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Seismic inhomogeneities in the upper mantle beneath the Siberian craton (Meteorite profile)

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Abstract

The upper-mantle structure was studied from first-arrival data along the Meteorite profile, run using underground nuclear explosions. Unlike the layered, slightly inhomogeneous models in the previous works, emphasis was laid on lateral inhomogeneity at the minimum possible number of abrupt seismic boundaries. We used forward ray tracing of the traveltimes of refracted and overcritical reflected waves. The model obtained is characterized by considerable velocity variations, from 7.7 km/s in the Baikal Rift Zone to 8.0–8.45 km/s beneath the Tunguska syneclise. A layer of increased velocity (up to 8.5–8.6 km/s), 30–80 km thick, is distinguished at the base of seismic lithosphere. The depth of the layer top varies from 120 km in the northern Siberian craton to 210 km in its southeastern framing. It has been shown that, with crustal density anomalies excluded, the reduced gravity field is consistent with the upper-mantle velocity model.

Keywords: nuclear explosion; upper mantle; seismic profile; Siberian craton

Introduction

The seismic estimate of the lithospheric thickness beneath the Siberian craton remains disputable despite the available unique observations of nuclear explosions along a network of long-range profiles. Upper-mantle models based on these data, which emphasize the presence of extensive layers with decreased and increased *P*-wave velocities, are widely discussed (Cipar and Priestley, 1997; Egorkin, 1999, 2004; Egorkin et al., 1987, 1996; Mechie et al., 1997; Nielsen and Thybo, 2006; Pavlenkova, 1996, 2011a,b; Pavlenkova and Pavlenkova, 2006; Pavlenkova et al., 1996, 2002; Thybo, 2006). Emphasis is laid on layers with a decreased velocity, often no thicker than 50 km. Such a layer (LVZ), which belongs to zone 8° (offset 800–1000 km), is the most evident in (Nielsen and Thybo, 2006; Thybo, 2006; Thybo and Perchuc, 1997). Its possible origin is also discussed in these publications: This layer was formed owing to partial melting caused by volatiles or variations in the mineral composition. Layer LVZ is presumed to be widespread on the continents, except the Canadian Shield (Lehmann, 1964; Thybo, 2006; Thybo and Perchuc, 1997).

The layers distinguished by the reflected-wave method are usually interpreted as homogeneous, with a velocity showing slight lateral variation (Cipar and Priestley, 1997; Egorkin, 1999, 2004; Egorkin et al., 1987, 1996; Mechie et al., 1997; Pavlenkova, 1996, 2011b; Pavlenkova and Pavlenkova, 2006; Pavlenkova et al., 1996, 2002). Note that reflected waves from the boundaries in the upper mantle were distinguished using adaptive filtration in (Egorkin, 1999, 2004; Egorkin et al., 1987, 1996). As a result, a set of near-horizontal layers with decreased and increased velocities (20–50 km thick) was obtained. The authors in (Pavlenkova, 1996, 2006, 2011b; Pavlenkova and Pavlenkova, 2006; Pavlenkova et al., 1996, 2002) use a different technique for distinguishing reflected waves in the later arrivals. These waves are characterized by an increased apparent velocity and are often not confirmed by reversed traveltime curves with required reciprocal times. Therefore, the reflecting boundaries are presumed to be gently inclined, and the variations in the apparent velocity are explained by vertical layering, though they might be due to the seismic-boundary slopes (Suvorov et al., 2010).

The LVZ are manifested in zones of anomalous attenuation in the first arrivals. However, the coverage area of such zones

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corresponding to individual layers might be of small extent, and one should take into account possible near-surface inhomogeneity producing similar effects in the wavefield. To obtain precise evidence for the existence of low-velocity layers, one should place transmitters within the coverage areas of attenuation zones, which could also record similar phenomena on the seismograms of reversed observations. The distances between the nuclear explosions are too long, so that no direct seismic evidence for the existence of extensive thin layers with a decreased velocity has been obtained from the upper mantle of the Siberian craton.

Generally, rare observation networks for first-arrival waves make it difficult to differentiate between layering and lateral inhomogeneity if the distance between the sources exceeds the coverage areas of corresponding waves and/or anomalous zones (including inhomogeneity in the upper part of the cross-section). Note the violation of a necessary condition for solving this problem—the completeness of the observation system, which ensures reliable detection of every anomaly from a system of catching-up (caught-up) and reversed traveltime curves, with reciprocal-traveltime correlation ((Epinat'eva, 1960; Epinat'eva et al., 1990; Gamburtsev et al., 1952) and (Palmer, 2010), where non-Russian publications on the refracted-wave method are cited extensively). Without such control, variations in the kinematic characteristics of first-arrival traveltime curves (areas up to 100–200 km in size) can be regarded as sources of lateral inhomogeneity in a model with the minimum number of layers. The problem consists in distinguishing such peculiarities in the cross-section, though the solution might be ambiguous depending on the available observation system and the density of the coverage of the studied areas with seismic rays.

Therefore, we consider an alternative upper-mantle model (with respect to the layered ones published in (Cipar and Priestley, 1997; Egorkin, 1999, 2004; Egorkin et al., 1987, 1996; Mechie et al., 1997; Pavlenkova, 1996, 2011; Pavlenkova and Pavlenkova, 2006; Pavlenkova et al., 1996, 2002)). In this model, local anomalies of the apparent velocity of first-arrival waves mainly correlate with lateral velocity inhomogeneity. In this way along the Rift profile, inhomogeneous upper mantle was shown to a depth of 200–220 km. Deeper down to a depth of 410 km, an almost homogeneous layer with a small increasing velocity is located (Suvorov et al., 2010). An interesting connection between the large basement structures of the Siberian craton and the upper-mantle velocity distribution was revealed.

In addition to the Rift profile, the upper-mantle structure along the parallel Meteorite profile is studied in the present paper (Fig. 1). This profile crosses the central Tunguska syneclise, which is a possible location of the central part of the mantle plume—the source of highly voluminous Siberian traps (Dobretsov, 1997; Zolotukhin and Al'mukhamedov, 1991).

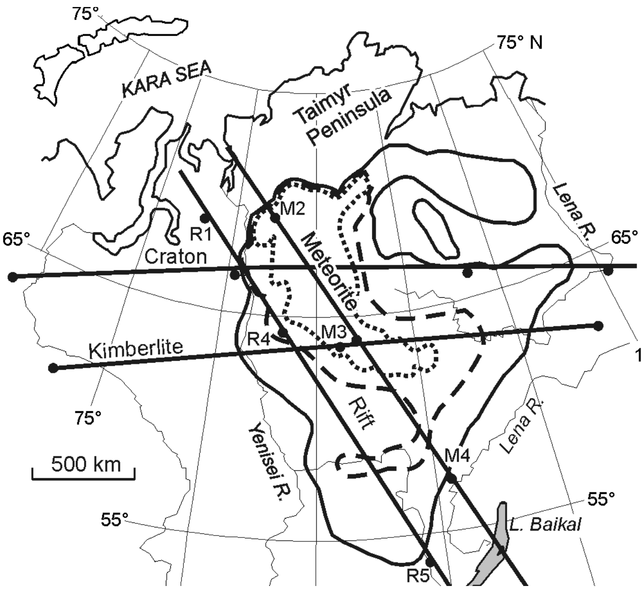

Fig. 1. Sketch map of the Rift and Meteorite profiles. Areas of predominant traps are shown by a dotted line; those of tuffaceous rocks, by a dashed line; and those of intrusive traps, by sills, dikes, and a solid line (Zolotukhin and Al'mukhamedov, 1991). Circles indicate the shotpoint positions and numbers in accordance with (Sultanov et al., 1999).

Seismic structure of the upper mantle

Figure 2 shows a model for the upper mantle constructed by forward 2D ray tracing of first-arrival times from nuclear explosions along the Meteorite profile in the software of Zelt and Smith (1992) by the trial-and-error method. We used a priori data on the relief of the basement and Moho, as well as velocity in the crust and at the Moho, obtained previously from the considerably more detailed data of chemical shots (Egorkin, 1991; Razinkova, 1987). To a considerable extent, this determined the possibility of the identification and localization of lateral velocity variations in the upper mantle. The main feature of the cross-section is the division of the upper mantle into two parts: (1) the laterally inhomogeneous upper layer with a base at a depth of 120–220 km, containing an additional high-velocity layer 30–80 km thick and (2) an almost homogeneous upper-mantle interval extending to the 410-km discontinuity. Velocity in the inhomogeneous layer varies from 7.7 km/s beneath the Baikal Rift Zone (Krylov et al., 1981; Puzyrev, 1993) to 8.0–8.45 km/s in the entire area and to 8.6 km/s in the local area within the Angara–Lena step (Egorkin, 1991; Razinkova, 1987). At the bottom of the inhomogeneous layer, velocity jumps to 8.5 km/s. The underlying layer is characterized by an increased velocity gradient (high-velocity layer, HVL), which varies from 8.5 to 8.55–8.6 km/s depending on thickness. The most inhomogeneous upper and the homogeneous lower parts of the upper mantle might be two structural stages, though the data on the velocity distribution in the lower stage are not detailed enough for a reliable conclusion. As it will be shown below, data from the reflected and refracted waves observed from the 410-km discontinuity can be used for an estimate of only the average