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Structure of the upper mantle in the Circum-Arctic region from regional seismic tomography

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Abstract

We present a new three-dimensional model of *P*-velocity anomalies in the upper mantle beneath the Circum-Arctic region based on tomographic inversion of global data from the catalogues of the International Seismological Center (ISC, 2007). We used travel times of seismic waves from events located in the study area which were recorded by the worldwide network, as well as data from remote events registered by stations in the study region. The obtained mantle seismic anomalies clearly correlate with the main lithosphere structures in the Circum-Arctic region. High-velocity anomalies down to 250–300 km depth correspond to Precambrian thick lithosphere plates, such as the East European Platform with the adjacent shelf areas, Siberian Plate, Canadian Shield, and Greenland. It should be noted that lithosphere beneath the central part of Greenland appears to be strongly thinned which can be explained by the effect of the Iceland plume which passed under Greenland 50–60 millions years ago. Beneath Chukotka, Yakutia, and Alaska we observe low-velocity anomalies which represent weak and relatively thin actively deformed lithosphere. Some of these low-velocity areas coincide with manifestations of Cenozoic volcanism. A high-velocity anomaly at 500–700 km depth beneath Chukotka may represent a relict of the subduction zone which occurred here about 100 million years ago. In the oceanic areas, the tomography results are strongly inhomogeneous. Beneath the Northern Atlantic, we observe very strong low-velocity anomalies which indicate important role of the Iceland plume and active rifting in opening of the oceanic basin. On the contrary, beneath the central part of the Arctic Ocean, no significant anomalies are observed that implies passive character of rifting.

Keywords: Circum-Arctic region; seismic tomography; upper mantle structure

Introduction

The processes of global warming and the decrease of the ice cover in the Arctic Ocean make it possible exploration of mineral deposits in the Circum-Arctic region. This task requires multidisciplinary and multiscale studying of the geological processes in this region. Reconstruction of geodynamic scenarios of the crustal and lithosphere evolution is impossible without robust knowledge of the deep structure. Unfortunately, due to some objective and subjective reasons, dense observation systems cannot be installed in hardly accessible Arctic areas that strongly limits the possibilities of geophysical investigations. Since the years of seventies there have been some attempts to study the crustal and lithosphere structure in the Circum-Arctic region based on gravity observations, heat flow and seismic data (e.g., Japart et al., 1998; Sacks et al., 1979). In particular, global compilation of the lithosphere thickness and shapes of the main Precambrian lithosphere blocks by Artemieva and Mooney (2001) was one of the first attempts to access the quantitative parameters on the deep structure beneath the Arctic region. Global seismic model of 3D shear wave distribution by Lebedev et al. (2009) based on surface wave data, which includes the Circum-Arctic region, clearly reveals the areas of thick lithosphere beneath the Canadian and Baltic Shields, Greenland, and Siberian Craton. In addition, regional *S*-velocity models beneath the Canadian and Baltic Shields were constructed by Shapiro et al. (2005) and Bruneton et al. (2004) based on the surface wave data. It should be noted that *P*-body waves, which normally enable higher lateral resolution than surface waves, were not previously used for studying the deep structure beneath the Arctic region. During the last decades, several active source seismic studies along profiles in Barentz and Kara Seas provided big amount of data (mostly for oil exploration). However these profiling data enable very local results which do not allow penetrating to big mantle depths. In addition, most of them are not accessible for the research purposes.

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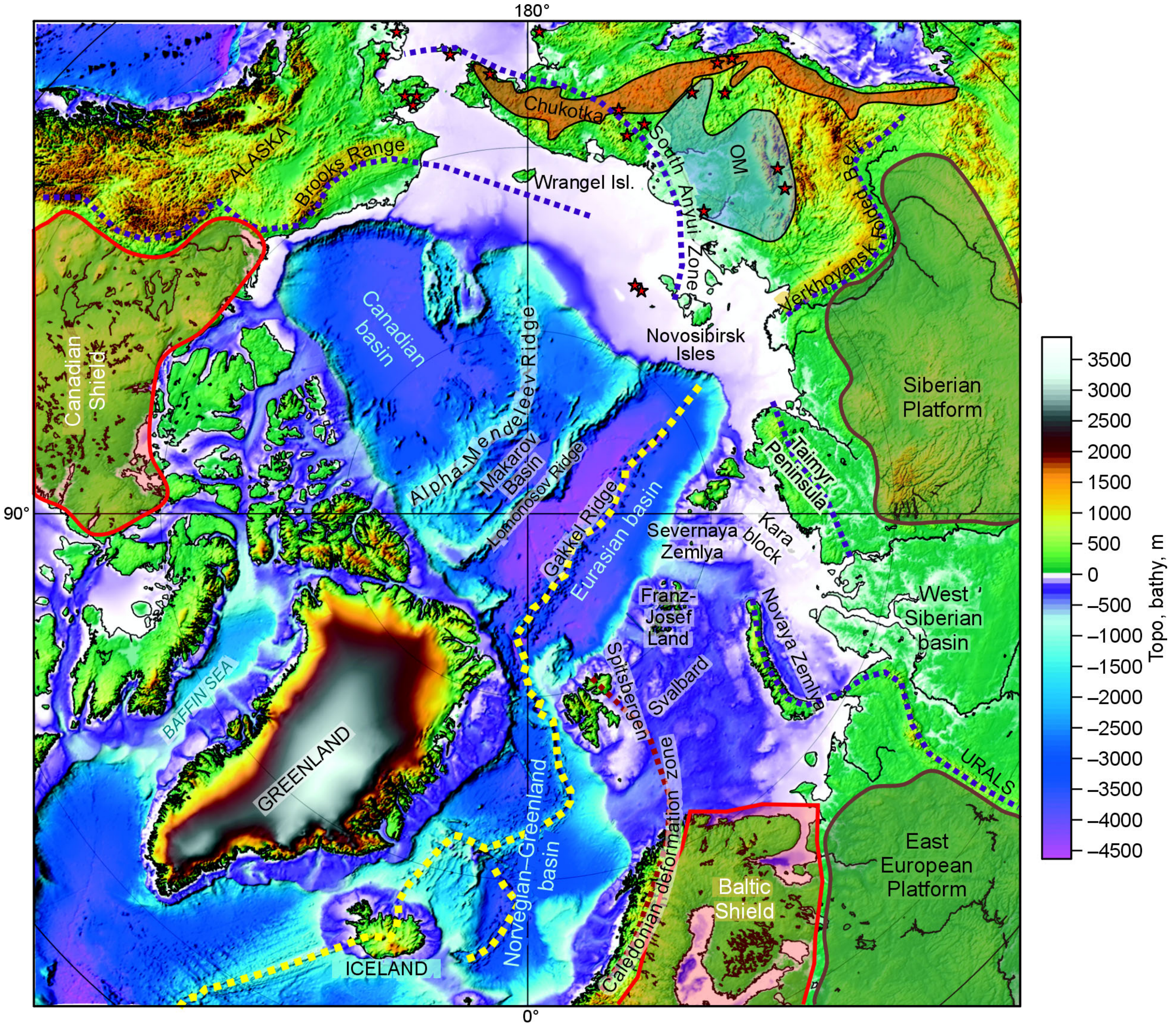


Fig. 1. Topography/bathymetry and main tectonic and geographic elements of study region. Yellow dashed line indicates ocean ridges position; blue dashed line shows boundaries of the main folded zones; red stars indicate Cenozoic basaltic volcanism within Chukotka, Yakutia, and Alaska. OM, Olomonsky massif.

The topography/bathymetry map of the Circum-Arctic region (Fig. 1) reveals complex block structure of the crust and the lithosphere. It can be seen that about half of the Arctic Ocean area is represented by very shallow shelf areas with presumably continental type of the crust. Deep water segments can be subdivided in several separate basins. The Norwegian–Greenland basin originates from spreading processes in the Northern part of the Atlantic Ocean close to the transition to the Arctic Ocean. Note that the most expressed deep segments of this basin in the European side do not coincide with the main spreading axis of the Mid Atlantic Ridge which passes through Iceland. Possible explanation of this observation might be related to straightening of the lithosphere in the axis area due to mass eruptions around the Iceland plume; this forced the spreading searching for alternative weaker areas for breaking the oceanic lithosphere.

Within the Arctic Ocean, three separated deep water basins are clearly seen in the bathymetry map (Fig. 1): two approximately equal in size Canadian and Eurasian basins and a smaller Makarov depression located in between. These basins are distinctively separated from each other with the Lomonosov and Alpha-Mendeleev Ridges. Eurasian basin appears to be a direct prolongation of the Norwegian–Greenland segment of the Atlantic Ocean. In this basin, there is a sharp spreading center along the Gakkel Ridge and clearly expressed linear magnetic anomalies (Gaina et al., 2010) which can be used to access the divergence rate of the ocean bottom. Two other basins, Canadian and Makarov, do not manifest any spreading activity: neither mid-ocean ridges, nor linear magnetic anomalies are detected there. The origin of these basins remains the subject for active discussions. They are interpreted either as relict ocean basins or as areas of strongly extended continental crust. However, specific mechanisms of their origin remain enigmatic because of lack on any data on deep structure beneath these areas.

Tectonic evolution of the Circum-Arctic region has been reconstructed based on multidisciplinary geological studies in a series of paleoreconstructions (Kabankov et al., 2004; Kosko et al., 2007; Sorokhtin et al., 2010; Vernikovsky et al., 2010; Ziegler, 1988). Some of these studies present the evidences of a relict platform which existed in the Arctic Ocean and changed its shape due to various tectonic processes. The remnant part of this platform is thought to be the Central Arctic Highland with outcrops of Mesozoic and Paleozoic rocks (so called Hyperborate Platform which was mentioned in earlier studies, such as Puscharovsky (1960, 1976), Shatsky (1963). According to Khain (2001) and Filatova and Khain (2007), the crust of the Lomonosov and Alpha-Mendeleev Ridges is composed of continental-type rocks. These segments are presumed to be of the same properties as cratonic areas of North American, Siberian, and East European Platforms. These authors propose that all these units might be the remnants of the Rodinia supercontinent broken down in the Late Proterozoic in a time period of 950–830 Ma (Metelkin et al., 2011).

Based on the consideration of tectonic history of the Arctic region and the present day tectonic activity, one cannot see a clear prolongation of the spreading axis along the Gakkel Ridge in the Asian part. It appears to be that since Early Carboniferous time, there is a diffused boundary between the Siberian and North American Plates (Bogdanov, 1998) composed of complex system of microblocks and terrains and covering a large area (Stein and Stella, 2002). The tectonic evolution of the Arctic region in the Carboniferous occurred separately from the Pacific and Atlantic segments of the Earth. In the Cenozoic time, the Arctic Ocean becomes a linking element between the main oceans in the Western and Eastern hemispheres of the Earth.

This overview shows that the lithosphere of the Arctic region has a rather complex structure and unclear evolution history which cannot be unambiguously deciphered based only on surface observations. Seismic tomography, which is one of the most powerful geophysical methods for imaging the present-day deep structure, is considered in this paper to clarify some of the above-mentioned questions on the structure and evolution of the Circum-Arctic region. Here we present the upper mantle structure beneath this region with the resolution which is compatible with scales of regional geological structures.

Data and algorithm

This study is based on travel times of body *P*-waves from the worldwide catalogue of the International Seismological Center (ISC) for the time period from 1964 to 2007. All data corresponding to seismic rays which propagated, at least partly, in the study volume were considered in this study. First of all, we used the data from earthquakes located in the study area (red dots in Fig. 2) which were recorded by worldwide seismic stations at any epicentral distances. Second, we included the data from remote events recorded by stations located in the study area (blue triangles in Fig. 2). For the Arctic region, the contribution of the second group was significantly lower. In total we used about 5 millions travel times of *P*-waves corresponding to almost 200,000 earthquakes from the ISC catalogue.

It should be noted that the initial quality of data in the ISC catalogue is rather poor. Outdated techniques used for source locations and a very large amount of outliers in the initial catalogues make it necessary the data preprocessing. All the events form the ISC catalogue were relocated using and algorithm described in (Koulakov and Sobolev, 2006) which also allows rejecting outliers. The tomographic inversion was performed based on an approach developed by (Koulakov et al., 2002) which was successfully tested in various regions, such as South Siberia (Koulakov, 2008), Kurile–Kamchatka subduction (Koulakov et al., 2011), Southern Europe (Koulakov et al., 2009) and the Asian collision belts (Koulakov, 2011). 1D spherical model AK135 (Kennett et al., 1995) was used as a basic reference model for this study. The travel times were also corrected for the Earth ellipticity, elevations of stations and the crustal thickness based on the global CRUST2.0 model (Bassin et al., 2000).

The calculations are performed in the framework of the linearized approach: the inversion is based on the ray paths traced in the 1D reference model in a single iteration. The nodes of the parameterization grid are distributed in the study volume down to the depth of 640 km in ten depth levels (50, 100, 150, 220, 290, 360, 430, 500, 570, and 640 km) and were installed according to the ray coverage. The minimal grid spacing was fixed at 50 km. To reduce any possible artifacts related to grid configuration, we performed several independent inversions for grids with different basic orientations (for example, four grids with 0°, 22°, 45°, and 67° orientations) which were then averaged in one model.

The velocity reconstruction was based on the matrix inversion. Besides the elements responsible for *P*-velocity anomalies, the matrix also included the *S*-velocity anomalies (though not considered here due to a small number of *S*-data for the Circum-Arctic region), the corrections for the sources (three coordinates and origin time for each source) and the station corrections. Damping of the solution was performed both by amplitude regularization (ridge regression) and damping of the velocity gradient (Laplacian regularization). The inversion of the full matrix was performed using the LSQR algorithm by (Paige and Saunders, 1982; Van der Sluis and van der Vorst, 1987].

The tomographic inversion was executed independently in fifteen overlapping circular areas of 10–15 degrees diameter (pink circles in Fig. 2) which cover the entire study area. The results obtained for the selected windows were then averaged into one model which is presented as the main result of this study. Note that the distribution of data in the study area is extremely uneven (Fig. 2). Regional tomography scheme is capable providing results without using data from regional stations; however, their existence is highly appreciated as it improves the quality of source locations and makes clearer the velocity structures. That is why, the interpretation of the results in the central part of Arctic, where there are not seismic stations, should be interpreted with prudence. In areas where the ray coverage is not sufficient for the inversion, the results are not shown.

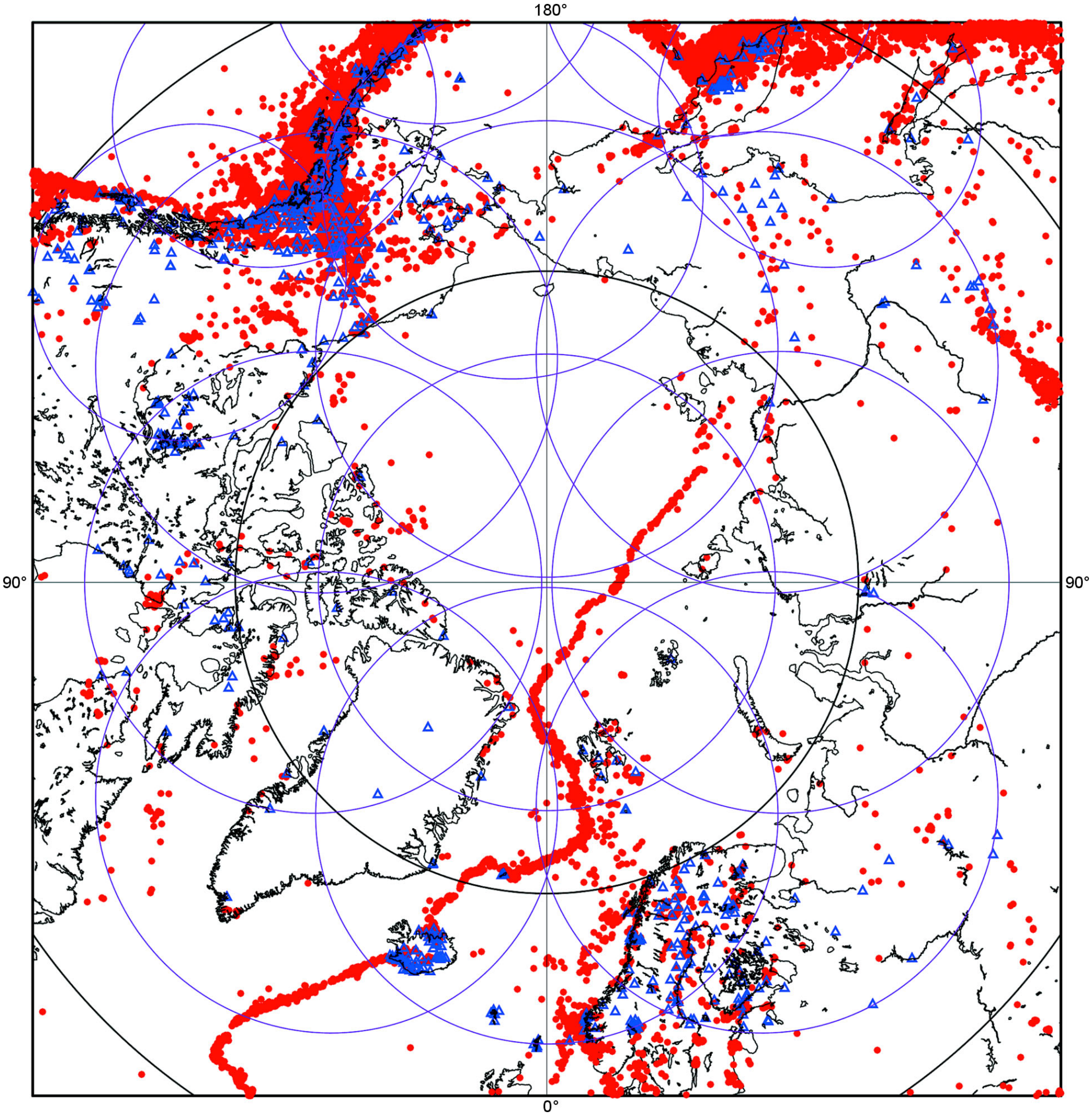


Fig. 2. Initial data distribution. Red dots indicate earthquakes from ISC catalogue; blue triangles show seismic stations position. Violet circles outline areas where independent tomographic inversion was performed.

Results and verification

The obtained 3D model of *P*-velocity anomalies in the upper mantle beneath the Circum-Arctic region are presented in four horizontal sections (Fig. 3) and five vertical sections (Fig. 4). Results are only shown in areas where the ray coverage is sufficient for performing the tomographic inversion. For example, in the shallower depth section and in vertical sections 2 and 5, there are large gaps in result images. At greater depth, the rays are distributed more uniformly; thus the gap areas disappear.

The robustness of the obtained structures can be estimated using a synthetic test presented in Fig. 5. The synthetic model for this test has been constructed based on the configuration of anomalies derived from the inversion of real data. The synthetic anomalies were defined as 3D prisms with lateral shapes unchanged in the depth interval from 0 to 350 km. The synthetic data were computed along the same ray paths as used for real data processing. The computed synthetic times were perturbed with random noise having the typical for seismological data statistical distribution and the mean absolute value equal to 0.5 s. Reconstruction of the synthetic model was performed using absolutely same approach and values of free parameters as in the case of real data processing. In Figure 5 we present the reconstruction results at the depth of

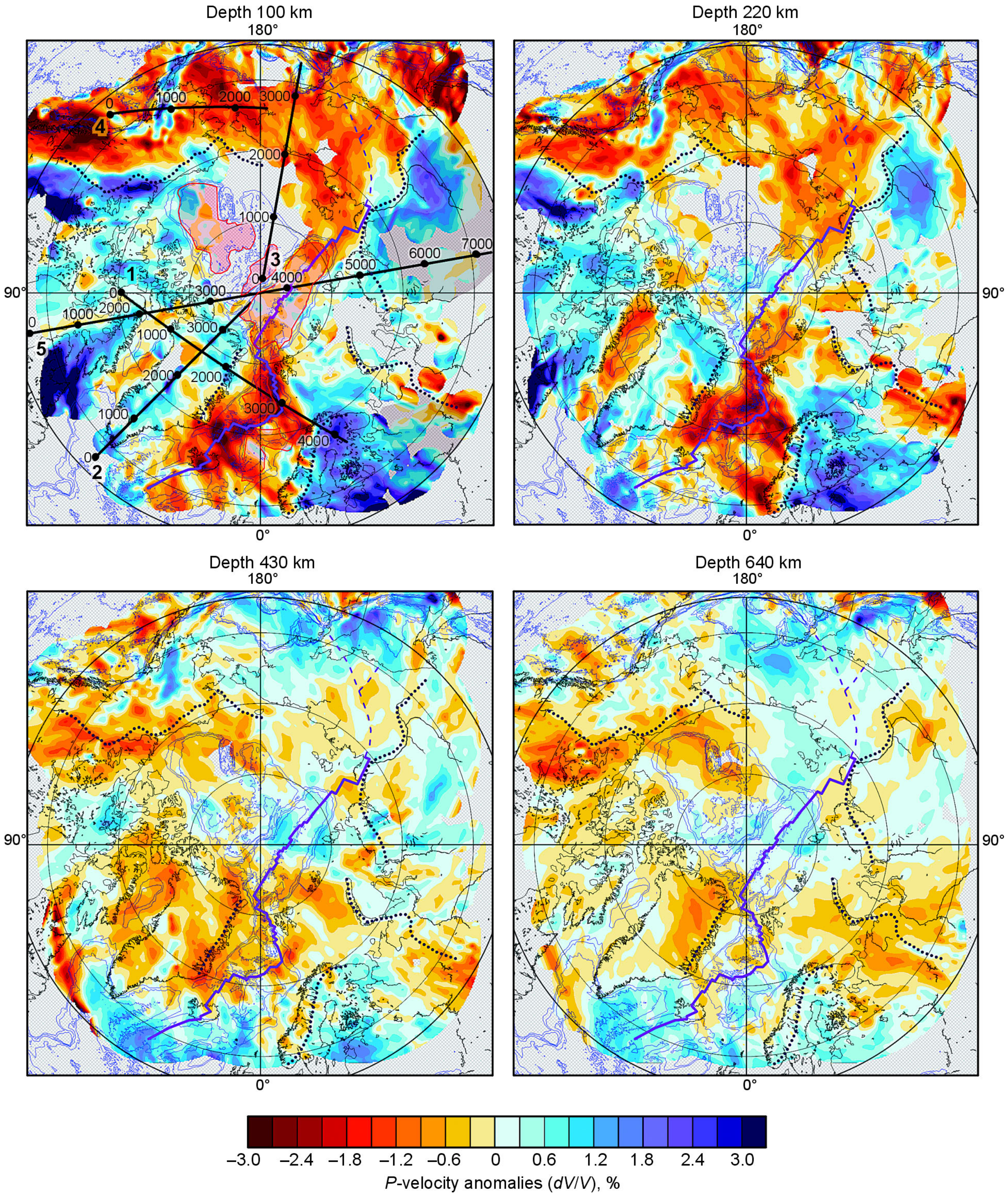


Fig. 3. Results of the real data inversion. *P*-wave velocity anomalies are shown in several horizontal sections. Violet line indicates mid-ocean ridge and its possible continuation. Dashed lines indicate boundaries of the main folded zones. Red transparent areas in the section of 100 km depth mark position of the oceanic basins (according to bathymetry). Thin blue lines are depth levels with 1000 m intervals.

220 km which generally support the reliability of most features which are discussed below.

In general, the derived seismic *P*-velocity distribution in the upper mantle beneath the Circum-Arctic region is consistent with models previously computed by other authors based on independent approaches and data. For example, high-velocity patterns beneath Canadian, Siberian, Baltic, and Greenland plates derived from analysis of surface waves by Lebebev et al., (2004) coincide with positive anomalies in our model. At the same time, as we can see from the synthetic modeling, our model is capable to resolve much finer structures than the surface-wave-based model. Similar conclusion can be done

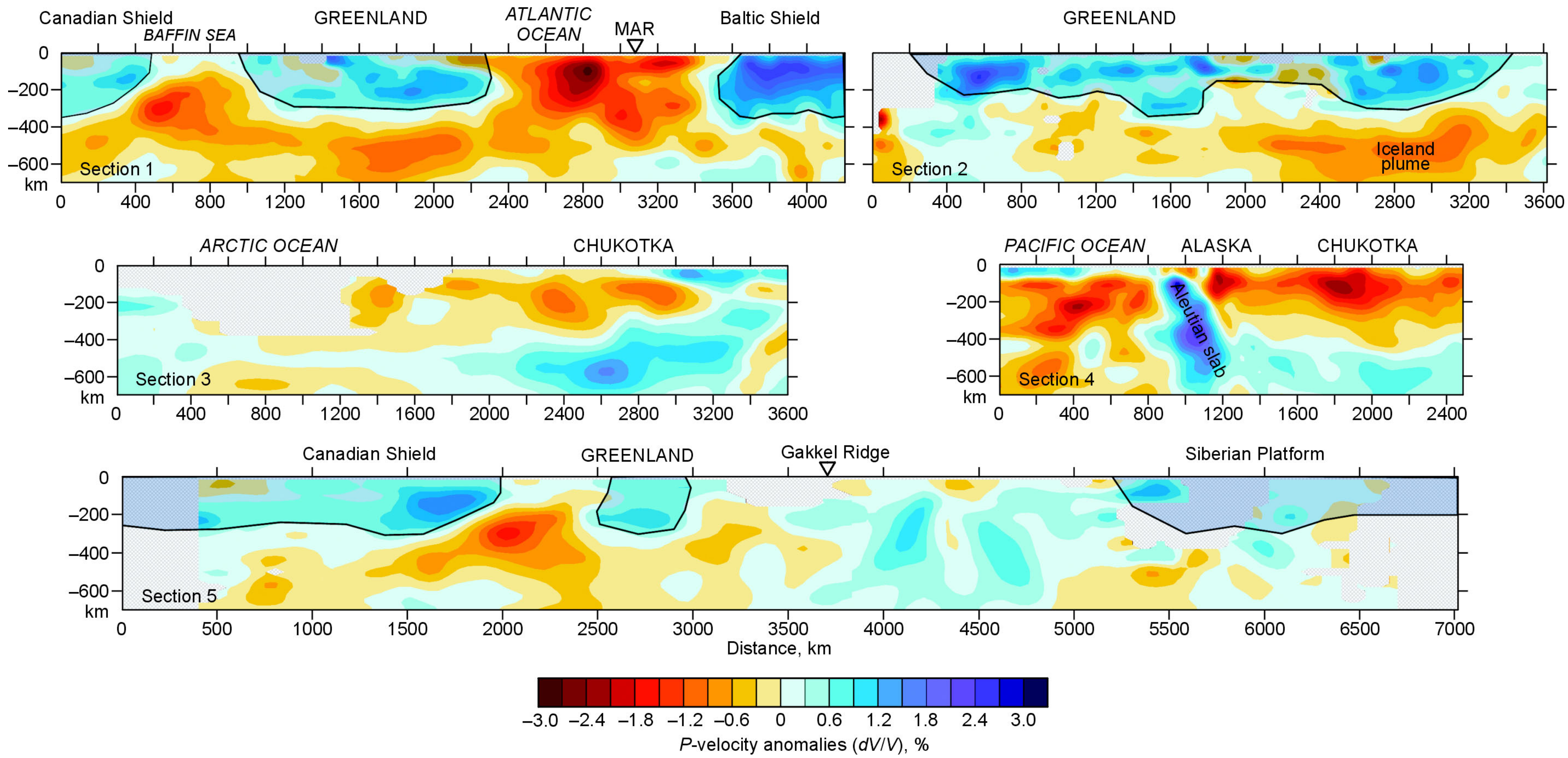
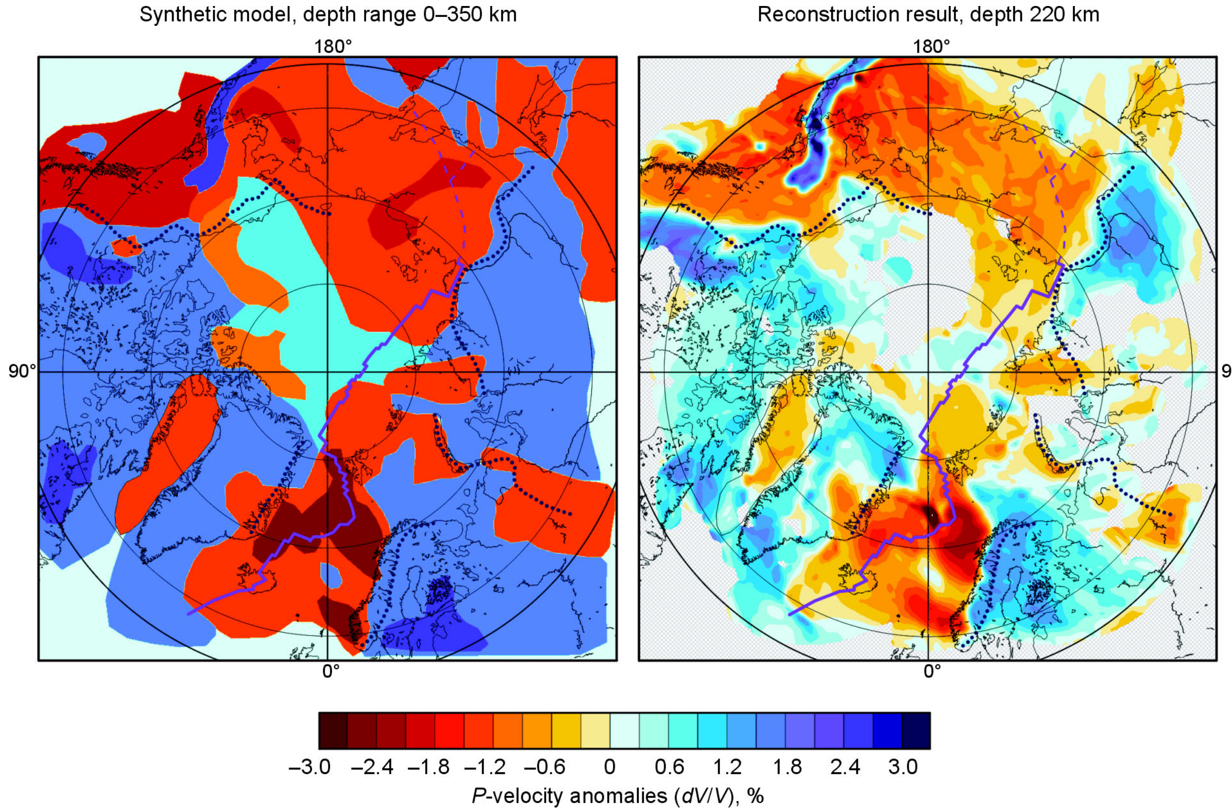


Fig. 4. Results of the real data inversion. *P*-wave velocity anomalies are shown along five vertical sections. Location of the sections is shown in Fig. 3 (in the horizontal section at 100 km depth). Continental lithospheric blocks are marked by blue transparent contours. Main geographical elements are indicted above the profiles. MAR, Mid-Atlantic Ridge.



Synthetic model, depth range 0–350 km

Reconstruction result, depth 220 km

Fig. 5. Results of the synthetic test with realistic anomalies distribution. Synthetic model defined in a depth range from 0 to 350 km is shown on the left plot. Results of the anomaly reconstruction, using tomographic inversion with real configuration of the rays, at 220 km depth shown on the right plot.

from comparison with other previously published models for the same area.

Discussion

In this section we discuss the main mantle structures displayed by the new seismic model in different segments of the Circum-Arctic region and provide some scenarios for explaining their evolution.

In the Atlantic segment, large amount of data enables relatively high resolution images of the mantle structures. At the depths of 100 and 220 km we can observe a very bright low-velocity anomaly beneath the Norwegian–Greenland basin. This feature is likely linked with the active-type of spreading processes which occur here along the periphery branches and avoids the central axis of the Mid-Atlantic Ridge. At greater depths, this low-velocity anomaly spread out in a larger area beneath the Baltic Shield and Greenland which is clearly seen in vertical section 1 in Fig. 4. Note that beneath Iceland, this anomaly is visible less prominently. The explanation of this paradox may be related to limited resolution of the regional tomography scheme which does not allow resolving a relatively narrow plume, but is able to image a large mantle upwelling beneath the active spreading center. Fairly similar features were displayed in other tomographic studies on regional and global scale (e.g., Bijwaard and Spakman, 1999).

An interesting low-velocity anomaly is observed at 100 and 220 km depth beneath the middle part of Greenland. This anomaly fits exactly to the large basaltic province in the eastern coast of Greenland erupted about 50 Ma (Ziegler, 1988). It is curious that this low-velocity feature coincides with the location of an anomalous zone with elevated heat flow and high rate of ice melting (Fahnestock et al., 2001). This anomaly might be a signature of the lithosphere thinning due to passing of the Iceland plume under the central part of Greenland. Some authors propose that at earlier stages this plume passed some other Arctic areas. For example, Forsyth et al. (1986) propose that the present location of the Alpha-Mendeleev Ridge is a relict trace of the plume migration in the Arctic basin. There are also opinions that the same plume might be located beneath the Siberian Craton in Permo-Triasic time and was responsible for mass eruption of the Siberian traps (Kuzmin et al., 2010; Smirnov and Tarduno, 2010).

The new seismic model clearly reveals the location of the main Precambrian lithospheric continental blocks. The Baltic Shield, which is considered as a continuation of the East European Platform, is observed as high-velocity anomaly down to 300 km depth as can be seen in the vertical section 1 (Fig. 4). Note that the northern boundary of this shield is located far offshore, more to the north compared to usually accepted boundaries. This allows making some revisions in the shape of the Baltic Shield. For the Siberian Craton and for the Canadian Shield, the boundaries of high-velocity anomalies (where sufficiently well resolved) correspond to the limits defined by geological data. Between the Canadian Shield and Greenland at shallower sections, we clearly observe a low-velocity anomaly which coincides with the location of the Baffin Sea. This is a possible signature of the active rifting processes which result at opining of this young oceanic basin.

Areas of active tectonic processes and mountain building in Yakutia, Chukotka, and Alaska are expressed as low-velocity areas in the shallower sections of our tomography results. This is a probable indicator of weak/thin lithosphere which is actively deformed due to moderate collisional processes. Note that all centers of recent Cenozoic volcanism in Yakutia and adjacent offshore areas (Akinin et al., 2008) perfectly fit to the low-velocity anomalies in the shallower sections. This probably indicates to the mantle origin of these volcanoes (overheated mantle, plume occurrence, etc.). In section 3 (Fig. 4) below 400 km depth we observe high-velocity anomaly beneath Yakutia and Chukotka. From the Alaska part we clearly observe the subduction of the Aleutian slab and this high-velocity anomaly might be a stagnant part of this slab. At the same time, it is known that the Aleutean subduction is relatively young and its age is not sufficient to produce this long horizontal continuation. Therefore we are more in favor with another hypothesis which explains this high-velocity body as a remnant part of the subduction zone occurred in the area of the Bering Sea and Yakutia between 130 Ma and 90 Ma (Akinin et al., 2009; Lobkovsky et al., 2010; Miller et al., 2010).

For the most parts of the Arctic Ocean the data coverage is rather poor and the robustness of the results is generally low. Nevertheless we can state that beneath the spreading centers around the Gakkel Ridge, no prominent low-velocity anomalies are observed, unlike the structures observed in North Atlantic. In this case we can propose that spreading in the Arctic Ocean is passive and only caused by relative divergence of Eurasia and America which are displaced by the forces located far outside the Arctic region. Spreading along the Gakkel Ridge causes local asthenosphere upwelling which is seen as minor low-velocity anomalies; however it does not cause any general overheating of the upper mantle as in the case of Northern Atlantics.

Conclusions

In this study we present an upper mantle *P*-velocity model of the Circum-Arctic region based on the analysis of body wave travel times. The resolution of this model is compatible with the scale of the major tectonic structures. This model is supported by results of synthetic testing and consistent with previously published results by other authors based on independent data and approaches. This model was used to clarify several important geodynamical issues of the Circum-Arctic region.

– The Precambrian platform (Baltic and Canadian Shields, Siberian Craton and Greenland) are represented by rigid lithosphere of more than 200 km thick.

– Beneath the central part of Greenland we observe low-velocity anomaly which may represent the partly destroyed lithosphere due to passing the Iceland plume under Greenland about 50–60 Ma ago.

– Beneath Chukotka, Yakutia, and Alaska we observe low-velocity anomalies which may represent relatively thin and weak lithosphere which is easily deformed due to moderate tectonic processes. These anomalies also fit with the distribution of recent basaltic volcanism having presumably the mantle origin.

– In the Northern Atlantic we observe a large low-velocity anomaly which may indicate to the active character of spreading. On the contrary, beneath the Arctic Ocean, no prominent anomaly is observed which may be in favor to the passive character of spreading.

– Beneath Chukotka below 400 km depth we observe a high-velocity anomaly which may represent a relic of the subduction zone occurred in the area of the Bering Sea and Yakutia about 130–90 million years ago.

Fairly low resolution in the most oceanic parts of Arctic is related to insufficient data amount for these areas. This problem can be partially solved by adding the reflected *PP* rays having the reflection points from the earth surface in target areas. Previous studies by Bushenkova et al., (2002) and Koulakov and Bushenkova (2010) shows that using this data allows successful covering the data gaps in areas where neither seismitity, nor seismic stations are present. Preliminary estimates shows that for the most of the Arctic region, there is a rather good coverage of the reflected PP rays and the next step will be to use these data to improve the resolution in poorly covered regions.

In addition we plan to create a model of thermo-mechanical convection in the Circum-Arctic region which will take into account the information from the tomographic study on the thickness of the main lithosphere blocks. This will allow building the geodynamic interpretation on a quantitative level.

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