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Tectonic Elements of the Arctic Region Inferred from Small-Scale Geophysical Fields

S. Yu. Sokolov

Geological Institute, Russian Academy of Sciences, Pyzhevskii per. 7, 119017, Russia
e-mail: geophys@ginras.ru

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Abstract—Satellite altimetry data, Bouguer anomalies, anomalous magnetic field, bottom topography, and Love wave tomography for the deepwater part of the Arctic Ocean Basin and East Siberian Sea have made it possible to detect several new regional tectonic elements. The basin area, 700 km wide and 1800 km long, extending from the Laptev Sea to the Chukchi Borderland is a dextral strike-slip zone with structural elements typical of shearing. The destruction of the Eurasian margin surrounding the Amerasia Basin occurs within this zone. The opening of the Amerasia Basin is characterized by intense plume magmatism superimposed on normal slow spreading in several areas of the paleospreading axis. Magma was supplied through three conduits with minor offsets, the activity of which waned partly or completely by the end of basin formation. The main central conduit formed the structure of the Alpha Ridge. The dextral strike-slip system, which displaces the Gakkel Ridge and structural elements in the basement of the Makarov Basin, most likely extends to the northern termination of the Chukchi Borderland.

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INTRODUCTION: CURRENT CONCEPTS, INITIAL DATA, AND APPROACH TO INVESTIGATION

Various aspects of Arctic tectonics (Fig. 1) have been considered by many researchers. Worth mentioning here are primarily the publications integrating voluminous geological and geophysical data on the onshore and offshore parts of the Arctic region: the 50th volume of the multivolume *The Geology of North America* [33], the monographs published by scientists from VNIIOkeangeologiya [16 and others], the book on geodynamics of seismoactive zones [1], and [28] as well. Most authors support the concept of regional tectonic evolution as the staged opening of the Amerasia Basin (from ~157 to ~120 Ma ago) followed by the opening of the Eurasia Basin (from 56 Ma and until now) with the spreading axis oriented perpendicular to the paleospreading axis of the former basin. At the same time, some aspects of this evolution, for example, the nature of the Alpha Ridge and its formation mechanism, the azimuth of accretion of the basinal lithosphere, and others, remain debatable. The combined analysis of new data and small-scale geophysical fields provides insights into the tectonic history of the region.

Tectonic mapping of the oceanic bottom and the adjacent shelf is mostly based on geophysical data. The coverage of oceans and seas (the Arctic Ocean, in particular) by detailed seismic survey and drilling is scanty in comparison with similar investigations on land. Therefore, an integral image of the tectonic structure in the Arctic Ocean is based on small-scale geophysical fields. Of particular importance is the uniform informational coverage of the region. Only in this case do the comparative characteristics of different regions become reliable. The density of available data may be higher or lower, but their uniformity is desirable. The uniform coverage is inherent to global seismic tomography, anomalous magnetic field, bottom topography, and satellite altimetry combined with on-board measurements and recalculation into free-air and Bouguer gravity anomalies. The tectonic and geodynamic interpretation of these integral parameters is given in [31]. The knowledge of the configuration of these fields and the relationships between zones and blocks with similar field patterns, as well as the joint analysis of different fields gives an opportunity to compile a small-scale (approximately 1 : 30000000) tectonic scheme of the Arctic Ocean. It should be noted that most geophysical maps used in this work (except for Love surface waves) were prepared on a scale of about 1 : 3000000 and their analysis was carried out at this scale, which cannot be reproduced here for technical reasons. These maps are free for access in digital formats compatible with geoinformation medium and can be used by the scientific community for various purposes.

In tectonic mapping, preference was traditionally given to bottom topography because of the better knowledge of bathymetry in comparison with geophysical fields. Precisely bottom topography was used as a basis for compiling the oceanic segment of the tectonic map of the world on a scale of 1 : 45000000 [18]. It should be noted that this map is a reproduction of the same map on a scale of 1 : 15000000, and its loading

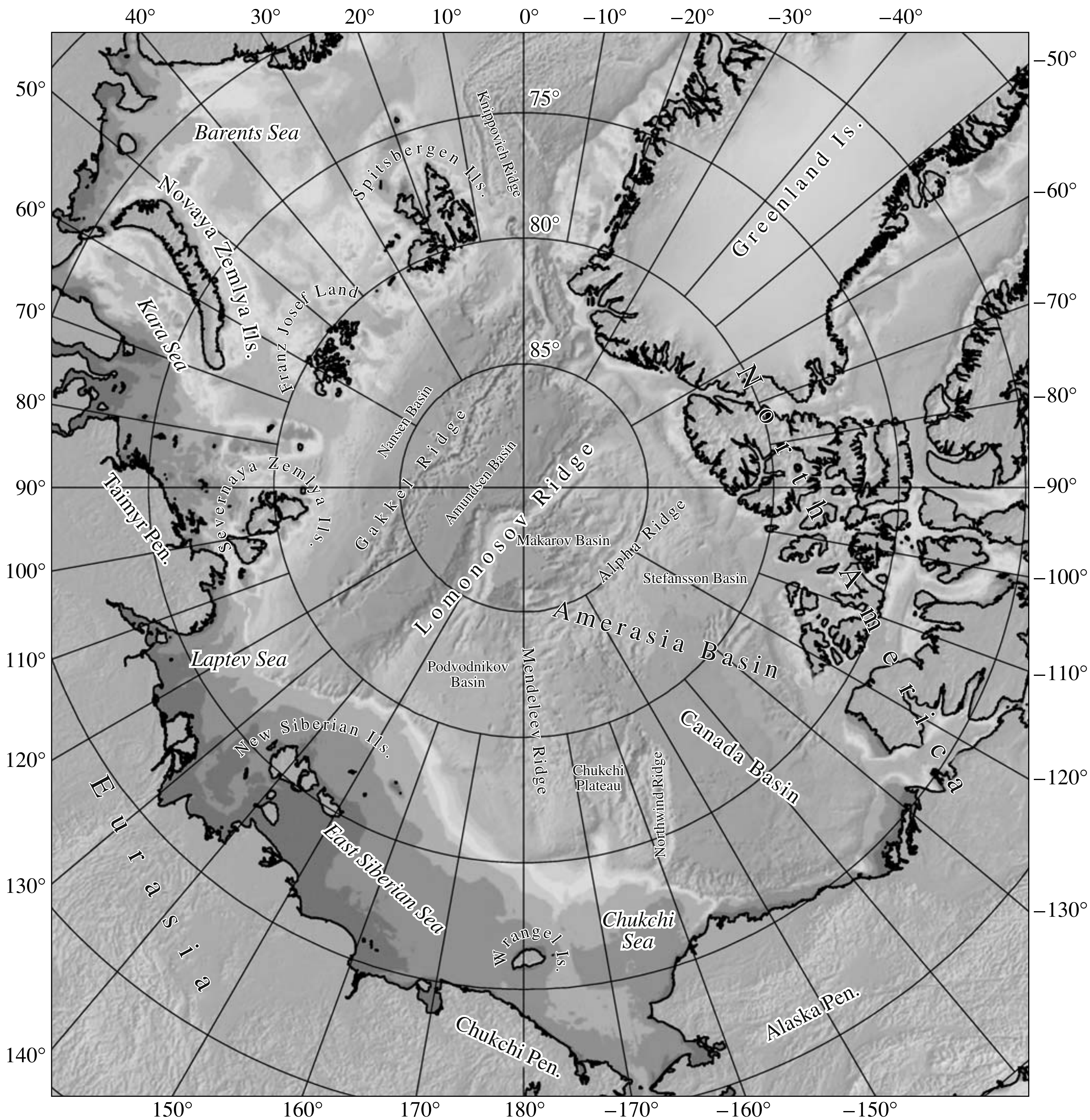

Fig. 1. Main geographic objects of the Arctic region (toponymy of the bottom and and the adjacent land).

with oceanic tectonic elements remains practically unchanged. The following structural elements are shown in the tectonic map of oceans: mid-ocean ridges; axial zones (flanks of ridges); deepwater basins; fault-line basins; zones of exposed rock of the second and the third oceanic crustal layers, including ultarmafics; intraplate rises; transform fracture zones and other disturbances of various kinematic types; transitional zones; continental microplates; and shelf areas. This set is retained in the given publication. The tectonic elements listed above are commonly expressed in topography, but diverse geophysical parameters make it possible to specify substantially their configuration, give a new perspective on their nature, and allow their detection in areas where bathymetric data are insufficient for this purpose.

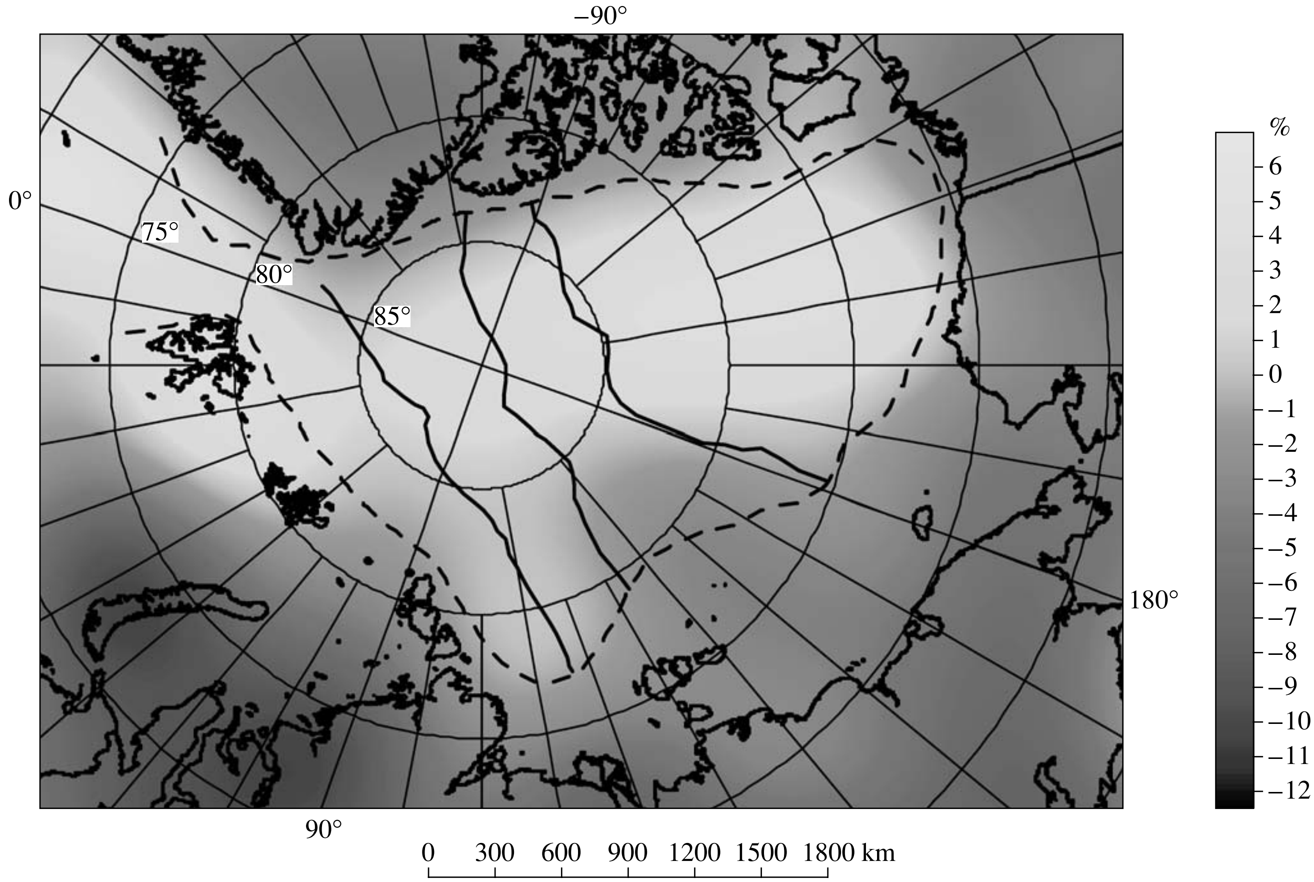

Fig. 2. Love surface wave tomography (harmonics period of 35 s), after [27]; position of axes of the Gakkel, Lomonosov, and Mendeleev ridges, and shelf edge (dashed line). The reference grid in this and other figures has 10-degree spacing of longitudes for the segments south of 80° N, and 30-degree and 90-degree spacings for the segments located north of 80° N. Latitudes are spaced at 5°. The polar stereographic projection on sphere 6370997 m is used; central meridian is 110° E; latitude is 90° N.

INTERPRETATION OF SURFACE WAVE TOMOGRAPHY

The Arctic Ocean comprises areas underlain by continental and oceanic crusts. In oceans with passive margins, the boundary between these domains is provisionally drawn along the shelf edge, except for the situation when geophysical data indicate the existence of detached blocks of the continental crust beyond the shelf, for example, the Rockall Plateau in the North Atlantic. The Love surface wave tomography [27] shows significant correlation of negative and positive anomalies with continental and oceanic crusts, respectively (Fig. 2).

The comparison of the zero position of this anomaly and the shelf edge indicates principal coincidence and two noteworthy exceptions. The first exception consists in the significant (approximately by 450 km) advancement of the “continental” anomaly in the Lomonosov and Mendeleev ridges and the adjacent oceanic area. Inasmuch as the horizontal accuracy of this coverage is 200 km, the configuration of the anomaly cannot indicate the exact limits of the block with the continental crust, although it is evident that continental fragments exist in this area. The second exception is related to the “oceanic” anomaly beneath the Spitsbergen Archipelago and western Franz Josef Land (Fig. 2). The horizontal and positive vertical movements, Quaternary volcanism, near-meridional magnetic anomalies, and elevated heat flow most likely testify to a new tectonic stage in the evolution of this segment of the Eurasian margin. This topic is omitted from further discussion.

INTERPRETATION OF ANOMALOUS MAGNETIC FIELD

The anomalous magnetic field shown in Fig. 3 after [35] is extremely important for recognition of tectonic elements. Such an interpretation is presented in [21, 32, 36]. All researchers were unanimous in their opinion that despite the spreading mechanism of ocean formation, the rises of the Arctic Ocean Basin, including the Alpha and Lomonosov ridges, are of the continental nature. This was confirmed by the apparent thickness of the magnetic layer (30 km) established from the MAGSAT and some DSS data. In addition, it was suggested that the

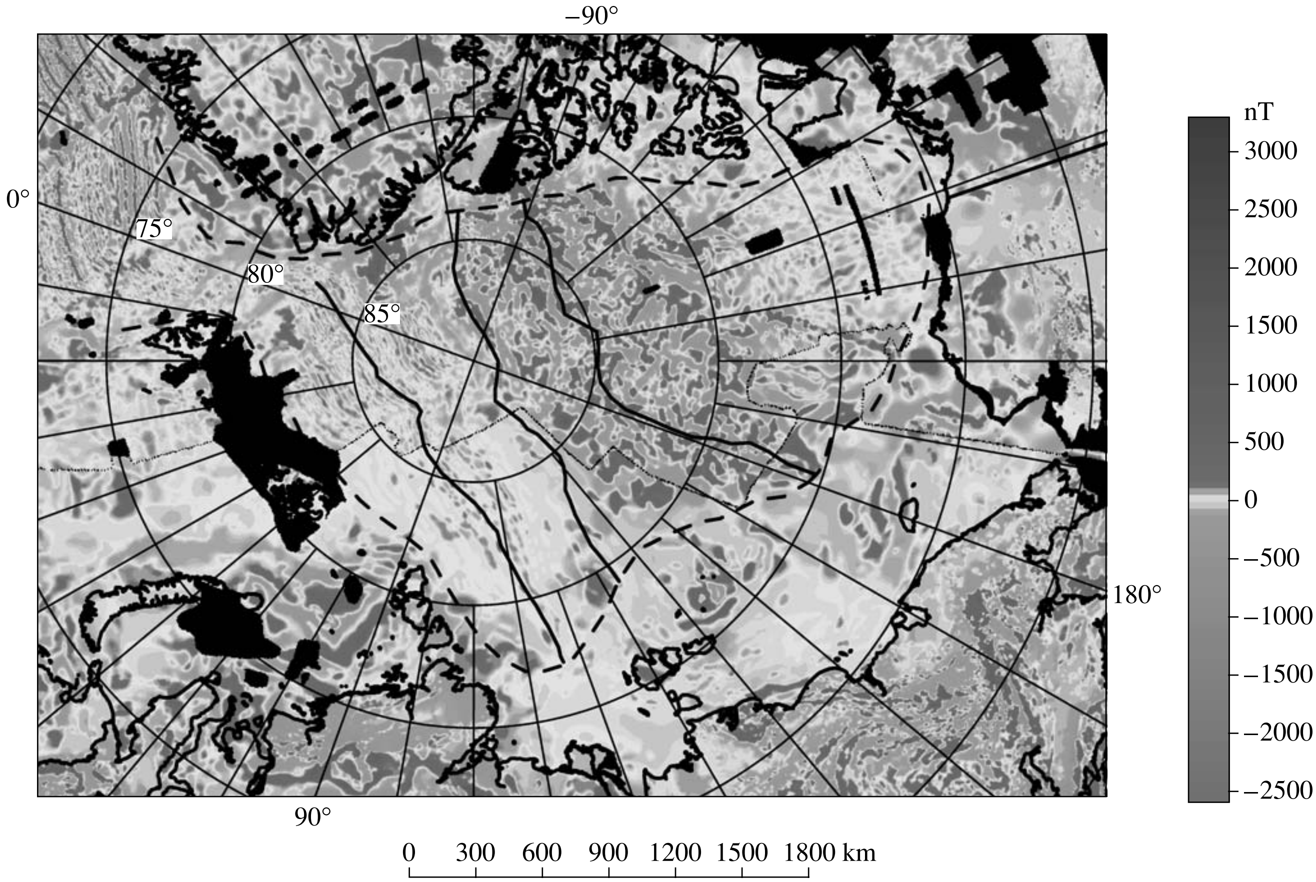

Fig. 3. The anomalous magnetic field, after [35] and position of axes of the Gakkel, Lomonosov, and Mendeleev ridges and shelf edge (dashed line). The areas devoid of data in the digital coverage are black.

present-day Alpha and Lomonosov ridges were separated by a spreading center that predated the onset of the opening of the Eurasia Basin beginning from the 24th anomaly (56 Ma ago). It was also suggested that the Chukchi Plateau occupied its position relative to the North America Plate owing to local spreading with the axis parallel to the eastern edge of the plateau from 157 to 141 Ma ago. Afterward, the paleospreading axis changed its orientation for the median position in the Canada Basin. The same hypothesis is considered in [5]. It should be noted that the most complete and adequate interpretation of the magnetic field of the Amerasia Basin as of 1990 was based on a system of profiles oriented perpendicular to the Lomonosov and Alpha ridges, and this circumstance determined, to a great degree, the hypothesis of the intermediate spreading center between these morphostructures.

Subsequently, a more adequate integration of data on the anomalous magnetic field was conducted, taking the results of a recent aeromagnetic survey into account; details can be found in [2, 3]. According to these data, the origin of the Eurasia Basin is the least debatable. The authors give a comprehensive review of existing hypotheses concerning the origin of the Central Arctic rises in the Amerasia Basin and arrive at the conclusion that they belong most likely to the continental lithosphere affected by mantle plume [2, p. 145]. The hypotheses of the origin of the Alpha–Mendeleev ridge system are discussed in [13]. According to the recent hypothesis, the autonomous spreading center existed between the Lomonosov and Alpha ridges, being connected by a triple junction with the spreading zone of the Canada Basin, which functioned from 157 to 140 Ma [6] or from 157 to 120 Ma [28].

It is understandable why the opening of the Amerasia Basin is constrained by the above time intervals. The period from 120 to 85 Ma ago was marked by calm magnetic field without polarity reversals and corresponding linear anomalies used for reconstruction of crust accretion in spreading zones. The authors tried to find the time for all events prior to this period. If this was the case, the segment of the basin adjacent to North America, which is approximately 1100 km wide, would have been opening in the period of 132 to 129 Ma ago at a rate of 36 cm/yr (the half-rate is 18 cm/yr) [28]. Such high velocities are not reported for any other basin of the Arctic Ocean and seem unrealistic. According to the triple junction model [6], the total rate of opening is estimated at ~8.4 cm/yr (half-rate 4.2 cm/yr), which is more realistic. However, this model requires the accre-

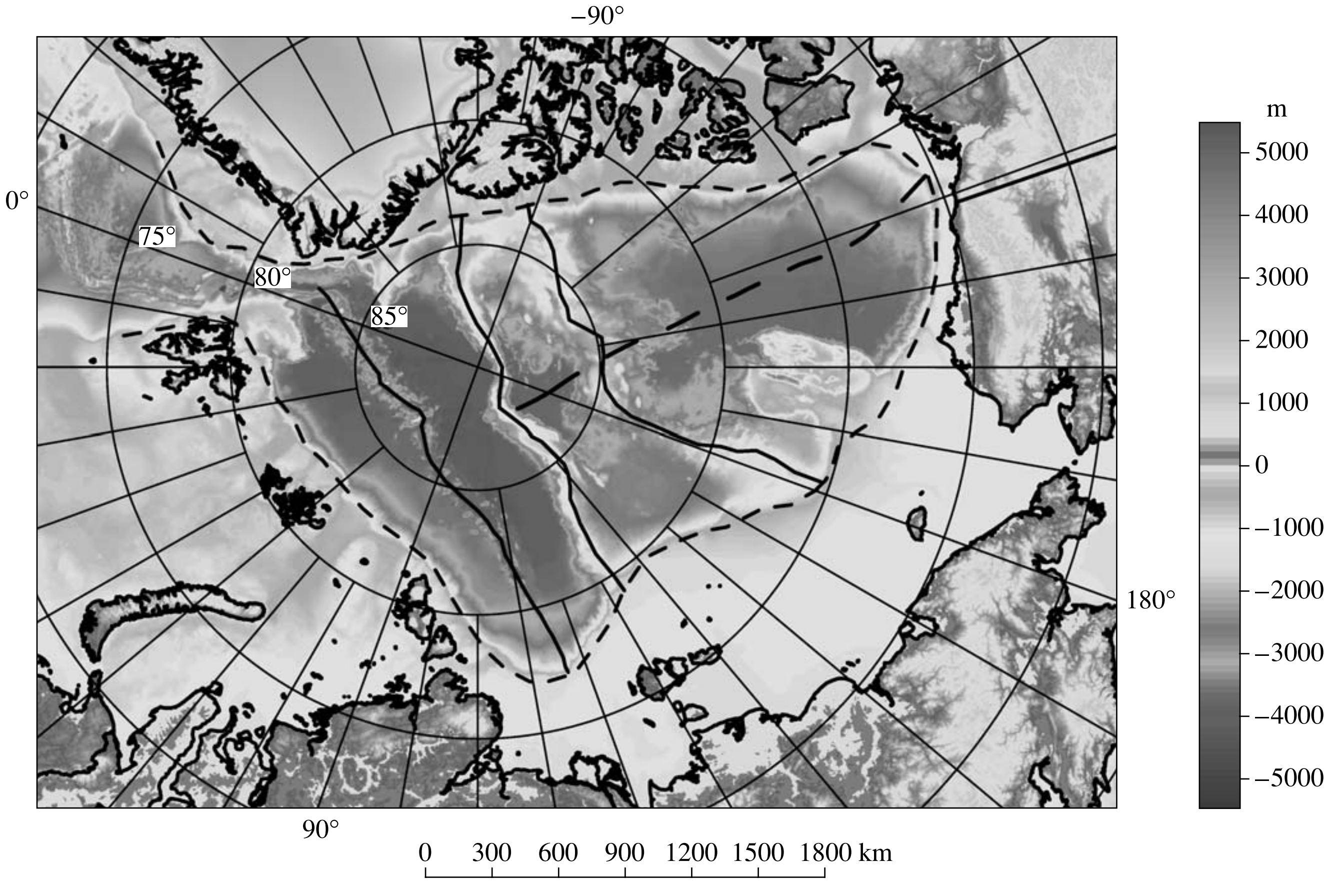

Fig. 4. The bottom topography, after [25]; position of axes of the Gakkel, Lomonosov, and Mendeleev ridges, shelf edge (dashed line), and paleospreading axis (sparse dashed line).

tion direction perpendicular to the Lomonosov Ridge and thus contradicts the tectonic structure of the basin framework, which is consistent with the rotation hypothesis [19] assuming that the basin opening in the Late Jurassic–Early Cretaceous followed the counterclockwise rotation of the surrounding structures of northeastern Eurasia and Alaska relative to the center in the northwestern Canadian Shield.

The recognition of linear magnetic anomalies in the Amerasia Basin meets difficulties. Weak trends are traditionally recognized in maps by shading technique. Shading of the anomalous magnetic field in the Arctic Ocean Basin from 125° W [3] allows identification of linear objects that fit the interpretation proposed in [6]. The shading of the anomalous magnetic field from other azimuths has shown that the intense mosaic field (Fig. 3) gives rise to pseudolinear objects perpendicular to the direction of light source at any shading. In addition, the cartographic image appears to be very sensitive to small variations in the field related to errors and artifacts caused by joining of the map segments or trails of observation systems. Because of this, I have rejected the shading technique. Visual analysis of the magnetic field in the area of Iceland shows that intense magmatism beneath spreading zone forms pseudolinear features in the newly formed crust, which are perpendicular to the real spreading axis, so that when its position is unknown, a mistake in determination of the accretion azimuth by 90° cannot be ruled out.

The structure and development of the Eurasia Basin deduced from anomalous magnetic field is the least debatable [13]. The system of linear anomalies is characterized here by the patterns typical of oceanic spreading zones distorted by the dextral transform offset at 63° E. The offset by about 25 km is confirmed by multibeam bathymetric survey performed under the ice in the Gakkel Ridge area in the framework of the SCICEX project [30]. In addition, the ridge in this area is characterized by a bend that mimics the configurations of the Eurasian margin and Lomonosov Ridge. Pseudosymmetrical paired anomalies characterized by similar rather than absolutely symmetrical patterns relative to the Gakkel Ridge are recognized in the western part of the basin. They occupy a large area devoid of linear anomalies on the Yermak and Morris Jessup plateaus. Similar pseudosymmetrical paired anomalies are also observed in the eastern part of the basin, where their sources are likely located in the acoustic basement overlapped by sedimentary cover. These anomalies are not expressed in uplifts or basement juts. The Amerasia Basin is characterized by a different pattern of anomalous magnetic field without distinct linear anomalies parallel to the spreading axis. The paleospreading axis in the Canada Basin is recognized explicitly only in the gravity field (see below). The anomalous magnetic field is a contrasting mosaic [3] more resembling the patterns on the continent [2] rather than the typical spreading field. As was mentioned above, the anomalous magnetic field in the area of Iceland demonstrates a similar pattern but within a small area, with interference of relatively weak spreading component and intense mosaic anomalies related to spacious eruptions of basaltic magma instead of a single fissure. Nevertheless, the linear anomalies in the Iceland area are identified reliably because the basaltic crust was formed during a relatively young epoch with distinct polarity reversals. As is suggested, e.g., in [2], opening of the Amerasia Basin was stimulated by development of the mantle plume, which produced basalts over a large area with the mosaic pattern of anomalous magnetic field. It should be noted that the absence of linear magnetic anomalies may be explained by real accretion of the oceanic crust later, in the Cretaceous (<120 Ma ago), and with a rate of 2.6 cm/yr characteristic of the Canada Basin [2]. Inasmuch as the similarity between the mosaic anomalous magnetic field of central ridges and the field of continental trap magmatic provinces [2] is determined by extensive plume magma source in the mantle rather than by the continental type of the crust, it would be reasonable to explain the magnetic field patterns of this area by its passage over a hotspot during the Canada Basin opening in the Jurassic–Cretaceous [13, 34].

The zone of the calm magnetic field in the shelf area of the Laptev and East Siberian seas is another feature of the anomalous magnetic field (Fig. 3). The exception is the zone of the De Long massif and Vrangel Island, which extends between the Lomonosov and Mendeleev ridges for a distance approximately equal to that established for the anomaly in the surface wave tomography (Fig. 2). Such a coincidence is hardly accidental. The segment of the Lomonosov Ridge adjoining Eurasia is characterized precisely by a low-amplitude uniform anomalous magnetic field similar to that of the abovementioned shelf areas. The anomalous magnetic field of the Chukchi Plateau is also mosaic, although it is more similar to the De Long massif than to the Amerasia Basin. Thus, we complete our review of the general features of the anomalous magnetic field in the Arctic Ocean Basin.

INTERPRETATION OF HETEROGENEOUS BOTTOM TOPOGRAPHY

The bottom topography is shown in Fig. 4 after [25]. A detailed geomorphic description of bottom topography in the Arctic Ocean Basin is presented in [12]. As is shown, the area between the Lomonosov and Men-

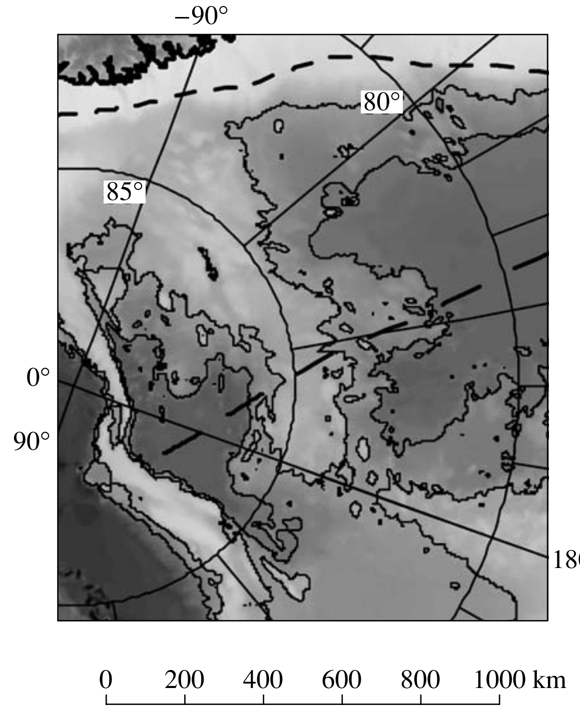

Fig. 5. The Alpha Ridge area (magnified).

deleev ridges contains many pseudosymmetrical pairs of bottom or acoustic basement uplifts (Fig. 5). Similar structural elements are known from all oceans as a result of superposition of deep plume magmatism with enriched TOP1 basalts (E-MORB) on the spreading axis characterized by background TOP2 basalts (N-MORB) principally different in chemical composition [7]. Displacements of the spreading axis relative to the deep plume source are accompanied by distortion in symmetry (for example, the pair of the Rio Grande Rise and Walvis Ridge). If the average depth of the abyssal zone is 4100–3800 m, then the rises composed of igneous rocks related to intense plume activity are contoured by isobaths 3600–3300 m. This difference is traced in all oceans as a response to interaction of the standard oceanic lithosphere with hotspots. It is also noted [10] that the crust thickness of such rises (for example, Iceland) is comparable to that of the continental crust (up to 30 km) and the seismic wave velocities of 6.0–6.2 km/s typical of the "granitic" layer are recorded in velocity sections. In my opinion, the combination of these features does not allow unambiguous interpretation of the crust in the Arctic Ocean Basin as pertaining to the continental type [14].

Several symmetrical pairs are recognized in the topography and gravity field in both the Eurasia (Fig. 4) and Amerasia (Fig. 5) basins (see below). Their contours are distinctly outlined by isobaths of 3300 and 2500 m and their configuration determines the position of the paleospreading axis as a line of symmetry drawn according to the median principle from the Canada

Basin to the Lomonosov Ridge (Figs. 4, 5). The location of this axis in the Canada Basin is emphasized by a distinct linear gravity minimum that marks the last basalt eruption. Such interpretation rules out paleospreading in the Makarov Basin along the axis parallel to the Lomonosov and Alpha–Mendeleev ridges and confirms the origin of central rises as a track of hotspot in the oceanic abyssal zone [13, 34] situated in the Arctic Ocean Basin at a depth of 3650 m. The interpretation assuming that these rises are blocks detached from Eurasia [19] is hardly valid. On the basis of anomalous magnetic field, the Alpha–Mendeleev Ridge was regarded in [12] as a residual continental jut. In my opinion, the anomalous magnetic field similar to that in extensive areas of hotspot magmatism and its combination with other parameters indicates the oceanic nature of the rises under consideration; heterogeneities in the topography confirm this conclusion.

The basalt sample dredged at station PS511040-1 (SL) (85°30.64′ N, 174°10.20′ W) and described in the field report of the Arctic Expedition of the Alfred Wegener Institute for Polar and Marine Research (Germany) in 1998 was dated at 83 Ma [8]. In the report, this sample is characterized as the most promising for determining the age of the Alpha Ridge, which is currently deduced from plate tectonic reconstructions. Taking into consideration that the dredging site is located 95 km from the paleospreading axis (the spreading rate is 4.2 cm/yr), this estimate should be decreased by 2.3 Ma. Thus, the final stage of the Amerasia Basin opening and formation of the Alpha Ridge should be dated at 80 Ma. The period of the basin formation is limited by 157 and 80 Ma ago. This implies that a tract of the oceanic crust approximately 1350 km wide was formed at a rate of 1.75 cm/yr (half-rate is 0.88 cm/yr).

This value seems more realistic taking into consideration the ultraslow spreading in the polar region. Nevertheless, this inference based on only a single sample cannot be deemed reliable.

The spreading axis (Fig. 4) divides the Canada Basin into two unequal parts. Its segment between the paleospreading axis and Eurasia is 200–300 km wider than that adjacent to North America. The position of structural elements relative to the paleospreading axis is close to symmetrical; therefore, the mentioned excess in area may be explained by the suggestion that the Eurasian part of the Mendeleev Ridge, Chukchi Plateau, and Lomonosov Ridge are detached fragments of the Eurasian continent: the Mendeleev Ridge and Chukchi Plateau are fragments of the shelf of the East Siberian Sea and the Lomonosov Ridge is a fragment of the Barents–Kara–Laptev Block [19]. Beyond the northern boundary of these structural elements, the continental crust is unknown. Some geophysical arguments confirming this viewpoint are presented above. Let us consider now the gravity field.

INTERPRETATION OF GRAVITY FIELD

The Faye's free-air gravity anomalies are shown in Fig. 6 after [22]. It is known that the Faye's anomalies are proportional to the bottom topography as the most contrasting density boundary, and, to a lesser extent, to density heterogeneities. As a rule, this requires calculating Bouguer anomalies, which eliminate the effect of bottom topography known from independent measurements. When the basin basement is overlain by a thick sedimentary sequence, contrasting in density with respect to the basement, the Faye's anomalies reflect the topography of the basement buried beneath sediments. The shelf edge coincides with a chain of marginal maximums, which mark zones with the greatest sediment thickness unaffected by isostatic compensation. The pattern of the Faye's anomalies reflects distinctly the basement topography and, in the areas with flat bottom topography due to the thick sedimentary cover, makes it possible to trace the basement roof. This is also true of the shelf basement. The features deduced for the Makarov Basin from the Faye's anomalies (Figs. 4, 5) confirm the interpretation given in the preceding section.

The relationships between anomalous blocks of the deep portion of the East Siberian Sea and its shelf may be explained by the development of NE-trending strike-slip faults, which cross both these structural elements. The localization of these faults is discussed in the final section of the article. The depressions oriented parallel to the edge of the shelf in the East Siberian Sea were formed in the Late Cretaceous approximately 70 Ma ago [23, 29]. They consist of a main trough extending for almost 1100 km and offsets that cross the De Long Rise and New Siberian Islands in the near-meridional direction (Fig. 6). The main trough started forming in response to forces that initiated the opening of the Eurasia Basin and created conditions favorable for dextral strike-slip transform fracturing [23] (see final section) in the Amerasia Basin under extension conditions [23]. A sedimentary sequence up to 7 km thick filled the depressions that arose in the Late Cretaceous. The minor near-meridional depressions near the De Long Rise are independent of the main trough. Nevertheless, the Faye's anomalies demonstrate that the small depressions are conjugated with the main trough as a system of splaying grabens that resulted from the dextral strike-slip displacement of the northern part of the shelf. The authors of [23] argue against the origin of these depressions under the effect of a hypothetical spreading axis in the Makarov Basin oriented parallel to the Lomonosov Ridge and contend that they are a system of pull-apart basins closely related to the strike-slip faulting in the region.

To the east, in the Chukchi Plateau area, the main trough bends to pass into the Hana Trough, whose orientation indicates the general dextral strike-slip displacement of basement structures [29]. Another depression broadly parallel to this bend is suggested in the area south of Vrangel Island. Thus, the dextral strike-

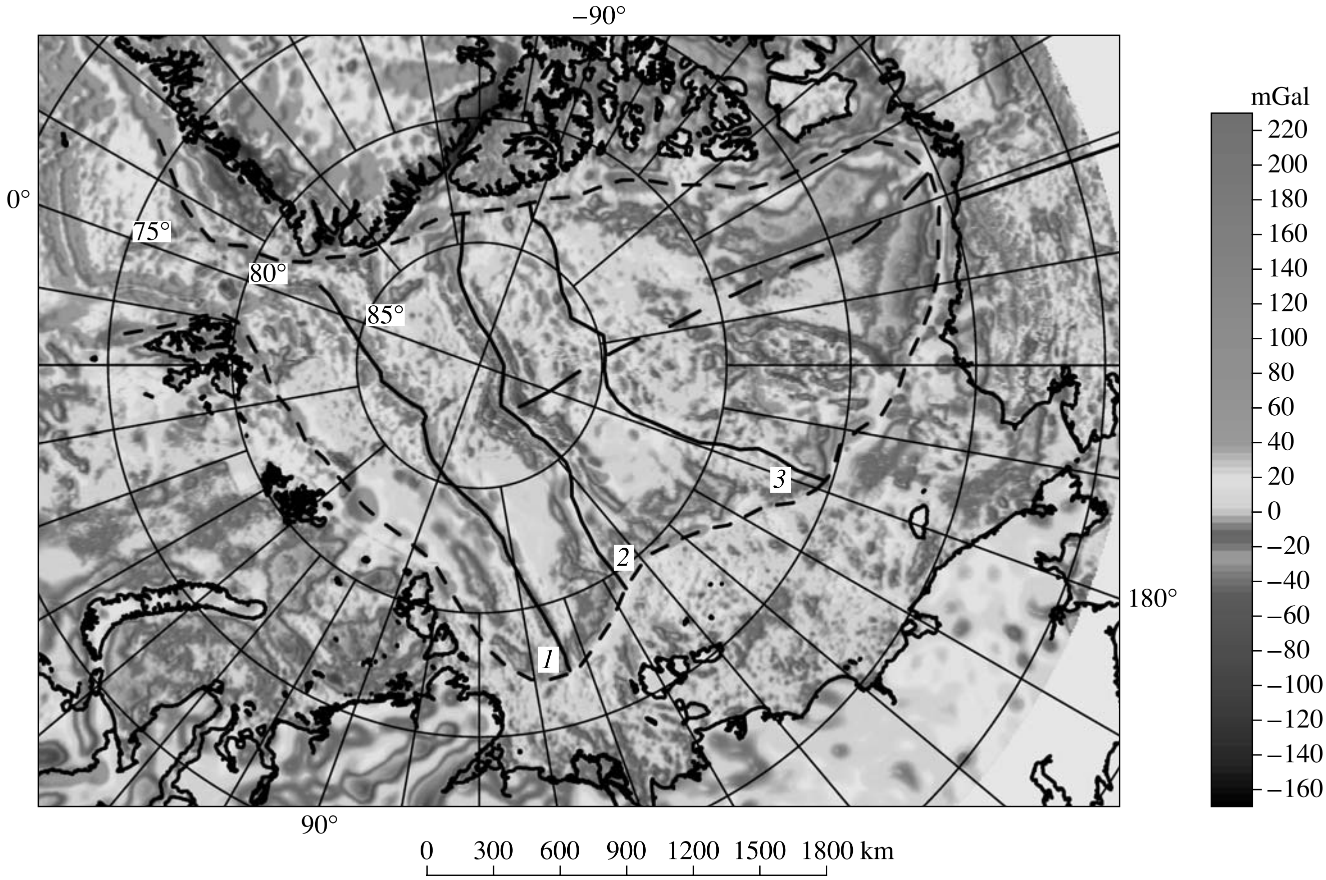

Fig. 6. Free-air gravity anomalies, after [22]; position of axes of the Gakkel (*1*), Lomonosov (*2*), and Mendeleev (*3*) ridges, shelf edge (dashed line), and paleospreading axis (sparse dashed line).

slip displacements along the Chukchi Plateau–Alaska line (see final section) and sinistral displacement along the NE-trending transform zones are established. Such kinematics of large blocks develops when they undergo centrifugal displacement from the pole southward rounding an immobile block. In this situation, opposite sides of this block should be bounded by dextral and sinistral strike-slip faults. The salient of the Elsmere basement (360–140 Ma) in the central part of the Chukchi Sea [29] together the Vrangel Island Block could serve as such a relatively immobile block. It should be noted that in the area of kinematic instability at northern latitudes, movements of different kinematics could interfere within a single block in different geological epochs.

The structural pattern of the Faye's anomalies in the Chukchi Plateau and southern Mendeleev Ridge (Fig. 6) resembles the gravity field of the Eurasian shelf to a greater extent than the typical field of basins and is displaced relative to the latter along the NE-trending transform zones. Between the De Long Rise and Vrangel Island, the shelf field includes "empty" areas devoid of intense mosaic field and similar in size to the above-mentioned segments displaced northward. Most likely, the blocks that previously occupied these areas were displaced to the basin. This hypothesis is supported by the Bouguer anomaly (see below) and characteristic pattern of reverse faulting established by seismic survey [24] in the Chukchi Plateau (Fig. 7) as a result of compression in response to horizontal movement.

As follows from the maximum Faye's anomalies related to uncompensated sedimentation, the area located in the back zone of the displaced block is occupied now by a sedimentary lens with a depocenter located 450 km northeast of Vrangel Island. In terms of field amplitude and anomaly size, this maximum has no analogues in the Arctic region. Its drop-shaped configuration implies migration of the depocenter in the northeastern direction following the space accessible for sedimentation in the opened back zone of the moving Chukchi Plateau. This zone and the southern Mendeleev Ridge are an extension area with intense sedimentation.

INTERPRETATION OF HIGH-FREQUENCY GRAVITY FIELD

The method of the field division in different-frequency components by filtration procedures is widely used in the analysis of geophysical data. The low-frequency, or long-period component of the potential field commonly reflects an effect of deep sources; in most cases, these are structural elements of basement. The high-frequency, or short-period component of the field reflects effects of small sources of various configuration or gradient zones related to faults of diverse kinematics. Inasmuch as the high-frequency component is usually characterized by low amplitude, its patterns are obliterated by low-frequency field. Since component frequencies are additive, they can be separated by the band filtration. The ratio between the source depth and characteristic anomaly size should be (very approximately) 1 : 3. An example of frequency division with separation of short-period components less than 200 km was considered in application to the Arctic region in [13, Fig. 2]. This wavelength of separation implies that the obtained field reflects the gravitational effect of sources located at a depth of 66 km. In other words, this field is a mixture of crust–mantle sources, where the amplitude of deep components remains prevalent. In this study, the high-frequency part of the gravity field was calculated with the separation wavelength of 25 km to obtain a greater effect of the upper crust (Fig. 8).

The pseudosymmetrical structures in the Makarov Basin established from the bathymetric data are supplemented by a linear structural element (see final section) oriented parallel to the Lomonosov Ridge 40–80 km apart from the latter. This structural element most likely is a track of the local pulse of intense plume magmatism. Its amplitude in high-frequency components of the Faye's anomaly is comparable with that in the Alpha Ridge area and is more contrasting than the bathymetric data. This indicates that the main source of the field is buried beneath the sedimentary cover of the Makarov Basin. Appearing under the paleospreading axis of the Amerasia Basin, this source formed the linear structure that differs from the crust accreted in neighboring segments of the paleospreading center (see final section). The Ninetyeast Ridge in the Indian Ocean is an analogue of this structural unit. Another specific feature characteristic only of this anomaly (Fig. 8) and not expressed in topography is the continuation of the transform fracture zone, along which the axis of the Gakkel Ridge is displaced at 63° E, to the Lomonosov Ridge, which turns out to be displaced by 25 km, like the Gakkel Ridge. There are some vague indications that the transform fracture zone continues further across the Makarov Basin and Alpha–Mendeleev Ridge up to the northern edge of the Chukchi Borderland (see final section). The localization of transform fault in this area may be caused by the sharp local bend that inherits configuration of the Eurasian margin, from which the Lomonosov Ridge has been detached [2, 13].

COMPARISON OF BOUGUER ANOMALIES AND DSS RESULTS

Bouguer anomalies were calculated from the Faye's anomalies and bottom topography. The average crust density was accepted at 2.75 g/cm^3 and correction for topography was calculated by integrating in the radius of 166 km (Fig. 9). Bouguer anomalies are correlated with DSS results, owing to the occurrence of the layer with velocities of 6.0–6.4 km/s conditionally termed as a "granitic" layer. Comparison of Bouguer anomalies and DSS data [11] in the northeastern margin of Eurasia conjugated with those from the Pacific Ocean, which has been particularly well studied by this method, shows that wedging-out of the "granitic" layer, which marks the continent–ocean transition, corresponds to a Bouguer anomaly of approximately 175 mGal. This value can be used as an indicator of the crust type: if the Bouguer anomaly exceeds 175 mGal, the crust is oceanic, except in the situations when intense magmatism of the hotspot creates a thick (up to 30 km) basaltic crust, e.g., in Iceland [10], where wave velocities characteristic of the "granitic" layer are recorded as well, although the oceanic nature of the crust is indisputable.

The practically ideal coincidence of the continent–ocean boundary drawn along the shelf edge (isobath 200 m; 400 m in the Barents Sea) and the contour line of 175 mGal validates the chosen criterion and implies that the Lomonosov Ridge marked by a Bouguer anomaly of <175 mGal is most likely underlain by the continental crust; i.e., the ridge was separated from Eurasia. This inference is also supported by other data, including density modeling [2, 13, 36]. Because the critical level of 175 mGal is reached in areas of intense plume-related magmatism, the probability that the Lomonosov Ridge is a track of hotspot that left behind the opening of the Amerasia Basin cannot be ruled out. The Yermak and Morris Jessup pseudosymmetrical structural elements are most likely tracks of a plume which was active from 56 to 30 Ma ago [26]. In addition, radiobuoy data show that wave velocities in the basement are 4.9–5.4 km/s and likely correspond to basalt. The DSS lines shut by Russian teams in the 1990s and in the current decade [15] (see Fig. 9 for line location) crossed a thick (up to 10 km) lens with velocities characteristic of the "granitic" layer at the base of the Lomonosov Ridge at 83° N, i.e., at a distance of over 400 km from the shelf edge. This makes interpretation of this structural element as a fragment detached from the continent highly probable. However, it should be kept in mind that the ultimate conclusion can be drawn only after drilling. According to the data from holes M0002A and M0004A drilled in Leg ACEX-302 (IPOD) on the Lomonosov Ridge [9] and the drilling results on the Leningradskaya structure in the Kara Sea, the sedimentation conditions in the Middle–Late Cretaceous were controlled by transgression that attained the lower reaches of the Yenisei River. Thus, the sedimentation settings in both areas were similar, and the Lomonosov Ridge belonged to the Eurasian shelf. Seismic complexes in the Amundsen and Podvodnikov basins are composed of marine shallow-water facies [9], testifying to erosion of the Lomonosov Ridge and

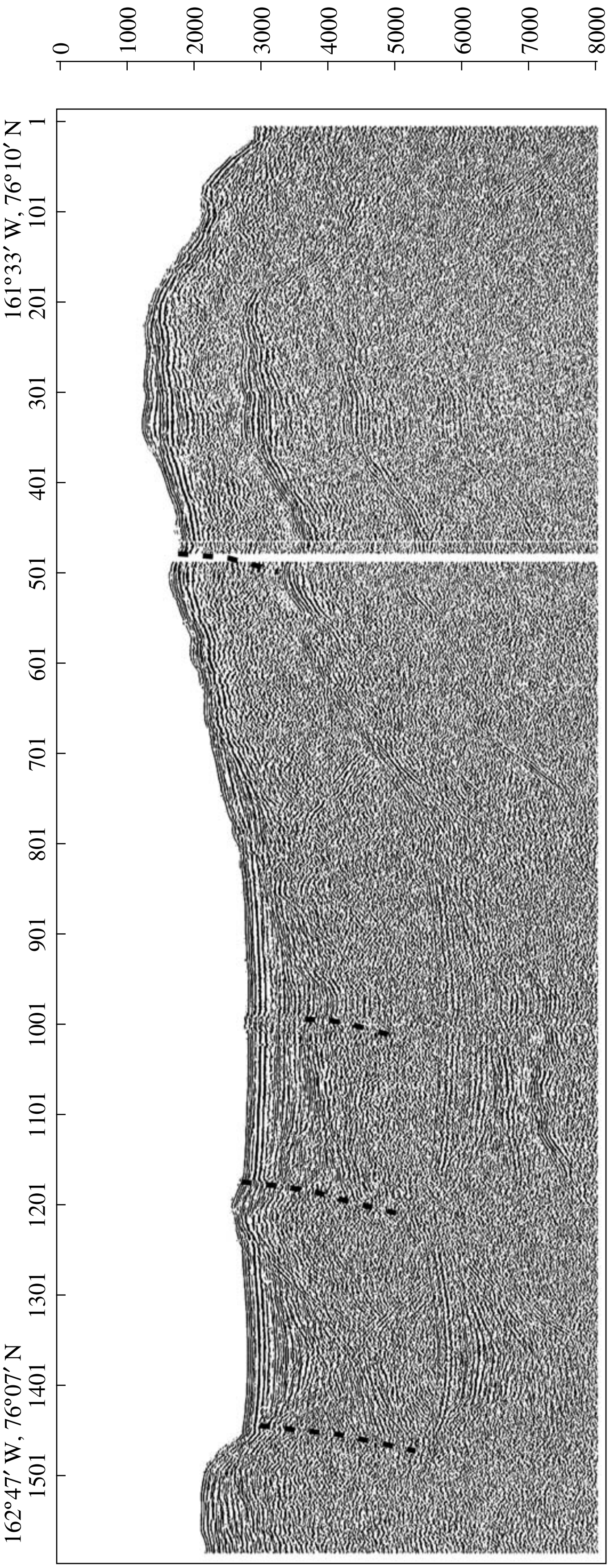

Fig. 7. Seismic record along line 92-10 across the Chukchi Plateau (the length is approximately 40 km, vertical scale is 8 s), after [24].

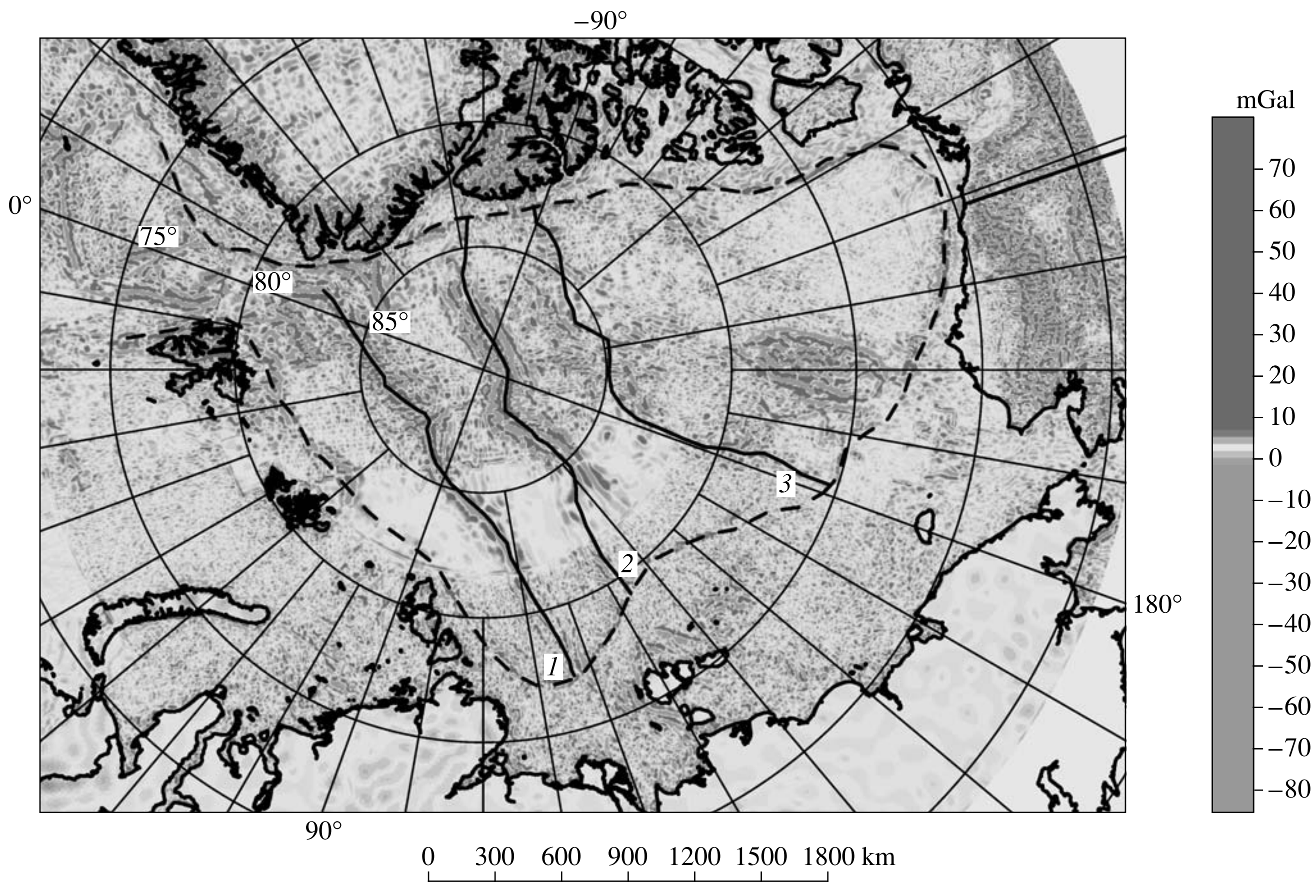

Fig. 8. High-frequency part of free-air gravity anomalies, after [22]; position of axes of the Gakkel (*1*), Lomonosov (*2*), and Mendeleev (*3*) ridges and shelf edge (dashed line).

redeposition of its sediments in the neighboring Eurasia and Amerasia basins.

Practically the entire tract of the excess space in the Amerasia Basin (Fig. 4) is covered by a Bouguer anomaly below 175 mGal. The southern segment of the Lomonosov Ridge and the Chukchi Plateau are characterized by substantially lower values. The DSS profile crosses the Mendeleev Ridge along 82° N, i.e., along the shelf edge with threshold Bouguer anomaly values (Fig. 9). According to [15], the values characteristic of the "granitic" layer pertain to the interval 1.5–2 km, which is insufficient for reliable validation of the continental crust. However, judging from the combination of other indications, the continental crust beneath the Mendeleev Ridge cannot extend beyond this latitude. Near-meridional seismic line SLO 89-91 trending almost parallel to the ridge shows the attributes of the "granitic" layer up to 85° N. Thus, the coincidence between the threshold value of Bouguer anomaly and DSS data in this segment of the ridge serves as the basis for interpreting this structural element as continental.

Fragments of limestones and dolomites dated by foraminifers and conodonts back to the Middle Silurian–Lower Permian were carried up by dredging at several stations along the line Arktika-2000 that crossed the southern segment of the ridge. According to [8], the dredged fragments characterize Paleozoic rocks of the eroded platform. These data are consistent with the continental nature of the region established from geophysical data.

The northern segments of the Lomonosov and Alpha ridges are characterized by Bouguer anomalies below 175 mGal. For the many reasons discussed above, these anomalies are most likely indications of intense plume magmatism. In addition, the plume had an offset that shifted along the spreading axis to the south, toward the Canada Basin. The southern segments of the Mendeleev Ridge and Chukchi Plateau are marked by Bouguer anomalies intermediate between typical oceanic (200 mGal and higher) and continental (<100 mGal). The position of these segments between the abyssal and shelf areas and Bouguer anomaly values may be explained by superposition of the detached continental fragments on the abyssal basin. This implies that these blocks were most likely detached as large crustal sheets, whereas local rifting separated a continental block entirely, retaining continental values of the Bouguer anomalies, as in the case of the Rockall Plateau. The detachment could have been driven by tangential

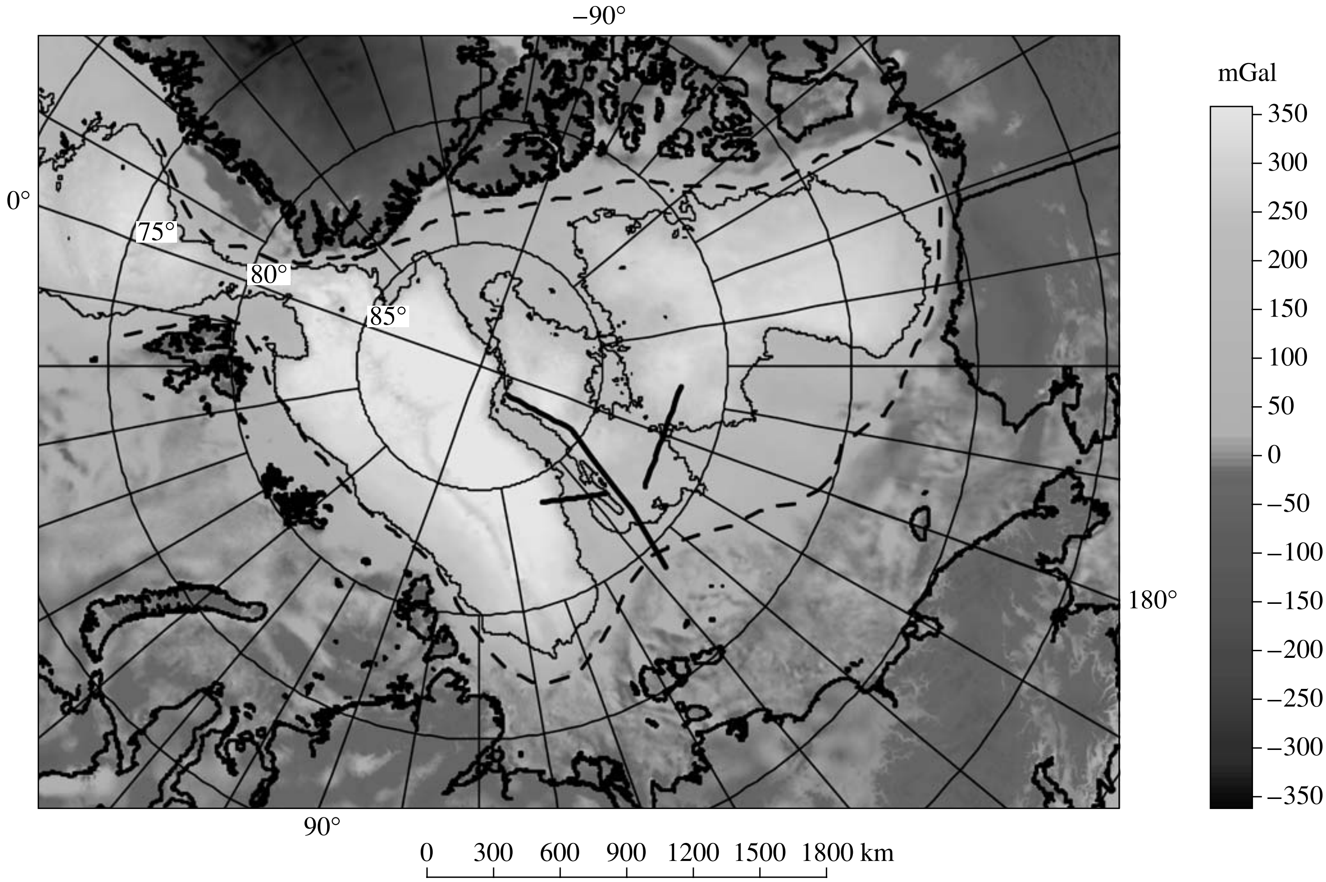

Fig. 9. Bouguer anomaly calculated after [22, 25]; the shelf edge (dashed line), contour line 175 mGal (solid line), and position of seismic lines (from the west eastward): DSS SLO-92, SLO-89-91, and Arktika-2000 (heavy line).

forces due to the redistribution of the moment of inertia of the crust during rotation of the Earth. This mechanism is discussed in [17].

TECTONIC SUMMARY AND GEODYNAMIC EVOLUTION

The tectonic scheme (Fig. 10) summarizes the data on the deepwater part of the Arctic Ocean and East Siberian Sea and their interpretation [29]. This scheme depicts the structural elements discussed in this article and takes into account the tectonic concepts currently developed for this region and supplemented by new interpretation of some tectonic features. According to this interpretation, the geodynamic evolution of the region proceeded in line with the following scenario.

The opening of the Amerasia Basin was accompanied by separation of the Chukchi Plateau, the southern part of the Mendeleev Ridge, and other structures of Eurasia from North America in the period from 157 to 140 Ma ago (or to ~120 Ma, according to [28]). The paleospreading axis advanced to the Lomonosov Ridge and opening of the Amerasia Basin was in progress along its entire length corresponding to the present-day configuration. This stage was marked by intense plume magmatism superimposed on slow spreading in several segments of the paleospreading axis (volcanic rises shown in Fig. 10). Magma from the plume ascended through three main conduits with second-order offsets, the activity of which partly or completely waned. The main (central) channel formed the structure of the Alpha Ridge and migrated at the final stage of plume activity by approximately 200 km toward the Canada Basin. The vast volcanic rises with pseudosymmetrical outlines relative to the spreading axis were devoid of distinct linear magnetic anomalies. Pseudosymmetrical continental blocks could have been separated from both the Eurasian and North America margins of the basin at that period. In my opinion, the described structural configuration makes impossible the opening of the basin along the spreading axis parallel to the Gakkel Ridge.

The initial opening of the Eurasia Basin approximately 56 Ma ago was coeval with subsidence of the main depression in the basement of the East Siberian Sea (according to [23], this event started approximately 70 Ma ago). Extension along the Gakkel Ridge was accompanied by formation of NE-trending transform faults. The shelf depression and its northern framework

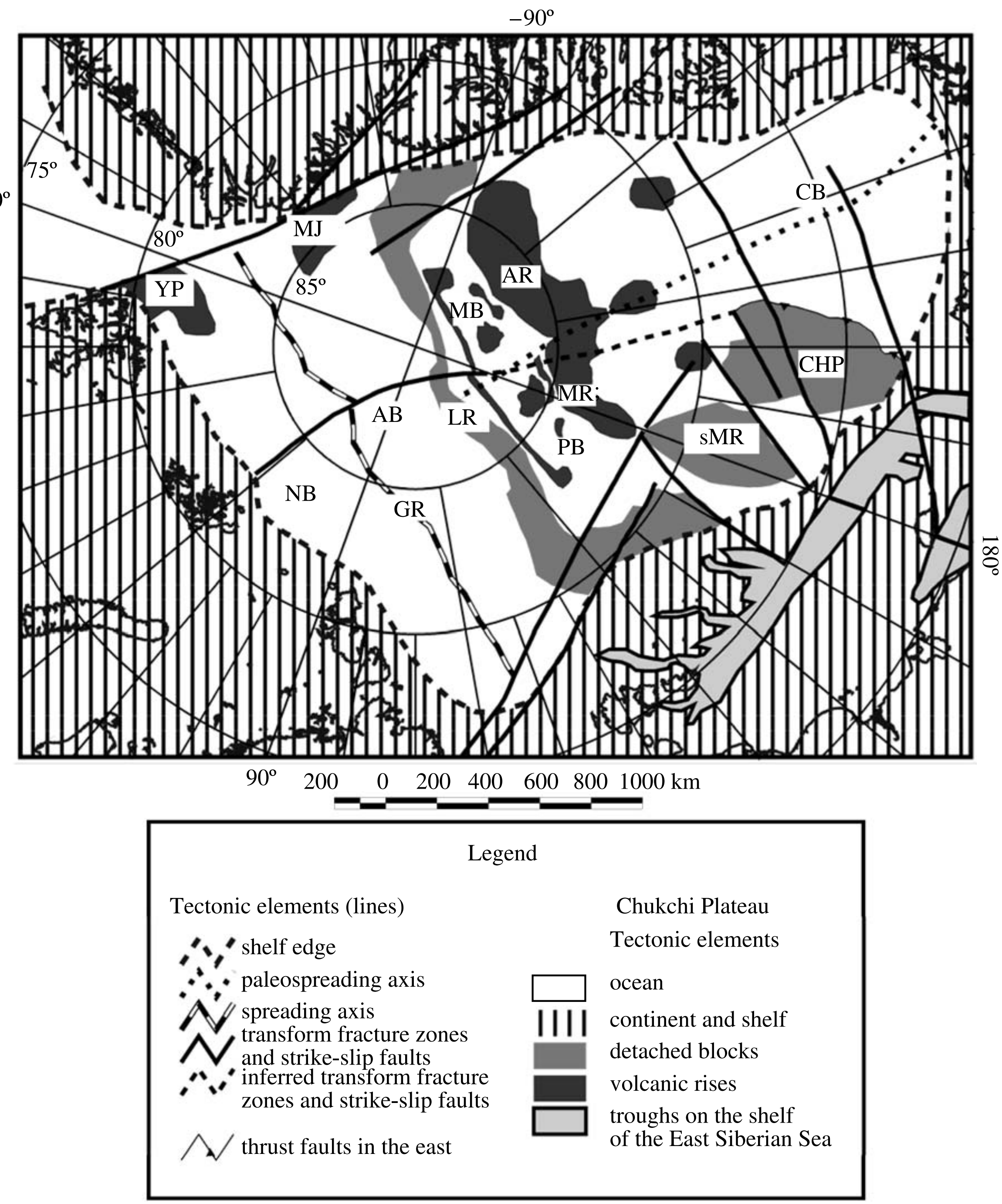

Fig. 10. Tectonic scheme of deepwater part of the Arctic Ocean Basin and East Siberian Sea, modified after [29]. Letters in figure: (LR) Lomonosov Ridge; (AR) Alpha Ridge, (MR) Mendeleev Ridge, (sMR) southern Mendeleev Ridge, (GR) Gakkel Ridge, (YP) Yermak Plateau, (MJ) Morris Jessup Plateau, (CHP) Chukchi Plateau, (NB) Nansen Basin, (AB) Amundsen Basin, (MB) Makarov Basin, (PB) Podvodnikov Basin, (CB) Canada Basin.

acquired dextral strike-slip kinematics with an insignificant extension component. In my opinion, the effect of the Eurasia Basin opening on the Amerasia Basin and East Siberian shelf was expressed in the formation of the splaying system of small grabens in the De Long Rise area and the separation of the southern part of the Mendelelev Ridge and Chukchi Plateau from the North America margin along the system of sinistral strike-slip faults in the area between the main trough on the shelf and the NE-trending transform zone. Thus, spreading in the newly formed Cenozoic basin gave rise to the destruction of the Eurasian passive margin of the Amerasia Basin. Separation of the Mendelelev Ridge and Chukchi Plateau along the system of sinistral NE-trending strike-slip faults is inactive now, because no deformation in front of the Chukchi Plateau is established [24]. Nevertheless, reverse faulting is noted on the plateau itself. In my opinion, the tectonic elements located between the northeastern transform fracture zones and the main depression on the shelf include not only splaying grabens but also reverse–thrust and strike-slip faults (Fig. 10). Thus, the structural pattern with typical elements of shear zones is established in an area approximately 700 km wide (from fracture zones to depression) and 1800 km long (from the Laptev Sea to the Chukchi Plateau) [4, 20].

The opening of the Eurasia Basin started with separation of the Lomonosov Ridge from the Eurasian margin. It also remains conceivable that this ridge is similar to that of volcanic rises in the Amerasia Basin, which are symmetrical relative to the spreading axis. After cessation of opening of this basin 120 Ma ago and until the onset of opening of a new basin, about 60 Ma elapsed. During this time, the magmatic block remained in close contact with the continental margin and was involved in sedimentation along with this margin. Volcanic plateaus symmetrical relative to the new spreading axis were formed in the western part of the Eurasia Basin. The dextral transform system, which reached the northern Chukchi Borderland, displaced the Gakkel and Lomonosov ridges, as well as structural elements in the Makarov Basin basement. In general, the region is characterized by several (at least three) systems of variously oriented faults, which could gave been reactivated under unstable polar conditions.

The proposed model is far from being finalized and will be modified as new information comes to light.

CONCLUSIONS

The statements concerning tectonic elements.

(1) The interpretation of geophysical data indicates that the area, about 700 km wide (from the NE-trending transform fracture zones to the main trough of the East Siberian Sea) and 1800 km long (from the Laptev Sea to the Chukchi Plateau), is characterized by a structural pattern typical of shear zones. This area comprises both the shelf and abyssal parts of the basin and is marked by destruction of the Eurasian margin of the Amerasia Basin that existed before the onset of opening of the Eurasia Basin 56 Ma ago.

(2) The opening of the Amerasia Basin from 157 to 140(120) Ma ago was accompanied by intense plume magmatism superimposed on slow spreading in several segments of the paleospreading axis. Magma ascended through three conduits with small offsets, whose activity waned partly or completely. The main (central) channel responsible for the formation of the Alpha Ridge migrated at the final stage of its activity ~200 km toward the Canada Basin.

(3) The transform dextral strike-slip system extended to the northern Chukchi Borderland, displacing the Gakkel Ridge and structural elements in the Makarov Basin.

Statements concerning interpretation of geophysical data.

(1) Love wave tomography demonstrates a "continental" anomaly approximately 300 km wide adjacent to the Eurasia shelf and an "oceanic" anomaly in the Spitsbergen Archipelago.

(2) The anomalous magnetic field in the Amerasia Basin confirms the hypothesis that assumes superposition of intense hotspot magmatism on the normal oceanic spreading setting with formation of structural elements symmetrical relative to the paleospreading axis that extends from the southern part of the Canada Basin to the Lomonosov Ridge.

(3) The free-air gravity anomalies reflect the development of the main trough and a system of auxiliary fractures in the East Siberian Sea and Amerasia Basin, which are traced from shelf to the abyssal part of the basin.

(4) The high-frequency part of gravity anomalies reflect linear structures in the basement of the Makarov Basin displaced by the transform fracture zone, which controls the offset of the Gakkel Ridge at 63° E.

(5) The contour line of the 175-mGal Bouguer anomaly is accepted to be the boundary between typical oceanic zones with the Bouguer anomaly exceeding 175 mGal and zones with the continental crust and zones of intense hotspot magmatism characterized by a Bouguer anomaly of <175 mGal.

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REFERENCES

1. G. P. Avetisov, *Seismoactive Zones of the Arctic* (VNIIOkeangeologiya, St. Petersburg, 1996) [in Russian].
2. V. V. Verba, A. P. Gubernov, V. D. Kaminsky, and L. V. Podgornykh, "The Nature of Potential Fields of the Arctic Region," in *The Russian Arctic: Geological History, Minerageny, and Geoecology*, Ed. by D. A. Dodin and V. S. Surkov (VNIIOkeangeologiya, St. Petersburg, 2002), pp. 142–149 [in Russian].
3. V. Yu. Glebovsky, A. V. Zaionchek, V. D. Kaminsky, and S. P. Mashchenkov, "Numerical Databases and Maps of Potential Fields of the Arctic Ocean," in *The Russian Arctic: Geological History, Minerageny, and Geoecol-*

ogy, Ed. by D. A. Dodin and V. S. Surkov (VNIIOkeangeologiya, St. Petersburg, 2002), pp. 134–141 [in Russian].

4. M. A. Goncharov, V. G. Talitsky, and N. S. Frolova, *Introduction to Tectonophysics* (KDU, Moscow, 2005) [in Russian].
5. N. I. Gurevich, S. A. Merkur'ev, and A. A. Abel'skaya, "Evolution of the Southern Canada Basin (Arctic Ocean) Based on Magnetometric Data," Dokl. Akad. Nauk **407** (1), 92–95 (2006) [Dokl. Earth Sci. **407** (2), 308–311 (2006)].
6. N. I. Gurevich and S. A. Merkur'ev, "Evolution of the Alpha Ridge (Arctic Ocean) from Magnetometric Data," Dokl. Akad. Nauk **401** (1), 75–79 (2005) [Dokl. Earth Sci. **401** (2), 280–284 (2005)].
7. L. V. Dmitriev, S. Yu. Sokolov, and A. A. Plechova, "Statistical Assessment of Variations in the Compositional and *P–T* Parameters of the Evolution of Mid-Ocean Ridge Basalts and Their Regional Distribution," Petrologiya **14** (3), 227–247 (2006) [Petrology **14** (3), 209–229 (2006)].
8. V. Ya. Kaban'kov, I. A. Andreeva, V. N. Ivanov, and V. I. Petrova, "The Geotectonic Nature of the Central Arctic Morphostructures and Geological Implication of Bottom Sediments for Its Interpretation," Geotektonika **36** (6), 33–48 (2004) [Geotectonics **36** (6), 430–442 (2004)].
9. B. I. Kim and Z. I. Glezer, "Sedimentary Cover of the Lomonosov Ridge: Stratigraphy, Structure, Deposition History, and Age of Seismic Facies Units," Stratigr. Geol. Korrelyatsiya **15** (4), 63–83 (2007) [Stratigr. Geol. Correlation **15** (4), 401–420 (2007)].
10. *International Geologic-Geophysical Atlas of the Atlantic Ocean* (Izd. MOK YuNESKO, Mingeo SSSR, Akad. Nauk SSSR, Gos. Uprav. Geol. Kartograf. SSSR, Moscow, 1990) [in Russian].
11. *International Geologic-Geophysical Atlas of the Pacific Ocean* (IOC UNESCO, Moscow, 2003) [in Russian].
12. G. D. Naryshkin, Doctoral Dissertation in Geography (Moscow, 2001) [in Russian].
13. A. L. Piskarev, "The Basement Structure of the Eurasia Basin and Central Ridges in the Arctic Ocean," Geotektonika **38** (6), 49–66 (2004) [Geotectonics **38** (6), 443–458 (2004)].
14. V. A. Poselov, V. V. Verba, and S. M. Zholondz, "Typification of the Earth's Crust of Central Arctic Uplifts in the Arctic Ocean," Geotektonika **41** (4), 48–59 (2007) [Geotectonics **41** (4), 296–305 (2007)].
15. V. A. Poselov, I. S. Gramberg, R. R. Murzin, et al., "Structure and Boundaries of Continental and Oceanic Lithosphere of the Arctic Basin," in *The Russian Arctic: Geological History, Minerageny, and Geoecology,* Ed. by D. A. Dodin and V. S. Surkov (VNIIOkeangeologiya, St. Petersburg, 2002), pp. 121–133 [in Russian].
16. *The Russian Arctic: Geological History, Minerageny, and Geoecology*, Ed. by D. A. Dodin and V. S. Surkov (VNIIOkeangeologiya, St. Petersburg, 2002) [in Russian].
17. S. Yu. Sokolov, "A New Mechanism of Horizontal Movement of Tectonic Activity Masses of the Earth's Crust and Lithosphere," in *Proceedings of XLI Tectonic Conference on General and Regional Problems of Tectonics and Geodynamics* (GEOS, Moscow, 2008), Vol. 2, pp. 278–282.
18. *Tectonic Map of the World. Scale 1 : 45000000*, Ed. by Yu. G. Leonov and V. E. Khain (Commission on Intern. Tectonic Maps, Leningrad, 1982) [in Russian].
19. V. E. Khain, *Tectonics of Continents and Oceans (2000)* (Nauchnyi Mir, Moscow, 2001) [in Russian].
20. V. E. Khain and M. G. Lomize, *Geotectonics with Principles of Geodynamics* (Moscow State Univ., Moscow, 1995) [in Russian].
21. R. L. Coles and P. T. Taylor, "Magnetic Anomalies," in *The Geology of North America, Vol. 50: The Arctic Ocean Region*, Ed. by A. Grantz, L. Johnson, and J. F. Sweeney (Geol. Soc. Amer., 1990), pp. 119–132.
22. R. Forsberg and S. Kenyon, *Gravity and Geoid in the Arctic Region—the Northern Polar Gap Now Filled* (2005). (http://earinfo.nga.mil/GandG/wgs84/agp/readme_new.html).
23. D. Franke, K. Hinz, and C. Reichert, "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 (2004). doi: 10.1029/2003JB002687.
24. A. Grantz, P. E. Hart, R. L. Phillips, et al., *Cruise Report and Preliminary Results, Cruise P1-93-AR. Northwind Ridge and Canada Basin, Arctic Ocean, Aboard the USCGC Polar Star August 16 to September 15, 1993* (US Geol. Surv. Open-File Report, 1993).
25. *IBCAO (International Bathymetric Chart of Arctic Ocean)* (2005). (http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/arctic.html).
26. Y. Kristoffersen, "Eurasia Basin," in *The Geology of North America, Vol. 50: The Arctic Ocean Region,* Ed. by A. Grantz, L. Johnson, and J. F. Sweeney (Geol. Soc. Amer., 1990), pp. 365–378.
27. E. Larson, G. Ekstrom, and J. Tromp, *Surface Waves Tomography Data* (Seism. Group, Dept. Earth Planet. Sci., Harvard Univ.,1990) http://www.seismology.harvard.edu).
28. L. A. Lawver, A. Grantz, and L. M. Gahagan, *Plate Kinematics Evolution of the Present Arctic Region since the Ordovician* (Geol. Soc. Am. Spec. Paper, Vol. 360, 2001), Chapter 18.
29. A. O. Mazarovich and S. Yu. Sokolov, "Tectonic Subdivision of the Chukchi and East Siberian Seas," Russ. J. Earth Sci. **5** (3), 185–202 (2003).
30. P. J. Michael, C. H. Langmuir, H. J. B. Dick, et al., "Magmatic and Amagmatic Seafloor Generation at the Ultraslow-Spreading Gakkel Ridge, Arctic Ocean," Nature **423** (26), 956–961 (2003).
31. S. Yu. Sokolov, N. S. Sokolov, and L. V. Dmitriev, "Geodynamic Zonation of the Atlantic Ocean Lithosphere: Application of Cluster Analysis Procedure and Zoning Inferred from Geophysical Data," Russ. J. Earth Sci. **10**, (2008), pp. 1–30, ES4001,doi: 10.2205/2007ES000218.
32. J. F. Sweeney, G. L. Johnson, and A. Grantz, "Summary," in *The Geology of North America, Vol. 50: The Arctic Ocean Region*, Ed. by A. Grantz, L. Johnson, and J. F. Sweeney (Geol. Soc. Amer., 1990), pp. 619–628.
33. *The Geology of North America, Vol. 50: The Arctic Ocean Region*, Ed. by A. Grantz, L. Johnson, and J. F. Sweeney (Geol. Soc. Amer., 1990).

34. N. A. van Wagoner, M. C. Williamson, P. T. Robinson, and I. L. Gibson, "First Samples of Acoustic Basement Recovered from the Alpha Ridge, Arctic Ocean: New Constraints for the Origin of the Ridge," Polar Geophys. J. Geodynam. **6** (1–4), 117–136 (1986).

35. J. Verhoef, W. R. Roest, R. Macnab, J. Arkani-Hamed, and Members of the Project Team, *Magnetic Anomalies of the Arctic and North Atlantic Oceans and Adjacent Land Areas* (Geol. Surv. Can., Dartmouth, 1996), GSC Open File 3125.

36. J. R. Weber and J. F. Sweeney, "Ridges and Basins in the Central Arctic Ocean," in *The Geology of North America, Vol. 50: The Arctic Ocean Region*, Ed. by A. Grantz, L. Johnson, and J. F. Sweeney (Geol. Soc. Amer., 1990), pp. 305–336.

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