Tectonics

Extension across the Laptev Sea continental rifts constrained by gravity modeling

S. Mazur[1,2], S. Campbell[1], C. Green[1,2], and R. Bouatmani[1]

[1]Getech, Leeds, UK, [2]School of Earth and Environment, University of Leeds, Leeds, UK

Abstract The Laptev Shelf is the area where the Gakkel Ridge, an active oceanic spreading axis, approaches a continental edge, causing a specific structural style dominated by extensive rift structures. From the latest Cretaceous to the Pliocene, extension exerted on the Laptev Shelf created there several deep subsided rifts and high-standing basement blocks. To understand syn-rift basin geometries and sediment supply relationships across the Laptev Shelf, accurate extension estimates are essential. Therefore, we used 2-D gravity modeling and 3-D gravity inversion to constrain the amount of crustal stretching across the North America-Eurasia plate boundary in the Laptev Shelf. The latest Cretaceous-Cenozoic extension in that area is partitioned among two rift zones, the Laptev Rift System and the New Siberian Rift. These rifts were both overprinted on the Eurasian margin that had been stretched by 190–250 km before the Late Cretaceous. While the Laptev Rift System, connected to the Gakkel Ridge, reveals increasing extension toward the shelf edge (190–380 km), the New Siberian Rift is characterized by approximately uniform stretching along strike (110–125 km). The architecture of the Laptev Rift System shows that the finite extension of about 500 km is sufficient to entirely eliminate crystalline continental crust. In the most stretched rift segment, continental mantle is exhumed at the base of the Late Mesozoic basement. The example of the Laptev Rift System shows that extension driven by divergent plate movement is a sufficient cause to produce almost complete continental breakup without an increased heat input from the asthenospheric mantle.

1. Introduction

The Laptev Shelf offshore eastern Siberia represents a rare tectonic setting, comparable to that of the Woodlark Basin and Afar region, where an active oceanic spreading center, the Gakkel Ridge, approaches a continental margin (Figure 1). The North America-Eurasia plate boundary, corresponding to the Gakkel spreading axis, continues farther south across the limit of the oceanic domain and passes into a continental area. As the plate boundary enters the Siberian Shelf, it becomes diffuse and poorly defined [e.g., *Cook et al.*, 1986; *DeMets*, 1992]. From the latest Cretaceous to the Pliocene, a continental rift system developed in that area comprising several deep, subsided grabens and high-standing basement blocks that have been identified in seismic sections [e.g., *Drachev et al.*, 1998; *Franke et al.*, 2001]. In line with these observations, *Gaina et al.* [2002] showed that plate reconstructions imply a large amount of Cenozoic crustal extension between North America and Eurasia within the Siberian Shelf. In this contribution, we use 2-D gravity profile forward modeling oriented perpendicular to the Laptev Rift System and inversion of regional gravity data to calculate the amount of continental stretching across the North America-Eurasia plate boundary.

We address the question of whether the high extension estimates indicated by plate modeling [*Gaina et al.*, 2002; *Koulakov et al.*, 2013] are supported by potential fields anomalies representing the architecture of the Siberian continental margin. We use the outcomes of our models to understand syn-rift basin geometries across the Laptev Shelf and extension partitioning within the continental crust. Performing our extension calculations separately for top prerift sediments and top crystalline crust, we were able to discriminate the effects of the Cenozoic North America-Eurasia interaction from the preexisting extension phases that also contributed to the finite crustal thinning.

2. Geological Setting for Late Cretaceous—Recent Extension

The east and west Siberian Shelf is underlain by Precambrian to Palaeozoic basement terranes of the North America and Eurasia Plates (Figure 2). The boundary between the two crosses the Laptev Shelf along the N-S oriented continental rifts that are overprinted on the Early Mesozoic Taimyr fold-and-thrust belt and
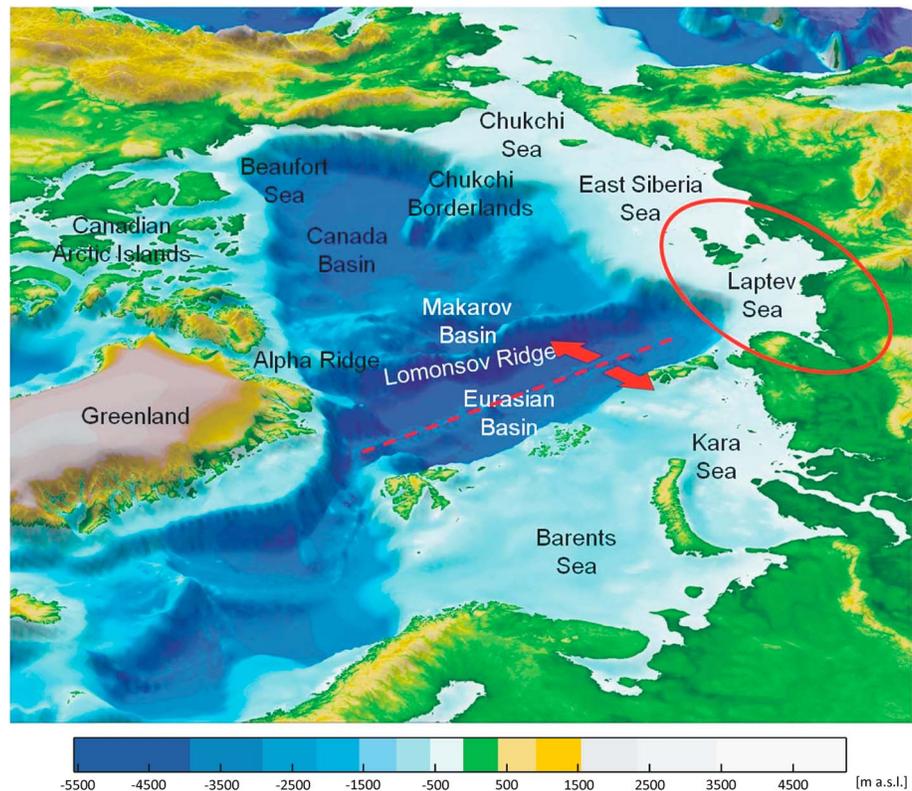
Figure 1. Setting of the Laptev Shelf, outlined in the red ellipse, overlaid on a perspective view of the bathymetry for the Arctic. Location of the Gakkel spreading center is highlighted with a red dashed line. Bathymetry/topography data after International Bathymetric Chart of the Arctic Ocean version 2.23 [*Jakobsson et al.*, 2008].

the Late Mesozoic Verkhoyansk and New Siberian-Chukchi fold-and-thrust belts [*Zonenshain et al.*, 1990; *Parfenov*, 1991]. These fold belts approach the shoreline and seem to continue offshore forming the heterogeneous basement of the Laptev Rift System concealed beneath a Cenozoic sedimentary cover [*Drachev et al.*, 1998; *Kuzmichev*, 2009]. Rifting shortly followed the cessation of orogenic compression in the Late Cretaceous resulting in significant stretching and subsidence of newly formed continental crust [*Drachev et al.*, 1998; *Miller et al.*, 2008]. The offshore sedimentary basins that developed at that time contain promising though not fully explored hydrocarbon resources [e.g., *Gautier et al.*, 2009; *Drachev*, 2011].

The Laptev Sea occupies the western part of the Siberian Shelf between the Taimyr Peninsula and the New Siberian Islands (Figure 1). In this area, an active oceanic spreading axis, the Gakkel Ridge, approaches a continental edge (Figure 2), causing a specific structural style dominated by extensive rift structures. The Laptev Rift System (Figure 3) consists of several deep subsided rifts and high-standing basement blocks [*Drachev et al.*, 1998; *Franke et al.*, 2001]. From west to east, these are the South Laptev Rift, unnamed horst block, Ust'Lena Rift, South and North Laptev Horsts, Bel'kov-Svyatoi Nos and Anisin Rifts, East Laptev and Kotelnyi Horsts, and New Siberian Rift/Basin (Figure 3) [*Drachev et al.*, 1998; *Drachev*, 2000; *Franke and Hinz*, 2005]. The rifts contain up to five seismic stratigraphic units bounded by clear regional reflectors and are underlain by folded heterogeneous basement. It has been suggested [*Drachev et al.*, 1998; *Franke et al.*, 2004; *Franke and Hinz*, 2005; *Shkarubo and Zavarzina*, 2011] that they are Late Cretaceous to Holocene in age and reflect different stages of spreading ridge/continental margin interaction. The estimated total thickness of the rift-related sediments varies between 4 and 10–15 km while the sedimentary cover on the structural highs is significantly reduced and generally does not exceed 1–2 km [*Drachev et al.*, 1998; *Franke et al.*, 2004; *Franke and Hinz*, 2005]. An eastward decrease of the total thickness of the sedimentary sections, from about 10–15 km in the South Laptev Basin to 4–5 km in the Bel'kov-Svyatoi Nos Rift (Figure 3) is observed [*Drachev et al.*, 1998]. The entire rift system is covered by the uppermost seismic unit, which probably reflects a deceleration of rifting during the last reorganization of the North America/Eurasia Plate interaction since
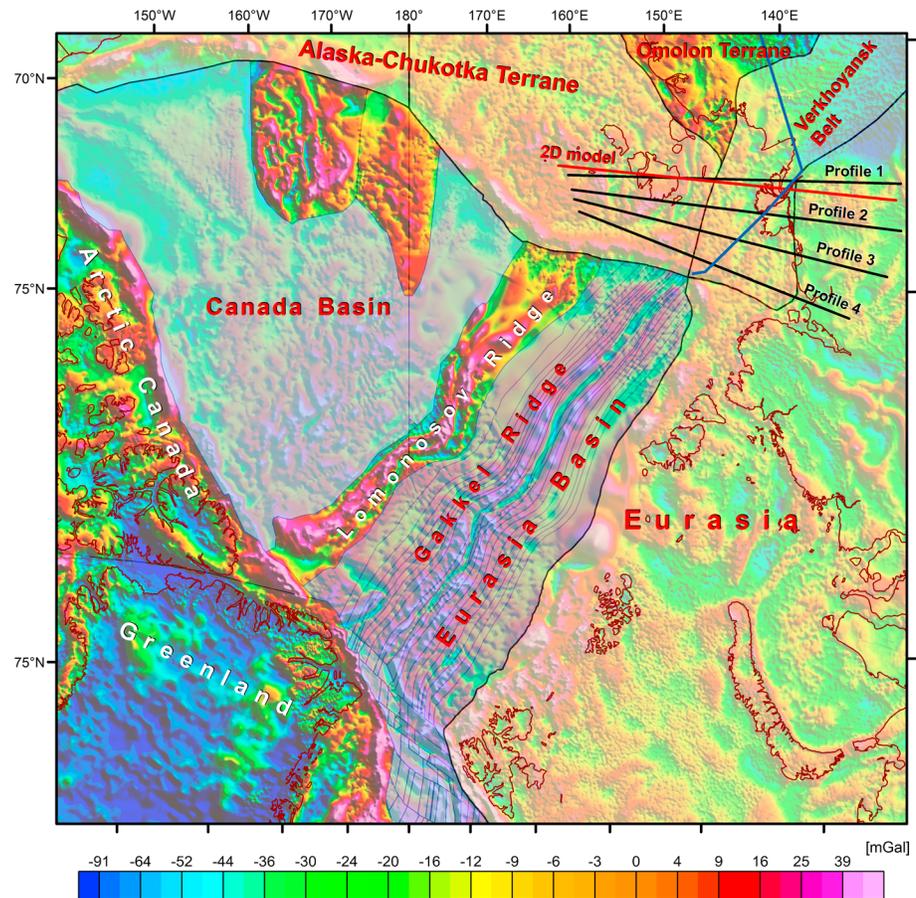
Figure 2. Tectonic plate boundaries for the eastern Arctic overlaid on a gravity anomaly map—free air anomaly offshore and Bouguer anomaly onshore. The map over this large area has been compiled from a number of sources [*Kenyon et al.*, 2008; *Green and Fairhead*, 1996; *Fairhead et al.*, 2004, 2009]; some of the apparent artifacts (e.g., at ~81°N) are from internal links within the ArcGP data set [*Kenyon et al.*, 2008]. Oceanic crust is shown as bluish semitransparent polygons. The synthetic seafloor magnetic anomalies for 5 Ma intervals are adopted for the Eurasia Basin from *Müller et al.* [2008]. Continental plates and terranes boundaries are defined based on analysis of potential field data and depth to basement maps as well as published literature [*Webb et al.*, 2013]. The Alaska-Chukotka Terrane, Verkhoyansk Thrust-and-Fold Belt, and Eurasia are highlighted by semitransparent polygons. The location of a 2-D model and profiles used for extension calculation is depicted by red and black lines, respectively. Blue line shows the seismicity-derived, present-day North American/Eurasian plate boundary according to *Chapman and Solomon* [1976].

about 2 Ma [*Drachev et al.*, 1998; *Franke et al.*, 2004]. The basement of the rift basins is well exposed within the coastal areas and in the western part of the New Siberian Islands. It is composed almost everywhere of Palaeozoic and Mesozoic carbonate and clastic complexes of an ancient passive continental margin deformed by folds and thrusts during the Early Cretaceous.

The extension of the Laptev continental margin was related to the opening of the Eurasia Basin [*Grachev*, 1983], an oceanic basin created by seafloor spreading since the early Cenozoic [*Karasik*, 1974; *Vogt et al.*, 1979; *Karasik et al.*, 1983; *Kristoffersen*, 1990; *Brozena et al.*, 2003; *Glebovsky et al.*, 2006]. Its spreading axis, the Gakkel Ridge, separates the North American and Eurasian lithospheric plates in the Arctic and represents an ultraslow spreading ridge, with recent spreading taking place with a pole of plate rotation near the Lena Delta [*Cook et al.*, 1986; *Franke et al.*, 2000]. The finite opening rate in the Eurasia Basin decreased from approximately 16.5 mm per year near Greenland to 6 mm per year at its Laptev termination [*DeMets et al.*, 1990]. The near-Laptev part of the Eurasia Basin south of 80°N has received a large amount of terrestrially derived sediments, supplied by several large Siberian rivers, of which the Lena River is the largest. A thick sedimentary cover extends down to the 3500 m isobath and further into the ocean basin [*Sekretov*, 2002], burying the basement topography of the Eurasia Basin including the Gakkel Spreading Ridge.
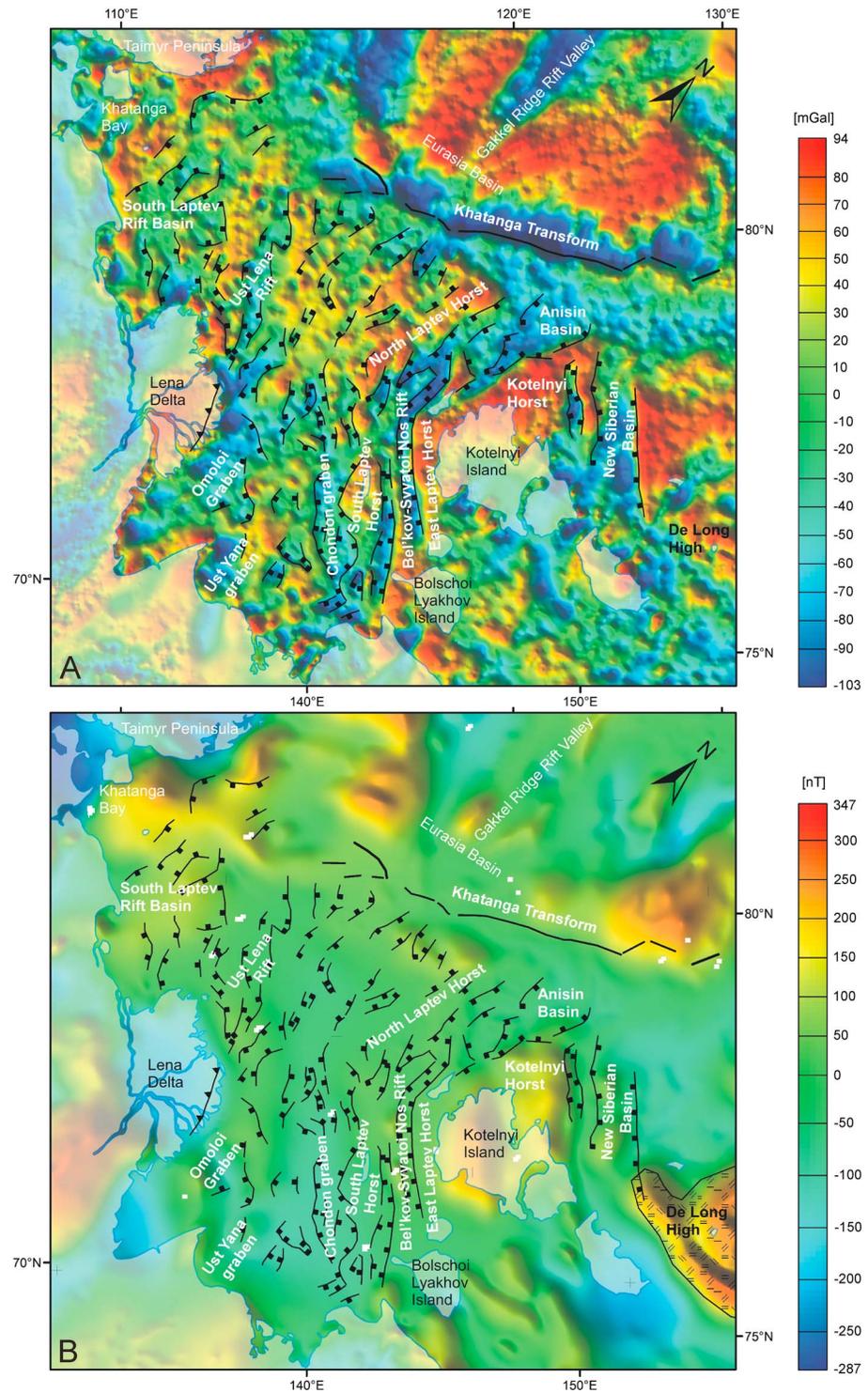
Figure 3. (a) Gravity and (a) magnetic anomaly maps showing the major horsts, grabens, and faults within the Laptev Rift System. Magnetic data were low-pass filtered with a cutoff wavelength of 120 km. The De Long High in Figure 3b is shown with a hatched polygon. Gravity data are after *Kenyon et al.* [2008] and *Green and Fairhead* [1996]; magnetic data are after *Verhoef et al.* [1996].

The Gakkel Ridge vanishes almost completely under this Siberia-derived sedimentary pile at ~ 80°40′N, 122°E. However, it is manifested on seismic profiles as a high-standing block of acoustic basement complicated by a median rift valley [*Sekretov*, 2002]. The thickness of the overlying sediments varies from 0.4 km over the flanks of the buried ridge to 6–7 km above the rift valley and in the surrounding oceanic basins. The Khatanga-Lomonosov Transform striking from the Khatanga River Inlet to the shelf edge of the Eurasia Basin (Figure 3) is a major SW-NE trending transcurrent fault, which represents a sheared boundary between the spreading-dominated Eurasia Basin and the stretched continental crust of the Laptev Shelf [*Drachev et al.*, 1998]. Distribution of earthquake epicenters, increased heat flow, and currently active normal faults allow estimation of a 140–150 km left-lateral offset of the present-day divergent plate boundary along the Khatanga-Lomonosov Transform [*Drachev et al.*, 2003]. Farther to the south, the North America-Eurasia plate boundary is found in the Cherskii Mountain Belt, as shown by *Savostin and Karasik* [1981], *Grachev* [1983], *Cook et al.* [1986], *Parfenov et al.* [1988], and *Fujita and Cook* [1990].

3. Methodology

Several plate tectonic reconstructions of the North Atlantic and the Arctic have been proposed to date based on the fitting of magnetic anomalies, transform-fracture zone systems, continent-ocean boundaries, and/or bathymetry of previously adjacent segments of lithosphere [e.g., *Karasik et al.*, 1983; *Savostin et al.*, 1984; *Srivastava*, 1985; *Rowley and Lottes*, 1988; *Torsvik et al.*, 2001; *Lawver et al.*, 2002; *Glebovsky et al.*, 2006]. The plate reconstructions of *Gaina et al.* [2002] demonstrated the inevitability of vast Cenozoic extension in East Siberia generated by the relative displacement of Eurasia with respect to North America. This extension was implied by the divergent movement of the two plates as constrained by seafloor magnetic anomaly identifications in the North Atlantic and Eurasia Basin [*Verhoef et al.*, 1996]. The essence of our approach is to put an additional constraint on the amount of continental extension in East Siberia that is independent from plate reconstructions. This way we attempt to better understand the evolution of the Laptev continental rifts as a consequence of North America-Eurasia plate interactions.

3.1. Two-Dimensional Gravity Modeling

We used a crustal cross section based on a 2-D gravity model to estimate the extension of the continental crust across the Laptev Rift System. The 2-D gravity profile, supported by published seismic data [*Drachev et al.*, 1998; *Franke et al.*, 2001], constrained the limit of undeformed crust and provided estimates of the cross-sectional area of the deformed continental crust [*Mazur et al.*, 2012]. The gravity response of the model was calculated and compared to the observed gravity profile; then the model was interactively adjusted until a satisfactory fit between the synthetic response and the observed gravity was obtained. Gravity for the 2-D models was compiled from public domain data from the Arctic Gravity Project [*Kenyon et al.*, 2008] integrated with Getech gridded gravity onshore [*Green and Fairhead*, 1996].

Two-dimensional gravity modeling was performed using GM-SYS^{TM} (Geosoft Inc.) version 7.0.1. The onshore and offshore sections of the 2-D profiles were modeled using the Bouguer and free air gravity anomalies, respectively. The location of the 2-D model (Figure 2) was selected to measure extension induced by the relative displacement between the North America and Eurasia plates. The profile is therefore chosen to be a straight line which crosses the rifts and horsts of the Laptev Sea as close to perpendicular as possible, although some compromise is always required in selecting profiles for 2-D modeling. The profile runs for approximately 1500 km from onshore Siberia, across the Lena Delta, through the Laptev Sea and the New Siberian Islands, terminating in the vicinity of the De Long Archipelago in the East Siberian Sea. It crosses a number of intracontinental rift basins rather than the oceanic Eurasia basin. Subsidence of rift basins appears to be satisfactorily explained by depth-uniform lithosphere stretching [*McKenzie*, 1978; *Kusznir and Karner*, 2007, and references therein]. For this intracontinental extension zone, we can calculate the extension based on the modeled cross section using the method of *Mazur et al.* [2012]. The extension *e* can be calculated from the crustal cross-sectional area *A*, the distance *x* between the rift flanks, and the initial thickness *T* of the unstretched continental crust from the expression:

$$e = x - \frac{A}{T} \tag{1}$$

It should be noted that this approach and this expression do not assume stretching which is constant for all depths (McKenzie stretching) at each point along the profile, but for simplicity such a uniform stretching model would generally be the starting point for fitting the gravity data.

MAZUR ET AL.   439
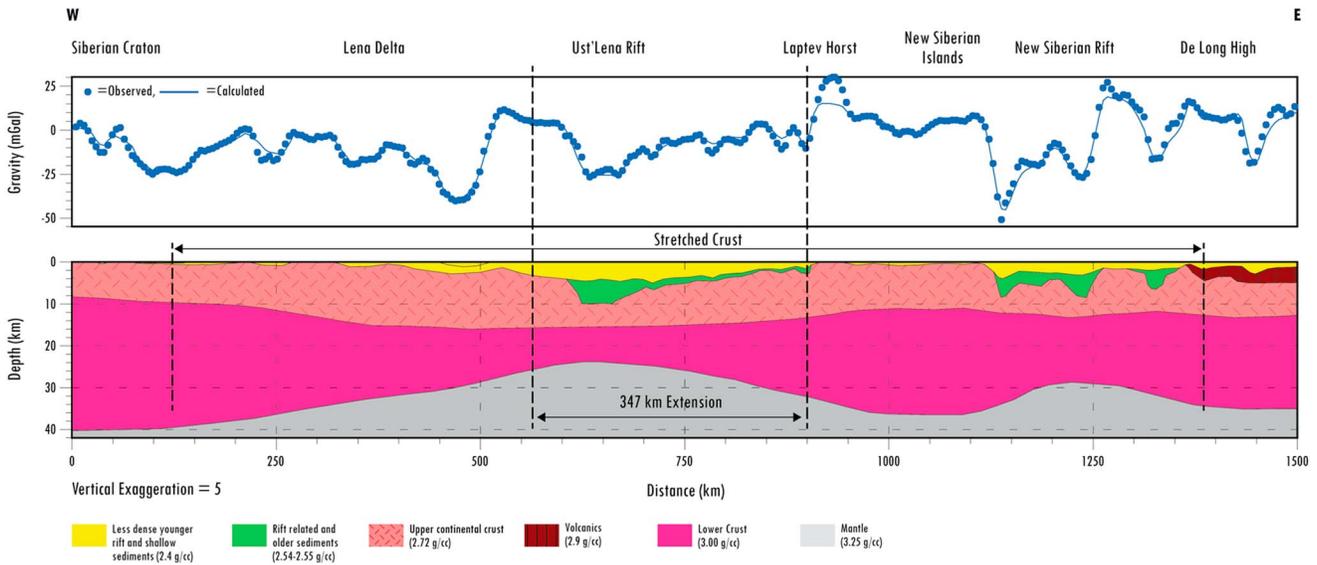
Figure 4. Two-dimensional gravity profile model (from the Lena Delta, through the Laptev Sea and the East Siberian Islands to the De Long High). Assuming an unstretched crustal thickness of 40 km, c. 350 km of SW-NE extension is calculated.

3.2. Three-Dimensional Gravity Inversion

A 3-D gravity inversion was performed in order to investigate how the crustal extension across the Laptev Rift System varies along its length. The Bouguer gravity anomaly grid was inverted using the iterative gravity inversion method of *Cordell and Henderson* [1968] to generate a depth to basement grid for the area. This inversion used a simple two-layer model with density contrast of 0.2 g/cc at the basement. Seismic depth to basement values across the area [*Franke et al.*, 2001] was used as control points where gravity anomalies were predicted; the difference between observed and calculated gravity at these points was used to generate a smooth correction which was applied to the compiled gravity grid before inversion. In this inversion technique [*Cordell and Henderson*, 1968], the sedimentary fill is represented by a series of square-topped vertical prisms—one for each node in the gravity grid. An initial 1-D estimate of the thickness of each prism is based on the gravity value at that grid node, and an iterative procedure is used to derive a model of sediment thickness for the whole grid area whose 3-D gravitational response matches the observed gravity data.

The Moho depth map of *Franke et al.* [2001] based on seismic refraction and reflection data was digitized and used to constrain a gravity inversion for depth to Moho from a long wavelength version of the gravity field, assuming a density contrast at the Moho of 0.25 g/cc. This allowed the calculation of crustal thickness and hence crustal stretching (Beta) factor.

In contrast to gravity inversion, more complicated geological models with several layers can be used in forward modeling. Therefore, we used a 2-D gravity forward model to test the quality of inversion outputs. Although both methods utilize the same gravity data, they use different approaches and calculation algorithms and thus might be considered partly independent from one another.

4. Results

4.1. Qualitative Review of Gravity and Magnetic Data

The northwest trending deep rifts identified from seismic data in the Laptev Sea [*Franke and Hinz*, 2005; *Franke et al.*, 2001; *Drachev et al.*, 1998] are generally represented by narrow gravity lows, with their edges delineated by steep gravity anomaly gradients (Figure 3). Some of these rifts are apparently offset or truncated by NE-SW to E-W discontinuities observed in the gravity data. The currently mostly inactive Khatanga-Lomonosov Transform Fault is clearly imaged in the gravity data as a discontinuity running perpendicular to the Gakkel Ridge at its southern end (Figure 3). The magnetic data in the Laptev Sea [*Verhoef et al.*, 1996] are generally low amplitude and relatively flat. This is partly because of the large thickness of sediments in these basins meaning deep basement and hence low-amplitude magnetic
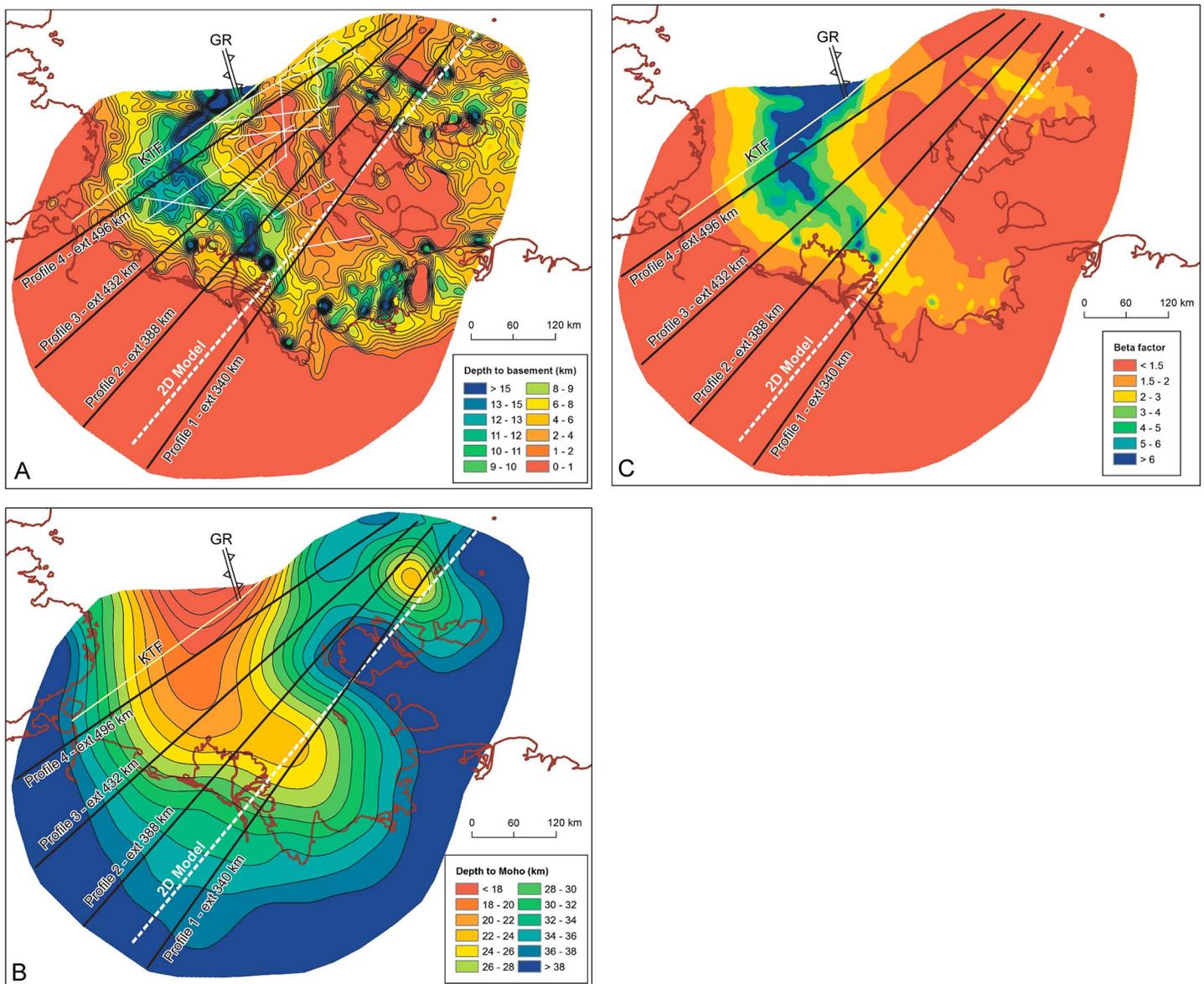
Figure 5. Three-dimensional gravity inversion for the Laptev Shelf: (a) Depth to Late Mesozoic basement (km) based on 3-D gravity inversion, (b) Depth to Moho (km) —inverted from gravity data constrained by seismic refraction and reflection interpretation of *Franke et al.* [2001]. Transects marked on both maps are profiles along which extension calculations are made (solid) and the 2-D modeled profile (dashed). Thin white lines (solid) in Figure 5a show the locations of seismic lines from *Franke et al.* [2001] that were used to constrain gravity inversion. GR, Gakkel Ridge; KTF, Khatanga Transform Fault. (c) Calculated Beta factor map from crustal thickness results (Figures 5a and 5b). Transects marked on the map are profiles along which extension calculations are made (solid) and the 2-D modeled profile (dashed). GR, Gakkel Ridge; KTF, Khatanga Transform Fault. (d) Perspective view of top Late Mesozoic basement for the Laptev and New Siberian Rifts. (e) Perspective view of Moho for the Laptev and New Siberian Rifts.

signature. The high-amplitude magnetic anomalies in the vicinity of the De Long High suggest a volcanic origin. Volcanic units of some tens of meters thick have been mapped on Bennett Island, and the entire basalt section is c. 250 m in thickness [*Vol'nov and Sorokov*, 1961; *Fujita and Cook*, 1990]. The basalts show an intraplate geochemical signature and were interpreted as part of the Early Cretaceous Arctic large igneous province [*Drachev and Saunders*, 2006]. The area of the De Long High is also defined by a gravity high, which extends further to the west than the high-amplitude magnetic anomalies. Between this De Long province and the New Siberian Islands lies the NW-SE trending New Siberian Rift [*Drachev et al.*, 1999], defined by a distinct gravity low with a second similar trending narrower rift directly to the southwest (Figure 3).
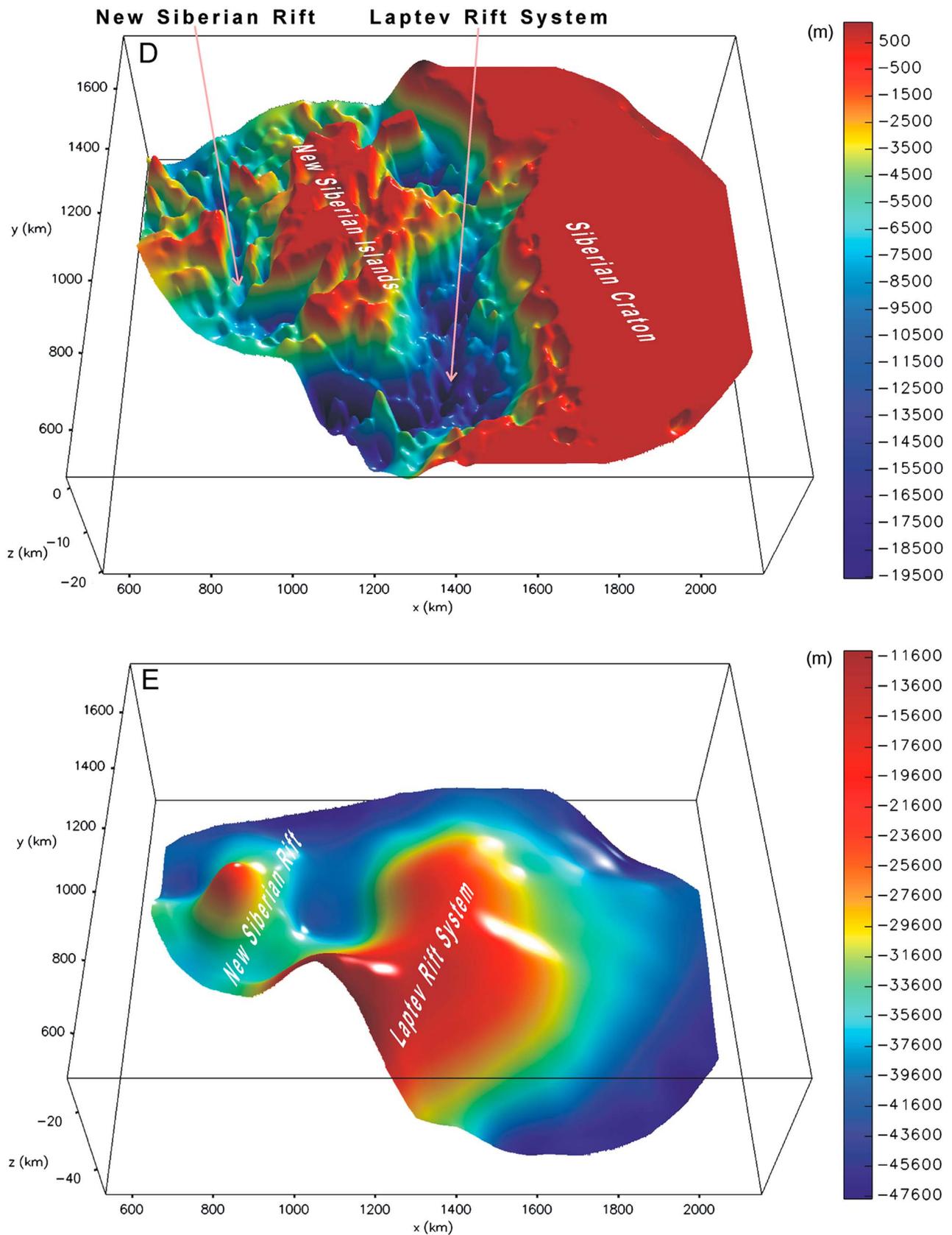
Figure 5. (continued)
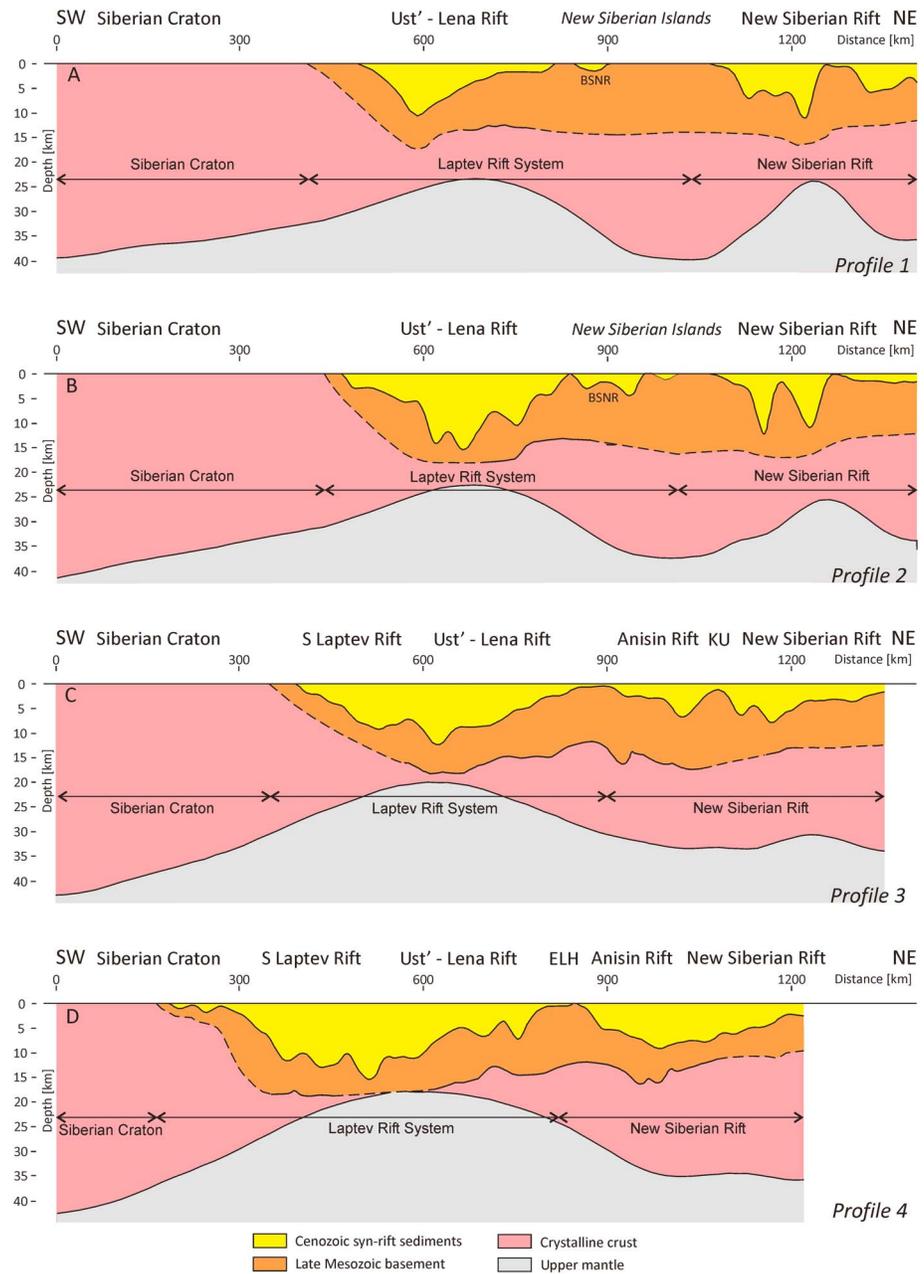
Figure 6. Profiles (marked in Figure 5) extracted from 3-D inversion results: (a) Profile 1: 340 km of extension, (b) Profile 2: 388 km of extension, (b) Profile 3: 432 km of extension, (d) Profile 4: 496 km of extension. The total extension values calculated along the profiles are partitioned among three tectonic domains: the Siberian Craton, the Laptev Rift system, and the New Siberian Rift (see Table 1). The depth to the Late Mesozoic basement (base yellow unit) is constrained by the results of gravity inversion (see Figure 5a). The depth to Moho is inverted from the gravity data constrained by the Moho map of *Franke et al.* [2001]—see Figure 5b. The depth to crystalline basement (base orange unit) is partly defined by seismic reflection data of *Franke et al.* [2001] (black solid line) and partly inferred from seismic time sections [*Franke et al.*, 2008; *Franke and Hinz*, 2009] and gravity anomalies (dashed line). The crystalline basement (pink unit) in the area of the Siberian Craton is merged with the relatively thin, mostly Palaeozoic sediments of the Anabar anteclise and an overlying Cretaceous foredeep basin.

4.2. Two-Dimensional Modeling

The southwest part of the profile shows the dramatic, predominantly Cenozoic (initial rifting possibly Late Cretaceous) rifts of the Laptev Sea (Figure 4) [*Roeser et al.*, 1995; *Drachev et al.*, 1998; *Drachev*, 2000; *Franke et al.*, 2001]. Precise ages of the interpreted seismic reflectors remain uncertain, with no well ties in the area. However, there are clearly large amounts of sedimentary fill in these rifts with the Ust'Lena

Table 1. Latest Cretaceous-Cenozoic and Pre-Late Cretaceous Extension in Kilometers as Calculated Along Profiles 1–4 of Figure 6

		Siberian Craton	Laptev Rift System	New Siberian Rift	Full Profile
Latest Cretaceous-Cenozoic extension	Profile 1	40	190	110	340
	Profile 2	45	235	108	388
	Profile 3	20	287	125	432
	Profile 4	0	379	120	496
Pre-Late Cretaceous extension	Profile 1	0	156	88	244
	Profile 2	0	132	110	242
	Profile 3	0	103	121	224
	Profile 4	0	124	66	191

Rift modeled with up to 12 km of sedimentary fill using a two-layer density model (Figure 4). The extent to which the basin is floored by prerift sediments is uncertain, based on gravity modeling, but crystalline basement could be deeper still. That is, the modeled "basement" could be deformed heterogeneous Mesozoic basement (as proposed by *Drachev* [2000], in his interpretation of seismic lines MAGE87722 and MAGE86705) largely indistinguishable in density terms from crystalline basement. To balance the gravity response of such dramatic rifting, the Moho shallows to 24 km in this region (see also the Moho map of *Franke et al.* [2001]). This indicates that there has been a huge amount of crustal extension in this basin.

To the northeast of the Ust'Lena Rift, a broad basement high incorporating the Laptev Horst and the New Siberian Islands is modeled with the crust thickening to in excess of 35 km [*Franke et al.*, 2001]. Northeast of the New Siberian Islands is the 100 to 150 km wide New Siberian Rift, modeled with a similar two-density model as the Ust'Lena Rift (Figure 4). Northeast of here is the De Long High province characterized by high-amplitude, high-frequency gravity and, particularly, magnetic anomalies. *Lebedeva-Ivanova et al.* [2004] provided seismic evidence for crustal thickening beneath the De Long High and also interpreted a crustal velocity model. The De Long High is considered by several authors to have a volcanic heritage and relatively highly magnetic rocks/basement are required to model the magnetic anomalies in this part. It is possible that the volcanics modeled in this area are related to the proposed [*Maher*, 2001; *Drachev and Saunders*, 2006] high Arctic large igneous province of Early to mid-Cretaceous times.

The amount of total net crustal extension has been estimated from this model by reconstructing the crust to its prerift thickness and configuration (the profile was extended into the onshore Siberian Craton for this calculation to ensure a stable depth to Moho was reached). This calculation estimated the total net crustal extension to be 347 km across the central region of the Laptev Sea (Figure 4). This result provides a good match with the extension estimate based on 3-D gravity inversion along the nearly coincident pseudo profile 1 (see below and Figure 5).

4.3. Three-Dimensional Gravity Inversion

Maps of depth to basement and depth to Moho calculated from the 3-D gravity inversion are shown in Figures 5a and 5b, respectively. Perspective views of top basement and Moho horizons are presented in Figures 5d and 5e. In order to test the absolute crustal extension across the Laptev Sea Shelf, four pseudo profiles extracted from our 3-D inversion results were created (Figures 2 and 5), oriented

Figure 7. Extension partitioning between the Laptev Rift System and the New Siberian Rift. The diagram shows the amount of stretching for the latest Cretaceous-Cenozoic rifting (Table 1). For location of profiles 1–4, see Figures 2 and 5.

perpendicular to the axis of the rift system with profile 1 in the south at the narrow end of the rift and profile 4 in the north, close to the Eurasia Basin. The 2-D profile model (Figure 4) is close to profile 1. Depth to basement and depth to Moho were extracted along these profiles from the appropriate grids (Figure 5). It is clear from the maps (Figures 5a and 5b) that the basement is generally deeper in the north, and the Moho is generally shallower—implying that stretching increases from south to north as confirmed by the calculated Beta factor map (Figure 5c). Figure 6 shows cross sections for profiles 1–4. The depth to basement along the profiles is taken straight from the inverted depth to basement grid and hence is rather smooth. However, this should not affect their value in calculating stretching along the profile. Top crystalline crust was partly defined based on seismic reflection data of *Franke et al.* [2001] (black solid line) and partly inferred from seismic time sections [*Franke et al.*, 2008; *Franke and Hinz*, 2009] and gravity anomalies (dashed line). The crustal extension along each profile was estimated in the same manner as for the 2-D profile (Figure 4). Initially, the extension was assessed for the latest Cretaceous-Cenozoic rifting event. The calculations were done for the full length of the profiles and separately for three structural domains: the Siberian Craton, the Laptev Rift System, and the New Siberian Rift (Table 1). The same exercise was performed using top crystalline crust instead of top Late Mesozoic basement (Table 1). The results obtained provided the total amount of extension experienced by crystalline crust during all stretching events. Table 1 provides estimates of the pre-Late Cretaceous extension that were obtained by subtracting the latest Cretaceous-Cenozoic stretching from the total extension calculated.

The latest Cretaceous-Cenozoic extension is seen to increase uniformly from 340 km along profile 1 to 496 km along profile 4—see Figure 6. However, of this overall extension, 110–125 km is localized within the New Siberian Rift (Figure 7 and Table 1). An additional 0–45 km of extension was accommodated by fragments of the Siberian Craton sampled by the pseudoprofiles. Consequently, the magnitude of the latest Cretaceous-Cenozoic extension for the Laptev Rift System ranges from 190 to 379 km—increasing steadily and significantly from south to north. The amount of pre-Late Cretaceous extension is fairly uniform for all the pseudoprofiles (Table 1). If anything, there is even a slight decrease of extension from profiles 1 to 4 in the Laptev Rift System, i.e., in the direction opposite to the trend characteristic of the latest Cretaceous-Cenozoic rifting.

5. Discussion

Cenozoic extension within the studied segment of the Siberian Shelf is partitioned between two separate structural domains, the Laptev Rift System and the New Siberian Rift, that are separated by the high-standing block of the New Siberian Islands (Figure 5d). The rift zones are separated by a distance of c. 500 km from one another (Figure 5e), the Laptev Rift System oriented approximately N-S and the New Siberian Rift NW-SE. However, while extension is rapidly increasing toward the shelf edge in the Laptev Rift System, it remains roughly constant along the strike of the New Siberian Rift (Figure 7). This is probably because the Laptev Rift System is connected (via the Khatanga-Lomonosov Transform) to the presently active spreading center of the Gakkel Ridge, whereas the New Siberian Rift is terminated by a passive Siberian margin (Figure 2). An open question remains whether the Cenozoic extension in the Laptev Shelf was exclusively related to a divergent movement between North American and Eurasian plates. This seems obvious in the case of the Laptev Rift System that overlaps a diffuse divergent plate boundary between North America and Eurasia. If the origin of the New Siberian Rift was the same, a horizontal extensional stress had to be transferred at a large distance toward the interior of the Alaska-Chukotka Terrane. The reason for strain localization along the New Siberian Rift to the NE of the New Siberian Islands is uncertain based on data currently available.

The latest Cretaceous-Cenozoic syn-rift extension was overprinted on the already stretched Siberian margin. When the finite extension results, based on the interpreted thickness of crystalline crust (see section 4), are reduced by the amount of syn-rift extension, they suggest pre-Late Mesozoic extension roughly uniformly distributed across the study area in the range of c. 200–250 km (Table 1). Consequently, the presence of the preexisting stretched margin of Siberia must have largely enhanced the development of the Laptev and New Siberian Rifts. It also constrained in a broad sense the location of new rifts since they avoided those parts of the Siberian Craton that were unaffected by the pre-Late Cretaceous stretching, but the orientation and exact setting of the Laptev and New Siberian Rifts were not inherited from earlier Mesozoic or Palaeozoic rifting events that stretched the Siberian margin.

A series of cross sections (Figure 6) shows a rapid increase of latest Cretaceous-Cenozoic extension in the Laptev Rift System toward the shelf edge. Profile 4 crosses the axis of the Laptev Rift c. 40 km away from the

Khatanga Transform Fault defining the continent-ocean boundary. Crystalline continental crust is practically eliminated by extension in that area (Figure 6d) although the gravity data clearly preclude the occurrence of oceanic or transitional crust (Figure 3). As a result, the Late Mesozoic basement seems to be directly underlain by continental mantle in the center of the rift, alternatively expressed as very high values of stretching factor exceeding 6 at the intersection of profile 4 with the Laptev Rift (Figure 5c). This is a consequence of c. 380 km of extension in the latest Cretaceous-Cenozoic that was overprinted on 120 km of extension in the pre-Late Cretaceous time (Table 1). These values might be representative for stretching of the entire lithosphere assuming after *McKenzie* [1978] uniform extension for continental rifts. Thus, the results obtained show that extension in the range of 500 km for a single rift is sufficient to produce almost complete continental breakup. They also suggest that there is no jump in finite crustal extension across the Khatanga Transform Fault despite the fact that the Gakkel Ridge and the axis of the Laptev Rift System are right laterally displaced along this fault by c. 220 km (Figures 3 and 5). However, ongoing seafloor spreading within the Eurasia Basin suggests higher overall lithospheric mantle extension in that area exceeding 500 km. Thus, cumulative extension values for the entire lithosphere are likely to differ across the Khatanga Transform Fault even if they remain unconstrained in the present study.

Geological evidence summarized by *Franke* [2013] points to a magma-poor setting for the Laptev Rift System. In line with this evidence, the results of our study provide an example of almost complete continental breakup across a magma-poor rift that was produced by lithospheric extension alone in response to a divergent plate movement. In the case of the Laptev Rift System a breakup of the entire crust precedes the breakup of the continental mantle. This situation is a precondition for ensuing mantle exhumation, the phenomenon widely described for present and fossil magma-poor continental margins [e.g., *Whitmarsh et al.*, 2001; *Manatschal*, 2004]. Consequently, the Laptev Rift represents an embryonic nonvolcanic margin where crystalline crust is already entirely eliminated across the most stretched rift section but continental mantle has not yet broken up.

The results obtained put new constraints on the amount of stretching across the North America-Eurasia plate boundary in the area of Laptev Shelf and can be used for calibration of Cenozoic plate models for the Arctic. Although our modeling approach makes use of several assumptions and more data are needed to ground truth it, the previously published extension estimates for the Laptev Rift System in the range of 600–700 km [*Gaina et al.*, 2002; *Franke and Hinz*, 2009] appear too high in the light of present results. This seems to be the case especially because the earlier calculations, based on plate kinematics [*Gaina et al.*, 2002] or assessment of seismic data [*Franke and Hinz*, 2009], were assigned by their authors only to the latest Cretaceous-Cenozoic rifting event. Therefore, they did not account for crustal thinning associated with Late Devonian to Early Carboniferous rifting of the Arctic margin and successive passive margin stage that predated a Late Mesozoic orogeny [*Sokolov et al.*, 2009; *Sokolov*, 2010; *Drachev et al.*, 2010].

6. Conclusions

The latest Cretaceous-Cenozoic extension across the North America-Eurasia plate boundary in the area of the Siberian Shelf is focused into two continental rift zones, the Laptev Rift System and the New Siberian Rift [*Drachev et al.*, 1999]. The joint interpretation of Moho depth from gravity inversion and public domain seismic data [*Franke et al.*, 2001; *Franke et al.*, 2008; *Franke and Hinz*, 2009] suggests that both these features overprinted the Eurasian margin that was already considerably stretched in the pre-Late Cretaceous time. More data on the geometry of top crystalline basement would be desirable to further substantiate this corollary. The Laptev Rift System is connected to the Gakkel Ridge—an active spreading axis of the Eurasia Basin and thus reveals rapidly increasing extension toward the shelf edge. In contrast, the New Siberian Rift is terminated by the continent-ocean boundary and consequently characterized by approximately uniform stretching along strike.

The Laptev Rift System represents a mature continental rift zone, the architecture of which provides new insight into the development of magma-poor passive margins. Our study suggests that an estimate of total extension in the range of 500 km is sufficient to entirely eliminate crystalline continental crust. Continental mantle is already exhumed at the base of the Late Mesozoic basement before the breakup of lower lithosphere and upwelling of asthenospheric mantle. This situation appears to be a prerequisite for the potential exhumation of continental mantle after initiation of spreading. An example of the Laptev Rift System shows that extension driven by divergent movement of continental plates is a sufficient factor to produce almost complete continental breakup without a considerable heat input from asthenospheric mantle.

References

Brozena, J. M., V. A. Childers, L. A. Lawver, L. M. Gahagan, R. Forsberg, J. I. Faleide, and O. Eldholm (2003), New aerogeophysical study of the Eurasia Basin and Lomonosov Ridge: Implications for basin development, *Geology*, 31, 825–828.

Chapman, M. E., and S. C. Solomon (1976), North American-Eurasian plate boundary in northeast Asia, *J. Geophys. Res.*, 81, 921–930, doi:10.1029/JB081i005p00921.

Cook, D. B., K. Fujita, and C. A. McMullen (1986), Present-day plate interactions in Northeast Asia: North American, Eurasian, and Okhotsk plates, *J. Geodyn.*, 6, 33–51.

Cordell, L., and R. G. Henderson (1968), Iterative three-dimensional solution of gravity anomaly data using a digital computer, *Geophysics*, 33, 596–601.

DeMets, C. (1992), A test of present-day plate geometries for northeast Asia and Japan, *J. Geophys. Res.*, 97(B12), 17,627–17,635, doi:10.1029/92JB01335.

DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein (1990), Current plate motions, *Geophys. J. Int.*, 101, 425–478.

Drachev, S. S. (2000), Laptev Sea rifted continental margin: Modern knowledge and unsolved questions, *Polarforschung*, 68, 41–50.

Drachev, S. S. (2011), Tectonic setting, structure and petroleum geology of the Siberian Arctic offshore sedimentary basins, in *Arctic Petroleum Geology, Memoirs*, edited by A. M. Spencer et al., vol. 35, pp. 369–394, Geol. Soc., London.

Drachev, S. S., and A. Saunders (2006), The Early Cretaceous Arctic LIP: Its geodynamic setting and implications for Canada Basin opening, in *Proceedings of the Fourth International Conference on Arctic Margins*, edited by R. A. Scott and D. K. Thurston, pp. 216–223, Anchorage, Alaska.

Drachev, S. S., L. A. Savostin, V. G. Groshev, and I. E. Bruni (1998), Structure and geology of the continental shelf of the Laptev Sea, Eastern Russian Arctic, *Tectonophysics*, 298, 357–393.

Drachev, S. S., G. L. Johnson, S. W. Laxon, D. C. McAdoo, and H. Kassens (1999), Main structural elements of Eastern Russian Arctic continental margin derived from satellite gravity and multichannel seismic reflection data, in *Land-Ocean Systems in the Siberian Arctic: Dynamics and History*, edited by H. Kassens et al., pp. 667–682, Springer, Berlin - Heidelberg.

Drachev, S. S., N. Kaul, and V. N. Beliaev (2003), Eurasia spreading basin to Laptev Shelf transition: Structural pattern and heat flow, *Geophys. J. Int.*, 152, 688–698.

Drachev, S. S., N. A. Malyshev and A. M. Nikishin (2010), *Tectonic History and Petroleum Geology of the Russian Arctic Shelves: An Overview*, *Petroleum Geology Conference series*, vol. 7, pp. 591–619, Geol. Soc., London.

Fairhead, J. D., C. M. Green, and K. M. U. Fletcher (2004), Hydrocarbon screening of the deep continental margins using non-seismic methods, *First Break*, 22(11), 59–63.

Fairhead, J. D., S. E. Williams, K. M. U. Fletcher, C. M. Green, and K. Vincent (2009), Trident—A new satellite gravity model for the oceans, 71st EAGE Conference and Exhibition, doi:10.3997/2214-4609.201400174.

Franke, D. (2013), Rifting, lithosphere breakup and volcanism: Comparison of magma-poor and volcanic rifted margins, *Mar. Pet. Geol.*, 43, 63–87.

Franke, D., and K. Hinz (2005), The structural style of sedimentary basins on the shelves of the Laptev Sea and the western East Siberian Sea, Siberian Arctic, *J. Petrol. Geol.*, 28(3), 269–286.

Franke, D., and K. Hinz (2009), Geology of the shelves surrounding the New Siberian Islands, RussianArctic, *Stephan Mueller Spec. Publ. Ser.*, 4(4), 35–44.

Franke, D., F. Krüger, and K. Klinge (2000), Tectonics of the Laptev Sea-Moma 'Rift' region: Investigation with seismological broadband data, *J. Seismol.*, 4, 99–116.

Franke, D., K. Hinz, and O. Oncken (2001), The Laptev Sea rift, *Mar. Pet. Geol.*, 18, 1083–1127.

Franke, D., C. Reichert, and K. Hinz (2004), Geology of the East Siberian Sea, Russian Arctic from seismic images: Structures, evolution and implications for the evolution of the Arctic Ocean Basin, *J. Geophys. Res.*, 109, B07106, doi:10.1029/2003JB002687.

Franke, D., C. Reichert, V. Damm, and K. Piepjohn (2008), The South Anyui suture, Northeast Arctic Russia, revealed by offshore seismic data, *Norwegian J. Geol.*, 88, 189–200.

Fujita, K., and D. B. Cook (1990), The Arctic continental margin of eastern Siberia, in *The Arctic Ocean Region: The Geological Society of America*, edited by A. Grantz, L. Johnson, and J. F. Sweeny, pp. 289–304, The Geology of North America.

Gaina, C., W. R. Roest, and R. D. Müller (2002), Late Cretaceous-Cenozoic deformation of northeastern Asia, *Earth Planet. Sci. Lett.*, 197, 273–286.

Gautier, D. L., et al. (2009), Assessment of undiscovered oil and gas in the Arctic, *Science*, 324(5931), 1175–1179.

Glebovsky, V. Y., V. D. Kaminsky, A. N. Minakov, S. A. Merkur'ev, V. A. Childers, and J. M. Brozena (2006), Formation of the Eurasia Basin in the Arctic Ocean as inferred from geohistorical analysis of the anomalous magnetic field, *Geotektonika*, 4, 21–42.

Grachev, A. F. (1983), Geodynamics of the transitional zone from the Moma Rift to the Gakkel Ridge, in *Studies in Continental Margin Geology*, *Am. Assoc. Pet. Geol. Mem.*, vol. 34, edited by J. S. Watkins and C. L. Drake, pp. 103–114.

Green, C. M., and J. D. Fairhead (1996), New 5′ × 5′ digital gravity and terrain models of the Earth, in *Global Gravity Field and its Temporal Variations: IAG Symposia*, vol. 116, edited by R. H. Rapp, A. A. Casenave, and R. S. Nerem, Springer.

Jakobsson, M., R. Macnab, L. Mayer, R. Anderson, M. Edwards, J. Hatzky, H. W. Schenke, and P. Johnson (2008), An improved bathymetric portrayal of the Arctic Ocean: Implications for ocean modeling and geological, geophysical and oceanographic analyses, *Geophys. Res. Lett.*, 35, L07602, doi:10.1029/2008GL033520.

Karasik, A. M. (1974), The Eurasia Basin of the Arctic Ocean from the point of view of plate tectonics [in Russian], in *Problems in Geology of Polar Areas of the Earth*, Nauchno-Issledovatel'skii Institut Geologii Arktiki, Leningrad, pp. 23–31.

Karasik, A. M., L. A. Savostin, and L. P. Zonenshain (1983), Parameters of the lithospheric plate movements within Eurasia Basin of North Polar Ocean [in Russian], *Trans. USSR Acad. Sci. Earth Sci. Sect.*, 273, 1191–1196.

Kenyon, S., R. Forsberg, and B. Coakley (2008), New gravity field for the Arctic, *Eos Trans. AGU*, 89(32), 289–290, doi:10.1029/2008EO320002.

Koulakov, I. Yu, C. Gaina, N. L. Dobretsov, A. N. Vasilevsky, and N. A. Bushenkova, 2013, Plate reconstructions in the Arctic region based on joint analysis of gravity, magnetic, and seismic anomalies, *Russ. Geol. Geophys.*, 54(8), 859–873.

Kristoffersen, Y. (1990), Eurasia Basin, in *The Geology of North America, Vol. L., The Arctic Ocean Region*, edited by A. Grantz, L. Johnson, and J. F. Sweeney, pp. 365–378, Geol. Soc. Am., Boulder, Colo.

Kusznir, N. J., and G. D. Karner (2007), Continental lithospheric thinning and breakup in response to upwelling divergent mantle flow: Applications to the Woodlark, Newfoundland and Iberia margins, in *Imaging, Mapping and Modelling Continental Lithosphere Extension and Breakup*, edited by G. D. Karner, G. Manatschal, and L. M. Pihero, *Geol. Soc. London Spec. Publ.*, 282, 389–419.

Kuzmichev, A. B. (2009), Where does the South-Anyui suture go in the New-Siberian islands and Laptev Sea?, Implications for the Amerasia Basin Origin, *Tectonophysics*, 463, 86–108.

Lawver, L. A., A. Grantz, and L. M. Gahangan (2002), Plate kinematic evolution of the present Arctic region since the Ordovician, in *Tectonic Evolution of the Bering Shelf-Chukchi Sea-Arctic Margin and Adjacent Landmasses*, edited by E. L. Miller, A. Grantz, and S. L. Klemperer, *Geol. Soc. Am. Spec. Pap.*, *360*, 333–358.

Lebedeva-Ivanova, N., A. Y. Langinen, and Y. Y. Zamansky (2004), A seismic model of the Earth's crust along the 'Transarctic—1989–1991' (East Siberian continental margin-Podvodnikov Basin-Arlis Rise-Makarov Basin) geotransect: NGF abstracts and proceedings, vol. 2, pp. 93–94.

Maher, H. D., Jr. (2001), Manifestations of the Cretaceous high Arctic large igneous province in Svalbard, *J. Geol.*, *109*(1), 91–104.

Manatschal, G. (2004), New models for evolution of magma-poor rifted margins based on a review of data and concepts from West Iberia and the Alps, *Int. J. Earth Sci.*, *93*(3), 432–466.

Mazur, S., C. Green, M. G. Stewart, J. M. Whittaker, S. Williams, and R. Bouatmani (2012), Displacement along the Red River Fault constrained by extension estimates and plate reconstructions, *Tectonics*, *31*, TC5008, doi:10.1029/2012TC003174.

McKenzie, D. (1978), Some remarks on the development of sedimentary basins, *Earth Planet. Sci. Lett.*, *40*, 25–32.

Miller, E. L., A. Soloviev, A. Kuzmichev, G. Gehels, J. Toro, and M. Tuchkova (2008), Jurassic and Cretaceous foreland basin deposits of the Russian Arctic: Separated by birth of the Makarov Basin?, *Norwegian. J. Geol.*, *88*, 201–226.

Müller, R. D., M. Sdrolias, C. Gaina, and W. R. Roest (2008), Age, spreading rates, and spreading asymmetry of the world's ocean crust, *Geochem. Geophys. Geosyst.*, *9*, Q04006, doi:10.1029/2007GC001743.

Parfenov, L. M. (1991), Tectonics of the Verkhoyansk-Kolyma Mesozoides in the context of plate tectonics, *Tectonophysics*, *199*, 319–342.

Parfenov, L. M., B. M. Koz'min, O. V. Grinenko, V. S. Imaev, and L. P. Imaeva (1988), Geodynamics of the Chersky seismic belt, *J. Geodyn.*, *9*, 15–37.

Roeser, H., M. Block, K. Hinz, and C. Reichert (1995), Marine investigations on the Laptev Sea and western part of the East Siberian Sea, Russian-German Cooperation: Laptev Sea System, pp. 367–377.

Rowley, D. B., and A. L. Lottes (1988), Plate kinematic reconstruction of the North Atlantic and Arctic, Late Jurassic to present, *Tectonophysics*, *155*, 73–120.

Savostin, L. A., and A. M. Karasik (1981), Recent plate tectonics of the Arctic basin and of northeastern Asia, *Tectonophysics*, *74*, 111–145.

Savostin, L. A., A. M. Karasik, and L. P. Zonenshain (1984), The history of the opening of the Eurasian basin in the Arctic, *Trans. USSR Acad. Sci. Earth Sci. Sect.*, *275*, 79–83.

Sekretov, S. B. (2002), Structure and tectonic evolution of the southern Eurasia Basin, Arctic Ocean, *Tectonophysics*, *351*, 193–243.

Shkarubo, S. I., and G. A. Zavarzina (2011), Stratigraphy and characteristics of the sedimentary cover sequences of the western Laptev Sea shelf, Neftegazovaya geologiya, Teoriya i praktika, 6(2), 21 pp. [Available at http://www.ngtp.ru/rub/2/14_2011.pdf.]

Sokolov, S. D. (2010), Tectonics of Northeast Asia: An Overview, *Geotectonics*, *44*, 493–509.

Sokolov, S. D., G. Y. Bondarenko, P. W. Layer, and I. R. Kravchenko-Berezhnoy (2009), South Anyui suture: Tectono-stratigraphy, deformations, and principal tectonic events, in *Geology, Geophysics and Tectonics of Northeastern Russia: A Tribute to Leonid Parfenov, Stephan Mueller Publication Series*, vol. 4, edited by D. B. Stone et al., pp. 201–221, European Geosciences Union.

Srivastava, S. P. (1985), Evolution of the Eurasian basin and its implications to the motion of Greenland along the Nares Strait, *Tectonophysics*, *114*, 29–53.

Torsvik, T. H., R. Van der Voo, J. G. Meert, J. Mosar, and H. J. Walderhaug (2001), Reconstructions of the continents around the North Atlantic at about the 60th parallel, *Earth Planet. Sci. Lett.*, *187*, 55–69.

Verhoef, J., W. R. Roest, R. Macnab, J. Arkani-Hamed, and Project Team (1996), Magnetic anomalies of the Arctic and North Atlantic Oceans and adjacent land areas, Geological Survey of Canada, Open File 3125a.

Vogt, P. R., P. T. Taylor, L. C. Kovacs, and G. L. Johnson (1979), Detailed aeromagnetic investigation of the Arctic Basin, *J. Geophys. Res.*, *84*, 1071–1089, doi:10.1029/JB084iB03p01071.

Vol'nov, D. A., and D. S. Sorokov (1961), Geology of Bennett Island, Collected Papers on Geology and Hydrocarbon Potential of the Arctic [in Russian], NIIGA, Leningrad, pp. 5–8.

Webb, P., S. Masterton, and D. Eue (2013), Plate tectonic models derived from multiple data sources: Examples from the Arctic, Geophysical Research Abstracts, 15, EGU2013-9291.

Whitmarsh, R. B., G. Manatschal, and T. A. Minshull (2001), Evolution of magma-poor continental margins from rifting to seafloor spreading, *Nature*, *413*(6852), 150–154.

Zonenshain, L. P., M. L. Kuzmin, and L. M. Natapov (1990), Geology of the USSR: A plate tectonic synthesis, *Am. Geophys. Union Geodynamics Ser.*, *21*, p. 242.