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Petrophysical Features of the Upper Mantle Structure beneath Northern Eurasia and Their Nature

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Abstract—Deep seismic studies of the upper mantle conducted in Russia with the use of nuclear explosions and laboratory studies of mantle materials at high pressure and temperature have revealed new structural and petrophysical features of the upper mantle beneath Northern Eurasia. These features are hard to explain within the framework of current understanding of the structure of the continental lithosphere. For example, in the region of the asthenosphere distinguished according to the thermal field, no corresponding decrease in seismic velocities has been detected, but instead low-velocity layers have been identified at a depth of 100–150 km within the lithosphere. However, the asthenosphere may be distinguished by structural features of the seismic boundaries. This means that it is represented by a layer of elevated plasticity without partial melting. The laboratory studies also indicate that seismic velocities do not depend on the composition of mantle rocks and are controlled primarily by their temperature. This made it possible to infer the temperature regime of the upper mantle from seismic data. Calculations carried out on this basis have shown that the thickness of the lithosphere beneath the Siberian Craton does not vary and is 300–350 km. These data are inconsistent with evaluations of the lithosphere bottom depth based on the heat flow at the surface. This discrepancy may be explained by a stronger effect of deep fluids on the heat flows and on petrophysical parameters of mantle rocks. At depths where mechanical properties of rocks drastically change and their porosity increases, the density of the deep fluids decreases, and the fluids release much heat. As a result, low-velocity domains (plumes), which may contain partial melts, are formed and the surface heat flow increases. This may explain how low-velocity layers can be formed at a depth of 100–150 km and why the temperatures determined from seismic data differ from those derived from the heat flow data. Deep fluids also initiate physical and chemical transformations in mantle rocks, for instance, produce depleted material that has a reduced density but is characterized by the unvarying seismic velocity. Deviations from linear relationship between seismic velocity in a material and its density is also detected at integrated interpretations of seismic and gravimetric data. Physicochemical transformations of rocks in areas where deep fluid flows are focused can also account for the origin of complex reflective boundaries identified in the lithosphere.

Keywords: lithosphere, asthenosphere, petrophysics, deep fluids, seismic boundaries, layers of lower velocities

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INTRODUCTION

The structure of the upper mantle is currently studied mostly by means of deep seismic sounding, using big explosions, and by detailed seismic studies. These methods are significantly appended with other geophysical data, for example, gravimetric measurements and those of the heat flow. Much fresh information has also been acquired by means of laboratory studies of the petrophysics of mantle materials at high P–T parameters. However, the more experimental data are acquired on the structural heterogeneity of the upper mantle, on the variability of its heat regime, and on characteristics of geophysical fields, the more obvious their inconsistencies are when principal features of the Earth's upper shells are determined and their origin is interpreted. Also, many methods currently applied in interpreting geophysical materials turned out to be inapplicable to solving these problems. This is discussed below in this publication, and an attempt is made to find reasonably well justified solutions of these problems.

STRUCTURAL FEATURES OF THE UPPER MANTLE

The most reliable geophysical data on the structure of the upper mantle have been acquired in Russia based on seismic sounding along long-range profiles, with registering seismic waves from nuclear explosions (Fig. 1) (Egorkin et al., 1981; Egorkin and Chernyshov, 1983; Egorkin, 2004; Pavlenkova and Pavlenkova, 2014). These data enabled constructing detailed velocity sections to a depth of 700 km for such first-order structural features as the East European and Siberian ancient platforms and the West Siberian young plate. Detailed information has also been acquired on the gravity and magnetic fields and on the heat flow at the territory (Polyak, 1988; Pollak et al., 1993; Gordienko, 2010), and its seismological studies have been carried out (Oreshin et al., 2002; Koulakov and Bushenkova, 2010). All of these data are widely utilized for their complex interpretations: the seismic materials are used to study structural features of the crust and upper mantle, the heat flow is needed to evaluate the thickness of the lithosphere (Artemieva and Mooney, 2001), and the gravity field is needed to identify the density heterogeneity (Grachev and Kaban, 2006; Egorova and Pavlenkova, 2015). These studies have provided an insight into the plentitude of previously unknown and unusual structural features of the regional mantle.

Figure 2 shows a generalized seismic section of the crust and upper mantle, based on two long-range profiles: *Quartz* and *Kimberlite* (Fig. 1). The profile extends across all major structures of Northern Eurasia. The crustal thickness varies insignificantly, from 40 to 45 km on average, and the seismic velocities in the upper mantle gradually (without jumps) increase from 8.1–8.3 km/s at the M discontinuity to 8.6 km/s at the top of the transition zone to the lower mantle at a depth of 400 km. An important feature of this section is that the regional upper mantle is subdivided into a number of layers with clearly defined reflective boundaries in between. These are boundaries N1, N2, L, and H at depths of approximately 100, 150, 200, and 300 km, respectively.

This stratification of the lithosphere in platform regions is hard to explain by the variability of its material, and there is no evidence of any phase transitions at these depths. The layers differ from one another mostly in rheological characteristics: plasticity, viscosity, porosity, etc. These differences are particularly well seen between the uppermost rigid layer of the lithosphere 100–150 km thick, which is characterized by a significant horizontal heterogeneity, and its deeper part, which has no such heterogeneity because of higher plasticity. The two lithospheric layers are separated from each other by a complicated transition zone between seismic boundaries N1 and N2 (Fig. 2), and by lower velocity layers (waveguides), which are atypical of the lithosphere of ancient platforms. This zone will be referred to as zone N below, and it is named 8° boundary in (Thybo and Perchuc, 1997), because waves from it are registered 8° away from the source.

The structure of the other seismic boundaries also turned out to be unusual: there are no drastic changes in the velocities, but waves reflected from these boundaries have higher intensities and yield a complicated multiphase record. Figure 3 displays a typical record section obtained from a nuclear explosion at point C1 along the *Craton* profile. At a distance of 750 km from the source (close to 8°), the first arrivals clearly show a discontinuity ("shadow zone") corresponding to a waveguide at a depth close to 100 km, and multiphase waves P_{N1}, P_{N2}, P_L, and P_H reflected from boundaries N1, N2, L, and H, respectively, are registered in the secondary arrivals. Mathematical modeling show that such reflections are generated in layers of complicated inner heterogeneity (Pavlenkova, 2011).

Another unusual feature of this seismic model for the upper mantle is the absence of a clearly pronounced asthenosphere. Heat flow data indicate that the top of the regional asthenosphere as a layer of partly molten material occurs at a depth of 150–200 km (Fig. 2) (Artemieva and Mooney, 2001). This asthenosphere would have been registered by seismic data as a region of lower velocities, but this is not the case, and no such regions were identified anywhere in the long-range profiles in spite of the highly detailed studies.

However, the asthenosphere has not necessarily to be interpreted as a layer of partial melting (so-called *thermal asthenosphere*), but instead it can be a layer of lower viscosity. Then it can be identified based on studying the Q factor of the upper mantle material (its plasticity and viscosity) with regard for structural features of the velocity model. The probable occurrence of such asthenosphere beneath Northern Eurasia was confirmed with the use of long-range profiles. According to the spectral characteristics of seismic waves, the Q factor of the mantle material drastically decreases at depth >250 km (Egorkin et al., 1981), and the seismic boundaries at these depths have some structural features that characterize the isostatic equilibrium of the density heterogeneity of the lithosphere. For example, boundary H is bent beneath bends of boundary L (Fig. 2), and this provides grounds to suggest that it is the top of the asthenosphere.

In general, the above facts and considerations make it possible to suggest the following model for the upper mantle beneath Northern Eurasia (Fig. 4a). The lithosphere 300 km thick is subdivided into three layers of different plasticity with seismic boundaries of complicated inner structure in between. The asthenosphere is conventionally distinguished (based on certain circumstantial evidence) as a layer of lower viscosity. Additional data on the probable depth of this asthenosphere are provided by information on the deep earthquake hypocenters: these data indicate that the depth range from 300 km to the top of the zone transitional to the lower mantle (410 km) is a "silent area", i.e., a weakened zone absolutely devoid of earthquakes (Fig. 4b). This model is remarkably different from the model based on heat flow data.

Results of recent detailed studies of the inner structure of the lithosphere and petrophysical characteristics of upper mantle rocks have revealed some structural features of the lithosphere that still have not been

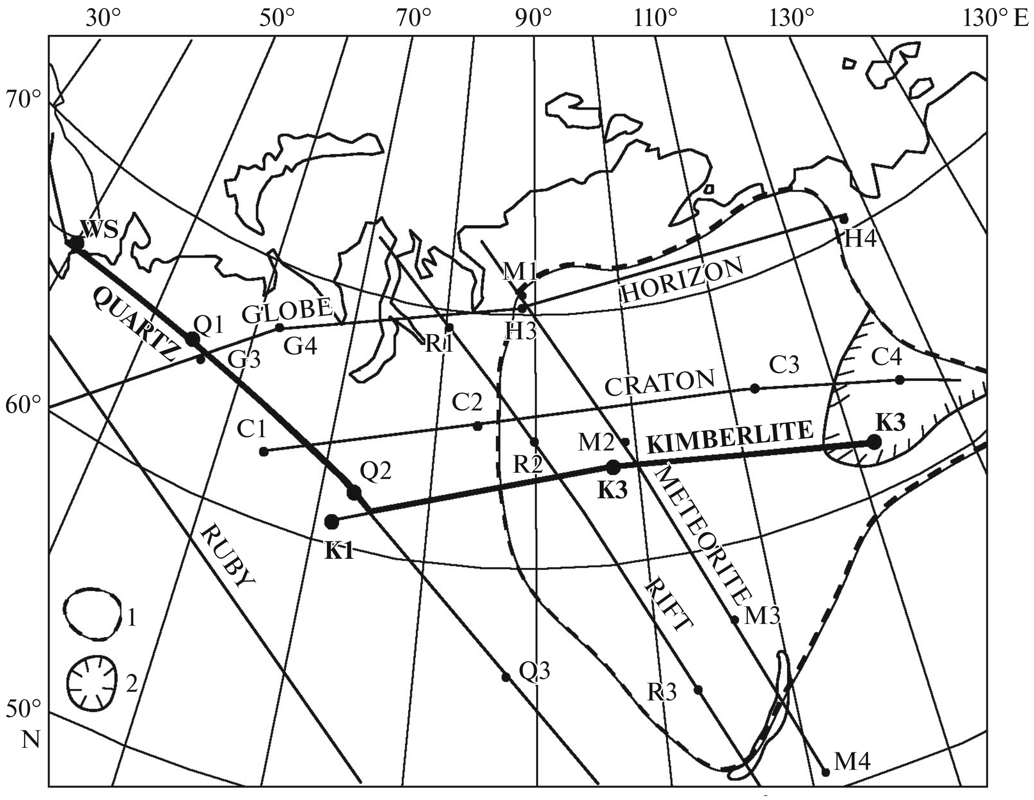

Fig. 1. Schematic map of long-range deep seismic sounding profiles acquired using nuclear explosions. Heavy lines show the Quartz and Kimberlite profiles for which seismic sections are shown in Fig. 2. Words at the profiles are their names, solid circles on the profiles are the nuclear explosion shot points, and characters near them are their names. (1) Contours of the Siberian Craton; (2) contours of the Vilyui basin.

consistently explained. The nature of drastic changes in the rheology of the lithosphere is still not fully understood, as also are the facts that it includes complicated seismic boundaries and layers of lower velocities. Contradictory data on the thickness of the lithosphere were derived from the heat flow and from seismic materials. Also, it is still uncertain whether the asthenosphere does occur beneath old platform territories.

To explain all of these unusual structural features of the upper mantle, much importance is attached to recently acquired results of laboratory studies of mantle rocks at high P–T parameters.

Petrophysical Characteristics of Mantle Materials

The most comprehensive studies of petrophysical properties of mantle rocks have been made for the Siberian Craton. Laboratory data on large collections of deep xenoliths at high P–T parameters have provided much new important information (Boyd et al., 1997; Glebovitskii et al., 2001; Ionov et al., 2010; Ashchepkov et al., 2010; Doncet et al., 2014; and others). These data have demonstrated that relationships between principal physical parameters of mantle material, its composition, and temperature significantly change with depth. The trends and patterns of these changes differ from those discovered earlier in the Earth's crust and upper mantle.

Figure 5 shows the measured velocities of primary waves V_p and density of mantle rocks of different composition for two conductive geotherms corresponding to heat flows of 35 and 50 mW/m^2 (Kuskov et al., 2014). As expected, the seismic velocity and density systematically vary with increasing temperature and pressure, but it was not anticipated that the seismic velocities in mantle rocks of different composition are practically indiscernible from one another, in spite of that the densities of these rocks are different. For example, a lower density is typical of depleted mantle material (garnet harzburgite Hzb and garnet peridotite GP), but velocities in them are practically exactly equal to those in other mantle rocks.

The dependence of seismic velocities on temperature alone, as was determined for the upper mantle, significantly limits the capabilities of the seismic method in interpreting gravity fields but also opens new possibilities for determining the temperature regime of the upper mantle and, correspondingly, geo-

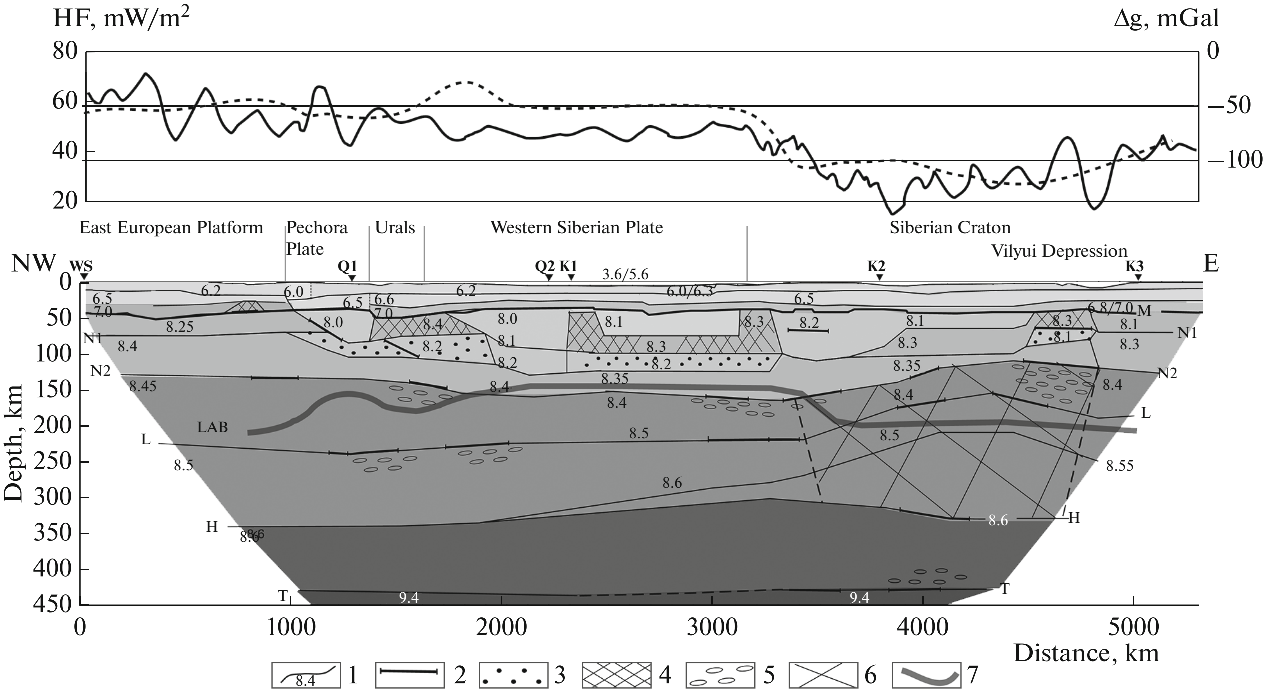

Fig. 2. Combined velocity cross section along the Quartz and Kimberlite profiles across the East European, Western Siberian, and Siberian platforms, from the Baltic Shield to Vilyui basin (Pavlenkova and Pavlenkova, 2008). (1) Boundaries between layers with different P-wave velocities (km/s); (2) reflectors; (3) low-velocity layers; (4) high-velocity blocks; (5) domains of highly heterogeneous upper mantle; (6) lithospheric domains of density lower by 0.03–0.05 g/cm^3 beneath the Siberian Craton (identified based on gravimetric data) (Egorova and Pavlenkova, 2015); (7) lithosphere–asthenosphere boundary (LAB) inferred from the heat flow (Artemieva and Mooney, 2001). WS, Q1, Q2, and K1–K3 are the loci of the nuclear explosions; M is the Earth's crust bottom (Moho discontinuity); N1, N2, L, and H are seismic boundaries in the upper mantle: T is the top of the transition zone to the lower mantle. Geophysical fields: HF is heat flow (mW/m^2), and Δ*g* is Bouguer anomalies (mGal).

dynamic processes in it (Kuskov and Kronrod, 2007; Cammarano et al., 2009).

The temperature regime of the upper mantle was determined in (Kuskov et al., 2014) from seismic velocities for all long-range profiles across the Siberian Craton, using as specialized technique with regard for petrological and geochemical data on the composition of garnet peridotite (GP) xenoliths and the fertile material of the primitive mantle (PM). For the first time, the thermal state of the lithospheric mantle beneath the Siberian Craton was then reproduced for depths of 100–300 km with regard for the effects of phase transitions and variations in elasticity (Kronrod and Kuskov, 2007). Figure 6 displays the results of such calculations for three points on the Craton profile between shotpoints K2 and K3 at distances of 1100, 1900, and 2300 km, respectively, from the beginning of the profile (Fig. 1).

The calculations have shown that the thickness of the lithosphere (according to the depth of the isotherm 1300ºC) does not vary beneath the Siberian Craton and is 300 km. This is in good agreement with the depth of the lithospheric bottom (boundary H) inferred from seismic data but is in conflict with the current understanding of the temperature regime in the upper mantle, inferred from the heat flow. According to these data, the boundary between the upper mantle and asthenosphere (LAB) occurs at a depth of 200 km (Fig. 2).

In general, the calculations demonstrate that the temperature regime of the lithosphere is reasonably realistically determined from seismic velocities. This does not pertain, however, to the bottom of the lithosphere. The volume of seismic data dramatically diminishes starting at a depth of 250 km (Fig. 6), and a partial melt zone (thermal asthenosphere) is thought to merely occur at a depth of 300 km, where the temperature reaches 1450°C, but no corresponding layer of lower velocities was detected there. The acquired data thus do not provide a solution of the ambiguity problem in identifying the top of the asthenosphere and its nature.

The situation is further aggravated by the fact that the zone of lower velocities (waveguide) is often detected in the upper part of the lithosphere at depths of 100–150 km (Fig. 2). In regions of elevated heat flow, this waveguide is often interpreted as the asthenosphere. However, these waveguides are commonly relatively thin (20–30 km) and are underlain by a

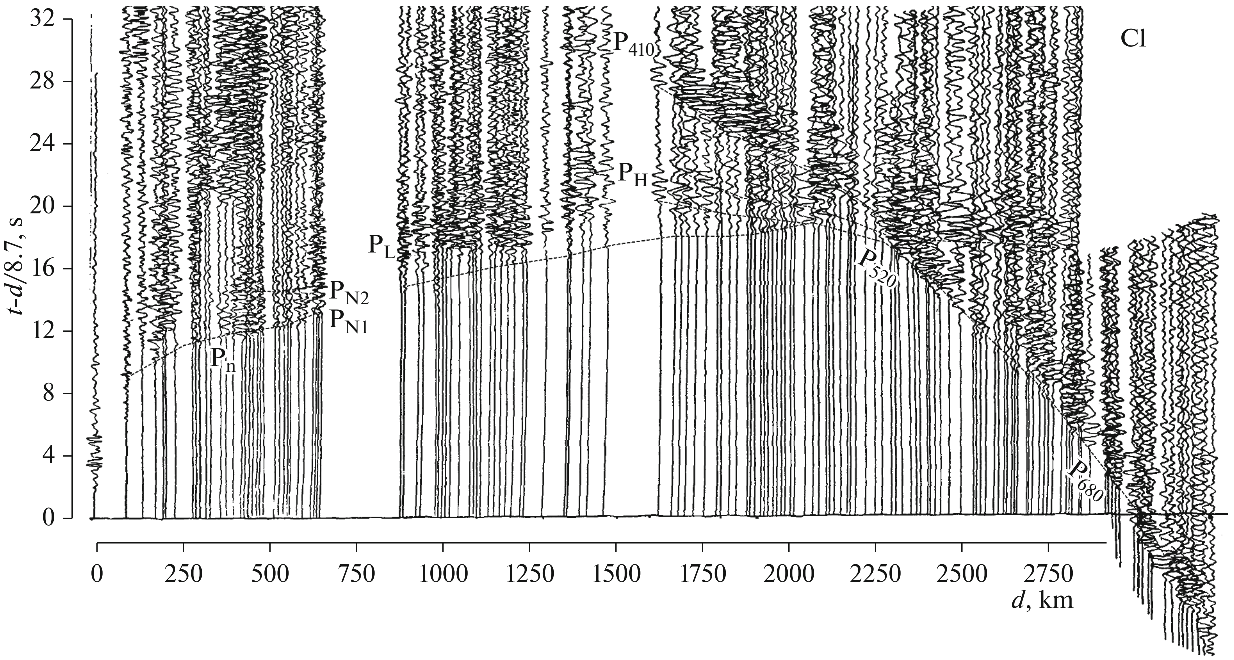

Fig. 3. Record-section along the Craton profile from the nuclear explosion at site C1 (Fig. 1). The record section is given in a reduced form, with the distance from the shotpoint *d*, km, divided by reduction velocity of 8.7 km/s subtracted from the recorded time *t*, s. P_n is waves refracted in the upper mantle (from boundary M); P_{N1}, P_{N2}, P_L, and P_H are waves reflected from boundaries N1, N2, L, and H in the upper mantle; P_{410}, P_{520}, and P_{680} are waves from the boundaries of the transition zone between the upper and lower mantle at corresponding depths.

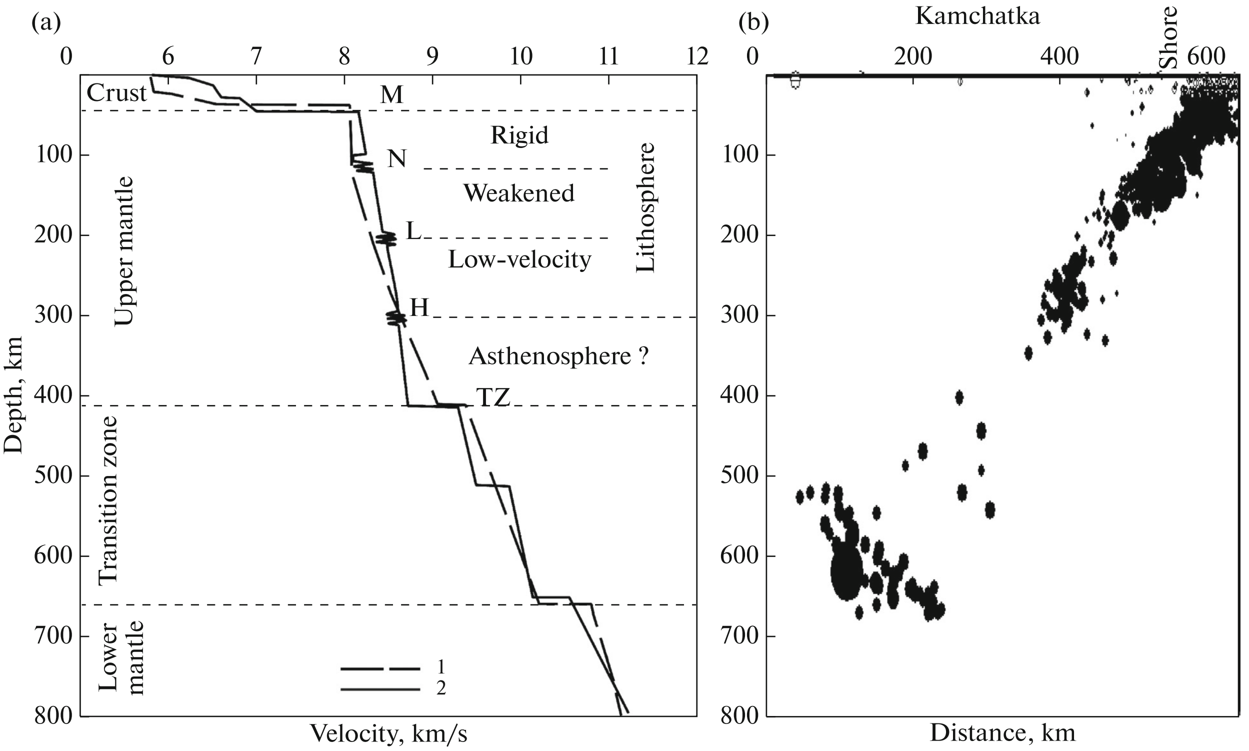

Fig. 4. (a) Generalized velocity model for the upper mantle beneath Northern Eurasia, based on long-range profiles (line 2) in comparison with reference seismological model IASP-91 (Kennet and Engdahl, 1991) (line 1). In the generalized model, seismic boundaries N, L, and H are shown as multilayer units, TZ is the top of the transition zone to the lower mantle, M is the bottom of the crust (Moho). (b) Distribution of earthquake hypocenters with depth for the territory of Kamchatka.

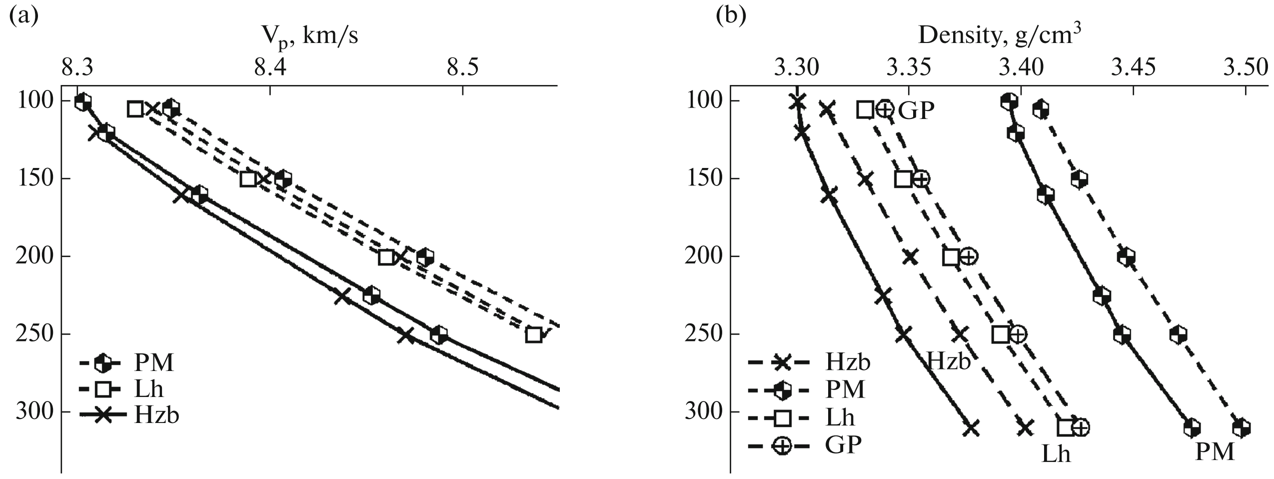

Fig. 5. (a) Variations in physical parameters of mantle rocks with depth; V_p is P-wave velocities; (b) densities of garnet harzburgite (Hzb), lherzolite (Lh), garnet peridotite of average composition (GP), and fertile material of the primitive mantle (PM) calculated along the geotherms of 35 mW/m^2 (dashed lines) and 50 mW/m^2 (continuous lines) (Kuskov et al., 2014).

clearly distinguishable reflective boundary with a seismic velocity of 8.1–8.3 km/s, as is typical of the mantle.

As mentioned above, studies of mantle xenoliths resulted in the formulation of another problem, namely, deviations were detected from direct correlations between seismic velocities and densities: at unvarying velocity, the density of the depleted rocks is much lower than the average density of the mantle material (Fig. 5). This offers the possibility of explaining the above discrepancies between the velocity models and gravity field at the Siberian Craton, when high seismic velocities, explained by a lower thermal regime of the lithospheric mantle of the craton, are correlated with a gravity minimum (Fig. 2). It was hypothesized (Grachev and Kaban, 2006) that linear relations between the velocity and density are still preserved for mantle material, and the detected gravity minimum may be explained by the occurrence of a plume beneath the Siberian Craton. However, seismic data do not provide evidence of any plume beneath that area. With regard for newly obtained data on the lower density of the depleted rocks of the Siberian Craton, it seems to be more realistic to explain the gravity minimum by a decrease in the density throughout the whole lithospheric thickness (Egorova and Pavlenkova, 2015) (Fig. 2).

Fresh important results have been obtained by laboratory studies of mantle rocks rich in fluids and by studying the fluids themselves and the variability of their physical properties with depth. These studies provide grounds to suggest that many structural features of the upper mantle, the occurrence of layers of lower seismic velocity in it, the presence of complicated seismic boundaries, and even changes in the composition of the mantle material may be explained by some energetic and geochemical features of deep fluids, i.e., by the degassing of the Earth.

ROLE OF FLUIDS IN THE DEVELOPMENT OF SEISMIC HETEROGENEITIES IN THE UPPER MANTLE

Degassing of the Earth and Distinguishing Features of the Advection of Deep Fluids

Extensive information is nowadays available on the degassing of the Earth and on the composition and physical properties of deep fluids. Extensive and comprehensive research of the Earth with the application of a wide spectrum of geological, geophysical, geochemical, and astronomical studies has shown that one of the important characteristics of the Earth, which makes this planet different from the others, is that it contains much fluids, whose dominant components are hydrogen, helium, and carbon. These fluids not only formed the atmosphere and hydrosphere of the Earth but also played a significant role in its geodynamic processes and in transformations of its materials.

In this context, an important avenue of research pursued to solve geodynamic problems is studying factual materials on the Earth's degassing, properties of its deep fluids, and their role in transformations of materials of the planet (Williams and Hemley, 2001; Gilat and Vol, 2005). Fist of all, it is pertinent to mention that much information is now accumulated on natural gases (Polyak, 1988; Griffin et al., 2003; O'Reilly and Griffin, 2006; Valyaev and Dremin, 2015), and there are extensive experimental data on the planet's hydrogen degassing. This was made possible by recent direct measurements of hydrogen degassing made in various parts of the planet but still not published (V.N. Larin, personal communication) and by global studies of the ozone layer, which is destructed under the effect of hydrogen fluxes (Syvorotkin, 2002). These studies have shown that current

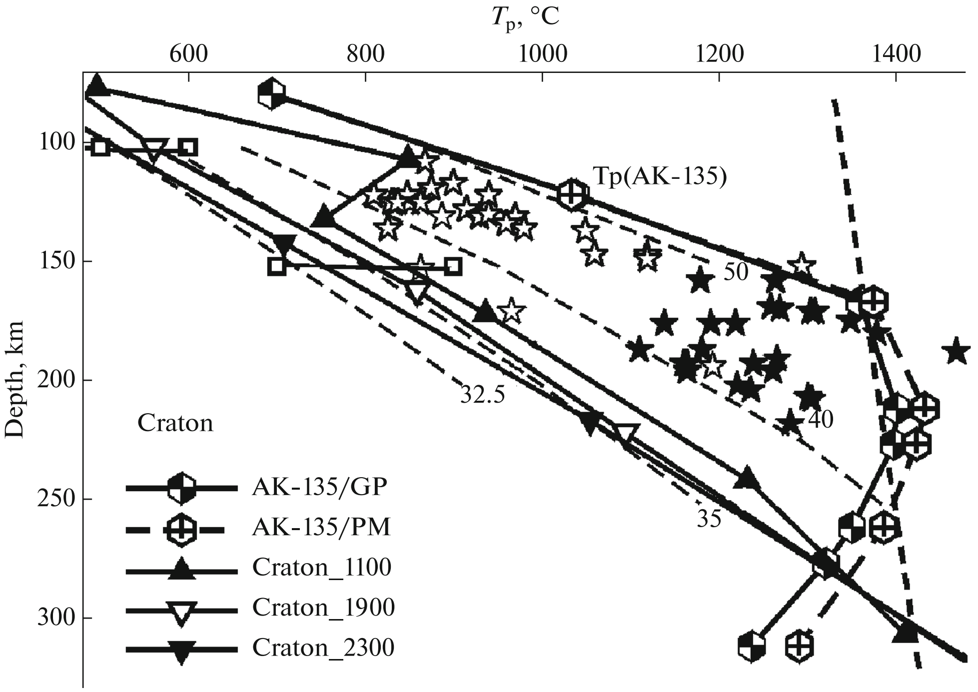

Fig. 6. Temperature distribution in the upper mantle beneath the Siberian Craton, inferred from seismic models along profile Craton for three spots on the profile (1100, 1900, and 2300) and for the garnet peridotite composition GP) (Kuskov et al., 2014). Solid and open stars are the equilibrium *P–T* parameters of low- and high-temperature xenoliths (Glebovitskii et al., 2001; Ionov et al., 2010). The dashed line is the mantle adiabat with a potential temperature of 1300°C. Tp(AK-135) is the averaged continental geotherm determined from the reference seismological model AK-135. Thin dashed lines are conductive geotherms for heat flows of 32.5 to 50 mW/m^2.

hydrogen degassing of the planet is most active in the southern hemisphere and is the main reason for the development of large ozone holes above Antarctica. Intense hydrogen flows were also recorded at mid-oceanic ridges and other disturbed zones of the tectonosphere.

Extensive experimental data are also now available on physicochemical transformations of materials with the involvement of fluids and on the effects of fluids on the physical properties of these materials. The term *fluids* means in geological literature in Russian not simply a liquid, as could be directly translated from English. The concept of *geofluids* was explored most thoroughly in (Letnikov, 1999, 2006) with the employment of extensive experimental data on physical characteristics of mantle material and dynamic characteristics of geofluids under elevated *P–T* parameters. Fluids in these materials are understood as water–gas or gas systems consisting of a number of components in compounds with major, ore, and other elements. The dominant components of deep fluids are hydrogen (H), helium (He), carbon (C), and their various compounds, including oxides (H_2, CO_2, CH_4, and CO) (Gilat and Vol, 2005). It is thought that the proportions of these components systematically varied with time, with a tendency toward general oxidation of the fluid systems.

Fluids in the upper mantle are gas mixtures, whose H_2O is gas, because aqueous solutions can be stable only in the upper crust. It has also been determined that, in contrast to liquids, which are practically incompressible, gas mixtures can be compressed to high densities, and small gas volumes then possess much thermal energy. Consequently, gaseous fluids serve as universal heat-transfer agents and can accumulate heat and chemical energy in the Earth's interiors and then transfer it to the surface. It was, however, hypothesized that the lithosphere is saturated with fluids as a consequence of subduction and subsequent degassing of slabs (Williams and Hemley, 2001). These fluids cannot transfer thermal energy and cannot play any significant part in global processes.

Deep fluids with much thermal energy spread at significant depths in sheared rocks on a submolecular level (Letnikov, 1999, 2006). They do not lose their energy when coming from significant depths but release it only at drastic changes in the *P–T* parameters and at an increase in the porosity and fracturing of the rocks. This leads to a decrease in the density of the fluids, a process coupled with the release of much heat.

Fluid advection thus can result in uneven changes in temperature with depth, along an adiabat, as is assumed in interpreting data on the heat flow, and relatively thin layers of elevated temperature (low-velocity layers) are formed at depths where mechanical properties of mantle materials drastically change and where the physical states of the fluids themselves are modified. These uneven temperature changes with depth were calculated within the scope of the advection–polymorphic hypothesis (Gordienko, 2010). This conclusion is able to explain the aforementioned structural layering of the upper mantle inferred from seismic velocities. This also explains discrepancies between the seismic data and those of the heat flow on the temperature regime at significant depths.

The advection of deep fluids can explain processes transforming mantle materials, with changes in their densities at an unchanging seismic velocity. These processes form the roots of continents consisting of depleted material. The depletion of mantle materials was previously thought to had occurred in the Archean, at very high temperatures in the mantle (Walter, 1998). It was hypothesized that the derivation of komatiites and basaltic components had depleted the upper mantle in Fe, Al, and Ca and, hence, had decreased its density within the depth range of 200–300 km (Griffin et al., 2003).

According to the model (Letnikov, 2006), the continental upper mantle, which is made up of depleted material, was formed during a long period of geological time. At high P–T parameters typical of the upper mantle, the fluids became enriched in such components as SiO_2, K_2O, and Na_2O and then brought these components from the mantle to crust and thus produced its granite-gneissic layer. The mantle material was thereby depleted, i.e., a lithosphere of lower density was formed. This consistently settles the aforementioned discrepancies between the high-temperature lithosphere model of the Siberian Craton and the gravity field.

The properties of deep fluids described above make it also possible to explain the nature of the development of waveguides and long seismic boundaries in the lithosphere.

Nature of Mantle Waveguides and Seismic Boundaries

The nature of waveguides (layers of lower seismic velocity) found at depths about 100 km is actively and widely discussed in the literature. Their occurrence at tectonically active territories is explained by high temperature and even partial melting of the material, and these layers are often ascribed to the asthenosphere (Artemieva and Mooney, 2001; Heit et al., 2007). This explanation is, however, hardly applicable to ancient shields (Pavlenkova, 2011). It seems to be more natural to explain the waveguides by layers of high porosity and high concentrations of deep fluids. This explanation is warranted by laboratory studies, according to which the occurrence of fluid in a material significantly decreases seismic velocities in it (Lambert and Wyllie, 1970; Lebedev et al., 1989; Kern, 1993; Doncet et al., 2014). This interpretation is also consistent with data acquired by electromagnetic studies, according to which zone N at a depth of 100–150 km is often distinguished by its higher conductivity (Jones et al., 2009).

The properties of the layers of lower seismic velocity can also be explained by various metasomatic processes in mantle materials, with these processes modifying physical properties of these materials, for example, decrease their seismic velocities. For example, laboratory studies have shown that the velocity of P-waves in dunite decreases by 0.3 km/s under a high water pressure and temperature of ~400–800°C, which are typical of the continental lithosphere at depths of 100–150 km (Lebedev et al., 2017). This is explained by physicochemical transformations of the dunite texture: the rock is fractured, and the fractures are filled with water and serpentinite.

The most important factor of the development of layers of lower velocities is likely transformations of the fluids themselves. Changes in the extent of fracturing of the rocks is coupled with changes in the physical states of some of the fluid components, with the gas components passing into a liquid state. Therewith the heat energy of the gases is intensely released. Consequently, layers of lower velocity can also be produced at a temperature increase at these P–T parameters. A significant heat release when gaseous fluids become liquid can form layers of partly molten material (low-velocity layers).

Figure 7 schematically illustrates the advection of deep fluids through the continental lithosphere. The intensity of a fluid flow ascending from significant depths is uneven, and it is hard to tell how it is formed, focused, and transformed in the lower mantle. The character of fluid advection through the lithosphere is not as uncertain, and can be inferred from results of laboratory studies. According to these data, the intensity of the fluid flow is controlled (see above) by the permeability of the lithosphere (which varies with depth) and the physical state of the fluids themselves.

The permeability of the lithosphere largely depends on its structural heterogeneity and the rheology of its materials. The lithosphere is subdivided into two clearly distinct layers of principally different structure, and the nature of fluid advection in these layers is also notably different. In the lower and more plastic part of the lithosphere, the most intense fluid flows are constrained within strongly stressed zones. Fluids at these depths are dense gases, which migrate on a submolecular level along stressed zones in sheared rocks.

The upper, rigid part of the lithosphere is characterized by higher porosity, and deep fault zones in this part are intensely fractured. This principally modifies the physical nature of migration of deep fluids, which readily propagate along pores and fractures. The most intense fluid flows are constrained to the hypocentral

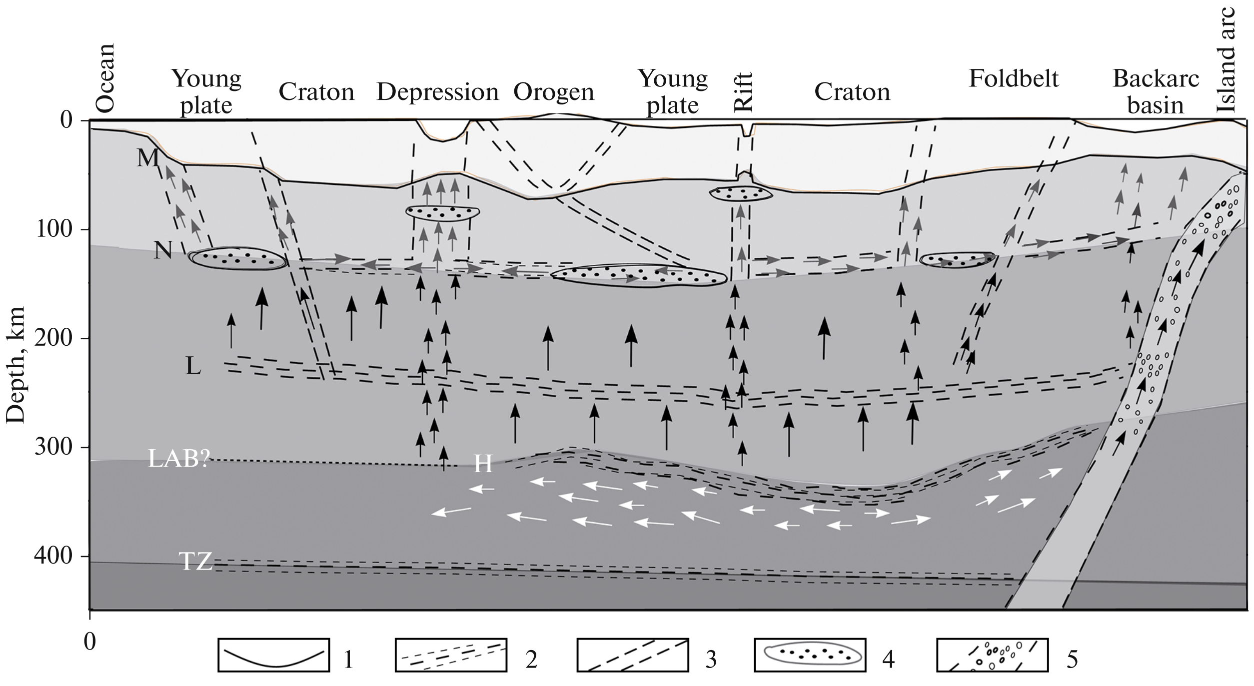

Fig. 7. Model for the advection of deep fluids in the upper mantle. (1) Contours of the consolidated Earth's crust: (2) complicatedly layered seismic boundaries; (3) deep faults; (4) low-velocity layers (waveguides); (5) Benioff zone of the deep earthquakes hypocenters; LAB is the probable lithosphere bottom, TZ is the top of the transition zone between the upper and lower mantle. Progressively darker gray colors show an increase in the Q factor of the upper mantle material in its three major layers.

zones of deep earthquakes at continental margins (in so-called subduction zones) and other boundary zones between lithospheric plates.

What is the most important (see above), some components of deep fluids contained in a porous material pass into a liquid state at certain *P*–*T* parameters, and this processes are associated with the release of much heat. Such processes are the most intense in zone N at the bottom of the rigid lithosphere, where low-velocity layers of partly molten rocks can be formed. As a result, it is these exactly layers, rather than the asthenosphere, that are the main source of heat energy that maintains transformations in the crust and various tectonic processes.

Fluid advection is also able to explain deeper seismic boundaries L and H. Obviously, at depths of 200 to 300 km, fluids also undergo physicochemical transformations and release heat. This is associated with the development of weakened layers, in which material can flow and which are responsible for velocity anisotropy detected at boundary L. Moreover, elevated fluid contents suppress the melting temperatures of rocks, and this can lead to the partial melting of mantle material at these depths. This is confirmed by data on xenoliths: the statistics of these data on kimberlite provinces in the Siberian Craton (Solov'eva et al., 1994) shows that kimberlites coming from the depths of these boundaries also show traces of film melting.

Note that fluid advection plays an important role in forming plumes, and the nature of the plumes is therewith principally modified. It is now thought that plumes are formed as a result of thermal convection, i.e., as a result of the ascent of hot material from greater depths. This is a long-lasting process, at which energy is mostly lost when this material ascends. In a seismic model, such a plume shall be interpreted as a wide and deep channel with lower velocities. In fact, plumes are distinguished based on seismic data in the upper lithosphere in the form of local anomalies. This exactly shape is typical of plumes produced by fluid advection, because fluids do not lose their energy when migrating at significant depths and release this energy in the upper layers of the lithosphere. As was demonstrated above, this occurs when rheological characteristics of lithospheric materials change, most commonly in layer N (Fig. 7).

Hence, it is the unequal heat release with depth that makes fluid advection and related geodynamic processes significantly different from thermal convection. This explains the detected layering of the lithosphere, the nature of the complicated seismic boundaries, and the uneven variations in the temperature regime with depth. The advection of deep high-energy fluids may also explain the aforementioned discrepancies between estimates of the lithosphere thickness based on seismic data and on the heat flow.

The Lithosphere–Asthenosphere Problem

The lithosphere–asthenosphere model is fundamental to many geotectonic concepts, particularly those of plate tectonics. It is thereby important to know whether such a layer (or, even more, a sphere) does actually occur and can enable large-scale motions of lithospheric plates (Eaton et al., 2009).

As was mentioned above, data on long-range profiles acquired by Russian researchers indicate that the asthenosphere as a layer of possible partial melting and lower seismic velocities has never been distinguished anywhere. This is typical of all continents. According to seismic data, only surface waves show a decrease in velocity in the bottom part of the upper mantle (Artemieva and Vinnik, 2016), but the velocity decrease starts at a depth of about 200 km, and this is absolutely inconsistent with data on the travel of primary (P) waves. In occasional instances, thin layers of lower velocity were distinguished at a depth of >300 km by the receiver functions method of primary and converted waves (Vinnik and Farra, 2007; Vinnik et al., 2009). According to the reference velocity models of P-waves, for example, IASP-91 and AK-135, which are based on the same seismologic data, the velocity of P-waves in the bottom part of the upper mantle drastically increases from 8.6 to 9.1 km/s (Kennett and Engdahl, 1991) (Fig. 4a), which is in conflict with the velocity model for the upper mantle based on long-range profiles, according to which the velocity at depths >300 km is no higher than 8.6 km/s (Fig. 2).

This uncertainty in the identification of the asthenosphere based on seismologic and seismic data may be explained by the limited abilities of these methods in determining velocities in layers above sharp seismic boundaries, in this instance, in the layer above the top of the transition zone to the lower mantle (Fig. 4, boundary TZ). Velocity models in seismology are built based on interpretations of the first arrivals alone, i.e., waves travelling to depths >250 km and registered only in the secondary arrivals (Fig. 3, waves P_H) are not used at all in this method, and velocities in the bottom part of the mantle are actually not determined at all. In reference models based on the first arrivals, velocities in this "silent" zone are somewhat averaged, and their values turn out to be much greater than those determined using nuclear explosions. An overestimation of the velocities in the bottom part of the upper mantle in references models also follows from data on temperature in the bottom part of the upper mantle in references model AK-135 (Fig. 6). The isotherm obtained with this model has a bend toward very low temperatures at a depth of 200 km, and this is difficult to explain.

The reliability of velocity evaluations in the bottom of the upper mantle based on long-range profiles is much higher than that based on seismological data because of the use not only of the first arrivals (refraction waves) but also of reflected waves in further arrivals (Fig. 3, waves P_H and P_{410}). Because of the complicated records of these multiphase wave, the accuracy of velocity determinations between boundaries H and T is relatively low: ±0.2 km/s. This means that the velocity in the bottom of the upper mantle can be lower within this error, but this still cannot be proved.

Generally speaking, there are no sound grounds to conclude that no asthenosphere occurs beneath the ancient cratons of Eurasia. Still, it can be considered proved that the asthenosphere is not a thick layer of partly molten material (thermal asthenosphere). Instead, it can be a layer of lower viscosity. As mentioned above, the occurrence of such a layer beneath the Siberian Craton also follows from the value of the Q factor, determined from seismic records from nuclear explosions and based on extensive information on kimberlites, which were formed at depths no greater than 230 km even at higher temperatures in the Proterozoic (Fig. 6). Indirect data on the depth of the asthenosphere beneath continents are provided by data on distribution of deep earthquake hypocenters (Fig. 4b): according to these data, earthquakes practically completely disappear at a depth of about 300 km.

The occurrence of a layer of lower viscosity in the bottom of the upper mantle beneath Northern Eurasia also follows from the detected isostatic equilibrium of its density heterogeneity. It was mentioned above that this equilibrium occurs by means of bending boundary H beneath the lower density lithosphere of the Siberian Craton (Fig. 2). This is also confirmed by the amazingly little varying depth of boundary T (the bottom of the upper mantle) at a high heterogeneity of its upper part.

All of these indirect data provide evidence of a layer of higher plasticity and lower viscosity in the lowermost upper mantle, but the structure of this layer is still uncertain, as it is also unclear whether its thickness varies depending on the heat flow and on how much its physical parameters change, which can be used to determine the depth of the lithosphere bottom. This uncertainty does not permit estimating the role of this layer in geodynamic processes in the upper mantle, for example, determining whether lithospheric plates can motion on this layer. With regard for this, which may not be viewed as the asthensphere, which is commonly thought to be an energy-capacious layer of partial melting.

In spite of currently available extensive geophysical material on the structure of the upper mantle and much results of laboratory studies of upper mantle materials, the problem of the lithosphere is still not resolved.

CONCLUSIONS

Detailed seismic studies of the upper mantle at long-range profiles, with the use of nuclear explosions, resulted in the discovery of new unusual structural features of the continental mantle and their inconsistency with interpretations of data of other geophysical methods:

- the determined from thermal field asthenosphere cannot be distinguished as a layer of lower seismic velocity;
- the lithosphere is definitely subdivided into two layers of different petrophysical features (an upper rigid layer 100–150 km thick and more plastic underlying layer);
- these layers are separated by seismic boundaries and lower velocity zones (waveguides);
- clearly defined boundaries N, L, and H are identified at depths of 100, 200, and 300 km, respectively, and are characterized by a complicated inner structure;
- the direct correlation between the seismic heterogeneity of the upper mantle and the gravity field is violated.

Interesting results have also been recently obtained by laboratory studies of mantle materials, including deep fluids:

- the seismic velocities are not controlled by the composition of the mantle rocks, but the density does depend on them and drastically decreases in the depleted material;
- the seismic velocities strongly depend on rheological characteristics of the materials, their plasticity, porosity, fracturing, and fluid content in them;
- deep fluids possess much energy and can release much heat if the permeability of the host materials changes; this is associated with significant changes in the petrophysical properties of the mantle materials.

These results of laboratory studies of mantle materials and deep fluids make it possible to explain most of the aforementioned structural features of the upper mantle and why these features are inconsistent with geophysical fields.

The subdivision of the lithosphere into two layers of different rheology and a transition zone, which are separated by waveguides and seismic boundaries of complicated structure, can be explained by the effect of an additional heat source related to fluid advection (Earth's degassing). For example, at a depth of 100–150 km, where mechanical properties of the material change and its porosity increases, deep fluids undergo physicochemical transformations, their gas constituents are transformed into liquid, and much heat is thereby released. This results in the development of plumes (low-velocity domains), which may contain melt, and the surface heat flow increases. In this instance, the heat flow characterizes not the depth of the asthenosphere but the temperature regime of the upper lithosphere. The advection of deep fluids also leads to the stratification of deeper parts of the upper mantle into layers of different rheological properties with complicatedly structured seismic boundaries in between.

Many of the discovered structures of the upper mantle can be explained by a significant role of deep fluids in transformations of the deep materials. The effects of the fluid flows containing much energy vary in time and space and can thus form different types of the lithosphere, for example, the thick lithosphere of ancient platforms. This lithosphere consists of materials of lower density. This explains the relationships between the contours of the high-velocity mantle of ancient platforms and negative gravity anomalies.

The nature of the lithosphere is largely uncertain, mostly because of the limited capabilities of seismic and seismological methods applied to study the bottom part of the upper mantle at depths greater than 300 km. Only indirect data suggest that asthenosphere occurs as a lower plasticity layer in the bottom part of the upper mantle. The nature of the lower plasticity in this asthenosphere is ambiguous, and it is not certain whether it is related to melting or any other changes in the physical state of the material. Studies of this problem call for designing new methods for processing seismic wave fields of different nature and a new methodology of comprehensive interpretations of geophysical data. This pertains, first of all, to methods for studying the physical nature of the temperature regime and mechanisms of material and energy transfer from significant depths. Modern techniques of determining the heat regime of the upper mantle assume conductive or convective heat transfer from the asthenosphere and do not take into account the advection of deep fluids possessing much energy.

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