

The Relation of Seismicity to Lithospheric Density Inhomogeneities in the Russian Far East

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Abstract—A well-defined relationship has been identified between the belts, zones and areas of higher seismicity in the Russian Far East on the one hand and, on the other, maxima in the gradient of surface density of spherical sources that give rise to gravity anomalies (μ_z) equivalent to quasi-isometric density inhomogeneities in the lower crust and upper mantle. The highest epicenter density is observed in the marginal parts of maxima of the μ_z parameter, these parts being interpreted as boundaries of rigid (sialic metamorphic and oceanic mafic) tectonic blocks and plates. The overwhelming majority of crustal seismicity is spatially related to uplifts of the asthenospheric layer reflected in the minima of the μ_z parameter, and is concentrated in uplifted crustal blocks. In addition to the linear type of seismicity due to deep-seated faults, the crust shows a concentrically zonal type of epicenter location associated with plume-generated central-type features (the Olekma–Stanovoi seismic zone). It is shown that seismic fields can be ranked by the depths of earthquake source zones using 3D models, $\mu_z(x,y,z)$.

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The stresses in the lithosphere due to tectonic interactions between blocks and sheets in the crust and upper mantle generate earthquakes, a sharp release of tectonic loads that are related to the fulfillment of two conditions: (a) the existence of rigid tectonic masses in the lithosphere that are capable of storing elastic stresses; (b) the existence of media (layers) of lower viscosity or higher ductility to provide for instantaneous mutual local displacements of masses of higher rigidity and density that accompany the sharp releases of tectonic loads. The conventional methods used for gravity modeling of deep-seated crustal and upper mantle features (those that find density inhomogeneities that would fit the observed gravity anomalies) are only capable of estimating the relative (excess or effective) density of geologic media, which is subject to extreme nonuniqueness under complex geological conditions. These estimates (in favorable cases) establish spatial relationships between zones of higher concentration (frequent occurrence) of earthquakes and vertical interfaces at the contacts of media of different densities, that is, deep-seated faults [3, 7, 8, 15, 16, etc.], and the horizontal interfaces between tectonophysical layers [16, 17]. However, the extremely unstable parameterization of the density properties of complex geologic media makes it impossible to objectively (i.e., independent of prior information) estimate and to make three-dimensional traces of the lithospheric stress fields related to moderate-sized and low magnitude seismicity.

A more sensitive indicator of the degree of rigidity, hence of the seismic potential of a tectonic medium compared with its density, is the vertical gradient of the surface density of a spherical mass (μ_z), which is equivalent to the 3D source of gravity anomalies [23, 24, 27, 28]. The high values of μ_z in the lithosphere of the Russian Far East correlate with terrains composed of old crystalline complexes [24, 28, 30], with metamorphic aureoles of intrusive dome structures [21], with ore fields and ore areas [21–23], and with rigid earthquake-generating slabs of oceanic origin in the subcrustal and subasthenospheric layers of the upper mantle [24, 26, 29]. Comparison of the distributions of density gradients in the crust and upper mantle with the locations of near-surface ore mineralization [23, 41] suggested the hypothesis that high-contrast maxima of the μ_z parameter are confined to dense crystalline masses of protomagmatic chambers as sources of Mesozoic and Early Cenozoic mineralizing fluid systems. The minima of that parameter correlate with chambers of molten magma beneath Cenozoic volcanoes of Kamchatka [26] and in the asthenosphere [24, 28, 29], and are accompanied by zones of low seismic velocity, low electrical resistivities, and heat flow anomalies.

The purpose of the present paper is to illustrate the relationship between anomalies of higher and lower density gradient (μ_z) and the locations of earthquake epicenters in the seismic zones and belts of the Russian Far East.

THE DATA SET

3D models $\mu_z(x, y, z)$ are developed from multiple interpretations of quasiisometric local gravity disturbances in a wide and continuous spatial range. The first step of the calculation is to find the depths of centers of density inhomogeneities (Z_0) at points of extrema of gravity anomalies and to measure the amplitudes of the disturbances (V_{zm}), which are stored in the information array $Z_0, V_{zm}(x, y, z)$; the second step yields the array $\mu_z(x, y, H_c)$ using the algorithm

$$\mu_z = \frac{Z_0 V_{zm}}{4\pi K (Z_0 - H_c)^2},$$

where K is the gravitational constant and H_c is the depth to a tentative horizontal plane onto which the masses of tectonospheric layers are condensed.

In order to calculate $\mu_z(x, y, H_c)$, we divide the 3D geologic space into a continuous sequence of layers and calculate the gradient of surface density of spherical sources that are tangent to the top of the layers (H_c). The condition $Z_0 > H_c$ is imposed such that the function (μ_z) suffers no discontinuity at the points $Z_0 = H_c$. The source of information on the structural and material inhomogeneity of the crust and upper mantle is the 3D model $\mu_z(x, y, H_{c1}, H_{c2}, \dots, H_{ck})$ which is interpolated at the grid points of the 3D matrix $\mu_z(x, y, z)$, from which construction of cross-sectional maps of $\mu_z(x, y, H_c = \text{const})$ and sections $\mu_z(x, H_c)$ for the distribution of that parameter is performed. The construction of μ_z models is described in detail in [23, 24, 28], both from the standpoint of physics and mathematics, and the technology of construction.

The target areas are the Baikal–Stanovoi and Chersky seismic belts, the Kuril–Kamchatka and Sakhalin seismic zones.

COMPARISON BETWEEN DENSITY GRADIENT ANOMALIES AND SEISMICITY FIELDS IN THE RUSSIAN FAR EAST

The Sea of Okhotsk. The seismicity in this region is confined to three depth levels of hypocenter concentration (swarms when viewed in cross-section) [1, 34]: 5–70 km (the maximum concentration is at depths of 40–45 km), 100–200 km (the maximum concentration is at depths of 120–150 km), and 300–600 km (the maximum concentration is at depths of 350–450 km). The first depth level corresponds to the crust–mantle transition layer, the second is close to the lithosphere–asthenosphere boundary in continental regions and to the bottom of the asthenosphere in oceanic areas, while the third is situated in deep mantle layers, outside the gravity models to be considered below (Fig. 1). The successive westward displacement of earthquake swarms from shallow to deeper levels is attributed by most investigators to the subduction of the Pacific litho-

spheric plate, even though some evidence is available [1, 35] to contradict that hypothesis.

Our gravity models (Fig. 1) show that the tectonosphere of the Sea-of-Okhotsk region has a four-layered distribution of the density gradient (1 unit = 10^{-2} kg/m²/km): a shallow volcanogenic–sedimentary layer down to 15–20 km depth involving low values of the parameter ($\mu_z < 10$ units), the crust–mantle layer in the depth range 20 to 60 km ($\mu_z = 15$ –30 units), the asthenosphere at depths of 40 to 130 km ($\mu_z < 15$ units), and a subasthenospheric layer ($\mu_z = 20$ –50 units). The third (asthenospheric) layer in central areas of the Sea of Okhotsk, in the Magadan continental area, and in Kamchatka is spatially identical with the layer of low electrical resistivity, as derived from magnetotelluric soundings [4, 28, 40], and with the zone of partial melting, as given by thermal physical modeling [33, 37, 39]. The second and fourth high-gradient, and relatively more rigid layers in the Sea-of-Okhotsk region show definite correlation with zones of crust–mantle and mantle (deep-focus) earthquakes.

The cross-sectional map of the 3D-density gradient model at a depth close to the average depth of the crustal bottom in the region (Fig. 1a) illustrates the correlation of anomalies of high μ_z values with the Sakhalin and Kuril–Kamchatka zones of crustal and subcrustal seismicity. The correlation is best expressed in Sakhalin, Hokkaido, in the southern Kurils, and in the east coast of Kamchatka, and less well in the middle part of the Great Kuril Islands, where local maxima of μ_z alternate with minima in the northeast linear zone.

Vertical cross-sections of the 3D-density gradient model (Fig. 1c) clearly reveal that zones of crustal and subcrustal seismicity are confined to deep-seated faults (plate boundaries), which are identified from sharp changes in the morphology of μ_z isolines: sharp shifts of isolines (the southeastern part of section 2–2 and the northwestern part of section 3–3), terminations (section 3–3), or shifts of anomalous layers (section 2–2). It is one of these faults that the disastrous Neftegorsk earthquake ruptured (section 2–2); in addition, that event occurred at the center of a local crust–mantle maximum of the density gradient (Fig. 1a). In the southeastern parts of sections 1–1 and 2–2 (Fig. 1c), deeper earthquakes occur on the deep-seated faults. A detailed examination of the shallow part of sections 2–2 and 3–3 down to 50 km depth (Fig. 1c) showed that the zones of crustal and subcrustal seismicity correlate with local density inhomogeneities bounded by subvertical contacts. The crustal seismicity in the Kuril–Kamchatka zone coincides with maxima of the density gradient, while in Sakhalin it is confined to the western flank of a maximum in that parameter—to the edge of an uplifted rigid block at the base of the crust (sections 2–2 and 3–3).

The cross-sectional map of density inhomogeneities at 80 km depth, which is the average depth of the top of

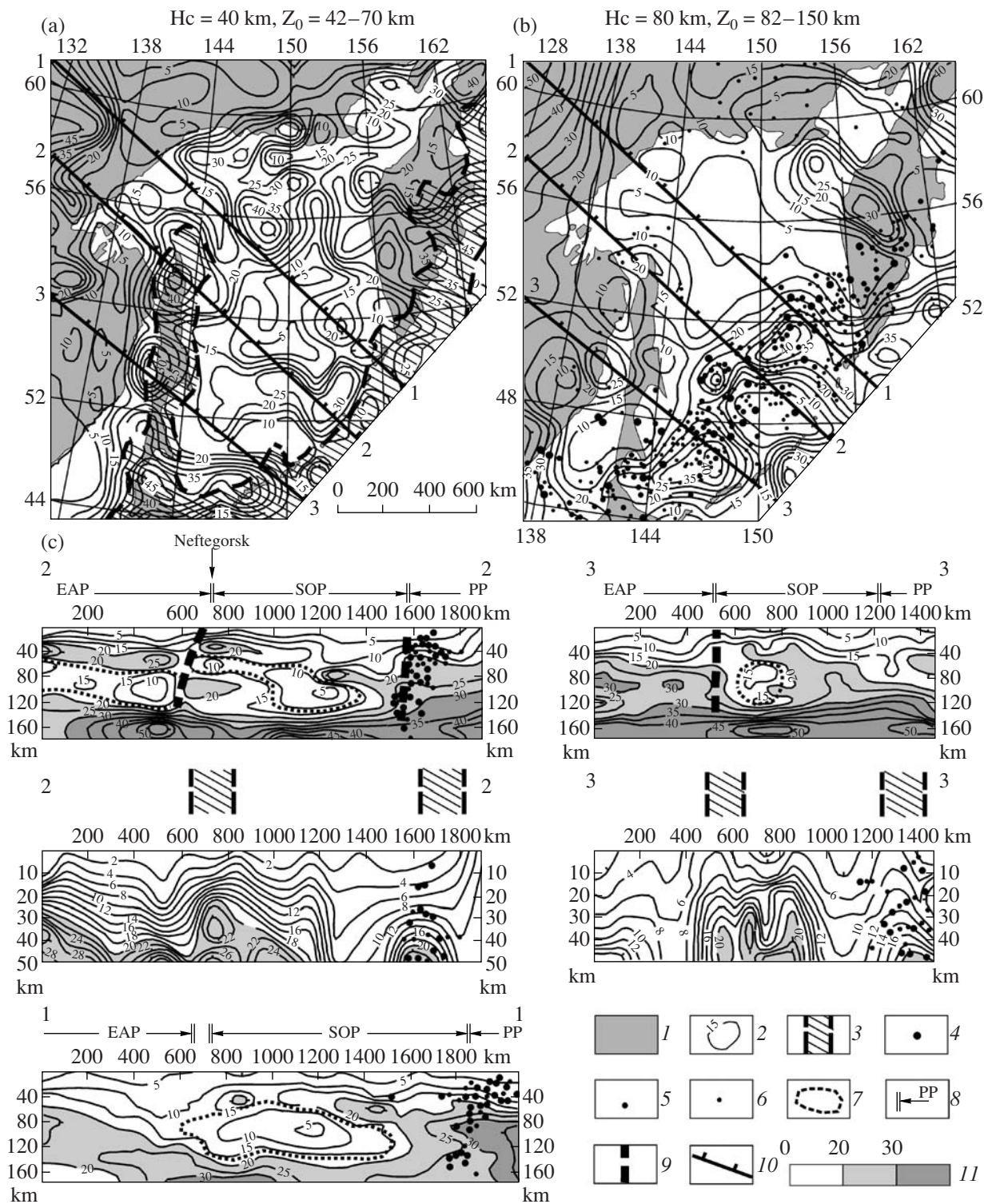


Fig. 1. Cross-sectional maps (a, b) and sections (c) of a 3D model representing density gradients for the upper mantle of the Sea-of-Okhotsk region: (1) land, (2) isolines of surface density gradient in layers (1 unit = $10^{-2} \text{ kg/m}^2/\text{km}$), (3) belts of mostly crustal seismicity [34], (4–6) epicenters of earthquakes [34] with magnitudes: (4) greater than 6.5, (5) 3.5–6.5, (6) less than 3.5; (7) outlines of asthenospheric lenses, (8) plate boundaries, (9) deep-seated faults, (10) positions of sections on maps, (11) graded shading for μ_z . Plate designations: EAP Eurasian, SOP Sea-of-Okhotsk, PP Pacific.

the asthenospheric layer in the region (Fig. 1b), shows the two following leading features:

(1) There is an extensive minimum in μ_z in the middle of the Sea of Okhotsk, whose outline is close to that of the asthenospheric lens in a thermometric model [24, 28]. The southern flank of the lens branches out southwest in the shape of a linear zone 200 km wide, which separates two areas of high and increased density gradient. The eastern boundary of the western high- μ_z area corresponds to the deep-seated boundary of the Eurasian plate [29], while the western boundary of the eastern area is subparallel to the Kuril island arc and the deep-sea trench (the present-day near-surface boundary of the Pacific plate). Since the asthenosphere is shallow (30–60 km, see [33, 39, 40]) in this area of the Sea of Okhotsk, one is certainly entitled to associate the eastern area of maximum μ_z with the subasthenospheric layer of the oceanic upper mantle [29]. Sections 1–1 and 2–2 (Fig. 1c) clearly reveal the splitting of that layer into two slabs, the upper being overthrust onto the Sea-of-Okhotsk asthenosphere (i.e., it is actually the lithosphere of the Sea-of-Okhotsk plate [28]), while the lower layer has been subducted under it.

(2) The subasthenospheric layer of the Pacific upper mantle that has been subducted beneath the Sea-of-Okhotsk plate for a distance of 400–500 km from the deep-sea trench is seismically active. The area of subasthenospheric seismicity correlates with a horseshoe-shaped zone of high μ_z values (Fig. 1b) in the marginal (frontal) part of the rigid slab, while the greatest frequency of deep earthquakes is observed in the zones of concentrated μ_z isolines (at the boundaries of blocks with increased rigidity).

The Chersky seismic belt. The Chersky belt is a wide (600–800 km) zone of crustal earthquakes extending from the mouth of the Lena River to the Magadan coast of the Sea of Okhotsk, and which is conformable with the southwestern boundary of the Kolyma–Omolon superterrains [36]. Most investigators attribute the generation of earthquakes in the region to the existence of faults [3, 11, 12, 14, 36], mostly strike–slip, normal–oblique and reverse–oblique faults, and also overthrust and separation faults, which are due to the collision of the Eurasian and North American plates and have persisted in activity until the present [12, 36]. It has been pointed out that the seismicity was associated with the location of Mesozoic granitoids [10] and with the degree of maturity in the metamorphic granitic layer [3], which indicates a relationship between the seismic processes and the degree of crustal rigidity. There is also some evidence for correlation between zones of higher seismicity and uplifts of the earth's surface, which would suggest a relationship between the earthquakes and the isostatic processes beneath mountain edifices (the submergence of “mountain roots”), in particular, the Polousnyi, Moma, Selennyakh, Chersky, Kular, Verkhoyansk (the northern fragment), and Stanovoi mountain ranges (Fig. 2a). However, this rela-

tionship does not seem to control the spatial occurrence of earthquakes in the Russian Far East, since many mountain ranges (Anyui, Dzhugdzhur, Suntar-Khayata, etc.) are located in aseismic areas, while patches of high seismicity are recorded outside mountain edifices (Fig. 2a). The fact that the earthquakes in the Chersky belt are shallow (15–35 km, more rarely as deep as 55 km [36]) is explained by the closeness of the asthenosphere, whose upper surface lies at depths of 50–70 km there as can be gathered from magnetotelluric sounding studies [4].

The data plotted in Fig. 2c reveal a sharp difference in the tectonosphere of the northeastern margin of Asia between the deep-seated features in the North Asian craton and in the Kolyma–Omolon superterrains. The craton crust and upper mantle are characterized by a 6-layered low-angle section consisting of a crust–mantle layer (depth range 35–50 km) and an asthenospheric layer (60–130 km), but with lower viscosity, and three layers of higher rigidity: the lower crust (15–30 km), the lower lithosphere (50–90 km), and the subasthenospheric layer (below 140 km depth). The lower lithospheric layer in the Kolyma–Omolon upper mantle gently dips under the Verkhoyansk–Kolyma folded thrust system (VKFTS), and the crust–mantle layer is thicker than the corresponding layer in the North Asian craton and is overthrust onto the VKFTS asthenosphere. It thus appears that the lower lithosphere is split in the junction zone between the folded thrust system and the Kolyma–Omolon superterrains, and accordingly, between the Eurasian and North American plates, with the splitting being very similar to that of the Pacific upper mantle in sections 1–1 and 2–2 for the Sea-of-Okhotsk tectonosphere (Fig. 1c). The underthrusting of the stiffer crust–mantle layer at the base of the Kolyma–Omolon superterrains under the folded thrust system was accompanied during Late Mesozoic time by imbricated overthrusting of the Verkhoyansk–Kolyma upper crustal complexes onto the craton, of the Kolyma–Omolon terrain onto the Verkhoyansk–Kolyma system, and of the Anyui–Chukchi system onto the Kolyma–Omolon terrain [19, 38]. The accretion (compression) and thrusting going on at the southeastern boundaries of the Kolyma–Omolon superterrains were replaced by extension and strike–slip displacements during Late Cenozoic time (Miocene/Pliocene) [36, Fig. 1.16].

The source of present-day seismicity in the Chersky belt seems to be the rigid lower crustal (crust–mantle) slab of vertical thickness 20–25 km, which overlies the asthenospheric layer (Fig. 2c). This conclusion is corroborated by a definite correlation between the seismicity and the zone of the maximum density gradient in the horizontal section of the crust–mantle layer at the depth $H_c = 35$ km (Fig. 2b).

Intensive Late Mesozoic tectonic processes and present-day seismicity in the Chersky belt have been, and still are, possible, owing to an upward bulge of the asthenospheric layer identified by two independent

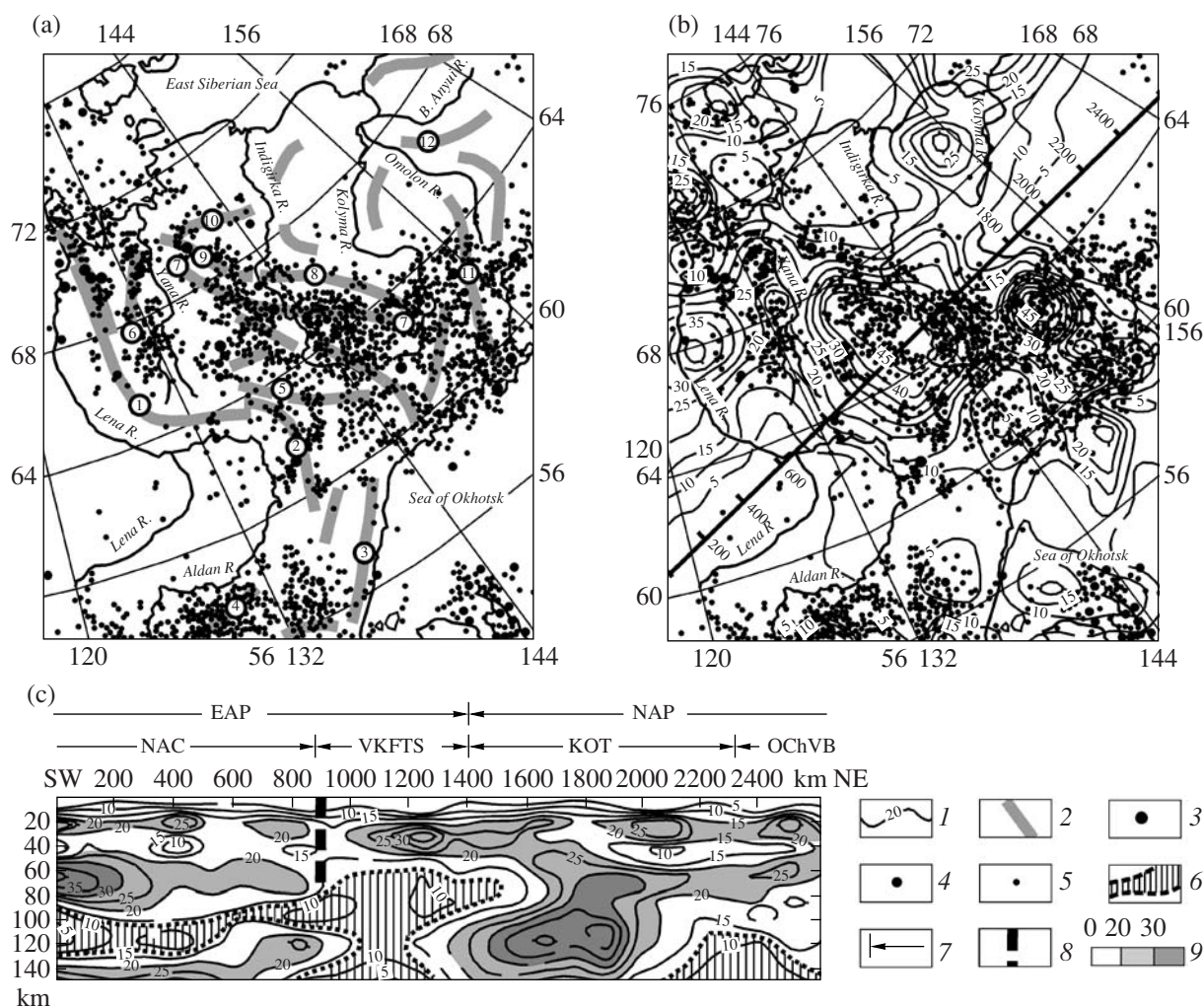


Fig. 2. Maps of mountain ranges (a) and gradient of surface density for the upper mantle (b) of eastern Yakutia with a section (c): (1) isolines of surface density gradient in layers (1 unit = 10^{-2} kg/m² km), (2) mountain ranges, (3–5) epicenters of earthquakes [36] with magnitudes: (3) greater than 6, (4) 4–6, (5) less than 4; (6) areas and zones of disturbed phase state in the upper mantle (the asthenosphere), (7) boundaries of tectonic features, (8) deep-seated fault, (9) graded shading for μ_z . Designations of mountain ranges, the numerals in circles referring to map (a): (1) Verkhoyansk, (2) Sette-Daban, (3) Dzhugdzhur, (4) Stanovoi, (5) Suntar-Khayata, (6) Kular, (7) Chersky, (8) Moma, (9) Selennyakh, (10) Polousnyi, (11) Kolyma upland, (12) Anyui. Designations of tectonic features in sections: NAC North Asian craton, VKFTS Verkhoyansk–Kolyma Folded Thrust System, KOT Kolyma–Omolon superterrains, SOChVB Sea-of-Okhotsk–Chukchi volcanic belt. Plate designations: EAP Eurasian plate, NAP North American plate.

methods, viz., magnetotelluric [4] and gravimetric methods (the 1000–1600 km range of coordinates along the line in Fig. 2c). During the Mesozoic, a viscous, possibly molten, layer underlying the crust was producing displacements (and still produces them at present) of the overlying tectonic masses in different directions and a sudden release of tectonic loads in the rigid blocks giving rise to seismic events.

The Baikal–Stanovoi seismic belt. The belt is situated in the junction zone between the North Asian craton on one side and the Baikal–Vitim and Amur Proterozoic/Paleozoic superterrains on the other, and can be divided into two zones using the character of seismicity, the Baikal zone and the Olekma–Stanovoi, the boundary between the two being the divide of the Chara

and Olekma rivers [25, 36]. The Baikal zone exhibits a linear type of seismicity field due to the Baikal Rift System [5, 18], while the Olekma–Stanovoi zone is characterized by a concentrically zonal distribution of earthquake epicenters (Figs. 3a–3c) related to the existence of a central-type feature, viz., the Aldan–Zeya lithospheric plume [30].

Some elements of a central-type feature are clearly expressed in anomalies of density gradient (μ_z) in cross-sectional maps of the Amur area and southern Yakutia tectonosphere at depths of 5 (Fig. 3a), 20, 35 (Figs. 3b), and 70 km (Fig. 3d). The maxima of μ_z in the middle and lower crustal layers are located in the flanks of the belt, where they correlate with swarms of increased earthquake concentration, while in the sub-

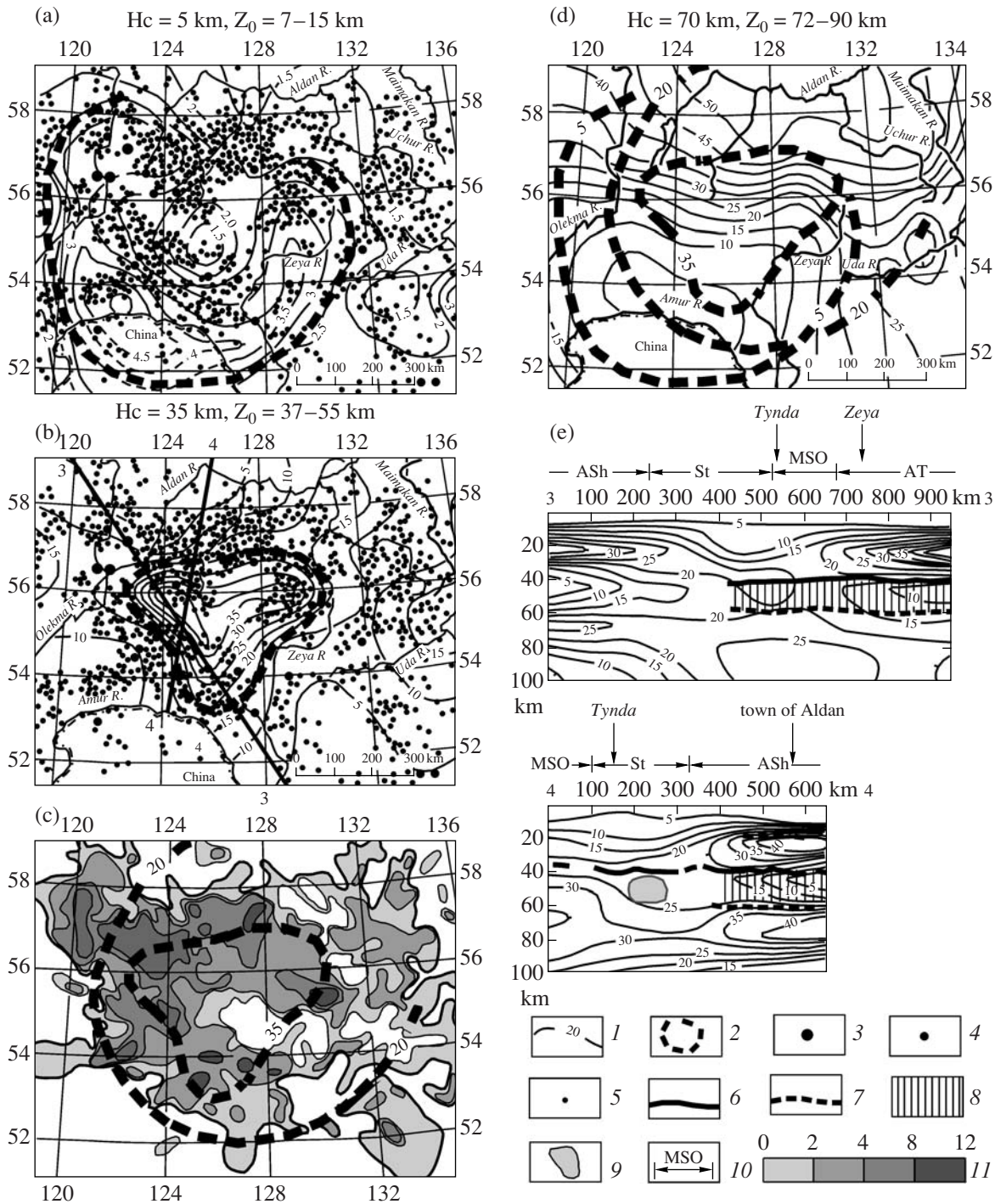


Fig. 3. Density inhomogeneity and seismicity of the Olekma–Stanovoi zone: cross-sectional maps of surface density gradient for the middle crustal (a) and the subcrustal (b) layers, a map of earthquake density (c) [13] and a cross-sectional map of surface density gradient for the asthenosphere (d) with vertical sections (e) of the 3D model $\mu_z(x,y,H_c)$: (1) isolines of surface density gradient in layers (1 unit = 10^{-2} kg/m² km), (2) outline of the Aldan–Zeya plume in horizontal sections (numerals indicate the section depth), (3–5) epicenters of earthquakes [36] with magnitudes: (3) greater than 6, (4) 4–6, (5) less than 4; (6–7) velocity discontinuities in sections, in particular, (6) the Moho, (8) zones of low seismic velocity [2, 9], (9) zone of partial melting as identified by thermal modeling [37] for section 4–4, (10) boundaries of tectonic features in sections, (11) graded shading for earthquake density (c), the numerals denoting the numbers of seismic events in 0.2×0.4 grid rectangles [13]. Designations of tectonic features: ASH Aldan Shield; folded systems: MSO Mongolia–Sea-of-Okhotsk, St Stanovoi, AT Amur superterrains

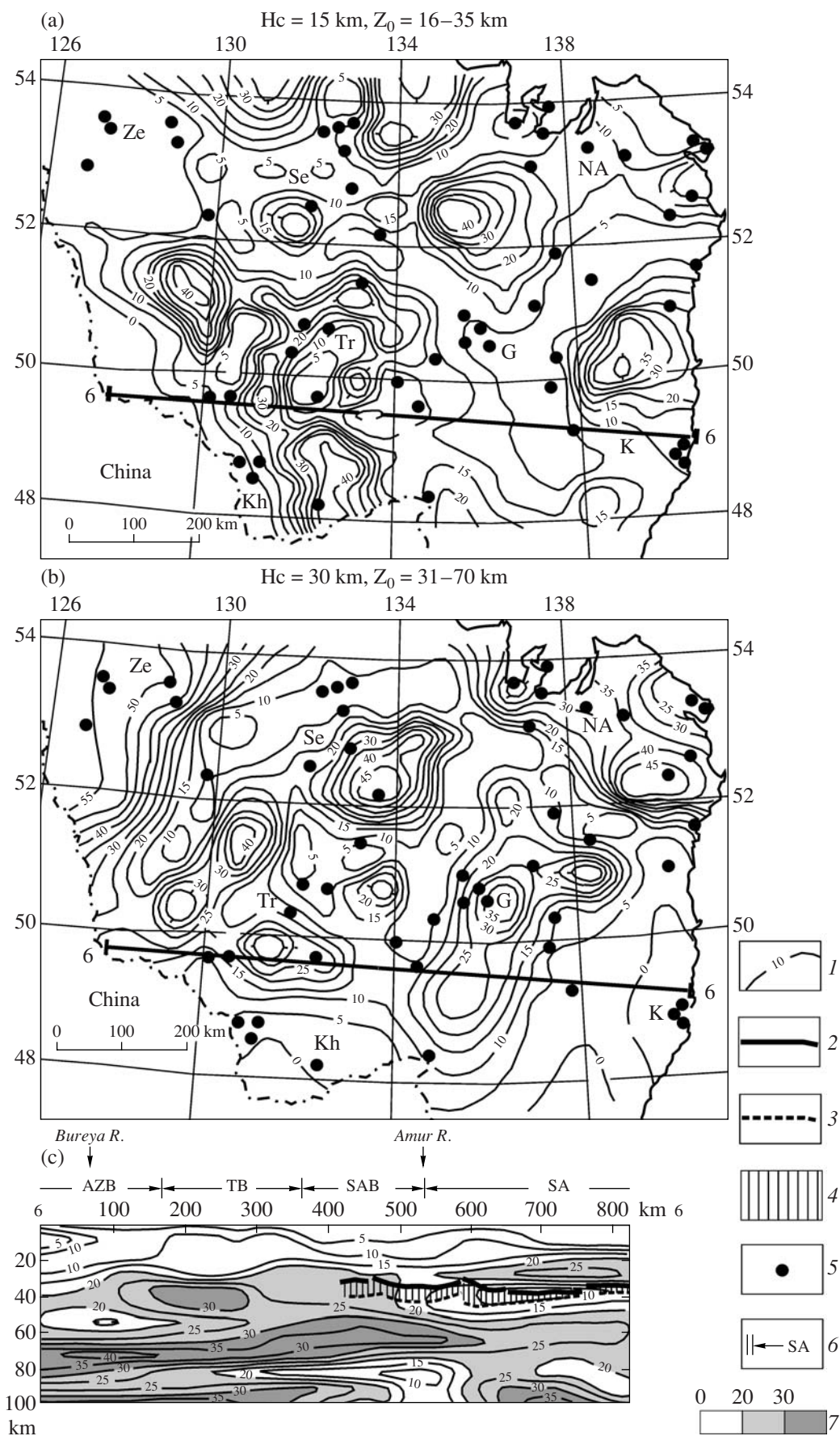


Fig. 4. Cross-sectional maps (a, b) and a section (c) to display the 3D-density gradient model for the crust and upper mantle of the eastern Amur area: (1) isolines of surface density gradient (1 unit = 10^{-2} kg/m² km), (2, 3) velocity discontinuities, in particular, (2) Moho, (4) zone of low seismic velocity [32], (5) epicenters of earthquakes with magnitudes greater than 4.5 [16], (6) boundaries of tectonic features, (7) graded shading for μ_z . Designations of tectonic features: Amur–Zeya and Sredne-Amur basins (AZB and SAB, respectively), Sikhote-Alin' accretionary folded system (SA), Turan block (TB) of the Amur superterrains. Designations of seismic areas: Ze Zeya, Se Seledmdzha, NA Nizhne-Amur, G Goryun, K Koppi, Kh Khingan, Tr Tyrma.

crustal layer of the upper mantle a high maximum of the density gradient occurs at the aseismic center of the tectonomagmatic structure (Fig. 3b). This distribution is explained by an inversion (subsidence) of the dome of the central-type structure expressed in a downward shift of μ_z isolines in the cross-section (Fig. 3e) and the corresponding character of recent vertical crustal movements, namely, subsidence at a rate of 10–12 mm/yr [30].

Viewed in a cross-section, the earthquake hypocenters are confined to the rigid lower crustal slabs of the Aldan Shield and the Amur superterrains [16, 17], which are composed of strongly metamorphosed (granulite-gneiss and greenstone) crystalline complexes. The lower crust is underlain by a layer of low μ_z (Fig. 3e), lower seismic velocity [9], and low electrical conductivity [31], that is, a layer of lower viscosity. Similarly to the northeastern areas of the North Asian craton (Fig. 2c), it is the relatively more rigid lower lithospheric layer, which has high values of density gradient in the depth range 50–80 km (section 4–4 in Fig. 3e).

Judging from the studied section of the Olekma–Stanovoi seismic zone, a layer of low-density gradient must lie at depths below 80 km, which coincides with the zone of lower seismic velocity and high attenuation in the southern segment of the Katanga–Shilka deep seismic sounding line [6], the asthenosphere. Based on our data (Fig. 3d), we believe that the asthenospheric layer in the Olekma–Stanovoi seismic zone has the shape of a lens whose top rises at the base of the plume and is accompanied by circular magnetic minima and heat flow anomalies [30].

It thus appears that the character of the relationship between the Olekma–Stanovoi seismicity and crustal and upper mantle density inhomogeneities is similar to that in the regions discussed above: Sakhalin, Kuril–Kamchatka, and Southern Yakutia (Chersky belt). In all these regions, an increased concentration of earthquake epicenters correlates with maxima of the density gradient at the depths corresponding to these earthquakes (Figs. 1, 2, 3a–3c). The other requirement for high frequency and a corresponding high concentration of earthquake epicenters is the existence of zones of lower viscosity at the base of the rigid blocks (Figs. 1c, 2c, 3d, 3e), which provides for rapid release of tectonic loads and displacement of tectonic masses in the overlying layers.

The eastern Amur area. The seismicity field of the eastern Amur area is characterized by a complex, mosaic pattern [7, Fig. 5; 15, Fig. 1] due to the intersec-

tion of two seismic belts at that location, viz., the Baikal–Stanovoi [12, 36], or the Baikal–Sea-of-Okhotsk [8, 16], and the Tanlu belt [8].

The cross-section of the eastern Amur area (Fig. 4c), in a similar manner to that of the western area (Fig. 3e), contains two layers of increased rigidity (maxima of μ_z) and two layers of lower viscosity (minima of μ_z) in the distributions of density gradient. The lower viscous layer (the asthenosphere) is rather thin at this location (15–20 km) at 70–80 km depth. Only on a short segment of the line (near the eastern side of the Sredne-Amur basin) does the layer descend deeper than 100 km. A second, subcrustal, viscous layer is observed at the base of the crust in the Sikhote-Alin' accretionary folded system, where it coincides with the seismic waveguide (Fig. 4c). The layer with a high density gradient and, accordingly, the rigid lithospheric layer, are both thicker beneath the Turan Proterozoic–Early Paleozoic block of the Amur superterrains and thinner beneath the Cenozoic basins, viz., the Sredne-Amur and the Amur–Zeya basins, which is a typical feature characterizing the lithosphere structure in the margins of the Russian Far East [33, 37, 39, 40].

The distributions of density inhomogeneities at the lower crustal (Fig. 4a) and subcrustal (Fig. 4b) levels clearly reveal a sharp structural difference. The former is characterized by a dominant northwest orientation of the isolines and axes of clustering for local μ_z anomalies, corresponding to the northeast Late Paleozoic–Early Mesozoic tectonic stress vector related to the interaction of the Amur microplate with the southeastern margin of the North Asian craton [20], while the latter has a northeastern orientation of μ_z anomalies, coinciding with the prevailing orientation of Late Mesozoic and Cenozoic structures in the Sikhote-Alin' (except for the lower reaches of the Amur River area), the northwestern Sea-of-Okhotsk coastal region, Sakhalin, and Kamchatka. The Tanlu seismic belt has an orientation that agrees with the northeastern anomalies of density gradient in the subcrustal layer. The data considered here provide evidence that the Cenozoic structural rearrangement of the crust in the portion of the continental Asian margin discussed here (Fig. 4) proceeds upward, from the subcrustal layer of the upper mantle, while the middle and lower crustal tectonic features that are taking part in present-day seismic processes retain traces of preceding Late Paleozoic and Early Mesozoic deformation. Our models (Figs. 4a, 4b) are essentially consistent with the results of cluster correlation analysis applied to the Amur seismicity and deep-seated structure [8], which demonstrated the existence

of two structural environments for seismogenic crustal deformation, the lower of which is characterized by a northeastern orientation.

The overwhelming majority of earthquakes in the eastern Amur area are within the crust, and the depth histograms show a bimodal distribution, one maximum being at 10 km depth and the other at 25 km [7]. Based on the patterns discussed above, these earthquakes may emanate from rigid tectonic slabs in the lower crustal layer (15–35 km) and the subcrustal (35–70 km) layer of the upper mantle (Fig. 4c). The distributions of density gradient in these layers were compared with the locations of the epicenters of moderate (magnitudes greater than 4.5) earthquakes (Figs. 4a, 4b) to reveal that the deep-seated source zones of most earthquakes of this energy class reside in the subcrustal layer of the upper mantle. The $H_c = 30$ km cross-sectional map (Fig. 4b) shows that the maxima of μ_z coincides with the positions of the Zeya, Tyrma, Goryun, and Nizhne-Amur seismic areas, and the southern part of the Selezhdzha seismic area, while it is only the Tyrma and Koppi (less so) seismic areas which correlate with similar anomalies in the lower crustal layer (Fig. 4a). A comparison of the maps in Figs. 4a and 4b reveals a sharp difference in the character of the relationship between seismicity and the crustal and upper mantle density inhomogeneities in the Zeya and Koppi areas. In the first of these, the earthquakes are associated with subcrustal inhomogeneities, while in the second they have a relationship with an extensive lower crustal anomaly of the density gradient. This difference corresponds to the hypsometric positions of the rigid slabs accompanied by maxima of μ_z in the sections across the coastal areas of the Sikhote-Alin' and the Amur superterrains (Fig. 4c). The subcrustal viscous layer is missing in the Turan block, and consequently, the Tyrma earthquakes correlate equally well with the μ_z anomalies (situated at the periphery of the maxima) observed both in the lower crustal (Fig. 4a) and the subcrustal (Fig. 4b) gravitationally active layers.

The vertical cross-section of the μ_z parameter (Fig. 4c) shows the relationship between increased earthquake concentrations and uplifted crustal blocks, which are accompanied by increased density gradients in the near-surface layer (for the intervals $x = 180$ – 340 km and $x = 550$ – 650 km along the line), which is consistent with the statistical seismic zonation for the Amur area [8] and, in a more pronounced form, with sections of present-day island systems in the Sea of Okhotsk (Fig. 1c).

CONCLUSIONS

The data we have considered show that areas in the Russian Far East that are distant from one another and have different geologic structures exhibit similar features of spatial correlation between earthquake epicenters and the crustal and upper mantle density inhomogeneities as modeled by non a priori formalized compu-

tational procedures. In all the areas studied by the present author, the spatial positions of source zones (swarms) and belts of present-day seismic activity correlate with maxima of the surface density of spherical masses equivalent to quasiisometric, or compact, sources of gravity disturbances lying at the depth levels that correspond to these earthquakes. The greatest earthquake concentration is observed at boundaries of the maxima that are identified as being due to rigid crystalline blocks of older continental metamorphic complexes or basic oceanic slabs in the lower crust and upper mantle (Figs. 1b, 1c, 2b, 3a, 3b, 4b). The belts and zones of high crustal seismicity in continental areas and island arcs of marginal seas are confined to uplifts of low viscosity layers (the subcrustal and the asthenospheric layers), above which the rigid blocks and slabs interact seismically (Figs. 1a, 1c, 2c, 3d). The middle and upper crustal layers in different areas exhibit a similar relationship between the zones and sites of increased earthquake concentration and uplifted, relatively more rigid, blocks (Figs. 1c, 4c).

As well as the well-known linear type of seismic activity due to deep-seated faults (Figs. 1a, 1c), the tectonosphere of the Russian Far East shows a concentrically zonal type of seismicity field related to deep-seated central-type features of plume origin (Fig. 3c).

The above evidence shows that the μ_z parameter can be used for seismic zonation and for long-term prediction of seismic hazard. Anomalies of the surface density of spherical masses (μ_z) equivalent to quasiisometric, or compact, sources of gravity disturbances can be used, not only for refining the spatial boundaries of known seismic areas and identification of new potentially seismic ones [23], but also as an additional parameter for use in sorting seismic fields by the depth of earthquake source zones (Figs. 1, 4) in those areas where seismological observations (especially earlier ones) do not provide enough evidence (the vertical coordinates of earthquakes have not been determined or are approximate).

REFERENCES

1. Aver'yanova, V.N., *Glubinnaya tektonika ostrovnnykh dug (Severo-zapad Tikhogo okeana)* (Deep Tectonics of Island Arcs: The Pacific Northwest), Moscow: Nauka, 1975.
2. Bulin, N.K., Afanas'eva, E.A., Pronyaeva, E.N., and Erglis, E.I., A Deep Cross-Section of the Southeastern Siberian Platform and its Folded Circumference Based on Seismological Data, *Sov. Geologiya*, 1972, no. 11, pp. 134–139.
3. Vashchilov, Yu.Ya., Sakhno, O.V., and Kalinina, L.Yu., *Geologo-geofizicheskie usloviya vozniknoveniya zemletrasenii na Severo-Vostoke Rossii* (Geological and Geophysical Conditions for Earthquake Generation in the Russian Northeast), Magadan: SVKNII DVO RAN, 1996.
4. Vashchilov, Yu.Ya., Gaidai, N.K., Maksimov, A.E., et al., The Polyasthenosphere of the Russian Northeast: Meth-

- ods of Study, Structure, Kinematics, and Dynamics, in *Astenosfera i litosfera Severo-Vostoka Rossii (struktura, geokinetika, evolyutsiya)* (The Asthenosphere and Lithosphere of the Russian Northeast: Structure, Geokinematics, and Evolution), Magadan: SVKNII DVO RAN, 2003, pp. 135–142.
5. *Geologiya i glubinnoe stroenie zony BAM. Seismichnost'* (The Geology and Deep Structure of the BAM Zone: Seismicity), Novosibirsk: Nauka, 1985.
 6. *Glubinnoe stroenie territorii SSSR* (Deep Structure of the USSR Area), Moscow: Nauka, 1991.
 7. Gorkusha, S.V. and Malyshev, Yu.F., Deep Structure and Seismicity of the Junction Zone between the Pacific Belt and the Central Asian Belt, *Tikhookean. Geol.*, 1993, no. 2, pp. 32–51.
 8. Gorkusha, S.V., A Study in the Seismicity and Deep Structure of Eastern Amur Area Using Cluster Analysis, *Tikhookean. Geol.*, 1996, vol. 15, no. 4, pp. 67–76.
 9. Zolotov, E.E. and Rakitov, V.A., The Structure of the Amur Area Lithosphere Derived by the Method of Reflected Earthquake Waves and Deep Seismic Sounding, *Regional'naya geologiya i metallogeniya*, St. Petersburg: Izd-vo VSEGEI, 2000, no. 10, pp. 235–240.
 10. Imaev, V.S., The Relationship between the Distributions of Granitoid Intrusions and Earthquake Activity in the Russian Northeast, in *Sovremennaya geodinamika, aktivnye razlomy i seismicheskoe raionirovanie* (Present-Day Geodynamics, Active Faults, and Seismic Zonation), Moscow: GIN AN SSSR, 1990, pp. 5–7.
 11. Imaev, V.S., Imaeva, L.P., Koz'min, B.M., and Fudzhita, K., Active Faults and Present-Day Geodynamics of the Yakutian Seismic Belts, *Geotektonika*, 1994, no. 2, pp. 59–71.
 12. Imaev, V.S., Imaeva, L.P., and Koz'min, B.M., Earthquake Ruptures in the Yakutian Seismic Belts, *Geotektonika*, 1995, no. 1, pp. 79–92.
 13. Imaev, V.S., Imaeva, L.P., and Koz'min, B.M., The Seismotectonics of the Olekma–Stanovoi Seismic Zone: Southern Yakutia, *Litosfera*, 2002, no. 2, pp. 21–40.
 14. Kalinina, L.Yu., The Role of Faults and Deep Structure in the Spatial Control of Earthquake Occurrence in the Russian Northeast, Extended Abstract of Cand. Sci. (Geol.-Mineral.) Dissertation, Magadan: SVKNII DVO RAN, 2005, 26 p.
 15. Kuznetsov, V.E., The Deep Structure and Present-Day Geodynamics of the Amur Area, *Tikhookean. Geol.*, 1998, vol. 17, no. 2, pp. 61–67.
 16. Malyshev, Yu.F., Deep Structure, Geodynamics, and Seismicity in the Junction Zone between the Central Asian and Pacific Mobile Belts, *Tikhookean. Geol.*, 1998, vol. 17, no. 2, pp. 21–27.
 17. Misharina, L.A., Ruzhich, V.V., and Vertlib, M.B., On the Relation of the Epicenter Field and Source Mechanisms for Earthquakes in the Chara–Vitim Region to Crustal Structure, in *Seismicheskie i seismologicheskie issledovaniya na tsentral'nom uchastke BAMA* (Seismic and Seismological Studies in the Central Area of the BAM Region), Yakutsk: Izd-vo Yakut. Filiala SO AN SSSR, 1978, pp. 33–50.
 18. Nikolaev, V.V. and Semenov, R.M., Seismotectonics of the Baikal Rift Zone and of its Mountain Circumference, *Geologiya i Geofizika*, 2004, no. 5, pp. 638–648.
 19. Parfenov, L.M., Natapov, L.M., Sokolov, S.D., and Tsukanov, N.V., Terrains and Accretionary Tectonics of Northeast Asia, *Geotektonika*, 1993, no. 1, pp. 68–78.
 20. Parfenov, L.M., Popeko, L.I., and Temurtoogo, O., Problems in the Tectonics of the Mongolia–Sea-of-Okhotsk Orogenic Belt, *Tikhookean. Geol.*, 1999, vol. 18, no. 5, pp. 24–43.
 21. Petrishchevsky, A.M., *Statisticheskie gravitatsionnye modeli litosfery Dal'nego Vostoka* (Statistical Gravitational Models for the Lithosphere of the Russian Far East), Vladivostok: Izd-vo Dal'nevost. Gos. Un-ta, 1988.
 22. Petrishchevsky, A.M., Deep Structure and Metallization of the BAM Region Based on Gravity Data, *Sov. Geologiya*, 1990, no. 1, pp. 86–92.
 23. Petrishchevsky, A.M., The Gravitational Instability of the Earth's Crust and Upper Mantle in the Amur Area: Spatial Statistical Models, *Tikhookean. Geol.*, 2004, vol. 23, no. 1, pp. 20–36.
 24. Petrishchevsky, A.M., Gravity Tomography of the Tectonosphere of the Russian Far East in the Class of Spherical Sources, *Geofizika*, 2005, no. 5, pp. 47–57.
 25. Petrishchevsky, A.M., Deep Structure and Cenozoic Geodynamics of the Olekma–Stanovoi Seismic Zone, in *Sovremennaya geodinamika i opasnye prirodnye protsessy v Tsentral'noi Azii. Vypusk 3, Mater. Vseross. soveshch. "Sovremennaya geodinamika i seismichnost' Tsentral'noi Azii: fundamental'nyi i prikladnoi aspekty"* (Present-Day Geodynamics and Natural Hazards in Central Asia. Issue 3. Materials of the All-Russia Conf. "Present-Day Geodynamics and Seismicity of Central Asia: The Basic-Science and Applied Aspects"), Irkutsk: SO RAN, 2005, pp. 60–63.
 26. Petrishchevsky, A.M., A Tectonic Interpretation of Density Inhomogeneities in the Kamchatka Crust and Upper Mantle, *Tikhookean. Geol.*, 2006, vol. 25, no. 1, pp. 31–46.
 27. Petrishchevsky, A.M., The Gravitational Instability in the Tectonosphere of the Northeastern Margins of Russia, in *Tektonika, glubinnoe stroenie i minerageniya Vostoka Azii. V Kosygin'skie chteniya* (Tectonics, Deep Structure, and Mineralization of East Asia. The Fifth Kosygin Lectures), Khabarovsk: DVO RAN, 2006, pp. 105–108.
 28. Petrishchevsky, A.M., A Gravity Indicator of Rheologic Properties in the Tectonosphere of the Far East Margins of Russia, *Fizika Zemli*, 2006, no. 7, pp. 1–17.
 29. Petrishchevsky, A.M. and Zlobin, T.K., The Density Inhomogeneity of the Sea-of-Okhotsk Tectonosphere, in *Uchenye zapiski Sakhalinskogo gosudarstvennogo universiteta. Sb. nauchnykh statei* (Transactions of the Sakhalin State University. A Collection of Scientific Papers), Issue 4, Yuzhno-Sakhalinsk: Izd-vo SakhGU, 2004, pp. 10–20.
 30. Petrishchevsky, A.M. and Khanchuk, A.I., A Cenozoic Plume in the Upper Reaches of the Amur River, *Dokl. RAN*, vol. 406, no. 3, pp. 116–119.
 31. Pospeev, A.V., Geological Aspects in the Geoelectricity of the Earth's Upper Lithosphere, *Geofizika*, 2004, no. 4, pp. 35–38.
 32. Potap'ev, S.V., The Relationship between the Surface and Deep Crustal Structure in the Amur Area and the Primorskii Krai, in *Glubinnoe stroenie litosfery Dal'nevost-*

- tochnogo regiona* (Deep Structure of the Lithosphere of the Russian Far East), Vladivostok: Izd-vo DVNTs AN SSSR, 1980, pp. 43–53.
33. *Struktura i dinamika litosfery i astenosfery Okhotomorskogo regiona. Rezul'taty issledovaniy po mezhdunarodnym geofizicheskim proektam* (The Structure and Dynamics of the Sea-of-Okhotsk Lithosphere: Studies in the Framework of International Geophysical Projects), Moscow: RAN, Natl. Geophysical Committee, 1996.
 34. Tarakanov, R.Z., Estimation of Maximum Possible Earthquake Magnitudes for the Kuril–Kamchatka Region, in *Prirodnye katastrofy i stikhiinye bedstviya v Dal'nevostochnom regione* (Natural Catastrophes and Disasters in the Russian Far East), Ivashchenko, A.I., Ed., Vladivostok: DVO AN SSSR, vol. 1, 1990, pp. 28–47.
 35. Tarakanov, R.Z., A New View of the Origin of the Benioff Zone and Associated Processes in the Ocean–Continent Transition Region: An Alternative to A Subducted Lithospheric Slab, in *Stroenie, geodinamika i metallogeniya Okhotskogo regiona i prilegayushchikh chastei Severo-Zapadnoi Tikhookeanskoi plity. Mater. Mezhdunar. nauchnogo simpoziuma* (The Structure, Geodynamics, and Mineralization of the Sea-of-Okhotsk Region and Adjacent Areas of the Northwestern Pacific Plate. Materials of an International Symposium), Yuzhno-Sakhalinsk, 2002, vol. 1, pp. 133–134.
 36. *Tektonika, geodinamika i metallogeniya territorii respubliki Sakha (Yakutiya)* (The Tectonics, Geodynamics, and Mineralization in the Republic of Sakha (Yakutia)), Moscow: MAIK “Nauka/Interperiodica,” 2001.
 37. *Tektonosfera Tikhookeanskoi okrainy Azii* (The Tectonosphere of the Pacific Margin of Asia), Vladivostok: DVO RAN, 1992.
 38. Til'man, S.M. and Bogdanov, N.A., *Tektonicheskaya karta severo-vostoka Azii* (A Tectonic Map of Northeast Asia), Scale 1 : 1 500 000, Komitet po Geodezii i Kartografii MPR RF, 1992.
 39. Tuezov, I.K., *Geotermicheskaya struktura litosfery i astenosfery Aziatsko-Tikhookeanskoi zony sochleneniya i prilegayushchikh chastei Azii i Tikhogo okeana* (The Geothermal Structure of the Lithosphere and Asthenosphere in the Asia–Pacific Junction Zone and Adjacent Areas of Asia and the Pacific Ocean), Vladivostok: Dal'nauka, 1990.
 40. Tuezov, I.K., *Geoelektricheskiy razrez litosfery i astenosfery severo-vostochnoi Azii i prilegayushchikh chastei Tikhogo okeana* (A Geoelectric Section of the Lithosphere and Asthenosphere in Northeast Asia and Adjacent Areas of the Pacific), Vladivostok: Dal'nauka, 1994.
 41. Khomich, V.G. and Petrishchevsky, A.M., Protomagmatic Chambers of the Amur Area Gold-Bearing Systems, *Vulkanol. Seismol.*, 2004, no. 1, pp. 25–38.