Tectonic Model and Evolution of the Arctic

O. V. Petrov, S. N. Kashubin, S. P. Shokalsky, S. D. Sokolov, E. O. Petrov, and M. I. Tuchkova

Abstract A key achievement of compilation of the Tectonic Map of the Arctic is a creation of a modern plate-tectonic model of the Circumpolar Arctic. This model demonstrates that the Arctic structure is determined by interaction of three lithosphere plates: two continental—North American and Eurasian—and one oceanic—namely Pacific. Modern seismicity serves as an indicator of tectonic processes and outlines boundaries of lithosphere plates.

1 Tectonic Model of the Arctic

The main achievement of geological and tectonic studies within the framework of the work on the creation of the Tectonic Map of the Arctic (TeMAr) and the Tectonic Stratigraphic Atlas of the eastern regions of Russia and the north-east of the Atlantic region (Hopper et al. 2014) involves the construction of a state-of-the-art tectonic model of the Arctic region.

The tectonic model of the Arctic region is based on up-to-date seismicity data indicating all present-day tectonic processes along the boundaries of lithospheric plates (Fig. 1). The belts of shallow earthquakes in the spreading zone of the Mid-Atlantic Ridge and the Gakkel Ridge on the border of the North American and Eurasian lithospheric plates form a narrow chain of seismic activity, which is characterised by shallow earthquake foci, no more than 35–45 km in depth. The boundaries of the Pacific Ocean lithospheric plate are delineated by a wide band of deep-focus earthquakes. Here, the deepest foci of earthquakes are presented, up to 300 km and deeper. On the continental shelf of the Laptev Sea and the land of Northern Eurasia,

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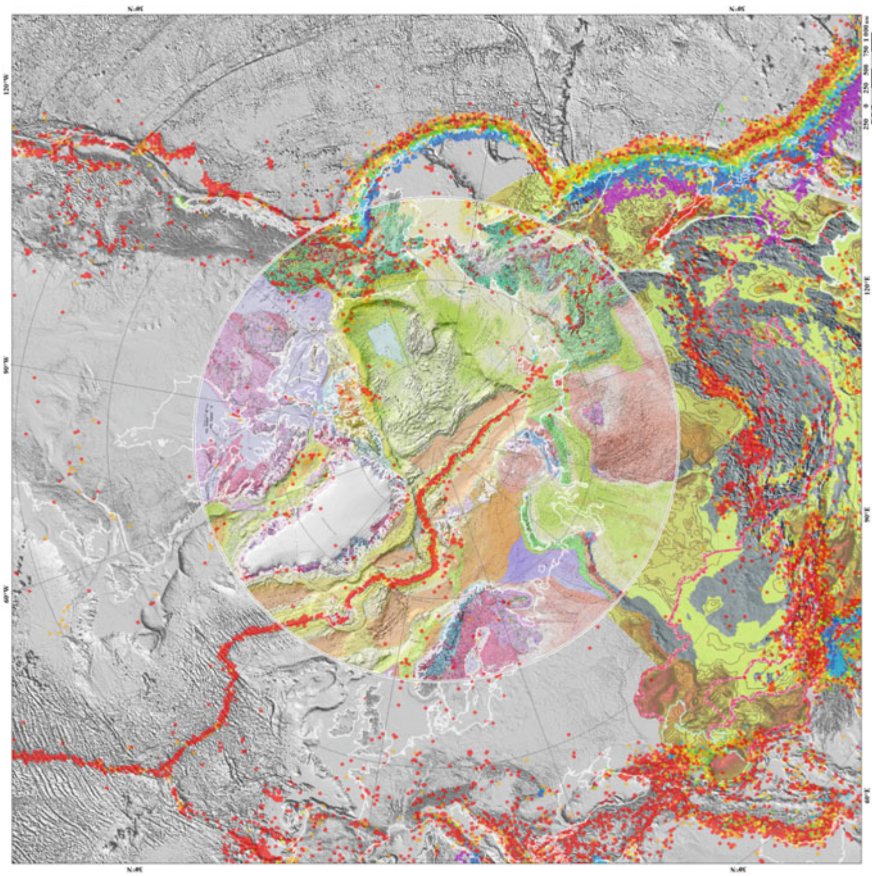

Fig. 1 Tectonic map of the Arctic superposed bathymetry map and scheme of modern seismicity

the boundary of the North American and Eurasian lithospheric plates is marked by small-focus seismic activity with an areal distribution of epicentres (www.iris.edu).

According to the latest plate-tectonic model, the present-day tectonic structure of the Arctic is determined by the interaction of three lithospheric plates: two continental North American and Eurasian and Pacific Oceanic (Figs. 2 and 3).

The Pacific Oceanic Plate, plunging at different velocities under the North American and Eurasian plates largely determines the kinematics and the age of the boundaries of the lithospheric plates. This is evidenced by the different nature of the subduction zones on the east and west coasts of the Pacific Plate.

On the west coast, interaction of the Pacific and Eurasian lithospheric plates with the formation of active island arcs and marginal basins is observed. Subduction processes of the Andean type are characteristic of the eastern margin of the Pacific Ocean with a gentle subsidence of the oceanic plate and the formation of coastal ridges. The age of the border margins of the Pacific Ocean plate from the

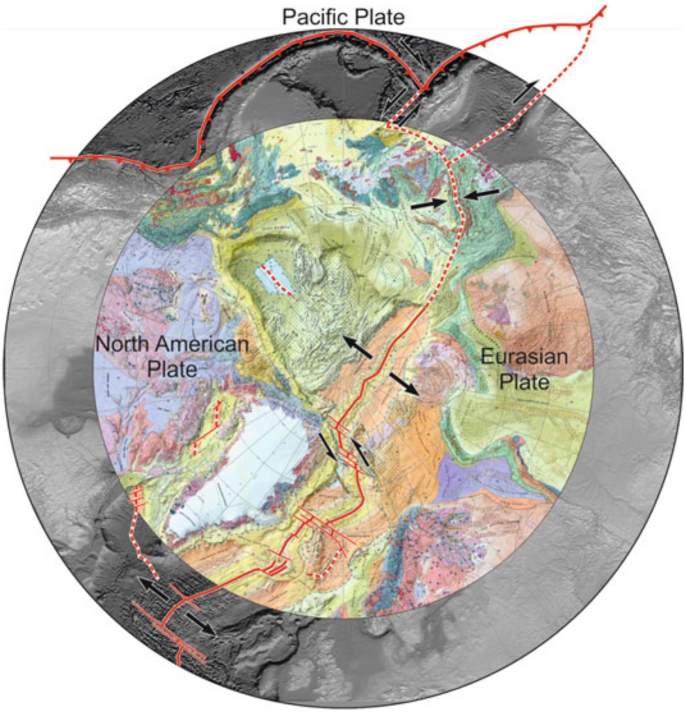

Fig. 2 Tectonic superposed bathymetry map showing boundaries of three lithosphere plates: two continental—North American and Eurasian—and one oceanic—Pacific

North American and Eurasian lithospheric plates is different due to the pronounced asymmetry of the Pacific mid-ocean ridge. The Eurasian and the North American Plates are bordered by the ancient Jurassic-Cretaceous part of the Pacific Plate and Paleogene-Neogene part, respectively.

Due to the different subsidence rates of the Pacific Ocean plate under the North American and Eurasian continental plates, the position of the boundary between the latter varied in the Late Mesozoic-Cenozoic interval. In the early Cretaceous, the boundary between the North American and Eurasian plates passed along the nascent continental rift within the present Canadian Basin. This boundary clearly separates the marginal basins of the Eurasian and North American plate. The formation of high-latitude Early and Late Cretaceous magmatic province, represented today by manifestations of tholeitic and alkaline magmatism in the Svalbard region, on Franz Josef Land, in Arctic Canada and on the Alfa-Mendeleev Rise, is associated with this stage of geodynamic development of the Arctic.

In the Early Paleogene, a change in the kinematics of the North American and Eurasian Plate led to the formation of a young Arctic Ocean defined by the Gakkel Ridge, as well as the Nansen and Amundsen basins. The initial stage of continental rifting and the formation of a new boundary of the North American and Eurasian

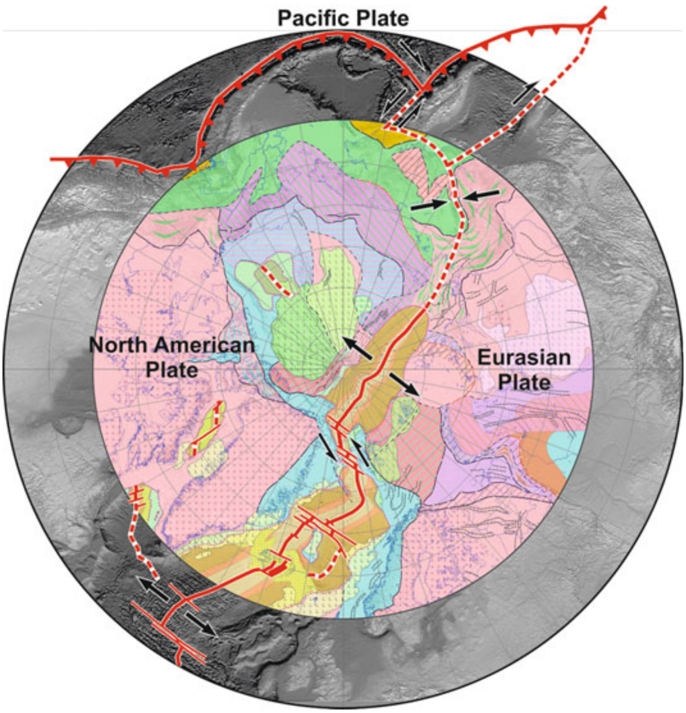

Fig. 3 Tectonic zoning of the Arctic with the lithosphere plates boundaries

lithospheric plates are fixed by manifestations of alkaline magmatism, including in the north of Greenland and on the New Siberian Islands.

The Nansen and Amundsen basins are underlain by a young oceanic crust. The thin (6–8 km) earth crust in the Amundsen basin possesses a two-layer structure (Petrov et al. 2016). The relatively thin low-velocity layer (presumably formed by sedimentary rocks with basalt interlayers) overlaps the thin crystalline crust, which corresponds to the lower mafic crust in its velocity parameters. Such thickness and structural characteristics of the earth's crust are typical of the oceans, as well as the deep-sea soundings of up to 4 km in the Amundsen basin.

The contemporary boundary of the North American and Eurasian continental plates can be traced in the Laptev Sea through a series of following rift depressions, including Ust-Lena, South Laptev, Omoloy Graben and others, which were formed in the Late Cretaceous and Paleogene (Fig. 6). In the continental part of the North-East of Russia, the lithospheric plate boundary passes through the Momsk rift zone presenting itself a series of neotectonic Paleogene-Neogene depressions linearly extended in the north-west direction with manifestations of Cenozoic alkaline-gabbroid magmatism.

At the marginal part of the Eurasian plate within the Barents-Kara passive margin, the crust, which has a thickness of 35–40 km, appears to consist of a three-layer structure (Petrov et al. 2016; Sakoulina et al. 2015, 2016; Roslov et al. 2009; Sakoulina et al. 2000). The thick sedimentary cover is underlain by crystalline crust represented by the upper, low-velocity and—apparently, mostly acidic-crust, and the lower, higher-speed and—possibly—more mafic crust. Such thickness and structure are characteristic of the crust in shallow marginal continental seas.

The Amerasian basin is located within the margin part of the North American Plate and includes the region of the Central-Arctic uplifts, composed by the continental-type crust and modified by deep-water rift induced basins of Podvodnikov and Makarov.

In recent years, earth crust of Alpha and Mendeleev Rises has been studied using Russian and Canadian deep seismic sounding profiles (Petrov et al. 2016; Poselov et al. 2011; Lebedeva-lvanova et al. 2006; Funck et al. 2011; Kashubin et al. 2016, 2018). The crust of the Alpha and Mendeleev Rises was identified to be similar to the crust of the Lomonosov Ridge, yet having greater thickness (32–34 km compared to 17–19 km of the Lomonosov Ridge) due to the increased thickness of the lower crust. This is likely to be due to magmatic underplating, which, in turn, led to intraplate basite volcanism and the HALIP formation in this part of the Arctic.

The crust on the Lomonosov Ridge was studied both in the central part of the Arctic Ocean and in the regions of its junction with Greenland and Eastern Siberia. Russian and Danish-Canadian studies have shown the presence of an intermediate (meta-sedimentary) complex and a two-layer structure of the crystalline crust under the sedimentary cover (Poselov et al. 2011; Jackson et al. 2010). The total thickness of the crust of the Lomonosov Ridge comprises 17–19 km. At present, the continental character of the Lomonosov Ridge is recognised by most Arctic researchers (Jokat 2005; Mooney 2007 etc.).

The crust of the Podvodnikov basin is thinner than that of the surrounding uplifts, reaching a value of 14–27 km. However, its crystalline part is comprised of two layers. The most likely explanation for this is the rift character of the sedimentary basin, formed as a result of stretching of the continental crust followed by its subsidence to depths of 3.5–4 km (Petrov et al. 2016; Kashubin et al. 2013; Lebedeva-lvanova et al. 2011).

Thus, the Amerasian basin is found to be underlain primarily by continental crust, thinned and processed to varying degrees by Cretaceous trap basalt magmatism and characterised by a mosaic magnetic field. The relict of the Cretaceous oceanic crust in the Amerasian basin is assumed only in a limited area of the central Canadian basin (according to the refracted wave velocities) as well as, according to some Canadian and American researchers (Miller et al. 2017), in the Makarov basin.

The results are reflected in the map of the crustal thickness of the Circumpolar Arctic (Fig. 4), which includes seismic profiling and interpolation data constructed from the correlation between the depth of the Moho discontinuity, topography and gravitational anomalies. The areas of continental crust, reduced continental crust and oceanic crust highlighted on the map are also reflected in maps of magnetic and

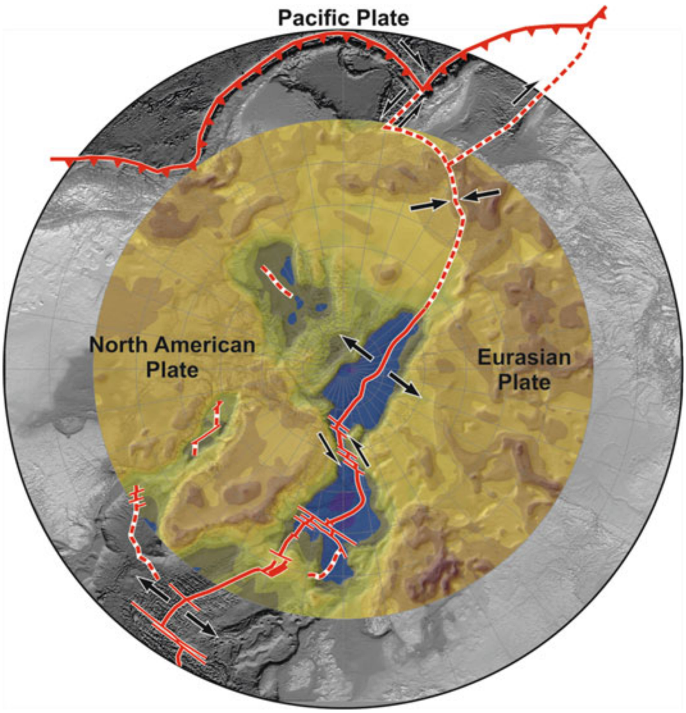

Fig. 4 The map of earth's crust thickness shows that the earth's crust in the Canada, Podvodnikov and Makarov basins has a structure typical for deep sedimentary basins such as South Barents or Peri-Caspian depressions

gravitational fields; these are in good agreement with all current data obtained from studying Arctic islands and carrying out geological sampling of the Arctic seabed.

An analysis of the crustal thickness of the Podvodnikov and Makarov basins—as well as of the Canadian basin—showed that they have a structure typical of inland deep-water sedimentary basins, such as the South Barents Sea or the Peri-Caspian depressions.

The map of the sedimentary cover shows that this reaches a thickness of more than 6–12 km within the Podvodnikov, Makarov and Canadian basins (Fig. 5). This is similar to the sedimentary cover thickness in the South Barents Sea and Peri-Caspian depressions, but is not typical of the oceanic floor (Fig. 6).

Geological testing of underwater escarps carried out by Russian and international expeditions in the Arctic from 2000 to 2016 established that the consolidated sedimentary cover of the zone of Central-Arctic uplifts is composed of terrigenous-carbonate formations aged from upper Vendian to Permian and formed in epicontinental, mostly shallow waters. This overlaps with the poorly lithified, predominantly terrigenous sediments of Meso-Cenozoic origin. All igneous intrusive and effusive formations are represented by a platform trap formation.

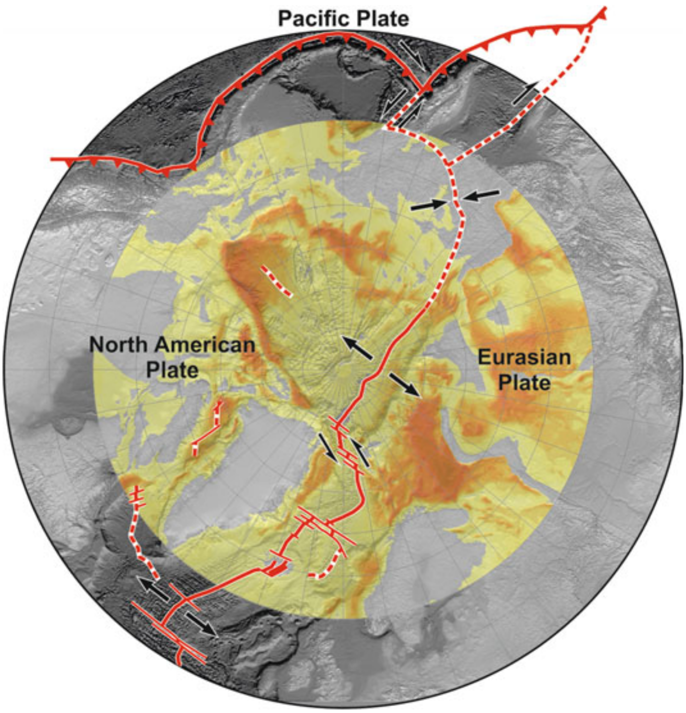

Fig. 5 The map of the sedimentary cover thickness of the Circumpolar Arctic

An analysis of the seismic profiles of the SRM CDP, which intersect all the major tectonic structures of the aquatorial part of the eastern regions of the Russian Arctic, showed close geological connections between the deep-water uplifts of the Central Arctic and the structures of the adjacent shallow-water shelf. The composite profiles presented in the atlas intersect all the most important tectonic structures of the eastern regions of the Russian Arctic.

The composite seismic profile Es10z22m–AR 1401 (1527 km long) crosses the shelf of the East Siberian Sea and the Podvodnikov basin. This profile illustrates continuous tracking of seismic complexes from the shelf to the deepwater part of the North Arctic Ocean. The minimum thickness of sediments (0–3.0 km) is recorded in the south-east along the profile ES10z22m to a stake of 180 km. In the area of this stake there is a serious disturbance in seismic dataset. The basement in the southern block at shallow depths is divided into blocks and characterised by the absence of a constant reflector as well as relatively low velocities (from 4.1 to 4.5 km/s). All these features are characteristic of the young Cimmerian basement. To the north of the 180 km stake, there is a sharp increase in the number of seismic complexes (up to 5), as well as in the thickness of sediments (up to 19 km). The same record structure is traced further northward into the deep-sea part of the Arctic Ocean, into

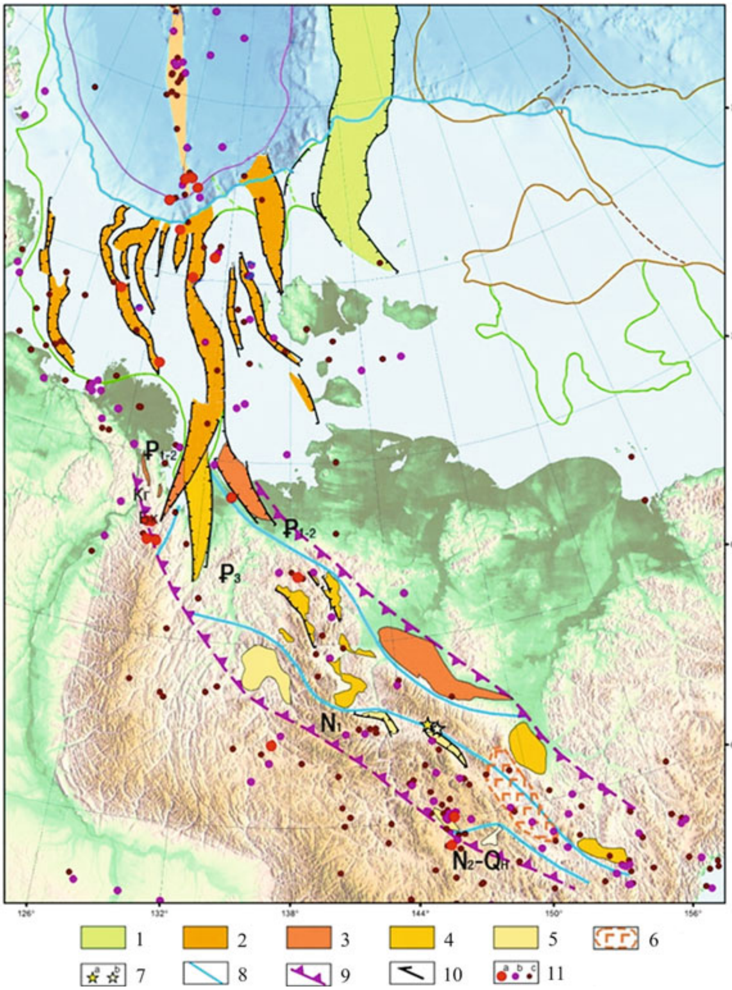

Fig. 6 The Laptev Basin depressions and the Momsky rift system. 1 to 5—age of the basins: 1—Late Cretaceous; 2—Oligocene (P3); 3—Paleocene-Eocene (P1–2), 4—Miocene (N1), 5—Pliocene-Eopleistocene; 6—areal of Early Eocene sodium alkaline-gabbroid magmatism; 7—Cenozoic volcanoes: a—Miocene (Urasa-Khaya volcano), b—Neopleistocene (Balagan-Tas volcano); 8—boundaries of the Mom-sky rift system; 9—boundaries of zones according to the age of riftogenic depressions; 10—general direction of shear movements; 11—earthquakes epicenters

the Podvodnikov basin, along the AR 1401 profile to a stake of 700 km (see paper of Daragan-Sushcheva et al. in this volume).

The AR1402 and AR1406 seismic profiles were obtained by JSC "MAGE" in 2014 as a result of seismic work at the R/V "Akademik Fedorov". The composite profile starting in the north of the East Siberian Sea (AR1402) crosses the De Long uplift, the Podvodnikov basin, the Toll saddle (AR1406), the Makarov basin and the

Lomonosov Ridge. The section along the AR1402–AR1406 profile, as well as the previously mentioned ES10z22m–AR 1401 profile, gives an idea of the structure and characteristics of the sedimentary cover during the transition from the shelf of the East Siberian Sea to the deep part of the Arctic Ocean. The stratigraphic volume of the pre-Cenozoic part undergoes significant changes: the greatest thickness is observed within the limits of the Zhokhovsky trough and the Podvodnikov basin (up to 7–8 km). The most ancient complex, composed of Carboniferous-mid-Permian sediments, lies between the basement and the PU horizon, which is mapped only in the north of the East Siberian Sea within the stakes of 700–725 km.

According to the plate-tectonic model, the region of the Central-Arctic uplifts comprises the marginal part of the North American Continental Plate and all modem tectonic processes within it belong to the in-traplate (Fig. 7). At present, the Neoproterozoic (Epigrenville) craton modified by the Mesozoic-Cenozoic structures is confidently asserted to occupy the entire polar region, including islands, shelves and the Central Arctic uplifts of the Amerasian basin. This plate tectonic model confirms the assumptions of Academicians N. S. Shatsky, Yu. M. Push-charovsky, V. E. Khain, Soviet and Russian scientists L. P. Zonenshain, L. M. Natapov and others, who, in the middle of the last century, identified this structure as the Hyperborea platform, known in later literature as Arktide.

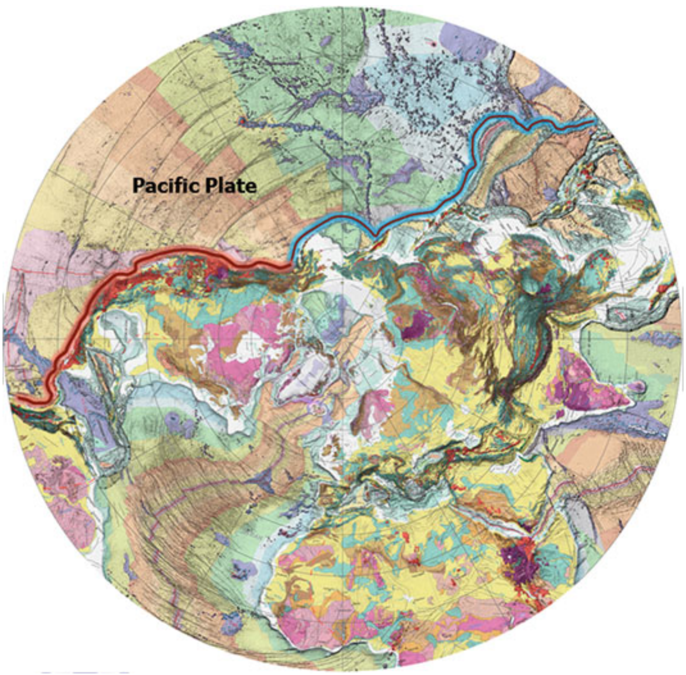

Fig. 7 Geological map of the Northern Hemisphere compiled by Commission for the Geological Map of the World (CGMW) and subduction zones of Pacific oceanic plate submerges under the North-American (red) and Eurasian (blue) plates

Thus, the modern plate-tectonic model of the Arctic is based on a set of reliable geological data on this territory, obtained over the past 15 years as a result of geological and geophysical work by geological services, national academies of sciences and universities of Russia, USA, Canada, Norway, Denmark, Germany and France. These works were supported by the UNESCO Commission for the Geological Map of the World (CGMW), the International Union of Geological Sciences (IUGS), the International Commission on Stratigraphy (ICS) and national programmes for the scientific substantiation of the extension of the continental shelf (ECS).

In particular, this work includes data on modern seismicity accumulated in the Global Seismographic Network in recent years (www.iris.edu) (Figs. 8 and 9), which includes data on potential fields formed on the basis of the magnetic and gravitational field maps included in the set of additional maps for the Tectonic Map of the Arctic. This also comprises more than 300 seismic profiles of the DSS with a total length

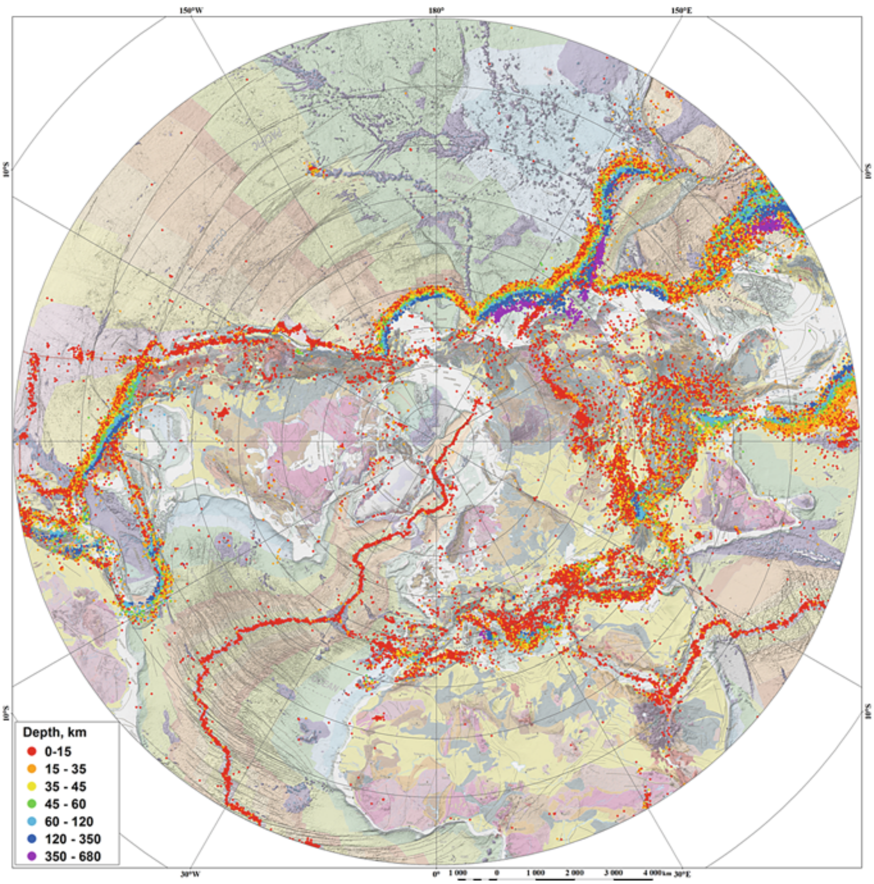

Fig. 8 Scheme of modern seismicity of Northern Hemisphere [data from Global Seismographic Network (www.iris.edu)]

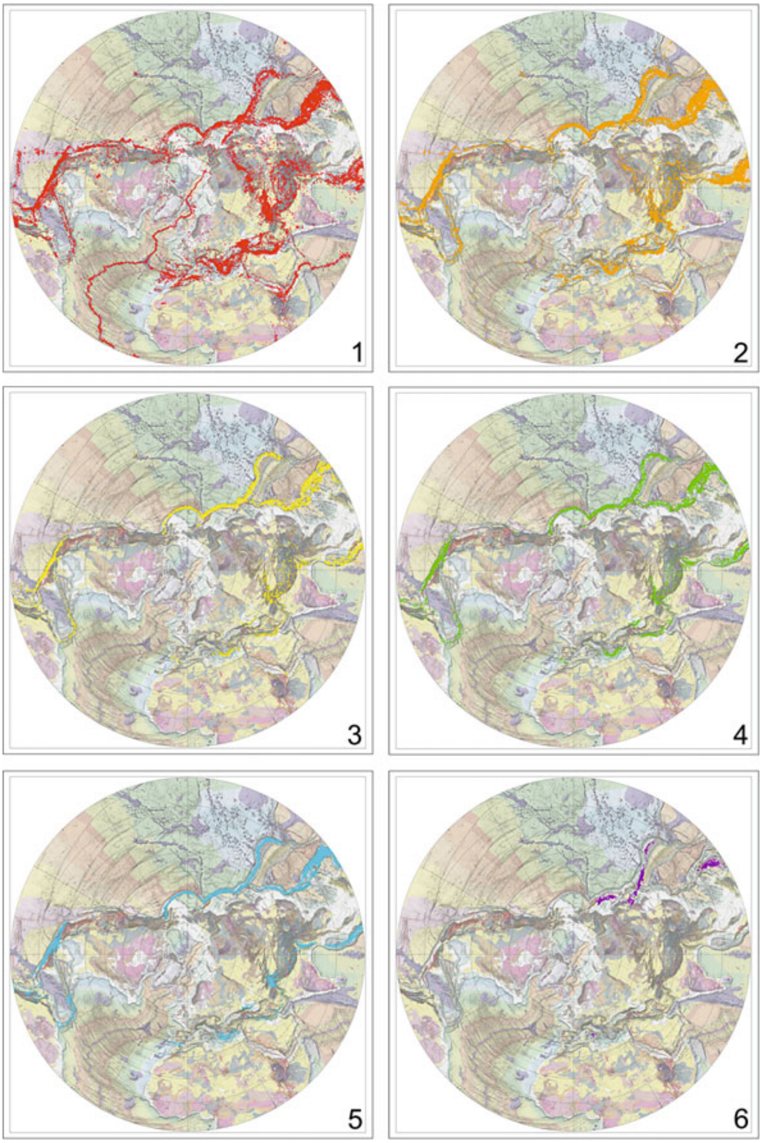

Fig. 9 Scheme of earthquake centers depths

of over 140,000 km, obtained during national and international geophysical studies of the continental shelves and deep-water areas of the North American and Eurasian lithospheric plates. The obtained geological and geophysical data is reflected in the maps of the thickness of the earth's crust and sedimentary cover. These are the results of a comprehensive study of bottom-rock material and materials of deep-water drilling from the Lomonosov Ridge, Alpha and Mendeleev Rises and Chukchi

Plateau (expedition Arctic-2004; 2005; 2012, Polarstern-2006, Heally-2002, etc.), as well as new data on geological structure, isotopic geochronology and geo-chemistry of sedimentary strata of arctic islands and continental land-mass.

The combined geological and geophysical data collected by the international community in recent years thus permitted the achievement of a significant breakthrough in scientific knowledge of the deep structure of the Arctic basin, providing a reliable basis for the creation of a state-of-the-art Arctic plate tectonic model.

2 Tectonic Evolution of the Eastern Arctic

Tectonic zoning of the Arctic displays distinct relationship between geological structures, crustal types, and the consolidated basement age. There are several major stages of folding in the tectonic evolution of the Arctic: (1) Baikalian or Timanian (Late Vendian—Early Cambrian), Ellesmerian (Late Devonian—Early Carboniferous), Chukchi or Brooks (late Early Cretaceous), and Eurekan (Middle Eocene). Each epoch followed the closure of paleoceanic basins and completed the formation of fold belts.

Formation of the lithosphere structures of the Eastern Arctic took place under the impact of three oceans (Paleo-Asiatic, Atlantic, Pacific) and is closely related to their tectonic history, which is clearly expressed in paleotectonic reconstructions.

The Paleo-Asiatic Ocean was linked with the Pacific via the Polar Urals and Taimyr. After the closure of the paleocean at the end of the Paleozoic and the formation of the Central Asian Fold Belt, the location of the emerging continental and oceanic structures predetermined further tectonic history of the Eastern Arctic in the Mesozoic.

The preserved "Pacific" branch of the Paleo-Asiatic Ocean, the Proto- Arctic Ocean neighboured the Pacific, whose influence is clearly pronounced in geodynamic settings of the active margin with the formation of island arcs and back-arc basins (Fig. 10).

At the same time, in the tectonic evolution of the Arctic, divergent processes typical of the Atlantic took place resulting in the formation of passive margins. For the Eastern Arctic, the influence of the Atlantic was the most distinct in the Cenozoic, when the Eurasian ocean basin formed.

Thus, Eastern Arctic structures formed under the influence and superposition of geodynamic regimes of the Atlantic-type passive continental margin and the active margin of the Pacific Ocean, and the closure of the Paleo-Asian Ocean predetermined the Mesozoic history of the Eastern Arctic and the spatial distribution of continental and oceanic structures.

Formation of the main types of Arctic structures, the way we see it today, started in the Early Mesozoic (Fig. 11).

By the Early Mesozoic (210 Ma), the Ural paleocean had already closed, and in its place, on the border between Euroamerica and Siberia, the oceanic basin (the Proto-Arctic Ocean) remained in the form of a large Pacific Bay (Zonenshain et al.

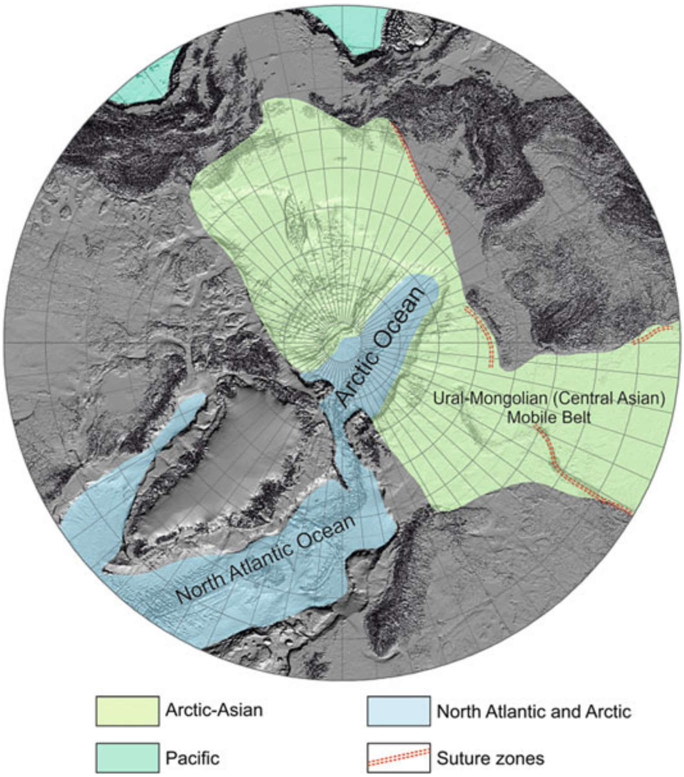

Fig. 10 Map of relationships of recent oceans and Fold Belts in the Arctic. The maps show the relationships between domains with different styles of tectonic evolution: Indo-Atlantic style with spreading-collision events (Scandinavian Caledonides, Appalachian, east Greenland and others) and Pacific accretionary style—with numerous ancient and recent island arcs and marginal seas (whole Arctic-Asian domain and Pacific domain of Russian Northeast and Far East)

1990a, b, Lawver et al. 2002; Sokolov et al. 2014, 2015). The Proto-Arctic Ocean comprised the ocean basins of South Anui and Angayucham.

The northern, American continental margin was passive. Turbidite features the Triassic sediments, which accumulated on the shelf, continental slope, and foothills (Tuchkova 2011). The sandstone composition (Tuchkova et al. 2014) evidences the continental provenance area, which could be the Hyperborean platform (Shatsky 1935), Arctida (Zonenshain et al. 1990a, b) or Crockerland (Embry 1993) in accordance with various reconstructions.

At the end of the Permian and the beginning of the Triassic, in the north of the Siberian continent, intraplate trappean volcanism became widespread. At the same time, the passive Arctic margin of Chukotka underwent destruction (Tectonics… 1980; Ledneva et al. 2011). Numerous sills and hypabyssal bodies of diabase, gabbro and dolerite feature Permian-Lower Triassic sediments of Chukotka. Tuff and basalt that are geochemically similar to the Siberian platform trap (Ledneva et al.

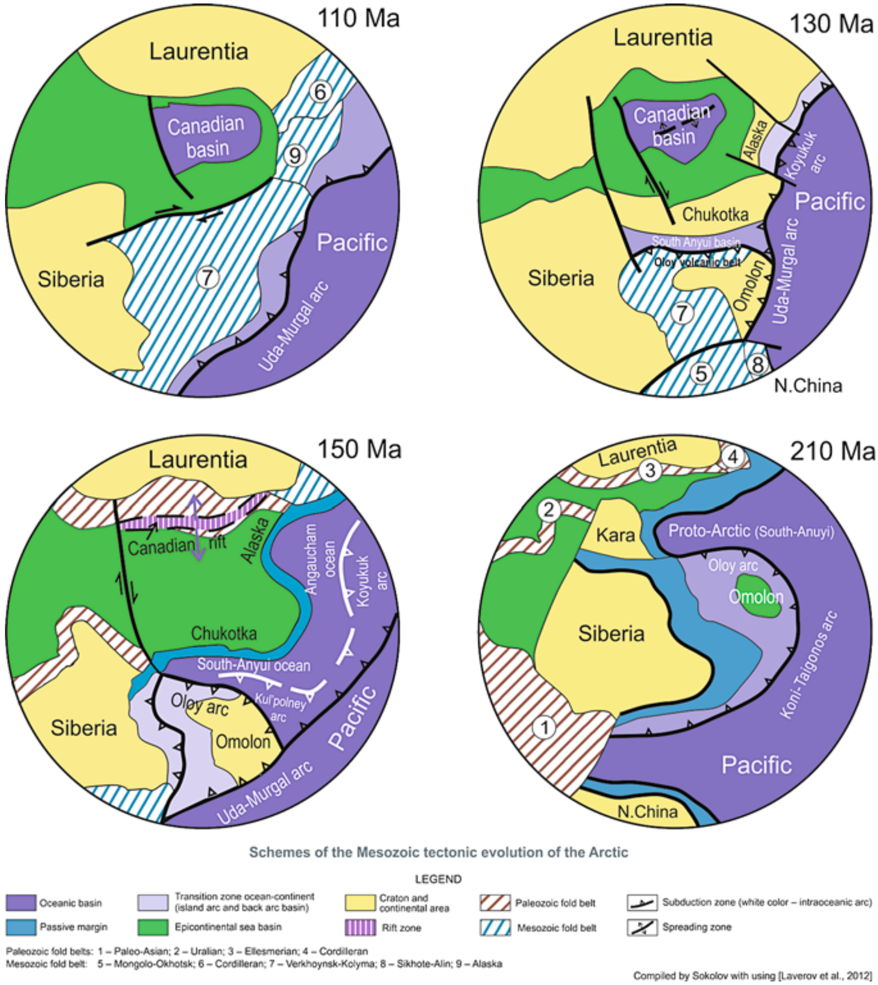

Fig. 11 Schemes of the Mesozoic tectonic evolution of the Arctic

2011, 2014) occur sporadically. The processes of stretching and destruction of the continental crust were interrelated with plume tectonics and the break-up of Pangea (Sokolov et al. 2014).

The southern, Siberian margin of the South Anyui Ocean basin was active. The Alaiai-Oloi island-arc terranes were located along the convergent boundary (Sokolov et al. 2014; Ganelin 2015). The Koni-Taigonos (Koni-Mural according to Parfenov et al. 1993a, b) Island Arc (Sokolov 1992; Sokolov and Tuchkova 2015) occurred on the border with the Pacific. Behind the convergent boundary, there was a system of marginal seas and island arcs with the Omolon and Okhotsk microcontinents.

In Triassic sediments of the passive margin of Siberia, shallow-water shelf facies were replaced eastwards by a more deep-water continental slope and a foot (Parfenov et al. 1993a, b). Lithologically, they differ significantly from the Triassic sediments of Chukotka and accumulated on different continental margins (Tuchkova et al. 2014).

At the turn of the Middle and Late Jurassic and in the Late Jurassic (150–130 Ma), significant restructuring took place in continental and oceanic structures. Between Siberia and the Pacific Ocean, there were two zones of convergence. In the northwest of the Pacific along the new convergent boundary, the Udsko-Murgal island-arc system was formed, under which the Pacific Ocean lithosphere was subducted. The Uyandina-Yasachnaya island arc emerged in the Verkhoyansk region, near the Siberian continent (Zonenshain et al. 1990a, b). The subduction caused movement and accretion of terrains of the Kolyma Loop and subsequent collision of the Kolyma-Omolon superterrain (Parfenov et al. 1993a, b).

In the Oxfordian-Cimmerian (150–130 Ma), spreading in the Proto-Arctic (South-Anyui) ocean was accompanied by intra-oceanic subduction in the Kulpollney island arc (Sokolov et al. 2015). As of the Volgian, a new stage in the tectonic evolution of the ocean begins. The ocean began to close and turned into the syncollision South-Anyui basin, which kept being filled with terrigenous sediments. At the same time, the convergent border with Siberia restructured and the Oloy volcanic belt was formed on the amalgamated terrains of the Kolyma Loop. The subduction reduced the turbiditic oceanic basin. After the accretion of the Kulpolney Arc, the continental lithosphere of the Chukchi microcontinent began to subduct, which resulted in its collision with the active margin of Siberia. The geodynamic model of the formation and location of the main types of paleostructures can be seen on reconstructions.

In Alaska, the oceanic crust of the Angayucham Basin kept being merged in the subduction zone of the Koyukuk island arc (Moore et al. 1994; Plafker and Berg 1994; Nokleberg et al. 2000a, b). The island arc was in existence for 160–120 million years.

The merge of the oceanic lithosphere southward in the subduction zones of the Kulpolney and Koyukuk island arcs as well as the Oloy volcanic belt caused tension, rupture and separation of the Alaska-Chukotka microplate from the continental margin of Arctic Canada. Riftogenesis began in the Early Jurassic and resulted in the formation of the oceanic crust of the Canada Basin (Embry 1993; Grantz et al. 1990, 2011). According to Shephard et al. (2003), Grantz et al. (2011), the riftogenesis lasted for 195–142 million years, and the spreading lasted for 142–126 (or 120) million years.

It should be noted that the Hauterivian-Barremian reduction and closure of the ocean process occurred simultaneously with the spreading in the Canada Basin. The spreading in the Canada Basin stopped as soon as the collision and the formation of the South Anyui suture in Chukotka and the Kobuk suture in Alaska was over.

The South Anyui suture was formed at the beginning of the Aptian (Fig. 12). Post-collisional granites are 117–108 million years old (Katkov et al. 2010). The collision of the Chukchi microcontinent with the structures of the active Siberian margin resulted in the formation of the Arctic margin of Eurasia in Eastern Arctic. A large continental block, including Chukotka, the shelf with islands and the structures of the Central Arctic elevations (the Mendeleev Rise, the Chukchi Plateau) joined the Asian continent and became its part (Sokolov et al. 2014, 2015).

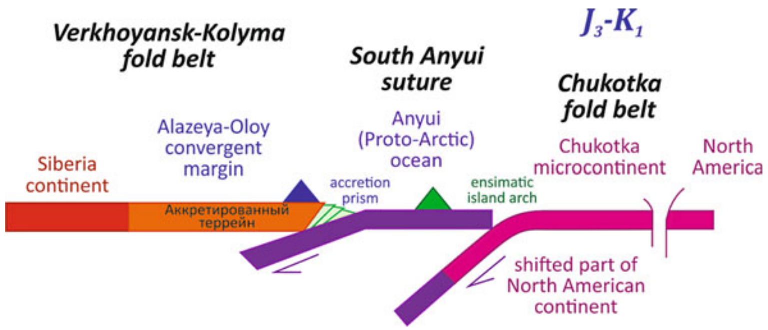

Fig. 12 Geodynamic model of the South Anyui suture. (1) Northern margin (North America) of the Proto-Arctic ocean was passive, and its southern margin (Siberia) was active. There was two south dipping subducted zone: Oloy volcanic belt along Alazeya-Oloy convergent margin and Kul'polney ensimatic arc. Chukotka microcontinent was a shifted block of North America continent. (2) During collision, the passive margin of the Chukotka microcontinent, subducted below the active margin of the North Asian continent. (3) In result of collision the large continental block (Chukotka microcontinent included Chukotka Peninsula, Chukchi Plato, Mendeleeva Uplift. Podvodnikov basin) accreted to Siberia and became a part of Eurasia

Later, in the Aptian-Albian in response to extension, the Ainakhkurgen, Nutesyn and other orogenic depressions filled in volcanic-sedimentary deposits were formed, and the granite-metamorphic domes grew larger (Bering… 1997; Luchitskaya et al. 2010).

Intense intraplate volcanism (HALIP, 120–110 Ma) and continental riftogenesis are typical of this stage of development in the Arctic. The formation of the South Chukchi Trough (Verzhbitsky et al. 2009; Miller and Verzhbitsky 2009) and the synrift complexes of the Podvodnikov Basin and the Chukchi Plateau (Arctic… 2017) takes its beginning in the studied area.

In the Eastern Arctic, the formation of the Mesozoic folded belts completed by the Aptian–Albian. The spatial position and relation of the continents acquired modern outlines. The Okhotsk-Chukotka volcanic belt emerged on the Pacific margins of Eurasia (the Late Albian–Early Campanian). Since that time, the geodynamic regime of regional extension and thermal immersion has prevailed in the Eastern Arctic. There are several stages of riftogenesis related to the formation of the Arctic Ocean (Drachev 2011; Grantz et al. 2011; Arctic… 2017, etc.).

The formation of the Eurasian Ocean basin started in the late Cretaceous-Early Paleogene. As a result, the Lomonosov Ridge began to move away from the Barents-Kara continental margin. The first stage of rifting occurred in the Late Cretaceous–Early Eocene (80–55 Ma), the second stage corresponds to the late Middle Miocene–Late Miocene (Franke et al. 2001; Drachev 2011). Thick sedimentary cover had been accumulated in the Canada Basin during the Late Cretaceous (Mosher et al. 2012a, b).

Seismic lines across the Eurasian margin of the Eastern Arctic clearly show extensional structures in the form of grabens and semi-grabens of different ages (Jokat et al. 2003; Arctic Basin… 2017). There are submeridional structures extending from the land to the shelf and to the deep-water part (Vinogradov et al. 2016). The Lower Cretaceous, Brookian, post-Campanian, pre-Miocene and Messinian unconformities have been identified in seismic sections.

The extension of the continental crust was periodically accompanied by volcanic activities. Volcanic rocks, dredged and drilled in the Alpha-Mendeleev Rise, correspond to continental basalts (Mukasa et al. 2015; Morozov et al. 2013). In the Podvodnikov Basin, the Early Cretaceous synrift complex of the same age as the first stage of HALIP volcanism (130–110 Ma) and the Late Cretaceous one associated with the last stage of HALIP (90–80 Ma) have been distinguished.

Along with the general regime of extension, fold-thrust structures were formed on continental margins of Arctic Canada and Alaska. In northern Alaska, the Middle Late Cretaceous and Early Cenozoic deformations lead to the junction of the southern flank of the Colville Basin and the Brooks Fold Belt (Moore et al. 2002). Apatite tracks determine the time of deformations of 60, 45 and 23 Ma (O'Sullivan et al. 1997).

The collision of Greenland and the Ellesmere Islands in the Paleocene and Eocene (Eurekan deformation) resulted in the accumulation of detrital sediments in the Sverdrup Basin and the formation of fold-and-thrust structures in the eastern part of the basin (Harrison et al. 1999; Von Gosen and Piepjohn 2003).

Geodynamic model. When developing tectonic models, it is necessary to explain why the opening of the Eurasian Basin in the Cenozoic was accompanied by the extension in the Eastern Arctic. Attempts to explain such a geodynamic regime by compensation in the subduction zone (Zonenshain et al. 1990a, b, Scotese 2011) turned out to be unsuccessful after ascertaining the composition and age of volcanic rocks from the Alpha Ridge and the Mendeleev Rise.

Analysis of geological and geophysical information, including tomography data for the Northern Pacific and the Arctic, made it possible to propose a new geodynamic model developed by the RAS staff (Lobkovsky et al. 2011; Laverov et al. 2013; Lobkovsky 2011) (Fig. 13).

Seismic tomography data for North-East Asia and the North-West Pacific evidence that the cold matter submerging into the subduction zone reaches the transition zone between the upper and lower mantle and changes its direction of movement and then passes into the extended horizontal layer of cold mantle matter, which spreads out to distances of first thousand kilometers under the Eurasian continent (Zhao et al. 2010).

In this case, a recurrent ascending upper mantle flow emerges, which creates the effect of dragging the Arctic lithosphere towards the Pacific Ocean and provides regional sublatitudinal extension that began in the Aptian–Albian (Lobkovsky et al. 2011; Laverov et al. 2013). As a result, blocks in the form of Alpha and Mendeleev Rises separated from the Barents-Kara margin (Fig. 13). The separation and subsequent moving apart of the Alpha and Mendeleev Rises took place 110 to 60 million years ago and were accompanied by rift-related extension of the Makarov and Podvodnikov Basins.

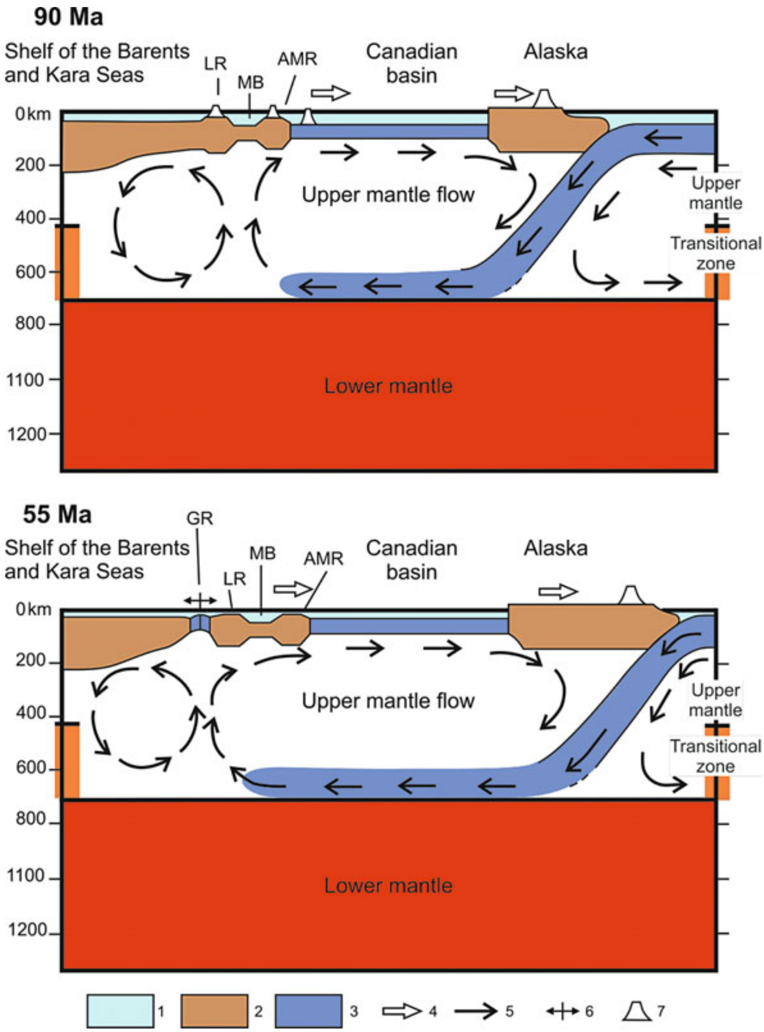

Fig. 13 Model of the upper mantle cell under the continent caused by the Pacific lithosphere subduction (Laverov et al. 2013). 1—ocean water layer, 2—continental lithosphere, 3—ocean lithosphere; 4—continental blocks movement vector towards the Pacific subduction zone due to the convection cell of the upper mantle, 5—direction of flows in the upper mantle and transitional zone, 6—spreading in the Eurasian Basin, 7—magmatism manifestations. Abbreviations: *AMR* the Alpha-Mendeleev Ridge, *GR* the Gakkel Ridge, *LR* the Lomonosov Ridge, *MB* Makarov Basin

Later, the opening of the Eurasian Basin began in the Cenozoic accompanied by the formation of a system of submeridional grabens and horsts.

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References

Bering Strait Geologic Field Party (1997) Koolen metamorphic complex, northeastern Russia: Implications for the tectonic evolution of the Bering Strait region. Tectonics 16:713–729

Drachev SS (2011) Tectonic setting, structure and petroleum geology of the Siberian Arctic offshore sedimentary basins. In: Spencer AM, Embry AF, Gautier DL, Stoupakova AV, Sørensen K (eds) Arctic petroleum geology, vol 35. Geol. Soc., London, Mem, pp 369–394

Embry A (1993) Crockerland—the northern source area for the Sverdrup Basin, Canadian Arctic Archipelago. In: Vorren, Bergsager E, Dahl-Stamnes O, Holter E, Johansen B, Lie E, Lund T (eds) Arctic geology and petroleum potential, vol 2. T. Norwegian Petroleum Society, Special Publication, pp 205–216

Franke D, Hinz K, Oncken O (2001) The Laptev Sea Rift. Mar Pet Geol 18:1083–1127

Funck T, Jackson HR, Shimeld J (2011) The crustal structure of the Alpha Ridge at the transition to the Canadian Polar Margin: results from a seismic refraction experiment. J Geophys Res 116:B12101. https://doi.org/10.1029/2011JB008411

Ganelin AV (2015) Ophiolites of Western Chukotka (structure, age, composition, geodynamic setting). GIN RAS, Moscow, 31 p (in Russian)

Grantz A, May SD, Taylor PT, Lawver LA (1990) Canada basin. In: Grantz A, Johnson L, Sweeney JF (eds) The Arctic Ocean region. The geology of North America. L. Geological Society of America, Boulder, CO, pp 379–402

Grantz A, Hart PE, Childers VA (2011) Geology and tectonic development of the Amerasia and Canada Basins, Arctic Ocean. In: Spencer AM, Embry AF, Gautier DL, Stoupakova AV, Sørensen K (eds) Arctic petroleum geology, vol 35. Geological Society London, Memoirs, pp 771–799

Harrison JC, Mayr U et al (1999) Correlation of Cenozoic sequences of the Canadian Arctic region and Greenland; implications for the tectonic history of northern North America. Bull Can Pet Geol 47:223–254

Hopper JR, Funck T, Stoker MS, Arting U, Peron-Pinvidic G, Doornenbal H, Gaina C, Danmarks geologiske undersøgelse (2014) Tectonostratigraphic atlas of the North-East Atlantic region. Geological Survey of Denmark and Greenland, Copenhagen, 338 p

Jackson HR, Dahl-Jensen T, the LORITA working group (2010) Sedimentary and crustal structure from the Ellesmere Island and Greenland continental shelves onto the Lomonosov Ridge, Arctic Ocean. Geophys J Int 182:11–35

Jokat W (2005) The sedimentary structure of the Lomonosov Ridge between 88 °N and 80°N. Geophys J Int 163:698–726

Jokat W, Ritzmann O, Schmidt-Aursch MC, Drachev S, Gauger S, Snow J (2003) Geophysical evidence for reduced melt production on the Arctic ultraslow Gakkel mid-ocean ridge. Nature 423:962–965

Kaminsky VD (ed) (2017) The Arctic Basin (geology and morphology). VNIIOkeangeologiya, St. Petersburg, 291 p (in Russian)

Kashubin SN, Pavlenkova NI, Petrov OV, Milshtein ED, Shokalsky SP, Erinchek YuM (2013) Crust types in the Circumpolar Arctic. Reg Geol Metallogeny 55:5–20 (in Russian)

Kashubin SN, Petrov OV, Artemieva IM, Morozov AF, Vyatkina DV, Golysheva YuS, Kashubina TV, Milshtein ED, Rybalka AV, Erinchek YuM, Sakulina TS, Krupnova NA (2016) Deep structure of the Earth's crust and upper mantle of the Mendeleev Rise along the Arctic-2012 DSS line. Reg Geol Metallogeny 65:16–35 (In Russian)

Kashubin SN, Petrov OV, Milshtein ED, Vinokurov IYu, Androsov EA, Golysheva YuS, Efimova NN, Yavarova TM, Morozov AF (2018) The structure of the earth's crust of the junction zone of the Mendeleev Rise with the Eurasian continent (according to geophysical data). Reg Geol Metallogeny 74:5–18 (in Russian)

Katkov SM, Miller EL, Toro J (2010) Structural paragenes and age of deformation of the Anyui-Chukotka fold system (Northeastern Russia). Geotectonics 44(5):61–80 (in Russian)

Laverov NP, Lobkovsky LI, Kononov MV, Dobretsov NL, Vernikovsky VA, Sokolov SD, Shipilov EV (2013) Geodynamic model of tectonic evolution of the Arctic in the Mesozoic and Cenozoic and the problem of the outer boundary of the Russia's continental shelf. Geotectonics 1:3–35 (in Russian)

Lawver LA, Grantz A, Gahagan LM (2002) Plate kinematic evolution of the present Arctic region since the Ordovician. In: Miller EL, Grantz A, Klemperer SL (eds) Tectonic evolution of the Bering Shelf–Chukchi Sea–Arctic Margin and adjacent land masses. Special Papers, vol 360. Geological Society of America, Boulder, Colorado, pp 333–358

Lebedeva-Ivanova NN, Zamansky YY, Langnen AE, Sorokin MY (2006) Seismic profiling across the Mendeleev Ridge at 82 °N evidence of continental crust. Geophys J Inter 165:527–544

Lebedeva-Ivanova NN, Gee DG, Sergeyev MB (2011) Chapter 26 Crustal structure of the East Siberian continental margin, Podvodnikov and Makarov basins, based on refraction seismic data (TransArctic 1989–1991). In: Spencer, Embry, Gautier, Stoupakova and Sørensen (eds) Arctic petroleum geology, vol 35. Geological Society of London, pp 395–411

Ledneva GV, Pease VL, Sokolov SD (2011) Permo-Triassic hypabyssal mafic intrusions and associated tholeiitic basalts of the Kolyuchinskaya Bay, Chukotka (NE Russia): links to the Siberian LIP. J Asian Earth Sci 40:737–745

Ledneva GV, Bazylev BA, Layer PW, Ishiwatari A, Sokolov SD, Kononkova NN, Tikhomirov PL, Novikova MS (2014) Intra-plate gabbroic rocks of permo-triassic to early-middle triassic dike-and-sill province of Chukotka (Russia). In: Stone DB, Grikurov GE, Clough JG, Oakey GN (eds) ICAM VI: proceedings of the international conference on Arctic Margins VI. VSEGEI, Petersburg, pp 115–156

Lobkovsky LI (2011) Tectonics of deformable lithospheric plates: generalization of the classic concept, vol 5. Geology of Seas and Oceans, Moscow, pp 24–25 (in Russian)

Lobkovsky LI, Verzhbitsky VE, Kononov MV, Shreider AA, Garagash IA, Sokolov SD, Tuchkova MI, Kotelkin VD, Vernikovsky VA (2011) Geodynamic model of the evolution of the Arctic region in the Late Mesozoic—cenozoic and the problem of the external border of the continental shelf of Russia. Arctic. Ecol Econ 1:104–115 (in Russian)

Luchitskaya MV, Sokolov SD, Bondarenko GE, Katkov SM (2010) Composition and geodynamic setting of granitoid magmatism in the Alyaramaut Uplift (West Chukotka). Geochemistry 9:946–972 (in Russian)

Miller EL, Verzhbitsky VE (2009) Structural studies near Pevek, Russia: implications for formation of the East Siberian Shelf and Makarov Basin of the Arctic Ocean. In: Stone DB, Fujita K, Layer PW, Miller EL, Prokopiev AV, Toro J (eds) Geology, geophysics and tectonics of Northeastern Russia: a tribute to Leonid Parfenov. EGU Stephan Mueller Publication Series, vol 4, pp 223–241

Miller EL, Meisling KE, Anikin VV et al (2017) Circum-Arctic Liotsphere Evolution (CALE) Transect C: displacement of the Arctic Alaska-Chutkotka microplate towards the Pacific during the opening of the Amerasia Basin in the Arctic. In: Pease V, Coakley B (eds) Circum-Arctic litosphere evolution, vol 460. Geol. Soc. London, Spec. Publ. https://doi.org/10.1144/sp460.9

Mooney WD (2007) Crust and lithospheric structure—global crustal structure. In: Romanowicz B, Dziewonski A (eds) Treatise on geophysics, vol 1: seismology and structure of the Earth. Elsevier, pp 361–417

Moore ThE, Dumitru TA, Adams KE et al (2002) Origin of the Lisbume Hills-Herald Arch structural belt: stratigraphic, structural, and fission-track evidens from the Cape Lisbum area, Northwestern Alaska. In: Miller EL et al (eds) Tectonic evolution of the Bering Shelf-Chukchi Sea-Arctic Margin and adjacent landmasses. Geol. Soc. Amer., Boulder, pp 77–109

Moore TE, Wallace WK, Bird KJ, Karl SM, Mull CG, Dillon JT (1994) Geology of northern Alaska. In: Plafker G, Berg HC (eds) The geology of Alaska. Geology of America v. G-1. Geological Society of America, Boulder, Colorado, pp 535–554

Morozov AF, Petrov OV, Shokalsky SP, Kashubin SN, Kremenetsky AA, Shkatov MYu, Kaminsky VD, Gusev EA, Grikurov GE, Recant PV, Shevchenko SS, Sergeev SA, Shatov VV (2013) New geological data substantiating the continental nature of the Central Arctic Uplifts area. Reg Geol Metallogeny 53:34–56 (in Russian)

Mosher DC, Shimeld J, Hutchinson D, Chian D, Lebedova-Ivanova N, Jackson R (2012) Canada Basin revealed. Society of petroleum engineers—Arctic technology conference, vol 2. https://doi.org/10.4043/23797-ms

Mosher DC, Shimeld JW, Chian D, Lebedeva-Ivanova N, Li Q, Hutchinson D, Edwards B, Mayer L, Chapman B (2012) In: Stone DB, Clough JG, Thurston DK (eds) Sediment distribution in Amerasian Basin, Arctic Ocean. Geophys. Institute Report UAG-R-335/. University of Alaska, Fairbanks, Alaska, pp 148–149

Mukasa SB, Mayer LA, Aviado K, Bryce J, Andronikov A, Brumley K, Blichert-Toft J, Petrov OV, Shokalsky SP (2015) Alpha/Mendeleev Ridge and Chukchi Borderland 40Ar/39Ar Geochronology and geochemistry: character of the first submarine intraplate lavas recovered from the Arctic Ocean. Geophysical Research Abstracts, vol 17, EGU2015-8291-2

Nokleberg WJ, Scotese CR, Khanchuk AI, Monger JWH, Dawson KM, Norton IO, Parfenov LM (2000) Dynamic computer model for the Phanerozoic tectonic and metallogenic evolution of the Circum-Pacific. Geol. Society of America Abstracts with Programs, vol 32, No 6, p 59

Nokleberg WJ, Parfenov LM, Monger JWH, Norton IO, Khanchuk AI, Stone DB, Scotese CR, Scholl DW, Fujita K (2000) Phanerozoic tectonic evolution of the Circum-North Pacific. Professional paper 1626.U.S. Geological Survey, 122 p

O'Sullivan PB, Murphy JM, Blythe AE (1997) Late Mesozoic and Cenozoic thermotectonic evolution of the central Brooks Range and adjacent North Slope foreland basin, Alaska: Including fission track results from the Trans-Alaska crustal transect (TACT). J Geophys Res 102(B9):20821–20845. https://doi.org/10.1029/96JB03411

Parfenov LM, Natapov LM, Sokolov SD, Tsukanov NV (1993a) Terrane analysis and accretion in North-East Asia. Geotectonics 1:68–78 (in Russian)

Parfenov LM, Natapov LM, Sokolov SD, Tsukanov NV (1993b) Terrane analysis and accretion in North-East Asia. Island Arc 2:35–54

Petrov O, Smelror M, Morozov A, Shokalsky S, Kashubin S, Artemieva IM, Grikurov G, Sobolev N, Petrov E, Ernst RE (2016) Tectonic model and map of the Arctic region (TeMAr). Earth Science Review

Plafker G, Berg HC (1994) Overview of the geology and tectonic evolution of Alaska. In: Plafker G, Berg HC (eds) The geology of Alaska. Geological Society of America, Boulder, CO, Geology of North America, G-1, pp 989–1021

Poselov VA, Avetisov GP, Kaminsky VD et al (2011) Russian Arctic geotraverses. FGUP VNIIOkeangeologia, St. Petersburg, 172 p (in Russian)

Poselov V, Butsenko V, Chernykh A, Glebovsky V, Jackson HR, Potter DP, Oakey G, Shimeld J, Marcussen C (2011) The structural integrity of the Lomonosov Ridge with the North American and Siberian continental margins. In: ICAM VI: Proceedings of the international conference on Arctic Margins VI, Fairbanks, Alaska, May 2011, pp 233–258. http://www2.gi.alaska.edu/icam6/proceedings/web/

Roslov YuV, Sakoulina TS, Pavlenkova NI (2009) Deep seismic investigations in the Barents and Kara Seas. Tectonophysics 472:301–308

Sakoulina TS, Telegin AN, Tikhonova IM, Verba ML, Matveev YI, Vinnick AA, Kopylova AV, Dvornicov LG (2000) The results of deep Seismic investigation on Geotravers in the Barents Sea from Kola peninsula to Franz-Jozeph Land. Tectonophysics 329:319–331

Sakoulina TS, Pavlenkova GA, Kashubin SN (2015) Structure of the earths crust in the northern part of the Barents-Kara region along the 4-AR DSS profile. Russ Geol Geophys 56(11):1622–1633 (in Russian)

Sakoulina TS, Kashubin SN, Petrov OV, Morozov AF, Krupnova NA, Dergunov NT, Razmatova AV, Tabyrets SN, Kashubina TV, Yavarova TM (2016) The deep structure of the earth's crust and upper mantle of the North-Chukot trough along the GSL Dream-line profile. Reg Geol Metallogeny 68:52–65 (In Russian)

Scotese CR (2011) Paleogeographic reconstructions of the Circum-Arctic Region since the Late Jurassic. Search and Discovery Article #30193. Adapted from oral presentation at AAPG Annual Convention and Exhibition, Houston, Texas, April 10–13, 2011. Posted September 30, 2011

Shatsky NS (1935) On tectonics of the Arctic. Geology and mineral resources of the USSR's North. Glavsevmorput', Leningrad, pp 149–165 (in Russian)
Shepherd GM, Pologruto TA, Svoboda K (2003) Circuit analysis of experience-dependent plasticity in the developing rat barrel cortex. Neuron 38:277–289
Sokolov SD (1992) Accretionary tectonics of the Koryak-Chukotka segment of the Pacific belt. Trans. of Geological Institute Russian Academy of Sciences, 479, Moscow, Nauka, 182 p (in Russian)
Sokolov SD, Tuchkova MI (2015) Mesozoic tectono-stratigraphic terranes of the Koryak-Chukotka region. Special Paper Geol Soc Am 513:461–481
Sokolov SD, Ledneva GV, Tuchkova MI, Luchitskaya MV, Ganelin AV, Verzhbitsky VE (2014) Chukchi Arctic continental margins: tectonic evolution, link to the opening of the Amerasian Basin. In: Fairbanks A, Stone DB, Grikurov GE, Clough JG, Oakey GN, Thurston DK (eds) ICAM VI: Proceedings of the international conference on Arctic Margins VI. A.P. Karpinsky Russian Geological Research Institute (VSEGEI), St. Petersburg, pp 97–114
Sokolov SD, Tuchkova MI, Ganelin AV, Bondarenko GE, Leier P (2015) Tectonics of the South Anyui suture (Northeast Asia). Geotectonics 1:5–30 (in Russian)
Tectonics of the continental margins of the northwestern Pacific Ocean (1980) In: Leytes AM, Fedorovsky VS, Tilman CM, Shilo NA (eds) Nauka Publisher, Moscow, 285 p
Tuchkova MI (2011) Lithology of terrigenic rocks from Mesozoic fold belt of the continental margin (Great Caucasus, North-East Asia), vol 600. Trans. of Geological Institute Russian Academy of Sciences, LAP, 334 p (in Russian)
Tuchkova MI, Sokolov SD, Khudoley AK, Hayasaka Y, Moiseev AV (2014) Permian and Triassic deposits of Siberian and Chukotka passive margins: sedimentation setting and provenance. In: Fairbanks A, Stone DB, Grikurov GE, Clough JG, Oakey GN, Thurston DK (eds) ICAM VI: Proceedings of the international conference on Arctic Margins VI. A.P. Karpinsky Russian Geological Research Institute (VSEGEI), St. Petersburg, pp 61–96
Verzhbitsky VE, Sokolov SD, Tuchkova MI (2009) Tectonics, stages of structural evolution and oil and gas prospects of the shelf of the Chukchi Sea (Russian Arctic). Geology of the polar connections of the Earth. XLII Mater Tecton Appl 1:85–90 (in Russian)
Vinogradov VA, Gusev EA, Rekant PV, Pyatkova MN (2016) Specific features of sedimentary cover formation in the Taimyr-Alaska area of the Arctic (in terms of structural relations in the shelf-ocean system). Petrol Geol Theor Appl Stud 11(1) (in Russian)
Von Gosen W, Piepjohn K (2003) Eurekan transpressive deformation in the Wandel Hav Mobile Belt (northeast Greenland). Tectonics 22(4):1039, 13–28
Zhao D, Piraino F, Liu L (2010) The structure and dynamics of the mantle under East Russia and adjacent regions. Geol Geophys 51(9):1188–1204 (in Russian)
Zonenshain LP, Kuzmin MI, Natapov LM (1990a) Geology of the USSR: a plate tectonic synthesis. In: Page BM (ed) Geodynamics series, vol 21. American Geophysical Union, Washington, DC
Zonenshain LP, Kuzmin MI, Natapov LM (1990) Tectonics of lithospheric plates of the USSR, vol 2. M.: Nedra, Book. 334 p (in Russian)