SCIENTIFIC CONTRIBUTIONS TO THE TECTONIC MAP OF THE ARCTIC

Editors-in-chief

O. V. Petrov, M. Pubellier

CGMW
Paris • 2019

UDC: 551.24(98)(084.3)

Scientific contributions to the Tectonic Map of the Arctic / eds. O. V. Petrov, M. Pubellier (VSEGEI/CGMW). Paris: CGMW, 2019. 64 p.

This booklet is devoted to the Tectonic Map of the Arctic (TeMAr) that has been compiled under the International project "Atlas of Geological Maps of the Circumpolar Arctic in scale 1:5M". The project has been carried out since 2004 by Geological Surveys of the Arctic countries supported by the UNESCO Commission for the Geological Map of the World (CGMW) and national programs for scientific substantiation for the United Nations Commission for the Law of the Sea (UNCLOS). The TeMAr working group coordinated by Russia (VSEGEI) includes leading scientists from Geological Surveys, universities and national Academies of Sciences of Denmark, Sweden, Norway, Russia, Canada, the USA, France, Germany and Great Britain.

The booklet includes brief descriptions of the Tectonic Map of the Arctic; the descriptions of the geotransect, scheme of the Arctic tectonic provinces, geophysical maps that illustrate the deep structure of the Earth's crust and upper mantle of the Circumpolar Arctic, and brief notes on tectonic model and geodynamic evolution of the Arctic.

The Tectonic Map of the Arctic is attached to the booklet.

The Tectonic map is recommended for publishing by the expert council of the Commission for the Geological Map of the World

Manuel Pubellier, *President, Commission for the Geological Map of the World*
Philippe Rossi, *President (till 02.2018) of the Commission for the Geological Map of the World*
Oleg Petrov, *Vice-President of the CGMW for Northern Eurasia*
Sergey Shokalsky, *Secretary General of the CGMW Subcommission for Northern Eurasia*
Marc St-Onge, *Vice-President of the CGMW for Northern and Central America*
Alexander Khanchuk, *President of the Subcommission for Tectonic maps*
Igor Pospelov, *Secretary General of the Subcommission for Tectonic maps*

© CGMW, 2019
© A.P. Karpinsky Russian Geological
Research Institute, 2019

CONTENT

INTRODUCTION

The Tectonic Map of the Arctic (TeMAr) has been compiled under the aegis of the Commission for the Geological Map of the World (CGMW) and carried out since 2004 by the Geological Surveys of the Arctic countries under the general coordination of VSEGEI, and with the support of UNESCO. This map is part of the project of Atlas of Geological Maps of the Circumpolar Arctic at scale 1:5M (fig. 1). The TeMAr working group coordinated by Russia (VSEGEI) includes leading scientists from Geological Surveys, universities and national Academies of Sciences of Denmark, Sweden, Norway, Russia, Canada, the USA, France, Germany and Great Britain.

Focussed active work on the legend for the Tectonic Map of the Arctic (TeMAr) took place during a series of meetings of the working group held jointly with representatives of the Commission for the Geological Map of the World in 2010: January and April (St. Petersburg), February (Paris). The first working draft of TeMAr was presented at the 4th international project workshop in April 2012 in Vienna in conjunction with the General Assembly of the European Geosciences Union (EGU). An updated version, including a crustal thickness map, a chart of crustal types, and a transarctic cross-section, was displayed at the 34th session of the International Geological Congress in Australia in August 2012.

Fig. 1. The frame of the International project "Atlas of Geological Maps of the Circumpolar Arctic in scale 1:5M"

The updated TeMAr map was also shown at the 11th International Conference and Exhibition for Oil and Gas Resources Development of the Russian Arctic and Continental Shelf in September 2013 in St. Petersburg. The fifth meeting of the international TeMAr working group was held in February 2014 in Paris on the invitation of the Commission for the Geological Map of the World. It was attended by twenty participants from Canada, France, the USA, Denmark, Norway, Sweden, Germany, and Russia.

In April 2015, the TeMAr map, including a full range of maps and charts with marginal information, was displayed at the meeting of the special session of the General Assembly of the European Geosciences Union in Vienna. In May 2015, the Canadian portion was published by the Geological Survey of Canada and made available to the working group as Canadian Geoscience Map (CGM) 187.

The international testing of the updated layout of the Tectonic Map of the Arctic took place at the meeting of the TeMAr international working group within the framework of the General Assembly of the European Geosciences Union (EGU) in Vienna in April 2016. The complete versions of the map was prepared for the Geological Congress in Cape Town in August, 2016.

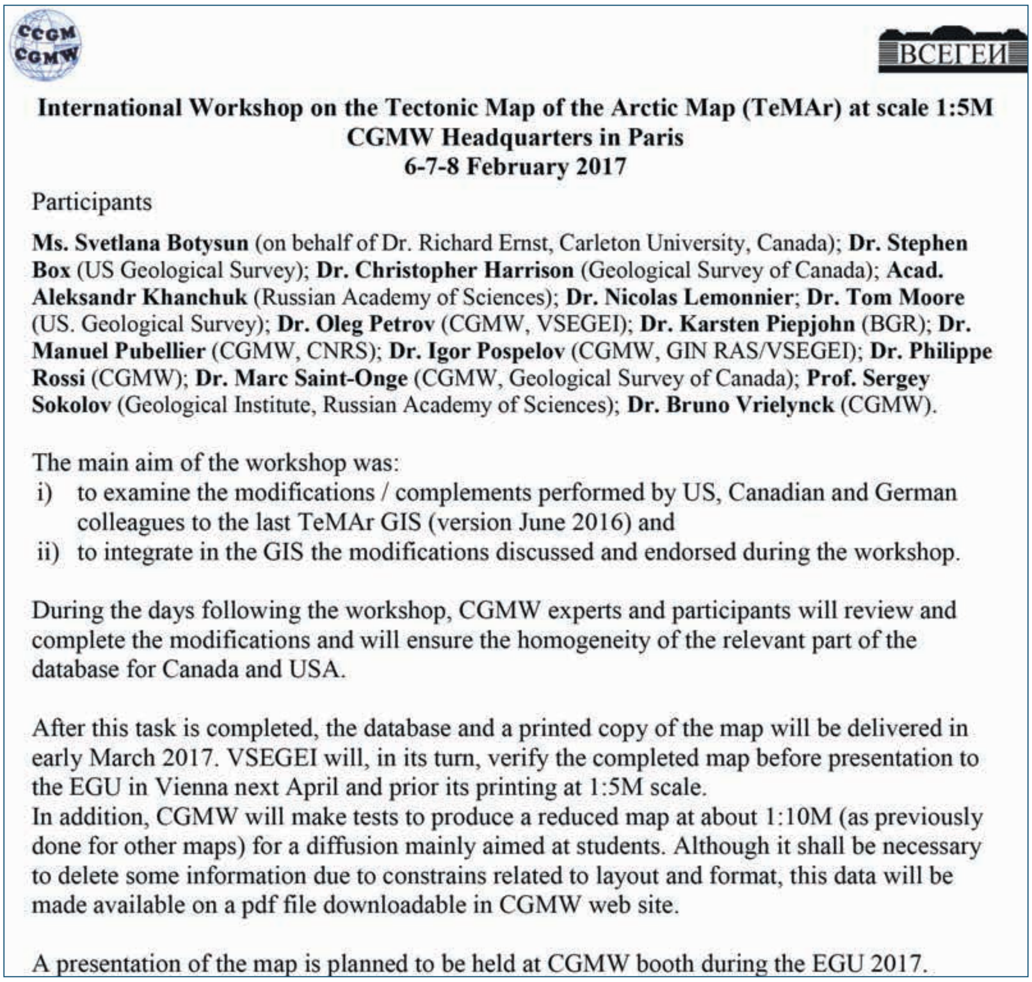
During the course of deliberations by the TeMAr international working group, it became apparent that despite the concordant opinion of various experts on the structure of bounding continental margins and most of the Arctic basin, some issues still remained on the table to be resolved. One such topic is the tectonic nature of the least understood deep-water part of the Arctic. Russian and some other members of the working group, relying on domestic and international geological and geophysical studies in the Arctic in recent years, have argued for the existence of Precambrian/Paleozoic continental

Fig. 2. The participants of the workshop on the Tectonic Map in February, 2017 (Paris)

crust in the central Arctic Basin. US experts and other researchers favour a different interpretation that features a much more widespread distribution of oceanic crust in the region.

In February 2017, in Paris, GGMW decided to publish the 1:10M Tectonic map, as it was done for other maps in order to distribute it among students and the scientific community (fig. 2, 3).

The compilation of the Tectonic Map incorporated the results of a decades of the geological and geophysical works in the Arctic area undertaken by numerous international and national expeditions



CCGM
CGMW

ВСЕГЕИ

International Workshop on the Tectonic Map of the Arctic Map (TeMAr) at scale 1:5M
CGMW Headquarters in Paris
6-7-8 February 2017

Participants

Ms. Svetlana Botysun (on behalf of Dr. Richard Ernst, Carleton University, Canada); **Dr. Stephen Box** (US Geological Survey); **Dr. Christopher Harrison** (Geological Survey of Canada); **Acad. Aleksandr Khanchuk** (Russian Academy of Sciences); **Dr. Nicolas Lemonnier**; **Dr. Tom Moore** (US. Geological Survey); **Dr. Oleg Petrov** (CGMW, VSEGEI); **Dr. Karsten Piepjohn** (BGR); **Dr. Manuel Pubellier** (CGMW, CNRS); **Dr. Igor Pospelov** (CGMW, GIN RAS/VSEGEI); **Dr. Philippe Rossi** (CGMW); **Dr. Marc Saint-Onge** (CGMW, Geological Survey of Canada); **Prof. Sergey Sokolov** (Geological Institute, Russian Academy of Sciences); **Dr. Bruno Vrielynck** (CGMW).

The main aim of the workshop was:

i) to examine the modifications / complements performed by US, Canadian and German colleagues to the last TeMAr GIS (version June 2016) and
ii) to integrate in the GIS the modifications discussed and endorsed during the workshop.

During the days following the workshop, CGMW experts and participants will review and complete the modifications and will ensure the homogeneity of the relevant part of the database for Canada and USA.

After this task is completed, the database and a printed copy of the map will be delivered in early March 2017. VSEGEI will, in its turn, verify the completed map before presentation to the EGU in Vienna next April and prior its printing at 1:5M scale.
In addition, CGMW will make tests to produce a reduced map at about 1:10M (as previously done for other maps) for a diffusion mainly aimed at students. Although it shall be necessary to delete some information due to constrains related to layout and format, this data will be made available on a pdf file downloadable in CGMW web site.

A presentation of the map is planned to be held at CGMW booth during the EGU 2017.

Fig. 3. Resolution of the International Workshop on the Tectonic Map in the CGMW where the last version of the Tectonic Map was accepted

Fig. 4. Icebreaker "Akademik Fedorov" during expeditions Arctic-2005 and Arctic-2010, "Heally" and "Polarstern" (expedition in 2008)

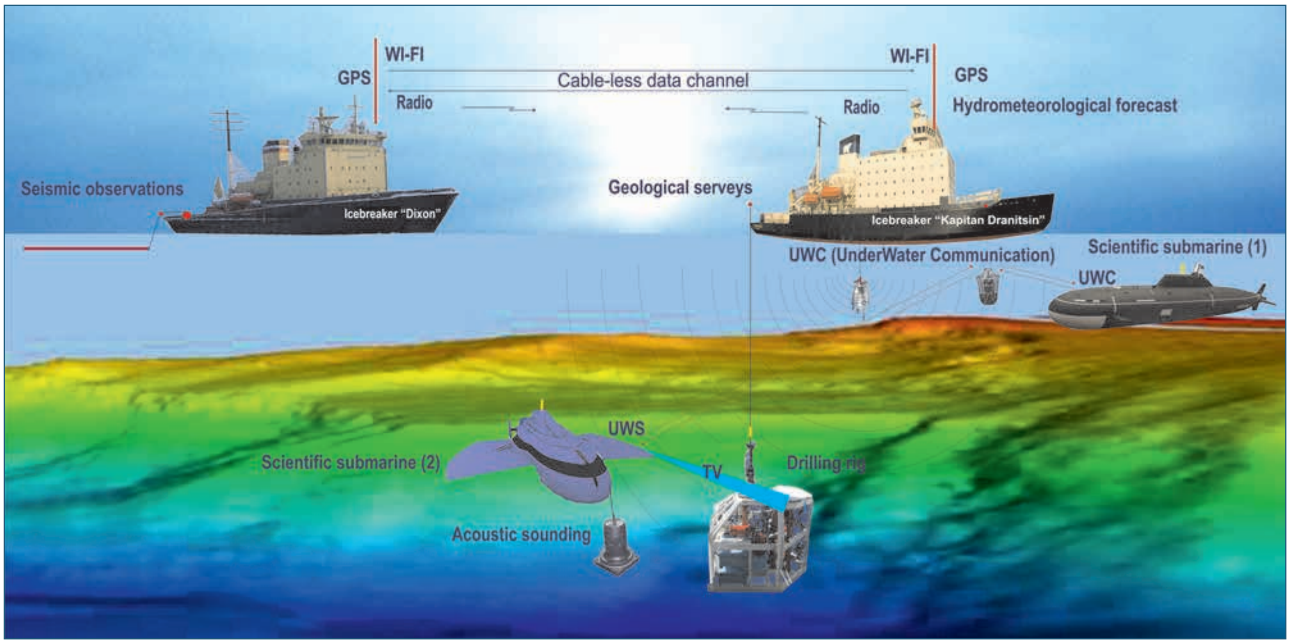


Fig. 5. Comprehensive study of seafloor scarps with bedrock outcrops on the Mendeleev Rise using shallow drilling and the manipulator of the research submarine in 2012 (expedition "Arctic-2012")

between 2000 and the present. Among these were the Arctic-2005, 2007, and 2010 expeditions (icebreaker "Akademik Fedorov"), ARK-XXI-II/3 (icebreakers "Polarstern" and "Heally") (fig. 4).

In 2012 important results were obtained by expedition Arctic-2012 (icebreakers "Captain Dranitsin" and "Dixon" aimed at comprehensive geologic investigation of the Mendeleev Rise (fig. 5).

The results of the expeditions include geophysical studies of the Arctic Ocean, diverse investigations of bedrock material from the Central Arctic Uplifts, magnetic studies and research of the geological structure of Svalbard, Novaya Zemlya and the New Siberian islands archipelagos.

In 2014 and 2016, the Geological Institute of the Russian Academy of Sciences (GIN RAS) in cooperation with the Geological and Geophysical Survey of the Geological Institute (GEOSLUZHBA GIN) and the Main Directorate for Deepwater Research of the Ministry of Defense of the Russian Federation conducted expeditions in area of the Alpha-Mendeleev Rise to collect data for studying geological section of the Rise. Rocks were sampled by research submarine manipulators directly from cliffs, ledges, elevations, as well as from debris beneath them and loose rocks formed on their terraces and peaks resulted from bedrock destruction.

The Tectonic Map of the Arctic is a qualitatively new product of present-day mapping. It includes a set of additional (marginal) maps and charts, which are based on the most recent integrated geological and geophysical data and demonstrates the deep structure of the Earth's crust and upper mantle of the Circumpolar Arctic. They are as follows: zoning map of the Circumpolar Arctic by nature of potential fields, the map of sedimentary cover thickness, the map of crust thickness, the map of crust types, the 7600-km transpolar geotransect, the tectonic zoning map.

The compilation of the Tectonic Map of the Arctic has marked the beginning of a new supra-regional level of geological-geophysical, isotope-geochronological and metallogenic knowledge of this inaccessible area. It called for comprehensive studies, integrating efforts of experts in various fields that promoted the development of fundamental geological sciences, the development and implementation of scientific innovation bases for the organization of cooperation between representatives of geological surveys, national academies and universities. Studies conducted by international communities have demonstrated successful experience of international cooperation and are highlighted in numerous publications and monographs. The Tectonic Map of the Arctic not only solves scientific problems, but it also is the most important basis for assessing the Arctic region mineral potential.

The Tectonic Map of the Arctic under the international project Atlas of Geological Maps of the Circumpolar Arctic at 1:5M was compiled at the A.P. Karpinsky Russian Geological Research Institute, the leading enterprise of the Federal Agency on Mineral Resources of the Russian Federation responsible for ensuring the state geological study of Russia and its continental shelf. At VSEGEI, state mapping at 1:1,000,000 and 1:200,000 scales as well as composite and areal mapping is carried out using modern regional geophysical, geochemical and remote research methods, precision laboratory-analytical, mineralogic-petrographic, and isotope-geochronological technologies. The institute houses the Isotope Research Centre and the Depository, in which the materials obtained from the Mendeleev Rise bottom are stored.

Arctic studies, very intensive over the last 15 years, allowed propelling the knowledge of this region to a new level of generalization of geological information and justification of the model of its structure, reconstruction of its geological history. The new Tectonic Map of the Arctic – on one hand – is a modern geologic information system and – on the other hand – demonstrates innovative methods of 3D-geological mapping (fig. 6). While compiling the Tectonic Map, main attention of the international community was given to the Central Arctic.

Main scientific results include 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. The Pacific oceanic plates descend under the North American and Eurasian plates leading to a formation of active continental margins. Young Arctic Ocean develops within the Gakkel Ridge, Nansen and Amundsen Basins at the boundary between the North American and Eurasian continental plates. Thus, the Lomonosov Ridge, Mendeleev Rise and other highs and depressions of the Central Arctic Submarine Uplifts Complex are marginal basins of the North American lithosphere plates and form a single continental "bridge" between Eurasia and North America, continuously passing into the shallow Eastern Siberian and Laurentian shelves. Continental nature of the Earth crust of the Central Arctic Submarine Uplifts and close ties of the "bridge" between the two continents and their shallow shelves are reliably confirmed by seismic data and the geological sampling of outcrops on the seabed. This point of view is reflected in the materials of the Tectonic Map of the Arctic and is shared by most authors of the international map TeMAr.

O.V. Petrov, M. Pubellier

EXPLANATION OF THE TECTONIC MAP OF THE ARCTIC

O.V. Petrov, S.P. Shokalsky, S.N. Kashubin, A.F. Morozov, N.N. Sobolev, I.I. Pospelov, S. Box, H. Brekke, R. Ernst, Y. Faleide, C. Gaedicke, C. Gaina, L. Gernigon, I.F. Glumov, A. Grantz, G.E. Grikurov, P. Guarnieri, J.C. Harrison, V.D. Kaminsky, Yu.B. Kazmin, L. Labrousse, N. Lemonnier, Yu.G. Leonov, N.A. Malyshev, E.D. Milshtein, T. Moore, R. Orndorff, E.O. Petrov, K. Piepjohn, V.A. Poselov, M. Pubellier, V.N. Puchkov, M. Smelror, S.D. Sokolov, M. Stephens, M.R. St-Onge, T.Yu. Tolmacheva, M.L. Verba, V.A. Vernikovsky

The Tectonic Map of the Arctic (TeMAr) that has been compiled under the International project Atlas of Geological maps of the Circumpolar Arctic in scale 1:5M. The project has been carried out since 2004 by Geological Surveys of the Arctic countries supported by the UNESCO Commission for the Geological Map of the World (CGMW) and national programs for scientific substantiation for the United Nations Commission for the Law of the Sea (UNCLOS). The TeMAr working group coordinated by Russia (VSEGEI) includes leading scientists from Geological Surveys, universities and national Academies of Sciences of Denmark, Sweden, Norway, Russia, Canada, the USA, France, Germany and Great Britain. The Tectonic Map compilation activities were aimed at acquiring thorough understanding of deep-water geological formations of the Arctic and Norwegian-Greenland basins, shelves of the marginal seas and the adjacent continental onshore areas of the oceans. The Tectonic Map is supplemented with a set of geophysical maps, schematic maps and sections that illustrate the deep structure of the Earth's crust and upper mantle of the Circumpolar Arctic.

Keywords: *Tectonic Map of the Arctic, Circumpolar Arctic, legend, regional geology, tectonics.*

The Tectonic Map of the Arctic (TeMAr) is based upon the Polar Stereographic Projection (WGS 84). In the south the map is bounded by 60° N. The shadow relief base of the map was compiled using superposed images, synthesized from the Landsat 7 ETM+ (in three bands: 7 (2.08–2.35 μm), 4 (0.76–0.90 μm and 2 (0.52–0.60 μm) and a digital landform model. The landform model has been constructed from the SRTM radar data (Shuttle Radar Topographic Mission with 900 m = 30" resolution) and the IBCAO chart (version 2.23 with 2 km resolution) in the offshore areas.

The compilation of the 1:5M Tectonic Map of the Arctic was based on its legend constructed by the following principles:

– integral cartographic representation of geological structures in deepwater parts of the Arctic and Norwegian-Greenland basins, shelves and onshore areas of the ocean margins, allowing structures correlation;

– two main types of the Earth's crust: oceanic and continental;

– in oceanic domains – spreading zones, crust of various ages and intraplate volcanic structures with a thickened crust (oceanic plateaus and aseismic ridges);

– in structures with continental crust – two groups of geological complexes – indicators of the main tectonic processes of a continental crust accretion and its destruction with formation of large igneous provinces (LIPs) that mark the Paleocontinents break-up episodes;

– sedimentary covers are shown as an independent group of mapped objects (70 % of the total area);

– tectonic map is accompanied by a set of additional digital maps (as a single GIS project), depicting the region deep structure, its basement tectonic subdivision and thickness of the sedimentary cover, nature of the Earth crust and large igneous provinces. Deep geological and geophysical cross–sections are provided as well.

The legend of the Tectonic Map of the Arctic has been compiled by two CGMW Subcommissions (for Tectonic Maps and Northern Eurasia), applying an experience in legend construction for newest tectonic maps under the aegis of CGMW and UNESCO.

In this Tectonic Map of the Arctic the latest data obtained by ECS national programs on the delimitation of the continental Arctic shelf outer boundaries have also been used.

At the first stage, the existing legends of the Structural maps Atlantic and Indian oceans as well as tectonic and geological maps of continents were analyzed. Possible approaches were discussed by experts from CGMW, VSEGEI, VNIIOkeangeologia, Sevmorgeo and GIN RAS (workshop on January 11–13, 2010, St. Petersburg) to construct the legend for TeMAr. Some drafts of it and the map fragments have been prepared basing on the workshop results.

Then the legend was tested internationally at the workshop on the Tectonic Map of the Arctic (April 7–9, 2010 in St. Petersburg) attended by participants from 20 organizations (geological surveys and

---

To cite: Explanation of the Tectonic Map of the Arctic / O.V. Petrov [et al.] // Scientific contributions to the Tectonic Map of the Arctic. Paris, 2019. P. 8–17.

Map compilers
Russia: Oleg PETROV, Sergey SHOKALSKY, Igor POSPELOV, Sergey KASHUBIN, Andrey MOROZOV, Nikolay SOBOLEV, Evgeniy PETROV, Aleksandr BALUEV, Sergey SOKOLOV, Garrik GRIKUROV, Valery VERNIKOVSKY.
Canada: Richard ERNST, Christopher HARRISON, Marc ST-ONGE.
Denmark: Pierpaolo GUARNIERI.
France: Loïc LABROUSSE, Nicolas LEMONNIER, Manuel PUBELLIER.
Germany: Karsten PIEPJOHN.
Norway: Morten SMELROR, Harald BREKKE, Jan FALEIDE.
Sweden: Michael STEPHENS.
USA: Stephen BOX, Arthur GRANTZ, Thomas MOORE, Randall ORNDORFF

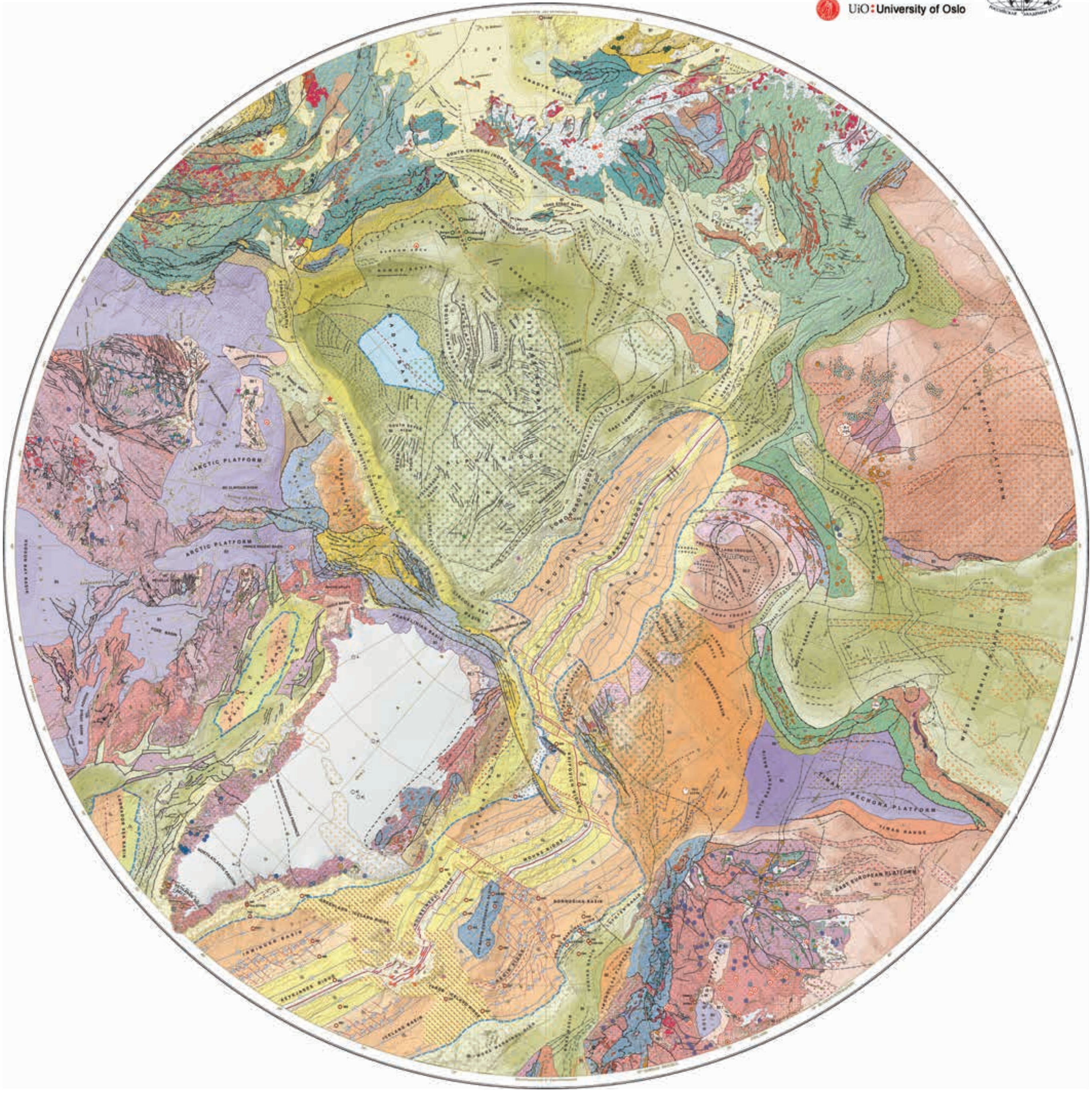


Fig. 6. Tectonic Map of the Arctic at 1:10M scale [Petrov et all. 2019]. The map with the legend and additional maps and schemes are available on the site of VSEGEI: http://www.vsegei. com/en/intcooperation/ temar-5000

scientific institutions) from the Arctic countries (Russia, Canada, Norway, Denmark) with representatives from France, Sweden, Great Britain, Germany, and Leaders of the Commission for the Geological Map of the World (CGMW). Discussion on the Legend revealed different approaches of national tectonic schools and showed a necessity of settling a unified position and resolving of major contradictions.

At this workshop, an international working group has been formed with the head O.V. Petrov (CGMW Vice-president for Northern Eurasia), S.P. Shokalsky (Secretary General of the CGMW Subcommission for Northern Eurasia), Yu.G. Leonov (President of the CGMW Subcommission for Tectonic Maps), I.I. Pospelov (Secretary General of the CGMW Subcommission for Tectonic Maps), Philippe Rossi (CGMW President), Manuel Pubellier (CGMW Secretary General).

The first version of the legend on eight sheets with an explanation has been sent to all the working group members. Then a written discussion followed, revealing disagreements in the approaches to the compilation of the tectonic map and its database. It took another round of coordination of the positions of Russian, American and European geologists. It has been decided to display in the most disputable Amerasian Basin region a distribution of the Cretaceous High Arctic Large Igneous Province (HALIP), overlapping the basement structures, whose continental nature was disputed by some authors of the map.

After a series of additional discussions and transformations, the legend to the Tectonic Map was finally approved and adopted at the workshop of the international working group (CGMW, Paris, April 15, 2011). In July 2011, the CGMW experts tested the database of the map digital version. Then in November 2011, the updated legend, database and digital fragment of the map of the Russian part have been provided to members of the international working group to compile national map fragments.

The first draft of the Tectonic Map of the Arctic with inset maps of deep structure and tectonic zoning, and with the Transarctic Geotransect were discussed at the Austrian Geological Survey workshop (Vienna, April 24, 2012). The legend and the first map draft have been suggested to be ready.

This TeMAr draft was presented and discussed in August 2012 at a session of the 34th International Geological Congress in Brisbane.

After that, the draft of the Tectonic Map of the Arctic was regularly updated by introduction of new geological and geophysical data obtained in Central Arctic, New Siberian Islands, Franz Josef Land, and Severnaya Zemlya Archipelago.

In February 2014, the 5th meeting of the TeMAr international working group with participants from Canada, France, the USA, Denmark, Norway, Sweden, Germany, and Russia was held at the General Assembly of the Commission for the Geological Map of the World in Paris. There the Russian party presented an updated draft of the Tectonic Map of the Arctic.

Canadian, Danish and Swedish geologists delivered new regional fragments of the map to be incorporated into the Tectonic Map of the Arctic, with the exception of the Alaska, contiguous shelf of the Chukchi Sea and the Alaska North Slope. Since April 2014, Russian and CGMW experts have been working on the compilation of these missing fragments of the Tectonic Map using materials of Thomas Moore and Stephen Box (US Geological Survey).

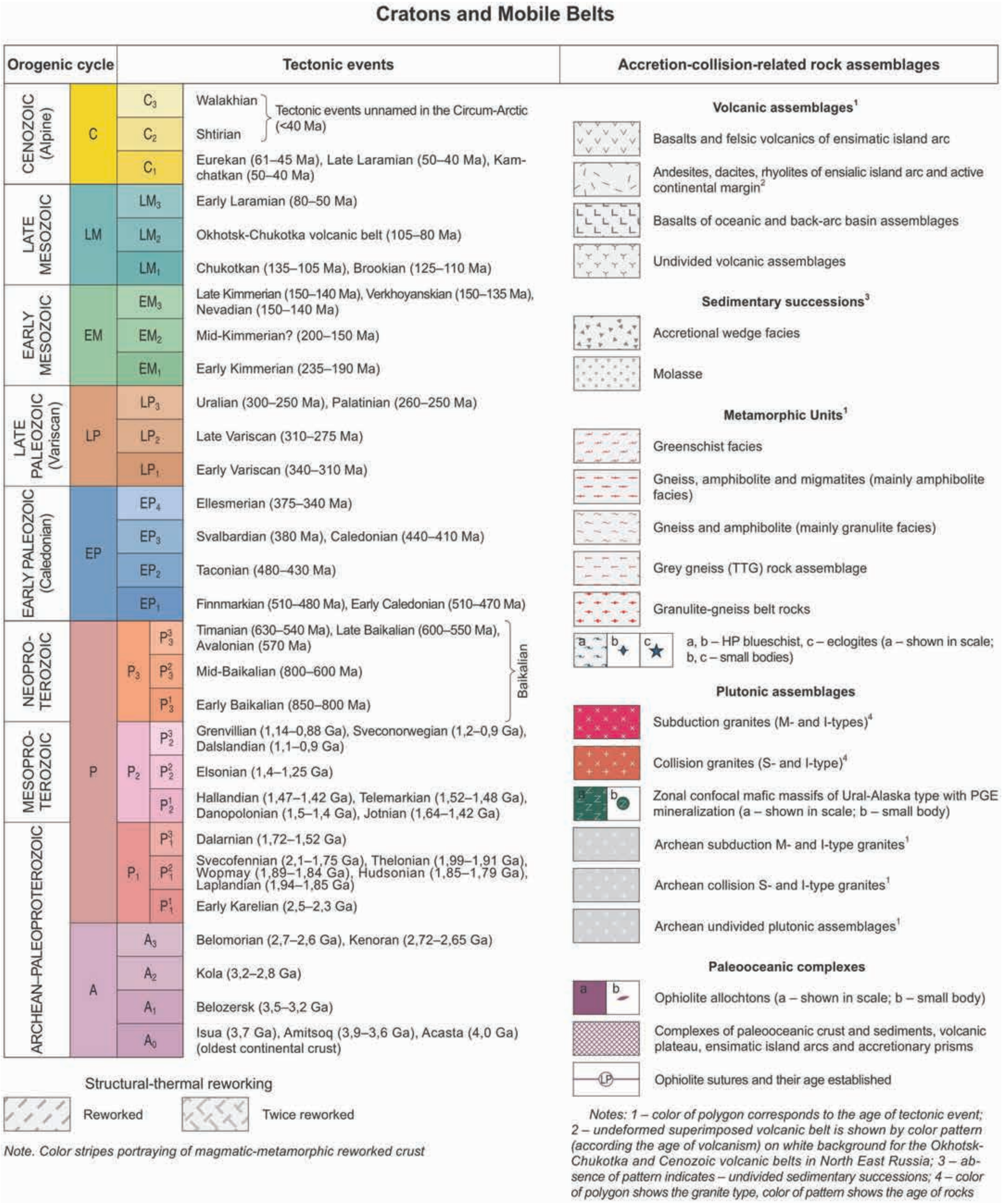
Later the Russian TeMAr group compilers came into a close contact with colleagues from Norway, Denmark, Canada and the USA participating in national programs on definition of outer limits of the continental shelf (ICAM-VI–VIII in 2014–2018). When compiling and correcting the map draft, new seismic data and results of dredged bottom material study (2008–2016) have been introduced.

Regular General Assembly was held during the European Geological Union (EGU) in Vienna in April 2016. An this meeting was devoted to a discussion of the state-of-the-art and further promotion of TeMAr. At the meeting, the latest draft of the Tectonic Map of the Arctic was demonstrated and discussed, and the issue of geological correlation of structures of the Northeast of Russia, Alaska and Arctic Canada was thoroughly debated.

The TeMAr Review Meeting Workshop took place in February 2017 in Paris at the CGMW Headquarters. The Expert Council included the leaders of the CGMW, Subcommissions for Northern Eurasia, Tectonic maps and North America, representatives of Geological Surveys of the USA, Canada, and Germany, as well as the Russian Academy of Sciences. The Expert Council approved the latest changes in the tectonic map legend regarding structures of the Northeast Russia and Alaska. It was noted in the Minutes that the Tectonic map of the Arctic may be submitted to the international geological community at the General Assembly of the European Geosciences Union (Vienna) in April 2017.

In March 2017, a short workshop was held at the CGMW Headquarters to review a GIS version of the Tectonic Map of the Arctic.

In 2018, during the CGMW General Assembly (Paris, February 2018), results of the work on TeMAr were summed up and the map publication



Cratons and Mobile Belts

Orogenic cycle				Tectonic events	
CENOZOIC (Alpine)	C	C_3		Walakhian	Tectonic events unnamed in the Circum-Arctic (<40 Ma)
		C_2		Shtirian	
		C_1		Eurekan (61–45 Ma), Late Laramian (50–40 Ma), Kamchatkan (50–40 Ma)	
LATE MESOZOIC	LM	LM_3		Early Laramian (80–50 Ma)	
		LM_2		Okhotsk-Chukotka volcanic belt (105–80 Ma)	
		LM_1		Chukotkan (135–105 Ma), Brookian (125–110 Ma)	
EARLY MESOZOIC	EM	EM_3		Late Kimmerian (150–140 Ma), Verkhoyanskian (150–135 Ma), Nevadian (150–140 Ma)	
		EM_2		Mid-Kimmerian? (200–150 Ma)	
		EM_1		Early Kimmerian (235–190 Ma)	
LATE PALEOZOIC (Variscan)	LP	LP_3		Uralian (300–250 Ma), Palatinian (260–250 Ma)	
		LP_2		Late Variscan (310–275 Ma)	
		LP_1		Early Variscan (340–310 Ma)	
EARLY PALEOZOIC (Caledonian)	EP	EP_4		Ellesmerian (375–340 Ma)	
		EP_3		Svalbardian (380 Ma), Caledonian (440–410 Ma)	
		EP_2		Taconian (480–430 Ma)	
		EP_1		Finnmarkian (510–480 Ma), Early Caledonian (510–470 Ma)	
NEOPROTEROZOIC	P	P_3	P_3^3	Timanian (630–540 Ma), Late Baikalian (600–550 Ma), Avalonian (570 Ma)	Baikalian
			P_3^2	Mid-Baikalian (800–600 Ma)	
			P_3^1	Early Baikalian (850–800 Ma)	
MESOPROTEROZOIC		P_2	P_2^3	Grenvillian (1,14–0,88 Ga), Sveconorwegian (1,2–0,9 Ga), Dalslandian (1,1–0,9 Ga)	
			P_2^2	Elsonian (1,4–1,25 Ga)	
			P_2^1	Hallandian (1,47–1,42 Ga), Telemarkian (1,52–1,48 Ga), Danopolonian (1,5–1,4 Ga), Jotnian (1,64–1,42 Ga)	
ARCHEAN–PALEOPROTEROZOIC		P_1	P_1^3	Dalarnian (1,72–1,52 Ga)	
			P_1^2	Svecofennian (2,1–1,75 Ga), Thelonian (1,99–1,91 Ga), Wopmay (1,89–1,84 Ga), Hudsonian (1,85–1,79 Ga), Laplandian (1,94–1,85 Ga)	
			P_1^1	Early Karelian (2,5–2,3 Ga)	
	A	A_3		Belomorian (2,7–2,6 Ga), Kenoran (2,72–2,65 Ga)	
		A_2		Kola (3,2–2,8 Ga)	
		A_1		Belozersk (3,5–3,2 Ga)	
		A_0		Isua (3,7 Ga), Amitsoq (3,9–3,6 Ga), Acasta (4,0 Ga) (oldest continental crust)	

Structural-thermal reworking

Reworked

Twice reworked

Note. Color stripes portraying of magmatic-metamorphic reworked crust

Accretion-collision-related rock assemblages

Volcanic assemblages[1]

Basalts and felsic volcanics of ensimatic island arc

Andesites, dacites, rhyolites of ensialic island arc and active continental margin[2]

Basalts of oceanic and back-arc basin assemblages

Undivided volcanic assemblages

Sedimentary successions[3]

Accretional wedge facies

Molasse

Metamorphic Units[1]

Greenschist facies

Gneiss, amphibolite and migmatites (mainly amphibolite facies)

Gneiss and amphibolite (mainly granulite facies)

Grey gneiss (TTG) rock assemblage

Granulite-gneiss belt rocks

a, b – HP blueschist, c – eclogites (a – shown in scale; b, c – small bodies)

Plutonic assemblages

Subduction granites (M- and I-types)[4]

Collision granites (S- and I-type)[4]

Zonal confocal mafic massifs of Ural-Alaska type with PGE mineralization (a – shown in scale; b – small body)

Archean subduction M- and I-type granites[1]

Archean collision S- and I-type granites[1]

Archean undivided plutonic assemblages[1]

Paleooceanic complexes

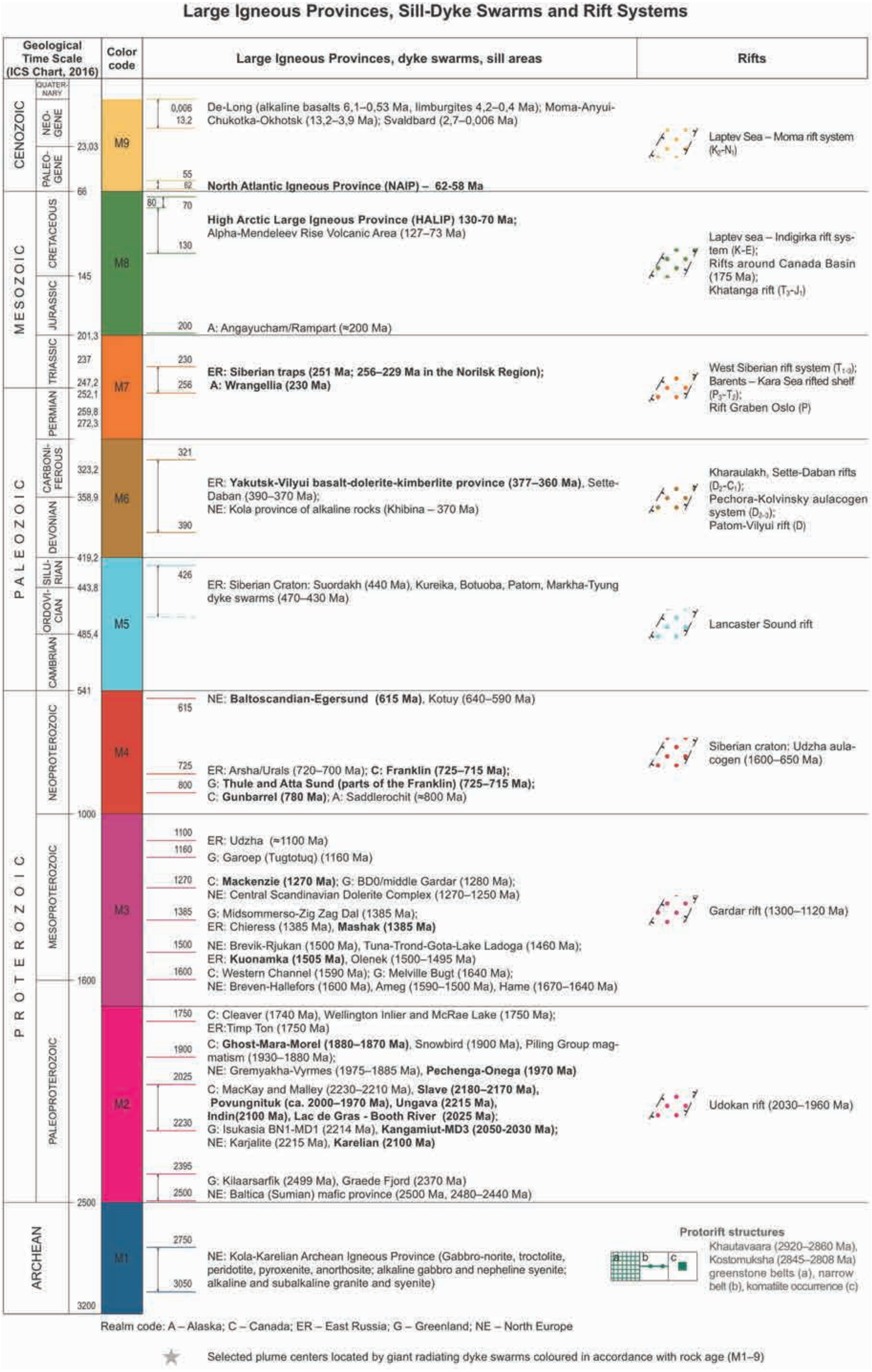
Ophiolite allochtons (a – shown in scale; b – small body)

Complexes of paleooceanic crust and sediments, volcanic plateau, ensimatic island arcs and accretionary prisms

Ophiolite sutures and their age established

Notes: 1 – color of polygon corresponds to the age of tectonic event; 2 – undeformed superimposed volcanic belt is shown by color pattern (according the age of volcanism) on white background for the Okhotsk-Chukotka and Cenozoic volcanic belts in North East Russia; 3 – absence of pattern indicates – undivided sedimentary successions; 4 – color of polygon shows the granite type, color of pattern shows the age of rocks

Fig. 7. Legend for cratons and mobile belts



Large Igneous Provinces, Sill-Dyke Swarms and Rift Systems

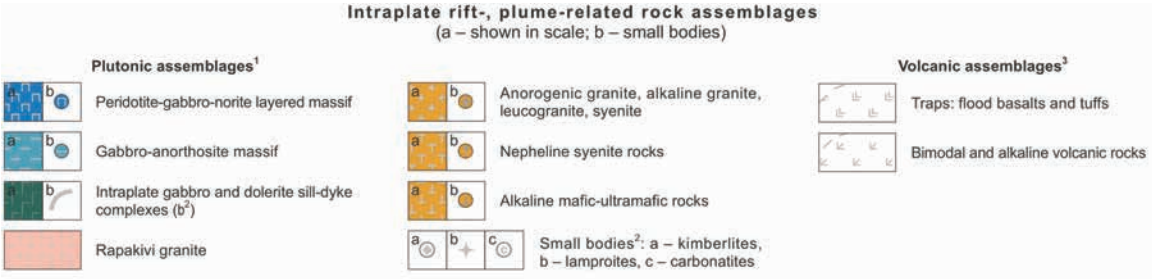
Geological Time Scale (ICS Chart, 2016)			Color code		Large Igneous Provinces, dyke swarms, sill areas	Rifts
CENOZOIC	QUATERNARY NEOGENE PALEOGENE	23,03 66	M9	0,006 13,2	De-Long (alkaline basalts 6,1–0,53 Ma, limburgites 4,2–0,4 Ma); Moma-Anyui-Chukotka-Okhotsk (13,2–3,9 Ma); Svaldbard (2,7–0,006 Ma)	Laptev Sea – Moma rift system (K_2-N_1)
				55 62	**North Atlantic Igneous Province (NAIP) – 62-58 Ma**	
MESOZOIC	CRETACEOUS JURASSIC	145 201,3	M8	80 70 130	**High Arctic Large Igneous Province (HALIP) 130-70 Ma;** Alpha-Mendeleev Rise Volcanic Area (127–73 Ma)	Laptev sea – Indigirka rift system (K-E); Rifts around Canada Basin (175 Ma); Khatanga rift (T_3-J_1)
				200	A: Angayucham/Rampart (≈200 Ma)	
	TRIASSIC PERMIAN	237 247,2 252,1 259,8 272,3	M7	230 256	**ER: Siberian traps (251 Ma; 256–229 Ma in the Norilsk Region);** **A: Wrangellia (230 Ma)**	West Siberian rift system (T_{1-3}); Barents – Kara Sea rifted shelf (P_3-T_2); Rift Graben Oslo (P)
PALEOZOIC	CARBONIFEROUS DEVONIAN	323,2 358,9 419,2	M6	321 390	ER: **Yakutsk-Vilyui basalt-dolerite-kimberlite province (377–360 Ma)**, Sette-Daban (390–370 Ma); NE: Kola province of alkaline rocks (Khibina – 370 Ma)	Kharaulakh, Sette-Daban rifts (D_2-C_1); Pechora-Kolvinsky aulacogen system (D_{2-3}); Patom-Vilyui rift (D)
	SILURIAN ORDOVICIAN CAMBRIAN	443,8 485,4 541	M5	426	ER: Siberian Craton: Suordakh (440 Ma), Kureika, Botuoba, Patom, Markha-Tyung dyke swarms (470–430 Ma)	Lancaster Sound rift
PROTEROZOIC	NEOPROTEROZOIC	1000	M4	615	NE: **Baltoscandian-Egersund (615 Ma)**, Kotuy (640–590 Ma)	Siberian craton: Udzha aulacogen (1600–650 Ma)
				725 800	ER: Arsha/Urals (720–700 Ma); **C: Franklin (725–715 Ma);** G: **Thule and Atta Sund (parts of the Franklin) (725–715 Ma);** C: **Gunbarrel (780 Ma)**; A: Saddlerochit (≈800 Ma)	
	MESOPROTEROZOIC	1600	M3	1100	ER: Udzha (≈1100 Ma)	Gardar rift (1300–1120 Ma)
				1160	G: Garoep (Tugtotuq) (1160 Ma)	
				1270	C: **Mackenzie (1270 Ma)**; G: BD0/middle Gardar (1280 Ma); NE: Central Scandinavian Dolerite Complex (1270–1250 Ma)	
				1385	G: Midsommerso-Zig Zag Dal (1385 Ma); ER: Chieress (1385 Ma), **Mashak (1385 Ma)**	
				1500	NE: Brevik-Rjukan (1500 Ma), Tuna-Trond-Gota-Lake Ladoga (1460 Ma); ER: **Kuonamka (1505 Ma)**, Olenek (1500–1495 Ma)	
				1600	C: Western Channel (1590 Ma); G: Melville Bugt (1640 Ma); NE: Breven-Hallefors (1600 Ma), Ameg (1590–1500 Ma), Hame (1670–1640 Ma)	
	PALEOPROTEROZOIC	2500	M2	1750	C: Cleaver (1740 Ma), Wellington Inlier and McRae Lake (1750 Ma); ER:Timp Ton (1750 Ma)	Udokan rift (2030–1960 Ma)
				1900	C: **Ghost-Mara-Morel (1880–1870 Ma)**, Snowbird (1900 Ma), Piling Group magmatism (1930–1880 Ma); NE: Gremyakha-Vyrmes (1975–1885 Ma), **Pechenga-Onega (1970 Ma)**	
				2025 2230	C: MacKay and Malley (2230–2210 Ma), **Slave (2180–2170 Ma), Povungnituk (ca. 2000–1970 Ma), Ungava (2215 Ma), Indin(2100 Ma), Lac de Gras - Booth River (2025 Ma)**; G: Isukasia BN1-MD1 (2214 Ma), **Kangamiut-MD3 (2050-2030 Ma);** NE: Karjalite (2215 Ma), **Karelian (2100 Ma)**	
				2395 2500	G: Kilaarsarfik (2499 Ma), Graede Fjord (2370 Ma) NE: Baltica (Sumian) mafic province (2500 Ma, 2480–2440 Ma)	
ARCHEAN		3200	M1	2750 3050	NE: Kola-Karelian Archean Igneous Province (Gabbro-norite, troctolite, peridotite, pyroxenite, anorthosite; alkaline gabbro and nepheline syenite; alkaline and subalkaline granite and syenite)	**Protorift structures** a b c Khautavaara (2920–2860 Ma), Kostomuksha (2845–2808 Ma) greenstone belts (a), narrow belt (b), komatiite occurrence (c)

Realm code: A – Alaska; C – Canada; ER – East Russia; G – Greenland; NE – North Europe

★ Selected plume centers located by giant radiating dyke swarms coloured in accordance with rock age (M1–9)

Fig. 8. Legend for large igneous provinces (LIPs), sill-dyke swarms and rift systems

(continued in fig. 9)



Notes: 1 – color of polygon shows the composition of intraplate magmatic rock; color pattern shows the age of these rocks from color chart M1–9. 2 – color of symbol reflects the age of rocks (color chart M1–9). 3 – color pattern (according the age of rocks by color from M1–9) on light grey background (if they are post-orogenic) or on color sedimentary covers (if the rocks are pre-orogenic)

Fig. 9. Legend for large igneous provinces, sill-dyke swarms and rift systems

at scales of 1:10M and 5M has been supported and endorsed.

How to read the tectonic map. On the tectonic map, all areas except those underlain by definitive oceanic crust are subdivided into polygons that designate deformed areas and relatively undeformed sedimentary cover. Deformed areas are colored to reflect the age of their initial tectonic overprint, as shown in the column named “Tectonic events”. The age of the first subsequent tectonic overprint is given by diagonal lines from upper right to lower left, colored as above; the age of the second subsequent tectonic overprint is given by diagonal lines from upper left to lower right, colored as above. Polygons are also overprinted by patterns that reflect the tectonic setting of their rock assemblages as shown in the legend. Areas of relatively undeformed sedimentary cover are colored by the age of onset of sedimentation and thickness of basin strata, as shown in the column labelled “Sedimentary Cover”. Areas underlain by unambiguous oceanic crust are colored by their crustal age, as shown in the columns under “Oceanic Realms”, and the thickness and age of sedimentary cover is ignored. More details are given in the Legend below.

Contents of the tectonic map legend. The symbols are grouped according to their relation to continental or oceanic domains.

Continental Realms embrace cratons and mobile belts of various ages, large igneous provinces and rift systems areas with thinned and extended earlier formed continental crust, as well as epicontinental sedimentary basins, platforms cover and passive Arctic margins of the Eurasian and North American continents. Faults, folds, salt tectonics and other structural elements, typical for the continental crust, are shown separately.

This part of the legend comprises two groups of rock associations, formed in different tectonic regimes (compression and extension) in corresponding tectonic settings.

Cratons and mobile belts. The first group include complexes indicating the crust compression, shortening and thickening (“Accretion-collision-related rock assemblages”) and was formed by the processes of the continental crust growth. It comprises volcanic, plutonic, sedimentary and metamorphic complexes of various ages (fig. 7). These rock assemblages are shown on the map by a colour corresponding to a time of orogenesis and/or cratonization. The age of orogen is determined by a time of subduction-collision processes, structural deformations (folding, faulting etc.), metamorphism, syncollision granitoid intrusive magmatism and molasse accumulation.

Volcanic formations encompass rock associations of ensimatic island arcs, Andean-type continental margins, and back-arc basins. Related sedimentary rocks are accretion complexes mélange, olistostromes and molasses. This group also includes metamorphic complexes of various facies (greenschist, amphibolite, granulite), Archean TTG complexes and Paleoproterozoic granulite belts (marked with red patterns) along with high-pressure blueschist and eclogite complexes (marked by blue symbols). M- and I-type accretion granitoids, S- and I-type collision granites and zonal mafic intrusions of Ural-Alaska type are also included in to this group.

All rock associations of this group (except Paleoproterozoic and younger granitoids as well as ophiolites and mafic rocks) are shown according to the age colour chart (fig. 7). The Paleoproterozoic and younger granitoids are shown in two shades of red. Crimson colour shows M- and I-type subduction granites, and bright red is used for S- and I-type collisional granites. The age of granitoids, apart from the oldest Archaean granitoids, which are subdivided to I- and S-types, is shown by color patterns in accordance with the tectonic time scale.

Paleooceanic complexes (ophiolite allochthons) are depicted in violet and subdivided into ophiolite mélange and blocks with preserved ophiolite

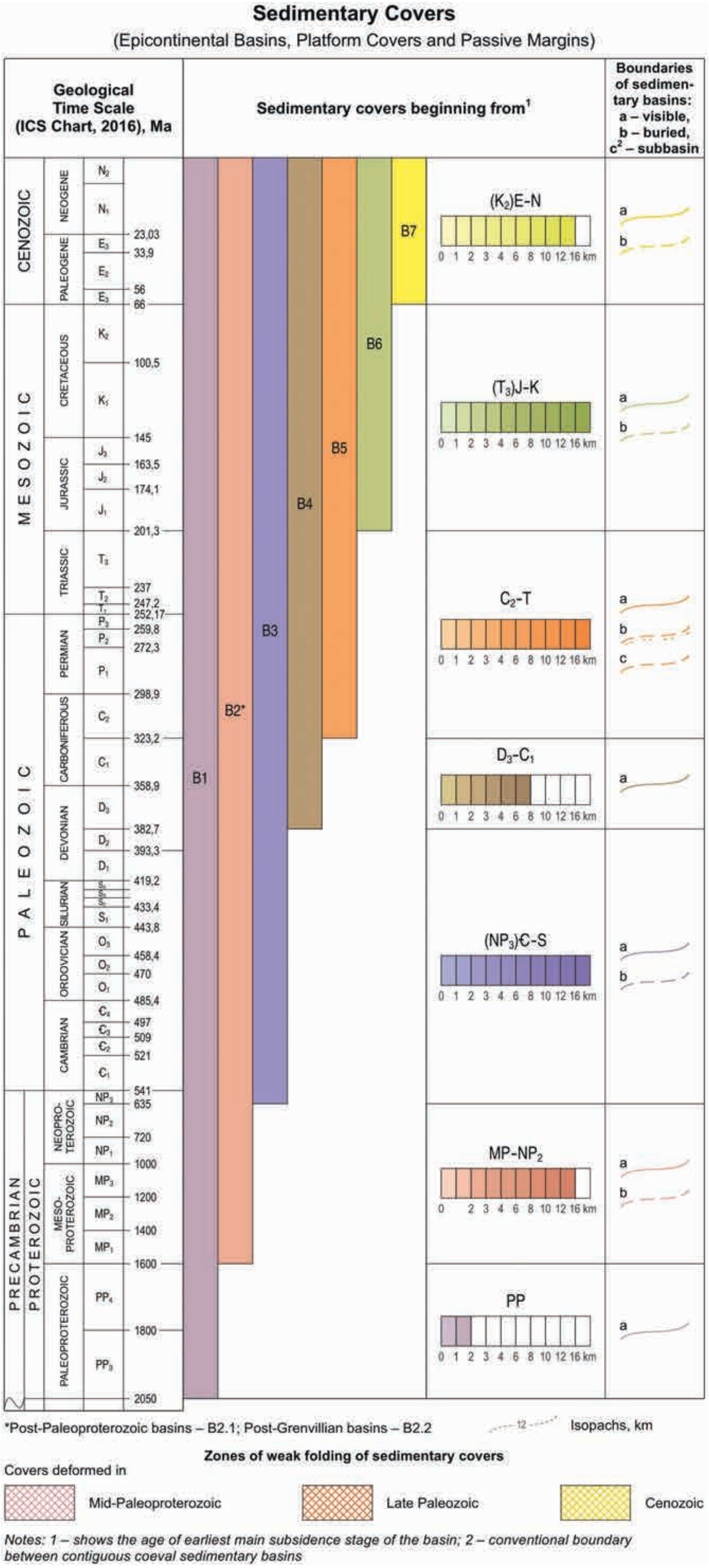


Fig. 10. Legend for epicontinental basins, platform covers and passive margins

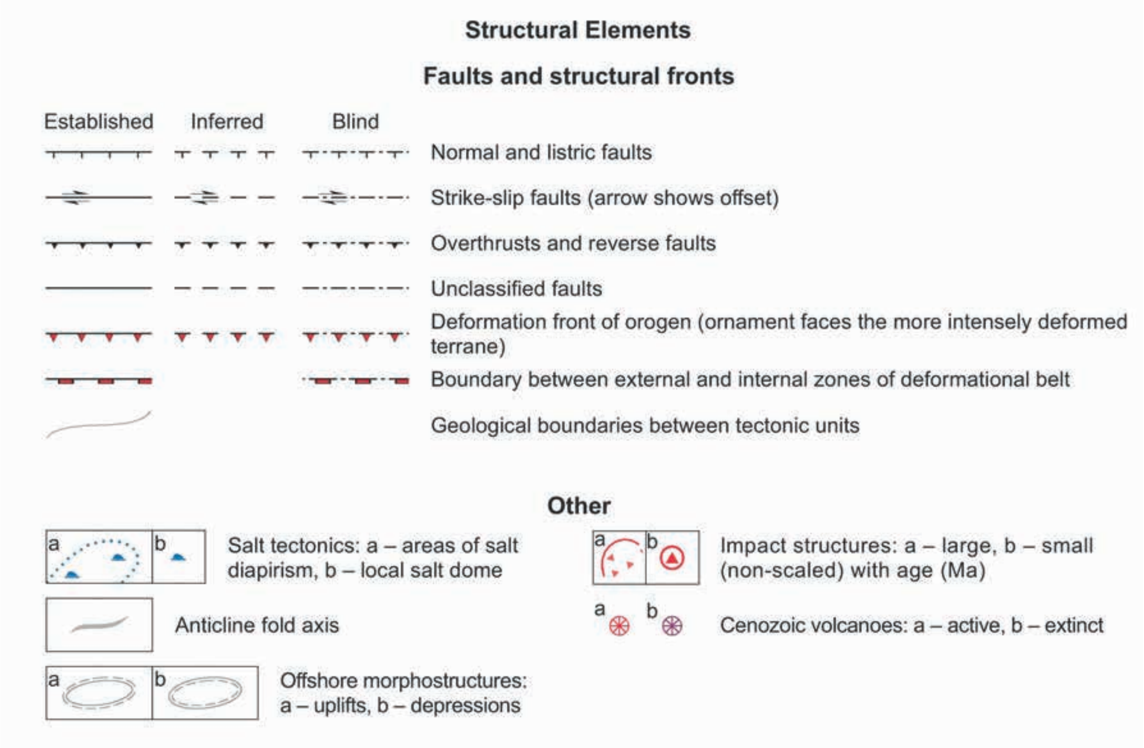


Fig. 11. Legend for structural elements

sequence indicating a paleooceanic crust. Extended narrow tectonic zones with ophiolite mélange can be shown by the symbol of ophiolite sutures with age indication.

The Legend permits demonstration of older crust by younger tectonic processes (faulting, folding, granitoids, metamorphism etc.). Superimposed orogenic events are depicted as colour strips superimposed upon a main background colour, allowing display of a general sequence of formation and transformation of tectonic structures.

General succession of geodynamic events can be divided into four turn points (most prominent events) from the assembling to break-up of supercontinents: Kenorland (2500 ± 200 Ma), Nuna (1800 ± ± 200 Ma), Rodinia (1000 ± 150 Ma) and Pangea (250 ± 10 Ma).

Large igneous provinces, sill-dyke swarms and rift systems. The second group includes magmatic complexes-indicators, typical for crustal extension and thinning regime (fig. 8, 9). They are correspond with intraplate postorogenic and anorogenic tectonic settings.

A separate time scale is used for this group of magmatic complexes with nine stages of intraplate magmatism and rifting shown by different colours from the Archean-M1 to the Cenozoic-M9 (fig. 8). Each stage is exemplified by large igneous provinces, dike complexes and rifts in Greenland, Canada, Alaska, Eastern Russia and Northern Europe. The most prominent magmatic complexes are noted in bold. Most of the examples of large igneous provinces and dike belts are depicted in accordance with recommendations of the International Commission on Large Igneous Provinces (Ernst R.E. 2014).

Greenstone belts are assumed to be Archean protorift structures with komatiite occurrences marked by dot sign. Younger rift areas are outlined by black contour with dots, coloured in accordance with the colour chart (M2 to M9). Colour lines indicate boundaries of volcanic areals and LIP areas. Colour patterns display flood basalts and intraplate gabbro-dolerite occurrences in accordance with their ages (M2 to M9). Plutons are shown in different colour according to their compositions: ultramafic-mafic layered bodies are painted blue, gabbro and dolerite – green, rapakivi – pink, and alkaline massifs are orange. Small (nonscale) intrusive bodies are depicted by dot symbols of a relevant age colour. The pattern colour taken from the chart (M1 to M9) indicates an age of magmatic body. Coloured dot symbols on the map indicate kimberlite pipes, lamproite, carbonatite and occurrence of plume centers. Colours of all tectonic elements of this group correspond to the age of magmatism and/or volcanogenic-sedimentary filling of rifts. Names of the most prominent intrusions and their age (in Ma) are given in the database.

Undeformed and weakly deformed sediments more than 1 km as thick are considered in the le-

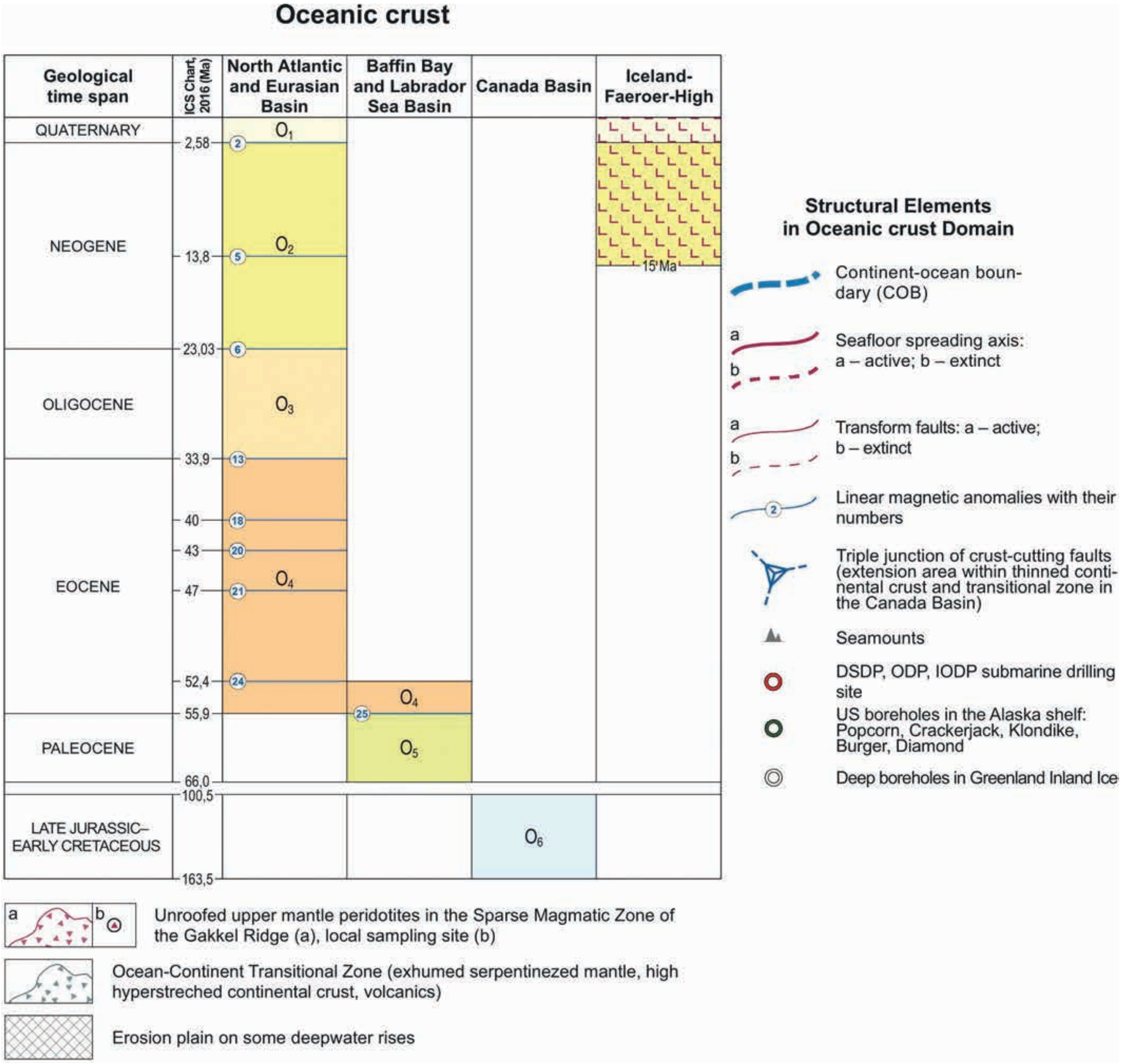


Fig. 12. Legend for the Oceanic Realms

gend as *Sedimentary covers* (fig. 10). Depending on a starting time of a basin's main stage of sagging and formation of its sedimentary cover, they are subdivided into seven generations (B1 to B7), from the late Paleoproterozoic to the Cenozoic, being painted in an appropriate colour. Isopach lines show the total thickness of sediments. A change in a cover thickness is displayed by colour intensity: the thicker sediments – the darker colour. In superposed basins of different age, a total thickness of sediments is displayed by a single isopach system. Boundary of basin buried under sediments off younger basin is shown by double-dash-dot line with dots located at an inner side. Dash lines indicate boundaries of separate sub-basins. Coloured grid indicates a "cold" structural reworking (weak folding) of sedimentary covers. It is best pronounced in the Middle-Paleoproterozoic, Late-Paleoizoic and Cenozoic basins.

The oldest Paleoproterozoic basins (B1) typically have a sedimentary cover that began to fill in the second half of the Paleoproterozoic (2050–1600 Ma). Their relics occur within the Canadian Shield. Formation of the youngest basins (B7) began as the Paleogene-Neogene grabens, usually under rifting regimes. They are confined to the shelf margins of the Canadian Arctic Archipelago and located in the Laptev, East Siberian and Chukchi seas.

In the structure of the Circum-Arctic sedimentary cover forms a peripheral belt of deep marginal-shelf depressions (East Barents, North Kara, North Chukchi, Beaufort Sea, McKenzie delta, Lincoln Sea, etc.). The sedimentary cover thickness in these depressions reaches 14–18 km with up to a half of total thickness being composed of the Paleozoic – Early Mesozoic sediments, overlain by the Late Mesozoic – Cenozoic deposits. These depressions are a result of successive two or more tectonic events of a continental rifting and sedimentation, e.g., the Permian-Triassic and the Late Mesozoic in the North Chukchi Basin and the Hanna Trough.

Structural elements in the continental crust realms are represented by disjunctive dislocations of various kinematics: normal faults and listric faults, strike-slip faults, reverse faults, and thrusts (fig. 11). Other linear elements show deformation fronts, boundaries between internal and external zones in wide deformation belts and geological boundaries, with exposed, assumed, and buried linear structures depicted by different line types, positive and negative offshore (shelf) morphostructures.

The map demonstrates areas of intensive linear folding, salt tectonics areas and individual salt domes, impact craters, old and active volcanoes.

Oceanic Realms. Domains with oceanic crust in accordance with the recommendations of the Commission for the Geological Map of the World (CGMW) and the practice of compiling of the structural maps of Atlantic and Indian oceans are shown by colour (fig. 12). The legend contains special colours for the standard thin (5–7 km) mafic crust formed by the Early Cretaceous spreading in the central part of the Canadian Basin, in the Paleocene-Eocene in the Baffin Bay and the Labrador Sea and in the Eocene – Holocene in the North Atlantic and the Eurasian Basin (O1 to O6). Some data for the crust's age of the North Atlantic has been provided from GEUS publication (Tectonostratigraphic Atlas of the North-East Atlantic Region / J.Hopper [et al.]. Copenhagen, 2014).

The Iceland-Faroe Ridge and the Iceland Plateau are depicted by a special pattern using for the oceanic plateau an aseismic ridges with these areas over thick oceanic crust and intraplate mafic volcanism. Within the Iceland Plateau, the spreading volcanism of the Mid-Atlantic Ridge interacts with intraplate magmatism of ocean plateau type. There the Mid-Ocean Ridge virgates to the Western and the Eastern branches, displaced by transform faults in the northern and southern edges of the plateau. The oceanic crust of the Iceland-Faroe Ridge is split by ages to Pleistocene–Holocene (< 2.6 Ma) and Middle Miocene – Pliocene (15–2.6 Ma).

The legend allows display on the map of the key magnetic chrons 2, 5, 6, 13, 18, 20, 21, 24 and 25. They mark heterochronous parts of the oceanic crust, show the most bright and extensional magnetic linear anomalies.

In addition, the legend contains polygonal symbols the Continent-Ocean Transition Zone with co-occurrence of an exhumed serpentinizated mantle, peridotites fragments of an extremely stretched continental crust and oceanic volcanic rocks (Iberian-type margin): it is assumed in the central Canada Basin, as well as in the Sparsely Magmatic Zone with numerous mantle peridotite samples dredged from the crest of the ultra-slow spreading Gakkel Ridge (fig. 12).

Linear symbols mark the continent-ocean boundary (COB), active and extinct spreading axes, active, and extinct transform faults and linear magnetic anomalies with their numbers. Dot symbols show seamount, black cross hatching displays the plain surfaces of the Chukchi Plateau and central Lomonosov Ridge, which apparently have been formed in sub-aerial environments during low stand of sea and active erosion of the ridges by seawater and glaciers.

A triple junction symbol denotes triple-junction fault area revealed in the Moho map in the Canada Basin and Nautilus Basin. It indicates a considerable spatial extension of the continental crust, accompanied by crest-like mantle uplift and controls the location of the Cretaceous volcanic field of HALIP.

The sedimentary cover upon the oceanic crust (Lena and Mackenzie rivers underwater fans) are shown only by isopachs.

The Legend also provides display of well sites of the deep-oceanic drilling, as well as five key parametric wells in the American sector of the Chukchi Sea, and few boreholes, that show the basement rocks under the Inner Ice of Greenland.

REFERENCES

Petrov O.V., Shokalsky S.P., Kashubin S.N., Morozov A.F., Sobolev N.N., Pospelov I.I., Box S., Brekke H., Ernst R., Faleide Y., Gaedicke C., Gaina C., Gernigon L., Glumov I.F., Grantz A., Grikurov G.E., Guarnieri P., Harrison J.C., Kaminsky V.D., Kazmin Yu.B., Labrousse L., Lemonnier N., Leonov Yu.G., Malyshev N.A., Milshtein E.D., Moore T., Orndorff R., Petrov E.O., Piepjohn K., Poselov V.A., Pubellier M., Puchkov V.N., Smelror M., Sokolov S.D., Stephens M., St-Onge M.R., Tolmacheva T.Yu., Verba M.L., Vernikovsky V.A. 2019: Tectonic Map of the Arctic, scale 1:10,000,000.

GRAVITY AND MAGNETIC DOMAINS OF THE ARCTIC

S.N. Kashubin, O.V. Petrov, E.D. Milshtein, T.P. Litvinova, E.A. Androsov

Scheme of crustal blocks is based on a joint analysis of magnetic and gravity anomalies. Summary maps compiled by the Geological Survey of Norway under the CAMP-GM project were used. The selected blocks outline the different-rank tectonic structures of the crystalline crust.

Keywords: *Circumpolar Arctic, Bouger anomalies, magnetic anomalies, tectonic zoning*.

Anomalous potential field zoning makes it possible to delineate blocks with different types of crust and reveal similarities in the nature of potential field and tectonic structures (fig. 13).

Maps of the anomalous magnetic field (AMF) and the anomalous gravity field (AGF) of the Arctic at 1:5M scale are basic elements in the zoning. The Russian part of the maps has been supplemented with data obtained during modern medium-scale surveys. The maps are supplied with matrices of the magnetic and gravity fields with the size of the cell of 5×5 km and 10×10 km respectively [Litvinova et al. 2012a,b].

Transformations of potential fields and a set of specialized maps (geological, topography and bathymetry, sedimentary cover and crustal thickness) were used as auxiliary materials for the delineation of the units shown on the scheme [Petrov, Smelror 2015a,b; 2016]. The delineation was carried out in an iterative mode directly on the computer screen using GIS ESRI ArcMap v.9.3.

The analysis is based on principles of tectonic zoning proposed by Yu.A. Kosygin [Kosygin 1975], which fully correspond to the concept of comprehensive zoning of potential fields. In compliance with principles, the zoning was considered as a set of methods of space division (including the 3D version) according to the selected systematics of the bodies (ranks), following the rules of complete space division with no remainder, no border crossing, and the identity of characteristics of distinguished elements [Voronin 2007].

When delineating the areas, the following ranking system was used (in descending order): anomalous province, anomalous district, and anomalous area. Morphostructural features (including zonality) of potential fields were adopted as a main criterion in zoning. The distinguishing of taxa of the first (anomalous province) and second (anomalous district) orders was to a great extent based on the assessment of crustal alterations and mean values of the crustal thickness [Kashubin et al. 2011; 2014].

Morphostructure of the fields, intensity and the sign of anomalies are taken as a basis for the characterization of these structures.

The research resulted in a comprehensive map of potential fields zoning of the Circumpolar Arctic (fig. 13, table 1), which was used as the basis for compilation of a base map of crustal types and tectonic zoning sketch-map.

The compiled map of complex zoning makes it possible to demonstrate rather specific similarities in the character of the potential field and tectonic structures in the Arctic basin and its continental margins. Fig. 13 shows an example of distinguishing on the maps of potential fields large magmatic provinces corresponding to the region of the Mendeleev-Alpha rises within the Arctic Basin and the Tunguska Block in the Siberian platform. It is possible to see similar blocks in potential fields described by almost similar encodings “AGF” and “AMF” (55–55 for the Mendeleev-Alpha rises and 56–55 for the Tunguska block).

Therefore, it uses the latest experience in the compilation of new digital geological and tectonic maps at 1:2.5–1:5M scale for Asia, Europe, North and South America, Atlantic and Indian oceans.

REFERENCES

Kashubin, S.N., Petrov, O.V., Androsov, E.A., Morozov, A.F., Kaminsky, V.D., Poselov, V.A. 2011: Map of crustal thickness in the Circumpolar Arctic. *Region. geology and metallogeny*. 46. 5–13.

Kashubin, S.N., Petrov, O.V., Androsov, E.A., Morozov, A.F., Kaminsky, V.D., Poselov, V.A. 2014: Crustal thickness in the circum Arctic. *ICAM VI: Proceedings of the International Conference*. 1–17.

Kosygin, Yu.A. 1975: Fundamentals of tectonic zoning: *Principles of Tectonic Zoning*. Vladivostok. 8–24.

Litvinova, T.M., Kashubin, S.N., Petrov, O.V. 2012a: Zoning of the Circumpolar Region after the potential fields character. *Geophysical Research Abstracts*. EGU2012–4436, EGU General Assembly. 14.

Litvinova, T.M., Petrov, O.V., Kashubin, S.N., Erinchek, Y.M., Milshteyn, E.D., Shokalsky, S.P., Glebovsky, V.Yu., Chernykh, A.A. 2012b: Arctic tectonic provinces from gravity and magnetic data. *34th International*

To cite: Gravity and Magnetic domains of the Arctic / S.N. Kashubin [et al.] // Scientific contributions to the Tectonic Map of the Arctic. Paris, 2019. P. 18–21.

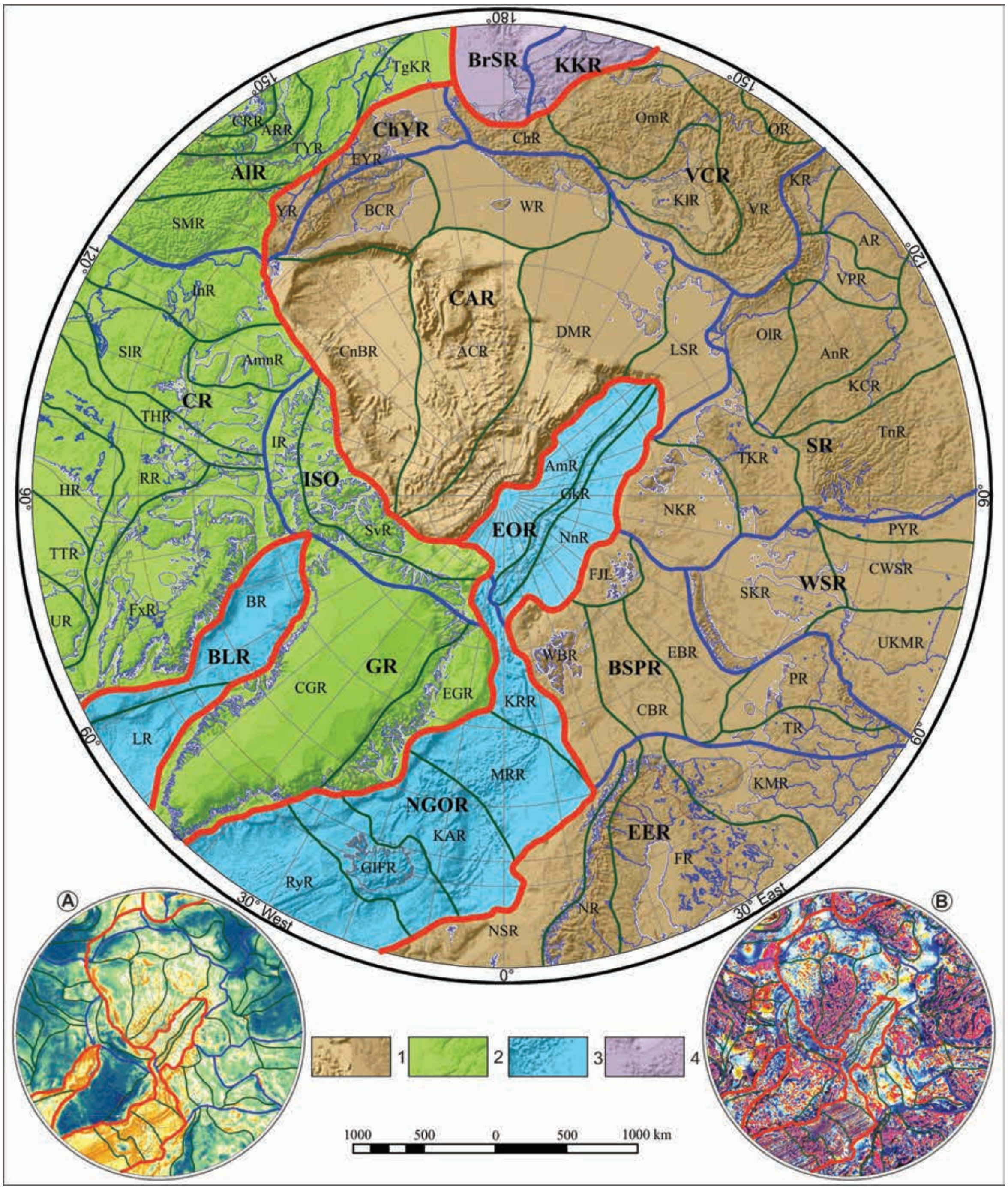


Fig. 13. Circumpolar Arctic zoning map based on the character of potential fields

Color indicates provinces: *1* – Eurasian (lighter tone corresponds to areas submerged to bathyal depths), *2* – North American, *3* – Mid-oceanic ridges, *4* – Pacific. Blue lines indicate boundaries of regions (bold); green lines show borders of areas. Digital encoding of potential field types and corresponding tectonic units are shown in table 2. At the bottom: gravity anomalies map (*A*) and anomalous magnetic field map (*B*)

Geological Congress (abstracts), 5–10 August 2012. Brisbane, Australia.1916.

Petrov, O.V., Smelror, M. 2015a: Cooperation of geological surveys of Arctic states to study the Arctic. *Arctic Journal.* 1 (13). 22–28.

Petrov, O.V., Smelror, M. 2015b: Uniting the Arctic frontiers – International cooperation on Circum-Arctic geological and geophysical maps. *Polar Record.* 51 (5). 530–535. http://dx.doi.org/10.1017/S0032247414000667.

Petrov, O.V., Smelror, M., Morozov, A.F., Shokalsky, S.P., Kashubin, S.N., Artemieva I.M., Sobolev N.N., Petrov E.O., Ernst R.E., Sergeev S.A. 2016: Crustal structure and tectonic model of the Arctic region. *Earth-Science Reviews*. 154. 29–71.

Voronin, A.Yu. 2007: Zoning of areas on the basis of artificial intelligence and image identification in nature management objectives. *Abstract of thesis for the degree of Doctor of Technical Sciences*. Moscow. 44.

Table 1

Matching of letter symbols (indices) on the zoning map (fig. 28) to the units identified

Index on the map	Potential fields' zoning (units names)	Tectonic zoning
	EURASIAN PROVINCE	
EER	**East Europe Realm**	**East European Platform**
NSR	Norwegian Sea Region	Norwegian Shelf (Voring Plateau etc.)
NR	Norwegian Region	Scandinavian Caledonides
FR	Fennoscandian Region	Fennoscandian Shield
KMR	Kola-Mezen Region	Kola – White Sea and Mezen' blocks
BSPR	**Barents Sea – Pechora Realm**	**Timan-Pechora and Barents Sea Shelf**
WBR	West Barents Region	Svalbard and structural elements of the West Barents Sea Shelf
CBR	Central Barents Region	Central Barents Rises
EBR	East Barents Region	East Barents Trough
FJL	Franz Josef Land Region	Franz Josef Land Uplift
TR	Timan Region	Timan-Varanger dislocation zone
PR	Pechora Region	Pechora Sea Block
WSR	**West Siberia Realm**	**East Uralian Fold Belt, West Siberian Basin**
SKR	South Kara Region	South Kara Block
UKMR	Uralian Khanty-Mansi Region	East Ural Fold Belt, Uvat-Khanty-Mansi Block
CWSR	Central-West Siberian Region	Central-West Siberian Fold System
PYR	Pre-Yenisei Region	Pre-Yenisei Fold-Thrust Zone
SR	**Siberian Realm**	**Siberian Platform**
NKR	North Kara Region	North Kara Block
TKR	Taimyr-Khatanga Region	Taimyr Fold Belt, Khatanga Trough
TnR	Tunguska Region	Tunguska Block
KCR	Kotui-Chon Region	Magan Block
AnR	Anabar Region	Anabar Shield
OlR	Olenek Region	Olenek Block
AR	Aldan Region	Aldan Shield
KR	Khandyga Region	Pre-Verkhoyansk Foredeep
VPR	Vilyuy-Patom Region	Patom-Vilyuy Aulacogen
VCR	**Verkhoyansk-Chukotka Realm**	**Verkhoyansk-Chukotka Fold-Thrust area**
VR	Verkhoynask Region	Verkhoyansk-Chukotka Fold-Thrust System
OR	Okhotsk Region	Okhotsk Block
KlR	Kolyma Region	Kolyma Loop
OmR	Omolon Region	Omolon Block
ChR	Chukchi Region	Chukchi Fold-Thrust System
ChYR	**Chukotka-Yukon Realm**	**Eastern Chukchi-Seward Fold-Thrust Belt**
EYR	East Yukon Region	Seward Peninsula Block, Yukon-Koyukuk Basin
YR	Yukon Region	Ruby and Central Alaskan Terranes
CAR	**Central Arctic Realm**	**Amerasian Basin**
LSR	Laptev Sea Region	Laptev Sea Shelf
DMR	De Long-Makarov Region	De Long High, Lomonosov Ridge, Podvodnikov Basin, Makarov Basin
ACR	Alpha-Chukchi Region	Chukchi Plateau, Mendeleev-Alpha Rise
CnBR	Canada Basin Region	Canada Basin
BCR	Brooks-Colville Region	Brooks Fold-Thrust Belt, Colville Basin, Alaska North Slope
WR	Wrangel Region	Wrangel-Herald Fold-Thrust Arch

Table 1 continued

Index on the map	Potential fields' zoning (units names)	Tectonic zoning
	NORTH AMERICA PROVINCE	
ISR	**Innuitian-Sverdrup Realm**	**Innuitian Orogen, Sverdrup Basin**
SvR	Sverdrup Region	Sverdrup Basin
IR	Innuitian Region	Innuitian Orogen
AlR	**Alaska Realm**	**Alaska Superterrane**
TgKR	Togiak-Koyukuk Region	Togiak-Koyukuk Terrane
TYR	Tanana-Yukon Region	Yukon Terrane
ARR	Alaska Range Region	Alaska Range
CRR	Coast Range Region	Coast Range
SMR	Selwyn-Mackenzie Region	Selwyn-Mackenzie Fold Belt
CR	**Canada Realm**	**North America Craton**
InR	Interior Region	Interior Platform
SlR	Slave Region	Slave Block
AmnR	Amundsen Region	Amundsen Block
THR	Trans-Hudson Region	Trans-Hudson Fold Belt
RR	Rae Region	Rae Block
HR	Hearne Region	Hearne Block
UR	Ungava Region	Ungava Block
TTR	Teltson-Thelon Region	Teltson-Thelon Fold Belt
FxR	Fox Region	Fox Block
GR	**Greenland Realm**	**Greenland Shield, East Greenland Caledonides**
CGR	Central Greenland Region	Greenland Shield
EGR	East Greenland Region	East Greenland Fold-Thrust Belt
	PROVINCE OF MID-OCEANIC RIDGES	
BLR	**Baffin-Labrador Realm**	**Baffin-Labrador Oceanic Basin**
LR	Labrador Region	Labrador Sea Basin
BR	Baffin Region	Baffin Bay Basin
NGOR	Norway-Greenland Oceanic Realm	Norway-Greenland Oceanic Basin
RyR	Reykjanes Region	Icelandic Basin, Reykjanes Ridge, Irminger Basin
GIFR	Greenland-Iceland-Faroe Region	Greenland-Iceland Ridge, Iceland-Faroe Ridge, Iceland Plateau
KAR	Kolbeinsey-Aegir Region	Greenland Basin, Kolbeinsey Ridge, Norwegian Basin, Aegir Ridge
MRR	Mohns Ridge Region	Mohns Ridge
KRR	Knipovich Ridge Region	Knipovich Ridge
EOR	**Eurasian Oceanic Realm**	**Eurasian Oceanic Basin**
NnR	Nansen Region	Nansen Basin
GkR	Gakkel Region	Gakkel Ridge
AmR	Amundsen Region	Amundsen Basin
	PACIFIC OCEAN PROVINCE	
BrSR	**Bering Sea Realm**	**Bering Sea Basin**
KKR	**Koryak-Kamchatka Realm**	**Koryak-Kamchatka Fold Area**

CRUSTAL THICKNESS MAP OF THE ARCTIC

S.N. Kashubin, O.V. Petrov, E.D. Milshtein, E.A. Androsov, A.F. Morozov, V.D. Kaminsky, V.A. Poselov

Crustal Thickness Map is based on results of deep seismic studies and gravity field anomalies in the Circumpolar Arctic. Over 300 profiles of total length of about 140,000 km and equations of correlation, which link the depth of the Moho discontinuity occurrence with Bouguer anomalies and the topography, were used for the map compilation. The digital layout of the Crustal Thickness Map of the Circumpolar Arctic compiled from these data is represented by the grid of 10 × 10 km.

Keywords: *Moho discontinuity, Earth's crust thickness, deep seismic sounding, Bouguer anomalies.*

The Earth's crust is commonly seen as an external hard sialic shell located above the Moho. Information about crustal thickness plays an important role in studying the deep structure of the Earth. In seismic and global geophysical constructions, knowledge of crustal thickness is necessary for the calculation of appropriate corrections, and in geological interpreting, it is important to know crustal thickness both for structural and geodynamic constructions. While studying areas of transition from continents to oceans, changes in crustal thickness are often a determining criterion for the identification of continental and oceanic crustal types.

Determination of crustal thickness is primarily carried out by seismic methods. The generally accepted method is the determination by means of deep seismic sounding (DSS) when the sole of the crust is identified with the Moho (M), determined from data of refracted and overcritically reflected waves [Mooney 2007]. Sometimes the base of crust is determined in seismic sections obtained by reflected waves (RW-CDP) [Suleimanov et al. 2007] and remote earthquake converted wave (ECW) methods [Zolotov et al. 1998]. In the absence of seismic data, the crustal thickness is estimated using the correlation relationship between the M-discontinuity depth, topography, and Bouguer anomalies [Demenitskaya 1967; Kunin et al. 1987].

The crustal thickness map shown in fig. 14 was been compiled as part of the international project for compiling the Atlas of geological maps of the Circumpolar Arctic under the auspices of the Commission for the Geological Map of the World (Petrov et al. 2015). For this purpose, all available deep seismic sections north of 60 °N (see list of publications of major seismic sections shown at the end of this section) were used. This array of information includes more than 300 seismic sections with total length of over 140,000 km. Approximately 75% of the sections are results of studies performed by means of DSS, and the rest is represented by deep seismic sections using RW-CDP and ECW methods.

The Map of crustal thickness was built in several steps [Kashubin et al. 2011; 2014]. First, the depth values to the M discontinuity obtained from seismic cross-sections with a 25-km interval of were plotted on the physical and geological maps. Totally, 5500 Zm (Moho depth) values within the Circumpolar Arctic were plotted on the map based on seismic and seismological data. Digital layouts of the anomalous gravity field map [Gaina et al. 2009] and maps of surface relief and depths of the ocean floor (IBCAO ver 2.23) were used to show the depth values to the M discontinuity in the space between the profiles and vast areas where seismic data were lacking. Zm values were calculated separately for the continental and marine parts of the area following the network of 10 × 10 km based on Bouguer anomaly values and relief data averaged within a radius of 100 km using correlation equations [Kashubin et al. 2011]. The resulting digital arrays were integrated into one database along the coastline border with subsequent correlation of isolines in the area of their intersections. On the basis of adjusted data, the calculation of the new digital array was made, which was integrated with pre-existing digital maps of M discontinuity depths [Ritzmann et al. 2006; Grad et al. 2007; Erinchek et al. 2007; Artemieva & Thybo 2013]. The final map is presented in the form of a Zm digital model with the cell size of 10 × 10 km for the entire study area. In the course of recalculation of Zm values to uniform values, the interpolation error was estimated by comparing interpolated and initial values in 3600 spots, in which depth values were plotted using seismic data. Mean-square deviation between the interpolated and initial values was ±1.7 km, and the area between the isolines in the resulting map was taken as 5 km. After subtracting the depths of the ocean and the introduction of corrections for the height of the observation on

---

To cite: Crustal thickness Map of the Arctic / S.N. Kashubin [et al.] // Scientific contributions to the Tectonic Map of the Arctic. Paris, 2019. P. 22–25.

land, the map of depth values to the M discontinuity was transformed into the Circumpolar Arctic crustal thickness Map (fig. 14).

The compiled crustal thickness Map of the Circumpolar Arctic differs from the global model CRUST2.0 available for this area [Laske et al. 2000] greatly because, first, significantly more new seismic data were used for its compilation, and, second, global data averaging was not used in this work. As can be seen from the figure, the crustal thickness in the Circumpolar Arctic changes quite significantly: from 5–10 km within the Norwegian-Greenland and the Eurasian ocean basins to 55–60 km in Scandinavia and in the Urals. Areas with oceanic and continental crust are identified on the map of crustal thickness rather confidently and the

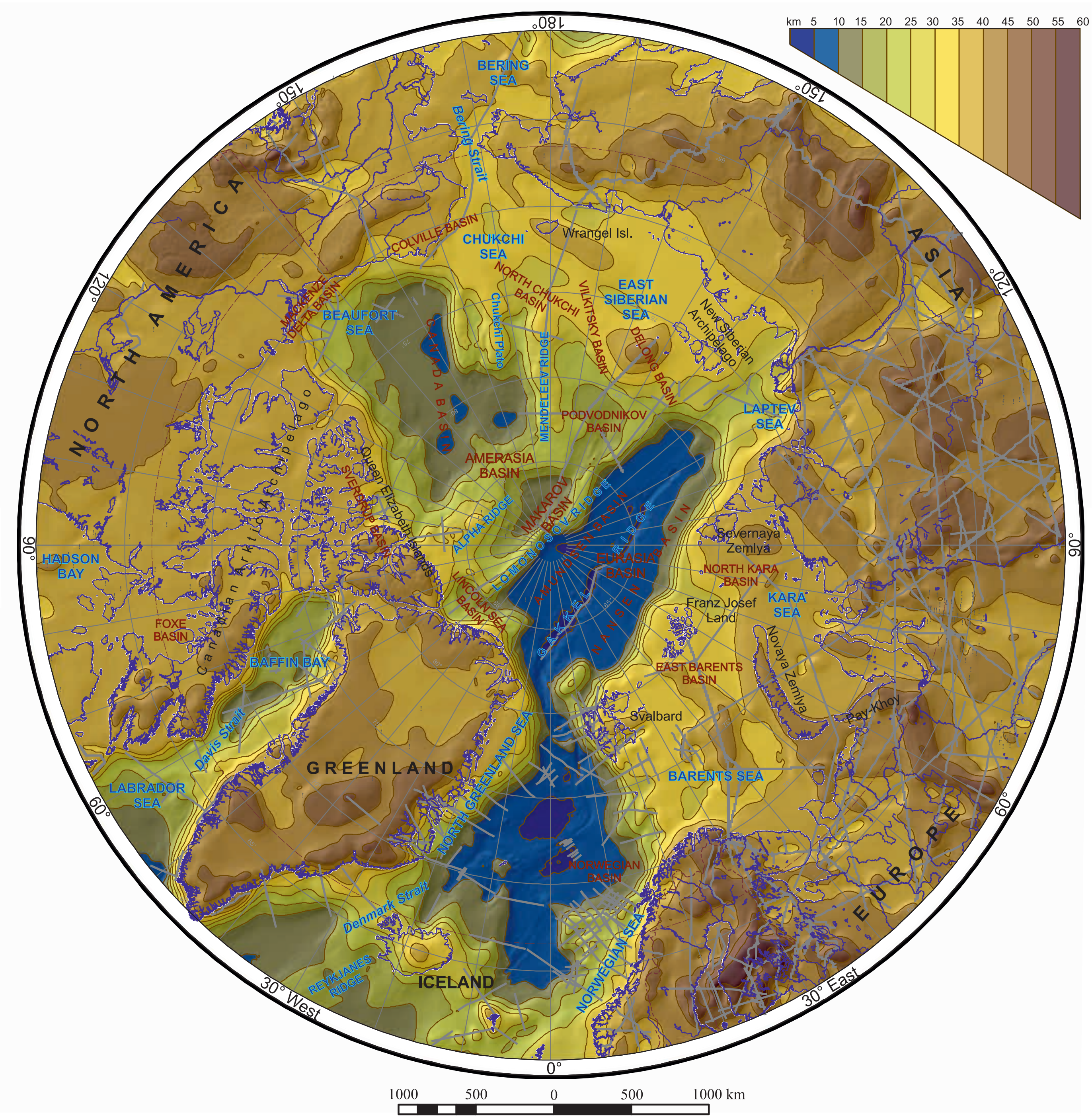


Fig. 14. Circumpolar Arctic crust thickness Map [Kashubin et al. 2011; 2014].
Gray lines indicate main seismic lines and grey dots show seismic stations which materials were used for map compilation

size and configuration of individual lateral variations of the thickness are quite comparable to the size of the regional geological structures. So, the new map is not only suitable for the introduction of corrections during seismological and planetary geophysical constructions, but it can also be used for tectonic constructions in the Arctic basin.

The map of Arctic basin crustal thickness generally shows the structure of the area of the Central Arctic uplifts including the Lomonosov Ridge, the system of Mendeleev-Alpha rises, and separating them Podvodnikov-Makarova basins, Chukchi Borderland, and the Northwind Ridge. Results of the most recent Russian and foreign deep seismic surveys (“Transarctic-1989–92”, “Arctic-2000”, “Arctic-2005”, “Arctic-2007”, “Lorita-2006”, “Arta-2008”, “Arctic-2012”) [Jackson et al. 2010; Funck et al. 2011; Lebedeva-Ivanova et al. 2006; 2011; Poselov et al. 2011] were used for the map of crustal thickness of the Central Arctic uplifts and areas of their intersection with structures of the Eurasian and North American continental margins.

Seismic data indicate that the area of the Central Arctic uplifts has the lowest degree of destructive transformations of the continental crust. What we see is its thinning caused by rifting continental crust transformations while preserving vertical layering. Thus, in the Lomonosov Ridge, the crustal thickness is 17 to 19 km with an equal ratio of the upper and lower crust. In the Podvodnikov-Makarov Basin, the crustal thickness varies widely: from 19–21 km in the southern part of the Podvodnikov Basin to 7–8 km in the northern part of the Makarov Basin. In the Mendeleev Rise, the total thickness of the crust is 31–34 km with upper crust varying in the range of 4–7 km. The available geological and geophysical data [Grantz et al. 2011a,b; Kabankov et al. 2004] indicate that the Northwind Ridge and the Chukchi Borderland are relatively shallow submerged ledge of the continental crust.

Thus, the area of the Central Arctic uplifts and the Eurasian and North American continental margins represent an ensemble of continental geologic structures with the common history of geological evolution. Subdivision of the ensemble into shelf and deepwater parts is a result of neotectonic submergence of the central Arctic Basin. With the present level of knowledge of the Arctic Basin, there are no relevant data concerning the structural isolation of the Central Arctic uplifts area from the adjacent continental margins.

REFERENCES

Artemieva, I.M., Thybo, H. 2013: EUNAseis: A seismic model for Moho and crustal structure in Europe, Greenland, and the North Atlantic region. *Tectonophysics*. 609. 97–153. doi: 10.1016/j.tecto.2013.08.004.

Demenitskaya, R.M. 1967: *The Earth’s crust and mantle*. Moscow, Nedra. 280.

Erinchek, Yu.M., Milstein, E.D., Egorkin, A.V., Verba, V.V. 2007: Moho structure in Russia and adjacent water areas. Models of the Earth’s crust and upper mantle from results of deep seismic profiling. *Proceedings of the International Scientific and Practical Seminar*. VSEGEI, St. Petersburg. 241–244.

Funck, T., Jackson, H.R., 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. doi:10.1029/2011JB008411.

Gaina, C. and CAMP-GM working group. 2009: *Gravity anomaly map of the Arctic* [map]. Geological Survey of Norway.

Grad, M., Tiira, T. and working group. 2007: *The Moho depth of the European plate.* http://www.seismo.helsinki.fi/mohomap, http://www.igf.fuw.edu.pl/mohomap2007.

Grantz, A., Scott, R.A., Drachev, S.S., Moore, T.E., Valin, Z.C. 2011a: Sedimentary successions of the Arctic Region (58–64 to 90 degrees N) that may be prospective for hydrocarbons. *Arctic Petroleum Geology*. Geol. Soc., London, Mem. 35. 17–37.

Grantz, A., Hart, P.E., Childers, V.A. 2011b: Geology and tectonic development of the Amerasia and Canada Basins, Arctic Ocean. *In* Spencer, A.M., Embry, A.F., Gautier, D.L., Stoupakova, A.V., Sörensen, K. (eds.): *Arctic Petroleum Geology.* Geol. Soc., London, Mem. 35. 771–799.

Jackson, H.R., 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.

Kabankov, V.Ya., Andreeva, I.A., Ivanov, V.I., Petrova, V.I. 2004: About geotectonic nature of the system of Central Arctic morphostructures and geological significance of bottom sediments in its definition. *Geotectonics.* 6. 33–48.

Kashubin, S.N., Petrov, O.V., Androsov, E.A., Morozov, A.F., Kaminsky, V.D., Poselov, V.A. 2011: Map of crustal thickness in the Circumpolar Arctic. *Region. geology and metallogeny.* 46. 5–13.

Kashubin, S.N., Petrov, O.V., Androsov, E.A., Morozov, A.F., Kaminsky, V.D., Poselov, V.A. 2014: Crustal thickness in the Circum Arctic. *ICAM VI: Proceedings of the International Conference.* 1–17.

Kunin, N.Ya., Goncharova, N.V., Semenova, G.I. et al. 1987: *Map of the mantle surface topography in Eurasia* [map]. Moscow: IPE Ac. Sci. USSR, Ministry of Geology of the RSFSR.

Laske, G., Masters, G., Reif, C. 2000: CRUST 2.0: *A new global crustal model at 2 × 2 degrees.* http://igppweb.ucsd.edu/~gabi/rem.html.

Lebedeva-Ivanova, N.N., Zamansky, Yu.Ya., Langnen, A.E., Sorokin, M.Yu. 2006: Seismic profiling across the Mendeleev Ridge at 82°N evidence of continental crust. *Geophys. J. Intern.* 165. 527–544.

Lebedeva-Ivanova, N.N., Gee, D.G., Sergeyev, M.B. 2011: Crustal structure of the East Siberian continental margin, Podvodnikov and Makarov basins, based on refraction seismic data (TransArctic 1989–1991). *In* Spencer, A.M., Embry, A.F. Gautier, D.L., Stoupakova, A.V., Sørensen, K. (eds.): *Arctic Petroleum Geology*. Geol. Soc., London, Mem. 35. 395–411.

Mooney, W.D. 2007: Crust and Lithospheric Structure – Global Crustal Structure. *In* Romanowicz, B. & Dziewonski, A. (eds.): *Treatise on Geophysics: Seismology and Structure of the Earth*. Elsevier. 1. 361–417.

Petrov, O.V., Daragan-Sushchova, L.A., Sobolev, N.N., Daragan-Sushchov, Yu.I. et al. 2015: Geology and tectonics of the northeast of the Russian Arctic: (from seismic data). *Geotectonics.* 6. 3–19.

Poselov, V.A., Avetisov, G.P., Kaminsky, V.D. et al. 2011: *Russian Arctic geotraverses*. VNIIOkeangeologia, St. Petersburg. 172.

Ritzmann, O., Maercklin, N., Faleide, J.I., Bungum, H., Mooney, W.D., Detweiler, S.T. 2006: A 3D-geophysical model of the crust in the Barents sea region: model construction and basement characterization. *28th Seismic Research Review: Ground-Based Nuclear Explosion Monitoring Technologies*. 229–237.

Suleimanov, A.K., Zamozhnyaya, N.G., Andryushchenko, Yu.N., Lipilin, A.V. 2007: Deep seismic studies based on reflected waves. *In* Salnikov, A.S. (Ex. ed.): *Crustal Structure of the Magadan Sector of Russia from Geological and Geophysical Data: Collection of scientific papers.* Nauka, Novosibirsk. 22–26.

Zolotov, E.E., Kostyuchenko, S.L., Rakitov, V.A. 1998: Tomographic sections of the lithosphere Eastern European Platform. *In* Mitrofanov, F.P., Sharov, N.V. (eds.*): Seismological model of the lithosphere of Northern Europe: the Barents Region*. KSC RAS, Apatity. 1. 71–79.

MAP OF CRUSTAL TYPES IN THE ARCTIC

O.V. Petrov, S.N. Kashubin, E.D. Milshtein, E.A. Androsov,
N.I. Pavlenkova, S.P. Shokalsky, Yu.M. Erinchek

Correlation sketch map of crustal types, which differ in velocity and density parameters, structure, and total crust thickness, has been compiled based on the data of deep seismic studies on continents and in oceans. The sketch map of crustal types distribution, which was compiled based on seismic profiles in the Arctic, demonstrates the position of the oceanic and continental crust in the structures of the Circumpolar Arctic.

Keywords: *deep seismic studies, oceanic, transitional, continental crust.*

Through the lens of current views, based primarily on geophysical data, oceanic and continental crust naturally differ in their basic physical properties including density, thickness, age, and chemical composition. The continental crust is characterized by average thickness of about 40 km, density of 2.84 g/cm^3, and the average age of 1500 Ma, whereas the oceanic crust's average thickness is 5 to 7 km, density is about 3 g/cm^3 and it is younger than 200 Ma all over the Arctic area. There is a common view that oceanic crust consists mainly of tholeiitic basalts formed from quickly cooling magma, whereas the continental crust, which has a long history of development, is characterized by more felsic composition [Blyuman 2011].

Deep seismic studies conducted in different regions of the world, continents and oceans make it possible to identify the main patterns in the velocity model of the crust and their variability depending on tectonic setting and history of development of the Arctic region. Typical features of velocity models of the crust, their relation to the tectonic structure and history of development of various geological structures have been widely discussed [Belousov, Pavlenkova 1989; Meissner 1986; Mueller 1977; Mooney 2007; McNutt & Caress 2007, etc.]. Some of the researchers made attempts to distinguish main types of crust. They were based on crustal thickness data and seismic wave velocities in the crust. According to these parameters, typical features of the continental crust are: great thickness (usually over 25–30 km) and the presence in the consolidated crust of thick (up to 10 km or more) upper layer with the P-wave velocity of 5.8–6.4 km/s. This layer is often referred to as "granite gneiss." The oceanic crust is thin (typically less than 8–10 km); the granite gneiss layer is lacking in it, and it is almost entirely represented by rocks with seismic wave velocities of more than 6.5 km/s.

Detailed seismic surveys covering active and passive continental margins and oceanic uplifts have shown that in addition to typical continental and oceanic crust, the crust with intermediate parameters is also common. It is characterized by the thickness of 10 to 30 km and the "granite-gneiss" layer in it is significantly reduced or completely absent. The assignment of this crust to the oceanic or continental type is often ambiguous, so some researchers have even suggested that this crust should be defined as a separate type – interim or transitional crust [Belousov, Pavlenkova 1989], but most researchers suggest using in tectonic constructions two main genetic types of the Earth's crust – continental and oceanic.

Differences in the composition of the oceanic and continental crust are most evident when comparing their velocity models constructed from data of multi-wave seismic surveys. It turns out that the oceanic and continental crust differ greatly in ratios of P-waves and S-waves (Vp/Vs) [Hyndman 1979]. In the consolidated continental crust, the Vp/Vs rarely exceeds 1.75, while in the second and third oceanic layers, Vp/Vs is 1.85–1.90. At the same time, in the sediment layer and in the oceanic and continental crusts, Vp/Vs varies widely, generally exceeding values of 1.9–2.0. These data are confirmed by numerous DSS studies in oceans performed by bottom stations providing registration of S-waves and converted waves [Breivik et al. 2005; Ljones et al. 2004; Mooney 2007, etc.]. Taking into account the relation between the total content of silica in crystalline rocks and the Vp/Vs ratio [Aleinikov et al. 1991], these differences seem quite natural and evidence different basicity of the oceanic and continental crust. Thus, the generalized data on the structure and velocity parameters of the oceanic and continental crust can be represented as follows (table 2).

As can be seen from the table, in contrast to the continental crust, the oceanic crust lacks upper (felsic) crust that is recorded most reliably from Vp/Vs ratio. It is more difficult to distinguish the

---

To cite: Map of crustal types in the Arctic / O.V. Petrov [et al.] // Scientific contributions to the Tectonic Map of the Arctic. Paris, 2019. P. 26–32.

Table 2

Generalized model of the structure and velocity parameters of the oceanic and continental crusts [Kashubin et al. 2013]

Oceanic crust			Vp, км/с	Continental crust		
Main layers		Vp/Vs		Vp/Vs	Main layers	
Water	⬜	–	1.45–1.50	–	⬜	Water
Sediments	🟨	2.1–2.5	2.0–4.5	2.1–2.5	🟨	Sediments
Second layer of oceanic crust	🟩	1.8–2.2	4.2–6.0	1.8–2.2	🟩	Basalts, interbedded with sediments
–	–	–	5.8–6.4	1.69–1.73	🟥	Upper crust
–	–	–	6.3–6.7	1.73–1.75	🟫	Intermediate crust
Third layer of oceanic crust	🟩	1.81–1.87	6.6–7.2	1.75–1.77	🟩	Lower crust
Crust-mantle layer	🟦	1.78–1.84	7.2–7.6	1.78–1.84	🟦	Crust-mantle layer

oceanic crust from the continental crust based on absolute P-wave velocity values because of significant overlap of P-wave velocity values in the second oceanic layer and in the upper part of the consolidated continental crust. However, velocities in the second oceanic layer rarely reach values of more than 6.0 km/s, so this problem can be partly solved without information about Vp/Vs.

Following the generally accepted characteristics of seismic velocity for the oceanic and continental crust (table 2), following types of the Earth's crust can be distinguished in the Circumpolar Arctic (fig. 15, table 3) [Kashubin et al. 2013; Petrov et al. 2016].

Normal oceanic crust (type 1, fig. 15), which includes normal oceanic crust of spreading basins (less then 10 km thick) and thickened crust of oceanic plateaus and hot zones (about 15–30 km thick, type 2), is common in the Circumpolar Arctic, in the Norwegian-Greenland, Eurasian, and Baffin-Labrador ocean basins [Bohnhoff & Makris 2004; Ljones et al. 2004; Funck et al. 2007]. It includes two oceanic layers overlain by thin sediments [Ljones et al. 2004, etc.]. In the Baffin-Labrador ocean basin, the crust thickens to 15–17 km mainly due to magmatic underplating in the lower crust [Thybo & Artemieva 2013], where P-wave velocity reaches 7.4–7.6 km/s [Funck et al. 2007]. Thick (more than 20 km) crust of oceanic plateaus and hot zones also forms the Greenland-Iceland-Faroe Ridge [Bohnhoff & Makris 2004; Ljones et al. 2004], which apparently continues to the west of the southern Greenland via the Baffin Bay and forms a single zone of thickened crust – the Baffin Island-Greenland-Iceland-Faroe Islands Ridge [Artemieva & Thybo 2013]. Main increase in the thickness is a result of the third oceanic layer, whose thickness reaches more than 15 km thick.

Transitional crust. Nature of the thinned crust of deep rift basins (type 3, fig. 15) is a question under discussion. E. g., the crust thickness in the Canada Basin is more than 10–15 km, and the single-layer crystalline crust with the thickness of less than 10 km and Vp of 6.8–7.2 km/s is typical of the third oceanic layer [Mair et al. 1981; Baggeroer et al. 1982; Stephenson et al. 1994]. Based on the seismic velocity structure, it is traditionally believed that the Canada Basin was formed on the oceanic crust [e. g., Mooney 2007; Grantz et al. 2011].

Nevertheless, the comparison of velocity models in the crust of the Canada Basin and the South Barents Basin [Faleide et al. 2008], as well as the Caspian Basin [Volvovsky et al. 1988] shows that the depth-velocity models are very similar whereas the nature of the crystalline crust (oceanic and continental) is viewed differently by different researchers. One viewpoint is that these depressions have oceanic crust, which forms so-called "oceanic crust windows" on the shelf and continents [Mooney 2007; Grantz et al. 2011]. An alternative interpretation [Volvovsky et al. 1988] suggests that thick sedimentary strata in these depressions cover the

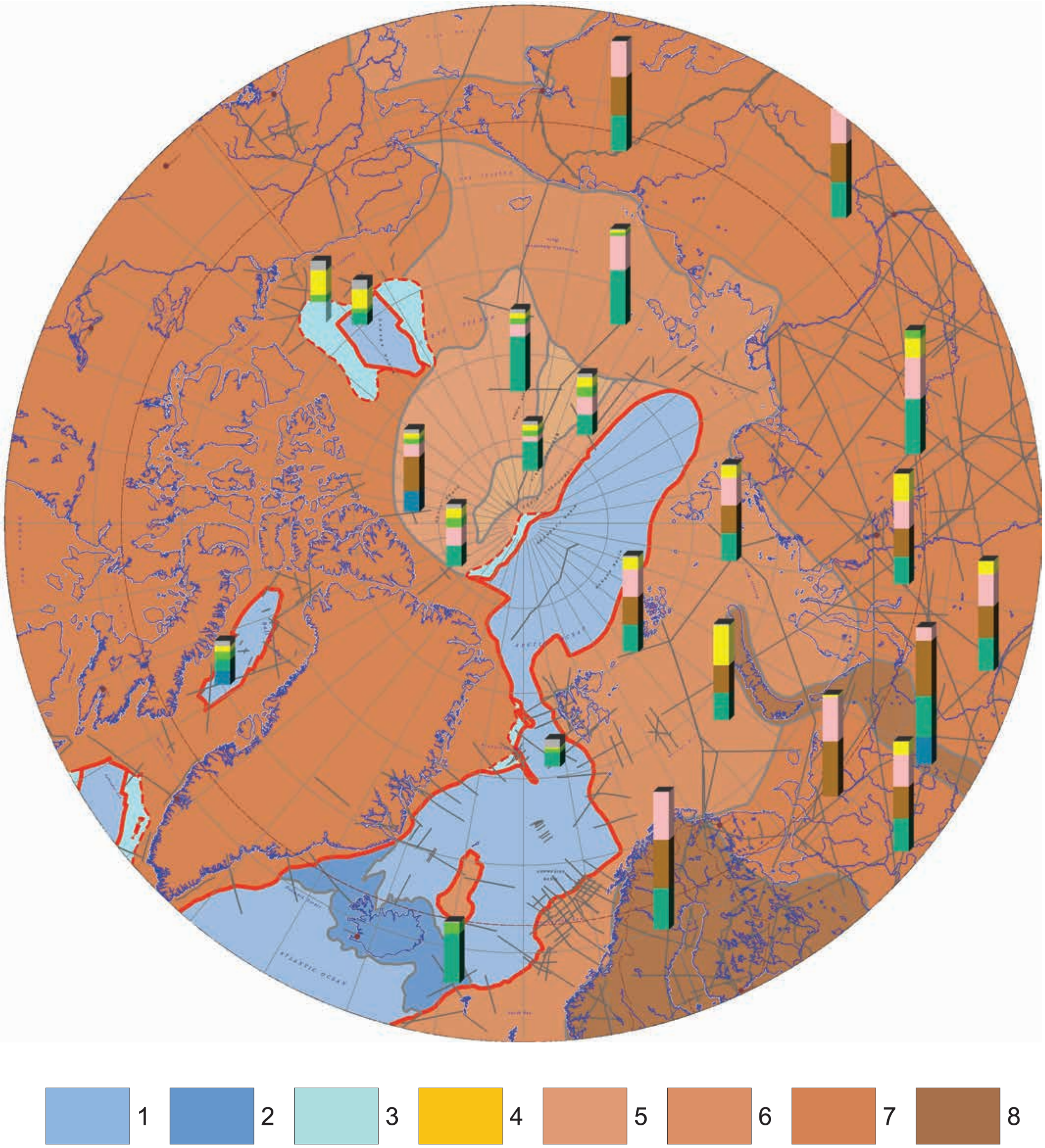


Fig. 15. Map of crust types in the Circumpolar Arctic

1–2 – oceanic crust: 1 – normal crust of spreading basins, *2* – thickened crust of oceanic plateaus and hot spots; *3* – reduced (transitional to oceanic) crust of deep depressions; *4–8 – continental crust: 4* – thinned crust of submarine rifts and basins, *5* – thinned crust of submarine ridges and rises, *6* – thin crust of shelf seas, *7* – normal crust of platforms and fold systems, *8* – thick crust of shields and collision areas. Gray lines show seismic-refraction and DSS profiles; type columns of the crust from seismic data are the same as in table 3 reduced (thinned) continental crust that lacks the upper (or intermediate) layer. In our approach, we do not take any side in the dispute (continental or oceanic origin), but, instead, we consider the crust of the Canada Basin transitional. It should be noted that the P-wave velocity models are not enough to understand the nature of the crystalline crust in deep rift basins. Further studies using data from S-waves and deep drilling will provide substantial arguments in favor of a particular interpretation.

Marine continental crust. In contrast to the oceanic crust, continental crust in the Circumpolar Arctic is studied based on a large number of deep seismic sounding(DSS) profiles (for regional reviews see Faleide et al. 2008; Drachev et al. 2010; Artemieva & Thybo 2013; Cherepanova et al. 2013, and in the publications that are referred to in these papers; Russian publications: Volvovsky et al. 1975; Druzhinin et al. 1983; 1985; 2000; Egorkin et al. 1980; 1988; 1991; 2002; Isanina et al. 1995; Poselov et al. 2007; 2010; 2011; Roslov et al. 2009; Sharov et al. 2010; Ivanova et al. 2006, etc.).

These studies resulted in the identification of the thin crust of *submarine rifts and basins* as a separate type of continental crust (type 4, fig. 15). An example of this type of the crust is the Podvodnikov-Makarova Basin. According to the interpretation of the DSS profiles obtained during expeditions Transarctic-89–91, Transarctic-92, Arctic-2000 [Poselov et al. 2011; Lebedeva-Ivanova et al. 2011], seismic records of Pg-waves are typical of the crustal complex with Vp = 6.1–6.3 km/s at the top of the consolidated crust, which is typical of the continental crust. Therefore, in spite of low thickness typical of the oceanic crust (12–15 km), the crust in this basin is interpreted as thinned continental crust.

Thinned crust is typical of *submarine ridges and rises*: the Lomonosov Ridge and the Alpha-Mendeleev Rise (type 5, fig. 15), as it can be seen from interpretations of Russian seismic profiles Arctic-2005 and Arctic-2007 in the Lomonosov and Mendeleev structures [Lebedeva-Ivanova et al. 2006; Poselov et al. 2007; 2010; Poselov et al, 2011; Sakoulina et al. 2011], seismic experiment LORITA in the Lomonosov Ridge [Jackson et al. 2010], and the seismic profile obtained by seismic refraction in the Alpha Ridge [Funck et al. 2011]. According to these interpretations, the crustal thickness of the ridges varies greatly from 15–17 km to 30–35 km [Artyushkov 2010]. The crystalline crust is represented by slightly thinned upper crust as compared to the normal continental crust and the thick lower crust; thick crust-mantle complex was recorded under the Alpha Ridge where the normal lower crust is apparently lacking [Funck et al. 2011].

The continental nature of the crust in the Lomonosov Ridge has been recognized by most researchers of the Arctic, while the nature of the crust in the Alpha-Mendeleev Ridge has long been a subject of debate. In particular, Funck et al. (2011) proposed to classify the Alpha Ridge crust as volcanic crust similar to hot zone crust such as that of the Greenland-Iceland-Faroe Ridge. However, the results of Russian studies [Poselov et al. 2011; Lebedeva-Ivanova et al. 2006; Arctic-2012 (in press)] show that main stratified sedimentary complexes, the intermediate complex, and crystalline complexes of the Earth's crust are traced to the Mendeleev Rise from the shelf of the East Siberian Sea. Thus, Mendeleev Rise should be considered as the continuation of the Eurasian continent (type 5, fig. 15). Although the relationship between the crustal structures of the Alpha and Mendeleev ridges is still not clear. Similarities between the Vp velocity models and depth models suggest that the crust both of the Lomonosov Ridge and the Alpha-Mendeleev Ridge is thinned continental crust. It should be noted that the general thinning of the Alpha Ridge crust is somewhat veiled due to the presence of thickened lower crust and may result from intraplate magmatism related to LIP (magmatic underplating) [Thybo & Artemieva 2013].

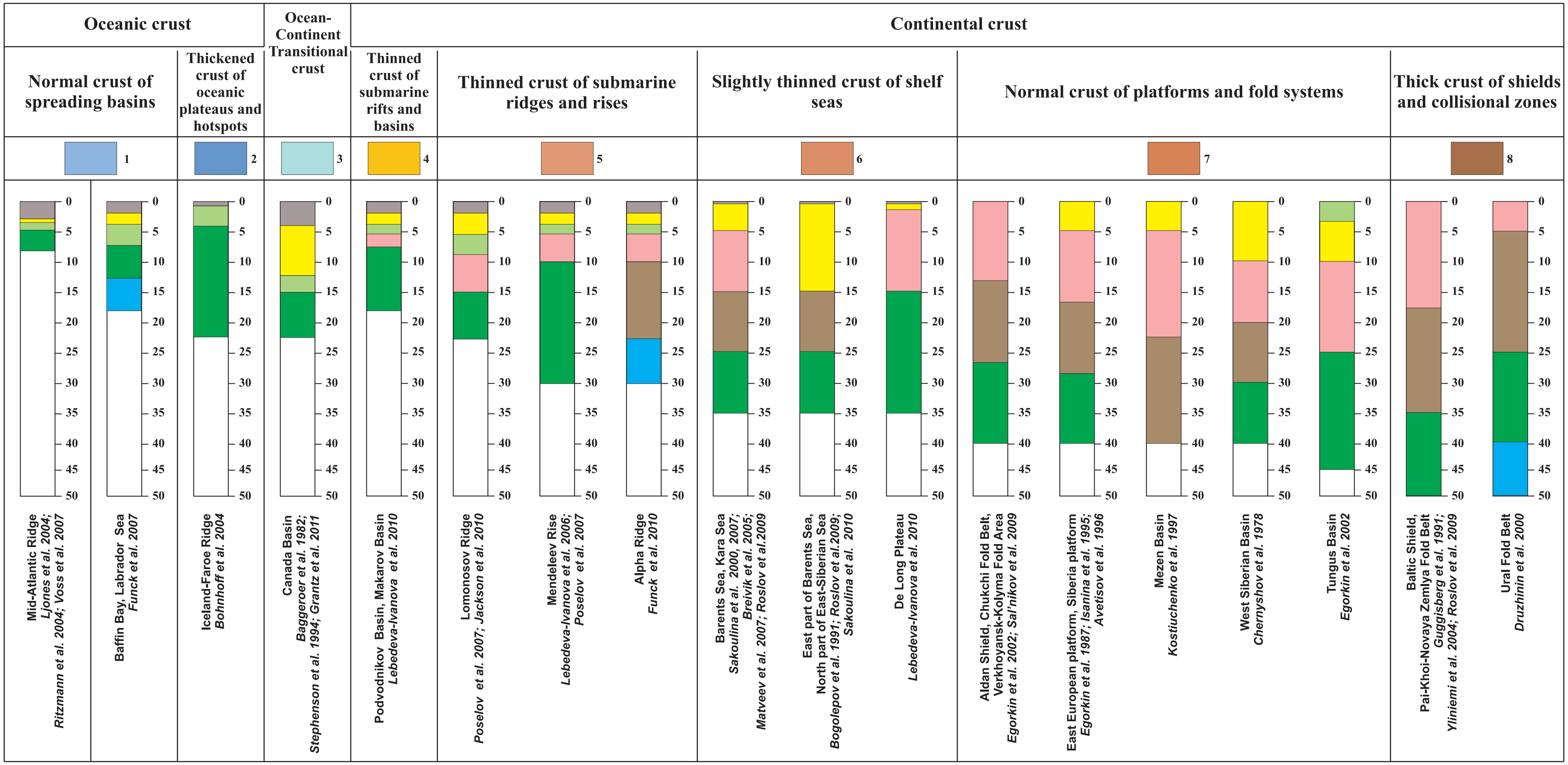
Shelf seas' crust (type 6, fig. 15) occupies almost all shallow-water areas of the Arctic Ocean; it is somewhat thinned continental crust characterized by very similar thickness (about 35 km) but highly variable structure. Sedimentary cover thickness varies widely from a few meters near islands up to 15 km or more in the East Barents and North Chukchi troughs. The crystalline crust structure on the shelf is usually three-layered as in most of the Barents and Kara seas [Breivik et al. 2005]; however, two-layer structure was recorded in the East Barents Basin and the northern part of the East Siberian Sea [Roslov et al. 2009; Sakoulina et al. 2000; Ivanova et al. 2006] where the upper crust is apparently lacking, and in the De Long plateau where the intermediate crust is lacking on the graphs of seismic velocities [Lebedeva-Ivanova et al. 2011].

Normal continental crust of platforms and fold systems (types 7 and 8, fig. 15) occupies most of the Circumpolar Arctic covering almost the entire land area. Thickness, internal structure and composition of the crust vary considerably, which reflects its complex tectonic evolution. Detailed information on the crust structure and tectonic evolution of the European continent, Greenland, Iceland, the North Atlantic region, the West Siberian Basin and the Siberian Platform can be found in recent reviews published by Artemieva and Thybo (2013) and Cherepanova et al. (2013).

Table 3

Type columns of the crust of Circumpolar Arctic structures based on seismic profiles in accordance with generalized velocity parameters given in Table 2

[Kashubin et al. 2013; Petrov et al. 2015]



Oceanic crust			Ocean-Continent Transitional crust	Continental crust													
Normal crust of spreading basins		Thickened crust of oceanic plateaus and hotspots		Thinned crust of submarine rifts and basins	Thinned crust of submarine ridges and rises			Slightly thinned crust of shelf seas			Normal crust of platforms and fold systems					Thick crust of shields and collisional zones	
1		2	3	4	5			6			7					8	
Mid-Atlantic Ridge *Ljones et al. 2004;* *Ritzmann et al. 2004; Voss et al. 2007*	Baffin Bay, Labrador Sea *Funck et al. 2007*	Iceland-Faroe Ridge *Bohnhoff et al. 2004*	Canada Basin *Baggeroer et al. 1982;* *Stephenson et al. 1994; Grantz et al. 2011*	Podvodnikov Basin, Makarov Basin *Lebedeva-Ivanova et al. 2010*	Lomonosov Ridge *Poselov et al. 2007; Jackson et al. 2010*	Mendeleev Rise *Lebedeva-Ivanova et al. 2006;* *Poselov et al. 2007*	Alpha Ridge *Funck et al. 2010*	Barents Sea, Kara Sea *Sakoulina et al. 2000, 2007;* *Breivik et al. 2005;* *Matveev et al. 2007; Roslov et al.2009*	East part of Barents Sea, North part of East-Siberian Sea *Bogolepov et al. 1991; Roslov et al.2009;* *Sakoulina et al. 2010*	De Long Plateau *Lebedeva-Ivanova et al. 2010*	Aldan Shield, Chukchi Fold Belt, Verkhoyansk-Kolyma Fold Area *Egorkin et al. 2002; Sal'nikov et al. 2009*	East European platform, Siberia platform *Egorkin et al. 1987; Isanina et al. 1995;* *Avetisov et al. 1996*	Mezen Basin *Kostiuchenko et al. 1997*	West Siberian Basin *Chernyshov et al. 1978*	Tungus Basin *Egorkin et al. 2002*	Baltic Shield, Pai-Khoi-Novaya Zemlya Fold Belt *Guggisberg et al. 1991;* *Yliniemi et al. 2004; Roslov et al. 2009*	Ural Fold Belt *Druzhinin et al. 2000*

Thus, different types of the Circumpolar Arctic crust form a global structure, one of the centers of which is the area of Central Arctic Uplifts including the Lomonosov Ridge and the system of Alpha-Mendeleev rises with separating them Podvodnikov-Makarov Basin. The zone of volume strain, areas of intraplate basic magmatism (Cretaceous HALIP Province) [Filatova & Hain 2009; Mukasa et al. 2009], and submergences of shallow-water volcanic structures to bathyal (up to 3.5 km) depths [Brumley et al. 2009] in the absence of pronounced spreading structures with typical linear magnetic anomalies do not allow structures of the Central Arctic Uplifts to be assigned to the oceanic type. It is assumed that this type of the crust could be formed by processes of basification and eclogitization of the normal continental crust [Petrov et al. 2016].

REFERENCES

Aleinikov, A.L., Nemzorov, N.I., Kashubin, S.N. 1991: *Rocktype determination from seismic data.* Author's certificate No 1642416 A1 cl. G 01 V1/30.

Artemieva, I.M., Thybo, H. 2013: EUNAseis: A seismic model for Moho and crustal structure in Europe, Greenland, and the North Atlantic region. *Tectonophysics*. 609. 97–153. doi: 10.1016/j.tecto.2013.08.004.

Artyushkov, E.V. 2010: Continental crust in the Lomonosov Ridge, Mendeleev Ridge, and the Makarov basin. The formation of deep-water basins in the Neogene. *Russian geology and geophysics*. 51 (11**)**. 1179–1191. doi:10.1016/j.rgg.2010.10.003.

Baggeroer, A.B., Falconer R. 1982: Array Refraction Profiles and Crustal Models of the Canada Basin. *J. Geophys. Res*. 87. 5461–5476.

Belousov, V.V., Pavlenkova, N.I. 1989: Types of the Earth's crust of Europe and North Atlantic. *Geotectonics*. 3. 3–14.

Blyuman, B.A. 2011: *Earth's crust of oceans. Based on data of international programs for deepwater drilling in the World Ocean*. VSEGEI Publishing House, St. Petersburg. 344.

Bohnhoff, M., Makris, J. 2004: Crustal structure of the southeastern Iceland-Faeroe Ridge (IFR) from wide aperture seismic data. *J. Geodynamics*. 37. 233–252.

Breivik, A.J., Mjelde, R., Grogan, P., Shimamura, H., Murai, Y., Nishimura, Y. 2005: Caledonide development offshore-onshore Svalbard based on ocean bottom seismometer, conventional seismic and potential field data. *Tectonophysics*. 401. 79–117.

Brumley, K. 2009: Tectonic geomorphology of the Chukchi Borderland: constraint for tectonic reconstruction models. *Thesis for the Degree of Master of Science*. University of Alaska, Fairbanks. 116.

Cherepanova, Yu., Artemieva, I.M., Thybo, H., Chemia, Z. 2013: Crustal structure of the Siberian Craton and the West Siberian Basin: an appraisal of existing seismic data. *Tectonophysics*. 609. 154–183.

Drachev, S.S., Malyshev, N.A., Nikishin, A.M. 2010: Tectonic history and petroleum geology of the Russian Arctic Shelves: an overview. *In* Vining, B.A., Pickering, S.C. (eds.): *Petroleum Geology: From Mature Basins to New Frontiers. Proccedings of the 7th Petroleum Geology Conf.* Geol. Soc., London. 7. 591–619.

Druzhinin, V.S. 1983: Deep structure characteristic of the West Siberian Plate along the DSS Khanty-Mansiysk profile. *Geology and Geophysics*. 4. 3–9.

Druzhinin, V.S., Karmanov, A.B. 1985: Study of the crustal structure in the north-western part of the West Siberian Plate. *Soviet Geology*. 9. 39–48.

Druzhinin, V.S., Karetin, Yu.S., Kashubin, S.N. 2000: Deep geological mapping of the Ural region from DSS data. *Region. geology and metallogeny*. 10. 152–161.

Egorkin, A.V., Chernyshov, N.M., Danilov, E.G. et al. 1980: Regional cross section across the north of the Asian continent, the Vorkuta-Tiksi profile. *Seismic Models of the Lithosphere of Main Geological Structures in the USSR*. Nauka, Moscow. 61–67.

Egorkin, A.V., Zyuganov, S.K., Pavlenkova, N.A., Chernyshev, N.M. 1988: Results of lithospheric structure investigations along profiles in Siberia. *Geology and geophysics*. 5. 120–128.

Egorkin, A.V. 1991: Crustal structure from seismic geotraveses. *In* Belousov, V.V., Pavlenkova, N.I. (eds.): *Deep structure of the USSR*. Nauka, Moscow. 118–135.

Egorkin, A.V., Akinshina, L.V., Artemenko, L.S. et al. 2002: Crystalline crust structure in Siberia along the Khanty-Mansiysk – Lena Line. *Exploration and Protection of Mineral Resources*. 2. 33–35.

Faleide, J.I., Filippos, T., Asbjorn, J.B., Mjelde, R., Ritzmann, O., Engen, O., Wilson, J., Eldholm, O. 2008: Structure and evolution of the continental margin off Norway and the Barents Sea. *Episodes*. 31. 82–91.

Filatova, N.I., Hain, V.E. 2009: Structures of the Central Arctic and their relationship with the Mesozoic Arctic plume. *Geotectonics*. 6. 24–51.

Funck, T., Jackson, H.R., Louden, K.E., Klingelhofer, F. 2007: Seismic study of the transform-rifted margin in Davis Strait between Baffin Island (Canada) and Greenland: What happens when a plume meets a transform. *J. Geophys. Res*. 112. B04402.

Funck T., Jackson, H.R., 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, doi:10.1029/2011JB008411.

Grantz, A., Hart, P.E., Childers, V.A. 2011: Geology and tectonic development of the Amerasia and Canada Basins, Arctic Ocean. *In* Spencer, A.M., Embry, A.F., Gautier, D.L., Stoupakova, A.V., Sörensen, K. (eds.): *Arctic Petroleum Geology*. Geol. Soc., London, Mem. 35. 771–799.

Hyndman, R.D. 1979: Poisson's ratio in the oceanic crust – a review. *Tectonophysics*. 59. 321–333.

Isanina, E.V., Sharov, N.V. et al. 1995: *Atlas of regional seismic profiles of the European North of Russia*. Rosgeofizika, St. Petersburg.

Ivanova, N.M., Sakoulina, T.S., Roslov, Yu.V. 2006: Deep seismic investigation across the Barents-Kara region and Novozemelskiy Fold Belt (Arctic Shelf). *Tectonophysics*. 420. 123–140.

Jackson, H.R., 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.

Kashubin, S.N., Pavlenkova, N.I., Petrov, O.V., Milshtein, E.D., Shokalsky, S.P., Erinchek, Yu.M. 2013: Crust types in the Circumpolar Arctic. *Region. geology and metallogeny*. 55. 5–20.

Lebedeva-Ivanova, N.N., Zamansky, Yu.Ya., Langnen, A.E., Sorokin, M.Yu., 2006: Seismic profiling across the

Mendeleev Ridge at 82°N evidence of continental crust. *Geophys. J. Int.* 165. 527–544.

Lebedeva-Ivanova, N.N., Gee, D.G., Sergeyev, M.B. 2011: Crustal structure of the East Siberian continental margin, Podvodnikov and Makarov basins, based on refraction seismic data (TransArctic 1989–1991). *In* Spencer, A.M., Embry, A., Gautier, D., Stoupakova, A., & Sørensen, K. (eds.): *Arctic Petroleum Geology.* Geol. Soc., London, Mem. 35 (26). 395–411.

Ljones, F., Kuwano, A., Mjelde, R., Breivik, A., Shimamurac, H., Murai, Y., Nishimura, Y., 2004: Crustal transect from the North Atlantic Knipovich Ridge to the Svalbard Margin west of Hornsund. *Tectonophysics.* 378. 17–41.

Mair, J.A., Lyons, J.A., 1981: Crustal structure and velocity anisotropy beneath the Beaufort sea. *Can. J. Earth Sci.* 18. 724–741.

McNutt, M., Caress, D.W. 2007: Crust and lithospheric structure – Hot spots and hot-spot swells. *In* Romanowicz, B. & Dziewonski, A. (eds.): *Treatise on Geophysics*. Elsevier. 1. 445–478.

Meissner, R. 1986: The continental crust, a geophysical approach. *International Geophys. Series.* Academic Press, INC, Orlando. 34. 426.

Mooney, W.D. 2007: Crust and lithospheric structure – Global crustal structure. *In* Romanowicz, B., Dziewonski, A. (eds.): *Treatise on Geophysics*. Elsevier. 1. 361–417.

Mueller, St. 1977: A new model of the continental crust. *Am. Geophys. Un. Mon.* 20. 289–317.

Mukasa, S., Andronikov, A., Mayer, L., Brumley, K. 2009: Geochemistry and geochronology of the first intraplate lavas recovered from the Arctic Ocean. *Portland GSA Annual Meeting (18–21 October 2009).* 138. 11.

Petrov, O., Smelror, M., Morozov, A., Shokalsky, S., Kashubin, S., Artemieva, I.M., Sobolev, N., Petrov, E., Ernst, R.E., Sergeev, S. 2016: Crustal structure and tectonic model of the Arctic region. *Earth-Science Reviews.* Elsevier. 154. 29–71.

Poselov, V.A., Verba, V.V., Zholondz, S.M., 2007: Crust typification in the Central Arctic Uplifts, the Arctic Ocean. *Geotectonics*. 4. 48–59.

Poselov, V.A., Kaminsky, V.D., Ivanov, V.L., Avetisov, G.P., Butsenko, V.V., Trukhalev, A.I., Palamarchuk, V.K., Zholondz, S.M. 2010: Crustal structure and evolution in the junction area of the Amerasian Subbasin uplifts and the East Arctic Shelf. *Structure and History of the Lithosphere Evolution.* Paulsen, Moscow. 599–637.

Poselov, V.A., Avetisov, G.P., Kaminsky, V.D. et al. 2011: *Russian Arctic geotraverses.* VNIIOkeangeologia, St. Petersburg. 172.

Roslov, Yu.V., Sakoulina, T.S., Pavlenkova, N.I. 2009: Deep seismic investigations in the Barents and Kara Seas. *Tectonophysics.* 472. 301–308.

Sakoulina, T.S., Telegin, A.N., Tikhonova, I.M., Verba, M.L., Matveev, Y.I., Vinnick, A.A., Kopylova, A.V., Dvornikov, L.G. 2000: The results of deep seismic investigations on Geotraverse in the Barents Sea from Kola peninsula to Franz-Joseph Land. *Tectonophysics.* 329 (1–4). 319–331.

Sakoulina, T.S., Verba, M.L., Kashubina, T.V., Krupnova, N.A., Tabyrtsa, S.N., Ivanov, G.I. 2011: Comprehensive geological and geophysical studies along the reference profile 5-AR in the East Siberian Sea. *Exploration and Preservation of Mineral Resources*. 10. 17–23.

Sharov, N.V., Kulikov, V.S., Kulikova, V.V., Isanina, E.V., Krupnova, N.A. 2010: Seismogeological characteristic of the Earth's crust in the south-eastern part of the Fennoscandian Shield (Russia). *Geophys. J.* 32. 3–17.

Stephenson, R.A., Coflin, K.C., Lane, L.S., Dietrich, J.R. 1994: Crustal structure and tectonics of the southeastern Beaufort Sea continental margin. *Tectonics.* 13. 389–400.

Thybo, H., Artemieva, I.M. 2013: Moho and magmatic underplating in continental lithosphere. *Tectonophysics.* 609. 605–619.

Volvovsky, I.S., Volvovsky, B.S. 1975: *Sections of the Earth's crust in the USSR from deep seismic sounding.* Soviet Radio, Moscow. 258.

Volvovsky, B.S., Volvovsky, I.S. 1988: Structures of continents with "granite-free" crust type. *Problems of Deep Geology in the USSR*. Moscow. 169–187.

GEOTRANSECT ACROSS THE CIRCUMPOLAR ARCTIC

S.N. Kashubin, O.V. Petrov, E.D. Milshtein, S.P. Shokalsky

Summary geotransect is composed of DSS seismic line fragments and supplemented with density modelling. The geotransect demonstrates structure of the Earth's crust and upper mantle along the line 7,600 km long, which crosses the continental crust of the East European Platform, Barents-Kara shelf seas, Eurasian Basin oceanic crust, reduced crust of the Central Arctic Submarine Elevations, shelf seas of Eurasia passive margin, and crust of the Chukotka-Kolyma folded area.

Keywords: *Circumpolar Arctic, velocity and density models, oceanic and continental crust*.

7600 km long Geotransect across the Circumpolar Arctic is constructed along the line joining DSS seismic geotraverses: 1-EV–1-AR–Transarctic-92–Arctic-2000–Arctic-2005–5-AR–2-DV (5400 km) from Petrozavodsk in the west to Magadan in the east (fig. 16, 17). It includes: velocity, density models and geological-geophysical section. Sedimentary cover base (B), upper crust base, lower crust roof, Earth's crust base – M discontinuity are shown in this geotransect. When determining interfaces, velocity parameters (Vp) are specified: sedimentary cover – 2.0–4.5 km/s; upper crust – 5.8–6.4 km/s; middle crust – 6.3–6.7 km/s; lower crust – 6.6–7.2 km/s; upper mantle – 7.8–8.4 km/s. Geological-geophysical section crosses the Eurasian oceanic basin with the Eocene, Oligocene-Early

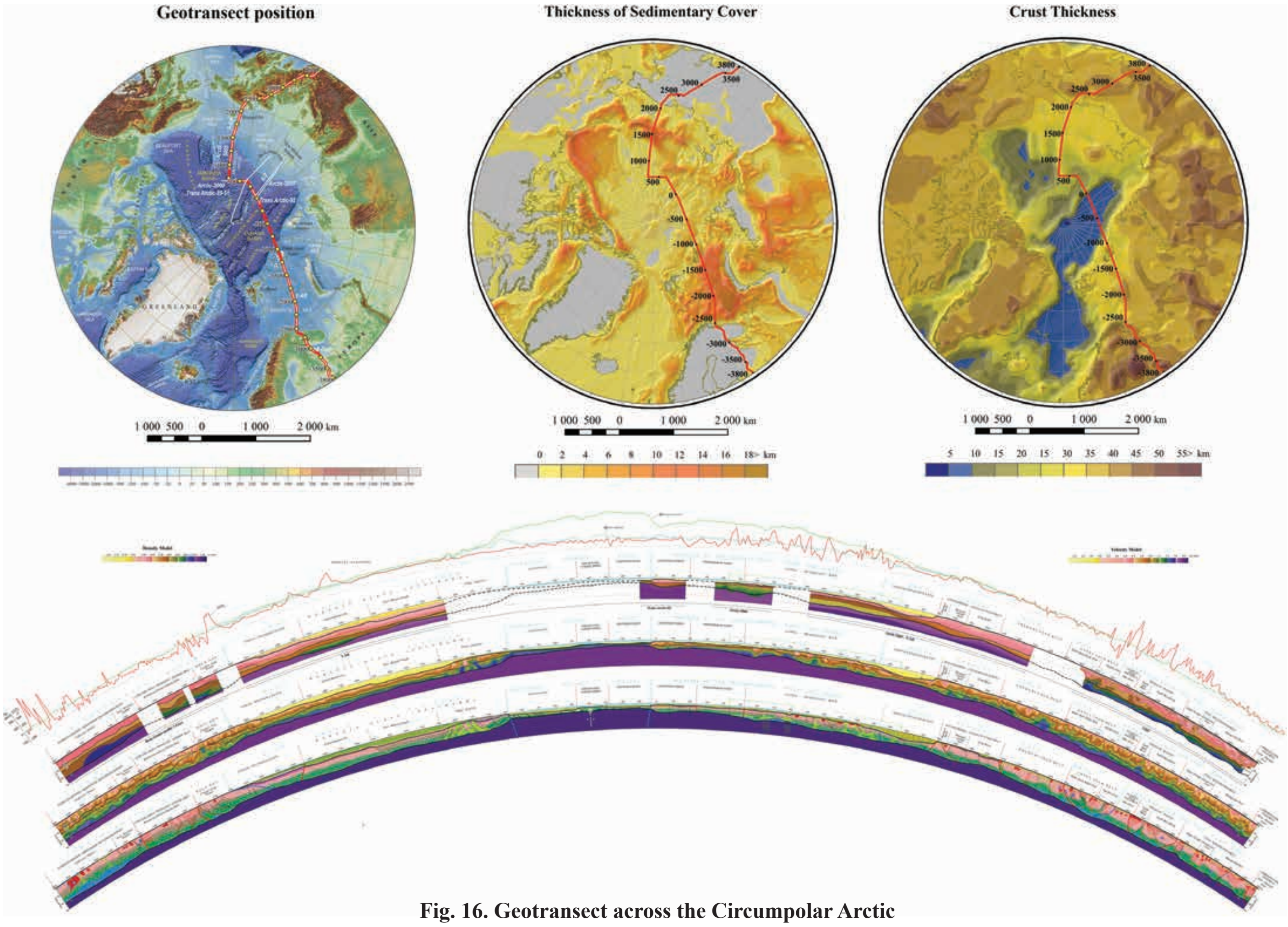
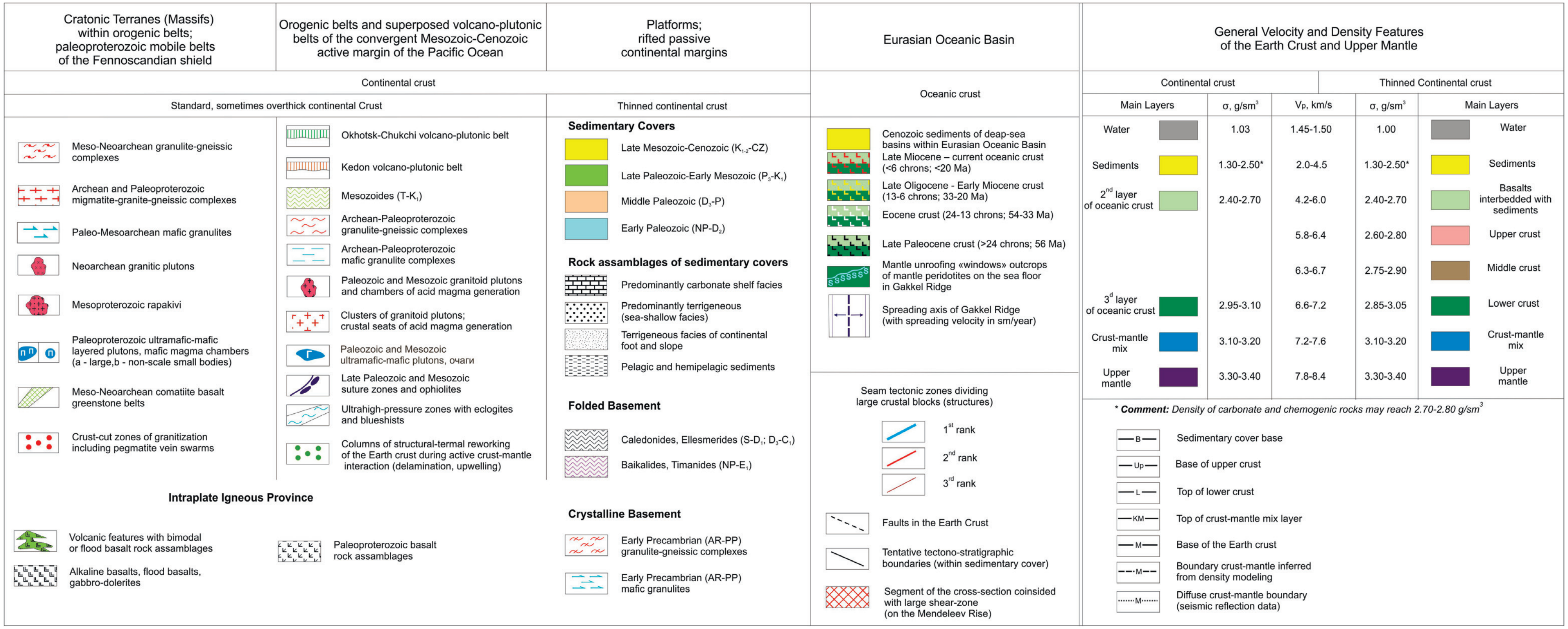


Fig. 16. Geotransect across the Circumpolar Arctic

To cite: Geotransect across the Circumpolar Arctic / S.N. Kashubin [et al.] // Scientific contributions to the Tectonic Map of the Arctic. Paris, 2019. P. 33–35.



Continental crust					Thinned Continental crust	
Main Layers		σ, g/sm^3	V$_P$, km/s	σ, g/sm^3		Main Layers
Water	◼	1.03	1.45-1.50	1.00	◼	Water
Sediments	🟨	1.30-2.50*	2.0-4.5	1.30-2.50*	🟨	Sediments
2nd layer of oceanic crust	🟩	2.40-2.70	4.2-6.0	2.40-2.70	🟩	Basalts interbedded with sediments
			5.8-6.4	2.60-2.80	🟥	Upper crust
			6.3-6.7	2.75-2.90	🟫	Middle crust
3d layer of oceanic crust	🟩	2.95-3.10	6.6-7.2	2.85-3.05	🟩	Lower crust
Crust-mantle mix	🟦	3.10-3.20	7.2-7.6	3.10-3.20	🟦	Crust-mantle mix
Upper mantle	🟪	3.30-3.40	7.8-8.4	3.30-3.40	🟪	Upper mantle

* ***Comment:*** *Density of carbonate and chemogenic rocks may reach 2.70-2.80 g/sm^3*

Fig. 17. Legend for the combined geological and geophysical section

Miocene, and Late Miocene-Quaternary oceanic crust (less than 10 km thick), Baltic Shield and folded areas of Northwestern Russia.

Passive continental margins of the Eurasian oceanic basin – the Barents-Kara, Laptev rift and submerged Amerasian Basin with the Lomonosov Ridge and Mendeleev Rise – are distinguished with thinned crust. This uplift is interpreted as a block of three-layer Archean – Mesoproterozoic crust reaching up to 30 km in thickness with the Late Precambrian and Paleozoic cover deposits under the Late Mesozoic and Cenozoic sediments and HALIP basalts. The limits and deep structure of the Anyui-Chukchi and Upper Yana-Kolyma regions in the section band are specified. Karelian granite-greenstone region has a thick (up to 45 km) three-layered crust and the presence of high-density and high velocity crust-mantle lens as manifestation of underplating and mafic-ultramafic magmatism.

Alpha-Mendeleev Ridge is characterized by velocity and density parameters, which allow to present it as a tectonic block with a three-layered crust of 30 km thickness. Crustal thickness is maximum for the Central Arctic Uplifts Area. High velocity and high density local sites similar to the crust-mantle complex are observed in the lower crust bottom. This allows to suggest the presence of mafic magma chambers under the vast HALIP basalt areal assumed by the specific magnetic field.

Basalts are dated to Cretaceous (82 Ma) at Alpha Ridge to the north of the geotransect. The supracrystal complex of late Precambrian and Paleozoic sediments is supposed to be sometimes within the acoustic basement of the Mendeleev Rise, North Chukchi basin within Anyui-Chukotka Fold Area. Seafloor debris of gneiss-granite raised by piston-corer (geological sampling of the steep slope of the Geophysicists Spur) showed younger ages (1139±15, 688±5, 448.7±4, 407.5±5.1 Ma), than granite samples at the Mendeleev Rise.

The crust structure similarity of the Alpha-Mendeleev Rise and the Karelian granite-greenstone Area allow to suggest the presence of Early Precambrian tectonic blocks in the Rise basement. This assumption is supported by isotopic dating of seabed rock specimens sampled during the expeditions “Arctic-2000” and “Arctic-2005”. Pieces of granite-gneisses dredged and raised by boxcorers or piston corers from the Mendeleev Rise showed 2.7, 2.6, 2.3, 1.9 Ga, fragments of gabbro-dolerite demonstrated 790±20 Ma and 2650 Ma (from xenogenic zircon grains). Paleozoic sandstones and quartzites 430–300 Ma from the Mendeleev Rise also contain Archean (3.1 Ga) detrital zircons, which indicate participation of the Early Precambrian provenance.

The Lomonosov Ridge south – Lomonosov Ridge passes the pole and thus both ends are South – cut by the geotransect differs by two-layer structure and thinner (about 25 km) Earth’s crust. Velocity and density of the lower crust are noticeably smaller than those of the Mendeleev Rise. The main parameters of consolidated crust of the Lomonosov Ridge are similar to thinned crust of orogenic belts within the North-East Russia.

MAP OF THICKNESS OF UNDEFORMED SEDIMENTARY COVER IN THE ARCTIC

O.V. Petrov, S.N. Kashubin, L.A. Daragan-Suschova, E.D. Milshtein, E.A. Androsov, E.O. Petrov,
K. Piepjohn, V.A. Poselov, I.I. Pospelov, S.P. Shokalsky, S.D. Sokolov

Summary map of the Circumpolar Arctic sedimentary cover was compiled according to seismic reflection studies and summarizing all the available sediment thickness maps north of 60° N. The isopach section in the summary map corresponds to 1.0 km, grid 5 × 5 km.

Keywords: *Circumpolar Arctic, reflection seismics, sediment thickness*.

By sedimentary cover is meant a sequence of sedimentary, slightly dislocated, and usually unmetamorphosed rocks characterized by gentle dipping that form the upper part of the Earth's crust. On continents, as a rule, on continents the sedimentary cover lies on consolidated crust and in oceans – on the second oceanic layer. However, in some sedimentary basins, between the sedimentary cover and crystalline basement, there are intermediate complexes represented by metamorphosed and sediments dislocated to a varying degree. Sometimes, these sediments are included in the sedimentary layer [Gramberg et al. 2001], but more often they are treated as formations of the so-called intermediate structural stage [Poselov et al. 2011a,b; 2012]. In geological mapping, the thickness of sediments lying on heterochronic basements is shown by isopach lines.

As a rule, the sedimentary cover is confidently identified in seismic cross-sections by the nature of seismic record and values of elastic wave velocities, so seismic methods play a key role in the study of the sedimentary cover. In RW-CDP time cross-sections, the base of the sedimentary cover is usually recorded from the sharp change of extended and subhorizontally oriented lineups to dashed variously oriented field of reflectors or complete cessation of regular seismic record. This horizon, indexed in RW-CDP cross-sections as AB (acoustic basement), usually coincides with the first-order velocity boundary identified when observing with P-wave method, DSS, and corresponding to sharp increase in P-wave velocity values from less than 3.5–4.0 km/s to 5.0 km/s and higher. As a rule, the base of the sedimentary cover is constructed from seismic data using these features.

The thickness map of the Circumpolar Arctic sedimentary cover shown in fig. 18 was compiled as a part of the international project on the compilation of the Atlas of geological maps of the Circumpolar Arctic carried out under the auspices of the Commission for the Geological Map of the World [Petrov et. al. 2016]. The map was compiled on the basis of all available recent maps showing the structure of the sedimentary cover and seismic cross-sections [Gramberg et al. 2001; Smelror et al. 2009; Grantz et al. 2011a,b; Drachev et al. 2010; Divins 2008; Laske & Masters 2010; Poselov et al. 2011a,b; 2012; Artemieva & Thybo, 2013, etc.]. All available data on the thickness of the sedimentary cover collected from various sources were converted into a single coordinate system and presented in a unified grid with a cell size of 5×5 km. In overlapping areas of original maps, priority was given to more detailed studies. Areas with no seismic data were filled by means of sediment thickness interpolation using the global model CRUST1.0 built on a grid of 1×1 degree [Laske et al. 2010].

In its present form, the map can serve as a factual basis for the distribution of sediments' thickness in the Arctic region for the analysis of the geological structure and tectonic evolution of the Arctic. The structure of the sedimentary cover reflects the location of rift systems in continental margins, orogenic belts, and also allows identifying borders of sedimentary basins.

The sedimentary cover of the Arctic, which includes the total thickness of undeformed rock sequences lying on the tectonic basement, reveals a belt of deepwater shelf and marginal shelf basins (East Barents Basin – North Kara Syncline, Vilkitsky Trough – North Chukchi Basin; Colville Trough; Beaufort Sea – Mackenzie River delta; Sverdrup Basin and Lincoln Sea Basin, etc.). In these basins, the sedimentary cover reaches 18–20 km.

System of submeridional (NS) deep-sea basins (Eurasia – Laptev Sea, Makarov Basin – Podvodnikov Basin – De Long Basin and others) with sedimentary cover of 6–10 km, is apparently a younger system superimposed on Paleozoic–Mesozoic marginal shelf basins and troughs.

To cite: Map of thickness of undeformed sedimentary cover in the Arctic / O.V. Petrov [et al.] // Scientific contributions to the Tectonic Map of the Arctic. Paris, 2019. P. 36–39.

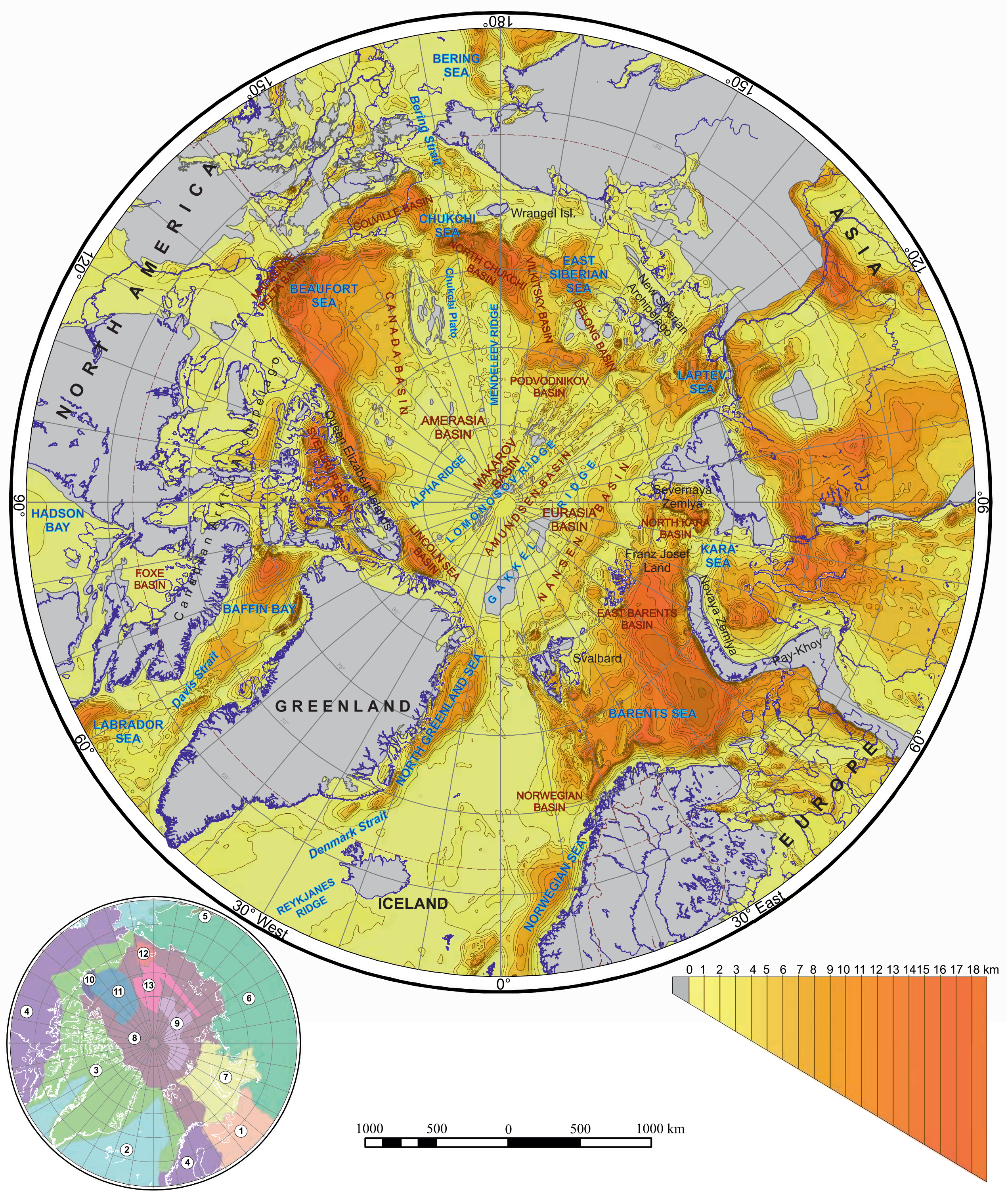


Fig. 18. Thickness map of Circumpolar Arctic sedimentary cover [Petrov et al. 2016]

Index map of authors' layouts: 1 – Yu.M. Erinchek et al. 2002 (unpublished material). Relief map of the basement of various ages of the East European Platform and the Timan-Pechora Province; 2 – D.L. Divins 2003 (unpublished material). NGDC Total Sediment Thickness of the World's Oceans & Marginal Seas; 3 – Grantz et al. 2009. Map showing the sedimentary successions of the Arctic Region that may be prospective for hydrocarbons; 4 – Laske, Masters 2010. Global Digital map of Sediment Thickness; 5 – Sakoulina et al. 2011. Sedimentary basins of the Sea of Okhotsk region; 6 – S.P. Shokalsky et al. 2010 (unpublished material). Schematic thickness map of the sedimentary cover of the Urals, Siberia and the Far East; 7 – Sakoulina et al. 2011. Thickness map of the Barents-Kara sedimentary cover; 8 – Poselov et al. 2012. Thickness map of the Arctic Ocean sedimentary cover; 9 – K.G. Stavrov et al. 2011 (unpublished material). Thickness map of sedimentary cover at 1:5M; 10 – N. Kumar et al. 2010 (unpublished material). Tectonic and Stratigraphic Interpretation of a New Regional Deep-seismic Reflection Survey offshore Banks Island; 11 – D.C. Mosher et al. 2012 (unpublished material). Sediment Distribution in Canada Basin; 12 – N.A. Petrovskaya et al. 2008 (unpublished material). Main features of the geological structure of the Russian Chukchi Sea; 13 – I.Yu. Vinokurov et al. 2013 (unpublished material). Sedimentary cover thickness from seismic profiles of the expedition Arctic-2012

Sedimentary cover thickness decreases to 1 km and less on the ridges separating the basins (Lomonosov – New Siberian, Alpha – Mendeleev – Wrangel), where the basement with different age of formation and folding is outcropped. Among positive structures, the Gakkel Ridge should be noted as one of the youngest oceanic spreading systems with outcrops of Cenozoic oceanic basement, which is formed in the axial part of the Eurasian sedimentary basin.

The map of sedimentary cover thickness of the Arctic is of extraordinary importance for evaluation of oil and gas resources. It is shown by the map of sedimentary successions prospective for hydrocarbons compiled by A. Grantz in 2010.

Assessment of the petroleum potential of the Arctic Region is handicapped by incomplete knowledge of the location, character, age and geologic setting of the sedimentary successions that underlie this large, remote and incompletely mapped region.

The map attempts to fill this void by displaying all of the supra-continental and submarine sedimentary successions in the Arctic Region (variously 58–64 to 90°N) that are known or inferred to lie at or near the land surface or the seafloor on the basis of currently available data. The map consists of four quadrants – Alaska and Arctic Canada, East Siberia, Barents/Kara, and Greenland) at a uniform of 1 : 6.76M scale. This scale was chosen because it is the largest that will allow the map to be printed on standard 42 inch wide printer paper.

A total of 143 sedimentary successions known to contain hydrocarbons that were either generated internally or expelled from other successions, or which appear to be sufficiently thick to warrant at least consideration of their hydrocarbon potential based on their known or inferred thermal gradients, were identified in the Arctic Region in the present study. The successions range in age from Late Mesoproterozoic (mid-Riphean) to Cenozoic and, within the confines of the Arctic Region, range in size from less than 100 to more than 50,000 sq. km.

Among the greatest uncertainties concerning future energy supply is the volume of oil and gas remaining to be found in high northern latitudes. The potential for resource development is of increasing concern to the Arctic nations, to petroleum companies, and to all concerned about the region's fragile environments. These concerns have been heightened by the recent retreat of polar ice, which is changing ecosystems and improving the prospect of easier petroleum exploration and development. For better or worse, limited exploration opportunities elsewhere in the world combined with technological advances make the Arctic increasingly attractive for development. To provide a perspective on the oil and gas resource potential of the region, the US Geological Survey (USGS) completed a geologically based assessment of the Arctic, the Circum-Arctic Resource Appraisal (CARA), which exists entirely in the public domain [Gautier et al. 2011].

About 30% of the world's undiscovered gas and 13% of the world's undiscovered oil may be in the Circum-Arctic, mostly offshore under less than 500 meters of water. Undiscovered natural gas is three times more abundant than oil in the Arctic and is largely concentrated in Russia. Oil resources, although important to the interests of Arctic countries, are probably not sufficient to substantially shift the current geographic pattern of world oil production.

These estimates do not include technological or economic risks, so a substantial fraction of the estimated undiscovered resources might never be produced. Development will depend on market conditions, technological innovation, and the sizes of undiscovered accumulations. Moreover, these first estimates are, in many cases, based on very scant geological information, and our understanding of Arctic resources will certainly change as more data become available.

REFERENCES

Artemieva, I.M., Thybo, H. 2013: EUNAseis: A seismic model for Moho and crustal structure in Europe, Greenland, and the North Atlantic region. *Tectonophysics*. 609. 97–153. doi: 10.1016/j.tecto.2013.08.004.

Divins, D.L. 2008: *NGDC Total Sediment Thickness of the World's Oceans & Marginal Seas*. http://www.ngdc.noaa.gov/mgg/sedthick/sedthick.html.

Drachev, S.S., Malyshev, N.A., Nikishin, A.M. 2010: Tectonic history and petroleum geology of the Russian Arctic Shelves: an overview. *In* Vining, B.A., Pickering, S.C. (eds.): *Petroleum Geology: From Mature Basins to New Frontiers. Proccedings of the 7th Petroleum Geology Conf.* Geol. Soc., London. 7. 591–619.

Gautier, D.L., Bird, K.J., Charpentier, R.R., Grantz, A., Houseknecht, D.W., Klett, T.R., Moore, T.E., Pitman, J.K., Schenk, C.J., Schuenemeyer, J.H., Sörensen, K., Tennyson, M.E., Valin, Z.C., Wandrey, C.J., 2011: Chapter 9. Oil and gas resource potential north of the Arctic Circle. *Arctic Petroleum Geology.* Geol. Soc., London, Mem. 35. 151–161.

Gramberg, I.S., Verba, V.V., Verba, M.L., Kos'ko, M.K., 2001: Sedimentary Cover Thickness Map – Sedimentary Basins in the Arctic. *Polarforschung*. 69. 243–249.

Grantz, A., Scott, R.A., Drachev, S.S., Moore, T.E., Valin, Z.C. 2011a: Sedimentary successions of the Arctic Region (58–64 to 90 degrees N) that may be prospective for hydrocarbons. *Arctic Petroleum Geology.* Geol. Soc., London, Mem. 35. 17–37.

Grantz, A., Hart, P.E., Childers, V.A. 2011b: Geology and tectonic development of the Amerasia and Canada Basins, Arctic Ocean. *In* Spencer, A.M., Embry, A.F., Gautier, D.L., Stoupakova, A.V., Sörensen, K. (eds.): *Arctic Petroleum Geology*. Geol. Soc., London, Mem. 35. 771–799.

Laske, G., Masters, G., 2010: *A Global Digital map of Sediment Thickness.* EOS Transactions American Geopfisical Union. 78. F 483. http://igppweb.ucsd.edu/~gabi/sediment.html.

Poselov, V., Butsenko, V., Chernykh, A., Glebovsky, V., Jackson, H.R., Potter, D.P., Oakey G., Shimeld, J. and Marcussen, C. 2011a: The structural integrity of the Lomonosov Ridge with the North American and Siberian continental margins. *Proceedings of the International Conference on Arctic Margins VI, Fairbanks, Alaska, May 2011*. 233–258. http://www2.gi.alaska.edu/icam6/proceedings/web/

Poselov, V.A., Avetisov, G.P., Kaminsky, V.D. et al. 2011b: *Russian Arctic geotraverses*. VNIIOkeangeologia, St. Petersburg. 172.

Poselov, V.A., Zholondz, S.M., Trukhalev, A.I. et al. 2012: Map of sedimentary cover thickness in the Arctic Ocean. *Geological and geophysical characteristics of the lithosphere of the Arctic region.* VNIIOkeangeologia, St. Petersburg. 223 (8). 8–14.

Petrov, O., Smelror, M., Morozov, A., Shokalsky, S., Kashubin, S., Artemieva, I.M., Sobolev, N., Petrov, E., Ernst, R.E., Sergeev, S. 2016: Crustal structure and tectonic model of the Arctic region. *Earth-Science Reviews.* Elsevier. 154. 29–71.

Smelror, M., Petrov, O., Larssen, G.B., Werner, S. (eds.). 2009: *Atlas – Geological history of the Barents Sea.* Geological Survey of Norway, Trondheim. 135.

TECTONIC PROVINCES OF THE ARCTIC

O.V. Petrov, S.P. Shokalsky, S.N. Kashubin, G.E. Grikurov, E.O. Petrov, K. Piepjohn,
N.N. Sobolev, I.I. Pospelov, S.D. Sokolov, T.Yu. Tolmacheva

The Map of tectonic provinces of the Arctic compiled in a result of work on the tectonic map under the project Atlas of Geological Maps of the Circumpolar Arctic is based on recent geological and geophysical studies of the Arctic Ocean and Arctic islands, investigations of dredged seafloor material from Central Arctic uplifts. The tectonic provinces of the Arctic areas were defined considering the types of Earth crust, age of consolidated basement, and characteristics of geological structures of the sedimentary cover.

Keywords: *Tectonic zones, Circumpolar Arctic, regional geology, tectonics*

The Map of tectonic zoning of the Arctic (fig. 19) was compiled as a result of work on the tectonic map under the project Atlas of Geological Maps of the Circumpolar Arctic and is based on results of processing geological and geophysical data obtained over recent years during field studies. The tectonic zoning of the Arctic areas was made taking into account crustal types, age of consolidated basement, and characteristics of geological structures of the sedimentary cover. The legend for the map of zoning includes five main groups of elements: continental and oceanic crust, folded platform covers, accretion-collision systems, and provinces of continental basalt cover (fig. 20). An important feature of the map of tectonic zoning is showing the continental crust in central regions of the Arctic Ocean, the existence of which is assumed from numerous geological data.

It should be noted that suggestions on the existence of continental blocks in the Arctic Ocean were made at the very beginning of studying the tectonic structure of the Arctic. In 1959, first color tectonic map of the Arctic was compiled under the supervision of N.S. Shatsky. It was made in the polar map projection at 1:7M scale and in 1960 a black and white version was published. It showed outlines of two platforms in the water area of the Arctic: Barents Platform (or Barentsia) in the western part and Hyperborean Platform in the eastern part. The outlines of these two platforms were used again in the Tectonic map of the Arctic at 1:10M scale (1963) compiled by M.V. Muratov and A.L. Yanshin based on the N.S. Shatsky's map. On this map, the Hyperborean Platform occupies most of the Chukchi and East Siberian seas from the Lomonosov Ridge to Mesozoides of Alaska, Chukotka and Verkhoyansk Range, Variscides of the Canadian Arctic Archipelago. The Barents Platform fully occupied the Barents Sea between Severnaya Zemlya and Novaya Zemlya, Svalbard with the center in the Franz Josef Land Archipelago. In fact, the Northeast and the Canadian Arctic Archipelago were directly connected by the structures of the Eurasian Basin and the Lomonosov Ridge via the Hyperborean Platform.

The Tectonic Map of the Arctic and Subarctic at 1:5M (1967) prepared under the guidance of I.P. Atlasov, for the first time ever showed the existence of transitional structures between the cratons and folded systems, between continental and oceanic crust. This study suggested much more widespread occurrence of fold belts in the Arctic water area and cast some doubt on the existence of a single large and homogeneous Hyperborean Platform.

The detailed Tectonic Map of the Arctic by B.H. Egiazarov [Egiazarov et al. 1977] reflected the conception of the existence of heterogeneous Arctic Fold Belt formed on the periphery of the Hyperborean Platform with Archaean – Paleoproterozoic and Early-Middle Paleozoic basement.

Tectonic structure of the Arctic was also discussed by V.E. Hain and his followers [Hain, 2001; Filatova & Hain 2007, etc.; Drachev 2011]. In the central part of the Arctic Ocean, he identified areas of heterochronic oceanic crust with continental-type crust, and intraplate oceanic crust elevations. The possibility of the assignment of the crust in the Makarov and Toll (Podvodnikov) basins to the transitional type is assumed. He classified the Lomonosov, Alpha, Mendeleev structures and the Chukchi Plateau as the continental-type crust.

Currently, the Central Arctic is regarded as a collage of fragments of a Neoproterozoic craton, which underwent destruction during the Paleozoic-Cenozoic evolution and covers almost the entire of the Arctic region exposing along the continental framing of the North Atlantic and Eurasian ocean basins at Novaya Zemlya, Taimyr Peninsula, Kara Massif, New Siberian Islands, De Long Archipelago, Wrangel Island, Seward Peninsula, Canadian Arctic

---

To cite: Tectonic provinces of the Arctic / O.V. Petrov [et al.] // Scientific contributions to the Tectonic Map of the Arctic. Paris, 2019. P. 40–52.

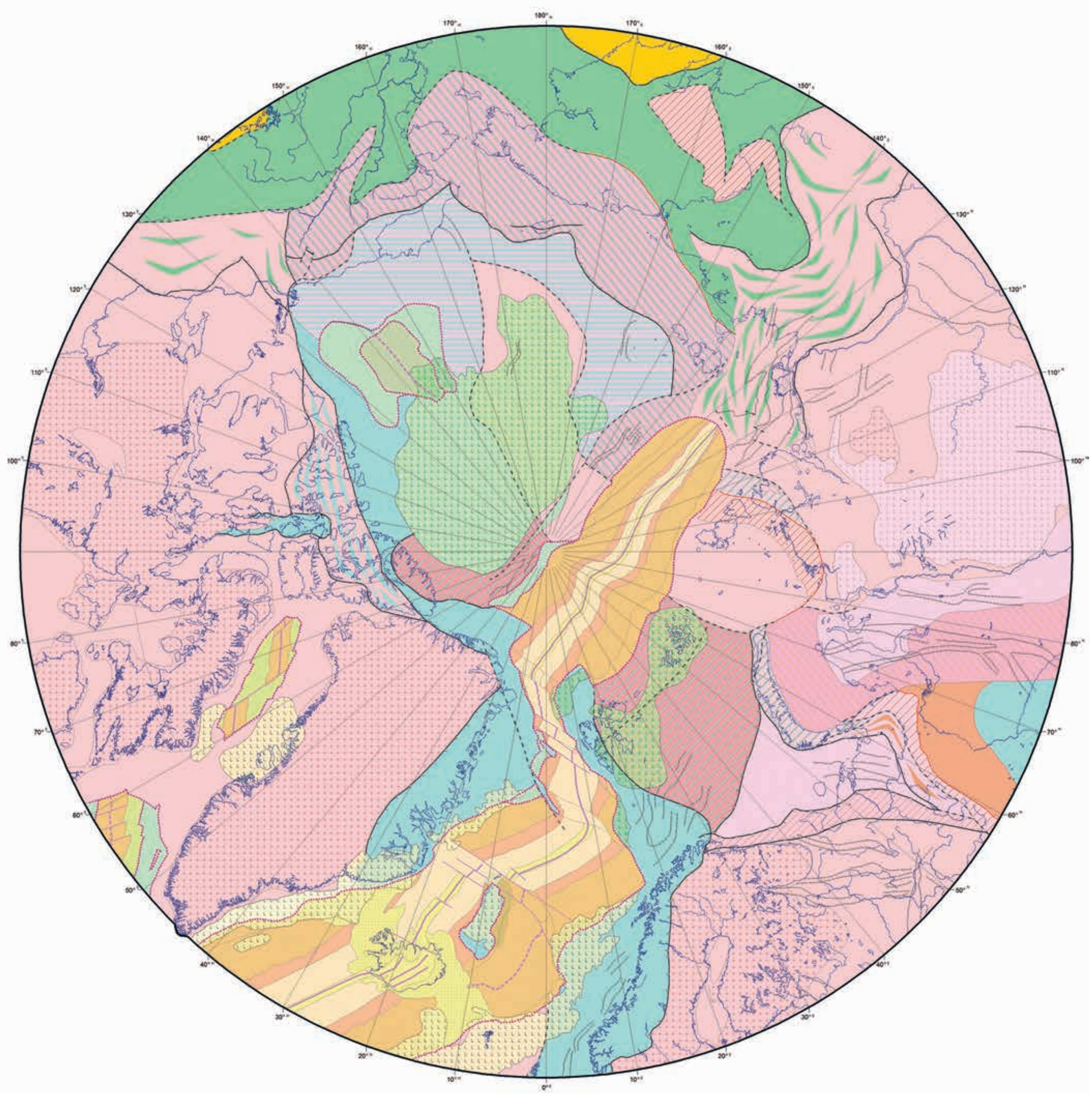


Fig. 19. Map of the Arctic basement tectonic provinces. Materials used: Pease et al. 2014; Harrison et al. 2011; Grantz et al. 2009; Petrov et al. 2015; Morozov et al. 2013; Proskurnin et al. 2012; Daragan-Sushchova et al. 2014; Vernikovsky et al. 2013; and other data

Archipelago and elsewhere [Zonenshain & Natapov 1987; Lawver et al. 2002].

Reliable evidences of the oceanic crust expressed as well-defined structures of the Late Cretaceous – Cenozoic spreading are inherent in the Baffin Bay, Norwegian-Greenland and Eurasian basins. In two small areas located in the center of the southern part of the Canada Basin and in the Makarov Basin, there are indistinct signatures of abandoned spreading, which suggest the presence of enclaves of Mesozoic oceanic crust (Transition O/C Zone).

More than half of the modern distribution area of the continental lithosphere in the Arctic is occupied by the Archaean-Paleoproterozoic continental crust. Its original and/or changed crystalline complexes are preserved in the basement of Precambrian Eastern European, Siberian and North American cratons. Tectonic activation of marginal parts of the cratons adjacent to (Meso?)-Neoproterozoic-Phanerozoic accretion-collision belts caused folded deformations of old platform covers transformed to Ellesmerides of the Franklin Fold Belt and Mesozoides

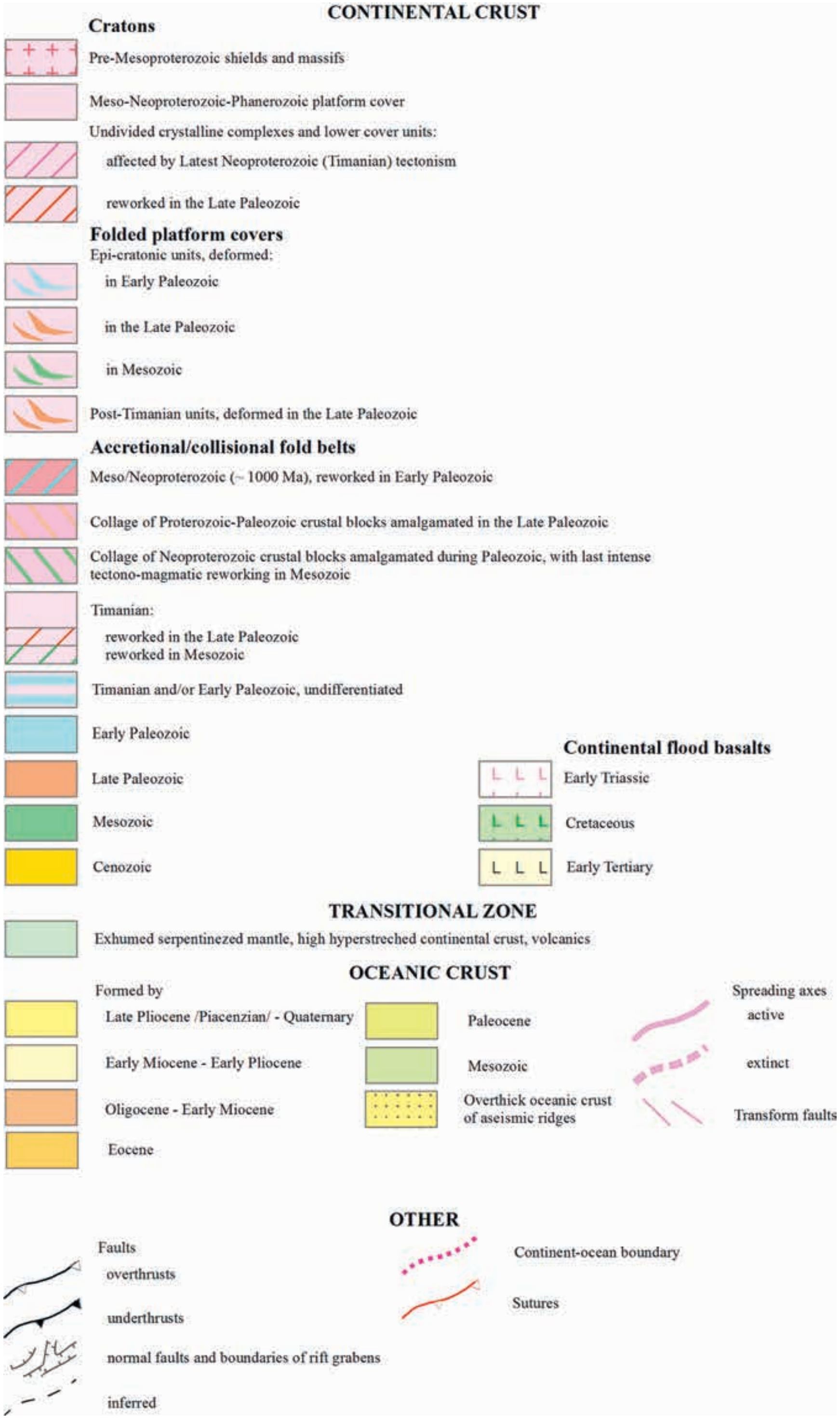


Fig. 20. Legend to the map of the Arctic tectonic provinces

of the Verkhoyansk and South Taimyr fold belts. Archean – Mesoproterozoic convergent processes not only modified peripheral areas of the cratons, but also significantly increased the old continental basement. Grenvillian crust reworked by Early-Middle Paleozoic (Caledonian-Ellesmerian) tectogenesis is identified in the northern part of Ellesmere Island (Pearya Terrane), on the Svalbard and Franz Josef Land archipelagoes and in the basement of the Barents Sea Basin and the near-Greenland segment of the Lomonosov Ridge combined in the pre-spreading reconstruction with the Barents Sea continental margin.

Timanides of the Polar Urals and Pay-Khoy suffered the impact of the Late Paleozoic (Uralian) orogeny that completed the consolidation of the West Siberian and South Kara basins basement. In continuation of the Timan Fold Belt across

Novaya Zemlya and Central Taimyr, the strongest reworking of the Late Neoproterozoic crust occurred during the Early Cimmerian orogeny in the Late Triassic–Early Jurassic. Continental crust of Kolyma and south Chukotka increased during the Cretaceous due to the structures of the Okhotsk Volcanic Belt that formed at that time.

Vast “superterrane”, which extends from central Alaska to the New Siberian Archipelago across north Chukotka and southern parts of the Chukchi and East Siberian seas, is interpreted as a collage of Neoproterozoic protoliths, which amalgamated into a single continental block during the Paleozoic. During the Mesozoic collision of this block with Northeastern Asia and south Alaska, it underwent tectonomagmatic reworking to form the compound Late Mesozoic Novosibirsk-Chukotka-Alaska Fold Belt most of which was buried under the Upper Cretaceous-Cenozoic cover in the inland shelf.

Within the outer shelf of the East Siberian and Chukchi seas, Chukchi Borderland, the Beaufort Sea and the North Slope of Alaska, the folded basement is almost entirely hidden under the Middle(?)-Upper Paleozoic – Cenozoic cover reaching in places up to 20 km in thickness. Scarce geological data (observations on De Long northern islands, drilling in the American part of the Chukchi Sea, dredging of bottom rocks of the Chukchi Borderland) suggest mostly Timan-Caledonian formation of the crust, which locally probably also hosts Grenville and older protoliths.

The continental crust, transformed to various degrees by stretching and intensive basaltic magmatism, which led to the HALIP formation, also underlies the Alpha Ridge and Mendeleev Rise and most of negative elements of bottom topography [Poselov et al. 2007; Pease et al. 2014]. Seismic data show that the thickness of the continental crust varies widely: from 30–32 km in the Mendeleev Rise to 18–20 km in the Lomonosov Ridge, decreasing to 8–10 km in rift structures of the Makarov Basin due to the reduction of the upper crust layer.

Taking into account the current level of knowledge of the Alpha Ridge and the Mendeleev Rise, the crust of which is armored by volcanic products and modified by deep magmatism, its internal structure cannot be identified and this area is shown on the map of tectonic zoning without subdivision into individual tectonic provinces. The same approach is used for mapping Mendeleev and Chukchi submarine plains and the eastern part of the Podvodnikov Basin wherein the crust that underwent magmatogenic impact is moderately submerged beneath the basement of sedimentary basins, as well as the periphery of the south Canada Basin, where the extremely stretched crust is buried under thick sedimentary cover and almost five kilometers of the water layer.

More detailed descriptions including the justification of the continental crust age are given below for individual morphostructures of the Central Arctic Ocean (fig. 21).

The Arctic Ocean is the smallest and youngest Earth’s ocean [Gramberg 2002]. It is subdivided into Eurasian and Amerasian Basins that differ in topography and geological and geophysical characteristics of the seafloor.

The **Eurasian Basin** includes abyssal basins (Nansen and Amundsen Basins) separated by the mid-oceanic Gakkel Ridge with axial rift valley (fig. 22). Along the continent-ocean boundary (COB), it borders the Barents-Kara, Amerasian, and Laptev sea rift passive margins [Jokat, Micksch 2004]. The Eurasian Basin has a length of about 2000 km and a width of up to 900 km. To the west, its tectonic boundary corresponds to the Svalbard transform fault system (De Geer Fault), to the east – the Lomonosov Ridge and the Laptev Sea continental margin. The Gakkel Ridge separates the basin into two basins: the Amundsen Basin, adjacent to the Lomonosov Ridge, and the Nansen Basin that emborders the Eurasian shelf.

Gakkel Ridge is an extended linear rise with a dissected relief. The ridge is surrounded by abyssal plains along the entire length (1800 km), but close to the Laptev Sea shelf, it gets in contact with an elevation. East of 70° E, a distinct asymmetry is recorded in the structure of the ridge. In the Nansen Basin part, it is noticeably narrower, and the abyssal plain is almost in contact with the rift valley, and from the Amundsen Basin part, a broad plateau, elevated above the abyssal plain at 200–400 m and complicated by mountains and ridges, is clearly traced in the relief of the ridge. Topography of the rift valley, its depth and other features are impermanent and experience consistent alterations in four blocks of the ridge, which follow one another along the strike. The width in the ridge zone topography is less than 200 km, rift valley depths range from 5000–5200 m near the Laptev Sea shelf to 4300 m in the central and 4500–5000 m in the Greenland part [Naryshkin 1987; Orographic... 1995, etc.].

In the **Nansen and Amundsen Basins**, the bottom is represented by subhorizontal abyssal plains. The greatest depths reach about 4000 m in the Nansen Basin and about 4,500 m in the Amundsen. In the Amundsen Basin, maximum depths are concentrated in its axial part, whereas in the Nansen Basin the area with the greatest depths is located in the western part of the basin settings [Orographic... 1995].

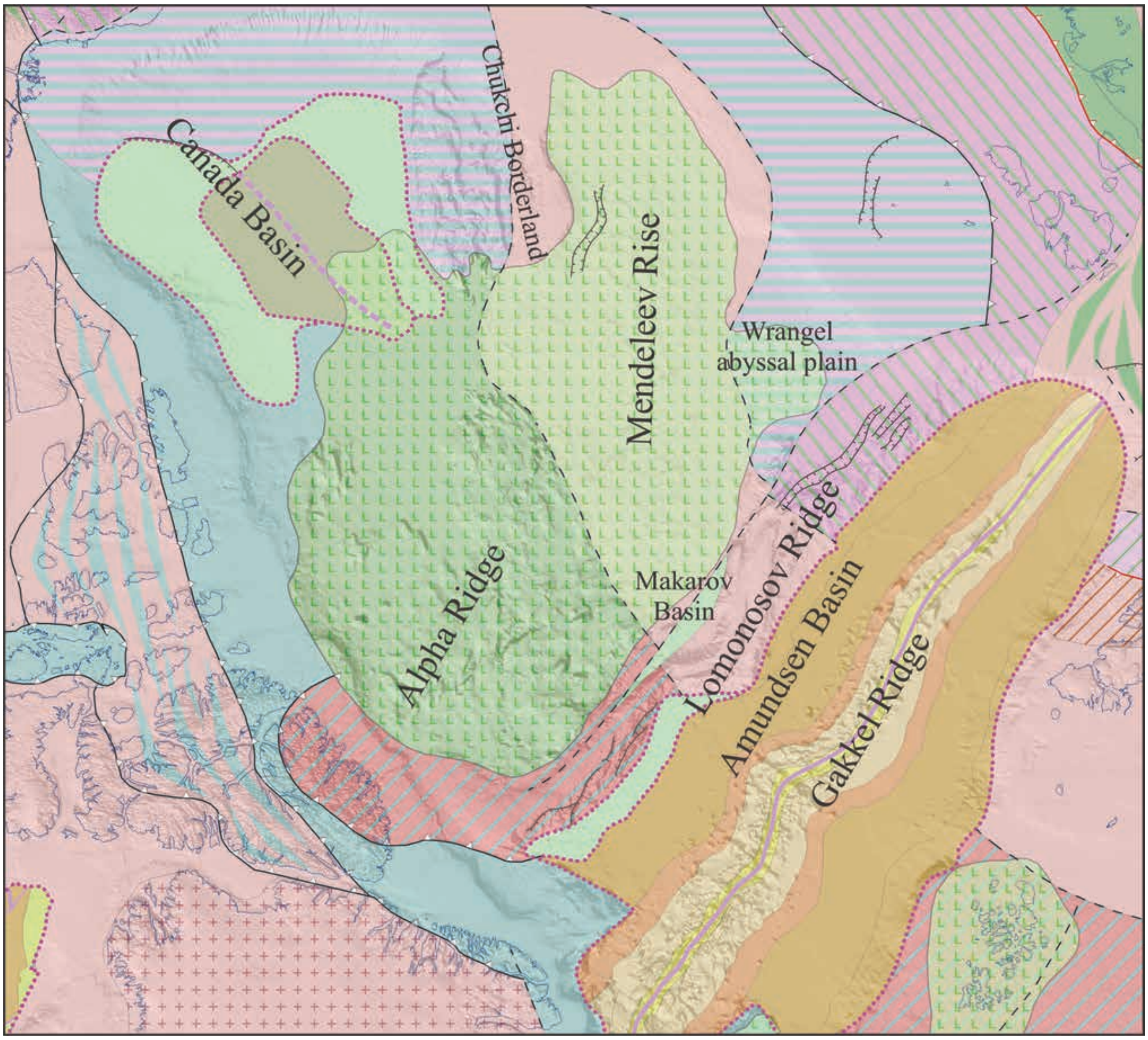


Fig. 21. Map of the Arctic basement tectonic zoning combined with the bathymetric map of the Central Arctic (symbols in fig. 34)

The Amerasian Basin boundary is located along the base of the western slopes of the Lomonosov Ridge. It is the largest deep-water basin in the Arctic, and issues related to its structure and history of formation are fundamental for reconstructing the history of the evolution of the Earth.

A significant part of the Amerasian Basin is occupied by extensive Central Arctic uplifts (Alpha and Lomonosov Ridges, Mendeleev Rise, Chukchi Borderland). The area of the Central Arctic uplifts “partitions” the central part of the Arctic Ocean between the Greenland and the Canadian Archipelago shelves on one side and the East Asian one on the other. This area includes not only large positive forms of the seafloor topography, but also dividing extensive depressions (Podvodnikov, Makarov and Nautilus Basins, Mendeleev and Chukchi abyssal plains) and a variety of smaller morphostructures in the intermediate depth interval that complicate first-order features.

The **Makarov Basin** is separated from the Eurasian Basin by the Lomonosov Ridge. According to some last publications [Miller et al. 2017] it is an enclave of the ocean floor, surrounded by continental slopes, namely the outer, tectonically dissected continental slopes. The slope of the basin, shared with the Lomonosov Ridge, is called the Shmakov Escarpment. It is much steeper and higher than the opposite side of the depression. From the Greenland-Ellesmere shelf, the deep Marvin Spur opens to the Makarov Basin. The abyssal plain in the basin floor is outlined by an isobath of 3,800 m.

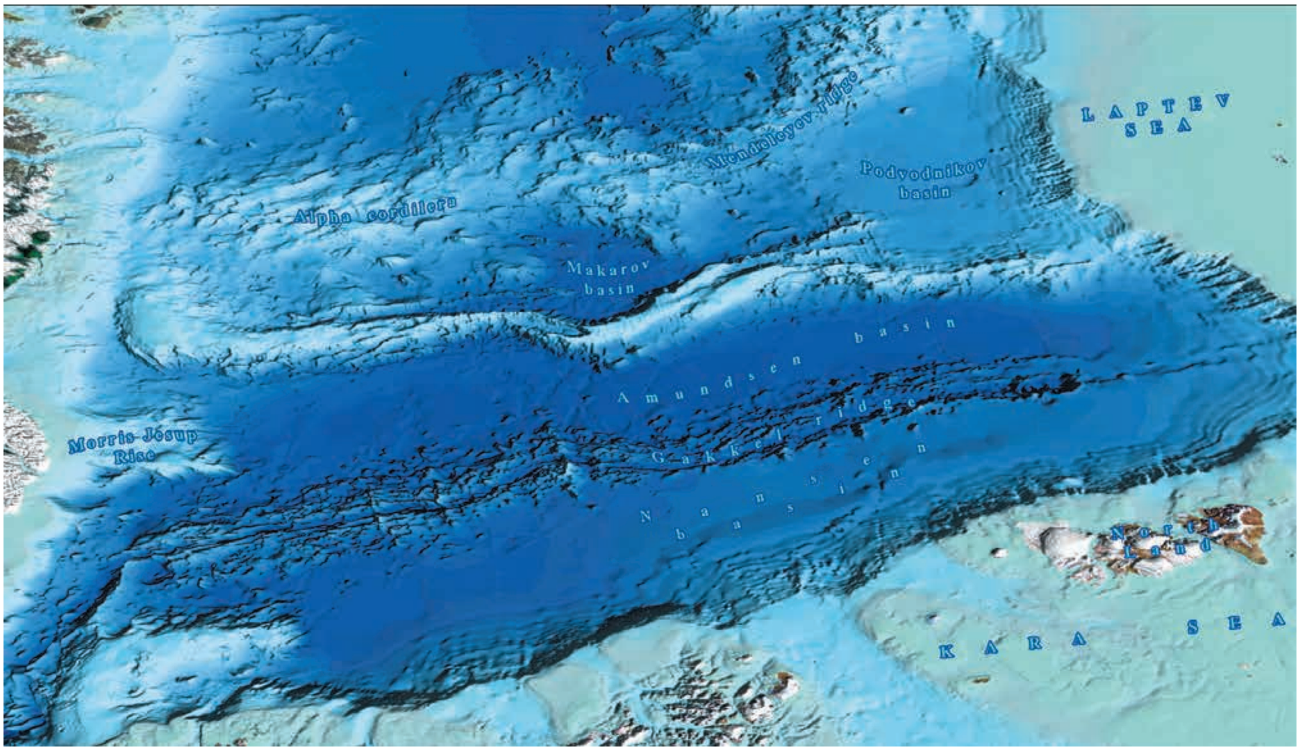


Fig. 22. 3D-image of the Nansen and Amundsen Basins with the continental slope foot of the Laptev Sea shelf (IBCAO model, version 3.0)

Only in some small areas, the depths in the basin exceed 4000 m. The bottom of the basin is flat, leveled, complicated by an extended asymmetric ridge about 800 m high, which continues westward the Marvin Spur.

Lomonosov Ridge is a rise of the seabed, which extends for almost 1,800 km across the Arctic Ocean from the Lincoln Shelf to the East Siberian Shelf. The width of the rise, which has a flat top slightly rounded on the crest, is 45 to 200 km, the height runs up to 4200 m. Seismostratigraphic analysis shows that the formation of the Lomonosov Ridge as a positive structure began in the Cretaceous. During the late Early Cretaceous (Aptian-Albian), the Lomonosov Ridge developed as a sediment-covered rise, which supplies clastic material to the adjacent depressions. This is evidenced by pinching-out of the Lower Cretaceous seismostratigraphic complex towards the dome of the Lomonosov Ridge. Taking into account that Cretaceous sediments both in the Lomonosov Ridge [Dove et al. 2010] and the Laptev Sea Shelf are represented by continental and onshore-offshore coal-bearing formations, this rise is interpreted as intracontinental.

Lomonosov Ridge as a morphostructure of the modern Arctic Ocean formed during the Miocene. At that time the shallow-water sediments turned into deep-water ones [Dove et al. 2010]. At present, the continental nature of the Lomonosov Ridge uplifting is practically undebatable. The seismostratigraphic analysis showed that structures of the Laptev Sea Shelf continue in the Lomonosov Ridge. The structural-tectonic zoning of the Laptev Sea Shelf with the involvement and partial processing of 35,000 liner km of seismic profiles enabled identification (based on features of the basement and sedimentary cover structure) of two subbasins in the Laptev Sea Shelf: Western and Eastern Laptev Sea. Comparative analysis of composite seismic profiles showed similar features in the structure of the basement and sedimentary cover of the Lomonosov Ridge and the East Laptev Subbasin. In the basement of these structures there is an intermediate complex, which similar to the New Siberian Islands is interpreted as slightly dislocated Paleozoic – Early Mesozoic deposits. Surveys carried out on the New Siberian Islands showed thet the East Laptev Subbasin is filled with an assemblage of platform carbonate and terrigenous sediments formed in the Baikalian crystalline basement reprocessed during the Caledonian and Cimmerian phases of tectonogenesis. On the shelf, in the acoustic basement of the continental block, there are fragments of a layered seismic record corresponding to slightly dislocated Paleozoic and Mesozoic strata known on the New Siberian Islands.

Lomonosov Ridge underwent HALIP magmatic manifestations only in local areas. Spreading processes are mainly reflected there in the formation in the upper crust of numerous contrasting horst-graben structures that were not leveled by sedimentation and are well pronounced in the bottom relief. The upper crust is slightly thinned, and between its surface and the acoustic basement there is an almost ubiquitous intermediate seismic layer, conventionally referred to as "metasedimentary" [Poselov et al. 2011a,b; Jackson et al. 2010]. This layer is apparently composed of moderately metamorphosed folded complexes of a wide age range silicaclastic rocks [Knudsen et al. 2017; Morozov et al. 2013; Kabankov et al. 2004; Rekant et al. 2012; Vernikovsky et al. 2014a; Grikurov et al. 2014].

Dominant distribution of these rock groups in different segments of the Lomonosov Ridge is shown on the map of zoning on the assumption of an echelon alternation of heterochronic crust blocks correlated with the conjugate Barents-Kara continental margin.

Mendeleev Rise as a denudation area, which has existed at least since the Paleozoic – since the formation of the Post-Ellesmerian North Chukchi Trough. Formation of the eastern flank of the Mendeleev Rise is related to the Early Cretaceous rifting. The Charlie Rift, at that time, separated the Mendeleev Rise from the Chukchi Plateau. The Mendeleev Rise, as a morphostructure of the Arctic Ocean, similar to the Lomonosov Ridge, was formed during the Neogene-Quaternary.

Judging by prevailing Paleozoic carbonate dredged bottom rocks, the Mendeleev Rise, similar to the Chukchi Borderland and Northwind Ridge, is represented by submerged (during the neotectonic phase) fragments of a continental crust block with old Precambrian crystalline basement (fig. 23). This block includes a Paleozoic platform cover of the continent, known in literature as Hyperborea, Eastern Arctic Platform [Kabankov et al. 2004] or Arctida [Hain et al. 2009]. It is quite possible that the Paleozoic cover of the Mendeleev Rise was slightly affected by the Caledonian folding recorded southwards, in the North Chukchi Trough.

As shown by the data obtained during the expedition "Arctic-2012", overwhelming amount of large-size bottom rock material (BRM), dredged from steep submarine scarps is represented by sedimentary littoral and shallow marine carbonate and terrigenous rocks [Morozov et al. 2013] (fig. 24). The composition of the sediments and their ages indicate the presence of the platform unmetamorphosed Ordovician-Devonian Carboniferous-Permian sedimentary cover in the Mendeleev Rise (fig. 25).

In 2014 and 2016, the Geological Institute of the Russian Academy of Sciences (GIN RAS) in cooperation with the Geological and Geophysical Survey of the Geological Institute (GEOSLUZHBA GIN) and the Main Directorate for Deepwater Research of the Ministry of Defense of the Russian Federation conducted expeditions in the Alpha-Mendeleev Rise.

Rocks sampled by research submarine manipulators directly from bottom outcrops proved the existence of the Lower Paleozoic mainly carbonate cover on the Mendeleev Rise [Skolotnev et al. 2017; 2019]. Among sedimentary rocks exposed in steep slopes of the Mendeleev Rise, three stratigraphic units were identified: the Ordovician-Silurian, Middle-Late Devonian and Early Cretaceous.

On the other hand, seismic data show that in the Mendeleev Rise, the sedimentary cover is represented by Cretaceous and Cenozoic sediments overlying the acoustic basement. To explain this controversy, it should be mentioned that in the Central Arctic Uplifts, primarily in the Alpha-Mendeleev Rise, large intense magnetic anomaly was recorded [Verba 2006]. According to its image, amplitude-frequency characteristics and the scale, this vast region is comparable with the areas of flood basalt large igneous provinces. This assumption was confirmed by the results of seismic interpretation obtained during the cruise of the US icebreaker "Healy" in 2005. Several seismic facies interpreted as sequences of basaltic sheets and sills, intercalating with thick tuff layers and, probably, sedimentary rocks were identified below hemipelagic sediments in the Mendeleev Rise and the north-western part of the Alpha Ridge at the top of the acoustic basement [Bruvoll et al. 2010]. Observed cut tops of basement highs are treated as surface erosion of the Mendeleev Rise in a shallow sea, which took place simultaneously with or immediately after its formation. The time of formation of the volcanic rocks in the investigated part of the Alpha Ridge and the Mendeleev Rise is defined as the Aptian-Campanian (112–73 Ma) by Ar/Ar analysis [Mukasa et al. 2015] (fig. 26).

The Ar/Ar isotopic analysis of dolerites from Mendeleev Rise obtained in Arctic-2012 expedition shown an Early Paleozoic age. The oldest ages obtained for amphibole reach 471.5 ± 18.1 and 466.9 ± ± 3.3 Ma, which corresponds to the Early–Middle Ordovician [Vernikovsky et al., 2014b].

Updating of the areas of cretaceous volcanic complexes' distribution is based on the seismostratigraphic analysis of wave fields from seismic profiles. In the Central Arctic Uplifts, anomalies of wave fields were recorded in the sedimentary cover that can be related to magmatic activity in the study area. In the Mendeleev Rise, areal covering volcanics occur over a large area, covering moderately layered weakly folded strata. Their approximate

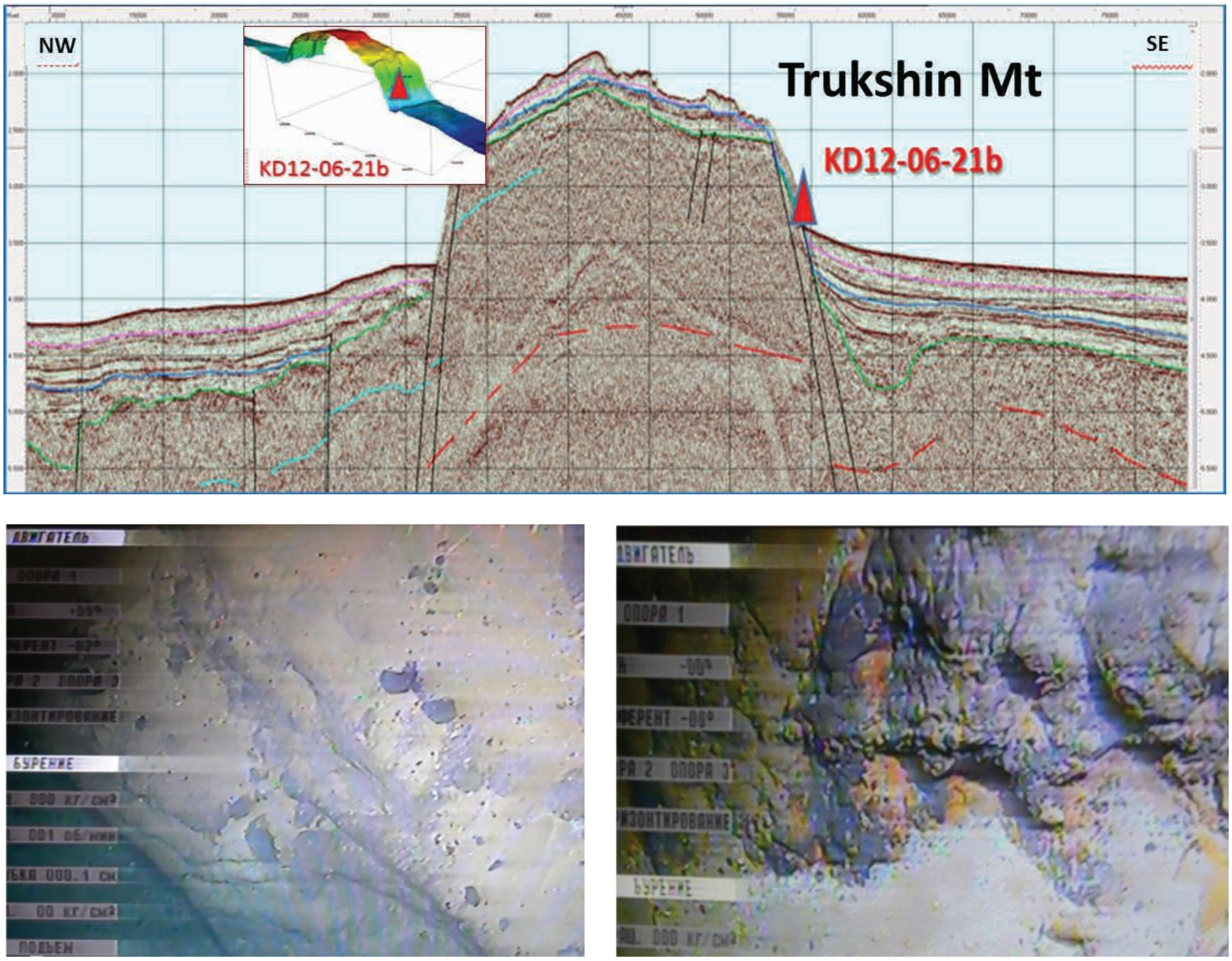


Fig. 23. Outcrops of basement rocks traced in seismic profiles and taken (captured) on videocamera from a drilling rig (site 06, Trukshin Mt in the North of the Mendeleev Rise, exp. "Arctic-2010")

thickness varies greatly, from a few hundred meters in local highs to 1–1.5 km in recent sinking of the basement. Volcanic sheets are exclusively localized in the bottom of the sedimentary cover that allows approximate assessment of the age of acoustic basement from the age of traps, as well as the evaluation of stratigraphic extent of the sedimentary cover. According to sampling results, in the Alpha Ridge, the oldest sediments of the cover and the underlying basalts are Campanian (~ 82 Ma) [Jokat 2003]. This age is much younger than the expected time of the opening of the Canada Basin (~148–128 Ma) and older than the time of the opening of the Eurasian Basin (~56 Ma) (fig. 27).

In the Mendeleev Rise, the Russian expedition "Arctic-2012" drilled 3 short (⩽ 2 m) wells in two locations. All of them penetrated the acoustic basement composed of Cretaceous basalts and trachybasalts in the south (~102–73 Ma) and late Cretaceous volcanic breccia (73 Ma) in the northern part of the rise (Ar-Ar method). Similar Cretaceous subalkaline and tholeiitic basalts were dredged in the northern spur of the Northwind Ridge [Brumley et al. 2015]. Ar-Ar determinations showed later Cretaceous age than U-Pb method [Morozov et al. 2013]. Based on available basalt datings, the age of riftogenic movements can be defined as the late Early Cretaceous – Late Cretaceous. Judging by correlated reflectors, next stage of activation of tectonic movements is Paleocene – Oligocene. Formation of the largest seamounts of the Mendeleev Rise is related to them. Wells in the American sector of the Chukchi Sea recorded deep erosion with missing Oligocene and even Miocene sediments that correspond to eustatic minimum of about 33 million years. Since the thickness of Miocene-Holocene sediments on the raised areas of the Mendeleev Rise is minimal, it is quite possible that the process of uplifting of Paleocene-Oligocene highs has intensified again.

Fig. 24. Rock samples from the bottom outcrops of the Mendeleev Rise ("Arctic-2010")

The Mendeleev Rise is the main area of HALIP distribution (fig. 27). In this area, along with intensive basaltic magmatism and block-faulting structures, the spreading is evidenced by significant thinning of the upper crust, which nevertheless retains the "continental" total thickness due to the increase of the lower layer by magmatic underplating. Similar to the Lomonosov Ridge, between the acoustic basement and the upper crust surface, there is an intermediate (metasedimentary) layer, whose seismic transparency is caused by abundant magmatic rocks.

Podvodnikov Basin has a block structure. There are western and eastern blocks separated by the uplift of the Geophysists Spur. Analysis of seismic profiles showed that this separation occurred during the Cretaceous. Despite the fact that the total thickness of sedimentary cover in the basin is almost the same, the eastern and western parts of the basin are characterized by different wave fields. Abundant seismic complexes are recorded in the eastern part. Layer velocities in the basement in the east Podvodnikov Basin reach 5.9–6.3 km/s which is typical of mature basements. Such characteristics of the basement are also observed in the North Chukchi Basin. Unfortunately, there are no reliable velocities in the basement in the western part of

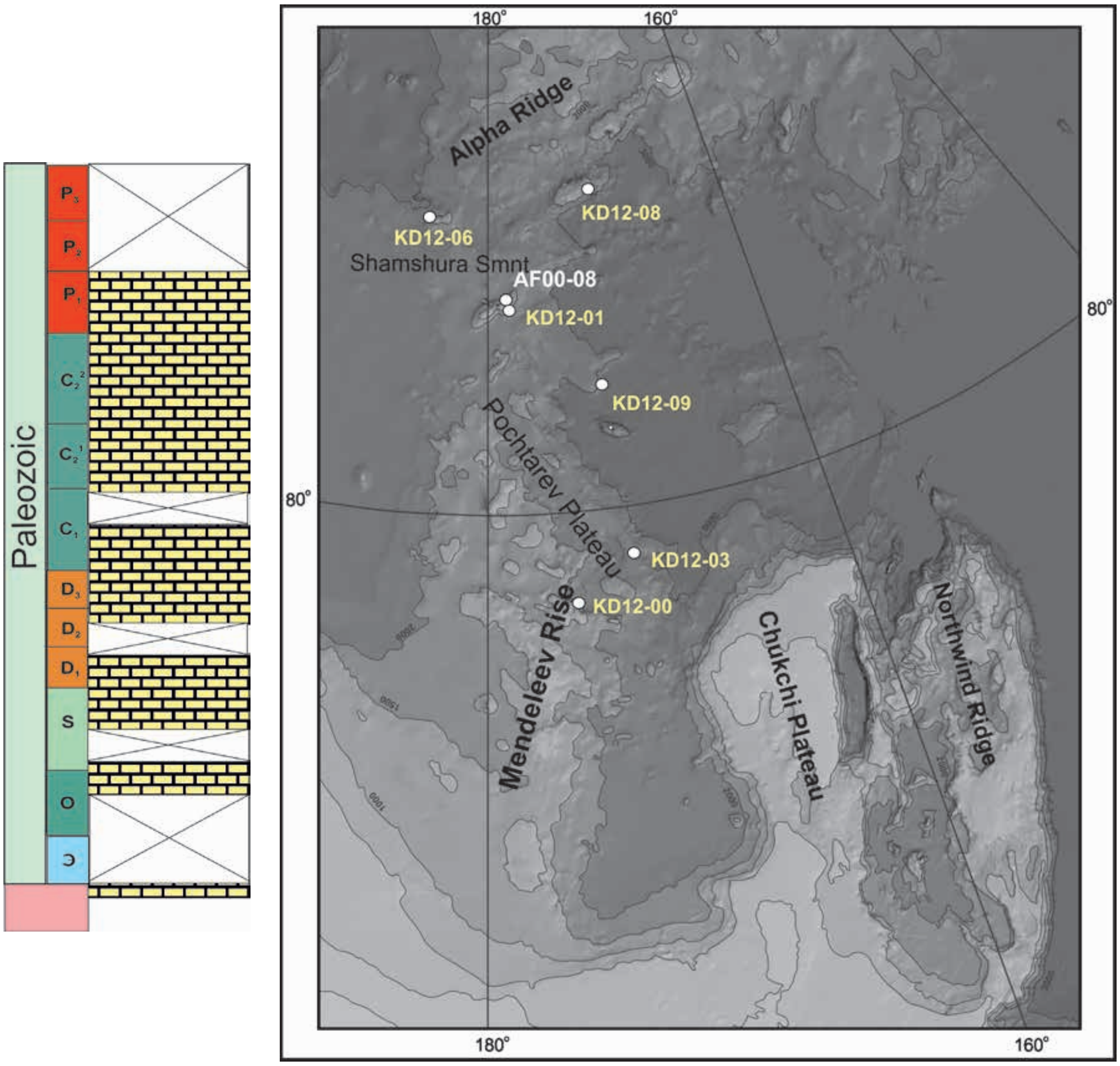


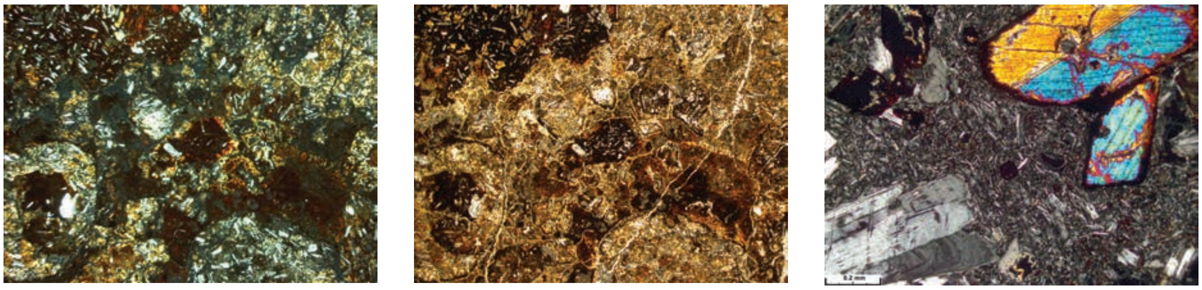
Fig. 25. Hypothetical Paleozoic section and localities of the sampled carbonate rocks of the Mendeleev Rise

the basin, but it is possible that the basement of the Podvodnikov Basin is heterogeneous. By analogy with the North Chukchi Basin, the sedimentation in the east Podvodnikov Basin is assumed to begun in the Late Paleozoic – Early Mesozoic. In the late Early Cretaceous, the basin was divided into eastern and western parts as a result of tectonic movements.

In the western basin during the Cretaceous, relatively thick layer of sediments deposited in the environment of avalanche sedimentation (chaotic seismic record) as a result of drifting from the Lomonosov Ridge and Geophysists Spur. Complete compensation of Cretaceous grabens occurred during the Neogene-Quaternary.

The Laptev Sea Shelf (fig. 28) is a plain gentle sloping to the north, which is complicated by a few uplifts with islands located in the middle of the shelf, as well as banks and underwater valleys, including those associated with geological features of the seafloor structure. Depths in the area do not exceed 50 m. A trough with depths of up to 40–45 m extends from the Khatanga River mouth along the Taimyr Peninsula coast. The shelf plain is divided into terraces, so the downcutting of underwater valleys is different. In separate segments it reaches 20 m and it does not exceed 5–10 m on flat sections. Submarine valleys continue arterial waterways of the land. The shelf edge is determined from a sharp change in the inclination of the seafloor, which in the Laptev Sea occurs at depths of about 100 m. The orientation of the shelf edge varies from northwestern in the west to sublatitudinal in the central part of the Laptev Sea and to northeastern in the eastern part of the sea.

Specific features of the continental margins in the Laptev Sea are its location at the junction with the underwater Gakkel Ridge, the northernmost segment of the world system of mid-oceanic ridges, and



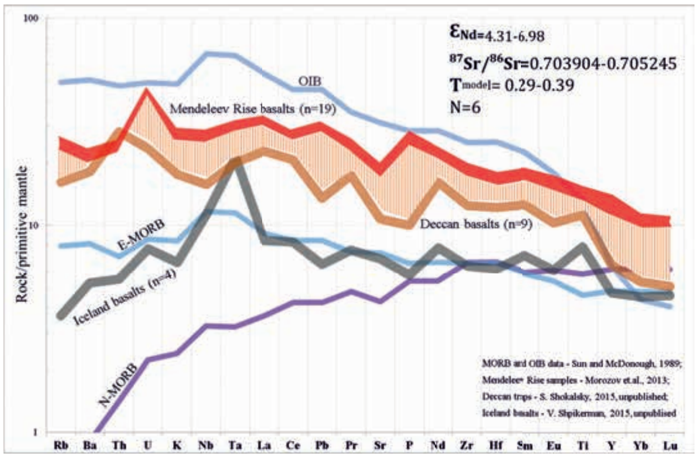


Fig. 26. Thin sections of volcanic rocks of the Mendeleev Rise and it's chemical composition in comparision with different basalt types

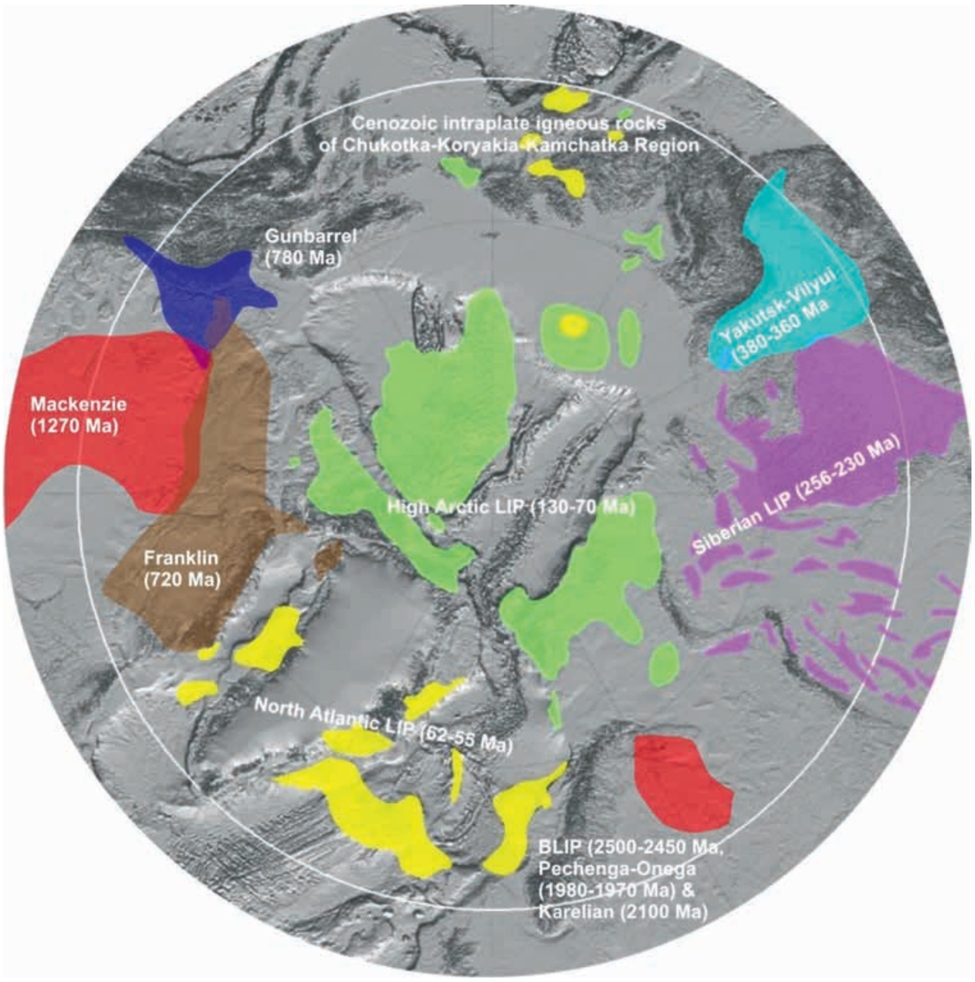


Fig. 27. Map of Arctic region with major Large Igneous Provinces (Petrov et al. 2016)

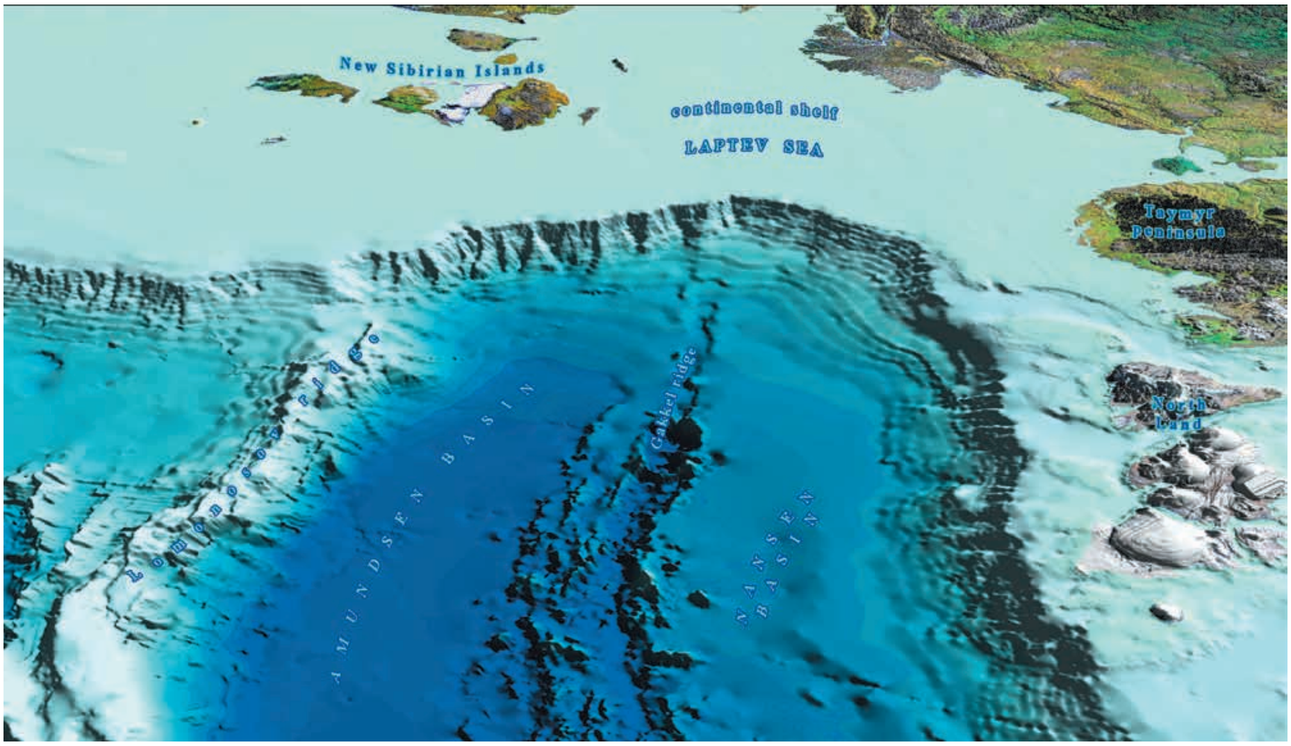


Fig. 28. 3D-image of the Laptev Sea continental margin (IBCAO model, version 3.0)

the extremely smooth flattening of the continental slope with depth. It is due to the presence of a thick plume of sediments from the shelf.

Over the recent years, VSEGEI focused its activity on the Russian part of the Eastern Arctic where new detailed geological and geophysical data were obtained. These data became the basis for the creation of the modern tectonic model of the Arctic.

REFERENCES

Brumley, K., Miller, E.L., Konstantinou, A., Grove1, M., Meisling, K.E., Mayer, L. 2015: First bedrock samples dredged from submarine outcrops in the Chukchi Borderland, Arctic Ocean. *Geosphere*. 11 (1). 76–92.

Bruvoll, V., Kristoffersen, Y., Coakley, B.J., Hopper, J.R. 2010a: Hemipelagic deposits on the Mendeleev and northwestern Alpha submarine ridges in the Arctic Ocean: Acoustic stratigraphy, depositional environment and an inter-ridge correlation calibrated by the ACEX results. *Mar. Geophys. Res.* 31. 171. doi:10.1007/s11001-010-9094-9.

Daragan-Sushchova, L.A., Sobolev, N.N., Petrov, E.O., Grinko, L.R., Petrovskaya, N.A., Daragan-Sushchov, Yu.I. 2014: On substituation of stratigraphic control of reference seismic horizons in the East Arctic Shelf and in Central Arctic Uplifts. *Region. geology and metallogeny.* 58. 5–21.

Dove, D., Coakley, B., Hopper, J., Kristoffersen, Y. and HLY0503 Geophysics Team. 2010: Bathymetry, controlled source seismic and gravity observations of the Mendeleev ridge; implications for ridge structure, origin, and regional tectonics. *Geophys. J. Int.* doi: 10.1111/j.1365-246X.2010.04746.x.

Drachev, S.S. 2011: Tectonic setting, structure and petroleum geology of the Siberian Arctic offshore sedimentary basins. *In* Spencer, A.M., Embry, A.F., Gautier, D.L., Stoupakova, A.V. and Sørensen K. (eds.): *Arctic Petroleum Geology.* Geol. Soc., London, Mem. 35. 369–394.

Egiazarov, B.X., Ermakov, B.V., Anikeeva, L.I., Romanovich, B.S., Pol'kin, Ya.I., Atlasov, I.P., Dementskaya, R.M., Grachev, A.F., Karasik, A.M., Kiselev, Yu.G., Andreev, S.I. and Kos'ko, M.K. 1977: *An explanatory note to a tectonic map of the northern polar area, scale 1:5,000,000.* Leningrad. NIIGA. 190.

Filatova, N.I., Hain, V.E. 2007: East Arctic tectonics. *Geotectonics*. 3. 3–29.

Gramberg, I.S., Piskarev, A.L. 2002: Stages of sedimentation and tectogenesis in the Laptev Sea basin. *Doklady Earth Sciences.* Moscow. 382 (1). 1–4.

Grantz, A., Scott, R.A., Drachev, S.S., Moore, T.E. 2009: *Maps showing the sedimentary successions of the Arctic Region (58–64 to 90 degrees N) that may be prospective for hydrocarbons.* American Association of Petroleum Geologists GIS-UDRIL Open-File Spatial Library. http://gisudril.aapg.org/gisdemo/.

Grikurov, G., Petrov, O., Shokalsky, S., Recant, P., Krylov, A., Laiba, A., Belyatsky, B., Rozinov, M., Sergeev, S. 2014: Zircon geochronology of bottom rocks in the central Arctic Ocean: analitical results and some geological implications. *Proseedings of the International Conference on Arctic Margins VI, Fairbanks, Alaska, May 2011.* Press VSEGEI, St. Petersburg. 211–232.

Hain, V.E. 2001: *Tectonics of continents and oceans.* Scientific World, Moscow. 606.

Hain, V.E., Filatova, N.I., Polyakova, D.I. 2009: Tectonics, geodynamics and petroleum potential of Eastern Arctic seas and their continental framing. *Proceedings of the Geological Institute.* Nauka, Moscow. 601. 227.

Harrison, J.C., St-Onge, M.R., Petrov, O.V., Strelnikov, S.I., Lopatin, B., Wilson, F., Tella, S., Paul, D., Lynds, T., Shokalsky, S., Hults, C., Bergman, S., Solli, A., Jepsen, H.F. 2011: *Geological map of the Arctic*. Geological Survey of Canada, Ottawa. 9.

Jackson, H.R., 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. 2003: Seismic investigations along the western sector of Alpha Ridge, Central Arctic Ocean. *Geophys. J. Int*. 152 (1). 185–201. doi:10.1046/j.1365-246X.2003.01839.x

Jokat, W., Micksch, U. 2004: Sedimentary structure of the Nansen and Amundsen basins, Arctic Ocean. *Geophysical Res. Lett.* 31. L02603.

Kabankov, V.Ya., Andreeva, I.A., Ivanov, V.I., Petrova, V.I. 2004: About geotectonic nature of the system of Central Arctic morphostructures and geological significance of bottom sediments in its definition. *Geotectonics.* 6. 33–48.

Knudsen, C., Hopper, J.R., Bierman, P.R, Bjerage, M., Funck, T., Green, P.F., Ineson, J.R., Japsen, P., Marcussen, C., Sherlock, S.C., Thomsen, B. 2017. Samples from the Lomonosov Ridge place new constraintson the geological evolution of the Arctic Ocean. In *Geological Society London Special Publications*, 460, https://doi.org/10.1144/SP460.17

Lawver, L.A., Grantz, A., Gahagan, L.M. 2002: Plate kinematic evolution of the present Arctic region since the Ordovician. *In* Miller, E.L., Grantz, A., Klemperer, S.L. (eds.): *Tectonic Evolution of the Bering Shelf – Chukchi Sea – Arctic Margin and Adjacent Land Masses*. *Special Papers*. 360. 333–358. Geological Society of America, Boulder, Colorado.

Morozov, A.F., Petrov, O.V., Shokalsky, S.P., Kashubin, S.N., Kremenetsky, A.A., Shkatov, M.Yu., Kaminsky, V.D., Gusev, E.A., Grikurov, G.E., Rekant, P.V., Shevchenko, S.S., Sergeev, S.A., Shatov, V.V. 2013: New geological evidence grounding the continental nature of the Central Arctic Uplifts. *Region. geology and metallogeny.* 53. 34–56.

Mukasa, S.B., Mayer, L.A., Aviado, K., Bryce, J., Andronikov, A., Brumley, K., Blichert-Toft, J., Petrov, O.V., Shokalsky, S.P., 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*. 17, EGU2015-8291-2.

Naryshkin, G.D. 1987: *The Middle Ridge of the Eurasian Basin of the Arctic Ocean*. 72. Nauka, Moscow.

Orographic map of the Arctic basin [map]. 1995: Gramberg, I.S., Naryshkin, G.D. Scale 1:5,000,000. Helsinki, Karttakeskus. 1.

Pease, V.L., Kuzmichev, A.V., Danukalova, M.K. 2014: The New Siberian Islands and evidence for the continuation of the Uralides, Arctic Russia. *J. Geol. Soc.* 172. 1–4.

Petrov, O.V., Smelror, M. 2015. Uniting the Arctic frontiers – International cooperation on Circum-Arctic geological and geophysical maps. *Polar Record.* 51 (5). 530–535. http://dx.doi.org/10.1017/S0032247414000667.

Petrov, O., Smelror, M., Morozov, A., Shokalsky, S., Kashubin, S., Artemieva, I.M., Sobolev, N., Petrov, E., Ernst, R.E., Sergeev, S. 2016: Crustal structure and tectonic model of the Arctic region. *Earth-Science Reviews.* Elsevier. 154. 29–71.

Poselov, V.A., Verba, V.V., Zholondz, S.M. 2007: Crust typification in the Central Arctic Uplifts, the Arctic Ocean. *Geotectonics.* 4. 48–59.

Poselov, V., Butsenko, V., Chernykh, A., Glebovsky, V., Jackson, H.R., Potter, D.P., Oakey, G., Shimeld, J. and Marcussen, C. 2011a: The structural integrity of the Lomonosov Ridge with the North American and Siberian continental margins. *Proceedings of the International Conference on Arctic Margins VI, Fairbanks, Alaska, May 2011.* 233–258. http://www2.gi.alaska.edu/icam6/proceedings/web/

Poselov, V.A., Avetisov, G.P., Kaminsky, V.D. et al. 2011b: *Russian Arctic geotraverses*. VNIIOkeangeologia, St. Petersburg. 172.

Proskurnin, V.F., Petrov, O.V., Sobolev, N.N., Remizov, D.N., Vinogradova, N.P., Yudin, S.V. 2012: First data on the manifestation of Oligocene-Lower Cretaceous continental magmatism in the Belkovsky Island (New Siberian Islands). *Region. geology and metallogeny.* VSEGEI, St. Petersburg. 52. 49–58.

Rekant, P.V., Pyatkova, M.N., Nikolaev, I.D., Taldenkova, E.E. 2012: Bottom-rock material from the Geofizikov Spur as a basement petrotype for the southern part of the Lomonosov Ridge (the Arctic Ocean). *Geology and Environmental Geology of Eurasia Continental Margins.* GEOS, Moscow. 4. 29–40.

Skolotnev, S.G., Fedonkin, M.A., Korniychuk, A.V. 2017: New Data Concerning the Geological Structure of the South-West Part Mendeleev Rise (Arctic Ocean). *Doklady RAS.* 476. 190–196.

Skolotnev, S.G., Isakova, T.N., Aleksandrova, G.N., Tolmacheva, T.Yu. et al. 2019: Fossils and lithology of the consolidated basement of the Alfa-Mendeleev Rise in the Arctic Ocean. *Marine Geology.* 407. 148–163.

Verba, V.V. 2006: Nature of the anomalous magnetic field in the Central Arctic Uplifts Province in the Amerasian Basin of the Arctic Ocean. *Geophysical Journal*. Kiev. 28 (5). 95–103.

Vernikovsky, V.A., Metelkin, D.V., Tolmacheva, T.Yu., Malyshev, N.A., Petrov, O.V., Sobolev, N.N., Matushkin, N.Yu. 2013: On the problem of paleotectonic reconstructions in the Arctic and the tectonic unity of the New Siberian Islands terrane: New paleomagnetic and paleontological data. *Proceedings of the Russian Academy of Sciences*. 451 (4). 423–429.

Vernikovsky, V.A., Metelkin, D.V., Vernikovskaya, A.E., Matushkin, N.Yu., Lobkovsky, E., Shipilov, V. 2014a: Early evolution stages of the arctic margins (Neoproterozoic-Paleozoic) and plate reconstructions. *In* Stone, D.B. et al. (eds.): *Proceedings of the International Conference on Arctic Margins VI, Fairbanks, Alaska, May 2011.* Press VSEGEI, St. Petersburg. 265–285.

Vernikovsky, V.V., Morozov, A.F., Petrov, O.V. et al. 2014b: New data on the age of dolerite and basalt in the Mendeleev Rise: on the problem of the continental crust in the Arctic Ocean. *Proceedings of the Russian Academy of Sciences*. 454 (4). 431–435.

Zonenshain, L.P., Natapov, L.M. 1987: Tectonic history of the Arctic. *Current Problems of the Tectonics of Oceans and Continents*. Nauka, Moscow. 31–57.

TECTONIC MODEL AND GEODYNAMIC EVOLUTION OF THE ARCTIC

O.V. Petrov, S.N. Kashubin, S.P. Shokalsky, E.O. Petrov

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.

Keywords: *Tectonic zones, Circumpolar Arctic, regional geology, tectonics*

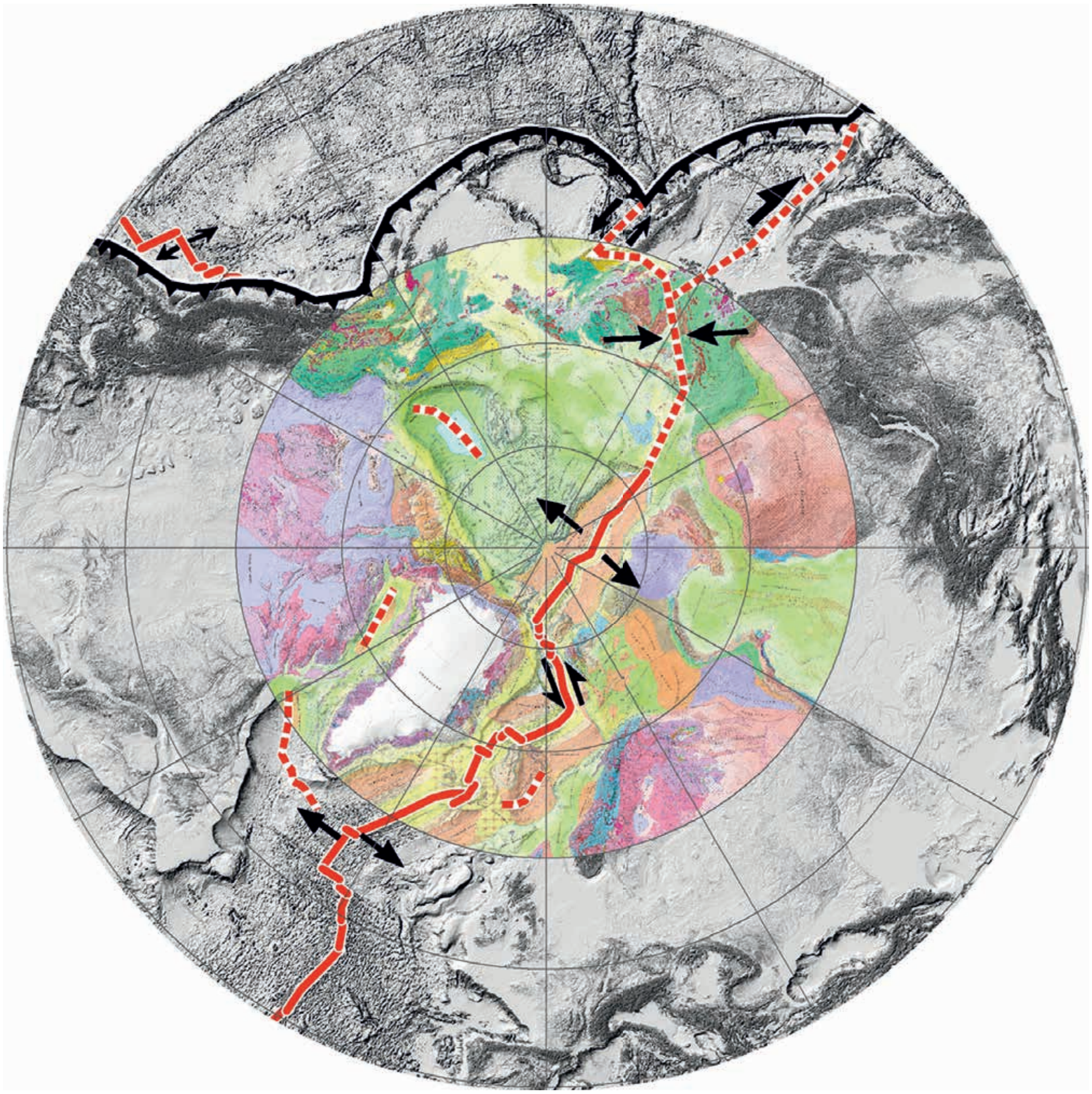


Fig. 29. Tectonic map superposed bathymetry map showing boundaries of three lithosphere plates: two continental – North American and Eurasian – and one oceanic – Pacific

---

To cite: Tectonic model and geodynamic evolution of the Arctic / O.V. Petrov [et al.] // Scientific contributions to the Tectonic Map of the Arctic. Paris, 2019. P. 53–61

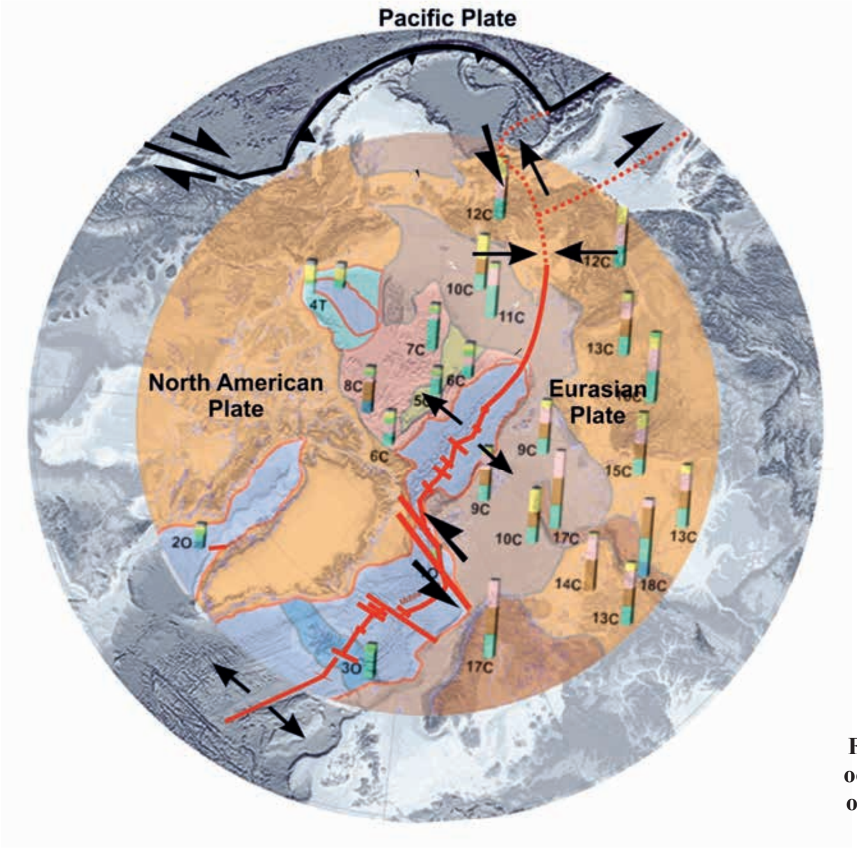


Fig. 30. The map of crustal types shows that oceanic crust is present only at the boundary of the lithosphere plates within the Eurasian basin

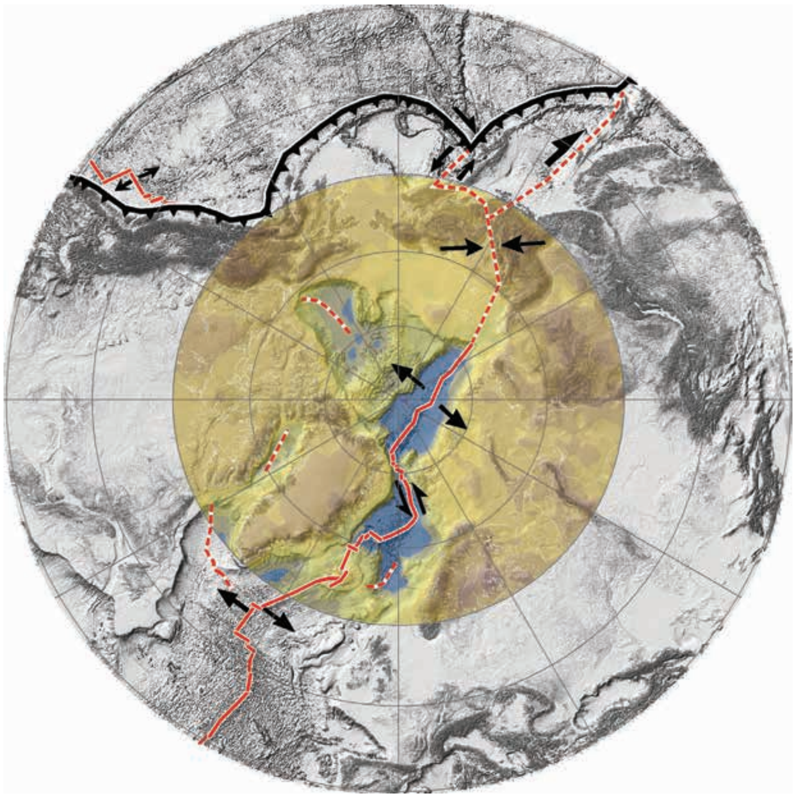


Fig. 31. Crustal thickness map of the Arctic showing the oceanic crust at the boundary of the lithosphere plates within the Eurasian basin

One of main results of studying the geological and tectonic structure of the Arctic region is a subsequent reconstruction of its tectonic evolution. Models of the plate tectonic evolution of the Central Arctic are currently being discussed in many publications [Lawver et al. 2011; Vernikovsky et al. 2014; Metelkin et al. 2015; Miller et al. 2017; Shephard et al. 2013; Dore et al. 2015], but there is still no unified view on the tectonic evolution of the region.

Reconstruction of the position of consolidated basement blocks in the Arctic in the Proterozoic

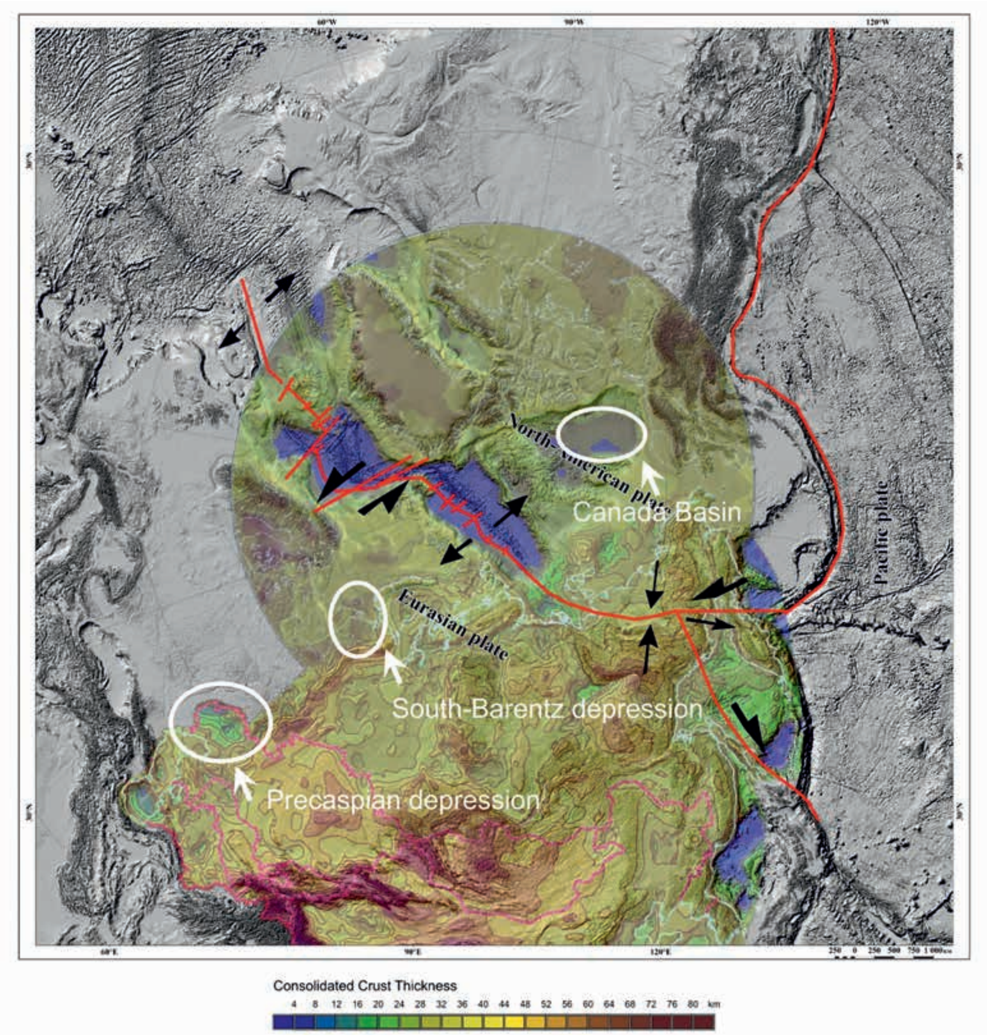


Fig. 32. The map of earth's crust thickness shows that the earth's crust in the Canada, Podvodnikov and Makarov basins has a structure typical for deep sedimentary basins such as South Barents or Peri-Caspian depressions

and Paleozoic [Lawver et al. 2011; Vernikovsky et al. 2014; Metelkin et al. 2015; Piepjohn et al. 2015; Harrison 2017; Kossovaya et al. 2018; Ershova et al. 2018a,b] are based on rare paleomagnetic data, detrital zircons distribution, and fossil fauna biogeography.

The Mesozoic-Cenozoic geodynamic history of the Arctic, including the formation of the Canada basin, the Makarov-Podvodnikov basin and the disclosure of the Eurasian ocean basin, is treated ambiguously [Vernikovsky et al. 2014; Metelkin et al. 2015; Piepjohn et al. 2016; Toro et al. 2016; Jacobsson et al. 2012; Coakley et al. 2016; Lopez-Mir et al. 2017; Chernykh et al. 2018].

Time of the Canada basin opening, considered by different authors in the interval between the Late Triassic and the Early Cretaceous, is established from geophysical data on the crustal structure and structural deformations on islands of the Canadian Arctic [Lopez-Mir et al. 2017; Chernykh et al., 2018]. Most experts agree that the fundamental change in the direction of movement of lithospheric plates and the progradation of the Mid-Atlantic Ridge to the Arctic Ocean began in the early Eocene (57–54 Ma) [Jokat et al. 2013; Knudsen et al. 2017]. It should be noted that in the majority of recent scientific publications, no doubt is expressed concerning the continental nature of the Central Arctic Elevations – the Alpha-Mendeleev Rise [Bruvoll et al., 2012; Døssing et al. 2013; Gaina et al. 2014; Oakey and Saltus 2016; Funck and Shimeld 2018; Jackson et al. 2018].

Modern morphology of the seafloor and bathymetry of the Central Arctic are caused by complex Cenozoic history of the sea level rise and lowering associated, among other things, with a series of arctic glaciations over the last 2.58 Ma.

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.

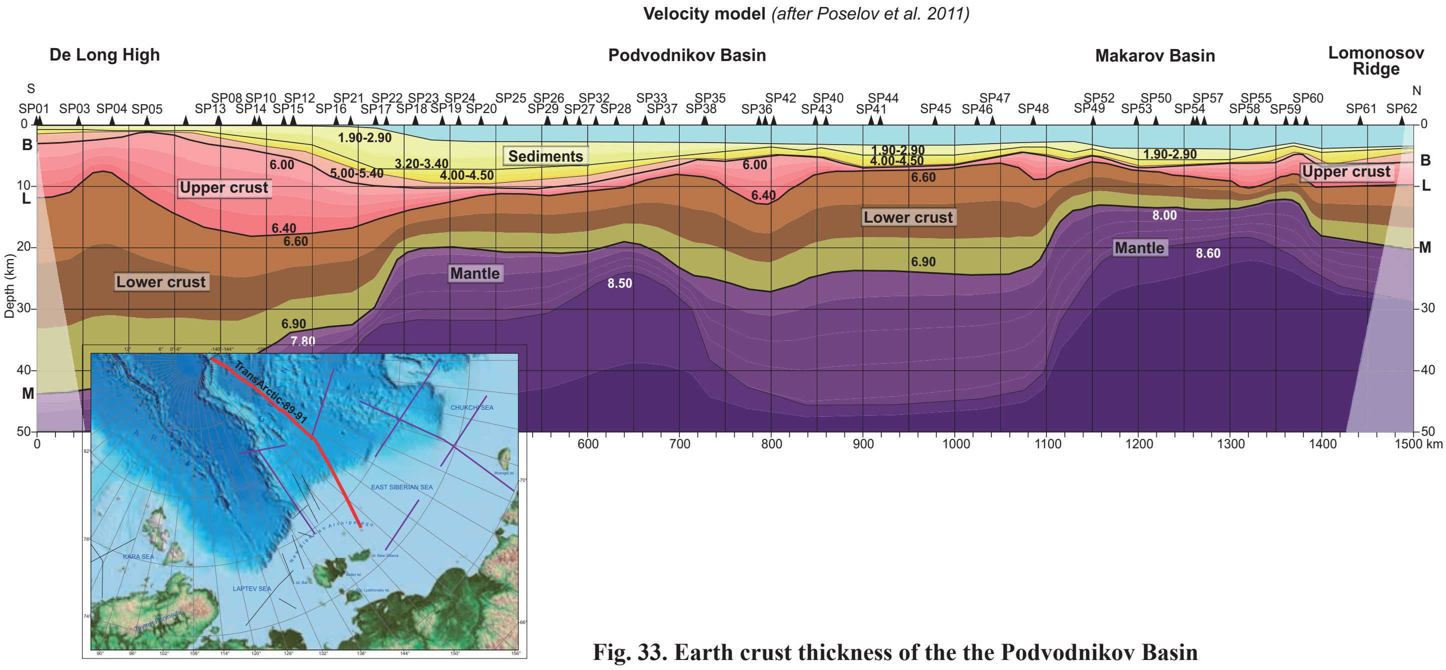


Fig. 33. Earth crust thickness of the the Podvodnikov Basin

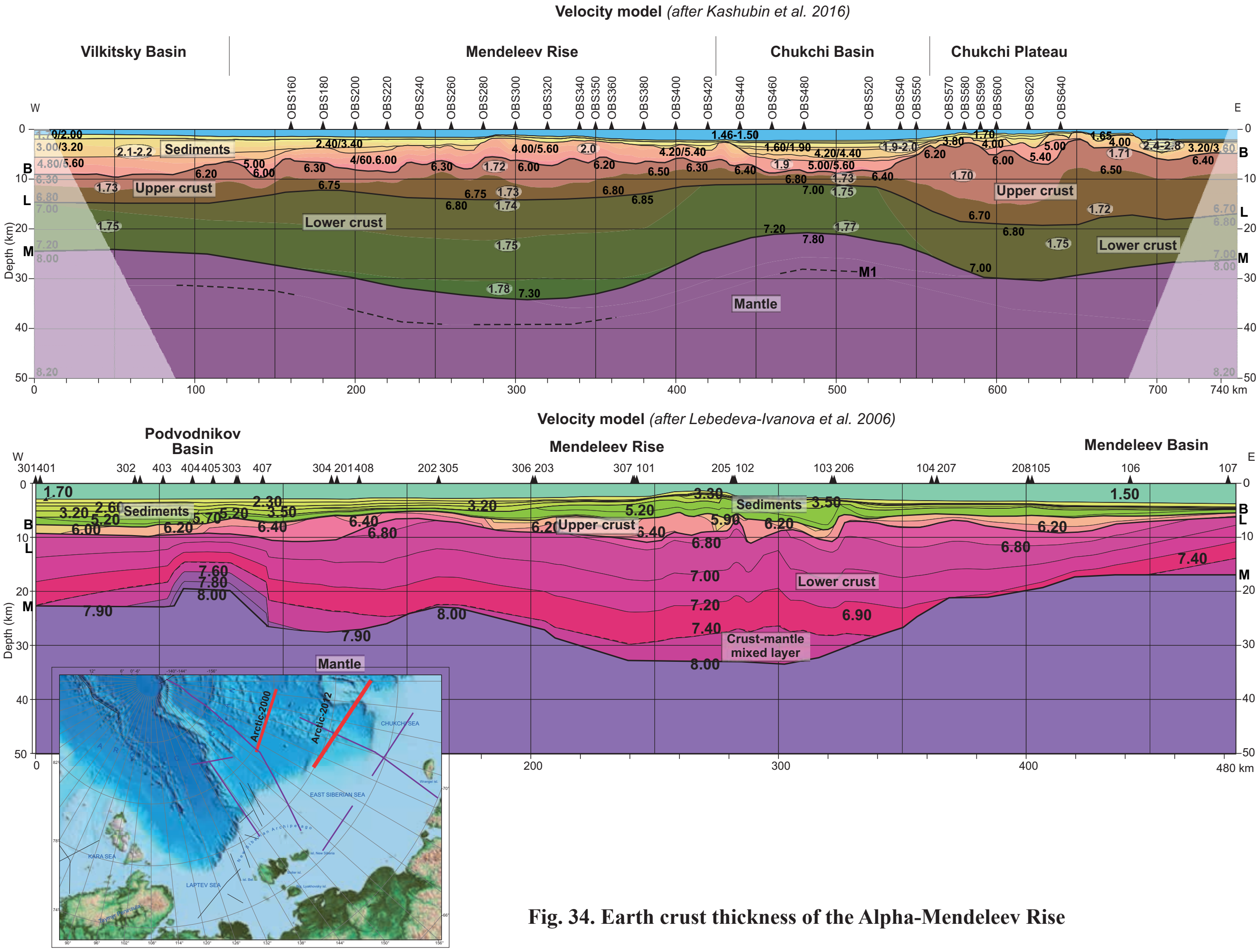


Fig. 34. Earth crust thickness of the Alpha-Mendeleev Rise

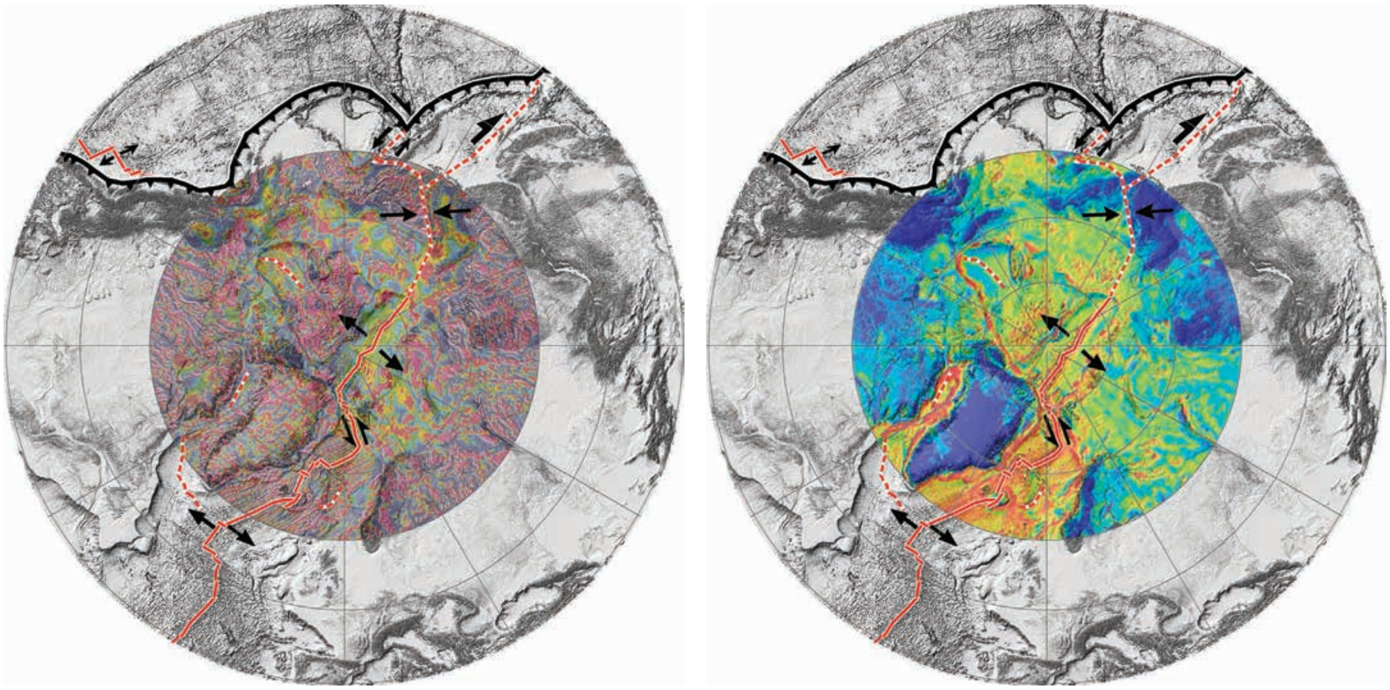


Fig. 35. The gravity and magnetic maps superposed on the bathymetry map of the Arctic

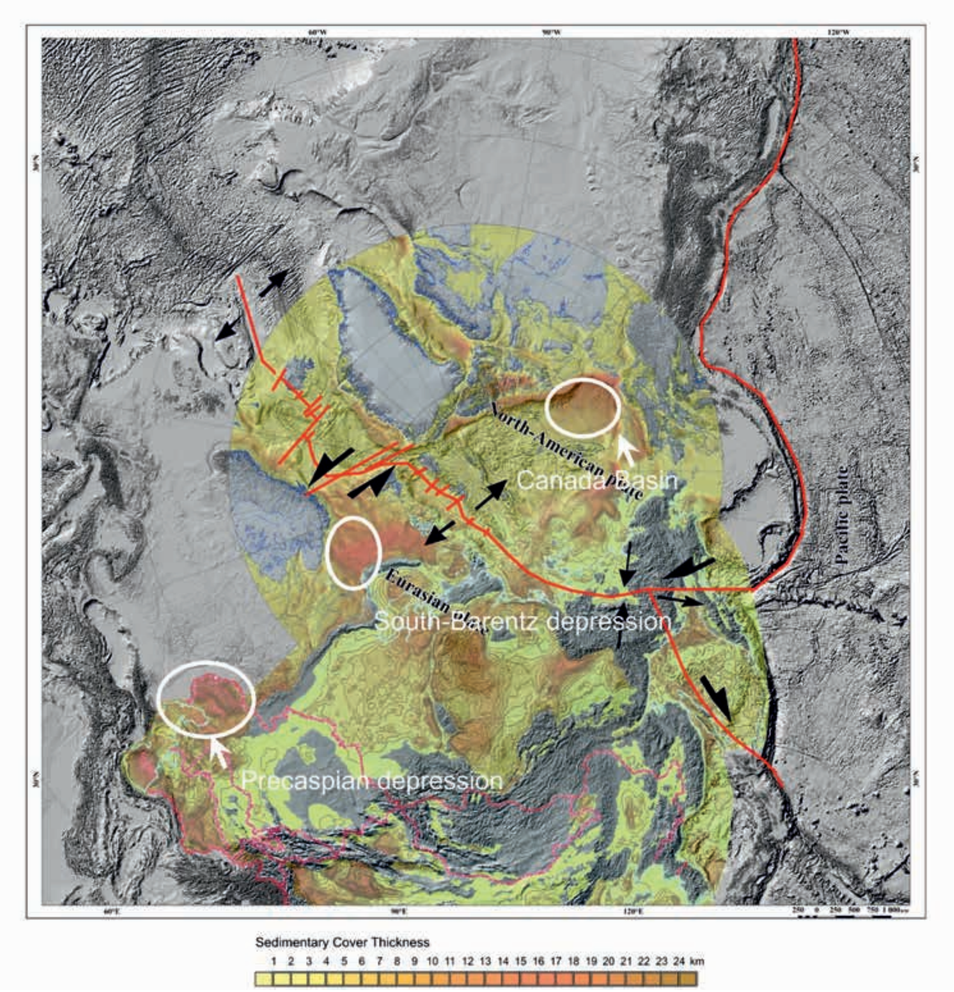
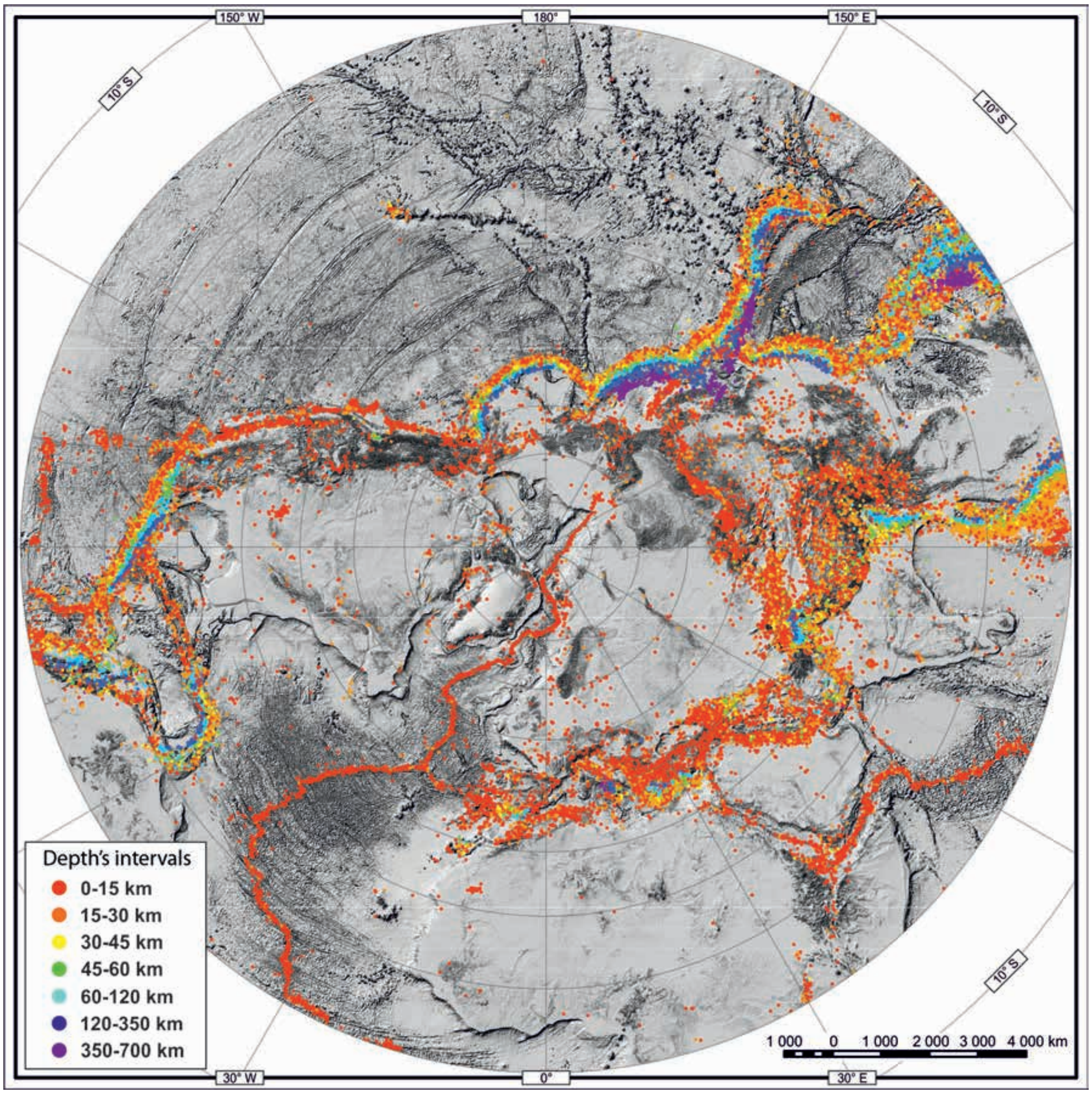
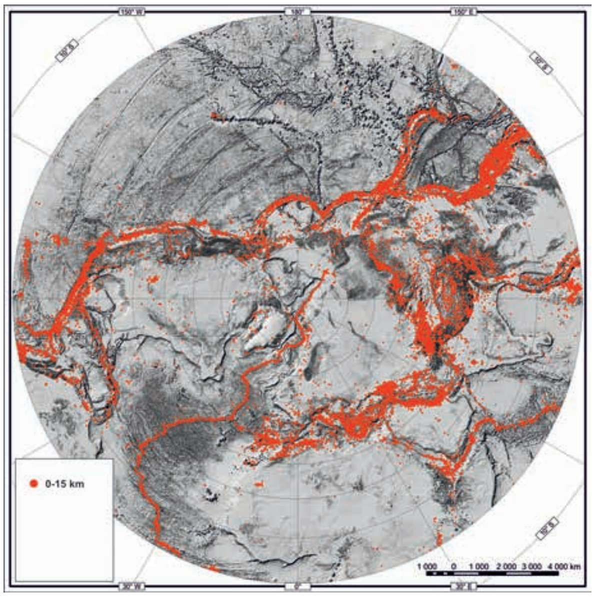
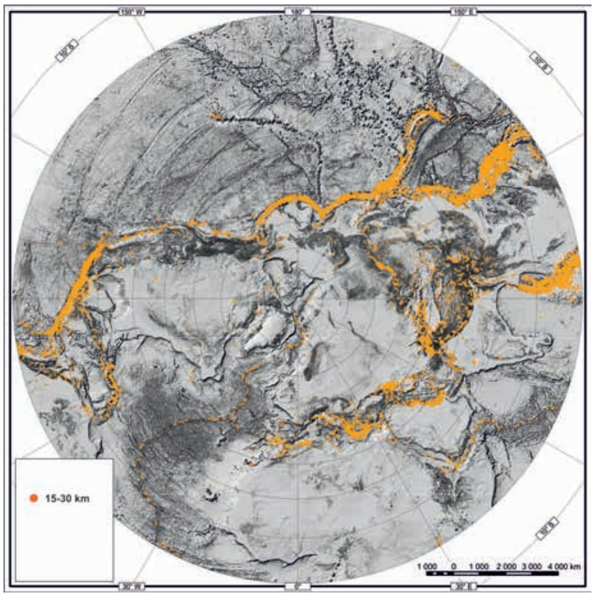


Fig. 36. The map of the sedimentary cover thickness of the Arctic and Asia demonstrates that sedimentary basins associated with intraplate rifting typically have the total thickness of sedimentary rocks of 10–12 km and greater


150° W
180°
150° E
10° S
10° S
10° S
Depth's intervals
● 0-15 km
● 15-30 km
● 30-45 km
● 45-60 km
● 60-120 km
● 120-350 km
● 350-700 km
1 000 0 1 000 2 000 3 000 4 000 km
30° W
0°
30° E


● 0-15 km
1 000 0 1 000 2 000 3 000 4 000 km


● 15-30 km
1 000 0 1 000 2 000 3 000 4 000 km

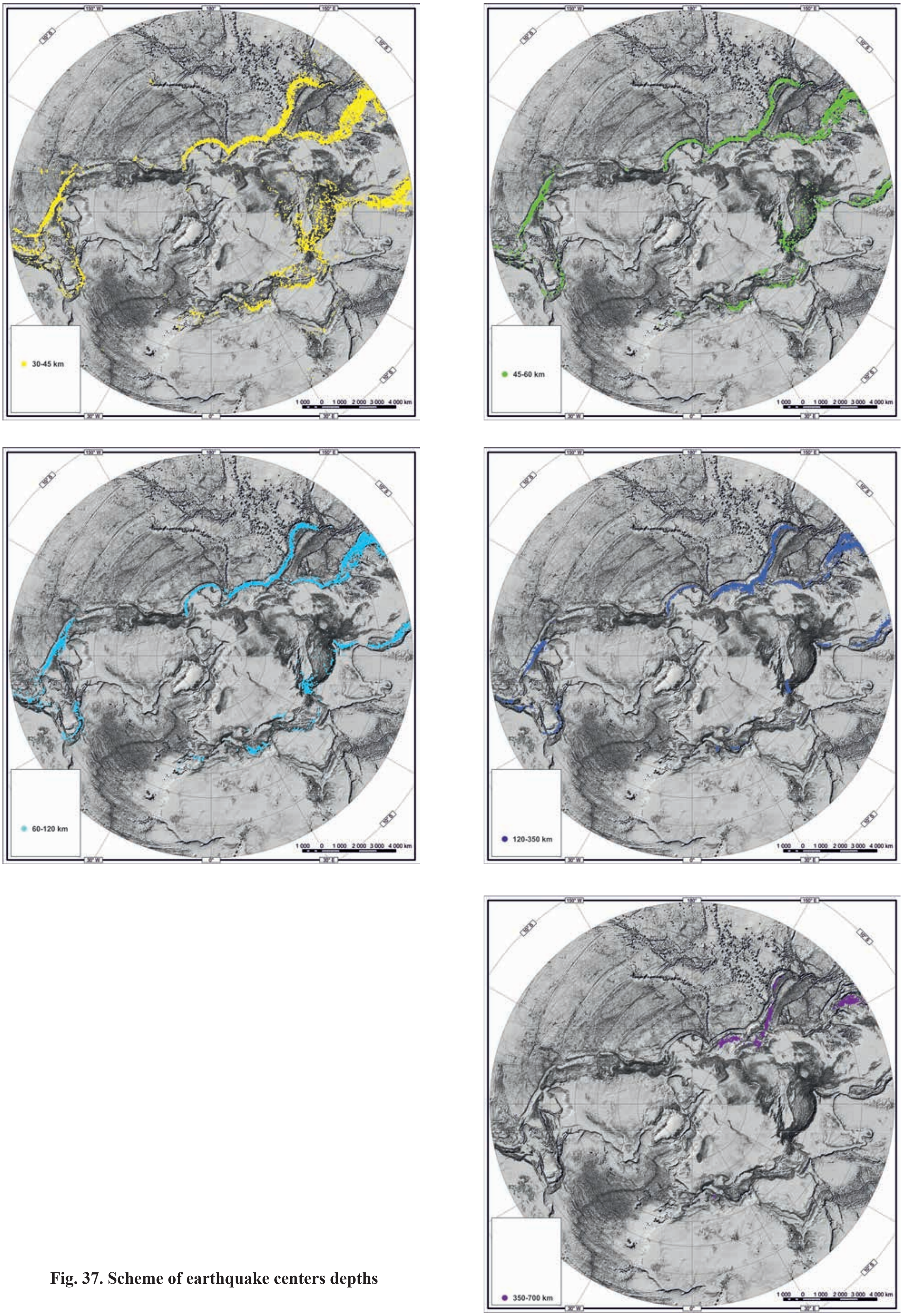


Fig. 37. Scheme of earthquake centers depths

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 (fig. 29).

The Pacific oceanic plate descends under the North American and Eurasian plates leading to a formation of active continental margins. Young Arctic Ocean develops within the Gakkel Ridge, Nansen and Amundsen Basins at the boundary between the North American and Eurasian continental plates.

Within the North American plate, the Alpha-Mendeleev and Lomonosov Ridges are represented by reduced continental crust (fig. 30). This is shown on the map of crustal thickness in the Circumpolar Arctic (fig. 31) based on regularly updated seismic data containing interpolation between profiles by correlation dependence of the depth of Moho location, gravity anomalies and relief. Up to date, the map takes advantage of about 300 seismic profiles of total length over 140 000 km.

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 within the bounds of which some experts presume the presence of oceanic crust (fig. 15, 32, table 3).

Results of studies within the Barents and Kara seas show that the earth's crust of the Barents-Kara passive margin measuring 35–40 km has 3-layer structure. The thick sedimentary cover is underlain by crystalline crust represented by upper low-velocity and apparently mostly acidic crust and lower higher-velocity and possibly more mafic crust. Such thicknesses and structure are typical for earth's crust of shallow-water marginal continental seas.

The earth's crust in the Amundsen basin is thin (6–8 km) and has 2-layer structure (fig. 15, table 3). Relatively thin low-velocity layer (presumably formed by sediments interstratified with basalts) overlies thin crystalline crust, which in its velocity parameters corresponds to the lower mafic crust. Such thicknesses and structure are typical for the majority of oceans, as well as the sea depth that reaches 4 km in the Amundsen basin.

The earth's crust on the Lomonosov Ridge has been studied both – in the central part of the Arctic Ocean and in areas of its junction with Greenland and East Siberia. Results of Russian and Danish-Canadian studies correspond well and demonstrate presence of intermediate (metasedimentary) complex and 2-layer structure of the crystalline crust under the sedimentary cover. Total thickness of the earth's crust on the Lomonosov Ridge located 1–2 km sub sea measures 17–19 km (fig. 15, table 3). Presently, the continental nature of the Lomonosov Ridge is recognized by the majority of Arctic researchers.

The earth's crust of the Podvodnikov Basin is thinner in comparison with the crust of surrounding it rises and reaches 14–27 km (fig. 33). However, its crystalline part also has 2-layer structure. The most probable explanation is believed to be the rift-related nature of the basin, which formed as a result of continental crust stretching followed by its submergence to bathyal depths up to 3.5–4 km.

The earth's crust on the Alpha-Mendeleev Ridge has been studied over last years by means of Russian and Canadian deep seismic sounding profiles (fig. 34). Results of these studies correspond well. Overall, the earth's crust on the Alpha-Mendeleev Ridge is similar to that of the Lomonosov Ridge; however, its thickness is greater (32–34 km as opposed to 17–19 km on the Lomonosov Ridge) due to increased thickness of the lower crust. Current geological interpretation of this fact is so that increased thickness of the lower crust is presumably connected with magmatic underplating, which, in its turn, led to intraplate basic volcanism and formation of HALIP in this part of the Arctic.

This tectonic model is well reflected on gravity and magnetic maps and conforms well to all up-to-date geological and geophysical materials as well as to the data obtained while studying the Arctic islands and performing geological sampling of the Arctic seafloor. Circum-Arctic magnetic anomaly grid (CAMP-M) bear information related to regional deeper and/or thicker portions of the magnetic sources within the crust (fig. 35).

The map of sedimentary cover thickness within the Canada, Podvodnikov and Makarov basins also demonstrates characteristics determined by intraplate rifting. These basins typically have the total thickness of sedimentary complexes greater than 10–12 km, akin to the South Barents and Caspian depressions, but uncommon for oceans (fig. 36).

Modern seismicity serves as an indicator of tectonic processes and outlines boundaries of lithosphere plates (fig. 37). The wide belt of seismicity in the Pacific belt (Benioff-Zavaritsky zone) determines the boundaries of the Pacific oceanic lithosphere plate. Earthquake belts of the Mid Atlantic and Gakkel Ridges form a narrow chain of shallow earthquakes associated with divergence of two continental plates and formation of young oceanic crust.

REFERENCES

Bruvoll, V., Kristoffersen, Y., Coakley, B.J., Hopper, J.R., Planke, S., Kandilarov, A. 2012: The nature of the acoustic basement on Mendeleev and northwestern Alpha ridges, Arctic Ocean. *Tectonophysics.* 514–517. 123–146.

Chernykh, A., Glebovsky, V., Zykov, M., Korneva, M. 2018: New insights into tectonics and evolution of the Amerasia Basin. *J. Geodynamics*. https://doi.org/10.1016/j.jog.2018.02.010.

Coackley, B., Brumley, K., Lebedeva-Ivanova, N., Mosher, D. 2016: Exploring the geology of the central Arctic Ocean; understanding the basin features in place and time. *J. Geol. Soc.* London. 173. 967–987.

Dore, A.G., Lundin, E.R., Gibbons, A., Somme, T.O., Tørudbakken, B.O. 2015: Transform margins of the Arctic: a synthesis and re-evaluation. *In* Nemcˇok, M., Ryba´r, S., Sinha, S.T., Hermeston, S.A., Ledve´nyiova, L. (eds): *Transform Margins: Development, Controls and Petroleum Systems.* Geol. Soc., London, Spec. Publ. 431. https://doi.org/10.1144/SP431.8.

Døssing, A., Jackson, H.R., Matzka, J., Einarsson, I., Rasmussen, T.M., Olesen, A.V., Brozena, J.M. 2013: On the origin of the Amerasia Basin and the High Arctic Large Igneous Province – results of new aeromagnetic data. *Earth Planet Sci. Lett.* 363. 219–230.

Ershova, V., Anfinson, O., Prokopiev, A., Khudoley, A., Stockli, D., Faleide, J.I., Gaina, C. 2018a: Detrital zircon (UTh)/He ages from Paleozoic strata of the Severnaya Zemlya Archipelago: deciphering multiple episodes of Paleozoic tectonic evolution within the Russian High Arctic. *J. Geodynamics*. https://doi.org/10.1016/j.jog.2018.02.007.

Ershova, V., Prokopiev, V., Andersen, T., Khudoley, A., Kullerud, K., Thomsen, T.B. 2018b: U-Pb and Hf isotope analysis of detrital zircons from Devonian-Permian strata of Kotel'ny Island (New Siberian Islands, Russian Eastern Arctic): insights into the Middle-Late Paleozoic evolution of the Arctic. *J. Geodynamics*. https://doi.org./10.1016/j.jog.2018.02.008.

Funck, T., Shimeld, J. 2018: *The crustal structure of the Lomonosov Ridge, Marvin Spur and Alpha Ridge*. https://icamviii.geo.su.se/en/program/ Marine%20G&G_funck.shimeld.pdf.

Gaina, C., Medvedev, S., Torsvik, T.H., Koulakov, I., Werner, S. 2014: 4D Arctic: a glimse into the structure and evolution of the Arctic in the light of new geophysical maps, plate tectonics and tomographic models. *Surv. Geophys.* 3. 1095–1122.

Harrison, J.C. 2017: Intersecting fold belts in the Bathurst Island region, Nunavut. *J. Geodynamics*. https://doi.org/10.1016/j.jog.2017.11.003.

Jackson, R., Chain, D., Shimeld, J. 2018: *Continental Affinities of the Mendeleev Ridge*. https://icamviii.geo.su.se/en/program/Marine%20G&G_jackson.et.al.pdf.

Jakobsson, M., Mayer, L., Coakley, B. et al. 2012: The international bathymetric chart of the Arctic Ocean (IBCAO). Version 3.0. *Geophys. Res. Lett*. 39. L12609.

Jokat, W., Ickrath, M., O'Connor, J. 2013: Seismic transect across the Lomonosov and Mendeleev Ridges: constraints on the geological evolution of the Amerasia Basin, Arctic Ocean. *Geophys. Res. Lett.* 40. 5047–5051.

Knudsen, C., Hopper, J.R., Bierman, P.R., Bjerager, M., Funck, T., Green, P.F., Ineson, J.R., Japsen, P., Marcussen, C., Sherlock, S.C., Thomsen, T.B. 2017: Samples from the Lomonosov Ridge place new constraints on the geological evolution of the Arctic Ocean. *In* Pease, V., Coakley, B. (eds*.): Circum-Arctic Litosphere Evolution.* Geol. Soc., London, Spec. Publ. 460. https//doi.org./10.1144/SP460.17.

Kossovaya, O., Tolmacheva, T., Petrov, O., Isakova, T., Ivanova, R., Mirolyubova, E., Rekant, P., Gusev, E. 2018: Palaeozoic carbonates and fossils of the Mendeleev Rise (Eastern Arctic): a study of dredged seafloor material. *J. Geodynamics.* https://doi.org/10.1016/j.jog.2018.05.001.

Lawver, L., Gahagan, L.M., Norton, I. 2011: Palaeogeographic and tectonic evolution of the Arctic region during the Palaeozoic. *In* Spencer, A.M. (ed.): *Arctic Petroleum Geology.* Geol. Soc., London, Mem. 35. 61–77.

Lopez-Mir, B., Schneider, S., Hülse, P. 2017: Fault activity and diapirism in the Mississippian to Late Cretaceous Sverdrup Basin: New insights into the tectonic evolution of the Canadian Arctic. *J. Geodynamics*. doi.org/10.1016/j.jog.2017.11.002.

Metelkin, D.V., Vernikovsky, V.A., Matushkina, N.Yu. 2015: Arctida between Rodinia and Pangea. *Precambrian Research.* 259. 114–129.

Miller, E.L., Meisling, K.E., Anikin, V.V. 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.* Geol. Soc., London, Spec. Publ. 460. 1–6. https//doi.org./10.1144/SP460.9.

Oakey, G.N., Saltus, R.W. 2016: Geophysical analysis of the Alpha-Mendeleev ridge complex: Characterization of the High Arctic Igneous Province. *Tectnophysics.* 691. 65–84.

Piepjohn, K., von Gosen, W., Tessensohn, F., Reinhardt, L., Mc-Clelland, W., Dallmann, W., Gaedicke, C., Harrison, J.C. 2015: *Tectonic map of the Ellesmerian and Eurekan deformation belts on Svalbard, North Greenland, and the Queen Elizabeth Islands (Canadian Arctic).* Arktos 1, 12. https://doi.org/10.1007/s41063-015-0015-7.

Piepjohn, K., von Gosen, W., Tessensohn, F. 2016: The Eurekan deformation in the Arctic: an outline. *J. Geol. Soc.* 173. 1007–1024.

Shephard, G., Muller, D., Seton, M. 2013: The tectonic evolution of the Arctic since Pangea breakup: Integrating constraints from surface geology and geophysics with mantle structure. *Earth-Science Reviews*. 124. 148–183, doi: 10.1016/j.earsscirev.2013.05.012.

Toro, J., Miller, E.L., Prokopiev, A.V., Zhang, X., Veselovskiy, R. 2016: Mesozoic orogens of the Arctic from Novaya Zemlya to Alaska. *J. Geol. Soc.* 173. 989–1006.

Vernikovsky, V.A., Metelkin, D.V., Vernikovskaya, A.E., Matushkin, N.Yu., Lobkovsky, E., Shipilov, V., 2014: Early evolution stages of the arctic margins (Neoproterozoic-Paleozoic) and plate reconstructions. *In* Stone, D.B. et al. (eds.): *Proceedings of the International Conference on Arctic Margins VI, Fairbanks, Alaska, May 2011.* Press VSEGEI, St. Petersburg. 265–285.

INTERNATIONAL TECTONIC MAP OF THE ARCTIC (TeMAr) WORKING GROUP

Russia (coordinator), Canada, Denmark, France, Germany, Norway, Sweden, USA

🇷🇺 **O.V. Petrov (VSEGEI), A.F. Morozov (Rosnedra), S.N. Shokalsky (VSEGEI), I.I. Pospelov (VSEGEI, GIN RAS), S.N. Kashubin (VSEGEI), N.N. Sobolev (VSEGEI), A.I. Khanchuk (RAS), I.F. Glumov (MNRE), Yu.B. Kazmin (MNRE, VSEGEI), S.D. Sokolov (GIN RAS), G.E. Grikurov (VNIIOkeangeologia), V.A. Poselov (VNIIOkeangeologia), M. Kos'ko (VNIIOkeangeologia), V.A. Vernikovsky (IPGG SB RAS), A. Nikishin (MSU), N.A. Malyshev (Rosneft), Yu.G. Leonov (GIN RAS), L.A. Daragan-Suschova, E.D. Milshtein (VSEGEI), E.O. Petrov (VSEGEI), T.Yu. Tolmacheva (VSEGEI), M.L. Verba (Sevmorgeo)**

🇨🇦 **M.R. St-Onge (GSC), J.C. Harrison (GSC), R. Ernst (Carleton University)**

🇩🇰 **P. Guarnieri (GEUS)**

🇫🇷 **N. Lemonnier (CNRS), L. Labrousse (Sorbonne University)**

🇩🇪 **К. Piepjohn (BGR), C. Gaedicke (BGR)**

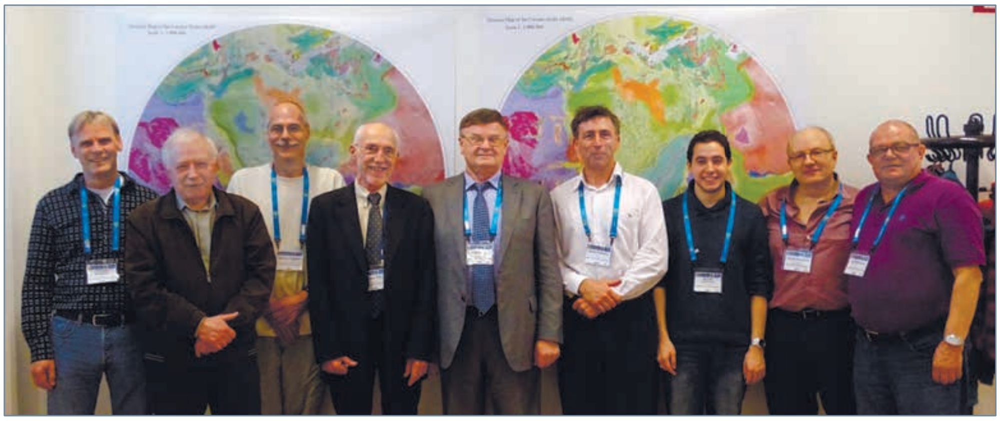
🇳🇴 **J.I. Faleide (Oslo Univ.), M. Smelror (NGU), A. Solli (NGU), L. Gernigon (NGU), C. Gaina (Oslo Univ.), H. Brekke (NPD), E. Gillebo (NPD)**

🇸🇪 **M. Stephens (SGU)**

🇬🇧 **S.S. Drachev (ArcGeoLink Ltd)**

🇺🇸 **A. Grantz (USGS), T. Moore (USGS), S. Box (USGS)**

Vienna, April 2012



Vienna, April 2016

Paris, February 2017

Paris, February 2014

Paris, February 2017

Paris, February 2017

St. Peterburg, February 2016

ACKNOWLEDGEMENTS

Authors are particularly grateful to leadership of the Federal Agency on Mineral Resources at the Ministry of Natural Resources and Environment of the Russian Federation for their continuous support and attention to the process of implementing the international project on the Tectonic map of the Arctic.

The Tectonic map of the Arctic, as one of the largest international mapping projects, has been supervised from the very beginning by the Commission for the Geological Map of the World (CGMW), its President Dr. Philippe Rossi and the Secretary General, Dr. Manuel Pubellier. CGMW undertook the responsibility for organizing international workshops on the project in Paris in 2010, 2014, 2016, 2017, and 2018, and during the General Assembly of the European Union on Geosciences in Vienna in 2012, 2015, 2016, and 2017. CGMW also coordinated the activities of project participants from the USA, Canada, Germany, France and other countries. The authors express their sincere gratitude to the Commission for the Geological Map of the World for this invaluable assistance.

The author are also very grateful to those whose materials were used in compiling the Tectonic map of the Arctic and would like to mention them. They are D. Hatchnson, R. Jackson, D. Mosher, T. Funck, J. Shimeld, G. Oakey, V.V. Akinin, B.V. Belyatsky, V.B. Ershova, E.A. Gusev, A.K. Khudoley, E.A. Korago, T.N. Koren, O.L. Kossovaya, B.G. Lopatin, N.Yu. Matushkin, D.V. Metelkin, A.V. Prokopiev, P.V. Rekant, S.A. Sergeev, S.S. Shevchenko, N.M. Stolbov.

The research was supported by RFBR (grant 17-05-00795) and RSF (grant 16-17-10251).