Abstract

The Chukchi Edges project was designed to establish the relationship between the Chukchi Shelf and Borderland and indirectly test theories of opening for the Canada Basin. During this cruise, ~5300 km of 2D multi-channel seismic profiles and other geophysical measurements (swath bathymetry, gravity, magnetics, sonobuoy refraction seismic) were collected from the RV Marcus G. Langseth across the transition between the Chukchi Shelf and Chukchi Borderland.

These profiles reveal extended basins separated by faulted high-standing blocks. Basin stratigraphy can be subdivided on the basis of gross stratal geometry, reflection terminations and inferred unconformities. The wedge-shaped synrift sequences terminate against the basement highs and/or major faults, burying the basement topography. The inferred postrift seismic units are more nearly tabular, but thicken locally due to compaction of underlying synrift sediments.

Reflection character is dominated by alternating high and low amplitude continuous reflectors which may be consistent with pelagic or turbidite sediments. Chaotic units are also observed, which may indicate mass-flow deposits. The truncated sediments over the basement highs of the Chukchi Shelf, Chukchi Plateau and Northwind Ridge suggest major erosion due both to glacial planation and earlier erosional events perhaps associated with basement uplift prior to or during rifting and extension.

It is believed that the bulk of the synrift sediments are Mesozoic in age. Certainly Cenozoic sediments are also preserved in these basins, but the position of the boundary is uncertain. Locally, continuous reflectors are observed underlying the rift basin fill. These older units, of very uncertain age, would, if sampled, provide constraint on the history and affinities of the Chukchi Borderland.

In addition to the extensional basins, a number of small symmetric basins are observed on the flanks of the Chukchi Plateau. These basins may be transtensional and argue for a 2nd phase of tectonism, which overprinted the obvious extensional fabric of the Borderland. This is supported by the observation of uplifted postrift sediments on the flanks of some of the intermedial basement highs. Understanding the timing, distribution and extent of these two phases of tectonism, relative to the known history of N-S extension on the Chukchi shelf and the apparent orthogonal extension observed on the Beaufort Shelf will further constrain the unknown history of the Canada Basin.

Introduction

The Chukchi Borderland, a block of extended continental crust embedded in oceanic crust in the Canada Basin, figures prominently in all tectonic models proposed for the opening of the Amerasian Basin. While there are other examples of continental crust stranded within oceanic crust (e.g. Jan Mayen Ridge), the Chukchi is unique both in its areal extent (~200,000 sq. km) and in that it's size, position and orientation preclude simple geometric reconstruction to any of the nearby continental shelves. It is one piece that most clearly does not fit the simple "windshield wiper" model of Mesozoic opening of the basin (Carey, 1958).

Each edge of the Borderland has been proposed as a plate boundary. Proposed reconstructions place the Chukchi anywhere from the McKenzie Delta margin in the Beaufort Sea, to the Sverdrup Basin along the northern Canadian coast near Ellesmere Island. In addition, there is disagreement on which edge of the Chukchi properly reconstructs to the Canadian and Alaskan margins. While most models assume that the eastern edge along the Northwind Ridge is conjugate to some part of arctic Canada or Alaska, Miller et al. (2006) proposed instead that the northern edge of the plateau reconstructs to the Sverdrup Basin.

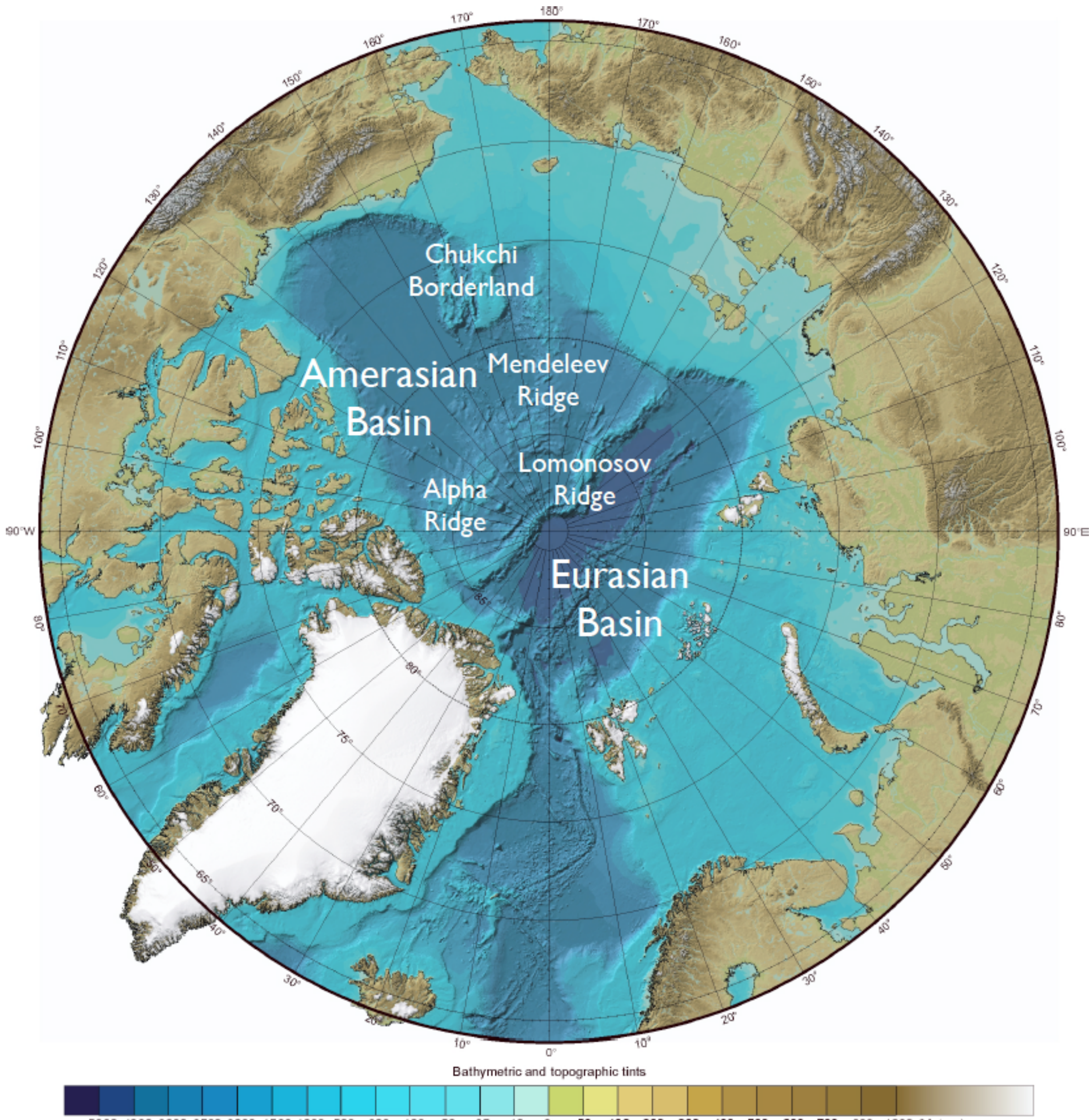


Figure 1 – Arctic Ocean basin with the major features mentioned in the text.

The ambiguity the composition, origin and evolution of the Chukchi Borderlands has been, in part, due to the limitations on collecting geophysical data in the Arctic Ocean. In the last decade, this situation has changed dramatically. New data acquired by airplanes, icebreakers, and submarines has dramatically improved maps of the Arctic Ocean. These data have made it possible to formulate specific, testable hypotheses about the origin and structure of the ridges and basins that make up the Amerasian Basin. Existing data sets are, as yet, inadequate to resolve many of these questions, but acquisition of seismic reflection data sets and direct sampling through drilling can begin, by providing substantial new constraints, to reject some models for the development of the basin.

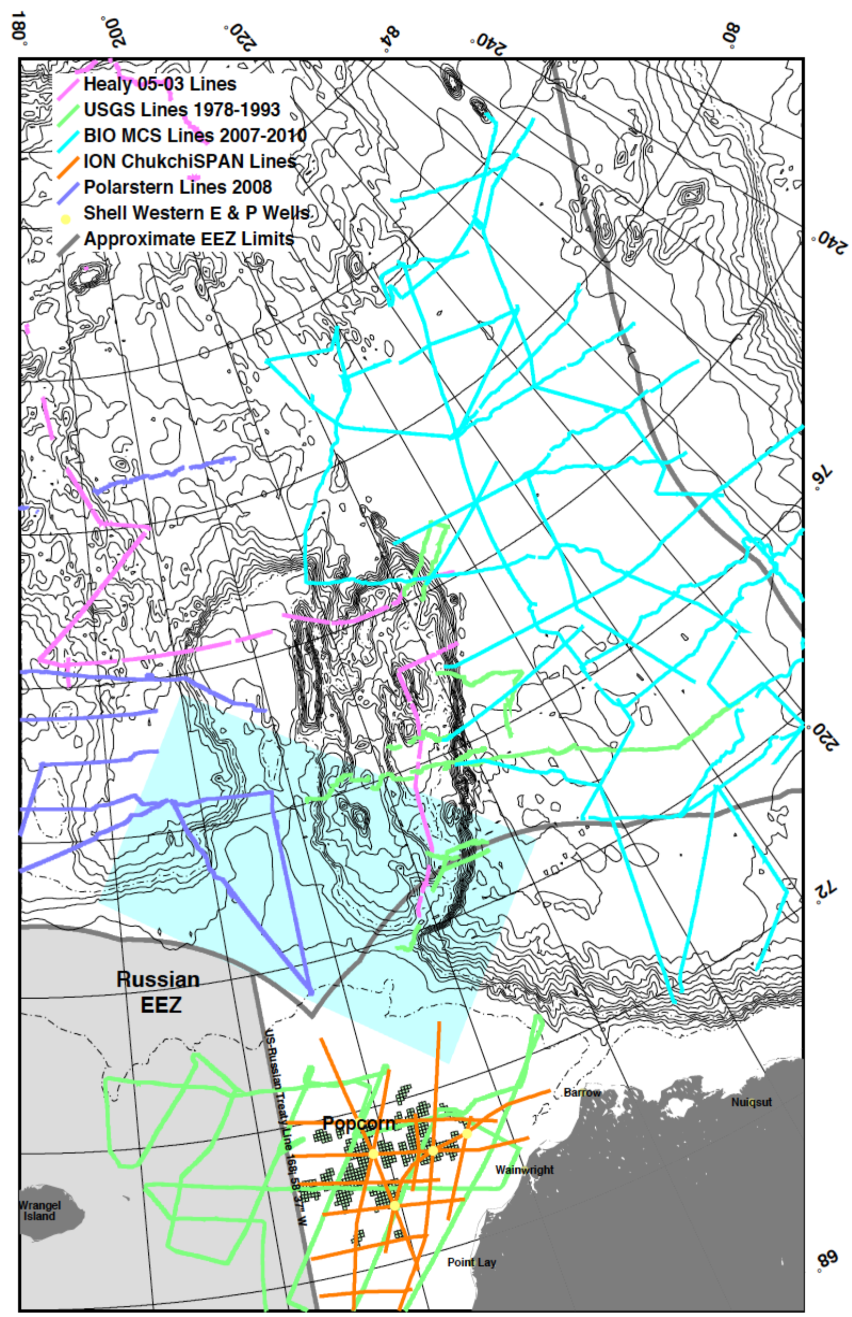


Figure 2 – Location of existing MCS data in the area superimposed on contoured bathymetry (interval = 250 meters). The 100 meter and 1000 meter contours are indicated by dashed lines.

Background and Tectonic Setting

The geological history of the Amerasian Basin (Figure 1) is poorly understood, in part due to the lack of identified plate boundaries. These boundaries must exist to explain the basin history. Identification of these structures will make it possible to reconstruct the development of the basin, which will substantially improve our understanding of the surrounding continents.

According to Carey's (1958) model, the Canada Basin opened like a pair of scissors. This was accomplished by a counter-clockwise rotation of the North Alaskan-Chukchi microplate (Arctic Alaska Plate) by 66 degrees. The microplate collided with the Siberian margin. Most of the existing models for the development of the Amerasian Basin accept the basic pattern of scissors-like or, classically, the "windshield wiper" opening for the basin. This theory finds some support in the identification of a probable relict mid-ocean ridge axis in the central Canada Basin (Brozena et al., 2002). Since the continental Chukchi Borderland (Figure 1) creates a space problem for any simple opening model, the greatest differences between models revolve around how to accommodate that block.

Fundamental differences among the proposed models include the paleo-location of the Chukchi Borderlands as well as whether the Borderlands represents a single entity (e.g. Lane, 1997; Miller et al., 2006) or is instead comprised of small terranes which behaved as independent microplates (Grantz et al., 1998; Lawver, 2002). A consequence of these models is the prediction that the Chukchi Borderland is distinct from the adjacent Chukchi Shelf.

There are currently 3 main competing models for the tectonic evolution of the Amerasian Basin. The most popular model was proposed by Grantz et al. (1998). This model assumes that a single spreading center with a uniform orientation created the Canada Basin. The Borderlands consist of 5 distinct continental microplates, each of which reconstruct to the seaward edge of the Sverdrup Basin along the northern Canadian Coast. To restore the independent terranes into position requires that the boundaries between them be predominantly strike-slip boundaries. The Northwind Ridge, for example, does not rift off the Canada margin, but rather is sliced off as a left-lateral transform system. This model provides a simple explanation for the differences in crustal affinity between the various pieces of the Canada Basin and the crust onshore along the Chukchi shelf.

Two alternatives to the Grantz model consider the Borderlands as a single entity and differ significantly from the Grantz model. Recognizing the similarity in coastlines and structural trends between the Northwind Ridge and the onshore area of the McKenzie Delta, Lane (1997) proposed to reconstruct the Chukchi Borderlands into the Beaufort Sea region. In his model, opening of the Amerasian Basin began along a trend defined by the Mendeleev and Alpha ridges, resulting in separation of the Lomonosov Ridge from the Canadian margin and the western edge of the Chukchi Borderlands. A major ridge jump opened the Canada Basin, stranding the Chukchi as a continental block between an abandoned rift system to the west and a newly formed spreading system to the east. The northern and southern edges are expected to show significant strike-slip deformation, similar to the Grantz et al. (1998) model. The trend of the present day geophysical anomalies in the Canada Basin is explained as a major re-orientation of the spreading system during the final stage of opening.

Another alternative to the Grantz et al. (1998) model was recently proposed by Miller et al. (2006). This model proposes that the Mendeleev Ridge is composed of highly extended continental crust. The Chukchi Borderlands is the eastern edge of a major continental rift system bounded to the west by Siberia. The northern edge of the Chukchi reconstructs to the Sverdrup Basin; the eastern edge rifted from the northern Alaska coast. In this model, some component of strike-slip must occur along the southern boundary, but the northern boundary should be dominated by extension. There should not be a significant difference in crustal affinity between the Chukchi Borderlands and the Mendeleev Ridge in this scenario. This model does not attempt to explain the present day geophysical trends in the Canada Basin and it is not clear in this model where any spreading center(s) should be located.

Significantly, each edge of the Chukchi Borderland (Figure 2) has been proposed as a plate boundary. Here are described each of the edges and what is known from the collection of geophysical data to date.

Transition from the Chukchi Borderland to the Canada Basin abyssal plain (northern edge)

A strike-slip fault has been predicted along the northern edge of the Chukchi Borderland by Grantz et al. (1998). Questions about the existence of this fault are raised by the small spur (Figure 2), which continues northwest from the Northwind Ridge. These questions are reinforced by recent data acquisition conducted from *USCGC Healy* by Larry Mayer from the Center for Coastal and Ocean Mapping at the University of New Hampshire, which seems to indicate that his feature continues beyond the spur itself, to the NW at least a few 100 km.

The spur itself seems to indicate that the extensional structures from the interior of the Borderland plunge off the bathymetric high below the sediments of the deeper basin, continuing north. At a minimum, this would seem to eliminate a significant strike-slip fault at the northern edge of the plateau. The continuity of extended continental crust beyond the edge of the plateau is supported by the bathymetry and sub-bottom profiler data collected from USCGC Healy (K. Brumley, pers. comm.. 2010).

Transition from the Chukchi Borderland to the Mendeleev Ridge (western edge)

If, as is commonly held, the Mendeleev Ridge (Figure 1) is a Large Igneous Province emplaced on oceanic crust (Lawver and Mueller 1994), then a continent-ocean boundary should be found somewhere on the western edge of the Chukchi Borderland. Recent gravity anomaly modeling appears to support that idea (Dove, 2007), suggesting there is a substantial change in crustal density approximately coincident with the bathymetric low that separates these two ridges.

Miller et al.'s (2006) model of the formation of the Amerasian Basin is unique in that it rejects the "windshield wiper" model and re-imagines much of the basin as a composite of oceanic crust and hyper-extended continental material. Imaging the deep structure of this transition is critical to understanding the relationship between the two features. While seismic reflection data has been collected data across this transition, it is not possible to see any of the deeper structures here.

Transition from Chukchi Borderland to the Canada Basin - Northwind Ridge (eastern edge)

The Northwind Ridge is one of the most striking features in the Arctic Ocean. The steep scarp that defines the eastern edge of the Chukchi Borderland has been sampled in a piston coring campaign (Grantz et al., 1998), which sampled sediments from almost all of the Phanerozoic periods, directly indicating the complex history of this continental crust.

This feature has been imaged by seismic techniques on at least three cruises (Grantz et al., 2004; Coakley et al., 2007). If there is substantial left lateral offset along a strike-slip fault at the northern edge of the Borderland the Grantz et al. (1998) model predicts substantial compression and shortening across this interface. The observed structures along the Northwind Ridge are entirely consistent with extensional deformation at this edge. For this reason, it seems unlikely that there has been any relative motion across this feature since the formation of the adjacent crust to the east.

Transition from the Chukchi Borderland to the Chukchi Shelf (southern edge)

The transition between the Chukchi Shelf and Borderland has been mapped as a strike-slip fault trimming the base of the Borderland. Shelf edge perpendicular extensional structures (Sherwood, 2002) beneath the Chukchi Shelf sediments on a parallel trend to the extensional structures that dissect the Borderland raise questions about the existence of this discontinuity. Tracking reflectors from these grabens across the marginal high is one means to both bring age control into the Arctic Ocean section and test the relative timing of these two sets of features.

Data Acquisition from the RV Marcus G. Langseth

The NSF proposal that funded this work was based on using the icebreaker USCGC Healy with a portable multi-channel seismic reflection (MCS) acquisition system during the 2010 arctic season. It was not possible to find all the pieces for a complete system in time for that cruise. It was particularly difficult to find an appropriate streamer. For this reason, the cruise was rescheduled for the following season.

In preparation for the 2011 arctic season, it became clear that USCGC Healy was heavily oversubscribed. Three programs, funding by three different government agencies, had requested the same period of time. At this time, it also became clear that the RV Marcus G. Langseth had a heavy schedule of work for the US Extended Continental Shelf program in the Bering Sea and the North Pacific and for NSF in south central Alaska. The RV Langseth is the primary MCS acquisition vessel in the academic fleet. It is 3-D capable and can tow 4 six kilometer streamers and four strings of airguns, totaling ~7200 cubic inches. While the full capabilities of the ship were beyond what was required for a 2-D survey, it was clear the Chukchi Edges cruise could be well served by the vessel.

The RV Langseth is not ice reinforced. Research conducted to prepare for the original proposal made it clear that the bulk of the survey area had been ice free around the date of the ice minimum (roughly September 15th) during the previous five years. Still, even with optimal conditions, there was some risk in taking this ship into the peripheral Arctic Ocean. Having realtime documentation of regional ice conditions during cruise, which also straddled the equinox and would require significant nighttime operations to be successful, was absolutely necessary to ensure the success of the cruise and the safety of the ship.

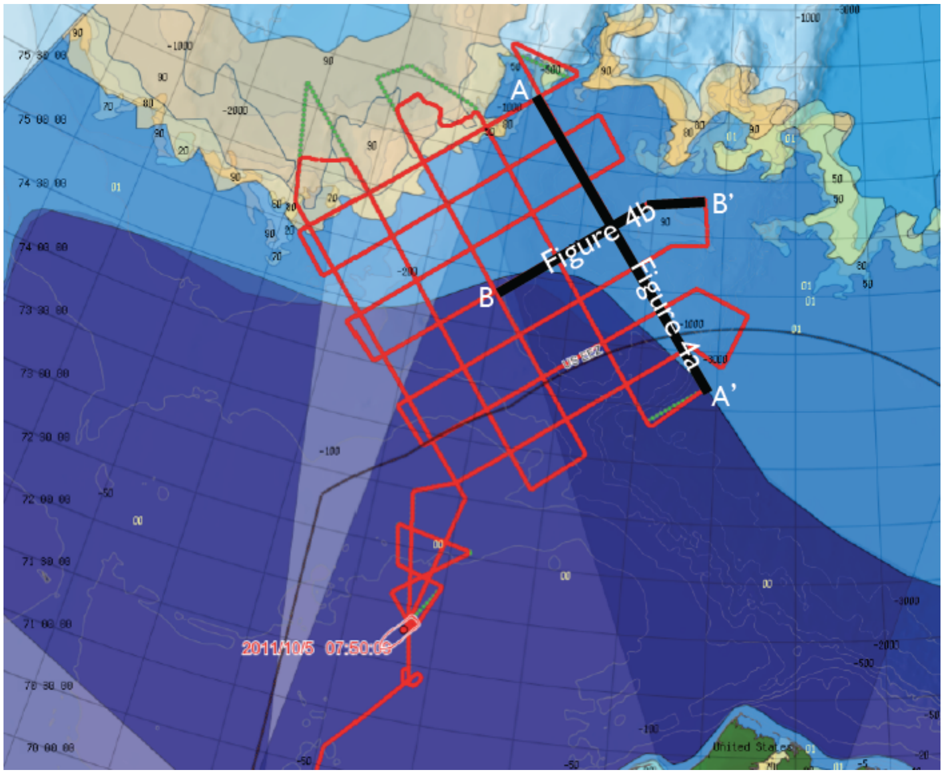


Figure 3 – Final survey grid superimposed on Canadian Ice Service map of ice concentration. The red lines indicate the track sailed by the RV Langseth. Green lines indicate where the planned track could not be followed due to ice conditions at the time of acquisition. Ice concentration, indicated by the tan coloration and percentage concentration, at the end of the survey (October 4th, 2011) would have prevented acquisition of the lines at the northwestern edge of the survey grid. Bathymetric contours on the shelf are shown as pale silver lines. Locations of profiles shown in Figure 4 are indicated.

Ship Operations

Realtime ice concentration data was necessary to be able to plan the cruise, day by day, and avoid significant concentrations of drift sea ice. This was made possible by receiving updated ice concentration charts, interpreted from satellite imagery, from the Canadian Ice Service (CIS). The CIS has long experience supporting ice operations in the Arctic Ocean. Multiple daily updates, downloaded at sea from a server onshore, and displayed on the realtime navigation display, enabled cruise planning and facilitated operations in the vicinity of ice.

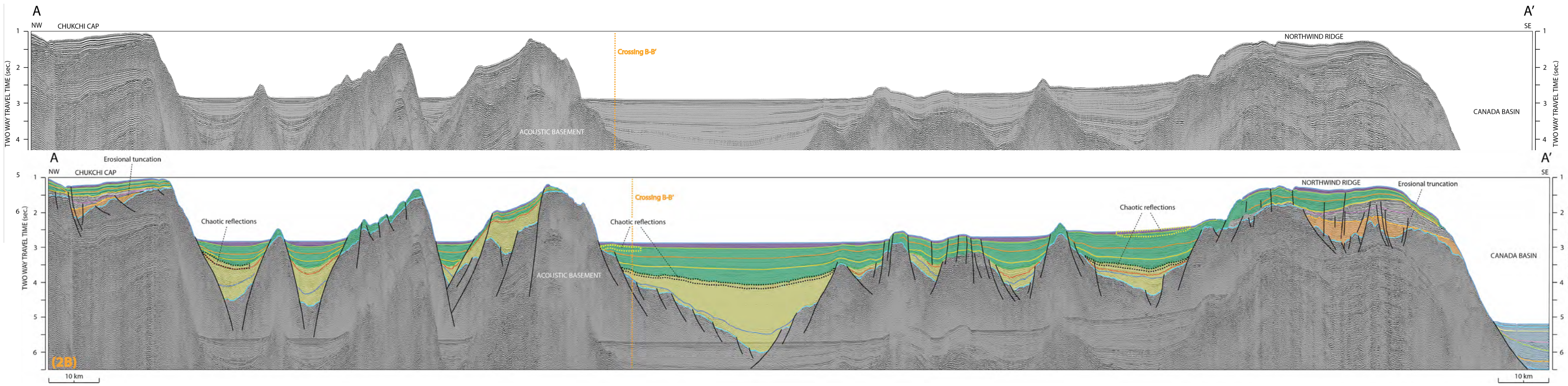
The realtime track display was available on the helm, and assisted steering the ship, with gear in the water, in the vicinity of the ice edge. The first encounter with the ice took place in full daylight. The ice edge was observed exactly where the ice concentration map predicted it. This demonstration of data validity increased confidence on the helm in their ability to effectively operate in the presence of sea ice. The second encounter occurred at night. The helm spent 5 hours maneuvering between isolated ice floes (~10% ice cover) with gear out, before returning to open water.

As expected, the bulk of the survey was conducted in open water. Only on the northwestern edge of the survey grid did the sea ice limit the survey, eliminating the western ends of four survey lines. Figure 3 shows ice conditions at the end of the survey. Ice crowding in from the northwest has started to override the lines sailed earlier. RV Langseth was in these waters at the best possible time to collect the maximum extent of data possible with a non-ice reinforced vessel.

Data Acquisition

Marine seismic data acquisition can be grouped into two categories; the streamer (receivers) and the source (air-guns). For this cruise, a single streamer with 468 channels, towed at 9 m depth, group spacing 12.5 m was used as the receiver. The total volume of the airgun array was 1830 cubic inches. The near offset, the distance between center of source and center of near hydrophone group, was 206.7 m. For the most part, shots were keyed to GPS positions and set as a multiple of the group spacing. For this survey the shot spacing was 37.5 m. In some parts of the survey area, the satellite GPS positioning system became unreliable. In these areas, the RV Langseth shot on time (13 seconds), the time it takes to cover 37.5 meters at our nominal survey speed (5.6 knots).

The gun array was tuned by varying the sizes of the guns, which were shot simultaneously. The resulting pulse is a clean spike, with minimal ringing. The spectrum for this signal is flat in the range of 5-120 Hz and falls off rapidly.


A
NW
CHUKCHI CAP
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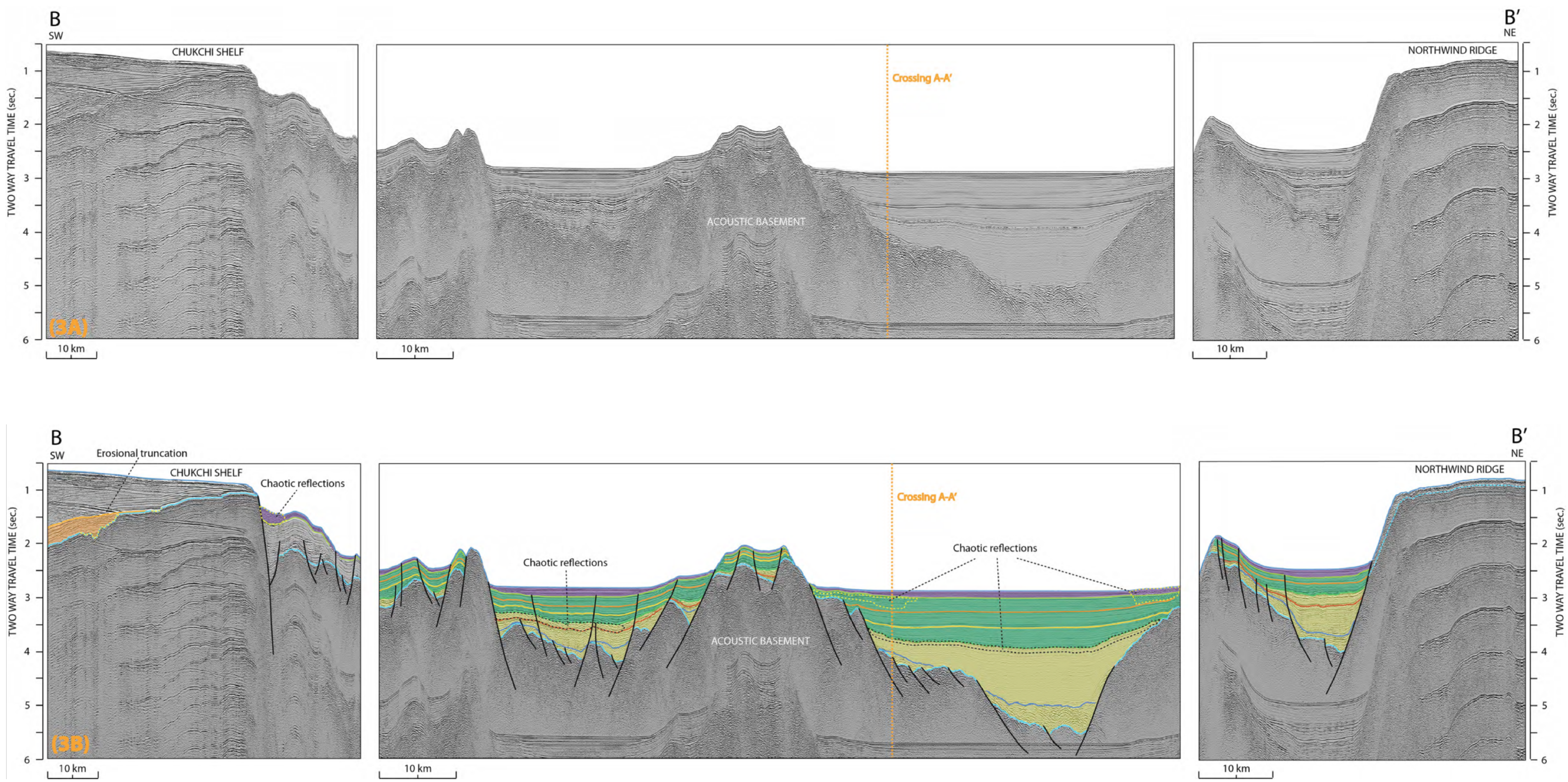
B
SW
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NORTHWIND RIDGE
Crossing A-A'
ACOUSTIC BASEMENT
TWO WAY TRAVEL TIME (sec.)
(3A)
10 km
Erosional truncation
Chaotic reflections
(3B)

Figures 4a and b (previous page)- Two crossing lines from the RV Langseth survey of the Chukchi Borderland. Crossing points are indicated by vertical orange lines. Scales are indicated and slightly different on each figure. Stratigraphic interpretation is discussed in the text. Line locations are shown on Figure 3.

Data Processing

Shown here (Figure 4) are single channel, near trace plots. These maximize the horizontal and vertical resolution in the data. The data in Figure 4 was plotted with time varying gain to equalize amplitude of the later arrivals. Development of processing for these lines is underway. The primary goals will be to reduce multiples, a serious problem in Chukchi Shelf lines and to enhance the weak reflectivity seen in the "basement" beneath the rift infill.

Preliminary Interpretation

Figure 4 shows the MCS lines collected during this survey. Two crossing lines are displayed here (Figure 4a and 4b) to give some sense of three-dimensional basin stratigraphy. While the MCS database for the Arctic Ocean has grown substantially since the pioneering work of Grantz (Figure 2; Grantz et al., 2004) the complete lack of age control for individual reflectors greatly restricts interpretation of the complex stratigraphy. Without age control, it is not possible to relate the imaged stratigraphy to other dated events and expand the history of these basins beyond simplistic interpretations based on stratal geometry.

The initial cruise plan was based on two primary objectives; 1) image the stratigraphy of the Chukchi Borderland and 2) by sailing across the Chukchi Shelf exploration wells (Figure 2) carry age control from these dated sequences into the Arctic Ocean. These data reveal the infill of the basins that dissect the Borderland (Figure 2) and hint at deeper stratigraphy below the probably Mesozoic and Cenozoic basin fills. As processing advances, it is hoped that this deep coherence, occasionally glimpsed in these single channel records will be enhanced. The second objective will be more difficult to achieve.

The left hand side of the line shown in Figure 4b crosses the Chukchi Shelf. While some stratigraphy can be seen clearly seen before the 1st multiple, subsequent multiples obscure the deeper section. Achieving the 2nd objective will require developing effective strategies to mitigate the multiples. Experiments are underway to find a solution.

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Conclusions

This MCS data will make it possible, in conjunction with other information, to test existing tectonic models and develop new constraints on the development of the Amerasian Basin. By accepting or rejecting existing models, this project will substantially advance our understanding of the Mesozoic history of the Arctic Ocean. In addition, these data will be the basis for the formulation of new tectonic models for the history of this region, which will substantially expand our understanding of the surrounding continents. This dataset will also make other science and deeper exploration of the history possible.

The sediments beneath the seafloor of the Arctic Ocean's deep basin and the seafloor itself preserve the history of the Arctic Ocean. Sediment accumulation in the deep polar basin is intimately linked to environmental factors such as erosion on the surrounding continents, absence or presence of sea ice, oceanographic circulation, and water mass productivity. Scientific drilling is needed to access this formidable archive of paleo-environmental history beyond the short geological time spans captured by conventional sediment cores.

Until the recent Arctic Coring Expedition (ACEX) drilling (Moran et al., 2006) on the Lomonosov Ridge, no scientific drilling had been done in the Arctic Ocean, partly due to the paucity of site survey data sets (Kristoffersen and Mikkelsen, 2004). Retrieving continuous records of the Cenozoic and Mesozoic stratigraphy of the Arctic will require sediment cores of several hundred meters length. The data collected during this proposed program would establish, with other geophysical information and seismic reflection data collected by other programs (eg. Grantz et al., 2004), an integrated site survey data base for the Chukchi Borderlands, enabling cruise planning, proposals, and eventually drilling in what is one of the less logistically onerous regions of the Arctic Ocean.

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