Deep Structures of the Circumpolar Arctic

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Abstract The deep model of the Earth's crust and upper mantle of the Arctic basin is represented by a series of velocity sections along the DSS profiles and a set of maps showing the thickness of the sedimentary cover, the thickness of the Earth's crust as a whole and the distribution of the continental and oceanic types of the Earth's crust in the Circumpolar Arctic. 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. 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. 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 7600 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.

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1 Gravity and Magnetic Anomaly Maps

Compilations of the magnetic and gravimetric maps was coordinated by the Geological Survey of Norway and Carmen Gaina was chosen as the leader of the «Circum-Arctic Mapping Project-Gravity and Magnetic Maps» (CAMP-GM) working group. In August 2008 the geophysical maps were displayed at the 33rd International Geological Congress in Oslo (Saltus and Gaina 2007; Gaina et al. 2007, 2008, 2011). In 2009, the final report from the CAMP-GM working group was published as an open file in the Geological Survey of Norway report series (NGU Report 2009.010) (Gaina 2009; Gaina et al. 2010). In 2011, the gravity and magnetic anomaly maps were published at the CAMP-GM web-site (Figs. 1 and 2) (Gaina et al. 2011).

The maps were compiled in the Polar Stereographic projection (datum: WGS 84) and compose gridded data that were provided from Polar Regions by Russia, Canada and USA. As the "master grid" the Alaska USGS aeromagnetic compilation was used. The original projections are listed in NGU Report 2009.010 (Gaina 2009). Preliminary the MF4 and MF5 models were used CAMPGM-M compilation, but for the compilation of the final version of CAMPGM-M magnetic anomaly model MF6l was used (e.g. Hemant et al. 2007; Maus et al. 2007, 2008).

For the compilation of the gravity map a polar-stereographic projection as well as the IBCAO bathymetry was used. The digital gridded data for it was presented in a grid-cell size of 10 km by 10 km (Gaina 2009). The final product included one map of the Free Air gravity anomaly and one map of combined Free Air and Bouguer) in a 1:5,000,000 scale, both at 10 × 10 km grid resolution. A new grid of the Free Air gravity anomaly was produced under the lead of René Forsberg (DNSC) (Kenyon and Forsberg 2000; Kenyon et al. 2008).

Taking into account the lack of direct geological data in Arctic both of these maps we actively used in tectonic compilations.

2 Earth's Crust Velocity Models by Wide-Angle Seismics

At present, data from more than 35,000 km of refraction and wide-angle reflection (deep seismic sounding—DSS) lines have been acquired in the Arctic Ocean, including over 12,000 km done in course of Russian high-latitude expeditions. The sketch-map (Fig. 3) shows main Russian DSS lines in the central and eastern Arctic studied in 1989–2014.

Main technologies for refraction and wide-angle reflection seismic surveys in the Arctic are: (1) observations with ocean bottom seismometers using high-power air-guns and (2) ice-based observations using TNT blasts. With both technologies, seismic waves are recorded at offsets up to 250–300 km, which allows recording all the main reference phases containing information on the crustal structure and velocity parameters through the whole crustal and uppermost mantle. The most informative are detailed seismic soundings with 3-component ocean bottom seismometers.

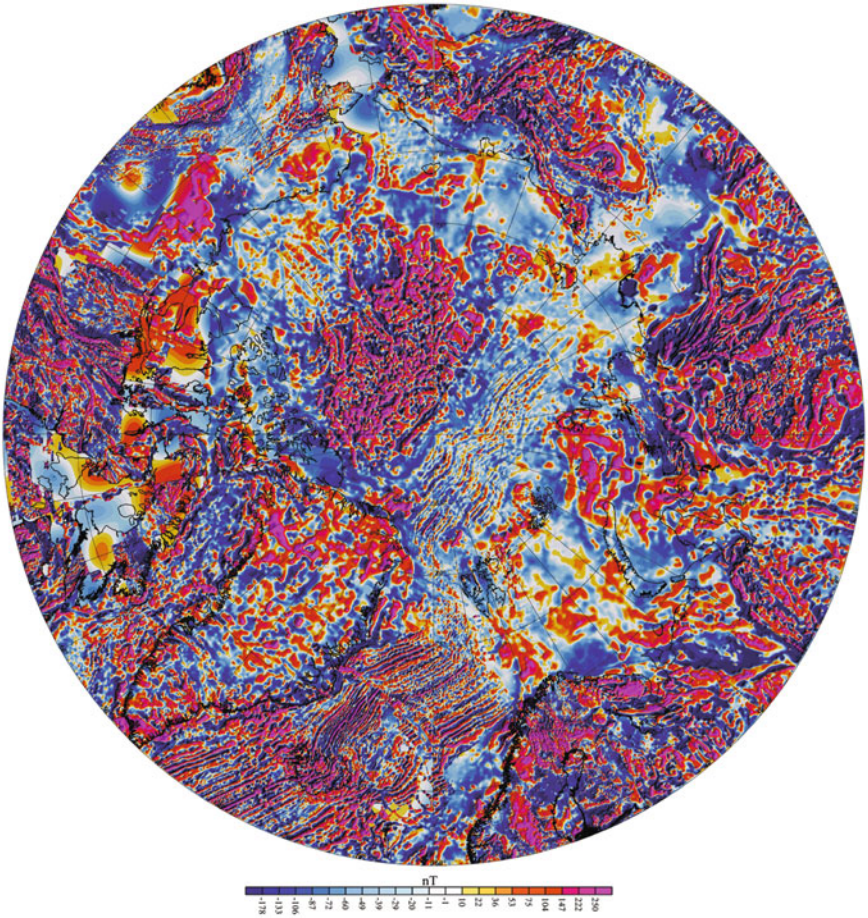


Fig. 1 CAMPGM-M magnetic anomaly compilation of gridded data (to 60 °N) based on ground/airborne regional compilations and global model of lithospheric field, based on satellite data (MF6) (Gaina et al. 2011) (http://www.geodynamics.no/Web/Content/Projects/CIRCUM-ARCTIC%20MAPPING%20PROJECT)

However, in areas with the perennial ice cover, where ocean bottom observations are impossible, ice-based seismic surveys with pure Z-component recording also provide recording of main target P-waves.

In 1989–1992, ice-based DSS surveys were performed using airborne method, i.e. using air delivery of seismic recording equipment to receiver points on ice surface. Later, in 2000–2007, research vessels were used. TNT explosive charges of 0.2 to 1.2 tons were used to excite seismic energy. Seismic signal was recorded by autonomous low-channel “land” seismometer equipped with vertical seismic receivers (Z). Shot point spacing varied from 35 to 70 km, receiver point spacing varied from 3 to 15 km.

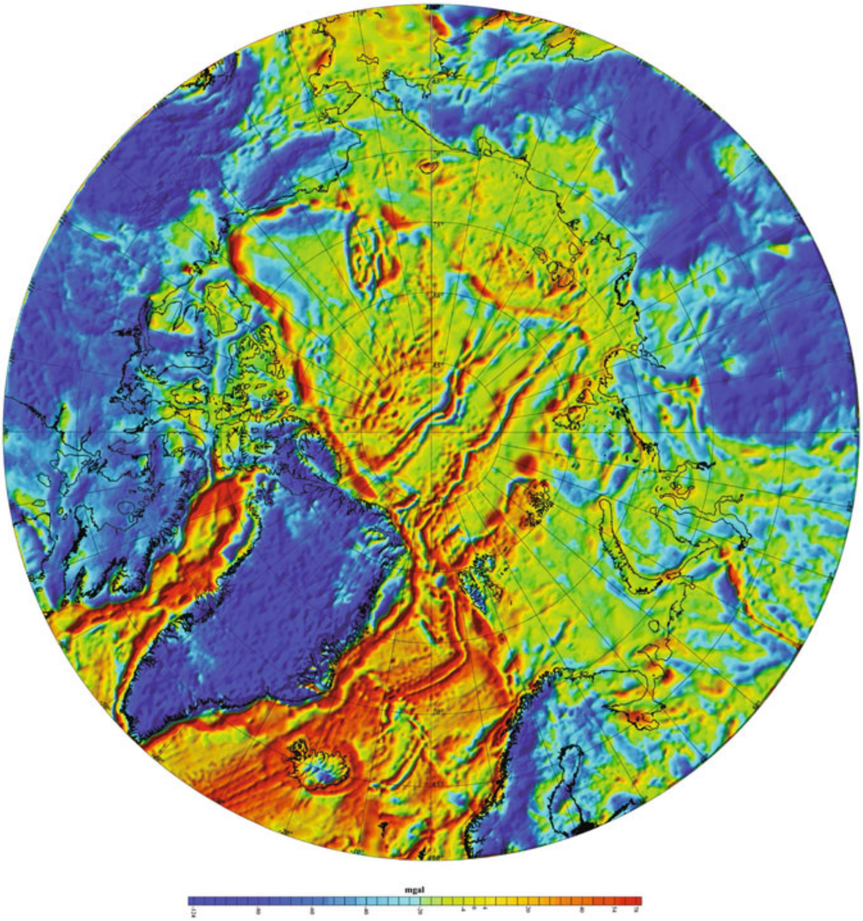


Fig. 2 Gravity map of the Circum-Arctic, with Bouguer gravity anomaly data onshore and Free Air gravity anomaly data offshore, at a grid resolution of 10 × 10 km in a polar stereographic projection (Gaina et al. 2011) (http://www.geodynamics/mno/Web/Content/Projects/CIRCUM-ARCTIC%20MAPPING%20PROJECT)

DSS observations with ocean bottom seismometers were carried out “in open water” in 2008–2014. Powerful air-guns with the chamber volume of 80–120 L (4880–7320 in.^{3}) with a working pressure of up to 150 atm were used. Seismic signal was recorded by autonomous ocean bottom seismometers equipped with a hydrophone (H) and 3-component geophones (X, Y, Z). Observations were made with receiver spacing of 10 to 20 km and shot point spacing of 250 to 315 m.

TransArctic-89-91 (Podvodnikov Basin) (Fig. 4). S-N geotransect Transarctic-89-91 extending for 1500 km from the shelf of the De Long islands in the East Siberian Sea across the Podvodnikov and Makarov basins to the circumpolar part of the

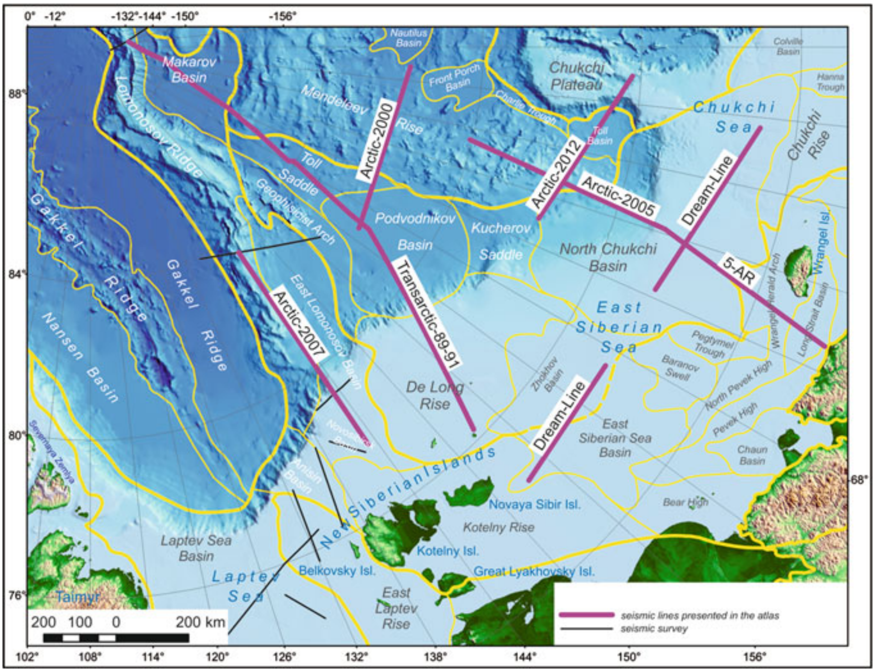


Fig. 3 DSS-profiles in the Eastern Arctic

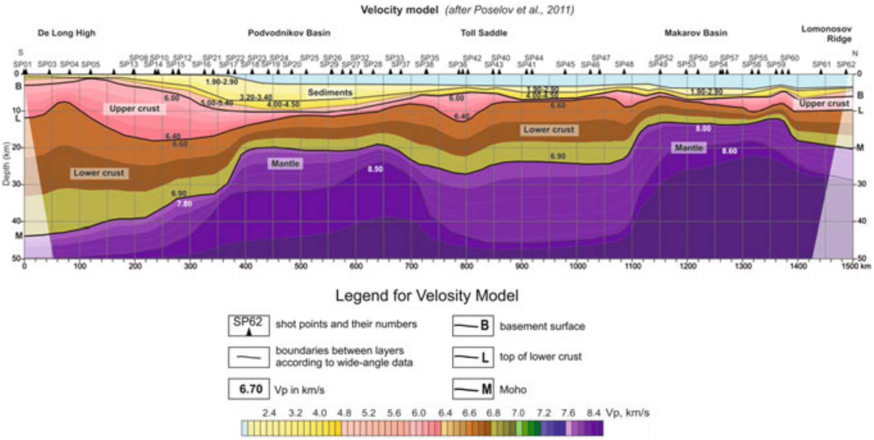


Fig. 4 Velocity model along TransArctic-89-91 profile (Poselov et al. 2011a). Profile position is shown in Fig. 3. Numeric designations of the Vp in km/s. B—basement surface; L—top of lower crust; M—Moho

Arctic Ocean was shot by airborne method from drifting ice bases. The set of studies included DSS and reflection seismic surveys, ice-based airborne gravimetric surveys, and aeromagnetic surveys.

The crustal velocity model along the line made it possible to trace: (1) sedimentary cover with Vp of 1.9 to 4.5 km/s and thickness from 7 km in the Vilkitsky Trough to 2–4 km in the Makarov Basin; (2) intermediate sequence with Vp from 5.0 to 5.4 km/s and thickness from several hundred meters in the Makarov Basin to 2–2.5 km under the continental slope; (3) the upper crust (Vp of 6.0–6.4 km/s) with greatly varying thickness from 15 km in the De Long Rise to 1–2 km in the Makarov Basin; (4) the lower crust (Vp of 6.6–6.9 km/s) with 9 km thickness in the Makarov Basin to 25–35 km thickness in the De Long Rise; (5) the upper mantle (Vp of 7.8–8.0 km/s). The crustal thickness changes rather sharply from 44 km under the De Long Rise to 20–21 km under the Podvodnikov Basin and to 13–14 km under the Makarov Basin. Thus, stratified sedimentary sequences, the intermediate sequence, and the crystalline two-layer crust are traced from the outer shelf of the East Siberian Sea to the Podvodnikov and Makarov Basins, which corresponds to the model of the thinned continental crust.

Arctic-2000 (Mendeleev Rise) (Fig. 5). The 485-km-long W-E profile Arctic-2000 extending from the Podvodnikov to the Mendeleev Basin across the submarine Mendeleev Rise was shot using the airborne method from the research vessel Akademik Fedorov. The set of geophysical studies included DSS and single channel seismic (SCS) reflection observations (with ~5 km station spacing), ice-based gravimetric measurements. Geophysical explorations were supplemented with bottom geological sampling.

The crustal and upper mantle velocity model demonstrates: (1) the sedimentary cover (Vp of 1.7–3.5 km/s) reaching up to 3.5 km in thickness in the Podvodnikov Basin; (2) the intermediate sequence with Vp of 5.0 to 5.4 km/s and the thickness

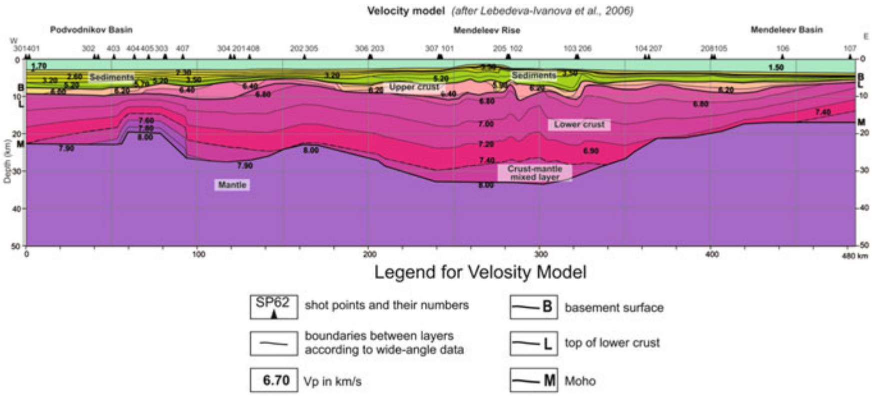


Fig. 5 Velocity model along Arctic-2000 profile (Lebedeva-Ivanova et al. 2006). Profile position is shown in Fig. 3. The basic notation is the same as in Fig. 4

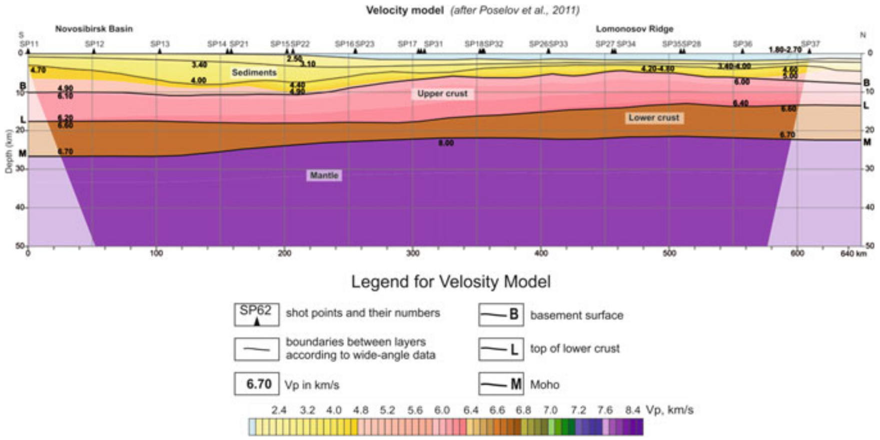


Fig. 6 Velocity model along Arctic-2007 profile (Poselov et al. 2011a). Profile position is shown in Fig. 3. The basic notation is the same as in Fig. 4

of up to 4 km in the Lomonosov Ridge; (3) the upper crust (Vp of 5.9–6.5 km/s) varying from 2 to 4 km in thickness; (4) the lower crust (Vp of 6.7 to 7.3 km/s) having the thickness of 10 km under troughs to 20 km under the Lomonosov Ridge; (5) presumably crust-mantle mixture (Vp of 7.4 to 7.6 km/s); (6) upper mantle (Vp of 7.9 to 8.0 km/s). The crustal thickness varies from 13 km under the Mendeleev Basin to 32 km under the Lomonosov Ridge. According to existing conceptions, such velocity model is typical of the continental crust.

Arctic-2007 (Lomonosov Ridge) (Fig. 6). The 650-km-long S-N DSS line Arctic 2007 stretching along axial zone of the Lomonosov Ridge towards the zone of its junction with the Laptev and the East Siberian shelves was shot using the airborne method from the Rossiya nuclear icebreaker.

In the same year, another survey was made along the line using multi-channel seismic (MCS) reflection technique with a 8100-m-long streamer and shot point spacing of 37.5 m. The northern end of the Arctic-2007 line adjoins the Transarctic-92; similar sequences have been traced along both of them (see earlier). The southern end of Arctic-2007 goes towards the shelf near the New Siberian Islands. As can be seen from the above cross-section, all the main sequences typical of the continental crust with insignificant variations in thickness and velocity are continuously traced from the shelf to the Lomonosov Ridge. Currently, the continental nature of the Lomonosov Ridge and its relationship with the shelf of Northern Eurasia are recognized by most Arctic researchers.

Composite line 5-AR—Arctic-2005 (East Siberian Shelf, Mendeleev Rise) (Fig. 7). The 650-km-long DSS line Arctic-2005 along the crest of the submarine Mendeleev Rise was shot using the airborne method from the research vessel Akademik Fedorov in 2005. In 2008, DSS seismic survey was carried out with ocean bottom seismometers along the 550 km line 5-AR directly adjacent to the line Arctic 2005 in the south.

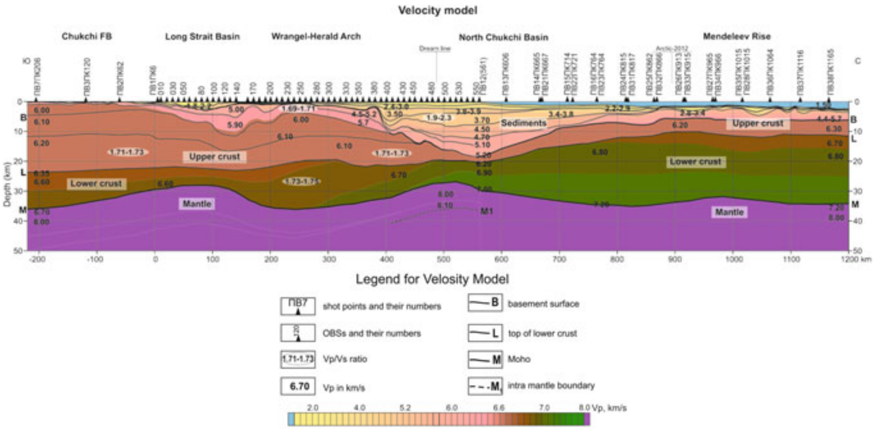


Fig. 7 Velocity model along Composite line 5-AR—Arctic-2005 (Kashubin et al. 2018b). Profile position is shown in Fig. 3. The basic notation is the same as in Fig. 4. The numbers in the circles correspond to the Vp/Vs ratio

It was supplemented by onshore-offshore surveys along the 220 km segment of the ground line 2-DV. In addition, MCS survey with a towed streamer of 8100 m length and shot point spacing of 50 m was carried out along 5-AR, and in 2012, near the line Arctic 2005, MCS survey was carried out using the 600-m-long towed streamer and shot point spacing of 50 m. Thus, based on results of all these seismic surveys, it was possible to construct the composite crustal and upper mantle velocity model along the 1400-km-long line extending from the continental land in the south to the submarine Mendeleev Rise in the north.

All major seismic sequences were traced along the profile based on the crustal velocity model: stratified sedimentary sequences, the intermediate sequence, and crystalline crust sequences. The change in the crust type is also clearly visible in the transition from the continental shelf through the thick sedimentary basin to the submarine Mendeleev Rise. The typical continental crust having the thickness of 32–35 km with the thick upper part (thickness of the "granite gneiss" layer is 15–20 km and more) is observed on the land and in the shelf part. Within the Mendeleev Rise, the crustal thickness practically does not change, but the thickness of the upper crust significantly decreases. This type of the crust (with typical or somewhat reduced thickness but significantly increased thickness of the lower crust) is rare on continents, but is common for the most Central Arctic Elevations.

Dream-line (North Chukchi Basin) (Fig. 8). Deep seismic soundings with ocean bottom seismometers along the 925 km Dream-line profile in the East Siberian and the Chukchi Seas were carried out by order of the BP PLC in 2009.

The data of these studies and the MSC data obtained from studying the Russian lines RU2-1350, OGT-2, and ARS10Z01 located not far from the DSS Dream-line resulted in the development of the Vp and Vp/Vs crustal and upper mantle velocity models of the North Chukchi Trough.

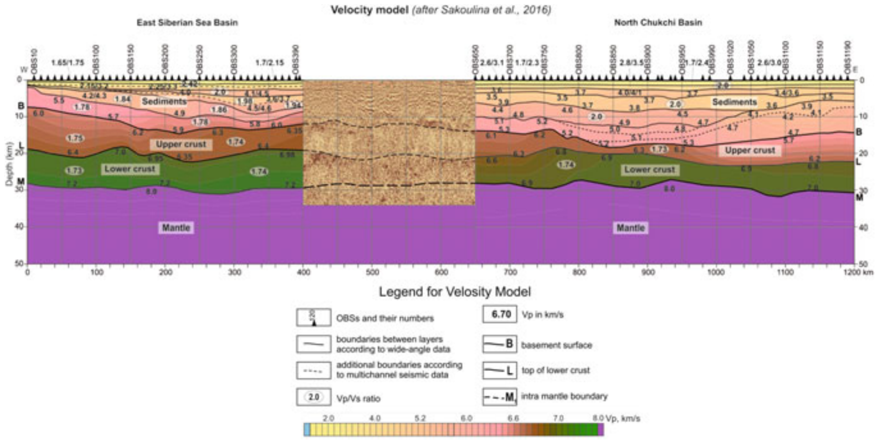


Fig. 8 Velocity model along Dream-line profile (Sakoulina et al. 2016). Profile position is shown in Fig. 3. The basic notation is the same as in Fig. 4. The numbers in the circles correspond to the Vp/Vs ratio

In the crust section, there are: (1) the sedimentary cover (Vp from 1.6–1.9 km/s in the upper part to 4.8–5.6 km/s on its bottom, Vp/Vs from 1.9 to 2.4); (2) the intermediate (meta-sedimentary) sequence (Vp of 4.6–6.0 km/s, Vp/Vs, 1.8–1.9); (3) the upper crystalline crust (Vp of 6.0–6.4 km/s, Vp/Vs, 1.73–1.75); (4) the lower crystalline crust (Vp of 6.6–7.2 km/s, Vp/Vs, 1.73–1.74); (5) the upper mantle (Vp of 8.0 km/s).

The average crust thickness along the Dream-line is 28–30 km. The greater part of the crust (7 to 16 km) corresponds to the sedimentary cover. Such velocity parameters and thickness of the Earth's crust in the North Chukchi Trough are typical of the crust of continental deep depressions.

Arctic-2012 (Mendeleev Rise) (Fig. 9). The 740-km-long DSS profile Arctic 2012 crosses the Mendeleev Rise approximately at the latitude of N77°. Integrated MCS and DSS seismic surveys were carried out along the line. DSS surveys were done with the use of ocean bottom seismometers deployed with 10–20 km spacing. A powerful 120-l (7320 in.^{3}) air-gun was used. Vp and Vp/Vs crustal and upper mantle velocity models were developed.

In the crustal section, there are: (1) the sedimentary cover (Vp of 1.6–1.9 km/s in the upper part to 4.8–5.6 km/s in the bottom, Vp/Vs from 1.9 to 2.8); (2) the intermediate (meta-sedimentary) sequence (Vp of 4.6 to 6.0 km/s; Vp/Vs, 1.9–2.0); (3) the upper crystalline crust (Vp of 6.0–6.3 km/s in the upper part to 6.7 km/s in the bottom, Vp/Vs, 1.70–1.73); (4) the lower crystalline crust (Vp of 6.8 to 7.3 km/s, Vp/Vs, 1.74–1.78); (5) the upper mantle (Vp of 7.8–8.0 km/s).

The crustal thickness in the Mendeleev Rise is about 32 km, 20 km being the lower crust. In general, the velocity parameters and crustal thickness in the Mendeleev Rise are typical of the continental crust. The increased thickness of the lower crust

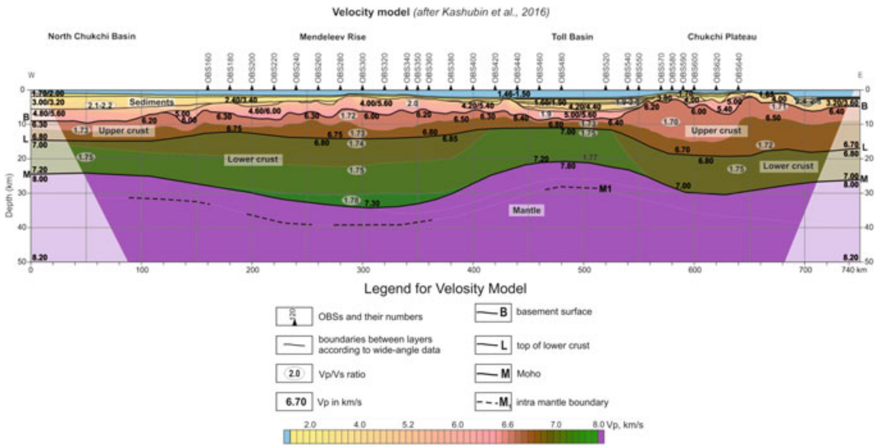


Fig. 9 Velocity model along Arctic-2012 profile (Kashubin et al. 2016, 2018a; Kashubin and Petrov 2019). Profile position is shown in Fig. 3. The basic notation is the same as in Fig. 4. The numbers in the circles correspond to the Vp/Vs ratio

is probably due to magmatic underplating, which in its turn led to intraplate basic volcanism and the High Arctic large igneous province (HALIP) formation in this part of the Arctic.

3 Set of Deep Structure Maps

Gravity and magnetic domains of the Arctic. 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. 10).

Maps of the anomalous magnetic field (AMF) and the anomalous gravity field (AGF) of the Arctic at 1:5 M 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 and Smelror 2015a, b, Petrov et al. 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 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

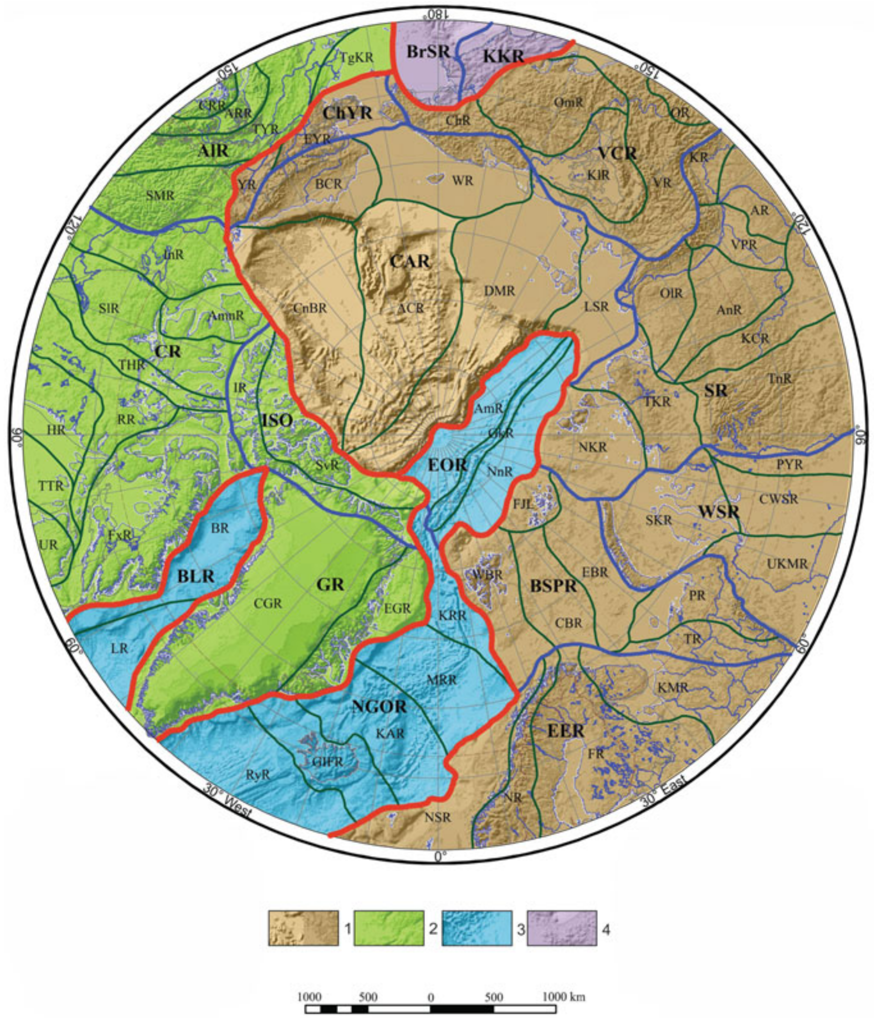


Fig. 10 Circumpolar Arctic zoning map based on the character of potential fields. Color indicates provinces: 1—Eurasian (lighter tone corresponds to areas submerged to bathyal depths), 2—North American, 3—Mid-oceanic ridges, 4—Pacific. Blue lines indicate boundaries of regions (bold); green lines show borders of areas. Digital encoding of potential field types and corresponding tectonic units are shown in Table 1. At the bottom: gravity anomalies map (**a**) and anomalous magnetic field map (**b**)

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. 10; 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. Figure 10 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.

Map of thickness of undeformed sedimentary cover in the Arctic. 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 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 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. 11 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

Table 1 Matching of letter symbols (indices) on the zoning map (Fig. 10) 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

(continued)

Table 1 (continued)

Index on the map	Potential fields' zoning (units names)	Tectonic zoning
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
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

(continued)

Table 1 (continued)

Index on the map	Potential fields' zoning (units names)	Tectonic zoning
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**

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 and Masters 2010; Poselov et al. 2011a, b, 2012; Artemieva and 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

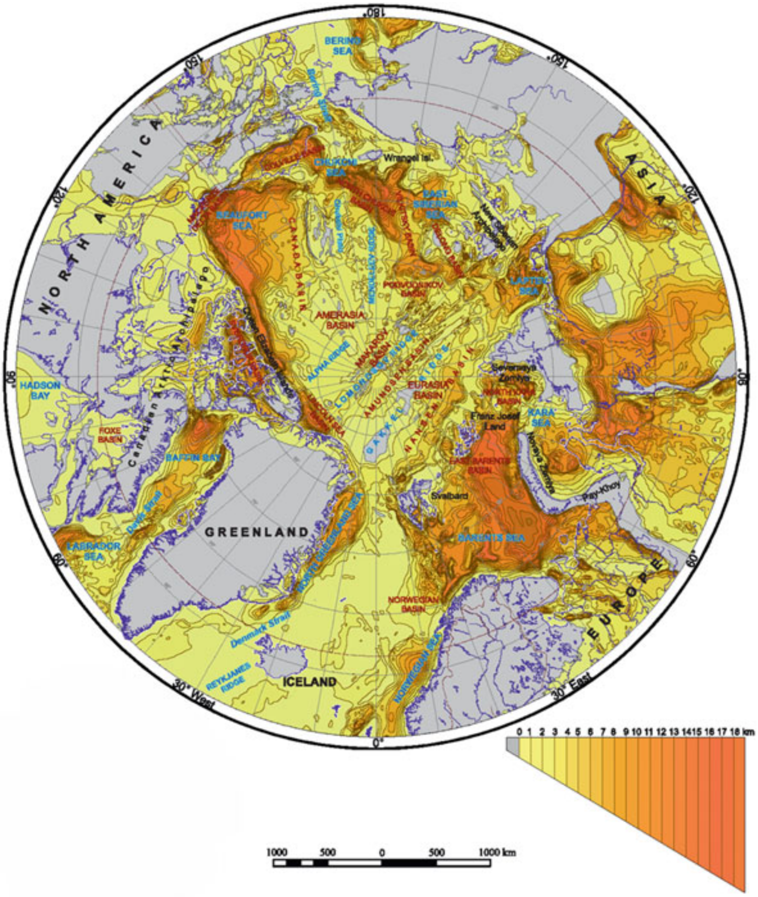


Fig. 11 Thickness map of circumpolar Arctic sedimentary cover (Petrov et al. 2016; Petrov and Smelror 2019). Index map of authors' layouts: 1—Erinchek et al. (2002) (unpublished material). Relief map of the basement of various ages of the East European Platform and the Timan-Pechora Province; 2—Divins (2003) (unpublished material). NGDC Total Sediment Thickness of the World's Oceans and Marginal Seas; 3—Grantz et al. (2009). Map showing the sedimentary successions of the Arctic Region that may be prospective for hydrocarbons; 4—Laske and Masters (2010). Global Digital map of Sediment Thickness; 5—Sakoulina et al. (2011). Sedimentary basins of the Sea of Okhotsk region; 6—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—Stavrov et al. (2011) (unpublished material). Thickness map of sedimentary cover at 1:5 M; 10—Kumar et al. (2010) (unpublished material). Tectonic and Stratigraphic Interpretation of a New Regional Deep-seismic Reflection Survey off shore Banks Island; 11—Mosher et al. (2012) (unpublished material). Sediment Distribution in Canada Basin; 12—Petrovskaya et al. (2008) (unpublished material). Main features of the geological structure of the Russian Chukchi Sea; 13—Vinokurov et al. (2013) (unpublished material). Sedimentary cover thickness from seismic profiles of the expedition Arctic-2012

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.

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 2009 (Grantz et al. 2009) and maps for the the oil and gas resource potential for the Arctic produces by the US Geological Survey (USGS) (Gautier et al. 2011).

Crustal thickness map of the Arctic. 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. 12 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.

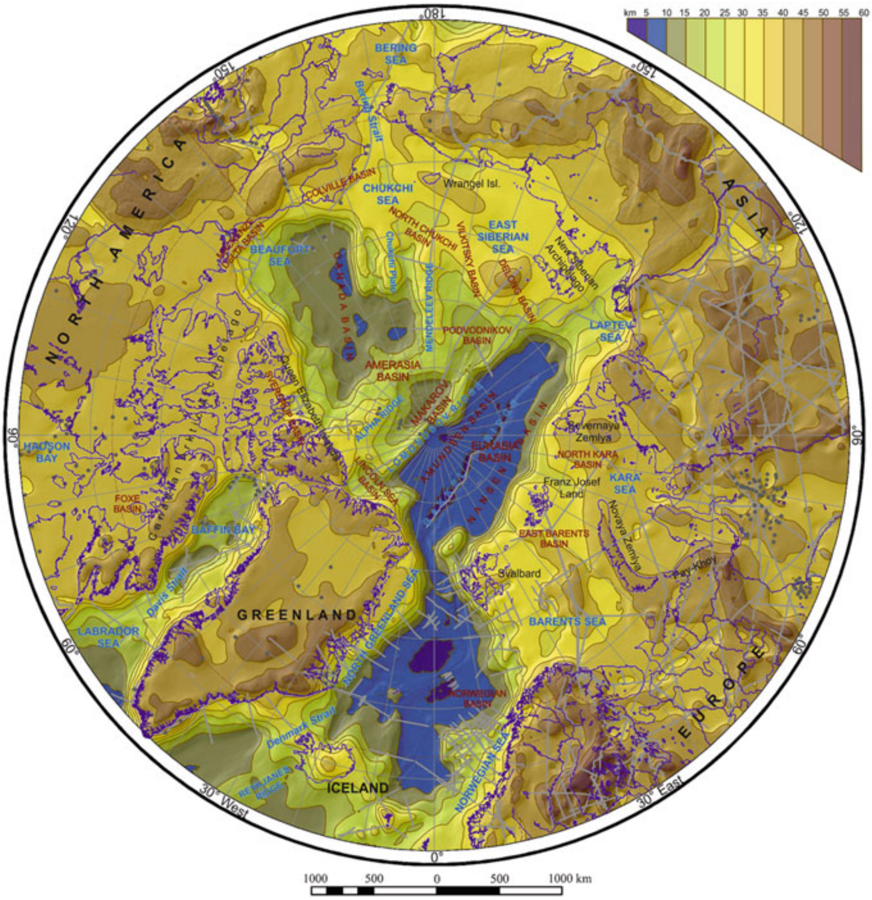


Fig. 12 Circumpolar Arctic crust thickness Map (Kashubin et al. 2011, 2014). Gray lines indicate main seismic lines and grey dots show seismic stations which materials were used for map compilation

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 CDP and RF 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 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 and 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 land, the map of depth values to the M discontinuity was transformed into the Circumpolar Arctic crustal thickness Map (Fig. 12).

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 to 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 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. 2011a; Kashubin et al. 2016, 2018a) 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 17–19 km with an equal ratio of the upper and lower crust. In the Podvodnikov-Makarov Basin, the crustal thickness varies widely: from 19 to 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.

Map of crustal types in the Arctic. 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 5–7 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).

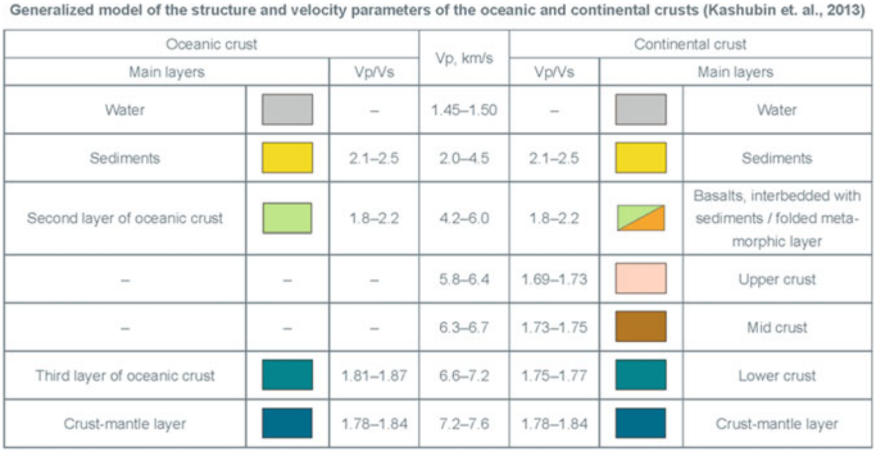
Deep seismic studies conducted in different regions of the world, continents and oceans make it possible to identify the main patterns in the velocity model of the crust and their variability depending on tectonic setting and history of development of the Arctic region. Typical features of velocity models of the crust, their relation to the tectonic structure and history of development of various geological structures have been widely discussed (Belousov and Pavlenkova 1989; Meissner 1986; Mueller 1977; Mooney 2007; McNutt and 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 and 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 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.

Table 2 Generalized model of the structure and velocity parameters of the oceanic and continental crusts (Kashubin et al. 2013, 2018b)



Generalized model of the structure and velocity parameters of the oceanic and continental crusts (Kashubin et. al., 2013)

Oceanic crust			Vp, km/s	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 / folded metamorphic layer
–	–	–	5.8–6.4	1.69–1.73	🟧	Upper crust
–	–	–	6.3–6.7	1.73–1.75	🟫	Mid 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

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. 13; Table 3) (Kashubin et al. 2013; Petrov et al. 2016).

Normal oceanic crust (type 1, Fig. 13), which includes normal oceanic crust of spreading basins (less then 10 km thick) and thickened crust of oceanic plateaus and

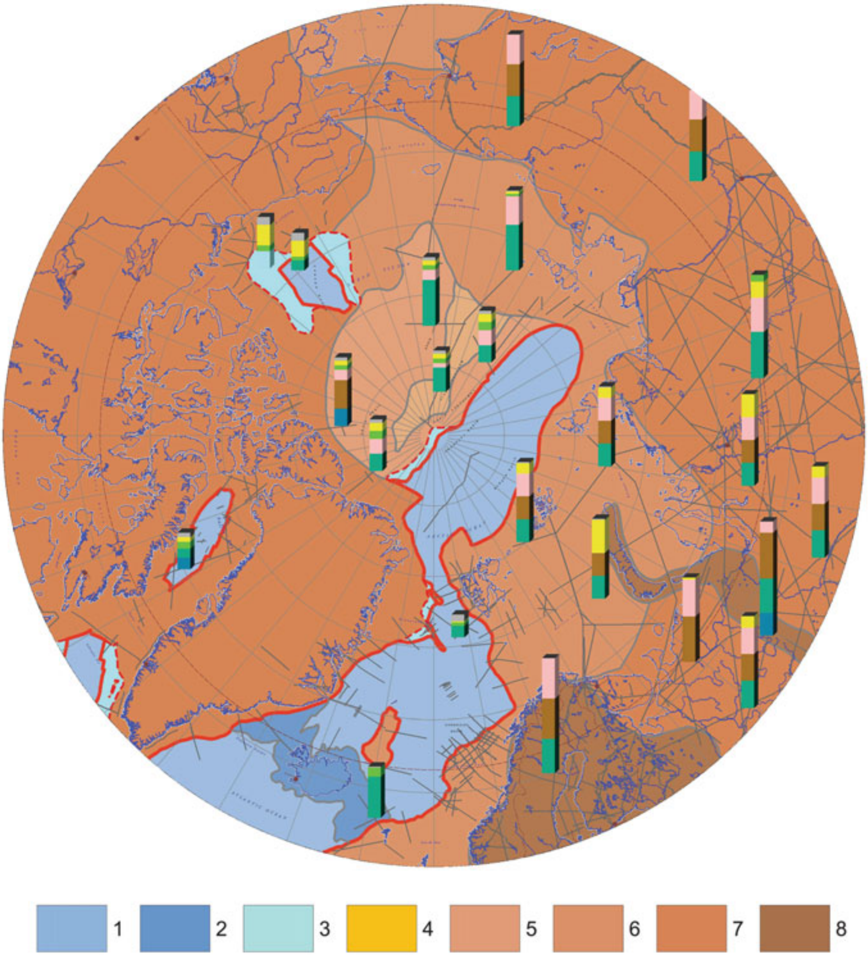
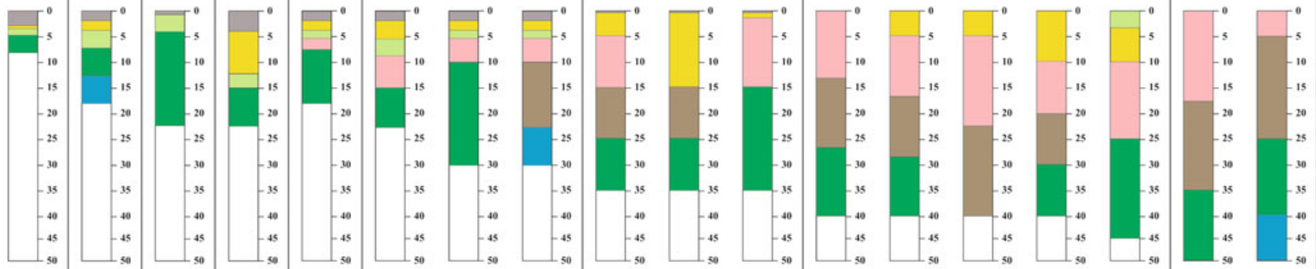


Fig. 13 Map of crust types in the circumpolar Arctic (Kashubin et al. 2013; Petrov and Pubellier 2019). 1–2—oceanic crust: 1—normal crust of spreading basins, 2—thickened crust of oceanic plateaus and hot spots; 3—reduced (transitional to oceanic) crust of deep depressions; 4–8—continental crust: 4—thinned 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

Table 3 Type columins of the crust of circumpolar Arctic structures based on seismic profiles in accordance with generalized velocity parameters given in Kashubin et al. (2013), Petrov and Pubellier (2019)



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*

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 and 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 and 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 and 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 and 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. 13) 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 and Lyons 1981; Baggeroer and Falconer 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. 2011a).

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 and Volvovsky 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 and Volvovsky 1988) suggests that thick sedimentary strata in these depressions cover the 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 and Thybo 2013; Cherepanova et al. 2013, and in the publications that are referred to in these papers; Russian publications: Volvovsky and Volvovsky 1975; Druzhinin 1983; Druzhinin et al. 2000; Druzhinin and Karmanov 1985; Egorkin 1991; Egorkin et al. 1980, 1988, 2002; Isanina et al. 1995; Poselov et al. 2007, 2010, 2011a, b; 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. 13). 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. 2011a, b; 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. 13), as it can be seen from interpretations of Russian seismic profiles Arctic-2000, Arctic-2005, Arctic-2007 and Arctic-2012 in the Lomonosov and Mendeleev structures (Lebedeva-Ivanova et al. 2006; Poselov et al. 2011a, b; Kashubin et al. 2016, 2018a), 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 (Lebedeva-Ivanova et al. 2006; Poselov et al. 2011a, b; Kashubin et al. 2016, 2018a) 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. 13). 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 and Artemieva 2013).

Shelf seas' crust (type 6, Fig. 13) 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. 13) 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).

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 and Hain 2009; Mukasa et al. 2015), and submergences of shallow-water volcanic structures to bathyal (up to 3.5 km) depths (Brumley 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).

4 Geotransect Across the Circumpolar Arctic

The 7600-km geotransect across the Circumpolar Arctic has been created along the line, which unites following DSS seismic geotraverses: 1-EB-1-AR—"Transarctica-89-92"—"Arctic-2000"—"Arctic-2005"—5-AR-2-DV (5400 km) from Petrozavodsk in the west to Magadan in the east (Berzin et al. 1998; Kashubin et al. 2018c; Sakoulina et al. 2011, 2016; Salnikov 2007; Lebedeva-Ivanova et al. 2006, 2011) (Figs. 14 and 15). It includes velocity and density models and geological and geophysical sections. The sedimentary cover bottom (B), the upper crust bottom, the upper crust roof, the Earth's crust bottom—Moho discontinuity are shown in the geotransect. For the determination of boundaries, velocity parameters (Vp) are indicated: sedimentary cover, 2.0–4.5 km/s; upper crust, 5.8–6.4 km/s; intermediate crust, 6.3–6.7 km/s; lower crust, 6.6–7.2 km/s; upper mantle, 7.8–8.4 km/s. The geological-geophysical section crosses the Eurasian oceanic basin with the Eocene, Oligocene-Early Miocene and Late Miocene—Quaternary oceanic crust (less than 10 km thick), the Baltic Shield and fold areas of northeastern Russia.

Passive continental margins of the Eurasian oceanic basin (Barents-Kara Basin, Laptev Rift and the submerged Amerasian Basin with the Lomonosov Ridge and the Alpha-Mendeleev Rise) have thin crust. The rise is thought of as a block of a three-layer Early Precambrian crust up to 30 km thick with Late Precambrian and Paleozoic

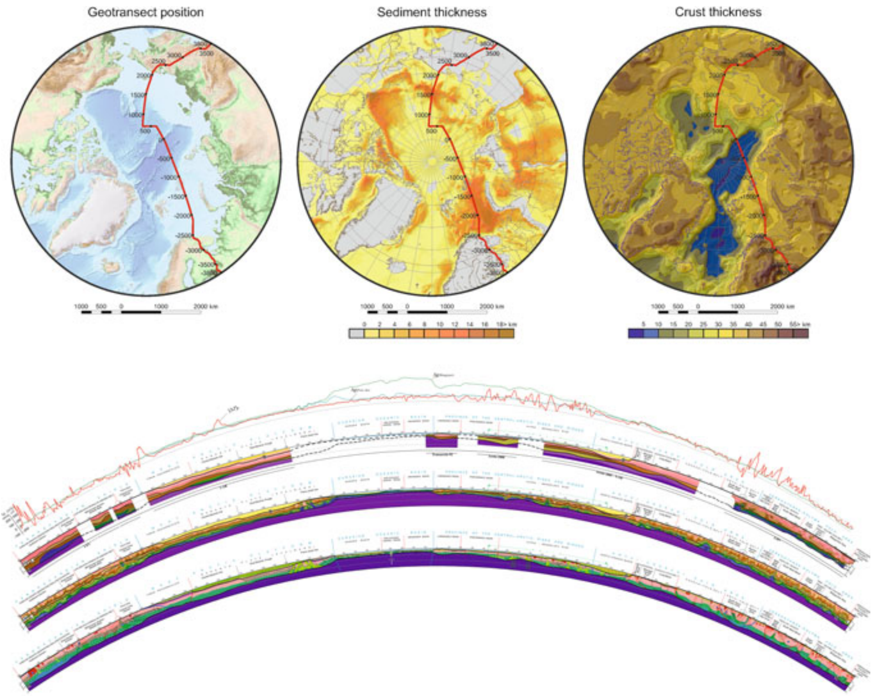
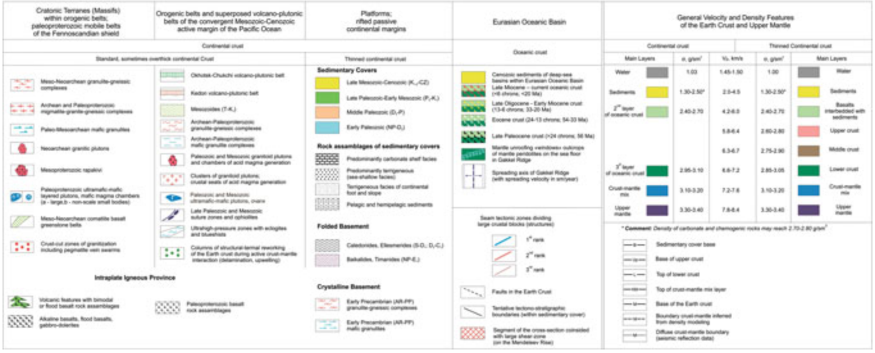


Fig. 14 Geotransect across the circumpolar Arctic



Continental crust			Thinned Continental crust	
Main Layers	ρ, g/cm³	Vp, km/s	ρ, g/cm³	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
3rd 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	7.6-8.4	3.30-3.40	Upper mantle

* **Comment:** *Density of carbonate and chemogenic rocks may reach 2.70-2.80 g/cm³*

Fig. 15 Legend for the combined geological and geophysical section in Fig. 14

sedimentary cover under Late Mesozoic and Cenozoic sediments and basalts of the HALIP. Limits and deep structure of the Anyui-Chukotka and Verkhoyansk-Kolyma regions are indicated within the limits of cross-sections. The Karelian granite-diabase region has thick (up to 45 km) three-layer crust and crust-mantle lenses of high density and velocity indicative of underplating and mafic-ultramafic magmatism.

The Alpha-Mendeleev Rise has speed and density parameters, which suggest that this is a tectonic block with a three-layer crust 30 km thick. The crust thickness is maximum for the Central Arctic uplifts area. At the bottom of the lower crust, there are local areas of high speed and high density, similar to the crust-mantle complex. This suggests the occurrence of mafic magma chambers beneath the vast HALIP basaltic areal, interpreted from the typical magnetic field.

Alpha Rise basalts north of the geotransect date back to the Cretaceous (82 Ma). It is believed that the supracrustal complex of Late Precambrian and Paleozoic sediments occurs in the acoustic basement of the Mendeleev Rise. The North Chukchi Basin is located within the Anyui-Chukchi fold area.

Gneiss granite fragments raised from the seabed using a piston sampler (sampling of the Geophysicists Spur slope) also showed the age (1139 ± 15, 688 ± 5, 48.7 ± 4, 407.5 ± 5.1 Ma) younger than granite samples on the Mendeleev Rise.

Structural similarity of the Alpha-Mendeleev Rise crust and the Karelian granite-diabase area suggests the presence of Early Precambrian tectonic blocks in the rise basement. This assumption is confirmed by isotopic dating of the seabed rock samples obtained during the Arctic-2000 and Arctic-2005 expeditions. The granite-gneiss fragments taken out and raised by box or piston samplers from the Mendeleev Rise, showed the age of 2.7, 2.6, 2.3 and 1.9 Ga; gabbro-dolerite fragments showed the age of 790 ± 20 Ma and 2650 Ma (from allogenic zircon grains). Paleozoic sandstone and quartzite (430–300 Ma) from the Mendeleev Rise also contain Archean (3.1 Ga) detrital zircons indicating the participation of Early Precambrian sources.

The Laptev Sea part of the Lomonosov Ridge, crossed by the geotransect, is characterized by two-layer structure and thinner (about 25 km) crust. The velocity and density of the lower crust is noticeably lower than that of the Mendeleev Rise. Main parameters of the consolidated crust of the Lomonosov Ridge are similar to the thin crust of orogenic belts in northeastern Russia.

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