ORIGIN AND EVOLUTION

OF THE CHUKCHI BORDERLAND

A Thesis

by

VERONICA ARRIGONI

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2008

Major Subject: Geophysics

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Approved by:

Chair of Committee,	J.R. Hopper
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ABSTRACT

Origin and Evolution of the Chukchi Borderland.

(December 2008)

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Chair of Advisory Committee: Dr. J.R. Hopper

The origin of the Amerasia Basin, in the Arctic region, is nowadays a highly controversial topic due to the paucity of geophysical data available and the difficulties in interpreting possible seafloor spreading magnetic anomalies. The Chukchi Borderland, that extends into the Amerasia Basin north of the Chukchi Sea, has proven to be one of the more difficult features of the arctic to understand in any model for the tectonic evolution of the Amerasian Basin.

In the summer of 2005, *USCG Icebreaker Healy* crossed the Arctic Ocean from Dutch Harbor, Alaska, to Tromsø, Norway, to collect geophysical data and take shallow cores in an effort to gain greater insight into the paleo-oceanographic, depositional and tectonic history of the Arctic basins. 780 km of new seismic lines from the Chukchi Borderland are presented along with a preliminary interpretation of the tectonic evolution of the Amerasia Basin in light of the new observations.

The data provide high quality images of the region down to the basement and, in areas, images below the basement. The pelagic sediment cover varies along the profiles with thicknesses ranging from less than 0.1 s to a maximum of 1.5 s TWT. Significant extensional normal faults, striking approximately north-south, are observed throughout the dataset with strong evidence of growth faults below a major unconformity. Along the reflection images oriented E-W, young sediments and possibly the seafloor show small offsets. While this may be due to differential compaction or fluid expulsion, the presence of low amplitude folds above the footwalls suggests a recent fault-propagation folding process. This may indicate recent reactivation and rotation of the crustal blocks, although the total amount of displacement and strain are very small. We do not observe compressional or inversion structures anywhere in the dataset. The orientation of the structures imaged is similar to those observed along the Mendeleev Ridge to the west, which may support recent models that propose the Chukchi Borderlands and Mendeleev Ridge comprise a single extensional province that rifted from the Siberian margin.

DEDICATION

To Myself.

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TABLE OF CONTENTS

Page

Page

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

The Arctic Ocean consists of two distinct basins, the Eurasia Basin and the Amerasia Basin (fig. 1). It is generally accepted that the Eurasia Basin was created by seafloor spreading in the late Paleocene times (Vogt et al., 1979; Kristofferson, 1990; Cochran et al., 2003). The origin of the Amerasia Basin, however, is highly controversial due to the paucity of geophysical data available and the difficulties in interpreting possible seafloor spreading magnetic anomalies. Various models proposed for the opening of the Amerasia Basin have been discussed by Lawver and Scotese (1990) in a comprehensive review of the subject. While there exist several alternatives, (Lane, 1997; Embry, 2000; Miller et al., 2006), the most widely accepted models invoke a counterclockwise rotation of the Chukchi Borderlands, Siberian, and Northern Alaskan margins from the Canadian arctic island margin (Grantz et al., 1979; Embry and Dixon, 1990; Lawver et al., 2002, Grantz, 2006).

The Chukchi Borderland occupies an area of 600 by 700 km and extends into the Amerasia Basin north of the Chukchi Sea, between eastern Siberia and western Alaska. It has proven to be one of the more difficult features of the arctic to understand in any model for the tectonic evolution of the Amerasian Basin. It consists of several approximately north-south-trending segmented regions, including the Northwind Ridge and the Chukchi Cap and Rise, and the several western plateaus.

This thesis follows the style of *Geophysical Journal International.*

The Northwind Ridge is bounded to the east by a steep escarpment that defines the boundary to the Canada Basin(fig.2).

Grantz and others (1998) have cored Phanerozoic sediments from Northwind Ridge that are similar to the basement rocks found within the Sverdrup basin of the Canadian Arctic margin. This evidence, together with modeling of gravity data (Laxon and McAdoo, 1994), confirms that at least part of the Borderland is continental. This has led to the suggestion that the Chukchi Borderland rifted away from the eastern Canadian arctic margin and through various strike-slip movements and rotations, was eventually brought to its present position (e.g. fig. 3, Grantz et al., 1998).

In the summer of 2005, *USCG Icebreaker Healy* crossed the Arctic Ocean from Dutch Harbor, Alaska, to Tromsø, Norway, to collect geophysical data and take shallow cores in an effort to gain greater insight into the paleo-oceanographic, depositional and tectonic history of the Arctic basins. In total, nearly 2,200 km of new seismic reflection data were collected during the expedition. In this paper, seismic lines from the Chukchi Borderland are presented along with a preliminary interpretation of the tectonic evolution of the region in light of the new observations. A comprehensive review of the main models describing the origin and evolution of the Canada Basin is provided with the main purpose of highlighting the main points of controversy. A brief overview of the data acquisition and processing precedes a detailed description of the processed multi-channel seismic (MCS) reflection lines acquired.

Our observations show that the Chukchi Borderland is an extensional terrain, with extensive E-W dipping normal faults visible throughout the region. Growth faulting clearly affected older sediments below a major unconformity. However, many faults appear to have been reactivated quite recently and may displace the seafloor. This latter observation indicates that the present day stress field of the Central Arctic is overall extensional, contrary to some models that predict a compressional stress field in the region. The lack of evidence for inversion structures further supports this conclusion.

2. TECTONIC SETTING

The Arctic Ocean is broadly divided into two large basins, the Eurasia Basin and the Amerasia Basin (fig. 1). They are separated by the Lomonosov Ridge, a continental fragment that rifted off the Barents shelf, at the Arctic Russian margin (Heezen and Ewing, 1961; Jokat et al., 1992 and 2005; Moran et al., 2006). The Amerasia basin includes the Canada Basin, the Alpha and Mendeleev Ridges, the Makarov Basin and the Chukchi Borderland (fig. 1). The latter includes the Northwind Ridge, the Chukchi Rise and Cap and the Chukchi Plateau (fig. 2). The Eurasia Basin includes the Amudsen and Nansen Basins and the Barents and Laptev Seas. The basic plate tectonic setting of the Eurasia Basin is reasonably well understood. It opened with the splitting of the North America-Eurasia lithospheric plates along the ultra-slow spreading Gakkel Ridge at time of magnetic anomaly 24/25, about 52 - 56 Ma (Ostenso and Wold, 1973; Coles et al., 1978; Kristofferson, 1990; Vogt et al., 1979; Cochran et al., 2003).

In contrast, the kinematic history of the opening of the Amerasia Basin is an unresolved, first-order scientific problem. Much of the basic geophysical mapping work used in other parts of the global oceans to elucidate the history of plate motions is significantly hampered in the Arctic region by ice cover and extreme environmental conditions. In addition, seafloor spreading anomalies in the Canada Basin are difficult to analyze because of their relatively low amplitude (Coles and Taylor, 1990; Grantz et al., 1990), and may be masked in some areas by thick volcanic sequences associated with the Alpha Ridge (Vogt et al., 1982). Because of the lack of well defined magnetic anomalies, spreading centers and fracture zones, the geologic history of Amerasia basin remains very controversial. The current geologic framework is based primarily on data coming from the continental margins, which is insufficient to understand the deeper parts of the basin.

2.1 The Role of the Chukchi Borderland in the Central Arctic

Understanding the kinematics that drove the Chukchi Borderland to its present position is essential for resolving the evolution of the Canada Basin. The provenance and the processes that moved this isolated continental fragment through the central region of the Arctic could help to reveal the overall tectonic framework that formed the Amerasia Basin as we see it today. Because of this, much of the current geological and geophysical research focuses on this region, with the goal of enlarging the stratigraphic and structural databases.

2.2 Tectonic Models for the Opening of the Canada Basin

Many different tectonic reconstructions have been proposed for the Amerasia Basin, distinguished primarily by assumptions of how and when the Canada Basin opened. The deep basin is almost certainly oceanic and is most likely Cretaceous in age. Competing models, however, disagree in the number and orientation of spreading centers.

Lawver and Scotese (1990) provided a comprehensive review of the main ideas which have been proposed to explain the Canada Basin. They divided the models into four categories. The first category assumes that seafloor spreading was parallel to, and possibly coincident with, the Alpha and Mendeleev Ridges (Hall, 1970; Ostenso and Wold, 1973; Crane, 1987; Smith, 1987). In this class of models the North Slope of Alaska (located on the northern slope of the Brooke Range along the coast of the Chukchi and the Beaufort seas) is a passive margin that rifted from the Lomonosov Ridge or from the Alpha Mendeleev Ridges. In these models, the Canadian Arctic Islands are bounded by a left-lateral transform fault. The second group of models can be characterized as “Arctic Alaska strike-slip” models (Herron et al., 1974; Vogt et al., 1982). These models describe east Siberia as rifting away from the Arctic Canadian Islands along a transform fault that parallels the northern Alaskan margin. They predict little or no motion of the Alaska block with respect to cratonic North America. The third group includes the models suggested by Jones (1980, 1982, 1983). He described the origin of the Canada Basin as trapped Paleozoic crust attached to Arctic Canada as part of the North America plate. The North Slope of Alaska and Eastern Siberia formed a single terrain bounded by a large right-lateral strike-slip fault. Both regions were translated northward along this fault until the initiation of seafloor spreading along the Alpha Ridge 90 Ma ago.

The fourth, and most widely accepted, group of models calls for a counter-clockwise rotational opening of the Canada Basin. Based on the simple observation of an apparent paleogeographic fit between Arctic Alaska and Arctic Canada, Carey (1955) was the first to propose a rotational model for the formation of the Canada Basin. Most current rotational models are just minor modifications to Carey’s hypothesis. In its simplest form, the rotational models assume that during the Paleozoic, northern Alaska, northeastern Siberia and the Chukchi Borderland were contiguous with the Canadian Arctic Island region of the North America craton. During the Mesozoic, the Arctic Alaska - Chukotka microplate rotated approximately 66º counter-clockwise from Arctic Canada about a pole near the Mackenzie Delta leading to seafloor spreading and opening of the Canada Basin (Carey, 1958; Tailleur and Brosge, 1970; Grantz, 1979; Vogt et al., 1979; Forsyth et al., 1986; Fujita and Newberry, 1982; Coles and Taylor, 1990; Laxon and McAdoo, 1994; Lawver et al., 2002; Grantz, 2006). According to this model, both the Canadian Arctic margin and the Alaskan-Siberian margin are rifted margins with a major transform boundary along the North American side of the Lomonosov Ridge. The Chukchi Borderlands, however, are difficult to place in these models.

Grantz's reconstruction of the opening of the Amerasia Basin is probably the most widely known rotational model. Based on the stratigraphy of the Northwind Ridge and the interpretation of the weak magnetic anomalies in the Canada Basin, together with the orientation and the age of possible rift-margin structures, Grantz accounted for most of the major crustal elements of the Amerasia Basin, supporting Carey's hypothesis of the anticlockwise rotational rifting of Arctic Alaska from North America. His reconstruction of the rifting history of Amerasia Basin is summarized in figure 3 (Grantz et al., 1998), going from the actual features of the present-day basin (fig. 3A) back to its pre-rifting configuration in the Jurassic (fig 3D). Although this rotational model is today widely accepted, details regarding timing of rifting and spreading remain controversial. In particular, simple closure about the pole of rotation results in significant crustal overlap that is difficult to explain. To account for this, Grantz describes the borderland as an ensamble of small, independent microplates that were able to re-organize their position in time in ways that are difficult to explain geodinamically (fig. 3).

In addition to the controversy over the basic kinematics of the Amerasia Basin, the exact timing of initiation of seafloor spreading remains unconstrained. Nevertheless, the general time frame is very likely mid to late Cretaceous and is supported by several lines of evidence. Tailleur and Brosge (1970) suggested that spreading occurred in the Early Cretaceous based on of the age of the thick Brookian sequence deposits on the western North Slope of Alaska. A change in the direction of sediment progradation associated with a Hauterivian unconformity (135 Ma) is considered to indicate the time at which the Arctic-Alaska microplate was transported away from the proto-Canadian Arctic margin. Heat flow observations and lithospheric cooling models for the central Canada Basin have been interpreted to indicate that seafloor spreading occurred between the Barremian and Campanian (130 - 80 Ma) (Lawver and Baggeroer, 1983). Magnetic anomaly data in the central Canada Basin may support spreading from the early Kimmeridgian to Valanginian (155-140 Ma) (Taylor et al., 1981; Vogt et al., 1982). Paleomagnetic data from the North Slope Kuparup formation seem to indicate that the central North Slope was still adjacent to the Canadian Arctic Island in the Valanginian (140 Ma) (Halgedahl and Jarrard, 1987) and that its motion relative to North America ceased in the late Albian (100 Ma). Embry and Dixon (1994) similarly point out that the Hauterivian unconformity, present on the Alaskan North Slope and the Canadian Arctic Islands, is the best evidence of the initiation of spreading and may represent a breakup unconformity. According to them, two other major unconformities, an Aptian unconformity on the North Slope and a Cenomanian unconformity in the Mackenzie delta region, conflict with the paleomagnetic indications of timing and, thus, are unlikely candidates for a breakup unconformity. Recent studies of biostratigraphic formation tops and foraminiferal biofacies performed in wells of the both North Slope and Canadian Arctic Islands (Mickey et al., 2002) provide good evidence for incipient rifting in the Hettangian-Sinemurian (198 Ma). In summary, while Mesozoic seafloor spreading is certain, the evidence available cannot constrain the precise timing of breakup events anywhere around the Canada Basin.

2.3 Evidence Supporting the Rotational Model

The clearest evidence for understanding the evolution of an oceanic basin is derived from the identification of spreading centers, magnetic anomalies and fracture zones. Unfortunately, these features are not easily identifiable in the Amerasia Basin, although several attempts have been made to interpret such elements (Coles and Taylor, 1990; Grantz et al., 1990; Vogt at al., 1982). Despite the paucity of magnetic and gravity data, recent surveys of the area have shown the existence of a major, north-trending gravity low that bisects the basin and terminates in the Mackenzie Delta (fig. 4, from Kenyon and Forsberg, 2001). A bilaterally symmetric pattern of magnetic lineations, 300 km wide, appears to be centered over this gravity low supporting the interpretation of a fossil spreading center, consistent with the rotational model (Brozena et al., 1998).

Further evidence in support of the rotational model comes from Halgedahl and Jarrad (1987). They determined the paleomagnetic poles of a Valangian (140 Ma) sandstone from the North coast of Alaska and showed that a 66º clockwise rotation of northern Alaska results in the coincidence of the Alaskan-Valangian poles with that of the cratonic pole for the same age, located 1000 km southeast. Embry (1990) found that a restoration of northern Alaska and northeastern Siberia against the Canadian Arctic Islands provides a good match of several different geological trends that are older than the formation of the Amerasia Basin. Furthermore, he showed that the Devonian tectonic features of northern Alaska and the Canadian Arctic can be reconciled by the counter-clockwise rotational model. For example, granitic intrusions dated as Early-Middle Devonian (390 Ma) have been mapped in Alaska, Northern Yukon and the Canadian Arctic Islands. More recently Grantz (Grantz et al., 1998) presented data obtained from shallow cores taken along the Northwind Ridge. These show strong similarities to the stratigraphy of the Sverdrup Basin, further reinforcing his reconstruction for the opening of the Canada Basin.

In general, although the magnetic anomalies are difficult to identify and are often of uncertain interpretation, the available paleomagnetic data from northern Alaska and the analysis of structural and depositional trends along the continental margins of the Amerasia Basin seem to strongly support the rotational model.

2.4 Alternatives to the Rotational Model

Despite the broad range of geological, geophysical, paleomagnetic and paleontologic data supporting the rotational opening of the Canada Basin, no single model has yet been proposed that comprehensively accounts for all the data. A complication to the overall picture is that more than one simple spreading event may have occurred to produce the present-day geometry of the basin. In addition, subsequent tectonic events in northern Alaska may have altered the original spreading characteristics, further complicating tectonic history reconstructions (Taylor et al., 1981; Grantz et al., 1998).

As a result of this lack of solid and unequivocal evidence for the rotational model, several alternatives have been proposed.

Lane (1997) summarized some of the major inconsistencies of the rotational model. First, the it creates a substantial overlap of the Chukchi Borderland and the East Siberian Shelf onto the Canadian landmasses. Second, the rotational model juxtaposes an area that was undergoing extension in the Middle-Late Devonian (Northern Alaska) with one that was undergoing compression (Canadian Arctic). Third, Lane interpreted the age of the rift-drift transition of these two areas as 130 Ma for the first and 100 Ma for the latter, which would imply distinct extensional events for these two margins. Lastly, he noted that the rotational model demands the existence of a major transform fault along the base of the Lomonosov Ridge, the evidence for which is weak.

Based on these and other major observations, Lane (1994, 1997) proposed a multistage evolutionary model that constrains the kinematics of ocean spreading to be north-westward, perpendicular to the direction predicted by the rotational model. His model involves three distinct stages of oceanic crust formation following protracted intracontinental extension. Stage 1 resulted in the formation of oceanic crust in the western Makarov Basin and along the Arctic Alaska continental margin. Stage 2 formed the Canada Basin and rifted the Chukchi Borderland North-Westward away from the

Beaufort-Mckenzie region. Stage 3 formed a zone containing North-South trending magnetic anomalies in the center of the southern Canada Basin. Lane's model, by invoking a general NW stretching with varying extinct spreading axes, interprets the Arctic Alaskan and Canadian margins as adjacent to the same margin and not conjugate segments separated by an oceanic basin.

A more recent alternative to the rotational model was proposed by Miller et al. (2006). To test the existing models for the formation of the Amerasia Basin, they dated several detrital zircon suites from samples of a Triassic sandstone from the circum-Arctic region. The calculated ages indicate that Chukotka is not part of the Arctic-Alaska microplate as would be required by the rotational models, but instead originated from the east, near Taimyr and Verkhoyansk, east of the Polar Urals of Russia. The striking differences between Triassic sedimentation in Arctic Alaska and Chukotka, supports the idea that these two areas experienced completely distinct rifting events. Miller et al. (2006) propose that the Arctic-Alaska block moved by counterclockwise rotation from the Canadian margin, opening the southern Canada Basin. However, the Chukchi Borderland, as well as the Alpha and Mendeleev Ridges, moved to their present-day position from an area close to the Barents Shelf as a result of extensive continental rifting. This model, which does not preclude a rotational opening for the southern Canada Basin, instead invokes an origin of the Chukotka region closer to Russia to explain the sediment infill of the Triassic basins. Interestingly, however, Miller et al.'s (2006) reconstructions place the northern rather than the eastern boundary of the Chukchi Borderland close to the Sverdrup basin. Finally, their model predicts that the

Alpha-Mendeleev Ridges and Chukchi Borderland were originally part of a single extensional terrain.

2.5 The Chukchi Borderland

The combined Northwind Ridge and Chukchi Plateau are considered to be a single continental fragment dissected by extension (Taylor et al., 1981; Vogt et al., 1982; Grantz et al., 1990; Hall, 1990; Klemperer et al., 2002). The precise origin of this feature is still uncertain. It is clear, however, that the Chukchi Borderland was created by processes associated with the opening of the Amerasia Basin. Therefore, any model attempting to describe the tectonic evolution of the borderland must also reflect the opening history of the adjacent ocean basin(s).

Piston cores collected on the flanks of the Northwind Ridge sampled stratigraphic units that range in age from Paleozoic to Late Jurassic (fig. 3). Permian red bed sediments and other dredged rocks correlate with coeval rocks of the Sverdrup Basin of the Canadian Arctic Archipelago, supporting the theory that the borderland was originally attached to Arctic Canada and Arctic Alaska prior to any rifting that generated the Amerasia Basin (Grantz et al., 1998). The earliest syn-rift sediments recovered from the Northwind Ridge are early Jurassic in age, suggesting that the Chukchi Borderland began rifting from the Sverdrup Basin by that time. According to Grantz et al. (1998), new oceanic crust started forming by late Jurassic or earliest Cretaceous, ending no later than the Aptian time (Grantz et al., 1998).

Nevertheless, the present position of the Chukchi Borderland and the orientation of its main structures cannot be explained by a single-stage 66º counterclockwise rotation from North America. To account for its misalignment, Grantz (2006) recently refined his model by adding a 22º clockwise rotation away from the eastern Siberian shelf. This last stage is possibly contemporaneous with the spreading of the Canada Basin but must have occurred prior to the emplacement of the Alpha and Mendeleev Ridges. This may be supported by the paleomagnetic analysis of Lower Cretaceous strata conducted by Halgedahl and Jarrard (1987) and the analysis of the magnetic anomalies of the Southern Canada Basin described by Gurevich et al. (2005) and Gurevich and Merkouriev (2006).

However, the paucity of geological and geophysical data strongly limits the possibility of drawing conclusions over the tectonic evolution of the Chukchi Borderland. The most recent speculations over its kinematic history and paleogeographic placement make distinct predictions about the structures that should be observed. For example, Grantz et al. (1998) propose recent compression along the Northwind Ridge as a way to adjust the alignment of the borderland after the opening of the Canada Basin (fig. 3A). This should result in compressional structures and basin inversion in the borderlands.

3. DATA ACQUISITION AND PROCESSING

3.1 Healy-0503 Arctic Transect

The *USCG icebreaker Healy* crossed the Arctic Ocean from Dutch Harbor, Alaska, to Tromsø, Norway, during August and September 2005. Multi-channel seismic (MCS) acquisition on icebreakers in the Arctic Ocean is a challenging undertaking as far as satisfying the rigorous quality criteria of modern seismic industry standards. The severe ice conditions encountered during the cruise varied from 7/10 to 10/10 ice cover and permitted only intermittent acquisition of MCS data. Additional practical limitations in heavy ice included: a very short active streamer length (200-300 m) towed at 90 m offset; limited to no control on source depth and cable depth because of the absence of birds and ice chunks interfering with towed equipment; an irregular vessel trajectory often constrained to follow patchy leads; irregular vessel speeds while breaking ice; irregular engine speeds which generated significant water column noise and excessive wash behind the ship interfering with towed equipment. Nevertheless, 2,200 km of new MCS reflection data were acquired during the cruise, including 780 km along the Chukchi Borderland (fig. 5).

Data were acquired using two 250 cubic inch (4 l) Sodera G-guns. Shots were recorded on a 24-channel analog streamer (Geco HSSG) with a group spacing of 12.5 m. The signals were anti-alias filtered and digitized at 1 ms sampling interval using two Geometric Geode seismographs and then stored to disk in SEG-Y format. Guns were fired at a slightly randomized 20 s interval for a nominal average shot spacing of about

50 m. Shots were binned into common midpoint gathers spaced every 6.25 m along the profile, assuming a simple straight-line geometry. Wear and tear from towing the analog streamer through ice randomly affected the hydrophone response, diminishing the number of active channels, which varied from 11 to 24, and resulting in a data fold as low as 4.

3.2 2D MCS Lines Processing

The initial processing phase focused mainly on noise removal. Two different noise sources were recognized throughout the dataset: random noise bursts and low frequency linear noise. The former, most likely resulted from electrical noise produced by the ship prior to digitizing the signal. These bursts were then "smeared out" by the anti-alias filter. As a result, the bursts have frequency and amplitude characteristics comparable to real seismic events and are therefore difficult to remove with automatic noise filters. A noise-burst filter window of 10 ms length and trip threshold of 3 was used as a first pass and the noise bursts were replaced by trace segments interpolated from adjacent traces. The shots were then manually edited to eliminate any remaining noise bursts.

The second noise source, low frequency linear noise, is believed to have resulted from the occasional tugging motion of the ship on the streamer while cruising through ice cover. Since this noise was observed to be propagating at velocites of 1000-1400 m/s, an *f-k* velocity filter was designed to suppress it. To optimize the results of *f-k* filtering, it was essential for all the noise bursts to be completely removed. An iterative process of manual edits and f-k filtering was therefore required.

A minimum phase predictive deconvolution was applied to the filtered dataset to minimize the ringing of the bubble pulse visible on all the raw data. An operator length of 100 ms and an operator distance of 45 ms were used. Data were then amplitude corrected using a time raised to a 1.5 power function and band-pass filtered from 8 to 85 Hz .

Because of the limited offsets and low data fold, standard semblance velocity analysis was not practical on this dataset. However, because the offsets are small, ranging from 90-380 m, the actual move-out even for low velocities is small. Thus, stacking the data is insensitive to large errors in stacking velocities. For this reason, we did not derive a proper stacking velocity table but instead digitized a major unconformity visible throughout the data set, corresponding to the top of the basement, and stacked at an RMS velocity of 1480 m/s above and 2300 m/s below.

Due to the absence of any true interval velocity information, the post-stack migration was performed using a Stolt *f-k* constant velocity algorithm (Yilmaz, 2001) at water velocity (1480 m/s). The resulting images are therefore only partially migrated. The initial migrations resulted in significant migration artifacts in several areas. This was a result of incomplete noise removal during the pre-stack editing. Therefore, to further enhance the reflection images, a new manual editing stage was performed on the stacked section to kill the noisy CDPs. A new trace interpolation was run and the cleaner stacks were then migrated at water velocity. The final time sections are shown in figure 6. Table 1 summarizes the survey geometry and the processing parameters used.

The MCS survey over the Chukchi Borderland was broken into the following seismic lines: lines 1 to 6, oriented N-S and acquired parallel to the Northwind Ridge; lines 7 to 9, oriented W-E and acquired across the Northwind Ridge; and lines 11 to 16, oriented E-W from the Northwind Escarpment onto the Chukchi Rise. Line 10 did not contain any useful data. These lines cover a total of 780 km. Considering the difficult conditions encountered during the acquisition stage and the limitations that a challenging environment such as the Arctic imposes, the overall quality of the reflection images is very good. In general, the shallow structures are well imaged, revealing small scale (tens of meters) details of the seafloor morphology and the sedimentary structures. Reflections deeper than 3-4 s are usually absent or hidden by the multiple energy. Nonetheless, clear images at least down to basement were obtained for the entire data set.

4. RESULTS

The seismic sections selected for the purpose of this paper are shown in figure 6. They can be more generally separated into two sub-parallel lines, oriented approximately E-W, one crossing the Northwind Ridge at about 77 degrees latitude (lines 7 to 9) and the other at 78 degrees latitude (lines 11 to 16). Line 5, acquired parallel to the Northwind Ridge, is also included (refer to the cruise map in fig. 5).

The sedimentary package overlying the acoustic basement was divided in two units, Unit I and Unit II. Unit I is the uppermost sedimentary drape and consists of coherent strata that blankets most of the area. Unit II is separated from Unit I by a regional unconformity, named U1, and lies above the basement. It is significantly affected by the normal faults that cut the underlying crust and shows clear evidence of syn-tectonic deposition. The underlying continental basement is highly dissected by numerous normal faults that result in horst-and-graben like structures across the whole area.

Unit I is laterally continuous and can be easily correlated across the distinct lines. This unit does not appear to be affected by any major tectonic event although some small displacements, discussed further below, are observed. This conformable layer is relatively transparent and ranges in thickness from 0 to 0.35-0.4 s TWT (approximately 0 to 240-320 m). A clear reflection, marked as P1 in the figures, locally separates this sedimentary drape into two distinct packages. It could represent a minor hiatus between two successive pelagic sedimentation stages or else could be related to bottom currents redistributing the sediments. Along line 05, where the seafloor is very shallow, only a thin veneer of sedimentary drape is observed and the sediment is, in some places, totally absent. Within this thin drape, P1 commonly appears as an erosional surface (fig. 7 for a detail of Healy0503 – Line 05). Because the water is very deep, 1500 m and greater, it is difficult to associate such erosional feature to recent ice-rafting over the area, although it cannot be ruled out. A more probable scenario could be related to erosion and redistribution of deep sediments by bottom currents or slumping along the steep scarps created by the major normal faults present in the region.

The sedimentary layers composing Unit I are generally unaffected by recent faulting. The small offsets visible throughout the lines seem to be mainly related to differential compaction acting on young, unconsolidated sediments. However, more pronounced displacements are observed in some locations, possibly suggesting recent reactivation of the major normal faults that dissect the region, and are discussed further below (fig. 8 and 10 of Healy0503 - Lines 07 and Line 12).

Separating Unit I from the underlying Unit II is an unconformity, U1, that is easily traceable across the entire Northwind Ridge and Chukchi Rise. Compared to Unit I, Unit II shows more variable characteristics and more complex features. The top is marked by high-amplitude reflectors whose pattern is clearly recognizable among the different lines even though it can locally appear disrupted. The thickness of this unit varies from 0 s on the ridge flanks up to 0.9 s TWT (~700 m) in the deepest grabens. In these grabens, sediments appear to wedge towards the faults, clearly suggesting deposition concurrent with the extensional deformation of the borderland. In some lines, there is a clearly imaged sedimentary wedge at the base of Unit II (Unit II B), topped by a surface marked as P2 (fig. 8, 10 and 11 of Healy0503 – Line 7, 12 and 13). This wedge has thicknesses locally reaching 0.6 s TWT (~550 m) and it differs from the upper part of Unit II where the syn-tectonic characteristics produced by growth faulting are less evident (Unit II A). Numerous normal faults affect the entire package, locally creating large offsets both in the sedimentary cover and the underlying basement. In areas of intense faulting, the sediments of Unit II have displacements of up to 0.5 s TWT and the basement shows displacements up to 1.0 s TWT.

At the base of Unit II, a second package of bright reflections defines the top of the basement. Without direct sampling, it is difficult to determine whether the basement is crystalline rock or consolidated Paleozoic sediment. In general, most of the basement appears to be transparent with no distinct reflection pattern, most likely indicating a crystalline nature. Locally, however, the presence of some discrete sub-horizontal reflectivity seems to suggest a more “stratified” character of this unit (fig. 8 and 9 of Healy0503 – Line 07 and 11). High-angle normal faults, usually dipping eastward, displace the basement several hundred meters in the deepest part of the basin. The data clearly show intense dissection caused by E-W rifting.

Line 5, similar to the other sections, shows a high density of faults that displace the basement and upper sediments, locally up to seafloor. However, the absence of any wedging or splaying in the sedimentary layers may suggest the presence of a strike-slip component of the movement (fig. 7 of Healy0503 – Line 05). The bathymetric chart of the Chukchi Borderland shows a morphologic character consistent with the presence of small sub-basins that open in a NW-SE direction. Thus, we interpret this as an area affected by strike-skip faulting with a number of trans-tensional basins.

5. DISCUSSION

The data shown in this paper have several important implications for unraveling the Mesozoic and Cenozoic history of the Arctic basins. Here, we primarily focus on the regional tectonic implications. First, we discuss the depositional history as it relates to possible major tectonic events. Then, we discuss the structural evolution as inferred from the data and as it relates to various hypotheses formulated for the opening of the Canada Basin.

5.1 Depositional History

The most useful constraint on the depositional history of the Chukchi Borderland comes from the stratigraphic analysis of the Northwind Ridge by Grantz et al. (1998) who collected several cores from the eastern flank of the escarpment at 74.8º N latitude (fig. 5). A seismic line acquired in 1988 by the USGS (Grantz et al., 1998) shows a strong similarity to Line 11, both of which cross the eastern flank of the Northwind Ridge out into the Canada Basin. Based on Grantz's description of the sedimentary units cored and the depositional units identified in this MCS data, it is reasonable to correlate Unit I and Unit II with his findings as described below.

Unit I – Pelagic Drape. Layers sitting above the horizon P1 can be associated with Grantz's Lower Pliocene and Miocene Pelagite. Layers below P1 can be ascribed to Lower Pliocene and Miocene Northwind Breccia. This would make P1 a paraconformity that represents a short depositional hiatus during the Pliocene or Miocene.

Unit II – Pre and Syn-rift deposits below the regional unconformity. Upper Unit II is described by Grantz as Upper Cretaceous air-fall volcanic ash. Lower Unit II, lying below a second paraconformity P2, is described as Lower Cretaceous shale.

While the pelagic nature of Unit I is almost certain, without drilling it is impossible to confirm the presence of volcanic ashes or shales below the regional unconformity observed in the seismic lines. While the strong similarity in reflection characteristics between Unit I and II might lead one to conclude that Unit II could also be pelagic, it seems more likely that it correlates to Cretaceous sediments sampled by Grantz et al. (1998).

Interestingly, the volcanic ash described by Grantz et al. (1998) completely lacks terrigenous detritus. This layer lies below the regional unconformity and dates to 90-92 Ma (Turonian). This suggests that by late Cretaceous time, the Northwind Ridge was isolated from the adjacent continent. Additional evidence for this is seen in Line 11 (fig. 9) where the sediment layers of Unit II onlap the basement over the flank of the escarpment and give the appearance of being syn-rift sediments. This indicates that the Chukchi Borderland was very close to its present position relative to the Canada Basin prior to the major extension that dissected the Borderlands.

The unconformity U1 is present in all the seismic lines and has been observed in the MCS lines acquired over the Mendeleev Ridge (Dove, 2007). Over the Alpha Ridge, Jokat (2003) also identified an unconformity lying over blocks of basement displaced and rotated by extensive rifting. The unconformity therefore appears to mark the cessation of a large-scale, regional extensional deformation event.

The age of the unconformity can be estimated through a simple calculation using an average sediment thickness of 0.3 s TWT to the unconformity and a sediment velocity of 1.6 km/s (appropriate for poorly consolidated, water-saturated sediments) and by knowing the sedimentation rate of the uppermost sediment layer, Unit I. Several studies performed in different locations of the Amerasia Basin generally report very slow depositional rates for the Central Arctic, on the order of 1-3 m/Ma (Thiede et al., 1990; Clark et al., 1996; Polyak et al., 2004). More recently, however, the coring expedition over the Lomonosov Ridge (ACEX) revealed significantly higher values, indicating sedimentation rates for the Neogene and Paleogene of 11.4 m/Ma and 15.4 m/Ma respectively (Moran et al., 2006). Given these extreme bounds on possible sedimentation rates, we consider two distinct possibilities for the age of the unconformity with dramatically different implications for the evolution of the region. For simplicity, we ignore any possible depositional hiatus and assume constant depositional rates for the entire sediment thickness.

Using the more traditionally reported values of 1-3 m/Ma, U1 formation dates back to the Mesozoic, at about 120 Ma. According to this scenario, the rifting of the Chukchi Borderland would then be nearly contemporaneous to the opening of the Amerasia Basin (153-127 Ma) and the formation of the Alpha Mendeleev Ridge (120-78 Ma). This implies a long period of tectonic quiescence since the formation of U1, mainly characterized by very slow and undisturbed pelagic sedimentation.

A completely different scenario results if we assume that the Lomonosov Ridge data can be applied to the Chukchi Borderland. In this case, U1 dates back to 22 Ma, or Early

Miocene. This would allow for continued extension of the Chukchi Borderland to well after the formation of the Amerasia Basin, the Alpha Mendeleev Ridge and also the Eurasia Basin (56 Ma). This would indicate that the rifting of this continental fragment represented the very last and isolated stage of the tectonic history of the Central Arctic. The hypothesis of such a young regional unconformity also supports the idea that the regional extensional stress field weakened only recently and could still be affecting the sedimentation in the Chukchi Borderland.

The importance of understanding the characteristics and ages of the uppermost sedimentary units is therefore fundamental to the understanding of the tectonic development of the Chukchi Borderland.

Given the large uncertainty in the sedimentation rates for the Central Arctic, several points should be emphasized. Although the Lomonosov Ridge drilling program produced the most accurate sedimentation rate data so far, it is possible that the Lomonosov Ridge and the Chukchi Borderland represent two completely distinct depositional environments. Thus, any attempt to date the regional unconformity from cores not drilled along the borderland itself should be viewed with caution. At best, the estimates above are speculation. Every factor that could have interfered with the local depositional environment needs to be considered. Redistribution of material by bottom currents, hiatuses and erosional events, and subsidence history, can all have a dramatic influence on the position of the unconformity.

5.2 Structural History

Figure 12 shows the regional bathymetric contours from the International Bathymetry Chart of the Arctic Ocean (IBCAO) and the regional gravity grid along with the location of the seismic profiles. The main extensional faults interpreted in the lines are marked in red solid lines whereas the others, marked in red dashed lines, have been extrapolated based on the similarity of bathymetric and gravity characters with the recorded ones. In addition, we show faults along the Mendeleev Ridge mapped by Dove (2007) marked in blue. This allows for a broader regional pattern to be discerned for comparison to various models for the tectonic history of the area.

The seismic data, together with the regional geophysical data, clearly reveal that the Chukchi Borderland is an extended terrain. The overall picture confirms the main regional extension developing along an N-S to NE-SW axis in the northeastern corner of the Amerasia Basin. The bathymetry is highly controlled by normal faults that dissect this continental fragment in graben and half-graben structures throughout. There is little evidence for any deformation overprinting this extension. Thus, any model must consider a major, E-W directed extensional event as the last phase of tectonic deformation.

The traditional rotational models (Carey, 1958; Tailleur and Brosge, 1970; Grantz, 1979; Vogt et al., 1979; Forsyth et al., 1986; Fujita and Newberry, 1982; Coles and Taylor, 1990; Laxon and McAdoo, 1994; Lawver et al., 2002; Grantz, 2006), lack this fundamental component. While they can successfully explain the similarity in the stratigraphic record of the Northwind Ridge and the Sverdrup Basin, they cannot completely explain the orientation of the extensional structures that dissect the region. Instead, the borderland would have to rotate from the Canadian Arctic along N-S trending strike-slip faults and then re-adjust itself with a smaller clockwise rotations that, in the original model, could have produced a recent compressional front. Such convergence of the Northwind Escarpment against the Canada Basin would have resulted in the reactivation of the normal faults as reverse faults and the formation of inversion structures and compressional features. No such features are observed in the seismic lines. Some low amplitude folds in the upper sedimentary layers could be mis-interpreted as indicative of regional compression. However, this type of folding is common in extensional areas as the result of fault-propagation folding (Bosworth and McClay, 2001).

Based only on the structural features observed from the MCS lines, some other models can probably better explain the evolution of the area, each supported by different evidence.

<u>Late clockwise rotation from the Eastern Siberian Shelf</u>. The E-W dip of the normal faults evolving to a more NE-SW dip on the Mendeleev Ridge would be consistent with a rifting process that began along the Eastern Siberian Shelf and drove the Chukchi Borderland to its current position by a clockwise rotation about a pole located somewhere in the southern Chukchi Sea. This model would imply the presence of a spreading axis in the Chukchi Sea and the development of a transform fault system north of the borderland across the Alpha and Mendeleev Ridges. A schematic of this tectonic model is presented in fig. 13A.

Grantz et al. (2007) recently refined his original rotational model (Grantz et al., 1998) to better fit these structural details in the Chukchi Borderland. In this latest model, the formation of the Amerasia Basin consists of four distinct extensional events. The first two resulted from counterclockwise rotations about a pole in the McKenzie Valley and produced the detachment of the Eastern Siberia from the Northwest Canada in the Sinemurian – Early Hauterivian. The last two stages were the result of two successive clockwise rotations of the Chukchi Microplate out of the East Siberian Shelf and date back to Late Barremian and Paleocene, respectively. These later clockwise movements of the Chukchi Microplate are responsible for the basin and range style structural morphology of the borderland and the extensive thinning of the continental crust underlying the sediments. Grantz et al., lacking magnetic and reflection data, speculate that the pole of rotation for the Chukchi microplate is located on the Chukchi Shelf. In this scenario, the North Chukchi Basin is the result of a localized seafloor spreading related to the emplacement of the Large Igneous Province of the Alpha Mendeleev Ridges (Grantz et al., 2007).

This model is able to reconcile both the stratigraphic evidence that connects Northwind Ridge to the Sverdrup Basin and it provides an explanation of the E-W extension dissecting the Chukchi Borderland. The main limitation is that a significant clockwise rotation of the Chukchi Borderland out of the Siberian Shelf, 45º as per Grantz’s model, is expected to create a compression front, at least in the Northeastern corner of the Chukchi microplate. No sign of tectonic inversion has been reported in the area. In addition, the driving mechanism for such a microplate rotation is difficult to understand.

Rifting from the Siberian margin related to oceanic spreading parallel to the Mendeleev Ridge. This model was proposed by Dove (2007) as one hypothesis for the formation of the Mendeleev Ridge. In this case, the Chukchi Borderland rifted off the Eastern Siberian Sea before the emplacement of the Mendeleev Ridge at a spreading center (fig. 13B). This hypothesis is strongly supported not only by the extensional character of the Chukchi Borderland, and possibly the Alpha and Mendeleev Ridges, but is also consistent with the data presented by Miller et al. (2006).

The main difference between Miller et al. (2006) and Dove (2007) is that Miller argues for continental crust along Mendeleev Ridge, whereas Dove argues for oceanic seafloor spreading.

“Arctic Island Strike-Slip” model. The original idea for this model dates back to the 1970s and is based mainly on the observation of magnetic anomalies that are locally sub-parallel to the Alpha Ridge as well as the straight geometry of the Canadian margin, which strongly resembles a transform margin. Several interpretations have been proposed (Hall, 1970; Vogt and Ostenso, 1970; Ostenso, 1974; Smith, 1987). In its simplest form, this model explains the opening of the Canada Basin as rifting of the North Slope away from the Alpha Ridge. The Chukotka terrain translated dextrally with the respect to the Siberian margin. In the last stages, the Chukchi Borderland and the Mendeleev Ridge would have been stretched and rifted away completely from the Lomonosov margin terminating the spreading of the Canada Basin. The Canadian

Arctic margin acted as a left-lateral transform fault (fig. 13C). This model can also be related to the “rifted volcanic continental margin” model proposed by Dove (2007), who explains the emplacement of the Alpha Mendeleev Ridges as rifting off the Barents Shelf similar to that of the Lomonosov Ridge. The rifting of the Chukchi Borderland and North Slope could probably be contemporaneous to the rifting of the Alpha Mendeleev Ridges, as the whole area could have undergone a regional stretching out of the Barents margin.

Lane’s multistage kinematic model. Lane has repeatedly challenged the rotational model for the opening of the Canada Basin mainly based on the structural data from the Beaufort continental margin. Based on the known extensional nature of the eastern Beaufort margin, he studied several fractured zones of that area and constrained the seafloor spreading in the Canada Basin to be oriented North-Westward, perpendicular to that required by the rotational model (Lane, 1997). As the Chukchi Borderland rifted away from the Beaufort-McKenzie region during the opening of the Canada Basin, the Siberian margin may have acted as transform margin, similar to the “Arctic Island Strike-Slip” model, but with sinistral movement (fig. 13D).

The MCS lines presented are clearly consistent with Lane’s model, which requires a general E-W extension of the Chukchi Borderland. Nevertheless, Lane’s model cannot explain the transition of the dip of the normal faults to North-East in the northern corner of the borderland. In addition, NW extension out of the McKenzie delta would predict fault strikes at a high angle, and even perpendicular to those observed on our data. Thus, significant rotation of the borderland would have to have occurred after opening to make the region fit with Lane's reconstructions.

6. CONCLUSIONS

In summer 2005, a new, integrated geophysical dataset was acquired by the *USCG Iceabreaker Healy* across the Chukchi Borderland parallel and transverse to the Northwind Ridge and Chukchi Rise.

The MCS lines reveal that the Borderland is an extensional terrain, with large, east-west dipping graben structures that affect the basement and part of the overlying sedimentary units. Domino-style, rotated blocks displace the basement and recent sediments and locally produce fault-propagation folds in the overlying layers. In addition, some evidence for strike-slip faulting is seen on a line acquired parallel to the Northwind Ridge, where a high-angle fault dipping NW-SE appears to create a small trans-tensional basin.

Two distinct sedimentary units are observed throughout the region. The uppermost one, Unit I, is at most 300 m thick in the deep basins. It appears to be a pelagic drape that covers the entire area. In some locations, normal faults appear to cut the most recent sediments up to seafloor. While these types of structures may originate from differential compaction, the presence of fault propagation folding in some areas may indicate relatively recent re-activation of the normal faults, suggesting that the present day stress field in the Central Arctic is extensional.

Unit II, which varies from a few meters to a few hundreds of meters thick, is separated from Unit I by a regional unconformity that can be traced throughout the entire Chukchi Borderland. Unit II shows fanning of the sediments towards the normal faults and thus is clearly a syn-rift sedimentary unit.

The regional unconformity that lies between Unit I and Unit II appears to represent the end of the extensional phase that stretched and dissected the Chukchi Borderland. Its age remains uncertain due to the lack of precise sedimentation rate data for this region of the Central Arctic and could represent a gap in sedimentation from Late Cretacious to Oligocene.

The overall consistency of structures observed in the seismic reflection images shows that the latest tectonic deformation of the borderland was significant E-W extension. It is not clear that the orientation of this major extension is consistent with what would be predicted by the widely accepted rotational model for the opening of the Canada Basin. The main E-W extension of the terrains seems to support an origin from the Siberian or Barents Shelf margin more than from the Canadian Arctic, as recently proposed by Miller et al. (2006).

Overall, the structural features of the Chukchi Borderland show a strong similarity with those of the Mendeleev Ridge (Dove, 2007) and possibly of the Alpha Ridge (Jokat, 2003). Both of these latter areas seem to have experienced intense extension oriented E-W to NE-SW, producing a significant normal faulting in the basement and lower sediments with an apparent development of horst and graben structures.

More robust data are needed to unlock the complete tectonic evolution of the borderland: deep drilling cores and higher resolution 3D seismic can provide much stronger constrains and finally clarify the mechanism that drove the opening of the

Amerasia Basin. However, it is indisputable that the clear E-W extensional character of this continental terrain must be accounted for by any model for the opening of the Canada Basin.

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APPENDIX

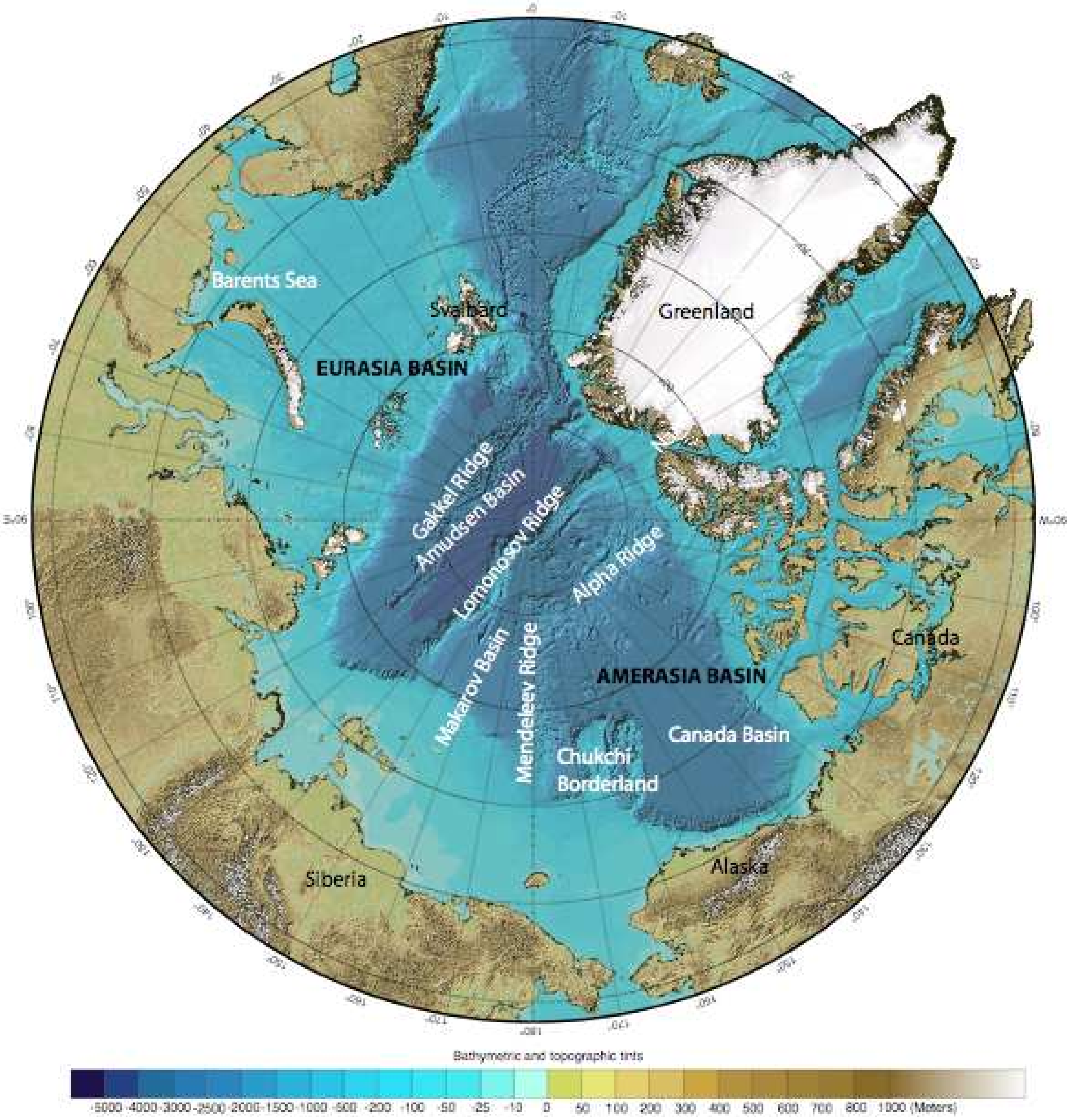


Figure 1. Location map of the Arctic Ocean Region showing the main physiographic features from the International Bathymetry Chart of the Arctic Ocean. Map projection is Polar Stereographic, horizontal datum WGS 84 (from the IBCAO, http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/)

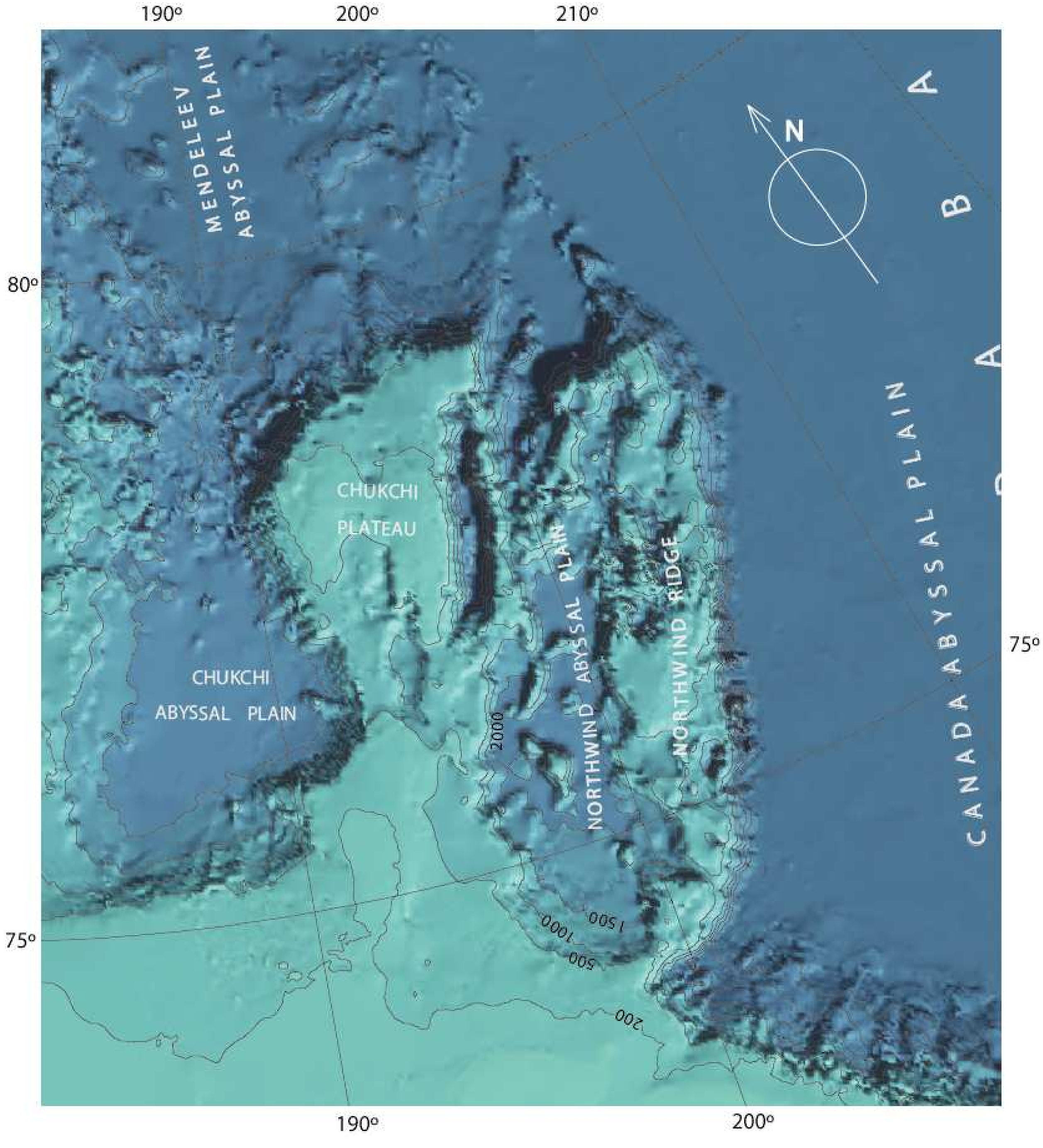


Figure 2. Bathymetric map of the Chukchi Borderland region extracted from the International Bathymetry Chart of the Arctic Ocean. The detailed map shows the main physiographic features of the borderland. (http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/).

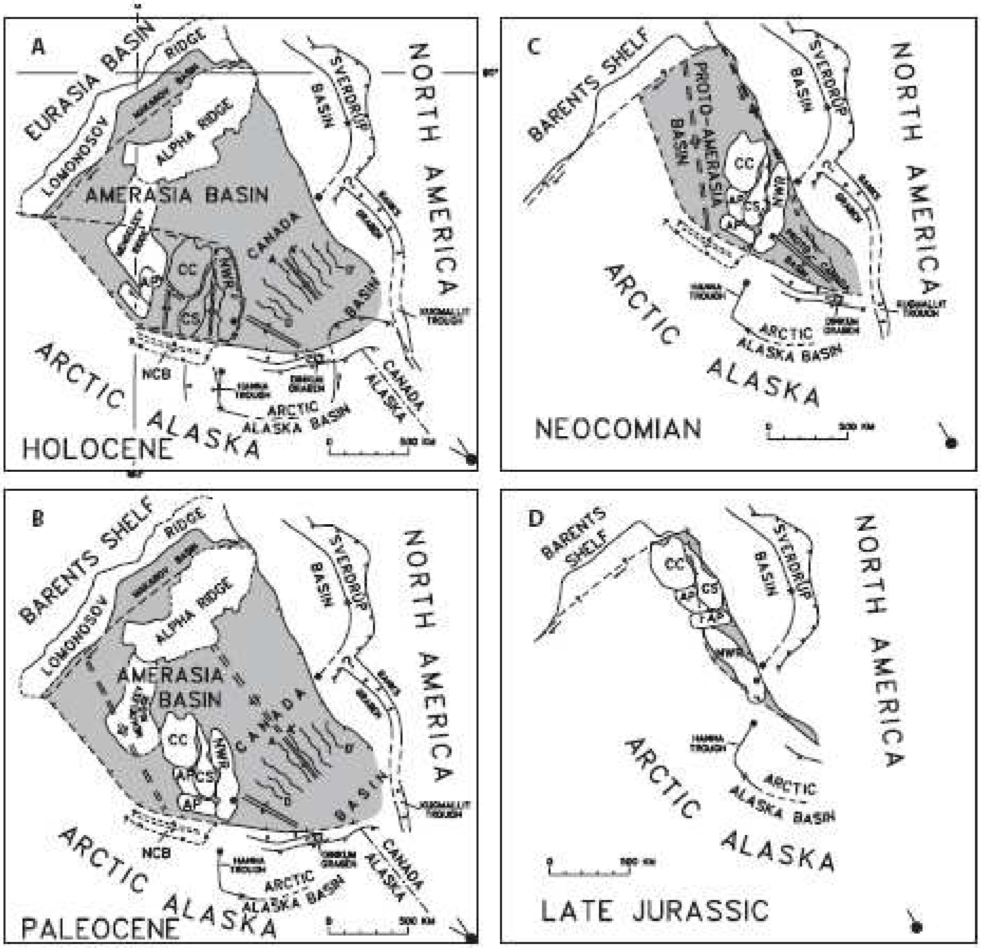


Figure 3. The rotational model proposed by Grantz et al. (1998). Reconstruction of the Amerasia basin from Holocene (A) to Late Jurassic time (D), using the closing Tertiary extension in the Chukchi Borderland (Grantz et al., 1993) and Late Jurassic to Neocomian extension in the Amerasia basin.

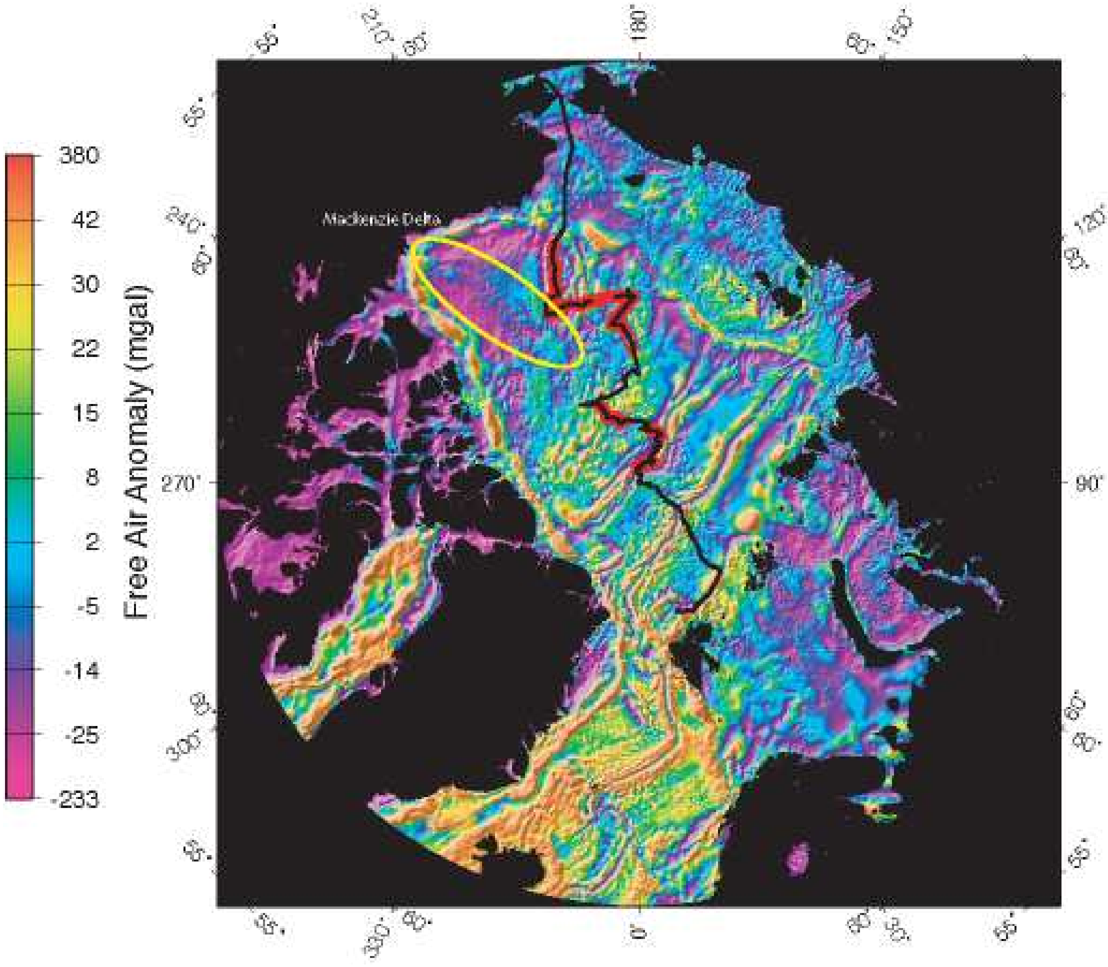


Figure 4 – Arctic Gravity Project free-air gravity anomalies (mgal), from Kenyon and Forsberg, 2001. The yellow oval highlights the gravity low bisecting the Canada Basin from the McKenzie Delta region to the north of the Northwind Ridge. The black solid line represents the *Healy-0503* cruise track and the red shade the locations where MCS reflection data were acquired.

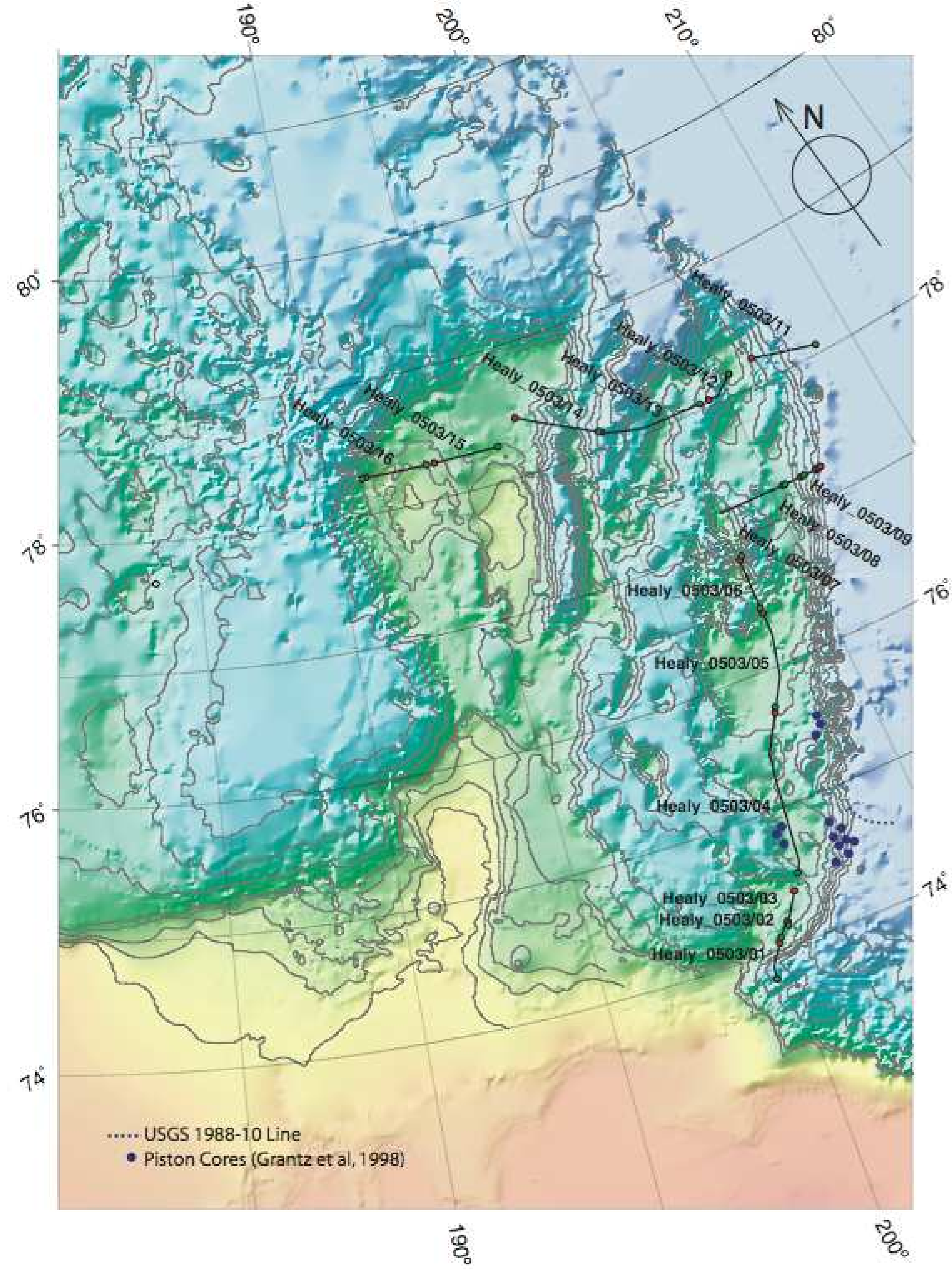
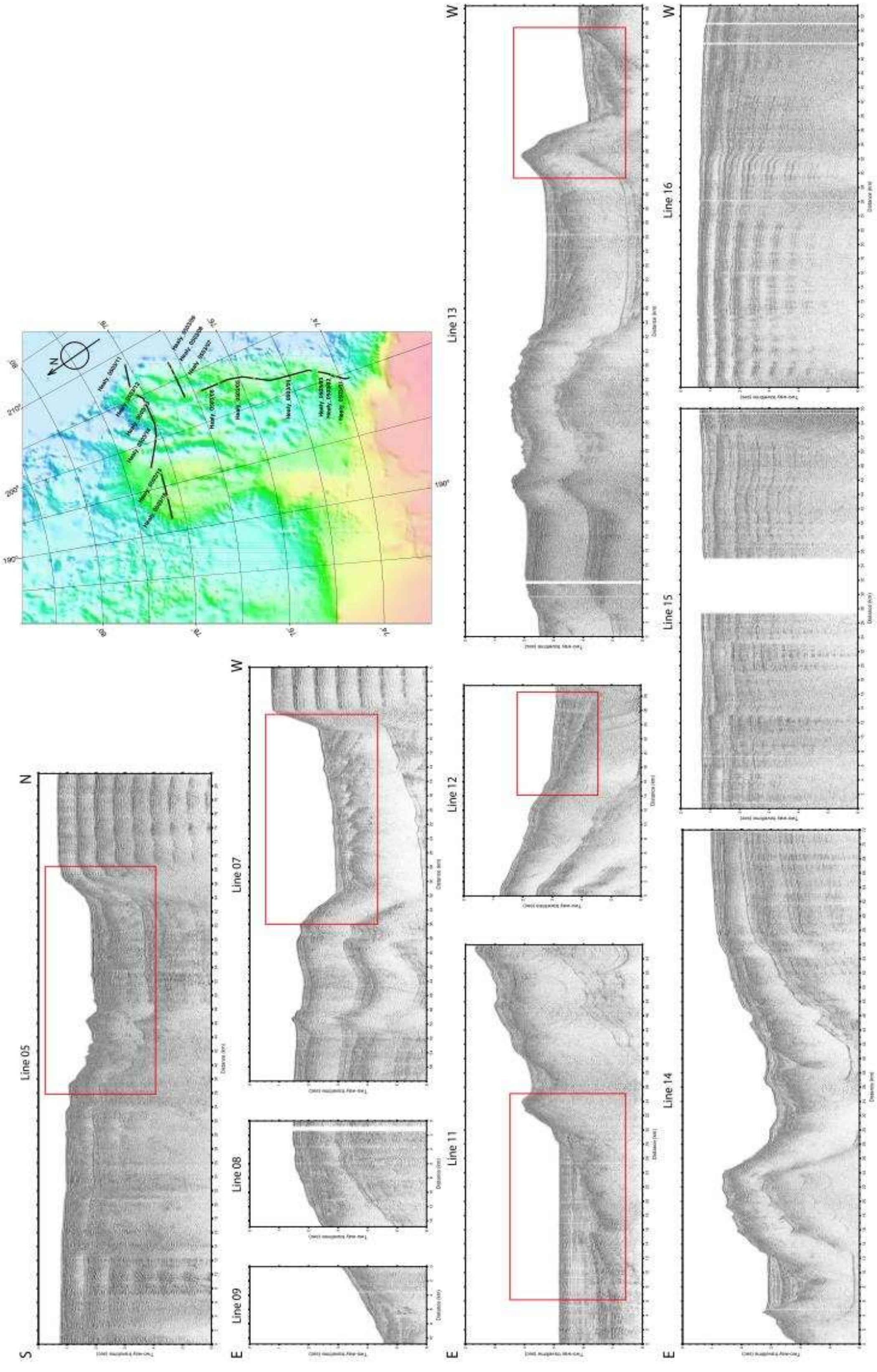


Figure 5. Chukchi Borderland study area. *Healy-0503* MCS lines over the borderland are plotted on the regional bathymetry map. Blue dots in the Southern Northwind Ridge indicate the location of piston cores collected in the 90s (Grantz et al., 1998). The dashed blue line is the location of USGS reflection line acquired in 1988 (Grantz et al., 1998).

Figure 6. Post stack partial-time migrations of *Healy-0503* lines 05, 07-16 (location shown in inset and fig.5). The red boxes indicate the locations of the selected seismic details shown.


S
Line 05
N
E
Line 09
Line 08
Line 07
W
E
Line 11
Line 12
Line 13
W
E
Line 14
Line 15
Line 16
W
Two-way traveltime (sec)
Distance (km)
190°
200°
210°
80°
78°
76°
74°
N

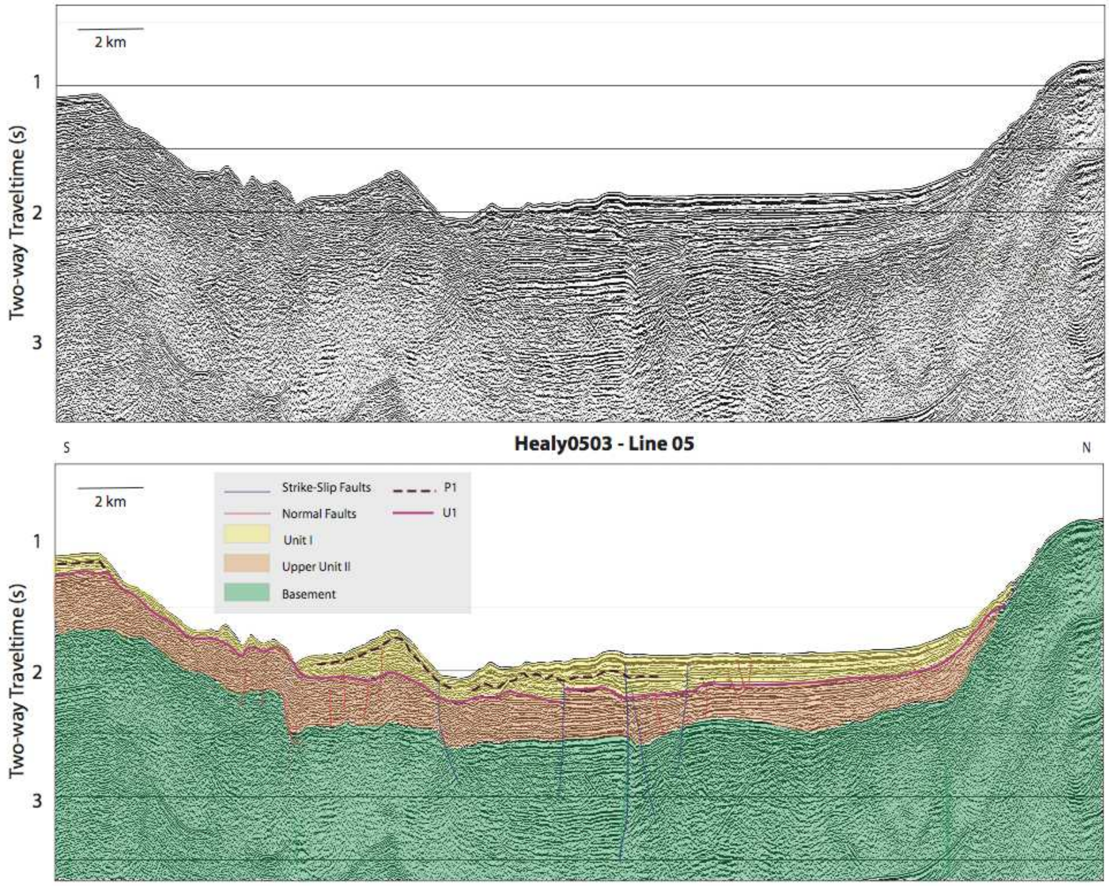


Figure 7. *Healy-0503* Line 05 seismic data detail uninterpreted (above) and interpreteted (below). The line was acquired along the Northwind Ridge (refer to fig. 5 for exact location). Several sub-vertical strike slip faults displace the basement and Unit II and do not appear to produce fanning or splaying of the sediments as observed in all the other lines. The sharp offset and the indication of the presence of a small sub-basin oriented NW-SE (see bathymetry map, fig 2 and 3) suggest that these faults are strike-slip faults. Interpreted horizon P1 discussed in the text appears to be an erosianl surface below a thin veneer of sediments.

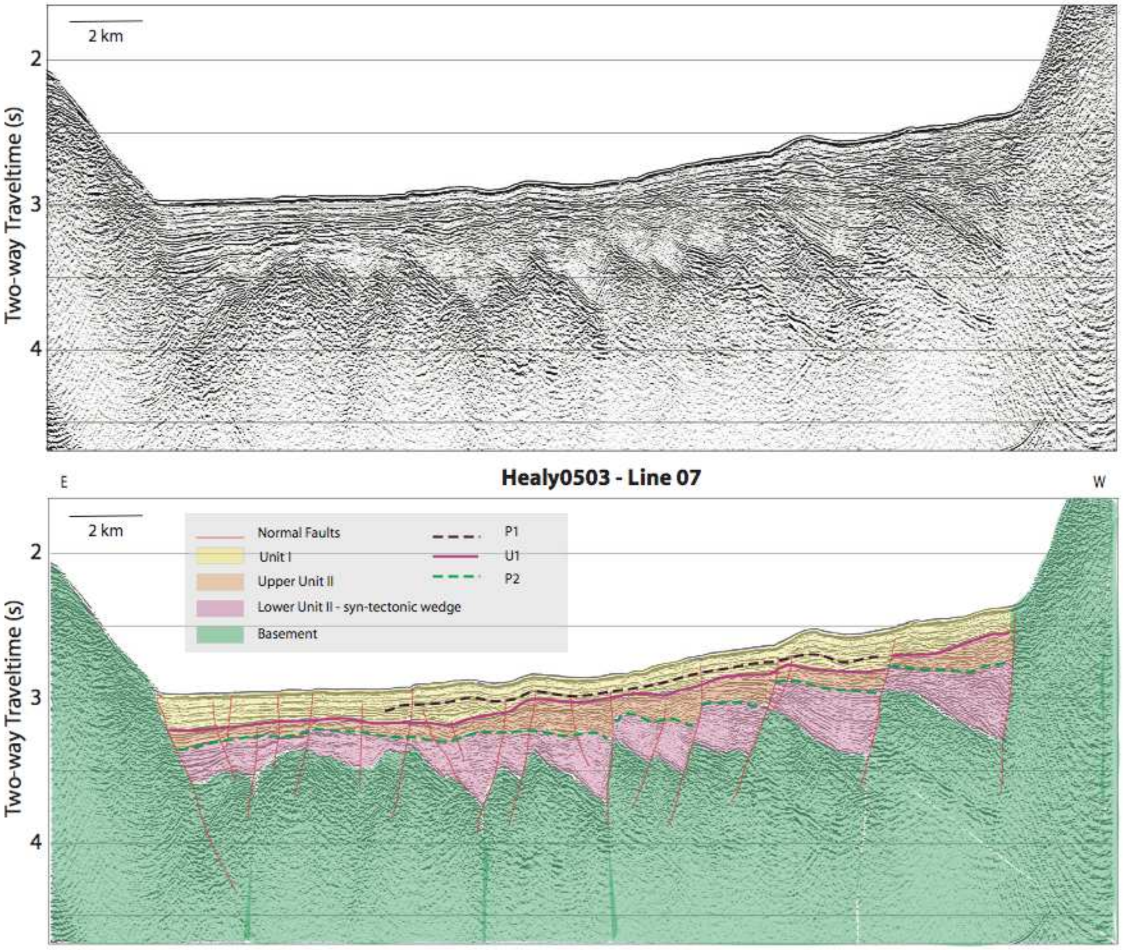


Figure 8. *Healy-0503* Line 07 seismic data detail uninterpreted (above) and interpreteted (below). The line was acquired across the Northwind Ridge (refer to fig. 5 for exact location). An evident horst and graben structure dissects the basement and displaces the blocks up to 1 s TWT (~ 750 m). Unit II is strongly affected by the normal faults, showing splaying and fanning of strata into the normal faults. Surface P2 separates the bottom syn-rift wedge from the upper sedimentary package, which is less affected by the faulting. The uppermost Unit I does not show large offsets along the faults but it appears to be locally displaced up to seafloor. Fault propagation folds affecting unit I and the seafloor may indicate recent activation of the faults.

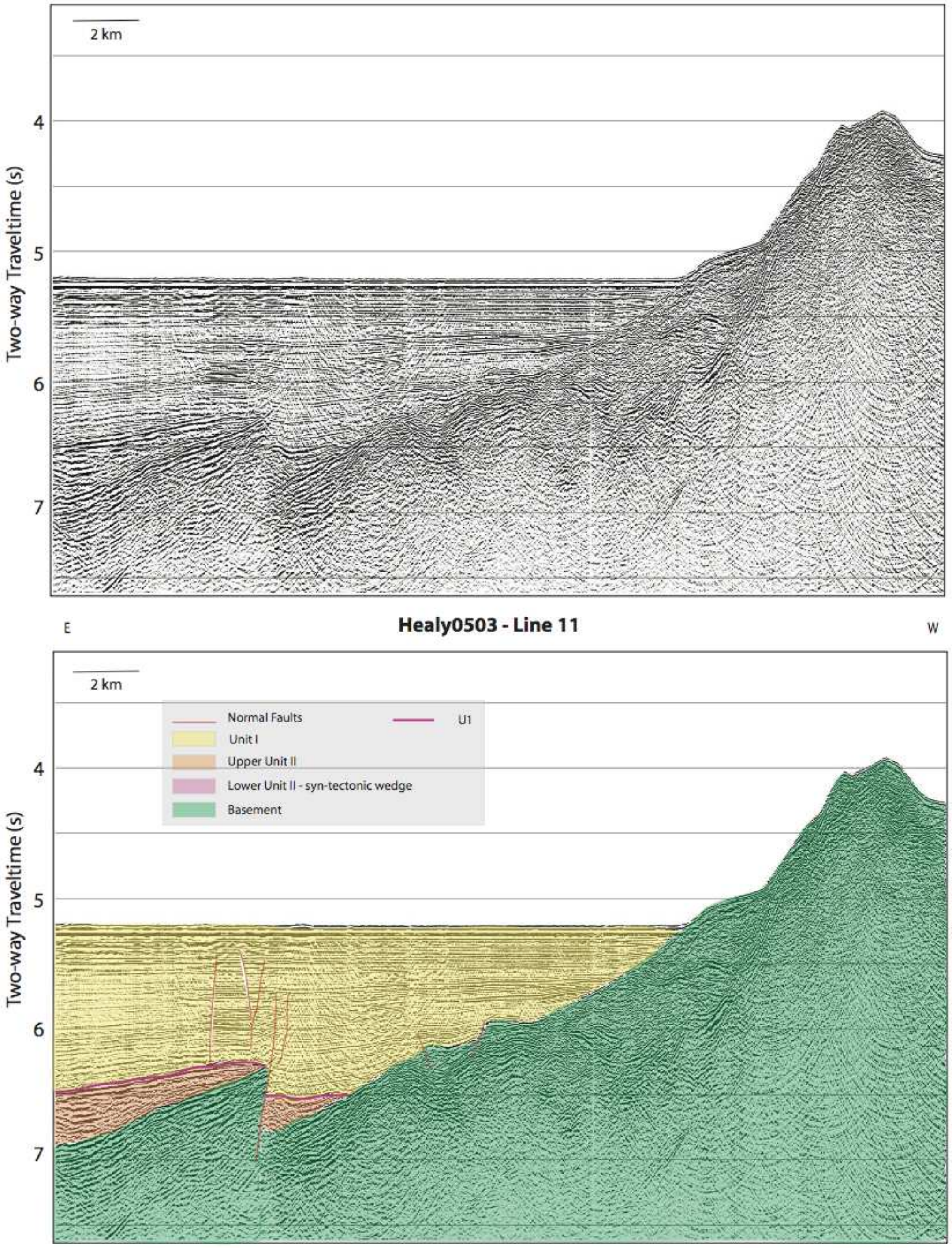


Figure 9. *Healy-0503* Line 11 seismic data detail uninterpreted (above) and interpreteted (below). The line was acquired across the Northwind Escarpment (refer to fig. 5 for exact location). High-angle normal faults mainly dipping East displace the basement and overlying Unit II with offset of 1 s TWT (~ 750 m).

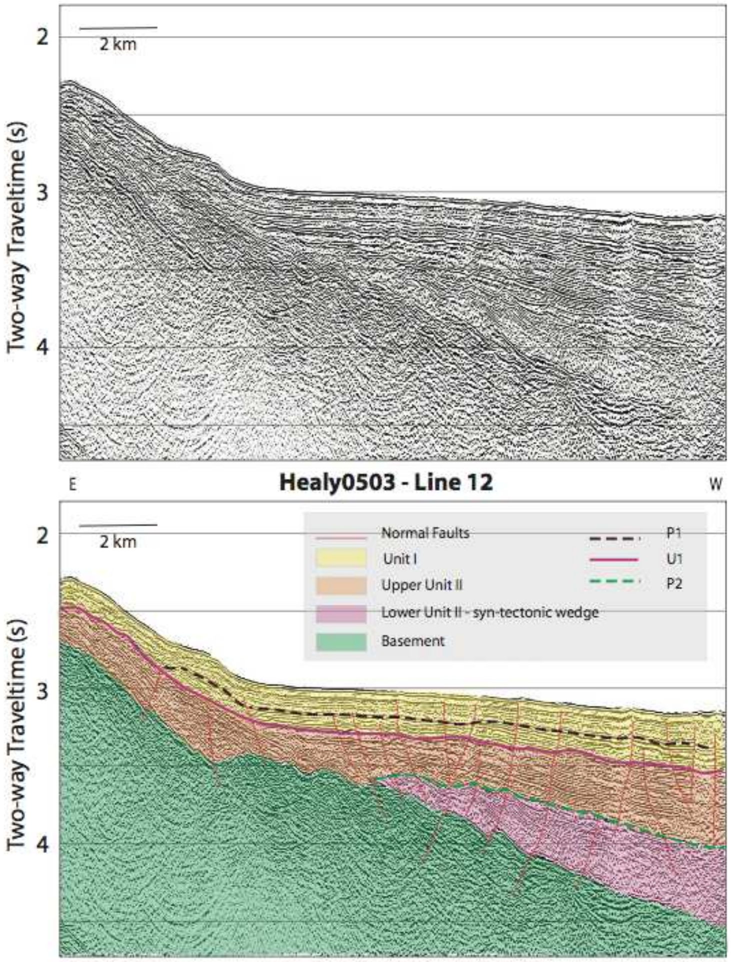


Figure 10. *Healy-0503* Line 12 seismic data detail uninterpreted (above) and interpreteted (below). The line was acquired across the Northwind Ridge (refer to fig. 5 for exact location).

Normal faults affect the entire area, but significant offset is not observed. Unit II, with a thickness ranging 0.5 to 2 s TWT (~ 350-1500 m) can be easily divided into two sedimentary packages, the lower showing evidence of syn-tectonic deposition along growth faults.

Figure 11. *Healy-0503* Line 13 seismic data detail uninterpreted (above) and interpreteted (below). The line signs the transition from the Northwind Ridge to the Chukchi Rise (refer to fig. 5 for exact location). Large scale faulting of basement is observed. Unit II fans into the normal faults whereas Unit I is undisturbed. The faults create offsets of 1.5 s (~1100 m) and affect the overlying Unit II creating a lower syn-tectonic wedge of sediments fanning at the growth faults. The upper Unit II suggests to reconnect to a less intense rifting stage.

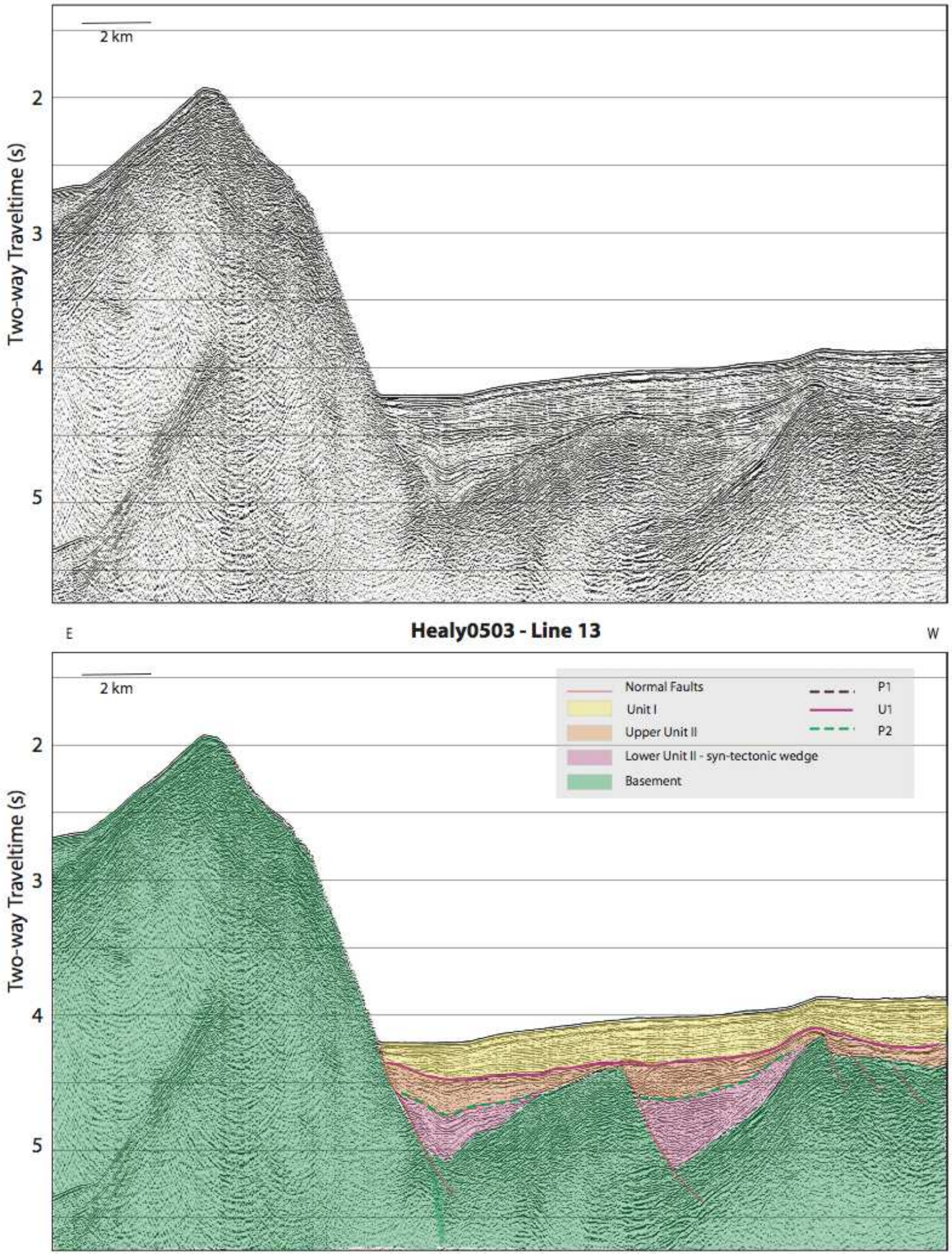

2 km
2
3
4
5
Two-way Traveltime (s)
E
Healy0503 - Line 13
W
2 km
Normal Faults
Unit I
Upper Unit II
Lower Unit II - syn-tectonic wedge
Basement
P1
U1
P2
2
3
4
5
Two-way Traveltime (s)

Figure 12. Structural interpretation of the Chukchi Borderland region. The regional free-air gravity map is overlain with 500 m regional bathymetry contours. Solid lines indicate structural features observed from the MCS lines over the Chukchi Borderland as well as the Mendeleev Ridge (Dove et al., 2007). The dashed lines indicate faults inferred by the gravity field and bathymetry map.

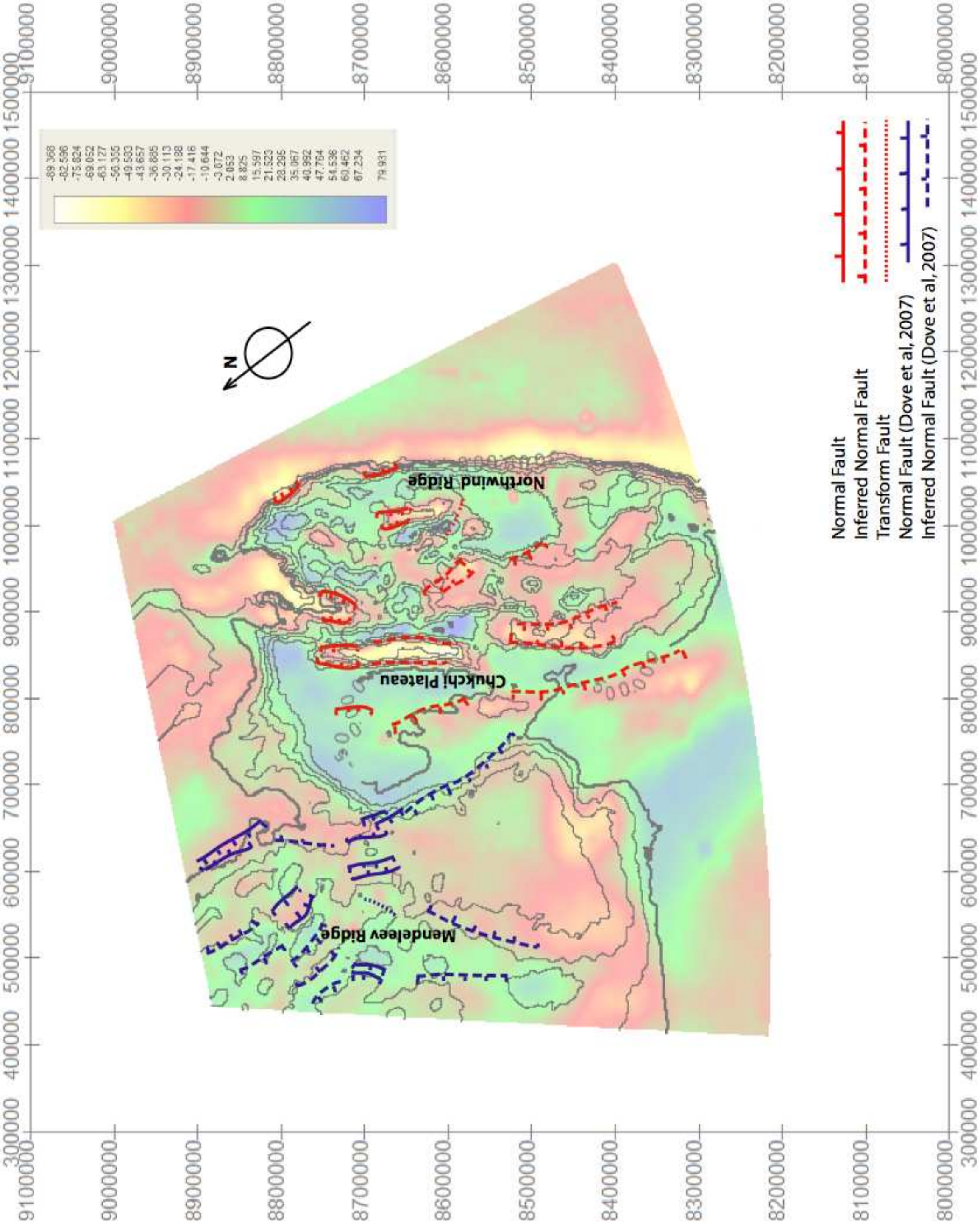

Northwind Ridge
Chukchi Plateau
Mendeleev Ridge
N
Normal Fault
Inferred Normal Fault
Transform Fault
Normal Fault (Dove et al, 2007)
Inferred Normal Fault (Dove et al, 2007)
-89.368
-82.596
-75.824
-69.052
-63.127
-56.355
-49.583
-43.657
-36.885
-30.113
-24.188
-17.416
-10.644
-3.872
2.053
8.825
15.597
21.523
28.295
35.067
40.992
47.764
54.536
60.462
67.234
79.931
300000
400000
500000
600000
700000
800000
900000
1000000
1100000
1200000
1300000
1400000
1500000
8000000
8100000
8200000
8300000
8400000
8500000
8600000
8700000
8800000
8900000
9000000
9100000

Figure 13. Simplified tectonic models for the emplacement of the Chukchi Borderland.
A - Late Clockwise rotation from the Eastern Siberian Shelf
B - Rifting from the Siberian margin related to oceanic spreading parallel to the Mendeleev Ridge
C - “Arctic Island Strike-Slip” model
D -Lane’s multistage kinematic model.

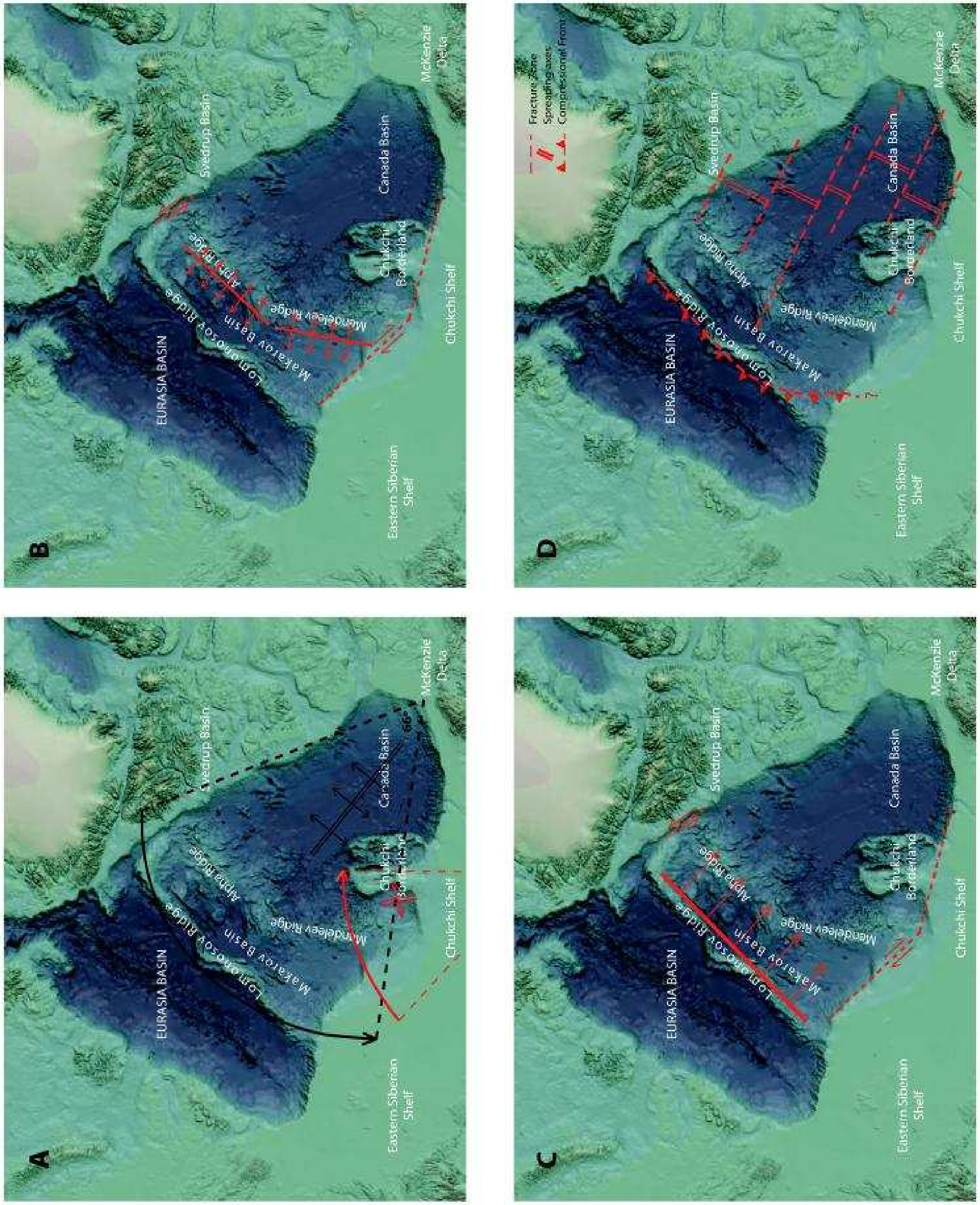

A
B
C
D
EURASIA BASIN
Lomonosov Ridge
Makarov Basin
Mendeleev Ridge
Alpha Ridge
Chukchi Borderland
Canada Basin
Svedrup Basin
McKenzie Delta
Chukchi Shelf
Eastern Siberian Shelf
66°
Fracture Zone
Spreading axes
Compressional Front

Table 1 – *Healy-0503* Survey geometry and Processing Parameters.

HEALY0503: MCS SEISMIC SURVEY - Chukchi Borderland	
Survey Geometry	**Processing Parameters**
2 Sodera G-Guns (250 cc.in. each)	Noise Filtering:
300 m – 200 m analog streamer	- bandpass 12-85 Hz
12.5 group spacing (24 - 16 channels)	- spike and noise bursts edits
5 m towing depth	- *f-k* filtering
90 m towing distance	Minimum Phase Predictive Deconvolution
20 s shot interval	NMO
1.0 m sampling rate	Mean Stack
16 s recording length	Trace Equalization
	Stolts' FK Constant Velocity Migration

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