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Structure of the upper mantle of Northern Eurasia from 2D density modeling on seismic profiles with peaceful nuclear explosions

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ABSTRACT

Seismic data, obtained on the territory of Russia along the super-long seismic profiles, acquired with the Peaceful Nuclear Explosions (PNE), provide new possibilities for setting up joint geophysical models for the continental upper mantle structure. The PNE profiles show that the upper mantle is heterogeneous and its structure correlates with tectonics and the heat flow data. Since the upper mantle composition affects the density to a greater extent than seismic velocities, we initiated a 2D gravity modeling along the PNE profiles Quartz, Craton and Kimberlite in order to get new constraints on the composition of the Northern Eurasia upper mantle. The profiles cross the East European Platform, the Urals, the West-Siberian Plate and the Siberian Craton. The initial density models were constructed from the seismic data using the density/velocity relation of the Earth reference models. The initial gravity data are taken from the satellite GOCE global models. The modeling shows that the upper mantle of Archean-Early Proterozoic Siberian Craton, distinguished by higher velocities in the upper 150–200 km layer, should have the decreased densities responsible for a strong gravity low (−100 mGal). It could be indicative of variation in the composition due to depletion of the cratonic upper mantle. The composition of the upper mantle of the East European Platform, regarding its high velocities and high densities, resembles the composition of the primitive mantle fertile matter. The Paleozoic suture zone of the Urals is characterized by anomalous structure of the crust and of the uppermost mantle with the high-density and velocity bodies indicative of the eclogite presence.

1. Introduction

The upper mantle structure is usually studied by seismological methods using the records from earthquakes. However, the seismological data are limited for the aseismic regions of Russia with a poorly developed network of seismic stations. The super-long seismic profiles made in these regions with large chemical and Peaceful Nuclear Explosions (PNE) provide unique data for setting up the velocity models of the Northern Eurasia upper mantle. The PNE profiling gives a possibility to constrain in more detail and more reliable velocity models than that from the seismology data, because the PNE records contain clear secondary arrivals with the reflections from the seismic boundaries and with the refractions from all mantle layers down to the depth of 700 km. Such profiles are a good basis for developing a combine interpretation of other geophysical data, for instance, for construction density models of the upper mantle and of the transition zone to the lower mantle. The combine interpretation of seismic and gravity data seems to be rather effective since the composition of the upper mantle material affects differently on the seismic velocities and on the densities. In general, changes in the upper mantle composition from the fertile substance of the primitive mantle to the strongly depleted matter exhibit velocities about 1% lower for P-waves and about 1.5% lower for S-waves (Carlson et al., 2005; James et al., 2004; Jones et al., 2009; Lee, 2003). These changes lead to a higher (up to 2.5%) density decrease (Boyd and McCallister, 1976; Carlson et al., 2005; Hawkesworth et al, 1990; James et al., 2004; Lee, 2003; Poudjorm Djomani et al., 2001; Schutt and Lesher, 2006). Therefore density modeling of the upper mantle could be an effective method to derive new information on the upper mantle composition.

The velocity/density modeling is a widely developed method for studying the crust. The combined interpretations of seismic and gravity data were made in Russia for a large system of seismic profiles crossing different tectonic domains (Gordienko, 1999; Krasovsky, 1981; Romanyuk, 1995). These studies show that the main gravity effect of the crust is caused by its inner heterogeneities, which generate intense local anomalies. The sedimentary basins have less influence in the platform regions because their gravity effect is usually compensated by the Moho uplift beneath the basins and by the density increase in the underlain crystalline crust. The density modeling of the crust has shown a stable relation between the average velocity and the density

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of the consolidated crust in the large area of the Northern Eurasia (Romanyuk, 1995).

The use of the velocity/density modeling for deeper layers of the Earth meets certain limitations. These limitations are connected with a lack of our knowledge on density/velocity relation for the mantle material. We also have little information on the influence of the transition zone between upper and lower mantle on the gravity field. The first gravity studies of the upper mantle structure were made in Russia with the method of the isostatic gravity anomalies (Artemjev et al., 1994). The averaged topography, the basement and Moho depths, sedimentary density and gravity data have been used to determine the isostatic anomalies of the Northern Eurasia. It was shown that the long wavelength components of these anomalies of probable mantle origin do not vary strongly in the area of the PNE profiles. The gravity modeling for the uppermost mantle along the Craton profile was made by Grachev and Kaban (2006). They revealed a negative density anomaly beneath the Siberian Craton, which is explained by the effect of a mantle plume below the craton.

The main objective of our study is to reconstruct density distribution in the upper mantle of the Northern Eurasia using the P-wave velocity models along the PNE seismic profiles. We have performed a 2D density modeling along the three most representative PNE profiles Quartz, Craton and Kimberlite (Fig. 1). The initial density models for the upper mantle were constructed from P-wave velocities which were converted into densities using the velocity/density relation of the Earth reference models. In addition, the density modeling incorporates gravity data from the global models of the satellite GOCE mission. The presented below results of the density modeling along the PNE seismic profiles are the first experience of setting up the density models for the upper mantle and transition zone to the lower mantle for the region of the Northern Eurasia. Our gravity modeling of the upper mantle structure along the PNE profiles was based on the techniques of the joint interpretation of gravity and seismic data, described in Strakhov and Romanyuk (1984), Starostenko and Legostaeva (1998), Martyshko (2010) and others, and in many similar gravity studies carried out worldwide (Kaban et al., 2003, 2010; Romanyuk, 1995; Yegorova and Starostenko, 2002; Yegorova et al., 2007, 2011, 2013).

2. Crustal structure and tectonics

The PNE long-range seismic profiles cross the major tectonic provinces of the Northern Eurasia: Precambrian East European Platform (mainly its north-eastern part) and Siberian Craton, the Palaeozoic units of suture zone of the Urals, the West-Siberian and Timan-Pechora Plates (Fig. 1). They differ in age, tectonic evolution and accretional history, in crustal structure and patterns of geophysical fields (Artemieva and Mooney, 2001; Khain, 1985; Pavlenkova, 1996a). The East European Platform is composed of the Paleoproterozoic and Archean blocks. Their crustal thickness ranges from 40 to 50 km and the average velocity in the crystalline crust is about 6.5 km/s. The potential fields (gravity and magnetic) show rather complicated mosaic patterns related to a complex structure of the basement and crystalline crust. The heat flow density ranges from 40 to 50 mW/m^2.

The Timan-Pechora Plate of the Palaeozoic age is overlain by rather thick, in particular within the Fore-Urals region, sediments. The crust has approximately the same thickness (40 km) as in the NE East European Platform. The surface heat flow values are elevated up to 60 mW/m^2. The Palaeozoic suture of the Urals is distinguished by a thick (up to 55 km) crust. Its notable feature is a presence of high density rocks in the upper crust responsible for the significant magnetic and gravity anomalies along the orogenic belt. The heat flow values are lowered to 40 mW/m^2.

The West-Siberian Plate of Palaeozoic age is covered by the Mesozoic sediments as thick as 3–15 km (Cherepanova et al., 2013). The thickest sediments (more than 15 km) occur in the northern part of the plate. The magnetic and gravity fields show anomalies of lower magnitudes than those on the East European Platform. In contrast to the latter, the heat flow over the West-Siberian Plate exhibits higher values attaining 60–70 mW/m^2. The Siberian Craton is of the mainly Archean age (Proterozoic rocks are less abundant). Two large basins are developed within the cratonic area: the Tunguss Basin in the western part of the craton with 8–10 km thickness of the meta-sediments and volcanics (plateau-basalts) of high densities and the deep Vilyui Basin, in the eastern part, filled with younger sediments. The crustal thickness of the Siberian

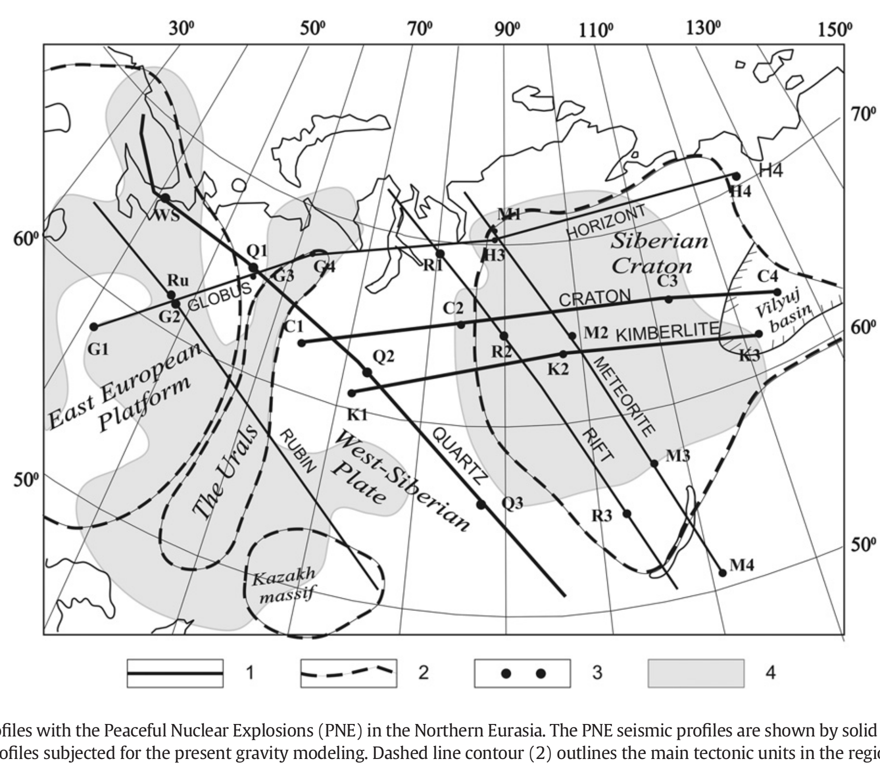

Fig. 1. Location of the seismic profiles with the Peaceful Nuclear Explosions (PNE) in the Northern Eurasia. The PNE seismic profiles are shown by solid black lines, thick lines (1) indicate Quartz, Craton and Kimberlite profiles subjected for the present gravity modeling. Dashed line contour (2) outlines the main tectonic units in the region. Black circles (3) with labels indicate the location of the PNE and the areas with gray filling (4) show the regions of low heat flow on the surface.