TECTONIC GEOMORPHOLOGY OF THE CHUKCHI BORDERLAND:  
CONSTRAINT FOR TECTONIC RECONSTRUCTION MODELS

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Aug 3, 2009
TECTONIC GEOMORPHOLOGY OF THE CHUKCHI BORDERLAND:
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A

THESIS

Presented to the Faculty

of the University of Alaska Fairbanks

In Partial Fulfillment of the Requirements

For the Degree of

MASTER OF SCIENCE

By

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Fairbanks, AK

August 2009
ABSTRACT

The Chukchi Borderland is a region of extended continental crust within the Amerasia Basin and is bounded on one side by oceanic crust of the Canada Basin. Because of its central location within the basin, tectonic models for the reconstruction of the Arctic Ocean, must include the Chukchi Borderland although there is no consensus about its pre-rift location or kinematic development. In recent years bathymetric data have been collected that can offer constraint on the tectonic evolution of the Amerasia Basin by providing details about the geomorphology of the intra-basinal ridges allowing comparison of bathymetric features to those in other ocean basins. Bathymetric information in conjunction with multi-channel seismic and chirp sub-bottom profiler data show the location and strike of inferred faults used to determine rift directions which then provide constraint on tectonic reconstructions.

The central Amerasia Basin, which includes the Chukchi Borderland, Mendeleev Ridge and south central Alpha Ridge, has experienced significant extension in generally the same direction and probably during one event. This type of plate boundary scale extension requires the development of accommodation faulting or transfer zones that facilitate the amalgamation of long fault segments. Features consistent with this type of faulting are observed throughout the Chukchi Borderland. There is no evidence of compression along the Northwind Ridge nor is there any indication of a strike-slip boundary within the Northern Chukchi Borderland as some tectonic models suggest. Whichever model is preferred, the geomorphology of the intra-basinal ridges must be taken into account and used as constraint for the reconstruction of the Amerasia Basin.
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ACKNOWLEDGMENTS

The Arctic Ocean has long been the destination for explorers like Henry Hudson, Fridtjof Nansen, Roald Amundsen, Louise Boyd and many others who were lured to this unknown region where the difficulties associated with the journey, prevented most from reaching their initial goal. The modern Arctic scientist experiences the same lure, and often with the same result. As with the first Arctic explorers, modern scientific investigation in the Arctic Ocean requires the use of customized ice breaking vessels with equipment and crew robust enough to survive the harsh environment. Thanks to the men and women of the USCGC Healy for making possible modern Arctic exploration and to Shell International Exploration & Production Inc. for financial support of this thesis.

I would like to thank my adviser, Dr. Bernard Coakley for luring me to the Arctic and offering me the chance to experience a true frontier. Thanks to Dr. Larry Lawver for inviting me on my first trip on the Healy and for the warm year at University of Texas. Thanks to Dr. David Stone for his calm humor and to the rest of my committee, Dr Wes Wallace and Dr. Steve Bergman for their expertise and support. Thanks also to Dr. Larry Mayer who continues to invite me to map the Arctic and to Dr. Larry Phillips who is a dear mentor and friend. Thank you to Dr. Elizabeth Miller and Dwight Harbaugh who opened their home and provided much wisdom and laughter.

This thesis would not be possible without the unique gifts of Steve Roberts who created and continues to develop the Mapserver used aboard the Healy while we are underway, and make it available for my use while on land. It is an invaluable tool that I have come to rely on greatly and Steve’s friendship and help are also greatly appreciated.

Thanks to Dale Chayes for teaching me how to be successful on the Healy, to Marcy Davis for her friendship, support and expert eye for detail as well as guiding me through the academic maze, and of course, thank you to family and friends who have put up with me through stressful times and have supported my efforts in so many ways. I mustn’t forget appreciation to my faithful dog, Tika, for following me all over North America, and waiting for me to come home from sea.
1. INTRODUCTION

*Just to go out and, you know, learn the section, collect the rocks, be able to identify them. Observe the different land forms.* – Marie Tharp (Doel, 1994)

Because of the difficulty associated with data collection and interpretation in the Arctic Ocean, an understanding about the geologic history of the Arctic Ocean is still in its nascent stages. Whatever tectonic model is preferred for the opening of the Amerasia Basin, the constraint offered by the bathymetric data must be taken into account. Various models for the tectonic reconstruction of the Arctic have been proposed, yet only recently has the quality of bathymetric data been of sufficient quality to offer constraint on tectonic models.

1.1 Overview

The Arctic Ocean can be divided into two basins, namely, the Eurasia and Amerasia Basins which formed independently at different periods of time (Fig. 1). These basins are separated by the Lomonosov Ridge, a strip of thinned continental crust about 100 km wide that rifted from the Barents shelf during the Paleogene propagation of the Mid-Atlantic Ridge into the Arctic Ocean (Heezen and Ewing, 1961; Ostenso and Wold, 1973; Coles et al., 1978; Vogt et al., 1982; Jokat et al., 1992; Cochran et al., 2003). While the Eurasia Basin is well-understood to have formed during a single phase of seafloor spreading, which is ongoing, the history of the morphologically complex Amerasia Basin remains a mystery. The tectonic history of the Amerasia Basin has mostly been inferred from observations made around its margins. However, the variety of intra-basinal structures which were either formed or affected by the formation of the basin, provide another means to study this history and provide constraint on the tectonic development of the Amerasia Basin.
Fig. 1 Bathymetry of the Arctic Ocean. The International Bathymetric Chart of the Arctic Ocean (IBCAO, 2.0 km grid; Jakobsson et al., 2003). The Lomonosov Ridge (LR) separates the Amerasia Basin and the Eurasia Basin which is currently developing due to sea floor spreading. White box outlines the central Amerasia Basin study area (see Fig. 2) which includes the Chukchi Borderland, Mendeleev Ridge and south central Alpha Ridge.
1.2. Amerasia Basin Provinces

"One step beyond the pole, you see, and the north wind becomes a south one." -- Robert Peary

(Schweikart, 1986)

The Amerasia Basin can be divided into several distinct crustal regions (Fig. 1): The Canada Basin, Chukchi Borderland, Alpha and Mendeleev Ridges, and Lomonosov Ridge. The intra-basinal ridges within the central Amerasia Basin have been separated here into several provinces (Fig. 2) in order to investigate their individual bathymetric features, as well as their structural relationships. The Chukchi Borderland encompasses the Northwind Ridge, the Northwind Basin and the Chukchi Plateau. The area to the north of the Chukchi Plateau has traditionally been called the “Mendeleev Abyssal Plain” but here is divided into the Northern Chukchi Borderland and the Nautilus Basin (Fig. 2). The Mendeleev Ridge and south central Alpha Ridge are separated into two provinces. The possible geomorphic relationships of all of the intra-basinal ridges are investigated here and compared to similar features in other ocean basins.

All tectonic reconstruction models for the development of the Amerasia Basin agree that the Lomonosov Ridge and the Chukchi Borderland are fragments of continental crust (Dietz and Shumway, 1961; Hall, 1990; Jokat et al., 1992) and that the Canada Basin is underlain by oceanic crust formed by seafloor spreading (Baggeroer and Falconer, 1982; Grantz et al., 1990). A generally north/south linear gravity low in the center of the basin which is coincident with some low relief (≤ 12 nT) magnetic anomalies is interpreted to be a fossil spreading center (Taylor et al., 1981; Coles and Taylor, 1990; Grantz et al., 1990). Although there is agreement about the existence of oceanic crust in the Canada Basin, and about the continental nature of the Chukchi Borderland, there is little consensus about the formation of the Alpha and Mendeleev Ridges or the kinematic history of the Amerasia Basin.
Fig. 2 Bathymetric Provinces of the Chukchi Borderland. Large map (left) also shows locations of dredge sites (HLY0805) and seismic lines from HLY0503 (Hopper et al., 2006) and those collected on USCGC PolarStar 1988, 1992, 1993 (Grantz et al., 2004). Mapserver image (above right) shows locations of shiptracks where multibeam data were collected between 2003 and 2008.
Each tectonic reconstruction of the Amerasia Basin proposes a different set of plate boundaries and sense of motion along them, and implies or invokes different explanations for the enigmatic features observed in and around the basin (for a review of published Amerasia Basin reconstruction models see Lawver and Scotese, 1990). One model returns the Arctic Alaska-Chukotka micro-plate to the Barents Shelf utilizing transform faults along the Canadian and Siberian margins (Fig. 3b) and requires seafloor spreading parallel to the Lomonosov Ridge. Extensional faults along the Canadian Margin indicate that it is a passive margin (Grantz and May, 1990) although the deep structure of the Canadian Arctic is unknown.

Another translational model (Fig. 3c) utilizes transform faults along the Alaska margin and the Lomonosov Ridge to accommodate spreading along a ridge axis in the Canada Basin. This returns the Chukchi Borderland to the Canadian margin utilizing rift directions consistent with normal faulting in the Chukchi Borderland and the Canadian Arctic, however there is no evidence for transform motion along the Alaskan shelf.

The model which seems to have survived the longest is informally called the “Rotational Model” (Fig. 3a) also referred to as the “Windshield Wiper Model” (Carey, 1958; Tailleur, 1969; Freeland and Dietz, 1973; Sweeney; 1985; Lawver and Scotese, 1990; Embry and Dixon, 2000; Gurevich et al., 2006). Although there are variations on this theme, the models all involve a ~60-90° counterclockwise rotation of a continental mass known as the Arctic Alaska/Chukotka micro-plate which rifted from Arctic Canada during the Cretaceous, about a pole of rotation located near the Mackenzie Delta. In this model, the Lomonosov Ridge serves as a transform boundary with over 2600 km displacement (Fig. 3a, white dashed line, Rowley and Lottes, 1988; Grantz et al., 1990; Dixon and Dietrich, 1990; Embry, 1990; Lawver et al., 2002; Grantz et al., 2009). The Alpha and Mendeleev Ridge system is interpreted by some to be the result of hot-spot
Fig. 3 Tectonic Reconstruction Models of the Amerasia Basin. The “Rotational Model” or “Windshield Wiper Model” (a) suggests that the Amerasia Basin was formed as the Siberian Shelf and Chukchi Borderland rotated from the Canadian Margin about a pole of rotation located in the McKenzie Delta area (star) initiating seafloor spreading which created the Canada Basin. This necessitates a large right lateral transform fault along the Lomonosov Ridge (white dashed line) to accommodate spreading. The Arctic Canada transform model (b) shows motion of Alaska-Chukotka plate rifting from Barents shelf utilizing transform faults on either side of the micro-plate (from Halgedahl and Jarrard, 1987). Arctic Alaska transform model (c) shows spreading axis in Canada Basin with Arctic Alaska and the Lomonosov Ridge as transform faults accommodating the Chukchi Borderland’s rifting from the Canadian Margin (from Lane, 1997).
induced, intra-plate volcanism which built a volcanic pile on oceanic crust that was previously formed by sea floor spreading in the Canada Basin (Grantz et al., 1998, 2009; Lawver et al., 2002).

Because of their enigmatic origin, the Alpha and Mendeleev Ridges have been given every possible tectonic designation most of which have been termed “oceanic” but with the disclaimer that the presence of continental crust cannot be ruled out. Supporters of the rotational/hotspot model point to the presence of thickened crust (25-40 km), lateral continuity of crustal densities (sediments, 2.0 g/cm³; upper crust, 2.88 g/cm³; lower crust > 26 km, 3.04 g/cm³; Weber, 1986), high amplitude magnetic anomalies (1500-2500 nT), and the fact that the trend of Alpha and Mendeleev Ridges generally fits a small circle about the hypothesized pole of rotation in the Mackenzie Delta (Cochran et al., 2006). This seems consistent with the Alpha and Mendeleev Ridges resulting either from a fixed ridge-centered hotspot, emplacing voluminous volcanic material onto the newly forming oceanic crust of the Canada Basin (Williams, 2006) or from a Hawaiian type hotspot track forming a volcanic pile on pre-existing oceanic crust after the basin formed (Grantz et al., 1998, 2009; Lawver et al., 2002).

There have also been many comparisons of the Alpha and Mendeleev Ridges with other intra-plate oceanic plateaus like the Kergulean, Ontong Java, and Manihiki Plateaus (Forsyth et al., 1986; Jackson et al., 1986; Asudeh et al., 1988). None of these models explain how an “oceanic” Alpha and Mendeleev Ridge system could have developed on both sides of the Chukchi Borderland utilizing only one spreading center in the central Canada Basin. Therefore, many models invoke complex plate boundaries and multiple spreading centers within the Amerasia Basin (Lane, 1997; Grantz et al., 1998, 2009) to explain the structure and geophysical characteristics of the Alpha and Mendeleev Ridges.
There also is no consensus about whether or not the Alpha and Mendeleev Ridges are a single feature. The topography of the two ridges, however, is similar and recent studies (Williams, 2006; Dove, 2007) suggest that their crustal structures and thicknesses give no indication that they are separate features but that Alpha and Mendeleev Ridges are in fact one continuous ridge with the same tectonic origin, whatever that origin may be. Williams (2006) found that the lithosphere of both the Alpha and Mendeleev Ridges was weak and locally isostatically compensated. This restricts interpretation of the Alpha and Mendeleev Ridges to have either formed at a mid-ocean ridge axis or to be extended continental crust. The inferred lithospheric weakness is incompatible with any tectonic model that proposes a long time separation between the formation of the underlying lithosphere and the eruption of volcanics to create the ridge. Depending on the model, the Alpha and Mendeleev Ridges can either have been in existence before the basin was formed and was modified by that process, or were created concurrently with the basin and imposed on the lithosphere after the basin was formed. These uncertainties associated with the nature of the Alpha and Mendeleev Ridges do not provide the necessary constraint on tectonic reconstruction models to bring about consensus about the development of the Amerasia Basin.

Because questions of its composition are largely resolved by its elevation, the Chukchi Borderland can provide constraint to tectonic models. There is agreement as to its continental origin and because this large fragment juts out into the center of the Amerasia Basin, and is probably bounded on at least one side by oceanic crust, any reconstruction must include at least one ancient plate boundary adjacent to the Chukchi Borderland. While the composition of the Chukchi Borderland is not an issue, its affinities with other circum-Arctic provinces are not resolved. The position and sense of motion along its boundaries are critical to reconstructing this feature back to its pre-spreading position and orientation.
The proposed spreading center in the central Canada Basin allows for the separation of the Chukchi Borderland from Arctic Canada as is promoted by many models, but does not explain how the Borderland is separated from the other intra-basinal ridges and therefore another boundary must be invoked. Whatever type of plate boundary (or boundaries) one chooses to place around it, the inferred kinematic history must return the Chukchi Borderland to an adjacent continental margin with similar geology and a pre-opening history that can be observed in the Chukchi Borderland itself (Grantz et al., 1998).

Although land based geologic investigation around the Arctic margins provides clues and constraints for the tectonic development of the Amerasia Basin, interpretation of the marine geophysical evidence has not produced a consensus. To date there has only been one successful drilling mission in the Arctic Ocean (IODP-ACEX, 2004), a handful of dredged rock samples (Forsythe et al., 1986; Van Wagoner et al., 1986; Mayer et al., 2008a) and small chips of bedrock from talus slopes in the bottom of piston cores (Grantz et al., 1998; Clark et al., 2000). Therefore, interpretation of marine geophysical data in the Arctic has been attempted before the geologic nature and relationship of the intra-basinal ridges has been understood.

During recent years favorable ice conditions have resulted in more publically available information about the Chukchi Borderland than anywhere else in the Amerasia Basin. Very good bathymetric maps (IBCAO, Jakobsson et al., 2000) and several recent multibeam bathymetric surveys (Mayer, 2003, 2004; Mayer and Armstrong, 2007, 2008; Mayer et al., 2008b) of the area, as well as advancements in 3D visualization of bathymetric data now make it possible to do the type of basic geologic description of fault strike and apparent offsets employed by geologists utilizing aerial photographs and topographic maps. These observations are critical in understanding the history of the
Chukchi Borderland. Any useful tectonic reconstruction must propose the pre-rift location and kinematic history of the Chukchi Borderland. In addition, given the adjacent continental and oceanic crust, there must be fossil plate boundaries along the flanks of the high-standing continental block. To constrain these potential boundaries, this thesis focuses on the Chukchi Borderland. By analyzing bathymetric observations, subsurface (chirp) profiles and other geophysical data, this thesis will constrain the kinematic history of the Chukchi Borderland. These constraints will be used to test the validity of various tectonic reconstruction models.

1.3 Bathymetry and Tectonic Reconstructions

The development of ideas about the tectonic history of the Arctic Ocean has been both restricted and enabled by the parallel development of bathymetric maps. In the centuries before any part of the Arctic Ocean had been delineated, a map by Gerard Mercator (1595) explained the earth’s magnetic field by illustrating a continent divided into four quadrants positioned at the North Pole with a magnet at its center (Fig. 4 (a)). This belief in the existence of a polar landmass pervaded until Fridtjof Nansen measured water depths of over 3000 m along the entire drift of the Fram on his expedition between 1893-1896 (Nansen, 1904). After this it was thought that the Arctic Ocean was one deep ocean basin.

1.3.1 Early Ideas

R. A. Harris (1904) hypothesized that there must be a barrier that divides the Arctic Ocean into two basins based on observed current deflections and disruption of Alaskan tides (Fig. 4b). It was not until 1948 that the Lomonosov Ridge was discovered by Soviet scientist and it did not appear on any published maps until 1954. The first tectonic
Fig. 4 Early Maps of Arctic Ocean Bathymetry. In 1575 a map by Gerard Mercator (a) shows a landmass at the North Pole with a large magnet at its center which explained the earth’s magnetic field. (b) In 1904, R.A. Harris hypothesized that there was a shoaling barrier in the center of the Arctic Ocean based on tidal and current data. Creative contouring by Hakkel in 1959 (c) using the same data points that Heezen and Ewing used to create their map (d) by comparing Arctic Ocean slopes to analogous bathymetric features.
models suggested by Shatskiy (1935) and Belousov were based on the idea that the Arctic Ocean was a single deep basin. They explained its existence as a subsided piece of eroded cratonic material which developed into a Hyperborean Basin (Shatskiy, 1935; Hope, 1959; Belousov, 1970).

The theory of plate tectonics was not yet accepted among most American geoscientists during the presentation of the first models for the geologic history of the Arctic Ocean. S.W. Carey (1958) proposed the first rotational model for the formation of the Canada Basin based on the idea that the bend in the Canadian Rockies through the Alaska Range was an orocline. According to his model, the bending of this mountain range due to the rotation of Asia from North America created a basin behind it which could be accommodated by an expanding earth. Although he included the Lomonosov Ridge, his model neglected an explanation of the other mapped features within the ocean basin. By 1959 the Alpha and Mendeleev Ridges had also been discovered (Eardley, 1961). It then became necessary to explain the existence of these ridges (then called “Ranges”) in models reconstructing the Arctic Ocean. Bathymetric maps created from 4000 Soviet soundings, were contoured to represent the various authors’ particular beliefs about the nature of the features. For instance, in 1958 Hakkel assumed that the Lomonosov and Alpha Ranges were a continuation of the Hercynian Ural fold belt. His bathymetric map reflects this preconception (Fig. 4 (c); Hakkel, 1958).

1.3.2. Heezen and Ewing

When Bruce Heezen and Maurice Ewing investigated the Arctic in the mid 1950’s they said, “…As a result of years of experience in evaluating bathymetric interpretations, we are reluctant to accept contours without supporting evidence” (Heezen and Ewing, 1961). Because of this distrust of artistic contouring, they performed comparisons of bathymetric
profiles in the Arctic Ocean to analogues from other ocean basins and determined that the Chukchi Cap was a detached segment of continental crust similar to the Flemish Cap off the Grand Banks, and that the Lomonosov Ridge and parallel trending Marvin Spur were similar bathymetrically to the Walvis Ridge in the South Atlantic, another asymmetrical aseismic ridge. Heezen and Ewing also carefully explained their observations of the earth-circling feature called a mid-ocean ridge, and its continuation into the Arctic. They measured seismicity along the ridge, calling it the Arctic Seismic Belt, and correctly concluded that the Eurasia Basin was currently extending. Ewing believed this ridge development was due to convection in the mantle while Heezen believed the extension was resulting from internal expansion of the earth; neither had yet fully accepted plate tectonics as a valid theory (Heezen and Ewing, 1961).

Regardless of the mechanism, there was now an understanding that the Arctic Ocean’s basins probably developed separately. The bathymetric map that Heezen and Ewing produced from their 1959 cruise reflected their comparative studies and discussed the morphology of the Gakkel Ridge (then called the Nansen Ridge) as a continuation of the Mid-Atlantic Ridge (Fig 4 (d)). That same year, Heezen and Marie Tharp published their now famous bathymetric map of the North Atlantic (Heezen et al., 1959; Heezen and Tharp, 1965).

1.3.3. Plate Tectonics and Cold War Data

Ten years after the International Geophysical Year (1957-1958) when the theory of plate tectonics started to become widely accepted, Warren Hamilton wrote about “Continental Drift in the Arctic” (Hamilton, 1968) and in 1970 showed the first published plate tectonic reconstruction of the Arctic Ocean. This model still assumed a simultaneous
Fig. 5 Early Maps and Tectonic Models. Dietz and Shumway (1961) described the bathymetric features in the Arctic Ocean (a). The Chukchi Borderland was thought to be two separate features called the Chukchi Cap and the Northwind Seahigh (b). Hamilton’s 1970 reconstruction of the Arctic did not include features within the Canada Basin (c) nor was bathymetry a consideration in the reconstruction by Freeland and Deitz (1973 (d)).
Cenozoic opening for both of the Arctic Ocean basins by spreading in the Eurasia Basin and by opening of the Canada Basin behind a counter-clockwise-rotating Alaska (Hamilton, 1970). The map used to illustrate this model, however, showed Lomonosov Ridge to be the only bathymetric feature within the Arctic Ocean (Fig. 5(c)) and the pre-rift geometries of the intra-basinal ridges were not addressed even though all of the major bathymetric features within the Arctic Ocean had been discovered by 1967 (Weber, 1983).

Although many publications addressed the tectonic features of the Canada Basin individually, geomorphology was rarely used as constraint on tectonic models due to the fact that most of the available geologic data was from the Arctic margins. At the time when Hamilton published his reconstruction model, the first General Bathymetric Chart of the Oceans was produced by the Canada Hydrographic Service and widely available, yet map view bathymetry was not interpretable for use in reconstructions.

Also available were earlier maps by the Canada Defense Research Board which appeared in a paper by Dietz and Shumway (1961) describing the Amerasia Basin geomorphology from the first bathymetrical profiles in the center of the Arctic Basin during a 1958 cruise aboard the SSN Nautilus (Fig. 5(a)). Even at the resolution of those first maps, the floor of the Canada Basin was reported by Dietz and Shumway (1961) to be a consistent 3820m water depth which is the same depth measured using modern high resolution multibeam bathymetric profiles (Mayer and Armstrong, 2007). Yet, perhaps due to uncertainty associated with the low resolution of the bathymetric data, the features inside the basin (Fig. 5(c-d)) were not included in many illustrations of early reconstruction models (Hamilton, 1970; Freeland and Dietz, 1973). That is not to say, however, that bathymetry was ignored. Bathymetric features were described as information became available. Although the Chukchi Borderland was first contoured as a thin promontory
connected to the Alaskan margin, by 1961 it was mapped as two distinct features called the Chukchi Cap and the Northwind Seahigh (Fig. 5 (b); Dietz and Shumway, 1961). The two features were assumed to be of similar rock structure and to be outliers of the continental shelf. Possibly because they were first mapped as separate plateaus, subsequent tectonic models have suggested that the ridges and basins of the Chukchi Borderland were discrete micro-plates that were tectonically assembled into their current location from complicated pre-rift geometries (i.e. Grantz, et al., 1998).

Most models, however, assume that the Chukchi Plateau and Northwind Ridge (as it is now called) are part of the same extensional continental block probably connected to the Chukchi Shelf which was separated from the Canadian margin by seafloor spreading in the Canada Basin (see Lawver and Scotese, 1990). Also, this separation of the Chukchi Plateau and Northwind Ridge in early bathymetric maps has resulted in a confusing nomenclature that continues today. The only name on non-Russian maps that encompasses this province of parallel ridges and basins west of the Northwind Escarpment is “Chukchi Borderland” which was an antiquated term even in 1961, a complaint that Dietz and Shumway (1961) mentioned. Although the Chukchi Borderland is usually included in tectonic discussion on the history of the Canada Basin, and its geomorphology is generally considered to be a result of extension, rarely were the location and trends of the ridges and basins considered as constraint on paleo-rift directions (Hall, 1990).

The paucity of data within the Amerasia Basin continued to hinder the use of bathymetry as a constraint on tectonic models for the remainder of the twentieth century. The bathymetry of the Alpha and Mendeleev Ridges, even on maps as late as the 1990’s, appears as a chain of separate seamounts which has contributed to the great range of interpretations about its geologic nature. The Alpha-Mendeleev Ridge system has been
interpreted to be a hot spot track (Forsyth et al., 1986; Weber, 1986; Asudeh et al., 1988; Lawver et al., 2002; Jokat, 2003), an extinct spreading center (Hall, 1970), an oceanic plateau (Vogt et al., 1970; Jackson et al., 1986) or highly stretched continental material (Crane, 1987; Ivanova et al., 2006; Miller et al., 2006). Although all of these ideas have sound geological and geophysical evidence, bathymetry has usually only been used to correlate with magnetic and gravity anomalies resulting in the same conclusion that the Lomonosov Ridge and Chukchi Borderland are continental fragments and that the Alpha and Mendeleev Ridges are of enigmatic origin.

1.3.4. New Data, New Methods

Regardless of the model chosen for the tectonic reconstruction of the Arctic Ocean the geomorphology of the intra-basinal ridges must be taken into account. The use of bathymetric profiles by Heezen and Ewing (1958) to re-contour sparse bathymetric data by comparing features to similar looking profiles in other oceans, resulted in conclusions about the evolution of the Eurasia Basin that were later supported after the acceptance of the theory of plate tectonics. A similar method was used by Johnson et al., (1990) to describe the bathymetry and physiography of the Arctic Ocean utilizing bathymetric data available from the U.S. Naval Research Laboratory (Perry et al., 1985). The authors lamented that the Arctic data were unevenly distributed making detailed descriptions impossible, and that classified Soviet and U.S. military data would greatly enhance the knowledge of the seafloor and of its tectonic history.

By 1999 much of U.S. data had been declassified. U.S. Navy data as well as gravity measurements collected on the SCICEX submarine cruises (Edwards and Coakley, 2006) were used to generate computerized 2.5 x 2.5 km gridded digital terrain models and Version 1.0 of the International Bathymetric Chart of the Arctic Ocean (Fig. 1; IBCAO,
Jakobsson et al., 2000) was released in 2000. Jakobsson et al. (2003) then used the
IBCAO grid to organize the Arctic Ocean into physiographic provinces based on slope
models calculated from every grid point, compared the slopes to analogous features from
other ocean basins, and then made inferences about their geologic origin.

Following the creation of the first IBCAO, the data from multiple ice breaker multibeam
mapping cruises have been added to the digital elevation model and new versions of the
IBCAO are available and regularly updated (Jakobsson, et al., 2008; http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/arctic.html/).

While the growing Arctic Ocean database has improved our view of the Amerasia Basin
and understanding of the individual features within the basin, the combined geologic and
geophysical data remains inconclusive as to the tectonic development of the Arctic
Ocean. Since the release of the International Bathymetric Chart of the Arctic Ocean
(IBCAO, Jakobsson et al., 2000) and multibeam bathymetric surveys along ship tracks of
the USCGC Healy, the bathymetry of the Amerasia Basin has provided useful constraint
on tectonic reconstruction models. This thesis will utilize the IBCAO data set and high
resolution multibeam data from five ice breaker cruises aboard the USCGC Healy (Table
1), as well as subsurface and geophysical data to refine understanding of the Amerasia
Basin and to constrain models for its tectonic reconstruction.
Table 1  **Data Used in this Study.**  This includes year collected, name of mission and Principal Investigators.

<table>
<thead>
<tr>
<th>Cruise</th>
<th>Year</th>
<th>PI (s)</th>
<th>Multibeam (Seabeam 2112)</th>
<th>Chirp (Knudsen 320/BR)</th>
<th>Other</th>
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<td></td>
<td></td>
<td>Dennis Darby</td>
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<tr>
<td>HLY0602</td>
<td>2006</td>
<td>Larry Lawver</td>
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<td>✓</td>
<td>Sediment cores (piston,</td>
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<tr>
<td></td>
<td></td>
<td>Larry Phillips</td>
<td></td>
<td></td>
<td>gravity)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Harm VanAvendonk</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HLY0703</td>
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<td>Larry Mayer</td>
<td>✓</td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td>Andy Armstrong</td>
<td></td>
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<tr>
<td>HLY0805</td>
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<td>Larry Mayer</td>
<td>✓</td>
<td>✓</td>
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<td></td>
<td></td>
<td>Andy Armstrong</td>
<td></td>
<td></td>
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<td>SCICEX missions</td>
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<td>Margo Edwards</td>
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2. METHOD

“We used data from wherever we could get it, from different disciplines and different sources, but took great care to ensure that these data from various sources were all plotted on the same scale. We used hypotheses of ocean floor structure to fill in areas where we had meager data. Constantly adding new data, we changed our minds quite a bit as the panorama took shape.” —Marie Tharp (Doel, 1994)

This study begins with the Amerasia Basin as a whole, its tectonic setting prior to opening, and compares it to modern ocean basins. Because the kinematic development of the Amerasia Basin is still under question it may be instructive to compare it to other oceans, either ancient or incipient, which contain rifted continental fragments and/or rift related volcanism in an attempt to explain the location and nature of the intra-basinal ridges within the Amerasia Basin.

The premise of this study is that although the Arctic Ocean is somewhat exotic in its location and environment the geologic processes that formed it have geomorphologic responses that are universal and comparable to other ocean basins with a similar tectonic setting. Most previous tectonic models for the development of the Amerasia Basin did not employ bathymetric data. Because submarine erosion is slow, surface expressions of structures can be observed. Therefore the bathymetry was used here for tectonic interpretation and combined with subsurface information to define the location and trend of faults in order to gain a sense of fault displacement and extension directions. The bathymetry of the Amerasia Basin, both at the resolution of the International Bathymetric Chart of the Arctic Ocean (IBCAO) and the higher resolution multibeam bathymetry data, was compared to analogues of features with geomorphologic and geophysical similarities found in other world oceans and on land.
2.1 Bathymetric Comparisons

The bathymetric grids for oceans outside of the Arctic were obtained from the ETOPO1 1arc minute by 1 arc minute satellite altimetry dataset at NGDC (Amante and Eakins, 2008). Also used were Shuttle Radar Topography Mission (SRTM) 90m topographic data from CGIAR-CSI GeoPortal (Jarvis et al., 2008). The ETOPO1 and SRTM data were represented and examined using the IVS/Fledermaus/Dmagic software (Mayer et al., 2000). Digital elevation models were created for three-dimensional visualization of various regions. Using the interactive tools available in Fledermaus, slopes were measured and bathymetric/topographic cross sections were produced for comparison between the Amerasia Basin and other ocean basin features.

After the investigation of the Basin as a whole, the focus then narrows to individual features, slopes, areas, subsurface comparisons of the Amerasia Basin’s intra-basinal ridges, and to comparisons with possible analogues from other areas. The most extensive Arctic bathymetric data set is on and around the Chukchi Borderland. For this reason, and because plate boundaries must exist around its borders, most of the detailed focus is on the Chukchi Borderland, although other features within the basin are discussed.

2.1.1. Healy Data

Multibeam bathymetry data were collected with a Seabeam 2112 on various cruises aboard the USCGC Healy (See Fig. 2 for locations). In this study the term “multibeam” will refer to this multibeam bathymetric data. These data were processed with Caris HIPS and SIPS software and gridded to 100 m. The data were then imaged with Fledermaus 3D imaging software (Mayer et al., 2000, 2008b). The multibeam data were draped directly onto the IBCAO data set providing high resolution detail especially of the bounding slopes of the Northwind Ridge and northern limits of the Chukchi Borderland.
Because the multibeam is typically a single swath, gravity data from SCICEX submarine cruises were converted to polar stereographic xyz files and imported into Fledermaus as points. These data were also draped over the IBCAO base map and, because subsea gravity anomalies are generally controlled by bathymetry, the data were used to assist in the placement of bathymetric elements. The ArcGP gravity map (Kenyon and Forsberg, 2001), and Arctic Aeromagnetic map (Verhoef et al., 1996) were also draped over the IBCAO data for direct comparison with bathymetry which was particularly useful in detecting structures with subtle bathymetric expressions.

“Chirp” sub-bottom profiler data were also collected on Healy and provide high resolution 2D images of the sediments to approximately 50-75 m penetration. The Healy uses a Knudsen 320 B/R which has two transceivers and is capable of operating as a sub-bottom profiler (3.5 kHz or frequency modulated chirp from 2 kHz to 6 kHz) and a conventional single beam echo sounder at 12 kHz although the 12 kHz mode is generally not used as it interferes with the multibeam system. (Henkardt, 2006). No post-processing was done on the chirp data.

The chirp profiles, multibeam data, and ship tracks were all available via a geospatial “Mapserver” browser developed aboard the Healy by Steven Roberts (Roberts et al., 2007). This provided live database connectivity and allowed for direct comparison of surface and subsurface data collected along ship tracks. A bathymetric feature can be viewed using the IBCAO, or the Russian Bathymetric Map of the Arctic Ocean, as well as archived multibeam data, and then investigated in the subsurface using chirp profiles which are available at each coordinate along the ship track. The Mapserver can also measure slopes, and provides a graph of the multibeam profile compared to that of the IBCAO.
For analysis of multibeam data, both Fledermaus and Mapserver were used for different applications. Where available, multibeam data were examined utilizing Fledermaus software which allows for 3D visualization and representation of the data as well as the creation of color maps highlighting details of various bathymetric features. The Mapserver provided archived multibeam swaths which were not available for use in Fledermaus, as well as geo-referenced chirp profiles. The Mapserver was also used to measure azimuth trends of fault traces, and to provide latitude/longitude coordinates which is not available in Fledermaus.

2.1.2. **Seismic Reflection**

Multi-channel seismic reflection profiles collected from the USCGC Healy in 2005 (HLY0503, Hopper, et al., 2006) were used in conjunction with bathymetric observations on the Chukchi Borderland. The seismic images were imported into Fledermaus as georeferenced vertical images, which provided direct comparison of surface and subsurface features in that area (Fig. 6). Publicly available USGS single channel seismic profiles collected aboard the USCGC Polar Star (Grantz, et al., 2004) were also incorporated into this study (See Fig. 2 for line locations).
Fig. 6 Location of HLY0503 Seismic Profiles. Oblique perspective view of the Chukchi Borderland with multi-channel seismic profiles collected from the USCGC Healy (Hopper et al., 2006) placed as vertical images for direct comparison with bathymetry data.
2.2 Geomorphic Considerations

The process employed in this study has been to make observations about bathymetric features utilizing data of many types, in order to study their tectonic significance. The location of faults and the offsets observable at the resolution of the available data sets have been mapped and appear in Plate 1. The legend outlines the type of bathymetric features that were deemed important to this type of study; namely, fault trend and apparent motion, landslide features, slope gullies and channel patterns, pockmarks, ice scours, and bedforms. Because the coverage of high resolution multibeam data is sparse, information must be extrapolated from the partial view of features captured by the multibeam swath utilizing the lower resolution data.

2.2.1 Landslides

Steep arcuate scarps at the head of a landslide provide information about the direction of down slope movement during a mass wasting event. Visible in the multibeam data are scarps both primary and secondary, transverse cracks, talus creep, hummocks, and lobate toes in the zones of accumulation, all indicative of slope failure and mass wasting (Fig. 7). The existence of landslides is associated with exposed normal fault scarps.

The chirp profiles were used to determine the boundaries of landslide affected areas which helps to constrain the location of fault segments. Within a landslide, sediments either slump as broken blocks, or are completely disrupted and appear acoustically chaotic or transparent in chirp profiles. The seafloor surface in a landslide area is hummocky and sediment blocks that are displaced and/or tilted can be observed in the sub-bottom profiles buried beneath the surface when they are not visible in the multibeam data.
Fig. 7 Examples of Landslide and Slump Features. These features are indicative of what is seen along major faults throughout the Amerasia Basin. Features include (a) talus creep, sags (black arrows) shallow listric faulted blocks (red arrows), hummocky topography, lobate toes of slides and (b) arcuate scarps at the head of landslides. The profile (top) along A-A’ shows steep slope at the scarp and sag caused by a back-titled block and typical rounded slope of the slide toe.
2.2.2 Slope Gullies

Slope gullies are shallow channels that develop on continental slopes and are important as indicators of sediment movement in response to low sea level stands and near bottom transport (Spinelli and Field, 2001). One control on the variability of gully density and channel patterns is the underlying geologic structure. Even in a marine environment the formation of channelized flow is controlled by slope and sediment load, and the erodibility of the surface. Therefore an abrupt change in slope gulley pattern along a fault trace may indicate that the erodibility of the surface is different than in an adjacent slope gully system, or it may indicate that the system is more proximal to the potential sediment source. It could also be an indication that the fault segment exhibiting the unusual gully pattern was more tectonically active resulting in more down cutting up slope, headward erosion, and the formation of well developed channel patterns. Variations in slope gullies observable in the multibeam data were examined and reported on Plate 1.

2.2.3 Pockmarks

Other possible geomorphic indicators of fault locations are pockmarks which appear in many areas within the Amerasia Basin in a variety of sizes and types. Pockmarks are increasingly being recognized as widespread morphological phenomena on the seafloor that are caused by fluid and gas which vent through the sediments in the seabed (King and MacLean 1970; Hovland et al., 1984; Max et al., 1992; Judd and Hovland, 2007). Because pockmarks occur over wide areas in Earth’s oceans, they are of interest as markers for possible hydrocarbon resources. Also, because they show location and possibly extent of methane release, there is also interest in pockmarks as sources of greenhouse gases which may have had an impact on global climate at various times throughout history.
Chirp sub-bottom profiler data show areas of acoustic turbidity or interrupted bedding beneath pockmarks which can be indicative of fluid conduits and free gas (Anderson and Bryant, 1990; Richardson and Davies, 1998; Hornbach, et al., 2007). The linear trends of pockmark groups may also reveal the underlying fault structure and may help constrain paleo-tectonic strain for reconstruction models.

The first type of pockmark considered here appears in linear groupings which parallel fault scarps inferred from seafloor morphology. These linear pockmark chains can appear above the headwall of a downthrown block or along the top of a ridge parallel to the strike of the footwall. These pockmarks are generally between 300-500 m in diameter and about 25 m deep, although several as large as a kilometer across were mapped. Pockmarks of this type commonly coalesce to form linear troughs that parallel the trend of local fault traces. Chirp profiles across linear pockmark groups indicate that the pockmarks appear at changes in slope and that bedding below them is disturbed, possibly from rising fluids. These types of pockmarks are interpreted to have formed due to the upward movement of gas along growth faults in the sediments above faulted areas in the basement. An example of this type of pockmark can be seen on the Mendeleev Ridge where multibeam, chirp and MCS data show pockmarks on the surface above growth faults (Fig. 8).
Fig. 8 Fault Controlled Pockmarks on the Eastern Mendeleev Ridge. Multibeam image (area outlined on map inset) shows location of 12 km long HLY0503 multi-channel seismic line (bottom) and black arrows point to pockmarks along the line visible in both data sets. Thick black arrow points to a large blow-out feature (~1.5 km) that formed directly above a faulted area seen in the seismic profile. Buried pockmarks indicate multiple fluid release events over time. Bright spots and “pull-downs” of reflectors below pockmarks are indicative of the acoustic impedance contrast between gas and sediments and appear above faults in the bedrock (red lines).
There are also many examples of pockmarks which have developed on slumps or sags. A slump is the downhill movement of a block which maintains some internal cohesion, and can be found along the steep slopes of the major faults within the Chukchi Borderland. A sag is a circular depression that is caused when a coherent sedimentary mass moves along a discrete shear plane resulting in back tilting rotation. Sag features appear in many locations within the study area on bathymetric highs along the Northwind Ridge, Chukchi Plateau and Mendeleev Ridge (Fig. 9). Both of these sag and slump processes promote preferential pockmark formation along the footwall of the back tilted block. This is where the sudden change in lithostatic pressure in the fluid layer is released allowing the fluids to rise to the surface along the shear plane (Pilcher and Arjent, 2007). Because the slumps and sags themselves may be triggered by sub-surface movement or seismic activity, the pockmark development may be indirectly fault controlled. Pockmarks provide an important clue to the underlying structure in an area, so were therefore studied and appear in Plate 1.

2.2.4 Fault Scarps

In this study a fault “scarp” is considered to be the slope created by a fault. Position and orientation of faults were deduced from visible offsets of bathymetric features, linear scarps, and from gravity lows in basins linking fault scarps interpreted from the bathymetry data. The Chukchi Borderland has been eroded by landslides and gravity flows, and although there has been obvious vertical offset along faults, these are probably not recent in most locations. As a result the actual fault surface is usually hidden and its slope altered by erosion. Slope angles of fault scarps have been somewhat altered by mass wasting and pelagic sedimentation. The fault plane, then, is the tectonic feature while the fault scarp is the eroded surface expression of the fault plane. The fault trace is the linear contact of the fault plane with the basin floor (Fig. 10).
Fig. 9 Slump Controlled Pockmarks in the Healy Hole. This feature (a) on the Mendeleev Ridge is probably a sag depression, a common feature in the Chukchi Borderland. The pockmarks are concentrated on the side with the steepest scarp. Chirp profile along A-A’(b) shows disruption of sediments in fluid pathways below pockmarks which commonly develop above the footwall contact of tilted blocks where the drop in lithostatic pressure in the fluid layer during tilting occurs allowing the fluids to rise to the surface along the shear plane ((c), after Pilcher and Arjent 2007). These type of slump pockmarks are found throughout the Chukchi Borderland. The multibeam swath appears to have imaged the sides of two more sags similar to the Healy Hole which also contain pockmarks ((a), yellow arrows).
Fig. 10  Fault Terminology. Fault scarps are the eroded surface expression of the fault plane. The fault trace is the linear contact with the basin floor (after Moores and Twiss, 1995).
"Classic" tilted fault block styles are created by propagation of planar faults with approximately 60° dip, followed by "bookshelf" or "domino" rotation of the fault blocks during extension (Stewart and Redds, 2003). Bookshelf fault arrays merge downward into a detachment for smaller scale faults and slumps or to a ductile layer for the major fault blocks which accommodates extension by another stretching mechanism. When measuring fault dips from bathymetric cross-sections, the slope angle was eroded and is therefore less than the expected 60° dip due to talus material on the slopes. However, the fault scarp slope angle is still greater than at the toe of a landslide or within a slump feature by comparison. This fact is used to distinguish between slopes measured on fault scarps and those produced from gravity driven mass wasting processes.

Although it is possible to measure slopes utilizing the multibeam data, it is only possible to measure average slope over an area. The strike and dip of the fault can only be averaged over the smallest grid unit, or 100 m. The multibeam images show that there was also substantial mass wasting by landslides (see Fig. 7 and Plate 1 for locations) which can also result in decrease of slope angles. Therefore the true dip of the fault cannot be determined. However, the geomorphology of various types of ridge forming structures including normal faults, transform faults, several types of volcanism, and erosional processes are all observable at the scale of the available data. These observations are presented here in an attempt to constrain the possible tectonic events that could have modified the Chukchi Borderland.

Finally, the implications of the combined observations are discussed with regard to published tectonic reconstructions in order to provide some constraints on the kinematic history of the Amerasia Basin.
3 Observations

"...on the Arctic Ocean physiography, we have drawn attention to the great similarity of morphologic development between the Arctic and the major oceans. This similarity is interpreted by the present writers as a clear indication that the Arctic Basin is a true ocean basin and that tectonic interpretations which imply a special character to the Arctic are improbable."
-- Bruce Heezen and Maurice Ewing (1961)

3.1 Amerasia Basin

The Amerasia Basin is approximately 1500 x 1900 km and is surrounded by continental margins. The interior of the Basin contains the high-standing continental fragment of the Chukchi Borderland and the enigmatic Alpha and Mendeleev Ridges which also seem to be rifted. This is based on the sub-parallel bathymetric ridges and basin features that appear to be normal fault blocks (Plate 1) as well as seismic reflection profiles that show extension created the structures imaged (Jokat, 2003; Ivanova et al., 2006; Dove, 2007).

The tectonic setting of the Arctic region in the Late Jurassic and Early Cretaceous must be considered in order to compare and contrast the features within the Amerasia Basin to features seen in modern oceans. The Late Jurassic and Early Cretaceous is the time when most authors agree that the Amerasia Basin began to form (Tailleur, 1973; Grantz et al., 1979; Maill, 1979; Grantz and May, 1983; Lawver et al., 2002). The Amerasia Basin, its pre-rift geometry and overall tectonic setting prior to its opening are not well constrained. It has been inferred from the geology along the margins that the North American Plate and Eurasia Plate had not yet separated in the early Mesozoic and that the Ural and Taimyr mountains were shedding sediments into basins along the broad shelf that existed between the two continents (Lawver et al., 2002; Miller et al., 2002).
The Brooks Range of Arctic Alaska hosts a Late Jurassic-Early Cretaceous deformational belt believed to have been developed as a consequence of arc-continent collision (Miller and Hudson, 1991; Moore et al., 1994). Imbricated shelf sequences are structurally overlain by oceanic and ultramafic allochthons of the Angayucham terrane (Moore et al., 1994). Syn-orogenic sediments were shed northward during thrusting in the Brooks Range, providing sedimentologic and fossil age control on the timing of deformation (the Okpikruak Fm., Miller and Hudson, 1991 and references therein; Moore et al., 1994). The Chukotka fold belt was formed when an arc collision, or back-arc basin closure, caused the deformation that is recognized by tectonic slivers of upper Paleozoic to Jurassic arc rocks found along and to the south of the South Anyui suture zone. This deformation is also observed along the southern tip of the New Siberian Islands, and in the inner part of the Verkoyansk belt in Siberia (Miller et al., 2008; Kuzmichev, 2009).

3.1.1 Subduction in the Arctic

Voluminous subduction related magmatism, mostly Jurassic and Cretaceous in age, developed across Alaska and northeast Russia, but not across other regions of the Arctic, where basaltic magmatism was common. The 158-143 Ma convergence-related plutons of the Verkoyank belt (Akinin et al., 2009) are succeeded by the emplacement of plutons in the Northern belt which range in age from 135-120 Ma (Toro et al., 2007). Widespread plutons beween 120 -105 Ma in Chukotka cut convergence-related deformational fabrics and their intrusion was coeval with EW to NE-SW extension (Miller et al., 2009 ; Miller and Verzhbitsky, 2009). The Okhotsk-Chukotsk Volcanic Belt is mostly 90-80 Ma and thus younger than the Chukotka belt plutons (Hourigan and Akinin, 2004; Akinin et al., 2009). These younger volcanics developed as a consequence of subduction along the northern Pacific margin. In the Russian Arctic this southern jump of magmatism probably represents the end of any possible tectonic activity or rifting in the Arctic ( Rubin et al., 1995; Miller and Verzhbitsky, 2009). However, east of
there and into Alaska, 80-90 Ma age magmatism is superimposed on earlier Cretaceous magmatism.

There is a record of subduction related volcanism throughout the entire Alaska/Siberia region, from at least the Late Jurassic, moving southward through time (Rubin et al., 1995; Miller and Verzhbitsky, 2009). The geologic remnants of this volcanism have been involved in subsequent deformation making the exact location of the ancient subduction zones poorly constrained. But it can be assumed, based on the location of the ophiolites, and arc related granitic plutons, and volcanic rocks throughout the region, that the subduction zone was much closer to the Alaskan and Siberian margins of the Amerasia Basin than where it is currently located. This seems to indicate that island arc accretion and back-arc spreading, driven by the Pacific subduction zone, was one of the major tectonic drivers affecting the Arctic at this time.

A modern day analogue of the Early Cretaceous tectonic setting of the Amerasia Basin region, then, must include a small ocean basin (=1500 x 1900 km) surrounded by broad continental shelves which is being extensively affected by interaction of complicated subduction boundaries with continental collision, island arc accretion and back-arc basin development, as opposed to a simple and linear Andean type subduction zone. Today such a setting can be found along the western Pacific margin where extensional breakup of wide continental shelves forms multiple oceanic basins behind major arcs (Fig. 11). Although none of these examples are perfect analogues, modern back arc basins share important tectonic and morphological similarities to the Amerasia Basin. The Sea of Japan (or East Sea), for instance, is a small confined basin with rifted intra-basinal ridges which formed behind an active subduction zone. Although it is not completely confined in continental crust, the Tasman Sea is another example of extensional formation of an
Fig. 11 Location of Modern Back-Arc Basins. Google Earth image of the western Pacific subduction zone and location of back-arc basins (yellow arrows). Extensive plutonic belts and ophiolitic rocks found around the Arctic indicates that the Pacific subduction zone (red line) was much closer to the margins of the Amerasia Basin than it is today (red dashed line, Miller et al., 2002) as island arc accretion began in the Jurassic (Moore et al., 1994)
oceanic basin far within continental crust and of rotational opening of an ocean basin. The Coral Sea is an example of an oceanic basin completely confined within continental crust and the South China Sea, has morphology very similar to the Amerasia Basin, especially if one considers the location of the Early Cretaceous Arctic/Pacific subduction zone to have been much closer to the Amerasia Basin (Fig. 11).

The South China Sea is considered a marginal sea, and thought to have originated from Atlantic style spreading beginning in the mid-Oligocene (32 Ma), some say unrelated to any back-arc extension (Taylor and Hayes, 1980, 1982), and has continued to evolve as a result of rotation interactive with extrusion tectonics in South China (Zhou, 1997). The broad continental shelves are similar to those found surrounding the Amerasia Basin, although their expanse is much less than in the Arctic Ocean which has the world’s most extensive shelf area, and the eastern boundary of the South China Sea is formed by an island arc system.

The Amerasia Basin and the South China Sea both have regions made up of ridges and valleys, attached to the margins that surround the oceanic basin that range between 300-3800 m water depths (Fig. 12). In the South China Sea region, both of these marginal zones were at one time connected. The ridges to the north are genetically related to the enveloping 170–330 km wide zone of ridges to the south known as Dangerous Grounds. Both ridge systems are extended continental material.

The Amerasia Basin’s marginal ridge system, the Alpha and Mendeleev Ridges, probably sparks the most contentious discussions about the development of the Amerasia Basin.
Fig. 12 The South China Sea /Amerasia Basin Bathymetry Comparison. Both small ocean basins formed by continental rifting behind an arc. Both are bounded by broad continental shelves and contain extensive intra-basinal ridge systems that border the margins with relief between 300-3800m water depth. In the South China Sea these bathymetric ridges along the margins are composed of extended continental crust. Along with the influence of the High Arctic Large Igneous Province (HALIP), the proximity of Mesozoic subduction zone(s) to the Amerasia Basin, suggest that back-arc rifting may also have been one of the controls on the formation of its intra-basinal ridges. South China Sea bathymetry from ETOPO 1 database (see Section 2.1).
Volcanic (Jackson et al., 1986) and volcaniclastic rocks (Van Wagoner et al., 1986; Brumley et al., 2008) as well as metasedimentary rocks (Clark et al., 2000) have been dredged from the Alpha Ridge. While geophysical evidence for an oceanic origin of a basaltic Alpha Ridge is substantial (Jackson et al., 1986; Weber and Sweeney, 1990; Tarduno et al., 1998), a continental origin has also been repeatedly suggested (King et al., 1966; Coles et al., 1978; Johnson et al., 1994; Ivanova, et al., 2006; Miller, et al., 2006). Bathymetrically at least, the Alpha and Mendeleev Ridges are very similar to other marginal ridge systems observed in back-arc ocean settings. Because the Mesozoic tectonic setting of Arctic region was greatly influenced by subduction, back-arc rifting may have been a control on the formation of the intra-basinal ridges of the Amerasia Basin as well.

A distinction can be made between the Early Cretaceous Amerasia Basin and the contemporary South China Sea due to the voluminous volcanism that accompanied the onset of rifting in the Arctic. Although the South China Sea’s Dangerous Grounds has experienced volcanism in its pre-rift and post-rift history (Hutchison, 2004), the High Arctic Large Igneous Province (HALIP), which affected the Arctic during the Cretaceous, has been estimated to have a magmatic footprint of over a million square kilometers if the Alpha-Mendeleev Ridge was built entirely from HALIP magmatism (Maher, 2001). The Amerasia Basin was certainly affected by the HALIP and its effects could provide considerable constraint on the history of the basin.

3.1.2 High Arctic Large Igneous Province (HALIP)

The association of large igneous provinces (LIPs) with continental breakup is well recognized (Coffin and Elderholm, 1994; Sheth, 1999) and multiple authors suggest a connection with the High Arctic Large Igneous Province (HALIP), Alpha Ridge, and the
opening of the Amerasia Basin (Bailey and Rasmussen, 1997; Lawver and Muller, 1994; Maher, 2001; Grantz et al., 2009). Most models for the formation of the Alpha and Mendeleev Ridges include a hot spot component, either as a time progressive hot spot track on oceanic crust, or hot spot interaction with a spreading ridge. While the history of Alpha-Mendeleev ridge system formation is unclear, it has the appropriate age and geophysical character to be a LIP, with Svalbard, Franz Josef Land, North Greenland, and Ellesmere Island as distal portions penetrating into surrounding continental margins (Maher, 2001).

HALIP volcanic rocks have been found around the margins of the entire Arctic Ocean, from Arctic Canada, Greenland, Svalbard, Franz Josef Land and the Delong Islands in the form of dyke swarms and flood basalt. Most HALIP volcanic rocks do not have reliable radiometric ages but samples from the Sverdrup Basin, Franz Josef Land, and northern Greenland (Kontak et al., 2001) have $^{40}$Ar-$^{39}$Ar ages of 128-82 Ma (Villaneuve and Williamson, 2003) which seems to indicate that dyke emplacement spanned a minimum of about 50 million years (Buchan and Ernst, 2006). Early Cretaceous basalts of Franz Josef Land and Bennett Island are mostly evolved tholeiites with variable concentration of Ba and Sr, consistent with their emplacement in a continental setting (Drachev and Sanders, 2003). Those found in the Canadian Arctic Islands are geochemically comparable to continental flood basalts (Estrada et al., 1998).

Although the age data are sparse, they do offer some constraints on models for the development of the Alpha Ridge. Given the distance between Svalbard and Franz Josef Land and their alignment parallel to an inferred time-progressive hotspot track on Alpha Ridge predicted by many reconstruction models, an observable difference in age would be expected. Yet, dykes and flood basalt on Svalbard and Franz Josef Land are very similar to each other in age (Maher, 2001). Sediment core studies by Maher (2001) in
Svalbard and Franz Josef Land show that a transgression occurred in both of these locations before development of a Late Cretaceous unconformity indicating two periods of uplift in the region. This is consistent with two phases of the HALIP development and associated thermal uplift separated by about 25–30 Ma.

Two phase LIP development seems to be common in various settings. The Ontong Java and Kerguelen-Broken Ridge LIPs also exhibit two magmatic peaks at 120–115 and 90–85 Ma similar to what has been observed with the HALIP. It is also common with volcanic rifted margins to experience periods of volcanism during the transition from the formation of a large igneous province to eventual ocean ridge processes, should rifting continue (Menzies et al., 2002). In the North Atlantic (Greenland and UK) volcanism straddled break-up with a pre-rift LIP followed by a syn-rift stage (Laursen and Sanders, 1998) and this protracted period of volcanism may explain the attenuated and heavily intruded nature of the broad continent-ocean transition in this region (Menzies et al., 2002).

The thick dense crust and high amplitude magnetic anomalies of the Alpha and Mendeleev Ridges, as well as their arcuate trend about the hypothesized pole of rotation in the Mackenzie Delta (Cochran et al., 2006), suggest that the HALIP certainly affected the Alpha and Mendeleev Ridges and may have even been completely responsible for their formation. The question is not whether the Amerasia Basin was affected by the HALIP, but if the Alpha and Mendeleev Ridges were, 1) built on oceanic crust like the Ontong Java Plateau, 2) the result of a time progressive hotspot track leaving a volcanic pile on oceanic crust, 3) formed as a result of hotspot interaction with a spreading ridge, or 4) from volcanism associated with continental rifting leaving faulted, intruded and under-plated fragments of continental crust to create the structures of the ridges. The geophysical evidence has not provided a consensus on this point.
3.1.3 Dredged Rock Samples, 2008

Basaltic rocks were sampled by dredging in the summer of 2008 from the USCGC Healy (HLY0805, Mayer et al., 2008a) north of the Chukchi Plateau from the side of a small horst block on the boundary of the Northern Chukchi Borderland and the Canada Basin (Dredge site 6, Fig. 2). More basalt samples were also dredged on the western edge of the Northwind Ridge (Dredge site 7, Fig. 2). Although it must be emphasized that analysis on these basalts is not complete, preliminary major oxide, trace element and isotopic analyses indicate that the basalt samples from dredge sites 6 and 7 are of two different chemical and isotopic compositions, one erupted in water (site 6) while the other was probably sub-aerially erupted (site 7). Based on the extent of alteration, the basalt samples are probably also of different ages (Andronikov et al., 2008). The existence of two lava populations in the Northern Chukchi Borderland is comparable to other large igneous provinces which typically accompany the development of volcanic rifted margins during both syn-rift and post-rift stages (Menzies et al., 2002), but as mentioned above, are also indicative of oceanic LIPs.

The Northwind samples (Dredge site 7) display surfaces and columnar jointing consistent with subaerially erupted lava lobes which are common in continental flood basalt and compositionally may be transitional between tholeiitic basalts and basaltic andesite. The other basalt population from Dredge 6 displays pillow structures indicating eruption in water and has a tholeiitic composition with Sr ratios similar to continental flood basalt (Andronikov, personal communication, March 2009). Details of the trace element analysis are not yet available, but the occurrence of this type of volcanism away from any obvious spreading centers and with these geochemical characteristics identify the dredged samples as having originating from either a deep-seated hot spot sources or from the shallower mantle partially melted by decompression. The chemistry of these lavas indicate that they erupted through continental crust (Andronikov et al., 2008) and the
greater than 3600 m water depth at which the basalts are now located, is consistent with large degrees of extension and/or subsidence, likely related to the event(s) that formed the Amerasia Basin. This suggests that the Northern Chukchi Borderland is not underlain with oceanic crust but is probably an extended part of the Chukchi Plateau.

Also in 2008, rocks were dredged from basement outcrop on a fault bound block along the edge of the Nautilus Basin on the south central Alpha Ridge (Dredge Site 1, Fig 2; Mayer et al., 2008a). Preliminary thin section analysis (Brumley et al., 2008) of the samples indicate that they are volcaniclastic sediments from a phreatomagmatic eruption in shallow water. Based on the style of vesiculation observed in the glass fragments as well as the normal grading of pumice fragments which rules out deposition from air fall (Fig. 13). Because of the density contrast between pumice and other volcaniclasts like glass and basalt fragments, airfall deposits with pumice tend to be inversely size graded within beds. Because of its low density, pumice is unable to penetrate the air/water interface until it is waterlogged and will either be absent from the airfall deposits or appear as inversely graded layers commonly mixed with non-volcanic material that also fell through the water column (Fisher, 1984; Stix, 1991). The samples have graded beds that were not significantly reworked based on the fact reworking of the sediments would have caused destruction of the delicate scoriaceous clasts and vesicular glass fragments which was not observed in the dredged samples. Also, had considerable time elapsed before the reworking that resulted in the graded bedding, clasts other than purely volcaniclastic fragments would be present in the samples. No fossils, non-volcanic lithic fragments, or marine sediments were found in the dredged samples. The volcaniclastic rocks from the south central Alpha Ridge are not air fall deposits from a distal volcanic source subsequently deposited in deep water in the vicinity of Alpha Ridge.
Fig. 13 Dredged Rock Sample from South Central Alpha Ridge. This sample from dredge site #1 (see Fig. 2) displays graded beds of volcaniclastic sediments from a phreatomagmatic eruption in shallow water (Brumley et al., 2008), similar to samples dredged from the north eastern Alpha Ridge by Van Wagoner et al., (1986). Manganese crust on outside (top) with fresh surface on the other side (bottom), as well as the monolithology of the over 50 samples in the dredge, indicate these are bedrock samples and not ice-rafterd debris. These are shallow water sediments, and were dredged from over 3600m water depth, which indicates that the south central Alpha Ridge has undergone substantial extension since these rocks were deposited.
The pumice fragments which appear in the Alpha Ridge rocks are sorted along with basalt fragments, vesicular glass and plagioclase crystals indicating that the deposit was from a subaqueous pyroclastic flow or mass flow deposit of volcaniclastic debris (Stix, 1991).

These volcaniclastic sedimentary rocks, which can be termed hyalotuffs (Honnorez and Kirst, 1976), were deposited soon after a shallow water volcanic eruption, yet they were dredged from a basement outcrop currently located at 3622 m water depth. Because these rock samples are from basement outcrops and are not part of the sediment drape which covers the structures of the Alpha Ridge, they were deposited prior to the extension that resulted in the formation of the fault block from which they were collected. This indicates that south-central Alpha Ridge was a shallow water setting, perhaps less than 200m water depth (Van Wagoner et al., 1986) prior to the extension that formed the basin, and that it was not built in deep water long after the basin formed.

Other rock samples dredged from Alpha Ridge have been used as an argument for the “oceanic” origin of the Alpha and Mendeleev Ridges. The rocks that were reported to be the first samples of acoustic basement from the Alpha Ridge were not basalt, but were also volcaniclastic sedimentary rocks probably from a phreatomagmatic eruption in water less than 200m deep (Van Wagoner et al., 1986). Van Wagoner et al., (1986) describe results from whole rock and trace chemistry analyses as well as mineralogical constraints on the tectonic setting. They reported that alkalic rocks of this type are generally not associated with island arcs, mid-ocean ridges or transform faults.

No suitable minerals for radiometric dating have been found in any of the sedimentary rocks from Alpha Ridge. However, Van Wagoner et al., (1986) reported that the Alpha
Ridge basement rocks had to be older than the Campanian marine sediments that overlie them (Mudie and Blasco, 1985) and concluded that the Alpha Ridge is an aseismic ridge which formed due to hot spot activity and may have been responsible for initiating rifting and dispersal that eventually formed the Canada Basin.

3.1.4 Radiating Dyke Swarm

The locations and the geometry of dyke swarms may also eventually help to reconstruct the pre-rift locations of volcanic features, assuming a central magmatic source for the HALIP. Dyke swarms in the Sverdrup Basin Magmatic Province radiate across the Queen Elizabeth Islands, suggesting the existence of a large magmatic source at the southern end of Alpha Ridge (Fig. 14; Forsyth et al., 1986; Embry and Osadetz, 1988; Buchan and Ernst, 2006). Cretaceous dykes of northern Greenland, Svalbard and Franz Josef Land also have a radial pattern centered on Alpha Ridge (Maher, 2001). Although this is not obvious in the present post-rift continental configuration, models for the tectonic reconstruction of this region should consider the location and geometry of these dyke swarms as a constraint on the pre-rift geometry of the Arctic Ocean.

It is common for volcanic margins to be defined by dyke complexes that strike parallel to the margin and eruptive fissures at form morphological ridges (McHone, 1988; Klugel et al., 2005). Therefore, linear dyke swarms can be used as piercing points for continental reconstruction by matching the strike and distribution of dykes on each continental block (Bleeker and Ernst, 2006). Published paleo-continental reconstructions in the Arctic have not considered the distribution and orientation of volcanic features of Cretaceous age found around the Arctic margins. Observations of radiating dyke swarms and flood
Fig. 14 Radiating Dyke Swarms of the Cretaceous HALIP. Dykes in the Canadian Archipelago, northern Greenland and Franz Joseph Land and possibly within the Amerasia Basin, seem to radiate from a central focus near the Alpha Ridge (red star) once pre-rift locations are considered. (After Buchan and Ernst, 2006) Possible igneous dykes observed in multibeam data in the southern Northwind Basin (a) and along the edge of the South Central Alpha Ridge (b).
basalts associated with the HALIP which have been dismembered and dispersed around the Arctic Ocean, may help constrain the timing of rifting in the Amerasia Basin, and may also provide clues to the pre-rift locations of features within the basin.

Since the Chukchi Borderland is a continental fragment that was rifted from an adjacent margin, and since the margins of the Arctic Ocean were affected by HALIP volcanism, it is probable that remnants of the HALIP can be found within the Chukchi Borderland as well. Linear and sinuous bathymetric features that follow similar trends are observed in multibeam data in the Chukchi Borderland and Alpha Ridge and have been interpreted here as possible igneous dykes (Fig. 14). Without rock samples they cannot be confirmed as such, but I have been mapped them here to record their location, in the event that future studies desire to use the location and strike of dykes for constraint on reconstruction models.

3.2 Amerasia Basin Summary

The Alpha Ridge has been compared to LIP generated oceanic plateaus like the Ontong Java or Manahiki Plateaus that were formed on an oceanic plate, not associated with continental break-up. While the velocity structure and crustal thickness of these plateaus are similar to Alpha Ridge (Forsyth et al., 1986) they are different from the Alpha and Mendeleev Ridges in both tectonic setting and morphology (Fig. 15) and neither display the significant rifting found on the Alpha and Mendeleev Ridges. Nor do the Alpha and Mendeleev Ridges share a morphology with other intra-plate hot spot tracks on oceanic crust, like the Hawaiian chain or the 90 East Ridge, that are composed of a series of seamounts which are very different from the broad fractured arch composed of long ridges and valleys striking parallel to the axis of the Alpha and Mendeleev Ridges (Fig. 15).
Fig. 15 Oceanic Plateaus/Alpha-Mendelev Bathymetric Comparison. The Alpha-Mendelev Ridge complex (c) has been compared to oceanic plateaus like the Ontong Java (a; ETOPO 1) and the Kerguelen Plateau (b; ETOPO 1). Although similar in size, the oceanic plateaus do not exhibit the rift fabrics of the Alpha and Mendeleev Ridges and are located in very different tectonic settings. The Alpha Ridge is completely surrounded by and connected to continental shelves.
The contemporary nature of igneous activity, as indicated by both stratigraphic and geochronologic constraints in the Canadian Archipelago, Svalbard, Franz Josef Land, Greenland, the Delong Archipelago, and Alpha Ridge (Maher et al., 2001; Drachev and Sanders, 2003; Buchan and Ernst 2006), is not consistent with a time-progressive hot spot track. If the Alpha-Mendeleev ridge system is the result of either a hot spot track on pre-existing Canada Basin oceanic crust, or from interaction of a hot spot with the Canada Basin spreading center (Williams, 2006) then the age of basalt found on the Delong Islands should be much older than those dated in Svalbard and the Canadian Arctic Islands. Yet the similar age dates found around the region do not seem to support the time progressive, Hawaiian style hot spot idea, but rather that two pulses of magmatic activity affected the HALIP region between 130-85 Ma. (Maher, 2001). The local isostatic compensation and lack of lithospheric flexure around the Alpha and Mendeleev Ridges also indicates that they did not form as a hot spot track on old oceanic crust but must have formed either by rifting continental crust, or on new oceanic crust near an active spreading center in conjunction with the HALIP hot spot (Williams, 2006).

The comparison of the Alpha Ridge to the Iceland hot spot shows that similar crustal thicknesses and velocity structures (Jackson et al., 1986), as well as voluminous volcanism and large scale rifting is indicative of both systems. Iceland is formed by the interaction of a hotspot with an active spreading center which is causing the rifting parallel to the ridge axis (Fig. 16). Although it was been suggested that the Alpha-Mendeleev Ridge system is an ancient spreading center (Hall, 1970; Vogt and Ostenso, 1970), or that it formed as a result of hot spot activity located near a spreading center (Forsyth et al., 1986; Jackson et al., 1986; Williams, 2006) the bathymetry raises questions about this proposed hot spot/spreading axis geometry. The major rift structures that appear along the Alpha Ridge axis in the bathymetry data as well as in seismic profiles (Jokat, 2003) run perpendicular to the inferred rift direction of the near ridge/hot spot model, unlike the rift structures found on Iceland (Fig. 16).
Fig. 16  Iceland / Alpha-Mendelev Comparison.  If the Alpha-Mendelev Ridge system formed as a result of hotspot interaction with a spreading center in the early Cretaceous in a manner similar to Iceland (top, ETOPO 1), then it would have to have formed symmetrically around the hypothesized spreading center in the Canada Basin (Red line, bottom) with the locus of the hotspot around Cooperation Gap (above) with the oldest rocks on the outside edges. Basalts dredged from Alpha Ridge (star) are only 82 million years old. Red arrows indicate extension as a function of rift segment distribution and in Iceland rift structures develop along a parallel trend with the spreading center (Angelier et al., 2004). Rift structures on Alpha Ridge, however, have formed at high angles to the inferred spreading center and it is difficult to imagine how hotspot material could be found between the Chukchi Plateau and the Siberian margin utilizing this model.
In order for the Alpha and Mendeleev Ridges to have formed from the interaction of a hotspot and spreading ridge during the rotational opening of the Canada Basin and to have developed an Iceland-type volcanic plateau that is symmetrical on either side of the paleo-spreading ridge, the ridge axis would have to have been located near the center of the feature in the area called Cooperation Gap which marks the division between the Alpha and Mendeleev Ridges (Fig. 16). The oldest volcanic material, then, should be found at the ends of the Alpha and Mendeleev Ridges along the Canadian and Siberian margins. The older crust should also be found at greater water depths than the younger material near the center of the feature given the increased time for lithospheric cooling and subsidence of the older crust. However the highest standing topography of the Alpha-Mendeleev Ridge complex is along the margins with the greatest water depths in the central region. Also, basalt samples dredged from the central rift of the Alpha Ridge have a Late Cretaceous $^{40}\text{Ar} - ^{39}\text{Ar}$ age of 82 ±2 Ma (O’Connor in Jokat, 2003). If these are the oldest basalt ages on the Alpha Ridge as their position near the Canada Margin entails in this model, then the basin is far younger than its current depth and the body of geologic evidence seems to indicate.

If the Alpha and Mendeleev Ridges were formed by a hot spot funnelling material into a spreading ridge, tracking the opening of the Canada Basin, then it is difficult to understand how this ridge axis could have been fed by the same hot spot throughout the entire 20-30 Ma period of basin development (Williams, 2006), or how it could have delivered volcanic material between the Chukchi Borderland and the Siberian margin. It may be argued then that the hot spot that formed the Alpha and Mendeleev Ridges emplaced material along a ridge parallel to the Alpha Ridge axis. But then the plateaus should have formed symmetric about the ridge axis along its length. This is not evident in the bathymetry of the Alpha-Mendeleev ridge system.
The geomorphology of the Alpha and Mendeleev Ridges do not seem to support this hot spot/spreading ridge model for its formation, but shares more in common with the highly attenuated and intruded continental rift structures like those seen along the margins of the South China Sea and other back-arc basins.

The scale and bathymetric similarities of the Amerasia Basin to other back-arc basins like the South China Sea are marked (Fig. 12). Yet, the Amerasia Basin is unique in its tectonic history in that it was a back-arc basin that was also affected by a large igneous province associated with continental breakup of Laurentia which probably also helped drive its tectonic development. Although this eventually resulted in the Atlantic spreading center propagating into the Arctic long after the Amerasia Basin ceased forming, during the Basin’s early history it was completely surrounded by continental crust behind an active subduction zone and the intra-basinal ridges share more geomorphic similarities to back-arc basin features than to volcanic constructs on large oceanic plates.

3.2.1 Extension on Alpha and Mendeleev Ridges

*Alas! Alas! Life is full of disappointments; as one reaches one ridge there is always another and a higher one beyond which blocks the view* – Fridjof Nansen (1887)

Because the Amerasia Basin was located near the Pacific subduction zone during the Cretaceous and shares morphological similarities to back-arc basins, the Alpha and Mendeleev Ridges can be compared to analogous features found in other small ocean basins in similar back-arc settings such as the South China Sea (See Section 3.1.1). The Mendeleev Ridge is remarkably similar bathymetrically to the rifted continental crust that lies adjacent to the northern margin of the South China Sea (Fig. 17). Studies of multi-channel seismic profiles across the Mendeleev Ridge indicated that the acoustic basement
was normal faulted in what appears to be a continuation of the faulting that affected the Chukchi Borderland (Dove, 2007). The extension that affected the analogous region of the South China Sea was more complete and oceanic crust borders the northern marginal ridge system and therefore created more relief than what is observed on the Mendeleev Ridge. The overall geometry of the two ridges is very similar (Fig. 17).

The Dangerous Grounds area of the South China Sea is also bathymetrically very similar to the Alpha Ridge in its placement within the ocean basin as well as its scale and relief. Dangerous Grounds was formed of attenuated continental crust that was affected by pre and post-rift volcanism during its 32 million year history. Bathymetric features of the south central Alpha Ridge, which borders the Nautilus Basin, are consistent with those found in extensional settings. These include parallel ridges and basins, sharp fault scarps, and rift valleys which all trend in the same direction as the normal faults of the Chukchi Borderland (Plate 1).

The Alpha Ridge also has features of the type of volcanism indicative an extensional setting along a volcanic rifted margin. Besides the fact that two different fault bound blocks are made up, at least in part, of volcanlastic sedimentary rocks deposited in a shallow water environment (see Section 3.1.3; Van Wagoner et al., 1986; Brumley et al., 2008), there are also bathymetric features that seem to have a volcanic origin. Along the south central edge of the Alpha Ridge, is a linear feature, similar to those observed in the Northwind Basin (Fig. 14).
Fig. 17 South China Sea / Alpha-Mendeleev Comparison. The Mendeleev Ridge (top right) is bathymetrically comparable to the northern China Sea Region (top left) where the ridges are formed from thinned continental crust. The Alpha Ridge (bottom right) is bathymetrically comparable to the Dangerous Grounds (bottom left) which is also attenuated continental crust. Each has a lobate feature (circled) bounded on each side by linear ridges which run parallel to a thin linear continental fragment (Lomonosov Ridge and Palawan Province respectively). South China Sea bathymetry from ETOPO 1 database (see Section 2.1)
The feature is approximately 20 km long, less than 0.5 km wide and has three cone shaped hills along its length, one of which has a central crater-like depression. A landslide scarp, seen both in the multibeam and chirp data, has worn away a section of the hill to which the feature is attached, but the resistant material which forms this linear feature did not move with the landslide (Fig. 14). Bathymetrically it appears to be a fault controlled dyke where magma was injected into a fracture, with small extrusions on the surface.

A subsidiary ridge located in the central Alpha Ridge was surveyed by multibeam along the HLY0503 ship track (Hopper, et al., 2006). The poor quality of the multibeam data here shows that difficult ice conditions were a factor when it was collected. However, there seem to be three steep sided, cone shaped hills along the edges of the ridge which could be small mono-evolutionary volcanoes or cinder cones (Plate 1). The ridge itself is fault bounded and has experienced mass wasting along its southeastern flank.

If the Alpha and Mendeleev Ridges are indeed analogous to the marginal ridge systems found in other Pacific back-arc basins they may have formed as a result of the extension that formed the Amerasia Basin. Like the attenuated continental crust that surrounds most margins of the South China Sea, the Alpha and Mendeleev Ridges are located along the margins of the Amerasia Basin; this includes the Lomonosov Ridge which formed the margin with the Barents Shelf in the Early Cretaceous. Even if the Alpha and Mendeleev Ridges are composed of completely different material than the Chukchi Borderland, the consistent strike of the bathymetric features that have been mapped, as well as the existence of shallow water volcaniclastic rocks, which are now below 3600m water depth, suggests that the Alpha Ridge has undergone a significant amount of extension and therefore the fault scarps can be used as a constraint on rift directions. The trends of fault traces captured in the multibeam data on Alpha and Mendeleev Ridges were measured
and their azimuthal directions recorded in rose diagrams on Plate 1. The faults which appear on the Mendeleev Ridge along the edges of the study area were mapped previously by Dove (2007) utilizing seismic data and gravity modeling, while others are visible in the multibeam data.

The normal faulting imaged in seismic profiles indicate that the Mendeleev Ridge also rifted in the same regional direction (Dove, 2007). Their geomorphology suggests that the Alpha and Mendeleev Ridges are not fundamentally different than other marginal ridge systems created in attenuated continental crust found around the margins of other back-arc ocean basins. Although no subsurface data are available to help constrain the type of faulting observed in the Northern Chukchi Borderland and south-central Alpha Ridge, the morphological similarities to other extensional terrains with parallel ridges and basins over an extensive area suggest that Chukchi Borderland extension also affected the central Amerasia Basin.

The continued rift fabric across the Nautilus Basin suggests that the south-central Alpha Ridge may also be related to the extension that formed the Northern Chukchi Borderland. A possible reconstruction of the Northern Chukchi Borderland to the south central Alpha Ridge across the Nautilus Basin appears in Fig. 18. The position of Northwind Ridge was held steady, dip-slip motion along the faults was assumed, and by matching ridge edges across rift basins perpendicular to strike at each step, features begin to align into their possible pre-rift positions. If the Alpha Ridge structures were formed from the same extensional stresses that resulted in the consistent fault directions on the Chukchi Borderland, perhaps the south central Alpha Ridge and Northern Chukchi Borderland were rifted during the same tectonic event(s). This suggests that the south-central Alpha Ridge may be a continuation of the rifted continental crustal fragment that makes up the Chukchi Borderland.
Fig. 18 Reconstruction Model of the Northern Chukchi Borderland. This model (a-e) suggests that the south central Alpha Ridge was connected to the Chukchi Borderland across the Nautilus Basin. The position of Northwind Ridge is held constant and rift basins are closed in the direction of the arrows perpendicular to the trend of faults at each step.
4. CHUKCHI BORDERLAND

"The ‘good’ of Polar exploration cannot be so definitely translated into terms of human comfort or of money saved to the world. It remains a something that man has not yet conquered and every mystery made plain, every unknown land explored, exalts the spirit of the whole human race” — Roald Amundsen (1927)

The Chukchi Borderland (Fig. 2) is an approximately 500 x 600km bathymetric high composed of a series of northwest-southeast trending parallel linear basins and gently rounded ridges. The eastern boundary is the steep Northwind Escarpment. Slopes along this escarpment range between 10 and 20 degrees. On the western boundary the edge of the Chukchi Plateau is separated from the Mendeleev Ridge by the Chukchi “Abyssal Plain” (Weber, 1983) also called the Chukchi Perched Rise (Jakobsson et al., 2003). Here this basin will be called the Chukchi Basin. The northern boundary of the roughly rectangular Chukchi Borderland is the Mendeleev Abyssal Plain on some maps, or the Nautilus Basin by Jakobsson et al. (2003). Here the basin will be called the Nautilus Basin. The southern boundary of the Chukchi Borderland can be recognized as the northern edge of the Chukchi Shelf. The Borderland has usually been divided on bathymetric maps as two distinct plateaus called the Northwind Ridge and the Chukchi Plateau which are separated by the Northwind Basin (Northwind Abyssal Plain on some maps). The many sub-basins and ridges within the Northwind Basin have not been officially named or described.

4.1 Chukchi Borderland Bathymetric Analogue

In an effort to understand the tectonic circumstances that created the geomorphology of the Chukchi Borderland, comparisons with similar seafloor features is useful. The overall scale and general geometry of the Chukchi Borderland is remarkably similar to that of the Rockall Plateau in the North Atlantic region (Fig. 19) and although it did not form in a
Fig. 19  **Chukchi Borderland / Rockall Plateau Comparison.** The Chukchi Borderland (top) and Rockall Plateau (bottom; ETOPO 1) share a similar morphology. Each is a high-standing continental fragment with a major rift basin between high standing plateaus, and each is flanked by a steep normal faulted escarpment with several thousand meters of relief (red lines) bounded by oceanic crust. In the Rockall region, the deeper areas between Endoras Bank and the Charlie Gibbs Fracture Zone are rifted continental crust. This may be analogous to the Northern Chukchi Borderland region which seems to contain structures that are a continuation of those in the higher standing regions of the Borderland.
back-arc setting, it is a result of continental rifting. Like the Chukchi Borderland the Rockall Plateau is a rifted continental fragment also in a region with a possibly complicated tectonic history (Hauser, 1995; Bull and Masson, 1996). The generally north-south striking normal faults of the Rockall Plateau were formed during the separation of Greenland from Eurasia in the earliest Eocene (Hauser, et al., 1995). The area includes parts of the North Atlantic Tertiary Volcanic Province and voluminous volcanic rocks have been recognized on the southern edges of the Rockall Plateau (Bull and Masson, 1996). Gravity anomaly modeling and continental reconstructions indicate that this vulcanized southern region of the Rockall Plateau is also underlain by thinned continental crust (Bull and Masson, 1996). The Rockall Plateau itself, however, seemed to have escaped the volcanic underplating that affected the crust around its edges (Hauser, 1995).

The bathymetric similarities between the Rockall Plateau and the Chukchi Borderland are pronounced (Fig. 19). Each is a high standing relatively flat-topped, rifted continental fragment with a continental shelf on one side and oceanic crust on the other; the North Atlantic borders the Rockall Plateau and the Canada Basin borders the Chukchi Borderland. The opposite boundary of each plateau is a basin of thinned continental crust which is connected to a continental shelf; the Rockall Trough and Porcupine Bank in the Rockall Plateau example and the Chukchi Basin and Arlis Rise (Fig. 2) for the Chukchi Borderland.

This may be a good analogue for the Chukchi Borderland in several ways. The Chukchi Borderland is also a continental fragment along a rifted margin that was affected by voluminous volcanic activity, namely, the High Arctic Large Igneous Province (HALIP), which accompanied the onset of rifting of the Amerasia Basin (see section 3.1.1; Lawver and Muller, 1994; Bailey and Rasmussen, 1997; Maher, 2001). The velocity structures
of the Alpha and Mendeleev Ridges have been used to argue for both an oceanic and continental origin (Forsyth et al., 1986; Ivanova et al., 2006). Although the thick high velocity crust beneath the Alpha Ridge is similar to oceanic plateaus or Iceland (Jackson et al., 1986), this structure is also similar to the wide continent ocean transitions in volcanic rifted margins like the Voring basin (Menzies et al., 2002; Gernigon et al., 2004; Ivanova et al., 2006). Therefore, it is consistent with the geophysical data that the areas surrounding the Chukchi Borderland could also be composed of rifted and intruded continental crust similar to what is found around the Rockall Plateau. This is consistent with the Amerasia Basin forming due to back-arc spreading that created rifted fragments around its margins while still acknowledging the influence of the HALIP on its development. The bathymetric similarities of Rockall Plateau and Chukchi Borderland, as well as their tectonic similarities as rifted continental fragments bounded on one side by oceanic crust within a volcanic rifted margin, suggests that the relatively well-studied features of the Chukchi Borderland developed by extension in a similar fashion to the relatively well-studied features of the Rockall Plateau.

The bathymetric relief along the western edge of the Rockall Plateau is similar to that of the Northwind Ridge (Fig. 20). It drops about 2800m from the top of the plateau to the Atlantic floor and the Northwind Ridge rises almost 3000m from the floor of the Canada Basin. Both the Rockall Plateau and Northwind Ridge have an along strike spur-like extensions on the ocean-side edge which forms the boundary of a bathymetrically deeper region with pronounced relief. In the Rockall region this area is called the Endoras Bank and is situated between the high standing Rockall Plateau and the Charlie Gibbs Fracture Zone. The analogous area in the Amerasia Basin is located between the high standing Chukchi Plateau and the Nautilus Basin, which is bounded by the Northwind Spur. This region in the Rockall analogue has been determined from multiple seismic surveys to be highly extended continental material associated with a Cretaceous rift-stage triple junction, which was later affected by Tertiary volcanism (Hauser et al., 1995;
Fig. 20 Bathymetric Profiles of the Chukchi Borderland and Rockall Plateau. These profiles show the morphologic similarities across the high-standing rifted continental fragments of the Northwind Ridge to the Chukchi Plateau (A-A’), and from the Hatton Bank to the Rockall Bank (C-C’). The stepping down of rift structures from the Rockall Bank to the Charlie Gibbs Fracture Zone (D-D’) is very similar to the structures which continue off the Chukchi Plateau through the Northern Chukchi Borderland (B-B’). Rockall bathymetry is from the ETOPO1 database (see Section 2.1).
Bull and Masson, 1996). This may also be the case with the area north of the Chukchi Borderland.

There is an observable structural continuation of the Chukchi Borderland to the edge of the Nautilus Basin (Fig. 21). The northeastern end of the Chukchi Plateau continues northward as a thin promontory, or spur, bordering the Healy Seamount and called here the Healy Spur (Fig. 16). The multibeam swath that runs its length reveals that this is a single feature that is bathymetrically continuous to the Chukchi Plateau. The edge of the Healy Spur matches the edge of the Northwind Spur across the S-shaped basin which is the northernmost continuation of the Northwind Basin (striped area, Fig. 21). This suggests that they were separated by rifting along the same regional trend observed in the rest of the Chukchi Borderland. The Northwind Spur’s connection to the Northwind Ridge seems to indicate that the extensional structures from the interior of the Chukchi Borderland, continue northward for hundreds of kilometers from the high standing topography of the Plateau, below the sediments of the deeper basin. This coupled with the continental affinity of the basalt samples dredged from the Northwind Spur and along the edge of the Healy Spur (Andronikov et al., 2008; Mayer et al., 2008a; see Section 3.1.3), suggests that this region is also rifted continental material.
Fig. 21 Northward Continuation of the Northwind Basin. Interpretation of seismic profile (A-A’ top, HLY0503) shows the Central Chukchi Ridge to be a tilted horst block, and the Healy Seamount and Healy Spur appear to be a continuation of it. The edges of the Northwind and Healy Spurs match, also suggesting that they rifted from each other. Dredges from sites 7 and 6 (above, Mayer et al., 2008) contained basalt samples geochemically similar to continental flood basalts suggesting that this area is rifted continental material.
4.1.2 Northern Chukchi Borderland and Nautilus Basin

“Let’s go explore!” – Larry Mayer (personal communication, 2007)

The continuity of extended continental crust beyond the edge of the Plateau is also supported by the bathymetry and chirp data. During the summer of 2007, a joint University of New Hampshire/NOAA science cruise aboard the USCGC Healy mapped the 2500m isobaths around the Chukchi Borderland for the U.S. Extended Continental Shelf (ECS) claim for the United Nations Convention for Law of the Sea (UNCLOS). One of the considerations for a country’s ECS is to define their continental shelves to the “foot of the slope” which is loosely defined in UNCLOS Article 76 this way: "In the absence of evidence to the contrary, the foot of the continental slope shall be delineated as the point of maximum change in the gradient at its base” (UNCLOS 1982: 76(4)(b)). This is assumed to be the legal ocean/continent boundary.

Before the 2007 survey, the ocean/continent boundary was assumed to be at the foot of the high standing topography of the Chukchi Borderland. Bathymetric and chirp profiles north of the Chukchi Plateau revealed over 1000 m of relief across this region, with structures that continue from the top of the Chukchi Plateau for several hundred kilometers north and does not appear to be an “abyssal plain” as its name “The Mendeleev Abyssal Plain” implied (Fig. 22 (b and c)). The “foot of the slope” is far north of the Chukchi Plateau were a morphologic boundary can be recognized as a final step down to a flat lying abyssal plain where basin sediments onlap the structures (Fig. 22 (d)).

The set of isolated highs, on trend with the Northwind and Healy Spurs, suggests that the limit of continental crust here may be well north of the plateau itself. The area seems to
Fig. 22  Northern Continuation of the Chukchi Plateau. Oblique perspective view of the northern edge of Chukchi Borderland (a) shows the location of the conventionally assumed edge of Chukchi continental remnant (white line). Bathymetric profile along A-A’ (b) with red and blue boxes showing location of corresponding chirp profiles below and the almost 1000m of relief on trend with the spurs discussed in the text. Chirp profile (c) showing draped sediment package seen on Chukchi Plateau. Chirp profile (d) indicates final step down to the abyssal plain onlap of basin sediments. This suggests that the limit of continental crust here may be well north of the plateau edge itself (Mayer et al., 2008b).
be a geomorphologic extension of the Chukchi Borderland, similar to the thinned crustal region that represents the southern-most extension of the Rockall Plateau in the North Atlantic (see Fig. 21). Although not covered by multibeam to the same extent as the Healy Spur, there is a third promontory along the morphologic edge of the Nautilus Basin which looks to also be bathymetrically continuous to the Chukchi Plateau, and separated from the Healy Spur by another S-shaped rift basin (Healy Basin, see Fig. 2). This suggests that the entire region north of the Chukchi Plateau to the Nautilus Basin is a continuation of the continental crust that also underwent the extension which affected the Borderland.

If this area between the Chukchi Plateau and the Nautilus Basin is indeed rifted continental material, similar to what is found in the analogous region on the Rockall Plateau, it underwent more extension than the high standing parts of the Borderland given its water depth. Because it is a geomorphic continuation of the Chukchi Borderland and because it contains basalt with a continental affinity this region is called here the Northern Chukchi Borderland. This has implications for tectonic reconstructions and implies that a plate boundary does not exist on the northern edge of the Chukchi Plateau, as suggested by some tectonic models.

4.2 Northwind Ridge

At the resolution of the International Bathymetric Chart of the Arctic Ocean (IBCAO) the transition from the top of the Northwind Ridge, which averages around 1000 m water depth, to the Canada Basin floor at 3820 m is a steep drop off the Northwind Escarpment. Its trace is a relatively straight 16° (NNE) or so for almost 600 km. The steep slope and consistent strike indicate that this is one continuous feature, but raises questions about its formation as a normal fault block, a transform boundary, or a zone of compression.
The Phanerozoic stratigraphy of the Northwind Ridge was described from chips recovered from piston cores (Grantz et al., 1998). These sediments have been correlated to the Sverdrup Basin suggesting that the two features were contiguous before breakup. Northwest striking aeromagnetic anomalies (Taylor et al., 1981; Kovacs et al., 1985) that parallel a linear gravity low in the central Canada Basin have been interpreted to be indicators of an ancient spreading center (Laxon and McAdoo, 1994). This suggests that the Northwind Ridge rifted from a position along the Canadian margin and was moved to its current location by sea floor spreading in the Canada Basin. Reconstruction models have proposed that the Northwind Ridge was a transform boundary (Halgedahl and Jarrard, 1987), a collisional front (Grantz et al., 1998, 2009) or was created by normal faulting during rifting (i.e. Vogt et al., 1982; Lane, 1997). The geomorphology of the Northwind Ridge suggests the latter.

4.2.1 Northwind Escarpment

The scale and geometry of the eastern edge of the Northwind Ridge is similar to that of the Sierra Nevada in California, or the Wasatch Range of Utah (Machette et. al., 1992; Bruhn et al., 2005), or as discussed above, like the western edge of the Rockall Plateau. All of these examples are bounded by steep range front fault systems that are hundreds of kilometers long with over a thousand meters of relief. A range front does not rupture along a single long fault in one seismic event, but breaks along segments which eventually displace the entire range front (Burbank and Anderson, 2001). This segmentation also occurs in strike-slip boundaries but the geomorphologic responses are different along strike-slip faults than on boundaries created due to normal faulting. Features seen along strike-slip boundaries include restraining bends which cause thrusting or uplift, rotated folds, horsetail splays, and pull-apart basins formed at the releasing bend. These features are not observed along the Northwind Ridge.
The range-front fault system of the Northwind Ridge displays fault rupture geometries similar to those described along the Wasatch Range (Machette et. al., 1992; Bruhn et al., 2005) and because of the relatively slow erosion in the marine setting, these features can still be observed along the now inactive range front fault segments. Some segment boundaries are delineated by a series of en echelon steps in the range bounding faults (Fig. 23 (a)), bedrock spurs or salients against which the fault segment terminates, or the absence of rupture between two active range front segments (Fig. 23 (b)). Some faults are also intersected by cross faults at high angles to the range front, examples of which also appear along the Northwind Escarpment (Fig. 23 (c)).

Another geomorphologic response to normal faulting at the scale of the Northwind Ridge is the production of faceted spurs and “wineglass” valleys along the range front (Fig. 23 (c)). Facets represent spurs that have been abruptly truncated by the fault zone at the front of the range. Faceted spurs indicate the most recent uplift because the triangular-shaped regions between the canyons experienced little erosion since faulting began. Wineglass valleys result from rapid down-cutting of a streambed to form a slot canyon after rapid uplift along the front (Easterbrook, 1999). Both of these features can be observed along the central Northwind Escarpment in an area that seems to have been less affected by mass wasting relative to other segments of the Escarpment. The greatest relief between the basin floor and the top of Northwind Ridge is located near the center of any fault segment (Fig. 23 (d); Burbank and Anderson, 2001). Studies of displacement vs. distance along normal fault segments in central California (Dawers and Anders, 1995) and along the Wasatch front (Machette, et al., 1991, 1992) indicate that slip deficits occur near the ends of the fault segments, while the overall displacement along the segment is greatest near the center. This creates the bow shaped rupture traces and the dome shaped topography along the strike of individual fault segments.
Fig. 23  **Segmented Faults of the Northwind Escarpment.** These faults display the same fault rupture geometries as the Wasatch Range of Utah. Faults terminate at salients or in en echelon steps (a). There can be an absence of fault rupture between two segments (b). Faceted range front and “wineglass” valleys indicate normal faulting (c). Slip deficits occur near the end of fault segments with overall displacement greatest in the center as can be seen in this along strike profile below (d) where the highest relief is in the center of the fault segment (between red lines).
4.3 Boundaries of the Major Northwind Ridge Fault Block

The eastern boundary of the Northwind Ridge as illustrated in Fig. 2, is defined by the steep slopes of the main fault blocks evident in the HLY0503 seismic data (Fig. 6), then extrapolated along its length by utilizing bathymetry and chirp data. Steep slopes in this region experience landslides that move the sediment from the fault scarps into the adjacent lows, including the Canada Basin and the Northwind Basin. By mapping the arcuate landslide scarps and associated landslide features along the flanks of the Northwind Ridge, its boundaries were determined (See Plate 1).

4.3.1 Hanna Canyon

The southern end of the Northwind Escarpment makes a sharp turn to the west forming a perpendicular contact with the Alaska margin in an area called the Hanna Canyon (Fig. 24). Multibeam bathymetry has not been collected in the canyon itself, but there is a noteworthy geomorphologic change along the Northwind Ridge in this area. Along most of the slopes of the Northwind Escarpment, the slope gullies are linear elongate basins that are closely spaced (between 3 and 5 km apart). In the Hanna Canyon area a unique channel pattern has formed that is not typical along the Northwind Escarpment (Fig. 24). The channels here are dendritic and much more incised than in those observed elsewhere along the Northwind Escarpment. The development of dendritic channels is an index of the homogeneous nature of the eroding material, and is generally not structurally controlled (Easterbrook 1999). The tributary systems are determined by random headward erosion into rocks or sediments of uniform resistance. Because the slope measures an average 10 degrees which is typical for the Northwind Ridge, a variation in slope angle is not the reason for the channel morphology change, but the addition of unconsolidated sediments, either from mass wasting of the slopes above, input from the continental shelf, or even glacial debris may provide the homogenous material which has
Fig. 24  The Hanna Canyon Region. On the south end of the Northwind Escarpment is a down dropped fault block which has a unique dendritic channel pattern (left) compared to the elongate channels (right) seen along most of the Northwind Escarpment. The down dropped area (orange dashed line) has a sag depression at its center (white dashed line).
allowed the formation of dendritic channels at the southern end of the Northwind
Escarpmcnt. This whole corner section of the Northwind Ridge has been down dropped
in the Hanna Canyon region, creating a 700 km² plateau between the Escarpment and the
top of the Ridge (area outlined in orange, Figs. 24, 25). This plateau has a central
depression that measures 17 km x 11 km. A chirp profile across the depression shows
that it contains a series of slumps that have occurred periodically through time, and that
thick landslide deposits fill this sag. This landslide debris originated from out of the
plane of the profile, but the arcuate landslide scarps on the western edge of the sag
indicate a probable source. On the other side of the bathymetric high that forms the
western edge of the sag, several landslides delivered sediments into the Northwind Basin.
This indicates the location of the southwestern edge of the Northwind Ridge (See Plate
1).
**Fig. 25  Sag Depression on the Southern Northwind Ridge.** A multibeam swath (middle, A-A’) across the sag shows pockmarks (black arrows), and scarps from two slumped blocks (red and blue arrows). A chirp profile (bottom) across the same line shows two landslide deposits (1,2) within the sag that originated from out of plane along the western edge where landslide scarps (white arrows, top) are visible in the bathymetry data (also see Plate 1 for locations).
4.3.2 *Sags and Listric Slump Faulting*

The scarp of another sag depression is visible in the multibeam data and is discussed here because of its similarities to the Hanna Canyon sag, as well as to features seen in other areas around the Chukchi Borderland and Mendeleev Ridge (see Pockmark Section 2.2.3). The development of sags and related hanging-wall pockmarks have been described in the Gulf of Mexico (Abrams, 1996) and along the continental margin of West Africa (Pilcher and Argent, 2007). These features are the result of listric slump faulting in areas of over-steepened slopes. The faults sole downward into detachment zones and pockmarks developed along the hanging-wall (Fig. 9(c)). At the very top of the slope just north of the Hanna Canyon area is a scarp that at first glance appears to be the head of a large landslide that is wasting into the Northwind Basin. However, the scarp is not an indication of the western flank of the Northwind Ridge but is instead, a sag that is 20 km by 15 km across which is riddled with pockmarks (Fig. 26 (a)).

A chirp profile across the feature shows that the sediments next to the northern edge of the sag appear to have been compressionally deformed during the slumping event (red and blue layers Fig. 26 (c)). A thick unlayered sediment package, probably landslide material from out of plane, was deposited soon after or during the slump event (layer 1, Fig. 26 (b)). A second acoustically transparent layer created an erosional boundary after the deposition of layer 1, and probably represents a second landslide event (layer 2, Fig. 26 (b)). Finally a thin sediment drape was deposited along the entire profile, which indicated that it was not involved in the slump event, but was deposited afterward.
Fig. 26  Sag on the Central Northwind Ridge. Multibeam image draped on IBCAO base map of a sag on the central Northwind Ridge ((a), orange dotted outline) with pockmarks along its eastern side. A chirp profile across A-A’ (b) shows several tilted blocks between sharp scarps. Close ups of the chirp profiles shows that the tilted blocks within the sag experience some internal deformation (c) as they rotated against the fault plane and at least two landslide deposits (from out of plane) lie unconformably on the tilted blocks (1,2). An acoustic impedance contrast in the disturbed sediments may indicate the presence of shallow gas ((c) blue arrow). A close up opposite end of the sag (d) shows pockmark development on the headwall of the down-thrown block (red arrows).
This central region of the Northwind Ridge contains many examples of sag development between the major fault segments that form the flanks of the Northwind Ridge. The major faults can be recognized by the intense eastward directed mass wasting off the Escarpment as well as westward from the western edge of the Northwind Ridge, into the Northwind Basin (See Plate 1). The transition of the Northwind Ridge to the Northwind Basin is predicted in some reconstruction models to be a transform boundary in its early history, and a compressional boundary in the later stages of the development of the Chukchi Borderland (Grantz et al., 1998, 2009). Seismic data across the Northwind Ridge, however, shows that there is only evidence of extensional deformation across this interface.

4.4. Compression in the Borderland?

In one reconstruction model (Grantz et al., 1998) the Chukchi Borderland is made up of disparate continental fragments which were arranged in the early Cretaceous to their present geometries along a series of strike-slip faults located on the flanks of each fragment (Fig. 27(d)). This re-arrangement of continental fragments was driven by sea floor spreading in the Canada Basin along one spreading center, while another spreading center was initiated at some point on the western margin of the Borderland opening the “Proto-Amerasia Basin” (Fig. 27 (c)). During the Canada Basin spreading phase, the Northwind Escarpment was interpreted by Grantz et al. (1998) to be a dextral transform boundary as the Canada Basin opened orthogonal to it. If the Chukchi Borderland developed in this manner, it must have experienced substantial compressional and translational deformation while being located between two spreading centers during this complicated assembly.
Fig. 27  Reconstruction Model from Grantz et al. (1998). Modern configuration (a) showing Charlie Fault along northern edge of the Borderland along with several spreading centers and compression along the Northwind Ridge (b) Paleocene emplacement of Alpha/Mendelev Ridge on cold crust of the “Proto Amerasia Basin” (c) Assemblage of Chukchi Borderland fragments with transform fault along the Northwind Ridge and spreading centers on either side of the Borderland. (d) Disparate pieces of Chukchi Borderland along the Canadian Margin.
In the Grantz et al. model, extension of the Chukchi Borderland is interpreted to have occurred *after* the formation of the Canada Basin, during the early Tertiary. A 1000 km long arcuate strike-slip fault, named the Charlie Fault (Fig 27 (b), Grantz et al., 1998, 2009) that is located along the northern edge of the Chukchi Plateau, accommodated a clockwise rotation of the Chukchi Borderland along this sinistral transform causing a collision with the oceanic crust of the Canada Basin. The authors of this model go on to speculate that Tertiary extension in the Borderland was “isolated” and may have been driven by the opening of the Eurasia Basin. The Charlie Transform Fault accommodated this extension along the Borderland’s northern edge.

The bathymetry and chirp data do not support the existence of the Charlie Fault given the continuation of bathymetric structures north of the Chukchi Plateau (Section 4.1.2). The Grantz et al. (1998) interpretation also requires substantial convergence along the Northwind Ridge and only localized extension within the Amerasia Basin to justify the model (Fig. 27 (a)). Geomorphologic observations of the bathymetry data in conjunction with interpretation of publicly available multi-channel seismic profiles collected aboard the USCGC Polar Star (Grantz et al., 2004) and aboard the USCGC Healy (HLY0503, Hopper, et al., 2006; see Fig. 2 for seismic line locations) can help investigate the existence of a compressional boundary along the Northwind Ridge, as well as the other plate boundaries within the Borderland suggested by this model.

### 4.4.1 Seismic Evidence for Extension

Line 88-10 from the 1988 Polar Star cruise (Grantz et al., 2004, see Fig. 2 for locations) is the only seismic line from either the 1988, 1992 or 1993 Polar Star cruises that has been published to date (Grantz et al., 1998). The profile was collected in an area of the south-central Northwind Escarpment.
The interpreted profile (Fig. 28) shows the Northwind Escarpment devoid of sediment cover, and small thrust faults dipping toward the Northwind Ridge which displace what are interpreted to be Cretaceous sediments, leaving what is described as the Tertiary sediments undisturbed. These faults are distributed over an area approximately 10 km from the Northwind Escarpment range front into the Canada Basin. The model describes the Chukchi Borderland as “continental fragments isolated by extended continental crust beneath the Northwind Basin” and suggests that the Northwind Ridge actually rotated 4° counterclockwise during its separation from the Canadian Margin and then clockwise during the late stage extension/compression event (Fig. 27).

My reinterpretation of the same profile (Fig. 29) shows as a series of normal fault blocks that extend the length of the profile beneath the overlying Canada Basin sediments. Thrust faults are not obvious and no clear evidence is visible that basin sediments have been altered by compression. Line 88-10 crossed over a listric slump that can be seen in the bathymetry data, and on the seismic profile, as a sharp scarp below which listric faulted sediments are distorted against the slump scarp (Fig. 29). This scarp does not appear in the Grantz et al. (1998) interpretation (Fig. 28).

The seismic lines collected from the USCGC Healy (HLY0503, Hopper, et al., 2005), viewed together across the entire Chukchi Borderland, reveal only extensional normal faulting and possible localized transtension in the over 2200 km of data collected across the Chukchi Borderland and Mendeleev Ridge (Fig. 6; Arrigoni et al., 2007). There is no evidence of thrust faulting on the scale that would be expected in an area uplifted during a collision with the Canada Basin. Although the quality of the image of line 11 from the HLY0503 survey is poor due to difficult ice conditions, it appears to image rotated and
Fig. 28 Grantz et al. (1998) Interpretation of Polar Star Line 88-10. The interrupted profile shows the Northwind Escarpment devoid of the sediment cover seen in the uninterrupted line, and in the multibeam data (Fig. 29). The small offset thrust faults interpreted basinward of the Escarpment are required for the late stage transform-extension-compression event that is predicted in their reconstruction model (see Fig. 26). It is difficult to understand, however, how the amount of compression predicted by the model would result in such small offsets and be confined to the basin.
Fig. 29 Interpretation of Polar Star Line 88-10. Inset map shows location of line 88-10. Normal faulting and shallow listric fault development produced slumps (inset) and sag seen in multibeam data (Fig. 25)
normally faulted blocks which correspond to a visibly faulted segment along the Northwind Ridge observed in the multibeam data (Fig. 30).

In the same seismic lines from HLY0503, the normal fault blocks appear to be composed of layers which were tilted during normal faulting, with some evidence of thickening of syn-rift layers toward the faults in the hanging wall. This is also inconsistent with the very complicated Northwind compressional reconstruction model outlined in the Grantz et al. (1998) model above (See Fig. 27). According to their model the Borderland was assembled from discrete pieces of continental fragments while undergoing compression along the Northwind Ridge due to its location between multiple spreading centers. It was then deformed by subsequent late stage extension accompanied by compression on one side due to convergence with oceanic crust from the Canada Basin.

If this model is correct more internal deformation would be expected. The folding and thrusting predicted by this model are not observed either in the bathymetry or the available seismic data. The transition from the Canada Basin, across the Northwind Ridge to the Northwind Basin, appears to be extensional along its entire length.
Fig. 30 Interpreted Seismic Profiles Across the Borderland. The profile (bottom, see Fig. 6 lines 11-16) showing extensional faulting across the entire Chukchi Borderland. Multibeam image (left) of faulted segment along Northwind Escarpment and the steep slopes of the Central Chukchi Basin (below).
4.5 Northwind Basin

The Northwind Basin is a wide rectilinear rift basin which formed between the Northwind Ridge and the Chukchi Plateau. Within it are many parallel to sub-parallel ridges rising several hundred meters from the basin floor. The Healy seismic data (Hopper, et al., 2006) indicate that normal fault blocks create the topography across the entire Chukchi Borderland (Fig. 30). Therefore, sub-parallel ridges in the Northwind Basin were probably also created by normally faulting. The Basin is broader to the south and deepens to the north with less topographical relief in the southern half probably due to sediment from the 100 km wide slope that marks its southern boundary with the continental shelf.

Massive and extensive scarps, slumps and landslides line the flanks of the Northwind Basin (Plate 1). In some places, the entire sediment cover from Northwind Ridge has fallen into the basin, or has been scoured off, leaving only a very thin veneer of pelagic drape covering the structures on the top of the Ridge. Visible in the multibeam data are scarps both primary and secondary, transverse cracks, talus creep, hummocks, and lobate toes in the zones of accumulation, all indicative of mass wasting (see Plate I for locations).

Several isolated ridges dot the floor of the basin in the southern half and rise to water depths between 900 and 1500 m, compared to the shallower ridges in the north basin which are between 500 and 900 m water depths. The three most southerly ridges have sinuous low relief structures that trend between 350 and 10 degrees and are 12-19 km long and less than 0.3 km wide (Fig. 14). They may be the buried continuation of the fault blocks, or perhaps structurally controlled dykes. These features are too small for the resolution of the aeromagnetic map to define a magnetic signature. Without further
bathymetric data it is impossible to say if these features are unique to this particular location, or are something common in the region.

The northern half of the Northwind Basin is characterized by much more bathymetric relief than in the southern basin, but has still been affected by mass wasting from the Northwind Ridge. There is also evidence of slumps and slides between the subsidiary ridges. These ridges are sub-parallel to a prominent central ridge (here called the Central Chukchi Ridge, Fig. 30) which is about 30 km wide at its southern end and narrows to only 9 km at its northern tip. The Central Chukchi Ridge varies between about 600-1000 m water depth along its length. The HLY0503 seismic profile (Fig. 21) reveals that this ridge is a horst block which is tilted to the east. The sediment cover has undulating surface disruptions and is thinner than is observed on the Chukchi Plateau. Landslide scarps seen in the bathymetry data along its length indicate that the Central Chukchi Ridge has also experienced a good deal of mass wasting both into the Northwind Basin on its eastern edge as well as into the Central Chukchi Basin which separates it from the Chukchi Plateau on its eastern boundary.

Prior to collection of either multibeam or seismic data it was thought that there was no connection of the Northwind Basin into the Canada Basin from its northern end (Hall, 1990). With the advent of 3D visualization it is possible to look for a bathymetric connection between the Northwind Basin and the Canada Basin. Bathymetrically, at least, there does seem to be a continuation of the northern Northwind Basin, between the Northwind and Healy spurs (see Fig. 21). Therefore it is likely that the Northwind Spur and the Healy Sea Mount are related, were separated by rifting, and together represent the most northerly boundary of the Northwind Basin.
4.6 The Chukchi Plateau

The Chukchi Plateau is the westernmost boundary of the Chukchi Borderland. It is approximately 140 km wide east to west and 400 km long south to north. It has been traditionally separated into two regions called the Chukchi Rise (the southern high) which has a water depth of 180 m at its highest point, and the Chukchi Cap (the northern high) which rises to 282 m water depth at its highest point. The HLY0503 multi-channel seismic profiles (Fig. 30) that cross the Chukchi Plateau show that it is formed by a series of normal fault blocks with a central horst forming the highest point. The western edge is a series of half grabens, tilted to the east, which cause the relief between the Chukchi Plateau and the Mendeleev Ridge. Extensional structures continue from the western edge of the Chukchi Plateau across the Mendeleev Ridge (Dove, 2007). Given its depth, the Chukchi Plateau has undergone less extension than in the Northwind Basin, but it still has well preserved rift valleys at its center.
5. **Plate Boundary Scale Rifting in the Chukchi Borderland**

As discussed above, the entire Chukchi Borderland was deformed by extensional normal faulting, westward from the Northwind Ridge to the Mendeleev Ridge and northward from the Chukchi Sea to the Nautilus Basin. Normal faults form in settings where the maximum compressive stress ($\sigma_1$) is vertical and there is deviatoric minimum stress ($\sigma_3$) in a horizontal orientation (Burbank and Anderson, 2001). Assuming a predominantly dip-slip motion along the major normal faults mapped here, the average stretching direction can be estimated from the strike directions of each inferred fault surface. The trace of each normal fault was plotted on frequency-azimuth rose diagrams. These show the dominant trends of the structural elements and the perpendicular direction of spreading (Plate 1).

The geometries of the various rift structures observed both bathymetrically and in the subsurface also indicate that although there are expected local variations in strike and amount of offset, the fault patterns seem to be composed of three fault systems (Fig. 31). The major boundary faults on the Chukchi Plateau and Northwind Ridge strike between about 0° and 20°. Within the Northwind Basin and in areas between major faults, visible fault traces trend between about 38° and 45° with an apparent conjugate of around 345°. Strike-slip faults which appear at high angles to the major faults strike between about 90° and 100°. Because of the consistency of these trends throughout the Chukchi Borderland it appears that there were different events which produced the major rift directions, or that the region was subject to a single episode of plate boundary scale rifting that affected the entire central Amerasia Basin. The geomorphology of the Chukchi Borderland suggests the latter.
Fig. 31 Fault Trace Trends from the Chukchi Borderland. Interpreted as major normal faults, orthogonal transfer faults, and conjugate accommodation faults, these fault traces show a remarkable consistency throughout the region. Map shows only some examples of fault traces of accommodation faults that were measured. Major normal faults and transfer faults are not shown. See Plate 1 for complete data set.
5.1 Transfer Zones

The whole of the Chukchi Borderland displays geomorphic examples of the various tectonic structures that form a continental scale rift system at different stages of evolution: from discrete rift segments to a fully developed range front fault like the Northwind Escarpment. In continental rift systems, the border faults or fault systems are traceable tens to hundreds of kilometers laterally before dying out, at which point the strain may be transferred to a new fault or fault system that is offset from the original and may have the same or different direction of dip (van der Pluijm and Marshak, 2004). The transitional regions between major border faults are referred to as transfer or accommodation zones (Bosworth, 1985; Mack and Seager, 1995). Transfer zones are defined here as through-going faults or fault systems (90-100°) with a significant strike-slip component that form perpendicular to the major normal faults (striking 0-20°) in order to accommodate differences in structure across them. Accommodation zones refer to places where there is distributed deformation between major normal faults with the creation of normal and/or strike-slip faults that form apparent conjugates striking about 45° and 345°.

One of these accommodation zones can be observed between the southern and northern fault segments which create the eastern edge of the Chukchi Plateau (Fig. 32). This area is riddled with pockmarks that form linear groupings which trend between about 38 and 45 degrees and run parallel to visible fault scarps that have formed on either side of the pockmarked area (Fig. 32(a)). This seems to indicate that fluids utilize faults as pathways to the surface, an observation which provides information about the underlying geology here. The trend of the pockmarks, scarps, and small rift basins that developed in this area create a geometry indicative of an accommodation zone between two large normal fault segments. The accommodation faults appear to have developed as conjugates that strike about 45° and 345°, or about 30° from the strike of the major normal faults (Fig. 32(b)).
Fig. 32 An Apparent Accommodation Zone. Along the eastern flank of the Chukchi Plateau (b, left) where the amalgamation of the major border faults (black lines) extension is being accommodated by normal faults striking ≈45° (orange lines ≈30° from the strike of the major faults). The blue rectangle (b) outlines the location of the multibeam image above (a) which shows linear pockmark groups that run parallel/sub-parallel to scarps and changes in slope suggesting fault control on the pockmark groupings. In the East African Rift, accommodation zones (c) facilitate displacement between major faults which are characterized by series of alternating half grabens.
The sense of slip along the faults within the accommodation zones and along transfer faults is dependent on the polarity of the major normal faults. Although the slip directions are difficult to resolve on the scale of the available data, the scarps created by these faults are visible on both the multibeam and IBCAO data, creating a fabric consistent with accommodation faulting and transfer zone development. This type of morphology has been observed in the East African Rift system (Moores and Twiss, 1995 and citations therein) and in the Rio Grande Rift (Mack and Seager, 1995) where the major segments were found to be a series of alternating and partly overlapping half grabens, with normal and strike slip faults accommodating their amalgamation (Fig. 32 (c)). This is very similar to the rift geometry on the Chukchi Borderland.

5.1.1 Central Chukchi Rift

In the Central Chukchi Rift, transfer faults that accommodate the interaction between rift segments developed orthogonal to the rift segments (90 to 100°) and at oblique angles (≈345°) (Fig. 33). In accommodation zones where fault segments connect, it is common to observe transfer faults, step-over faults, shutter ridges and relay ramps. In this particular area, the accommodation zone is relatively simple because stretching is probably perpendicular to the trace of the faults and the offset is predominantly dip-slip. The conjugate faults predicted by the regional strain ellipse can be observed in the bathymetry data as steep-sided scarps which trend between 38° and 45° (Fig. 33).
Fig. 33 Accommodation Zones in the Central Chukchi Rift. Accommodation faults (≈45° and 345° orange and white lines) and orthogonal transfer faults or transfer zones (90-100°) accommodate rifting perpendicular to major normal faults (0-20°, black lines). Major normal faults with opposite polarities die out in accommodation zones, or strain is transferred across them utilizing orthogonal transfer faults. Within the accommodation zone (red circle), pockmark chains trend parallel to scarps visible in the bathymetry data.
5.1.3 Remnant Accommodation Zones

Both the Chukchi Plateau and Northwind Ridge have developed range front boundary fault systems from the successful amalgamation of major fault segments utilizing accommodation faults in transfer zones. The boundary faults give rise to major fault escarpments like the Northwind Escarpment and the western escarpment of the Chukchi Plateau which are separated by rift depressions, namely the Northwind Basin and Central Chukchi Basin.

A complex polygonization of the crust can occur in accommodation zones between major fault segments (Burbank and Anderson, 2001; van der Pluijm and Marshak, 2004) which cause areas of local compression, and the development of smaller step-over or synthetic faults, relay ramps and shutter ridges, all of which are impossible to observe at the resolution of the data in this area. Although the bathymetry data cannot resolve this amount of detail, what can be observed is that given its depth, the Northwind Basin has undergone more extension than the high standing Northwind Ridge or Chukchi Plateau and the amalgamation of the major border faults along its flanks has been complete. This has left possible remnants of the transfer faults that accommodated the connection of the border faults in the form of fault-bounded bathymetric highs (Fig. 34).

The strike of the faults that bound the subsidiary ridges in the Northwind Basin is the same, approximately 45° and 345°, observed in the inferred accommodation zones on the Chukchi Plateau (Fig. 31). This suggests that the features are structural remnants of the polygonized crust found in accommodation zones which helped accommodate the extension between the major faults of the Northwind Ridge and Chukchi Plateau. The faults have been mapped in orange and purple on Plate 1.
Fig. 34  Possible Remnant Accommodation Zones. Within the Northwind Basin (a) where the amalgamation of boundary faults has been complete, bathymetric features have formed along the same strike as accommodation faults. Yellow boxes on map (a) show locations of accommodation zones discussed in the text where faults striking about 45° and 345° form as major normal faults continue to rupture (b). After the major fault segments join, small high standing fault blocks are left as remnants in the basin, and scarps striking at a high angle line edges of the basin (a, black lines) striking parallel to 90° transfer faults.
Along the Northwind Ridge these remnant accommodation zones, which strike the same as the other accommodation faults in the region, seem to be the locations that display the most intense mass wasting and the large circular sags discussed in Section 4.3.2. Also in these areas, narrow valleys have developed that bisect the narrowest parts of the Northwind Ridge, creating gaps at high angles through the Northwind escarpment (Fig. 34) that may be the locations of east-west strike-slip transfer faults which defined the boundaries of the transfer zones.

The Chukchi Borderland, including the provinces introduced here (Fig. 2), is about the same size as the Basin and Range Province of the western U.S. Therefore, only a very broad definition of the regional tectonic pattern is attempted here. However, the rift history of the Chukchi Borderland seems to be consistent with an extensional tectonic setting with little variation in rift direction. If an average dip-slip motion is assumed on the normal faults across the region, then spreading directions were perpendicular to the trace of those faults, which in this case is between 95° and 100°. The consistency of the deformation due to normal faulting observed in the Chukchi Borderland seems to indicate that it has not undergone an extremely complicated rift history that is suggested in some models (e.g., Grantz et al., 1998, 2009). The scale of the Northwind Escarpment which forms its eastern boundary as well as the extent of the normal faulting almost parallel to the escarpment is comparable to other continental scale extensional settings like the Basin and Range Province of Nevada and the East African Rift. The available data show that tilted fault blocks define the bathymetry on the Chukchi Borderland and that they are deformed only in ways consistent with normal faulting and do not suggest compression of any kind (Arrigoni et al., 2007). The consistent rift direction of the Chukchi Borderland does not seem to be confined only to the regions of high standing topography, but extends to the entire central Amerasia Basin.
6. Summary and Conclusions

To date, geologic and geophysical data in the Amerasia Basin remain inconclusive as to the nature of the intra-basinal ridges and the roles they played in the tectonic development of the Arctic Ocean (Lawver and Scotese, 1990). The enigmatic nature of the Alpha and Mendeleev Ridges has allowed for their designation as every type of tectonic boundary or volcanic edifice, and has therefore offered little constraint for tectonic reconstructions (Hall, 1970; Vogt and Ostenso, 1970; Herron et al., 1974).

Consensus as to the continental nature of the Chukchi Borderland is well established, and its central location within the Amerasia Basin makes it impossible to be ignored in any reconstruction model. Determining the direction of rifting and the crustal boundaries of this continental fragment provides information about the kinematic history of the Chukchi Borderland and offers constraints on the tectonic processes that formed the Amerasia Basin.

The bathymetric and subsurface data collected on the Chukchi Borderland indicate that the region has undergone deformation by normal faulting due to significant regional extension. The entire Chukchi Borderland, as described here, encompasses an area of over 360,000 km² that has rifted in generally the same direction. This plate boundary scale of extension requires the development of accommodation or transfer zones that facilitate the amalgamation of long fault segments like the Northwind Escarpment. These transfer zones can eventually become transform faults between rift segments, or produce complicated polygonization of the crust within these zones which accommodated the transfer of strain between the major normal fault segments. This suggests that the multiple fault directions observed within the Borderland are caused by a single tectonic event, and not from several overprinted spreading directions.
The bathymetric features associated with mass wasting and sag slumping are also consistent with a normal fault controlled province. The tilted sides of the major fault blocks, namely the Northwind Ridge, the Central Chukchi Ridge, and the Chukchi Plateau, have continued to shed overlying sediments into the basins off the steep sided flanks that define their boundaries. The development of shallow listric slump faults is common in marine settings with over-steepened slopes (Pilcher and Argent, 2007), and appear to underlie large sag depressions and gravity slides observed throughout the Chukchi Borderland and southern Mendeleev Ridge. Linear pockmark chains also provide evidence for the direction of fault strike in transfer zones, and about the location of back tilted blocks on sags and slumps. All of these features follow regional fault trends and help to define major border faults of the extensional province in the central Amerasia Basin.

A geomorphic and bathymetric connection seems to indicate that the Northern Chukchi Borderland is a continuation of the high standing provinces of the Chukchi Borderland similar to the analogous southern region of the Rockall Plateau. A clear geomorphic boundary exists between the Northern Chukchi Borderland and the Nautilus Basin, although it is unclear whether or not the Nautilus Basin is underlain with the same oceanic crust as the Canada Basin.

Parallel ridges and valleys on the south-central Alpha Ridge trend in the same direction as those observed in the Chukchi Borderland and suggest a shared rift history between the two provinces. The existence of possible volcanic landforms observed on Alpha Ridge observed in the multibeam data likely signifies the influence of the High Arctic Large Igneous Province which probably accompanied the onset of rifting within the Amerasia Basin and possibly during the syn-rift phase as well.
The tectonic setting geomorphology of the Alpha and Mendeleev Ridges is very similar to other ridge systems along the margins of back arc basins suggesting that they may have formed similarly as extended continental crust. The continuation of rift structures across the entire Chukchi Plateau to the large graben and half graben structures which control the bathymetry of the Mendeleev Ridge (Dove, 2007), as well as the existence of shallow water volcaniclastic sedimentary rocks dredged in two locations on Alpha Ridge at a current water depth of over 3600 m (Van Wagoner et al., 1986; Brumley et al., 2008), suggests that the Alpha and Mendeleev Ridges underwent a significant amount of extension. The rift structures mapped on the Mendeleev Ridge (Dove, 2007) and along the south central Alpha Ridge (Mayer and Armstrong, 2008) are along the same strike as faults within the Chukchi Borderland, suggesting that they were all rifted during the same extensional event. Although the nature of the crust beneath the Alpha and Mendeleev Ridges is not constrained, the amount of extension is not consistent with their development as an oceanic plateau on over-thickened, cold oceanic crust. Rifting prefers continental crust (Vink et al., 1984) and if the Alpha and Mendeleev Ridges are a product of continental rifting, the lithosphere would be weak and extending the Alpha and Mendeleev Ridges to their present state would not be difficult (Dove, 2007).

The Chukchi Borderland, which encompasses the Northwind Ridge, Chukchi Plateau, Northern Chukchi Borderland, and Chukchi Basin, rifted in a generally east-west direction (90-100°) and the parts of the Alpha and Mendeleev Ridges which border this region experienced extension in this direction as well. This spreading direction is consistent with returning the Northwind Ridge to a position along the Canadian margin. This regional rift direction within the Amerasia Basin is inconsistent, however, with a very complex plate geometry that requires multiple rift directions coupled with compression, rotation and translation (Grantz et al., 1998), and the popular rotational model (Carey, 1958) does not return the Chukchi Borderland to the Canadian margin utilizing the rift directions apparent in the bathymetry.
Most versions of the rotational model, as well as other models, assume oceanic crust forms all of the features within the basin except for the Chukchi Borderland. If the Amerasia Basin developed due to a combination of back-arc spreading and continental breakup accompanied by a large igneous province, then the intra-basinal ridges could be rifted continental material similar to those found in other back arc basins like the South China Sea and the amount of new oceanic crust produced in the basin could then be much smaller than the rotational model implies. Although the mafic characteristics, velocity structure, crustal thickness and magnetic signature have generally been used to suggest an “oceanic” origin for the Alpha/Mendeleev Ridges, the possibility that they are formed of rifted continental material on a volcanic rifted margin is also consistent with the geophysical evidence. This, coupled with the geomorphic similarities of the Amerasia Basin’s intra-basinal ridges to the attenuated continental crust that defines the margins of back-arc basins and the regions surrounding the Rockall Plateau, also suggests that the entire basin is not underlain with oceanic crust but that the bathymetric structures within the basin are rifted remnants of an area torn apart by back-arc extension accompanied by a large igneous province.

Consensus about the formation of the Amerasia Basin is still in the future, but what has been presented here are constraints on the apparent motion within the Basin and the areas surrounding the Chukchi Borderland. The tectonic geomorphology of the central Amerasia Basin gives clues to the kinematic history of the Arctic Ocean and should be used in conjunction with geologic information about the Arctic margins. Only through an understanding of the bathymetric features within the Amerasia Basin will its tectonic reconstruction be possible.
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