ISSN 1028-334X, Doklady Earth Sciences, 2007, Vol. 415A, No. 6, pp. 850–855. © Pleiades Publishing, Ltd., 2007.
Original Russian Text © V.E. Khain, N.I. Filatova, 2007, published in Doklady Akademii Nauk, 2007, Vol. 415, No. 4, pp. 518–523.

GEOLOGY

Main Stages in Tectonic Evolution of the Eastern Arctic Region

Academician of the RAS V. E. Khain and N. I. Filatova

Received March 15, 2007

DOI: 10.1134/S1028334X07060050

In terms of tectonics, the Arctic realm of the Earth represents a mosaic consisting of blocks of the old Precambrian continental crust amalgamated by belts of the younger (Late Proterozoic–Mesozoic) crust and separated by basins with the newly formed Late Jurassic–Cenozoic oceanic crust. The largest Precambrian North American (with associated Greenland representing an element of the former Laurentia), East European (Baltica), and Siberian cratons occupy peripheral positions. The central Arctic region includes fragments of another continental massif that are exposed in the Northeastern Land of Spitsbergen (Svalbard), Franz Josef Land, Northern Island of Novaya Zemlya, Severnaya Zemlya, the New Siberian and De Long archipelagoes, and Peary Land of the Canadian Arctic Archipelago, as well as in the underwater Lomonosov, Mendeleev, and Chukchi ridges. In integrity, this massif was named Arctida in [1]. However, as early as 1935, Shatsky termed its eastern Arctic fragment as the Hyperborean Platform. Therefore, the use of term Hyperborea for this massif is also valid. Judging from data obtained for the Northeastern Land of Spitsbergen and the Northern Island of the Novaya Zemlya Archipelago and data on detrital zircons from eastern areas [2], the basement beneath Hyperborea–Arctida has most likely the Grenvillian age and includes probably older fragments. Thus, it can be assumed that Hyperborea–Arctida was incorporated, along with Laurentia, Baltica, and Siberia, into the supercontinent Rodinia by the initial Proterozoic; i.e., all these cratons represented its fragments 1.0 Ga ago. It should be emphasized that Rodinia was formed and existed beyond the present-day Arctic region. Moreover, this assumption concerns not only Rodinia but also the younger Baikalian and Caledonian foldbelts, as is evidenced by the development of carbonates, redbeds, and evaporites in their Lower–Middle Paleozoic sedimentary covers. All these blocks as components of Wegener's supercontinent Pangea reached Arctic latitudes only in the terminal Paleozoic.

Geological Institute, Russian Academy of Sciences, Pyzhevskii per. 7, Moscow, 119017 Russia

The least investigated Russian East Arctic region is the main object of this communication. Since structures of this region continue to the western Arctic Alaska, it is impossible to discuss major stages of the tectonic evolution of this region without the consideration of materials pertaining to Alaska.

The East Arctic region includes fragments of the Precambrian Hyperborean Craton, as well as fragments of the Baikalian, Caledonian, and Late Cimmerian (Middle Cretaceous) orogenic belts (Fig. 1). The latter belt is bordered in the south by the Middle Cretaceous South Anyui–Kobuk collision suture and represented by the New Siberia–Chukchi–Brooks fold–thrust system, which includes the internal Chukchi zone (with associated granite gneiss domes) and the frontal thrust zone adjoined by Cretaceous synthrusting basins. The polar part of the East Arctic region comprises the Late Jurassic–Cretaceous oceanic basins (Canada and Podvodnikov–Makarov) and intervenient microcontinental blocks (Lomonosov, Mendeleev, and Chukchi) [3, 4]. The continental crust adjacent to the basins is distorted by the Late Mesozoic–Cenozoic De Long magmatic dome and riftogenic synthrusting sedimentary basins (Fig. 1).

The synthesis of available data revealed four major epochs of tectogenesis that were of cardinal significance for the development and transformation of the continental crust within the East Arctic region (Fig. 2): Mesoproterozoic (Grenvillian), Late Vendian–Early Cambrian (Baikalian), Late Devonian (Ellesmerian), and Middle Cretaceous (Late Cimmerian or Brooksian).

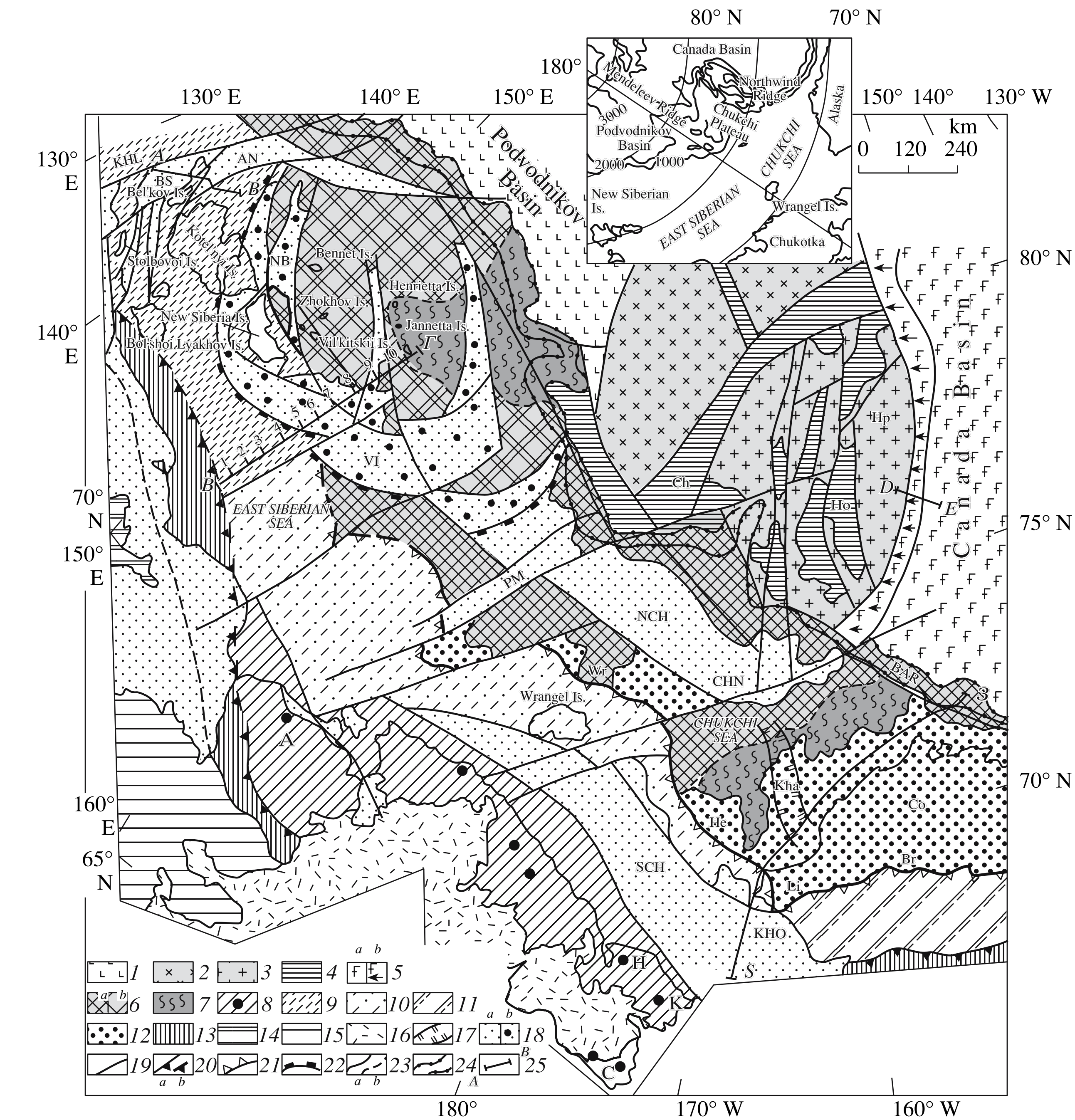
The Precambrian development history of the present-day Arctic region is most problematic. During the Mesoproterozoic, this territory represented likely an element of the supercontinent Rodinia [3, 5, 6]. The supercontinent formed as a result of the Mesoproterozoic Grenvillian Orogeny that amalgamated fragments of the Early–Middle Proterozoic supercontinent Pangea II (known also as Megagea or Columbia). The Grenvillian orogenic belt extended probably northeastward to the present-day Central Arctic region [3]. Thus, the future East Arctic region that was incorporated into the supercontinent Rodinia was underlain largely by the

Grenvillian basement by the initial Neoproterozoic (Fig. 2).

The breakup of the epi-Grenvillian supercontinent Rodinia commenced in the Neoproterozoic approximately 850–830 Ma ago [3, 6, and others] and resulted in the separation of the individual continents Laurentia, Baltica, Siberia, and, probably, proto-Hyperborea, where terrigenous–carbonate sediments were accumulated in the shelf zone. Separation of these continents by oceanic basins is evidenced, for example, by orogenic belts of the Timanides and their continuation in the Polar Urals, Pai-Khoi, Vaigach Island, and Southern Island of the Novaya Zemlya Archipelago, as well as by the Baikalides of the central Taimyr Peninsula and East Arctic region [3, 5, 7]. In the last region, rocks of the amphibolite–greenschist facies (592–547 Ma) are known on the shelf south of the Barrow Arch, granite gneiss domes of the eastern Chukchi Peninsula, and northern Alaska [8–10 and others]. Orthoamphibolites, gabbro, and gabbro–dolerites dated approximately at 700 Ma are established in Wrangel Island [9]. In the terminal Neoproterozoic–initial Cambrian (approximately 660–550 Ma ago), a new phase of orogenesis of Hyperborea with the Proterozoic–Grenvillian basement resulted in amalgamation of the Baikalian orogenic belt. It is likely that Hyperborea joined the Siberian continent at this stage. Structures of the Baikalian orogenesis include also orthogneisses with the protolith estimated at 750–547 Ma in Wrangel Island, the Chukchi Peninsula, and Alaska [8–12 and others]. It is established that these granitoids formed synchronously with collision [9].

In the Early Paleozoic, the terrigenous–carbonate sediments Craton continued to accumulate in the Hyperborean. Judging from the distribution of deep-water facies, oceanic basins occupied at that time the western Canadian Arctic Archipelago (Ellesmere Island with the allochthon of Ordovician Pearya ophiolites [3, 10], western Alaska, and present-day southern framing of the Canada and Podvodnikov basins (including Henrietta and Jannetta islands). They were probably united with the Iapetus Ocean [1, 3, 7, 10], which opened approximately 570–530 Ma ago [6, 10]. In Alaska and the East Arctic region, the Lower Paleozoic oceanic, margin-sea, and island-arc rocks are usually united into the Franklin Complex [8, 10, 13, and others]. The latter includes, for example, the Ordovician and Silurian turbidites, hemipelagic shales, jaspers, cherts, and volcanogenic rocks recovered by boreholes east of the Barrow Arch [8]. In Henrietta Island of the De Long Archipelago, this complex is represented by tuffstones and tuffaceous siltstones that are overlain by trachybasalts with K–Ar ages of 390–300 Ma [7]. According to other data [9], volcanogenic turbidites, basaltic andesites, and basalts of Henrietta Island belong to the calc-alkaline series and have Ordovician age (440 Ma, $^{40}Ar/^{39}Ar$ method). Reconstruction of the position of the Early Paleozoic ocean in the East Arctic region is difficult, because the corresponding rocks experienced subsequent tectonic fragmentation and displacement. During the Silurian–Devonian, the Iapetus Ocean with its western Innuit continuation (Canada, Alaska, Chukchi Peninsula) was closed in several stages. Each stage of the Caledonian—pre-Middle Devonian (Scandian) and Late Devonian (Ellesmerian)—collision (Fig. 2) was accompanied by dislocations, metamorphism, and formation of the structural unconformity surface and terminated by accumulation of subcontinental rudaceous facies frequently associated with bimodal volcanics. During the Scandian phase, the Innuit fold–thrust system formed in northern Canada [10]. However, the Late Devonian (Ellesmerian) Orogeny, which terminated, with some delay, the Caledonian stage, was most important in the East Arctic region. During this orogenic phase, oceanic and island-arc rocks of the Franklin Complex experienced intense deformations. Late Devonian syncollisional granitoids transformed subsequently into orthogneisses are known in the Koolen Dome of the eastern Chukchi Peninsula, where protoliths are dated at 374.8 and 369.6 Ma [11], and in the Brooks Ridge (395–375 Ma) [13 and others]. Consequently, the Devonian–Carboniferous transition period witnessed the formation of the spacious epi-Caledonian Euramerica (Laurussia) continental plate [1, 7, 10], the East Arctic sector of which is considered in this paper. The East Arctic (present-day sea shelves included) and Siberian regions were marked in the terminal Devonian–initial Carboniferous period by intense continental rifting, which resulted, for example, in the formation of the Hanna Rift. This stage corresponded probably to the opening of the Oimyakon and Angayuchan oceanic basins [7, 10]. The South Anyui Basin, which fringed along with the Angayuchan Basin the passive Hyperborean margin on the south, is considered either as an element of this Paleozoic ocean [14 and others] or as a result of Jurassic rifting [7, 10]. More likely is the stage-by-stage opening of the Angayuchan–South Anyui Ocean with the gradual northwestward progradation of the spreading zone. Judging from data in [14], this zone reached approximately the present-day meridian 165° E in the Carboniferous and extended westward up to the meridian of Bol'shoi Lyakhov Island only in the terminal Early–initial Middle Mesozoic.

The terminal Carboniferous was marked by the initiation of convergence of cratons; gradual closure of the Uralian Ocean; and the formation of Pangea, which included also structures of the future Arctic region. The East Arctic segment of the epi-Caledonian plate accumulated shelf sediments from the Late Carboniferous to the Middle Triassic (Fig. 2). In the Late Triassic, the continental crust began to experience extension and destruction. These processes served as percursors of the formation of the Amerasia oceanic basin (consisting of the Canada and Makarov–Podvodnikov basins), which advanced toward the future North Atlantic. The extension regime was responsible for the subsidence of the continental plate and its rifting in the late Triassic–



Jurassic (Fig. 2) accompanied by accumulation of thick turbidites and shales in the newly formed Middle Mesozoic system of grabens. Destruction of the continental crust terminated in the Middle Cretaceous (terminal Neocomian–early Albian) with spreading in the Canada Basin that separated the epi-Caledonian plate from the Chukchi–Alaska microplate [1, 10] and divided the Caledonian orogenic belt. Therefore, its structures are now located on different sides of this basin. The mechanism of opening of the Amerasia Basin remains debatable: in addition to the rotation mechanism [1, 10], the synthrusting model of its formation was developed in [2]. According to this model, the integrity of the Chukchi–Alaska microplate is called into question. Instead, it is assumed that the Chukchi Peninsula and adjacent sea shelf were already located close to the Siberian Craton prior to the opening of the Amerasia Basin [2].

The rotation model of the Canada Basin opening based on the distribution and age of linear magnetic anomalies [1, 10, and others] suggests counterclockwise rotation of the Chukchi–Alaska microplate (with

Fig. 1. Schematic tectonic structure of the Eastern Arctic region. (*1–5*) Structures of the Central Arctic region: (*1*) Makarov–Podvodnikov basins with the presumably Late Cretaceous oceanic crust, (*2*) Mendeleev Ridge of presumably continental origin, (*3*) Chukchi Ridge (fragment of the Hyperborean Craton), (*4*) rifts distorting the Mendeleev and Chukchi ridges: (Ch) Charley, (No) Northwind, (*5*) Late Jurassic–Middle Cretaceous Canada oceanic basin (*a*), underthrust zone (*b*); (*6, 7*) East Arctic sector of the epi-Caledonian continental plate (epi-Baikalian Hyperborean Craton and Caledonian orogenic belts): (*6*) epi-Baikalian Hyperborean Craton with (*a*) slightly deformed cover, (*b*) distorted by the De Long Dome (Cretaceous–Cenozoic mantle diapir), (*7*) fragments of presumed Caledonian orogenic belts (Ellesmerian Orogeny) under Middle Paleozoic–Mesozoic sedimentary cover; (*8–11*) New Siberian–Chukchi–Brooks fold–thrust system (passive margin of the epi-Caledonian plate involved into the Late Jurassic–Middle Cretaceous orogenesis: (*8*) internal Chukchi zone (solid circles designate granite gneiss domes): (A) Alyarmaut, (K) Koolen, (N) Neshkan, (S) Senyavin; (*9–11*) frontal thrust zone with hinterland fragments: (*9*) New Siberian segment, (*10*) Wrangel segment, (*11*) Brooks Range segment; (*12*) Cretaceous syn- and postcollision basins: (Co) Colville Basin; (*13*) Middle Cretaceous South Anyui–Kobuk collision suture; (*14, 15*) Late Jurassic–Middle Cretaceous Verkhoyansk–Kolyma fold–thrust system: (*14*) Ulakhan–Tas zone, (*15*) Alazeya–Oloi zone; (*16*) Albian–Cenomanian Okhotsk–Chukchi continental-margin magmatic belt; (*17, 18*) structures of extension zones: (*17*) Late Devonian–Early Carboniferous riftogenic grabens: (H) Hanna; (*18*) Cretaceous–Cenozoic riftogenic grabens and basins related to strike-slip faults: (AN) Anisin, (BS) Bel'kovskii–Svyatoi Nos, (NCH) North Chukchi, (H) Hope, (SCH) South Chukchi (*a*), Cretaceous arcuate and radial grabens related to the formation of the De Long magmatic dome: (NS) New Siberian, (VI) Vil'kitskii (*b*); (*19*) normal and strike-slip faults; (*20*) frontal thrust system of the South Anyui–Kobuk collision zone: (*a*) traceable, (*b*) assumed; (*21*) frontal thrusts of the Middle Cretaceous orogen: (Br) Brooks, (Li) Lisburne, (Ge) Gerald, (Wr) Wrangel; (*22*) arcuate faults in the Cretaceous–Cenozoic De Long Dome fringing; (*23*) boundaries of structural units: (*a*) traceable, (*b*) assumed; (*24*) contours of the continental slope edge and foot; (*25*) lines of seismic profiles. Additional letter designations: (BAR) Barrow arch, (NW) Northwind horst; strike-slip fault systems: (CHN) Chukchi–Northwind, (PM) Pevek–Mendeleev, (KHL) elements of the Khatanga–Lomonosov strike-slip fault.

the pole located in the present-day Mackenzie River mouth), resulting in collision between the microplate margin and the Siberian Craton (with fringing structures) and closure of the South Anyui–Angayuchan Ocean with development of the collision suture [7, 13, 14, and others]. These processes fostered the synchronous formation of extension and compression structures within the Chukchi–Alaska microplate: the extension structures (grabens bounded by listric normal faults) are confined to the Amerasia Basin framing, while the compression-related New Siberia–Chukchi–Brooks orogenic system appeared along the collision suture at the southern margin of the microplate. The first collision pulses are dated back to the Late Jurassic, but the main development stage of the Middle Cretaceous orogenic system is related to the late Hauterivian–early Albian (132–115 Ma ago). This stage is marked by deformation of the continental microplate margin adjacent to the collision suture and development of north-vergent fold–thrust structures in its cover, which were overlapped by ophiolitic and island-arc rock sheets overthrusted from the closing ocean [11, 13, 14]. The Middle Cretaceous orogeny was characterized by intense compression and crust thickening up to 46–50 km [13, 14, and others] accompanied by granulite–amphibolite metamorphism and granite–gneiss dome tectonics, which were typical of the internal Chukchi orogenic zone. The peak of high-pressure (6–8 kbar) metamorphism, an indicator of maximal compression, occurred 125–115 Ma ago and was synchronous with the stage of maximal deformation of rocks and maximal amplitudes of obduction of allochthons from the closing ocean [11, 13, and others]. The zone of numerous granite–gneiss domes, which extends along the Chukchi–Alaska continental margin near the collision suture, was exhumed during the subsequent Late Cretaceous uplift of the orogen and its tectonic relaxation. The thermogeochronological data [10, 11, and others] indicate at least three stages of exhumation of the orogen and development of granite gneiss domes under conditions of adiabatic decompression 104–84 Ma ago. Since the Aptian, a chain of synthrusting basins was forming in front of the Middle Cretaceous orogen. The northward propagation of frontal thrusts of the orogen was accompanied by advancement of these basins in the same direction and their rolling over the epi-Caledonian plate.

It is remarkable that the De Long magmatic dome appeared synchronously with the opening of the Canada (and, probably, Podvodnikov–Makarov) oceanic basins in the adjacent part of the epi-Caledonian plate (Fig. 1). According to gravimetric and seismostratigraphic materials, the dome consists of a concentric system of arcuate horsts and grabens bordered by arcuate (in combination with radial) faults. The system of arcuate grabens includes, for example, the New Siberian and Vil'kitskii sedimentary basins (Fig. 1). The most uplifted (due to magmatic diapirism) central part of the dome is characterized by the reduced Mesozoic–Cenozoic sedimentary section. Alkaline basaltoids, which facilitated the formation of the De Long Dome, erupted in its central part during the Middle Cretaceous and Miocene–Pleistocene [15]. However, such discreteness of magmatism may be imaginary and related to low degree of exposure of the region. Volcanics characterized by intraplate properties are probably related to the mantle plume [15 and others]. The occurrence of a spacious magma chamber in this area is confirmed by magnetometric data. The distribution of smaller chambers (and basaltoid fields) is controlled by peripheral arcuate faults. Magmatism of the De Long Dome is presumably related to upwelling of the Arctic lower mantle synchronously with the Pacific superplume.

The Late Cretaceous–Cenozoic was marked by subsidence of shelves of the East Siberian and Chukchi seas and origination of the NW-trending pull-apart

PR_2	Grenvillian Orogeny
PR_2/PR_3	Hyperborea, an element of the continent Rodinia with the Mesoproterozoic basement
PR_3	Breakup of Rodinia. Isolation of Proto-Hyperborea (Arctida), Laurentia, and Siberia continents separated by oceanic basins
V/Є	Baikalian Orognye
Є–C_1	Hyperborea continent separated from the Siberian continent by continuation of the Iapetus Ocean (including island arcs)
D_{1-2}	Scandian phase of the Caledonian Orogeny
D_3/C_1	Ellesmerian phase of the Caledonian Orogeny
	Franklin Complex
	Formation of the epi-Caledonian continent Laurussia (Euramerica) that included Hyperborea
D_3–C_1	Continental rifting of the epi-Caledonian plate (Endicott Group) and probable formation of oceanic basins
C_1–T_2	East Arctic sector of the epi-Caledonian continental plate consisting of Hyperborea and Caledonian orogenic belts with shelf terrigenous-carbonate sedimentation (lower Ellesmerian Complex) Since the Late Carboniferous, an element of Pangea South Anui--Angayuchan Ocean Island arcs, marginal seas, and microcontinents of the Verkhoyansk-Kolyma tectonic region
T_3–J_1	Subsidence of the East Arctic sector of the epi-Caledonian continental plate and its rifting (upper Ellesmerian Complex) preceding the opening of Arctic basins
J_3–K_1	Opening of the Canada Subbasin of the Amerasia Basin and separation of the Chukchi-Alaska microplate (with riftogenic complex in the latter)
K_2?	Opening of the Makarov-Podvodnikov Basin
K_1–KZ	Formation of the De Long magmatic dome in continental framing of the Amerasia Basin due to mantle upwelling
K_1/K_2	Middle Cretaceous (Late Cimmerian or Brooksian) orogeny, granite gneiss dome tectogenesis and synthrust sedimentary basins with the lower Brooksian Complex synchronous with thrusting
K_2–KZ	Postcollision pull-apart sedimentary basins on the shelf of Arctic seas with the upper Brooksian Complex
KZ	Opening of the Eurasia Basin

Fig. 2. Stages of tectonic events in the East Arctic region. Names of complexes are given after [13]; age indices correspond to the standard geochronological scale.

basins (North Chukchi, South Chukchi, Hope, and others) within the seas. The dextral strike-slip displacements (and relevant transtension) were widely developed on shelves of the East Arctic region and their continental framing during the Late Cretaceous as the result of termination of development of the Middle Cretaceous orogen. The younger stage of the formation of both NW- and NE-trending strike-slip faults (Fig. 1) in the study region corresponded to the opening of the Cenozoic Eurasian Ocean [1].

ACKNOWLEDGMENTS

This work was supported by the Division of Earth Sciences of the Russian Academy of Sciences (program no. 14), the Russian Foundation for Basic Research (project no. 05-05-64198), and the Program for the Support of Leading Scientific Schools (NSh-748.2006.5).

REFERENCES

1. L. P. Zonenshain and L. M. Natapov, in *Crucial Problems of Geotectonics* (Nauka, Moscow, 1987), pp. 31–57 [in Russian].
2. E. L. Miller, J. Toro, G. Geherels, et al., Tectonics **25**, 1 (2006).
3. V. E. Khain, *Tectonics of Continents and Oceans (Year 2000)* (Nauchnyi Mir, Moscow, 2001) [in Russian].
4. N. N. Lebedeva-Ivanova, Yu. Ya. Zamansky, A. E. Langinen, and M. Yu. Sorokin, J. Geophys. Int. **165**, 527 (2006).
5. N. G. Bondarenko and S. B. Sekretov, Dokl. Earth Sci. **389**, 145 (2003) [Dokl. Akad. Nauk **388**, 646 (2003)].
6. P. A. Cawood, Earth Sci. Revs. **69**, 249 (2005).
7. *Tectonics, Geodynamics, and Metallogeny of the Sakha Republic (Yakutia),* Ed. by L. M. Parfenov and M.I. Kuz'min (MAIK Nauka/Interperiodika, Moscow, 2001) [in Russian].
8. S. L. Klemperer, E. L. Miller, and D. W. Scholl, in *Tectonic Evolution of the Bering Shelf–Chukchi Sea–Arctic Margin and Adjacent Landmasses* (Geol. Soc. Am., Boulder, 2002), pp. 1–24.
9. M. K. Kos'ko, M. P. Cecile, J. C. Harrison, et al., Geol. Surv. Can. Bull. **461**, 1 (1993).
10. L. A. Lawver, A. Grantz, and L. M. Gahagan, in *Tectonic Evolution of the Bering Shelf–Chukchi Sea–Arctic Margin and Adjacent Landmasses* (Geol. Soc. Am., Boulder, 2002), pp. 333–358.
11. B. A. Natal'in, J.M. Amato, J. Toro, and J. E. Wright, Tectonics **18**, 977 (1999).
12. B. E. Patrick, P. B. Cans, W. C. McClelland, and T. A. Dumitru, in *Tectonic Evolution of the Bering Shelf–Chukchi Sea–Arctic Margin and Adjacent Landmasses* (Geol. Soc. Am., Boulder, 2002), pp. 111–132.
14. S. D. Sokolov, G. E. Bondarenko, M. I. Tuchkova, and P. Leyer, Dokl. Earth Sci. **411**, 1199 (2006) [Dokl. Akad. Nauk **410**, 784 (2006)].
15. S. A. Silantiev, O. G. Bogdanovskii, P. L. Fedorov, et al., Russ. J. Earth Sci. **6** (3), 1 (2004).