**Abstract**

Prior to 2004, the geological sampling in the Arctic Ocean was mainly restricted to near-surface Quaternary sediments. Thus, the long-term Pre-Quaternary geological history is still poorly known. With the successful completion of the Arctic Coring Expedition - ACEX (IODP Expedition 302) in 2004, a new era in Arctic research has begun. Employing a novel multi-vessel approach, the first Mission Specific Platform (MSP) expedition of IODP has proven that drilling in permanently ice-covered regions is possible. During ACEX, 428 meters of Quaternary, Neogene, Paleogene and Campanian sediment on Lomonosov Ridge were penetrated, providing new unique insights into the Cenozoic Arctic paleoceanographic and climatic history.

While highly successful, the ACEX record also has three important limitations. Based on the original age model, the ACEX sequence contains a large hiatus spanning the time interval from late Eocene to middle Miocene, i.e., 44.4 to 18.2 Ma. This is a critical time interval, as it spans the time when prominent changes in global climate took place during the transition from the early Cenozoic Greenhouse world to the late Cenozoic Icehouse world. Furthermore, generally poor recovery during ACEX prevented detailed and continuous reconstruction of Cenozoic climate history. Finally, a higher-resolution reconstruction of Arctic rapid climate change during Neogene to Pleistocene times, could not be reached during ACEX in 2004. We believe, this justifies a return to the Lomonosov Ridge for a second MSP-type drilling campaign within IODP to fill these major gaps in our knowledge on Arctic Ocean paleoenvironmental history through Cenozoic times and its relationship to the global climate history.

Overall goal of the proposed drilling campaign is the recovery of a complete stratigraphic sedimentary record on the southern Lomonosov Ridge to meet our highest priority paleoceanographic objective, the continuous long-term Cenozoic climate history of the central Arctic Ocean. Furthermore, sedimentation rates two to four times higher than those of ACEX permit higher-resolution studies of Arctic climate change in the Pleistocene and Neogene. As demonstrated in the proposal, this goal can be achieved by careful site selection, appropriate drilling technology, and applying multi-proxy approaches to paleoceanographic, paleoclimatic, and age-model reconstructions. We propose one primary drill site with three APC/XCB/RCB holes to recover multiple sections of the sediment sequence to ensure complete recovery for construction of a composite section.

ACEX2 objectives are key elements in the IODP New Science Plan, Theme 1 Climate and Ocean Change, especially Challenges 1 and 2.
Scientific Objectives

A complete Cenozoic sedimentary sequence from the central Arctic Ocean will be studied to answer the following key questions:

- Did the Arctic Ocean climate follow the global climate evolution during its course from early Cenozoic Greenhouse to late Cenozoic Icehouse conditions?
- Are the Early Eocene Climate Optimum (poor recovery in the ACEX record) and the Oligocene and Mid-Miocene warmings also reflected in Arctic Ocean records?
- Did extensive glaciations (e.g., the Ol-1 and Mi-1 glaciations) develop synchronously in both the Northern and Southern Hemispheres?
- What is the timing of repeated major (Plio-)Pleistocene Arctic glaciations as postulated from sediment echosounding and multi-channel seismic reflection profiling?
- What was the variability of sea-ice in terms of frequency, extent and magnitude?
- When and how did the change from a warm, fresh-water-influenced, biosilica-rich and poorly ventilated Eocene ocean to a cold, fossil-poor, and oxygenated Neogene ocean occur?
- How critical is the exchange of water masses between the Arctic Ocean and the Atlantic and Pacific for the long-term climate evolution as well as rapid climate change?
- What is the history of Siberian river discharge and how critical is it for sea-ice formation, water mass circulation and climate change?
- How did the Arctic Ocean evolve during the Pliocene warm period and succeeding cooling? How do the ACEX2 record correlate with the terrestrial record from the Siberian Lake Elgygytgyn?
- What is the cause of the major hiatus recovered in the ACEX record? Does this hiatus in fact exist?

Non-standard measurements technology needed to achieve the proposed scientific objectives.

The sites are located in the seasonally ice-covered central Arctic Ocean (southern Lomonosov Ridge), and will need mission specific vessels to perform the drilling in the pack ice (marginal ice zone). A well organized ice-management strategy and support by an icebreaker (e.g., RV Polarstern) are needed.

Proposed Sites

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Position (Lat, Lon)</th>
<th>Water Depth (m)</th>
<th>Penetration (m)</th>
<th>Brief Site-specific Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>LORI-5B</td>
<td>83.80, 146.48</td>
<td>1334</td>
<td>1250 0 1250</td>
<td>Recovery of a complete stratigraphic sedimentary record on the central Lomonosov Ridge to meet our highest priority paleoceanographic objective, the continuous long-term Cenozoic climate history of the central Arctic Ocean. (Alternate Site)</td>
</tr>
<tr>
<td>LORI-16A</td>
<td>80.78, 142.78</td>
<td>1752</td>
<td>1850 0 1850</td>
<td>Recovery of a complete stratigraphic sedimentary record on the southern Lomonosov Ridge to meet our highest priority paleoceanographic objective, the continuous long-term Cenozoic climate history of the central Arctic Ocean. (Alternate Site)</td>
</tr>
<tr>
<td>LR-02A</td>
<td>80.97, 142.47</td>
<td>1450</td>
<td>1300 0 1300</td>
<td>Recovery of a complete stratigraphic sedimentary record on the southern Lomonosov Ridge to meet our highest priority paleoceanographic objective, the continuous long-term Cenozoic climate history of the central Arctic Ocean (Alternate Site)</td>
</tr>
<tr>
<td>LR-01A</td>
<td>80.95, 142.97</td>
<td>1405</td>
<td>1225</td>
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Recovery of a complete stratigraphic sedimentary record on the southern Lomonosov Ridge to meet our highest priority paleoceanographic objective, the continuous long-term Cenozoic climate history of the central Arctic Ocean (Primary site)
Acrtic Ocean Paleoceanography: Towards a Continuous Cenozoic Record from a Greenhouse to an Icehouse World (ACEX2)

R. Stein¹, W. Jokat¹, H. Brinkhuis², L. Clarke¹, B. Coakley⁴, M. Jakobsson⁵, J. Matthiessen¹, M. O’Regan⁵, C. Stickley⁶, K. St. John⁷, E. Weigelt¹

¹Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany
²Institute of Environmental Biology, Utrecht University, Utrecht, The Netherlands
³School of Science and the Environment, Manchester Metropolitan University, Manchester, UK
⁴Geophysical Institute, University of Alaska, Fairbanks, USA
⁵Department of Geological Sciences, Stockholm University, Stockholm, Sweden
⁶Department of Geology, University of Tromsoe, Tromsoe, Norway
⁷Department of Geology & Environmental Science, James Madison University, Virginia, USA

1. Introduction and Background

A major element in the global climate evolution during Cenozoic times has been the transformation from warm Paleogene oceans with low latitudinal and bathymetric thermal gradients into the more recent modes of circulation characterized by strong thermal gradients, oceanic fronts, cold deep oceans and cold high-latitude surface waters (e.g., Miller et al., 1987; Zachos et al., 2001, 2008). Throughout the course of the Cenozoic, the climate on Earth has thus changed from one extreme (Paleogene Greenhouse lacking major ice sheets) to another (Neogene Icehouse with bipolar glaciation).

A strong greenhouse effect probably contributed to global warmth during the early Cenozoic. CO₂ concentrations of more than 2,000 ppm have been estimated for the late Paleocene and earliest Eocene periods (about 60 to 52 Ma) (Fig. 1; Pearson and Palmer, 2000; Lowenstein and Demicco, 2006; Royer, 2006; Zachos et al., 2008). Bottom temperatures in the early Eocene, the time of maximum Cenozoic warmth that peaked with the early Eocene Climatic Optimum (about 52 to 50 Ma), were of the order of 12-14°C, and large-scale continental ice sheets were probably absent (Fig. 1; Miller et al., 1987; Lear et al., 2000; Pearson and Palmer, 2000; Zachos et al., 2008; Escutia, Brinkhuis, Klaus et al., 2010). The climate in lowland settings along the Wilkes Land coast/Antarctica, for example, supported the growth of highly diverse, near-tropical forests characterized by mesothermal to megathermal floral elements (Pross et al., 2012). Based on stable isotope data of fossil mollusk shells from Ellesmere Island and Alaska, Paleocene temperatures of Arctic (80°N) coastal waters of about 10 to 22°C were reconstructed (Bice et al., 1996; Tripati et al., 2001).
The long-term history of Cenozoic high-latitude cooling starting at about 48 Ma, is characterized by four major steps in the early mid-Eocene (about 48-45 Ma), at the
Eocene/Oligocene boundary (near 34 Ma), in the mid-Miocene (at about 15 Ma), and in the late Pliocene (at about 3.5-2.6 Ma) (Fig. 1; Miller et al., 1987; Zachos et al., 1994, 2001; Lear et al., 2000). Reconstructions of past atmospheric CO₂ concentrations based on isotopic markers from marine algae (Pagani et al., 2005) and boron isotope composition of planktonic foraminifers (Pearson and Palmer, 2000), show – although with obvious differences in absolute values – distinct drops in atmospheric CO₂ between about 50 and 25 Ma that generally correspond to the global cooling trend and development of major polar ice sheets, except for the interval around the early mid-Eocene cooling (Fig. 1).

On Antarctica, large ice sheets likely first appeared near the Eocene/Oligocene boundary at about 34 Ma (“Oi-1 glaciation”; e.g., Shackleton and Kennett, 1975; Kennett and Shackleton, 1976; Miller et al., 1987, 1991; Lear et al., 2000; Zachos et al., 2008), coincident with decreasing atmospheric carbon dioxide concentrations and a deepening of the calcite compensation depth in the world’s oceans (van Andel, 1975; Pearson and Palmer, 2000; Coxall et al., 2005; Tripati et al., 2005). For the Northern Hemisphere, on the other hand, it was indirectly inferred from sub-Arctic ice-rafted debris records in the Norwegian-Greenland,
Iceland, and Irminger seas and Fram Strait area that glaciations began much later, i.e., in the middle Miocene as early as about 14 Ma (e.g., Fronval and Jansen, 1996; Wright and Miller, 1996; Thiede et al., 1998, 2011; St. John and Krissek, 2002). Based on more recent modeling results as well as new ODP/IODP sediment core data, however, this general picture has to be revised significantly (see below).

Although it is generally accepted that the Arctic Ocean is a very sensitive and important region for global climate change (IPCC reports: Houghton et al., 1996, Solomon et al., 2007; Serreze et al., 2000; ACIA 2004, 2005), this region is the last major physiographic province on Earth where the short- and long-term geological history is still poorly known (Fig. 2). Our ignorance is due to the major technological/logistical problems in operating within the permanently ice-covered Arctic region which makes it difficult to retrieve long and undisturbed sediment cores. Prior to 1990, the available samples and geological data from the central Arctic Basins were derived mainly from drifting ice islands such as T-3 (e.g., Clark et al., 1980) and CESAR (Jackson et al., 1985). During the last ~20 years, several international expeditions, e.g., Polarstern/Oden 1991 (Füttner, 1992), Louis St. Laurent/Polar Sea 1994 (Wheeler, 1997), Healy/Polarstern 2001 (Thiede, 2002), Healy/Oden 2005 (“HOTRAX“; Darby et al., 2005), Oden 2007 (“LOMROG“ 2007; Jakobsson et al., 2008), and Polarstern 2008 (Jokat, 2009), have greatly advanced our knowledge on central Arctic Ocean paleoenvironment and its variability through Quaternary times (for review see Stein, 2008). Prior to 2004, however, in the central Arctic Ocean piston and gravity coring was mainly restricted to obtaining near-surface sediments, i.e., only the upper 15 m could be sampled. Thus, all studies were restricted to the late Pliocene/Quaternary time interval, with a few exceptions. These include the four short cores obtained by gravity coring from drifting ice floes over the Alpha Ridge, where older pre-Neogene organic-carbon-rich muds and laminated biosiliceous oozes were sampled. These were the only samples recording the Late Cretaceous/Early Cenozoic climate history and depositional environment (e.g., Jackson et al., 1985; Clark et al., 1986; Firth and Clark, 1998; Jenkyns et al., 2004; Davies et al., 2009, 2011). In general, these data suggest a warmer (ice-free) Arctic Ocean with strong seasonality and high paleoproductivity, most likely associated with upwelling conditions.

With the successful completion of the Arctic Coring Expedition – ACEX (Expedition 302, the first Mission Specific Platform (MSP) expedition within IODP) in 2004, a new era in Arctic research began. For the first time, scientific drilling in the permanently ice-covered central
Arctic Ocean was carried out, penetrating 428 meters of Quaternary, Neogene, Paleogene and Campanian sediments (Fig. 3) on the crest of Lomonosov Ridge between 87 and 88°N (Backman, et al., 2006, 2008; Moran et al., 2006; Backman and Moran, 2008, 2009). This record provided a unique glimpse of the early Arctic Ocean history and its long-term change through Cenozoic times (see Chapter 3 for results and highlights). To date, the ACEX sites remain the one and only drill holes in the central Arctic Ocean (Fig. 2)!

While highly successful, the ACEX record also has three important limitations. Based on the original age model (Backman, et al., 2008), the ACEX sequence contains a large hiatus spanning the time interval from late Eocene to middle Miocene, i.e., 44.4 to 18.2 Ma, and encompassing nearly 45% of the Cenozoic history of Lomonosov Ridge (Fig. 3). This is a...
critical time interval, as it spans the time when prominent changes in global climate took place during the transition from the early Cenozoic Greenhouse world to the late Cenozoic Icehouse world (Fig. 1). Furthermore, generally poor recovery prevented detailed and continuous reconstruction of Cenozoic climate history. Finally, the second overall paleoceanographic objective of the original ACEX program, the high-resolution reconstruction of Arctic rapid climate change during Neogene to Pleistocene times, could not be reached because drilling on the southern Lomonosov Ridge was not carried out due to limited drilling time.

The above clearly justifies a return to the Lomonosov Ridge for a second MSP - type drilling campaign within IODP to fill these major gaps in our knowledge on Arctic Ocean paleoenvironmental history through Cenozoic times and its relationship to the global climate history. As will be demonstrated below, this goal can be achieved by careful site selection, appropriate drilling technology, and applying multi-proxy approaches to paleoceanographic, paleoclimatic, and age-model reconstructions.

2. Modern environment and geological setting of the Arctic Ocean

The Arctic Ocean is unique in comparison to the other world oceans: It is surrounded by the world’s largest shelf seas, is seasonally to permanently covered by sea ice, and is characterized by large, very seasonal river discharge which is equivalent to 10 % of the global runoff (Fig. 4; Aagaard and Carmack, 1989; Holmes et al., 2002; Jakobsson, 2002; for review see Stein 2008). The freshwater supply is essential for the maintainance of the ca. 200 m thick low-salinity layer of the central Arctic Ocean and, thus, contributes significantly to the strong stratification of the near-surface water masses, encouraging sea-ice formation. The melting and freezing of sea ice result in distinct changes in surface albedo, energy balance, and biological processes. Freshwater and sea ice are exported from the Arctic Ocean through Fram Strait into the North Atlantic. Changes in these export rates of freshwater would result in changes of North Atlantic as well as global oceanic circulation patterns. Because factors such as the global thermohaline circulation, sea-ice cover and Earth’s albedo have a strong influence on the earth’s climate system, climate change in the Arctic could cause major pertubations in the global environment.
Fig. 4. (A) Distribution of ice sheets and sea ice during past glacials, Present and a possible scenario of the future (Courtesy Martin Jakobsson, Stockholm University, 2012).

(B) Map showing the average distribution of sea-ice in the Arctic Ocean in September (1979-2004) and March (1979-2005); according to Maurer (2007; http://nsidc.org/data/atlas/). Locations of ACEX and ACEX2 sites are indicated.

(C) Arctic sea-ice cover and recent change. Locations of ACEX and ACEX2 sites are indicated.

(D) Arctic September sea-ice extent ($10^6$ km$^2$) from observations (thick red line) and 13 IPCC AR4 climate models together with the multi-model ensemble mean (solid black line) and standard deviation (dotted black line). The absolute minimum of 2007 is highlighted (from Stroeve et al., 2007, supplemented).
Due to complex feedback processes (collectively known as “polar amplification”), the Arctic is both the harbinger of change and the region that will be most affected by global warming. The need for further scientific drilling in the Arctic is motivated in part by climate change models predicting the greatest future temperature changes in polar regions, and because polar systems may be particularly sensitive to change now and in the past (e.g., IPCC Reports: Houghton et al., 1996; Solomon et al., 2007). There is a general consensus that the polar regions – and especially the Arctic Ocean and surrounding areas - are (in real time) and were (over historic and geologic time scales) subject to rapid and dramatic change. Over the last decades, for example, the extent and thickness of Arctic sea ice has decreased dramatically, and this decrease seems to be much more rapid than predicted by climate models (Fig. 4; e.g., Johannessen et al., 2004; ACIA, 2004, 2005; Francis et al., 2005; Serreze et al., 2007; Stroeve et al., 2007, 2011).

In order to study the Cenozoic climate evolution, we need to obtain undisturbed and complete sedimentary sequences. Scientific reasoning and seismic evidence indicate that such sequences in the Arctic Ocean have been accumulating on isolated ridges such as the Lomonosov Ridge. The elevation of the ridge, ~3 km above the surrounding abyssal plains, indicates that sediments on top of the ridge have been isolated from turbidites and are likely of purely pelagic origin (i.e., mainly biogenic, eolian, and/or ice-rafted) – an observation born out by countless shorter cores collected from icebreakers in the past decades, and previous drilling during ACEX. After Heezen and Ewing (1961) recognized that the mid-ocean rift system extended from the North Atlantic into the Arctic Ocean, it was realized that the 1800 km long Lomonosov Ridge was originally a continental fragment broken off of the Eurasian continental margin and became separated by sea-floor spreading. Regional aeromagnetic data indicated the presence of sea-floor spreading anomalies in the basins north and south of the Gakkel Ridge, the active spreading centre located in the middle of the Eurasian Basin (Kristoffersen, 1990 and references therein). The interpretation of the magnetic anomalies in terms of seafloor spreading and their correlation with the geomagnetic time scale allowed linking the evolution of the Eurasian Basin to the opening of the Norwegian-Greenland Sea. According to this correlation, seafloor spreading was probably initiated in the Eurasian Basin between chron 24 and 25 in the late Paleocene near 56 Ma (e.g., Kristoffersen, 1990). As the Lomonosov Ridge moved away from the Eurasian plate and subsided, pelagic sedimentation on top of this continental sliver began.
3. Results from previous drilling campaigns with special emphasis on ACEX results

Prior to ACEX, information on the long-term evolution of the paleoenvironmental Arctic Ocean history, especially the onset and variability of Northern Hemisphere glaciations, was restricted to the sub-Arctic region. For example, ODP Legs 151 (see Fig. 2 for site locations) and 152 recovered a series of Neogene pulses of ice rafting (14 Ma, 10.8-8.6 Ma, 7.2-6.8 Ma, 6.3-5.5 Ma, and in sediments younger than 5 Ma) in the North Atlantic and Yermak Plateau regions (Larsen et al., 1994; Thiede et al., 2011). However, it is not clear whether these reflect local Svalbard and Greenland ice expansion or whether the events can be correlated with processes in the central Arctic.

ACEX was an outstanding success for two reasons. First, the biggest technical challenge was to maintain the drillship’s location while drilling and coring in heavy sea ice over the Lomonosov Ridge. ACEX has proven that with an intensive ice-management strategy, i.e., a three-ship approach with two powerful icebreakers (Sovetskiy Soyuz and Oden) protecting the drillship (Vidar Viking) by breaking upstream ice floes into small pieces, successful scientific drilling in the permanently ice-covered central Arctic Ocean is possible. The icebreakers kept the drillship on location in 90% cover of multi-year ice for up to nine consecutive days, a benchmark feat for future drilling in this harsh environment. Second, the first scientific results comprise a milestone in Arctic Ocean research and future results of ongoing studies on ACEX material will certainly bring new insights into the Arctic Ocean climate history and its global significance. Some of these highlights are:

- The Arctic Ocean surface-water temperatures reached peak values around 25°C during the PETM Event (Sluijs et al., 2006, 2008) and at the end of the Early Eocene Climatic Optimum - EECO (Weller and Stein, 2008), which is notably higher than previous estimates of 10–15°C (Tripati et al., 2001) and indicates an even lower equator-to-pole temperature gradient than previously believed (Sluijs et al., 2006). In the middle Eocene, following the EECO, a strong step-wise drop in Arctic sea-surface temperature by about 15°C occurred (Fig. 5), contemporaneously with the onset/increase of Arctic sea ice as reflected in sea-ice diatoms and ice-rafted debris (St. John, 2008; Stickley et al., 2009, 2012; Stein et al., 2013).
- Near 49 Ma, a major occurrence of the freshwater fern *Azolla* and accompanying abundant freshwater organic-walled and siliceous microfossils indicate an episodic freshening of Arctic surface waters with cooler temperatures of about 10 °C during an 800,000-year interval. Although a deep-water connection did not exist between the Arctic Ocean basin and the other oceans at this time, the presence of freshwater in the Arctic may have triggered the initiation of sea-ice formation that increased albedo and contributed to global cooling (Brinkhuis et al., 2006; Moran et al., 2006).
Fig. 6. IRD mass accumulation rates (g cm$^{-2}$ ky$^{-1}$) in the $>$250 µm (dotted line and open circles) and 150-250 µm (black line and solid circles) size fractions of the Eocene to Pleistocene (270 to 0 mcd) section of the ACEX record (St. John, 2008, supplemented), along with isolated granules and pebbles (large gray circles) (from Backman, Moran, McInroy, et al., 2006) vs. age (Ma). Green line with red arrow marks onset of ice-rafting. Open arrows indicate major pulses of IRD input. The Mid-Miocene Climate Optimum (e.g., Flower and Kennet, 1995; Zachos et al., 2001) is marked as horizontal gray bar. Red numbers indicate “meters composite depth (mcd)”. On the right, an enlargement of the middle Eocene interval (44.5 – 47.5 Ma) of this dataset and the concentrations of needle-shaped sea-ice diatom Synedropsis spp. (Stickley et al., 2009) are shown.
Previous studies suggest that the Northern Hemisphere Glaciation (NHG) began no earlier than about 14 Ma (e.g., Thiede et al., 1998; Winkler et al., 2002), whereas glaciation of Antarctica began much earlier, i.e., as early as about 43 Ma (Lear et al., 2000). ACEX results, i.e., sea-ice diatom and IRD data, push back the date of Northern Hemisphere cooling and onset of sea ice into the Eocene as well. The first occurrence of sea-ice related diatoms, contemporaneously with IRD, was at about 47-46 Ma (when using the original ACEX age model of Backman et al., 2008) or ~ 43 Ma (when using the alternate chronology of Poirier and Hillaire-Marcel, 2011) (Figs. 3 and 6). Iceberg transport, however, was probably also present in the middle Eocene, as indicated by mechanical surface-texture features on quartz grains from this interval (St. John, 2008).

An early onset/intensification of NHGs during Eocene times is also supported by IRD records from the Greenland Basin ODP Site 913 (Eldrett et al., 2007; Tripati et al., 2008). These findings suggest that the Earth’s transition from the Greenhouse to the Icehouse world was bipolar, which points to greater control of global cooling linked to changes in greenhouse gases in contrast to tectonic forcing (Backman, et al., 2006, 2008; Moran et al., 2006; Stickley et al., 2009).

One of the most profound changes in the character of sedimentation in the ACEX record was the mid-Cenozoic shift from freshwater-influenced biosilica- and C\textsubscript{org}\textsuperscript{-}rich deposits of a poorly ventilated and isolated Eocene ocean to fossil- and C\textsubscript{org}\textsuperscript{-}poor glaciomarine silty clays of a well-ventilated Miocene Ocean (Fig. 7; Moran et al., 2006; Stein et al., 2006; Stein, 2007). Based on the original ACEX age model (Backman, et al., 2008), the transition between these two modes of sedimentation is obscured by a large hiatus spanning the time interval from late Eocene to middle Miocene, i.e., 44.4 to 18.2 Ma (Fig. 3). This change from euxinic to well-oxygenated open marine conditions was correlated to the tectonically controlled widening of the Fram Strait in the late early Miocene (~17.5 Ma), which allowed a critical two-way surface exchange between the Arctic Ocean and Norwegian Greenland Seas to commence (Jakobsson et al., 2007). The recent Os-Re isotope dates from the cross-banded and underlying Eocene age biosiliceous rich sediments, however, suggest that the transition from euxinic to well-oxygenated conditions may have occurred much earlier, i.e., already in the late Eocene (Poirier and Hillaire-Marcel, 2009, 2011).
Fig. 7. Record of total organic carbon (TOC) contents as determined in the composite ACEX sedimentary sequence (Stein 2007). Data on recovery, stratigraphy, and lithological units (1-4) and subunits (1/1 to 1/6) from Backman, Moran, McInroy et al. (2006). Cam = Campanian; LP = late Paleocene; Mid Mioc. = middle Miocene; L.Pl. = late Pleistocene. Map with Eocene paleogeography from Stickley et al. (2009).

- Dating of Arctic Ocean sediments is a classic problem in stratigraphy. However, ACEX could prove that, with combination of existing techniques such as micropaleontology, Be isotopes, cyclostratigraphy and magnetostratigraphy, a stratigraphic framework adequate to answer the key scientific questions, could be established for the Cenozoic time interval (Backman, et al., 2008; Fig. 3). ACEX results did also once and for all
confirm that we, at least in this part of the Arctic, have cm-scale rather than mm-scale sedimentation rates with implications for all paleoceanographic reconstructions based on sediment cores. A large mid-Cenozoic hiatus recognised in the original ACEX age model, however, was recently challenged by osmium isotope dates which suggest a condensed interval of very limited sedimentation (Fig. 3). The development of a multiproxy-based age model across a more expanded/continuous Eocene through Miocene section will be a major outcome of the proposed ACEX2 program. Furthermore, dating of Pliocene and Quaternary age sediments was also problematic in ACEX due to poor overlapping recovery. In ACEX2, the selection of sites in areas with higher surface water productivity (i.e. in the marginal ice zone), higher-resolution records, and complete and overlapping recovery in multiple holes, will provide a more robust framework for developing a Quaternary-Pliocene age model.

4. Scientific objectives and hypotheses to be tested

While the Arctic paleoceanographic and paleoclimate results from ACEX were unprecedented, key questions related to the climate history of the Arctic Ocean on its course from Greenhouse to Icehouse conditions during early Cenozoic times remain, largely due to the major mid-Cenozoic hiatus and partly low recovery of the ACEX record. In addition to elevated atmospheric $\text{CO}_2$ concentrations in the Cenozoic, other boundary conditions such as the freshwater budget, exchange between the Arctic and Pacific/Atlantic oceans as well as the advance and retreat of major circum-Arctic ice sheets have changed dramatically during the late Cenozoic. An understanding of how these boundary conditions have influenced the form, intensity and permanence of the Arctic sea ice cover can help improve our understanding of the complex modern ocean-atmosphere-ice system and how it has evolved with global climate (O’Regan et al, 2011). Therefore, the primary objectives of ACEX2 share several of those in the original 533-Full3 (ACEX) proposal, and also build on what we learned from ACEX:

**Scientific (Key) Objective 1: A complete characterization of the Cenozoic transition from Greenhouse to Icehouse in the Arctic.** The Cenozoic transition of the Earth’s climate from one extreme (Paleogene Greenhouse lacking ice) to another (Neogene Icehouse with bipolar glaciation characterized by an Antarctic continental ice-cap and seasonally variable but persistent sea-ice cover in the Arctic) is linked to increased latitudinal gradients and
oceanographic changes that connected surface and deep-sea circulation between high and low latitude oceans. The general Cenozoic cooling trend, however, is interrupted by warming intervals as well as short-term extreme cooling transients, such as the late Oligocene warming and the Mid-Miocene Climatic Optimum, and the Oi-1 Glaciation and the Mi-1 Glaciation (Fig. 1; Zachos et al., 2001, 2008; Coxall et al., 2005; Tripati et al., 2005).

Some of the related key questions for this objective are:

Did the Arctic Ocean climate follow the global trend shown in Figure 1? Are the Early Eocene Climate Optimum (poorly recovered in the ACEX record) and the Oligocene and Mid-Miocene warmings also reflected in Arctic Ocean records? Did extensive glaciations develop synchronously in both the Northern and Southern Hemispheres? Are the Oi-1 and Mi-1 glaciations bipolar (Fig. 1; Zachos et al., 2001, 2008), i.e., are there indications for major Northern Hemisphere glaciations at that time? The proposed ACEX2 sites are much closer to the Siberian shelf than the ACEX1 sites and thus should contain more clearly signals of past (Siberian) ice sheets if they have existed. What are the related scale and timing of short- and long-term sea-level changes? Does the mineralogical signature of sediments reveal changing source areas for Cenozoic glaciations, as was demonstrated in existing late Pliocene/Pleistocene records from ODP Leg 151 (Matthiessen et al., 2006)?

In addition, based on records of sediment and foraminiferal geochemistry, Tripati et al. (2005) report evidence for synchronous deepening and subsequent oscillations in the calcite compensation depth in the tropical Pacific and South Atlantic from 42 Ma, with a permanent deepening at 34 Ma, coinciding with changes in seawater oxygen isotope ratios. They suggest a lowering of global sea level through significant storage of ice in both hemispheres by at least 100 to 125 m. This hypothesis (not approved yet; cf., Edgar et al., 2007), i.e., the occurrence and variability of Northern Hemisphere glaciations during this time span, can be tested by the proposed drilling on southern Lomonosov Ridge.

During the major Pleistocene glaciations, it is generally accepted that huge ice sheets occupied western Eurasia, Greenland and North America and terminated at their continental margins (e.g., Svendsen et al., 2004; Ehlers and Gibbard, 2007). The exposed continental shelves in the Beringian region of Siberia, on the other hand, are thought to have been covered by a tundra landscape, i.e., large ice sheets did not exist at that time (Alekseev, 1997; Gualtieri et al., 2005). Based on detailed multibeam swath sonar system, sediment
echosounding and multichannel seismic reflection profiling along the East Siberian continental margin, Niessen et al. (2013) postulated that huge, km-thick marine ice sheets occurred repeatedly off Siberia during Pleistocene glacial intervals (Fig. 8), maybe even already since the Pliocene (Hegewald and Jokat, 2013). The existence of such huge ice sheets must have had a significant influence on Earth albedo and oceanic and atmospheric circulation patterns, not considered in climate models so far (Niessen et al., 2013). For proving this hypothesis, however, long complete, undisturbed and well-dated sedimentary sections are needed. These sequences are planned to be recovered from the southern Lomonosov Ridge by drilling at Site LR-01A (Fig. 8).
Even after several studies on ACEX material, the **variability of sea-ice in terms of frequency, extent and magnitude** remains a pressing scientific question. Specifically, there remains considerable debate concerning the onset and subsequent persistence of perennial sea-ice cover. Based on Fe-oxid and heavy-mineral data, Darby (2008) and Krylov et al. (2008) proposed that a perennial sea-ice cover was predominant in the central Arctic Ocean since the Middle Miocene. Matthiessen et al. (2009), on the other hand, stated that the co-occurrence of *Nematosphaeropsis* spp. and *Impagidinium* spp. found in the Neogene part of the ACEX sequence, points to seasonally open waters. How can these discrepancies be explained? New complete sedimentary sections from Lomonosov Ridge may prove or disprove the different hypotheses of onset, extent and variability of Arctic sea-ice cover.

**Scientific Objective 2: History of Arctic Bottom and Surface-Water Circulation.** Black biosiliceous silty clays and clayey silts rich in organic carbon were found throughout the upper early to middle Eocene section of the ACEX record, indicating poorly ventilated bottom waters and high but variable primary production (Stein et al., 2006; Jakobsson et al., 2007). When and how did the change to oxygenated bottom waters typical for the Neogene and Quaternary Arctic Ocean occur? Was it in the early-mid Miocene as proposed by Jakobsson et al. (2007) or the Late Eocene as proposed by Poirier and Hillaire-Marcel (2011)?

What are the implications for the gateway configurations of the Arctic and its connection to the World’s oceans? How critical is the exchange of water masses between the Arctic Ocean and the Atlantic and Pacific oceans for the long-term climate evolution as well as rapid climate change? High-resolution records of Neogene/Quaternary Arctic Climate in comparison with similar records from the North Atlantic (ODP Leg 151 and IODP Expeditions 303/306) and the Bering Sea (IODP Expedition 323) may help to answer this question.

**Scientific Objective 3: History of Arctic (Lena) River Discharge.** The more proximal location of the proposed sites in ACEX2 to the Siberian margin allows a detailed study of the history of Arctic (Lena) river discharge and its paleoenvironmental significance. In this context, the Miocene uplift of the Himalayan-Tibetan region is of particular interest as it may have triggered enhanced discharge rates of Siberian rivers and changed the fresh-water
balance of the Arctic's surface waters, considered to be a key factor for the formation of Arctic sea-ice and onset of major glaciations (Driscoll and Haug, 1998), a hypothesis to be tested by drilling.

**Scientific Objective 4: High-Resolution Characterization of the Pliocene Warm Period in the Arctic.** During the Pliocene warm period, sea surface temperature (SST) in several ocean basins was substantially warmer (Marlow et al., 2000; Haywood et al., 2005; Lawrence et al., 2006) and global mean surface temperature was estimated to be at least ~3°C higher than today (Haywood and Valdes, 2004). Furthermore, cooling in the surface ocean seems to have started at least 1 My before the intensification of the NHG as shown, for example, in the Eastern Equatorial Pacific (EEP), implying that while the growth of Northern Hemisphere ice sheets undoubtedly played a major role as a climatic feedback during the Plio-Pleistocene transition, it did not force or initiate EEP cooling (Lawrence et al., 2006). How did the Arctic Ocean evolve during the Pliocene warm period and succeeding cooling? How do the marine climate records correlate with terrestrial records obtained from the Siberian Lake Elgygytgyn (Brigham-Grette et al., 2013)?

**Scientific Objective 5: The “Hiatus Problem“.** What is the cause of the major hiatus spanning the late Eocene to early Miocene time interval in the ACEX record (based on the original age model of Backman, et al., 2008)? Does this hiatus in fact exist, or is it rather an interval of extremely reduced sedimentation rate as proposed by Poirier and Hillaire-Marcel (2009, 2011)? If there is a major hiatus, is it related to the subsidence history of Lomonosov Ridge? Was there a phase of uplift and exposure of the ridge in the Oligocene, tentatively linked to a transpressional/compressional episode in the formation of the Amundsen Basin caused in part by the northward motion of Greenland in the Paleogene (Brozena et al., 2003; O’Regan et al., 2008)? Was the hiatus a response to increased bottom-water currents during the opening of surface and deep-water connections via the Fram Strait (Moore et al., 2006)? Recovery of the complete mid-Cenozoic interval can be used to test these hypotheses.

**5. Relation to the IODP New Science Plan (NSP)**

Our highest-priority objective is getting a continuous record of the long-term climate history of the central Arctic Ocean, representing the transition from early Cenozoic Greenhouse
conditions to Neogene/Quaternary Icehouse conditions. This overall goal is directly related to Research Theme 1 of the NSP, *Climate and Ocean Change*, especially Challenges 1 and 2. It exactly follows a key element of the NSP (p. 74):

“If we consider the current increase of sea temperature in the Arctic and the rapid melting of ice sheets, and the potential for dramatic amplification of polar temperatures under elevated CO$_2$ conditions, we will have to consider the possibility of dramatic changes in the Earth’s climate. The differences between observations and simulations of past warmer climates are most profound in the polar regions, where the models tend to severely underestimate the warming inferred from paleo-proxy records. This potential for dramatic amplification of polar temperatures under elevated CO$_2$ conditions is important for predictions of sea ice and permafrost melting, and the future stability of ice sheets. The differences between north and south polar geography (a polar ocean versus a polar continent) offer an opportunity for ocean drilling to help resolve the complex linkages among the polar ocean, atmosphere, and high-latitude land surface processes. With such data we can better ground-truth Earth system models and quantify the strength of polar feedbacks.”

We will focus on the detailed reconstruction of Arctic ice-sheet history and sea-ice distribution under different boundary conditions during the Cenozoic, with a special emphasis on the comparison of the climatic evolution of the northern and southern high latitudes. Data from the high Northern Latitudes will provide critical boundary conditions needed to investigate discrepancies between proxy records and modeling results and may help to improve climate models. These key objectives are fully in line with the NSP (p. 16):

"Differences between observations and simulations of past warmer climates are most profound in the polar regions, where the models tend to severely underestimate the warming inferred from paleo-proxy records. This potential for dramatic amplification of polar temperatures under elevated CO$_2$ conditions is important for predictions of sea ice and permafrost melting, and the future stability of ice sheets. The differences between north and south polar geography (a polar ocean versus a polar continent) offer an opportunity for ocean drilling to help resolve the complex linkages among the polar ocean, atmosphere, and high-latitude land surface processes. With such data we can better ground-truth Earth system models and quantify the strength of polar feedbacks.“

The importance of proxy records for sea-ice variability, a key theme of the proposed expedition, is again highlighted in the NSP Summary:

"... decline of summer sea ice cover in the Arctic Ocean and polar ice covering Greenland and western Antarctica is occurring more rapidly than predicted by climate models. To better understand Earth’s response to rapid climate changes, and how different parts of Earth’s climate system interact to amplify or diminish the effects of increasing global temperatures, scientists must collect and analyze environmental information from deep-ocean sediments that were deposited millions to tens of millions of years ago when atmospheric CO$_2$ levels and global temperatures were much higher than today.“
ACEX2 records on the temporal and spatial variability will also provide information on time scales of ice-sheet variability and related sea-level change under different boundary conditions. This aspect is also a key theme in the NSP (p. 16):

“Proposed drilling strategy from pole to pole IODP drilling platforms to collect records linking climate, ice sheet, and sea level histories on geologic time scales. The climate history derived from these records is used to ground-truth and test the performance of numerical ice-atmosphere-ocean models, thus improving their ability to project future sea level rise.”

6. Drilling strategy: Site survey data, site characteristics, and drilling objectives

As the drill sites are located in the ice-covered Arctic Ocean, a mission-specific platform (MSP) is needed for the drilling operation. In comparison to the ACEX1 work area of 2004, ice conditions of ACEX2 are significantly less severe, especially when looking at the sea-ice cover in recent years. In 2007 and 2012, the area of proposed drilling operations was even completely ice-free during September (Fig. 4C). Furthermore, we will submit a Polarstern proposal for the next deadline (30 September 2014 for period 2016-2019) to get Polarstern as supporting icebreaker and laboratory ship (handling of ACEX2 cores: storing, logging, scanning; microscopy/stratigraphy, etc.; helicopter exchange; extended Science Party) during ACEX2. Polarstern may contemporaneously carry out some additional (and supplementary) research in the ACEX2 area (e.g., seismic profiling, sediment coring). If the Polarstern proposal will be reviewed positively and the ship will become available to support ACEX2, these activities may be handled as a complementary contribution with funding from a third party source outside IODP/ECORD (“Complementary Project Proposal (CPP)“?).

6.1. Site survey data

Deep-penetration reflection seismic profiles were acquired from the Lomonosov Ridge on icebreaker-based expeditions between 1991 and 2009 (Jokat et al., 1992, 1995, 1999; Jokat, 2005, 2009; Kristoffersen et al., 1997; Darby et al., 2005; Jakobsson, 2007b). The first high-resolution chirp profiles were collected in 1996 (Jakobsson, 1999). In 1999, the SCICEX
program collected high-resolution chirp sub-bottom profiler data, swath bathymetry and sidescan sonar backscatter data from an USN nuclear submarine (Edwards and Coakley, 2003), contributing significantly to the much improved bathymetric chart of the Arctic Ocean (Jakobsson et al., 2008, 2012). In 1995 and 1998, an intensive Parasound survey in conjunction with a coring program of near-surface (Quaternary) sediments was carried-out in the area of the proposed sites (Stein et al., 1997; 2001; Jokat et al., 1999). Some site survey data from this area (lines AWI 98550, 98565, and 98567; Fig. 9a) are already included in the IODP Site Survey Data Bank; the new data will be uploaded to the SSDB for the November 01 deadline.

Based on the more recent Polarstern site survey in 2008 (Jokat, 2009), the primary and alternate ACEX2 sites were selected (Fig. 9a). Main factor for the site selection based on seismic data is the mapping of continuous and laterally conformable reflectors indicating continuous sedimentary sequences. Locations with any indications of faults, slumps or hiatuses were avoided to ensure flat-lying, unfaulted, undeformed and well-stratified deposits. Furthermore, locations were selected indicating appropriate thicknesses and depths feasible for drilling into and through the strata of interest. Depth-velocity information for estimating the thickness of the sedimentary units was derived from sonobuoys (Ickrath and Jokat, 2009) and interval velocities calculated from stacking velocities of selected CDP gathers (Weigelt et al., 2013).

The age control for the sedimentary units (Fig. 9b) was estimated via links of seismic lines to drill site data of the Chukchi Shelf, ACEX-drilling on central Lomonosov Ridge, and onshore geology from the New Siberian Islands (Fig. 10; Weigelt et al., 2013). Referring to basin-wide similarities of reflection pattern and configuration of strata, two distinguished seismic units were mapped throughout the area and are the constraints for dating the remaining units.
Fig. 9. (a) Map indicating seismic profiles (bold numbers AWI lines) and location of IODP Expedition 302 (ACEX) drill site and the new proposed (ACEX2) drill sites on Lomonosov Ridge (LR-01A, LR-02A, LORI-5B, LORI-15A, and LORI-16A). (b) Seismic profile across Site LR-01A with main seismic units and mean sedimentation rate. Unit thicknesses were calculated using velocities from sonobuoys; see (a) for locations. Gray box in (a) shows HOTRAX study area.
Fig. 10: Example of seismic sections (locations on map: red lines) demonstrating conformities in reflection pattern, marker horizons and reflector configurations across large parts of the Siberian part of the Arctic Ocean. These similarities enable a data-transfer from remote drill sites (map: blue circles) onto seismic profiles (map: yellow lines) (Weigelt and Jokat, submitted). Age-information was extrapolated from 1. drill sites on the Chukchi Shelf (Sherwood et al., 2002), 2. ACEX-drilling on the central Lomonosov Ridge (Moran et al., 2006), 3. onshore geology from the New Siberian Islands (Franke et al., 2004; Kos’ko and Korago, 2009). In these examples marker horizons defined and inferred via the drill sites on the Chukchi Shelf after Hegewald and Jokat (2013) are shown: Top of Miocene (yellow), Top of Oligocene (pink), Base of Tertiary (blue), and lower Cretaceous Unconformity (green).

The lower one, a pronounced sequence of high-amplitude reflectors is the most striking feature in the Siberian Arctic Ocean. It indicates a strong and widespread change in depositional conditions. Originally - in the 708 prepoposal - the top of this reflector sequence (“pink” marker, Fig. 9b) was proposed as post-rift subsidence sequence. But based on the new data and correlations (Hegewald and Jokat, 2013; Weigelt et al, 2013), the top of the reflector sequence is interpreted to be much younger, i.e., presenting the base of the Miocene. Likely the whole high-amplitude reflector sequence developed during Eocene-Oligocene times after the breakup of the Eurasian Basin, followed by a reorientation of Arctic Plates during the Oligocene, and accompanied by a widespread regression of sea level. During the Oligocene,
the Fram Strait opened gradually, and a modern current system evolved in the Arctic Ocean since Early Miocene times. The reflector band likely corresponds to the hiatus, or extremely condensed lithologic unit recorded on the ACEX site on the central Lomonosov Ridge. Consequently, an age of latest Oligocene/Early Miocene is assigned to the top of the reflector sequence (i.e., the “pink” reflector in ~965 mbsf at Site LR-02A and in ~835 mbsf at Site LR-01A; Fig. 9b). An age estimate for the base of the reflector band ("orange" reflector in ~1270 mbsf at Site LR-02A and in ~1140 mbsf at Site LR-01A; Fig. 9b) is less clear, but most likely corresponds to base of Eocene (~56 Ma) times.

The second marker unit detected on the seismic lines parallels the seafloor in a depth of about 200ms (i.e., the “yellow” reflector in ~220 mbsf at Site LR-02A and in ~175 mbsf at Site LR-01A; Fig. 9b). It is characterized by a change from weak-amplitude to high-amplitude reflectors and interpreted to mark the transition to large-scale glaciation of the Northern Hemisphere during the Pliocene. From correlation of seismic profiles and drill site data (Hegewald and Jokat, 2013), the age of the yellow reflector is 5.3 Ma (base of the Pliocene). Based on this age model, the mean sedimentation rate for the entire LR-01A and LR-02A sequence is about 3.7 and 4 cm/ky, respectively, i.e., significantly higher than at the ACEX Site (see below).

The preferred Site LR-01A is located on perpendicular crossing seismic lines (Fig. 9a) on which continuous and widespread strata are documented. This site would enable an extrapolation of drilling data via seismic profiles onto strata along the Lomonosov Ridge, and across the Ridge into the adjacent Amundsen and Makarov Basins. Pliocene strata of 175 m, and Miocene strata of about 660 m thickness, respectively can be sampled. The target band of high-amplitude reflectors lies in a depth of 835 mbsf, Early Eocene/Palaeocene strata probably can be reached at 1140 mbsf (Fig. 9b). At the alternate site LR-02A, average sedimentation rates are slightly higher, but the basement depth (“purple” reflector) is significantly deeper (see below).

Although we are confident in reaching Eocene sediments in the lowermost part of the selected sites, we cannot guarantee that lower Eocene sediments will be drilled. We think, however, that even if we would miss these sediments, the recovery of a thick continuous Oligocene-Miocene sequence is such a major step forward in Arctic and global climate research and would enable us to address key primary scientific objectives described here, that it would
justify carrying out ACEX2 as proposed.

6.2. Site characteristics: Lithologies, age model, sedimentation rates

Some general predictions about the type of sediments that will be recovered at the proposed ACEX2 sites can be obtained from the ACEX sequence and a couple of gravity cores taken in the vicinity of the ACEX2 area. Based on the visual core description and smear slide analysis as well as TOC and XRD data determined in core catcher samples, the ACEX sequence was divided into four main lithologic units (Fig. 7):

**Unit 1** (Top to 223.6 mcd; Quaternary to Middle Eocene) is dominated by silty clay, ranging from light olive brown at the top, through olive and gray to very dark gray at the bottom; color banding is strong. Millimeter-to-centimeter-scale sandy lenses and isolated pebbles occur in Unit 1. Unit 1 is subdivided into 6 subunits. Based on the original ACEX age model, a major hiatus was identified at about 198.7 mcd separating subunits 1/6 and 1/5 and spanning the time interval from about 44.4 to 18.2 Ma; another shorter hiatus lasting 2.2 my, occurs within Subunit 1/3 in the late Miocene 9.4-11.6 Ma (Fig. 3; Jakobsson et al., 2007; Backman et al., 2008). Subunit 1/5 is outstanding due to its very prominent black and white color banding ("Zebra Unit“; Fig. 3).

**Unit 2** (223.6 to 313.6 mcd; Middle Eocene) is dominated by very dark gray mud-bearing biosiliceous ooze with submillimeter-scale laminations as well as isolated pebbles.

**Unit 3** (about 313.6 to 404.8 mcd; Late Paleocene to Early Eocene) is dominated by very dark gray clay with submillimeter-scale laminations. Units 3 and 4 are separated by a second major hiatus representing the time interval of about 56 to 79 Ma (Backman, et al., 2008).

**Unit 4** (424.50 mbsf to 427.63 mbsf; Campanian) is dominated by very dark gray clayey mud and silty sands.

Whereas the upper (middle Miocene to Quaternary) part of the ACEX sequence (Subunits 1/1 to 1/4) is composed of silty clay with very low OC contents of < 0.5%, i.e., values very similar to those in upper Quarternary records from Lomonosov Ridge (Stein et al., 2004), the
Campanian and Paleogene sediments (Units 2 to 4) are characterized by high TOC values of 1 to >5% (Fig. 7). In Subunit 1/5 (about 193 to 199 mcd; late early Miocene) characterized by distinct gray/black color bandings, even OC contents up to 14.5% were measured in samples from the black horizons (Fig. 7). Hence, organic rich sedimentation, with good potential for the preservation of organic and siliceous walled microorganisms, can be expected for Eocene age sediments and may also characterize Oligocene-Miocene sediments, if the early mid-Miocene opening of the Fram Strait was the major factor in driving the ventilation of the Arctic (Jakobsson et al., 2007).

Based on the original ACEX age model, sedimentation rates in the region of the ACEX sites (87°56’N, 140°E) are between about 0.8 and 2.4 cm/ky (Fig. 3; Backman, et al., 2008). Following the recent Os-Re isotope age model, the hiatus was instead interpreted as a period of very low sedimentation rates of 0.2 cm/ky for the middle part of the sequence representing the late Eocene to early Miocene time interval (Fig. 3).

During Polarstern Expedition ARK-XI/1 in 1995 (Rachor, 1997), 10 gravity cores were recovered on a transect across Lomonosov Ridge very close to the proposed ACEX2 primary sites (Fig. 11). Main lithologies of these <8 m long sediment cores are brown, beige, gray to dark gray, and olive green, partly bioturbated or laminated silty clays, representing Marine Isotope Stages (MIS) 6 to 1 (Fig. 11; Stein et al., 1997, 2001). The dark gray lithologies in the lower part of the more eastern cores (MIS 6) are characterized by increased organic-carbon contents of > 1% (Stein et al., 2001; Stein, 2008). Sand-sized material is more or less absent in these sequences. For cores PS2757 and PS2761, a huge amount of sedimentological, geochemical and mineralogical data (i.e., grain-size distributions; heavy, bulk and clay mineralogy; organic-carbon composition; biomarker data including IP_{25} as sea-ice proxy; MSCL logging data; paleomag, etc.) are available and successfully used for reconstruction of past glaciations, oceanic circulation patterns, depositional environment, etc. during the late Quaternary time interval (e.g., Behrends, 1999; Müller, 1999; Stein et al., 2001; Stein, 2008, unpubl. data). Mean sedimentation rates vary between 3.5 and 6 cm/ky. That means, these are values very similar to those estimated for the proposed Site LR-01A (and alternate LR-02A) based on seismic stratigraphy (Fig. 9b).
Fig. 11. Transect of sediment cores recovered across the southern Lomonosov Ridge during Polarstern Expedition ARK-XI/1. Main lithologies and isotope stratigraphy of six selected cores are shown (from Stein et al., 1997, supplemented).
6.3. Drilling and logging objectives

We propose one primary drill site on southern Lomonosov Ridge, Site LR-01A, located on crossing point of line AWI-98597 and line AWI-20080160 (Fig. 9a). At this site, we propose drilling three APC/XCB/RCB holes down to basement (the “purple” reflector in ~1225 mbsf; Fig. 9b). This is required to ensure recovery of a complete composite stratigraphic sediment record and to meet our highest priority paleoceanographic objective, the continuous long-term Cenozoic climate history of the central Arctic Ocean. Based on its protected location and the existing seismic profiles, a continuous record without a major hiatus is very probable. Logging should be carried out at one of the holes. For the entire drilling, coring, and logging activities, a total 29 days is estimated. As alternate drilling locations Site LR-02A, LORI-16A and LORI-05B (located on line AWI-20080160, AWI-98597 and AWI-98565, respectively; Fig. 9a) are proposed.

If time is left after finishing all activities at Site LR-01A, we propose a secondary drill site with three APC holes to about 250 mbsf (~4.5 days of operations) at alternate sites LR-02A or LORI-16A, both characterized by higher sedimentation rates. This permits some higher-resolution studies of Plio-Pleistocene Arctic climate change.

7. Methodology and scientific outcome

As shown by the ACEX studies, getting a reliable age model for a Cenozoic sedimentary sequence is possible when using a multi-proxy approach. Furthermore a large number of common as well as new proxies have been successfully used for reconstructions of past sea-ice cover, ice-sheet history, oceanic circulation patterns, primary productivity, oxygenation of deep-water sphere etc (e.g., Backman and Moran, 2008, 2009). In Figure 12, a large number of these different approaches applicable to studying Arctic sediments are summarized.

- An age model of the ACEX2 will be based on a combination of existing techniques such as micropaleontology (dinoflagellates, silicoflagellates, diatoms), Be isotopes, Os-Re isotopes, cyclostratigraphy and magnetostratigraphy (Backman et al., 2006, 2008; Frank et al., 2008; O’Regan et al., 2008; Poirier and Hillaire-Marcel, 2009, 2011).
Fig. 12. A compilation of methods to be used for studying ACEX2 material.

- For reconstruction of past sea-ice cover well established micropaleontological proxies (dinoflagellate cysts, diatoms etc.) (e.g., de Vernal et al., 2001; Stickley et al., 2009) as well as grain-size data/IRD and mineralogical and inorganic geochemical tracers (e.g., St. John, 2008; Darby, 2003, 2008; Stein, 2008; Krylov et al., 2008; Jakobsson et al., 2010; Polyak et al., 2010; Fagel et al., 2012; Immonen et al., 2011) will be studied. In addition, a newly developed biomarker approach based on the determination of specific highly-branched isoprenoids (\( \text{IP}_{25} \)) may give even more quantitative information of sea-ice distribution (e.g., Belt et al., 2007; Müller et al., 2009, 2011; Stein et al., 2012; Belt and Müller, 2013). Very recently, \( \text{IP}_{25} \) was found in sediments from ODP-Leg 151 sites 911 and 910, indicating that this biomarker approach for sea-ice reconstruction can be successfully used at least back to 4 Ma (Stein and Fahl, 2013 and unpubl. data).

- Grain-size and surface texture data, major and minor elements, mineral composition, neodymium and strontium isotopes, terrigenous biomarkers will all be used to reconstruct transport processes and pathways of sediments, terrigenous sediment input (by icebergs/sea ice, rivers, and winds), oceanic circulation patterns, and circum-Arctic ice-sheet history (e.g., Wahsner et al., 1999; Phillips and Grantz, 2001; Tütken
et al., 2002; Viscosi-Shirley et al., 2003; Spielhagen et al., 2004; Haley et al., 2008a, 2008b; Stein, 2008; St. John, 2008; Strand et al., 2008; Gleason et al., 2009; März et al., 2010; Martinez et al., 2009; Fagel et al., 2012; Immonen, 2013; Jang et al., 2013).

The reconstruction of sea-surface conditions (temperature, salinity, and primary productivity) will be carried out by means of specific biomarker approaches (TEX$_{86}$ and U$^{k}_{37}$; alkenones, sterols, n-alkanes, δD, etc.), Mg/Ca ratios of forams and ostracods, faunal and floral composition, and transfer function techniques, etc. (e.g., de Vernal et al., 2001; Brinkhuis et al., 2006; Sluijs et al., 2006, 2009; Stein, 2008; Weller and Stein, 2008; Cronin et al., 2012).

Information about deep-water ventilation can be obtained from faunal composition, specific biomarkers, and major and minor elements (Sluijs et al., 2006; Cronin et al., 2008; Weller and Stein, 2008; März et al. 2011; Kender and Kaminski, 2013).

**Summary**

The polar regions – and especially the Arctic Ocean and surrounding areas - are (in real time) and were (over historic and geologic time scales) subject to rapid and dramatic change because of complex feedback processes (collectively known as “polar amplification”). The cascades of feedback processes that connect the Arctic cryosphere, ocean and atmosphere remain incompletely constrained by observations and theory and are difficult to simulate in climate models. A complete Cenozoic record from the Arctic (as to be obtained within ACEX2) is needed to assess the sensitivity of the Earth’s climate system to changes of different forcing parameters (e.g. CO$_2$) and to test the reliability of climate models by evaluating their performance under conditions very different from the modern climate. Precise knowledge of past rates and scales of climate change are the only means to separate natural and anthropogenic forcings and will enable us to further increase the reliability of prediction of future climate change. While the Arctic paleoceanographic and paleoclimate results from ACEX were unprecedented, key questions related to the climate history of the Arctic Ocean on its course from Greenhouse to Icehouse conditions during Cenozoic times remain, largely due to the major mid-Cenozoic hiatus and partly low recovery of the ACEX record. We are convinced that our ACEX2 key goal, i.e., getting a complete record of Cenozoic climate history, can be achieved by careful site selection, appropriate drilling technology, and applying multi-proxy approaches to paleoceanographic, paleoclimatic, and age-model reconstructions.
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Arctic Ocean Paleoceanography: Towards a Continuous Cenozoic Record from a Greenhouse to an Icehouse World (ACEX2)

List of proponents

Ruediger Stein  Alfred Wegener Institute for Polar and Marine Research
Am Alten Hafen 26, 27568 Bremerhaven, Germany
E-mail: Ruediger.Stein@awi.de
(Organic Geochemistry, Sedimentology, Paleoceanography)

Wilfried Jokat  Alfred Wegener Institute for Polar and Marine Research
Am Alten Hafen 26, 27568 Bremerhaven, Germany
E-mail: Wilfried.Jokat@awi.de
(Geophysics)

Henk Brinkhuis  Institute of Environmental Biology, Faculty of Science,
Utrecth University, Laboratory of Palaeobotany and Palynology
Budapestlaan 4, 3584 CD Utrecht, The Netherlands
Email: H.Brinkhuis@uu.nl
(Palynology/Paleogene, Paleoecology, Paleoceanography)

Leon Clarke  Division of Chemistry and Environmental Sciences
School of Science and the Environment
Faculty of Science and Engineering
Manchester Metropolitan University
Oxford Road, Manchester, M1 5GD, UK
E-mail: l.clarke@mmu.ac.uk
(Inorganic Geochemistry, Paleoceanography)

Bernard Coakley  Geophysical Institute and
Chair Department of Geology and Geophysics
University of Alaska Fairbanks
E-mail: Bernard.Coakley@gi.alaska.edu
(Geophysics)

Martin Jakobsson  Department of Geology and Geochemistry
Stockholm University
106 91 Stockholm, Sweden
E-mail: martin.jakobsson@geo.su.se
(Sediment Acoustics, Bathymetry, Paleoceanography)

Jens Matthiessen  Alfred Wegener Institute for Polar and Marine Research
Am Alten Hafen 26, 27568 Bremerhaven, Germany
E-mail: Jens.Matthiessen@awi.de
(Palynology/Quaternary-Neogene, Paleoceanography)
Matthew O’Regan  Department of Geological Sciences
Stockholm University
SE-106 91 Stockholm, Sweden
E-mail: matt.oregan@geo.su.se
(Sedimentology, Physical Properties, Stratigraphic Correlation)

Catherine Stickley  Department of Geology
University of Tromsoe
Dramsveien 201
NO-9037 Tromsoe, Norway
E-mail: catherine.stickley@gmail.com
(Diatoms/Neogene-Paleogene; paleoceanography)

Kristen St. John  Department of Geology and Environmental Science
James Madison University, Harrisonburg, VA 22807, USA
E-mail: stjohnke@jmu.edu
(Sedimentology)

Estella Weigelt  Alfred Wegener Institute for Polar and Marine Research
Am Alten Hafen 26, 27568 Bremerhaven, Germany
E-mail: Estella.Weigelt@awi.de
(Geophysics)
Arctic Ocean Paleoceanography: Towards a Continuous Cenozoic Record from a Greenhouse to an Icehouse World (ACEX2)

List of potential reviewers of the ACEX2 proposal

Jan Backman  
Department of Geology and Geochemistry  
Stockholm University  
106 91 Stockholm, Sweden  
E-mail: Jan.Backman@geo.su.se

Hans-Jürgen Brumsack  
Institute for Chemistry and Biology of the Marine Environment (ICBM)  
Oldenburg University  
26111 Oldenburg  
Germany  
Tel.: (+49) 441-798-3584  
Fax: (+49) 441-798-3404  
Mail: brumsack@icbm.de

Tom Cronin  
Eastern Earth Surface Processes Team  
U.S. Geological Survey  
926A USGS National Center  
Reston VA 20192  
USA  
tcronin@usgs.gov

Dennis A. Darby  
Dept. of Ocean, Earth, & Atmospheric Sciences  
Old Dominion University  
Norfolk, VA 23529  
(757) 683-4701  
Email: ddarby@odu.edu

Ian Harding  
National Oceanography Centre  
University of Southampton  
Tel: 02380 592071  
Contact Email: ich@noc.soton.ac.uk
Hugh Jenkyns  
Department of Earth Sciences  
South Parks Road  
OXFORD OX1 3AN, UK  
Tel: 44-1865-272023  
Fax: 44-1865-272072  
Email: Hugh.Jenkyns@earth.ox.ac.uk

Rick Jordan  
Department of Earth and Environmental Sciences  
Faculty of Science  
Yamagata University  
1-4-12 Kojirakawa-machi  
Yamagata 990-8560, Japan  
sh081@kdw.kj.yamagata-u.ac.jp

Kate Moran  
NEPTUNE Ocean Networks Canada  
University of Victoria  
PO BOX 1700 STN CSC  
Victoria, BC V8W 2Y2, Canada  
Email: kmoran@uvic.ca

Ted Moore  
Micropaleontologist (radiolarians)  
Geological Sciences  
University of Michigan  
Ann Arbor MI 48109-1063  
USA  
tedmoore@umich.edu

Heiko Pälike  
MARUM, Bremen University  
Leobener Straße  
28359 Bremen, Germany  
Tel +49 (0)421 218 65980  
Fax +49 (0)421 218 9865980  
email: hpaelike@marum.de

James Zachos  
Earth & Planetary Sciences  
University of California Santa Cruz,  
Santa Cruz, Ca 95064, USA  
Email: jzachos@ucsc.edu
Curriculum Vitae

Born February 09, 1954, in Wilhelmshaven, Germany; married, five children.

1977: Vordiplom (B.S. degree) in geology, Technical University of Clausthal-Zellerfeld, Germany
1980: Hauptdiplom (M.S. degree) in geology, Kiel University, Germany
1984: Promotion (Ph.D.) in geology, Kiel University, Germany
1984-1986: Research scientist at the Institute for Petroleum and Organic Geochemistry, KFA Jülich, Germany
1986-1990: Assistant professor at the Institute for Geosciences and Lithosphere Research, Giessen University, Germany; November 1990: Habilitation and "Privatdozent" (Associate professor)
Since February 1991: Senior research scientist (PI of the Arctic Marine Geology Group) at the Alfred-Wegener-Institute for Polar and Marine Research, Bremerhaven, Germany
1991-2002: "Privatdozent" at the Faculty of Geosciences, Bremen University, Germany
February-June 2002: Research stay at the Institute of Ocean Sciences, Sidney/Canada
Since May 2003: Professor at the Faculty of Geosciences, Bremen University, Germany

Expertise Sedimentology - Organic Geochemistry - Paleoceanography

Major research interests (Key words)
- Paleoclimate and paleoceanography of the Arctic Ocean and adjacent Eurasian continental margin, and the North Atlantic Ocean.
- History of circum-Arctic ice sheets and paleoceanic circulation patterns.
- Arctic Ocean organic carbon flux and its relationship to surface-water productivity, sea-ice cover, sea-surface temperature, and terrigenous input; biomarker approach: IP25, Uk37, TEX86).
- The paleoenvironment of the early (Mesozoic/Cenozoic) Arctic Ocean and its transition from Greenhouse to Icehouse conditions.

Involvement in the Deep Sea Drilling Project (DSDP), Ocean Drilling Program (ODP), and Integrated Ocean Drilling Program (IODP)

  October 2005 - September 2007 co-chair of SSEP
- Representative of Germany/ECORD in the IODP Science Planning Committee (SPC) (2009 - 2011)
- Representative of Germany in the ECORD Science Support and Advisory Committee (ESSAC) (since 2007)
  Incoming ESSAC Vice-chair (October 2008 – September 2009)
  ESSAC Chair (October 2009 – September 2011)
  Outgoing ESSAC Vice-chair (October 2011 – March 2013)
- Representative of Germany/ECORD in the IODP *Scientific Implementation and Policy Committee* (SIPCOM) (2011 – September 2013)

- Co-Koordinator von IODP Germany (since 2009)
  http://www.bgr.bund.de/DE/Themen/MarineRohstoffforschung/IODP/Koordinationsbuero/koordinationsbuero_node.html

- Member of the ECORD *Magellan-Plus Steering Committee* (since 2011)

**Participant of international expeditions**

* Meteor-Cruise 60 (NE-Atlantic, Mar-Apr 1982)
* DSDP-Leg 90 (SW-Pacific, Nov 82-Jan 1983)
* ODP-Leg 105 (Baffin Bay, Labrador Sea; Aug-Oct 1985)
* ODP-Leg 108 (NE Atlantic; Feb-Mar 1986)
* ODP-Leg 128 (Japan Sea, Aug-Oct 1989)
* Polarstern-Cruise ARK-VIII/3 (Central Arctic, Aug-Oct 1991)
* ODP-Leg 151 (Arctic Gateways, Aug-Oct 1993)
* Polarstern-Cruise ARK-XI/1 (Kara/Laptev Sea and adjacent continental margin)
* ACSYS-Expedition (Swedish Icebreaker Oden; Central Arctic Ocean, Jul-Sep 1996)
* Polarstern-Cruise ARK-XIII/2 (Yermak Plateau, Jun-Aug 1997; Chief-scientist)
* Polarstern-Cruise ARK-XIV/1a (Alpha Ridge, Lomonosov Ridge; Aug-Sep 1998)
* Akademik Boris Petrov Cruise 1999 (Kara Sea, Aug-Sep; Co-chief-scientist)
* Akademik Boris Petrov Cruise 2000 (Kara Sea, Aug-Sep; Co-chief-scientist)
* Akademik Boris Petrov Cruise 2001 (Kara Sea, Aug-Sep; Co-chief-scientist)
* Polarstern-Cruise ARK-XX/3 (Yermak Plateau, Sep-Oct 2004; Chief-scientist)
* IODP-Leg 302 (Lomonosov Ridge, Aug 2004; Member of Science Party)
* IODP-Leg 306 (North Atlantic Paleooceanography, Mar-Apr 2005; Co-chief scientist)
* Merian-Cruise MSM 12/2 (Eirik Drift/Labrador Sea, Jun-Jul 2009)
* Araon (Test) Cruise (Japan Sea, June 2011)
* Polarstern-Cruise ARK-XXVI/3 (Mendeleev Ridge/East Sib. Sea, Aug-Oct 2014; chief scientist)

**Publications**

In total > 190 peer-reviewed publications in international scientific journals

**Five selected (ACEX-related) publications**


IODP Site Summary Forms:

Form 1 – General Site Information

Section A: Proposal Information

Title of Proposal: Arctic Ocean Paleooceanography: Towards a Continuous Cenozoic Record from a Greenhouse to an Icehouse World (ACEX2)

Date Form Submitted: 2013-10-04 22:40:44

Site Specific Objectives with Priority (Must include general objectives in proposal)
Recovery of a complete stratigraphic sedimentary record on the central Lomonosov Ridge to meet our highest priority paleoceanographic objective, the continuous long-term Cenozoic climate history of the central Arctic Ocean. (Alternate Site)

List Previous Drilling in Area:
IODP Expedition 302 (ACEX)

Section B: General Site Information

Site Name: LORI-5B

If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#

Latitude: 83.80

Longitude: 146.48

Coordinate System: WGS 84

Priority of Site: Primary: no, Alt:

Area or Location: central Lomonosov Ridge

Jurisdiction: International waters

Distance to Land: 900 (km)

Water Depth (m): 1334
### Section C: Operational Information

#### Proposed Penetration (m):

<table>
<thead>
<tr>
<th>Sediments</th>
<th>Basement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1250</td>
<td>0</td>
</tr>
</tbody>
</table>

Total Sediment Thickness (m): 1750

Total Penetration (m): 1250

#### General Lithologies:
- Silty clay, clay, biosiliceous ooze; siltstone, claystone; some ice-rafted debris

#### Coring Plan:
- (Specify or check)

<table>
<thead>
<tr>
<th>APC</th>
<th>XCB</th>
<th>MDCB</th>
<th>PCS</th>
<th>RCB</th>
<th>Re-entry</th>
</tr>
</thead>
<tbody>
<tr>
<td>✔</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>✔</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

One drill site with three APC/XCB/RCB holes down to about 1250 mbsf to recover multiple sections of the sediment sequence to ensure complete recovery for construction of a composite section (Alternate Site)

#### Wireline Logging Plan:
- Standard Measurements
  - WL
  - LWD
  - Porosity
  - Density
  - Gamma Ray
  - Resistivity
  - Sonic (∆t)
  - Formation Image (Res)
  - Check-shot (upon request)

- Special Tools
  - Magnetic Susceptibility
  - Magnetic Field
  - Borehole Temperature
  - Nuclear Magnetic Resonance
  - Geochemical
  - Side-Wall Core Sampling
  - Others:

#### Max. Borehole Temp.:

- °C

#### Mud Logging:
- (Riser Holes Only)
  - Cuttings Sampling Intervals
    - from m to m m intervals
    - from m to m m intervals

#### Estimated Days:
- Drilling/Coring: 27
- Logging: 2
- Total On-site:

#### Observatory Plan:
- Longterm Borehole Observation Plan/Re-entry Plan

#### Potential Hazards/Weather:
- Shallow Gas
- Hydrocarbon
- Shallow Water Flow
- Abnormal Pressure
- Man-made Objects (e.g., sea-floor cables, dump sites)
- H2S
- CO2
- Other:

- Complicated Seabed Condition
- Soft Seabed
- Currents
- Fracture Zone
- Fault
- High Dip Angle
- High Temperature
- Ice Conditions
- Sensitive marine habitat (e.g., reefs, vents)

- Hydrothermal Activity
- Landslide and Turbidity Current
- Gas Hydrate
- Diapir and Mud Volcano
- Fault
- High Temperature

#### Preferred weather window:
- August-September (time interval of minimum ice extent)
<table>
<thead>
<tr>
<th>Data Type</th>
<th>In SSDB</th>
<th>SSP Req.</th>
<th>Details of available data and data that are still to be collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a High resolution seismic reflection (primary)</td>
<td>no</td>
<td></td>
<td>High-resolution seismic reflection, line AWI-98565 (will be uploaded to the SSBD before the Nov 01 deadline) Location: CDP 2580</td>
</tr>
<tr>
<td>1b High resolution seismic reflection (crossing)</td>
<td>no</td>
<td></td>
<td>Location:</td>
</tr>
<tr>
<td>2a Deep penetration seismic reflection (primary)</td>
<td>no</td>
<td></td>
<td>Location:</td>
</tr>
<tr>
<td>2b Deep penetration seismic reflection (crossing)</td>
<td>no</td>
<td></td>
<td>Location:</td>
</tr>
<tr>
<td>3 Seismic Velocity</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Seismic Grid</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5a Refraction (surface)</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5b Refraction (bottom)</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 3.5 kHz</td>
<td>no</td>
<td></td>
<td>AWI Parasound profile</td>
</tr>
<tr>
<td>7 Swath bathymetry</td>
<td>no</td>
<td></td>
<td>AWI Hydrosweep profile</td>
</tr>
<tr>
<td>8a Side looking sonar (surface)</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8b Side looking sonar (bottom)</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 Photography or video</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 Heat Flow</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11a Magnetics</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11b Gravity</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 Sediment cores</td>
<td>no</td>
<td></td>
<td>sediment cores from Polarstern expeditions 1991 and 2007</td>
</tr>
<tr>
<td>13 Rock sampling</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14a Water current data</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14b Ice Conditions</td>
<td>no</td>
<td></td>
<td>more perennial sea ice (8-9/10)</td>
</tr>
<tr>
<td>15 OBS microseismicity</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 Navigation</td>
<td>no</td>
<td></td>
<td>Navigation data for seismic line AWI-98565 exist and will be uploaded to the SSBD before the Nov 01 deadline.</td>
</tr>
<tr>
<td>17 Other</td>
<td>no</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Key to SSP Requirements:

X=required; X*=may be required for specific sites; Y=recommended; Y*=may be recommended for specific sites; R=required for re-entry sites; T=required for high temperature environments; † Accurate velocity information is required for holes deeper than 400m.
### IODP Site Summary Forms: Form 3 – Detailed Logging and Downhole Measurement Plan

<table>
<thead>
<tr>
<th>Proposal #</th>
<th>708</th>
<th>Site #</th>
<th>LORI-5B</th>
<th>Date Form Submitted</th>
<th>2013-10-04</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Depth (m):</td>
<td>1334</td>
<td>Sed. Penetration (m):</td>
<td>1250</td>
<td>Basement Penetration (m):</td>
<td>0</td>
</tr>
</tbody>
</table>

Are high temperatures or other special requirements (e.g., unstable formations), anticipated for logging at this site?  

Estimated total logging time for this site: 2

<table>
<thead>
<tr>
<th>Measurement Type</th>
<th>Scientific Objective</th>
<th>Relevance (1=high, 3=low)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Check Shot Survey</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Nuclear Magnetic Resonance</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Geochemical</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Side-wall Core Sample</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Formation Fluid Sampling</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Borehole Temperature</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Magnetic Susceptibility</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Magnetic Field</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>VSP</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Formation Image (Acoustic)</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Formation Pressure &amp; Temperature</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Other (SET, SETP, ...)</td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

Page 1 of 1 - Detailed Logging and Downhole Measurement Plan

by if353_t_pdf / kk+w 2007 - 2011
(aeex 0.2818)
### IODP Site Summary Forms: Form 4 – Environmental Protection

**Proposal #:** 708  
**Site #:** LORI-5B  
**Date Form Submitted:** 2013-10-04 22:40:44

<table>
<thead>
<tr>
<th>Pollution &amp; Safety Hazard</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Summary of Operations at site.</td>
<td>Triple APC to refusal, continued by XCB and RCB to final depth</td>
</tr>
<tr>
<td>2. All hydrocarbon occurrences based on previous DSDP/ODP/IODP drilling.</td>
<td>N/A</td>
</tr>
<tr>
<td>3. All commercial drilling in this area that produced or yielded significant hydrocarbon shows.</td>
<td>N/A</td>
</tr>
<tr>
<td>4. Indications of gas hydrates at this location.</td>
<td>No</td>
</tr>
<tr>
<td>5. Are there reasons to expect hydrocarbon accumulations at this site?</td>
<td>No</td>
</tr>
<tr>
<td>6. What “special” precautions will be taken during drilling?</td>
<td>severe/perennial ice conditions</td>
</tr>
<tr>
<td>7. What abandonment procedures need to be followed?</td>
<td>support by an icebreaker needed (e.g., RV Polarstern)</td>
</tr>
<tr>
<td>8. Natural or manmade hazards which may effect ship's operations.</td>
<td>ice</td>
</tr>
<tr>
<td>9. Summary: What do you consider the major risks in drilling at this site?</td>
<td>ice could delay operations</td>
</tr>
</tbody>
</table>
# IODP Site Summary Forms:

## Form 5 – Lithologies

<table>
<thead>
<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, Unconformities, faults, etc</th>
<th>Age</th>
<th>Assumed velocity (km/sec)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. rate of sed. accum. (m/My)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-180</td>
<td>Reflector &quot;yellow&quot;</td>
<td>5.3</td>
<td>1.6</td>
<td>silty clay</td>
<td>pelagic</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>180-660</td>
<td>Reflector &quot;pink&quot;</td>
<td>23.8</td>
<td>2.2</td>
<td>silty clay</td>
<td>pelagic</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>660-1000</td>
<td>Reflector &quot;orange&quot;</td>
<td>54.8</td>
<td>3.4</td>
<td>silty clay, biosiliceous ooze</td>
<td>pelagic</td>
<td>&gt;10</td>
<td></td>
</tr>
<tr>
<td>1000-1250</td>
<td>below Reflector &quot;orange&quot;</td>
<td>&gt;54.8</td>
<td>&gt;5</td>
<td>silty clay</td>
<td>pelagic</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**IODP Site Summary Forms:**

<table>
<thead>
<tr>
<th>Proposal #:</th>
<th>708 - Full</th>
<th>Site #:</th>
<th>LORI-5B</th>
<th>Date Form Subm.:</th>
<th>2013-09-25 13:02:53</th>
</tr>
</thead>
</table>

**Site Summary Figure Comment**
Site Summary Form 6  IODP Proposal 708  Site LORI-5B

Profiles annotated using CDP numbers

Coordinates: 83° 48.03' N, 146° 28.5'E
Water-depth: 1334 m
Top Miocene (yellow): 180 mbsf
Top Oligocene (pink): 660 mbsf
Lower Eocene (orange): 1000 mbsf
Penetration: 1750 m

SSDB locations of these graphics and supporting data:
- Location map: LORI-5B_map.pdf
- Seismic figures: LORI-5B_AWI-98565.pdf
- SEGY data: AWI-98565stack.sgy
- Navigation data: 98565_cdplocs.asc
IODP Site Summary Forms:
Form 1 – General Site Information

Section A: Proposal Information

Title of Proposal: Arctic Ocean Paleooceanography: Towards a Continuous Cenozoic Record from a Greenhouse to an Icehouse World (ACEX2)

Date Form Submitted: 2013-10-04 22:40:44

Site Specific Objectives with Priority (Must include general objectives in proposal)
Recovery of a complete stratigraphic sedimentary record on the southern Lomonosov Ridge to meet our highest priority paleoceanographic objective, the continuous long-term Cenozoic climate history of the central Arctic Ocean. (Alternate Site)

List Previous Drilling in Area:
IODP Expedition 302 (ACEX)

Section B: General Site Information

<table>
<thead>
<tr>
<th>Site Name: LORI-16A</th>
<th>Area or Location: Southern Lomonosov Ridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>If site is a reoccupation of an old DSDP/ODP Site, Please include former Site#:</td>
<td>Jurisdiction: International waters</td>
</tr>
<tr>
<td>Latitude: Deg: 80.78</td>
<td>Distance to Land: (km) 590</td>
</tr>
<tr>
<td>Longitude: Deg: 142.78</td>
<td>Water Depth (m): 1752</td>
</tr>
<tr>
<td>Coordinate System: WGS 84</td>
<td></td>
</tr>
<tr>
<td>Priority of Site: Primary: no Alt:</td>
<td></td>
</tr>
</tbody>
</table>
Section C: Operational Information

<table>
<thead>
<tr>
<th>Proposed Penetration (m):</th>
<th>Sediments</th>
<th>Basement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1850</td>
<td>0</td>
</tr>
<tr>
<td>Total Sediment Thickness (m):</td>
<td>2160</td>
<td></td>
</tr>
<tr>
<td>Total Penetration (m):</td>
<td>1850</td>
<td></td>
</tr>
</tbody>
</table>

General Lithologies:
- Silty clay, clay, biosiliceous ooze; siltstone, claystone; some ice-rafted debris

Coring Plan: (Specify or check)
- one drill site with three APC/XCB/RCB holes down to about 1850 mbsf to recover multiple sections of the sediment sequence to ensure complete recovery for construction of a composite section (Alternate Site)

Wireline Logging Plan:

<table>
<thead>
<tr>
<th>Standard Measurements</th>
<th>Special Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>WL</td>
<td>Magnetic Susceptibility</td>
</tr>
<tr>
<td>LWD</td>
<td>Magnetic Field</td>
</tr>
<tr>
<td>Porosity</td>
<td>Borehole Temperature</td>
</tr>
<tr>
<td>Density</td>
<td>Nuclear Magnetic Resonance</td>
</tr>
<tr>
<td>Gamma Ray</td>
<td>Geochemical</td>
</tr>
<tr>
<td>Resistivity</td>
<td>Side-Wall Core Sampling</td>
</tr>
<tr>
<td>Sonic (Δt)</td>
<td></td>
</tr>
<tr>
<td>Formation Image (Res)</td>
<td></td>
</tr>
<tr>
<td>Check-shot (upon request)</td>
<td></td>
</tr>
</tbody>
</table>

Max. Borehole Temp.: 0°C

Mud Logging: (Riser Holes Only)

<table>
<thead>
<tr>
<th>Cuttings Sampling Intervals from m to m m intervals</th>
<th>Cuttings Sampling Intervals from m to m m intervals</th>
</tr>
</thead>
</table>

Estimated Days:
- Drilling/Coring: 33
- Logging: 2
- Total On-site: 35

Observatory Plan:
- Longterm Borehole Observation Plan/Re-entry Plan

Potential Hazards/Weather:
- Shallow Gas
- Hydrocarbon
- Shallow Water Flow
- Abnormal Pressure
- Man-made Objects (e.g., sea-floor cables, dump sites)
- H2S
- CO2
- Other:

Preferences:
- Complicated Seabed Condition
- Hydrothermal Activity
- Soft Seabed
- Landslide and Turbidity Current
- Currents
- Gas Hydrate
- Fracture Zone
- Diapir and Mud Volcano
- Fault
- High Temperature
- High Dip Angle
- Ice Conditions
- Sensitive marine habitat (e.g., reefs, vents)

Preferred weather window: August-September (time interval of minimum ice extent)

Basic Sampling Intervals: 5m

Page 2 of 2

generated: Tue Oct 8 21:48:26 2013 by if351_pdf / planiglobe 2007 - 2013 (user 0.2451)
## IODP Site Summary Forms:
### Form 2 - Site Survey Detail

<table>
<thead>
<tr>
<th>Proposal #:</th>
<th>708</th>
<th>Site #:</th>
<th>LORI-16A</th>
<th>Date Form Submitted:</th>
<th>2013-10-04 22:40:44</th>
</tr>
</thead>
</table>

### Key to SSP Requirements
- X = required; X* = may be required for specific sites; Y = recommended; Y* = may be recommended for specific sites;
- R = required for re-entry sites; T = required for high temperature environments; † = Accurate velocity information is required for holes deeper than 400m.

### Data Type | In SSDB | SSP Req. | Details of available data and data that are still to be collected |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1a High resolution seismic reflection (primary)</td>
<td>no</td>
<td></td>
<td>High-resolution seismic reflection, line AWI-98597 (will be uploaded to the SSBD before the Nov 01 deadline) Location: CDP 1060</td>
</tr>
<tr>
<td>1b High resolution seismic reflection (crossing)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>2a Deep penetration seismic reflection (primary)</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2b Deep penetration seismic reflection (crossing)</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Seismic Velocity</td>
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<td></td>
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</tr>
<tr>
<td>4 Seismic Grid</td>
<td>no</td>
<td></td>
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</tr>
<tr>
<td>5a Refraction (surface)</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5b Refraction (bottom)</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 3.5 kHz</td>
<td>no</td>
<td></td>
<td>Parasound profile</td>
</tr>
<tr>
<td>7 Swath bathymetry</td>
<td>no</td>
<td></td>
<td>Hydrosweep profile</td>
</tr>
<tr>
<td>8a Side looking sonar (surface)</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8b Side looking sonar (bottom)</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 Photography or video</td>
<td>no</td>
<td></td>
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</tr>
<tr>
<td>10 Heat Flow</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11a Magnetics</td>
<td>no</td>
<td></td>
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</tr>
<tr>
<td>11b Gravity</td>
<td>no</td>
<td></td>
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</tr>
<tr>
<td>12 Sediment cores</td>
<td>no</td>
<td></td>
<td>Numerous sediment cores from Polarstern expeditions 1995 and 2008</td>
</tr>
<tr>
<td>13 Rock sampling</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14a Water current data</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14b Ice Conditions</td>
<td>no</td>
<td></td>
<td>Seasonal sea ice</td>
</tr>
<tr>
<td>15 OBS microseismicity</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 Navigation</td>
<td>no</td>
<td></td>
<td>Navigation data for seismic line AWI-98597 exist and will be uploaded to the SSBD before the Nov 01 deadline.</td>
</tr>
<tr>
<td>17 Other</td>
<td>no</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
IODP Site Summary Forms:
Form 3 – Detailed Logging and Downhole Measurement Plan

<table>
<thead>
<tr>
<th>Proposal #:</th>
<th>708</th>
<th>Site #:</th>
<th>LORI-16A</th>
<th>Date Form Submitted:</th>
<th>2013-10-04</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Depth (m):</td>
<td>1752</td>
<td>Sed. Penetration (m):</td>
<td>1850</td>
<td>Basement Penetration (m):</td>
<td>0</td>
</tr>
</tbody>
</table>

Are high temperatures or other special requirements (e.g., unstable formations), anticipated for logging at this site?

Estimated total logging time for this site: 2

<table>
<thead>
<tr>
<th>Measurement Type</th>
<th>Scientific Objective</th>
<th>Relevance (1=high, 3=low)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Check Shot Survey</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Nuclear Magnetic Resonance</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Geochemical</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Side-wall Core Sample</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Formation Fluid Sampling</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Borehole Temperature</td>
<td>0</td>
<td></td>
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<tr>
<td>Magnetic Susceptibility</td>
<td>0</td>
<td></td>
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<tr>
<td>Magnetic Field</td>
<td>0</td>
<td></td>
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<tr>
<td>VSP</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Formation Image (Acoustic)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Formation Pressure &amp; Temperature</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Other (SET, SETP, …)</td>
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<td></td>
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</table>
**Summary of Operations at site:**
Triple APC to refusal, continued by XCB and RCB to final depth

<table>
<thead>
<tr>
<th>Pollution &amp; Safety Hazard</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Summary of Operations at site.</td>
<td>Triple APC to refusal, continued by XCB and RCB to final depth</td>
</tr>
<tr>
<td>2. All hydrocarbon occurrences based on previous DSDP/ODP/IODP drilling.</td>
<td>N/A</td>
</tr>
<tr>
<td>3. All commercial drilling in this area that produced or yielded significant hydrocarbon shows.</td>
<td>N/A</td>
</tr>
<tr>
<td>4. Indications of gas hydrates at this location.</td>
<td>No</td>
</tr>
<tr>
<td>5. Are there reasons to expect hydrocarbon accumulations at this site?</td>
<td>No</td>
</tr>
<tr>
<td>6. What “special” precautions will be taken during drilling?</td>
<td>ice management</td>
</tr>
<tr>
<td>7. What abandonment procedures need to be followed?</td>
<td>support by an icebreaker (e.g., RV Polarstern)</td>
</tr>
<tr>
<td>8. Natural or manmade hazards which may effect ship’s operations.</td>
<td>ice</td>
</tr>
<tr>
<td>9. Summary: What do you consider the major risks in drilling at this site?</td>
<td>ice could delay operations</td>
</tr>
<tr>
<td>Subbottom depth (m)</td>
<td>Key reflectors, Unconformities, faults, etc</td>
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<tr>
<td>---------------------</td>
<td>---------------------------------------------</td>
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<tr>
<td>0-195</td>
<td>Reflector &quot;yellow&quot;</td>
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<tr>
<td>195-1395</td>
<td>Reflector &quot;pink&quot;</td>
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<tr>
<td>1395-1850</td>
<td>Reflector &quot;orange&quot;</td>
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<tr>
<td>Proposal #:</td>
<td>708 -</td>
</tr>
<tr>
<td>------------</td>
<td>-------</td>
</tr>
</tbody>
</table>

**Site Summary Figure Comment**
Site Summary Form 6  IODP Proposal 708  Site LORI-16A

Coordinates: 80° 46.6’N, 142° 46.9’E
Water-depth: 1752 m
Top Miocene (yellow): 195 mbsf
Top Oligocene (pink): 1395 mbsf
Lower Eocene (orange): 1840 mbsf
Penetration: 2160 m

SSDB locations of these graphics and supporting data:
- Location map: LORI-16_map.pdf
- Seismic figures: LORI-16A_AWI-98597.pdf
- SEGY data: AWI-98597stack.sgy
- Navigation data: 98597_cdplocs.asc

Profiles annotated using CDP numbers

AWI-98597, CDP-numbers (25m/CDP)

Two-way travel time [s]
### Section A: Proposal Information

**Title of Proposal:** Arctic Ocean Paleceanography: Towards a Continuous Cenozoic Record from a Greenhouse to an Icehouse World (ACEX2)

**Date Form Submitted:** 2013-10-04 22:40:44

**Site Specific Objectives with Priority** (Must include general objectives in proposal)

Recovery of a complete stratigraphic sedimentary record on the southern Lomonosov Ridge to meet our highest priority paleocceanographic objective, the continuous long-term Cenozoic climate history of the central Arctic Ocean (Alternate Site)

**List Previous Drilling in Area:**

IODP Expedition 302 (ACEX)

### Section B: General Site Information

<table>
<thead>
<tr>
<th>Site Name: LR-02A</th>
<th>Area or Location: Southern Lomonosov Ridge</th>
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</thead>
<tbody>
<tr>
<td>Latitude: Deg: 80.97</td>
<td>Jurisdiction: International waters</td>
</tr>
<tr>
<td>Longitude: Deg: 142.47</td>
<td>Distance to Land: (km) 590</td>
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<tr>
<td>Coordinate System: WGS 84</td>
<td>Water Depth (m): 1450</td>
</tr>
<tr>
<td>Priority of Site: Primary: no Alt:</td>
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</tr>
</tbody>
</table>
## Section C: Operational Information

### Proposed Penetration (m):

<table>
<thead>
<tr>
<th>Sediments</th>
<th>Basement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1300</td>
<td>0</td>
</tr>
</tbody>
</table>

Total Sediment Thickness (m): 2150

Total Penetration (m): 1300

### General Lithologies:

- Silty clay, clay, biosiliceous ooze; siltstone, claystone; some ice-rafter debris

### Coring Plan:

(Specify or check)

- APC
- XCB
- MDCB
- PCS
- RCB
- Re-entry

**Coring Plan:**

one drill site with three APC/XCB/RCB holes down to about 1300 mbsf to recover multiple sections of the sediment sequence to ensure complete recovery for construction of a composite section (Alternate Site)

### Wireline Logging Plan:

<table>
<thead>
<tr>
<th>Standard Measurements</th>
<th>Special Tools</th>
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<tbody>
<tr>
<td>WL</td>
<td>Magnetic Susceptibility</td>
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<tr>
<td>LWD</td>
<td>Magnetic Field</td>
</tr>
<tr>
<td>Porosity</td>
<td>Formation Image (Acoustic)</td>
</tr>
<tr>
<td>Density</td>
<td>Magnetic Field</td>
</tr>
<tr>
<td>Gamma Ray</td>
<td>Formation Fluid Sampling</td>
</tr>
<tr>
<td>Resistivity</td>
<td>Formation Temperature &amp; Pressure</td>
</tr>
<tr>
<td>Sonic (Δt)</td>
<td>VSP</td>
</tr>
<tr>
<td>Formation Image (Res)</td>
<td>Side-Wall Core Sampling</td>
</tr>
<tr>
<td>Check-shot (upon request)</td>
<td>Others:</td>
</tr>
</tbody>
</table>

### Max. Borehole Temp.:

25 °C

### Mud Logging:

(Riser Holes Only)

#### Cuttings Sampling Intervals

- from m to m m intervals
- from m to m m intervals

#### Basic Sampling Intervals: 5m

### Estimated Days:

**Drilling/Coring:** 27

**Logging:** 2

**Total On-site:***

### Observatory Plan:

| Longterm Borehole Observation Plan/Re-entry Plan |

### Potential Hazards/Weather:

<table>
<thead>
<tr>
<th>Shallow Gas</th>
<th>Complicated Seabed Condition</th>
<th>Hydrothermal Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrocarbon</td>
<td>Soft Seabed</td>
<td>Landslide and Turbidity Current</td>
</tr>
<tr>
<td>Shallow Water Flow</td>
<td>Currents</td>
<td>Gas Hydrate</td>
</tr>
<tr>
<td>Abnormal Pressure</td>
<td>Fracture Zone</td>
<td>Diapir and Mud Volcano</td>
</tr>
<tr>
<td>Man-made Objects (e.g., sea-floor cables, dumpsites)</td>
<td>Fault</td>
<td>High Temperature</td>
</tr>
<tr>
<td>H2S</td>
<td>High Dip Angle</td>
<td>Ice Conditions</td>
</tr>
<tr>
<td>CO2</td>
<td>Sensitive marine habitat (e.g., reefs, vents)</td>
<td></td>
</tr>
</tbody>
</table>

**Preferred weather window**

**August-September**

(time interval of minimum ice extent)

**Other:**

---

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**IODP Site Summary Forms:**

**Form 2 - Site Survey Detail**

---

**Proposal #: 708**

**Site #: LR-02A**

**Date Form Submitted: 2013-10-04 22:40:44**

---

*Key to SSP Requirements*

<table>
<thead>
<tr>
<th>Data Type</th>
<th>In SSDB</th>
<th>SSP Req.</th>
<th>Details of available data and data that are still to be collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a High resolution seismic reflection (primary)</td>
<td>no</td>
<td></td>
<td>High-resolution seismic reflection, line AWI-20080160 (will be uploaded to the SSBD before the Nov 01 deadline). Site location close to crossing point AWI-20080160 and AWI-98597. Location: CDP 900</td>
</tr>
<tr>
<td>1b High resolution seismic reflection (crossing)</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2a Deep penetration seismic reflection (primary)</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2b Deep penetration seismic reflection (crossing)</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Seismic Velocity</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Seismic Grid</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>5a Refraction (surface)</td>
<td>no</td>
<td></td>
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</tr>
<tr>
<td>5b Refraction (bottom)</td>
<td>no</td>
<td></td>
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</tr>
<tr>
<td>6 3.5 kHz</td>
<td>no</td>
<td></td>
<td>Parasound profile</td>
</tr>
<tr>
<td>7 Swath bathymetry</td>
<td>no</td>
<td></td>
<td>Hydrosweep profile</td>
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<tr>
<td>8a Side looking sonar (surface)</td>
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<td></td>
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</tr>
<tr>
<td>8b Side looking sonar (bottom)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>9 Photography or video</td>
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</tr>
<tr>
<td>10 Heat Flow</td>
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</tr>
<tr>
<td>11a Magnetics</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11b Gravity</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 Sediment cores</td>
<td>no</td>
<td></td>
<td>Numerous sediment cores from Polarstern expeditions 1995 and 2008</td>
</tr>
<tr>
<td>13 Rock sampling</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>14a Water current data</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14b Ice Conditions</td>
<td>no</td>
<td></td>
<td>Seasonal sea ice</td>
</tr>
<tr>
<td>15 OBS microseismicity</td>
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</tr>
<tr>
<td>16 Navigation</td>
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<td>Navigation data for seismic line AWI-20080160 exist and will be uploaded to the SSDB before the Nov 01 deadline.</td>
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<tr>
<td>17 Other</td>
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</table>
IODP Site Summary Forms:

Form 3 – Detailed Logging and Downhole Measurement Plan

<table>
<thead>
<tr>
<th>Proposal #:</th>
<th>708</th>
<th>Site #:</th>
<th>LR-02A</th>
<th>Date Form Submitted:</th>
<th>2013-10-04</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Depth (m):</td>
<td>1450</td>
<td>Sed. Penetration (m):</td>
<td>1300</td>
<td>Basement Penetration (m):</td>
<td>0</td>
</tr>
</tbody>
</table>

Are high temperatures or other special requirements (e.g., unstable formations), anticipated for logging at this site?

Estimated total logging time for this site: 2

<table>
<thead>
<tr>
<th>Measurement Type</th>
<th>Scientific Objective</th>
<th>Relevance (1=high, 3=low)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Check Shot Survey</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Nuclear Magnetic Resonance</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Geochemical</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Side-wall Core Sample</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Formation Fluid Sampling</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Borehole Temperature</td>
<td></td>
<td>0</td>
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<tr>
<td>Magnetic Susceptibility</td>
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<td>Magnetic Field</td>
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<td>VSP</td>
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<tr>
<td>Formation Image (Acoustic)</td>
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<td>0</td>
</tr>
<tr>
<td>Formation Pressure &amp; Temperature</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Other (SET, SETP, …)</td>
<td></td>
<td>0</td>
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</tbody>
</table>
## Pollution & Safety Hazard

<table>
<thead>
<tr>
<th>1. Summary of Operations at site.</th>
<th>Triple APC to refusal, continued by XCB and RCB to final depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. All hydrocarbon occurrences based on previous DSDP/ODP/IODP drilling.</td>
<td>N/A</td>
</tr>
<tr>
<td>3. All commercial drilling in this area that produced or yielded significant hydrocarbon shows.</td>
<td>N/A</td>
</tr>
<tr>
<td>4. Indications of gas hydrates at this location.</td>
<td>No</td>
</tr>
<tr>
<td>5. Are there reasons to expect hydrocarbon accumulations at this site?</td>
<td>No</td>
</tr>
<tr>
<td>6. What “special” precautions will be taken during drilling?</td>
<td>Ice management</td>
</tr>
<tr>
<td>7. What abandonment procedures need to be followed?</td>
<td>Support by an icebreaker (e.g., RV Polarstern)</td>
</tr>
<tr>
<td>8. Natural or manmade hazards which may effect ship’s operations.</td>
<td>Ice</td>
</tr>
<tr>
<td>9. Summary: What do you consider the major risks in drilling at this site?</td>
<td>Ice could delay operations</td>
</tr>
</tbody>
</table>
### IODP Site Summary Forms:

**Form 5 – Lithologies**

<table>
<thead>
<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, Unconformities, faults, etc</th>
<th>Age</th>
<th>Assumed velocity (km/sec)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. rate of sed. accum. (m/My)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-220</td>
<td>Reflector &quot;yellow&quot;</td>
<td>5.3</td>
<td>1.6</td>
<td>silty clay</td>
<td>pelagic</td>
<td>41</td>
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<tr>
<td>220-965</td>
<td>Reflector &quot;pink&quot;</td>
<td>23.8</td>
<td>2.2</td>
<td>silty clay</td>
<td>pelagic</td>
<td>40</td>
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<td>965-1270</td>
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<td>54</td>
<td>3.4</td>
<td>silty clay, biosiliceous ooze</td>
<td>pelagic</td>
<td>&gt;10</td>
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<td>Site #:</td>
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</tbody>
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Site Summary Figure Comment
Site Summary Form 6  IODP Proposal 708  Site LR-02A

Coordinates: 80° 57.9’N, 142° 28.3’E
Water-depth: 1450 m
Top Miocene (yellow): 220 mbsf
Top Oligocene (pink): 965 mbsf
Lower Eocene (orange): 1270 mbsf
Basement (purple): 2150 mbsf
Penetration total: 2150 m

SSDB locations of these graphics and supporting data:
- Location map: LR-02A_map.pdf
- Seismic figures: LR-02A_AWI-20080160.pdf
- SEGY data: AWI-20080160stack.sgy
- Navigation data: 20080160_cdplocs.asc
### Section A: Proposal Information

**Title of Proposal:**
Arctic Ocean Paleooceanography: Towards a Continuous Cenozoic Record from a Greenhouse to an Icehouse World (ACEX2)

**Date Form Submitted:**
2013-10-04 22:40:44

**Site Specific Objectives with Priority (Must include general objectives in proposal):**
Recovery of a complete stratigraphic sedimentary record on the southern Lomonosov Ridge to meet our highest priority paleooceanographic objective, the continuous long-term Cenozoic climate history of the central Arctic Ocean (Primary site)

**List Previous Drilling in Area:**
IODP Expedition 302 (ACEX)

### Section B: General Site Information

<table>
<thead>
<tr>
<th>Site Name: LR-01A</th>
<th>Area or Location: Southern Lomonosov Ridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude: Deg: 80.95</td>
<td>Jurisdiction: International waters</td>
</tr>
<tr>
<td>Longitude: Deg: 142.97</td>
<td>Distance to Land: 590 km</td>
</tr>
<tr>
<td>Coordinate System: WGS 84</td>
<td>Water Depth (m): 1405</td>
</tr>
<tr>
<td>Priority of Site: Primary: yes Alt:</td>
<td></td>
</tr>
</tbody>
</table>

No Jurisdiction: International waters

No Distance to Land: 590 km

No Water Depth (m): 1405
Section C: Operational Information

<table>
<thead>
<tr>
<th>Proposed Penetration (m):</th>
<th>Sediments</th>
<th>Basement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1225</td>
<td>0</td>
</tr>
<tr>
<td>Total Sediment Thickness (m)</td>
<td>1225</td>
<td></td>
</tr>
<tr>
<td>Total Penetration (m):</td>
<td>1225</td>
<td></td>
</tr>
</tbody>
</table>

General Lithologies:
Silty clays, clays, biosiliceous ooze; siltsone, claystone; some ice-rafted debris

Coring Plan:
One primary drill site with three APC/XCB/RCB holes down to about 1225 mbsf to recover multiple sections of the sediment sequence to ensure complete recovery for construction of a composite section (Primary site)

<table>
<thead>
<tr>
<th>Coring Plan (Specify or check)</th>
</tr>
</thead>
<tbody>
<tr>
<td>APC</td>
</tr>
</tbody>
</table>

Wireline Logging Plan:

<table>
<thead>
<tr>
<th>Standard Measurements</th>
<th>Special Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>WL</td>
<td>Magnetic Susceptibility</td>
</tr>
<tr>
<td>LWD</td>
<td>Magnetic Field</td>
</tr>
<tr>
<td>Porosity</td>
<td>Borehole Temperature</td>
</tr>
<tr>
<td>Density</td>
<td>Nuclear Magnetic Resonance</td>
</tr>
<tr>
<td>Gamma Ray</td>
<td>Geochemical</td>
</tr>
<tr>
<td>Resistivity</td>
<td>Side-Wall Core Sampling</td>
</tr>
<tr>
<td>Sonic (Δt)</td>
<td></td>
</tr>
<tr>
<td>Check-shot (Res)</td>
<td></td>
</tr>
</tbody>
</table>

WL Magnetic Field
LWD Magnetic Susceptibility
Porosity Borehole Temperature
Density Nuclear Magnetic Resonance
Gamma Ray Geochemical
Resistivity Side-Wall Core Sampling
Sonic (Δt) Check-shot (Res)

Max. Borehole Temp.: 0°C

Mud Logging:
(Riser Holes Only)

Cuttings Sampling Intervals
from m to m m intervals
from m to m m intervals

Estimated Days:
Drilling/Coring: 27
Logging: 2
Total On-site: |

Observatory Plan:
Longterm Borehole Observation Plan/Re-entry Plan

Potential Hazards/Weather:
Shallow Gas Complicated Seabed Condition Hydrothermal Activity
Hydrocarbon Soft Seabed Landslide and Turbidity Current
Shallow Water Flow Currents Gas Hydrate
Abnormal Pressure Fracture Zone Diapir and Mud Volcano
Man-made Objects (e.g., sea-floor cables, dump sites) Fault High Temperature
H2S High Dip Angle Ice Conditions
CO2 Sensitive marine habitat (e.g., reefs, vents)

Other: |
<table>
<thead>
<tr>
<th>Data Type</th>
<th>In SSDB</th>
<th>SSP Req.</th>
<th>Details of available data and data that are still to be collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a High resolution seismic reflection (primary)</td>
<td>no</td>
<td></td>
<td>High-resolution seismic reflection, line AWI-20080160 (will be uploaded to the SSDB before the Nov 01 deadline) Location: CDP 475</td>
</tr>
<tr>
<td>1b High resolution seismic reflection (crossing)</td>
<td>no</td>
<td></td>
<td>High-resolution seismic reflection, line AWI-98597 (will be uploaded to the SSDB before the Nov 01 deadline) Location: CDP 184</td>
</tr>
<tr>
<td>2a Deep penetration seismic reflection (primary)</td>
<td></td>
<td></td>
<td>Location:</td>
</tr>
<tr>
<td>2b Deep penetration seismic reflection (crossing)</td>
<td></td>
<td></td>
<td>Location:</td>
</tr>
<tr>
<td>3 Seismic Velocity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Seismic Grid</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5a Refraction (surface)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5b Refraction (bottom)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 3.5 kHz</td>
<td>no</td>
<td></td>
<td>Parasound profile</td>
</tr>
<tr>
<td>7 Swath bathymetry</td>
<td>no</td>
<td></td>
<td>Hydrosweep profile</td>
</tr>
<tr>
<td>8a Side looking sonar (surface)</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8b Side looking sonar (bottom)</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 Photography or video</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 Heat Flow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11a Magnetics</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11b Gravity</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 Sediment cores</td>
<td>no</td>
<td></td>
<td>Numerous sediment cores from Polarstern expeditions 1995 and 2008</td>
</tr>
<tr>
<td>13 Rock sampling</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14a Water current data</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14b Ice Conditions</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 OBS microseismicity</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 Navigation</td>
<td>no</td>
<td></td>
<td>Navigation data for seismic lines AWI-20080160 and AWI-98597 exist and will be uploaded to the SSDB before the Nov 01 deadline</td>
</tr>
<tr>
<td>17 Other</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### IODP Site Summary Forms:

#### Form 3 – Detailed Logging and Downhole Measurement Plan

<table>
<thead>
<tr>
<th>Proposal #:</th>
<th>708</th>
<th>Site #:</th>
<th>LR-01A</th>
<th>Date Form Submitted:</th>
<th>2013-10-04</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Depth (m):</td>
<td>1405</td>
<td>Sed. Penetration (m):</td>
<td>1225</td>
<td>Basement Penetration (m):</td>
<td>0</td>
</tr>
</tbody>
</table>

Are high temperatures or other special requirements (e.g., unstable formations), anticipated for logging at this site?

Estimated total logging time for this site: 2

<table>
<thead>
<tr>
<th>Measurement Type</th>
<th>Scientific Objective</th>
<th>Relevance (1=high, 3=low)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Check Shot Survey</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Nuclear Magnetic Resonance</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Geochemical</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Side-wall Core Sample</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Formation Fluid Sampling</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Borehole Temperature</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Magnetic Susceptibility</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Magnetic Field</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>VSP</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Formation Image (Acoustic)</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Formation Pressure &amp; Temperature</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Other (SET, SETP, ...)</td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>
IODEP Site Summary Forms:

1. **Summary of Operations at site.**
   - Triple APC to refusal, continued by XCB and RCB to final depth

2. **All hydrocarbon occurrences based on previous DSDP/ODP/IODP drilling.**
   - N/A

3. **All commercial drilling in this area that produced or yielded significant hydrocarbon shows.**
   - N/A

4. **Indications of gas hydrates at this location.**
   - No

5. **Are there reasons to expect hydrocarbon accumulations at this site?**
   - No

6. **What “special” precautions will be taken during drilling?**
   - Ice management

7. **What abandonment procedures need to be followed?**
   - Support by an icebreaker (e.g., RV Polarstern)

8. **Natural or manmade hazards which may effect ship’s operations.**
   - Ice

9. **Summary: What do you consider the major risks in drilling at this site?**
   - Ice could delay operations
<table>
<thead>
<tr>
<th>Subbottom depth (m)</th>
<th>Key reflectors, Unconformities, faults, etc</th>
<th>Age</th>
<th>Assumed velocity (km/sec)</th>
<th>Lithology</th>
<th>Paleo-environment</th>
<th>Avg. rate of sed. accum. (m/My)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-175</td>
<td>Reflector &quot;yellow&quot;</td>
<td>5.3</td>
<td>1.6</td>
<td>silty clay</td>
<td>pelagic</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>175-835</td>
<td>Reflector &quot;pink&quot;</td>
<td>23.8</td>
<td>2.2</td>
<td>silty clay</td>
<td>pelagic</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>835-1141</td>
<td>Reflector &quot;orange&quot;</td>
<td>54</td>
<td>3.4</td>
<td>silty clay, biosiliceous ooze</td>
<td>pelagic</td>
<td>&gt;10</td>
<td></td>
</tr>
<tr>
<td>1141-1225</td>
<td>Reflector &quot;purple&quot;</td>
<td>&gt;5</td>
<td></td>
<td>Silty clay, clay-siltstones</td>
<td>(hemi-) pelagic</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Proposal #: 708 - Full  
Site #: LR-01A  
Date Form Subm.: 2013-09-25 08:51:04
<table>
<thead>
<tr>
<th>Proposal #:</th>
<th>708</th>
<th>Site #:</th>
<th>LR-01A</th>
<th>Date Form Subm.:</th>
<th>2013-09-25 08:51:04</th>
</tr>
</thead>
</table>

**Site Summary Figure Comment**
Site Summary Form 6  IODP Proposal 708  Site LR-01A

Coordinates:  80° 57.01’N, 142° 58.3’E
Water-depth:  1405 m
Top Miocene (yellow):  175 mbsf
Top Oligocene (pink):  835 mbsf
Lower Eocene (orange):  1141 mbsf
Basement (purple):  1225 mbsf
Penetration total:  1225 m

SSDB locations of these graphics and supporting data:
-Location map:  LR-01A_map.pdf
-SEGY data:  AWI-20080160stack.sgy  AWI-98597stack.sgy
-Navigation data:  20080160_cdplocs.asc  98597_cdplocs.asc