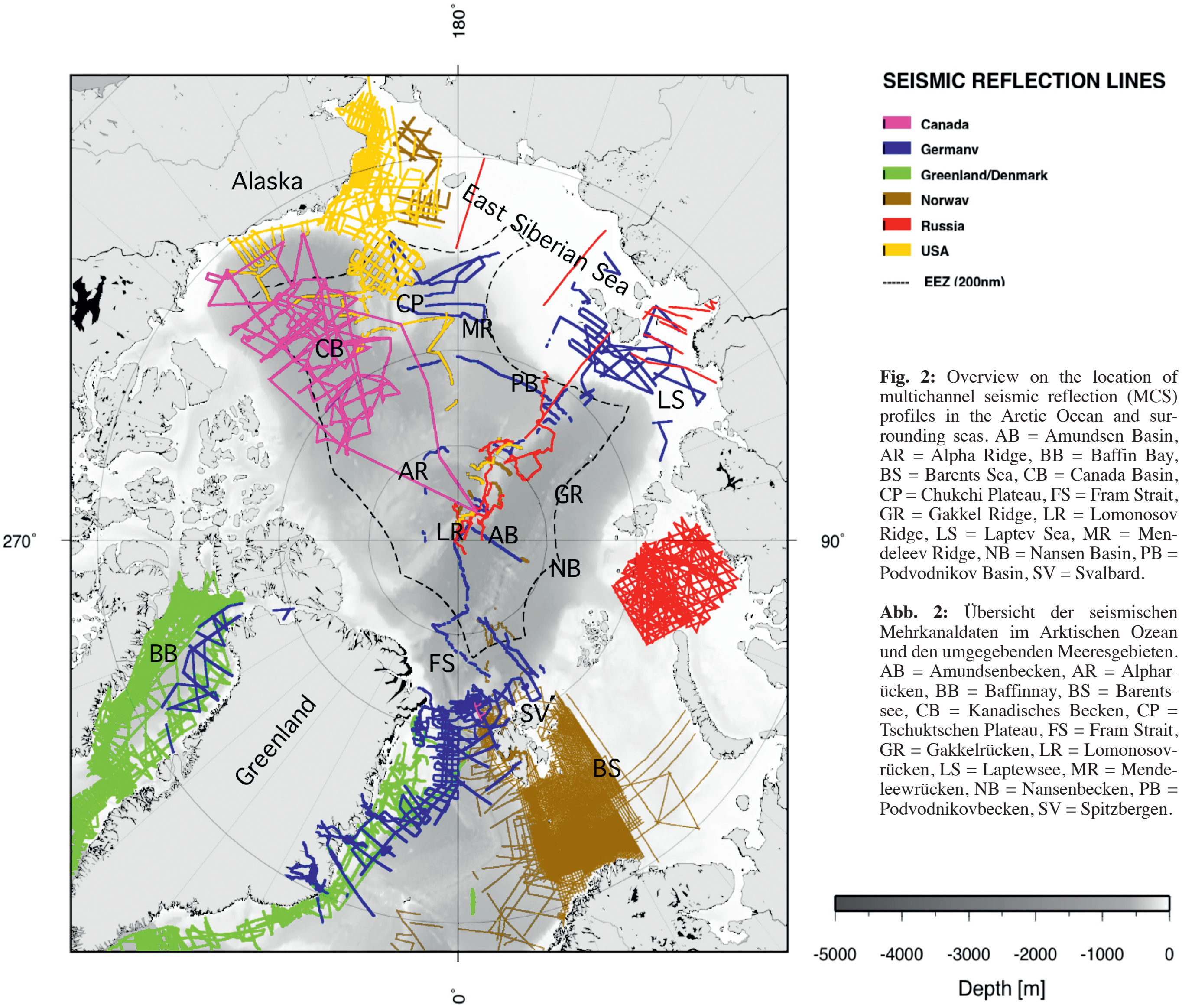

Fig. 2: Overview on the location of multichannel seismic reflection (MCS) profiles in the Arctic Ocean and surrounding seas. AB = Amundsen Basin, AR = Alpha Ridge, BB = Baffin Bay, BS = Barents Sea, CB = Canada Basin, CP = Chukchi Plateau, FS = Fram Strait, GR = Gakkel Ridge, LR = Lomonosov Ridge, LS = Laptev Sea, MR = Mendeleev Ridge, NB = Nansen Basin, PB = Podvodnikov Basin, SV = Svalbard.

Abb. 2: Übersicht der seismischen Mehrkanaldaten im Arktischen Ozean und den umgegebenden Meeresgebieten. AB = Amundsenbecken, AR = Alpharücken, BB = Baffinnay, BS = Barentssee, CB = Kanadisches Becken, CP = Tschuktschen Plateau, FS = Fram Strait, GR = Gakkelrücken, LR = Lomonosovrücken, LS = Laptewsee, MR = Mendeleewrücken, NB = Nansenbecken, PB = Podvodnikovbecken, SV = Spitzbergen.

SCIENCE AND DRILLING IN THE ARCTIC OCEAN

Advances towards a better understanding of the Arctic long-term tectonic history as well as short- and long-term climate changes are highly dependent on the availability of deep scientific drill holes in the central Arctic Ocean and its marginal seas. Though, there is, in general, a strong support from the scientific community to close the knowledge gaps in the Arctic, several issues have to be solved. One general problem in promoting scientific drilling in such remote areas is obvious: while drilling proposals in many other regions can rely on existing "old" data or industry information to justify their scientific objectives, Arctic Ocean drilling is, compared to the rest of the world's oceans, in an adverse stage. Beside numerous short piston and gravity cores, only one scientific deep drill site exists in the central Arctic Ocean (Backman et al. 2006, Moran et al. 2006). This 450 m long core from the Lomonosov Ridge was drilled during the Arctic Coring Expedition (ACEX) in 2004 with the assistance of three icebreakers. Here, the main scientific results can be summarized as follows:

- During the Paleocene-Eocene Thermal Maximum (PETM) event, surface water temperatures reached values as high as 25 °C (Sluijs et al. 2006, 2008)
- An anoxic deep-water environment, indicated by a high total organic carbon content (TOC) and specific biomarker composition, occurred from at least 56 to 44 Ma (Stein et al. 2006).
- Evidences for a freshwater fern Azolla were found in sediments dated around 49 Ma (Brinkhuis et al. 2006).
- First evidence of sea ice based on diatoms was already found at 47 Ma (Stickley et al. 2009). Evidence of ice rafted material (IRD) was found in sediments as old as 46.3 Ma, suggesting that the Earth's transition from a Greenhouse to an Icehouse world was bipolar (Moran et al. 2006, St. John 2008).
- During the middle Eocene (49 to 45 Ma), surface-water temperatures decreased from 25 to 10 °C; between 46.3 and Ma, with the onset of sea ice, an environment similar to the present-day Baltic Sea – warm ice-free water in the summer and sea ice in the winter – has been proposed (Weller & Stein 2008).
- Since approximately 14 Ma, perennial sea-ice cover may have possibly occurred (Darby 2008, Krylov et al. 2008).

Unfortunately, the ACEX sequence is incomplete as a hiatus lasting from 44.4 to 18.4 Ma occurred at about 198 mbsf. Up-to-date, there is a lot of speculation on the processes causing this hiatus. Currently, there are conflicting findings and hypotheses to explain such a pronounced hiatus on Lomonosov Ridge (LR):

- More or less strong currents at this part of the LR prevented the deposition of large amounts of sediment. Such strong currents may have played an important role as is visible also in the seismic section crossing the drill location (Jokat et al. 1992). Here, the flanks of the lowermost sediment package are eroded and overlain by a conformable Miocene drape.
- A more complex subsidence history of the LR, which consequently caused a much longer sub-aerial or shallow water exposure of the LR crest than previously assumed (Jokat et al. 1995). This model involves an uplift of LR during Oligocene times (O'Reagan et al. 2008, Minakov & Podladchikov 2012).
- Sub-aerial or shallow water position of LR caused by a sea level decline during Cenozoic times, and a subsequent erosion and/or non-deposition of ridge sediments (Poirier & Hillaire-Marcel 2011). Currently, there is no evidence for such a strong decline in sea level.

These hypotheses can only be addressed with a new deep drilling campaign. Though the ACEX drilling funded by IODP proved to be one of the most successful scientific expeditions in providing surprising results on the Arctic environment, it probably will not be repeated in the near future. Currently, the major problem is to provide seismic data on LR, which convincingly show that the hiatus is not present at selected drill sites in order to retrieve a more complete Cenozoic sediment section. This is especially important when justifying the expenses of a two- or three-ship drilling expedition.

Because of the strong global competition within IODP, it is of outmost importance to propose a set of sites in the Arctic and its marginal seas, which are suitable to answer the following questions:

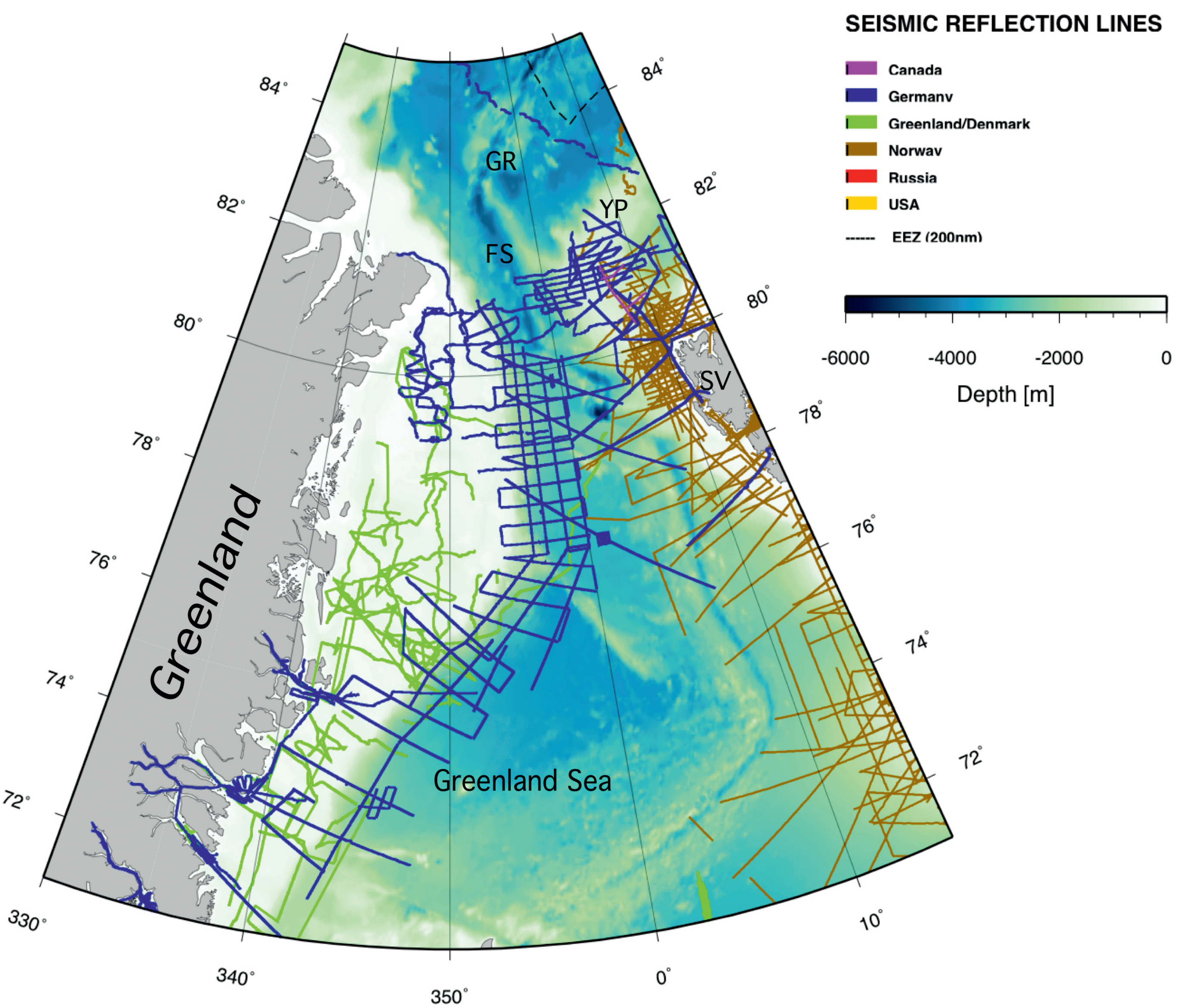

Fig. 3: Multichannel seismic reflection (MCS) profiles off East Greenland and in the Fram Strait. YP = Yermak Plateau, GR = Gakkel Ridge, FS = Fram Strait, SV = Svalbard.

Abb. 3: Seismische Mehrkanalprofile vor Ostgrönland und in der Framstraße. GR = Gakkelrücken, YP = Yermakplateau, FS = Stramstraße, SC = Spitzbergen.

- How long lasted the Arctic Ocean anoxic state; both in Mesozoic and Cenozoic times?
- Did the Arctic Ocean face strong sea level declines, which would explain the large hiatus on LR? If so, deeper sites have to be selected, which were not affected by these events.
- When did the sea-ice cover start to evolve and how did it fluctuate during Cenozoic times? How does this compare to Antarctica?
- What were the paleo-oceanographic consequences of a shallow and/or deep-water gateway in the Fram Strait?

In the central Arctic Ocean, the more or less continuous sedimentation on ridge systems has a greater potential to provide a complete sedimentary record than the in parts heavily eroded circum-Arctic shelf areas.

In summary, this contribution aims to describe the seismic database (Fig. 2), which is currently available from scientific institutions or commercial companies to support scientific drilling in the Arctic. The description focuses on the central Arctic Ocean and areas off East Greenland, Northern Svalbard and the East Siberian Sea, where at least IODP pre-proposals exist, and where seismic data acquisition has been quite a challenge because of the sea-ice cover. The seismic network on the shelves might be incomplete because of on-going industrial data acquisition or confidentiality of such information. Thus, industry navigation information on existing lines has been incorporated wherever available.

EAST GREENLAND

Today, the Greenland ice sheet is the last remnant of the vast Northern Hemisphere glaciations (NHG) of the past. It still has an ice thickness of up to 3000 m, and the question arises why the Greenland ice sheet has survived the global warming since the last glacial maximum. Based on current knowledge, there is clear evidence that glaciations have intensified since some 3 Ma (e.g. KLEIVEN et al. 2002). However, it is quite unlikely that ice sheets did not exist in polar regions before then. For example, TRIPATI et al. (2008) propose that already some 44–30 Ma, East Greenlandic glaciers or/and ice caps existed based on IRD found in an ODP drill hole off East Greenland. Before this finding, models proposed a stepwise intensification of the NHG after the Middle Miocene Climate Optimum (about 15-17 Ma) based on IRD records in the high northern latitudes (NANSEN ARCTIC DRILLING PROGRAM NAD SCIENCE COMMITTEE 1992, THIEDE et al. 2011). Also, dispute continues as to whether both polar regions have always been simultaneously glaciated or not. Furthermore, ice sheets located around the Arctic Ocean probably showed a different temporal and spatial behaviour.

In this context, more than 10,000 km of multichannel seismic data (MCS), (Fig. 3) (BERGER & JOKAT 2008, 2009), were acquired in the last decade north of the Jan Mayen Fracture Zone along the NE-Greenland margin. Again, partial heavy sea ice prevented the use of longer streamers (>1000 m active length) and large airgun arrays. However, the seismic network allows selecting several promising scientific drilling locations in the Greenland Basin in order to provide constraints for hypotheses on the history of Greenland's glaciations. Finally, one of the major problems in convincing IODP to accept a proposal for drilling off East Greenland is the limited sediment-age information from scientific drill holes, which are either non-existent or rather incomplete in their recovery.

FRAM STRAIT

When discussing the climate evolution of the Arctic Ocean, the kinematic history of the Fram Strait plays an outstanding role. Since the opening of this gateway, the Arctic Ocean environment most likely changed radically with the continuous widening of the Fram Strait. At some point, large volumes of water from the North Atlantic must have entered the Arctic Ocean and most likely have caused a complete ventilation of the Arctic Basin (JAKOBSSON et al. 2007), possibly no later than around 17.5 Ma. Here, it should be noted that the initial strike slip movements between North Greenland and Svalbard, which finally led to the formation of the Fram Strait, already started some 55 Ma ago. Thus, details on the widening/ deepening of the Fram Strait, or the existence of even older shallow water seaways through a "proto" Fram Strait are of great interest. Furthermore, the variability of the sea-ice cover and the current systems in the Fram Strait as a response to glacial and inter-glacial periods is also of interest when comparing the present-day situation.

To provide answers to these questions, the margins of the Fram Strait and the thick drift sediments along the Yermak Plateau are important target areas (GEISSLER et al. 2011). In the past decade, a large number of new MCS (Fig. 3) have been acquired, mainly in difficult ice conditions, along the northern part of the Yermak Plateau and the continental margin of NE Greenland. Along the Svalbard/Yermak margin, the objectives are twofold: i) mapping of the thick drift deposits as far north as sea ice conditions would allow, and ii) finding suitable drill locations more distant to the Svalbard mainland to recover sediments which are less influenced by local mountain glaciers.

LOMONOSOV RIDGE

While the previously discussed sites are located at the rim of the Arctic Ocean, the next target areas are located in the central Arctic Ocean. Most of the multi channel seismic data across the Lomonosov Ridge (LR) were acquired with a short streamer (300 m) and the support of a leading icebreaker (JOKAT 2005). Furthermore, LR was the location of a spectacular drilling campaign in 2004 (IODP Exp. 302, BACKMAN et al. 2006, MORAN et al. 2006). The Arctic Coring Expedition (ACEX) aimed to recover sediments dating back to early Cenozoic times to unravel the climate and environmental history of the Arctic Ocean. Two powerful ice breakers – the Russian "Sovetskiy Soyuz" and the Swedish "Oden" – and an ice strengthened drill ship ("Vidar Viking") managed to drill several scientific holes up to 450 m deep in heavy pack ice. The unexpected results completely changed the view on the evolution of the Arctic Ocean (see above).

Beside the tremendous success of the drilling campaign, several problems remain since a large hiatus between 44 and 18.2 Myr did not allow to obtain a complete and/or high resolution record on the climate history for the Cenozoic Arctic

Ocean. Currently, there are several hypotheses on the causes of this hiatus (see above). Although the seismic data across the LR are substantially more incomplete than off Svalbard / East Greenland, there are several portions of LR located closer to the East Siberian shelf at 81–80° N (Fig. 4) displaying no structural evidence in the seismic data that such a significant hiatus is present. Here, a reasonable seismic network exists to support this interpretation, but higher sedimentation rates require deeper drill holes to reach the same sediment ages as for the ACEX cores. Fortunately, these sites are located closer to the present-day ice edge, and might allow easier access for a drilling ship. Because of the current sea-ice retreat, an extensive ice management with two icebreakers might no longer be needed. Here, the site survey information is rather complete to launch a renewed effort for scientific drilling.

ALPHA-MENDELEEV RIDGE

The Alpha-Mendeleev Ridge (AMR) is a 1800 km long magmatic ridge system located in the part of the Arctic Ocean, which started to form already in the Mesozoic. The basement consists most likely of basalts and is covered by sediments with variable thickness. In the central part of the AMR, sediment thicknesses of 500 m and more than 1000 m close to the East Siberian Shelf are observed. These sediments have the potential to broaden our knowledge on the climate history of the Arctic Ocean back to 90 Ma. Shallow cores gathered from ice islands in the 1960's show that Maastrichtian black shales are present close the sea floor. Systematic probing will extend the time series of the ACEX drilling, terminating at around 56 Ma.

In the last decade, seismic data acquisition was almost impossible even with the help of two powerful icebreakers. Level sea ice of more than 5 m prevented any regular survey. However, the sea-ice retreat in the last years has radically changed the situation. Since 2007, e.g. RV "Polarstern" was able to reach the Alpha Ridge twice without any major problems, unfortunately without seismic gear on board to collect seismic data. While the junction of the AMR with the East Siberian shelf is reasonable well surveyed, this is absolutely not the case for the central part of this giant ridge system. Here, additional seismic surveys (Fig. 2) are needed to provide a sound network for a convincing selection of drill sites.

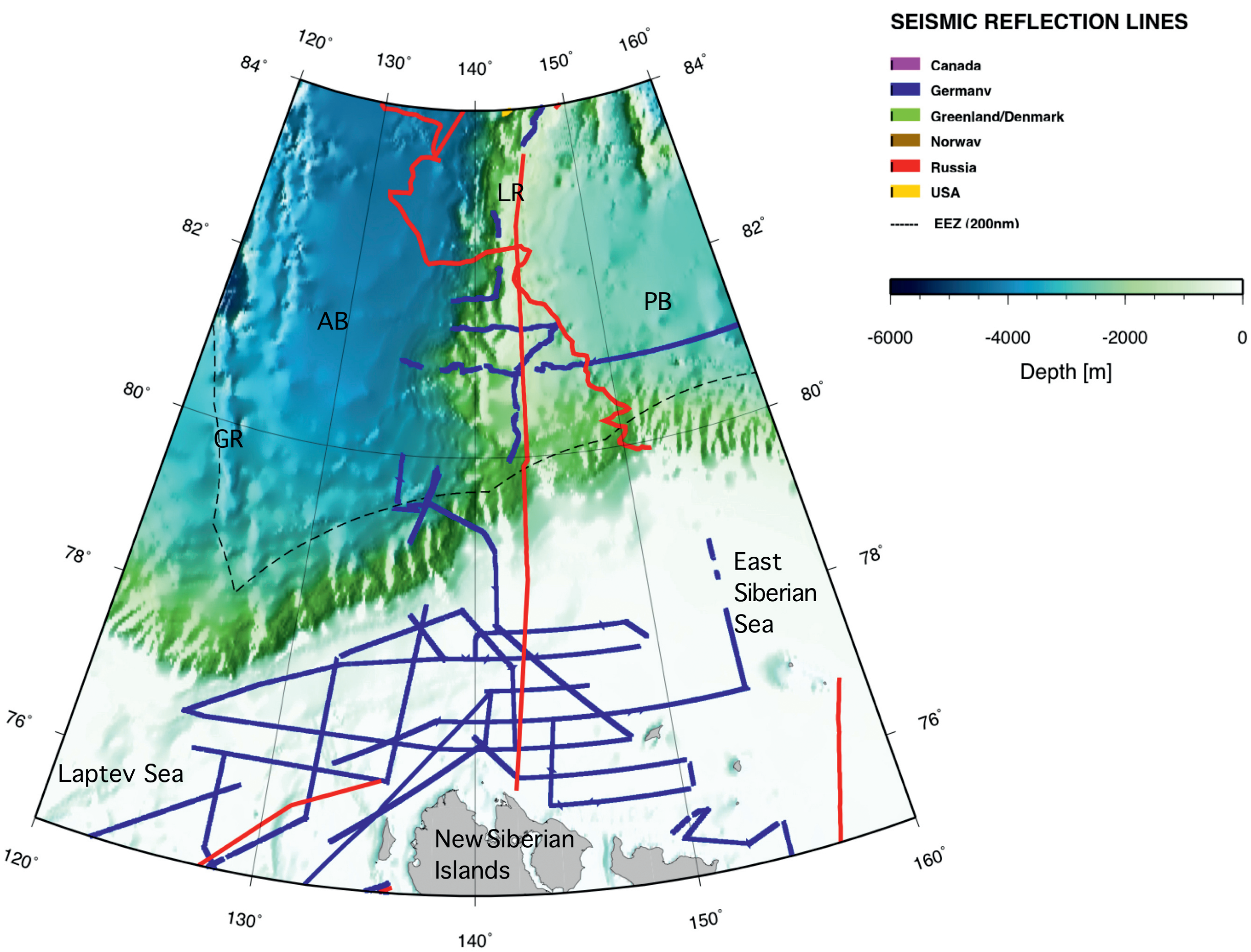

Fig. 4: Multichannel seismic reflection (MCS) profiles at the junction of the Lomonosov Ridge (LR) with the East Siberian Sea. GR = Gakkel Ridge, AB = Amundsen Basin, PB = Podvodnikov Basin.

Abb. 4: Seismische Mehrkanalprofile an der Schnittstelle zwischen dem Lomonosov Rücken (LR) und der Ostsibirischen See. GR = Gakkelrücken, AB = Amundsenbecken, PB = Podvodnikov Basin.

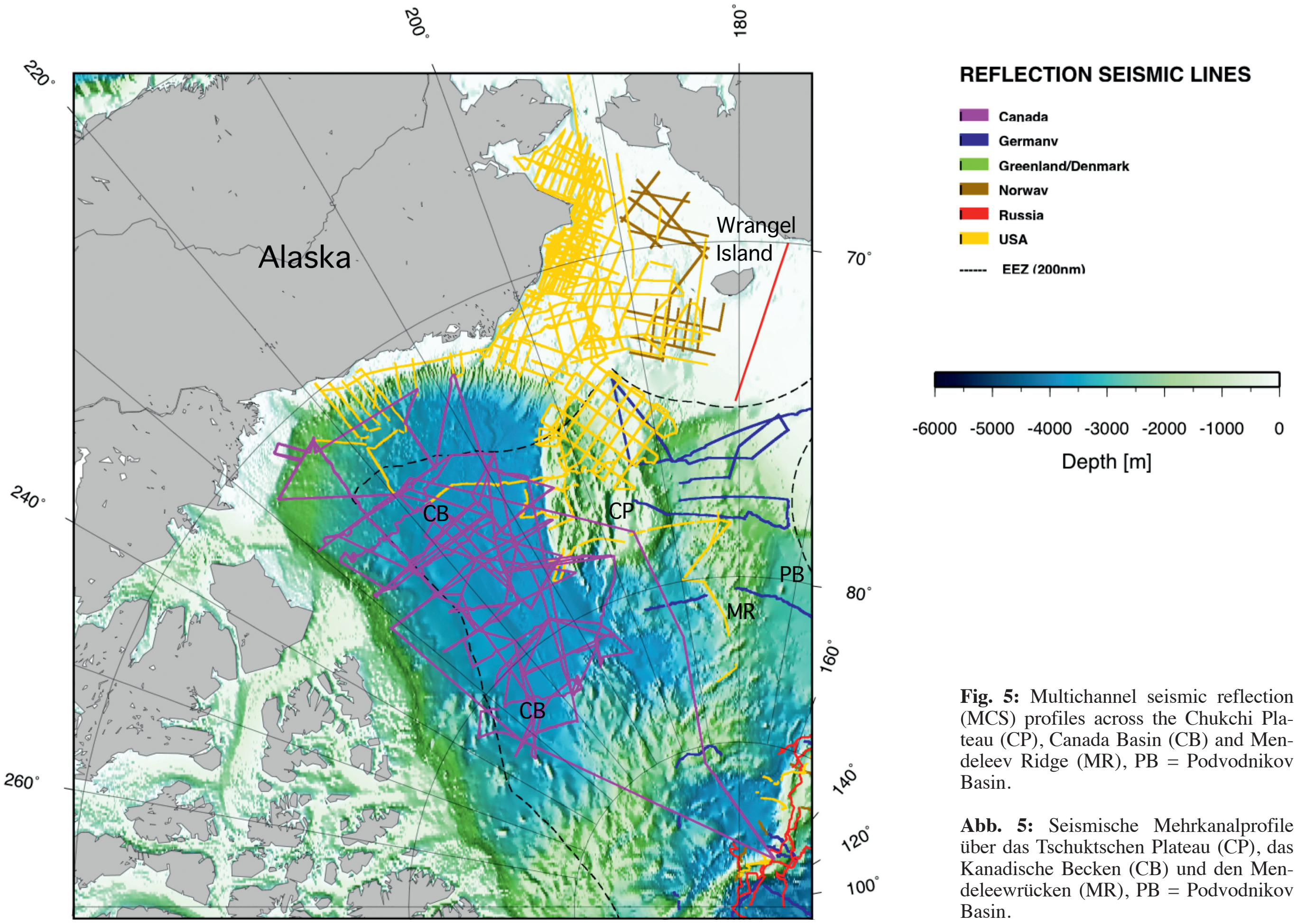

Fig. 5: Multichannel seismic reflection (MCS) profiles across the Chukchi Plateau (CP), Canada Basin (CB) and Mendeleev Ridge (MR), PB = Podvodnikov Basin.

Abb. 5: Seismische Mehrkanalprofile über das Tschuktschen Plateau (CP), das Kanadische Becken (CB) und den Mendeleewrücken (MR), PB = Podvodnikov Basin.

CHUKCHI PLATEAU / EAST SIBERIAN SEA

Glaciations have been considered to be the major short term driving process for sea level variations since the Middle Miocene. The advances and retreats of glaciers, ice sheets and ice streams are well documented in sedimentary sequences along many polar continental margins. Typical prograding sequences of unsorted material as well as eroded top sets are the direct evidences for a glacial overprint of such margins. However, these sequences are difficult to date because of the massive horizontal glacial transport. Furthermore, the sedimentary record is most likely incomplete because of unknown glacial erosion of older sequences during glacial times. Thus, we need data on parts of the Arctic margins not having experienced strong and repeated glacial erosion, and therefore possessing the capability of capturing sea level variations in sedimentary low/high stand system tracts. A comparison with global sea level curves as well as drilling results off Svalbard and Greenland and scientific drill holes especially from low latitudes will provide important insights into the impact of northern latitude glaciations on global sea level declines and rises during the Cenozoic.

Seismic profiles just south of the Chukchi Plateau (Fig. 5) indicate that this area might be the best region to provide a sound answer to this problem. The seismic data imaged a thick stack of prograding sequences, which were only affected in the upper part by glacial erosion. These two profiles were supplemented in 2011 by an US survey (Univ. Fairbanks) also covering the southern Chukchi Plateau. Furthermore, this network could be linked to several commercial drill holes, which allow a first order age classification of the sedimentary sequence. Thus, after the final processing and interpretation of these data sets, there should be an excellent seismic database available for a sound selection of scientific drill sites.

CONCLUSIONS

This short contribution indicates that today the seismic database available for the selection of locations for scientific drill sites has significantly grown compared to the early 90's of the last century. These changes are partially due to the regular use of scientific icebreakers for conducting scientific programs in the High Arctic as well as being a consequence of the retreat of sea-ice cover in the last five years. Areas previously not accessible for such experiments at the rim of the Arctic Ocean, like the Chukchi Plateau, can nowadays be seismically investigated with standard seismic vessels. However, the situation in the central Arctic Ocean has only slightly improved. Here, the major problem is still to organize two-ship experiments, which in combination allow some sort of standard seismic data acquisition in sea ice several metres thick.

However, even the growing seismic data base does not solve the major problem of being successful in the IODP proposal system: for most of the drilling proposals submitted up to 2011, there were no well constrained age models. Considering the global competition within the IODP programme, this fact remains to be one of the major issues to overcome now. Since the IODP programme is also facing strong budget cuts, there are tendencies to support proposals only where a sufficient level of knowledge already exists, rather than promoting drilling into "the unknown". This problem can only be tackled by: (i) an icebreaker with shallow or deep drilling capabilities, and (ii) making new funding available, which directly supports scientific drilling campaigns in the Arctic Ocean and the adjacent seas.

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