Photo: Freezing fog, Arctic Ocean (W. Huppertz, AWI, 1993)

The High-Arctic Drilling Challenge

Final Report of the Arctic's Role in Global Change Program Planning Group (APPG)

"The Arctic Ocean is about four times the size of the Mediterranean Sea"

Edited by Martin Hovland
Chairman APPG

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Contents

1 Organization

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2 Executive Summary

Global climate models demonstrate the sensitivity of the polar areas to changes in forcing of the ocean/climate system. The presence or absence of snow and ice influences the global heat distribution through its effect on the albedo, and the polar oceans are the source of dense, cold bottom waters which influence the thermohaline circulation in the world oceans. In spite of the critical role of the Arctic Ocean in climate evolution, only very little material from the Cenozoic is represented in available core material, representing one of the largest current gaps in the Earth Sciences.

Key scientific questions to be addressed by dedicated Arctic scientific drilling include:

- The response of the Arctic during periods of extreme polar warmth

- Variations in the physical and chemical characteristics of the water mass in an evolving polar deep ocean basin, and the oceanographic response to opening of gateways

- The history of marine polar biota and fertility

- What is the history of Arctic sea ice?

- Ice rafting and the history of local vs. regional ice sheet developments

- Processes of methane release from destabilized permafrost-associated gas hydrate accumulations

- The history of emplacement of Large Igneous Provinces (LIPs) in the Arctic Ocean and its environmental impact

The APPG concludes that:

- scientific drilling can be carried out in permanently ice-covered areas of the Arctic Ocean without harm to the environment. In the short-term (3-5 years), this can be achieved with present technology and the potential for scientific rewards are high.

- an Arctic scientific drilling campaign should start as soon as possible which would be the beginning of a long-term program in a climatically important, but largely unknown, ocean.

- in preparation for a long-term drilling program in the high Arctic, new geophysical data are urgently needed for drillsite definition. Site survey data exist from sections of the Yermak Plateau, Lomonosov Ridge and the Chukchi Plateau for the definition of targets for drilling in the near future (3-5 years) time frame (Fig. 1).

- stationary marine operations in drifting sea-ice require careful ice management, which combines modelling icebreaker performance, ice reconnaissance studies (weather forecasting, radar imaging, and ice floe tracking), and icebreaker operations.

- proven systems for drilling single-bit holes should be utilized in the short-term. As operational experience is gained, the system capability can be expanded to include re-entry and multi-cased boreholes with instrumentation.

- a long-term drilling commitment in the central deep Arctic, where drilling targets of high scientific priority are located, could ideally require a large icebreaker with deep-water drilling capability. It is recommended that a feasibility study for such a vessel be made.

Arctic Program Planning Group's prioritisation of drilling targets and status of site surveys

Priority	**Target**	Site survey?	Comments
1	Lomonosov Ridge	**Yes**	Mature proposal / DPPG (task force) exists
1	Alpha Ridge	No	Gateways/Tectonic. Difficult ice conditions
1	Northwind Ridge/ Chukchi borderld.	**Yes**, only partly	Gateways, tectonic, Palaeoclimate, but difficult ice conditions for stationary ops.
1	Beaufort Shelf	No	Gas hydrates/climate, shallow water (<120m), difficult ice conditions
1	Gakkel Ridge	**Yes**, partly	Tectonic, slow, but active spreading ridge, far from effects of equatorial forces
2	Yermak Plateau	**Yes**, partly	Major sediment drift. Atlantic gateways
2	Chukchi Sea	**Yes**, partly	Palaeoclimate. Pacific gateways history
2	Santa Ana Trough	No, only minimal data	Will obtain high-resolution records from trough and adjacent continental slope
2	Morris Jessup Rise	**Yes**, but limited	Gateways, palaeoclimate, and tectonic

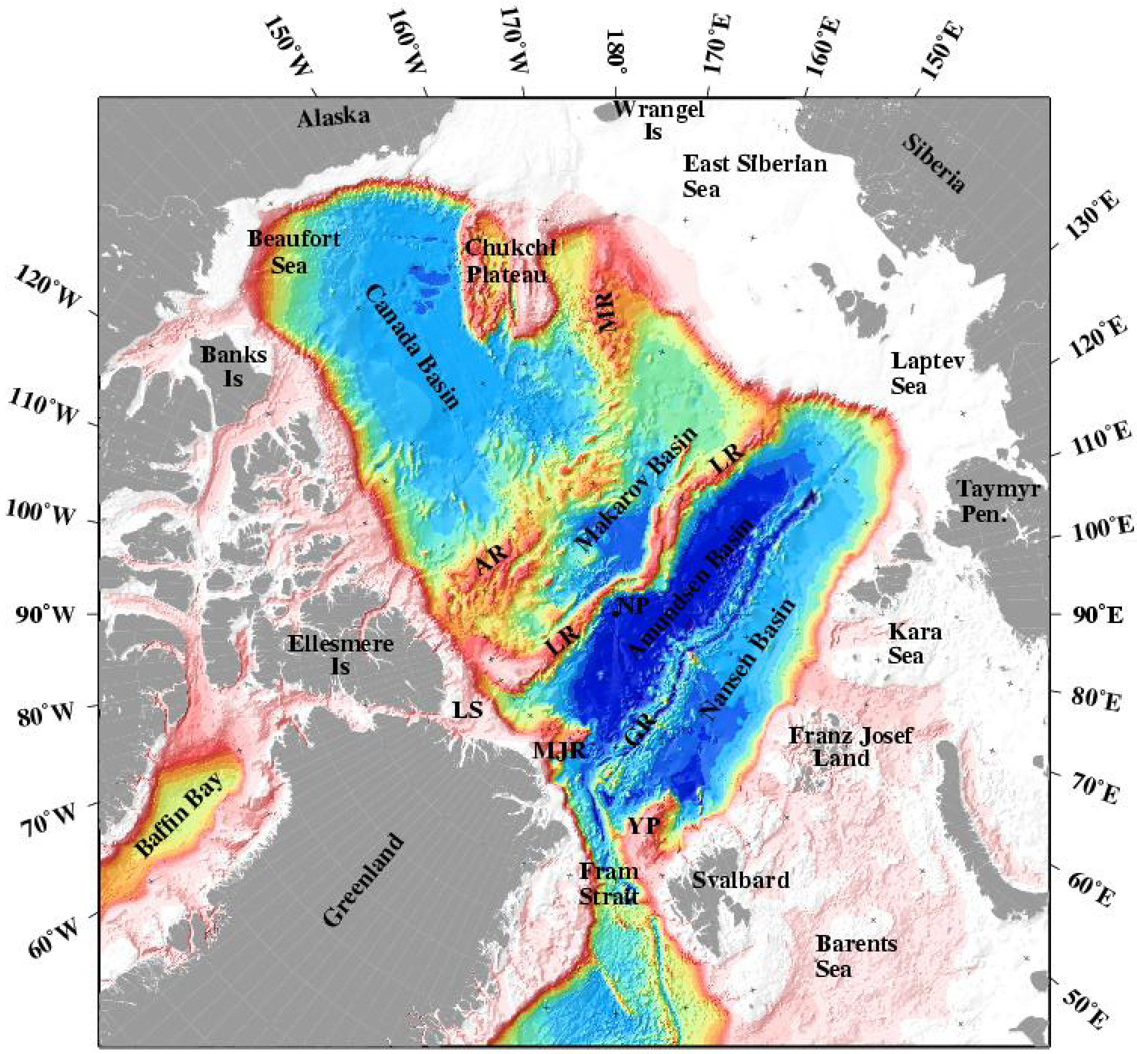

Fig. 1a Bathymetry and structure of the Arctic Ocean.

Abbreviations: AR-Alpha Ridge; MR-Mendeleev Ridge; LR-Lomonosov Ridge; GR-Gakkel Ridge; LS-Lincoln Sea; MJR- Morris Jessup Rise; YP-Yermak Plateau; NP-North Pole.

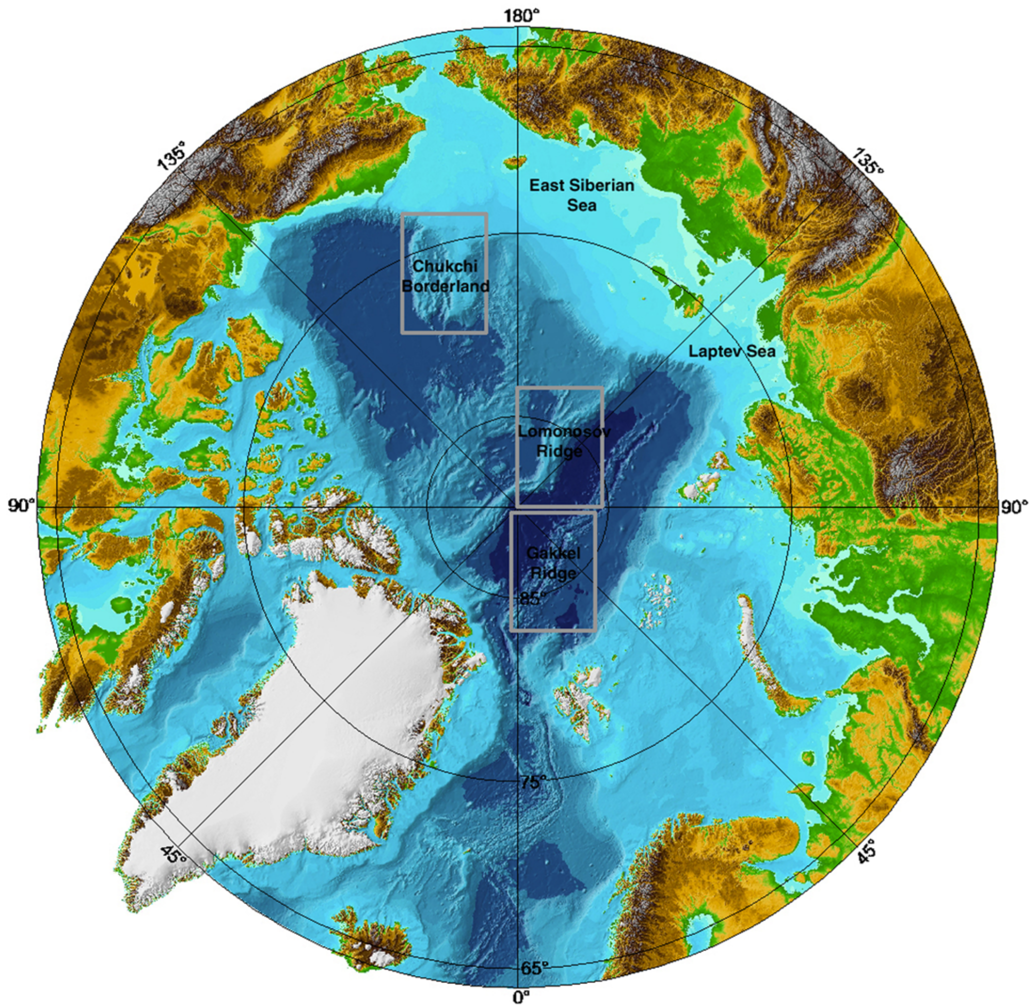

Fig. 1b The new IBCAO bathymetry map of the Arctic Ocean (Jacobsson et al., 2000). (Can be downloaded from: www.ngdc.noaa.gov/mgg/image/IBCAO)

3 Mandate

According to SCICOM Motion 99-1-6, the following mandate and overall goal was defined for the APPG:

Mandate

1. Design a scientific drilling strategy to investigate the role of the Arctic in influencing the global climate system. Besides climatic and paleoceanographic studies, this strategy may also address those aspects of the Arctic's tectonic development and magmatic history that may have significantly impacted global climate or that may otherwise relate to globally important problems.

2. Summarize the technical needs, opportunities, and limitations of drilling in the Arctic.

3. Encourage and nurture the development of drilling proposals.

Overall Goal
To develop a mature science plan concerning those aspects of Arctic drilling that bear on global problems, particularly with respect to the climate system on time scales from decades to millions of years. This PPG will build on the existing Implementation Plan of the Nansen Arctic Drilling (NAD) program and will consist partly of NAD scientists.

In order to meet this goal and fulfill its mandate, the APPG had three meetings: in Stavanger (Norway), March 2000; in Calgary (Canada), June 2000; and Stockholm (Sweden), Jan. 2001. This final report contains contributions by the APPG members and others, and was completed in March, 2001.

4 Scientific Objectives

Introduction
Earth's climate has undergone a significant and complex evolution, the finer details of which are just coming to light through investigations of deep-sea sediment cores (Fig. 2). This evolution includes gradual trends of warming and cooling driven by tectonic processes on time scales of 10^5-10^7 year, rhythmic or periodic cycles, driven by orbital processes with 10^4-10^6 year cyclicity, and rare rapid aberrant shifts and extreme climate transients with durations of 10^3-10^5 years. This history has been determined largely through investigations of cores recovered from the world´s oceans by DSDP and ODP, particularly the high latitude southern oceans where signals of climatic change tend to be amplified.

Very little is known about signals of climatic change in the Arctic Ocean. This represents a major and unacceptable gap in the global paleoclimatic database. What little information is available on Arctic paleoclimates comes from a few piston cores, exploration wells, and land based marine outcrops. While these provide glimpses of climate signals for a few brief intervals, the lack of continuous sediment records severely limits efforts to establish a chronologic sequence of climate and environmental change for this important region.

In essence, the history of Arctic climate and circulation is so poorly known that we can view the recovery of any material as a major advance and one that will, by definition, increase our knowledge and understanding of this critical region.

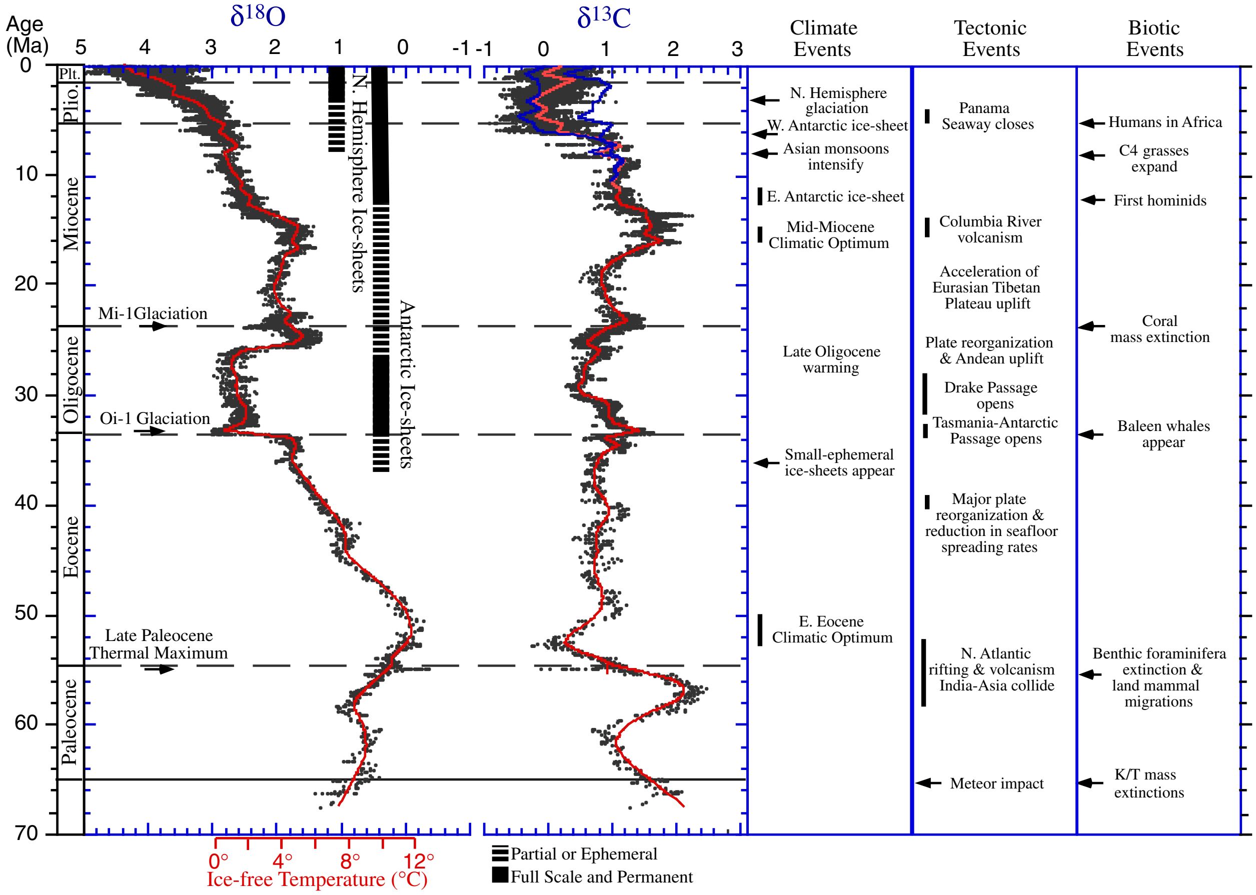

Fig.2 A global compilation of deep-sea isotope records based on isotope values of Cibicidoides and Nuttallides (Zachos et al., 2001). The records are based on benthic foraminifera isotope data from 50 DSDP and ODP sites. The raw data were smoothed using a 5 point running mean. The curve fits are locally weighted means. For the carbon isotope record, separate curve fits are shown for the Atlantic and Pacific to show the effects of basin to basin fractionation after 15 Ma. Also shown are the major tectonic, climatic, and biotic events of the Cenozoic (Zachos et al, 2001).

Questions

There are a number of specific outstanding questions that are critical to answer in order to understand the influence of the Arctic on global climate change, on all time scales, from tectonic to millennial.

- What is the history of Arctic sea ice? When did perennial sea ice first appear in the Arctic? Has it appeared and then disappeared on more than one occasion? Under what circumstances did this pack-ice form or disappear?

- When did the first circum-Arctic ice-sheets appear? Once established, what was the history of growth and decay of these cyclic ice-sheets?

- How has the circulation and stratification of Arctic water masses evolved over the Cenozoic? How have the changes in Arctic water mass characteristics influenced global thermohaline circulation (intermediate or deep water)?

- What was the nature of the Arctic environment during periods of extreme global warmth?

- Have there been major changes in the biogeochemical cycles of the Arctic, particularly those affecting methane hydrates?

- What is the history of marine polar biota and fertility?

- How has the tectonic evolution of the basin influenced regional and global climate?

The Arctic and Global climate

The Arctic Ocean plays a fundamental role in the global ocean/climate system: it is the primary northern hemisphere heat sink. It is a source of cold, dense intermediate- and bottom waters to most of the world's oceans. The permanent sea-ice cover has a tremendous influence on the Earth's albedo, atmospheric circulation, and the distribution of fresh water. It's variation both seasonally and over longer time periods thus has a direct influence on global heat distribution, climate, nutrients, biota, and sediments. Whether the Arctic ocean influences changes in global climate or how it responds to these changes is unclear.

<u>Perennial Sea-Ice History</u>

The factors that control sea-ice thickness and extent are poorly understood. However, their influences are manifested through: a) changes in albedo, b) water-column stability and bottom-water formation, c) ocean/atmosphere heat and evaporative exchange, and d) bio-productivity and carbon sinks. The distribution of perennial sea-ice is tied to several global boundary conditions including temperature, salinity, and atmospheric and oceanic circulation. We know that this pack-ice cover is sensitive to at least some of these conditions on decadal time scales (Cavaleri et al., 1997; Proshutinsky and Johnson, 1997). Establishing the initiation of Arctic perennial ice cover would permit correlation to global climate changes and thus a clearer understanding of the climate system. In this regard, when did perennial sea-ice cover develop? Under what boundary conditions did it develop, and disappear? Are fluctuations in sea-ice cover linked to the growth and decay of continental ice? What is the climatic feedback from an evolving ice pack in amplifying polar cooling by increasing albedo and restricting ocean-atmosphere heat transfer?

In order to accomplish this objective, the ridges in the central Arctic Ocean need to be cored, especially in areas where sedimentation rates might be high (>1 cm/kyr). While seasonal ice would occur in the periphery of the Arctic Ocean, only the central Arctic would record perennial pack-ice.

Circum-Arctic Ice-sheet Evolution

The evolution of Northern Hemisphere glaciation is complex. There is little doubt about the scale and timing of the major glacial cycles of the Pleistocene which are well constrained from both direct and indirect evidence (i.e., oxygen isotopes). In addition, the pre-Pleistocene evolution of the Greenland ice-sheets is known from the results of ODP exploration in the Nordic seas. What remains unclear is the pre-Pliocene evolution of small-scale ice-sheets. For example when did the first ice-sheets form, and what was their extent? Were they ephemeral?

Several major ice sheets calved icebergs into the Arctic Ocean as evidenced by the ice-rafted detritus (IRD) record (Polyak et al., 1995; Bischof and Darby, 1999; Phillips and Grantz, 1997). The timing, causes, and consequences of the repeated growth and decay of these ice sheets throughout their history must be closely linked to global climate. For example, are the growth and decay of the ice-sheets synchronous with sub-polar ice-sheets such as the Laurentide ice-sheet that collapsed periodically to produce Heinrich events in the North Atlantic?

In order to expand on the late Pleistocene record of the Arctic ice-sheet evolution we recommend drilling the continental slopes offshore of the known margins of these ice-sheets. For example, the slope off McClure Strait should contain a complete record of that portion of the Laurentide ice-sheet that calved into the Arctic Ocean. Similar areas offshore of the Innuitian and Barents Sea ice-sheets also should be targeted. In addition, sections of the Lomonosov Ridge that would intersect drift tracks of icebergs from the Canadian ice-sheets should be a prime target for obtaining the history of these ice-sheets.

Circulation/Stratification of the Arctic Ocean

The series of interconnected basins comprising the Nordic Seas contain about 0.7% of the volume of the world ocean, excluding the Amerasian Basin of the Arctic Ocean. Despite the small volume of these areas, they act as a primary source of a large portion of deep, ventilated waters in the World Ocean. Also, the export of ventilated deep waters to the Atlantic via the Fram Strait is compensated by a corresponding import of relatively warm and saline surface waters of Atlantic origin (Aagaard et al., 1985). The Arctic Ocean is hence commonly described as one of the lungs of the deep global ocean (the other being the Weddell Sea). The tectonic development and opening of the Fram Strait has determined the history of water mass exchange between the Arctic Ocean and the World Ocean, as the strait represents the only deep connection between the Arctic and all other oceans. The initial opening of the Fram Strait may have occurred as early as late Eocene, some 35 million years ago.

An understanding of the exchange of water masses between the Arctic Ocean and the world ocean is an essential element in modelling the change in global oceanographic conditions over the past ~40 million years. Such models require knowledge about, for example, when bottom water formation began in the Arctic, how chemical and physical characteristics of this water mass varied through time, and which cause and effect relationships governed the development of the Arctic water masses.

Extreme Warmth and the Arctic

Another important challenge in paleoclimatology /paleoceanography is to develop a quantitative understanding of the underlying mechanisms responsible for maintaining the extreme polar warmth observed for the Eocene and other intervals, older and younger. In terms of intervals of extreme warmth, there are seven key time intervals to examine in the Arctic, the Aptian – Albian, early Eocene, middle Miocene, early Pliocene, MIS 11, Cenomanian, and late Paleocene (Zachos et al., 2001). What was the climate of the Arctic during these periods? Studies of terrestrial floras suggest mean annual temperatures as high as 13°C during the Cenomanian greenhouse conditions (Spicer et al., 1999). What was the circulation and fertility of this open basin? Was there sea-ice during the Neogene warm intervals? Perhaps the most extreme greenhouse interval is the late Paleocene Thermal Maximum (LPTM). This event, which could have been driven by the release and oxidation of methane from clathrates, is characterized by as much as 8°C of warming in the high southern latitudes. What was the response of the Arctic to this warming?

At present, the existing climate proxy data for the Arctic are at odds with paleoclimate simulations (general circulation models) that produce polar regions characterized by sub-freezing temperatures and significant seasonality. And yet, the fossil record suggests mild climates characterized by winters that rarely see sub-freezing conditions. The reasons for the model/data discrepancies are not known. In terms of the dynamics of maintaining extreme polar warmth, climatologists have focused on heat transport processes as well as the effects of greenhouse gases (Lyle, 1997). Simulations have been run to test the effects of increased oceanic heat transport on high latitude climates, but have found this to be inadequate for sustaining polar warmth. Along these lines, the presence of a large body of water with its attendant heat capacity should have a major influence on high latitude temperature, daily and seasonal, although the impact of this quantitatively requires additional testing. One potential solution to the high-latitude warmth paradigm may involve methane in generating polar-stratospheric clouds which tend to insulate the poles.

Evolution of Polar Biota

What little we know about the composition of the Arctic floras and faunas is largely derived from isolated studies of the shallow-marine assemblages in the onshore sediments of Arctic Canada, Spitsbergen, the Pechora Basin, Western Siberia, and a few piston cores on the Alpha Ridge. Mesozoic microfossils (mostly foraminifera and palynomorphs) have been studied from Siberia (Azbel et al., 1991), Canada (Hedinger, 1993), and Spitsbergen. Cenozoic foraminifera and palynological assemblages have been studied in offshore exploration wells in the Beaufort-MacKenzie Basin (McNeil, 1989, 1997). These areas provide at least some insight into the nature of Arctic marine faunas.

A number of questions remain to be answered:

What is the taxonomic composition of the Polar marine faunas and floras? Is there any evidence for bipolarity of Polar faunas? Can we establish a workable microfossil biochronology for the Arctic that can be used for correlation purposes? Given the endemic nature of floras and faunas reported from the Arctic, to what extent has the Arctic fauna and flora evolved in isolation from the world ocean? Has the Arctic served as a refugium for species that suffered extinction elsewhere?

Can we use the microfossil record of the Arctic as proxies of watermass properties and productivity, or do we need to develop new proxies? Can we use fauna and flora to interpret the circulation history of the Arctic basins? What role has the Arctic Ocean played in the origin of cosmopolitan oceanic faunas and floras, and terrestrial biota? To what extent is the evolution of polar marine faunas and floras influenced by the evolution of the cryosphere? To what extent can we use the siliceous faunas and floras to interpret the history of sea-ice formation in the Arctic?

Arctic gateways and basin evolution

The tectonic environment of the Arctic Ocean evolved dramatically during the Mesozoic-Cenozoic. The Cenozoic opening of sea-gateways, especially Fram Strait, favoured the formation of continental ice sheets and sea-ice cover in the Arctic. The opening of these gateways may have played a key role in allowing the mean average temperature to decrease substantially to that of the present day. Knowledge of this history can only be obtained by sampling the rocks and sediment of the Arctic gateways.

During parts of the Mesozoic, the Arctic Ocean consisted of an isolated deep-sea area with no major deep-water connection to the other oceans. Current models suggest that the oldest Arctic deep-sea basin (Canada Basin) opened in the late Jurassic to Cretaceous (Vogt et al., 1979). Although this model is widely accepted, details of the Mesozoic evolution of the Arctic are very sketchy. Cenozoic spreading at Gakkel Ridge explains the opening of the Eurasian Basin and its relationship to Lomonosov Ridge, whereas the nature of the Alpha-Mendeleev Ridge in the Amerasian Basin, as well as the age of the surrounding deep-sea basins, is not known. The most important question to be addressed for the Cenozoic history is "when did the Arctic gateways open?". A number of key areas need to be investigated in order to unravel the geological history of the high Arctic and to answer this question.

The Alpha-Mendeleev Ridge is the single largest submarine feature of the Arctic Ocean. One model suggests the ridge complex may represent a Cretaceous LIP, and there is some supporting evidence in the form of terrestrial Cretaceous flood basalts exposed along parts of the Arctic Ocean margins. Recent geological and geophysical investigations support this idea, and the few dredged lavas have strong affinities to continental tholeiites (Muehe and Jokat, 1999). Seismic investiagations show that Alpha Ridge is covered by an undisturbed sedimentary sequence up 1 km thick (Hall, 1979; Jackson, 1985; Jokat et al., 1999). Shallow cores confirm that Cretaceous sediments are present (Clark et al., 1986). This area represents a unique opportunity to obtain a complete record of the post-Paleozoic history of the high-Arctic Ocean.

It has been suggested that Lomonosov Ridge is a continental fragment rifted from the Barents-Kara Sea margin. Seismic reflection data across the ridge show a continuous cover of flat-lying pelagic sediments on the ridge top, underlain by sediment-filled half grabens and diverging reflectors (Jokat et al., 1992). The sediments beneath the Cenozoic pelagic section represent the only preserved Mesozoic record from this margin, which comprises one boundary of the Amerasian Basin. Drilling through the unconformity will constrain the development of this passive margin, and provide age constraints for rifting of the Eurasian Basin.

Gakkel Ridge is unique among active oceanic ridges for its very slow spreading rate. The lavas, their peridotitic melt residues, and the direct interaction of mantle rocks with seawater all hold important information that can significantly add to our understanding of global mid-ocean ridge spreading systems. The drilling objectives here are to obtain relatively fresh basement samples from beneath the sediment covered central and eastern portions of the ridge, and to establish the depth and extent of crust/mantle-seawater chemical and thermal interactions on the ridge.

Geophysical data suggest that the Morris Jesup Rise and the northern section of the Yermak Plateau represent an oceanic LIP which once formed an Iceland-like massif at the junction of the North American/Greenland and European Plates. These features are presumably underlain by oceanic crust. Knowledge of the origin of these plateaux is essential for understanding the opening of the Fram Strait, and also for reconstructing the opening history of the Eurasian Basin.

The Amerasian Basin probably formed when Arctic Alaska rotated away from Arctic Canada during the Mesozoic, and the Chukchi Borderland is thought to be of continental origin (Grantz et al., 1999). However, the limited geological and geophysical data from these margins and the Canada Basin are insufficient to test this hypothesis. Furthermore, this simplistic model fails to explain either Alpha Ridge or the Chukchi Cap region.

Marine connections between the Arctic and other oceans during the Cretaceous were maintained through the Western Interior Seaway, whereas during the early Paleogene there were intermittent connections with the Tethys via Turgai Strait in Western Siberia. The two modern Arctic gateways, Fram Strait and Bering Strait, developed as a result of later plate motions and have since been influenced by vertical motions, volcanism and sea-level changes. The development of these gateways has had a profound impact on global oceanic circulation, and it is clear that an understanding of their tectonic evolution urgently requires further drilling, dredging and geophysical programs.

Potential for High Resolution Coring in the Arctic Ocean

The paleoclimate studies dealing with rapid climate change and short-lived climatic events require cores from areas with high sedimentation rates in the Arctic Ocean. In order to resolve changes such as Dansgaard-Oeschger events on the 1.5 kyr frequency, deposition rates of at least several cm/kyr are a must and >10 cm/kyr highly desirable. Besides paleoclimate, there are many processes that are unique to the Arctic such as sea ice-rafting from shelf to shelf across thousands of kilometers of ocean (Bischof and Darby, 1999). Such records could also be useful for investigations of biogenic and nutrient paleo-fluxes in the Arctic Ocean, especially those from the shelves to the basins. Other aspects to investigate with high-resolution records are the ventilation of the deep Arctic Ocean and the impact of fresh water fluxes and the effect of sea ice formation on the stability of the Arctic pack-ice.

Potential locations for high-resolution sediment records in the Arctic Ocean are reviewed below:

Continental Slopes

The most promising areas for both high sedimentation marine records and adequate amounts of biogenic proxies are the continental slopes in certain areas. The margins of the Arctic Ocean have the thinnest pack-ice and probably the shortest intervals of low productivity in the past. Aside from the problem of downslope transport from the shallow shelf or terrigenous sources swamping the marine signal, these locations offer the potential for a compromise between continuous deposition above 10 cm/kyr and adequate amounts of biogenic proxies. Most of these slopes have contour currents that could generate drift deposits with high sedimentation rates. Many canyons cut these slopes and high rates of downslope sediment transport and deposition should occur in fans or deltas associated with these canyons. While these may have a high proportion of terrigenous input, they do provide high resolution.

Not all continental slopes are equally promising. One example of a slope with good potential for high resolution cores with abundant proxies are the slopes off the Laptev, Chukchi, and Kara Seas (especially in and around the Santa Anna Trough). The Laptev Sea continental slope should contain a record of the western Russian Arctic Ocean as well as a signal from the Lena, Ob and Yenisey Rivers, and other important Russian rivers (Kassens et al., 1999; Stein, 2000; Stein and Fahl, 2000). The Kara and Barents Sea slopes leading into the depths of the eastern Arctic Ocean should contain an excellent detailed record of former ice sheets on these shelf areas (Stein et al., 1994). These fluvial signals are important to both paleoclimatology and paleoceanography. The Chukchi Sea continental slope should provide a marine record of the western Amerasian Arctic Ocean as well as the Bering Strait influx from the north Pacific. The Kara Sea continental slope should provide a marine record for the eastern Arctic Ocean and the influx of North Atlantic water that enters the Arctic Ocean via the Barents Sea. This later location could be critical for understanding the North Atlantic Oscillation and its potential relationship with Arctic paleoclimate changes.

Central Arctic Ocean Ridges

There are three sub-parallel ridge systems of quite different age, origin, and morphology in the central Arctic Ocean, the Alpha-Mendeleev, the Lomonosov, and the Gakkel Ridges. There are abundant graben features on each of these ridge systems that afford conditions for ponded sediment and higher sedimentation rates. In addition, there are locations where contour currents or geostrophic currents such as the North Atlantic Intermediate Water spill over these ridges in less than 1000 meters water depth. These afford the opportunity for drift deposits and thus high sedimentation rates. Seismic evidence on at least the Lomonosov Ridge indicates a two-fold thickening of the Tertiary sediment package in some areas (Jokat, 1999; Jokat et al., 1999). In addition, the Northwind Ridge/Chukchi Plateau area offers potential coring sites close to open water or favorable ice conditions in most summers.

Because of the generally thicker pack-ice conditions in the Amerasian half of the Arctic Ocean, the Alpha-Mendeleev Ridge and to a large extent, the Lomonosov Ridge have a lower potential for good biogenic proxy accumulations. Parts of the Gakkel Ridge should not be as severely affected and thus could have a much better proxy record than the other two ridges (Stein et al., 1994).

Deep Arctic Basins

While normal pelagic deposition occurs in the deep Arctic basins (e.g., core 94BC20, Darby et al., 1997), these basins are dominated by turbidite sequences (Campbell and Clark, 1977; Darby et al. 1989). The deposition rates for the normal pelagic sediment in these basins is usually no higher than on adjacent ridges (Darby et al., 1997). There are some exceptions where sedimentation rates of normal pelagic sediments were found to be up to 3.2 cm/kyr in the Canada Basin (Grantz et al., 1999). Turbidite sequences have sedimentation rates of 145 cm/kyr; however, unless someone can discover a way to interpret turbidite sequences for paleoclimatic or paleoceanographic problems, these areas should have a low priority for high resolution coring. Turbidite sequences do preserve a good record of the sporadic flux of sediment off the shelves or from large rivers (e.g., the Mackenzie fan). The main problem is the sporadic nature of turbidites and establishing a good stratigraphy without having to date nearly every turbidite layer.

Gas Hydrates in the Arctic

The distribution of gas hydrate in marine arctic environments is poorly documented, although conditions exist for gas hydrate to occur associated with permafrost on the submerged continental shelves of the circum-arctic sedimentary basin, much like their terrestrial counterparts (Kvenvolden and Grantz, 1990; Max and Lowrie, 1992). Gas hydrate may also be present in deep marine Arctic basins, as suggested by the recent observation of bottom-simulating reflectors (BSR) on seismic lines through the Lomonosov and Alpha Ridges (Jokat, 1999). The amount of methane that is trapped in gas hydrate is perhaps 3,000 times the amount contained in the atmosphere. A large portion of this methane reservoir is located on the Arctic continental shelf associated with permafrost.

Of particular relevance to global climatic change is the question: Could large quantities of methane be released to the water column and ultimately to the atmosphere as a consequence of destabilization of gas hydrate present in seafloor sediments? The exact link between global warming and gas hydrate dissociation is still debated. A unique site to document the on-going process of methane release from gas hydrate dissociation is the Arctic continental shelf. The process of methane release to the atmosphere may have been active on the extensive Arctic continental shelf since the end of the Pleistocene glaciations, when submergence of the shelf considerably increased the temperature at the sediment surface. This would have produced progressive warming of the shelf sediments with gas hydrate destabilization and methane release.

It should be noted that few continental shelves are broader than the shelf off Siberia (up to 1,600 km). Their potential importance as methane sources during sealevel lowstands is immense. However, the processes leading to permafrost and gas hydrate destabilization on the Arctic continental shelf has received little attention. Scientific drilling of destabilized permafrost and gas hydrate accumulations on the Arctic shelf would be of great benefit in characterizing the distribution of gas hydrate in the Arctic shelf sediments and in unveiling thermal and hydrogeological processes that control methane release. Such boreholes would provide important clues as to the interplay between permafrost-associated gas hydrate in Arctic shelf sediments and global climatic change.

The APPG recommends drilling a destabilized permafrost-associated gas hydrate accumulation on the Arctic shelf in order to characterize paleo- and active processes of methane release. This could be achieved through drilling a suite of 3-4 holes across the shelf, from an outer position at the former limit of permafrost, to an inner position where permafrost has been virtually preserved (reference site possibly on land). Drilling objectives should include determining the distribution of permafrost, solid gas hydrate and free gas, to establish the nature of the thermal regime, to investigate active gas transport processes and fluxes, and to develop models of methane release from destabilized permafrost-associated gas hydrate accumulations.

Other biogeochemical cycles, such as the silica cycle, should also be investigated in context of regional and global climate change. Very little is known about these elements and their record of nutrient flux in the Arctic Ocean (Aagaard et al., 1999).

Prioritisation of targets and scientific goals
Although questions on priority of drilling locations and scientific strategy were addressed during scheduled APPG meetings, a combination of lacking geophysical data (site survey data) and the great variety in scientific questions, discussed herein, made it more-or-less impossible to come up with unified decisions on target priority and scientific strategy, as mandated. Even so, the APPG has been able to establish the following (incomplete) table that suggests to potential proponents some prioritised recommended targets. The following table clearly illustrates the ultra-high priority there is in acquiring more general geophysical data and specific site survey data in the Arctic Ocean.

Arctic Program Planning Group's prioritisation of drilling targets and status of site surveys

Priority	**Target**	Site survey?	Comments
1	Lomonosov Ridge	**Yes**	Mature proposal / DPPG (task force) exists
1	Alpha Ridge	No	Gateways/Tectonic. Difficult ice conditions
1	Northwind Ridge/ Chukchi borderld.	**Yes**, only partly	Gateways, tectonic, Palaeoclimate, but difficult ice conditions for stationary ops.
1	Beaufort Shelf	No	Gas hydrates/climate, shallow water (<120m), difficult ice conditions
1	Gakkel Ridge	**Yes**, partly	Tectonic, slow, but active spreading ridge, far from effects of equatorial forces
2	Yermak Plateau	**Yes**, partly	Major sediment drift. Atlantic gateways
2	Chukchi Sea	**Yes**, partly	Palaeoclimate. Pacific gateways history
2	Santa Ana Trough	No, only mi-nimal data	Will obtain high-resolution records from trough and adjacent continental slope
2	Morris Jessup Rise	**Yes**, but limited	Gateways, palaeoclimate, and tectonic

5 The Arctic Environment

With a surface area of about 12 million sq. km, the Arctic Ocean is roughly four times the size of the Mediterranean, and a third of this ocean has a shallow shelf, less than 200 m depth. Compared to the other oceans of the world, the Arctic Ocean is virtually land-locked. About 80% of the water exchange is through the deep Fram Strait between Greenland and Svalbard. The rest (20%) passes through the Bering Strait.

Whereas the shelves off Canada and Alaska are of "normal" width, at 50 - 125 km, the north Asian shelves are up to 1,600 km, and nowhere less than 480 km. The upper 150 m of the water mass is strongly stratified, and leads to reduced vertical diffusion which effectively insulates the underlying warm Atlantic layer from the surface. This is the fundamental condition for more or less perennial sea-ice. The sea-ice cover in the Arctic Ocean acts to maintain the ocean in a low-energy state by creating a high surface reflectance and limiting turbulent heat exchanges between the ocean and the atmosphere, thereby contributing to the polar heat sink (Nakamura and Oort, 1988). The deep Arctic Ocean is, however, ventilated laterally from its shelves, thus, circumventing the strong upper-ocean stratification in the interior ocean (Aagard and Carmack, 1994).

Sea-ice concentration

The sea-ice concentration of the interior Arctic Ocean typically exceeds 97% coverage during the winter and 85-95% during the summer (Parkinson and Cavalieri, 1987). First-year ice normally represents up to 40% of the Arctic Ocean ice cover, having a thickness rarely exceeding 2 m (Barry et al., 1993). Away from the coastal regions, about 60% of the ice cover is ice which has survived one or more melt seasons. This multiyear ice is typically 3-5 m thick. Linear, open water areas, or areas of thin ice called "leads" are typically 10-1,000 m wide. They are broadly correlated with large-scale wind fields and have similar space and time scales (Milnes and Barry, 1989).

The maximal seasonal areal extent of the sea ice occurs in March, with a minimum in September. The seasonal ice cover variation is approximately a factor of 2 (Parkinson and Cavalieri, 1987). The standard deviation of mean monthly ice extent in individual sectors of 10 degrees longitude is about 20% in the summer and 10% in the winter (Walsh and Johnson, 1979). Longer term deviations have amounted to 25% of the average.

Ice dynamics

Since 1979, the Arctic Data Buoy Program has gathered synoptic observations of ice drift and surface pressure over most of the Arctic Basin. The main features of ice motion are the Beaufort gyre and the Transpolar drift (Fig. 3). The iso-lines represent the number of years required for the ice field to reach the Fram Strait.

Sea-ice dynamics can be described by a momentum balance where air and water stresses, the Coriolis force, and ice interaction are the dominant terms (Hibler, 1986). Ice interaction can be large during the winter and near the coasts, but is considered a small term during the summer season and away from the coasts. The latter case makes it appropriate to consider the ice pack to be wind driven. The ice moves at a velocity of about 2% of the wind speed and 30º to the right of the surface wind direction (Nansen, 1902). Seventy percent of the variance in the day-to-day or monthly ice motion is explained by the local geostrophic wind (hypothetical wind above the friction layer where the pressure gradient balances the Coriolis force).

The ice moves at an angle to the right of the geostrophic wind, ranging from 5º in the winter to 18º in the summer (Thorndike and Colony, 1982). During periods of decelerating wind, ice motion can become current driven, manifested both as skin drag and form drag on the underside of the ice. The ratio of the ice ”sail” height to ”keel” depth may reach 1:5 for first year ice, making form drag in the oceanic boundary layer of equal or greater importance to that of skin drag (Smith and McLean, 1977). Excluding eddies and other transient phenomena, currents in the upper waters tend to be relatively slow (<10 cm/s) and similar to the ice motion both in speed and direction (SCOR WG 58, 1979). Because winds are highly variable variations in ice motion are approximately 50% wind driven and 50% current driven on annual and longer time scales (Thorndike and Colony, 1982).

Typically, 5-10 years are required for ice to make one curcuit around the Beaufort Gyre with mean drift speeds of 1-3 cm/s (Thorndike, 1986). Ice island T-3 made two rounds in the gyre and exited the Fram Strait about 30 years after its discovery north of Canada. Average ice velocities in the Transpolar Drift increase towards the Fram Strait, and are 2-3 cm/s over the Asian part of the Lomonosov Ridge and 5-10 cm/s in the Fram Strait (Fig. 3). Approximately 20% of the total ice area of the Arctic Basin exits annually through the Fram Strait (Thorndike, 1986). This ice consists of 80% multiyear floes of 2-3 m thickness (Gow and Tucker, 1987).

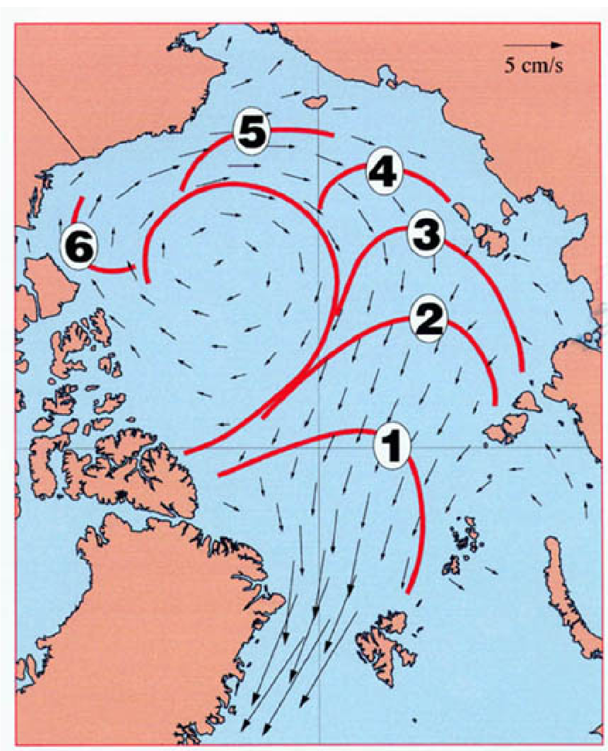

Fig.3 Average velocity and direction of motion of sea-ice in the Arctic Ocean based on results of the Arctic Ocean Data Buoy Program (from AODBP Newsletter 44).

Sea ice thickness

The sea-ice thickness is determined by two main factors; a thermodynamic effect controlled by fluxes of radiative, sensible, and latent heat in the adjacent atmospheric and oceanic boundary layers, and by a dynamic effect from surface tractions at the ice-air and ice-water interfaces. Wind traction on the ice surface and current traction on the underside of the ice cause mechanical compression and conversion from thin ice to thicker ice, as well as divergence and opening of new leads and opportunities for the generation of new ice.

The annual cycle of freezing and melting begins with freezing of meltwater ponds on the ice and open-water leads as the air temperature starts to drop rapidly in early September (Figs. 4 and 5). About 80% of the annual snowfall (10-15 cm water equivalent) takes place by early November. From this time until May, the air is too cool to carry significant amounts of moisture (Untersteiner, 1990). The accretion of ice continues until May, slowly under thick ice and more rapidly under thin ice.

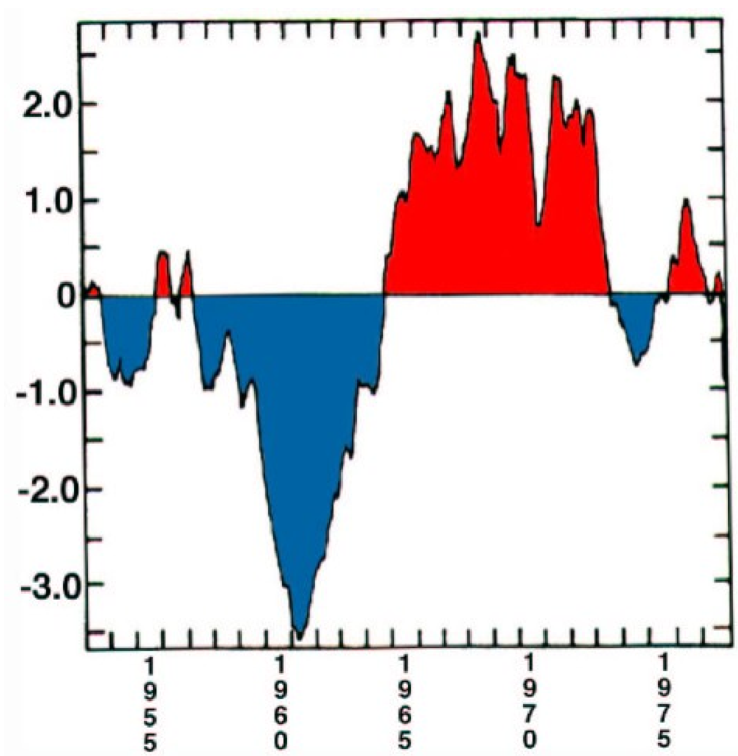

Fig.4   24-month mean of the area covered bt Arctic sea-ice (from Wlash and Johnson, 1979)

The onset of melting corresponds to a mean air temperature near –1.2º C (Doronin, 1974). Development of melt ponds at 85º N starts on average about July 1, and the melt season continues until late August. The extent of ponds increases to about 25% of the surface area (locally up to 45%) by mid-July. Through the annual cycle, ice is added at the bottom and melted away at the top. The seasonal variation in ice draft due to melting and freezing processes is approximately 0.3 m (Maykut and Untersteiner, 1971).

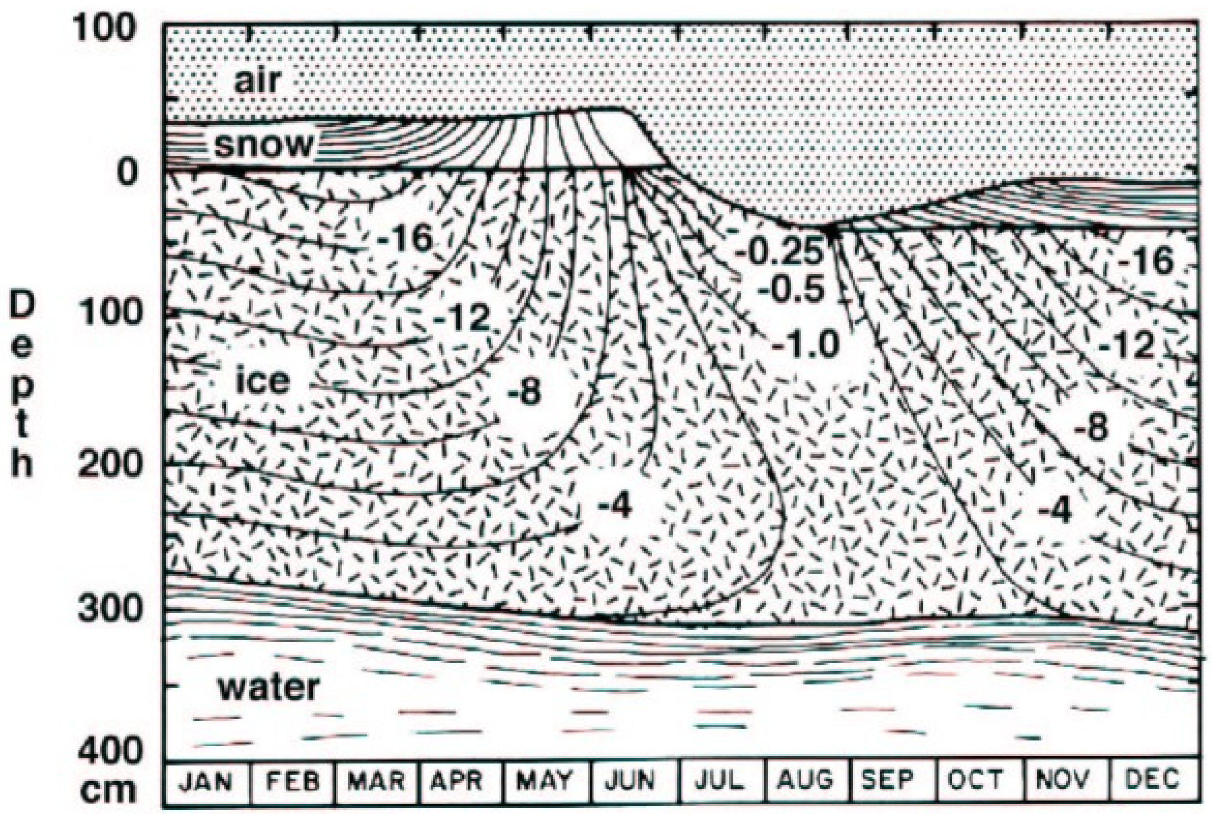

Fig.5 Predicted value of equilibrium temperature and thickness of sea-ice from Maykut and Untersteiner (1971). Temperatures are labeled in negative degrees Celsius.

The most extensive data base for ice thickness distribution in the Arctic Ocean comes from profiling with narrow-beam upward looking echo sounders installed in submarines for operational purposes. Data from 12 submarine cruises into the central Arctic Ocean during the period 1958-87 have been compiled (Bourke and McLaren, 1992). Mean ice draft and deep-draft keel statistics was calculated for 50 km segments along the track of the submarine (Fig. 6). The mean ice draft over the Siberian sector of the Artic Ocean is 3 m or less. The thickest ice occurs north of Canada and Greenland, and is a result of the general ice circulation pattern with convergence towards these landmasses (Fig. 3). Here, the mean ice thickness is determined by the mechanical strength of the ice, which sets a limit to the amount of deformation that can occur (Wadhams, 1994).

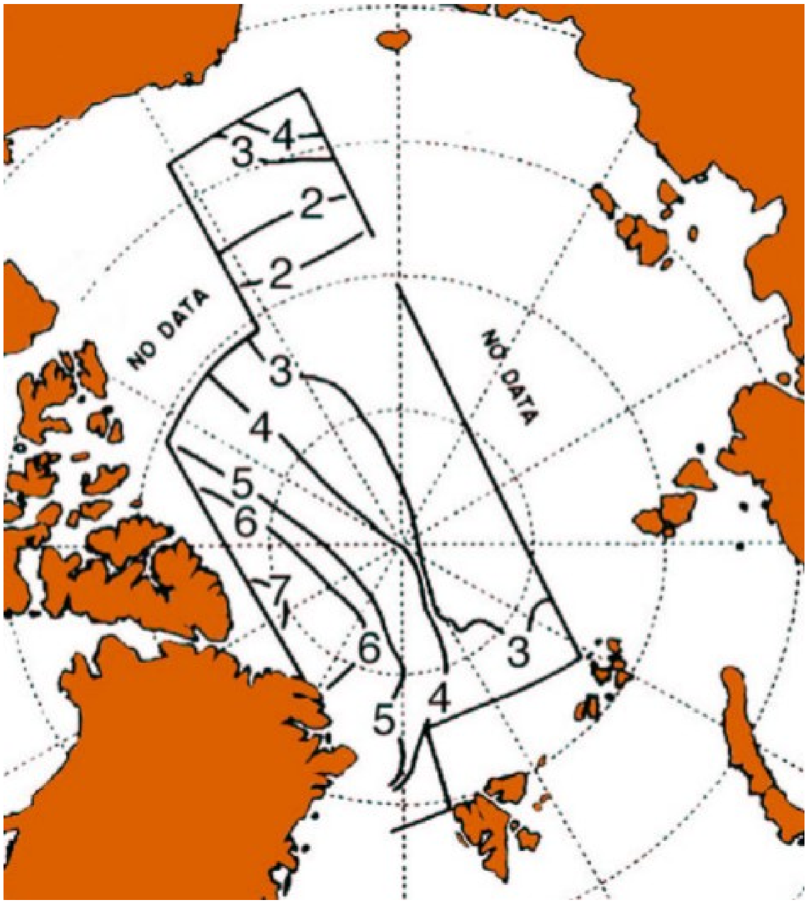

Fig. 6 Contours of mean sea-ice draft (meters) for summer after Bourke and McLaren (1992).

Visual observations of ice ridging taken during U.S. Navy Birdseye flights covering most of the Arctic Ocean, have been compiled and published (Weeks et al., 1971). In broad terms, 0.5-2 ridges per km characterize the ice surface (Fig. 7). Pressure ridges have keel draft to sail height ratios of 3-4:1, with larger ratios for first year ice (Tucker, 1989). Keels are usually wider than sails and cluster around 50-150 m with mean total widths around 70 m (Wadhams, 1994). The mean draft of pressure ridges exceeding a 9 m threshold is 10-12 m for most of the Arctic Ocean during summer. Their occurrence is 1-3/km (Fig. 8). The deepest ridge keel reported had a draft of 47 m (Lyon, 1961). The highest recorded free-floating sail was 13 m (Kovacs et al., 1973).

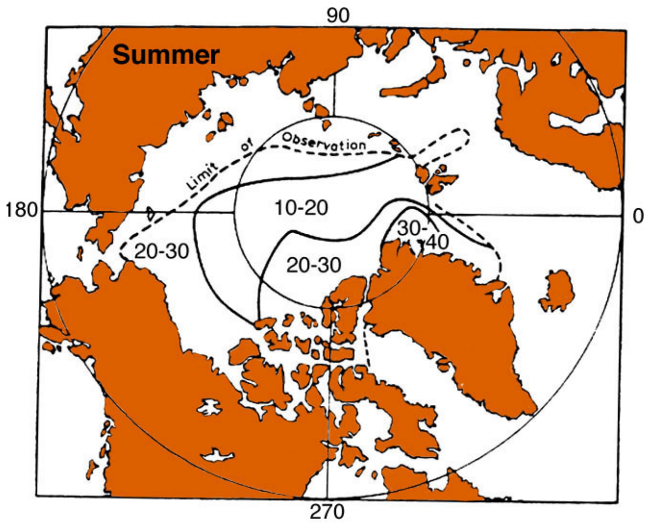

Fig. 7 Number of ridges per nautical mile on the sea-ice during summer, from Weeks et al. (1971).

Thinning of the sea ice in the Arctic Ocean as well as a reduction of the areal extent of the ice cover has recently been reported (Rothrock et al., 1999) although other sources report on unchanged conditions.

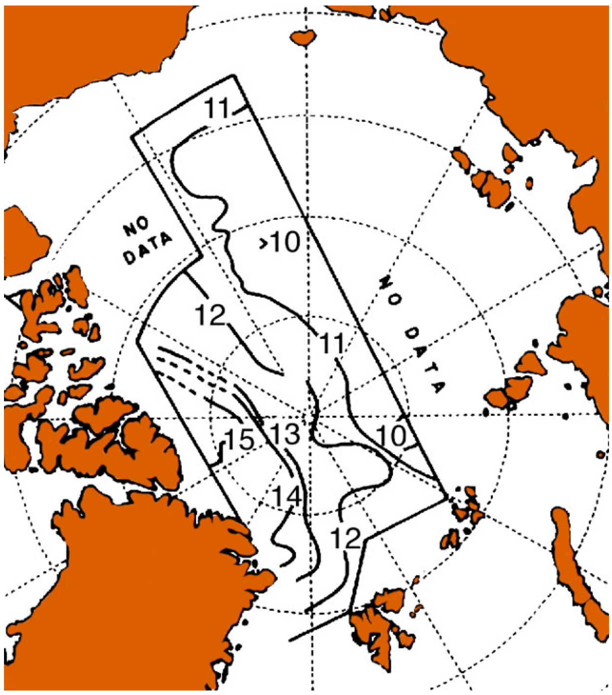

Fig. 8 Contours of mean pressure ridge keel draft (meters) exceeding a 9 m threshold for summer, after Bourke and McLaren (1992).

In the 1960s Russian scientists observed that drift of the pack ice was dependent on the air pressure distribution over the Arctic Ocean and that it alternated periodically between cyclonic and anticyclonic circulation (Proshutinsky and Johnson, 1997). The air pressure variations in the Arctic Ocean may be linked to the North Atlantic Oscillation, NAO (Kwok and Rothrock, 1999), and in this context it is interesting to note that the present warming coincides with a period of increasing amplitude of the NAO, two mechanisms that may reinforce each other.

Sea-ice variability

Using a comprehensive sea-ice model forced with daily varying winds and monthly mean air temperatures from 1951 to 1990, Flato (1995) examined spatial and temporal variability of monthly-average ice thickness fields over the Arctic Ocean. Regions exhibiting the largest inter-annual variability were the Beaufort Sea and the Siberian Shelf. The Laptev Sea and the central Arctic Ocean were much less variable. Some of the inter-annual variability may result from differences in wind-driven ridging, forming thick ice which survives several years.

Only in the vicinity of the North Pole are there sufficient submarine tracks to provide a temporal and consistent record of ice thickness (McLaren et al., 1994). Over a 34 year period, the overall draft was 3.6 m, but with large interannual variations ranging from 2.8 m in 1986 to 4.4 m in 1970. Figure 7 shows the variation of the mean draft and how the mean thickness varies in multiyear and deformed ice (>4 m). It also shows variations in young and first-year ice (<2 m) contribute to the total value. Ice with drafts less than 2 m generally comprise less than 20% of the surface area near the North Pole (Fig. 9a). Recent observations during the SHEBA project in the western Arctic Ocean, indicate about half a meter of pack-ice thinning between the early 1970's and 1999 (Rothrock and Maykut, 1999).

The peak strength of the Beaufort Gyre ice circulation during spring can be related to a seasonal shift toward increased anticyclonic activity over the Beaufort Sea with concurrent decrease in activity over Alaska/Yukon and Siberia (Serreze et al., 1993). During the summer, particularly August-September, temporary reversals of the mean clockwise ice motion in the Beaufort Gyre, lasting up to a month, are caused by a persistent low in the atmospheric sea-level pressure field of the central Arctic Ocean (Serreze et al., 1993). Anomalous halting of the Beaufort Gyre leads to convergence in some regions and divergence in other regions. During these periods, ice in the Transpolar Drift may move eastwards across the general drift direction (Serreze et al., 1989). Wadhams (1994) has related such events to as much as a 50% reduction of the regional mean ice draft north of Greenland in 1987.

Lower than normal sea-level pressure over the central Arctic Ocean is the characteristics of a high phase in the ”Arctic Oscillation” (AO). The AO can be interpreted as the surface signature of modulations of the strength of the polar vortex aloft, and is manifested as a seesaw pattern in which the atmospheric pressure at polar and middle latitudes fluctuates between high and low phases (Thompson and Wallace, 1998). Seven out of the last ten years have seen a high AO state and the high frequency variability is much greater than its decadal variability. Ice drift velocities are generally slower during a high AO state, the center of the Beaufort Gyre is several hundred kilometers closer to the Alaskan coast and the Transpolar Current is shifted more towards Canada with concurrent increased advection of ice from the Laptev Sea into the Transpolar Current (Rigor pers. comm., 2001).

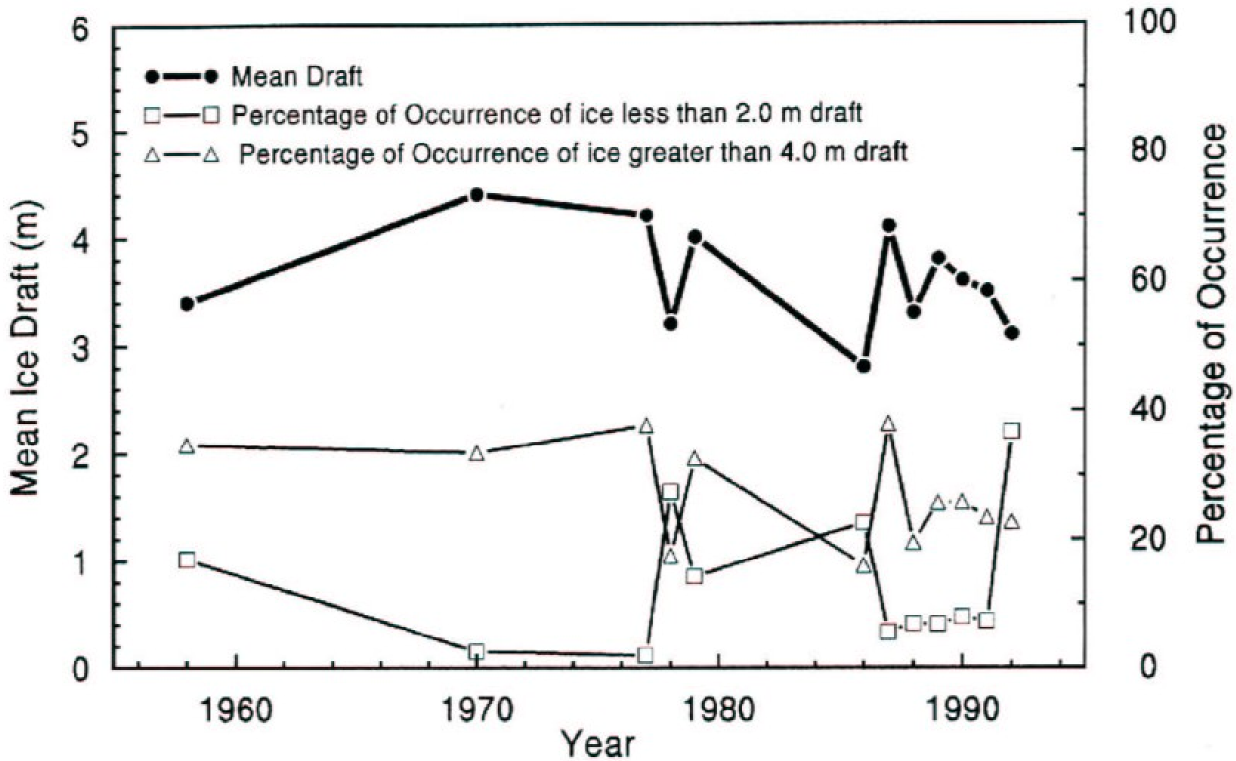

Fig. 9 Mean sea-ice draft and occurrence for 50 km long segments centered over the North Pole, after Mclaren et al. (1994).

(See http://tao.atmos.washington.edu/wallace/ncar_notes/ and http://iabp.apl.washington.edu/Deploy2001.gif)

Arctic Ocean weather

Summer cyclones and anticyclones in the Arctic, north of 65º N, are generrally more frequent, but weaker than their winter counterparts (Serreze et al., 1993). The increase in cyclonic activity occurs between April and June and is associated with an increase in the extent of low-level Arctic stratus clouds. The primary difference from winter is that cyclones are distributed more widely throughout the Arctic (Fig. 10). The average surface pressure over the Arctic Ocean is positive, but during the summer, low pressures frequently move into the central basin. The melting of the pack-ice in summer leads to the formation of persistent fog and low clouds. The cloud amount during July and August exceeds 90% and most of it is low-level stratiform clouds (70%) (Curry and Herman, 1985; Herman and Goody, 1976). Arctic stratus clouds tend to occur in well-defined layers of 300-500 m thickness.

Optimum Operation Time-Window

The optimum time-window for marine summer operations in the Arctic Ocean is the period between the peak of the melt season in early August and the rapidly falling temperatures in early September.

Fig. 10   Mean cyclone motion vectors for summer 1975-89, after Serreze et al. (1993).

Ice Forecasting

Ice forecasting requires reliable synoptic information of the wind field. Presently, forty automatic data buoys report surface pressure and temperature from the Amerasia Basin in the Arctic Ocean, but none from the Eurasia Basin. Plans for 2001 are to deploy fourteen buoys distributed along the trend of the Lomonosov Ridge. Coverage of synthetic aperture radar (SAR) satellite imagery extends to 88º N and allows for identification of ice types and ice concentration. A viable strategy would be to explore the target region by SAR imagery early in the season, project the ice motion from analysis of the wind field and follow up with more frequent coverage to identify the movement of characteristic ice fields into the target area.

6 Strategies for successful scientific drilling in the Arctic

Context

In the context of the Integrated Ocean Drilling Program (IODP), scientific drilling in the Arctic can only be accomplished by an alternate (”fit to mission”) platform. Neither the present ODP drillship JOIDES Resolution nor the riser and the non-riser vessels proposed for the IODP will ever penetrate into the permanently ice-covered areas of the deep polar basin. Furthermore, because operations will be restricted to summer months and because of the wealth of scientific problems that need to be addressed in the Arctic Ocean, a dedicated effort over 10-20 years is required.

More extensive geophysical site surveys of potential drilling targets are urgently needed. Underway geophysical surveys in the Arctic Ocean, carried out both from surface icebreakers and from submarines during the past decade, have considerably improved our knowledge of the principal features of the Arctic sea floor. This activity needs to continue in order to provide the detailed geophysical foundation from which the best scientific drilling targets can be selected. This site survey data needs to be shared throughout the scientific community. A successful scientific program is thus dependent on a flourishing program of marine geophysical surveys in the Arctic.

Jurisdiction

Five coastal states border the Arctic Ocean: Canada, Greenland (Denmark), Norway, the Russian Federation and the United States of America. A large proportion of the Arctic Ocean lies within the 200 nm jurisdiction of these states. However, no maritime boundaries have yet been agreed in the Arctic between adjacent states, and to date only two of the five Arctic coastal states (Norway [1996] and Russia [1997]) have ratified the United Nations Convention on the Law of the Sea (UNCLOS). UNCLOS has been in force since 1994, one year after achieving ratification by 60 countries.

Article 76 of UNCLOS specifies ways in which national jurisdiction may be extended beyond the 200 nm limit. A coastal state has 10 years from ratification of the treaty to assemble data on which to make such claims. Considerable efforts are underway in the Arctic Ocean to acquire new bathymetric and geophysical data on which claims for extended jurisdiction may be made. The existence of extended shelf areas and of prominent ridges extending into the Arctic Basin from the adjacent continental margins (e.g. Alpha Ridge, Lomonosov Ridge) implies that claims of extended jurisdiction will be made and may extend 350 n.m. or more. If all the Arctic coastal states extended their jurisdiction to 350 nm, the High Seas area of the Arctic Ocean would be much reduced.

The uncertainties about future jurisdiction in the Arctic Ocean, however, should not reduce the chances of getting clearance to conduct scientific drilling there, as all of the coastal states have an interest in increased scientific understanding of the region and in scientific ocean drilling. However, the decisions of some governments might be influenced by pressures from indigenous populations (e.g. Denmark by the indigenous population of Greenland and Canada by the indigenous population of Nunavut).

Environmental Issues

The sensitivity of low-temperature environments to oil pollution is recognized in Article 234 of UNCLOS (Taagholt, 1992):

Coastal States have the right to adopt and enforce non-discriminatory laws and regulations for the prevention, reduction and control of marine pollution from vessels in ice-covered areas within the limits of the exclusive economic zone, where particularly severe climatic conditions and the presence of ice covering such areas for most of the year create obstructions or exceptional hazards to navigation. Furthermore, pollution of the marine environment could cause major harm to or irreversible disturbance of the ecological balance. Such laws and regulations shall have due regard to navigation and the protection and preservation of the marine environment based on the best available scientific evidence. This article could be used by Arctic coastal states in the future to restrict navigation within their area of jurisdiction.

The sensitive and pristine nature of the Antarctic environment has already been recognised by the Antarctic Treaty and by the MARPOL Convention (International Convention for the Prevention of Pollution from Ships). MARPOL has designated all sea areas south of 60º S as a Special Area. This came into force in the mid nineties, so that the capabilities of the ODP drillship *JOIDES Resolution* for handling solid waste and oily water run-off from the rig floor had to be substantially improved in order for the vessel to be in compliance for Leg 178 (Antarctic Peninsula) in 1998. The techniques which had been used on Leg 113 (Weddell Sea) and Leg 119 (Prydz Bay) in the late eighties no longer sufficed.

The Arctic Ocean is not designated as a Special Area under MARPOL (though it might be in the future, especially if the Northern Sea Route (Northeast Passage) from Europe to the Far East became economically viable). However, numerous international bodies have come into being over the last decade which have responsibilities or jurisdiction for the Arctic environment:

The *Arctic Environmental Protection Strategy* (AEPS) was adopted by the eight Arctic nations in 1991 at Rovaniemi, Finland.

The *Arctic Monitoring and Assessment Programme* (AMAP) was set up in 1991 with responsibilities to monitor the levels of, and to assess the effects of, anthropogenic pollutants in all compartments of the Arctic environment, including humans.

The Working Group on the *Protection of the Arctic Marine Environment* (PAME) was established in 1993. PAME addresses policy and non-emergency response measures related to the protection of the marine environment from land and sea-based activities.

The *Arctic Council*, established in 1996, is a high-level intergovernmental forum to address common concerns and challenges in the Arctic. Protection of the Arctic environment and sustainable development are its main concerns. AMAP and PAME are now two of the five Working Groups of the AEPS, functioning under the auspices of the Arctic Council.

The *OSPAR (Oslo Paris) Convention* for the Protection of the Marine Environment in the North-East Atlantic entered into force in 1998. The maritime area it covers extends from 51º E to 42º W (longitude of Kap Farvel), and from 36º N (latitude of the Strait of Gibraltar) to the North Pole. Thus this convention applies to a substantial sector of the Arctic Ocean.

The *United Nations Environmental Programme* (UNEP) also maintains an interest in the Arctic environment.

In addition to these governmental bodies, environmental non-governmental organizations (NGOs) are also deeply concerned about the Arctic environment:

The *World Wildlife Fund* (WWF) created its Arctic Programme in 1992. In addition to implementing its own Arctic conservation strategy, it monitors the governmental steps that have been made in Arctic management. WWF has expressed concern at irresponsible oil and gas development.

The *Greenpeace Arctic Action* programme is hostile to oil developments and aims to stop any oil drilling projects in the Arctic.

It is clear from the above summary that any scientific drilling programme in the Arctic Ocean must make it absolutely clear that it has nothing to do with oil exploration and that the environmental impact of riserless scientific drilling is negligible.

Pollution Prevention

For over 30 years DSDP and ODP have maintained an unblemished record with respect to pollution. There have been no blowouts and no accidental releases of hydrocarbons into the sea from the wells drilled. The reasons for this are as follows:

Since the early days of DSDP, all proposed drill sites have been carefully scrutinised by the JOIDES Pollution Prevention and Safety Panel (PPSP) before approval is given for drilling. Sites at which geophysical or other data suggest that hydrocarbons might be encountered are either moved to acceptable locations or are not approved.

All sites are continuously cored from the sea floor. Cores recovered are monitored in the drillships chemistry laboratory for hydrocarbons. If significant quantities of migrated thermogenic hydrocarbons are detected, deeper drilling at that site is abandoned. About ten holes in DSDP and ODP have been terminated before reaching target depth due to rising levels of hydrocarbons in the cores.

Most holes in DSDP and ODP have been shallow by oil industry standards (penetrations typically in the range 300-1000 mbsf) and in much deeper water (generally 1,000-5,000 m). The diameter of the holes drilled in DSDP and ODP has been small (usually 25-30 cm). Because of the longevity and unblemished record of scientific ocean drilling, it is important that all drill sites proposed for the Arctic Ocean are reviewed in the same way as ODP holes are today by the JOIDES PPSP.

In order to emphasise the difference between riserless scientific drilling and exploration for oil and gas by riser drilling, the following points should be noted:

All drill cuttings in riserless scientific drilling operations are released at the sea floor. By contrast, in riser drilling operations the bottom hole cuttings (i.e. those produced once the marine riser is in place) are released near the sea surface. The volume of drill cuttings released from a scientific drill hole onto the sea floor is much less than from an industry well because the hole diameter and depth are generally much smaller. The drilling fluid used in scientific ocean drilling is seawater, with only occasional slugs of mud. The latter are simple muds of natural origin (e.g. bentonite, barite) and no complex chemical additives or oil-based muds are used.

Because the objectives for scientific drilling in the Arctic Ocean are primarily paleoceanographic and paleoclimatological, the proposed drill sites are likely to be of shallow penetration (< 500 mbsf). This in itself reduces the risk of hydrocarbon flows.

Management issues
Management tasks of high-Arctic drilling operations will include:

- Seek coastal state approvals, where necessary.
- Manage budgets and maintain auditable accounts.
- Select contractors for ice management, drilling operations, core handling and curation.
- Negotiate contracts.
- Monitor contracts and pay for work done.
- Invite scientific participants.
- Identify safety issues and develop contingency plans.
- Define operational plans and establish lines of responsibility.
- Organize logistics.
- Arrange insurance policies (Government backing may be needed, as with ODP).
- Submit appropriate reports to funding agencies and to the scientific community.
- Interact with international environmental organizations.

In order to carry out the above mentioned tasks, management will need to include experience from Arctic ice management, drilling operations, core handling, and project management / contracting. This is not something that can be relegated to a transitory committee of experts.

Health and Safety aspects
Because drilling in the high-Artic is, both within short and long-range time-frames, a multi-vessel operation, there are low risks associated with health and safety. In the event of an on-site need for vessel abandonment (fire, water-ingress, etc.), there will be a vessel nearby, which will be on-call within a maximum rendezvous period of less than one hour. Evacuation will therefore rely on one or two of the other participating vessels.

There is normally a hospital and health personnel available onboard the large participating icebreakers. However, in the event of a need for medical evacuation, transport will rely upon shore-based and/or ship-based helicopters.

Short-term strategy
A scientifically top-rated proposal for drilling the Lomonosov Ridge (533) already exists. This will be dealt with further by the recently established Arctic Detailed Planning Group (DPG).

Drilling within the permanently ice-covered regions of the Arctic should continue with operations on the periphery of the Arctic ice pack where some site survey data already exists, but for which drilling proposals have yet to be submitted. The approach adopted for these early legs will be:

a) use existing technology and ice management techniques already developed for drilling in ice covered areas;
b) ensure that many sites are available, over a considerable geographical area. This will prevent the operation from failing because of difficult ice conditions at just a few sites;
c) adequate site surveys must be available for all sites, including back-up sites.

Long-term strategy
In order to achieve the scientific goals of an Arctic drilling program, at least a decade of drilling is required. This long-term strategy assumes that a committment to long-term funding of an Arctic drilling program exists.

The long-term strategy will build on the results of the first drilling legs in the Arctic ice pack. Indeed, learning from the experience gained on earlier legs will be essential to the success of the whole program.

7 Technology for Arctic Drilling

Drilling Platform criteria
The general requirements for a drilling platform capable of operating in Arctic sea-ice areas include:
1. Dynamic positioning (DP)
2. High-Arctic ice-class
3. An adequate moon pool with a reinforced deck capable of supporting a drill rig
4. Sufficient deck space for drilling, coring, logging equipment, and tools
5. Provision for modular laboratory containers, including provision of services (water, fuel, power etc.)
6. Sufficient accommodation for crew and scientists
7. Helideck and other appropriate navigation and safety features for Arctic work.

Potential platforms

Drilling Vessel or barge

Dynamically positioned ice-class vessel or barge with a moon-pool and equipped with at least a 100-ton capacity, heave-compensated drill rig. This vessel will require support by icebreaker(s).

Icebreaker-based platform

A portable heave-compensated drill rig installed on a dynamically positioned icebreaker with a moon pool.

Ice supported drill rig

A portable drill rig transported by an icebreaker or by air and installed on land-fast (non-moving) ice.

Coring systems

There are several existing technologies and systems available for scientific drilling worldwide. The system selection will depend on scientific objectives, water, and borehole depth and the type of drilling platform. The currently available systems are:

ODP system - a unique heavy-duty offshore scientific coring system with abilities to operate from oil field size DP drill vessel (e.g., JOIDES Resolution).

Geotechnical Marine coring systems, including the *"Piggy-back"* option - used on geotechnical DP drill vessels and other platforms (e.g., Bucentaur).

Complete Coring System (CCS) - designed for the Russian deep ocean scientific drilling. The CCS is able to operate from oil-field or geotechnical type DP vessels.

"Baikal"- Nedra Coring system - a development based on ODP and CCS techniques. This system has been used from a drilling barge in Lake Baikal.

DOSECC/Cape Roberts style systems - hybrid, specially-designed mining style, multi-string systems used in scientific coring.

Coring Strategy

In the short-term (3-5 years), the technology should allow high-performance and high-resolution coring using single-bit drilling technology. The proposed technology includes hydraulic piston sampling (in ooze, soft clays), percussion sampling (in formations, such as sand, silt clays), and rotary coring.

Additional coring technology, compatible with single-bit operations should be part of the system (e.g., "Piggy-Back"/nested coring system, down-hole motor coring, HYACE or PCS sampling).

Drill string selection

Primary drillstring

Candidates for the main drill string include:

1. Modified 5”(127-mm OD) steel drill pipe, as used by ODP and geotechnical drilling vessels.
2. CCS 164-mm OD aluminum drill pipe, used by geotechnical vessels for deep-water operations.
3. 131-mm OD aluminium drill pipe with similar internal dimensions to the ODP steel drillstring.
4. Large diameter mining rods with heavy-duty connections (e.g. GLAD-800 application).

The use of an aluminum drill string extends the operating depth of any drillrig. The large diameter aluminum drillpipe allows increased core diameter and more versatile coring techniques.

Secondary drillstring

Standard mining drill rods are normally used for secondary drill string assemblies. The length of the secondary drill string is limited by the rig capacity and drill rod strength. In order to extend the secondary string capacity within the rig limits and to reduce the risk of connection failure, the secondary drillstring could comprise a bottom section of standard mining rod and top section of purpose built durable aluminum rods. Drill string parameters are presented in the Appendix, Table 1.

Drill rig selection

A dedicated drilling vessel will have an integral derrick and heave-compensated drilling capability. Alternatively, suitable vessels of opportunity can be equipped with portable, heave-compensated marine drilling rigs on a project-by-project basis. Either facility then needs to be equipped with a suitable coring system. Appendix, Table 2 illustrates the technical characteristics of different drill rigs available.

Coring tools/technology selection

The modular coring system will include:

1. Core bits suitable for single-bit operations
2. Hydraulic piston sampler
3. Hydropercussion Sampler
4. Rotary Coring tools
5. Mining style coring system operated through the secondary drill string.

Different coring tool parameters are presented in the Appendix, Table 3. Appendix, Table 4 summarizes an example of the Arctic Drilling Program technology and equipment selection process.

Logging system and strategy

A portable wireline logging system compatible with coring system and anticipated borehole diameter is required. This system should include a winch, cable, and data acquisition unit. The basic logging requirements include:

1. Natural gamma-radiation
2. Electrical resistivity
3. Acoustic velocity
4. Density
5. Neutron porosity
6. High resolution magnetic susceptibility and magnetic field
7. Formation micro-imaging
8. Well seismic tool.

The logging-while-drilling (LWD) system needs to be considered on a project-by-project basis.

On-board laboratories

Modular laboratories for core curation and safety assessment are required, as a minimum.

Other modular (containerized) laboratories on a project-by-project basis could include:

1. Physical properties
2. Geochemistry
3. Micro-paleontology
4. Microbiology.

Technical Quality Assurance

Although it will not guarantee success, an important part of the technical quality assurance is to test all major systems in advance, before entering into the "hostile" ice-covered Arctic waters for operation.

Site Survey Needs

Despite substantial efforts to collect seismic reflection data over the past decade, including the SCICEX program of the US Navy, the geophysical data base for the entire Arctic Ocean is scarce. Exceptions are selected sections of the Yermak Plateau, Lomonosov Ridge, and the Chukchi Plateau. The use of multiple platforms (surface and submarine vessels) of complementary capabilities should be employed for site survey and exploratory purposes.

In preparation for a long-term drilling program in the high-Arctic, the APPG urgently recommends acquisition of new geophysical data of adequate extent and depth of penetration to support drillsite definition.

Ice management

Drilling in drifting ice demands careful planning. Several companies have extensive experience in "Stationary Marine Operations in Drifting Ice" (STAMARDI) particulary offshore Sakhalin (Okhotsk Sea) and in the Beaufort Sea. One main consideration is to determine the maximum allowable lateral vessel movement. This parameter determines how much time is available for decisions to be made (i.e., response time). Therefore, all STAMARDI requires work to be carried out according to an "Operational and Alert / Response Plan" which predicts when appropriate actions need to be taken. In order to manage ice during a STAMARDI, at least one primary and one secondary icebreaker are required. Refuelling and fuel capacity of these vessels has to be carefully evaluated before embarking on a prolonged STAMARDI.

The appropriate ice management system can be modelled by combining icebreaker performance models, ice regime modification models, and ice drift-force models.

The important essentials of STAMARDI include:

1. Weather and ice data from all available sources
2. An ice management team capable of interpreting all data
3. An officer responsible for directing the ice management vessels
4. Forecasting of weather, ice drift and hazardous ice
5. Definition of hazardous ice and/or weather conditions within the parameters of the project
6. Definition of a "T-time", the decision time remaining for different operations (i.e. how much time remains before a final decision to abandon site)
7. Abandonment plan.

Operational flexibility

In order to maximise the chances of success the following operational approach should be adopted:

1. A multi-vessel approach is required for operational flexibility and safety.
2. A larger than normal fuel capacity is required (perhaps double) due to the nature of Arctic operations.
3. Alternate drill sites should be approved because the primary drill site may not be accessible. It is likely that the sites drilled will be heavily influenced by ice conditions.
4. An appropriate ice management plan is required.

8 Future Technological Developments

Although there exists technology to perform deep-water drilling in ice-covered regions, there is a need for particular developments for a long-term drilling commitment in the central deep Arctic, where the drilling targets of the highest scientific priorities are located. These developments may comprise several different systems, including remotely operated vehicles and submarines, but APPG only focus on the possibility of a new "conventional" system:

A New Surface Vessel?

Because commercially available barges and large icebreakers are either cumbersome in operation (often lacking proper DP), or are too small for scientific work in difficult ice conditions, a new large research icebreaker with a deep-water drilling capability could be recommendable for long-range planning of drilling activity in the Arctic Ocean. In order of finding out more about long-term availability and suitability of currently existing vessels and barges for Arctic drilling, the APPG recommends IODP to establish a team of experts who can carry out an evaluation and a technical feasibility study where the current situation is compared with what would be needed to build a new, purpose-built vessel for scientific drilling in the Arctic Ocean.

The main justifications for requiring such a measure are, besides the fact that such a vessel will guarantee a long-term (5 - 10 years) commitment to Arctic / Antarctic deep-drilling, concerns that there may be:

1) a potential future lack of readily available vessels and barges. The current availability is ad-hoc, and depends on market trends etc, i.e., there is no gurarantee that barges such as the Sea Sorceress, icebreakers such as Botnica / Fennica / Oden will be available for scientific drilling in a competitive market, in the long run (5 - 15 years from now)

2) a lack of scientific facilities onboard, and also space for extra equipment (biological lab containers, down-hole logging equipment and containers / extra drillpipe for deep-water drilling, etc.) on commercially available vessels

3) too severe ice conditions especially over the Alpha Ridge for currently available vessels and barges, i.e., a modern purpose-built vessel could have the adequate dynamically positioned (DP) power and hull required to perform (minimal assistance) operations in heavy ice conditions (although it still would have to depend on assistance for ice management).

In this context, it should be noted that any purpose-built scientific deep-drilling vessel, for heavy ice conditions, will also be able to drill elsewhere besides the Arctic and Antarctic. Thus, such a vessel will make IODP more flexible in the choice of hardware for its coming long-term operations, on a world-wide basis.

The APPG thus recommends the establishment of a technical feasibility study for such a vessel, which at present does not exist.

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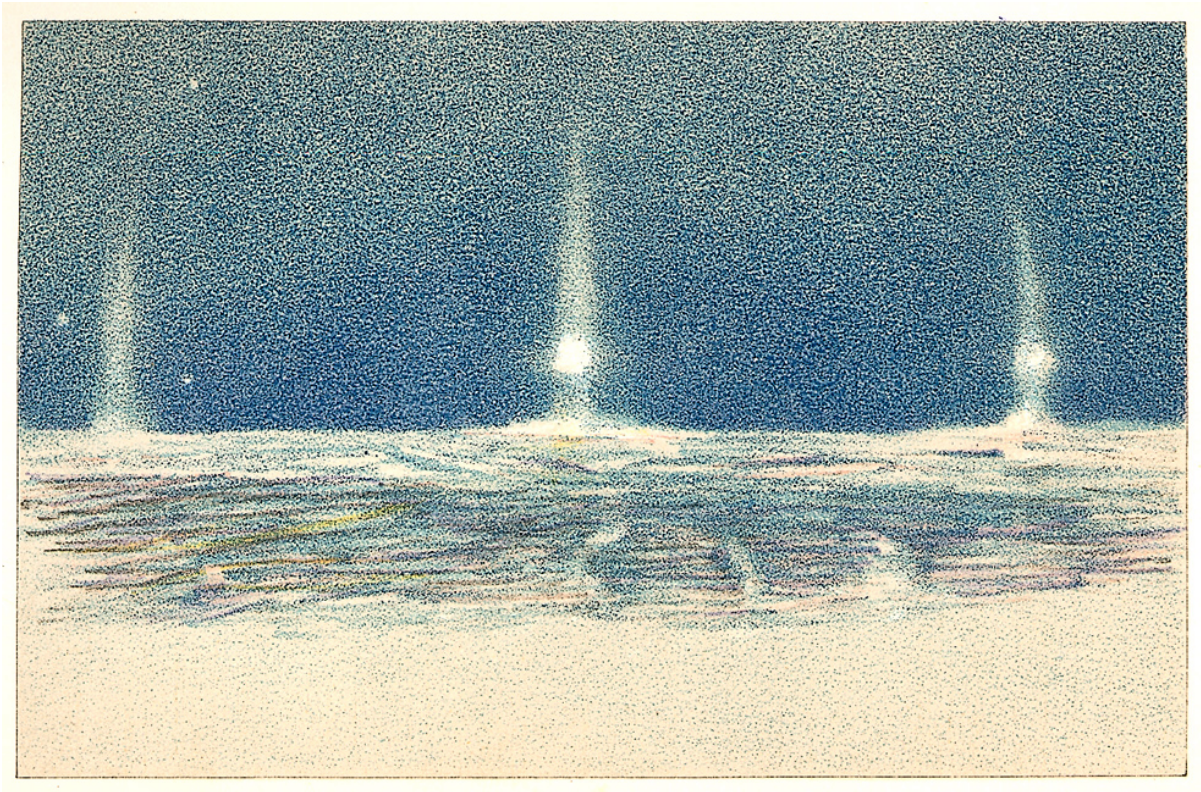

From Nansen, 1897 (*'Full moon'*)

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11 Appendices

Tables

Table 1 Drilling parameters

Table 2 Technical characteristics

Table 3 Tool parameters

Table 4 Example of Arctic Drilling technology parameters.

Candidate drill pipes basic parameters

Table 1

Description	5" API ODP	5" API Bucentaur	CCS (Aluminum)	AC 5 1/8" (Aluminum)	SHD SEACORE	Geobor S Craelius	Longyear PQ	Longyear HQ	H.DB.GR Diamond Boart
Borehole diameter	250 mm	220 mm	220 mm	212 - 240 mm	220 mm	150 mm	122.6 mm	96.04 mm	96.3 mm
Pipe OD	127 mm	127 mm	164 mm	131 mm	177.8 mm	140 mm	117.7 mm	88.90 mm	88.9 mm
Tool joint OD	177.8 mm	161.9 mm	195 mm	178 mm	200 mm	n.a.	117.7 mm	88.90 mm	?
Pipe ID	104.8 mm	101.6 mm	146 mm	104.8 mm	157.8 mm	125 mm	106.33 mm	77.79 mm	70.0 mm
Tool joint ID	104.8 mm	101.6 mm	145 mm	104 mm	157.8 mm	n.a.	103.03 mm	77.79 mm	?
Weight per joint	318 kg	287 kg	197 kg	162 kg	266 kg	73 kg	48.15 kg	34.44 kg	11 kg/m
Joint length	9.66 m	9.2 m	11 m	9 m	6 m	3 m	3 m	3 m	?
String weight for 100m (under water)	2880 kg	2734 kg	1230 kg	1221 kg	3876 kg	2433 kg	1404 kg	1005 kg	960 kg

Candidate drill rigs basic parameters

Table 2

Model No.	SLIMDRILL HTA 3000	Fugro FODR III	Longyear HD-600	Seacore C-100	SHRAMM T685W
Dimensions of rig	5 x 6 m				
Height of derrick	17.7 m	18.0 m	17.8 m	20.0 m	10.7 m
Weight of rig/ (ex truck)	60,000 kg *3)	20,000 kg			17,917 kg
Structure	Tubular steel	Square tubing	Square tubing	Square tubing	Tubular steel
Wind rating	90 – 100 km/hr				
Guy wires required	Yes	Yes	Yes x 4	Yes x 4	Recommended
Containerized load	Yes	Yes		Yes	
Top drive	Yes	Yes	Optional	Yes	Yes
RPM (rotor)	0 - 700	0 – 150	15 - 950	0 - 200	0 - 160
Torque (rotor)	11650 Nm, 273rpm	2720 Nm	4880 Nm	25000 Nm (max)	5424Nm,0-160rpm 12316Nm,0-80rpm
Max pull up	68100 kg	30,000 kg	45,360 kg	100,000 kg	31978 kg
Max pull down	13620 kg	N.a.	3563 kg	N.a.	16000 kg
Pipe lengths, handled	9 - 10 m	4.5 m	12 m - 18 m	12 m	7.62 m (max)
Casing lengths, handled	12 m	4.5 m		12 m	9.14 m (max)
Max diameter through slipbox	340 mm	700 – 800 mm		450 mm	559 mm
High speed piggy-back top drive	No	No	No	Yes	No
R.P.M.	n.a.	n.a.	n.a.	5 - 900	n.a
Torque	n.a.	n.a.	n.a.	37 - 875 Nm	n.a
Max pull up	n.a.	n.a.	n.a.	150 kN	n.a
Max pull down	n.a.	n.a.	n.a.	150 kN	n.a
Type of power supply	Hydraulic	Hydraulic	Hydraulic	Hydraulic	Hydraulic
General spec of system	6 pumps	1 pump	5 pump		6 pump open loop
Rod handling system	No	No	70 mm OD		114 mm OD, 8 pcs
Rooster box sampling	Yes	Yes	No	Yes	No
Heave compensation	No	Yes	No	Yes	No
Heave compensator stroke	No	3 m	n.a.	4.8 m	n.a.
Heave compensator capacity	No	20,000 kg	n.a.	60 ton	n.a.
Mud pump flow (3 pumps)	362 GPM	640 l /min			
Mud pump pressure	5000 PSI	20 bar			

Marine coring systems

Technical characteristics

Table 3

SAMPLERS										
	Long Stroke Push Samplers					**Hydraulic Percussion Samplers**				
	ODP APC	**CCS Rapid Piston Sampler**	**Baikal-2 Rapid Piston Sampler**	**Baikal-3 Rapid Piston Sampler**	**Fugro Rapid Piston Sampler**	**Fugro Small Hydraulic Percussion Sampler**	**Fugro Large Hydraulic Percussion Sampler**	**CCS Large Hydraulic Percussion Sampler**	**Baikal-2 Hydraulic Percussion Sampler**	**Baikal-3 Hydraulic Percussion Sampler**
Sample diameter	66 mm	93 mm	56 mm	~ 75 mm	58.2 mm	57 mm	96.8 mm	93 mm	56 mm	~ 75 mm
Length	9.84 m	4.0 m	6.0 m	~ 3m	3.0 m	1.8 m	3.7 m *3)	3.0 m	6.0 m	~ 3.0 m
Liner?	clear plastic	PVC liner	Plastic	Yes	PVC liner	Yes	Yes	Yes	Plastic	Yes
Length Tool	12.8 – 22.3 m	6.3 - 10.3 m	~ 7.5 to 13.5 m	~ 4 to 7 m	4.5 - 7.5 m	5.0 m	8.6 m	7.16 m	~ 8 m	~ 7.5 m
Driving Mech.	Mud Pressure	mud Pressure	Mud Pressure	Mud Pressure	mud pressure	Mud pressure percussion	Mud pressure Percussion	Mud pressure Percussion	Mud pressure Percussion	Mud pressure percussion
Mud pressure (bar)	170	30/60/90/120	40/80/120	~40/80/120	43/85/126	45 bar	45 bar	40 - 60 bar	40 - 60 bar	40 - 60 bar
Max. Tool Diam.	95 mm	142 mm	101 mm	136 mm	92 mm	70 mm	129 mm	142 mm	95 mm	136 mm
BHA bit ID	96.5 mm	136 mm	79 mm	~ 95 mm	84 mm	> 78 mm	> 118 mm	136 mm	79 mm	~ 95 mm
BHA bit OD	257 – 290 mm	220 mm	213 mm	240 mm	244 mm	244 mm	244 mm	220 mm	213 mm	240 mm
J /Blow	n.a.	n.a.	n.a.	n.a.	n.a.	50	200	200	50	200
BHA	Comp. with XCB (ODP BHA)	CCS	Baikal-2	Baikal-3	Comp. with CCS (Fugro BHA)	Comp. With CCS, XP Fugro BHA	Comp. With CCS, XP Fugro BHA	CCS	Baikal-2	Baikal-3

Marine coring systems (continued)

Technical characteristics

Table 3 (continued)

CORE BARRELS										
	Rotary Core Barrels				**Extended Core Barrels**					
	ODP Rotary Core Barrel	**Baikal-2 Rotary Corer**	**Christensen MWCB**	**Baikal-3 Rotary Corer**	**ODP XCB**	**Baikal-2 Pilot Rotary Corer**	**Baikal-2 Rotary-Percussion Corer**	**Baikal-3 Rotary Pilot Corer**	**CCS (SKV-127/67) Double Core Barrel**	**Christensen MWECB**
Core diam.	58.7 mm	79 mm	76.0 mm	~ 95 mm	60 mm	52 mm 65 mm	52 mm 65 mm	~ 73 mm	67 mm	66.7 mm
Length	9.5 m	~ 6.6 m	~ 4.0 m	~ 3.5 m	9.5 m	~ 6.6 m	>3.1 m	~ 3 m	4.5 m	~ 4.0 m
Liner?	Yes	No	No	Yes	Yes	plastic	Plastic	Yes	No	Steel liner
Length Tool	11.6 m	~ 8 m	~ 5.0 m	~ 5 m	12.8 m	~ 8.5 m	~ 8.5 m	~ 5 m	5.6	~ 5.0 m
Driving Mech.	drill string Rotary	drill string rotary	drill string Rotary	drill string Rotary	drill string rotary,	drill string rotary	Drill string Rotary	Drill string Rotary	Rotary, downhole motor (DM)	drill string rotary
Mud Pressure	n.a.	5 - 10 bar	n.a.	5 - 10 bar	n.a.	5 - 10 bar	40 - 60 bar	5 10 bar	5(rot.), 40-60(DM)	n.a.
Max. Tool Diam.	95 mm	101 mm	108 mm	136 mm	95.3 mm	101 mm	101 mm	136 mm	127 mm	108 mm
BHA Bit ID	62 mm	79 mm	76 mm	~ 95 mm	96.5 mm	79 mm	79 mm	~ 95 mm	136 mm	76 mm
BHA Bit OD	251 mm	240 mm	216 mm	240 mm	257 - 290 mm	213 mm	213 mm	240 mm	217-240 mm	216 mm
Coring bit OD	n.a.	n.a.	n.a.	n.a.	~ 93 mm	76 mm	76 mm	~ 93 mm	133.3 mm	~72 mm
WOB	1 - 7 ton	< 12 ton	1 - 5 ton	< 12 ton	1 - 7 ton	0.5 - 1.5 ton	< 1 ton	~ < 1 ton	1-5 ton	1 - 5 ton
R.P.M.	50 – 70	< 120	70 - 90	< 90	30 - 70	< 90	< 90	< 90	<400	70 - 90
J/Blow	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	50	n.a.	n.a.	n.a.
BHA	ODP BHA	Baikal-2	Christensen	Baikal-3	Comp. with ODP APC	Comp. with RPS and HPS	Comp. with RPS and HPS	Baikal-3	CCS	Christensen

Table 4

Example of the Equipment Selection Strategy for Arctic Drilling Program