Morphology and structure of the Lomonosov Ridge, Arctic Ocean

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[1] The Lomonosov Ridge is a band of continental crust that stretches across the Arctic Ocean and separates the Mesozoic Amerasian Basin from the Cenozoic Eurasian Basin. From about 87°N north of Greenland across the Pole to about 86°N, the Lomonosov Ridge is a single highstanding blocky ridge with minimum depths of ~950–1400 m. South of 86°N on the Siberian side, the ridge breaks up into a series of ridges spread over a width of about 200 km. In this region a highstanding blocky ridge with minimum depths of ~650–1400 m bounds the Eurasian Basin and continues to the Siberian continental margin. This ridge is continuous with the single ridge making up the Lomonosov Ridge toward North America and is the former outermost continental shelf of Eurasia bounding the Amerasian Basin. The Eurasian Basin margin of the Lomonosov Ridge consists of a series of rotated fault blocks stepping down to the basin that result from nearly orthogonal rifting to form the Eurasian Basin. No rotated fault blocks are observed on the Amerasian Basin margin of the Lomonosov Ridge. On the Amerasian Basin side, Marvin Spur, a linear ridge separated from Lomonosov Ridge by a deep basin, parallels Lomonosov Ridge on the North American side of the pole. At the bend in the Lomonosov Ridge near the North Pole, Marvin Spur continues along strike across the Makarov Basin. South of 86°N toward Siberia, a continuous outer ridge makes up the Amerasian Basin edge of the Lomonosov complex with a series of basins and ridges between it and the former Eurasian shelf. The outer ridge marks an abrupt boundary between the Lomonosov Ridge complex and the apparently oceanic crust of the Makarov Basin. The outer ridge and Marvin Spur very closely follow small circles about a pole located on the Mackenzie delta. The observed structure on the Amerasian Basin side of the Lomonosov Ridge is analogous to that observed at well-studied shear margins and supports rotational models for the development of the Amerasian Basin.

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1. Introduction

[2] The Arctic Ocean contains two distinct oceanic basins (Figure 1) of differing age. The younger Eurasian Basin formed during the Cenozoic by seafloor spreading at the active Gakkel Ridge [e.g., Karasik, 1968; Vogt *et al.*, 1979; Cochran *et al.*, 2003], while the Amerasian Basin is of late Mesozoic age [e.g., Sweeney, 1985; Sweeney *et al.*, 1990; Grantz *et al.*, 1990a, 1990b] and controversial origin [Lane, 1997; Embry, 1990, 1998; Lawver and Scotese, 1990]. The two basins are separated by the Lomonosov Ridge, a high-standing band of continental crust that extends across the Arctic Ocean (Figures 1–3) and forms a continental margin to both basins [e.g., Sweeney *et al.*, 1982; Forsyth and Mair, 1984; Jokat *et al.*, 1992].

[3] Detailed aeromagnetic surveys of the Eurasian Basin show a symmetric set of well-developed magnetic anomalies centered on the Gakkel Ridge [Karasik, 1968; Vogt *et al.*, 1979; Verhoef *et al.*, 1996; Brozena *et al.*, 2003]. The magnetic anomalies imply that the Eurasian Basin developed by nearly orthogonal rifting of the Lomonosov Ridge off of the northern margin of Eurasia with seafloor spreading beginning at paleomagnetic Chron 24 (~53 Ma) or perhaps Chron 25 (~56 Ma).

[4] The origin and tectonic development of the Amerasian Basin is unclear. Tessensohn and Roland [2000] describe the Amerasian Basin as “a rather enigmatic rounded deep hole surrounded by continents without a clearly detectable mid-ocean ridge and without clear connection to any other major spreading system.” Published data from the basin are inconclusive and can be used to support radically different models. In particular, the absence of a clear pattern of seafloor spreading anomalies [Kovacs *et al.*, 1985; Coles and Taylor, 1990] or a morphologically distinct mid-ocean ridge and fracture zone system [Perry and Fleming, 1986; Grantz *et al.*, 1990a] has hampered understanding of the development of the Amerasian Basin and allowed the development of numerous competing models emphasizing different observations (see Lawver and Scotese [1990] for a comprehensive review of the different classes of models). The different classes of models each predict a very different evolutionary history and structure for the Amerasian flank of the Lomonosov Ridge.

[5] Published studies of morphology and structure of the Lomonosov Ridge are based almost entirely on data collected from ice islands, notably the ARLIS II ice island that crossed the Lomonosov Ridge in 1963–1964 and the 1979 LOREX expedition, and from isolated icebreaker lines [Jokat *et al.*, 1992, 1995; Kristoffersen *et al.*, 2004; Jokat, 2005]. Bathymetric mapping from the ice islands was limited to a few portions of the ridge near the North Pole and on the North American side, totaling less than about 400 km of its length.

[6] Data obtained on U.S. Navy submarines during the SCICEX (SCience ICe EXercises) program [e.g., Edwards and Coakley, 2003] greatly expands the geophysical database available for the Lomonosov Ridge, both in the number of crossings of the ridge and in the geographic distribution of the data, which now extends from near the Siberian margin to near the North American margin (Figure 2). In addition, there have recently been international efforts to secure the release of previously classified bathymetry and gravity data in the Arctic Ocean and to reconcile and consolidate this data with public domain data to produce the best possible bathymetry and gravity grids of the entire Arctic Ocean. These efforts include, in particular, the “International Bathymetric Chart of the Arctic” (IBCAO) [e.g., Jakobsson *et al.*, 2000b] (<http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/arctic.html>) and the “Arctic Gravity Project” (ArcGP) (<http://earth-info.nga.mil/GandG/wgs84/agp/>).

[7] The recently available data show that published descriptions of the Lomonosov ridge, based on studies of limited portions of the ridge, primarily near the pole and toward the North American margin, do not adequately describe the variation of morphology and structure along the length of the Lomonosov Ridge. The purpose of this paper is to utilize this increased database to determine the structure of the Lomonosov Ridge, how the structure varies along the ridge, and in particular to investigate the unknown relationship of the Lomonosov Ridge to the Amerasian Basin.

2. New Bathymetry and Gravity Data From the Lomonosov Ridge

2.1. SCICEX

[8] Between 1993 and 1999, the U.S. Navy made six nuclear submarine cruises to the Arctic for

Figure 1. International Bathymetric Chart of the Arctic Ocean (IBCAO) [Jakobsson *et al.*, 2000b] map of the Arctic showing the relationship of the Lomonosov Ridge to the Mesozoic Amerasian Basin and the Cenozoic Eurasian Basin. Other geographic features identified are the Canada Basin (CB), Chukchi Borderlands (ChB), Mendeleev Ridge (MR), Alpha Ridge (AR), and Gakkel Ridge (GR). Red box shows the area of the maps in Figures 2 and 3.

unclassified scientific research through the SCICEX program. Crossings of the Lomonosov Ridge were obtained on all of these cruises (Figure 2). The SCICEX program greatly increased the amount and areal coverage of geophysical data over the Lomonosov Ridge. In particular, the ability of the submarine to move freely under the ice resulted in long straight traverses across the Lomonosov Ridge and systematic detailed surveys of selected portions of the ridge (Figures 2 and 4).

[9] All of the submarine cruises collected bathymetry and gravity data. The 1998 and 1999 cruises on USS *Hawkbill* (shown in red in Figure 2) utilized the SCAMP (Seafloor Characterization And Mapping Pods) geophysical system. SCAMP consists of two sonar systems, a

BGM-3 marine gravity meter [Bell and Watts, 1986] (also used on the pre-SCAMP cruises) and a data acquisition system that logs the data and provides onboard quality control [Chayes *et al.*, 1996, 1999]. One of the sonar systems is a bilateral interferometric swath mapper that provides coregistered bathymetry and side scan data. The second sonar is a “chirp” (swept frequency) subbottom profiler. The transducers were installed in a pod mounted along the keel of the submarine. Edwards and Coakley [2003] discuss the instrumentation and data processing in detail.

[10] Under-ice navigation was accomplished using the Navy’s “Submarine Internal Navigation System” (SINS) supplemented with occasional GPS fixes when the submarines surfaced. The navigation was adjusted on a line-by-line basis

Figure 2. Bathymetric map of the Lomonosov Ridge contoured at 250 m intervals. Black lines show ship tracks for SCICEX submarine cruises from 1993–1997 from which bathymetry and gravity data are available. Red lines are ship tracks for the 1998 and 1999 cruises on USS *Hawkbill* for which swath bathymetry and gravity data are available.

through comparison of crossing lines and adjacent tracks to produce an internally consistent data set. Comparison by *Kurras et al.* [2001] of SCICEX bathymetry with GPS-navigated swath bathymetry acquired in 2001 by USCGC Healy shows absolute positional accuracy of 3 km, with relative positioning estimated at better than 500 m.

2.2. Bathymetry and Gravity Compilations

[11] The International Bathymetric Chart of the Arctic (IBCAO) is an international project begun in 1997 under the auspices of the International Hydrographic Office to compile a bathymetric database of the region north of 64°N. The IBCAO project compiled and reconciled all available

bathymetric data from the Arctic, including data from SCICEX, to produce a 2.5 km × 2.5 km bathymetric grid. Techniques, data sources and the data distribution at that time are discussed by *Jakobsson et al.* [2000a, 2000b]. Since the IBCAO grid incorporates SCICEX bathymetry data and has significantly greater spatial coverage (Figures 3 and 4), bathymetry maps in this study are constructed using the most recent version of the IBCAO grid. Bathymetric profiles show the original digital data from the SCICEX submarine cruises.

[12] The Arctic Gravity Project (ArcGP) was a project under the auspices of the International Association of Geodesy to compile public domain 5' × 5' free-air and Bouguer gravity databases for

Figure 3. Bathymetric map of the Lomonosov Ridge contoured at 250 m intervals. Areas outlined in black show the locations of maps in Figures 5, 9, 10, 12, 13, and 15. The locations of the Makarov Basin, Marvin Spur, and Alpha Ridge relative to Lomonosov Ridge are also noted.

Figure 4. Shaded relief bathymetry map of the Lomonosov Ridge based on SCICEX swath bathymetry data collected by USS *Hawkbill*. Submarine tracks are shown in Figure 2.

the region north of 64°N. Techniques, data sources and data distribution are discussed by *Kenyon* [2000]. We have used the final ArcGP grid for the construction of gravity maps. Where we have gravity data from SCICEX submarine cruises, we are able to construct data grids with much greater resolution than the ArcGP 5' × 5' grid in which the N-S spacing of grid nodes is ~9 km. In these areas we will show both the higher resolution, but spatially limited SCICEX data and the lower resolution, but more complete ArcGP data. Gravity profiles utilize the original digital data from the submarine cruises.

[13] It is difficult to establish a consistent reference frame for a series of maps and profiles in polar areas, particularly when the North Pole is within the area under consideration. In this study, we will plot all maps of the Lomonosov ridge with the Siberian side at the top, even though this requires that south will be at the top on maps of regions on the Siberian side of the Pole. It will, however, mean that the Amerasian Basin is to the left and the Eurasian Basin to the right on all maps. All profiles will also be plotted in that manner, hopefully

establishing a simple, intuitive relationship between the maps and profiles.

3. Morphology and Structure of the Lomonosov Ridge

3.1. Seismic Refraction and Drilling Studies of Crustal Structure and Stratigraphy

[14] The continental nature of the Lomonosov Ridge was inferred from seismic refraction experiments conducted during the LOREX ice island expedition that showed a 25 km-thick crust with a 5 km-thick layer with a velocity of 4.7 km/s overlying a main crustal layer with a 6.6 km/s velocity [*Sweeney et al.*, 1982; *Mair and Forsyth*, 1982; *Forsyth and Mair*, 1984]. This structure is similar to sections determined from the Barents and Kara shelves on the northern margin of Eurasia [*Forsyth and Mair*, 1984]. Piston coring on the Eurasian Basin slope of the Lomonosov Ridge (location shown in Figure 5) recovered a coaly, nonmarine Jurassic to Cretaceous siltstone breccia containing reworked Devonian to Pennsylvanian spores [*Grantz et al.*, 2001]. *Grantz et al.* [2001] argue that the sample recovered in the core was in situ and not ice rafted, providing direct confirmation of the ridge's continental origin.

[15] IODP drilling was carried out at three sites near 88°N on the Siberian side of the Lomonosov Ridge during IODP Expedition 302 [*Expedition 302 Scientists*, 2005] (red stars in Figure 5). These sites were selected on the basis of two 12-channel seismic reflection lines across the Lomonosov Ridge acquired aboard the icebreaker *Polarstern* by *Jokat et al.* [1992, 1995] (Figure 5, lines 91090 and 91091). Sonobuoys provided sediment velocity information on the *Polarstern* lines. These lines showed the top of the Lomonosov Ridge is capped by a nearly flat-lying sequence of low-velocity (<2.2 km/s) sediment ~500 m thick that rests on a prominent unconformity. The unconformity is underlain by significantly higher velocity (>4.0 km/s) material [*Jokat et al.*, 1992, 1995].

[16] At places on the *Polarstern* lines, well-bedded dipping strata are imaged that appear to form a set of rotated fault blocks beneath the unconformity [*Jokat et al.*, 1992; *Grantz et al.*, 2001]. *Jokat et al.* [1992, 1995] interpreted these

Figure 5. Bathymetry map of the Lomonosov Ridge north of 86°N contoured at 100 m intervals. Location of the region with respect to the entire ridge is shown in Figure 3. Blue, red, and purple lines show the ship tracks for the submarine bathymetry and gravity profiles shown in Figures 6, 7, and 8, respectively. Black lines show the locations of icebreaker (91090, 91091, 98510, 98511) and ice island (B, D, E) seismic reflection lines discussed in the text.

as Mesozoic sediments that were affected by extensional block-faulting and then uplifted and eroded during the rifting that led to creation of the Eurasian Basin. The upper low-velocity layers were interpreted as Tertiary pelagic sediments that have accumulated since the Lomonosov Ridge subsided below sea level following the rifting. IODP drilling confirmed this general

history and constrains the onset of rifting between the Lomonosov Ridge and Eurasia to between 80 Ma and 58 Ma [Expedition 302 Scientists, 2005]. Identification of paleomagnetic Chron 25 (~56 Ma) in the Eurasian Basin near the base of the Lomonosov Ridge on aeromagnetic profiles [Brozena et al., 2003] is compatible with this interpretation.

Figure 6. SCICEX bathymetry and free-water gravity profiles across the Lomonosov Ridge south of 89°N on the North American side. Profiles are projected perpendicular to the local trend of the Lomonosov Ridge with the Amerasian Basin on the left and the origin at the center of the ridge. Arrows on each profile give the location of Marvin Spur shown by red stars in Figures 9 and 17. Map shows location of the profiles. Map is contoured at 250 m intervals, and colors are as in Figure 2.

3.2. Morphology and Structure From SCICEX Data

[17] There are significant along-strike variations in the morphology and structure of the Lomonosov Ridge (Figure 3). From about 86°N on the North American side past the pole to about 86°30'N on the Siberian side, the Lomonosov Ridge can be characterized as a single linear, blocky, usually flat-topped structure 60–120 km wide and reaching to within 1000–1500 m of the sea surface. This is the best mapped and most studied portion of the ridge [e.g., *Weber and Sweeney*, 1985, 1990; *Jokat et al.*, 1992, 1995; *Grantz et al.*, 2001]. South of 86°30'N on the Siberian side, the Lomonosov Ridge breaks up into a complex of subparallel ridges and basins spread over a width of 200 km (Figure 3). The

most prominent of these ridges lies along the western edge of the complex, bordering the Eur-Asian Basin.

3.2.1. Lomonosov Ridge Between 86°N, 60°W and 89°30'N, 175°E (The Blocky North American Sector)

[18] The blue lines in Figure 5 are track lines for the three southernmost SCICEX crossings of the Lomonosov Ridge on the North American side. These profiles are shown in Figure 6. The crest of the ridge is about 60 km wide with an irregular surface at depths of 1200–1600 m. Minimum depths on each of the three profiles are between 1210 and 1280 m. Free-water gravity highs with relative amplitudes of a few to as many as 50 mGal

coincide with bathymetric highs on the ridge crest (Figure 6). Seismic reflection data obtained from the ARLIS II ice island on a line running diagonally across the ridge crest near 88°30'N (Figure 5, line B) shows about 250–300 m of conformable sediment overlying a very irregular basement surface [Ostenso and Wold, 1977; Weber and Sweeney, 1985].

[19] The Eurasian Basin flank of the ridge is made up of a series of bathymetric peaks accompanied by large positive gravity anomalies stepping down toward the basin (Figure 6). The depressions between the highs are flat or slope gently down toward the main ridge. The ARLIS II ice island obtained a seismic reflection profile across a similar feature further south near 86°45'S [Ostenso and Wold, 1977; Weber and Sweeney, 1985] (Figure 5, line E). This line imaged a basement ridge forming the bathymetric high with the depression between it and the main Lomonosov Ridge partially filled by over 500 m of sediments. We interpret these features as a series of rotated fault blocks related to the rifting that formed the Eurasian Basin.

[20] The Amerasian Basin margin of this portion of the Lomonosov Ridge is much more abrupt. In all three submarine profiles, it is formed by a single 1000–1500 m scarp separating the ridge from a 40–50 km-wide trough located between the Lomonosov Ridge and Marvin Spur, a bathymetric ridge running parallel to the Lomonosov Ridge [Crary, 1954; Beal et al., 1966; Weber and Sweeney, 1985, 1990]. The northeastern flank of Marvin Spur, facing toward Lomonosov Ridge, is also a single 1500-m high linear scarp (Figures 5 and 6). LOREX seismic reflection data show that the trough between the Lomonosov Ridge and Marvin Spur is infilled with more than 2 km of horizontally stratified sediments (Overton [1982] as quoted by Weber and Sweeney [1990]). Jokar [2005] observed at least 1 sec two-way travel time (twtt) of sediment and perhaps more on seismic reflection lines across Marvin Spur and the basin separating it from Lomonosov Ridge just north of 88°N (Figure 5, lines 98510, 98511).

[21] Due to limitations placed on the operational area of the SCICEX missions, there are no submarine profiles south of 88°N toward the North American margin. The ARLIS II ice island obtained a bathymetry, gravity and seismic reflection profile diagonally across the crest of the Lomonosov Ridge between 87°45'N and 86°50'N. (Figure 5, profile D). This line shows depths that are slightly shallower (1100–1200 m)

and much more constant, with smaller gravity variations, than in the area to the north [Ostenso and Wold, 1977; Weber and Sweeney, 1985]. The seismic reflection line shows at least 500 m of flat, stratified sediment [Weber and Sweeney, 1985], similar to what was observed on the icebreaker seismic lines on the other side of the pole [Jokat et al., 1992; Kristoffersen et al., 2004].

[22] Further south toward North America, the IBCAO grid [Jakobsson et al., 2000b] shows the Lomonosov Ridge to widen into a broad plateau that reaches depths shallower than 500 m over a significant area (Figure 3). This area is separated from the North American margin by a 50 km-wide trough. We have no submarine geophysical data from this region and cannot comment on the structure of this region. Brozena et al. [2003] argue that the separation between the Lomonosov Ridge and North America results from the existence of an independent Greenland plate prior to paleomagnetic Chron 13 while the Labrador Sea spreading center was active.

[23] The Lomonosov Ridge narrows significantly north of about 89°N. Figure 7 shows four profiles across the ridge in this region near the Pole. Lomonosov Ridge is 70–80 km wide at its base, with a narrow summit (5–25 km wide) at depths of about 1100–1400 m (Figure 7). The Eurasian Basin flank of the two easternmost profiles at 123°W and 136°W consists of rotated fault blocks as observed further south. However, this does not appear to be case for the Pargo1 and Pogy1 profiles at 142°W and 172°W. In these crossings, the Lomonosov Ridge forms a single, compact bathymetric high rising monotonically from both the Eurasian and Makarov Basins (Figure 7).

[24] A significant free-water gravity low is present along the Eurasian Basin side of the Lomonosov Ridge (Figure 7) [Brozena et al., 2003]. The gravity low has an amplitude of 50–60 mGal relative to gravity values observed in the Eurasian Basin. The seaward edge of the Eurasian Basin gravity low is marked by an abrupt break in slope with a very steep gradient down to the gravity minimum. The break in slope coincides with the Lomonosov Ridge boundary of the lineated magnetic anomaly sequence mapped by Brozena et al. [2003] in the Eurasian Basin.

[25] Marvin Spur becomes much less prominent west of about 120°E and is not present as a major bathymetric feature on this set of profiles (Figure 7). However, there is a 300–500 m bathy-

Figure 7. SCICEX bathymetry and free-water gravity profiles across the Lomonosov Ridge between 89°N, 120°W and 89°N, 180°W. Profiles are projected perpendicular to the local trend of the Lomonosov Ridge with the Amerasian Basin on the left and the origin at the center of the ridge. Arrows on each profile give the location of Marvin Spur shown by red stars in Figures 9 and 17. Map shows location of the profiles. Map is contoured at 250 m intervals, and colors are as in Figure 2.

metric high protruding through the Makarov Basin sediments on line with Marvin Spur on each of the profiles that extends across the basin (Figure 7). Sobczak [1977] and Weber and Sweeney [1985, 1990] interpret these features as a series of individual seamounts that they call the Marvin Seamounts. However, the observation that there is a seamount present on every track combined with the large amplitude of the free-water gravity high associated with them strongly indicate that the Marvin Seamounts are actually a continuous ridge forming a lower relief continuation of Marvin Spur (Figure 7). A large gravity low is present between Marvin and Spur and the Lomonosov Ridge in the region. LOREX seismic reflection data show a deep basin containing over 2 km of sediment

between Marvin Spur and the Lomonosov Ridge near 165°W [Weber and Sweeney, 1985].

3.2.2. Lomonosov Ridge Between 89°30'N, 175°E and 86°, 150°E (The “Bend” in the Lomonosov Ridge)

[26] Figure 8 shows a series of SCICEX bathymetry and free-water gravity profiles across the Lomonosov Ridge from the region of the prominent polar “bend” in the ridge. Profiles Cavalla7 and hb9801 cross the North American side of the bend. Within this region, the ridge is a double peaked feature with an internal basin filled with sediments to a water depth of about 2600 m (Figure 8). A large negative gravity anomaly

Figure 8. SCICEX bathymetry and free-water gravity profiles across the Lomonosov Ridge from the region of the “bend.” Profiles are projected perpendicular to the local trend of the Lomonosov Ridge with the Amerasian Basin on the left and the origin at the center of the ridge. Arrows on each profile give the location of Marvin Spur shown by red stars in Figures 9 and 17. Map shows location of the profiles. Map is contoured at 250 m intervals, and colors are as in Figure 2.

(>100 mGal peak-to-trough amplitude) is found over the interior basin (Figures 8 and 9).

[27] The bathymetric peak on the Makarov Basin side of the Lomonosov Ridge continues the linear trend and steep slope of the Amerasian margin of the ridge observed further south on the North

American side (Figure 5). At about 175°E, this peak changes direction to a more westerly trend, becomes very sharp and narrow and increases steadily in depth from 980 m to a maximum observed depth of 1798 m. The bathymetric peak on the Eurasian Basin side also shows a systematic variation in depth with its depth increasing steadily

Figure 9. (a) Free-water and (b) free-air gravity anomaly maps, contoured at 10 mGal intervals, of the Lomonosov Ridge north of 86°N. The free-water map is based on SCICEX data, and the free-air map was constructed from the ArcGP grid. The SCICEX data have significantly greater resolution but much less spatial coverage than does the ArcGP map. Red stars show the location of Marvin Spur as identified by arrows on the profiles in Figures 6–8.

eastward from a measured depth of 1010 m on Profile Cavalla7 to about 2200 m near 180°E (Figure 8). *Timmermans et al.* [2005] argue that these two notches at either end of the internal basin allow the passage of deep water from the Eurasian Basin to the Amerasian Basin.

[28] The Eurasian Basin margin of this portion of the Lomonosov Ridge is oblique to the opening direction of the Eurasian Basin. The bend in the Lomonosov Ridge is reflected in the magnetic anomalies in the basin [Brozena *et al.*, 2003] and in the shape of the active Gakkel Ridge axis [Cochran *et al.*, 2003]. It is not manifest in the Gakkel Ridge as an offset, either transform or oblique, but rather as a change of trend, so spreading is oblique to the spreading direction in the area of the bend [Cochran *et al.*, 2003].

[29] On the Siberian side of the bend, the Lomonosov Ridge broadens out to 150 km wide at its base and consists of two distinct levels or terraces.

The two peaks found on the North American side of the bend merge to form a single 40–60 km wide upper terrace at a depth of about 1100 m. This ridge shallows gradually southward to a minimum depth of about 950 m near 87°N (Figures 5 and 8).

[30] The upper terrace is flanked on its Eurasian Basin side by a deeper terrace, also about 50 km wide, with depths of 2200–3000 m (Figure 5). The lower terrace is terminated abruptly at its northwest end by a scarp separating it from the deep Eurasian Basin. This scarp is parallel to the Eurasian Basin flank of the double-peaked portion of the Lomonosov Ridge. The northernmost end of the lower terrace is at a depth of 3000 m. The terrace steps up to 2500 m at 87°40'N and then decreases in depth slowly southward to 2200 m near 87°E (Figure 5). Profile Cavalla6 shows a narrow basement peak at the outer side of the lower terrace with a large gravity low coinciding with the terrace (Figure 8). The outer peak is not observed on Profile Pargo2,

located at about $87^{\circ}15'N$. However the gravity anomaly is similar and implies that the lower terrace consists of an outer basement high bounding a deep sedimentary basin.

[31] The *Polarstern* MCS seismic profiles presented by *Jokat et al.* [1992] cross the upper terrace and extend just onto the lower terrace (Figure 5, lines 91090, 91091), which is labeled as “Amundsen Basin” on *Jokat et al.*’s [1992] figures. In the MCS lines, a 500 m thick layer of flat-lying low-velocity ($v_p < 2.2$ km/s) sediments caps the upper terrace. These are separated by an erosional unconformity from higher velocity ($v_p > 4.0$) rocks [*Jokat et al.*, 1992, 1995]. A set of half grabens or rotated fault blocks is imaged below the unconformity. The sediments within the half-grabens show a constant dip and predate the faulting. Four drilling sites (M0001–M0004) were occupied along the *Polarstern* seismic line during IODP Expedition 302. Red stars in Figure 5 show the locations of these sites. The *Expedition 302 Scientists* [2005, p. 15] reported, “The regional unconformity was penetrated but not sampled except for a small bag sample. Fossils from this sample constrain timing of the initiation of rifting to between 80 Ma and the oldest age of the sediment overlying the unconformity at 58 Ma.” *Grantz et al.* [2001] suggests on the basis of a core on the Eurasian flank of the Lomonosov Ridge that the sediments below the unconformity may date from uppermost Triassic/lower Jurassic or mid-lower Cretaceous and thus predate the opening of both the Amerasian and Eurasian Basins. This is a reasonable conclusion, but the evidence is not conclusive because the dredge site (shown by a blue star in Figure 5) is more than 100 km from the seismic lines and drill sites in an area where the ridge morphology is different and it is not certain that the unconformity is present.

[32] The structure of the two terraces implied by gravity anomalies is very different. The upper terrace appears to be underlain by a sequence of consolidated pre-rift sediments that were block faulted and rotated during one or both of the rifting episodes and eroded when the Lomonosov Ridge was apparently above sea level during the Eurasian Basin rifting [*Jokat et al.*, 1992; *Grantz et al.*, 2001]. The buried structures imaged beneath the upper terrace are not apparent in the gravity anomalies (Figures 8 and 9), perhaps because there is not a great density contrast between the compacted and lithified sediments and the crystalline basement rocks. Gravity anomalies show the lower

terrace to consist of a large outer basement high bounding a deep basin filled with low-density sediments. This structure, located on the Eurasian Basin side of the Lomonosov Ridge, presumably developed during the Cenozoic rifting to form that basin. The low-density sediments filling the basin can then be interpreted as mainly syn-rift sediments related to the early Tertiary rifting event.

[33] Marvin Spur is not evident as a bathymetric feature to the west of the Pogy1 profile (Figure 7). However, a free-water gravity anomaly is found along strike with it implying that Marvin Spur extends across the Makarov Basin at least as far as profile Cavalla3 as a continuous basement feature buried by sediments (Figure 8). It may be present as a small feature on the side of a broader gravity high on profile Cavalla6 (Figure 8). If this is the case, then it can be argued on the basis of the gravity data from profiles Pargo2 and Cavalla5 that Marvin spur continues completely across the basin to join Lomonosov ridge near $86^{\circ}N$. Whether this is the case depends largely on whether a gravity low between profiles Cavalla3 and Cavalla6 in the ArcGP gravity map (Figure 9) is real or is a gridding artifact due to the lack of data in that area. Data distribution for the ArcGP grid is not available. In either case, Marvin Spur extends across the Makarov Basin at least to about $87^{\circ}30'N$, $166^{\circ}E$.

3.2.3. Lomonosov Ridge South of $86^{\circ}N$ on the Siberian Side (The Lomonosov Ridge Complex)

[34] Profile Cavalla5 is located at the transition between two very different portions of the Lomonosov Ridge. From $86^{\circ}30'N$, $150^{\circ}E$ to the North American margin, the Lomonosov Ridge is a single discrete ridge (Figure 5). South of $86^{\circ}30'N$, toward the Siberian margin, it breaks into a complex of subparallel ridges spread over a width of 200 km (Figure 10). The shallowest and widest ridge is located along the western edge of the complex, bordering the Eurasian Basin. This ridge has a minimum depth of 677 m to 1231 m on the SCICEX profiles within this region (Figure 11). The Eurasian Basin flank of this ridge usually consists of a series of basement highs stepping down to the basin, again interpreted as rotated fault blocks active during the continental rifting stage of the formation of the Eurasian Basin. In several profiles, particularly Pogy4, Pogy5 and Archerfish4, the main highstanding ridge also appears to consist of two or more large fault blocks

Figure 10. Bathymetry map of the Lomonosov Ridge from 86°N to 82°20'N on the Siberian side contoured at 100 m intervals. Location of the region with respect to the entire ridge is shown in Figure 3. Red lines show the ship tracks for the submarine bathymetry and gravity profiles shown in Figure 11. Black line shows the location of icebreaker seismic reflection line 98550 discussed in the text.

(Figure 11). This is also evident on seismic reflection profile 98550 recently published by *Jokat* [2005] (location shown in Figure 10).

[35] The Makarov Basin edge of the Lomonosov Ridge complex is a ridge that extends south near 158°E (Figures 10 and 11). This ridge is not shown as a continuous feature on maps derived from the IBCAO grid (Figure 10). However, two observations lead us to conclude that it is a single, uninterrupted ridge. The first is that, north of 83°30'N, there is a marked change in depth of up to 1000 m across the location where a continuous ridge would be located, implying a continuous basement dam to sediment transport from the former Eurasian shelf. Secondly, a ridge is present on every SCICEX line through the area, suggesting that the lack of a ridge elsewhere may be a gridding artifact. A free-water gravity map of this region (Figure 12) also clearly shows the presence of a continuous gravity high along 158°E.

[36] The outer ridge decreases in elevation and is buried under the Siberian continental ridge to the south of 82°30'N. There is a large gravity anomaly over the ridge on profile Pogy6 that crosses the ridge at about 82°45'S, indicating that it is still a significant structure at that latitude (Figures 11 and 12).

[37] The region between Lomonosov Ridge's Eurasian margin ridge and the outer ridge on the Makarov Basin edge of the Lomonosov Ridge complex is characterized by a complex pattern of ridges and basins. The largest ridge extends south of 84°40'E along 154°E. South of 83°45'N, this ridge splits into two ridges, one parallel to each of the two ridges bounding the Lomonosov complex, and then dies away rapidly to the south.

[38] The western branch of the Lomonosov Ridge complex bounding the Eurasian Basin continues to the south as a continuous, linear, shallow feature

Figure 11. SCICEX bathymetry and free-water gravity profiles across the Lomonosov Ridge between $86^{\circ}30'N$ and $83^{\circ}N$ on the Siberian side. Profiles are projected along an east-west line with the origin at $142^{\circ}E$. The Amerasian Basin is on the left. Arrows on each profile give the location of the outer ridge shown by blue stars in Figures 15 and 17. Map shows location of the profiles. Map is contoured at 250 m intervals, and colors are as in Figure 2.

until it disappears beneath the Siberian continental slope just south of $80^{\circ}N$ (Figures 10 and 13). Minimum depths are 780 m on Archerfish3 and 1128 m on Cavalla1. The minimum depth does increase to about 1400 m on profiles Cavalla3 and Archerfish2, just north of $80^{\circ}N$ (Figure 14), but the

ridge remains continuous and shallow to the Siberian continental slope.

[39] Profile Archerfish3 (Figures 13 and 14) extends into the Eurasian Basin and shows a series of bathymetry and gravity highs stepping down to

Figure 12. (a) Free-water and (b) free-air gravity anomaly maps, contoured at 10 mGal intervals, of the Lomonosov Ridge from 86°30'N to 82°20'N on the Siberian side. The free-water map is based on SCICEX data, and the free-air map was constructed from the ArcGP grid. The SCICEX data have significantly greater resolution but less spatial coverage than does the ArcGP map. Note the continuous north-south trending gravity high along 157°E–158°E, corresponding to the outer ridge of the Lomonosov complex.

the basin. A tilted fault block on the Eurasian margin of the main Lomonosov block is clearly visible in seismic reflection line 98590 presented by *Jokat* [2005] (location shown in Figure 13).

[40] The Makarov Basin-bounding ridge is not present as a bathymetric feature south of about 82°30'N (Figure 10). However the gravity high associated with the outer ridge continues south

Figure 13. Bathymetry map of the Lomonosov Ridge from 83°30'N to 79°30'N on the Siberian side contoured at 100 m intervals. Location of the region with respect to the entire ridge is shown in Figure 3. Red lines show the ship tracks for the submarine bathymetry and gravity profiles shown in Figure 14. Black line shows the location of icebreaker seismic reflection line 98590 discussed in the text.

Figure 14. SCICEX bathymetry and free-water gravity profiles across the Lomonosov Ridge between $81^{\circ}15'N$ and $80^{\circ}N$ on the Siberian side. Profiles are projected along an east-west line with the origin at $142^{\circ}E$. The Amerasian Basin is on the left. Arrows on each profile give the location of the outer ridge shown by blue stars in Figures 15 and 17. Map shows location of the profiles. Map is contoured at 250 m intervals, and colors are as in Figure 2.

along $157^{\circ}E$ to the Siberian margin (Figure 15). Arrows in Figure 14 show the location of this gravity high on profiles Cavalla1, Cavalla2 and Archerfish1.

4. Discussion

[41] A consistent feature of the Lomonosov Ridge is a highstanding, usually blocky, ridge with minimum depths of 600–1400 m that extends completely across the Arctic Ocean (Figures 2 and 3). The limited available seismic refraction data show this ridge to have a crustal thickness of about 25 km and a “continental” seismic velocity structure [Sweeney *et al.*, 1982; Mair and Forsyth, 1982; Forsyth and Mair, 1984]. This ridge is most simply interpreted as the outer edge of the Eurasian shelf prior to the late Cretaceous/early Tertiary rifting that resulted in the formation of the Eurasian Basin.

The rift structures exposed on the Eurasian side of the main blocky ridge must therefore have been produced during this rifting event.

[42] A stress envelope analysis of lithospheric strength variations across a continental margin by Steckler and ten Brink [1986] shows that a distinct minimum in lithospheric strength characteristically occurs 50–100 km landward of the hinge zone, which is defined as the region of most rapid change in crustal thickness across a continental margin [Watts and Steckler, 1979]. This lithospheric strength minimum provides a mechanism to localize the Eurasian Basin rifting parallel to and landward of the Mesozoic continental margin, resulting in the creation of a long, continuous sliver of continental crust.

[43] The stress envelope calculations of Steckler and ten Brink [1986] also show a marked increase

Figure 15. Free-air gravity anomaly map, contoured at 10 mGal intervals, of the Lomonosov Ridge from 83°30'N to 80°N on the Siberian side. The map was constructed from the ArcGP grid. Blue stars show the location of the outer ridge of the Lomonosov Ridge complex identified on SCICEX profiles. Note that the gravity high associated with the outer ridge continues uninterrupted to the Siberian margin.

in lithospheric strength seaward of the hinge zone, making it extremely difficult for a continental rift to propagate across a continental margin into thinned continental or oceanic crust. As a result, structures on the Amerasian side of the highstanding ridge are interpreted to predate the Eurasian Basin rifting and to result from the development of the Amerasian Basin. *Jokat et al* [1992] describe a prograded sedimentary sequence on the Amerasian Basin side of the Lomonosov Ridge on profile 91091 (Figure 5) that predates the uplift and erosion that accompanied formation of the Eurasian Basin margin. They interpret this as a Mesozoic continental slope sequence. The observation that it is preserved through the late Cretaceous/early Tertiary rifting supports the hypothesis that the rifting was constrained to landward of the Mesozoic shelf break.

4.1. Relationship of the Lomonosov Ridge to the Eurasian Basin

[44] A characteristic feature of profiles across the Eurasian flank of the Lomonosov Ridge is one or more narrow bathymetric highs accompanied by gravity highs that step down toward the Eurasian Basin (e.g., Figures 6, 7, 11, and 14). The depressions between the bathymetric highs appear to be partially or completely filled with low-density sediments. We interpret these as rotated crustal fault blocks, which are a common feature of the landward portion of non-volcanic rifted continental margins [e.g., *Montadert et al.*, 1979; *Chalmers and Laursen*, 1995; *Pickup et al.*, 1996; *Whitmarsh et al.*, 2001; *Cochran*, 2005]. These blocks have

limited extent along axis. Occasionally the same crustal block can be identified on nearby profiles, but in general the topographic pattern is different on each profile. This is consistent with observations that the continental fault blocks making up amagmatic margins are segmented at 40–70 km intervals [e.g., *Cochran*, 2005].

[45] The Lomonosov Ridge edge of the magnetic anomaly sequence in the Eurasian Basin corresponds to the top of a steep gravity gradient making up the seaward side of a large gravity low flanking the Eurasian Basin side of the Lomonosov Ridge [*Brozena et al.*, 2003] (Figures 7–9, 11, and 12). The termination of the magnetic anomaly sequence and the nearly coincident break in slope at the seaward edge of the gravity low probably mark the edge of oceanic crust with an area of “transitional” basement located between there and the extended continental crust at the base of the Lomonosov Ridge [*Pickup et al.*, 1996; *Whitmarsh et al.*, 2001]. On the basis of sonobuoy wide-angle seismic reflection/refraction data, *Jokat and Micksch* [2004] conclude that the ocean-continent transition is located within the area of the gravity low. This is a much narrower ocean-continent transition zone than observed at many amagmatic margins including in particular the well studied Iberian margin [e.g., *Whitmarsh et al.*, 1990, 1996; *Pickup et al.*, 1996; *Krawczyk et al.*, 1996; *Reston et al.*, 1996; *Pérez-Gussinyé et al.*, 2003].

[46] The Eurasian flank of the Lomonosov Ridge is generally parallel to the magnetic anomalies,

reflecting nearly orthogonal rifting of the Lomonosov Ridge off of the northern margin of Eurasia [Brozena *et al.*, 2003]. The bend in the Lomonosov Ridge near the Pole (Figure 5) is mirrored in the magnetic anomalies [Vogt *et al.*, 1979; Brozena *et al.*, 2003] and in the shape of the current Gakkel Ridge axis, where it is manifested as a region of oblique seafloor spreading [Cochran *et al.*, 2003]. However, the lateral offset of the bend in the magnetic anomalies is smaller than that in the Lomonosov Ridge. As a consequence, magnetic anomalies older than Anomaly 22 are truncated against the ridge [Brozena *et al.*, 2003].

[47] The high-resolution aeromagnetic data presented by Brozena *et al.* [2003] do not extend beyond the bend. However, it appears from the lower resolution magnetic anomaly map published by Glebovsky *et al.* [2000] that the oldest anomaly on the Siberian side of the bend is Anomaly 22. This observation implies that propagation of an organized spreading center within the continental rift, which had been nearly instantaneous (within the resolution of the magnetic anomalies) from the North American end of the rift to the bend, stalled for 3–6 m.y. at the bend. As a result, while seafloor spreading occurred at the North American end of the Eurasian Basin at this time, continental rifting continued at the Siberian end. A similar situation presently occurs in the Red Sea where seafloor spreading began at 5 Ma in the southern Red Sea [Roeser, 1975; Cochran, 1983] while late stage continental rifting is still occurring in the northern Red Sea [Martinez and Cochran, 1988; Cochran, 2005].

[48] The unique structure of the Lomonosov Ridge in the area of the bend (Figures 6 and 7), including in particular the steep linear nature of its Eurasian flank and the lack of fault blocks at its base may result from the presence of an oblique non-transform offset of the rift at this location prior to Anomaly 22 time. This offset subsequently must have become an area of oblique seafloor spreading as the oceanic spreading center propagated eastward.

4.2. Models for the Formation of the Amerasian Basin

[49] The Amerasian Basin is widely agreed to be of late Mesozoic age, but its origin and tectonic development have been the subject of considerable controversy. In particular, the absence of a clear pattern of seafloor spreading magnetic anomalies [Vogt *et al.*, 1982; Coles and Taylor, 1990; Lawver

and Gahagan, 2003] or a morphologically distinct mid-ocean ridge and fracture zone system [Grantz *et al.*, 1990a; Jakobsson *et al.*, 2000b] has hampered understanding of the development of the basin and has allowed the development of competing models.

[50] A major reason for the lack of information is that the Canada Basin, the southern portion of the Amerasian Basin (Figure 1), contains 6–10 km of sediment [Grantz *et al.*, 1990a] effectively masking the basement fabric. Aeromagnetic surveys in the southern Canada Basin show anomalies [Taylor *et al.*, 1981] that appear to be lineated in a N-S direction. However, Vogt *et al.* [1982] note that most of the anomalies do not correlate over more than a few tracks and they show three very different interpretations of the magnetic anomalies that fit the data equally well. A recent review concluded that “lineated magnetic anomalies in the Canada Basin are few and remain uncorrelatable” [Lawver and Gahagan, 2003, p. 3]. Laxon and McAdoo [1994] note a N-S trending gravity low at about 142°W in the Canada Basin that they suggest may result from an extinct ridge axis.

[51] The Alpha-Mendeleev Ridge has affected much of the northern portion of the Amerasian Basin (Figure 1). This ridge is a very broad 300–500 km-wide morphologic swell that reaches depths of 1000–1500 m and is characterized by rough local topographic relief [Weber and Jackson, 1985; Jackson *et al.*, 1986] and large amplitude, irregular magnetic anomalies [Vogt and Ostenso, 1970; Vogt *et al.*, 1979; Taylor *et al.*, 1981]. Aeromagnetic data suggest that the Alpha Ridge continues south under the sediments of the northern Canada Basin [Vogt *et al.*, 1982].

[52] The Alpha-Mendeleev Ridge has variously been proposed to be a rafted continental fragment [Sweeney *et al.*, 1982], a mid-ocean ridge spreading center [Vogt and Ostenso, 1970; Hall, 1973; Ostenso and Wold, 1977], a fossil subduction zone [Herron *et al.*, 1974], an oceanic plateau (analogous to the Manihiki Plateau) [Jackson, 1985; Jackson *et al.*, 1986] or a hot spot trace [Van Wagoner and Robinson, 1985; Asudeh *et al.*, 1988; Weber and Sweeney, 1990; Lawver and Müller, 1994]. The more recent studies tend to favor the hypothesis that it is related to hot spot activity.

[53] Late Cretaceous sediments recovered from cores on the Alpha Ridge [Clark, 1974; Kitchell and Clark, 1982] place a minimum age on forma-

tion of the Amerasian Basin. *Vogt et al.* [1982] argued that the apparent presence of lineated magnetic anomalies in the Canada Basin suggests that seafloor spreading predated the long Cretaceous interval of normal magnetization that began at

118 Ma. Sedimentation and subsidence patterns on the Arctic continental margin of Alaska led *Grantz et al.* [1998] to argue that rifting began in the late Valanginian (~135–132 Ma).

[54] The tectonic development of the Amerasian Basin is controversial [*Lane, 1997; Embry, 1998; Grantz et al., 1998*]. No fossil plate boundaries have been convincingly identified within the basin and this lack of constraints has allowed the development of numerous models. These models can be grouped into three main classes [*Lawver and Scotese, 1990*].

[55] “Rotational” models (Figure 16a) involve counterclockwise rotation of Alaska away from Arctic Canada about a pole located near the mouth of the Mackenzie River [e.g., *Carey, 1958; Tailleur, 1969, 1973; Grantz et al., 1979, 1981, 1998; Mair and Forsyth, 1982; Harland et al., 1984; Jackson and Gunnarsson, 1990; Embry, 1990, 1998*]. This model is supported by paleomagnetic data that suggests counterclockwise rotation of the North Slope of Alaska during the Cretaceous [*Halgedahl and Jarrard, 1987*] and by the observation that the rotational model restores truncated predrift facies trends [*Embry, 1985, 1990*]. It is also compatible with multichannel seismic data from the Alaskan margin interpreted as showing a rifted continental margin structure [*Eittreim and Grantz, 1979; Grantz et al., 1979, 1990b*]. The paleomagnetic evidence appears compelling, but opponents of this model argue that the almost vertical inclination combined with the “seemingly pervasive remagnetization problem on the North Slope” [*Harbert et al., 1990, p. 577*] make the results inconclusive, particularly since they only come from one location [e.g., *Stone, 1989; Lane, 1997*].

A

B

C

Figure 16. Sketches illustrating classes of models for the evolution of the Amerasian Basin. (a) Rotational model. In this model, Alaska rotates away from Arctic Canada about a pole located near the Mackenzie delta. The Lomonosov Ridge is a shear margin and is predicted to follow a small circle about the pole. (b) Arctic Islands transform model. In this model, Alaska rifted off of the Lomonosov Ridge margin of Eurasia. The Arctic Islands margin of Canada is a shear margin, and the Lomonosov Ridge is a rifted margin. (c) Arctic Alaska transform model. In this model, eastern Siberia rifted off of the Arctic Margin of Canada. The northern margins of Alaska and the Lomonosov Ridge are both shear margins. The rotational pole is distant, so the two transform margins are nearly linear.

[56] “Arctic Islands transform” models (Figure 16b) also assume that the northern margin of Alaska is a rifted margin, but that it rifted off of the northern Eurasian margin rather than Arctic Canada [e.g., *Ostenso*, 1974; *Christie*, 1979; *Kerr*, 1980, 1981; *Dutro*, 1981; *Crane*, 1987]. This model hypothesizes that the nearly straight continental margin of Arctic Canada is a transform margin [Kerr, 1981; Dutro, 1981]. Seismic data that could classify that margin as transform or rifted is not available. Advocates of this model argue that it is more consistent with Jurassic drainage and depositional patterns [Smith, 1987] and that Arctic Alaska needs to be positioned closer to Ellesmere Island, farther east than it is placed by the rotational model [Crane, 1987].

[57] The third class of models is also translational, but assumes that the Canadian Arctic Islands and East Siberian margins are rifted continental margins and that the Lomonosov Ridge and Alaska margin are transform margins [Herron *et al.*, 1974; Vogt *et al.*, 1982; Lane, 1997]. This “Arctic-Alaska transform” model (Figure 16c) most easily accounts for the Chukchi Borderland (Figure 1), which is made up of continental crust apparently extended perpendicular to the Northwind Escarpment. It also provides the best fit to the various relict spreading axes that have been proposed between the Northwind Escarpment and the Beaufort Shelf [Taylor *et al.*, 1981; Vogt *et al.*, 1982; Laxon and McAdoo, 1994; Brozena *et al.*, 1998] on the basis of aerogeophysics. Lane [1997] also argued that this model explains the difference in the age of the surface identified as the breakup unconformity in Arctic Alaska (Hauterivian) and in the Canadian Islands (Albian-Aptian).

[58] In order to address the complexities of the observed data, models for the evolution of the Amerasian Basin tend to become complex and multistage [e.g., Grantz *et al.*, 1998; Lane, 1997], but they still retain the basic characteristics of one of these classes of model. Thus the Grantz *et al.* [1998] reconstruction can be classified as a rotational model and that of Lane [1997] is basically an Arctic-Alaska transform model.

[59] These classes of models each predict a very different origin for the Amerasian flank of the Lomonosov Ridge. If the Arctic Islands transform model is valid, then the Lomonosov margin of the Amerasian Basin is a rifted continental margin. The rotational model predicts the Lomonosov Ridge to be a transform margin about a pole located in northern Canada near the Mackenzie delta. The

Arctic-Alaska transform model also predicts that the Lomonosov Ridge is a transform margin, but about a much more distant pole so that the Lomonosov margin is nearly linear.

4.3. Relationship of the Lomonosov Ridge to the Amerasian Basin

[60] The Amerasian Basin flank of the Lomonosov Ridge differs significantly from the Eurasian flank. Rotated crustal blocks, which are a consistent feature of the Eurasian flank, are not observed anywhere on the Amerasian flank. For 325 km from the southern limit of the SCICEX data near 88°N north of Greenland past the Pole to 89°N 170°E, the Amerasian flank of the Lomonosov Ridge consists of a steep, nearly linear, 1000 m–2700 m high scarp bounded by a deep trough lying between the ridge and Marvin Spur (Figures 5–7). Ice island seismic reflection data show the trough to contain over 2 km of sediment [Overton, 1982; Weber and Sweeney, 1985]. The IBCAO map [Jakobsson *et al.*, 2000b] indicates that the steep linear scarp extends south for another 150 km to about 86°40'N (Figure 5).

[61] South of about 89°20'N, 110°W, Marvin Spur is a prominent bathymetric ridge with minimum depths of 1400–2200 m (Figures 5 and 6), bounded by a linear scarp facing Lomonosov Ridge. This scarp has a slope of 7°–9° on the SCICEX lines (Figure 6). Marvin Spur decreases greatly in elevation west of 110°W, but is present as a bathymetric feature to 175°E (Figures 5 and 7) and continues across the Makarov Basin as a buried feature observable through its gravity anomaly to at least 87°30'N, 166°E (Figures 8 and 9). A deep basin containing over 2 km of sediment and marked by a large gravity low is present between Marvin Spur and Lomonosov Ridge. There is some gravity evidence (Figures 8 and 9) that Marvin Spur may continue across the Makarov Basin to join Lomonosov Ridge near 86°N on the Siberian side, but this is not conclusive.

[62] South of 86°N on the Siberian side, the Lomonosov Ridge ceases to be a single well-defined ridge and splits into a series of ridges and intervening troughs (Figures 4, 10, and 11). The shallowest and most massive ridge borders the Eurasian Basin and continues south to the Siberian margin. As discussed above, this ridge can be identified as the outermost portion of the Eurasian continental shelf prior to the rifting to form the Eurasian Basin.

Figure 17. (left) Map of the Lomonosov Ridge with location from SCICEX data of the outer ridge of the Lomonosov Ridge complex shown by blue stars and Marvin Spur shown by red stars. Purple lines show small circles at distances of 19.5° and 20° from the *Grantz et al.* [1979] pole at 69.1°N , 130.5°W . (right) Distance of crossings of Marvin Spur (in red) and the outer ridge of the Lomonosov Ridge complex (in blue) from the *Grantz et al.* [1979] pole at 69.1°N , 130.5°W plotted as a function of distance along the ridge.

[63] A second prominent ridge forms the Amerasian Basin boundary of the ridge complex. This ridge extends south at about 157°E as a continuous feature to at least $82^\circ30'\text{N}$ (Figures 10 and 11). Over much of that distance, there is a significant difference in depth across the ridge, indicating that it forms a continuous barrier to sediment transport off the former Eurasian margin. This depth difference decreases south of 84°N on the lower continental rise of Siberia and south of about $82^\circ30'\text{N}$, the ridge is buried under the continental rise sediments (Figures 10 and 13). The area between the two prominent ridges bounding the Lomonosov complex is occupied by a series of ridges and troughs subparallel to the outer ridges.

[64] The location of bathymetry and/or gravity peaks associated with the outer Makarov Basin-bounding ridge of the Lomonosov Ridge complex that were identified on SCICEX lines are shown as

blue stars on the map in Figure 17. The locations of crossings of Marvin Spur are shown as red stars. Small circles at distances of 19.5° and 20° from the *Grantz et al.* [1979] pole of opening for the Amerasian Basin, at 69.1°N , 130.5°W , are shown as purple lines. Figure 17 also shows a plot of distance from the *Grantz et al.* [1979] pole versus distance along the Lomonosov Ridge for crossings of Marvin Spur and of the outer ridge. Distances from the pole are all in the range of 19.37° to 20.16° . The mean is 19.777° with a standard deviation, σ , of 0.210° . However, the observations divide naturally into two groups, each of which provides an even better fit to small circles about the pole. If the crossings on the North American side of the Pogyl profile (302 km of Figure 17) are considered, the mean distance from the *Grantz et al.* [1979] pole is 19.397° ($\sigma = 0.023^\circ$). This area comprises the exposed portion of Marvin Spur. The

crossings on the Siberian side of Pogy1, making up the buried portion of Marvin Spur and the outer ridge are at a distance of 19.885 ($\sigma = 0.077^\circ$) from the pole. The extremely good fit of the Amerasian Basin edge of the Lomonosov complex to small circles suggests strongly that these structures were formed at a transform continental margin. The offset in the distance from the pole is at the location of the “bend” in the Lomonosov Ridge. This offset is in the correct sense to result from a short extensional segment between two long transforms. The excellent fit of the outer ridge and Marvin Spur to small circles about the *Grantz et al.* [1979] pole over a distance of 1200 km is particularly impressive since the pole location was determined on the basis of data from other parts of the Amerasian Basin and its margins, with no reference to the Lomonosov Ridge.

[65] The structure of the Amerasian Basin portion of the Lomonosov Ridge is consistent with observations made at well-studied shear margins. *Lorenzo* [1997] and *Bird* [2001] describe the characteristic elements of sheared margins as a very rapid change in crustal thickness across the margin, and a highstanding marginal ridge just on the continental side of the ocean-continent boundary. This ridge bounds a complex pattern of deep rift basins developed in the continental crust.

[66] At the Ivory Coast – Ghana margin, a marginal ridge is a dominant feature of the margin [e.g., *Basile et al.*, 1993]. The most studied portion of this margin is the western section where a prominent marginal ridge separates oceanic crust from the continental crust underlying the Deep Ivorian Basin [e.g., *Masclé and Blarez*, 1987; *Basile et al.*, 1993; *Lamarche et al.*, 1997; *Sage et al.*, 1997; *Clift and Lorenzo*, 1999]. The crust of the Deep Ivorian Basin was extended and thinned during rifting to form the portion of the Mid-Atlantic Ridge between the Romanche and St. Paul fracture zones [*Peirce et al.*, 1996].

[67] This well-studied area is therefore in a different setting than at the Lomonosov Ridge. However, there is limited data available further to the east, where the transition is from oceanic crust to unrifted continental crust. In that region, the very steep continental rise and slope “shows a highly diffractive reflection at the seabed, suggesting that basement rocks outcrop and any sedimentary cover is very sparse” [*Edwards et al.*, 1997b, p. 750]. Dredging on this slope recovered fragments of metamorphic rock from the African craton [*Blarez et al.*, 1987]. The continental slope in this area is

interpreted as consisting of a basement ridge [*Masclé et al.*, 1988; *Edwards et al.*, 1997a, 1997b] with a sharp transition from oceanic to continental crust at its base [*Edwards et al.*, 1997b]. The shelf landward of this ridge is made up of a series of thickly sedimented basins and ridges [*Blarez and Masclé*, 1988]. This structure is entirely analogous to observations at the Lomonosov Ridge. Similar marginal ridges are observed along the Falkland [*Lorenzo and Mutter*, 1988] and Agulhas [*Ben-Avraham et al.*, 1997] transform margins.

5. Summary and Conclusions

[68] 1. The Lomonosov Ridge is a continuous band of continental crust extending across the Arctic Ocean from just north of Greenland to the Siberian continental margin (Figures 1–3) [e.g., *Sweeney et al.*, 1982; *Forsyth and Mair*, 1984; *Jokat et al.*, 1992]. It separates the Mesozoic Amerasian Basin from the Cenozoic Eurasian Basin and forms a continental margin to both basins. From about 87°N , north of Greenland, across the Pole to about 86°N , the Lomonosov Ridge is a single highstanding blocky ridge with minimum depths of ~ 950 – 1400 m. South of 86°N , on the Siberian side of the Pole, the ridge breaks up into a series of ridges spread over a width of about 200 km. In this region, a highstanding blocky ridge bounds the Eurasian Basin. This ridge is continuous with the single ridge making up the Lomonosov Ridge toward North America and is the former outermost continental shelf of Eurasia bounding the Amerasian Basin.

[69] 2. The Eurasian Basin margin of the Lomonosov Ridge consists of sets of rotated fault blocks stepping down to the basin. This structural pattern, along with a sharp gravity gradient located just on the Lomonosov Ridge side of the termination of the seafloor spreading magnetic anomaly sequence in the Eurasian Basin, are characteristic of non-volcanic rifted continental margins and results from nearly orthogonal rifting to form the Eurasian Basin. This morphology is not observed on the Amerasian margin of the Lomonosov Ridge.

[70] 3. The “bend” in the Lomonosov Ridge, just on the Siberian side of the Pole, is reflected in the seafloor-spreading magnetic anomalies in the Eurasian Basin [*Karasik*, 1968; *Vogt et al.*, 1979; *Verhoef et al.*, 1996; *Brozena et al.*, 2003]. However the offset in the magnetic anomalies is less than the offset of the Lomonosov Ridge, so anoma-

lies older than Anomaly 22, present on the western (North American) side of the bend, truncate at the bend [Brozena *et al.*, 2003]. The available data from the eastern (Siberian) side of the bend [Glebovsky *et al.*, 2000] suggests that the oldest magnetic anomaly may be Anomaly 22. Thus, for 3–6 million years, there may have been a non-transform offset at the location of the bend connecting a region of seafloor spreading in the western Eurasian basin with a region of continued continental rifting to the east. Once seafloor spreading propagated farther east, the offset developed into an area of oblique spreading as observed at present.

[71] 4. From about 87°N north of Greenland to about 89°N, 180°W, the Amerasian Basin side of the Lomonosov Ridge is formed by a linear scarp with no evidence of the rotated blocks that characterize the Eurasian side. This portion of the Lomonosov ridge is paralleled on the Amerasian Basin side by Marvin Spur, a basement ridge separated from the Lomonosov Ridge by a 50 km-wide basin containing at least 2 km of sediments. South of about 89°20'N, 110°W, Marvin Spur is a highstanding ridge with minimum depths of 1400–2200 m, bounded by a linear scarp facing Lomonosov Ridge. Marvin Spur decreases sharply in elevation west of 110°W, but continues across the Makarov Basin as bathymetric or gravity feature to at least 87°30'N, 166°E.

[72] 5. South of 86°N to the Siberian margin, the Lomonosov Ridge to the east of the blocky ridge bounding the Eurasian margin (i.e., seaward of the former Eurasian shelf) is a complex of ridges and basins. A consistent feature of this region is a continuous outer ridge extending south to at least 82°30'N and, based on gravity data, perhaps to the Siberian Margin.

[73] 6. Marvin Spur and the Lomonosov outer ridge to the south of 86°N fall very closely along small circles along the Grantz *et al.* [1979] pole for rotational opening (Figure 17) of the Amerasian Basin. The structures observed on the Amerasian Basin side of the former Eurasian margin are consistent with those observed at transform margins such as the well-studied Ghanaian margin in the equatorial Atlantic Ocean. In particular, a marginal ridge separating oceanic and continental crust and bounding an area of ridges and basins on the continental side is a characteristic observation at long shear margins [e.g., Mascle *et al.*, 1988; Edwards *et al.*, 1997a, 1997b; Lorenzo and Mutter, 1988; Ben-Avraham *et al.*, 1997]. We conclude that the Amerasian Basin continental margin formed by

the Lomonosov Ridge is a shear margin about a pole close to that proposed by Grantz *et al.* [1979] pole. The prominent bend in the Lomonosov Ridge near the Pole corresponds to an approximately 50 km offset in Marvin Spur. The offset of the marginal ridge is consistent with the presence of a short extensional segment located between two long transforms.

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