**USSSP-Sponsored Workshop Report**

# "Catching Climate Change in Progress: Drilling on Circum-Arctic Shelves and Upper Continental Slopes"

**10-11 December, 2011**

**San Francisco, CA**


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*Prepared by Carolyn Ruppel, US Geological Survey (2013)*

## Executive Summary

The Circum-Arctic Drilling Workshop (CADW) held in late 2011 explored the potential for IODP drilling on Arctic Ocean shelves and upper continental slopes in pursuit of broad paleoclimate and contemporary climate objectives. These objectives include reconstruction of Late Quaternary sea level, sea ice distributions, water temperatures, and paleoceanography, as well as an analysis of the impact of climate change on relict permafrost beneath the shelves and on gas hydrate beneath the shelves or on upper continental slopes. The CADW was held between the Arctic site survey meeting in Europe in autumn 2011 and the Kananaskis IODP workshop on Beaufort Sea drilling in February 2012. The primary recommendations to emerge from the workshop are:

a) Use circum-Arctic Ocean drilling to explore new scientific problems not previously addressed through scientific ocean drilling (SOD).
b) Take advantage of changing Arctic Ocean conditions (e.g., diminishing summer sea ice) to access new locations for SOD.
c) Emphasize transects (e.g., shelf to slope) to capture the full range of dynamic conditions and records of both spatial and temporal changes across margins.
d) Design programs from the outset to include terrestrial and marine scientists in light of the mixed marine-terrestrial nature of sedimentary records on margins.
e) Build synergies with industry for site survey and for access to specialized platforms.
f) Prioritize sediment records that can constrain sea level history and consider targeting for drilling sections that can yield absolute date markers (e.g., tephras).
g) Pursue questions of relevance to both contemporary climate and paleoclimate.
h) Compare the histories of different Arctic Ocean margins (e.g., range of glaciation and inundation histories).
i) Identify locations that could be ready for drilling within the next decade with little additional site survey data collection.
j) Continue to investigate synergies with Russia.

## 1. Introduction

The Circum-Arctic Drilling Workshop (CADW) was one in a series of community meetings that have focused on Arctic drilling in the years leading up to the transition to the new IODP at the end of 2013. The CADW was motivated by a number of scientific, logistical, and structural issues, but primarily by the lack of drilling in most of the Arctic region. During the 1990s, the

Nansen Arctic Drilling Program made serious efforts to advance Arctic Ocean drilling, including numerous marginal sites. This effort was eventually superseded by other activities, although some small-scale drilling was completed from geotechnical vessels. In the history of international scientific ocean drilling (SOD), only six expeditions (including ACEX, IODP Exp. 302) have ever drilled north of the Arctic Circle. ACEX focused on the central Arctic Ocean, which is outside the scope of the CADW. The remaining five expeditions (the last in 1995) were all in the Atlantic sector (Table 1). This leaves thousands of kilometers of circum-Arctic Ocean margin that have never been explored by scientific drilling.

*Table 1. Previous SOD expeditions with sites above the Arctic Circle.*

| Expedition | Location | Goal | Year |
|---|---|---|---|
| DSDP 38 | Norwegian margin | tectonics, glacial history, paleoceanography | 1974 |
| ODP 104 | Norwegian margin | tectonics of Voring Plateau and Norwegian margin | 1985 |
| ODP 105 | Baffin Bay and Labrador Sea | glacial and tectonic history | 1985 |
| ODP 151 | west of Svalbard; Norwegian/Greenland Sea | North Atlantic-Arctic gateways I | 1993 |
| ODP 162 | west of Svalbard; Norwegian/Greenland Sea | North Atlantic-Arctic gateways II | 1995 |
| IODP 302 | Central Arctic Ocean | paleoceanography, paleoclimate, tectonics | 2004 |

International interest in increased scientific drilling in the Arctic Ocean is intense, but some constituencies have concerns that the IODP Initial Science Plan (ISP; IODP, 2011) for the post-2013 program does not seem to emphatically endorse this goal. Another driver for the CADW is rapidly changing climate conditions on the margins of the Arctic Ocean. If sustained into the future, the dramatically reduced summer ice cover makes it possible that site survey and drilling could be accomplished under open water conditions using conventional platforms. In 2010, the *JOIDES Resolution* successfully drilled within sight of ice floes during IODP Exp. 318 off Wilkes Land, Antarctica. This success has provoked interest among scientists in having the *JOIDES Resolution* deploy in 'ice-free' parts of the Arctic Ocean during summer months over the next decade.

The CADW sought to catalyze and coordinate proposals for high-latitude drilling programs, including those that could capture evidence of climate change on circum-Arctic Ocean margins since the Last Glacial Maximum (LGM). Thus, the workshop specifically did not focus on tectonics, the deep Arctic Ocean, or specialized programs to serve specific disciplines (e.g., geomagnetism, hot spots). While community interests might eventually drive such drilling programs, the philosophy of the CADW was promotion of a multidisciplinary focus for initial drilling programs and the integration of terrestrial and marine disciplines to study areas where both types of records will be present in core.

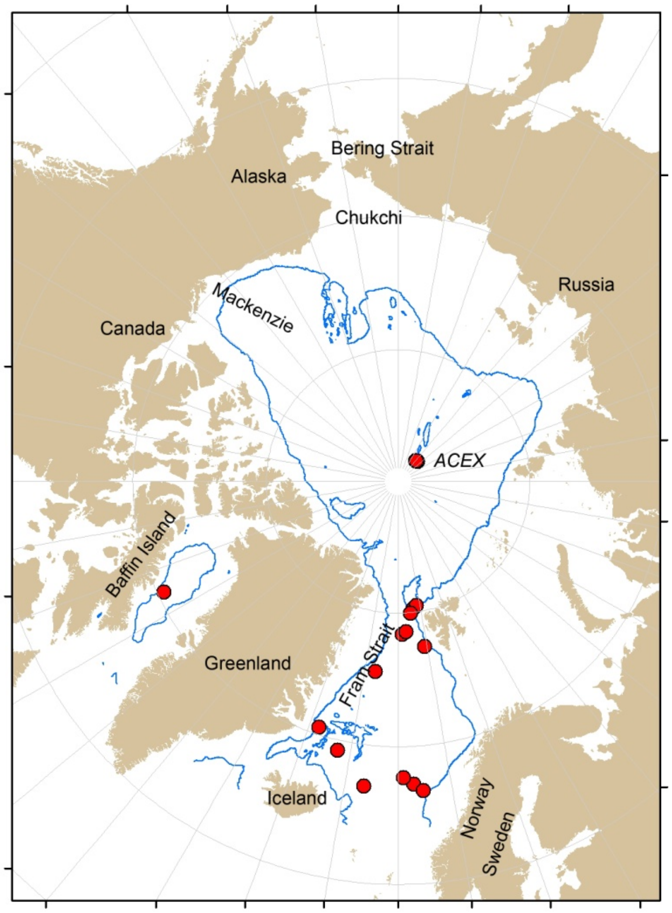


*Figure 1. Compilation of all DSDP/ODP/IODP sites drilled north of the Arctic Circle in the history of SOD, relative to the 1000 m isobaths (blue). Note that margins have been largely ignored and that all drilling (with the exception of ACEX in the high Arctic) has occurred in the Atlantic sector. None of the Bering Sea (IODP Expedition 323) holes were north of the Arctic Circle.*

For the CADW, the targeted locations included circum-Arctic Ocean shallow shelves (< 100 m water depth) and upper continental slopes (to approximately 2000 m water depth). Although the funding for the workshop came from the US Science Support Program (USSSP), scientists at the meeting represented expertise for the US, Canadian, Russian, Scandinavian, and Greenland margins. Through a combination of long- and short-format presentations, breakout groups, and informal discussions, the workshop provided a venue for sharing information about existing and planned IODP proposals; developments to support Arctic Ocean drilling, coring, and borehole monitoring; and key scientific and logistical challenges.

This report describes the scientific motivation for focusing on circum-Arctic Ocean drilling, provides an overview of the major presentations given at the workshop, and reviews the logistical constraints on high latitude northern drilling, particularly with a riserless platform like the *JOIDES Resolution*. The report also details the outcomes from the breakout sessions and provides recommendations, as well as information at workshop participants and activities occurring in the year following the workshop.

*Note on references:* Referencing in this report is not meant to be exhaustive. In many cases, the emphasis has been placed on review papers or providing a few examples from the literature. Because the conveners have the most expertise in the area of gas hydrates, methane dynamics, and permafrost, these disciplines are more poorly referenced in this report than are other topics.

## 2. Scientific Problem

Over the past decade, numerous researchers and planning groups have identified the importance of increased study of Arctic Ocean margins, here taken to mean both the shelves and upper continental slopes. In terms of traditional oceanographic issues, it is significant that the Arctic Ocean's shelves, which were mostly exposed subaerially and/or ice covered during the last glaciation, constitute about 25% of this ocean's area, more than in any other major basin. The shelves thus have an outsized influence on ocean circulation patterns in this basin. Because the Arctic Ocean is semi-enclosed, the strongly seasonal freshwater input from the ringing river systems is initially confined within the basin. This freshwater pulse spreads out over the Arctic Ocean and plays a role in sea ice formation, and the annual formation of sea ice in turn leads to the generation of dense brines. The seasonal extremes experienced at high northern latitudes mean that the organic carbon load that sustains productivity on the shelves is delivered mostly during a few short months, a pattern that has probably persisted for thousands of years.

While these observations attest to the overall importance of the circum-Arctic Ocean environment, the primary scientific problem motivating the CADW was more focused: Emerging research that implies the potential for massive, previously unaccounted for, methane outgassing to the ocean-atmosphere system from the East Siberian Arctic Shelf (ESAS; Shakhova et al., 2010). Such observations have contributed to the perception that continued global warming may trigger an Arctic methane catastrophe even though Shakhova et al. (2010) have been careful to link the methane emissions more closely to long-term (Late Pleistocene to contemporary) warming of shelf sediments during inundation by rising ocean waters. Nonetheless, through analysis of oceanographic data and numerical modeling, researchers have now documented decades' long warming of Arctic Ocean waters (e.g., Dmitrenko et al., 2008; Polyakov et al., 2004; Ferre et al., 2012), although mostly at greater water depths than the shelves. This contemporary ocean warming event, coupled with longer-term warming of the shelves due to sea level rise, leaves behind a record of climate change in the near-seafloor sediments. Scientific ocean drilling can access this record and "catch climate change in progress" through a tool more traditionally used to study events far in Earth's past.

The focus of the CADW was not entirely methane dynamics, but the importance of methane as a greenhouse gas (up to 20 times more potent than $CO_2$ in the present-day atmosphere) and the fact that circum-Arctic Ocean settings have the potential to release so much methane during climate change episodes provided an urgency to some of the scientific programs discussed at the workshop. Globally, methane hydrates, an icelike form of water and low molecular weight gas (usually methane), sequester huge quantities of methane in marine sediments and in and beneath permafrost. Methane hydrates also greatly concentrate methane, ideally about 164 times per unit volume compared to standard pressure and temperature conditions. As outlined by Ruppel (2011), five distinct methane hydrate settings are relevant at high northern latitudes (Figure 2), but only continental shelves and upper continental slopes, where the hydrate zone thins to vanishing, are strongly susceptible to climate change. On Arctic Ocean continental shelves, the gas hydrates are relict, leftover from a time when the shelves were previously exposed and formed thick permafrost. The shallowest gas hydrates in these settings are located ~200 m below the seafloor. Globally, the amount of hydrate in these settings may be fairly limited, depending on the availability of local, mostly thermogenic gas sources that might have fed hydrate formation during permafrost evolution. Much of the methane emitted at the seafloor on the shelves is likely produced not from dissociating gas hydrates, but rather through normal microbial processes in the shallow sediments, through microbial action on organic carbon newly released from thawing permafrost, and from previously thawed and now inundated lake thaw bulbs. Drilling in these settings will provide access to a record of marine transgressions and regressions; constraints on sea level rise since the Late Pleistocene; information about the evolution and breakdown of permafrost and gas hydrates; and a 21st century baseline for the distribution of subsea permafrost and gas hydrate. Since methane released from continental shelf water depths can reach the atmosphere, drilling to assess methane sources, sinks, and distribution may also assist in evaluating the "Arctic methane catastrophe" hypothesis.

Globally, upper continental slope settings (~300 m to 700 m) affected by warming intermediate ocean waters are also likely settings for methane hydrate dissociation (e.g., Kvenvolden, 1988; Wood and Jung, 2008). Here, the gas hydrate stability zone theoretically thins to vanishing, and small changes in bottom water temperature are enough to cause dissociation or re-formation of gas hydrate (e.g., Mienert et al., 2005; Westbrook et al., 2009; Phrampus and Hornbach, 2012). This very dynamic part of the gas hydrate zone may be a good laboratory for studying longer-scale perturbations to the gas hydrate system (e.g., Pliocene warm period or even the PETM) and their impact on a range of biological, chemical, and physical processes, as well as sediment structure and seafloor morphology. Methane released from these upper continental slope settings does not directly reach the atmosphere, but it may affect ocean acidity and oxygen levels (Archer et al., 2009).

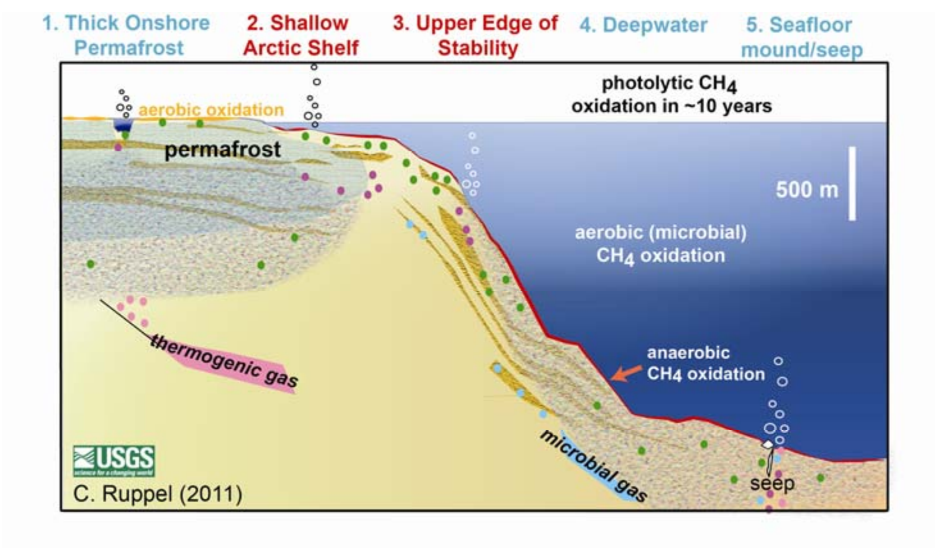


*Figure 2. Five gas hydrate settings on a high-latitude terrestrial to deep ocean profile. Only hydrates in zones 2 and 3 are highly susceptible to dissociation during global warming events. From Ruppel (2012).*

## 3. Workshop Goals

The workshop's goals were to:

1. Identify the best geographic area(s) for exploring active climate change processes affecting climate-susceptible geologic deposits (subsea permafrost and methane hydrates) using the drill as the primary tool.
2. Identify additional major knowledge gaps (e.g., in paleoceanography, sea level and sea ice reconstructions, sedimentology, etc.) that could be also be addressed by a drilling program in circum-Arctic regions. These issues were primarily addressed through breakout sessions.
3. Explore the unique scientific and technical challenges associated with drilling on (a) shallow Arctic shelves and (b) deepwater Arctic continental slopes to lay the groundwork for several anticipated pre-proposal submissions.
4. Develop an informal strategy for managing a series of scientifically-related proposals to be submitted to IODP or its successor program(s).
5. Education and Outreach: In particular, introduce IODP to new constituencies that will have to be entrained to ensure the success of these novel drilling efforts.

As detailed below, the plan by Canadian researchers to hold a workshop focused on the Beaufort Sea in February 2012 made it fairly urgent that the CADW, funded in August 2011, be held as soon as possible. Unfortunately, it was difficult to mesh the varying degrees of readiness of a number of proponent groups that had already submitted pre-proposals, were in the process of preparing them, or were considering this as a longer-term goal. While the workshop provided an opportunity to introduce the key issues to some new constituencies and to focus some of the drilling efforts, coordination among the various programs was not easily facilitated by this meeting. Still, there were informal discussions about synergies on the Beaufort margin, about coordinating timing of the US Beaufort deepwater drilling (>80 m water depth) and Chukchi drilling, and about the future of the Bering pre-proposal.

## 4. Previous and Related Workshops

Since 2008, there have been several scientific ocean drilling (SOD) workshops focused on the Arctic Ocean and nearby regions, particularly since the beginning of 2011. Some of these workshops were specifically reviewed at the CADW by their organizers or key attendees.

The Arctic Ocean Drilling Workshop held in late 2008 (Coakley and Stein, 2010) was a critical starting point for the current crop of Arctic Ocean proposals. Organized by AWI, the workshop largely focused on deepwater drilling for tectonic, paleoceanographic, and related targets as a follow-up to the successful ACEX drilling. Through mild advocacy, some of the CADW conveners and their colleagues successfully sought the incorporation of a breakout session on Arctic gas hydrates at the AWI workshop. The resulting breakout report was a minor component of the outcome of the AWI workshop. Some related ideas about circum-Arctic Ocean gas hydrates and permafrost were carried to the INVEST meeting in Fall 2009. These topics did not end up being explicitly represented in the ISP (IODP, 2011)

Earlier in 2011, three workshops with relevance to CADW objectives were organized by members of the extended IODP community:

1) *Fluid Flow in Arctic Continental Margins and Ocean Ridges*: This EU funded workshop was held in May 2011 in Tromso and was strongly focused on fluid flow issues. It included a consideration of deepwater Arctic Ocean scientific problems that were not covered by the CADW.

2) *Arctic Site Survey Workshop*: In November 2011, the European Magellan series held an Arctic site survey workshop co-sponsored by ESF, IASC and ECORD. The workshop's report is available at:

http://www.iasc.info/files/Marine/Magellan%20Workshop%20Final%20report%20November%202011(3).pdf.

Bernie Coakley, a co-convener of the Magellan workshop, gave an overview of that workshop's outcomes at the CADW. The site survey workshop built on the discussions at the 2008 AWI workshop and identified some areas of interest for drilling above the Arctic Circle and specific challenges for acquiring site survey data in the Arctic Ocean. Attendees reviewed available platforms for acquiring site survey data, particularly seismic data, and highlighted data gaps and areas where the existing data coverage could potentially support a drilling proposal. The Magellan workshop included discussions of the some of the circum-Arctic Ocean regions of interest to the CADW, but several key areas were not considered.

3) *Greenland Workshop*: Joe Stoner and colleagues hosted this USSSP-sponsored workshop focused on the deglacial history of Greenland in November 2011, and Stoner reported on the outcomes at the CADW meeting. The attendees at the Greenland workshop identified a range of critical paleoceanographic sections in the marginal seas around Greenland, and devised a strategy that includes drilling on the shelf and in fjords to access information about the fate of individual glaciers and drilling on the slope and at greater water depths to constrain the history of the ice sheet as a whole. Stoner reported that several proposals were likely to be submitted to IODP as follow-up and that some of these locations could be targeted for drilling even in the next few years. The full workshop report can be found at: http://iodp-usssp.org/wp-content/uploads/Workshop_Report_Greenland.pdf.

*Connection to IODP-sponsored Beaufort Sea workshop, Kananaskis, February 2012*: As the conveners were preparing the CADW proposal for USSSP in April 2011, we became aware that Matt O'Regan had recently submitted a proposal to IODP for a Beaufort Sea workshop to focus primarily on the Mackenzie area. That workshop was in part designed to seek efficiencies between O'Regan's paleoceanographic pre-proposal on the collapse of the Laurentide Ice Sheet and a planned proposal for permafrost/gas hydrates science in the same area from Dallimore and colleagues. Once the CADW funding decision was known in August 2011, CADW conveners immediately contacted O'Regan to begin coordinating the two workshops. Since the Beaufort Sea workshop was being planned for early 2012 in Canada and had partial sponsorship from IODP Canada, the decision was taken to rapidly organize the more general USSSP-sponsored CADW and ensure that it could be held prior to the Beaufort Sea workshop. After considering the scheduling of Fall AGU Meeting Arctic-focused sessions, the CADW conveners chose the weekend following the Fall Meeting for the workshop. This decision probably hurt attendance. For example, it was particularly difficult for European scientists to attend the CADW if they had booked their air tickets to the AGU Fall Meeting prior to knowing that the CADW would be held during the post-meeting weekend. There were also numerous project meetings being held in San Francisco during the same weekend, making it impossible for even some of the co-conveners of the CADW to attend the workshop at all times.

Two of the six CADW co-conveners were on the organizing committee for the Kananasksis meeting, and four CADW co-conveners attended the Kananaskis workshop. Outcomes of the CADW were reported in Kananaskis, and the Kananaskis meeting agenda expanded to include a component related to the Alaskan Beaufort margin.

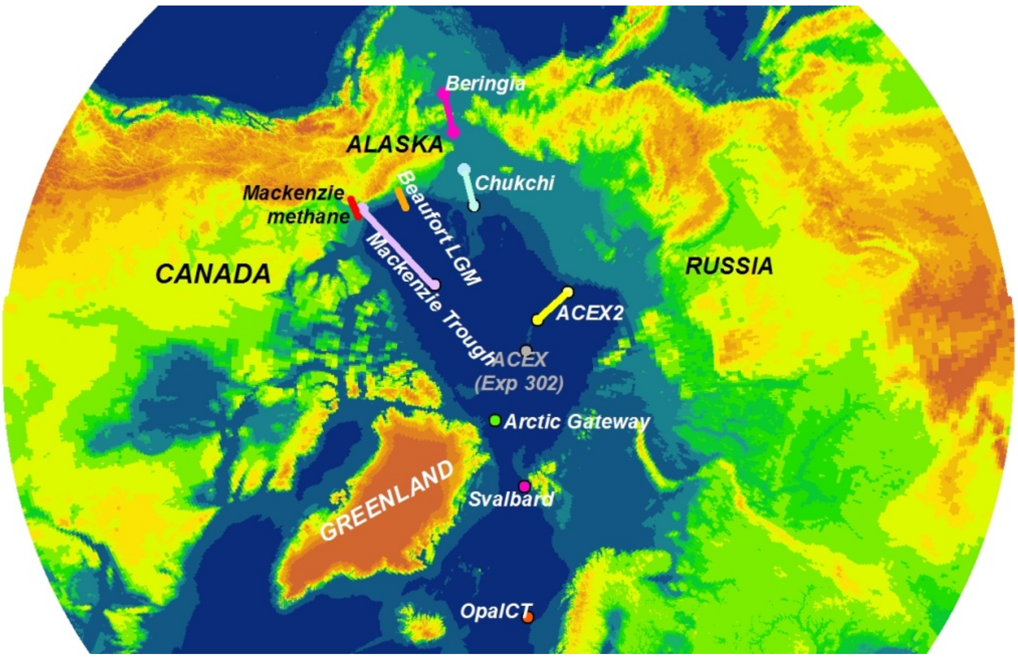


*Figure 3. Existing and potential drilling proposals in the circum-Arctic Ocean region, including the deep Arctic Ocean programs (ACEX—IODP Exp 302; and proposed ACEX2). Numerous proposals that may be formulated on Greenland's margins are not shown here.*

## 5. Geographic Areas

Figure 3 compiles the locations of existing and planned scientific ocean drilling proposals for the circum-Arctic area as of early 2012. At the CADW, attendees reviewed ongoing drilling efforts and potential drilling activities by geographic area for part of the first day.

***East Siberian Margin (Fast ice drilling in 2011 and 2012)***

Much of the interest in Circum-Arctic Ocean margin scientific problems has been catalyzed in recent years by high-profile research activities being conducted on the East Siberian Arctic Shelf (ESAS), under the leadership of Natalia Shakhova and Igor Semiletov of the University of Alaska-Fairbanks. Researchers have measured pervasive methane supersaturation in the water column in the ESAS area, documented the existence of methane plumes, and postulated substantial escape of methane to the atmosphere (Shakhova et al., 2010). If these methane fluxes are extrapolated to other Arctic Ocean continental shelf areas that have experienced similar inundation since Late Pleistocene time, the global atmospheric methane budget could be seriously affected. During the CADW, Shakhova and Semiletov detailed the background research conducted on ESAS and efforts to use a portable rig to drill to less than 200 mbsf into the shallow subsea permafrost section with partial support from the US NSF.

***Kara/Laptev Seas***

Drilling in the Kara and Laptev Seas has long been of interest to Russian researchers and colleagues in Germany. Indeed, the Laptev Sea was drilled with the *M/V Kimberlit*, a Russian geotechnical vessel able to penetrate up to 100 m subseafloor, during the Transdrift expedition in 2000. At the CADW, Georgy Cherkashov and Pavel Rekant presented some of the background material they have collected and compiled to support scientific drilling on this margin. Of particular interest are maps showing the extent of subsea permafrost and a database of gas seeps throughout the region (Rekant et al., 2005; Rekant and Vasiliev, 2011). There are substantial, high-quality industry data sets on parts of the margin, and some of these data have been available to Russian researchers reconstructing the tectonic, glacial, and sedimentation history of the Kara and Laptev seas. In 2012, German and Russian researchers drilled shallow boreholes in the nearshore part of the Laptev Sea and conducted towed resistivity surveys in an attempt to better delineate subsea permafrost.

***Canadian Beaufort Margin (now IODP Pre-Proposal 806)***

Just before the CADW meeting, a group of proponents formulated a proposal to drill targets on the Canadian Mackenzie margin to study methane leakage and climate change on the continental slope and on shelf areas underlain by subsea permafrost (e.g., Paull et al., 2011a). This proposal was submitted to ICDP in December 2011 and subsequently submitted to IODP in March 2012 (Paull et al., 2011b). At the CADW, Dallimore and Paull outlined the planned drilling effort and the background science. For several years, research activities on the Canadian Beaufort margin have included surveys of methane seepage from pingo-like features (Paull et al., 2007) that occur both on the shelf in areas still underlain by subsea permafrost and on the upper continental slope, where diapiric structures associated with the Canning-Mackenzie Deformed Margin promote methane flux towards the seafloor (e.g., Hart et al., 2011). The project would require both a mission-specific platform for the shallow water holes and a conventional drilling vessel for the deeper water holes. Part of the proposed drilling project emphasizes shallow geohazards (e.g., shallow overpressures), and there is consideration being given to how the drilling might be planned to accommodate the geohazards. Canadian researchers have access to some industry data to support Beaufort Margin drilling and plan to acquire more MCS data in summer 2013. ION acquired extensive data in the area in 2010, and British researchers have published some analyses of these data (Batchelor et al., 2013a, 2013b) near the area targeted for drilling in IODP pre-proposal 806 (Figure 4). Proponents also have access to older refraction data that were used to support the mapping of subsea permafrost in the Mackenzie area (Hunter et al., 1978; Pullan et al., 1987), as well as data from an extensive series of boreholes on the shelf.

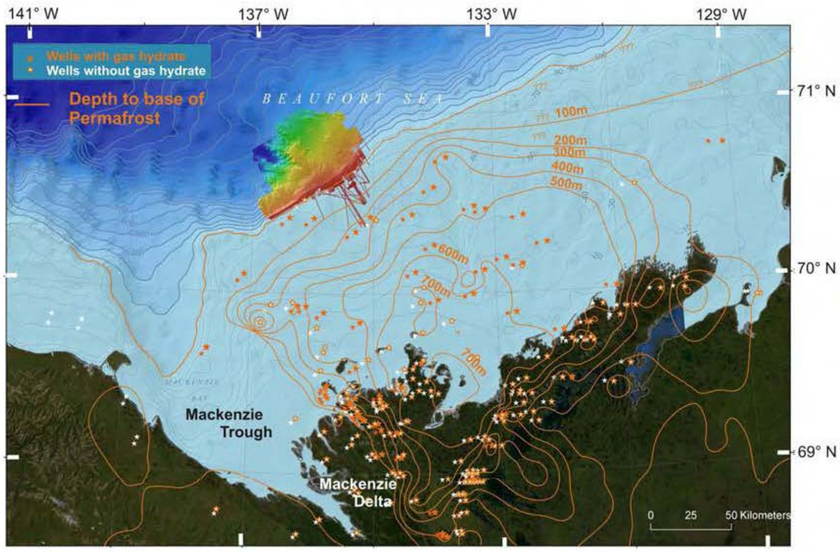


**Figure 2:** *Location map of Beaufort Shelf study area showing location of industry wells in which the occurrence of gas hydrate is documented and contours (in m) to the base of permafrost. The figure also shows a portion of the outer shelf where a multi-beam survey allows consideration of the detailed morphology of the shelf/slope transition area. The proposed transect will probably be in the area associated with the multi-beam surveys and on the adjacent shelf.*

*Figure 4. Map taken from IODP Pre-Proposal 806 (Paull et al., 2011), which focuses on investigating subsea permafrost and gas hydrates in the Mackenzie area. Drilling targets will likely cross from the shelf to the upper slope in the area that the multibeam data are shown.*

### *Canadian Mackenzie Trough (IODP Pre-Proposal 753)*

Drilling in the Mackenzie Trough for paleoceanographic objectives is described in a pre-proposal led by Matt O'Regan (Figure 5). Pre-Proposal 753 seeks to test the hypothesis that the collapse of the Laurentide ice sheet triggered the Younger Dryas (O'Regan et al., 2010). The drilling will target high resolution paleoceanographic records that can constrain Late Quaternary dynamics of the Laurentide ice sheet and freshwater flux history through the Mackenzie Trough. The focus region for Pre-Proposal 753 is close to the target area for Pre-Proposal 806. A critical challenge facing Pre-Proposal 753 is the lack of site survey data, specifically cores that can demonstrate the preservation of a high-resolution paleoceanographic record that covers the targeted time period. Cores, along with some subsidiary data, will likely be obtained in 2014, and sites may be moved to target paleoceanographic sequences that are more ideal for the study's goals. NSF OPP has funded a paleoceanography study to acquire cores to target the Younger Dryas in the same area aboard the *USCGC Healy* in 2013.

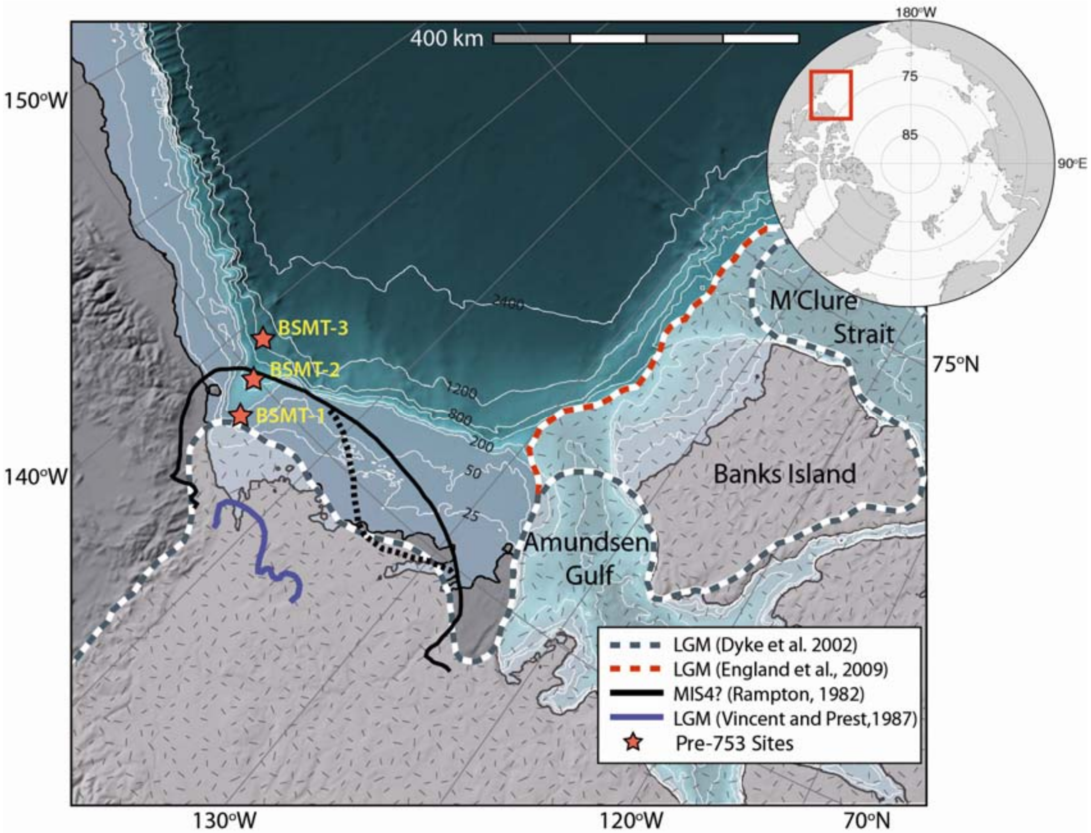


*Figure 5. Map (provided by M. O'Regan) of the Mackenzie Trough in the Beaufort Sea illustrating various reconstructions for the Laurentide Ice Sheet (LIS) glacial limits during the Last Glacial Maximum (LGM). These conflicting interpretations highlight the uncertainty in LGM glacial reconstructions for the western Beaufort Sea. Drilling locations for IODP Pre-Proposal 753 (O'Regan et al., 2010) are shown with red stars and labelled "BSMT." BSMT1 and 2 target high resolution records deposited during and since the retreat of glacial ice from the Mackenzie Trough. BSMT-3 is tentatively placed seaward of the last glacial advance of the LIS, with an aim to recover a more complete mid- to late Pleistocene sedimentary sequence.*

***US Beaufort Margin (now IODP Pre-Proposal 797)***

Drilling on the Alaskan Beaufort Margin focuses on a cross-shelf and upper continental slope transect (Figure 6) that would sample across the subsea permafrost/no permafrost transition at a location with identified relict hydrate (Collett et al., 2011) and then continue across the shelf and down the upper continental slope to capture the most dynamic part of the upper slope gas hydrate stability zone (IODP Pre-proposal 797, Ruppel et el., 2012). This is a two platform program that would require a shallow water rig for holes at < 80 m water depth and a riserless vessel for the remaining holes. The overarching goal is to track the impact of climate change from the LGM through contemporary times on climate-sensitive deposits like permafrost and methane hydrates. This goal involves reconstructing an appropriate sea level history for this part of the Beaufort Sea, identifying how microbial systems have reacted and possibly reactivated to changing conditions, developing total subseafloor methane budgets, determining how pore water characteristics and sediment structures reflect changing permafrost and gas hydrate conditions, and using a multiproxy approach to constrain paleoclimate (e.g., sea ice distribution, bottom water temperature fluctuations). The Beaufort slope is also the site of widespread slope failures

(Kayen and Lee, 1991), and geohazards play a subsidiary role in the drilling proposal. The USGS published a map of subsea permafrost on the US Beaufort margin in 2012 (Brothers et al., 2012) based on an analysis of available legacy seismic data. The USGS also completed site survey-type cruises in 2010 and 2011 on the inner shelf (in part to validate the subsea permafrost map) and in 2012 to water depths as great as 2000 m. The 2012 cruise acquired 500 km of new multichannel data on the shelf and upper continental slope, and coring from the shelf transition zone and through the dynamic upper continental slope area is scheduled for 2014. Scripps will lead the acquisition of controlled source electromagnetic data coincident with USGS seismic lines in 2014 and 2015 to better map the offshore extent of subsea permafrost. The USGS has also compiled all existing offshore borehole data, although coverage is far sparser than in the Mackenzie Delta.

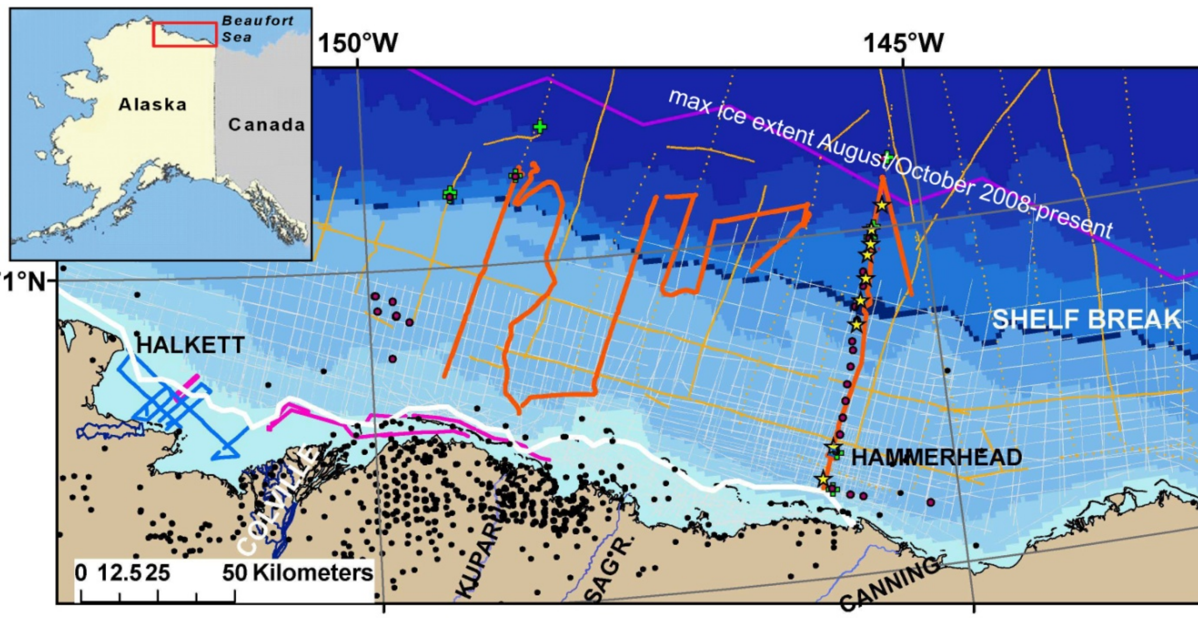


*Figure 6. Proposed drill sites (stars) on the Alaskan Beaufort passive margin, as outlined in IODP Pre-Proposal 797 (Ruppel et al., 2012). The orange and red lines show multichannel seismic (MCS) data collected by the USGS in 1977 and 2012, respectively. Gray lines show industry MCS data that are in the public domain. Black circles are the locations of existing wells. White curve near the coast is the minimal extent of subsea permafrost as delineated by Brothers et al. (2012), and purple line is the maximum southerly extent of sea ice between August and October from 2008 to the present. Blue and pink nearshore surveys were acquired by the USGS in 2010 and 2011.*

### *Chukchi/Bering (IODP Pre-Proposal 750 and Proposal 680)*

The Bering proposal (Proposal 680) is under the leadership of S. Howell and describes mission-specific platform drilling (water depths of 30-45 m) across the submerged Bering Land Bridge and sampling of the high-resolution Miocene to Holocene sedimentary records north and south of the bridge. Among the goals of the program are reconstruction of Pleistocene and Holocene sea level, sea ice, and climate history; determining the emergence history of the land bridge and its role in linking flora and fauna on the Eurasian and North American continents; and studying the links among climate change, land bridge emergence, and human migration. The proposal has not been updated since 2008. The Bering Strait targets described in Proposal 680 are different from and not proximal to the Bering Sea locations drilled by IODP Exp. 323, which targeted the Pliocene Warm Period in the deeper part of the basin, south of the Arctic Circle.

The Beringia pre-proposal (IODP Pre-proposal 750; Brigham-Grette et al., 2009) is complementary to the Bering Strait full proposal and targets the Quaternary history of the Arctic-Pacific Ocean oceanographic gateway. The proposal focuses on a shelf (< 100 m) to upper slope (up to 1000 m) transect from the Chukchi shelf to the Herald Trough and requires both a shallow water drilling platform and a traditional riserless vessel. The recovered core should contain a relatively complete record of sea level fluctuations through the Quaternary and possible earlier, which will in turn constrain the degree of communication between the Arctic and Pacific Oceans over time. Multiple paleoclimate proxies in the recovered sediments can be used to reconstruct sea ice histories, study intervals of warming (relevant to contemporary conditions), and infer how glacial ice may have interacted with the Chukchi margin (Polyak et al., 2001). NSF sponsored acquisition of site survey MCS data on the Chukchi margin under ice free conditions in 2011 (Coakley et al., 2011). Existing cores have been intensely studied (e.g., Farmer et al., 2011), and new coring is planned for 2013 and 2014.

***Svalbard***

While there is no existing proposal for the Svalbard margin, this site, which is characterized by widespread and spectacular methane seeps originating near the upper edge of gas hydrate stability (Westbrook et al., 2009), has often been discussed as a drilling target. The margin also sits in the Fram Strait, arguably the most important oceanographic gateway for the Arctic Ocean and one that was drilled during ODP Legs 151 and 162. Here Atlantic waters enter the Arctic Ocean and begin their circumpolar cyclonic circuit along the continental margins. The margin is also proximal to the mid-ocean ridge (MOR). Norwegian, German, and British scientists have conducted dozens of studies in this area over the past few years (e.g., Bunz et al., 2012; Chabert et al., 2012; Minshull et al., 2012; Rajan et al., 2012), and there is substantial high-quality industry data in some nearby areas as well. The most recent research in this area demonstrates that the seepage has been active for hundreds to thousands of years (Science Daily, 2012), meaning that these seeps are not a recent response to warming of intermediate ocean waters (e.g., Mienert et al., 2005; Biastoch et al., 2011). Researchers (Fisher et al., 2012) have also shown that methane detected in the atmosphere above the seeps originates in European wetlands, not emissions from the seafloor seeps. There have been several observatory efforts at this location (e.g., NOON, MASOX), and there may be a future program to install long-term observatories in boreholes (Figure 7).

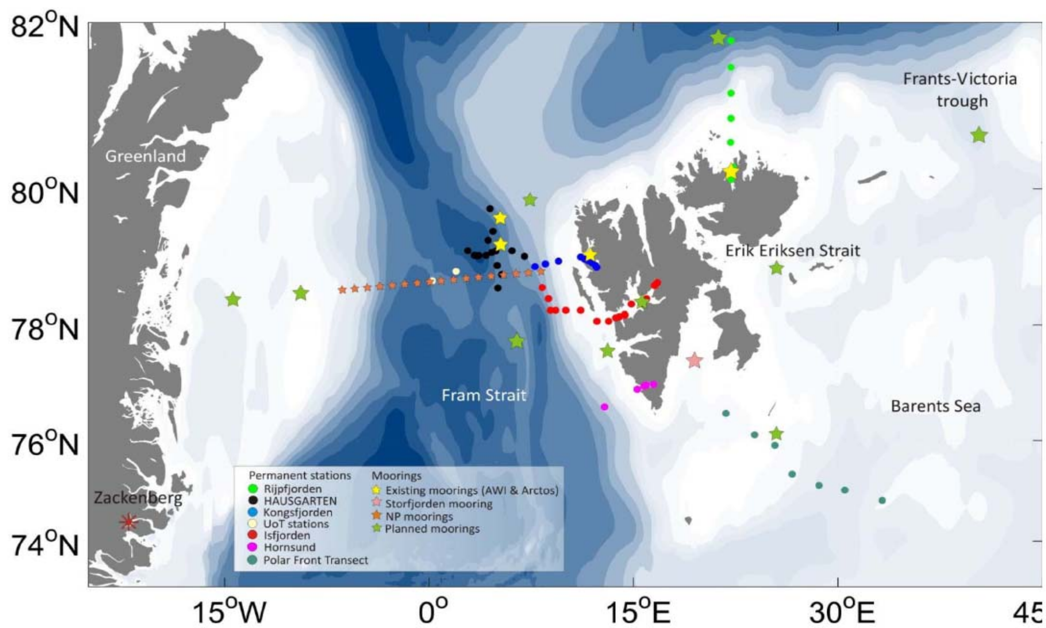


*Figure 7. This map from J. Mienert shows existing and planned observatory locations near Svalbard. There are numerous paleoclimate and tectonic drilling targets of interest near Svalbard, but an additional interest is drilling boreholes necessary to expand seafloor observatories (cabled or uncabled) in this area.*

***Greenland***

As the site of the only remaining ice sheet in the northern hemisphere, Greenland has marginal seas that are an important target for drilling. The Greenland drilling workshop was described above and in an extensive report at: [http://iodp-usssp.org/wp-content/uploads/Workshop_Report_Greenland.pdf](http://iodp-usssp.org/wp-content/uploads/Workshop_Report_Greenland.pdf). The scientific community has identified numerous objectives for drilling on all of Greenland's margins, including the margin bordering the Arctic Ocean (Figure 8). The drilling activities are focused primarily on the history of Greenland's ice sheet since the Late Neogene, including the ice-free interval of the Miocene, the period of ice sheet growth, the response of the ice to $CO_2$ fluctuations in the Pliocene, plus specific focus on the period from 40 to 100 ka (also well-covered by Greenland ice cores) and on certain marine isotope stages (MIS). A critical recommendation of the Greenland workshop was to emphasize sites where the large scale, regional processes associated with ice sheet evolution could be best captured by drilling. Substantial site survey needs exist for many sites around Greenland, although it is suspected that industry has some of the seismic data needed to provide an assessment of sites.

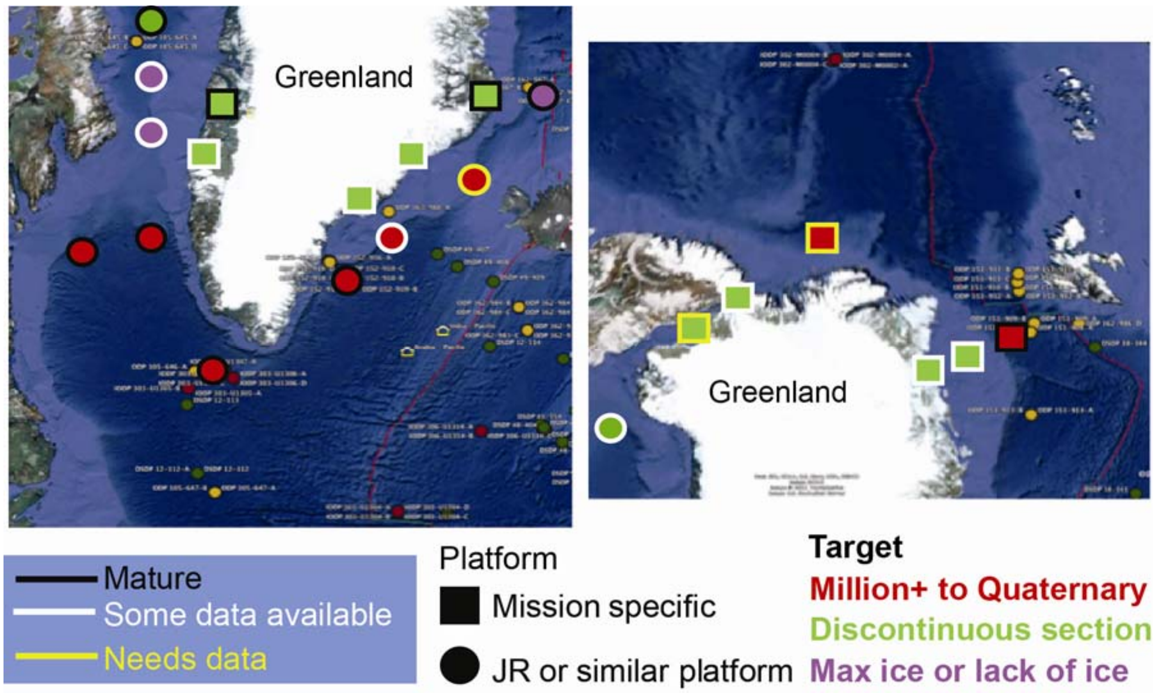


*Figure 8. Map by Stoner and DeGree showing existing DSDP/ODP/IODP drill sites on IODP's Google map database (small symbols) and potential drilling sites near Greenland for different targets. The symbol shapes denote the necessary drilling platform, and the symbols' outlines designate the sites' readiness for drilling. This summarizes the outcome of the Greenland margin drilling workshop.*

## 6. Logistical Issues

In contrast to many scientific drilling workshops, workshops focused on the Arctic Ocean have a particular need to discuss logistical issues. The inaccessibility of high latitude areas, the short open water season, the constantly shifting ice conditions, and the difficulty of acquiring complete site survey data all contribute to a unique set of challenges for Arctic Ocean drilling expeditions. For the topics discussed at the CADW, an additional issue is the range of potential targets, which will likely include both deepwater sites that might be studied using a riserless vessel and shelf sites that would require specialized capabilities. Unique to high latitudes, some of these targets might be reached by taking advantage of ice cover. Finally, some circum-Arctic Ocean drilling programs would focus on studying permafrost and/or hydrate-bearing sediments, meaning that special equipment and approaches might be required. The discussion below is divided into the components of general drilling conditions, potential platforms, and specialized approaches for permafrost and gas hydrate.

*General Conditions*

Since the days of DSDP, most scientific ocean drilling has been conducted in ice-free waters and in areas with few shallow geohazards (e.g., shallow gas). Petroleum basins have been drilled only rarely, and holes are usually abandoned at the first sign of petroleum shows or conditions conducive to petroleum maturation. Drilling expeditions often occur in remote parts of the world's oceans, although such expeditions have typically had the advantage of up to 2 months of operations, including transits.

For drilling operations in the circum-Arctic Ocean regions, some of these conditions will be difficult to meet. If drilling platforms are restricted to operating in truly ice-free waters, it is critical to understand the distinction between the technical use of that term in the Arctic Ocean (up to 10% ice cover) and vernacular use (0% ice). Even in late summer, parts of the marginal Arctic Ocean may have ice floes, loosely packed floating ice, or small icebergs that are mobilized by wind and currents. Modern radar makes these obstacles easy to avoid for ships conducting underway surveys, but stationary drilling platforms may need a strategy for quickly abandoning the hole or for using an ice-capable vessel to protect the drilling platform. An important observation often missed by those without experience in the Arctic Ocean is that ice conditions are highly localized in summer and early autumn. For example, a bay on the inner shelf may be blocked by floating ice, while the middle/outer shelf and upper slope at the same location can be ice-free. Conditions also vary tremendously along a margin. In the Western Arctic, the shelf from Barrow to Cape Halkett is often iced in long after the shelf from the Colville Delta to the US-Canada border is clear of ice. Accurate, frequently updated, satellite-based interpretative ice maps, like those provided for the Western Arctic by the Canadian Ice Service, are critical for the success of drilling expeditions and the safety of drilling platforms.

During much of the history of scientific ocean drilling, shallow drilling hazards have been avoided through judicious placement of holes to avoid structural traps for gas, known shallow gas pockets, overpressured sediments, shallow hydrocarbons, seismically active zones, and other features. In some cases, locations with shallow hazards have been drilled by adapting operational procedures to safeguard the drilling platform. For example, on IODP Exp. 308, which drilled overpressured sediments in a world-class petroleum basin (Gulf of Mexico), mud handling was a critical component of the program. In some parts of the marginal Arctic Ocean, significant planning and drilling platform adaptations may also be required to avoid shallow hazards. An example highlighted at the CADW was the Mackenzie Delta region, where numerous shallow hazards may present challenges for conventional riserless drilling and where scientists are targeting pingo-like features that are associated with fluid/gas flow through shallow sediments. MeBo, a German-built seafloor drilling tool that can be deployed from standard oceanographic vessels, may be one approach for shallow (<80 m) soft sediment drilling in areas plagued by shallow hazards in water depths up to 2000 m.

*Platforms*

To date, scientific drilling at high latitudes has been conducted aboard a specially modified ship (IODP Exp 302, ACEX), from the *JOIDES Resolution* under ice-free conditions in Arctic Ocean gateway areas (e.g., ODP 151, ODP 162) and offshore Antarctica, and using special rigs operated from fast ice (I. Semiletov's presentation at the CADW) or ice shelves. Missing from this list are mission-specific platforms that might be operated in shallow-water Arctic conditions from the ice or in open water during ice-free periods. Such MSPs, which are supplied by ECORD in the present-day structure of IODP, were not well-represented at the meeting, in part due to its US sponsorship and in part due to the need to hastily organize the workshop. Some alternate drilling methods that do not require specialized vessels were discussed in the presentation by Lembke-Jene and are mentioned below. Dallimore and Collett also covered some material related to alternate platforms that have been used in the past, particularly by the Geological Survey of Canada (GSC).

Dedicated drilling platforms for off-shelf programs (> 100 m water depth). Scott Dallimore presented an overview of potential drilling platforms that could be used at nominal water depths greater than 80 or 100 m. Traditionally, this has been an important cutoff in scientific ocean drilling since *JOIDES Resolution* operations are generally confined to these water depths. The four types of drilling approaches are: (a) riser drilling; (b) riserless drilling with open hole sweeps; (c) riserless drilling with continuous use of mud (pump and dump); and (d) riserless with mud recovery.

Riser drilling (a) has the advantage of penetrating far deeper below the seafloor and providing constant well control. However, there was no further discussion of riser drilling or use of the *Chikyu* or a commercially-operated riser vessel at the CADW. Realistically, it seems unlikely that such a program could be carried out in the Arctic Ocean in the near future under the auspices of IODP, and so far no drilling has been proposed that would require the complexity, profound subseafloor penetration depths, or geohazard management capabilities of riser drilling.

Conventional riserless drilling (b) like that conducted for most *JOIDES Resolution* operations can quickly complete numerous holes and has successfully reached depths of 1.5 km beneath the seafloor. A disadvantage in areas with known shallow hazards is the reactionary nature of well control on a riserless vessel in the absence of mud handling capabilities. The *JOIDES Resolution* is rated for use under some ice conditions, although ice is normally not permitted to touch its hull. In 2010, the *JOIDES Resolution* successfully drilled IODP Exp. 318 almost at the edge of the active ice sheet to study the glacial history of Wilkes Land in Antarctica. During that expedition, the ship operated in ice-free waters, but within sight of ice floes and without protection from an icebreaker. Similar conditions might be expected for parts of the continental shelf and upper continental slope in the Western Arctic Ocean (Chukchi, Beaufort) and in the Scandinavian Arctic during the summer season. One advantage that the *JOIDES Resolution* has when operating in conventional mode is the capacity to move quickly from a site with several hours' notice of an ice threat. Building on the experience on the Wilkes Land expedition, the *JOIDES Resolution* should be able to accomplish 'ice-free' Arctic drilling during the appropriate time window without having to rely on an ice escort.

Riserless drilling with continuous mud systems (c) was used by IODP on the *JOIDES Resolution* for completion of Exp. 308 in the Gulf of Mexico. Two key disadvantages make the use of such systems unlikely in the Arctic Ocean. First, mud is not recovered, but rather dumped on the seafloor. Industry efforts in the circum-Arctic Ocean tend to emphasize recovery of all mud to be consistent with regulatory restrictions (e.g., NMFS, 2013), and IODP should expect to operate under similar environmental rules. Second, this technique requires continuous replenishment of drilling mud from mud boats. The availability of either the mud or the vessels to transport it to the drillship poses a serious challenge for this type of drilling in much of the Arctic Ocean.

Riserless drilling platforms with recirculating mud systems have been successfully used in several earlier scientific programs in high-latitude areas. Frank Rack (ANDRILL) was unavailable to attend the CADW at the last moment. However, Dallimore described ANDRILL's 2006-2007 McMurdo Ice Shelf program, which was conducted with a special rig that recirculated mud during drilling from an ice shelf that moved over 20 m laterally and experienced tides in excess of 1 m during the operation. The McMurdo Ice Shelf program operated in water depths > 800 m and cored over a kilometer of seafloor using wireline technology. The Geological Survey of Canada (GSC) Foundex drilling program (discussed in the shallow water drilling section below) also used a recirculated mud riserless system, as does the DOSECC/ICDP Global Lake Drilling 800 m (GLAD 800) system. The GLAD 800 system can be used on waters up to 800 m deep and shipped in 20' vans, but has not previously been deployed in saltwater environments.

Shallow Water (< 80 m water depth) Drilling. Shallow water drilling rigs, while critical to the completion of many of the objectives of circum-Arctic Ocean drilling, were not discussed in detail at the workshop. The CADW came on the heels of successful jack-up rig drilling on the New Jersey Margin, and many of the lessons from that program would be applicable to circum-Arctic Ocean margins (Mountain et al., 2010). Timing of the CADW and its US sponsorship complicated involvement of the groups most knowledgeable about the mission specific needs for shallow water drilling. These topics were discussed in detail at the IODP-sponsored Kananaskis workshop held in February 2012.

Drilling from fast ice and ice shelves. Fast ice drilling may be possible in some shallow water circum-Arctic margins in the future. However, even locations where drilling from fast ice has previously been accomplished are now often viewed anecdotally as bad candidates for future fast ice drilling given the inconsistency in ice quality over the past few decades and the concern that ice is generally thinner and less firmly anchored than in the past in some areas. Still, the lessons from the previous fast ice drilling offshore Antarctica, Siberia, and Canada could inform choices of equipment, drilling approaches and timing if a viable fast ice site were located in the circum-Arctic Ocean area.

At the CADW, Igor Semiletov gave an overview of a Laptev Sea fast-ice drilling program that has been partially sponsored by the NSF's OPP in 2011 and 2012. Among the logistical challenges faced by that program were delays in staging of equipment at the coast and difficult ice conditions. The drilling itself did not pose major challenges once underway.

As described by Dallimore, the GSC conducted a program from fast ice in the early 1990s in water 32 m deep and also completed numerous programs with containerized drilling and scientific equipment starting in the early mid-1980s. Logistically, the drilling programs were relatively straightforward, but there were also important innovations such as chilling of the drilling mud to protect the integrity of permafrost-bearing sediments.

Specialized drilling tools. MeBo, short for the German term for "seafloor drill rig", can be deployed from a normal oceanographic vessel and should be able to drill up to 80 m in soft sediment in water depths up to 2000 m. MeBo is operated by MARUM (University of Bremen) and differs from other drilling systems in that most of the infrastructure sits on the seafloor and is run remotely from the ship. MeBo will undergo critical Arctic tests in the coming years and may be an option for shallow coring at a range of sites in the future.

Icebreakers. In many cases, icebreakers are considered a necessity for Arctic Ocean drilling, even under ice free conditions. Icebreakers are not only needed to provide access to some open water areas through the summer sea ice pack, but also are used to protect drilling platforms that are not permitted to have ice touching their hulls. While there were not representatives from these national programs at the CADW, Russia and some Scandinavian countries have excellent access to icebreakers, including some for dedicated research. One Russian icebreaker and the Swedish icebreaker *Oden* were involved in the IODP Exp. 302 ACEX program. Canada manages a fleet of 18 Coast Guard-operated icebreakers with a range of capabilities, and some of these have taken part in joint US-Canada scientific programs in the Arctic Ocean in recent years. For some locations in the Western Arctic, Canadian icebreakers may be an obvious partner when the *JOIDES Resolution* is conducting high-latitude drilling under mostly ice-free conditions. The US currently has one multi-use icebreaker for Arctic Ocean work (*USCGC Healy*). As of early 2013, the *USCGC Polarsea* had also been refurbished.

At the CADW, Lembke-Jene provided an update on the detailed planning for the *Aurora Borealis* research icebreaker, which was redesignated as the *Ericon (European Icebreaker Consortium)/Aurora Borealis* as of mid-2012, after the CADW. While the icebreaker *AURORA* will not be a dedicated drilling vessel, she will have a moonpool and carry equipment capable of recovering deep cores from permanently ice covered areas. She will also have capabilities for geotechnical drilling in ice-covered areas, in addition to long piston coring and drilling with the MeBo seafloor system. The *AURORA* may therefore serve as an alternate platform for drilling, one that could play an important role in future Arctic Ocean IODP efforts in areas where water depths are great enough to accommodate its equipment. More information can be found at the Ericon website:

http://www.eri-aurora-borealis.eu/fileadmin/user_upload/Home/download/RELEVANT_FINAL_DOCUMENTS/ERICON_2015-2030_SP.pdf

Ships for site survey. For proponents navigating the IODP proposal process, obtaining appropriate site survey data is always one of the biggest challenges. The lack of ships available to conduct site survey in some parts of the Arctic Ocean, coupled with the short open-water season, can frustrate attempts to progress pre-proposals to full proposals for some circum-Arctic Ocean targets.

As outlined by Lembke-Jene, German researchers have access to several vessels that routinely operate in high-latitude waters (including the *R/V Polarstern*). The *R/V Polarstern* is also available for collaborative activities between German researchers and partners from other countries (http://www.awi.de/en/infrastructure/ships/polarstern/submission_of_proposals/). German research groups supplement their own fleet with contract Russian vessels. UK researchers have taken the *James Cook* into areas such as Svalbard. Norway routinely operates at high latitudes, while information on operations of Russian research vessels that conduct site survey related activities is more difficult to ascertain. Canadian Arctic researchers use vessels operated by Canadian Coast Guard.

Since the CADW was sponsored by USSSP, it seemed particularly important to discuss the challenges faced by US researchers in the Western Arctic. The US will have no regional vessel routinely capable of Arctic Ocean research until the inaugural season of the *R/V Sikuliaq* in 2014, but NSF and USGS scientists have for many years used charter vessels (e.g., *R/V Ukpik* and *R/V Annika Marie*) for Beaufort shelf work. Contract research vessels like the *R/V Norseman* and *R/V Norseman II* are viable platforms for some shelf and slope site survey operations in Russian, US, and Canadian waters. The *R/V Langseth* was able to conduct extensive operations in the Chukchi late in the summer 2011 season under ice-free conditions, but such surveys are not yet considered fully routine for this vessel. NOAA's hydrographic vessel *Fairweather* collected data near the Beaufort shelf break in 2012, and several commercial interests have acquired seismic data or supported drilling operations in the Beaufort Sea, with activity expected to pick up considerably in the next few years.

*Drilling Capabilities*

Drilling, coring, and logging in permafrost-bearing and/or hydrate-bearing sediments will require a few special adaptations. Importantly, high saturations of either ice or hydrate as pore fill make advanced piston coring (APC) impossible, meaning that slower and more destructive coring techniques may be required. High saturation permafrost or hydrate deposits are most likely to be concentrated in coarse-grained layers, which are difficult to retrieve through almost any type of conventional deep ocean drilling technique. These challenges will be greater in shelf sediments (permafrost and/or hydrate possibly present and more proximal to sources of coarse-grained sediment) than on upper continental slopes. Even where permafrost or hydrate-bearing sediments are lacking, coring can be challenging on Arctic shelves owing to indurated sediments that lie within a few meters of the seafloor and that have proved impenetrable to standard piston corers. This is the case on the US Beaufort shelf, where the maximum length of a core obtained using conventional techniques has never exceeded ~1.5 m, except in locations known to be characterized by very high sedimentation/sedimentation due to storm events (e.g., barrier islands between the Colville River and Prudhoe Bay; Allison et al., 2010).

An additional challenge in SOD coring is represented by "special sediments" like permafrost or gas hydrate-bearing formations. These are susceptible to rapid degradation once taken outside of the temperature or pressure/temperature fields, respectively. Ice and gas hydrate are important for the integrity and cohesiveness of sediments, and melting/dissociation leads to a loss of sediment structure (e.g., the familiar soupiness of clay-rich sediments once hydrate has dissociated; Francisca et al., 2005), rapid loss of mechanical strength, changes in other soil physical properties and in pore water chemistry (particularly salinity), as well as the potential mobilization of fluids.

Pressure coring is now commonly used in gas hydrates drilling programs (e.g., Ruppel, 2011) to retrieve cores that retain in situ hydrostatic pressure, thus preventing some of the hydrate dissociation caused by changes in pressure-temperature conditions during coring. Restoration of in situ pressure on sediments retrieved through conventional coring will not yield samples representative of the properties of the sediments in situ. The hydrates community outside of IODP has therefore been aggressive in continuing to design and test improved pressure corers that can maintain in situ hydrostatic pressure throughout core retrieval. The newest generation of corer, which was used for the Japanese Nankai program in 2012 (Yamamoto et al., 2012), has been specially designed to retrieve up to 3 m of hydrate-bearing, coarse-grained sediments. While the corer is still being perfected, the capacity to core in these challenging sand-rich sediments is of particular relevance for Arctic Ocean shelves, where hydrate and ice are both more likely to be hosted by coarse-, rather than fine-grained, sediments. Once pressure cores are retrieved, they can be X-rayed, scanned, and manipulated by the Pressure Core Analysis and Transfer System (PCATS) device provided by Geotek, Inc. and analyzed in a range of Pressure Core Characterization Tools (PCCT, which includes a core manipulator, a cutter, the instrumented pressure testing chamber or IPTC, shear and effective stress cells, a microbiological cell, and other devices) built at Georgia Tech since ~2005 (Santamarina et al., 2012).

For permafrost cores, maintaining temperature, not pressure, is the key concern. The pressure corers in use now do not maintain the recovered sediments at in situ temperature during retrieval. Thus, the main challenge for permafrost cores is ensuring that the conventional core is retrieved quickly with minimal heating due either to coring-related friction or borehole fluid circulation. Chilled drilling mud has been used for some past programs (e.g., Ohara et al., 2000) and might be required for some drilling on Arctic Ocean shelves. After recovery, permafrost cores should be rapidly restored to subfreezing temperatures.

*Considerations for borehole monitoring/logging*

Borehole monitoring instrumentation could contribute to a much better understanding of near-seafloor and subseafloor conditions on circum-Arctic Ocean margins. For example, fiberoptic temperature monitoring strings (distributed temperature sensors or DTS) installed in boreholes can constrain the impact of bottom water temperature variations in the subseafloor and allow reconstructions of these perturbations going back hundreds or thousands of years (e.g., Harris et al., 2006). Circulation obviation retrofit kits (CORKs), DTS, borehole seismometers, and various biological and chemical samplers that can be deployed in boreholes all have a potential role in CADW-related drilling. On the other hand, borehole instrumentation is expensive, difficult to install in certain settings, and a financial drain on future resources if the instrumentation must be visited periodically to collect the data. In addition, some instruments may not function well under Arctic Ocean conditions.

CORKs provide critical information about formation fluids and borehole conditions (Becker and Davis, 2005), but they have a complicated funding structure that relies on both the international program and the national agencies. In addition, CORKs require additional drilling platform time to ready the borehole for the installation and to complete the emplacement. CORKs would be appropriate for a range of CADW scientific problems involving subseafloor hydrologic systems and methane hydrate dynamics, but probably would be difficult or impossible to emplace from certain drilling platforms and would be ill-advised at water depths shallow enough for the seafloor to be periodically affected by ice. CORKs could not be installed in the still-frozen section of shelf subsea permafrost, but a CORK beneath the relict permafrost could intersect lenses of freshwater and brine whose formation is related to contemporary or past thawing of permafrost. CORKs on the upper continental slopes could intersect fluids released by dissociating gas hydrates and possibly meteoric fluids (Pohlman et al., 2011) whose discharge on the slopes has been inferred through analysis of limited pore water data collected in some cores. Proponents of circum-Arctic Ocean proposals were cautioned to use CORKs judiciously in proposals. Even with appropriate scientific justification, the additional cost and logistics associated with CORKs in Arctic Ocean holes could be prohibitive or jeopardize key objectives for a drilling program. Nowadays CORKs are often coupled with biological or chemical sampling systems, which were not discussed at the CADW.

For shallow subseafloor monitoring, the Simple Cabled Instrument for Measuring Parameters in situ (SCIMPI; http://www.iodp.org/scimpi) will be tested by IODP in 2013. Although SCIMPI cannot monitor deep boreholes, it has advantages for providing relatively inexpensive monitoring of shallow subseafloor parameters (Lado Insua et al., 2012). Data can be downloaded during periodic visits by ROVs if a cabled network is not available. SCIMPI instrumentation might not be suitable for permafrost-bearing sediments, nor should it be deployed where ice movement may damage the seafloor instrumentation.

A long-term thermistor string deployment was completed in the Norwegian Sea as part of IODP Exp. 306 at Site U1315 (Harris et al., 2007). Thermistor strings or DTS could be among the most cost-effective instrumentation that might be deployed in boreholes in the Arctic Ocean and might constrain parameters (e.g., bottom water temperature fluctuations) not often recorded by physical oceanographers. The strong attenuation of fiberoptic signals at low temperatures could be an impediment to the use of DTS. Given the poor availability of ships in much of the Arctic Ocean, any borehole temperature monitoring deployment should have enough non-volatile memory to continue recording even if the time between visits to download data reaches 3 or 5 years.

The Arctic Ocean, which is ringed by only passive margins, is not subject to great earthquakes. Ongoing deformation on several margins (e.g., eastern part of US Beaufort margin, Laptev Sea) is associated with significant seismicity, which remains poorly characterized and monitored. Seismometers installed in IODP boreholes could be used to detect local and regional events, some of which might result in small-scale seafloor failures. The seismometers would also expand global networks to detect ray paths that are not currently recorded by other parts of the seismic network, even if the stored data were only periodically retrieved (not sent through ocean cable networks in real-time). The Svalbard margin has been most frequently discussed as a potential location for the installation of high northern latitude borehole seismometers. This area has several advantages, including proximity to the Mid-Atlantic Ridge and the Storegga slide, coincidence with an important seafloor seep field, potential to be hooked up to the cabled seafloor observatory (Norwegian Ocean Observatory Network or NOON), and frequent visits by European vessels that could be charged with servicing the seismometers or downloading data if the instruments were not cabled.

## 7. Industry Links

It was difficult to engage industry in the CADW meeting. The AGU meeting is dominated by academic interests, and engaging industry representatives for a post-AGU Fall Meeting weekend workshop was challenging. The CADW was also held at a particularly sensitive time for companies that were advancing plans to drill in Arctic Ocean waters in the coming seasons. Finally, due to timing of the IODP-sponsored regional meeting in Kananaskis, the CADW had to be organized rapidly and held within a few months of being funded, making it more difficult to engage industry interests that were already committed to participation in the IODP-sponsored meeting in February 2012.

Industry has invested heavily in geotechnical and seismic surveys on Arctic shelves offshore the US and Canada in recent years, and Norway has outstanding industry data sets on their Arctic Ocean margins, including extensive 3D seismic surveys. Significant industry data are also believed to exist on the Russian margin. While industry data is not typically optimized for the shallow, non-exploration targets that scientific ocean drilling plans to sample, past experience has shown that components of industry data (e.g., upper 1 s of seismic data) can be helpful in guiding the formulation of IODP proposals.

## 8. Breakout Sessions

Breakout sessions were designed to focus on identifying knowledge gaps and scientific questions in four areas. While there was an emphasis on identifying scientific issues that could be addressed by drilling, some groups took a broader approach.

***Subsea Permafrost***

Subsea permafrost is permafrost that formed in the uppermost hundreds of meters of the sedimentary section on present-day continental shelves that were exposed subaerially during the Late Pleistocene, when sea level was 100 to 125 m lower than today. As sea level rose following the end of the LGM, these permafrost-bearing sediments were inundated and subjected to top-down warming by year-round bottom water temperatures significantly higher (by more than 15°C) than the average annual air temperature to which they were exposed when the permafrost was forming. Not all circum-Arctic Ocean shelves host subsea permafrost. Shelves that were glaciated in the Late Pleistocene probably did not develop permafrost due to the insulating effect of the ice sheets. Permafrost dynamics on shelves that experienced only partial coverage from floating ice sheets is not yet fully understood.

The subsea permafrost breakout group focused on identifying research gaps, particularly those that could be well-addressed using ocean drilling. The group identified several critical themes that have not been fully linked to scientific drilling problems in the past:

1. Paleohydrology: How do past hydrologic conditions factor into the formation of now-subsea permafrost? Could complex relationships and feedbacks among paleohydrology, local lithology and paleo-salinity distributions, and warming and thaw cycles in part explain subsea permafrost differences that have been mapped between the US Beaufort (Brothers et al., 2012) and Canadian Beaufort (Hunter et al., 1987) margins? Drilling would provide access to pore waters (examine chemical characteristics, age, and origin) and to sediments affected by paleohydrologic conditions, allowing for their reconstruction.
2. Microbiology: Are sediment-hosted microbial communities re-activated in response to subsea permafrost thaw and marine transgressions? Drilling could provide access to the paleo-microbial communities whose metabolic processes have restarted as subsea permafrost has thawed.
3. Gas hydrate: How widely distributed are relict gas hydrates within and beneath subsea permafrost? Given the challenges of detecting gas hydrate within the permafrost zone through geophysical data acquisition or downhole logs, drilling will likely be required to assess this issue.
4. Boundaries in the permafrost system: What is the relationship of subsea permafrost to terrestrial permafrost systems, particularly in the coastal transition zones? How does terrestrial permafrost become subsea permafrost during the contemporary period and does this differ from previous modes of subsea permafrost evolution? Onshore-offshore drilling could directly address this issue.

The breakout group also identified some key questions that might be broached by drilling but that did not necessarily represent overarching themes.

- Conditions for subsea permafrost degradation: Even simple models show that subsea permafrost initially thaws from the top down in response to the sort of inundation to which it was subjected starting in the Late Pleistocene. However, eventually this permafrost starts thawing from both the top and bottom simultaneously. Drilling could provide critical data about the sub-permafrost temperature regime, thus better constraining the models for the degradation of subsea permafrost and predictions for the total disappearance of subsea permafrost under conditions of continued climate warming.

- Sedimentation history during complex transgression/regression cycles: The themes articulated above are all related at least in part to untangling the complex sedimentation and erosion history during sea level transgressions and regressions affecting circum-Arctic Ocean coastal plains over the Quaternary or even longer periods. The sedimentation history is particularly challenging compared to that on lower latitude margins because it is inextricably linked to the unique role of glacially-derived or glacially-transported sediments, ice-related deformation, and glacial events themselves.
- Validation of geophysical data: Refraction and reflection seismics and shallow subbottom profiling have been used by various groups to identify the distribution of subsea permafrost. Some of these approaches (refraction) are definitely more reliable than others in settings characterized by variegated sediments, complex climate histories, and widespread shallow gas charging. Drilling can be a critical tool for validating seismically-based inferences about the distribution of subsea permafrost. A related issue refers back to the theme of understanding boundaries within the permafrost system, perhaps through the use of geophysical techniques across the coastal-offshore transition.

***Methane dynamics***

The key theme of this breakout group was understanding Arctic Ocean methane. While the group was populated by experts in marine methane dynamics, the focus for these discussions was in part on the unique issues facing methane researchers at high northern latitudes, in an ocean that has been only poorly studied.

The group identified a host of uncertainties that should provoke further research on Arctic methane dynamics. While these issues cannot necessarily be addressed using the drill, the breakout group took an approach that emphasizes methane dynamics at a system level since the challenges can link in unforeseen ways to ocean drilling. This approach is consistent with that advocated for the IODP-successor program, in which finding innovative perspectives on scientific ocean drilling has been emphasized.

The systems approach to methane in the marine environment can be distilled into considering a vertical column from subseafloor to the atmosphere: In the subseafloor, methane is produced by in-situ microbial processes or migrate from deeper reservoirs to near-seafloor. Gas hydrate forms or dissociates within the hydrate stability zone, subject to local conditions and external forcing (e.g., changes in bottom water temperatures). Methane that enters the near-seafloor sulfate reduction zone (SRZ) undergoes anaerobic oxidation. Some methane escapes through the SRZ or may be released at high-flux seep sites (which typically lack a SRZ). As this methane enters the water column, it will usually dissolve and be subjected to aerobic oxidation (which transforms it to carbon dioxide) over short (days) or long (years) time-scales. Methane released at the seafloor as bubbles may rise through the water column, but the methane is mostly replaced by nitrogen and oxygen unless waters are very shallow (<100 m, e.g. continental shelves;

McGinnis et al., 2006). Methane bubbles may survive for longer in the water column if the bubbles become encased in gas hydrate for part of their ascent. Methane that persists to reach near-surface waters may transfer into the atmosphere, where it is subject to photolytic oxidation. A number of processes may modify methane budgets in the uppermost ocean waters, and these remain poorly understood and studied, particularly in high-latitude waters.

Among the challenges identified by the breakout group were those that focused narrowly on the arctic region, as well as others that apply more generically to methane studies globally:

- There is mismatch between the predictions of arctic atmospheric models and observations of the sources, fate, and distribution of methane. In part, this mismatch may be attributable to paucity of data on methane at high latitudes, particularly in the seasonally variable atmospheric marine boundary layer. In addition, there are few sites for routine, vertical atmospheric methane profiling over the Arctic Ocean, and circum-Arctic Ocean land stations that measure methane are not well-distributed, have sometimes failed to collect continuous data, and are sometimes overprinted by downwind anthropogenic methane inputs.
- Despite claims otherwise in the popular press, atmospheric methane in the arctic region has increased only minimally over the past decade, casting doubt on the idea of an ongoing "Arctic methane catastrophe" triggered by the release of methane from the thawing arctic.
- Currently we lack a uniform set (consistent precision and accuracy) of protocols for measurement of atmospheric and marine methane, making comparisons difficult.
- Remote sensing technology such as satellites plays a role in detecting methane outbursts. The use of this technology is currently limited to sun-illuminated parts of the year, requires cloudless skies for accurate spectroscopy, and offers limited temporal/spatial resolution. The satellite data also cannot replace in situ observations.
- Large-scale or long-term marine observations of real-time methane emissions are not likely to be implemented for the next decade given the financial and logistical constraints and the timeline for development of observatories, particularly in the US.

The breakout group also identified critical methane-related questions that can be addressed by studies on circum-Arctic ocean margins.

1. How can the transport and geochemistry of methane dissolved in the oceans be better constrained, particularly in arctic waters characterized by complex oceanography and strong seasonal changes in surface conditions (e.g., ice-covered vs. ice free, which has further implications for salinities and temperatures)?
2. Why do preliminary data hint at such significant differences in methane dynamics on different parts of circum-Arctic Ocean margins? Do the scenarios advocated for the Laptev Sea margin apply across the Arctic?
3. Can we confirm or deny the potential significance of catastrophic events that perturb methane-charged sediments? For example, if submarine slides develop within methane-charged sediments in circum-Arctic Ocean waters, will the potential methane release significantly affect marine or atmospheric methane budgets in this region?

4. Arctic methane sources: What is the relative importance of anthropogenic methane, release from gas hydrates, terrestrial permafrost thaw (Schuur et al., 2009; Walter Anthony et al., 2012), and other sources for the component of atmospheric methane derived from the Arctic? Are there ways to distinguish methane released from recently dissociated gas hydrate from other sources of methane?
5. For Arctic Ocean methane hydrates: How much remains on the shelf as a relict of pre-Holocene inundation of these areas? How much is destabilizing on these margins on either the shelf or the upper continental slope? Does such destabilization have significance for slope stability, ocean acidification, and ocean de-oxygenation? Do these gas hydrates have any significance for energy issues? What are the key factors (contemporary or longer time scales) that might be driving dissociation of marine hydrates on shelf and upper continental slope settings?

### *Paleoceanography*

The paleoceanography breakout group focused on the needs that are particular to the poorly studied circum-Arctic Ocean settings and the major questions that can be answered by drilling on high northern latitude continental shelves.

As noted earlier, there has been only one scientific ocean drilling expedition in the Arctic Ocean (ACEX), as well as several paleoceanography-focused drilling programs in Arctic gateways and regions just south of the Arctic Ocean (e.g., Bering Sea). While all of these expeditions provided cores that advanced understanding of paleoclimate and paleoceanographic conditions, there remains a paucity of long-duration paleorecords at high northern latitudes. Even conventional coring in these locations has been difficult, quite apart from the logistics of reaching key locations. For example, having been subjected to glaciations or repeated peneplanation during marine transgressions, sediments on some circum-Arctic Ocean continental shelves are highly indurated and missing critical sections from a continuous sedimentation record.

The critical needs for paleoclimate reconstructions and paleoceanography were identified as:

- Better chronostratigraphy: A clear but simple logistical effort to retrieve overlapping time records in multiple holes needs to be a priority for all paleoceanographic objectives. Although continuous $\delta^{18}O$ stratigraphies that can be correlated to global stacked records are unlikely in most Arctic settings, pronounced lithologic cyclicity in many shallow cores from the Arctic and in the Plio-Pleistocene ACEX record indicate that orbital tuning of continuously recovered Arctic sediments is possible. Absolute dating of core material is rare, but the proximity of volcanoes to some circum-Arctic Ocean margins makes it likely that analyses of tephra or ash deposits in cores could eventually provide better constraints on sediment ages. When supplemented with improved biostratigraphic age control, tephrochronology, and magnetostratigraphy, a reliable chronostratigraphic framework should be achievable for Arctic sediments.
- Better inventory of existing material: Few high-quality cores have been extracted from shelf and slope sediments in the western Arctic. Identification of the storage conditions and location of remaining core material could prove critical to providing background information for drilling proposals or filling in spatial or temporal gaps in the sparse

record. For the US Arctic, there have been challenges both in locating the original descriptions of coring programs and finding the remaining core material.

- Locating "best sites" for recovering terrestrial and marine biogenic climate recorders (e.g., diatoms, pollen, dinocysts, forams, ostracods): Due to ocean chemistry, both siliceous and calcareous material is often poorly preserved in deep Arctic Ocean sediments. Locating paleoceanographic sections with relatively good preservation and taking full advantage of the low concentrations of biogenic material that exists are the best strategies for rapidly advancing understanding of paleoclimate conditions on a regional to pan-Arctic scale.
- More magnetostratigraphic records: Recent studies have made important advances in the challenging area of high-latitude magnetostratigraphy (St. Onge and Stoner, 2012). Magnetostratigraphy could prove important in areas where traditional chronostratigraphy is difficult due to the challenges outlined above.
- Determining the likely locations of high-resolution records: The relatively limited amount of coring, the paucity of high-resolution seismic data, the lack of the information required to correlate shallow sedimentary packages over long distances, and the complicated Pleistocene history of circum-Arctic Ocean settings contribute to the difficulties of identifying locations likely to host high-resolution paleoceanographic records. It is likely that identifying such locations will require coordinated effort by several groups, as well as the acquisition of new cores and high-resolution seismic data.

The group also identified priority paleoclimate/paleostratigraphy issues that could be addressed through scientific ocean drilling. These include:

1. Sea ice: What is the history of sea ice in the Arctic Ocean and when did perennial ice first appear? This question was partially addressed by ACEX, but there will be regional differences and Arctic Ocean margin records may provide clues about the progression of perennial sea ice cover. A review by Polyak et al. (2010) delineates some of the key issues.
2. Ice sheet dynamics: While large-scale glaciation is primarily a terrestrial phenomenon, it has profound implications for offshore sedimentation patterns. In recent years, researchers have also postulated that floating ice sheets have played a role in controlling the morphology and sedimentation patterns in the Western Arctic (e.g., Polyak et al., 2001). Circum-Arctic Ocean scientific drilling could address the impact of the Laurentide, Greenland, and Eurasian ice sheets and their collapse. Even for Greenland, where warming climate conditions have led to degradation of parts of the ice sheet, margin drilling may be a way to constrain the impact of the melting processes. Throughout the circum-Arctic Ocean, drilling on continental shelves and slopes could constrain Quaternary glacial fluctuations, while drilling in large troughs (e.g., Mackenzie) may yield a longer-term glacial history.
3. Methane hydrate/permafrost history: As mentioned by other breakout groups, drilling can provide access to sediments affected by hydrate formation and dissociation (shelf and slope) and (shelf) permafrost formation and thaw. The tools of paleoceanography, including biomarkers, frequency maps of preserved biogenic materials, and isotopic data from these materials, can be used to inform the reconstruction of gas hydrate and subsea permafrost histories. As one example, $\delta^{18}O$ data from benthic forams constrain bottom water temperature fluctuations that are in turn an important driving force for methane

hydrate formation/dissociation in shallow sediments. A related issue that may be harder to discern is whether methane dissolution in the water column and corresponding aerobic methane oxidation affects ocean acidity and therefore the preservation of paleo-biogenic markers.

4. Arctic Ocean water masses: The oceanography of the circum-Arctic Ocean is complex, with layering of Pacific and Atlantic waters, the influence of deepwater gyres, an outsized impact for storm events in driving upwelling and overflow of waters onto the shelf, and coastal currents that are re-established each year after the ice pack disappears. Drilling on circum-Arctic Ocean margins provides access to very different water masses and water depths than those studied during ACEX.
5. Freshwater fluxes from major rivers: As a semi-enclosed ocean subject to annual ice pack thawing and re-formation, the freshwater dynamics of the Arctic Ocean are not only complex, but also important to a range of biological, chemical, and physical processes. One significant unknown that paleoceanographic studies can address is the history of riverine freshwater inputs to the Arctic Ocean. Of particular interest is constraining changes in freshwater flux across the onset of the Younger Dryas, which has been attributed to collapse of the North American ice sheets.
6. Arctic Ocean gateways—where ocean water masses enter the Arctic Ocean's circulation—have been the focus of some past drilling programs. Acquisition of long paleoceanographic records through drilling can provide insights to the establishment, persistence, and temperature history of the Pacific inflow through the Bering Strait; the strength, depth, and temperature of the Atlantic inflow through the Fram Strait; and outflows, particularly through the Canadian Arctic.
7. Interplay between atmospheric forcing and Arctic Ocean circulation/sea ice history: A key long-term goal in the paleoclimate community is to explore the possibility that paleoceanographic records can be better correlated with long-term atmospheric records gleaned from ice cores.
8. Accessing older sequences: Discontinuous sedimentation is a common problem for cores retrieved in shelf settings, and this will be particularly true in the Western Arctic, where the entire shelf expanse is relatively shallow and thus substantially affected by marine regressions and transgressions. Paleoceanographers can take advantage of shelf drilling through opportunistic targeting of older sequences beneath unconformities. These Paleogene and Neogene sequences are hard to retrieve in most margin settings, but accessing them beneath unconformities in shelf sequences could provide invaluable information.
9. An additional issue that emerged from discussions in this breakout group was the need for very high latitude (above 80°N) sites where high resolution records (> 50 m/kyr) might be recovered for magnetostratigraphic studies to test models of the tangent cylinder, a concept central to geomagnetism (Tarduno et al., 2002; Aurnou et al., 2003).

### *Sea-level Fluctuations*

The sea level breakout group contained only a few members and produced no breakout group notes. Some researchers continue to argue that global sea level fluctuations are well enough understood from the Late Pleistocene onward that local data in the Arctic Ocean may not be necessary or that the Arctic Ocean has experienced only minimal sea level change in the

Holocene (e.g., Mason and Jordan, 2002). That perspective seems to devalue several critical points about the regional peculiarities of the Arctic Ocean and about the complexities of the sea level record (e.g., Cronin, 2012).

- During LGM sea level lowstands, the relatively enclosed Arctic Ocean basin may have experienced a time lag in catching up to global sea level fluctuations.
- The circum-Arctic Ocean regions experienced differential loading by ice sheets and, possibly, grounded ice shelves (e.g., Engels et al., 2008; Polyak et al., 2001, 2007) during the Late Pleistocene, and some local rebound is expected to be continuing today.
- Some parts of the circum-Arctic Ocean margins are probably experiencing differential subsidence and relative sea level rise. Rapid degradation of permafrost may play an important role in local subsidence.
- The circum-Arctic Ocean region has traditionally been a challenging one for maintenance of tide gauge instrumentation on which direct measurements have relied. The information compiled at http://www.whoi.edu/science/PO/arcticsealevel/index.html provides more background.
- In some places (e.g., the US Beaufort), the short cores recovered to date often contain substantially reworked sediments that are not suitable for sea level reconstructions.
- The only Late Pleistocene to Holocene sea level curve available for the Western Arctic was formulated nearly three decades ago by using records from disparate locations in the Canadian Arctic (Hill et al., 1985).
- A much better understanding of local relative sea level rise is required to constrain the detailed Holocene inundation history of the very shallow shelves in the Beaufort Sea and along parts of the Russian margin. The inundation history has important implications for the degradation of subsea permafrost and the onset of marine sedimentation in areas where the 20 m isobath occurs many kilometers from the present day shoreline.
- Numerical models of past relative sea level (e.g., mid-Pliocene; Raymo et al., 2011) imply strong regional differences that are not fully accounted for by data compilations that are used to formulate global sea level curves.

Addressing these shortcomings will require both coring of the shallow section and drilling of the deeper section. Ideally, onshore geologic mapping (e.g., Brigham-Grette and Carter, 1992) will complement offshore drilling. Particular focus should be placed on shelf to slope transects that can sample marine transgressive/regressive sequences and supply information about sea level fluctuations in both space and time. Finding continuous records of Holocene and Late Pleistocene deposition that have not been reworked by interaction with ice will be challenging on some circum-Arctic Ocean margins, but increased effort should be made to identify where such sedimentary sections are likely to occur and to acquire cores of opportunity during expeditions that traverse key areas. Sea level reconstructions should be carried out in several places on circum-Arctic margins, in locations subjected to different glacial, tectonic, and sedimentary regimes. Interpreting the sediment records will require both marine and terrestrial expertise since both types of age proxies are likely to be present in recovered core. Finally, as shown by Raymo et al. (2011), careful research may make it possible to reconstruct local relative sea level variations and the intricacies of glacial histories in epochs before the Pleistocene if studies are properly designed.

## 9. Recommendations

Due to time constraints, the list of workshop recommendations was not discussed during the meeting. However, several issues were repeatedly highlighted in breakout groups and larger discussions and form the core of the workshop's recommendations.

a) *Explore scientific problems not previously addressed through SOD.* Circum-Arctic Ocean drilling has the potential to address scientific problems that have rarely been studied in the history of DSDP, ODP, and IODP. Most importantly, the Arctic regions are experiencing rapid climate change on present-day Earth, in addition to having been subjected to substantial change since the LGM. Drilling in circum-Arctic Ocean settings may present the chance to catch the record of contemporary climate change in progress. Other scientific issues unique to the circum-Arctic region also represent new directions for SOD. These include the timing and impact of high-latitude ice sheet collapse, the response of subsea permafrost and gas hydrate populations to short- and longer-term climate change, Late Pleistocene to contemporary fluctuations in high-latitude relative sea level, and sea ice dynamics.

b) *Take advantage of changing Arctic Ocean conditions to access new locations for SOD.* The history of SOD has included only one major expedition in the Arctic Ocean (Exp. 302) and five that have drilled holes north of the Arctic Circle, all in the Atlantic sector. The Arctic Ocean is very much the "last frontier" for SOD. As the Arctic Ocean moves towards an increasingly ice-free future, the marginal shelves and slopes will provide months' long annual access to previously-inaccessible sedimentary sections that might be drilled with conventional platforms or slightly modified versions of these platforms. These sediment records could dramatically change our understanding of glacial and sea ice history, oceanographic gateway establishment, riverine inputs, and other processes. Given the outsized role that the polar regions play in modulating Earth's ocean and climate processes, studies in the Arctic Ocean have potential significance far beyond the local region.

c) *Emphasize transects to capture the full range of dynamic conditions.* Scientific ocean drilling programs have often relied on drilling along transects to sample material of different ages or to capture spatial variations in sedimentation patterns, LIP emplacement, or continental margin structure. On circum-Arctic Ocean margins, which have been strongly affected either directly or indirectly by repeated Pleistocene glaciations and by marine transgressions and regressions, drilling on margin-perpendicular transects provides access to material that should simultaneously capture spatial and temporal gradients.

d) *Design programs from the outset to include terrestrial and marine scientists.* Drilling on shelves intersects sedimentary sections that have been affected by both terrestrial and marine depositional processes and in which both terrestrial and marine paleoclimate (e.g., pollen vs. marine forams) and geochronologic proxies may be present. On circum-Arctic shelves, relict permafrost that formed during the Late Pleistocene froze in ancient meteoric waters and associated microbes, and some of the offshore processes producing methane now (e.g., thermokarsting) may have commenced onshore. Thus, the need to involve terrestrial geoscientists in the formulation stage of any drilling program is even greater. SOD has experience dealing with terrestrial material for other marginal drilling, and drilling programs should be designed from the outset to ensure that non-marine samples are properly preserved and analyzed.

e) *Build synergies with industry.* Oil and gas resources located beneath circum-Arctic Ocean shelves have provoked strong interest from private sector firms. The logistical and financial challenges associated with operating in these environments make them well-suited to collaborations among industry, academe, and government to establish basic scientific data sets of interest to all parties. For example, industry might be interested in geotechnical data for shallow sedimentary sections, while academic/governmental organizations may pursue scientific questions (sea level change, glacial history, constraints on riverine inputs) with the same core.

f) *Prioritize sediment records that can constrain sea level history.* Better constraints on the magnitude and timing of marine transgressions and regressions will be required before the key processes that have shaped the present-day circum-Arctic Ocean margins can be fully understood. Of particular importance are better relative sea level histories, which rely on reconstruction of local ice loading and isostatic rebound conditions.

g) *Pursue large scale climate questions of contemporary relevance through Arctic Ocean drilling.* The role of climate in modulating the gas hydrate stability field on the shelves (relict gas hydrate) and upper continental slopes (deepwater gas hydrate system) that ring the Arctic Ocean can be elucidated by drilling locations where gas hydrate remains intact, is currently dissociating, and has completely broken down. Drilling can also constrain total methane budgets in the subseafloor and may provide information about the relative importance of different methane sources (newly generated microbial methane, methane released from gas hydrates, methane generated from organic carbon previously frozen in permafrost) that contribute to seafloor emissions on Arctic Ocean shelves. On upper continental slopes, drilling may provide information about the sediments affected by temperature-driven fluctuations in the feather edge of the upper continental slope hydrate stability zone and the relationship of these sediments to initiation of slope failures.

*h)* *Compare the histories of different Arctic Ocean margins.* Ideally, the next 10-20 years will see numerous expeditions to drill circum-Arctic Ocean margins, thereby elucidating why even parts of the margins located fairly proximal to each other appear to have starkly different histories. One example of this contrast is the difference between the subsea permafrost distribution in the US Beaufort Sea relative to that in the nearby Mackenzie Delta area.

*i)* *Identify locations that could be ready for drilling within the next decade.* Adopting the term “shovel ready” from other parts of the US government, the Greenland margin workshop identified locations for which the site survey data and ancillary science were mature enough to permit them to be drilled within the first few years of a new IODP program. The same strategy applied to circum-Arctic margins would likely see proposals brought to maturity in areas with well-curated borehole databases, several generations of seismic data, and a recent history of summer ice conditions that make the sites conducive to drilling without the use of complex technologies or specialized platforms.

j) *Continue to investigate synergies with Russia.* Much of the circum-Arctic Ocean margin is in Russian territory, and losing access to this part of the record will delay progress on pan-Arctic scientific questions for decades. IODP should continue to pursue agreements that might eventually make possible an expedition on the Russian Arctic margin. Russian involvement in providing an icebreaker was critical to the success of ACEX 2. Russian knowledge of the Arctic, access to icebreakers and other vessels, and familiarity with the geology, tectonics, glacial history, and paleoclimate conditions on Russian margins will prove important as interest in Arctic Ocean science expands.

## 10. Outcomes and Updates (December 2012)

One goal of the CADW was to engage new constituencies. Over 25% of the participants were graduate students, postdoctoral researchers, or pre-tenure faculty members, and an estimated 10-15% had never had any formal contact with scientific ocean drilling. These participants also brought new disciplines to the fore at the CADW and educated workshop attendees about controlled source electromagnetics as a potential site survey tool, the importance of absolute dating of volcanically-sourced materials in offshore cores, onshore-offshore transects to provide clues to the evolution of subsea permafrost, hydrologic regimes associated with ice sheets, the use of SCIMPI, and methane oxidation sinks in the Arctic Ocean. Some of these attendees later participated in the Kananaskis IODP workshop.

In the year since the CADW, there have been activities (both related and unrelated) that have advanced some of the goals or addressed some of the knowledge gaps identified at the CADW.

- Publication of workshop brief in EOS (Transactions of the American Geophysical Union) in June 2012 (Ruppel, 2012).
- EGU presentation in April 2012 on Arctic Ocean IODP efforts (led by R. Stein) included a summary of the CADW workshop.
- IODP and Canadian IODP-sponsored Beaufort drilling workshop in Kananaskis, Alberta in February 2012 (O'Regan lead organizer)
- Submission of IODP pre-proposals: 797-Pre: Alaskan Beaufort Margin (Ruppel et al., 2012) and 806-Pre: Canadian Beaufort Margin (Paull et al., 2011) in April 2012.
- Acquisition of new high-resolution MCS data in the US Beaufort in August 2012 (USGS) and long-offset MCS data in Fall 2012 (ION Geophysical).
- Plans for coring programs in the Chukchi and Canadian Beaufort using the ARAON and Polarstern in 2013 and 2014, respectively.
- Funding for a coring and heat flow program in the US Beaufort in 2014.
- Scheduling of a workshop on Chukchi IODP drilling for March 2013.

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## 12. Acronyms

ACEX ........ Arctic Coring Expedition (IODP Exp. 302)
AGU ........ American Geophysical Union
ANDRILL ........ Antarctic Geologic Drilling
APC ........ Advanced piston coring
AWI ........ Alfred Wegener Institute
CADW ........ Circum-Arctic Drilling Workshop (this workshop)
CORK ........ circulation obviation retrofit kit
DOSECC ........ Deep, Observation, and Sampling of the Earth's Continental Crust
DTS ........ distributed temperature sensors
ESAS ........ East Siberian Arctic Shelf
EGU ........ European Geosciences Union
GSC ........ Geological Society of Canada
ICDP ........ International Continental Drilling Program
INVEST ........ IODP New Ventures in Exploring Scientific Targets (workshop and report)
IODP ........ Integrated Ocean Drilling Program
ISP ........ Initial Science Plan
LIS ........ Laurentide Ice Sheet
LIP ........ large igneous province
LGM ........ Last Glacial Maximum
MARUM ........ Center for Marine Environmental Sciences at University of Bremen
MIS ........ marine isotope stage
NOON ........ Norwegian Ocean Observatory Network
NSF ........ National Science Foundation
ODP ........ Ocean Drilling Program
OPP ........ Office of Polar Programs (NSF)
PCATS ........ Pressure Core Analysis and Transfer System (Geotek)
PETM ........ Paleocene-Eocene Thermal Maximum
PCCT ........ Pressure core characterization tools (Georgia Tech)
SOD ........ Scientific ocean drilling
SRZ ........ sulfate reduction zone
UK ........ United Kingdom
USGS ........ U.S. Geological Survey

## 13. Acknowledgements and Disclaimer

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## Appendix A: Attendees

***Circum-Arctic Ocean Drilling Workshop, 10-11 December 2011, San Francisco***

*denotes registrants unable to attend at last minute*

| Name | Affiliation |
|---|---|
| James Beard | NSF-Ocean Sciences |
| Nicole Biebow | Alfred Wegener Inst.-Aurora Borealis |
| Julie Brigham-Grette | U Mass-Amherst |
| Laura Brothers | USGS (Woods Hole)/NRC-DOE |
| Bruce Buffett | UC-Berkeley |
| Georgy Cherkashov | VNIIOkeangeologia |
| Evgeny Chuvilin | Moscow State University |
| Tim Collett | USGS (Denver) |
| Rick Colwell | Oregon State University |
| Bernie Coakley | U Alaska-Fairbanks |
| Ann Cook | LDEO/NRC-DOE (now Ohio State) |
| Scott Dallimore | Geological Survey of Canada |
| Li Erikson | USGS (Santa Cruz) |
| John Farrell | U.S. Arctic Commission |
| Niko Finke | University of Georgia |
| Jennifer Frederick | UC-Berkeley |
| Larry Gibson | Shell |
| Patrick Hart | USGS (Santa Cruz/Menlo) |
| Bruce Herman | BOEM-Anchorage |
| Jenna Hill | Coastal Carolina University |
| Tessa Hill | UC-Davis |
| Matt Hornbach | Southern Methodist U. |
| Ben Jones | USGS (Anchorage) & UAF |
| Tania Lado Insua | URI |
| Lester Lembke-Jene | Alfred Wegener Inst.-Aurora Borealis |
| Tom Lorenson | USGS (Santa Cruz/Menlo) |
| Paul Loubere | Northern Illinois U. |
| Hailong Lu | National Research Canada |
| Jurgen Mienert | University of Tromso |
| Matt O'Regan | Cardiff University |
| Paul Overduin | Alfred Wegener Inst. |
| Charlie Paull | MBARI |
| John Pohlman | USGS (Woods Hole) |
| Leonid Polyak | Ohio State |

| | |
|---|---|
| Ross Powell | Northern Illinois U. |
| Frank Rack | ANDRILL |
| Pavel Rekant | VNIIOkeangeologia |
| Michael Riedel | Geological Survey of Canada |
| Vlad Romanovsky | U Alaska-Fairbanks |
| Kelly Rose | DOE-Office of R&D (Oregon) |
| Carolyn Ruppel | USGS (Woods Hole) |
| Dave Scholl | USGS (Menlo) |
| Igor Semiletov | U Alaska-Fairbanks |
| Natalia Shakhova | U Alaska-Fairbanks |
| Andy Smith | UT-Austin |
| Joe Stoner | Oregon State University |
| Randy Stotler | University of Kansas |
| Karen Weitemeyer | Scripps (now at SOTON, UK) |
| Mike Whiticar | University of Victoria |
| Warren Wood | NRL-Stennis |

## Appendix B: Useful URLs distributed to CADW participants (updated May 2013)

**Drilling Program Websites**
ECORD Arctic brochure: http://www.ecord.org/pub/Arctic-brochure.pdf
IODP Proposals: http://www.iodp.org/drilling-proposals/ and
IODP FAQ: http://www.iodp.org/faq
Add yourself to US IODP listserve: http://lists.oceanleadership.org/mailman/listinfo/iodpnews
IODP post-2013 science plan: http://www.iodp.org/Science-Plan-for-2013-2023/
ICDP: http://www.icdp-online.org/front_content.php
DOSECC: http://www.dosecc.org/
US 2011 NRC report on IODP

- Report brief: http://dels.nas.edu/resources/static-assets/materials-based-on-reports/reports-in-brief/Ocean-Drilling-Report-Brief-Final.pdf
- Full report: http://www.nap.edu/catalog.php?record_id=13232

US IODP post-2013 science implementation planning: http://iodp-usssp.org/wp-content/uploads/Workshop_BuildingUSStrategies_Report.pdf
US Science Support Program for IODP, based at Consortium for Ocean Leadership: http://iodp-usssp.org/
NSF-Ocean Drilling (for site survey proposals & IODP related science): http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=13524&org=OCE&from=home

**Workshops**
Chukchi Drilling workshop (2013): http://bprc.osu.edu/workshops/sdcs_2013/
Canadian Beaufort workshop (Kananaskis, 2012): http://www.iodpcanada.ca/outreach/beaufort
Arctic Ocean drilling site survey workshop (Copenhagen, 2011) Report to ESF:
http://www.iasc.info/files/Marine/ESF_report_Magellan_November2011.pdf
Greenland ice sheet workshop: http://iodp-usssp.org/workshop/greenland/
Catching Climate Change workshop (our workshop) for Arctic Shelves/Upper Continental Slopes:
http://iodp-usssp.org/workshop/catching-climate-change/
Arctic Ocean History Drilling Workshop, Bremerhaven 2008

- http://iodp-usssp.org/workshop/arctic-ocean-history-from-speculation-to-reality/
- Related white paper for INVEST: http://www.marum.de/Binaries/Binary42266/

**Ships and platforms**
Ericon-Aurora Borealis: http://www.eri-aurora-borealis.eu/
Ericon related documents:
http://www.eri-aurora-borealis.eu/fileadmin/user_upload/Home/download/RELEVANT_FINAL_DOCUMENTS/ERICON_2015-2030_SP.pdf
ANDRILL rig: http://www.andrill.org/technology/rig
Eurofleets--European research vessel consortium: http://www.eurofleets.eu/np4/home.html
UNOLS portal for US research vessels: www.unols.org
Proposals for use of German vessel R/V Polarstern:
http://www.awi.de/en/infrastructure/ships/polarstern/submission_of_proposals/
Oden (Sweden) icebreaker: http://www.sjofartsverket.se/en/Maritime-services/Winter-Navigation/Our-Icebreakers/Research-VesselIcebreaker-Oden/
Canadian icebreakers: http://www.ccg-gcc.gc.ca/vessel-procurement/Polar-Icebreaker
US icebreaker report (2007): http://www.nap.edu/catalog.php?record_id=11753
US icebreaker Healy (non-UNOLS): http://www.uscg.mil/pacarea/cgcHealy/
US vessel Nathaniel Palmer (Antarctic)—non-UNOLS (support through Raytheon)
http://www.nsf.gov/od/opp/support/nathpalm.jsp
US high-latitude global-class vessel (under construction), R/V Sikuliaq: http://www.sfos.uaf.edu/arrv/

Small ships for coastal work in US Beaufort/Bering/Chukchi (?):
R/V Annika Marie: http://sites.google.com/site/rvannikamarie/
R/V Ukpik: https://sites.google.com/site/rvukpik/home/history-of-r-v-ukpik
R/V Norseman I and Norseman II: http://www.norsemanmaritime.com/index

**Selected Tools/Facilities**

SCIMPI: http://www.gso.uri.edu/files/u14/scimpi_imi_mar09_v9.pdf
MeBo (portable German drilling rig operable from normal vessels):
http://www.marum.de/en/Sea_floor_drill_rig_MeBo.html
Jumbo coring capabilities:

- R/V Marion Dufresne (France): http://www.institut-polaire.fr/ipev/bases_et_navires/le_marion_dufresne
- R/V Knorr (USA-WHOI): http://www.whoi.edu/corelab/hardware/systems_jpc.html

CORKs: http://www.corkobservatories.org/pmwiki/index.php?n=Main.HomePage
Pressure coring: State-of-the-art developments have occurred outside of IODP in recent years. Contact T. Collett (tcollett@usgs.gov)
Pressure core analyses/subsampling (IPTC and PCCT):
http://www.iodp.org/doc_download/3531-44-48sd14pressurecorepdf
Also: doi:10.1016/j.margeo.2006.03.012 , DOI:10.1021/ef100821t
Pressure core transfer, oriented X-ray, basic measurement (PCATS):
http://www.geotek.co.uk/services/pressure_core_analysis
Tiksi: http://iasoa.org/iasoa/index.php?option=com_content&task=view&id=81&Itemid=119%20

**Funding (US, UK)**

NERC Arctic Office (UK): http://www.arctic.ac.uk/
NSF Office of Polar Programs (OPP): http://www.nsf.gov/dir/index.jsp?org=OPP
NSF Ocean Drilling Program in OCE (for site surveys and ODP related science):
http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=13524

**Background**

National Snow and Ice Data Center (NSIDC): http://nsidc.org/
Alaska Satellite Facility--Remote sensing data: http://www.asf.alaska.edu/
NGDC--Geophysical and other data sets: http://www.ngdc.noaa.gov/
Marine Geoscience data: http://www.geomapapp.org/
USGS Arctic resource assessment data: http://energy.usgs.gov/RegionalStudies/Arctic.aspx
NAMSS USGS legacy seismic data: http://walrus.wr.usgs.gov/NAMSS/
Ocean Data View (AWI): http://odv.awi.de/ [physical/chemical oceanographic data]
Science needs, US Beaufort and Chukchi: http://pubs.usgs.gov/fs/2011/3048/
Arctic environmental atlas: http://www.arctic.noaa.gov/aro/atlas/

**Groups/Organizations/Institutes**

US Arctic Research Commission: http://www.arctic.gov/
Arctic Research Consortium of the US (ARCUS): http://www.arcus.org/
International Permafrost Association (IPA): http://ipa.arcticportal.org/
EU COST Pergamon Arctic methane: http://www.cost-pergamon.eu/
EU Page 21 (changing permafrost in the Arctic): http://www.page21.eu/
Arctic Portal: http://arcticportal.org/
NOAA Arctic program: http://www.arctic.noaa.gov/index.shtml
Alfred Wegener Institute (Germany): http://www.awi.de/en
Scott Polar Research Center, Cambridge UK: http://www.spri.cam.ac.uk/
Institute of Arctic and Alpine Research (INSTAAR), U Colorado: http://instaar.colorado.edu/

Byrd Polar Research Center, Ohio State University: http://bprc.osu.edu/
University of Alaska-Fairbanks:
IARC: www.iarc.uaf.edu
Geophysical Institute: www.gi.alaska.edu
Russia:
VNIIOkeanologia: http://en.vniio.ru/
Shirshov Institute-RAS: http://www.ocean.ru/eng/
Pacific Oceanological Institute (FEB RAS): http://pacificinfo.ru/en/
RAS Arctic and Antarctic Research Institute: http://www.aari.ru/index_en.html
International Polar Foundation: http://www.sciencepoles.org/
IPEV (France): http://www.institut-polaire.fr/
Korean Polar Research Institute (KOPRI): http://eng.kopri.re.kr/index.jsp
Norwegian Polar Institute: http://www.npolar.no/en/
Canadian Circumpolar Institute (U Alberta): http://www.uofaweb.ualberta.ca/CCI/

**Expeditions/Projects**

East Siberian shelf drilling 2011: http://www.iarc.uaf.edu/expeditions/?cat=8
Laptev Sea 2003-2006:
http://www.awi.de/en/research/research_divisions/geosciences/periglacial_research/research_themes/geomicrobiology_in_permafrost_regions/projects/laptev_sea_shelf/
NOON observatory (to include Svalbard): http://www.oceanobservatory.com/projects
Submarine programs (SCICEX): http://www.ldeo.columbia.edu/res/pi/SCICEX/
Feasibility for Canadian cabled observatory: http://www.onccee.ca/arctic-observatory-feasibility-study
AOOS (Alaska): http://www.aoos.org/
US Law of the Sea Project (including new Arctic seismic data):

- USGS/Canada—http://walrus.wr.usgs.gov/research/projects/lawofsea.html
- UNH (multibeam)—http://ccom.unh.edu/index.php?page=law_of_the_sea.php

**Some Industry Activities**

Shell:

- Chukchi plan: http://www.boem.gov/ShellChukchi2012/
- Beaufort plan: http://www.boem.gov/About-BOEM/BOEM-Regions/Alaska-Region/Leasing-and-Plans/Plans/2012-Shell-Beaufort-EP/Index.aspx

Statoil Chukchi:
http://www.statoil.com/en/About/Worldwide/NorthAmerica/USA/Alaska/Pages/default.aspx
Statoil Canadian Beaufort:
http://www.statoil.com/en/about/worldwide/northamerica/canada/offshorecanada/pages/beaufortsea.aspx
BP Canadian Beaufort exploration:
http://www.bp.com/modularhome.do?categoryId=7070&contentId=7052829
ConocoPhillips Chukchi:
http://alaska.conocophillips.com/EN/news/media/Documents/FactSheet-Chukchi.pdf
Exxon Mobil, US and Canadian Beaufort:
http://www.exxonmobil.com/Corporate/energy_production_arctic_future_beaufort.aspx
ION’s surveys in the Arctic: http://www.iongeo.com/Data_Library/Arctic/