USSSP-Sponsored Workshop Report

"Scientific Drilling in the Chukchi Sea: Linking North Pacific and Arctic Ocean History"

14-16 March, 2013
Columbus, Ohio

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Executive Summary

This workshop funded by the Ocean Leadership and IODP-MI brought together members of various research groups involved in the existing drilling proposals as well as surveying and investigation of the Chukchi and Beaufort seas and adjacent areas of the Arctic Ocean. The exchange of information and ideas between these groups is critical for outlining the major directions of further research, especially in relation to scientific drilling. To facilitate drilling development, the workshop explored the possibilities of linking the existing proposals within the IODP structure and discussed sites that could be drilled with the *JOIDES Resolution*. This entailed discussing a range of issues including: scientific themes/questions, key sites, site survey data needed, approach/proxies, research coordination and data exchange.

The workshop program included talks, posters, and breakout groups designed to address the fesability of drilling targets in addressing the key scientific themes. The themes discussed combine paleoclimate and tectonic objectives including the Amerasian basin evolution, the role of the Bering Strait gateway, the effect of sea-level fluctuations on sedimentation at the Chukchi/Beaufort margin, the impact of glaciations on this continental margin, and the histrory of sea ice and oceanic environments under changing climatic conditions.

Recommendations from the workshop emphasize exploring new scientific problems that could be solved by means of ocean drilling, coordinating research planning and activities between interested groups, maximizing the use of existing data, seeking synergies with industry for site surveys and potentially drilling, and developing research programs to address scientific challenges specific to the Arctic environments.

1. Introduction

The lack of deep-sea drilling is a huge impediment to our comprehension of the Arctic Ocean, one of the last remaining Earth Science frontiers and a stage for the most dramatic expression of climate change. Because of operational constraints in ice-covered waters, the only drilling in the Arctic Ocean thus far has been the 2004 IODP Leg 302, also known as the ACEX (Arctic Coring Expedition). The fast, climate-forced retreat of Arctic sea ice, which has dramatically accelerated in recent years, opens new prospects for drilling in the Arctic without the high-cost, multi-ship setup used in heavy ice conditions during the ACEX. The two areas of the Arctic, where seasonally ice-free water opens especially quickly are the Barents and Chukchi regions, which are affected by the warming influence of the Atlantic and Pacific oceans, respectively. These regions are therefore especially sensitive to climatic and paleoceanographic changes and constitute priority target areas for scientific drilling (Mikkelsen et a., 2012).

The Chukchi margin is one of the most sensitive high-latitude areas to both climate variability and sea-level fluctuations. It is in the Chukchi Sea and adjacent areas of the Arctic Ocean that vast expanses of open water now replace summer sea ice at accelerating rates (Fig. 1

insert) (e.g., Stroeve et al., 2011 and references therein). This dramatic change is likely enhanced by the effect of Pacific water inflow via the Bering Strait, which influences sedimentary, hydrographic, biological, and ice conditions in and beyond this region. Late Cenozoic climatic, sea-level, and tectonic changes radically impacted the Chukchi shelf, a gateway between the Pacific and Arctic oceans that turns into a Beringian land bridge between America and Eurasia during low sea-level stands.

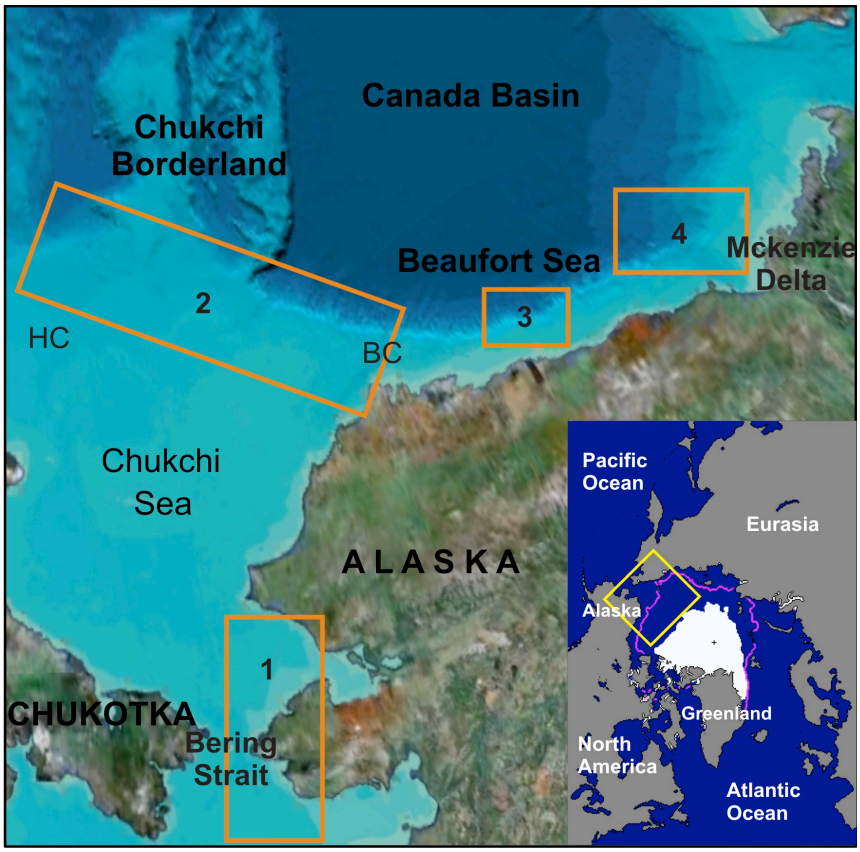

Figure 1. Index map of the Chukchi-Beaufort area with location of proposed drilling projects (boxes). HC - Herald Canyon, BC - Barrow Canyon. **Insert**: summer sea ice extent (15% concentration): grey fill – 2007 (all-time observation minimum), white – 2010 difference from 2007, orange line – 1979-2000 median. Yellow box outlines Chukchi-Beaufort area.

The significance of the Chukchi margin for studies of the Arctic-Pacific connection, sea-ice and glacial history, and high-latitude shelf-basin interactions makes it a natural attraction for research initiatives ranging from modern processes to geological history and prehistoric archeology. A number of research programs have targeted the Chukchi Sea and adjacent areas in recent years including expeditions with geological/geophysical components, and more are being planned for the coming years. These activities reveal a growing international interest in the Chukchi region, with a widening range of participating countries in addition to those that have traditionally worked in the Arctic in the 20th century. This reality creates incentives for broadening international cooperation, which can greatly increase the overall efficiency of the

scientific output. An excellent international research opportunity can be provided by bringing the Integrated Ocean Drilling Program into the western Arctic.

Two drilling proposals have been developed thus far for the Chukchi Sea, three more address the adjacent Beaufort margin, and another one is being considered for the Chukchi Borderland. Further development of these projects and related new proposals requires intellectual and organizational interaction between research groups involved.

The Beringian and the Beaufort-Mackenzie projects have already held successful workshops that allowed for a discussion of a broad range of scientific and technical issues related to drilling in these areas. There was a need for a workshop to nurture a discussion centered on the Chukchi margin that links together all potential drilling areas in the Pacific sector of the Arctic.

The workshop was held in March 14-16, 2013 at the Byrd Polar Research Center, Columbus, Ohio, and attended by a multidisciplinary group of 36 scientists from seven countries (Appendix A). The participants represent multiple key disciplines including sedimentology, geochemistry, micropaleontology, seismostratigraphy, tectonics, and climate modeling. Many of the participants have a working knowledge of the potential drilling targets in the western Arctic, which were discussed at the workshop. This report provides a description of the major scientific questions for the Chukchi/Beaufort region, existing drilling proposals, and results of the workshop presentations and discussions.

2. Scientific Background

The dramatic decline in summer sea ice and related hydrographic and biological changes in the western Arctic are associated with the Pacific water inflow via the Bering Strait (e.g., Woodgate et al., 2010). Sedimentary and hydrographic regimes in the western part of the Chukchi Sea and the Beaufort margin are also influenced by large east Siberian rivers and the McKenzie River, respectively. Late Cenozoic climatic, sea-level, and tectonic changes radically impacted the Chukchi shelf, a gateway between the Pacific and Arctic oceans that turns into a Beringian land bridge between America and Eurasia during low sea-level stands. New marine data indicate the complexity of the submerged Beringian history, with grounded ice caps covering parts of the Chukchi/Beaufort shelf and adjacent borderland during some glacial periods, which compounded the effects on climatic and sedimentary environments (e.g., Polyak et al., 2007; Jakobsson et al., 2008).

Results from the recent expeditions, combined with data collected on earlier exploration cruises, outline some significant aspects of the geological structure and paleoceanography of the Chukchi region. Despite these advances, there are a number of fundamental questions remaining to be addressed, notably:

- History of Beringia sea level and, thus, of water flow through the Bering Strait;
- Architecture, composition, and paleoclimate record of progradational wedges at the northern Chukchi/Beaufort margin such as large mouth fans of the Herald and Barrow canyons and off the Mckenzie River;
- Fluctuations of the summer sea-ice margin over the broad Chukchi shelf during past warm periods;
- Extent and timing of ice caps grounded on the Chukchi/Beaufort shelf during Pleistocene glaciations;
- Origin and tectonic evolution of the Chukchi Borderland and Canada Basin.

In addition to paleoceanographic and tectonic questions, sampling subsurface sediments is critical for addressing microbiological, chemical, and physical processes in the unique Arctic environment. In particular, there is a need to constrain boundary conditions and process linkages for permafrost and gas hydrates on the Arctic margins (e.g., Ruppel, 2011). Although the Chukchi Sea is a less important target for this objective than the Beaufort margin, investigating Chukchi shelf and slope will improve our understanding of permafrost/gas-hydrate distribution in the western Arctic. Altogether, scientific drilling of late Cenozoic sediments on the Chukchi/Beaufort shelf and on its continental slope is a critical component for answering these and related questions.

3. IODP proposals

Five drilling (pre)proposals have been developed thus far for the Chukchi Sea and the adjacent Beaufort margin, and another one is being considered for the Chukchi Borderland. Further development of these projects and related new proposals requires intellectual and organizational interaction between research groups involved.

Beringia (Box 1 in Fig. 1). IODP Proposal 680, *The Bering Strait, Global Climate Change, and Land Bridge Paleoecology* (S. Fowell and D. Scholl, 2008), describes mission-specific

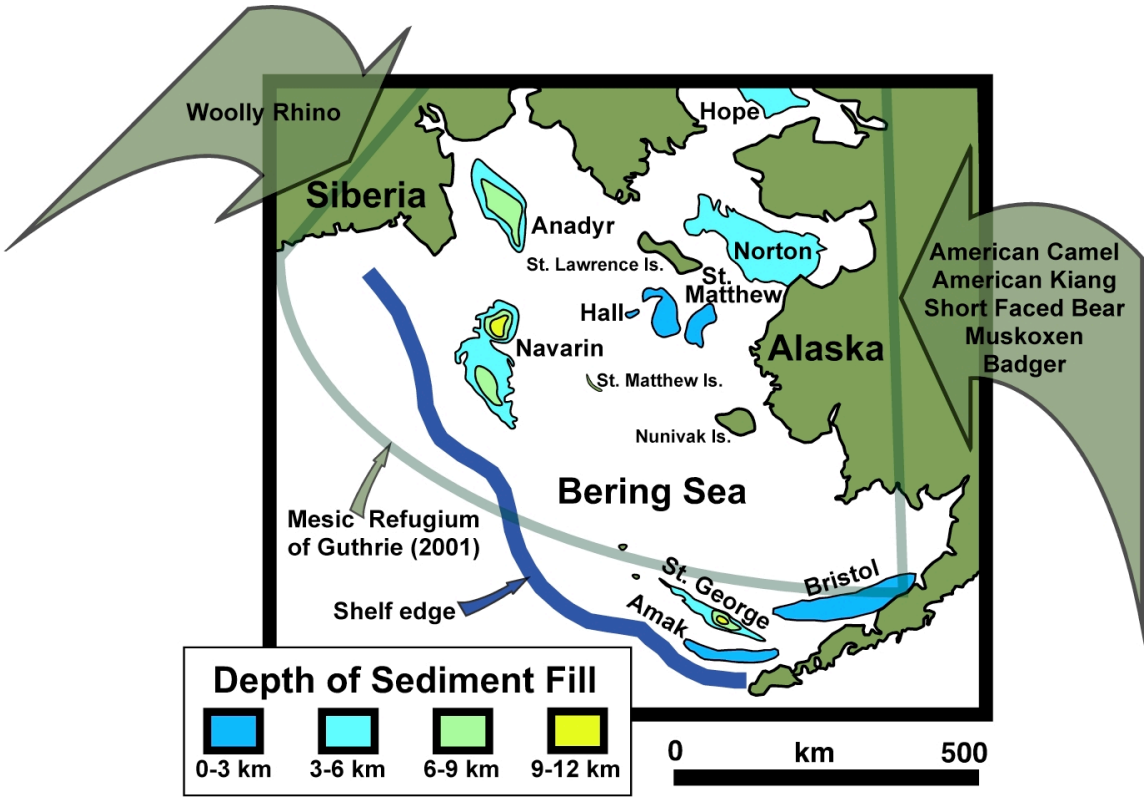

Figure 2. Distribution of Bering Shelf basins showing depth of sediment fill (after Worrall, 1991). Steppe-adapted mammals that failed to cross the Bering Land Bridge (arrows) may have been prevented from doing so by a mesic refugium (trapezoid) with a greater proportion of tundra vegetation (data from Guthrie, 2001).

platform drilling (water depths of 30-45 m) across the submerged Bering Land Bridge and sampling of Miocene to Holocene sedimentary records north and south of the bridge. Drilling of

Cenozoic sedimentary basins on both sides of the Bering Strait (Fig. 2) will provide data on the history of the Arctic-Pacific gateway. Choice of drilling sites is facilitated by numerous seismic lines available from the sedimentary basins adjacent to the Bering Strait on the Bering and Chukchi Sea side. Among the goals of the program are reconstruction of Quaternary 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 Bering Strait targets link to those of IODP Expedition 323, which drilled the Pliocene to Quaternary sediments in the deeper part of the Bering Sea basin, south of the Arctic Circle.

Chukchi Margin (Box 2 in Fig. 1). IODP Pre-proposal 750, *Chukchi Shelf to Slope Transect: Linking Beringian and Arctic Ocean history* (L. Polyak and J. Brigham-Grette, 2009**),** is complementary to the Bering Strait 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 across the Chukchi Sea and potentially requires both a shallow water drilling platform and a traditional riserless vessel. The recovered sediment 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 the history of glacial ice interaction with the Chukchi margin (Polyak et al., 2007; Dove et al., 2013). In addition to some, potentially available industry seismic data, a number of MCS lines have been collected from the Chukchi margin under favorable sea-ice conditions in 2008 and 2011 (Jokat et al., 2009; Coakley et al., 2011). Collection of multibeam and shallow subbottom profiler data as well as sediment cores is being augmented by ongoing research from various vessels (such as Healy, Araon, Mirai, etc). Several detailed studies have been performed on existing cores (e.g., Darby et al., 2009; Farmer et al., 2011).

Canadian Beaufort Sea (Mackenzie Trough) (Box 4 in Fig. 1; Fig. 3). IODP Pre-Proposal 753, *Late Quaternary Paleoceanography and Glacial Dynamics in the Beaufort Sea* (M. O'Regan et al., 2010), addresses drilling in the Mackenzie Trough for paleoceanographic objectives. 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. In particular, the proposal seeks to test the hypothesis that the collapse of the Laurentide ice sheet triggered the Younger Dryas. A challenge facing this project 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. A paleoceanography study funded by NSF-OPP has acquired cores and subbotom profiles to target the Younger Dryas in the same area in 2013.

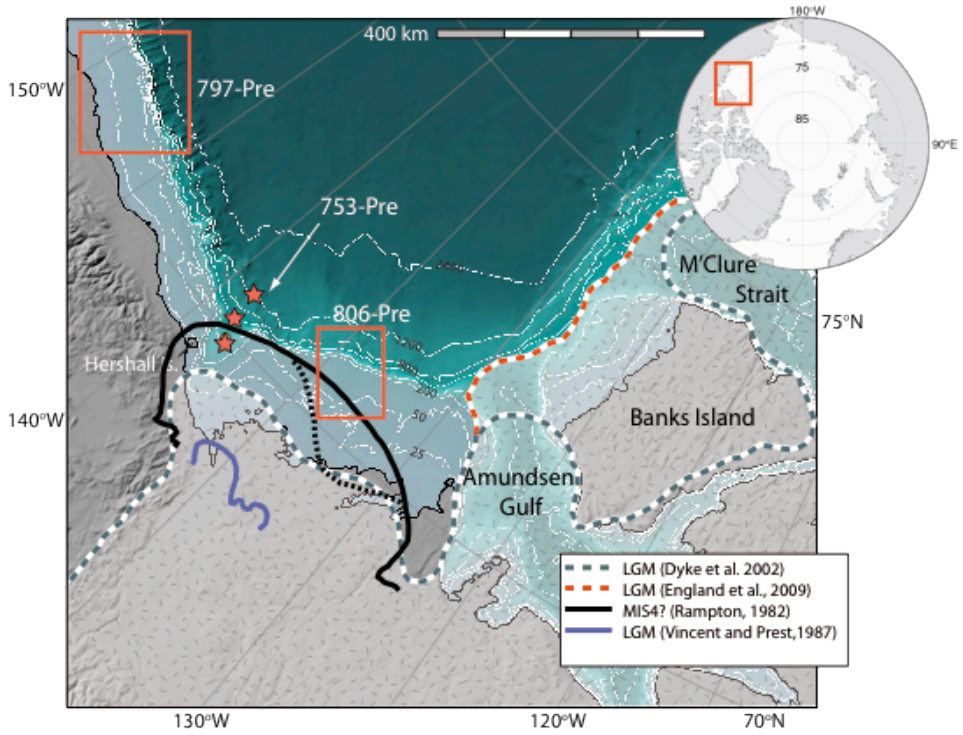

Figure 3. Map of the Beaufort Sea margin with location of proposed drilling projects (preproposals). Lines explained in the legend show limits of the Laurentide ice sheet according to various reconstructions.

US Beaufort Margin (Box 3 in Fig. 1; Fig. 3). IODP Pre-Proposal 797, *Alaskan Beaufort Margin: Investigating the Impact of Warming Since the last Glacial maximum on Climate-Sensitive Sediments in the Arctic* (C. Ruppel et al., 2012**)**. Drilling on the Alaskan Beaufort Margin focuses on a cross-shelf and upper continental slope transect 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 (Fig. 4). 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.

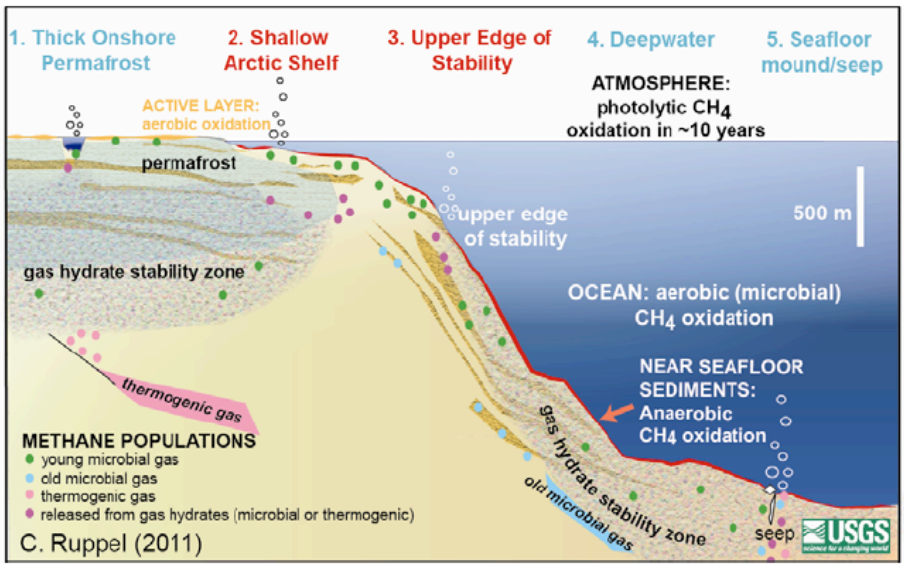

Figure 4. Schematic of Arctic margin permafrost/methane hydrate distributions, gas emissions, and methane sources/sinks highlighting sectors 2 and 3 (red), which are the most vulnerable to climate change.

Canadian Beaufort Margin (Fig. 3). IODP Pre-Proposal 806, "*Methane release and geologic processes associated with warming permafrost and gas hydrate deposits beneath the Beaufort Sea Shelf and upper slope*" (Paull et al., 2012), aims to drill targets on the Canadian Beaufort (Mackenzie) margin to study methane leakage and climate change on the continental slope and on shelf areas underlain by subsea permafrost. The proposal was submitted to ICDP in December 2011 and subsequently submitted to IODP in March 2012. 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 drilling 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 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. Several recent publications (Batchelor et al., 2013a, b) analysed MCS data near the targeted drilling area. Proponents also have access to older refraction data that were used to support the mapping of subsea permafrost in the Mackenzie area (Pullan et al., 1987), as well as data from an extensive series of boreholes on the shelf.

4. Drilling Operation in the Arctic Ocean

The drilling needs of the different interest groups may vary. The Chukchi margin project expects drilling primarily in water depths of <1000 m with an estimated penetration of up to 800-1000 m. The potential drilling at the Borderland will require sites at greater water depths, but with an overall smaller penetration. The workshop provided a forum to discuss the scientific needs of the different groups and the stratigraphic and lithologic units they anticipate encountering.

The previous IODP drilling operation in the Arctic Ocean (ACEX) required a very costly and complex setup involving two icebreakers (one nuclear-powered) and a drilling platform. Ongoing sea-ice retreat makes the Chukchi region much easier to access without the use of ships with high icebreaking capabilities. In 2011, >5000 km of Multi-channel Seismic Reflection data were collected at the northern margin of the Chukchi Sea from the RV *Marcus Langseth*, a vessel not reinforced for sea ice (Coakley et al., 2011). The ship operated entirely in ice-free waters for about 98% of the time, highlighting the potential for use of the JOIDES Resolution in this region during the months straddling the mid-September ice minimum.

The results of this cruise were presented to the IODP Environmental Protection and Safety Panel in March, 2012. The panel responded enthusiastically. This is excerpted from their draft meeting report; *"*Bernard Coakley discussed with the panel changes in Arctic conditions that could permit the use of the JOIDES Resolution for high latitude drilling. It was noted that there has been a significant reduction in sea ice. It was reported that the *RV Langseth* has been used for the acquisition of seismic data and that there has been steady growth in the seismic data available but there remains a lack of well control. This has led to the development of a stratigraphic test drilling proposal. The panel believed that a drilling program could be developed meeting EPSP requirements. The panel does suggest that when developing the drilling program multiple sites for each objective be planned to deal with contingencies."

5. Previous Related Workshops

Several scientific ocean drilling workshops focused on the Arctic Ocean and nearby regions in recent years. The workshop on the Bering Strait and Land Bridge (June 2005; Fowell and Scholl, 2005) laid foundation for the first IODP proposal dealing with the Chukchi region. The Arctic Ocean Drilling Workshop held in late 2008 (Coakley and Stein, 2010) was an important turning point that triggered a suite of Arctic Ocean proposals. The workshop largely focused on deepwater drilling for tectonic, paleoceanographic, and related targets as a follow-up to the successful ACEX drilling, but it also discussed the prospects of drilling at the continental margins including the Chukchi margin.

In November 2011, the European Magellan series held an Arctic Site Survey Workshop (http://www.iasc.info/files/Marine/Magellan Workshop Final report November 2011(3).pdf). 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 Arctic site survey workshop was closely followed by two related meetings: the USSSP-sponsored Circum-Arctic Drilling Workshop in December 2011 and the IODP Beaufort Sea workshop in February 2012. The Circum-Arctic Workshop explored the potential for IODP

drilling on Arctic shelves and upper continental slopes with broad paleoclimate and contemporary climate objectives and the analysis of the impact of climate change on relict permafrost and gas hydrates beneath the continental margins. The aim of the Beaufort workshop was to define and integrate the scientific questions and drilling strategies required to assess environmental change and geohazards in the Beaufort Sea. That workshop was designed to seek integration between the paleoceanographic pre-proposal in the Canadian Beaufort Sea and concurrent pre-proposals for permafrost/ gas hydrates science in the same area and on the Alaskan shelf further west (Fig. 3).

6. Workshop Presentations

In the first keynote presentation R. Stein provided a thorough update on international Arctic drilling initiatives. Following presentations covered three major topics: regional settings, target drilling areas (proposals), and ongoing research activities/programs.

A. Condron educated the mostly geology-oriented audience on physical oceanographic processes in the Chukchi region, which to a large extent control sediment focusing such as in front of major cross-shelf canyons. Another important aspect is changing sea-ice conditions, which are critical for the feasibility of drilling projects.

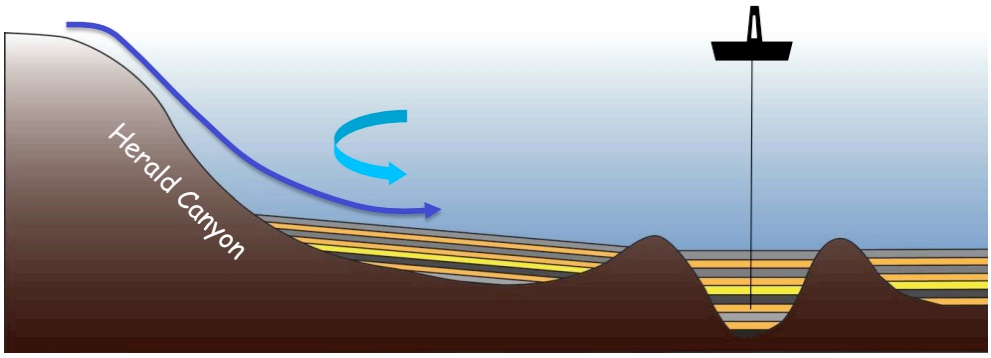

Figure 5. Schematic representation of sediment transport modeling that could help explain sedimentation patterns in the Herald Canyon mouth featuring ~3.5-km-thick sedimentary wedge (by A. Condron). Arrows show inputs from both the Pacific and Siberian sources.

Geological aspects were presented by D. Houseknecht, who has a vast experience with regional seismic-reflection and borehole data. The presentation outlined major regional tectonic events and sequences with examples of seismic records. Growth-faulted late Cenozoic sections and prograded sequences at the Chukchi margin were pointed out as potential drilling targets for paleoclimatic objectives; more target areas were suggested for deeper stratigraphic and tectonic goals.

The importance of warm paleoclimatic intervals for understanding the modern climate change in the Arctic was elucidated by J. Brigham-Grette. Interglacial time slices such as Marine Isotope Stages (MIS) 5e, 11, 31, and some earlier Plio-Pleistocene intervals may allow us to understand past change and system dynamics and to use this information to improve predictions about the future. Knowledge on these warming events is derived primarily from coastal deposits around the Chukchi and Beaufort seas and terrestrial data such as the recently recovered continuous record from Lake Elgygytgyn in central Chukotka (Melles et al., 2012). Comparable

marine paleoclimatic records are badly needed to comprehend interglacial climatic patterns in the Arctic.

The glacial periods representing the opposite paleoclimatic end member were characterized by L. Polyak with the new data on glacial impact on seafloor at the Chukchi margin and adjacent areas. The multibeam bathymetry, CHIRP subbottom profiling, and MCS data reveals a widespread grounded-ice presence at this margin with ice sources located further south, southwest, and east (Fig. 6). This picture indicates glaciation centers on the Chukchi and/or East Siberian shelf, combined with ice streaming from the Laurentide ice sheet. The latter also impacted the Alaska Beaufort margin (Engels et al., 2008). Constraining the timing of these glacial events and processes involved in the formation and propagation of these ice sheets/streams adds an important component to understanding the marine-based glacial systems. On the other hand, widespread glacial erosion and redeposition of sediment may complicate drilling operation and core interpretation and needs to be considered in the choice of target sites.

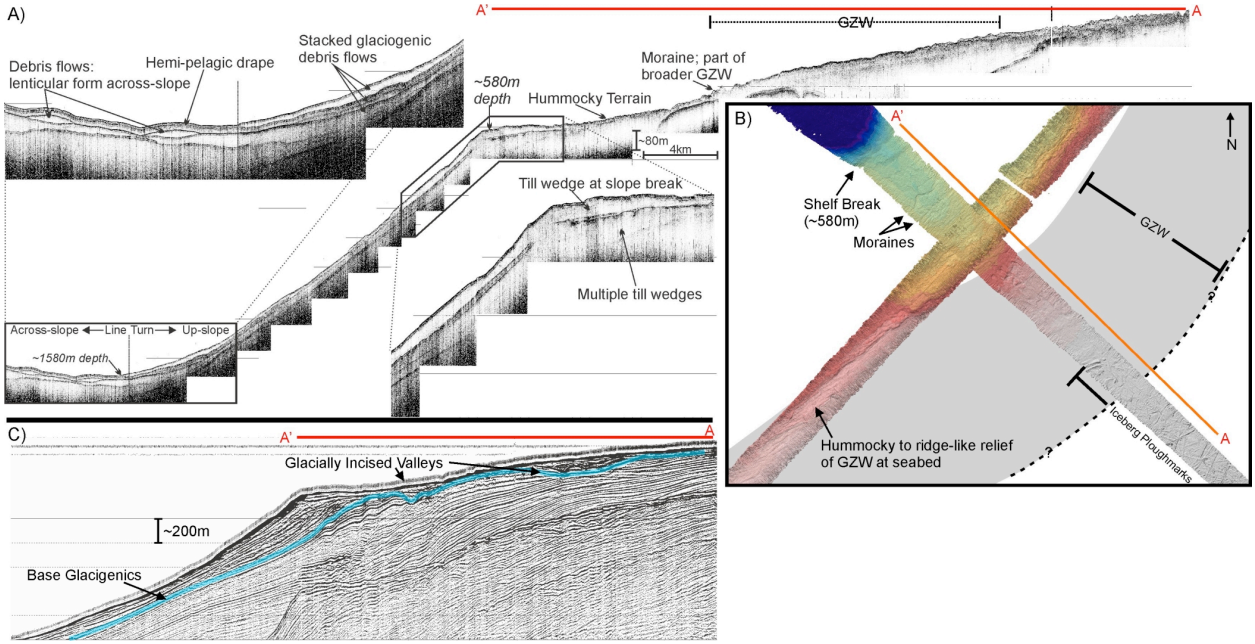

Figure 6. CHIRP (A), multibeam bathymetry (B), and multi-channel seismic (MCS) (C) data reveal a succession of glacigenic features near the Chukchi shelf break and down slope (from Dove et al., 2013). Panels A) and B) show the seabed and cross-sectional expression of grounding zone wedges (GZWs) of the past ice sheets. Panel B) shows multiple till wedges (also GZWs) extending the shelf break. C) Deeper penetrating MCS data (near-trace record) reveal the thick package of glacigenic sediments along the margin and glacially incised valleys.

Target drilling areas were characterized along the lines of existing proposals with relevant updates: Bering Strait area (S. Fowell), Chukchi margin (L. Polyak), Alaska Beaufort margin (C. Ruppel), and McKenzie area (M. O'Regan, presented by A. de Vernal). Potential drilling on the Chukchi Borderland for questions related to tectonic evolution and deep-time stratigraphy of the Pacific sector of the Arctic was outlined by B. Coakley.

Another set of presentations covered ongoing research activities/programs in the region including expeditions carried out by Germany (R. Stein), Korea (S.-I. Nam), China (R. Wang),

and Russia (S. Gorbarenko/ P. Rekant) as well as the US Extended Continental Shelf program in the Arctic (D. Hutchinson, presented by N. Lebedeva).

In addition to keynote talks, three-minute oral overviews were given for poster presentations (Appendix C), which delivered new scientific results dealing with research methods, paleoclimatic proxies, and geophysical data from the western Arctic or adjacent North Pacific region.

7. Discussion Synthesis

Breakout group discussions were designed to address the following tasks: identifying scientific objectives and discovery opportunities, most promising sites for drilling, site-surve strategy, coordination of pre-proposal activities and proposal submission, and existing challenges.

Opportunities for Regional and Arctic-wide Discovery

Paleoclimate

Climate changes in the Arctic are intimately related to ice dynamics, both on land and at sea. Whereas ice in general determines the albedo and heat budget, land ice affects the physiography at the Earth's surface, freshwater budget and sea level, while sea ice modulates ocean-atmosphere exchanges. From this point of view, the western Arctic, including the Bering Strait, Chukchi and Beaufort seas are extremely important. First, it is the Arctic area that has been marked by the largest changes of sea ice cover during the last decades, which points to a particularly high sensitivity. Second, any change in sea level is accompanied by variation in Pacific water inflow through Bering Strait, which in turn affects the heat and freshwater budget of the Arctic waters, which are ultimately exported to the North Atlantic.

The Bering Strait that connects the Pacific and Arctic ocean links the regional tectonic evolution to long-term shifts in Arctic climate. Its shallow depth (~50 m) also makes it very sensitive to variations in sea level, which result in feedbacks between sea level, sea ice and Arctic climate. During low sea level stands produced by continental glaciations the strait is emergent, forming the Bering Land Bridge connection between North America and Asia. This is the only area on Earth where the circulation between ocean basins has been repeatedly opened and closed, adding and removing a migration corridor for plants, animals, and humans between continental landmasses.

Despite the importance of the area with respect to global climate changes, our insufficient knowledge about historical regional changes of ice, climate and ocean prevents any testable forecast. As exemplified below, key questions about the dynamics of climate are to be resolved :

- What was the impact of the initial opening of Bering Strait at estimated 5.4-5.5 Ma on the Arctic Ocean ecosystem? Was it responsible for increased moisture and early onset of ice growth in the circum-Arctic?
- During the Plio-Pleistocene, how did the extent and history of ice sheets in the western Arctic vary? What role did they play in the evolution of the climate system during that time?
- On a more recent time scale, what was the extent of the Laurentide Ice Sheet in the western Arctic during the Last Glacial Maximum and can this be reconciled with the current geophysical models of LGM ice physiography and related isostatic adjustment?
- Did freshwater outburst from the Mackenzie River trigger the Younger Dryas?

- Does the Bering Strait through flow, which is controlled by sea level, play a determinant role in the North Atlantic circulation (Hu et al., 2010, 2012; Ortiz et al., 2012)?
- What is the variability of Arctic Sea ice during high sea level stands and interglacial stages and how does it relate to atmospheric circulation patterns and inflow of warm low saline waters from the Pacific?
- What biogeographic "filter" prevented certain plant and animal taxa from crossing central Beringia, while allowing humans and other taxa to migrate between continents?

In addition to answering these critical questions, completion of these drilling targets will place the Arctic in a consistent stratigraphic framework for comparison with existing results from the North Pacific and North Atlantic.

Tectonic/basin evolution

The geologic history of the Chukchi region is becoming better known from extensive grids of multi-channel and single channel seismic reflection data (Fig. 7). These data have been partially calibrated in geologic time from a few offshore industry boreholes (e.g., Popcorn). For the shelf stratigraphy this calibration provides adequate age constraints (Hegewald, 2012).

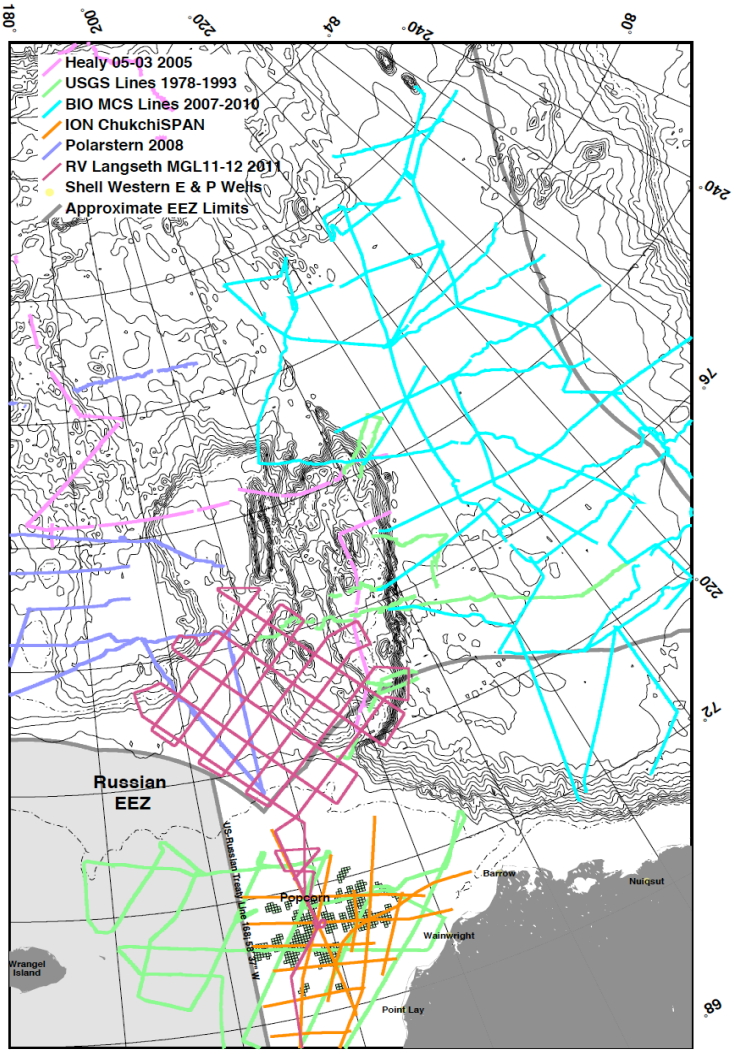

Figure 7. Distribution of Multi-channel Seismic Reflection data on the northern Chukchi Shelf and Borderland and in the adjacent part of the Arctic Ocean (see Fig. 9 for the Beaufort shelf).

Beneath the shelf, multiple events, extending back into the Mesozoic and earlier time, have structured the basement and created accommodation space for the accumulation of substantial thicknesses of sediment. These sequences, deposited on the pre-existing continental shelves and in a superimposed foreland basin, contain a record of the extension, compression and strike-slip deformation. The interaction of these multiple stages of deformation has created a set of complicated structures, which has drawn the interest of the industry. While the knowledge of the central Chukchi Shelf is far from complete, it is much better known than the regions to the north, the distal shelf, and the Arctic Ocean basin itself, which lack age control. Dating this stratigraphy, with evidence of substantial tectonic control on sedimentation, mass wasting and, possibly, multiple phases of deformation (e.g., Fig. 8), will substantially improve our ability to interpret the history of the Arctic Ocean.

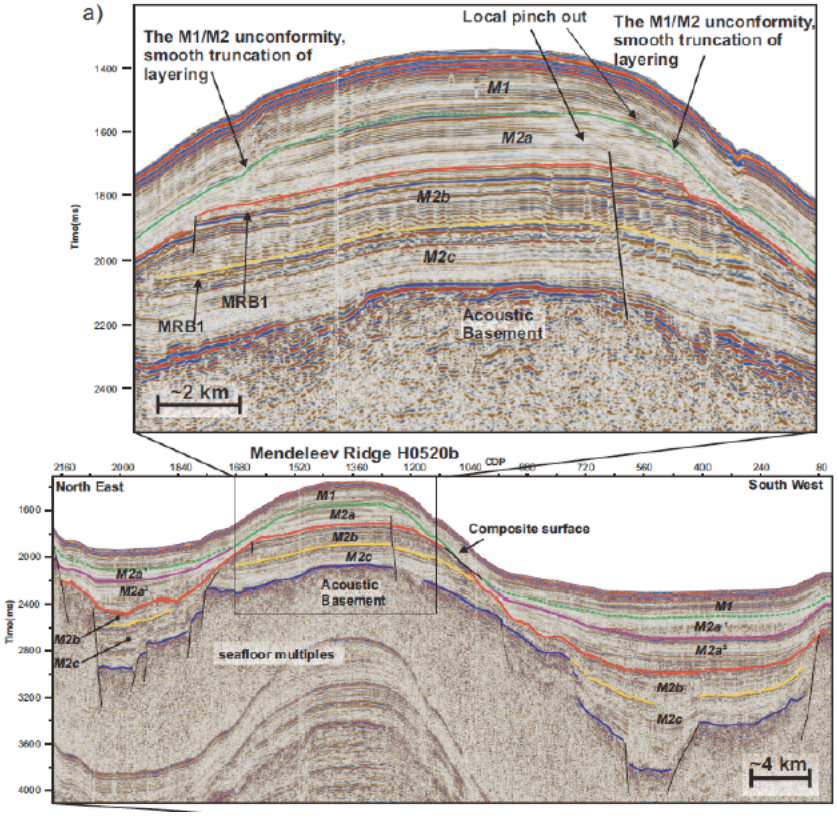

Figure 8. MCS data collected on the Mendeleev Ridge in 2005 from the USCGC Healy (Bruvoll, 2010). Data reveal a complex stratigraphy including apparent mass-wasted sediments and a post-tectonic drape.

The 2011 geophysical cruise on the RV Marcus G. Langseth collected ~5300 km of new MCS data across transition between the Chukchi Borderland and the shelf (Fig. 7; Coakley et al., 2011). This zone may have been a plate boundary during the development of the Canada Basin, so understanding the deformational history across this boundary provides a test for models of the opening of this basin. Initial results indicate, that the stratigraphy in the deep basin can be subdivided into a rifting sequence, a post-rift sequence and a later, relatively thin ponded sequence that fills the topography in the rifts (Coakley and Ilhan, 2012). There is evidence of mass-wasting in the reflection character of the rift basin fill. Uplift of the rift-related sediments seems to indicate a second phase of strike-slip tectonism affected the basin, particularly near the

southern and western margins. While these sediments seem to indicate a complex deformational and sedimentological history, we are unable to date any of the reflectors observed on the Chukchi Borderland without age control.

A second objective of the cruise was to bring age control into the deep basin by tying the exploration wells drilled by Shell on the Chukchi shelf in the late eighties. This has been complicated by the multiples, both surface related and peg-leg that are in the shallow water data set. After processing it is now possible to tie the shelf data set to the Shell wells and date reflectors on the shelf, correlating with the Alfred Wegener Institute lines collected in 2008 (Fig. 7; Jokat et al., 2009) and tying together the Chukchi Shelf stratigraphy from east to west and to the basement high on the shelf edge. Further processing will be necessary to carry these correlations across the high into the deep basin. These data can be used to plan an ocean drilling stratigraphic test leg to the Chukchi Shelf and Borderland. Sampling the sediments below the seafloor will make it possible to date and understand the apparently heterogeneous stratigraphy and complex structural relations that can be observed in the seismic reflection data. Dating the stratigraphy, and the tectonic events that created the accommodation space for the sediments, will enable reconstruction of the tectonic history of the region and provide strong constraints on the opening of the Amerasian basin.

Target Areas

Bering Strait

The Beringia proposal has not changed since its submission in 2008. The major targets are thick (up to 3 km) sedimentary basins north and south of Bering Strait (Fig. 2). Norton Basin on the Bering side, where the younger sediments are the thickest, provides opportunity to recover a high-resolution Plio-Pleistocene record. It is desirable to extend the record to at least 4.5 Ma to be able to correlate it with data from Expedition 323 in the Bering Sea further south (Takahashi et al., 2011). The Hope Basin north of the Bering Strait is suitable for recovering a longer stratigraphy, to at least 5.5 Ma (upper Miocene). Relatively shallow depths (mostly 30-40 m) are applicable for the use of a jack-up rig, although concerns exist about the amount of time it would take to go deeper with the rig.

Chukchi shelf

The outer Chukchi shelf/slope features large sediment accumulations both in the Holocene (sediment core data, e.g., Darby et al., 2009, 2012) and in older Plio-Pleistocene deposits (inference from seismic seismic data, e.g., Hegewald, 2012). These sediment depocenters provide opportunities for recovering potentially high-resolution stratigraphic sections covering significant portions of the Plio-Pleistocene. The initial pre-proposal focused on depocenters at the mouth of the Herald Canyon and on the system of buried channels on the shelf. The latter has been surveyed by subbottom profiling with some sediment cores collected (Hill et al., 2007; Hill and Driscoll, 2008). New data emerging from this margin (Langseth 2011 and Araon 2011-2013 cruises) indicate more of potentially prospective drilling sites (e.g., near Barrow Canyon mouth), but also numerous complications and disturbances in sediment distribution, especially down-slope processes and glacial erosion (e.g., Dove et al., 2013). The choice of sites for drilling requires continuing data collection for a detailed characterization of the target areas with multibeam bathymetry, subbottom profiling, and sediment coring.

Mackenzie Trough area

The Mackenzie River contributes today to the largest annual load of suspended sediment to the Arctic Ocean. The freshwater delivered into the Amerasian Basin affects both the freezing temperature of surface waters and the relative degree of upper ocean stratification, which are important controls regulating the formation and melting of sea ice. The impact of outbursts of freshwater from the Mackenzie river drainage basin continue to be invoked as viable hypotheses for the origin of abrupt and rapid climate change events in the late Quaternary. In addition, while considerable knowledge concerning the Late Quaternary glacial dynamics of the Barents/Kara ice sheet, there is large uncertainty about the limits of the Laurentide Ice Sheet (LIS) during the last glacial cycle, and very little is known about previous glacial advances in the area. The scientific objectives of drilling in the Mackenzie Trough are to recover high resolution mid- to late Quaternary sediments from a depth transect in the trough and seaward lying sediments to address three scientific themes:

1) The late Quaternary glacial dynamics of the Northwestern LIS;
2) The timing and flux of freshwater discharge from the Mackenzie River - *did a freshwater outburst flood from the Mackenzie River trigger the Younger Dryas?*
3) High-resolution paleoceanographic and paleoclimatic time-series to understand how sea ice variability is linked with oceanographic, atmospheric and terrestrial changes across mid- to late Quaternary glacial cycles.

To achieve these goals, the following proximal to distal transect is proposed (Fig. 3):

Site 1: This site targets a very high-resolution deglacial to Holocene sequence;

Site 2: This site has a lower resolution than the previous site and is aimed at dating the grounding zone wedge emplacement, and/or recovering older interglacial sediments;

Site 3: This site will be drilled seaward of the glacial limits and aims at recoveringa longer mid- to late Pleistocene paleoceanographic record. Recently published multibeam and seismic data (Batchelor et al. 2013a,b) reveal intervening ridges that seem to have contributed to themore coherent mid- to late Pleistocene stratigraphy observed seaward of the shelf break by preventingthe deposition of glaciogenic debris flows or similar deposits from submarine slope failures due their elevated position. The exact drilling site will be established in upcoming months by carefully examining existing multi-channel seismic lines and by obtaining a pilot core from that area to evaluate sedimentation rates and carbonate preservation.

Alaska Beaufort Margin

For the first time, the IODP has identified illuminating Earth's future and studying processes that occur on human timescales as goals of scientific drilling. Drilling proposed for climate-sensitive permafrost and hydrate-bearing sediments that have and will continue to experience degradation on the passive Alaskan Beaufort margin (ABM) would capture the impact of warming since the end of the Late Glacial Maximum (LGM) and address scientific goals identified by IODP. Relict permafrost and gas hydrates on unglaciated circum-Arctic continental shelves and shifting gas hydrate zones on upper continental slopes (Fig. 4) are among the most climate-sensitive sediments vulnerable to impact of past, contemporary and future warming of ocean temperatures. Climate-driven hydrate dissociation has implications for atmospheric methane concentrations, ocean acidification and anoxia, and slope destabilization. The proposed drilling program provides an opportunity to "catch climate change in progress" by drilling a shelf to upper continental slope transect on the ABM over a lateral distance of <100 km and under

seasonal ice-free conditions.

Drill sites on the Alaskan Beaufort Sea shelf will be pinned to onshore locations where permafrost and gas hydrate have been well characterized through prior non-IODP drilling (Fig. 9). The shelf IODP sites will sample from nearshore relict subsea permafrost to the now permafrost-free outer shelf, while also capturing a record of sea level changes. Drill sites from the shelf break (~100 m) seaward will sample across the upper feather edge of hydrate stability for the contemporary and LGM systems and downslope to the well-established, stable gas hydrate system in an area of widespread slope failures. ABM drilling will be conducted from the inner shelf to ~1350 m water depth. Transect drilling here will also capture temporal variations, from inner shelf sites that retain their Pleistocene character (permafrost/gas hydrate) to outer shelf sites, where thawing/dissociation has been complete, and slope sites, where the gas hydrate stability zone (GHSZ) is still equilibrating.

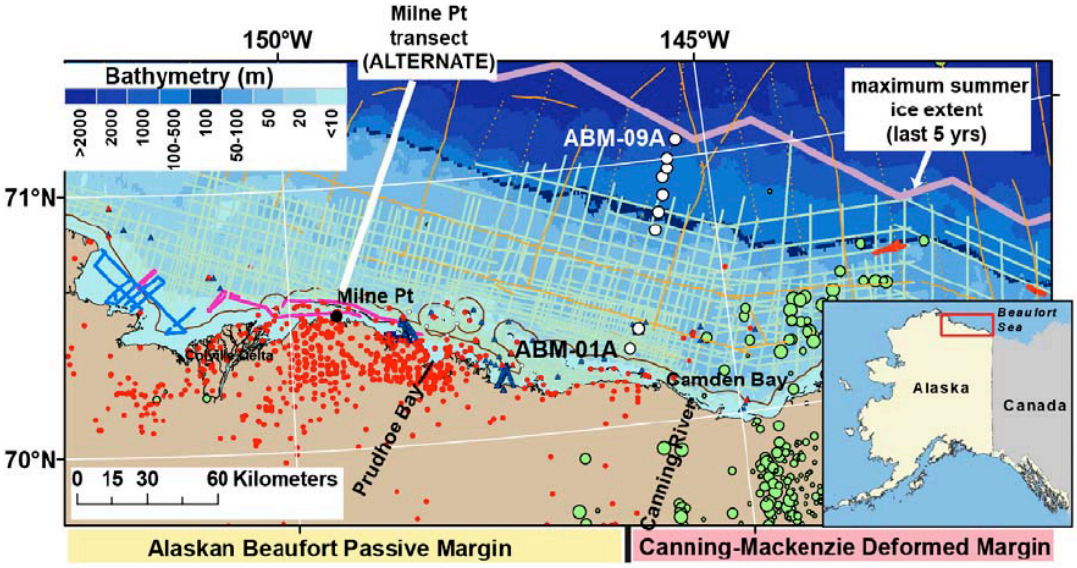

Figure 9. Central and eastern Alaskan Beaufort margin showing the boundary between the passive margin and the deformed margin, with earthquake distribution (green symbols up to M=5.3). The proposed drilling transect is shown as ABM-01A to ABM-09A, with the Milne Point transect as alternate. Red dots are deep legacy wells (mostly logged), and blue triangles are shallow geotechnical borings. Brown curve denotes the state water 3-mile limit. Public seismic data, all collected prior to 1985, are shown in orange (USGS) and green (industry). Red lines show paleo-shorelines on the outer shelf to east, and purple denotes the maximum southern 2007-2011 summer (August-October) ice extent compiled from NSIDC data. The shelf break is marked by the darker-gridded bathymetry.

Site Surveys

Thorough site-survey data are essential for a successful proposal and need to have the utmost attention paid to them. Although IODP is considering to drop the requirement that sites need to be located at crossing seismic lines, detailed seismic characterization of the target sites is essential, especially for deeper boreholes. We need to be confident in the absence of a

hydrocarbon charge issue, which is especially important in the Chukchi Sea region, where possibility of oil is high.

While prospects for getting dedicated support for site surveys are limited, the growing research activities in the western Arctic Ocean due to retreating summer sea ice provide numerous opportunities for data collection. These national and international activities include recurrent cruises performed by the US (Healy, Sikuliaq in the planning), Canada (Amundsen), Germany (Polarstern), Korea (Araon), China (Xuelong), potentially Sweden (Oden) and Russia (US-Russian RUSALKA program). For example, Polarstern-2008 and Langseth-2011 cruises provided the backbone of MCS data collected from the Chukchi margin for scientific purposes. The Araon works in the western Arctic Ocean every summer since 2010 collecting quality multibeam and CHIRP data and sediment cores. Joint Chinese-Russian expeditions may facilitate data collection in Russian waters.

Cluster Science

In order to maximize the efficiency of identified drilling targets for understanding the paleoclimate and tectonic history of the western Arctic Ocean and adjacent continental margins, these regional projects should be viewed as an integrated community effort aimed at the comprehension of the Arctic system. We therefore seek a coordinated collective approach to further our opportunities to use scientific ocean drilling for discovery in the Arctic region. Achieving a coherence in the scope of the overall objectives for each of the regional proposals discussed at the workshop will enhance both the logistical possibilities of drilling in the Arctic Ocean and the scientific output. Integration is a logical step in the development of existing proposals aiming at closely located target areas and sharing similar sets of objectives and similar drilling methods. For example, the Chukchi Margin and the Mackenzie Trough proposals pursue closely related objectives such as the history of Late Cenozoic glaciations, sea-ice conditions, and formation of sediment depocenters at the Chukchi/Beaufort margin. Drilling of the buried channels on the Chukchi shelf that could be done from a jack-up rig can be integrated with the Bering Strait proposal. Paleoclimate and tectonic questions can also be coordinated as the tectonic evolution of the Arctic impacted the dynamics of climate on broad timescales, and tectonic influences are well within the scope of the latest (Pleistocene) climatic cycles.

In practical terms, the coordination of various projects (cluster science) may range from a website posting relevant information and data for the collective use to combining several proposals into one drilling expedition. These options may need to be considered on a case to case basis for various sets of proposals. The workshop provided a forum for the initial discussion of how to link together potential drilling areas in the western Arctic; further steps in this direction are being discussed by the groups involved in the existing and potential proposals.

In addition to collaboration between various research groups, synergies with industry also need to be sought. The theme of tectonic basin evolution may provide an especially good opportunity to partner with industry, potentially including complimentary drilling proposals, where funding comes from both inside and outside the IODP. Paleoclimate-oriented projects might also benefit from contacts with industry, for example in the use of data that has no impact on industrial prospects such as the shallow (top second) part of seismic records.

Identified Challenges

- Data Availability

- Potential need for crossing seismic lines from the areas of interest
- Some of these seismic lines may already exist, but the data needs to be systematically cataloged (common database)
- Old lines may need to be reprocessed
- Some of the old lines may need to be re-run
- Access to pertinent industry seismic data, for example access to the top 1 sec of an existing seismic grid might be sufficient
- New seismic lines may need to be run
- Need to characterize the near-surface stratigraphy of the drill sites using gravity cores, piston cores, and dredging.
- The above challenges may delay submission of the proposals

- Work permissions
  - Permitting for work in US and Canadian waters (especially affects retrieving seismic data)
  - Obstacles to drilling in Russian waters
  - Marine Mammal Observers may need to be included for both site surveys and expeditions
  - An Environmental Impact Study may need to be developed
- Safety Panel Concerns
  - Mitigating hydrocarbon risk
  - Sea ice tracking—ship needs access to up to date sea ice prediction maps.
- Drilling constraints
  - Shallow water requires a jack-up rig
  - Deeper water (> 80 m) will be able to use the JOIDES Resolution
  - Potential recovery problems with sand facies within growth faulted basins and clinoforms
- Coordination between Proposals
  - The different drilling strategies and target sites for tectonic vs. paleoclimate questions and deep vs. shallow water may require submitting several concurrent proposals
- Scientific Challenges
  - Exploring a never-before drilled area means that we can not predict what we will find, but rather we will be on a discovery mission (these are high gain, high risk proposals). The dearth of knowledge in this area presents an exciting opportunity for major scientific advances in Arctic paleoclimate and tectonics.
  - Arctic sedimentation: low sedimentation rates and poor preservation of both carbonates and siliceous microfossils.
  - Abundance of terrestrial sediment material on the shallow continental margins.
  - Biostratigraphy and magnetostratigraphy may be difficult to construct.
  - We should consider alternative dating methods such as secular variation magnetostratigraphy and tephrochronology

8. Recommendations

- Explore new scientific problems that could be solved by means of ocean drilling, especially with relevance to the climate change and its impact on the Arctic natural system.

- Take advantage of diminishing summer sea ice in the Arctic to broaden the geographic scope of scientific ocean drilling.
- Coordinate research planning and activities to further our opportunities to use ocean drilling for scientific discovery in the Arctic region.
- Maximize the use of existing data to facilitate drilling without excessive additional site survey activities.
- Seek for contacts with industry for site surveys and potentially drilling (complementary drilling proposals).
- Develop research programs to address scientific challenges specific to the Arctic environments.

9. Outcomes and Updates

Workshop discussions and exchange of ideas resulted in a more targeted planning of the new data-collection cruises. The Araon expedition ARA04 to the Chukchi and Beaufort margin was accomplished in 2013, where the US and German geoscientists (L. Polyak and F. Niessen) joined the Chukchi leg, while collaborative Korean-Canadian works in the Mackenzie area were performed for the Canadian Beaufort Margin IODP proposal. CHIRP profiling data and sediment cores were also collected in the adjacent areas from USCGC Healy (HLY1302; PI's L. Keigwin and N. Driscoll). Several pertinent expeditions to the western Arctic Ocean are scheduled for 2014 including the Polarstern, Araon, Xuelong, and possibly more research ships.

A special session "Paleoclimatic history of the Pacific sector of the Arctic" has been organized for the 2013 AGU Fall Meeting (conveners L.Polyak, A. de Vernal, J. Brigham-Grette). The session brought together new data on the evolution of glaciations, sea ice, and oceanic and atmospheric environments in this key region and facilitated further development of a concerted strategy for future research including scientific ocean drilling.

More than a third of the workshop participants were graduate students, postdoctoral researchers, or early-career scientists, most of whom didn't have any experience with scientific ocean drilling. These participants also diversified the discussion and educated workshop attendees about a broad range of related issues and approaches such as silica and boron isotopes, oceanographic modeling, and more. Some of these attendees later participated in the AGU special session.

A dedicated webpage was created for the workshop and related topics: http://bprc.osu.edu/workshops/sdcs_2013. Some of the key workshop presentations have been posted on Vimeo: http://vimeopro.com/byrdpolarresearchcenter/iodp-workshop.

10. Acknowledgements

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Appendix A: Attendees

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Appendix B: Workshop Agenda

IODP Workhop "Scientific Drilling in the Chukchi Sea: Linking North Pacific and Arctic Ocean History", March 14-16, 2013, Byrd Polar Research Center, Ohio State University, Columbus, Ohio, USA.

March 14, Thursday

8:00 – 12:40 Morning session

8:00 Transportation from the hotel and breakfast gathering
Posters to be put on display

8:40 – 8:50 Welcome and statement of task – L. Polyak

8:50 – 9:00 Welcome from the Byrd Polar Research Center – E. Mosley-Thompson

9:00 – 10:30 Overview and keynotes on regional settings
Moderator: B. Coakley

9:00 – 9:20 International Arctic drilling initiatives – R. Stein

9:20 – 9:40 Oceanography (modern processes and paleo-modeling) – A. Condron

9:40 – 10:00 Geology – D. Houseknecht

10:00 – 10:20 Paleoclimate (with a focus on warm intervals) – J. Brigham-Grette

10:20 – 10:40 Glaciations – L. Polyak

10:40 – 11:00 Coffee break

11:00 – 12:40 Existing proposals in the Chukchi/Alaskan region
Moderator: G. St-Onge

11:00 – 11:20 Bering Strait area – S. Fowell

11:20 – 11:40 Chukchi margin – L. Polyak

11:40 – 12:00 Beaufort margin – C. Ruppel

12:00 – 12:20 Mackenzie area – M. O'Regan (presented by A. de Vernal)

12:20 – 1:00 Lunch at the site

1:00 – 2:30 3-minute talks (poster intro or any relevant info/ideas) and poster presentations

2:30 – 5:00 Afternoon session

2:30 – 4:30 Keynotes on related research activities in the region.

2:30 – 3:15 Research by countries
Moderator: L. Polyak

2:30 – 2:45 Germany – R. Stein

2:45 – 3:00 Korea – S.-I. Nam

3:00 – 3:15 China – R. Wang

3:15 – 3:30 Coffee break

3:30 – 4:30 Research by countries (continued) and programs
Moderator: S.-I. Nam

3:30 – 3:50 Russia – S. Gorbarenko/ P. Rekant

3:50 – 4:10 Extended Continental Shelf program – D. Hutchinson (presented by N. Lebedeva)

4:10 – 4:30 Potential drilling on the Chukchi Borderland – B. Coakley

4:30 – 5:00 Wrap-up discussion for Day 1

6:30 - bus from the hotel to the Conference dinner

March 15, Friday

8:00 – 12:00 Morning session

8:00 Transportation from the hotel and breakfast gathering
8:40 – 10:10 Break-out group discussion of drilling potential and strategy in the Chukchi Sea and adjacent sites:
- Scientific themes/questions
- Key sites
- Site survey data needed

10:10 – 10:30 Coffee break
10:30 – 12:00 Presentation and discussion of break-out group results on drilling potential and strategy in the Chukchi Sea and adjacent sites
Moderator: J. Brigham-Grette
12:00 – 1:00 Lunch at the site
1:00 – 1:30 Tour around the Byrd Polar Research Center
1:30 – 5:00 Afternoon session
1:30 – 3:00 Break-out group discussion of research strategy and data exchange:
- Approach/proxies
- Research coordination and data exchange

3:00 – 3:20 Coffee break
3:20 – 5:00 Presentation and discussion of break-out group results on research strategy and data exchange. Wrap-up discussion.
Moderator: R. Stein

March 16, Saturday
Steering committee and proposal PIs stay over for the morning of day 3 to summarize workshop results, collate the writing that was done, and outline the report and further steps. All other workshop attendees are welcome to participate.