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GEOLOGY

# Generations, Stages, and Specifics of Geodynamic Evolution of Young Ocean Formation in the Arctic

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The general trend in the Mesozoic–Cenozoic geological evolution of the Arctic region was governed mainly by the progressive breakup of the Wegener's Pangea lithosphere [1, 2] and its Laurasian fragments, which was responsible for the formation of a system of deepwater basins with the spreading basement structure.

The purpose of this communication is to define specific features of the geodynamic evolution, and geohistorical succession in the formation of deepwater basins, which processes govern the present-day structure and configuration of the Arctic Ocean (Fig. 1).

The analysis of chronological succession in the formation of oceanic structure [1–6] in the Arctic–Atlantic segment reveals a stepwise scenario with reciprocal or parallel quasi-synchronous changes in events. Pushcharovsky [6] attributes such a mode of development to the nonlinear geodynamic factors that were responsible for the discrete opening of the Atlantic Ocean [6].

As for the Arctic Ocean, the main phase in the opening of the Canada Basin in the Amerasian segment occurred during the second half of the Cretaceous, spanning from the Hauterivian to the Albian–Cenomanian. In terms of origination, this oceanic structure is close to the Aleutian Basin of the Bering Sea, on the one hand, and to the Atlantic, on the other. It is noteworthy that spreading in the North Atlantic commenced in the Albian–Cenomanian (100–80 Ma ago) at the same time that the spreading center in the Canada Basin was dying off (95–80 Ma ago). Therefore, the Atlantic Ocean could hardly have been connected with the newly forming Canada Basin at this stage, given the asynchronous processes of ocean formation. Nevertheless, the geological structure and evolution of the Barents margin, as well as its interrelations with oceanic structures, indicate that "attempts" were made by the spreading center to cross the Barents margin from the Amerasia Basin towards the opening North Atlantic [3].

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The first expansion of ocean-forming processes from the Atlantic into the Arctic region began at precisely that time. This was related to the northward propagation of the spreading system, which probably consisted of three major elements (Labrador, Baffin, and Makarov basins).

The development of this Atlantic spreading branch commenced in the middle of the Late Cretaceous (approximately 80 Ma ago) with the separation of Greenland from North America. The following process of the Labrador Basin opening continued in the Paleocene. Subsequently, spreading advanced northward to form the Baffin Basin during the Paleocene–Eocene. As follows from the analysis of the paleotectonic situation, the Baffin Basin was confined by the Wegener Fracture Zone (in the Neris Strait between the Canadian Arctic Islands), which feathers the main Spitsbergen–North Greenland Transform Zone [4]. Via these fracture zones characterized by coordinated kinematics, the Baffin Basin was geodynamically conjugated with the almost synchronously opening Makarov Basin, where spreading most likely occurred during the Late Senonian–Early Eocene [2]. Thus, the Baffin Basin existed and functioned, though in a waning stage, simultaneously with the spreading center of the Eurasia Basin, which had been developing since the Paleocene. These events were probably responsible for the disappearance of the Baffin Basin. In any case, the asymmetrical transverse horst-shaped structure of the Lomonosov Ridge, which separates the Makarov and Eurasia basins, and the structure of its sedimentary cover based on seismic studies [7], are consistent with the proposed scenario. It is remarkable that this stage of ocean formation was concluded in the reverse order: spreading terminated first in the Makarov Basin in the Early Eocene, and only later, in the terminal Eocene, in the Baffin Bay and Labrador Sea, i.e., in southern elements of the system.

The next stage in the penetration of ocean-forming processes from the Atlantic into the Arctic region occurred slightly later, though there was some overlap with the first phase. The spreading system passed to the east of Greenland almost parallel to the above-mentioned Labrador–Baffin–Makarov branch. Beginning in

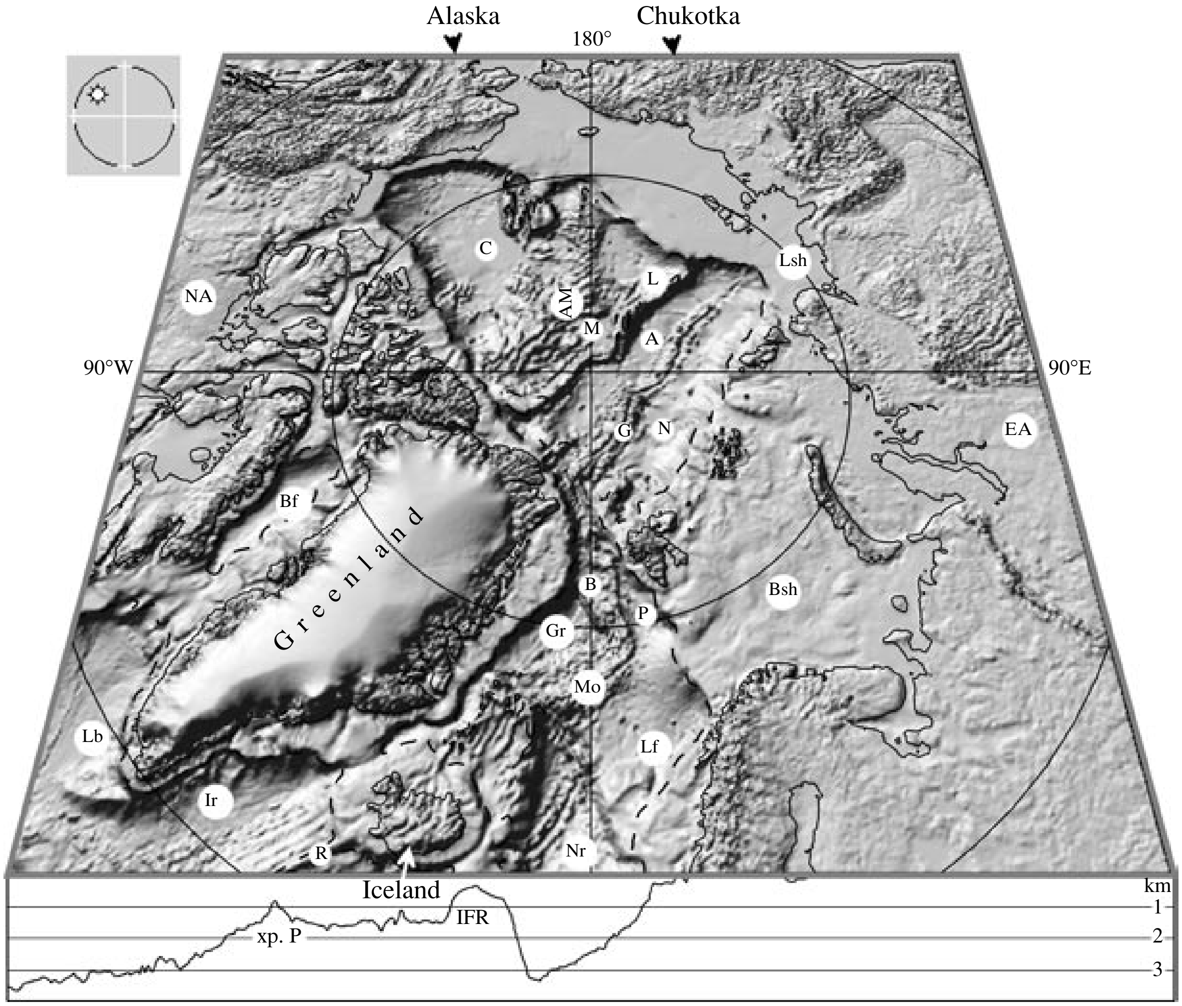


**Fig. 1.** Major elements of bottom topography in the Arctic Ocean (computer processing with the Surfer v8.0 program, compiled by V. A. Golubev using the data on the Earth's relief in regular points with the step of 2.5 km based on the International Bathymetric Chart of the Arctic Ocean, IBCAO, 2001). The dotted line designates isobath of 1000 m. (NA) North America; (EA) Eurasia; shelves: (Bsh) Barents, (Lsh) Laptev; basins: (C) Canada, (M) Makarov, (A) Amundsen, (B) Boreal, (Gr) Greenland, (P) Pomorskii Trough, (Lf) Lofoten, (Nr) Norwegian, (Ir) Irminger, (Lb) Labrador, (Bf) Baffin; mid-oceanic ridges: (R) Reykjanes, (Mo) Mohns, (G) Gakkel; ridges and rises: (L) Lomonosov, (AM) Alpha–Mendeleev, (IFR) Iceland–Faeroe (in the bathymetric profile). The position of the light source is in the upper left corner.

the Paleocene (anomalies 24–24b and, probably, 25), the spreading axis extended from the North Atlantic to the Charley Gibbs Fracture Zone and then, as the Reykjanes Ridge, toward Iceland. Then, the spreading axis jumped along an intricate fault system connected with the Iceland–Faeroe Rise to the east, where the Norwegian Basin was opening. Its spreading center (Aegir Ridge) functioned during the period spanning from 24c to 12–(7?) chrons [8, 9], i.e., from the Paleocene to the mid- or terminal Oligocene, when the process of oceanic crust generation ceased in this area. This process started instead in eastern Greenland with the formation of the Kolbinsey spreading ridge, which separates the continental block of the Jan Mayen Ridge from the continent.

In contrast to the study region, the northern oceanic segment located between the Jan Mayen and Greenland–Senja Fracture zones was characterized by relatively regular (without extinction of spreading centers) and almost symmetrical spreading during the entire Cenozoic. The spacious Greenland and Lofoten basins were formed on both sides of the Mohns mid-oceanic ridge. Therefore, the above segment has many features in common with the Eurasia Basin, where the Gakkel Ridge retains a direction subparallel to the Mohns Ridge and separates the Nansen and Amundsen basins with linear magnetic anomalies of virtually the same age. However, it should be noted that, at the dawn of Chron 13, the Yermak and Morris Jessup plateaus represented a common plateau basalt magmatism area, which very much resembled Iceland in terms of its geodynamic settings.

Sharply contrasting changes in the opening style of the northernmost Atlantic are observed beyond the

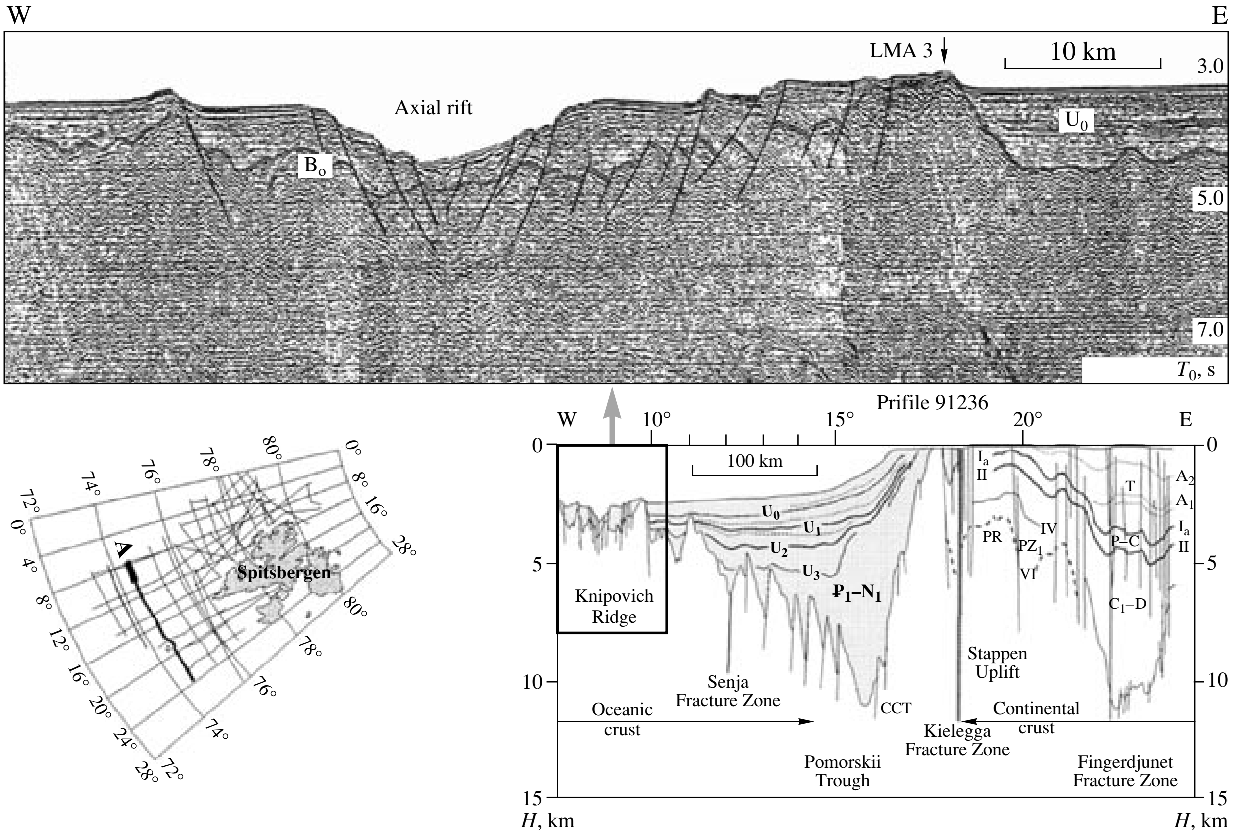


**Fig. 2.** Seismic–geological cross section of the West Barents (West Spitsbergen) margin–Knipovich Ridge profile and a fragment of its seismic record demonstrating neotectonic activation in the axial zone of the oceanic rift [5]. In cross sections: ($B_0$) oceanic basement; seismic horizons in the sedimentary cover of the Pomorskii Trough ($U_0$, $U_1$, $U_2$, $U_3$) and margin (Ia, II, IV); (CCT) continental crust of the transitional type; (LMA) linear magnetic anomaly. The inset shows location of the profile.

Greenland–Senja Fracture Zone. Then, the spreading axis of the Knipovich Ridge turned by almost 90° (with virtually no displacement relative to the Mohns Ridge), extended along the West Barents margin, and approached its Spitsbergen segment up to a distance of 80 km. When propagating northward, the Knipovich spreading axis was subjected to small-scale oblique segmentation. This is explained by the fact that the northward motion of Greenland gave way to northwestern motion as a consequence of the reorganization of plate kinematics and the geometry of the opening of the northernmost Atlantic segment in the Early Oligocene immediately after Chron 13 (approximately 33 Ma ago). In the course of this process, the Knipovich Ridge divided this segment of the Norwegian–Greenland Basin into two asymmetric areas, namely, the Boreal Basin connected with the Greenland continental margin, and the Pomorskii Trough located along the Spitsbergen margin and entirely buried under thick Neogene–Quaternary sediments such as the Senja Fracture Zone (Fig. 2). Therefore, both structures are almost invisible to bottom topography, in contrast to other basins and transform faults (Fig. 1).

As a result of the separation of Greenland, the transpressional regime, which had existed between Greenland and the Spitsbergen margin in the Paleocene–Eocene and formed the West Spitsbergen and Eurekan fold–thrust belts, was replaced by tension. It was this tension that was responsible for the formation of the relatively narrow (10–15 km) and extended (approximately 200 km) Forlandsunn Graben on the continental crust between West Spitsbergen and Prince Karl Land. The compression–tension regime promoted the formation of a new rhomboid deep structure in the northern part of the Greenland Sea (the Molloy segment of the spreading center). This new structure was displaced northwestward along the oblique transform zone relative to the Knipovich Ridge for a distance of approximately 100 km. These processes led to the formation of a narrow zone (the future Fram Strait) in the oceanic crust between Greenland and the Barents margin and ensured the northward propagation of the spreading axis of the Norwegian–Greenland Basin and its reunion with the Gakkel Ridge via the Lena Trough. According to [9], the Hovgaard Ridge was separated from the Barents margin at that time.

Since both the Labrador–Baffin–Makarov and Norwegian–Greenland–Eurasian branches of the spreading center were developing with some temporal overlapping, Greenland was completely separated from the continent for 30–35 Ma and thus transformed into an autonomous plate. The Greenland Plate had existed from the Cretaceous–Paleocene boundary time to the Early Oligocene, when spreading in the Labrador Sea ceased and the Molloy Ridge began to emerge. Therefore, it is conceivable that the Lomonosov microplate existed as an autonomous structure during the Paleocene–Eocene boundary period (approximately 10 Ma). This assumption minimizes several discrepancies in the available paleogeodynamic reconstructions related to notable differences in the interpretation of interrelations between the Lomonosov Ridge and Greenland. Thus, we can make the following conclusions. The young spreading basins described in the present paper developed in close contact with the oldest continental cratons. In this connection, the following interesting peculiarity in the development of the oceanic basin should be mentioned. Spreading centers either died off after 30–35 Ma of functioning or else the rates of oceanic crust generation decreased to the minimal values permissible for their existence. The present-day wedge-shaped closure of the Norwegian–Greenland and Eurasia basins with a high concentration of paired linear magnetic anomalies can illustrate such a situation [8–10]. All this indicates that spreading centers of both the Knipovich and Gakkel ridges are characterized by very low rates of oceanic crust generation (slow and ultraslow spreading zones) near the Spitsbergen–North Greenland and Khatanga–Lomonosov [3–5] transform zones, respectively, located at the continent–ocean transition boundary. Since continental plates prevailed in the Arctic region in the Late Cretaceous–Cenozoic, the limited space of oceanic lithosphere was unfavorable for triggering a mechanism of the full-scale (in terms of endogenic energy parameters) spreading "conveyor" that generally promotes subduction, collision and accretion [11], closure of small oceanic basins, and so on. Different versions of such geodynamic settings existed in the North Pacific [12] and in the Jurassic–Cretaceous history of the eastern Arctic region during the formation of the Canada Depression of the Amerasian Basin (for instance, the closure of the South Anyui Ocean). The scenario described above is typical of the geodynamic evolution of the North Pacific.

Thus, the Arctic Ocean genetically represents a "hybrid" ocean or, in other words, a composite heterogeneous structure related to the close spatial conjugation of two different (in age and style) geodynamic systems. These two systems existed until the Late Cretaceous when they were successively replaced by the Paleo-Pacific (Canada Basin) and the North Atlantic (Makarov and Eurasia basins) geodynamic settings. This is a specific feature of the evolution of the generally young Arctic Ocean.

Geological–geophysical data and paleotectonic reconstructions provide grounds for defining three stages in the generation of the young ocean. It should be noted that the Barents–Kara region was subjected to permanent destruction and gradual reduction because of the separation of continental segments. Nevertheless, the Barents–Kara region retained its position throughout all stages and represented the continental margin for newly forming oceanic basins. Such a structure was represented by the Canada Basin located north of the margin (first generation of the young ocean) in the mid-Cretaceous, the Makarov Basin (second generation) in the mid-Cretaceous, and the youngest Norwegian–Greenland and Eurasia basins (third generation), each of which mainly developed as a spreading center in the basite basement during the Cenozoic tectonogeodynamic evolution of the Arctic region. All the mentioned basins now surround the Barents–Kara continental margin on both the north and west. The analysis of available materials shows that the domination of Paleo-Pacific geodynamic settings (spreading, subduction and formation of back-arc basins, collision, and other phenomena) over the Arctic region was lost after the formation of the Canada Basin. The formation of the Makarov Basin marks a new stage, at which geodynamic settings typical of the North Atlantic (intercontinental rifting, slow and ultraslow spreading, separation of continental blocks or microcontinents, extinction of spreading centers, and so on) became dominant in the Arctic region. The general northward movement of spreading systems was relatively stable despite these changes in geodynamic settings. The brief period (a mere instant in geochronological terms) spanning from the extinction of the spreading center in the Canada Basin to the opening of the Makarov Basin can likely be characterized as a jump from the Paleo-Pacific type of geodynamic evolution to the North Atlantic type. In this case, in contrast to [2], it is more logical to consider the Alpha–Mendeleev Ridge as a boundary structure between these two geodynamic systems. Its debatable origin, genetic affinity that is interpreted in different ways (recent studies performed by the VNIIOkeangeologiya imply the existence of the transformed continental crust), and extremely intricate structure and morphology indicate compression settings. We believe that the contradictions discussed above can be explained not only (and not so much) by changes in the tectonogeodynamic settings of young ocean formation, but also by the motion of Paleo-Pacific and Atlantic spreading centers towards each other. Paleotectonic reconstructions [10] demonstrate that the Canada Basin was separated in the Late Mesozoic from the North Pacific by wandering blocks of the Chukotka–North Alaska microcontinent, which were colliding with the Eurasia and North America paleomargins to form an intricate boundary system of convergence zones [13]. Therefore, the Canada Basin, a conservative area and relict boundary of the North Pacific segment, can simultaneously be considered as its peculiar "protective" buffer, which suppresses expansion of geodynamic processes from the Atlantic segment. Such an interpretation of the geodynamic settings is consistent with the ideas put forward in [14] concerning the tectonogeodynamic relationships between oceanic segments of the Earth.

Thus, the breakup of the Wegener's Pangea in the Arctic region occurred in several stages and virtually from opposite sides. At the *first stage*, which lasted until the Late Cretaceous, it was destructed on the Paleo-Pacific side, resulting in the separation of Chukotka and northern Alaska from Canada and the formation of the Canada Basin. During the *second stage* (from the Late Cretaceous up to the present), destructive pulses acted from the North Atlantic to separate Greenland first from North America and then from Eurasia, resulting in the propagation of two Atlantic (Labrador–Baffin–Makarov and Norwegian–Greenland–Eurasia) spreading centers into the Arctic region.

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