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Seismic transect across the Lomonosov and Mendeleev Ridges: Constraints on the geological evolution of the Amerasia Basin, Arctic Ocean

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[1] We report on seismic and petrological data that provide new constraints on the geological evolution of the Amerasia Basin. A seismic reflection transect across the Makarov Basin, located between the Mendeleev and Lomonosov Ridges, shows a complete undisturbed sedimentary section of Mesozoic/Cenozoic age. In contrast to the Mendeleev Ridge, the margin of the Lomonosov Ridge is wide and shows horst and graben structures. We suggest that the Mendeleev Ridge is most likely volcanic in origin and support this finding with a $^{40}Ar/^{39}Ar$ isotopic age for a tholeiitic basalt sampled from the central Alpha/Mendeleev Ridge. Seismic reflection data for the Makarov Basin show no evidence of compressional features, consistent with the Lomonosov Ridge moving as a microplate in the Cenozoic. We propose that the Amerasia Basin moved as a single tectonic plate during the opening of the Eurasia Basin.
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1. Introduction

[2] Two major tectonic events have influenced the geological evolution of the Arctic Ocean in the last 130 Myr. The first was the opening in the Mesozoic of the Amerasia Basin consisting of the Canada and Podvodnikov Basins/Makarov Basin (MB) and the Chukchi Plateau and the Alpha-Mendeleev Ridge (AMR) complex (Figure 1). The Makarov Basin is most likely of Late Mesozoic age and covers a vast area between the AMR and the Lomonosov Ridge (LR). Part of the basin located close to the continental margin is referred to in some publications as the Podvodnikov Basin. However, for simplicity, we use only the term Makarov Basin hereafter. The second tectonic event was the opening in the Cenozoic of the Eurasia Basin, which formed via the drift of the Lomonosov Ridge away from the Siberian shelves. The evolution of the Cenozoic part of the Arctic is reasonably well constrained by seafloor spreading anomalies [*Karasik*, 1968; *Vogt et al.*, 1979]. However, because of the lack of such continuous spreading anomalies in the Mesozoic Arctic, there is much speculation about the tectonic history of the oldest part of the Arctic Ocean—the Amerasia Basin. Geological models for the evolution of the Amerasia Basin require different origins for the Alpha-Mendeleev Ridge (AMR) varying from formation as a mid-ocean ridge, a large transform, a continental fragment conjugate to the Lomonosov Ridge, or as part of the Iceland hot spot trace [*Vogt et al.*, 1982; *Lawver and Müller*, 1994]. These models rely mostly on aeromagnetic data, which show a marked irregular, high-amplitude pattern along the entire AMR. *Vogt et al.* [1979] first attributed this irregular magnetic pattern to the presence of basalts, which formed during the magnetic Cretaceous Normal Superchron (CNS, 120–84 Ma). Because the Makarov Basin and adjacent ridges hold the key to showing possible relative motion between the two ridges, the lack of seismic reflection data for the area represents a major gap in the information required to understand the evolution of the AMR. The aforementioned problems, taken together with a lack of basement samples/drill holes and the thick multiyear ice cover in the last few decades, present a major obstacle to the improvement of geological models for the evolution of the Makarov Basin/Alpha-Mendeleev Ridge complex.

[3] In 2008, an approximately 1200 km long seismic transect (Figure 1) was acquired with R/V *Polarstern* that imaged the sedimentary structure down to the acoustic basement across all the relevant ridges north of the East Siberian shelf in the Amerasia Basin. We use in this study the general sedimentary distribution along a 900 km long portion of the seismic transect to introduce a modified model for the relative movements of the Lomonosov Ridge to the Laptev Sea. A more detailed description of the seismic stratigraphy and wide/steep angle data gathered along the transect will be given in another contribution.

2. Methods

[4] The seismic data used in this study (Figures 2 and 3) were acquired in single-ship mode using R/V *Polarstern*. The streamer length was limited to 300 m (group spacing 6.25 m, 48 channels) because of the difficult ice conditions. The seismic reflection data were filtered and stacked. No detailed velocity analysis of the streamer data was possible because of the limited offset of the seismic channels. Figure 2 shows a line drawing of the seismic data gathered between the Mendeleev and Lomonosov Ridges. The white gaps in the line drawing indicate where the vessel stopped for other scientific programs or seismic equipment had to be recovered because of thick sea ice. The top Oligocene reflector was interpolated/correlated from the eastern termination of the transect into the Makarov Basin [*Hegewald and Jokat*, 2013a, 2013b]. Here the seismic signature of this reflector is the most

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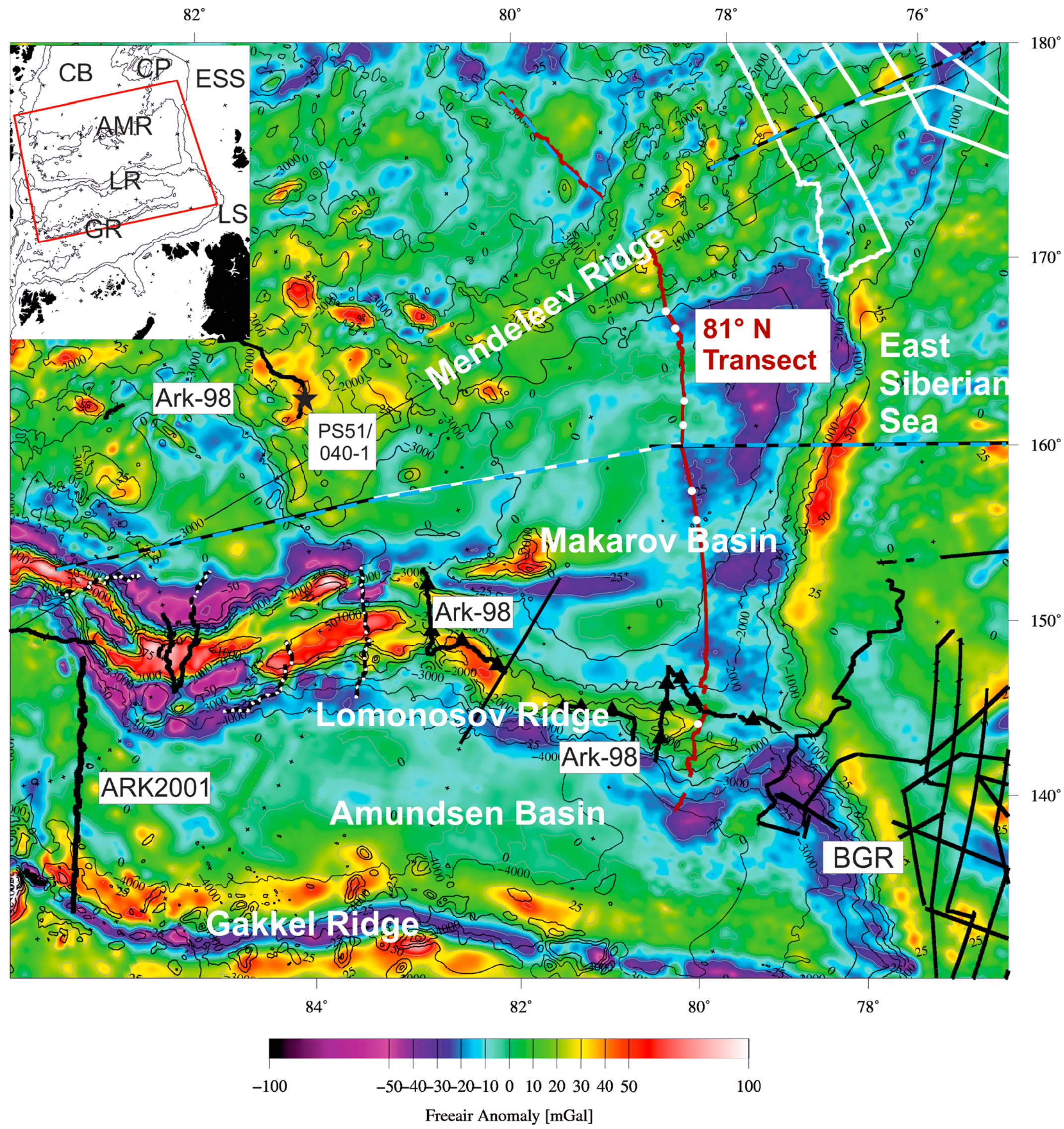

Figure 1. Free-air gravity map of the Arctic Ocean showing the geological features discussed in the text. The upper left inset shows the general tectonic ridges and basins relevant for this contribution. The dark red line indicates the 81°N seismic transect, and the white circles are for sonobuoys locations. The label PS51/040-1 marks the location where the rock sample was cored used in this study. Black-blue/white-blue dashed lines: Russian seismic refraction lines; ARK98 and ARK2001: seismic reflection lines [*Jokat*, 2003, 2005; *Jokat and Micksch*, 2004]; black-white dashed lines: seismic reflection lines from the Oden 96 cruise; white lines: seismic reflection data across the Mendeleev Ridge. Abbreviations: AMR = Alpha-Mendeleev Ridge, BGR = seismic network of the Federal Institute for Geosciences and Natural Resources, ESS = East Siberian Sea, LR = Lomonosov Ridge, LS = Laptev Sea, MR = Mendeleev Ridge, CB = Canada Basin, CP = Chukchi Plateau, GR = Gakkel Ridge.

important constraint. However, a more detailed discussion of the seismic data along the entire transect will be introduced in another article.

[5] The $^{40}Ar/^{39}Ar$ incremental heating experiment age reported here provides the first direct age constraint for the AMR basement. The dated volcanic sample (Figure 1) was recovered from the slope of a graben-like structure at the westernmost part of the Alpha Ridge (85°30.8′N, 174° 11.4′W) during the 1998 FS *Polarstern* research cruise ARK-XIV/1a [*Jokat et al.*, 1999; *Mühe and Jokat*, 1999; *Jokat*, 2003]. Approximately 1 kg of volcanic rock was recovered fortuitously when a sedimentary corer hit bedrock at a water depth of 2402 m [*Mühe and Jokat*, 1999]. Pieces of rock were selected for the age dating and crushed and sieved, following removal with a saw of outer surfaces and as much visible alteration as possible. We separated out sufficient plagioclase for our dating experiment using heavy liquid and magnetic separation and final handpicking to remove any remaining altered grains. After various unsuccessful dating experiments over the course of a number of separate irradiations, we succeeded in obtaining a statistically reliable analytical result using a 74–48 micron size fraction treated with 1 N HNO_3 for 60 min and washed in distilled H_2O. Plagioclase was spread across the base of 13 mm diameter flat-bottomed holes drilled in copper disks so as to ensure uniform sample heating. We incrementally heated the Alpha Ridge PS051-041-1CC plagioclase with a defocused argon laser probe (supporting information) [*Koppers et al.*, 2000;

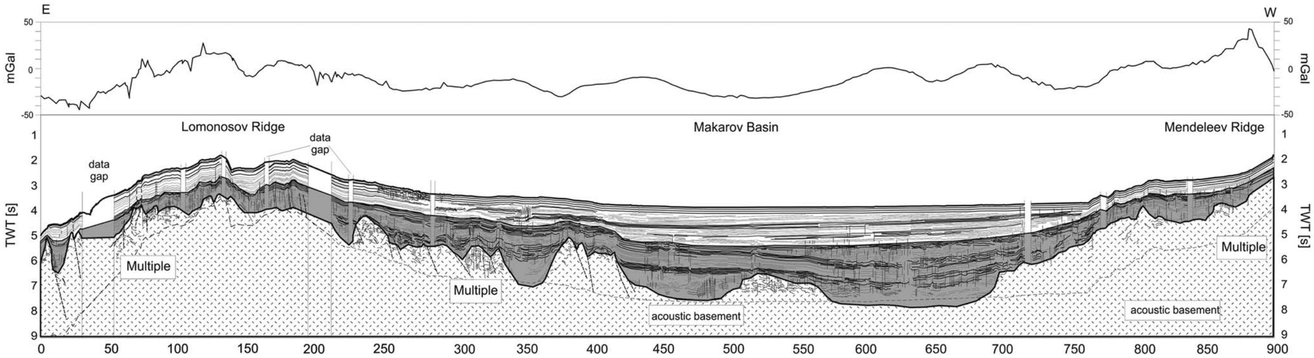

Figure 2. Line drawing of the 81°N seismic transect starting at the Mendeleev Ridge and terminating in the Amundsen Basin. The overall length is 1200 km, but only 900 km is shown here. The seismic data were gathered with a single icebreaker (R/V *Polarstern* ARK-XXIII/3), using a 300 m long streamer and an air gun cluster with a total volume of 32 L at 160 bar pressure. On top, the gravity data are plotted, which were gathered parallel to the seismic profiling. The grey shaded portion indicates the sediments deposited after the opening of the Fram Strait. The location of the first multiple is indicated to show which portions of the seismic data might be disturbed. However, this is only true for the very deep part of the MB. Other details are as in Figure 1.

Koppers, 2002; *O'Connor et al.*, 2004; *Kuiper et al.*, 2008]. Our incremental heating experiment gives an apparent age of 89 ± 1 Myr for a plateau containing 82% of the total ^{39}Ar released (supporting information). This plateau age is supported by a concordant inverse isochron and total fusion ages (supporting information).

3. Sediment Structure of the Makarov Basin

[6] The entire seismic 81°N transect (Figure 2) consists, in total, of 27 subprofiles. The data along the transect indicate that the sediment thickness between the AMR and the LR varies from 1000 to 1500 m on the Mendeleev Ridge (MR) to 6000 m in the central MB, thinning again to 1000 m on the crest of the LR. An intriguing observation is that the flank of the LR facing the Amerasia Basin extends significantly, almost to the center of the MB. Consequently, at least half of the MB basement consists of stretched continental crust covered by thick turbidite sequences. Another exciting observation is that the acoustic basement of the LR shows horst and graben structures, typical of stretched continental margins. West of km 700 (Figure 2), the acoustic basement of the MR is no longer masked by the seafloor multiple. Here the basement is gently shallowing. No horst and graben structures similar to those on the LR margin are visible. The sediment thickness across the MR varies between 1000 and 1500 km (Figure 2, km 700–900). Here the MR has a relief of more than 8 km between the deepest part of the MB and the ridge crest. Furthermore, the sediments filling the grabens of the LR flank are slightly faulted and thicken to a maximum toward the center of the basin (Figure 2, km 650). A pronounced high-amplitude layer sequence is evident close to the LR, which can be traced across the entire MB and is visible also on top of the MR. Weak faults occur below this layer sequence both in the basin and across the ridges, while almost no faulting can be observed above this remarkable strong reflector sequence (Figure 2; grey shaded area, Figure 3). The top of this sequence has, in our interpretation, a top Oligocene age correlated from a seismic network on the Chukchi Shelf [*Hegewald and Jokat*, 2013b].

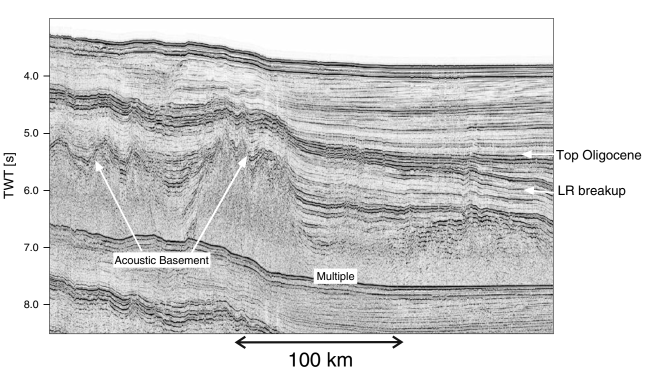

Figure 3. Stacked seismic section 20080145. Part of the 81°N transect (Figure 2, km 300–550) showing LR horst and graben structures and the center of the Makarov Basin. The labels indicate the age of the upper and lower boundaries of the seismic reflector band caused by significant oceanographic changes during the opening of the Fram Strait and the drift onset of the LR.

4. Implications for the Tectonic Evolution of the Amerasia Basin

[7] After a rifting period of unknown duration, the 1800 km long LR split off from the Siberian margins at 56 Ma, well documented by seafloor spreading anomalies in the Eurasia Basin [*Karasik*, 1968; *Vogt et al.*, 1979]. There is little doubt that during the rift-drift transition, rocks were eroded from the LR because it was subaerial, or at least close to sea level. Most of the debris was likely deposited in graben structures along the LR margin facing the Amerasia Basin and along the crest of the LR (Figure 2). In the younger sediment package, though incompletely cored because of the 20 Myr hiatus, the Arctic Coring Expedition cores show that black shales were deposited between 45 and 49 Myr on top of the ridge, indicating anoxic conditions in the Arctic Ocean. These sediments show up in the seismic data across the drill holes as a succession of high-amplitude reflectors just above the erosional unconformity. A similar band of seismic reflectors that varies in both depth and thickness is observed along the 81°N transect. Close to the LR, the strong seismic

amplitudes in this reflection sequence can be interpreted as the coarse-grained material deposited most likely close to sea level. Closer to the center of the MB, the amplitudes become subdued and split into several distinct reflectors (Figure 3). This indicates that the reflector band covers a larger time span. Even though on the LR we find a condensed section, it expands in the central MB, where it received more sediments that caused thicker sedimentary units to be deposited in medium to deep water. We infer from our depositional model that the age of the top layer is most likely top Oligocene (23 Myr) [*Hegewald and Jokat*, 2013b], while no age constraints exist for the lower boundary of the reflector band and the MB basement. However, we assume that the formation of the lower boundary of the layer package (Figure 3) can be related to the rift-drift of the LR and/or a massive change in Mesozoic depositional environment of the Arctic Ocean [*Jokat*, 2003; *Dove et al*., 2010]. This interpretation is supported by the observation that the reflector band is present even on the LR, and its lower boundary might here represent the breakup unconformity. The age of this unconformity predicted by our model is similar to that of the erosional unconformity (~57 Myr) based on seismic information [*Jokat et al*., 1992; *Jokat*, 2005] and drilling close to the North Pole [*Moran et al*., 2006]. The data support a model using this reflection sequence as a first-order time marker throughout the Mesozoic deep Arctic Ocean.

[8] One popular kinematic model for the early opening of the Arctic involves the rotational movement of Arctic Alaska [*Grantz et al*., 1990, 2011]. This model predicts that a basin-wide transform existed in the Amerasia Basin along the LR that allowed Arctic Alaska–Chukotia to rotate from the Canadian margin and to collide with northeastern Asia. The new data set can be interpreted to show either that the horst and graben structure along the western LR margin (Figure 2) formed (a) during a rift phase perpendicular to the LR or (b) by transtensional forces during the Arctic Alaska–Chukotia rotation. The present-day database does not allow one to distinguish between these two scenarios. The postulated transfer zone along the entire LR margin is most likely older than the sediments and, thus, cannot be imaged by our data. Thus, the geophysical data along the 81°N transect do not provide any new constraints on kinematic models for the initial formation of the Amerasia Basin.

5. Age Constraint on the Central Alpha-Mendeleev Ridge

[9] From the central AMR, only one rock sample (Figure 1) could be dated, which we use here to establish an upper age boundary for the AMR/MR basement. Immobile elements and pyroxene geochemistry suggest that the rock is tholeiitic and formed in a within-plate setting (supporting information). The location of the coring site [*Jokat*, 2003] shows that the basement sample might be typical for the youngest part of the AMR basement.

[10] Combining the existing seismic, magnetic, and $^{40}Ar/^{39}Ar$ age data reported in this study, we postulate that the AMR complex is at least slightly older than the sediments in the MB. We do not observe any deformation in the MB sediments that would support a synsedimentary or a postsedimentary formation of the AMR. All existing data, including the rock sample, support the model that the AMR most likely formed between 120 and 84 Ma as large igneous province. Formation of the AMR during the CNS explains why aeromagnetic data show no magnetic seafloor spreading anomalies [*Vogt et al*., 1979]. We assume that the initial volcanism along the AMR started well before 89 Ma, but still within the CNS. Finally, structural information inferred from seismic reflection and refraction data from the central AMR [*Jokat*, 2003; *Lebedeva-Ivanova et al*., 2006; *Dove et al*., 2010] and along the 81°N transect (this study) show that the MR flanks host no horst and graben structures typical for rifted continental margins and therefore expected to have formed, if the MR is the conjugate to the LR, or an old continental fragment.

[11] A consequence of our seismic data interpretation is that the Makarov Basin contains little, if any, normal oceanic crust along the 81°N transect. Almost half the basin is underlain by thinned continental crust belonging to the Amerasia flank of the LR, while the other half is occupied by the MR volcanic basement. The gap between the topographic expressions of the AMR and the LR disappears toward the Canadian margin, raising the question of how much of the former LR continental margin crust close to the Canadian margin was overprinted during the AMR formation.

6. Does/Did the Lomonosov Ridge Move Along a Transfer Fault or Not

[12] A widely discussed hypothesis for Eurasia Basin rifting is that the LR migrated to its present-day position along a major transfer fault zone located at the northern margin of the Laptev Sea [*Fujita et al*., 1990, Severnyi Transfer Zone; *Drachev et al*., 2003, Khatanga-Lomonosov Fracture], which might be still active. Consequently, the extension (400 km) in the Eurasia Basin was somehow decoupled from the extension in the Laptev Sea.

[13] *Drachev et al*. [2003] considered that the transfer zone model is supported by the asymmetric position of the Gakkel Ridge in the rift basins in the Laptev Sea, weak magnetic spreading anomalies, and other geometrical considerations. However, seismic data, critical for testing this fracture zone hypothesis, are sparse, and the few existing lines show little or no evidence of a major strike-slip zone. The only seismic line running from the shelf off the New Siberian Island onto the Lomonosov Ridge [*Laverov et al*., 2013] shows diffractions in the upper and lower crust, but a mainly undisturbed Cenozoic sediment cover. These seismic data indicate that the Mesozoic rifting and the final rupture of the LR from the Siberian Shelf caused faulting in the upper and lower LR crust, particularly during the initial phase of the rifting. However, the constant movement of the LR along a major strike-slip zone should have caused the development of faults in the Cenozoic sediments. Here our interpretation of the data differs from the original one [*Laverov et al*., 2013]. The absence of such faults strongly argues against a strike-slip zone being active during the entire Cenozoic. The sediment structure along the 81°N transect supports this view. A consequence of a relative movement of the LR along a strike-slip zone would be that the adjacent MB should be shortened and/or that at least some compressional features should be evident in the Cenozoic sediments. However, no such features are visible in the seismic data presented here. The weak faults below the top Oligocene unconformity might have been caused by movements of the LR but this cannot account for the space needed for the opening of the Eurasia Basin. In addition,

there is no evidence for significant present-day earthquake activity at the junction of the LR with the Siberian Shelf, or in the East Siberian Sea, where the eastern prolongation of the Khatanga-Lomonosov/Severnyi Transfer Zone might be located. Moreover, the seismic data support a two-phase model: (1) the Khatanga-Lomonosov/Severnyi Transform Zone existed during the initial rift-drift stage, with activity terminating in the Late Cretaceous before a significant amount of sediments were deposited in the MB. However, the relative movements were not large; and (2) the LR became attached to the East Siberian margin and the onshore extension was compensated by the Laptev Sea rift.

[14] Thus, we conclude that the LR was roughly in the same position relative to the Laptev Sea/East Siberian Island margin during the Cenozoic. The weak faulting of the deeper sedimentary column along the 81°N transect might be due to far-field stresses caused by the rifting and initial drift of the LR. In our interpretation, the sediment deposition imaged along the transect postdates any major tectonic activity. The MR formed as a volcanic structure during the CNS and does not represent a conjugate continental rifted margin to the LR. Finally, the structural elements in the Amerasia Basin transected by our profile did not move relative to each other, most likely since the termination of volcanic activity along the AMR and the early drift phase of the LR. Altogether, the seismic data support the interpretation that after the breakup of the LR from the Siberian margins, the entire Amerasia Basin, together with the LR, moved as a single plate.

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References

Dove, D., B. Coakley, J. Hopper, Y. Kristoffersen, and HLY0503 Team (2010), Bathymetry, controlled source seismic and gravity observations of the Mendeleev ridge; implications for ridge structure, origin, and regional tectonics, *Geophys. J. Int.*, *183*, 481–502, doi:10.1111/j.1365-246X.2010.04746.x.

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.

Fujita, K., D. B. Cook, H. Hasegava, D. Forsyth, and R. Wetmiller (1990), Seismicity and focal mechanisms of the Arctic region and the North American plate boundary in Asia, in *The Arctic Ocean Region*, Geol. North Am., vol. L, edited by A. Grantz, L. Johnson, and J. F. Sweeney, pp. 79–100, Geol. Soc. of Am., Boulder, Colo.

Grantz, A., S. D. May, P. T. Taylor, and L. A. Lawver (1990), Canada Basin, in *The Arctic Ocean Region*, Geol. North Am., vol. L, edited by A. Grantz, G. L. Johnson, and J. F. Sweeney, pp. 379–402, Geol. Soc. of Am., Boulder, Colo.

Grantz, A., P. E. Hart, and V. A. Childers (2011), Geology and tectonic development of the Amerasia and Canada Basins, Arctic Ocean, in *Arctic Petroleum Geology*, Geol. Soc. Mem., vol. 35, edited by A. M. Spencer et al., pp. 771–799, Geol. Soc. of London, London.

Hegewald, A., and W. Jokat (2013a), Relative sea level variations in the Chukchi region—Arctic Ocean—since the Late Eocene, *Geophys. Res. Lett.*, *40*, 803–807, doi:10.1002/GRL.50182.

Hegewald, A., and W. Jokat (2013b), Tectonic and sedimentary structures in the northern Chukchi region, Arctic Ocean, *J. Geophys. Res. Solid Earth*, *118*, 3285–3296, doi:10.1002/jgrb.50282.

Jokat, W. (2003), Seismic investigations along the western sector of Alpha Ridge, central Arctic Ocean, *Geophys. J. Int.*, *152*(1), 185–201, doi:10.1046/j.1365-246X.2003.01839.x.

Jokat, W. (2005), The sedimentary structure of the Lomonosov Ridge between 88°N and 80°N: Consequences for tectonic and glacial processes, *Geophys. J. Int.*, *163*, 698–726, doi:10.1111/j.1365-246X.2005.02786.x.

Jokat, W., and U. Micksch (2004), Sedimentary structure of the Nansen and Amundsen basins, Arctic Ocean, *Geophys. Res. Lett.*, *31*, L02603, doi:10.1029/2003GL018352.

Jokat, W., G. Uenzelmann-Neben, Y. Kristoffersen, and T. Rasmussen (1992), ARCTIC´91: Lomonosov Ridge—A double sided continental margin, *Geology*, *20*, 887–890.

Jokat, W., R. Stein, E. Rachor, I. Schewe, and Shipboard Scientific Party (1999), Expedition gives fresh view of central Arctic geology, *Eos Trans. AGU*, *80*(465), 472–473.

Karasik, A. M. (1968), Magnetic anomalies of the Gakkel Ridge and the origin of the Eurasia subbasin of the Arctic Ocean [in Russian], *Geofiz. Razved. Methods Arktika*, *5*, 8–19.

Koppers, A. A. P. (2002), ArArCALC—Software for ^{40}Ar/^{39}Ar age calculations, *Comput. Geosci.*, *5*, 605–619.

Koppers, A. A. P., H. Staudigel, and J. R. Wijbrans (2000), Dating crystalline groundmass separates of altered Cretaceous seamount basalts by the ^{40}Ar/^{39}Ar incremental heating technique, *Chem. Geol.*, *166*, 139–158.

Kuiper, K. F., A. Deino, F. J. Hilgen, W. Krijgsma, P. R. Renne, and J. R. Wijbrans (2008), Synchronizing rock clocks of Earth history, *Science*, *320*, 500–504.

Laverov, N. P., L. I. Lobkovsky, M. V. Kononov, N. L. Dobretsov, V. A. Vernikovsky, S. D. Sokolov, and E. V. Shipilov (2013), A geodynamic model of the evolution of the Arctic Basin and adjacent territories in the Mesozoic and Cenozoic and the outer limit of the Russian continental shelf, *Geotectonics*, *47*(1), 1–30.

Lawver, L. A., and R. D. Müller (1994), Iceland hotspot track, *Geology*, *22*, 311–314.

Lebedeva-Ivanova, N. N., Y. Zamansky, A. Langinen, and M. Sorokin (2006), Seismic profiling across the Mendeleev Ridge at 82°N: Evidence of continental crust, *Geophys. J. Int.*, *165*, 527–544.

Moran, K., et al. (2006), The Cenozoic palaeo-environment of the Arctic Ocean, *Nature*, *441*, 601–605, doi:10.1038/nature04800.

Mühe, R., and W. Jokat (1999), Recovery of volcanic rocks from the Alpha Ridge, Arctic Ocean: Preliminary results, *Eos Trans. AGU*, 80, San Francisco, F1000.

O'Connor, J. M., P. Stoffers, J. R. Wijbrans, P. Stoffers, and J. R. Wijbrans (2004), The Foundation Chain: Inferring hotspot-plate interaction from a weak seamount trail, in *Oceanic Hotspots*, edited by R. Hekinian, P. Stoffers, and J.-L. Cheminée, pp. 349–372, Springer, Berlin, Heidelberg, New York.

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

Vogt, P. R., P. T. Taylor, L. C. Kovacs, and G. L. Johnson (1982), The Canada Basin: Aeromagnetic constraints on structure and evolution, *Tectonophysics*, *89*, 295–336.