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Riftogenesis in the Arctic: Processes, Evolution Trend, and Hydrocarbon Generation

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Abstract—The article examines the regional patterns of rifting in the Arctic and assesses the impact of large (supra-regional) rift systems on the geological evolution of the region. Against the background of the description of main Arctic structures, the Atlantic–Arctic rift system (AARS) is described as a tectonotype of a large planetary geophorm that has evolved from continental rifting to spreading proper with the development of a full-fledged ocean. The main properties of this system are its development towards the North Pole, the longitudinal orientation of the rifts, their separation by latitudinal faults, and predominantly sinistral shear displacement of individual segments. We believe that such a structure reflects the influence of the rotational factor on distribution of lithospheric masses of the Earth. Their tendency to the equilibrium position relative to the rotation axis is implemented by movements towards the equator and along it. The outflow of masses to low latitudes makes possible the growth of the rift system, but does not contribute to its further development after reaching the Pole. This phenomenon is of general nature and determines the development of all longitudinal rift systems, which leads to their spatial convergence and attenuation of dynamics in the circumpolar space. Within the Arctic region, in addition to the Atlantic–Arctic system, areas of possible termination of the West Siberian, Okhotsk–Verkhoyansk, and East Pacific rift systems are considered. It is assumed that their evolution initiated the destruction of the continental lithosphere of the Arctic region and determined the subsequent transformations of its structure. Special attention is paid to the problems of the possible influence of rifting on the hydrocarbon generation due to serpentinization of hyperbasites, when the lithosphere is penetrated by faults to the upper mantle depths, as well as on the remobilization of gases as a result of the disturbance of both gas hydrate reservoirs and permafrost. It is shown that the greatest generation of methane is generally associated with the development of faults in the cold lithosphere and serpentinization of mantle rocks.

Keywords: Arctic, rifting, igneous province, degassing, hydrocarbons

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INTRODUCTION

The Arctic region is a unique geological test site demonstrating the evolution of the Earth's youngest ocean. Its development is accompanied by numerous processes, which affect the resource potential, hydrological regime, cryolithozone, and climatic variations of the Arctic region.

In 1951, A. Irdli formulated arguments in support of the fact that the "Arctic Ocean should not be considered as an ocean proper, but represents a Mediterranean sea", while the present-day "deep-water basin is only a subsided part of a single giant continent" (Irdli, 1954, pp. 566–567). Indeed, the modern structure of the Arctic region was formed through break-up of the former single continental massif: Hyperborean Platform (Shatsky, 1935) or Arctida (Zonenshain et al., 1990; Khain et al., 2009; Laverov et al., 2013).

The position of a large continental massif in the near-polar region shall determine the specifics of rifting marking the incipient destruction stages. In particular, the near-polar position of the region on the rotation spheroid causes the lowest lithosphere mobility compared to the low-latitude regions. In addition, the possibility of the horizontal extension depends on the presence of free space, i.e., on the evolution of adjacent territories.

The Arctic region demonstrates tight structural relations with continental platformal regions and fold belts. It has long been noted that orogenic systems are propagated to the pole (Irdli, 1954; Schiffer et al., 2019; and others) and likely serve for spreading of rifting basins. In the modern structure, this is best expressed by the penetration of Atlantic structures, which are restricted to the Caledonian orogenic belt.

Similar tendencies were found in opening of the North Atlantic and West Arctic basins. In particular, the present-day diachronous opening of the Norwegian–Greenland Basin was initiated in the initially

isolated spreading centers (Gernigon et al., 2019). In plan, the rift system is a fan-shaped, because separate spreading segments, being in active phase, tended to the local Euler pole (Gernigon et al., 2019). Similar pattern was noted for the Eurasian Basin, where the greater spreading of its Greenland flank led to the break-up and spatial separation of initially single Morris Jessup–Ermak volcanic rise (Khain, 1971; Daragan-Sushchova et al., 2020] (Fig. 1).

The Eurasian Basin can be used as an example of the interference of the local and external rift processes. The basin is ascribed to the Arctic region. At the same time, it is the youngest chain of riftogenic structures, with the Gakkel Ridge representing the continuation of the Mid-Atlantic Ridge (Fig. 1). Correspondingly, processes proceeding in this region should be controlled by the evolution of both Arctic and Atlantic regions.

In this aspect, an essential cognitive significance is acquired by transregional structures such as the Atlantic–Arctic Rift System (AARS), which extends submeridionally from pole to pole and reveals a common pattern of evolution in all its segments. There are no grounds to suggest that the properties of global rift system will change in the Arctic part. Therefore, they become an important key to understanding rift processes in this region.

These considerations determined the tasks of the study. The paper is aimed at revealing the regional rifting patterns of Arctic, estimating the influence of large (supra-regional) rift systems, and generalizing the available data within a consistent model.

Special attention was paid to the possible influence of rifting on the hydrocarbon generation at lithosphere fault penetration up to the upper mantle depths (serpentinization of hyperbasites) and remobilization of gas and gas hydrate accumulation in response to the disturbance of stability fields and permafrost.

This work is based on our long-term researches of a structural arrangement of large rift systems, degassing occurrences, and environments of the gas hydrates formation in the Atlantic, Indian, and Pacific oceans during cruises of the R/Vs *Akademik Nikolai Strakhov* and *JOIDES Resolution*, as well as on processing of seismic data on the Sakhalin shelf, Barents Sea, and Nansen Basin.

RIFT STRUCTURES IN THE ARCTIC REGION

The structures of the Arctic region include not only rises and basins presently hidden beneath the Arctic Ocean, but also continental platform regions and surrounding fold belts. Below we characterize several structures, the evolution of which was significantly affected by rifting processes.

Eurasian Basin

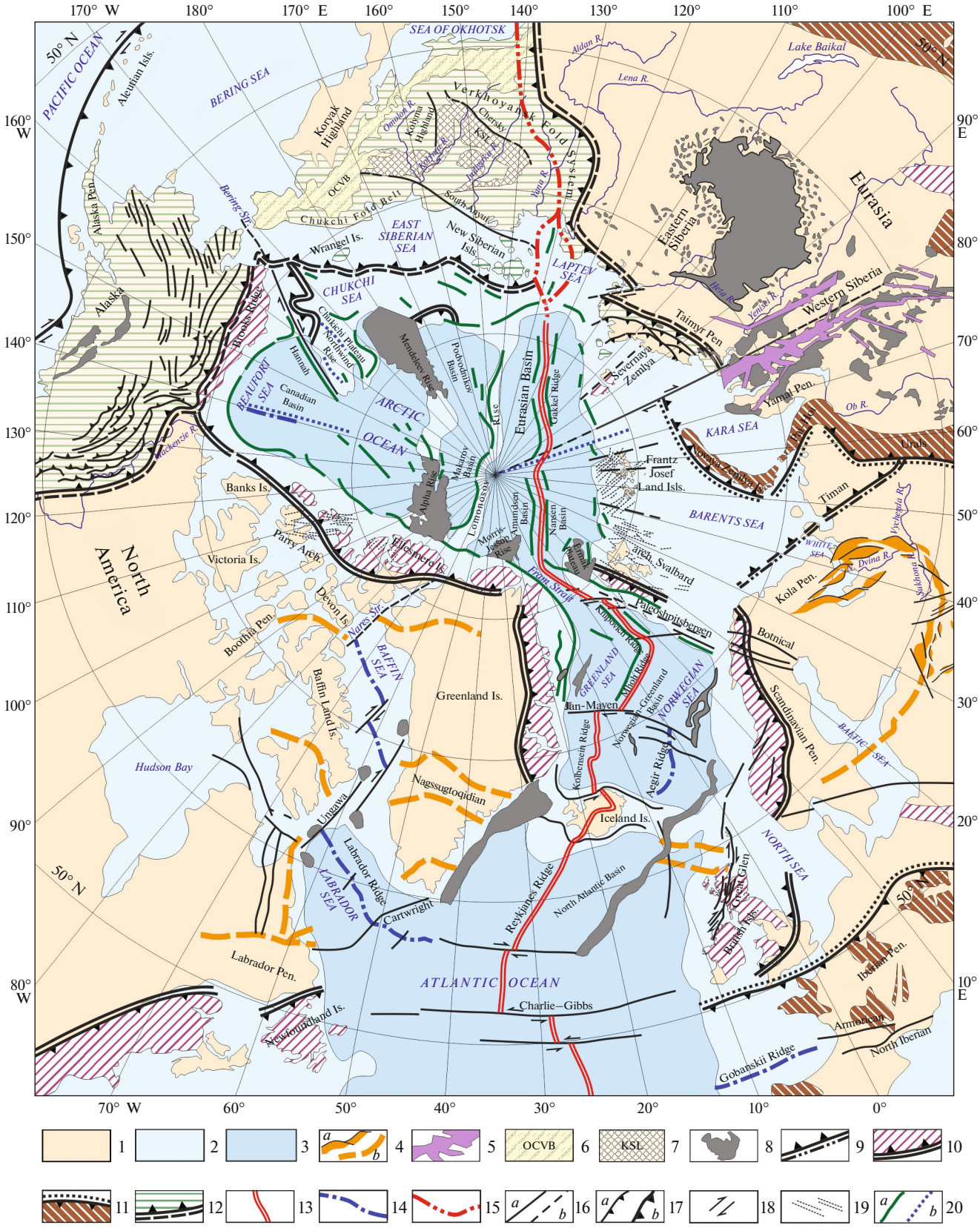
The Eurasian Basin extends from the Fram Strait to the Laptev Sea. On the Eurasian side, it is surrounded by the Barents, Kara, and Laptev sea shelves. On the Arctic Ocean side, the basin is bounded by the Lomonosov Rise. The Spitsbergen–Greenland fault zone separates the basin from the Atlantic Rift system. The axial part of the basin comprises an extended (1800 km) rift structure—the Gakkel Ridge, which is morphologically similar to the mid-oceanic structures in the North Atlantic axis (Fig. 1).

A **transverse asymmetry** of the Eurasian Basin is clearly expressed in the structure of the Amundsen and Nansen basins surrounding the Gakkel Ridge. Sedimentary sequences in them are similar, but their thicknesses vary from 4 km in the Nansen Basin to approximately two times higher in the Amundsen Basin (Nikishin et al., 2020).

The Lomonosov Rise slope surrounding the Amundsen Basin consist of numerous blocks, shifted along normal faults and inclined toward the Eurasian Basin. Such structure together with a sharp gravity gradient established directly near the Lomonosov Rise is typical of non-volcanic rift continental margins (Cochran et al., 2006; Poselov et al., 2012). A continental nature of the Lomonosov Rise follows from dredging data on its slopes. It was established that the rise is made up of Early Paleozoic fold and metamorphic complexes and belongs to the Early Paleozoic Caledonian orogen (Knudsen et al., 2017; Rekant et al., 2019).

In contrast, the Barents–Kara slope of the Nansen Basin has a simple structure, except for the segment along the Ermak plateau. In a plan view, the slope represents a very gentle north-trending arc. The slope usually has a concave transverse profile, with an angle 4°–8°, rarely more than 10° in the upper part (*Arkticheskii ...,* 2017).

Fig. 1. Schematic structure of the Arctic region and its nearest surrounding in the Khotin projection, according to (King, 1961; *Tekonicheskaya ...*, 1964, 1966, 1996; Zonenshain et al., 1990; Khain, 2001; Mazarovich and Sokolov, 2003; Peyve and Chamov, 2008; Karyakin et al., 2009; Filatova and Khain, 2009; Khain et al., 2009; Petrov et al., 2013; Chamov, 2016; *Arkticheskii ...,* 2017; Schiffer et al., 2019; Sokolov et al., 2020; and others). (1) Land; (2, 3) water area: (2) <500-m isobath, (3) >500-m isobath; (4) Precambrian structures: (*a*) grabens, (*b*) sutures; (5) Triassic rifts; (6, 7) Mesozoic structures: (6) Okhotsk–Chukotka volcanic belt (OCVB), (7) Kolyma structural loop (KSL); (8) igneous provinces; (9–12) orogenic fronts and areas of their distribution: (9) Baikalian, (10) Caledonian and Ellesmerian, (11) Hercynian, (12) Mesozoic; (13, 14) spreading ridges: (13) active, (14) extinct; (15) axial line of rifting and elevated seismicity; (16) faults: (*a*) proved, (*b*) inferred; (17) overthrusts: (*a*) local, (*b*) regional; (18) strike slips; (19) dikes; (20) strike of anomalies: (*a*) positive gravity anomalies, (*b*) negative magnetic anomalies ΔTa.


170° W
180°
170° E
160°
150°
140°
130°
120°
110°
100° E
50° N
PACIFIC OCEAN
Aleutian Isls.
BERING SEA
SEA OF OKHOTSK
Aldan R.
Lena R.
Lake Baikal
Verkhoyansk Fold System
Chersky
KSL
Kolyma Highland
Omolon R.
Kolyma R.
Indigirka R.
Yana R.
Korjak Highland
OCVB
Chukchi Fold Belt
South Anyuj
Bering Str.
Alaska Pen.
Alaska
Wrangel Is.
EAST SIBERIAN SEA
New Siberian Isls.
LAPTEV SEA
Eurasia
Eastern Siberia
Western Siberia
Taimyr Pen
Lena R.
Yenisei R.
CHUKCHI SEA
Brooks Ridge
Chukchi Plateau
Northwind Ridge
Hanna
Mendeleev Ridge
Podvodnikov Basin
Eurasian Basin
Gakkel Ridge
Severnaya Zemlya
Yamal Pen.
Ob R.
BEAUFORT SEA
Canadian Basin
ARCTIC OCEAN
Makarov Basin
Alpha Ridge
Lomonosov Ridge
Amundsen Basin
Nansen Basin
KARA SEA
Novaya Zemlya Is.
Frantz Josef Land Isls.
Urals
Mackenzie R.
Banks Is.
Victoria Is.
Parry Arch.
Ellesmere Is.
North America
Morris-Jesup Rise
Fram Strait
Bjørnøya
Spitsbergen
Svalbard
BARENTS SEA
Timan
WHITE SEA
Dvina R.
Pechora R.
Sukhona R.
Kola Pen.
Botnical
Boothia Pen.
Devon Is.
Nares Str.
BAFFIN SEA
Baffin Land Is.
Greenland Is.
Kniponich Ridge
GREENLAND SEA
Mohn Ridge
Jan-Mayen
Norwegian-Greenland Basin
NORWEGIAN SEA
Scandinavian Pen.
BALTIC SEA
Hudson Bay
Nagssugtoqidian
Kolbensein Ridge
Aegir Ridge
Iceland Is.
Ungava
Labrador Ridge
LABRADOR SEA
Cartwright
Reykjanes Ridge
North Atlantic Basin
NORTH SEA
Great Glen
British Isls.
Labrador Pen.
ATLANTIC OCEAN
Charlie–Gibbs
Newfoundland Is.
Iberian Pen.
Armorican
North Iberian
Gobanskii Ridge
70° W
60°
50°
40°
30°
20°
10°
0°
80° W
90°
10° E
20°
30°
40°
50°
60°
70°
80°
90°
100°
110°
120°
130°
140°
150°
160° W
1
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OCVB
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The slope is cut by riverbeds, which are located on the continuation of the Frantz–Victoria and St. Anna trenches and serve as the main channels for the terrigenous influx from the Barents Sea shelf.

The **along-axial segmentation and asymmetry** of the Eurasian Basin is expressed in the magnetic and gravity anomalies. In terms of some parameters, the line along 75° E meridian is distinguished as a peculiar discontinuity of the Eurasian Basin. Linear magnetic anomaly zone ΔTa becomes sharply narrower toward the Laptev Sea. Thereby, the area of banded magnetic anomalies in the Amundsen Basin is much wider than in the Nansen Basin (*Arkticheskii* ..., 2017). Seismic and bathymetric data indicate that the modern spreading axis in this area is shifted to the southern limb of the Gakkel Ridge (Jokat and Micksch, 2004). The spreading axis jump in this part of the ridge by 60–80 km supposedly occurred near 6 Ma (*Arkticheskii ...,* 2017].

This discontinuity also shows a sharp change in the distribution of a residual gravity anomaly pattern obtained by subtraction of anomalies, which were calculated from harmonics by 2D Fourier transform with a wavelength of $T > 200$ km, from observed Faye anomalies (*Arkticheskii ...,* 2017). West of 75° E, they are oriented along basin margin or transformed to the margin and the Gakkel Ridge. East of the discontinuity, the anomalies turn at an angle of 30°–40° relative to the margins and ridge and do not intersect the latter (*Arkticheskii ...,* 2017). It is noteworthy that a bend of the Lomonosov Rise is observed at the northern continuation of bends of the gravity and magnetic anomalies of the Eurasian Basin (Fig. 1).

The **linear magnetic anomalies** in the anomalous magnetic field (AMF) ΔTa are thought to be related to the gradual ocean floor spreading (Karasik et al., 1984; Kulakov et al., 2013). The wedge-shaped magnetic anomaly pattern conformable to the Eurasian Basin outlines is considered as evidence for the basin opening on the Fram Strait side, which in particular, led to the spatial separation of the initially single Morris Jessup–Ermak volcanic rise (Khain, 1971; Daragan–Sushchova et al., 2020).

Magnetostratigraphic estimates of the age of the Eurasian Basin are different. Based on the paired magnetic anomalies no. 24 distinguished along basin walls, some researchers ascribe the onset of spreading to the Eocene (53 Ma) (Cande and Kent, 1995; Grantz et al., 2001; Brozena et al., 2003; Glebovsky et al., 2006). Other researchers noted some uncertainties in the chronological identification of the magnetic anomalies (Gramberg et al., 1984; Gordin, 2002; *Arkticheskii ...,* 2017). Based on geological (first of all seismostratigraphic) data, it was recently proposed that the Eurasian Basin as a single structure was formed approximately 60–120 Ma earlier than the magnetostratigraphically dated onset of spreading, whereas the spreading began no earlier than Oligocene (~33 Ma), while the Gakkel Ridge was formed by the Miocene (23 Ma) (Daragan–Suchshova et al., 2020).

Obtained results of seismostratigraphic subdivision of sedimentary cover of the Nansen Basin also point to the age rejuvenation of the Gakkel Ridge. Analysis of data obtained during study of the Norwegian sector of the Eurasian Basin and materials of the Arctic-2011 Russian Project showed that NB-2 seismic complex (Early–Late Miocene, 23–10 Ma) is developed in the Nansen Basin, but is completely absent in the Gakkel Ridge area (Sokolov et al., 2021). The overlying NB–3 seismic complex (Late Miocene–Late Pliocene, 10–2.6 Ma) in the Nansen Basin unconformably onlaps the roof of NB–2 seismic complex. Towards the Gakkel Ridge, the NB–2 seismic complex disappears, and the NB–3 seismic complex with a sharp unconformity lies on the rocks of acoustic basement (Sokolov et al., 2021).

The **spreading velocity** in the Gakkel Ridge is 2–4 times lower than in the Atlantic and accounts for according to different estimates from 0.5–1.2 cm/yr (Jokat et al., 1995; Cochran et al., 2003) to 1–1.5 cm/yr (Glebovsky et al., 2006; Nikishin et al., 2018). It is noteworthy that the spreading velocity with the evolution of the rift structure showed a prograde decrease, as in the Reykjanes and Labrador ridges (Glebovsky et al., 1990; Glebovsky, 1995).

Active volcanic centers were found in the axial zone of the Gakkel Ridge (Müller and Jokat, 2000), but magmatic activity varies along the strike. Of three large segments established there, the central segment is characterized by a weak magmatism at the complete absence of basalts and the predominance of peridotites (Cochran et al., 2003; Mickhael et al., 2003). Based on the percentage of basalts dredged from ocean floor, a gradual transition from amagmatic to magmatic pattern of the floor is inferred near 70° E (Michael et al., 2003). The low content of basaltic material and strong ruggedness of the ridge topography indicate that the extension (at least over significant part of the ridge) occurred in a cold brittle crust.

Barents Sea Shelf

The base of the Barents Sea shelf consists of three lithospheric plates: Norwegian plate in the west, Svalbard plate in the central part, and Timan–Pechora plate in the southeast. The largest Svalbard plate includes the Svalbard, Frantz Josef Land (FJL), and Novaya Zemlya archipelagoes. The basement is represented by uplifted blocks of the pre-Baikalian rocks, which are separated by the Frantz-Victoria and St. Anna troughs (*Barentsovskaya ...,* 1988). These long-term rift structures oriented mainly orthogonally to the continental margin were initiated at the Permian–Triassic boundary (Vernikovsky et al., 2013).

The maximum basement subsidence was established in the Eastern Barents trough that is subparallel

to the Novaya Zemlya archipelago. In the sedimentary infill of its basins, the largest thicknesses (6–8 km) were determined for the Upper Permian–Triassic terrigenous and Devonian terrigenous rocks, whereas the Carboniferous–Permian carbonates are less than 1 km thick (Shipilov and Tarasov, 1998). The eastern part of the FJL is a deeply subsided block overlain by the Paleozoic–Triassic cover over 3.5 km thick. It was separated from the western part of the fault systems, along which narrow grabens were formed. The western part of the FJL is an uplifted Precambrian block, which according to drilling data was overlain by the Vendian, Triassic, and Jurassic sediments (*Barentsovskaya* ..., 1988; Shipilov and Tarasov, 1998).

Restyling of paleotectonic and paleogeographical sedimentation settings at the Triassic–Jurassic boundary provided conditions for the formation of plate sedimentary cover.

Rifting manifested itself by numerous dikes and sills both on the Svalbard archipelagoes and in the water basins (Fig. 1). In particular, the entire sequence of the East Barents trough up to the Lower Cretaceous is saturated in dolerite sills, which are similar in composition and age to those of the FJL (Shipilova and Tarasov, 1998).

Two magmatic complexes of different age and composition are distinguished in FJL (Karyakin and Shipilov, 2009). The Early Mesozoic magmatic complex is represented by tholeiitic basalts and dolerites of the Alexandra Land, Northbrook, Hooker, and Scott-Keltie islands with isotope ages of 189–156 Ma. Late Mesozoic magmatic complex is represented by basaltic covers and stocks of the Alexandra Land Island, as well as dikes and sills of tholeiitic dolerites of Haeys Island with an age of 137–124 Ma. At Aleksandra Land Island, the Late Mesozoic volcanic rocks are exposed in its northeastern part (Karyakin et al., 2009).

In terms of composition, the Early Mesozoic volcanic rocks correspond to the typical flood basalts of the Siberian Platform, whereas the Late Mesozoic rocks are similar to the plume volcanic rocks of hot spot-controlled oceanic islands (Karyakin et al., 2009).

Kara Sea Shelf

In terms of the basement type, structures, age, and thickness of sedimentary cover, the Kara Shelf is subdivided into the South Kara Sea and Kara Plate. They are separated by the North Siberian threshold in the northwest and by the adjacent Sverdrup Swell and Arctic Institute trough in the south (Mashchenko et al., 2002; Bogdanov, 2004).

Drilling at the Kara Shelf revealed the basement heterogeneity. Vendian metamorphic rocks were recovered by drilling in the plate cover, on Sverdrup Island (Gramberg et al., 1985; Timonin, 2009), while terrigenous, carbonate, metamorphic, and volcanogenic rocks intruded by basic dikes and minor Paleozoic granite intrusions were found on the Yamal Peninsula in the roof of the pre-Jurassic basement. The Paikhoi–Novaya Zemlya and Taimyr–Severnaya Zemlya fold deformation zones are distinguished in the basement topography as linearly extended rises (Bogolepov et al., 1990).

The largest structural discontinuity on the shelf is restricted to 80° E (Fig. 1). To the north of the Novaya Zemlya, it likely corresponds to the belt of the positive and negative magnetic anomalies, which is extended from the central segment of the Lomonosov Ridge through the Eurasian Basin into the St. Anna Trench to the eastern boundary of the FJL and further into the North Barents Basin (*Arkticheskaya* ..., 2017).

The lithospheric blocks on the other side of the discontinuity have principally different styles of relations with Eurasia: collisional on Taimyr and rifting in the rear part of Novaya Zemlya, which is expressed in oppositely directed vergence of orogenic fronts.

A model of the structural transformation of the Taimyr flank of Siberia during interaction with the Kara block is presented in (Vernikovsky et al., 2013). According to this model, the present-day structure was formed in three stages: Silurian–Devonian (430–400 Ma), Carboniferous–Permian (300–260 Ma), and Permian–Triassic (260–240 Ma). According to other data, the main orogenic stage occurred within 230–190 Ma and was completed prior to the accumulation of unconformably gently lying Early Jurassic sedimentary rocks (Walderhaug et al., 2005).

According to the paleomagnetic and $^{40}Ar/^{39}Ar$ geochronological data, the intrusive magmatism including sills of the Southern Taimyr occurred within 230–220 Ma, which is 20 Ma later than the main pulse of trap volcanism (Walderhaug et al., 2005). Only basalts from the southernmost Taimyr yield an old age (248.5±6.0 Ma) corresponding to the main phase of the trap volcanism. The presence of Late Triassic and Jurassic basalts and dolerites on Taimyr indicates that the magmatic activity was displaced toward the Kara Sea. It is suggested that the formation of the Arctic Igneous Province was related to the same long-term thermal anomaly that formed the Siberian Traps (Saunders et al., 2005).

Rifting processes to the west of the discontinuity line led to the formation of the South Kara Basin located on the continuation of the rift structures of the West Siberian Plate (*Tektonicheskaya* ..., 1996). The pre-Mesozoic basement of the basin (Riphean–Early Paleozoic metamorphosed rocks) is subsided to a depth of 12–14 km, while the central part is subdivided into several uplifted horst-type blocks (Rusanovsky, Rogozinsky, and others), above which the total thickness of the Mesozoic–Cenozoic sediments is reduced to 5–7 km. The blocks are subdivided by deep mainly submeridional rift troughs. In the graben

structures of the central part of the basin, the thickness of the synrift Permian–Triassic complex is estimated as 6–7 km. The relation of these structures with positive gravity and magnetic anomalies is regarded as evidence for deep reworking of the crust in rifting zone and the manifestation of Early Triassic basic magmatism corresponding to the early rifting stage (Bogdanov, 2004). This feature of the geological structure of the South Kara Basin reflects its genetic link with structures of the West Siberian Plate (Surkov et al., 2002).

West Siberian Plate

The West Siberian Plate (WSP) composes the basement of the West Siberian Plain. It is in contact with the Siberian Platform in the east, with Paleozoic systems of Central Kazakhstan, Altai, and Salair–Sayan region in the south, with the Uralian fold system in the west, and grades into the South Kara Basin in the north (Fig. 1).

The thickness of the lithosphere beneath the WSP is lower (100–150 km) than beneath the Siberian Craton (300 km). The depth of Moho seismic boundary is 46 km and decreases to 38 km beneath the central part and to 34 km further to the north beneath the Urengoi rift (Saunders et al., 2005). Unlike the Siberian Craton, this area lacks Archean rocks. Meso–Cenozoic sedimentary cover reaches 10 km in the north and decreases to the south and plate margins.

Three structural levels reflect the evolution of the territory. Two lower levels, the Paleozoic fold basement and rifting Triassic level are termed the pre-Jurassic basement of the West Siberian Plate (Ivanov et al., 2012). The Late Triassic produced mainly terrigenous sediments, while the Middle Jurassic was marked by the subsidence with formation of one of the world's largest West Siberian sedimentary basin.

Basaltic magmatism occurred in the early and beginning of the Middle Triassic near 250–245 Ma. Compositionally, the WSP basalts are similar to the Siberian traps and are regarded as the part of the Ural–Siberian igneous province (Puchkov, 2018). The main magma generation area is located beneath a relatively thin (50–100 km) lithospheric plate, rather than beneath the Siberian Craton lithosphere, which also comprises traps. This indicates very significant lateral displacements of the magma (Saunders et al., 2005).

Rifting has continued in the Triassic after completion of basaltic magmatism. The oldest sediments overlying rift rocks has an age of 165 Ma, i.e. rifting has continued for a long time (during 85 Ma).

Noteworthy is the sublongitudinal orientation of West Siberian extension structures. The central position is occupied by the Urengoi–Koltogor rift system extended for 1500 km from the Kara Sea to the latitude of the town of Omsk. The eastern flank of the rift system is extended along 80° E, the remarkable discontinuity traced up to the North Pole and separating regions with different anomalous magnetic and residual gravity patterns (Khain, 1979; *Arkticheskii ...*, 2017). The same longitude is mentioned in the hypothesis for opening of a wedge-shaped "Ob ocean", the spreading pole of which due to the Siberian rotation relative to East Europe at 13.4° supposedly was located in a point with coordinates 60° N and 80° E (Aplonov, 1987).

Laptev Sea Shelf

The shelf of the Laptev Sea is located on the continuation of the Eurasian Basin and separates it from Eurasia (Fig. 1). Morphologically, the shelf represents a north-dipping low-angle plain, which is practically devoid of contrasting landforms and located at a water depth no more than 500 m deep.

The Late Cretaceous–Holocene cover of the Laptev Sea shelf is likely underlain by the Late Mesozoic fold basement subjected to the intense extension and block differentiation prior to the opening of the Eurasian Basin (*Arkticheskii ...,* 2017).

In the shelf zone transitional to continent, magnetic field is almost homogenous unlike the banded pattern of magnetic anomalies on the Gakkel Ridge side (Imaev, 2004). From continental slope to the coast, the shelf shows linear negative free-air gravity anomalies, which are expressed in the alternation of narrow linear high-grade zones of the northwestern and sublongitudinal extension (*Arkticheskii ...,* 2017).

The gravity anomalies are confined to the narrow deep (4–12 km) NW-trending grabens and troughs (Ust-Lena, Omoloi, Ust–Yana, Bel'kovsk–Svyatoi Nos, and others), which are hidden beneath cover and have a length up to 200–250 km at a width of 40–60 km (Grachev et al., 1973; Gramberg et al., 1990; Avetisov and Guseva, 1991; Avetisov, 1996). The largest structure is the sublongitudinal Ust-Lena graben. It is traced from the southern termination of Buor-Khaya Bay to 75° N for a distance of 400–420 km. In the northern part, the graben width reaches 150–170 km. To the south, it gradually becomes narrower, decreasing to less than 30–40 km in the middle part of the Buor-Khaya Bay. In the northern and central parts of the graben, its walls record sublongitudinal strike-slip displacement along en-echelon faults (Grachev et al., 1973; Drachev, 2002).

Judging from earthquake mechanisms, the entire shelf of the Laptev Sea experiences extension, which leads to the sublatitudinal pulling apart of lithospheric blocks. Earthquake epicenters and focal mechanisms define a rhomboidal pattern. It can be considered as results of convergence of branches of two triple junction points: in the northern part of the shelf (approximately 78° N and 126° E) and south of Buro-Khaya Bay (Avetisov, 2000).

The Laptev Sea portion adjacent to the Eurasian Basin comprises a system of protrusions, which occurred no earlier than Pliocene (5 Ma) and are related to the manifestation of diffuse rifting (Daragan-Sushchova et al., 2020). The cited authors suggest that in future these separate rift structures at the boundary of the Laptev Sea shelf and Eurasian Basin shall be united in a morphologically extended longitudinal ridge.

Canadian Basin

The structure is a vast basin with smoothed floor topography and water depths of 3500–3900 m (Fig. 1). The northeastern boundary of the Canadian Basin from the Moris–Jessup Rise to the Beaufort Sea is the Canadian–Greenland continental uplift clearly expressed in the gravity anomalies. The southwestern and southern margins are bounded by the Beaufort terrace and the Beaufort continental margin, respectively. In the northwest, the Canadian Basin borders the flanks of the Alpha–Mendeleev Rise and the Mendeleev abyssal plain (*Arkticheskii ...,* 2017).

The Lower Cretaceous–Cenozoic basement of the Canadian Basin is overlain by the Cenozoic sedimentary cover, the thickness of which decreases from the east to the west from 12 to 6 km (Bogdanov, 2004).

The linear gravity minimum is established from the mouth of the Mackenzie River to the southern slope of the Alpha–Mendeleev Rise. This gravity anomaly is interpreted as the axis of old spreading (Laxon and McAdoo, 1998).

Linear magnetic anomalies have no clear expression. The anomalies M25–M12 likely corresponding to an interval of 154–127 Ma were identified in the axial zone of inferred spreading (Taylor et al., 1981). Based on this fact, it is suggested that the formation of the main present-day structures began at the end of Late Jurassic from the opening of the Canadian Basin in Kimmeridgian about 150 Ma. The main spreading phase is ascribed to the second half of the Early Cretaceous, from Hauterivian (136 Ma) to Albian–Cenomanian (99 Ma) (Shipilov, 2008).

The shape of the Canadian Basin and extension of indistinct magnetic anomalies are interpreted by some researchers as a result of counterclockwise rotation of the Arctica–Alaska–Chukotka microplate from the Arctic Canada at 66° with a pole around the Mackenzie River delta (Bogdanov, 2004; Dove et al., 2010; Laverov et al., 2013). It is suggested that the largest displacement of crustal structures with the separation of the European block from the Canadian block occurred along the dextral strike-slip at the boundary of the Lomonosov Rise and Makarov Basin (Dove et al., 2010; Døssing et al., 2013).

At the same time, some geological facts are inconsistent with this hypothesis. In particular, the rotation within the Canadian Basin cannot completely explain the formation of ophiolite suture, which extends for too large for this model, surrounding the continental block with the New Siberian Islands (Bogdanov, 2004). In addition, data on detrital zircons indicate that the Chukchi portion of the microplate was located in the vicinity of Taimyr and Verkhoyansk, rather than near the Canadian Arctic region (Miller et al., 2006).

It should be noted that in spite of the refined initial models and the appearance of new data on the structure of sedimentary cover and basement, the origin of the Canadian Basin remains unclear. The mechanism and stages of its evolution remain hotly debatable problems, with an extremely wide range of proposed models (Nikishin et al., 2020; and others).

Shelves of the Chukchi and East Siberian Seas

The development of shelves of the East Siberian and Chukchi seas, as of the entire structure of the Russian Northeast from the Chukchi Peninsula to the Taimyr Peninsula, is related to the Mesozoic (Jurassic–Cretaceous) orogeny (Fig. 1). The Jurassic–Cretaceous time was responsible for the formation of fold systems from the New Siberian Islands to Alaska. By the Late Cretaceous, the consolidation of acoustic basement of this territory and termination of significant fold deformations were followed by the formation of a single New Siberian–Chukchi–Brooks orogenic belt (Khain et al., 2009) or New Siberian–Chukchi–North Alaska microplate (Herron et al., 1974; McWhae, 1986; Zonenshain et al., 1990; and others). The belt is bounded by a system of extended overthrusts on the oceanic side (Filatova and Khain, 2009), includes the Arctic islands and Chukchi fold belt on the Eurasian side, and the Northern Alaska structures at the American continent.

Analysis of the anomalous free-air gravity value shows that continental shelves of the Chukchi and East Siberian seas are separated from the ocean floor by the clearly expressed maximum system corresponding to sediments that were precipitated on its margin and were not compensated by the basement sagging (Laxon and McAdoo, 1998; Mazarovich and Sokolov, 2003). The presence of Caledonides (Ellesmerides) fragments is inferred on the Alaska shelf and in the northern Chukchi Sea (Khain et al., 2009).

In spite of a sharp bend of the Mesozoic overthrusts front on the traverse of the Cape of Hope, the sublatitudinal orientation of deformation structures and related sedimentary basins is preserved on Northern Alaska (Fig. 1).

In addition to the sublatitudinal structures, the shelf also comprises sublongitudinal structures sometimes penetrating in the basement of the continental slope. At the shelf of the Chukchi Sea, toward the Canadian Basin, there are two sublongitudinal inliers of continental margin: Chukchi plateau and the Northwind Ridge (Kaban'kov et al., 2004; Grantz

et al., 2009). The plateau is intersected by sublongitudinal extension structures (*Arkticheskii* ..., 2017). The interpretation of seismic and gravity data indicates a continental nature of the Chukchi plateau crust. The Paleozoic complexes are represented by platform shallow mainly carbonate sediments, which are overlain by the Cretaceous–Cenozoic terrigenous cover (Grantz et al., 1998; Filatova and Khain, 2009).

Along 165°–168° W, the seismic survey revealed sublongitudinal dextral Hannah zone, which developed from the Paleocene to the Middle Eocene (Lothamer, 1992). This zone is variably traced in potential fields (Poselov et al., 2008). According to the complex processing of magnetic and gravity data, the disturbances of the Hannah zone along a system of subparallel en-echelon detachments are traced in the Bering Sea (Chekhovich et al., 2014). It is suggested that this is an extended dextral strike-slip shear zone spanning both the crust and upper mantle. The displacement amplitude along the sublongitudinal strike-slip zone is estimated as 400 km (Saltus and Bird, 2003).

Alpha-Mendeleev Rise and Adjacent Basins

The Mendeleev Rise is traced from the East Siberian Sea shelf northward to the Canadian shelf, where it grades into the Alpha Rise. The Podvodnikov and Makarov basins separate these structures from the Lomonosov Rise (Fig. 1).

Paleozoic sedimentary rocks with numerous fauna were found in the basement of the Alpha–Mendeleev Rise (Skolotnev et al., 2019). The oldest sediments on the Mendeleev Rise and northern part of the Alpha Rise above the acoustic basement could have an age of 70–75 Ma (Campanian–Maastrichtian) (Bruvoll et al., 2010). Within the rise, the basalts form covers, numerous dikes, and sills. The age of dredged basalts varies from 110–127 to 90–80 Ma (Coakley et al., 2016; Skolotnev et al., 2017). In terms of trace-element contents and ratios, the basalts of the Alpha Rise were obtained by melting of continental lithosphere (Døssing et al., 2013).

The Podvodnikov and Makarov basins were formed in the Early Cretaceous (Aptian–Albian, 125–100 Ma) simultaneously with rifting on the shelves of the Chukchi and East Siberian seas (Nikishin et al., 2019). The present-day morphology, including grabens and horsts, was formed under extension conditions after the termination of magmatism, but the latest manifestations of intrusive magmatism occurred in the Early Miocene (22–14 Ma). The intrusive bodies are marked by chaotic and diffuse reflections in the sequence 0.2–0.3 s thick (Bruvoll et al., 2012).

The northern part of the Alpha Rise, Makarov Basin, and adjacent areas reveals large and extended magnetic anomalies with a positive magnetization over 500 nTl, which are practically orthogonal to the Alpha Rise (Døssing et al., 2013). Recent interpretation of aeromagnetic and geological data (Oakey and Saltus, 2016) shows that magnetic anomalies of the Alpha Rise are propagated over coastal regions of the northern islands of the Canadian Arctic Archipelago. In Yelverton Bay, Ellesmere Island, magnetic anomaly coincides with lavas, dikes, and Wootton intrusive complex (Estrada et al., 2016).

The Cretaceous magmatic activity began 123–97 Ma from the emplacement of tholeiitic basaltic dikes (Estrada et al., 2006), which were followed by tholeiitic basalts of the Hansen Point series (97–93 Ma) and alkaline basalts of the Audhild Bay series (83–73 Ma) (Naber et al., 2021).

ATLANTIC–ARCTIC RIFT SYSTEM

The AARS extends for near 18 thou. km and includes the Mid-Atlantic Ridge (MAR) and the Gakkel Ridge, which is one of the main rift structures of the Arctic region (Fig. 2).

The presence of transform fracture zones is an integral feature of the AARS structure. Along strike, the rift system is split into separate segments displaced relative each other by numerous single transform faults or fault systems—megatransforms (Shipard, 1951; Heezen et al., 1959; Klenova and Lavrov, 1975; Emery and Uchupi, 1984; Puchsharovsky et al., 1988; Skolotnev et al., 2020; and others).

The displacement along the faults shows strong offset variations. The largest (demarcation) transform faults were established in the equatorial Atlantic (Romanche–San Paulo Fracture Zone from the south and 15°20' in the north with the total offset about 3300 km), between the Western Arctic and Northern Atlantic (Mohns and Knipovich rifts with the total offset of about 950 km), and fault-related Charlie–Gibbs polytransform system with offset of 350 km (Pushcharovsky et al., 1988; Bonatti et al., 1991; Hekinian et al., 2000; Ligi et al., 2002; Kelemen et al., 2004; Sokolov, 2018; and others).

Fig. 2. Scheme of the AARS structure in the Khotin projection, according to (King, 1961; White, 1988; Moore et al., 1994; Eldholm and Coffin, 2000; Jokat, 2000; Le Gall et al., 2005; Bryan and Ernst, 2008; Antobreh et al., 2009; Moulin et al., 2010; Hildebrand, 2015; Sokolov, 2018; Gernigon et al., 2019; Marzoli et al., 2019; Müller, Jokat, 2000; Schiffe et al., 2019; Sokolov et al., 2020; and others). (1) Land; (2, 3) basins; (3, 4) igneous provinces and the onset time of their formation: (3) pre-spreading, including: (CAIP) Central Atlantic (boundaries of fragments are shown by dashed line), (NAIP) North Atlantic, (HAIP) High Arctic, (USIP) Urals–Siberain, (4) syn-spreading; (5) number of the AARS segment and onset time of its opening; (6, 7) spreading ridges: (6) active, (7) extinct; (8) line of rifting and elevated seismicity; (9, 10) overthrusts: (9) regional, (10) local; (11) faults: (*a*) proved, (*b*) inferred; (12) shears.


160° W
170°
180°
170° E
150°
130°
110°
90°
80° E
150° W
140°
130°
120°
110°
100°
W 90°
0°
90° W
100° W
80°
60°
40°
20° W
0°
20° E
60° E
50°
30° N
30° S
PACIFIC OCEAN
BERING SEA
SEA OF OKHOTSK
Sakhalin Is.
Kamchatka Pen.
Alaska
Kolyma Highland
Chukchi Highland
Lena R.
Tien Shan
320 Ma
Tarim
280 Ma
USIP
250 Ma
Eurasia
Herald
Queen Charlotte Is.
Angaulchem
210 Ma
ARCTIC OCEAN
HAIP
130 Ma
8
54
Ma
FJL
189 Ma
CASPIAN SEA
Cascadia
Columbia
17 Ma
Sierra Nevada
Golconda Basin and Range Province
Laramide Rocky Mountains
Colorado Plateau
Rio Grande Rift
Transformation
Olympic
Hudson Bay
Greenland Is.
Khipovich
North America
Labrador
NAIP
62 Ma
7
59
Ma
BLACK SEA
MEDITERRANEAN SEA
Charlie–Gibbs
CAIP
201 Ma
6
130
Ma
Gulf of Mexico
Atlantis
5 Ma
5
170
Ma
ATLANTIC OCEAN
Africa
Caribbean–Columbian
92 Ma
15 degree
118
Ma
4
Sierra Leone
70 Ma
Ceara
70 Ma
Romanche
Sao Tome and Principe
South America
3
120
Ma
Trinidad
85 Ma
Parana
134 Ma
Walvis Ridge
Rio Grande
2
Karoo
183 Ma
Etendeka
134 Ma
130
Ma
Chon Aike
188 Ma
Georg
140
Ma
1
Agulhas
90 Ma
1
2
3
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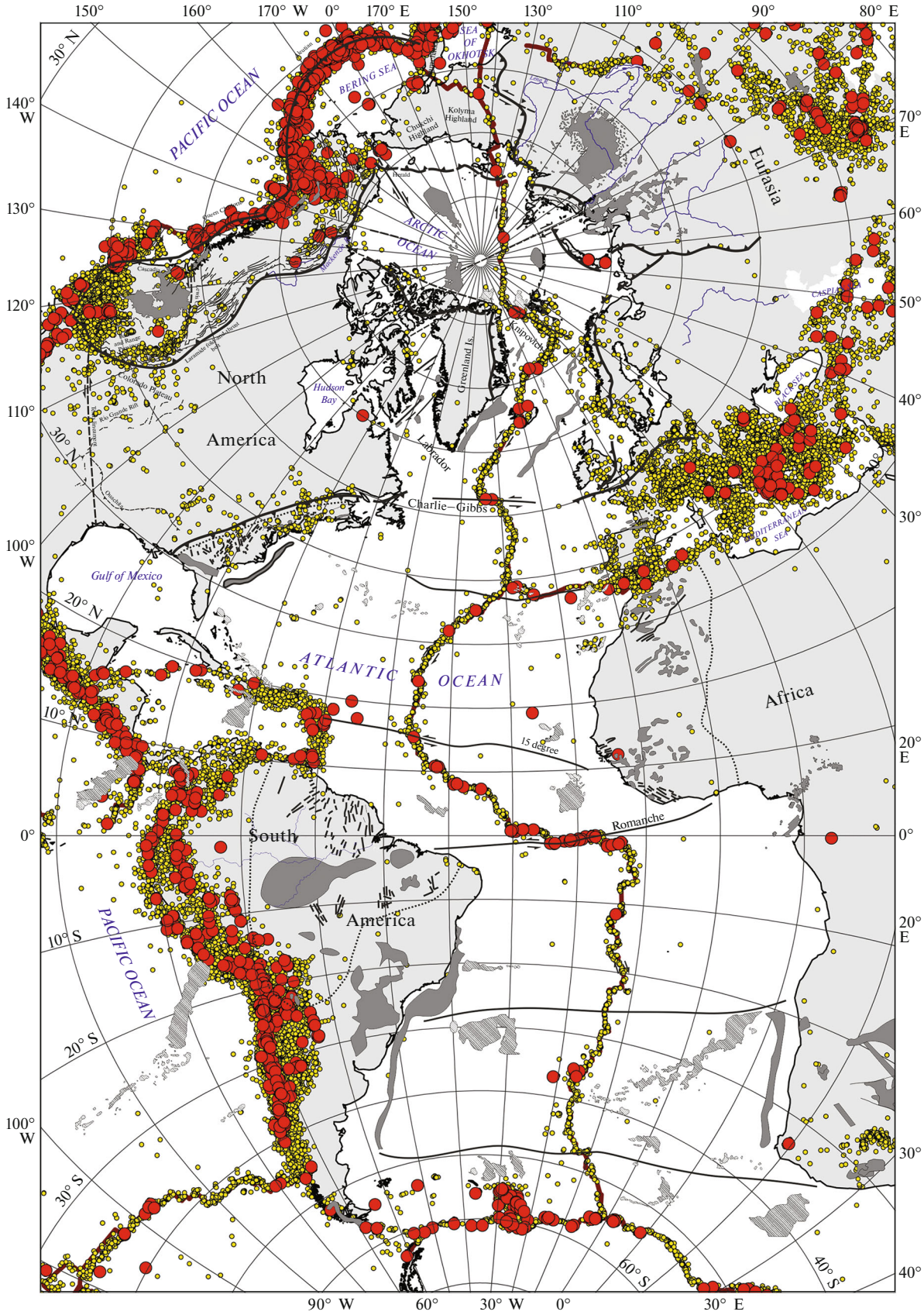

Fig. 3. Earthquake epicenters according to (ANSS, 2014) along the AARS and continental surrounding. Red circles show events with $M > 6.1$, yellow circles, with $M > 5$. For other symbols, see Fig. 2.

Seismicity with maximum energy release and strike-slip mechanisms is linked to the demarcation faults (Fig. 3, Boldyrev, 1998; Dmitriev and Sokolov, 2003; Sokolov et al., 2020). Therewith, the transition from the Atlantic to Arctic segments is marked by the deepest faults (seismic events below 35 km) (Sokolov et al., 2020). An inversion of the spreading half rates south of the zone from the western to the eastern part is observed near the third largest latitudinal displacement in the AARS, the transform Charlie–Gibbs Fracture Zone, having one of the maximum of the total seismic moment (Sokolov et al., 2020). Such kinematic relations of half rates calculated from magnetic data should intensify the lateral displacement of the AARS axis and initiate the high seismic background (Boldyrev, 1998).

Analysis of seismic velocity ratios Vp/Vs in mantle based on seismic tomography data showed that the "cold" anomalies in mantle within depths from 300 to 600 km are confined to the AARS intersection by demarcation transforms. Based on the thermal interpretation, the velocity anomalies correspond to the minimum geodynamic mobility (Sokolov, 2017).

The sinistral transform displacements of spreading axes with a wide range of offset amplitudes are best developed along the AARS strike (Figs. 1, 2). The subordinate role of dextral displacements is indicated by the absence of demarcation faults among them, which separate large AARS segments.

Authors of this paper suggest that the distinct predominance of the sinistral displacement of the spreading axes in the AARS structure reflects energetically more favorable way of strain smoothing in the lithosphere. The abortive development of the dextral strike-slip evolution could be exemplified by the rift system of the Labrador Sea, the extinct Iberian branch of the AARS, Aegir rift, and transition from the Kolbeinsey Ridge to the Mohns Ridge (Fig. 1). In all cases, the dextral strike-slip rift systems are either degenerated or replaced by sinistral displacements. In particular, the independent evolution of the Mohns rift system was adapted to the sinistral strike-slip Greenland–Spitsbergen demarcation zone.

The demarcation transforms serve as boundaries for the large AARS segments, which in spite of the general similarity of tectonic and sedimentary settings, possess several peculiar evolution features. This first of all concerns the initiation of spreading processes in a definite segment. By the time of spreading start along the AARS, two segment groups are clearly distinguished: from 5 to 8 and from 1 to 4 (Fig. 2). The evolution of the first group spans the entire time of the Atlantic spreading, while the opening of the second-group segments is restricted to the middle part of the total time interval. In each of the groups, the age values of spreading start form gradually increasing sequences, which reflect the general evolution of rifting toward the North Pole.

In a plan view, the trajectory of rifting structures of both groups are converged at 15° Fracture Zone, which serves as the southern boundary of the Central Atlantic segment of the AARS, from which the evolution of the entire rift system has began (Fig. 2). In the modern structure, the segment is located in the middle part of the AARS, while its axial MAR segment is located practically at an equal distance from fragments of the former common Central Atlantic igneous province.

These tendencies clearly indicate that 170 Ma spreading in the Central Atlantic Segment of the AARS was initiated by prograde divergence of continental lithosphere blocks significantly reworked during formation of giant igneous province CAIP near 200 Ma.

The restriction of the trajectory of the growing rift system to the weakened lithosphere areas is clearly expressed in relations between ages of pre-spreading igneous provinces and onset of spreading in other segments (Fig. 2).

Spreading in the Antarctic segment at 140 Ma was preceded by the manifestation of the Chon Aike and Ferrar igneous provinces (188 and 184 Ma, respectively). The appearance of the Parana and Etendeka igneous provinces at 134 Ma prepared continental lithosphere to the spreading of the South African and Brazil–African segments within 130–120 Ma. Northward, along the AARS strike, the time gap between formation of igneous provinces and spreading onset is reduced (Fig. 2).

A tight spatial relation of the AARS evolution with pre-spreading igneous provinces indicates a long-term, from initiation of intracontinental rifting to the beginning of spreading, dynamic impact on the definite regions of the lithosphere. This action did not terminate after the start of spreading and is reflected in the development of syn-spreading igneous provinces along trajectories of divergence of continental blocks (Fig. 2).

In addition to igneous provinces, the trajectories of the AARS growth were likely determined by rheological heterogeneities in continental lithosphere subjected to the collisional reworking at different stages of geological evolution.

The present-day structure of Greenland, Canadian Archipelago, and Europe clearly demonstrates sublatitudinal belts and sutures related to the Baikalian tectonogenesis (Fig. 2). Some of them are associated with fracture zones initiated during formation of the North Atlantic modern structural plan. An important role in the determination of the Atlantic rift trajectory was played by the regions of Caledonian and Hercynian tectonogenesis. In particular, following Caledonian deformations, the Great-Glen Fault is extended from the northwestern Ireland on the eastern wall of Atlantic to the Newfoundland Island in the west (Fig. 1), while the sublatitudinal Charlie–Gibbs Fracture Zone

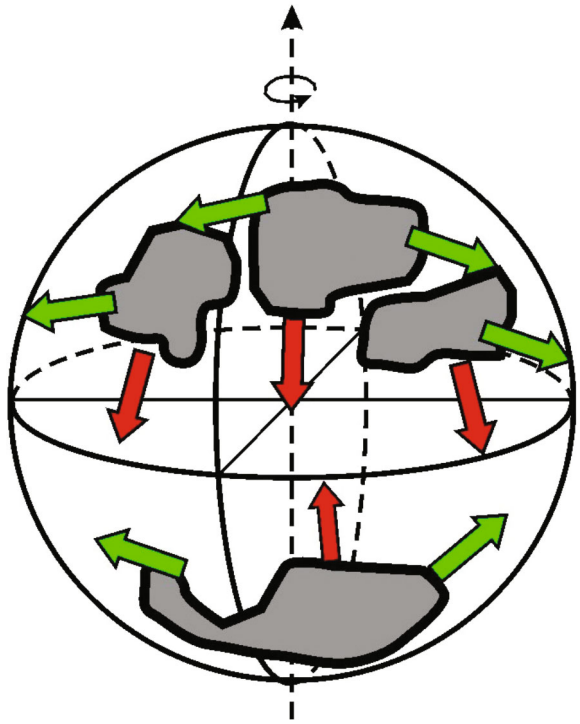

Fig. 4. Scheme of the migration of masses asymmetrically distributed over the surface of rotating spheroid: red arrows show a "pole fugal" movement to the equator with maximalization of the main axial component of inertia tensor; green arrows show trend to the even mass distribution along equator with minimization of tangential components of inertia tensors according to (Sokolov, 2018).

lies on the continuation of Hercynian orogeny front separated by North Atlantic (Figs. 1, 2).

DEVELOPMENT OF THE RIFT SYSTEM

The above considered tendencies in the evolution of the AARS indicate the existence of highly dynamic physical factors, which exert positive, unless constant influence on the geological medium. Among these factors are the dynamic stress system related to the Earth's rotation.

We suggest that the northward AARS development and systematic formation of typomorphic structures in each newly formed segment is defined by rotation factor. Such factor could provide a steady dynamic influence on the lithosphere and maintenance of tectonic regime in the global structure for the last 170 Ma. It is highly probable that inevitable cyclic variations of Earth rotation parameters are reflected in the deviations of the AARS trajectories.

In a general sense, the influence of rotation factor on the lithosphere is based on the tendency of its tectonically laminated elements to the equilibrium relative to the current rotation parameters, the angular velocity and position of rotation axis, after their global changes. This change is caused by the processes in the Earth's core (Trifonov and Sokolov, 2018), which are related to the migration in liquid core of masses many times exceeding the mass of lithospheric shell and therefore, having priority in cause-and-effect sequence of tectonic events. Physical principles of surface masses response on a change of rotation regime are considered in (Sokolov, 2018) and can be reduced to the following points. Masses of Earth's solid shells distributed asymmetrically relative to the spheroid rotation axis tend to occupy the position at which inertia tensor acquires diagonal components. This is attained by a combination of two types of movement: toward an equator with increasing the main axial component of inertia tensor and the redistribution of mass along equator with decreasing tangential components of inertia tensor (Fig. 4). Due to complicated distribution of lithospheric masses over spheroid surface and permanent wandering of rotation axis in the Earth, the trajectory of mass transfer into equilibrium state could be more intricate than trends shown in Fig. 4.

The tectonic implication of this process is the development of a characteristic set of conjugate structures. The movement of lithospheric masses from the pole facilitates the manifestation and possibility of northward progradation of sublongitudinal rifts, while movement along equator leads to the dissection of rifts by sublatitudinal transform faults into separate segments.

Tendencies in the migration of lithospheric masses asymmetrically distributed over the surface of rotating spheroid (Fig. 4) determine spatial boundaries of the developing rift system. The outflow of masses to the low latitudes provides a long-term growth of the rift system, but does not facilitate its further progradation after pole attainment. According to these concepts, the Gakkel Ridge is the end segment of the AARS, while the North Pole is the terminal point of its evolution.

The sequence of the evolution of a large sublongitudinal rift system can be represented by the example of AARS as follows. At some stage of rift evolution, a sublatitudinal weakened zone appears across its strike (Fig. 5a). Its initiation could be caused by either lithotectonic heterogeneity of the medium or approaching the tensile strength at the boundary of segments with different angular rotation velocity. Significant influence could be caused by tangential velocity on the spheroid surface increasing with distance from rotation axis at constant angular velocity, but at the presence of lithosphere heterogeneities.

The exceed of tensile limit leads to the sinistral displacement of adjacent segments 1 and 2 along fracture zone arising in the weakened zone (Fig. 5b). A relative displacement (turn) of segments likely reflects a delay in rotation of segment with the lower angular velocity. The deceletarion effect can be caused by the increased friction of lithosphere foot in the presence of cold

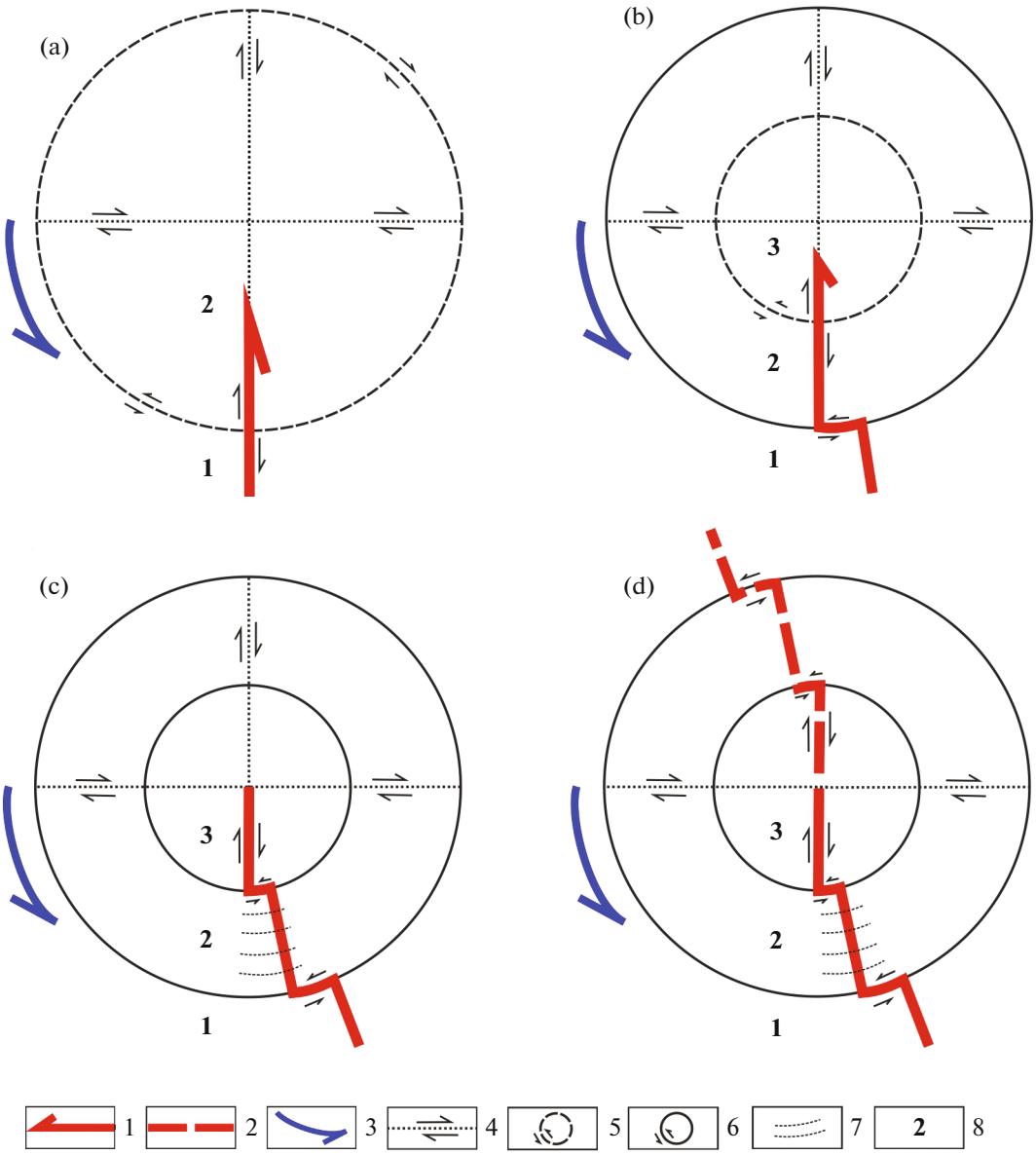

Fig. 5. Scheme of the subsequent initiation of sinistral latitudinal shears in the sublongitudinal rift structures (northern polar projection). (1, 2) Rift systems: (1) AARS, (2) OVRS; (3) direction of the Earth's rotation; (4, 5) protodetachments and their kinematics: (4) sublongitudinal after (O'Driscoll, 1980), (5) latitudinal; (6, 7) fracture zones and their kinematics: (6) demarcation, (7) local; (8) numbers of segments of rift systems in order of their opening.

blocks in sublithospheric mantle. The delay of near-polar segments compared to near-equatorial ones could be determined by the tidal influence, which at constant angular velocity could have the greater effect in the regions with the higher tangential velocity.

Further progradation of sublongitudinal structure leads to the appearance of a new sublatitudinal weakened zone between segments 2 and 3 (Fig. 5b), the initiation of demarcation transform, and the displacement of rift system axial parts along the latter (Fig. 5c). When pole will be attained, the longitudinal progradation of rift will be terminated due to the decay of driving forces (absence of arrow in Fig. 5c). Thereby, the continuing influence of rotation factor will facilitate an increase of amplitude of sublatitudinal displacements of axial parts of the rift system due to the growth of the existing and initiation of new fracture zones of different scale (Fig. 5c). This could be both individual faults spaced far from each other along longitude and polytransform systems with intricate faults typical of Equatorial Atlantic.

Obtained structural pattern corresponds to the strike-slip arrangement of the AARS, is consistent with the northward age rejuvenation of its segments opening, and well describes the evolution of the West Arctic zone as the youngest part of this system. The

proposed analogous model of the evolution of rift system seems to be sufficiently consistent, taking into account and explaining the main tendencies in the AARS evolution under the influence of rotation factor.

It should be noted that some of the naturally observed phenomena are ignored in the model or disagree with it. In particular, the proposed model excludes the AARS evolution after pole intersection. Nevertheless, the Laptev Sea flank of the Gakkel Ridge is beyond the inferred end point of evolution.

Two essential considerations suggest that this disagreement is not crucial for the developed models. First of all, it is necessary to take into account possible unless obligatory migration of the pole: the rift system observed in the modern structure of the region at the moment of initiation could evolve under different dynamic condition. In addition, the lithosphere breakup (especially cold lithosphere such as that of the Eurasian Basin) is ascribed to inertial processes and instant fixation of fault in a some theoretical point seems to the hardly possible. The model concepts are supported by following data, which are considered during description of the Eurasian Basin and indicate a gradual degradation of the Gakkel Ridge in the polar region:

1) a prograde reduction of the spreading velocity in the Gakkel Ridge with distance from the Atlantic ocean;

2) narrowing of magnetic anomaly zones toward the Laptev Sea;

3) the absence of gravity anomalies, which are transform to the ridge, to the east of 75° E;

4) small amount of basaltic material and strong ruggedness of the ridge topography, which points to rifting in a cold brittle crust.

The development of rift system according to the proposed model explains the appearance of only sinistral strike-slips under the influence of rotation factor. However, the dextral strike-slips nonetheless occur in the AARS structure. Subordinate development and geological inviability of such structures was considered above. Their appearance likely reflects the deviation from a general tendency under the influence of local lithosphere heterogeneity and/or is related to the cyclical variations of rotation parameters. The last assumption seems to be most probable, since explains the systematic appearance of low-amplitude dextral strike-slips at the complete absence of dextral demarcation fracture zones.

RELATIONSHIPS OF RIFT SYSTEMS

According to the rotation model of the evolution of rift system, the movement of tending to equilibrium lithospheric masses away from the pole facilitates the northward progradation of longitudinal rifts at the absence of dynamic reasons for their further growth after pole attainment. One more important implication of the considered process for understanding the evolution of the Arctic region is the convergence of sublongitudinal rift systems in the near-polar region.

The wide development of mainly longitudinal rift structures and their fan-shaped arrangement relative to the pole in plan were considered above during analysis of structure of the Arctic region. These structures include:

1) Gakkel Ridge in the Eurasian Basin;

2) Frantz Victoria, St. Anna, and Voronin troughs on the Barents Sea shelf;

3) rift troughs separating the basement blocks in the South Kara Basin;

4) rifts of the West Siberian Plate;

5) grabens on the surface of the Chukchi plateau-type rise;

6) Hannah shear zone and others.

Some morphologically indistinct sublongitudial structures such as grabens on the Laptev Sea shelf, dike swarms from the Eurasian continental margin to the Canadian Arctic Archipelago, and large faults are reflected in the potential fields (Grachev et al., 1973; Gramberg et al., 1990; Avetisova and Guseva, 1991; Shipilov and Tarasov, 1998; *Arkticheskii* ..., 2017; and others]. In addition, the sublongitudinal linear gravity minimum marks the Canadian Basin axis and interpreted as rifting and/or spreading axis (Laxon and McAdoo, 1998). Sublongitudinal orientation is traced in the spatial position and age rejuvenation of pre-spreading igneous provinces (Figs. 1, 2).

The presence of rift structures converging to the North Pole in the region suggests that some of them could be the Arctic termination of the larger supra-regional rift systems.

The possible existence of several sublongitudinal global structures has been repeatedly discussed in geological literature. It was suggested that the large sublongitudinal landforms are arranged over sphere with a step of ~ 90° (Hughes, 1973; Pan, 1985; Sholpo, 1986; Il'ichev and Shevaldin, 1986; Milanovsky and Nikishin, 1988). Although concepts concerning the spatial position of these structures have changed, they were generally regarded as a part of the global rift system and as the main channels for Earth's degassing (*Degazatsiya ...,* 1980; Milanovsky, 1991; Syvorotkin and Pavlenkova, 2014; and others).

The established tendencies in the evolution of the Atlantic–Arctic rift system coupled with seismological data and model concepts on the evolution of longitudinal structures allowed us to assume the possible presence of terminations (polar flanks) of several large extensional structures in the Arctic region (Fig. 6).

The **Okhotsk–Verkhoyansk rift system.** The Verkhoyansk orogenic system is of special interest as a continuation of the Gakkel Ridge and the Laptev Sea rifts. The orogenic system has a long-term evolution, but its

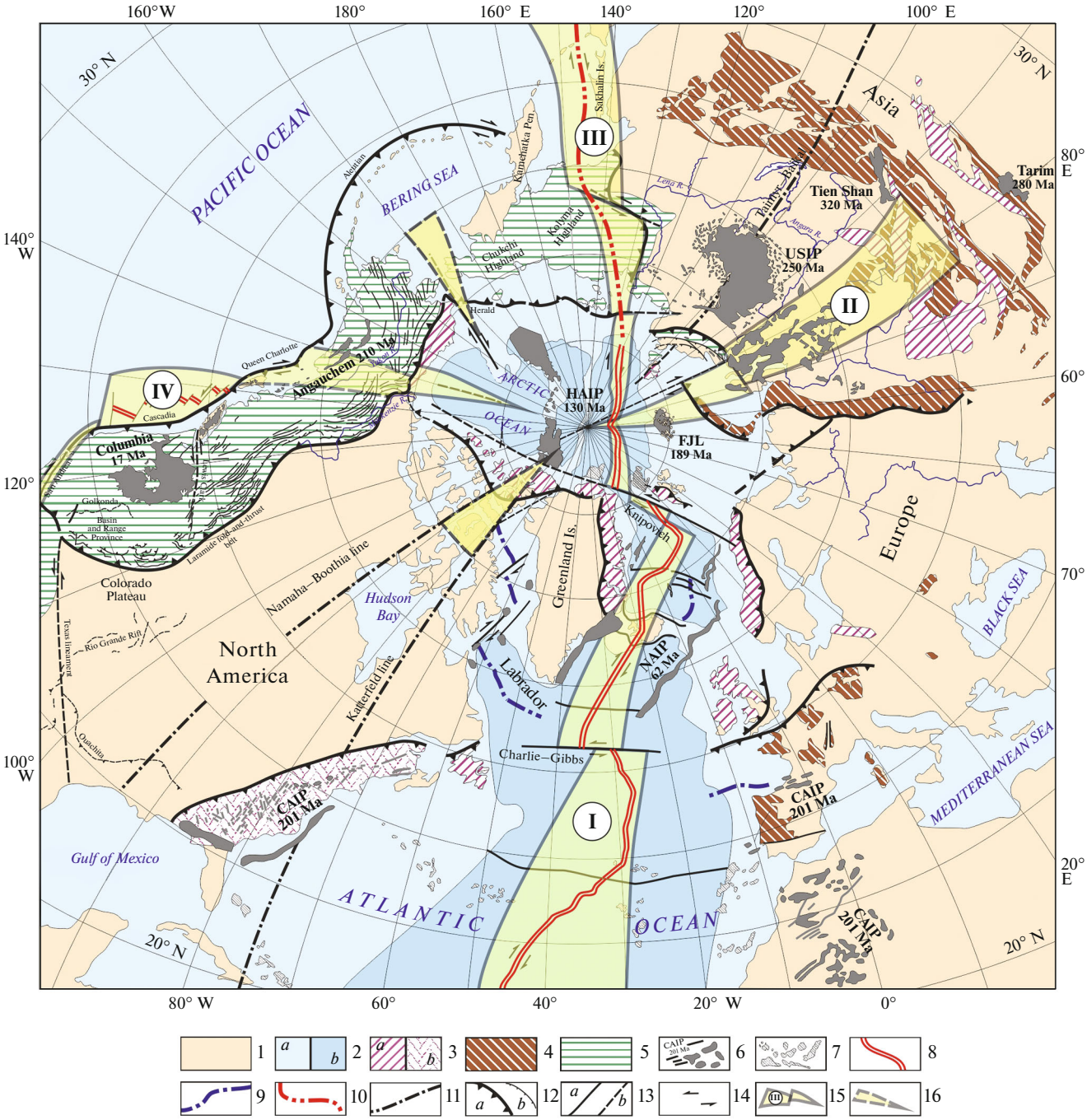

Fig. 6. Scheme of convergence of rift systems in the Northern Hemisphere in the Khotin Projection, according to (King, 1961; Katterfeld, 1962; *Tektonicheskaya ...,* 1964, 1966; Khain, 1971, 1979; White, 1988; Moore et al., 1994; Eldholm, Coffin, 2000; Le Gall et al., 2005; Bryan, Ernst, 2007; Hildenbrandt, 2015; Sokolov, 2018; Gernigon et al., 2019; Marzoli et al., 2019; Schiffer et al., 2019; Sokolov et al., 2020; and others). (1) Land; (2) basins: (*a*) <500 m isobath, (*b*) >500 m isobath; (3–5) orogenic areas: (3) Caledonian and Ellesmerian: (*a*) inactive, (*b*) involved in the Hercynian tectonogenesis, (4) Hercynian, (5) Mesozoic; (6, 7) igneous provinces and the onset time of their formation: (6) pre-spreading; (7) syn-spreading; (8, 9) spreading ridges: (8) active, (9) extinct; (10) line of rifting and elevated seismicity; (11) asymmetry line; (12) overthrusts: (*a*) regional, (*b*) local; (13) faults: (*a*) proved, (*b*) inferred; (14) shears; (15, 16) rifting branches: (15) proved, (16) inferred. Rift systems: (I) Atlantic–Arctic, (II) West Siberian; (III) Okhotsk–Verkhoyansk, (IV) East Pacific. For abbreviations, see Fig. 2.

structure is mainly made up of the Upper Paleozoic–Lower Mesozoic Verkhoyansk terrigenous complex up to 10–12 km thick (Khain, 2001; Andieva, 2008). The sediments are incorporated into the nappe-and-thrust structure with thrusting toward the Siberian Platform, with the Yenisei–Khatanga, Lena–Anabar, and pre-Verkhoyansk marginal troughs located in front of the orogeny. Large overthrusts are also present in the

frontal part of the Verkhoyansk orogenic system approaching the Laptev Sea coast (Khain, 2001).

The seismological and geological-structural data serve in support of the conjugation of the rift structures of the Eurasian Basin, the Laptev Sea shelves, and the Chersky Ridge (Grachev et al., 1970, 1973; Gramberg et al., 1990; Imaev et al., 2000, 2004; Engen et al., 2003). The continental part of this structural chain from the Laptev Sea to the Sea of Okhotsk coast is spatially restricted to the Verkhoyansk orogenic system. Up to the upper Pleistocene (0.126 Ma), it was evolved as the Moma continental rift system with all signs of continental rifting. By present, the system of Moma depressions is evolved in a transpressional mode owing to the convergence of the Eurasian and North American plates. It is believed that their convergence is caused by the migration of rotation pole of lithospheric plates from the Sea of Okhotsk coast to the Laptev Sea coast (Imaev et al., 2004).

Based on these facts, some researchers consider the Verkhoyansk fold system as the central segment of the giant presently active Arctic–Asian seismic belt, which connects the seismic manifestations in the Arctic and Pacific oceans (Cook et al., 1986; Imaev et al., 2000).

Concepts developed in this paper are consistent with ideas of previous researchers. The absence of geodynamic reasons for the AARS progradation toward the Sea of Okhotsk structures in combination with developed rift strike-slip sublongitudinal structures in the Verkhoyansk fold belt and in the Okhotsk Sea (Deryugin Depression) allowed us to consider them as ascribed to rift system opposite to the AARS rift system (Fig. 6).

Concept on the evolution of the young Okhotsk–Verkhoyansk rift system (OVRS) opposite to the AARS is consistent with data on the manifestation of modern seismicity (Fig. 3), the existence of the youngest rift structures along the Okhotsk–Verkhoyansk belt and in the Laptev Sea shelf (Figs. 1, 2). It is highly probable that this structure affected the structures of the Eurasian Basin. The established asymmetry in its structure and a change of gravity anomaly pattern relative to 80° E (*Arkticheskii* ..., 2017) can reflect the opposite development of the AARS and OVRS: a decreasing influence of the former at increasing role of the latter.

According to the analogous model, the OVRS developed toward the pole and is structurally similar to the AARS (Fig. 5d). High modern seismicity of the OVRS connecting the seismic manifestations in the Arctic and Pacific oceans indicates its relatively young age. Such concept is well consistent with data on the Miocene–Quaternary age of the Gakkel Ridge and signs of the Pliocene–Quaternary diffuse spreading in the Laptev Sea part of the Eurasian Basin (Daragan-Sushchova et al., 2020).

Our concepts also explain a sharp narrowing of linear magnetic anomaly zones in the Eurasian Basin on the Laptev Sea shelf side relative to the 75°–80° E discontinuity. The influence of different rifting branches explains a displacement of the modern spreading axis to the southern limb of the Gakkel Ridge (Jokat and Micksch, 2004) and inferred spreading axis jump, which supposedly occurred ~ 5 Ma (*Arkticheskii* ..., 2017].

The **West Siberian rift system.** The West Siberian system seems to be oldest of the rift systems (Fig. 6). The age of igneous provinces along it changes from the Permian–Triassic in the West Siberian rifts (250 Ma) to the Triassic–Jurassic at the Frantz Josef Land (189 Ma) and completed by the Cretaceous (130–80 Ma) near the North Pole (Fig. 2).

Structural changes along this branch are reflected in a gradual northward displacement of rifting. These processes also include the development of longitudinal grabens in western Siberia and formation of the South Kara Basin as their natural continuation, as well as the northwestern to sublongitudinal extension of lithosphere with formation of extended dike swarms at the shelf, FJL, and, nearpole space. In the modern structure, this branch is associated with the large negative magnetic anomaly ΔTa near 80°.

AARS was evolved later than the West Siberian branch and practically across it (Fig. 6). This led to the reworking or obliteration of some landforms. In the modern structure, the region of branch intersection is reflected in the structure of the magnetic and gravity potential fields and likely, in the bend of the Gakkel Ridge and adjacent Lomonosov Rise. In a plan view, this bend coincides with dextral strike-slip along 80° E Fracture Zone.

The position of the West Siberian branch in plan is close to that of the sublongitudinal Taimyr–Baikal line, which extends from Taimyr along the western slope of the Anabar anteclise to the East Sayan and Baikalian mountainous systems (Fig. 6). This large sublongitudinal lineament was regarded by Khain (1979) as the western boundary of the influence zone of the Pacific mobile belt. His assumption that this structural boundary continues southward beyond Siberia up to the Indian platform and even Ninety East Ridge in the eponymous ocean was confirmed by (Gatinsky and Prokhorova, 2020). These authors consider a sublongitudinal band from 102° to 105°–106° E as the discontinuity between the Central Asian and East Asian transitional zones on the junction of the North Eurasian, Indian, and Pacific lithospheric plates. This discontinuity practically coincides with the line of Katterfeld (Katterfeld, 1962), who demonstrated a well expressed asymmetry in zonal distribution of territories and basins relative to plane passing through meridians of 105° E and 75° W.

The **East Pacific rift system.** The discussed tendencies in the initiation of the Arctic structures on the

northern flanks of sublongitudinal rift systems arise a question of possible continental continuation of the Canadian Basin. In the modern structure, the clearly expressed rift systems linked with this system on the North American side are absent. However, the position of the Canadian Basin axis on the continuation of the spreading ridge of the Pacific Ocean does not exclude their possible relation, while the structures themselves could represent fragments of the former single East Pacific rift system (Fig. 6).

Such assumption is hypothetical, but it is supported by some concepts and direct observations. The modern structure of the East Pacific rifts shows the characteristic features that are typical of the AARS. Up to the junction of the East Pacific Rise to Californian Bay area and after transform migration of rifting to the west on the Juan de Fuca plate, the sublongitudinal segments of the ridge form a series of sinistral displacements up to the disappearance beneath the fold-and-thrust structures of the North American hinterland (Fig. 6).

In addition, Early Cretaceous rifting processes were determined by the interaction of lithosphere elements, which significantly differed from the modern ones and occurred at a significant distance westward of the modern position of the rift system (Rowley et al., 2016).

Rifting processes in the Canadian Basin (145–136 Ma) began prior to the manifestation of the Sevier (125–105 Ma) and Laramide (after 80 Ma) tectonogenesis (Fig. 2), which is consistent with assumption of its initiation on the northern flank of the East Pacific rift system. Cordilleran complexes overlie and obliterate rift structures, which however are traced in the modern structure. In particular, near the Mackenzie River mouth, the strike lines of the Laramide fold-and-thrust belt turn toward the axis of the Canadian Basin (Fig. 6).

The Laramide fold-and-thrust belt is similar to the AARS in some structural features: sublongitudinal orientation and sublatitudinal sinistral strike-slips such as the Texas lineament and Lewis–Clark shear zone (Fig. 6). Within the Cordilleras, the main events of the Mesozoic evolution occurred in sublongitudinal direction. The Laramide orogeny resulted in the formation of giant granitic belt and fold-and-thrust belt along the sublongitudinal boundary with Archean–Proterozoic crust of the craton (King, 1961; Khain, 1971). This was followed by the exhumation of post-collisional metamorphic core complexes in sublongitudinal direction. Three MSS belts, which were exhumed in the Tertiary and mark axes of the strongest compression in the Mesozoic, form a sigmoid dextral strike-slip from Canada to southern California (Armstrong, 1982; Coney and Harms, 1984; Lister and Davis, 1989; and others).

In addition to the above considered large rift systems, there are two regions with longitudinal development of riftogenic structures: Canadian Arctic Archipelago and Bering Sea.

Linear magnetic anomalies established in the Canadian Arctic Archipelago and extended toward the Alpha Rise and lavas and dikes of the Ellesmere Island indicate a longitudinal rifting. This extension system, like the West Siberian rift system, is restricted to the influence boundary of the Atlantic and Pacific tectonogenesis (Katterfeld asymmetry line). In this area, it joins the Namaha–Boothia line extending from the Gulf of Mexico Bay to the Parry Archipelago (Fig. 6). This line was regarded by Khain (1971) as the main longitudinal lineament of North America, which separates the continent into the western (near-Pacific) and eastern (near-Atlantic) parts. Relative to this line, the strike of the Innuit fold system (Greenland–Ellesmere front) in the Canadian Arctic Archipelago shows a sharp change from sublatitudinal in the west to northeastern in the east.

The Bering Sea rifting area is restricted to the sublongitudinal structures, first of all, to the Hannah dextral strike-slip zone, which evolved from the Paleocene to the Middle Eocene (Lothamer, 1992) and penetrated lithosphere up to the upper mantle depths (Saltus and Bird, 2003). In addition, the axis of this structural area intersects a sharp bend of the Mesozoic overthrusts front, which also indicates a regional scale of tectonic processes in this area.

HYDROCARBON GENERATION

Trends of the AAARS evolution reflect accompanying pervasive lithosphere reworking. The large-scale rifting leading to the divergence of the former adjacent blocks of continental crust, formation of oceanic crust and its spreading is inevitably accompanied by the manifestation of links between supergene and deep-seated, up to the upper mantle, rocks.

These processes result in the serpentinization of mantle peridotites, which is accompanied by the release of a huge amount of hydrogen and methane at the initial stage of rift generation (Dmitriev et al., 1999; Simonov et al., 1999; Charlou et al., 1998). The process is underlain by the reduction of seawater-dissolved CO_2 to methane.

Two groups of methane sources are distinguished. The first group is related to the active high-temperature (up to 400°C) hydrothermal sources in the mid-ocean ridges and back-arc spreading centers. They are characterized by methane content of 2.5–3.6 nmol/kg, methane correlation with manganese, and elevated ^3He (Charlou et al., 1998). This indicates that percolating water interacted mainly with basalts. The presence of methane is thought to be related to its inorganic synthesis at 300–400°C or to degassing of juvenile CH_4 (Welhan and Craig, 1983). The second group is represented by extensive methane anomalies, with CH_4 content up to 50 nmol/kg and hydrogen content

up to 13 mmol/kg. Such anomalies are restricted to the areas of slow spreading and low-budget basaltic magmatism (Dmitriev et al., 1999). They are confined to the exposures of mantle massive ultramafics near the fracture zones of the Mid-Atlantic Ridge.

Sources of the second group are most tightly related to the development of the rift system considered in this paper. Available data make it possible to relate the formation of the hydrocarbon deposits on the Sakhalin shelf with long-term (since Cretaceous to present) steady extension in the adjacent deep-water Deryugin Depression and exposure of upper mantle rocks on the seafloor with their involvement in the sedimentation processes (Raznitsyn, 2017). Riftogenic processes could facilitate the penetration of seawater in the ultramafic sequence, thus providing their large-scale serpentinization associated by hydrocarbon generation. Strike-slip–overthrust movements could cause a tectonic injection and lateral migration of hydrocarbons in the western direction with formation of petroleum reservoirs on the Sakhalin Shelf.

A unique potential of the West Siberian petroleum basin is supposedly related to the deep-seated hydrocarbon sources (Ivanov et al., 2013; Timurziev, 2016; Raznitsyn et al., 2019). According to traditional concepts, the Aptian–Albian complex is the main gas-generating formation in the West Siberian Basin, while main oil source rocks are represented by the bituminous clays of the Kimmeridgian–Volgian Bazhenov Formation (*Ob'yasnitel'naya* ..., 1998). However, these concepts do not explain all available geological data. In particular, the low generation potential of the Jurassic–Cretaceous sequence does not support balance calculations on explored reserves (Timurziev, 2016). In addition, petroleum reservoirs are present in the magmatic, metamorphic, and sedimentary rocks of pre-Jurassic complex (Gilyazova, 2009).

To explain these contradictions, a model was proposed for the formation of hydrocarbon deposits of the West Siberian petroleum basin based on the concept of abiogenic deep genesis of hydrocarbons through lizardite–chrysotile serpentinization of mantle peridotites (Raznitsyn et al., 2019). Inferred abiogenic synthesis of methane through serpentinization of ultramafic rocks well explains the petroleum replenishment of the West Siberian Basin deposits at present.

The wide development of gas seeps on all Arctic shelves indicates the existence of a very productive and huge hydrocarbon source. In particular, the Kara and Barents Sea regions are characterized by the sharp predominance of gas and gas–condensate hydrocarbon reservoirs over oil ones (*Ob"yasnitel'naya* ..., 1998). Concepts of the serpentinization of upper mantle rocks during development of rift processes in the Arctic region are well consistent with these observations and explain mainly gas generation.

Ascending migration of the gas-bearing fluids is the necessary condition for the formation of gas hydrates, which in appearance are similar with dry ice, where molecules of gases, mainly methane, are incorporated in water molecule lattice. During this process, the ascending gas-bearing fluid at definite depth reaches the level of gas hydrate stability–phase boundary dependent on the temperature–pressure relations (Hyndman et al., 1992; Shipley et al., 1979). The gas hydrate layer is formed above this boundary, while its bottom serves as cap rock for free gas supplying from below. Three main criteria are applied to distinguish gas hydrate accumulations: bottom simulating reflectors (BSR) on the gas hydrate bottom, drastic decrease of seismic wave velocities at the BSR boundary in subhydrate free gas reservoirs, and "blankings" related to the decrease of seismic wave amplitude (Valyaev, 1999].

Hydrate reservoirs are known in different geodynamic settings and not always related to the large petroleum provinces (Fig. 7). Many reservoirs are confined to the tectonically and seismically active regions. Gas hydrates are widely developed in accretionary wedges, where internal stress in deformed sedimentary sequences leads to squeezing of pore waters, their enrichment in hydrocarbons (mainly methane), and ascending migration of gas-bearing fluids (Chamov, 2002). In the Arctic region, the gas hydrate reservoirs are restricted to the rift structures of the considered rift systems (Fig. 7). In the AARS, reservoirs are known in the North Atlantic segment and along the strike of the Greenland–Spitsbergen fault zone. In the Canadian Arctic Archipelago, numerous reservoirs are concentrated in a zone of linear magnetic anomalies extending from the Alpha Rise and lavas and dikes at Ellesmere Island. The hypothetical East Pacific rift system is the most saturated in gas hydrate reservoirs both in the Beaufort Sea on the continental flank of the rift axis of the Canadian Basin and on the Cascadian accretionary continental margin. In the Bering Sea, the gas hydrate reservoirs were established on the strike of the Hannah wrench-fault zone. In the Okhotsk–Verkhoyansk rift system, gas hydrates are developed on the northeastern slope of Sakhalin Island, and are restricted to the 80° N discontinuity in the West Siberian system.

At intense generation of endogenous methane, the intense migration of gas-bearing fluids occurs both in subhydrate part of sedimentary succession and in their surrounding. In particular, the one-channel on-board seismic survey during Cruise of the R/V *Jan Mayen* in Summer, 2001 revealed intense BSR reflectors in the relatively young (0.78 Ma) sedimentary sequence along the western continental margin of the Svalbard Archipelago (Vanneste et al., 2005). This region of BSR observation and possible accumulation of gas hydrates is bounded by the large tectonic structures: Molloy Fracture Zone, Knipovich Rift, and Vestness Ridge representing a tectonic escarp. In 2006, to the

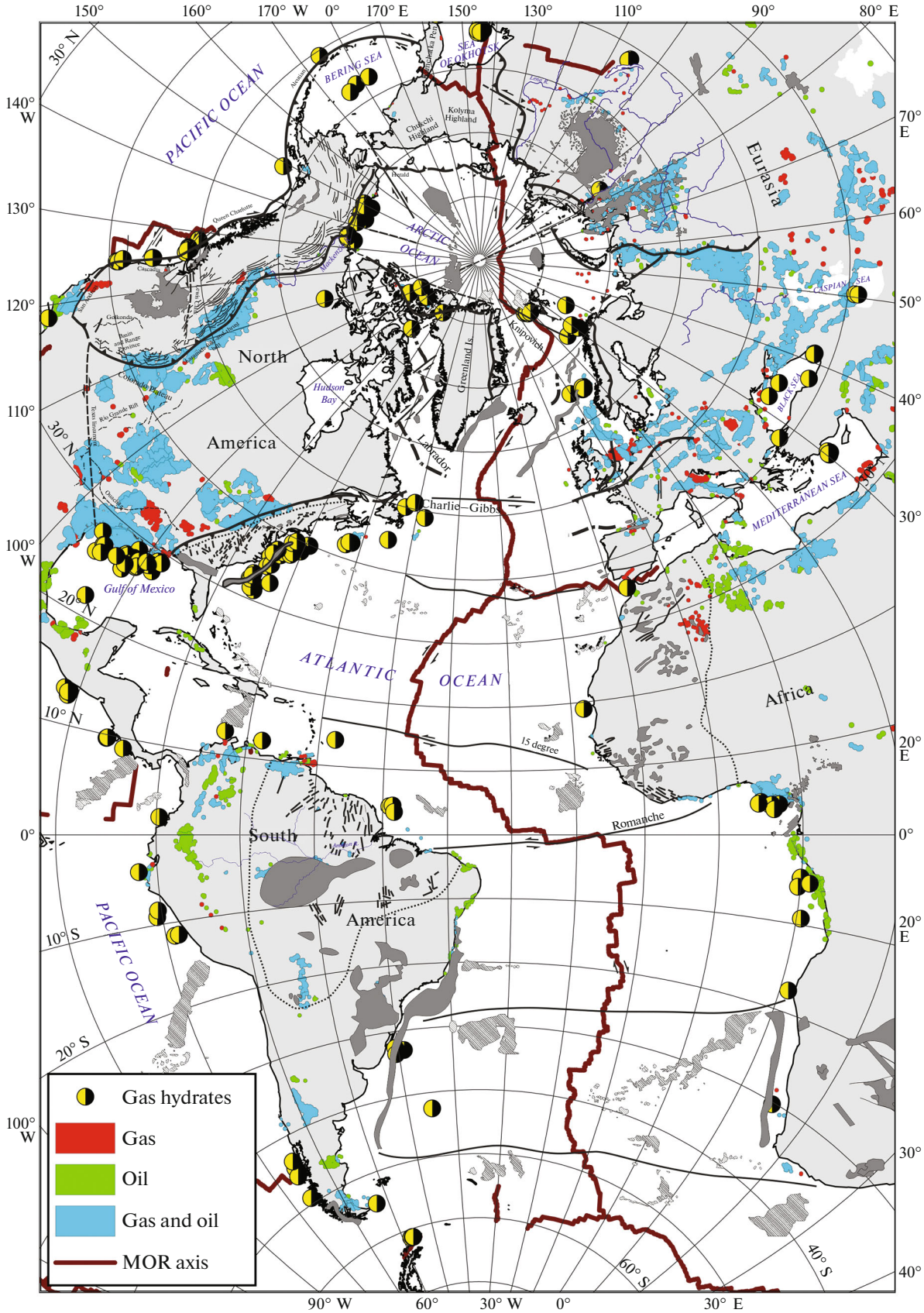

Fig. 7. Hydrocarbon provinces according to (PETRODATA, 2000) and proved gas hydrate occurrences according to (Waite et al., 2020). (MOR) Mid-ocean ridge. For other abbreviations, see Fig. 2.

southwest of the BSR discovery area, the structureless blankings of different size were distinguished in the well-stratified sediments on walls of the Molloy Fracture Zone by acoustic profiling during Cruise 24 of the R/V *Akademik Nikolai Strakhov* (Chamov et al., 2008). The appearance of the blankings is related to the decreasing amplitude of seismic waves within decompacted sediment intervals and is tightly correlated to their hydrate saturation. The established numerous small separate lenticular blankings are oriented conformably to bedding and do not intersect the roof or bottom of the sedimentary sequence. There are also larger round and vertically extended blankings that intersect general bedding of sedimentary rocks. They mark the migration pathways of fluids within sedimentary sequence. Some light spots are restricted to tectonic dislocations and resemble injection subvertical structures (channels) from a few meters to several tens of meters long.

An elevated fault density caused by the convergence of rift systems in the near-polar area facilitates the disturbance of gas hydrate reservoirs and permafrost. This causes secondary (tectonic) gas remobilization.

Degassing traces are widespread both in sedimentary cover and in water succession. Easily identified prospecting feature of bottom methane gas hydrate accumulations are flames—areas with elevated concentrations of floating gas bubbles. The density of flame occurrence strongly varies over an area and with depth. In particular, over 250 gas "flames" were established within depths of 160–1400 m in the area of the northeastern slope of Sakhalin Island (Salomatin and Yusupov, 2011). The "flames" are mainly accumulated near 500-m isobath (Baranov et al., 2011).

Sagging calderas (*pockmarks*) are formed in the gas seep sites on seafloor. They are extremely widely developed. For instance, on the eastern slope of Sakhalin Island, pockmarks show practically ubiquitous presence within depths of 500–1400 m, except for segment joining the Kurile Basin (Baranov et al., 2011).

A field of pockmarks, eight of which reached 170 m across and up to 7 m deep, was mapped in the northern part of the Barents Sea using multibeam echo sounder during cruises 25 and 28 of the R/V *Akademik Nikolai Strakhov* (Sokolov et al., 2020). The pockmark field coincides with the local anomaly of bottom sediment saturation in hydrocarbon gases with concentrations above 0.01 cm^3/kg (Yashin, 2004). At the same test site, blanking areas and vertical channels indicating the presence of a gas-saturated aqueous fluid were found by acoustic profiling in the upper part of sedimentary cover. The application of original processing of multibeam echo sounder data on the water column of test site (Sokolov et al., 2017) made it possible to reveal a "sound-scattering objects" (SSO) related to ascending migration of gas-bearing fluids from sedimentary cover. This confirmed the existence of mutually related processes: ascending migration of gas-bearing fluids, an increase of gas concentration in bottom sediments, and deformation of bottom surface with formation of pockmarks and partial discharge of fluids in water column.

CONCLUSIONS

The position of the Arctic region in the near-polar area predetermined some specific features of rift formation. Among these features are also the interference of the Arctic proper, regional, and supraregional riftogenic processes. This is related to the influence of rotation factor on the development of large sublongitudinal rift systems.

The influence of rotation factor on the lithosphere is based on the attempts of the latter to attain the equilibrium position relative to the spheroid rotation axis. This is reached by a combination of two types of movement: toward equator and along it. The movement of tending to equilibrium position lithospheric masses away from the pole facilitates the appearance and provides the possibility of the northward progradation of sublongitudinal rifts, while the movement along equator leads to their dissection by latitudinal fracture zones into separate segments.

Two implications of the northward propagation of rift systems due to the outflow of lithospheric masses seem to be especially important for understanding the processes in the Arctic region. They include the decay of driving forces for the further development of the rift after attainment of the pole and convergence of oppositely oriented sublongitudinal structures in the near-polar region.

The Arctic region, in addition to the Atlantic–Arctic rift, comprises the well-expressed terminations of the West Siberian, Okhotsk–Verkhoyansk, and East Pacific rift systems. The trajectory of their evolution was mainly determined by the presence of rheological heterogeneities in continental lithosphere, which were produced by tectonic and magmatic reworking at different stages of geological evolution.

The development and convergence of large sublongitudinal rift systems were the main triggers for the initiation of break-up of the continental massif of the Arctic region and subsequent transformation of its structure. In addition, they significantly affected the formation of hydrocarbons and degassing in the region.

The formation of deep graben structures filled with thick sedimentary sequences is favorable for the hydrocarbon accumulation. Thereby, the penetration of faults up to the upper mantle depths could cause serpentinization of ultramafic rocks with release of huge amount of methane. Giant gas hydrate reservoirs on the Arctic Sea shelves reflect the great scales of this process.

At the same time, the elevated fault density caused by the convergence of rift systems in the near-polar region facilitates the disturbance of gas hydrate reservoirs and permafrost, thus leading to secondary tectonically caused gas remobilization. One of the manifestations of these processes is the wide development of pockmarks in gas and/or gas-bearing fluid seeping sites.

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