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Structural-Density Model of the Earth's Crust within the Sakhalin Western Shelf and Its Geological Interpretation

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Abstract—Structural-density modeling of the Earth's crust carried out using a deep seismic sounding profile previously tested along the western shelf of Sakhalin Island offered a clearer view of the layered block structure of the main tectonic faults and their system within the crust of the region, which accumulate a large number of strong crustal earthquakes. The density structures of the resulting model were compared with geological data on the adjacent territory of Sakhalin Island. Our structural-density model made it possible to separate volcanic blocks and blocks of basified sialic crust and to trace the submarine prolongation of the largest geological complexes of the western margin of Sakhalin Island to the shelf. A spatial correlation between seismic events and some tectonic faults is observed.

Keywords: gravimetry, magnetometry, structural-density modeling, Earth's crust, western shelf of Sakhalin Island

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INTRODUCTION

Sakhalin Island is one of the geodynamically active structures in the Northwest Pacific Ocean–Eurasian continent transition zone. According to some researchers, the western Sakhalin margin marks the boundary between the Okhotsk and Amur lithospheric blocks [9, 22, 33], while the southern margin is affected by the subsiding Pacific Plate [34].

This caused significant geodynamic activity of island and adjacent submarine structures. Up to now, the formation and evolution of Sakhalin are hotly debatable and no consensus has been reached on its geological past.

Significant structural differences between eastern and western Sakhalin, as well as the tectonic features of its southern and northern parts are described in many studies by Russian geologists [6, 16, 20, 21, 23, 25].

At the same time, the deep structure of the island and its surroundings has been studied in less detail. Data on the deep structure are reported in some studies by Zlobin, Lomtev, Rodnikov, Tarakanov, Tikhonov, etc., and are mainly focused on the seismotectonics of Sakhalin and the Sea of Okhotsk region [8, 9, 15, 22, 24, 30]. The origin of the Tatar Trough adjacent to the western margin of Sakhalin also remains a matter of debate, while its petroleum potential was studied only within the sedimentary cover [7, 17, 18, 26].

The study of the deep structure of the western Sakhalin shelf provides insight into the formation and evolution of the Tatar Trough and the island. Seismic sections along deep seismic sounding (DSS) profiles obtained in 20th century [5] in the Tatar Strait were used to revise the previous studies.

Several marine expeditions have been carried out by the Il'ichev Pacific Oceanological Institute of the Far East Branch, Russian Academy of Sciences (POI FEB RAS) in 2017–2020. During these expeditions, a great number of gravimetric and magnetometric measurements were obtained and a representative collection of the bottom core was taken. The data were used to compile maps of the bottom topography, gravity, and magnetic fields. The results of the studies were reported in peer-reviewed publications [2, 3, 31, 32], including this journal in 2020.

In this study, the structure of the Earth's crust of the western Sakhalin shelf was studied using the above-mentioned expeditionary data to refine the deep structure and tectonics of the studied area, as well as to extrapolate the geological structures of West Sakhalin beneath the shelf waters. Further, it will facilitate interpretation of the formation and evolution of the Sakhalin Island–shelf–Tatar Strait Trough transition zone.

To this end, a new geophysical model of the crust was constructed based on a deep seismic sounding profile (DSS 18) recorded in 1960 [5]. The position of the profile, abbreviated MP18, is shown in Fig. 1. The

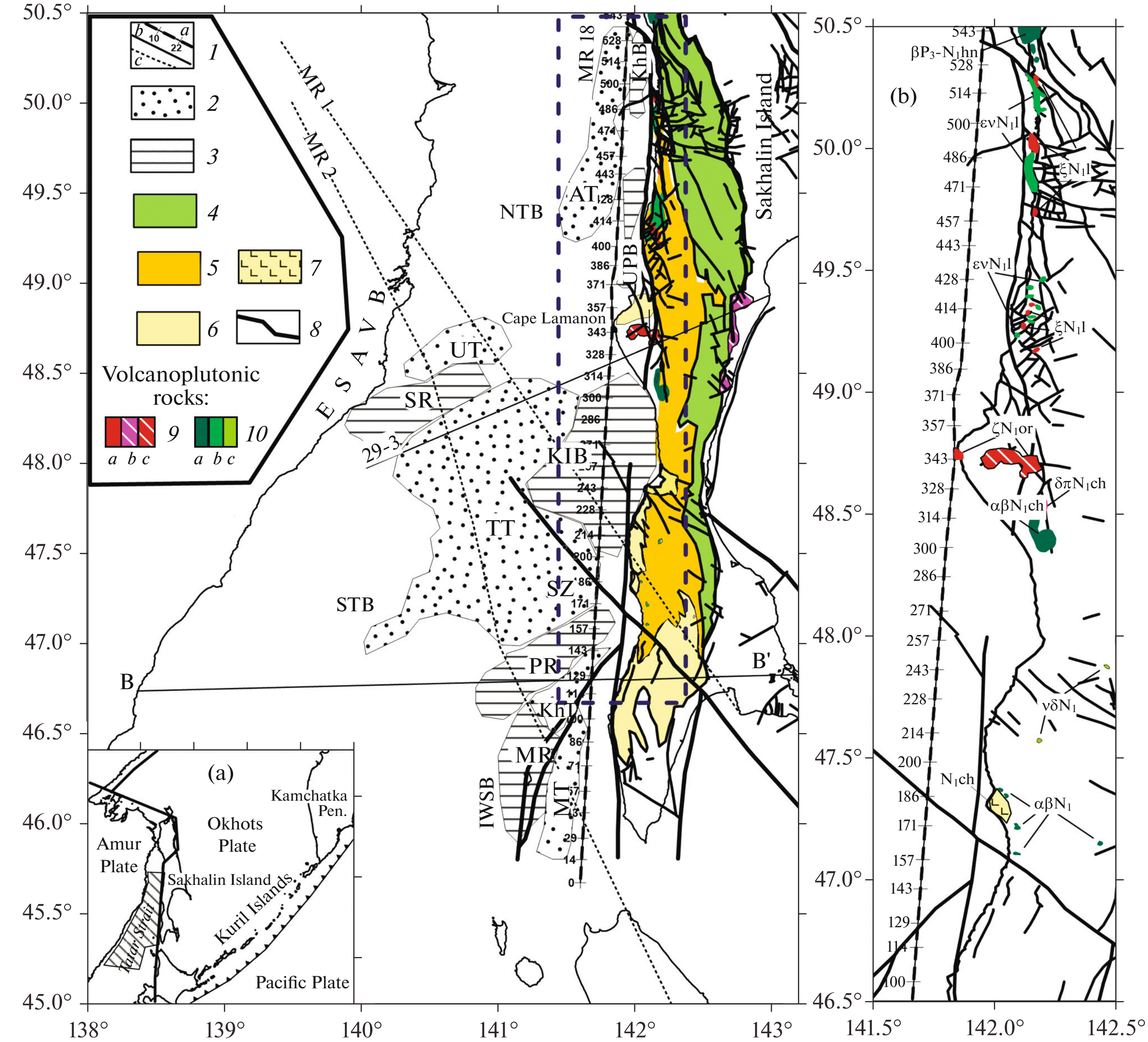

Fig. 1. Review map of studied area with a geological scheme of West Sakhalin: (*1*) profiles: (a) profile of structural-density modeling considered in this study; (b) DSS profiles, (c) profiles of previous structural-density modeling; (*2*) troughs; (*3*) rises; (*4*–*6*) volcanosedimentary complexes of West Sakhalin according to data [10, 11]: (*4*) Cretaceous; (*5*) Paleogene; (*6*) Neogene; (*7*) basalts of Chekhov Formation; (*8*) faults according to data [10, 11]; (*9*–*10*) Early Neogene volcanoplutonic complexes: (*9*) intermediate and felsic composition: (a) syenites of Lesogorsk Complex, (b) diorite porphyrites of Chekhov Complex; (c) dacites of Orlovsky Complex; (*10*) intermediate and mafic composition: (a) basalts and basaltic andesites, (b) subvolcanic rocks of hypabyssal syenite–essexite Lesogorsk Complex, (c) gabbro–diorite intrusions. Abbreviations: (ESAVB) Eastern Sikhote-Alin volcanic belt, (STB) South Tatar Basin, (NTB) North Tatar Basin, (IWSB) Isshikari–West Sakhalin Basin, (AT) Aleksandrovsk trough, (KhB) Khoindzha Block, (UPB) Uglegorsk–Pilva Block, (UT) Uspensky Trough, (SR) Sovgavan Rise, (TT) Terney trough, (KIB) Krasnogorsk–Ilinsky Block, (SZ) Slepikov zone, (PR) Pioneer Rise, (KhT) Kholmsky trough, (MR) Moneron Rise, (MT) Moneron trough [4]. Inset (a) shows: shading–position of studied area, black bold lines show boundary of lithospheric plates after [9]; inset (b) shows part of diagram bounded by blue dashed line.

profile intersects the main structures of the northwestern Sakhalin shelf in the Aleksandrovsk zone, as well as in the central part, including the Krasnogorsk–Ilinsky block and eastern flank of the Terney Trough, represented by the Slepikov zone. In the southwest, the profile passes through the underwater volcanic uplands of the Issikari-West Sakhalin basin.

This study can also shed light on the seismotectonics of the southwestern Sakhalin shelf, which accumulates the strongest crustal earthquakes with M ≥ 6: the

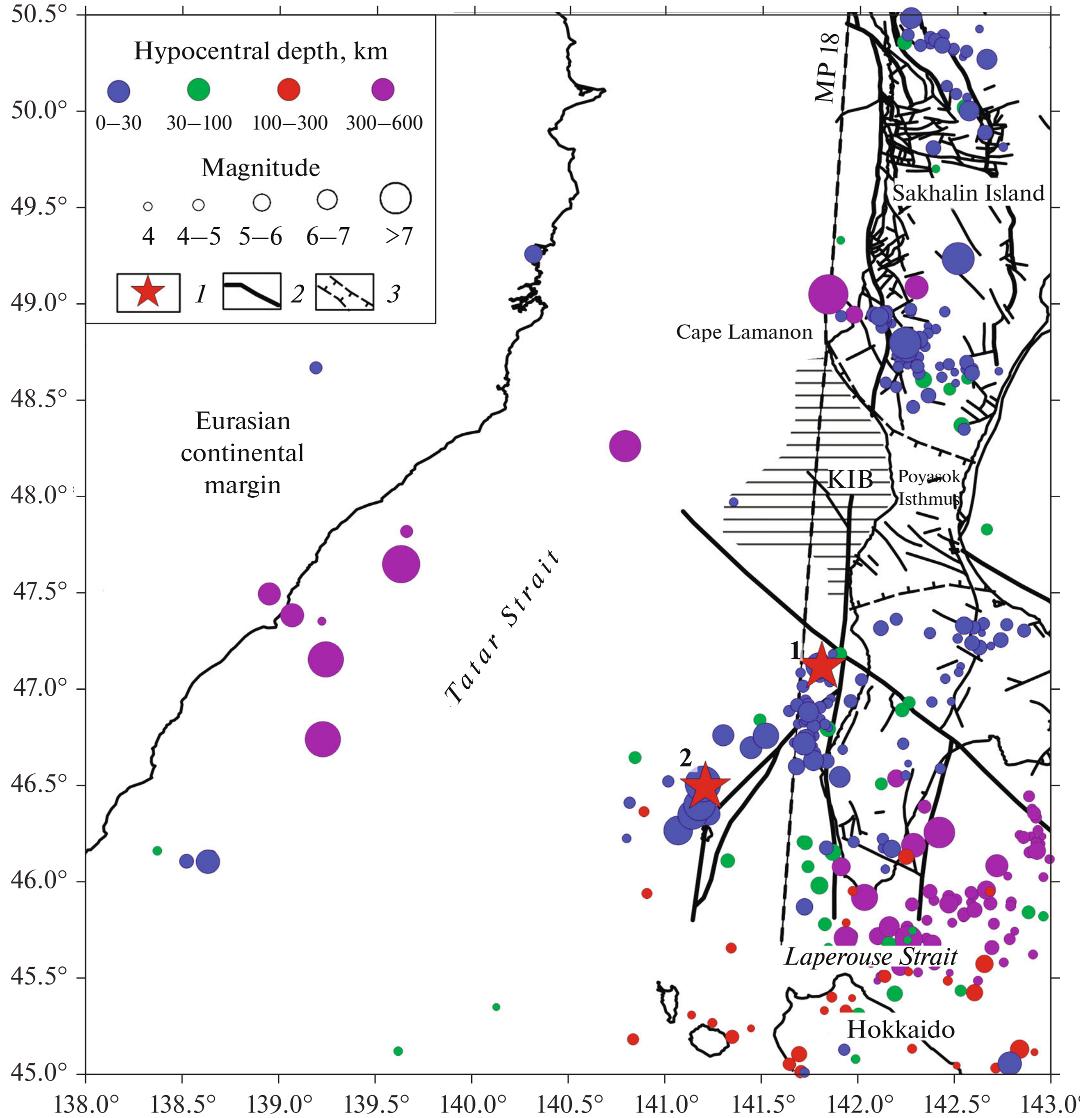

Fig. 2. Seismicity map of studied area from 1920 to 2020. Map shows earthquakes with magnitude M ≥ 4 [28]: (*1*) epicenters of strong crustal earthquakes, with nearby numerals showing (1) August 2, 2007 Nevelsk earthquake with M = 6.2; H = 5 km [7, 14]; (*2*) September 5, 1971 Moneron earthquake with M = 7.3; H = 18 km; (2) faults according to data [10, 11]; (*3*) boundary of area devoid of earthquakes with M ≥ 4. For KIB and dashed area around see note to Fig. 1.

August 2, 2007 Nevelsk earthquake [14], M = 6.2; H = 5 km, and the September 5, 1971 Moneron earthquake with M = 7.3; H = 18 km (Fig. 2).

RESEARCH METHODOLOGY

The study uses a standard approach to structural-density (gravity) 2D modeling of the crust. It is known that the modeling involves choosing the density (ρ, g/cm^3) and geometry of the model based on gravimetric data. To reduce the modeling variants and construct the model best fitting the observed setting, the gravity data are supplemented by all known geological and geophysical information. These are primarily the results of seismic studies, from which the velocity boundaries and values of seismic velocities were taken. In modeling, the velocity boundaries are used as unchangeable structural framework, while the velocities are recalculated into densities using the known velocity–density dependences. With these data, the model of the first (or zero) approximation was obtained. Then, the final structural-density model is run in several iterations within the indicated framework. This process is terminated when the difference between the calculated and observed fields reaches value less than threefold the error of the performed survey. The geological interpretation of the obtained structural-density model is based on combined geological and petrophysical data collected near the

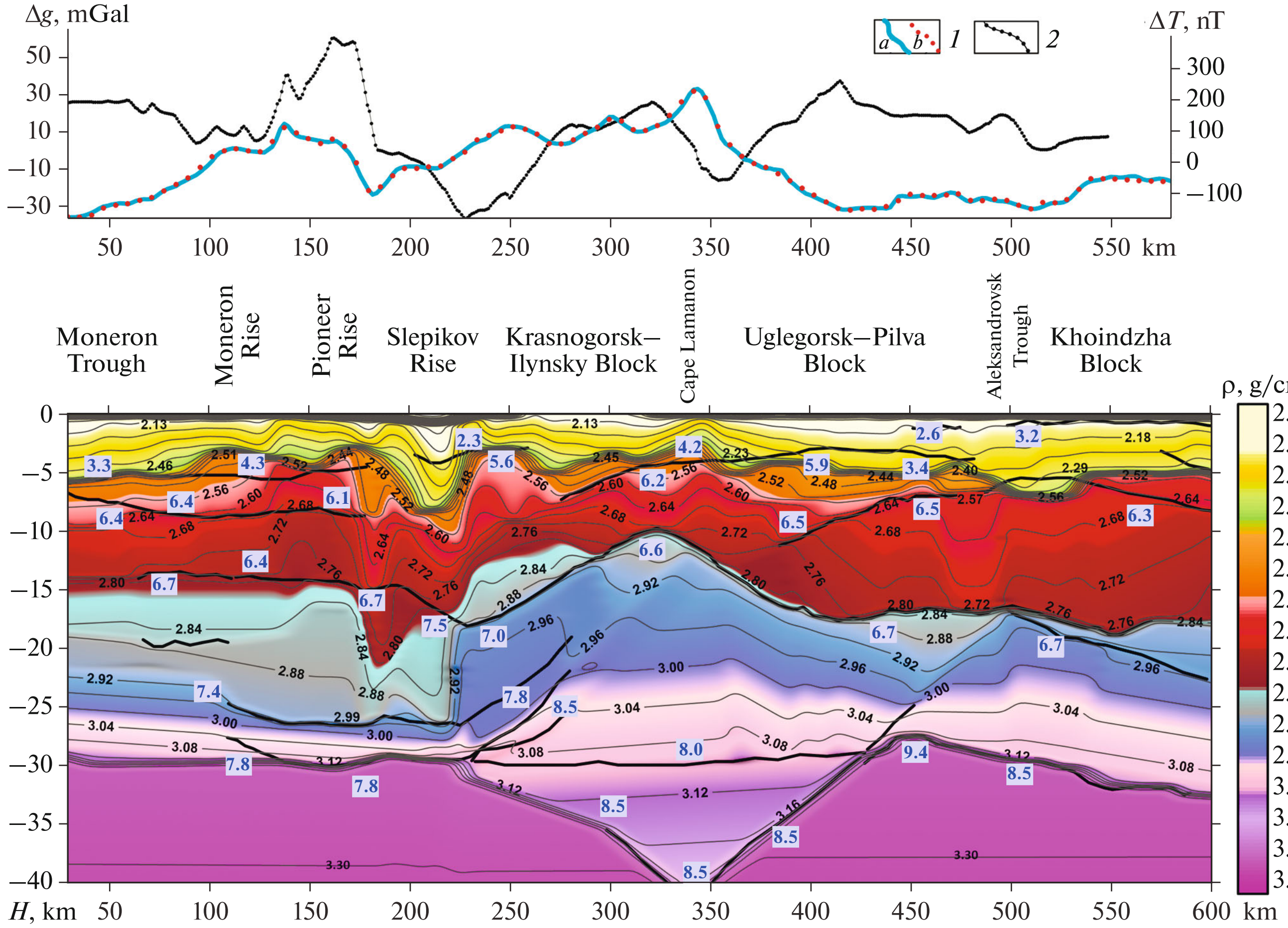

Fig. 3. Structural-density model of Earth's crust from western shelf of Sakhalin Island with density isolines (g/cm^3). Anomalous geophysical fields shown in top: (*1*) free air gravity field (Δ*g*): (a) observed, (b) calculated; (*2*) magnetic field (Δ*T*). Black bold lines show seismic boundaries taken from DSS 18, blue numerals near profile are values of *P*-wave velocities (km/s) [5].

model profile and density distribution in the obtained model.

Such an approach was implemented using software developed at the Laboratory of Gravimetry of POI FEB RAS [12]. The already mentioned DSS 18 profile was used as the reference framework [5]. The profile intersects the following main structures of the western Sakhalin shelf (from south to north): the Moneron Trough and eponymous rise, Pioneer Rise, Slepikov zone, Krasnogorsk–Ilinsky Block, and submarine structures of the Aleksandrovsk zone (Uglegorsk–Pilva Block, Aleksandrovsk Trough, and Khoindzha Block). The application of the seismic profile made it possible to reliably fix the main sources of regional gravity anomalies, the Moho discontinuity, as well as the inner seismic boundaries, which are of great importance for solving the problem of unambiguous structural-density modeling.

The bottom of the sedimentary layer was fixed using data taken from the State Geological Map of the Russian Federation [11] and controlled using the DSS 29-3 [5] and B-B` [4] profiles, as well as two model profiles MP 1 and MP 2 (Fig. 1), which were described in this journal in 2023.

The use of seismic boundaries and their boundary velocities from the DSS 18 profile [5] allowed us to calculate the structural-density model in the first approximation. During modeling, we followed the principle of stability of boundaries distinguished with confidence in the seismic profile [1] and bottom topography. The best fit between calculated gravity and observed data was reached by choosing the density using the regional velocity–density dependence [29] as well as by the extrapolation of seismic boundaries. Several iterations were performed to obtain the structural-density model, gravitational effect of which coincided satisfactorily with observed field (Fig. 3).

The structural geological scheme (Fig. 4) was compiled following the standard models of the Earth's crust [1]. According to classification [1], continental crust consists of sedimentary (2.0–2.45 g/cm^3), volcanosedimentary (2.2–2.45 g/cm^3), "granite" (2.55–2.7 g/cm^3), and "basalt" (2.85–3.2 г/cm^3) layers. An increase or

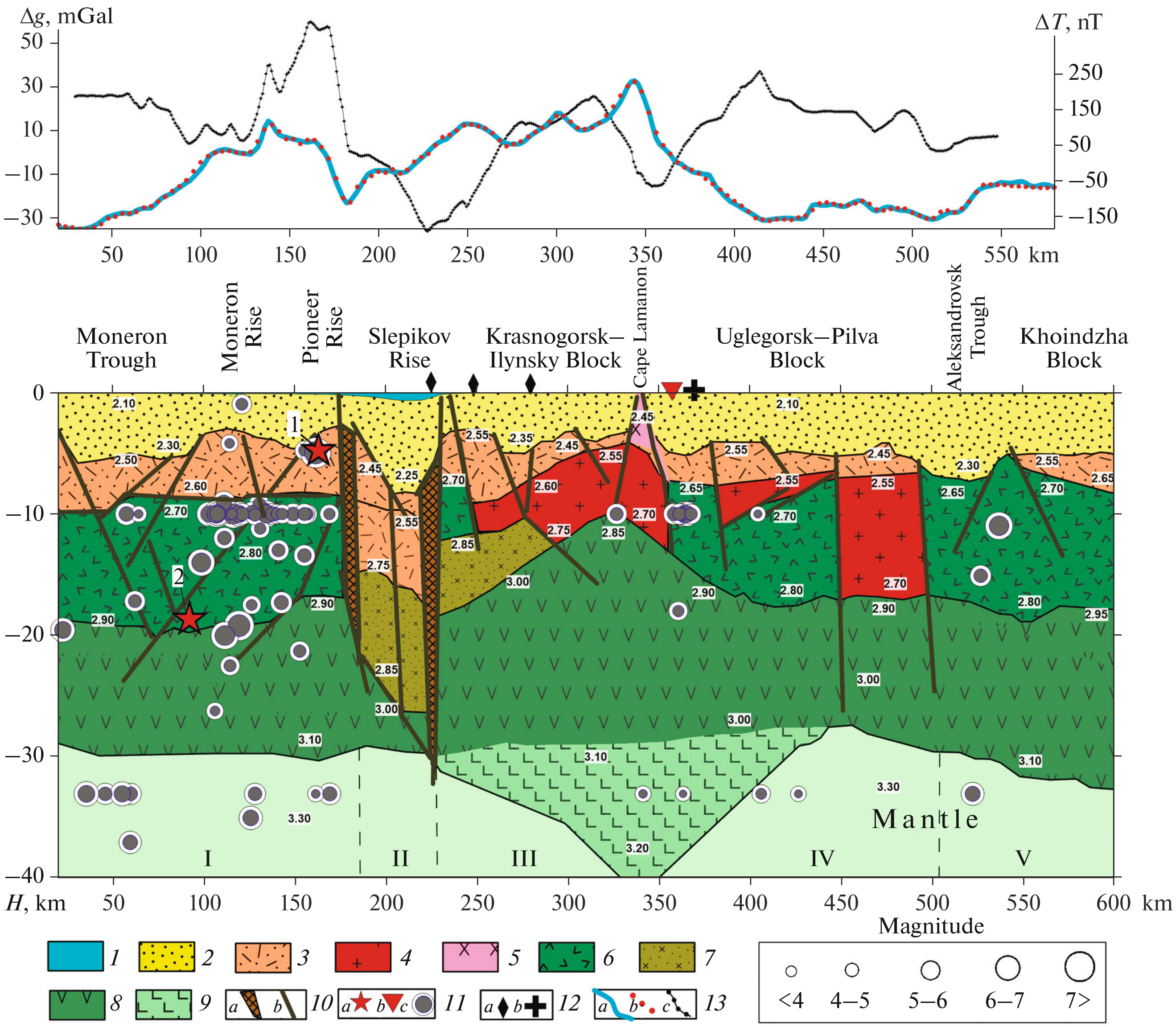

Fig. 4. Structural-geological scheme of Earth's crust of western Sakhalin shelf according to modeling data: (1) water layer; (2) sedimentary layer; (3) volcanosedimentary layer; (4) "granite-metamorphic complex", (5) subvolcanic bodies of Orlovsky complex [11]; (*6*) volcanogenic basement; (*7*) blocks of basified sialic crust; (*8*) lower crust, "basalt layer"; (*9*) dense lower crust; (*10*) faults: (a) Fault-related deconsolidated zones, (b) inferred at block boundaries; (*11*) projections of earthquake hypocenters on model profile [28]: (a) strong crustal (for nearby numerals, see Fig. 2), (b) deep-focus; (c) removed from model profile for a distance up to 25 km with $M \geq 3$, circle size is proportional to magnitude; (*12*) projections of gas anomaly seeps in model profile: (a) in sediment and water column in area of Krasnogrosk–Ilinsky block [2, 19, 27, 31, 32], (b) in area of Izyl'met'evsky deposit [4, 17]; (*13*) plots of anomalous geophysical fields: (a) free air Δg, (b) calculated Δg, (c) magnetic field, ΔT. Roman numerals denote areas of western Sakhalin shelf.

decrease in density within the layers is related to rifting, which leads, on the one hand, to basification, and, on the other hand, to breakup of the crust with the formation of deconsolidated zones. It should be emphasized that the use of term "granite" layer implies that it consists mainly of sialic rocks, while the "basalt" layer is dominated by mafic rocks.

In the model, the fault zones were determined by two ways: at sites where narrow vertical deconsolidated zones must be introduced in modeling to fit the observed and calculated fields, and where horizontal layering of the medium was disturbed in the structural-density model. It should also be noted that the density distribution within the block (modeled body) is determined by three points and varies within the block according to a linear law.

The geological interpretation of structural-density model and compilation of the structural-geological scheme were done using information from geological map sheets M-54 [11], L-(54)(55), and K-(55) [10] on a scale of 1 : 1000000, which are partially shown in Fig. 1, as well as in marine magnetometric data obtained on 2017–2020 expeditions [2, 3].

RESULTS AND DISCUSSION

The deep structure of the western Sakhalin shelf remains poorly studied, and only some works [5, 8, 9, 15, 18, 20–25] indirectly suggest the nature of certain peculiarities of its geological structure and relationship with the general geodynamic mode of the studied area. However, knowledge of the deep structure of this transition zone could provide insight into the formation and evolution of the Tatar Trough and surrounding land.

Using the performed structural-density modeling, the layered–block structure of the Earth's crust was recognized in more detail compared to that previously obtained from seismic data on the studied profile (Fig. 3). In addition to the layering of the medium with gently changing characteristics, we distinguished blocks of density heterogeneities, which, in our opinion, are bounded by tectonic faults.

As seen in Fig. 3, the main gravity boundary, which shows the most contribution to the distribution of the anomalous gravity field, is the roof of the lower crust distinguished in the seismic section based on the P-wave velocities of 6.6–6.7 km/s, which corresponds to the density of 2.84–2.85 g/cm^3 in the gravity model.

Thus, this area demonstrates the best fit between seismic and density boundaries, except for the area within 170–300 km in the gradient zone, which shows drastic changes in P-wave velocities. Within the interval of 170–230 km, this boundary plunges from 15 to 20 km, while the velocity increases from 6.7 to 7.5 km/s. Further, within an interval of 230–300 km, all seismic boundaries in the lower crust sharply ascend from 30 to 20 km, with wedging of a section having a velocity of 8.5 km/s. As well, at 240 km, the velocity decreases up to 7.0 km/s. Modeling within an interval of 170–300 km revealed a significant disagreement between calculated and observed gravity field at direct recalculation of velocity characteristics into density parameters. This caused a significant change of density boundary geometry in the roof part of the basaltic layer.

In the obtained structural-density model, the density values change from 2.1 to 3.2 g/cm^3. The upper part of the presented section is most persistent in density varying from 2.1 to 2.45 g/cm^3. The isoline pattern is gentle, without sharp jumps and differences and the elastic wave velocities within 2.3–3.4 km/s. A significant disturbance in horizontal layering is observed within 170–230 km in the area of the Slepikov zone, where the choice of densities revealed mismatches between the velocity boundaries described above. Modeling revealed narrow vertical deconsolidated zones bounding the structure from the north and south. On both sides of the vertical deconsolidated zones, dense masses (2.7–2.8 g/cm^3) are observed in the upper part of the section. At 230 km, a clear vertical boundary is observed in the basaltic layer, to the north of the roof part of this layer becomes much denser, but boundary values remain within 2.85–3.1 g/cm^3 and velocity changes from 6.7 to 8.5 km/s.

The middle part of the model is the most incised and inconstant in density, which varies there from 2.45 to 2.8 g/cm^3. Two seismic boundaries with a drastic change in velocity from 4.3 to 6.5 km/s are observed in the velocity section. The middle part of the section likely represents a consolidated part of the upper crust, which consists of a lithified volcanosedimentary layer with densities of 2.45–2.6 g/cm^3, and a differentiated crystalline basement with density characteristics varying depending on rock composition. According to reference data of N.B. Dortman, the density of 2.55–2.7 g/cm^3 is typical of blocks with more felsic rocks; with increasing basicity, the density increases up to 2.65–2.9 g/cm^3.

The structural-density model (Fig. 3) was used to obtain the structural-geological scheme of the western Sakhalin shelf (Fig. 4), the basement of which consists of domains with different density characteristics separated by tectonic boundaries.

The southern and northern parts (I, V) of the obtained section are similar in the structure of basement of supposedly volcanogenic origin with a density of 2.7(2.65)–2.9(2.8) g/cm^3. The southern part (I) is represented by the Pioneer and Moneron volcanic rises in the Isshikari–West Sakhalin Basin [4], which are separated by troughs filled with sedimentary deposits. This part of the western shelf has the most steady basement composition, but many of modeled faults and fault-related earthquakes indicate active geodynamic processes in the Earth crust of this area, which is presumably genetically related to the Sakhalin–Hokkaido system of volcanic rises. In addition, this part of the profile is characterized by the elevated values of magnetic field (Fig. 3), which supports the existence of rocks of elevated basicity in the crust composing the volcanic structures.

The majority of the structure in the southwestern part of the Sakhalin shelf was likely formed under the influence of rifting in the South Tatar Basin, which was accompanied by intense volcanic activity and reworking of sialic crust up to the early Neogene. This conclusion could be indirectly supported by the wide development of Early Neogene volcanosedimentary complexes (Kholmsky, Nevelsk, and Chekhov formations) in the southwestern part of Sakhalin. These complexes are intruded by small mafic extrusions of the same age. In this area, modeling confirms faults shown in the geological map (Fig. 1), one of which extends from the Pioneer Rise to the Moneron Rise, while other operates as the main axis of the West Sakhalin fault, which [23] serves as the boundary between the Amur and Okhotsk lithospheric plates. Both tectonic zones accumulate numerous crustal earthquakes (Fig. 2), the number of which increases in the area of their intersection. As seen in Fig. 4, earthquakes localized along the upper boundary of volcanogenic basement with hypocenter depth of 10 km are confined to the NS-trending West Sakhalin fault zone. Other seismically active zone is observed along fault subsiding from the Pioneer Rise to the Moneron Rise. This zone concentrates mainly crustal earthquakes with hypocentral depths from 5 to 20 km, including two strong events with M > 6 (Moneron and Nevelsk) (Fig. 2, 4).

Judging from the elevated densities (2.65–2.8 g/cm^3), the basement of the northern area (V) represented by the Aleksandrovsk Trough and Khoindzha Block is made up of mafic volcanic rocks, but its thickness is slightly greater than that of the southern area. The thickness of the volcanosedimentary layer decreases toward the Aleksandrovsk Trough, where modeling revealed its absence, which is confirmed by geological data (Fig. 1).

The volcanic nature of the southern and northern areas of the western Sakhalin shelf is indirectly confirmed by data from geological maps (Fig. 1) [10, 11], where the Early Neogene volcanosedimentary complexes (Chekhov, Kholmsky, and Nevelsk formations) are widespread within southwestern Sakhalin and are intruded by subvolcanic basalts, basaltic andesites, and andesites of the same age. In the northwestern part, in the area of inferred faults at 500 and 550 km marks, the exposures of Late Paleogene–Early Neogene basalts and Early Neogene essexites are observed in the geological map (Fig. 1). The latter crosscut Upper Cretaceous volcanogenic complexes of the Krasnoyarkovskaya Formation, which are widespread near the coastline within an interval of 500–530 km. The absence of young volcanogenic complexes within the northern part of western Sakhalin, in contrast to its southern part (Fig. 1), can indicate the attenuation of volcanic processes related to rifting in the South Tatar Basin.

The central part of the section comprises two areas (III and IV), where modeling revealed the fragments of sialic crust: Krasnogorsk–Ilinsky (III) and Uglegorsk–Pilva (IV) (Fig. 4). The Uglegorsk–Pilva Block (IV) has a heterogeneous basement, which likely consists of blocks of volcanogenic and "granite-metamorphic" nature. Based on modeling results, a thick basement block with density varying from 2.55 to 2.7 g/cm^3 was established within 450–500 km. According to geological data (Fig. 1) [11], the Early Neogene intrusive syenites of the Lesogorsk Complex are confined to fault zones bounding this block on island, which also support the presence of intermediate and felsic rocks in the basement.

Based on modeling data, moving along the profile from north to south, the "granite–metamorphic" complex is inferred in the upper part of the Uglegorsk–Pilva Block basement, while its foot is made up of a layer of denser rocks (2.7–2.8 g/cm^3) likely of volcanogenic nature. At the adjacent part of the island (Fig. 1) [11], intrusive and hypabyssal syenite–essexite bodies of the Early Neogene Lesogorsk Complex are noted on the profile transect within an interval of 400–430 km. A basement block of volcanogenic nature is inferred within an interval of 350–370 km. On island, this area is marked by volcanic rocks of both the Chekhov Formation and separate small mafic extrusions of the Orlovsky complex dated at the Late Neogene [11].

The thickness of the Earth's crust within the above-described areas (I, II, IV, V) is 30–32 km. The deep structure of the Krasnogorsk–Ilinsky Block (III) is dramatically different. The thickness of the Earth's crust in its central part increases up to 40 km due to the increase of thickness of its lower part represented by a "basalt" layer (2.9–3.1 g/cm^3), which is underlain by the high-density wedge-shaped salient in the mantle (3.12–3.2 g/cm^3). The entire central part of the block, judging from densities of 2.55–2.7 g/cm^3, consists mainly of "granite–metamorphic" basement. To the south, the basement becomes denser, reaching a maximum thickness of 2.7–2.8 g/cm^3 in the block in the contact with the Slepikov zone, representing the eastern part of the rift. The presence of the "granite–metamorphic" complex is confirmed by geological survey data on the island (Fig. 1) [11], where Early Neogene subvolcanic, mainly intermediate and felsic rocks of the Orlovsky Complex outcrop near the 350 km profile mark. One of them is confirmed by modeling results. Small subvolcanic diorite porphyrite bodies of the Early Neogene Chekhov Complex are mapped within the Krasnogorsk–Ilinsky Block (Fig. 1) [11]. This also confirms the presence of intermediate rocks at the base of the block. The consolidation of basement at the southern boundary of the Krasnogorsk–Ilinsky Block was likely facilitated by basification with replacement of granitic rocks by a substrate with a more mafic composition, which penetrated a thick NE-trending fault zone along which the central part of the Tatar Trough formed. This assumption is indirectly confirmed by the presence of Early Neoegene gabbrodiorite intrusion on the island, near the southern boundary of the block (Fig. 1).

In our opinion, the continental block of the Krasnogorsk–Ilinsky Rise served as a peculiar "barrier," northward of which active rifting from the central part of the Terney Trough did not spread. The lowered magnetic field anomalies above the Krasnogorsk–Ilinsky Block confirm the absence of a magnetically active layer in the upper part of the structure.

The Slepikov zone (II) adjacent to the eastern flank of the Terney trough, which is formed by rifting processes [4], was distinguished as separate area. The presence of layer with density of 2.50–2.7 g/cm^3 in the basement presumably is not related to the granite massifs, the presence of which within indicated structure was not confirmed. The "granite" density is presumably caused by a thick layer of volcanosedimentary deposits dominated by felsic volcanic rocks. A layer of basified continental crust with a density of 2.8–2.9 g/cm^3 supposedly lies in the lower part of the Slepikov zone. A similar structure was found previously in the northeastern part of the Terney Trough on the density section along the MP1 profile (Fig. 1) published by us in issue no. 2 of this journal in 2023. As mentioned above, the blocks of the Krasnogorsk–Ilinsky Rise likely served as a peculiar barrier beyond which active rifting did not spread from the central part of the Terney Trough, but basification spanned the basement of the northern and eastern flanks of the rift and adjacent structures.

Thus, our study revealed a change of magmatic complexes from south to north in the basement of the western Sakhalin shelf, which is observed in the coastal magmatic complexes. This is confirmed by geochemical studies, which revealed the difference in major and trace-element compositions between Middle and Late Cenozoic volcanic rocks from the western coast of Sakhalin, where the Chekhov and Lesogorsk zones derived from different magmatic sources were distinguished [20]. Studies [20] showed that the Chekhov zone, confined to volcanic structures of the Isshikari–West Sakhalin Basin, was formed on a heterogeneous protolith, which includes Cretaceous island-arc volcanic complexes. In the Lesogorsk zone, locally attributed to the structures of the Uglegorsk–Pilva Block, the island-arc volcanic complexes are absent, while the initiation of the block was related to the Cretaceous West Sakhalin turbidite trough [20].

A change of tectonic faults direction on Sakhalin Island, to the south of Poyasok Isthmus, from sublongitudinal to northwestern (Fig. 1) can indicate the influence of mechanisms of different strain types within submarine shelf, which is represented by both the extension structure (rift of the Terney trough) and compressional structure within the northern boundary of the Krasnogorsk–Ilinsky Block. This is confirmed by calculated data [23].

It should be noted that westward, on the latitude of the Krasnogorsk–Ilinsky Block, the directions of coastal changes from northeastern in the south of Sikhote-Alin to submeridional in the north (Fig. 1). This may indicate that at the final rifting stage, the formation of the southern Tatar Trough was more active and had a more serious effect on continental margin structures compared to the North Tatar Basin.

The presence of deep-seated conduits at the boundary of the Krasnogorsk–Ilinsky Block, as well as fragments of sialic crust in its basement, likely provided favorable conditions for petroleum formation in the structures adjacent to the Krasnogorsk–Ilinsky Block [13], which is confirmed by high methane concentrations in water and bottom ground samples along its periphery, as well as by the presence of gas flares and gas hydrate seeps [2, 19, 27, 31, 32]. The confirmed Izyl'met'evskoe gas field is located north of the described block.

The Krasnogorsk–Ilinsky Block and Poyasok Isthmus, which is adjacent to eastern Sakhalin, is characterized by the absence of strong earthquakes (Fig. 2). According to electronic catalog [28] and study [30], no earthquakes with $M > 4$ were revealed in this area for 100 years. However, the authors of [30] do not exclude intense geodynamic activity in this area.

The absence of strong seismic events in the Krasnogorsk–Ilinsky Block, as well as island land joining from east, could indicate the stability of this block and strain accumulation (elevated parameter of metastability after [30]) in this area. The presence of numerous shallow faults inferred by modeling does not exclude the future release of accumulated strain by their activation, which could lead to a series of weak crustal earthquakes and to rapid release through a powerful seismic event.

A similar pattern was observed in the frontal slope of the Central Kurils, where seismic quiescence up to 2006 was interrupted by two powerful crustal earthquakes with magnitudes over 8. The superimposed rifting process on the frontal slope of the Central Kurile split the basement of the Vityaz submarine ridge, which represented the outer arc of the Kuril–Kamchatka island arc system, into separate blocks. This resulted in the the long-term accumulation of seismic energy within the block structure and ultimately the catastrophic events of 2006–2007. The results of these studies have been published in numerous papers, including this journal, in 2007 and 2012. It is highly probable that the absence of strong earthquakes in the Krasnogorsk–Ilinsky Rise and adjacent island land was related to the revealed features of deep structure of this block, which was influenced by rifting that formed the deep-water portion of the Tatar Trough, as well as by collisional interaction [9] between the Amur and Okhotsk lithospheric blocks. The broken up basement and folded structure within this block could provoke seismic activity at a shallow depth in the Poyasok isthmus area owing to the long-term accumulation of energy in the system.

CONCLUSIONS

The main aim of this study was to refine the deep structure of the Earth's crust of the western Sakhalin shelf and to geologically interpret the obtained information. The structural-density modeling allowed us to reveal new features related to different tectonomagmatic stages that formed the western Sakhalin margin and the adjacent Tatar Trough. The following conclusions were drawn from our study:

—Based on modeling, five fault-bounded areas (I, II, III, IV, V) made up of different rocks were distinguished in the basement of main structures of the western Sakhalin shelf. The revealed features of the deep structure of the shelf spread into coastal structures of the western part of the island, which is confirmed by geological data.

—The basement of areas distinguished in the south contains volcanic blocks (area I) and blocks of basified sialic crust (area II), which are related to the Early Paleogene–Early Neogene rifting in the South Tatar Basin.

—It is suggested that the northern part of the profile is underlain by a basement of volcanic nature, which formed prior to the onset of active rifting in the South Tatar Basin (area V).

—The central part is represented by areas (III, IV), the basement of which is inferred to consist of sialic rock. It was concluded that at the late rifting stages in the South Tatar Basin, volcanic processes that formed the southwestern Sakhalin shelf attenuated in the northern direction. Also, the Krasnogorsk–Ilinsky Block served as a peculiar barrier that hampered active rifting and basification of the Earth's crust in the central part of the western Sakhalin shelf.

—Seismically active zones are confined to faults inferred from modeling and confirmed by geological data, including the southwestern Sakhalin shelf. The presence of tectonically active NS- and NE-trending fault zones in this part of the shelf and associated seismicity agree well with the modeling results. Earthquakes whose hypocenters are confined to the upper boundary of the basement of volcanic rises on the southwestern Sakhalin shelf are confined to the NS-trending West Sakhalin fault. There is also another earthquake zone, the hypocenters of which plunge along the fault from the Pioneer Rise to the Moneron Rise with depths from 5 to 20 km and which includes two powerful earthquakes: August 2, 2007 Nevelsk ($M = 6.2$; $H = 5$ km) [14] and September 5, 1971 Moneron earthquakes ($M = 7.3$; $H = 18$ km).

—The Krasnogorsk–Ilinsky Block and island land joining from the east and represented by the narrowest Sakhalin site—Poyasok Isthmus are devoid of strong earthquakes ($M \geq 4$). Given the results of our studies and previously published data [23, 30], we can suggest that this area is in a state of strain accumulation, which can be released by seismic activation. In our opinion, this area requires more detailed study.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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