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GEOLOGY

Spatial–Temporal Trends of Late Mesozoic Plume Magmatism in the Arctic during Formation of the Amerasian Basin

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Abstract—The spatial and temporal characteristics of magmatism caused by the Barents–Amerasian Jurassic–Cretaceous plume in conjunction with the geodynamics of destructive transformations of the lithosphere are presented here. The localities of manifestation of magmatism were concentrated mainly out of general contour of the areal occupied by the Siberian superplume, and they demonstrated certain gravitation to the Caledonide–Ellesmeride belts. This suggests an inherited position of both the J–K plume and the initial detachment zone produced by it: this led to formation of the Canadian Basin. The stages in the evolution and character of polycyclic multiphase plume magmatism are substantiated by the geochronology of magmatic provinces in the Arctic region during formation of the Amerasian Basin.

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One of the important issues of geodynamics is specification and reconstruction of the chronological sequence of tectonic–geodynamic events during the initial stages of the formation of the ocean in the Arctic region [3, 7].

This paper presents the results of analysis of geological and geophysical data that shed light on the processes of the Late Mesozoic (J–K) basaltic magmatism and on the existing tectonic and geodynamic settings produced by the destructive influence of the Barents–Amerasian plume on the lithosphere of the Arctic region [9]. The response of the lithosphere to the plume effect was expressed in the formation of a complex and heterogeneous structure of the Amerasian Basin, the initial phase of evolution of which is associated with formation of the Canadian Basin.

Several separate areas within the limits of the continental margins of the Arctic with manifestations of Late Mesozoic basaltic magmatism are known: the Barents Sea, the Sverdrup Basin (Canadian Arctic Archipelago), the northern edge of Greenland and the De Long archipelago (East Siberian Sea shelf) [6, 8, 12, 13, 15] (Figs. 1, 2).

Marine geological and geophysical surveys combined with dredging and drilling [2, 4] allowed mapping of the Central Arctic basaltic magmatic province: it occupies the Alpha–Mendeleev Ridge of continental nature with adjacent segments of the Canadian and Makarov–Podvodnikov basins, as well as the north of the Chukotka borderland and its spurs (Fig. 1).

The Barents Sea magmatic areal is one of the most spacious: it has been contoured by us as a result of geological field studies and observations in the high-latitude islands, coupled with interpretation of the results of marine geological and geophysical studies [8]. It covers the Svalbard archipelago, Franz Josef Land (FJL), and the adjacent shelf, and then an areal in the form of a tongue extending far to the south along the East Barents Megabasin.

Studies have demonstrated that the greatest diversity of magmatism types occurs in the Franz Josef Land archipelago. There, numerous sills, dikes, and lava flows are found in outcrops and recovered during drilling of parametric wells. Sometimes, remnants of volcanic apparatuses are preserved. Well-pronounced crests in the landscape of some islands, formed by dikes, are clearly seen even in satellite images. The Svalbard archipelago is different by the predominance of sills among the Early Cretaceous magmatics. The Barremian lava flows are only common in the Kong Karls Land archipelago. Volcanics forming a series of Early Cretaceous lava flows has also been revealed on Bennett Island (De Long Archipelago, East Siberian Sea).

In terms of paleotectonics, the manifestations of Jurassic–Early Cretaceous magmatism revealed are located primarily outside the outline of the overall areal occupied by the Siberian superplume and at the same time demonstrate a certain a distinct connection with the Caledonide–Ellesmeride belts. The lengthwise configuration conformable to the general ocean

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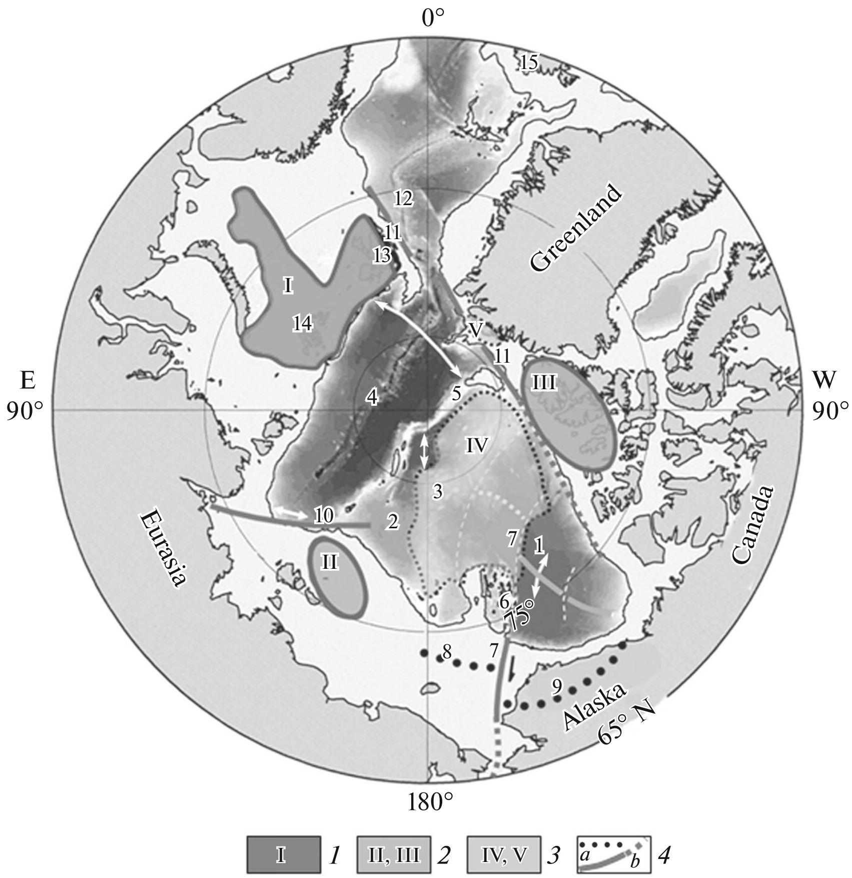

Fig. 1. Scheme of the main geological structures and provinces of the J–K plume magmatism in the Arctic region. *1–3*, magmatism: *1*, mainly Jurassic–Early Cretaceous; *2*, mostly Early–Middle Cretaceous; *3*, mostly Late Cretaceous; *4a*, deposition centers of basins; *4b*, main shear zones. Roman numerals on the scheme of the igneous province: I, Barents Sea; II, East Siberian Sea; III, Sverdrup Basin (Canadian Arctic Archipelago); IV, Central Arctic (Alpha Mendeleev Ridge and Northern Canadian Basin); V, Northern Greenland. Arabic numerals on the scheme: 1–3, geological structures of the Amerasian Basin (1, Canadian Basin and its spreading centers; 2, Makarova–Podvodnikov Depression; 3, Alpha–Mendeleev Ridge); 4, Eurasian Basin with the Gakkel Ridge spreading center; 5, Lomonosov Ridge; 6, Northwind Ridge; 7, Chukotka–Canadian (transform) shear zone and its possible continuation; 8, North Chukchi Basin; 9, Colville Basin; 10, Khatanga–Lomonosov shear zone; 11, Spitsbergen–North Greenland shear zone and its possible continuation; 12, spreading center of Knipovich Ridge; 13, Svalbard; 14, the Franz Josef Land archipelago; 15, Iceland.

position of the deepest Paleozoic basins of the continental margins (East Barents, Sverdrup, and North Chukchi), coinciding with the strike of the known fragments of Caledonide–Ellesmeride belts, allows us to assume an inherited position of the magmatic areals of the Barents–Amerasian plume as well as of the position caused by the initial spreading area of the plume, which led to opening of the Canadian Basin [9].

In general, the magmatic activity of the Barents–Amerasian plume resulted in six different in scale peaks of activity, grouped into two stages (Fig. 3). Their recognition has been accomplished with maximum account for $^{40}Ar/^{39}Ar$ dating results, including those obtained by the authors [8]. A generalized plot (Fig. 3) shows that the peak manifestations of basaltic magmatism occur in the following average age intervals (Ma): stage I, approximately 190, 157, and 133; stage II approximately 110, 95, and 82. These series of age datings imply that the "nonmagmatic" intervals of 33, 24, 23, 15, and 13 M.yr. long decrease with time beginning during stage II of the plume activity, which is almost twice as short; correspondingly, the frequency of magmatic activity increases. This suggests the pulsatory and polycyclic nature of igneous activity of the plume being considered.

Stage I. The initial phases of intrusion of the basalt melts into the continental lithosphere occurred in the Jurassic within the limits of arched–block uplift of the Franz Josef Land archipelago during 196–189 and 156–153 Ma, and in the East Barents trough system at 159 Ma [1, 8] mainly in form of sills and, rarely, lava flows. This Early Jurassic magmatism is represented by a low-potassium tholeiite, while the Late Jurassic magmatism additionally encompasses deeper subalkaline basalts. In general, the Late Jurassic phase of magmatism and destruction of the Arctic lithosphere, which was manifested in the convergence zone between Arctida and the North American plate, promoted weakening and breaking of the lithosphere. Accordingly, this was a preparatory and transition stage for the subsequent main tectonic–geodynamic event, namely the opening of the Canadian Basin.

The Early Cretaceous phase lasted 140–125 Ma. It is characterized by the maximal magmatic activity of the plume accompanied by powerful extensional pulses. They were manifested not only within the Barents Sea margin, but also within the Canadian Arctic Archipelago and the East Siberian margin of Eurasia, situated symmetrically relative to the extension and spreading zone, as well as some areas of the future Mendeleev Ridge [2, 4]. By this time, in the FJL the most prominent units of subalkaline basalts had formed and a mass intrusion of comagmatic sills and dikes had occurred [8]. It should be emphasized that the unconformity, revealed in seismic profiles, with an age of about 130–136 Ma at the margins of the continental Canadian Basin [11], caused by the main phase of lithospheric extension, is definitely correlated with the general time span of ages of parallel basalt dykes on Heiss Island (FJL archipelago). This gives a reason to believe that during accretion of the oceanic lithosphere of the Canadian Basin there was also emergence of a transregional extensional belt subparallel to its axis: it is marked by dykes and stretches from the FJL to Queen Elizabeth Island in the Canadian Arctic Archipelago.

Stage II. This stage of magmatic activity of the Barents–Amerasian superplume started after a very short but important pause, which coincides with the final episodes of collision between the New Siberian–Chukchi block (microplate) and Eurasia, closure of the South Anyui ocean (about 120 Ma), and as a consequence, slowing down of spreading in the Canadian Basin, reorientation of the stress field in the lithosphere by 90° with beginning of extension and rifting in the future Makarov–Podvodnikov Basin, and attempts of Alpha–Mendeleev Ridge to be detached from the Barents–Kara continental margin. Symmetric magmatism at the continental margins (Sverdrup Basin on one side, and Bennett Island and Chukchi borderland on the other) resumed in the time span of approximately 115–105 Ma. It is likely that this episode of magmatism in plume activity was not the most intense, but it started formation of the Central Arctic (or Alpha–Mendeleev) igneous province. Formation of the latter, in our opinion, began temporally after the Canadian Basin was formed, spatially in the place of the broken, as a result of plate divergence, Jurassic–Early Cretaceous magmatic areal, including Alpha Mendeleev Ridge as well. Thus, this magmatic province was surrounded on three sides by regions of older igneous activity once united in a single magmatic areal concentrated within the limits of the continental margins of the Barents Sea, the East Siberian Sea, and the Canadian Arctic Archipelago (Fig. 1). On the macro

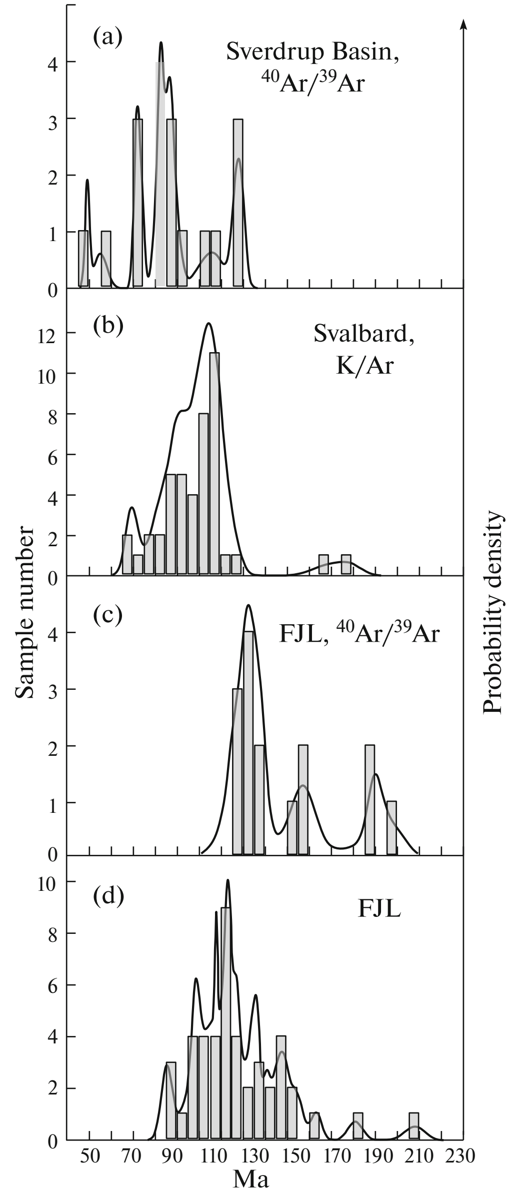

Fig. 2. The histograms and relative probability plots of age distribution of the Late Mesozoic basalt formations of continental margin archipelagos in the Arctic (plotted using Isoplot 4). Plots based on age determinations published in (a) [15]; (b) [14]; (c) [8]; (d) [5].

scale, the plume magmatism of the middle and younger Cretaceous phases of the entire Alpha–Mendeleev province may be qualified as telescopic in relation to the older Mesozoic areal of I stage, of a kind of "dike in a dike." Judging by the results of dredging and sea bottom drilling [2, 4] and the specific structure of the anomalous magnetic field, the occurrence area of the Middle–Late Cretaceous magmatism, which lasted over the interval from 115–112 to 82–76 Ma, covers not only the Alpha–Mendeleev Ridge, but adjacent segments of the Makarov–Podvodnikov Basin, north of the Canadian Basin and the northern

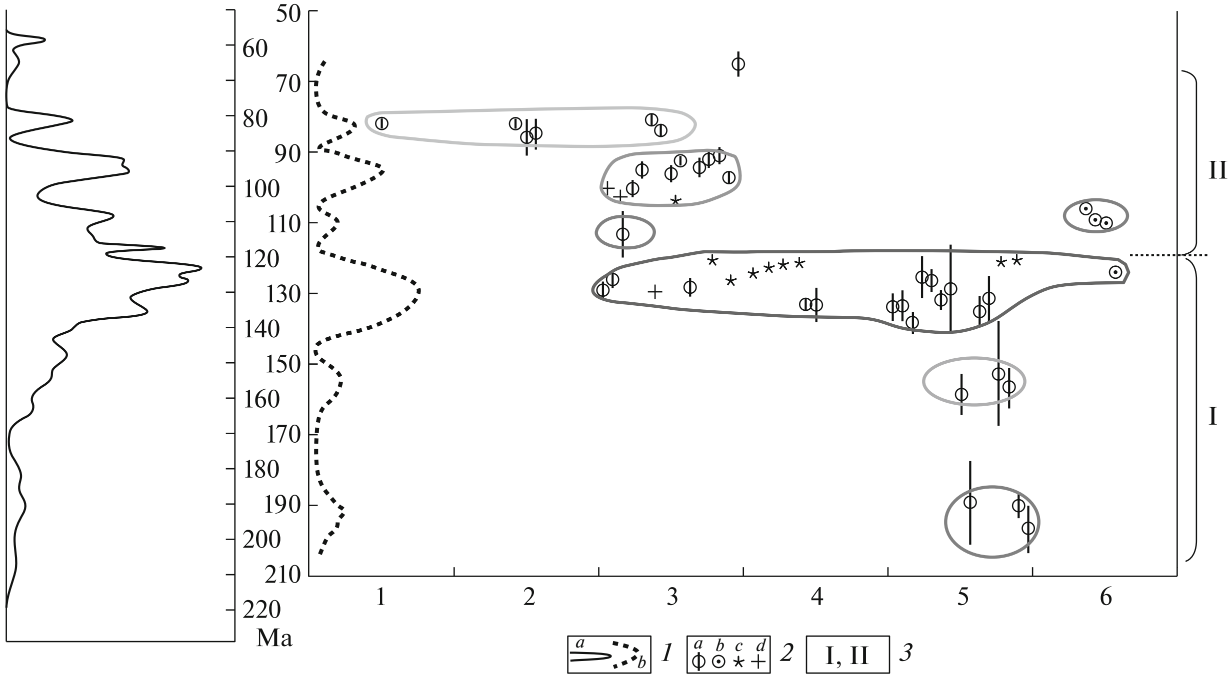

Fig. 3. Scheme of space–time characteristics and cyclic recurrence of the Late Mesozoic plume magmatism in the Arctic region. *1*, cumulative probability density plot of the basalt ages from diagrams in Fig. 2 (*a*), the generalized curve showing peaks of magmatism activization (*b*); *2*, ages: *a*, $^{40}Ar/^{39}Ar$; *b*, K/Ar; *c*, U/Pb; *d*, stratigraphic correlation; *3*, magmatic stages: *y*-axis age (Ma), *x*-axis, regions and areals of magmatism with ages of magmatism in columns 1, Alpha Ridge [4]; 2, North Greenland [13]; 3, Sverdrup Basin [12, 15]; 4, Svalbard [8, 10]; 5, FJL [8, 10]; 6, Bennett Island (De Long archipelago, East Siberian Sea) [6]. Delineated age groups are magmatic phases.

spurs of the Chukchi borderland. In this regard, it appears that some of the tectonic–geodynamic elements of the deep sea area (transform zones, segments of the spreading axial zones) could be masked by the areals of the second magmatic stage of the plume (Fig. 1). However, this stage of magmatism correlates quite clearly with the time span of the formation of Brooks Range fold belt in Alaska. In geodynamic terms this situation could be explained by the initial movement of the separate Northern Alaska plate during opening of the southern main part of the Canadian Basin and the following shift of the entire Amerasian Block southwards to the Paleopacific subduction zone in accordance with the direction of the sublithospheric backflow of the upper mantle convection [3].

On Alpha Ridge high-Ti alkaline and subalkaline basalts have been dredged [2, 4]. On the northern spurs of the Northwind Range and neighboring seamounts, moderately alkaline and alkaline basalts have been revealed. Moreover, by their geochemical characteristics, the basalts from the northern spur of the Northwind Range fit subaerial and continental plateau basalts similar to them. On the seamount tholeiitic pillow lavas occur.

Wells drilled at the foot of Mendeleev Rise [2, 4] recovered bedrock volcanics represented by moderate and low-alkaline types with isotope–geochemical characteristics of volcanics of islands and uplifts of the ocean floor. Gabbro–dolerite dredged from the slopes of this uplift are low in alkalis and also correspond in composition to rocks of continental origin.

It is noteworthy that no sample of the MORB affinity in the course of this work was dredged. The results of isotope geochemical studies have shown [2] that the igneous rocks of intermediate and basic composition on Mendeleev Rise are products generated in an enriched mantle, hence sharply in contrast to the MORB. However, comparison of the Sm–Nd isotope characteristics of Mendeleev Rise basalts with those from the De Long archipelago and FJL showed a good agreement, which gives grounds supporting the conclusion of a similar genesis of mantle melts and a unified deep plume source, which formed the whole Jurassic–Cretaceous magmatic province of the Arctic.

The plume magmatism of the discussed age occurred in the surrounding continental margin areas sporadically and in small areals. It is possible that igneous rocks at the northern edge of Greenland [13] are a continuation or a fragment of the Central Arctic province. The total duration of the three-phase stage II of plume activity that formed the Central Arctic province is 35–40 M.yr., while stage I lasted almost twice as long.

Thus, the plume magmatism that accompanied the development of the Amerasian Basin at almost all stages of its evolution was manifested at the continental margins as pulses (or cycles). The earliest Early Jurassic magmatism caused by the initial phase of the superplume action took place in the Franz Josef Land archipelago. This is the area of the Barents Sea continental margin where the center of magmatic activity of the Arctic region was located. Here, the magmatism in Franz Josef Land lasted until the Cenomanian (about 95 Ma) inclusive, i.e., in total about 100 M.yr.: some of the most active phases recognized in its evolution indicate the long-lasting and polycyclic nature of plume development.

While spreading beneath the lithosphere, during stage I, the plume considered first formed the Barents magmatic province and then spreading centers in the Canadian Basin. The younger but withering pulses of magmatism embraced the basin's peripheral parts (its continental margins). The Central Arctic igneous province was formed mainly during stage II and is chronologically linked to the formation of the Makarov–Podvodnikov Basin. Correspondingly, the individual phases of the plume magmatism should be considered not only in the context of enhancing breakup of the lithosphere, but also as tectonic and magmatic pulses, "pushing" plates (East Siberian–Chukchi and Northern Alaska) in stage I and then the new nascent Amerasian basin plate in stage II towards the subduction zones.

The results obtained in terms of the general geodynamics give a classic illustration of how in the space–time context the plume magmatism at the continental margins (Canadian Arctic Archipelago, East Siberian Sea), which were marginal areas of the Canadian Basin, accompanied the formation of that basin. In these terms, the fact itself of development of areals of Early Cretaceous basaltic magmatism symmetric and synchronous relative to the axial zone of the wedge-shaped Canadian Oceanic Basin appears to confirm the riftogenic–spreading rotational model of its opening.

Compared to the existing opinions on the parametric characteristics of plumes, the results of our study allow us to assume the uniqueness of the Jurassic–Cretaceous plume considered, sharply distinguishing it by the time of activity and multiphase character from the Siberian superplume.

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