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White Paper

Scientific Drilling in the Arctic Ocean: A challenge for the next decades

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Abstract

The modern Arctic Ocean appears to be changing faster than any other region. To understand the potential extent of high latitude climate change, it is necessary to sample the history stored in the sediments filling the basins and covering the ridges of the Arctic Ocean. These sediments have been imaged with seismic reflection data, but, except for the superficial record, which has been piston cored, they have been sampled only on the Lomonosov Ridge in 2004 during the Arctic Coring Expedition (ACEX-IODP Leg 302; Backman, Moran, McInroy, et al., 2006) and in 1993 in the ice-free waters in the Fram Strait/Yermak Plateau area (ODP Leg 151; Thiede, Myhre, Firth, et al., 1996).

In order to discuss and plan the future of scientific drilling in the Arctic Ocean, an international workshop was held at the Alfred Wegener Institute in Bremerhaven, Germany, in November 2008. About 95 scientists from Europe, US, Canada, Russia, Japan, and Korea and observers from oil companies participated in the workshop. Funding of the workshop was provided by the European Science Foundation, the Consortium for Ocean Leadership (US), the Arctic Ocean Sciences Board, and the Nansen Arctic Drilling Program as well as by sponsorships from British Petroleum, ConocoPhillips, ExxonMobil, Norwegian Petroleum Directorate, Shell International, and StatoilHydro. The major targets of the workshop were: (1) to bring together an international group of Arctic scientists, young scientists, and ocean drilling scientists to learn and exchange ideas, experience and enthusiasm about the Arctic Ocean; (2) to develop a scientific drilling strategy to investigate the tectonic and paleoceanographic history of the Arctic Ocean and its role in influencing the global climate system; (3) to summarize technical needs, opportunities, and limitations of drilling in the Arctic; and (4) to define scientific and drilling targets for specific IODP-type campaigns in Arctic Ocean key areas to be finalized in the development of drilling proposals.

Introduction and background

Although major progress in Arctic Ocean research has been made during the last decades, the short- and long-term paleoceanographic and paleoclimatic history as well as its plate-tectonic evolution are poorly known compared to the other world's oceans. That means - despite the importance of the Arctic in the climate system - the database we have from this area is still very weak. Large segments geologic time have not been sampled in sedimentary sections. The question of regional variations cannot be addressed. Prior to 2004, the geological sampling in the Arctic Ocean was restricted to obtaining near-surface sediments, i.e., only the upper about 5-15 m could be sampled by means of gravity and piston coring. Thus, more or less all studies were restricted to the (Late Pliocene/) Quaternary time interval, with one exception (Fig. 1; e.g., Clark et al., 1980, 1986; Thiede et al., 1990). In four short sediment cores from Alpha Ridge where older strata are cropping-out, upper Cretaceous and lower Tertiary sediments could be sampled by gravity coring from an ice flow. The 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 (for recent review of available geological data see Stein, 2008).

With the successful completion of IODP Expedition 302 ("Arctic Coring Expedition" – ACEX), the first Mission Specific Platform (MSP) expedition within the Integrated Ocean Drilling Program - IODP, a new era in Arctic research has begun. For the first time, a scientific drilling in the permanently ice-covered Arctic Ocean was carried out, penetrating about 430 meters of Quaternary, Neogene, Paleogene and Campanian sediment on the crest of Lomonosov Ridge close to the North Pole (Backman, et al., 2006, 2008; Moran et al., 2006). ACEX was an outstanding success for two reasons. First, ACEX has proven that with an intensive ice-management strategy, i.e., a three-ship approach with two icebreakers (*Sovetskiy Soyuz* and *Oden*) protecting the drillship (*Vidar Viking)* by breaking upstream ice floes into small pieces, successful scientific drilling in the permanently ice-covered central Arctic Ocean is possible. Second, the first scientific results comprise a milestone in Arctic Ocean research and brought new insights into the Arctic Ocean climate history and its global significance (Backman and Moran, 2008 and further references therein).

Despite the success of IODP Expedition 302, major 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 (Fig. 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 (Fig. 2; e.g., Miller et al., 1987, 1991; Lear et al., 2000; Pearson and Palmer, 2000; Zachos et al., 2001). Nevertheless, 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 by a series of drilling legs during the next decades.

Workshop on "Arctic Ocean History: From Speculation to Reality"

In order to discuss and plan the future of scientific drilling in the Arctic Ocean, an international workshop was held at the Alfred Wegener Institute in Bremerhaven, Germany, between November 3 and 5, 2008 (Coakley and Stein, 2008). Convenors of the workshop were Bernard Coakley (Geophysical Institute, University of Alaska Fairbanks/US) and Ruediger Stein (Alfred Wegener Institute Bremerhaven/Germany). About 95 scientists from

Europe, US, Canada, Russia, Japan, and Korea and observers from oil companies participated in the workshop (Table 1). All participants had the possibility to submit abstracts about their experience, ideas and/or plans of Arctic Ocean research with special emphasis on drilling; the abstracts were published in the Agenda and Abstract Book (Coakley and Stein, 2008). Funding of the workshop was provided by the European Science Foundation (ESF Magellan Workshop Series Programme), the Consortium for Ocean Leadership (US), the Arctic Ocean Sciences Board, and the Nansen Arctic Drilling Program as well as by sponsorships from British Petroleum, ConocoPhillips, ExxonMobil, Norwegian Petroleum Directorate, Shell International, and StatoilHydro.

The major targets of the workshop were: (1) to bring together an international group of Arctic scientists, young scientists and ocean drilling scientists to learn and exchange ideas, experience and enthusiasm about the Arctic Ocean; (2) to develop a scientific drilling strategy to investigate the tectonic and paleoceanographic history of the Arctic Ocean and its role in influencing the global climate system; (3) to summarize the technical needs, opportunities, and limitations of drilling in the Arctic; and (4) to define scientific and drilling targets for specific IODP-type campaigns in Arctic Ocean key areas to be finalized in the development of drilling proposals.

The first day of the workshop focused on presentations about the history of the Arctic Ocean, the legacy of high latitude ocean drilling, the existing site survey database, the possibilities of collaboration with industry and the process of developing ocean-drilling legs through IODP. The next day and a half was spent in thematic and regional break-out groups discussing the particular questions to be addressed by drilling and the particular targets for Arctic scientific drilling. Within the working groups, key scientific questions, site surveys (available and needed) as well as strategies for reaching the overall goals were discussed and – as one of the main results – core groups for further developing drilling proposals were formed. Based on discussions at this meeting, approximately ten new pre-proposals will be submitted to IODP in 2009/2010, i.e., at a critical time, both for the future of Arctic Ocean science and the future of scientific ocean drilling. At April 01, 2009, seven active Arctic-related proposals are listed in the IODP system (Table 2).

Major themes (hypotheses to be tested by drilling) identified by the workshop participants (Table 1) may be summarized by the following key words:

(1) Paleoceanography
Cyclicity between oxic, sub-oxic, and/or euxinic/anxoic conditions during the Cretaceous and Paleocene-Eocene; greenhouse vs. icehouse climate; polar amplification of greenhouse warming; hydrological cycle during greenhouse warming; onset of Eocene cooling; impact of Eocene-Oligocene transition in global pCO_2 and sea level on the Arctic; onset and variability of sea-ice cover (seasonal vs. perennial ice cover); circum-Arctic ice-sheet/ice-shelf history and dynamics; opening of Bering Strait/Fram Strait and its paleoceanographic consequences; causes of extended mid-Cenozoic unconformities; nature of Arctic environment during periods of extreme events (warm/cold); test bipolar synchronous vs. asynchronous climate variability

(2) Tectonics
Mode of crustal extension in the Laptev Sea shelf; development of Fram Strait gateway (mode of extension); identification of plate boundaries (Chukchi Plateau); age of magnetic anomalies (Canada Basin); age and evolution of Alpha Ridge, Mendeleev Ridge, Makarov Basin, and Chukchi Plateau; correlation of on-shore and off-shore geology (Paleozoic sediments,

Mesozoic magmatism); understanding the 'Amerasia' side of Lomonosov Ridge; along strike geologic variation of Lomonosov Ridge and consequences for Mesozoic evolution

(3) Petrology/Geochemistry
Gakkel Ridge (Fig. 3, area 9) mantle melting and geochemistry: western vs. eastern Gakkel Ridge (Global problem: how does continental lithospheric mantle contribute to melting of the asthenosphere? How does extent of melting change as spreading rate goes to zero?); nature and origin of the Chukchi Borderland volcanism; origin of Alpha Mendeleev Ridge (hotspot track or segment of a large LIP? Is the roughly synchronous volcanism recognized in America and Asia somehow related (High Arctic Large Igneous Province)?

(4) Gas hydrates
Gas hydrates and permafrost; aspects related to climate change (greenhouse gas reservoir) geohazards, biogeochemical processes/microbiology, energy resources. Pan-Arctic objective: Multiple sections that lie at different end-members and represent different aspects of gas hydrate (GH) questions and its relationship to climate and geologic history of the Arctic. MacKenzie shelf (most mature, representative of a deltaic end-member; Fig. 3, area 8) vs. Russian shelf (Laptev Sea, excellent location, wide shelf, but not as mature; Siberia excellent candidate for GH aspect; Fig. 3, area 4); deep-water observations of pockmarks and other seismic evidence for GH presence in Mendeleev Ridge area; role of GH in these areas (e.g., carbon cycle); operational issues (GH drilling requires pressure coring and other tools that are routinely used for GH programs, i.e., P-T measurements, lab facilities etc.; need for circulating mud systems); difficulty of achieving new surveys; compilation of existing data.

In order to study the long-term Mesozoic-Cenozoic evolution of the Arctic Ocean, 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 (Fig. 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 circum-Arctic continental margins characterized by high sedimentation rates. Key areas, for example, are the Kara and Laptev seas and the Mackenzie shelf/ slope characterized by large river discharge (Fig. 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 and Chukchi Plateau areas (Fig. 3, areas 3 and 6).

For the precise planning of future drilling campaigns including site selection, evaluation of proposed drill sites for safety and environmental protection aspects, etc., comprehensive site survey data are needed. For some of the potential study areas, the site survey data base is already quite good. For example from the Lomonosov Ridge, a large number of deep-penetration reflection seismic profiles were acquired on icebreaker-based expeditions in 1991, 1996, 1998, and 2005 (Fütterer, 1992; Kristoffersen et al., 1997; Darby et al., 2005; Jokat, 2005 and further references therein), an intensive PARASOUND survey (in combination with coring) was carried-out in 1995 and 1998 (Rachor, 1997; Jokat et al., 1999), and the first high-resolution chirp profiles were collected in 1996 (Jakobsson, 1999). In 1999, the SCICEX program collected high-resolution chirp sub-bottom profiler data, swath bathymetry and sidescan sonar backscatter data on Lomonosov Ridge from an US nuclear submarine (Edwards and Coakley, 2003), contributing significantly to the much improved bathymetric chart of the Arctic Ocean (Jakobsson, 2002; Jakobsson et al., 2008). During the 1995, 1996, and 1998 expeditions, a large number of sediment cores were taken by piston, gravity, and kastenlot corers in the Lomonosov Ridge area (Backman et al., 1997; Rachor, 1997; Jokat et al., 1999; Stein et al., 2001). That means, in combination with the results from the ACEX drilling campaign (Backman, et al., 2006, 2008), future drill areas/sites on Lomonosov Ridge can be identified more accurately. In other key areas for future drilling, for example the Alpha-Mendeleev Ridge, on the other hand, site survey expeditions still have to be carried-out before a detailed planning and drill site selection can start.

Outlook

While sampling the Arctic Ocean is called out as a priority in many of the sections of the lODP Science Plan, these priorities have yet to be realized in a sampling program of commensurate scope and urgency. 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 drilling in the Arctic Ocean needed to answer these questions, were already identified on several workshops during the last two decades and published in upcoming reports. Here, especially the Science Plan (Thiede and the NAD Science Committee, 1992) and the Implementation Plan of the “Nansen Arctic Drilling Program“ (NAD, 1997) as well as the final report of the “Arctic’s Role in Global Climate Change Program Planning Group (APPG)“ (Hovland, 2001), the recent report of the “2nd International Conference on Arctic Research Planning – ICARP II“ (Bowden et al., 2007), and the report of the Arctic Drilling 2009 workshop in Bremerhaven (Coakley and Stein, 2009) have to be mentioned. Over the years, however, scientific drilling in the ice-covered Arctic Ocean remained a dream. The ACEX drilling in 2004 (Backman, et al., 2006) was the first major step that part of this dream became reality. Now, further drilling campaigns are needed to follow-up in the future. Here, the construction of a new large icebreaker with deep-water drilling capability will certainly be the next milestone in Arctic Ocean research. Such a vessel will guarantee a commitment to Arctic deep drilling as well as a continuous drilling program, and could be a potential contribution to the IODP and succeeding programs, as already outlined in the APPG Report (Hovland, 2001). Plans for the development of *Aurora borealis*, an icebreaker with deep-water drilling capability, are pushed forward over the last years, and it seems to be not unrealistic that within the next decade *Aurora borealis* will become available for the international research community and open a new dimension in multidisciplinary Arctic Ocean research (Thiede and Egerton, 2004).

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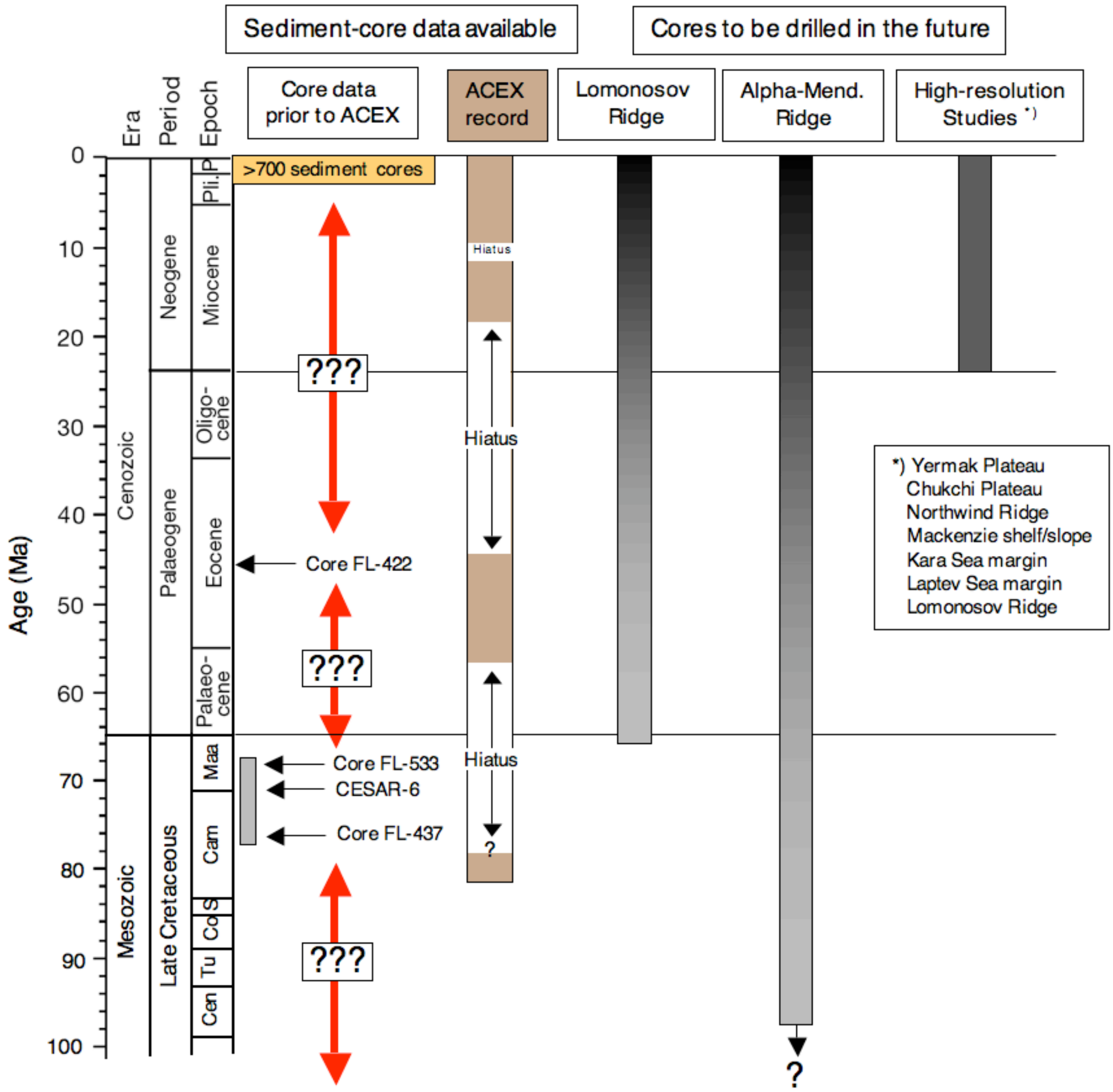

Fig. 1
Stratigraphic coverage of existing cores in the central Arctic Ocean prior to ACEX (based on Thiede et al., 1990) and the section recovered during the ACEX drilling expedition (Backman et al., 2006, 2008), and stratigraphic coverage and key locations of sites to be drilled in the future. Figure from Stein (2008).

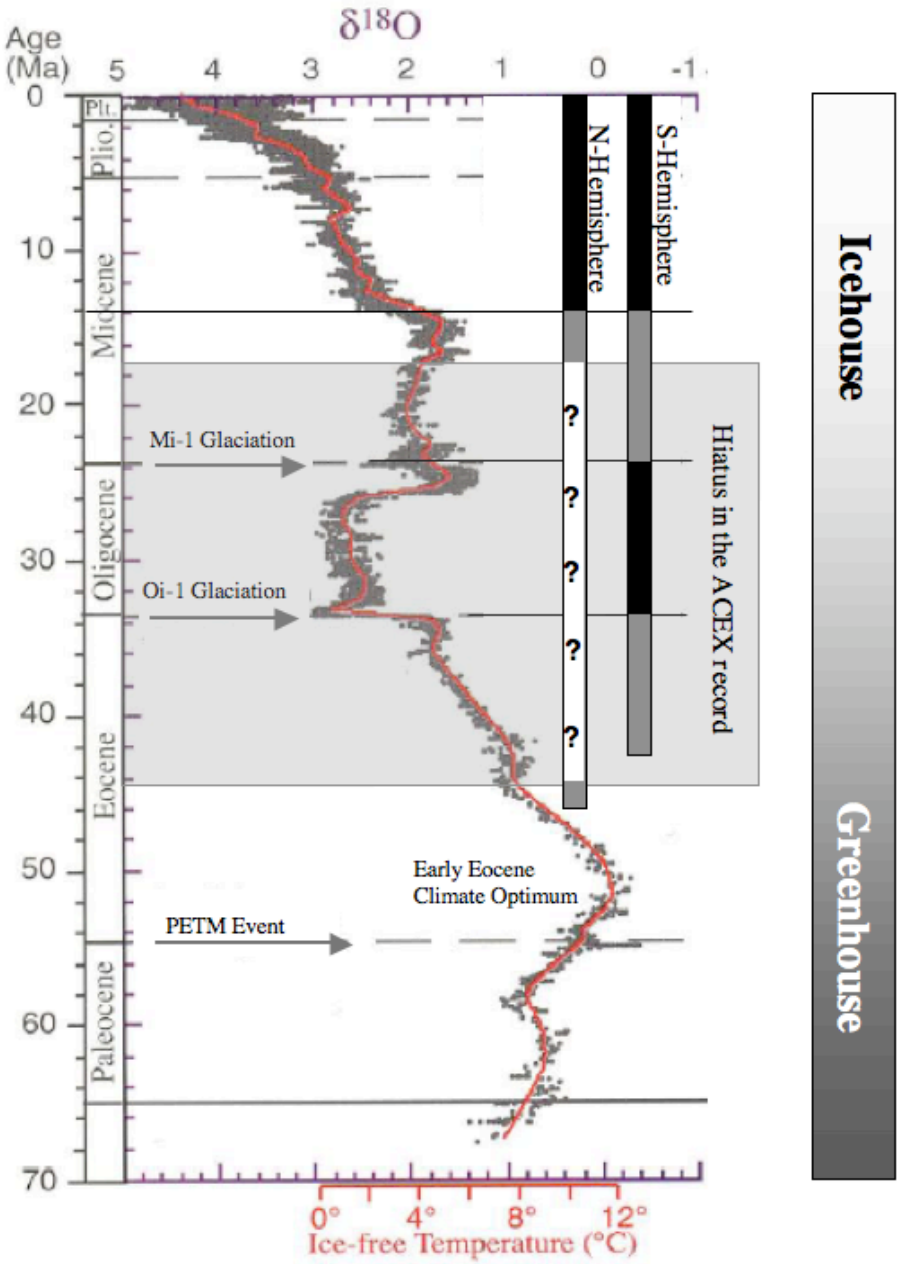

Fig. 2
A smoothed global benthic foraminifer d[18]O time series showing the long-term cooling and the Greenhouse/Icehouse transition through Cenozoic times (Zachos et al., 2001, supplemented). The occurrence of Cenozoic glaciations on the Northern and Southern Hemisphere are shown as black (strong glaciations) and dark gray (less intense glaciations) vertical bars, major glaciations Oi-1 and Mi-1 are indicated (based on Miller et al., 1987, 1991; Lear et al., 2000; Zachos et al., 2001; Backman, et al., 2006). The gray interval represents the hiatus in the ACEX record. Figure from Stein (2008); for further explanations and references see text.

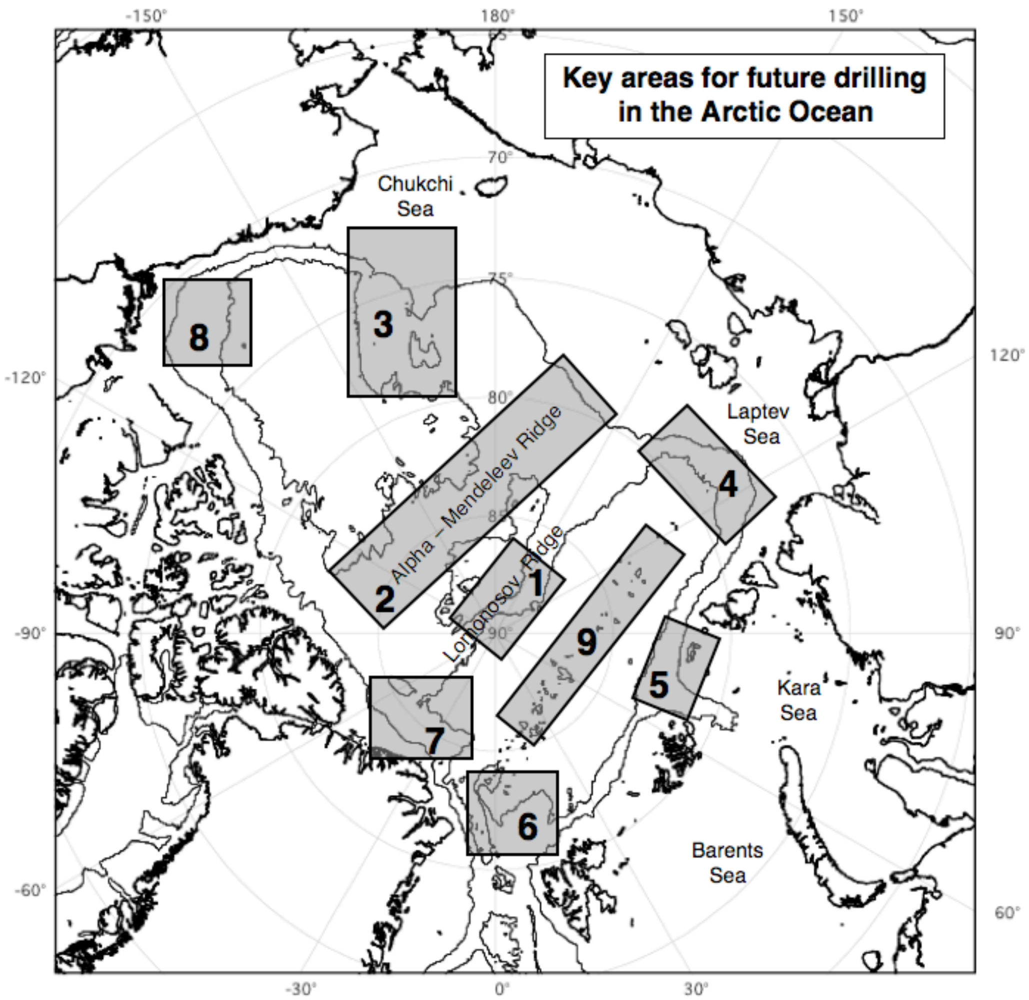

Fig. 3
Key areas for future drilling areas in the Arctic Ocean. 1 = Lomonosov Ridge; 2 = Alpha-Mendeleev Ridge; 3 = Chukchi Plateau/Northwind Ridge; 4 = Latev Sea continental margin; 5= Kara Sea continental margin; 6 = Fram Strait/Yermak Plateau; 7 = Morris Jessup Rise; 8 = Mackenzie shelf/slope; 9 = Gakkel Ridge.

Table 1:

Participants of Arctic Drilling Workshop (AWI Bremerhaven/Germany, Nov 03-05, 2008).

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35	Krylov	Alexey	akrylow@gmail.com	82	Thiede	Joern	joern.thiede@awi.de
36	Kusznir	Nick	n.kusznir@liverpool.ac.uk	83	Toro	Jaime	jtoro@wvu.edu
37	Lawver	Lawrence	lawver@ig.utexas.edu	84	Torres	Marta	mtorres@coas.oregonstate.edu
38	Lebedeva-Ivanova	Nina	Nina.Ivanova@geo.uu.se	85	Tripati	Aradhna	atri02@esc.cam.ac.uk
39	Lembke-Jene	Lester	Lester.Lembke-Jene@awi.de	86	Tuchkova	Marianna	tuchkova@ginras.ru
40	Mackay	Laura	laura.mackay@bp.com	87	van Oosterhout	Cees	C.VanOosterhout@shell.com
41	März	Christian	cmaerz@icbm.de	88	Vaughan	Alan	apmva@bas.ac.uk
42	Matthiessen	Jens	Jens.Matthiessen@awi.de	89	Wannier	Mario	Mario.Wannier@shell.com
43	Mayer	Larry	larry@ccom.unh.edu	90	Waszczak	Ron	Ron.F.Waszczak@conocophillips.com
44	McAllister	Niall	niall.w.mcallister@exxonmobil.com	91	Zachos	James	jzachos@pmc.ucsc.edu
45	Michael	Peter	pjm@utulsa.edu	92	Zarikian	Carlos	zarikian@iodp.tamu.edu
46	Mikkelsen	Naja	nm@geus.dk	93	Zhao	Xixi	xzhao@pmc.ucsc.edu
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Table 2:

Active Arctic-related IODP proposals (as 1 April, 2009).

More details on these proposals including the list of co-proponents and involved institutions can be found at the IODP website (http://www.iodp.org/active-proposals).

Active Arctic-related IODP proposals (as 1 April, 2009)

Number	Short Title	Contact Proponent	University/Institute	Country	Ocean	Platform	E-mail
477-Full4	Okhotsk/Bering Plio-Pleistocene	K. Takahashi	Kyushu University//Fukuoka	Japan	Pacific	NR	kozo@geo.kyushu-u.ac.jp
645-Full3	North Atlantic Gateway	W. Jokat	AWI Bremerhaven	ECORD/Germany	Arctic	MSP+NR	Wilfried.Jokat@awi.de
680-Full	Bering Strait Climate Change	S.J. Fowell	University of Alaska/Fairbanks	USA	Arctic	MSP	ffsjf@uaf.edu
708-Pre	Central Arctic Paleoceanography	R. Stein	AWI Bremerhaven	ECORD/Germany	Arctic	MSP	Ruediger.Stein@awi.de
746-Pre	Arctic Mesozoic Climate	W. Jokat	AWI Bremerhaven	ECORD/Germany	Arctic	MSP	Wilfried.Jokat@awi.de
750-Pre	Beringia Sea Level History	L. Polyak	Ohio State University/Columbus	USA	Arctic	MSP+NR	polyak.1@osu.edu
753-Pre	Beaufort Sea Paleoceanography	M. O'Regan	Stockholm University	ECORD/Sweden	Arctic	NR	matt.oregan@geo.su.se

NR: non-riser (JR) MSP: Mission-specific platform