Structure, Rheology, Petrology, and Geodynamics of the Tectonosphere of the Sea of Japan

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Abstract—The geological-structural, magmatic, seismic, and thermometric models of the Earth’s crust and upper mantle of the Sea of Japan region are considered in relation to three-dimensional rheological gravity models reflected in horizontal and vertical sections of density contrast of the tectonosphere. In the crust and the upper mantle, formal manifestations of a right-lateral strike-slip duplex were found, in association with rift-related extension zones and central vortex structures. In the central regions of the Sea of Japan, a mushroomlike low-viscosity zone of typical of plumes is mapped in the depth interval of 60–200 km. The gravity models show signs of Late Cretaceous subduction of the Pacific Plate under the continental margin and Eocene–Oligocene subduction of this plate under the Japanese island arc. The Pacific lithosphere is split into crustal and lower lithospheric plates. The depth and thickness of rigid crustal and lithospheric plates have been estimated, faults of which are observed in rift-related extension zones. Petrochemical analysis of volcanic rocks dredged from the floor of the Sea of Japan confirms the existence of two extension stages, accompanied by volcanism of an initially postsubduction (ACMB), then spreading (N-MORB) and postspreading plume (OIB) nature.

Keywords: Sea of Japan, gravity models, crust, upper mantle, rifting, plume, geochemistry of volcanics, geodynamics

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INTRODUCTION

The Sea of Japan region is located in a continent–ocean transition zone and is characterized by a complex geological structure. In addition to a directional change in the structural and material characteristics of the crust from continent to ocean, processes also occurred associated with the subduction of the Pacific Plate under the continental margin [8, 41, 42, 69], horizontal displacements of tectonic blocks on the transform margin of Asia [30, 48], rifting [9, 26, 57], and magmatic injections of different nature (continental, island arc, subduction and rift-related, plume). Some researchers suggest the primary oceanic origin of the crust in the Sea of Japan [3, 36]. Others associate its formation with tectonic-magmatic mantle processes, including asthenospheric and lower mantle plume nature [14, 26, 27, 30, 33].

There is also the competing hypothesis [64] that the Japanese Islands are a common island arc (orogenic belt) that formed in connection with subduction of the Pacific Plate, and the Sea of Japan is considered a back-arc basin.

Recently, the origin of the Sea of Japan and other marginal seas in the Western Pacific has been considered by many researchers from the standpoint of the “vortex” hypothesis [7, 22, 32, 68]. In this case, macroscale torsion fields are considered to be the source of vortex motions. According to L.A. Izosov et al. [17–19, 49], the Sea of Japan tectonosphere is a vortex structure that formed as a result of the lateral interaction of the Eurasian and Pacific lithospheric plates moving relative to each other [59, 60, 65].

There is also the hypothesis [62] that the tectonosphere of Asian eastern marginal seas has a predominantly plume origin and formed during migration of the hot mantle field along the continental margin. In this case, hot mantle fields could have resulted in giant magma chambers in the plume heads, which would have facilitated the horizontal movement of tectonic masses in the space above the plume. The result of such displacements could be stretching of the lithosphere and the formation of rifts [40] and vortex structures [19, 49].

The diversity of hypotheses on the origin of the Sea of Japan, the complexity of the geological structure,
and the absence of volumetric models of the Sea of Japan tectonosphere necessitates novel research methods, one of which is statistical modeling of the rheological properties of the crust and upper mantle based on density contrast anomalies [33–37].

The aim of the article is to tie a three-dimensional density heterogeneity model of the Sea of Japan tectonosphere to the tectonic structures, petrology, and geochemistry of volcanic rocks in the upper layer of the crust; heat flow and modern geodynamics; and the results of interpreting satellite images and geophysical anomalies.

**GEOLOGICAL–GEOPHYSICAL OVERVIEW**

The Sea of Japan basin is located in the zone of interaction between lithospheric Pacific Plate and second-order Amur Plate, which is part of the first-order Eurasian Plate [8]. The islands of the Japanese archipelago separate the basin of the Sea of Japan from the Pacific Ocean. The Sea of Okhotsk is adjacent to the Sea of Japan from the north and the Philippine Plate from the south. Based on the identity of the Jurassic and Lower Cretaceous accretionary complexes of the Japanese Islands (the Mino, Tamba, Ashio, Chichibu, and Shimanto belts) and Sikhote-Alin (Samarka and Tauha terranes) [30], as well as the similarity of metamorphic complexes in the Pre-Paleozoic basement of the Hida (Honshu) and Hangkai (Primorye) massifs [15, 16], it is generally accepted that the Japanese Islands are fragments separated from the Amur Plate as a result of the Eocene–Miocene extension and shear processes on its transform margin [8, 9, 26, 30]. According to other ideas [16], outcrops of the Precambrian complexes on Honshu and the Yamato Rise (Fig. 1) are displaced fragments of the Yangtze para-platform or the North China Craton.

It is believed that the opening of the Sea of Japan was caused by movements along two right-lateral strike-slip systems [57]. According to this mechanism, the marginal seas of the Eastern Pacific are sometimes equated with syn-strike-slip basins [47].

The most complex is the structure of the tectonosphere of the eastern Sea of Japan region, where two oppositely directed subduction zones [42] are distin-
anomalies for each layer were swept out onto the surface at depths of 10–105 km for the upper layers, 105–250, and 155–300 km. The sources of gravity anomalies were plotted, from which were calculated the depths of the centers of mass. Below there is an intermediate (granite-metamorphic) layer 2.0–2.5 km thick with velocities of 4.8–5.6 km/s. Below it lies a lower crustal mafic (basalt) layer (8–10 km) with velocities of 6.4–6.7 km/s. The question of the nature of the crust in the Sea of Japan remains unclear. Some researchers believe that in the Yamato and Tsushima basins the crust has a reduced continental nature, and in the east of the Central Basin, a newly formed oceanic nature [21]. R.G. Kulinich and M.I. Valitov [25] proposed a model of variable material composition of the crust, in which the type of crust changes in accordance with its thickness. In this model, the oceanic crust is located under the Central Deep-Sea Basin, and the reduced and deformed continental crust is located under the Yamato Rise and in the coastal continental margins of the Sea of Japan.

The thickness of the crust near the surface of the Moho varies from 7.8 to 8.2 km/s. The depth of the base of the crust varies from 12–17 km in deep-water basins to 20–24 km beneath seamounts [25].

The thickness of the lithosphere of the Sea of Japan, in the global thermophysical model [23] varies from 100 km at the continental margin to 50 km in the central Sea of Japan. In eastern parts of the region, the thickness of the lithosphere increases to 150 km, probably due to the inclined position (subduction) of the Pacific Plate.

MATERIALS AND METHODS

As a basis for model constructions, we used the global catalog of gravimetric data [61], which contains a digital dataset of Bouguer anomalies of a 0.42° × 0.42° grid in the Sea of Japan and adjacent continental regions.

On latitudinal profiles crossing the gravity map by 1°, with a step of 5 km, graphs of Bouguer anomalies were plotted, from which were calculated the depths of sources of quasi-symmetric anomalies and density contrast ($\mu_z$-parameter) in segments between centers of density inhomogeneities and surfaces of equivalent spheres, onto which anomalous masses of these sources were swept out, after Poincaré [53]. The crust and upper mantle were subdivided into 12 layers in the following depth intervals: 11–20, 16–25, 21–30, 26–35, 31–40, 36–50, 42–60, 52–70, 62–80, 82–120, 105–250, and 155–300 km. The sources of gravity anomalies for each layer were swept out onto the surface of equivalent spheres tangent to the surfaces of the layers at depths of, respectively: 10, 15, 20, 25, 30, 35, 40, 50, 60, 80, 100, and 150 km, according to the algorithm

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

where: $Z_0$ is the apparent depth of the center of mass, uniquely determined at a random intersection of the field of the source of the gravitational anomaly. $V_{zm}$ is the amplitude of the local symmetric gravitational disturbance, $Hc$ is the depth of the surface to which the masses of the sources are swept out, and $K$ is the gravitational constant. The following condition was met: $Hc < Z_0$.

As a result of calculations, a digital 3D model $\mu_z(x, y, Hc)$ was formed, which was the initial material for plotting density contrast distributions in horizontal and vertical sections of the tectonosphere.

This procedure is inherently statistical, since the elementary sources of gravity anomalies were not directly associated with specific geological bodies or structures. It is similar to the procedure for localizing sources with the Euler deconvolution and the Troshkov method [37], using the ratios of the derivatives of the gravitational potential. However, measuring the amplitudes of gravitational disturbances expands the capabilities of these methods and makes it possible to investigate the material properties—rheology—of the modeled media [33].

The experience of [33–36, 38] shows that the density contrast of geological media described by the $\mu_z$-parameter is an indicator of their rheological state. High and elevated $\mu_z$-parameter values correspond to ancient rigid metamorphic blocks of cratons and cratonic terranes; low values correspond to crush and fracture zones, accretionary prisms, and turbidite terranes, as well as zones of fluid-hydrothermal development in faults and the apical parts of central structures of different ranks. In the upper mantle, high $\mu_z$-parameter values correspond to the lower hard layer of the lithosphere, while low values are recorded in the asthenosphere. In the sections of the tectonosphere, low $\mu_z$-parameter values ubiquitously coincide with low seismic wave velocity and resistivity zones [34–36]. The coincidence of density contrast minima with the heat flow and temperature maxima in many cases suggests the existence of viscous or molten magmas in the crust–mantle transition layer and the asthenosphere.

The described technique was used to construct a model of spatial density contrast distributions $\mu_z(x, y, Hc)$, reflecting the rheological state of the geological setting and represented as horizontal slices and vertical sections. As will be shown below, this model is indirectly related to structural-material inhomogeneities of the tectonosphere, reflecting the deep structure of the crust and upper mantle of the Sea of Japan region.
As additional data correlated with gravity models, we used materials on the radioisotope age, petrology, and geochemistry of volcanic rocks dredged from the floor of the Sea of Japan [2, 12, 13, 27], heat flow [5, 10], crustal seismic models [21, 25], a 3D seismological model of earthquake hypocenter distributions [6], and the results of structural interpretation of satellite photographs (ETOPO1) and topographic and bathymetric maps [17, 18, 49]. The results of heat flow measurements were processed by the authors with the Surfer-8 package into contour diagrams with different smoothing levels. The results of laboratory studies of volcanic rocks of the Sea of Japan were reconsidered from the aspect of their relation to geodynamic settings and elements of the deep structure of the crust and upper mantle. The results of structural interpretation of satellite images and geophysical anomalies are compared with gravity rheological and seismological models to clarify their tectonic causes and determine the vertical range of vortex structures. This is the first time such work has been done in the Sea of Japan region.

RESULTS

A fundamental feature of the structure of the tectonosphere of the Sea of Japan region, as well as of the entire Western Pacific margin [36], is its stratification into two rigid (the crystalline layer of the crust and lower layer of the lithosphere) and two viscous (subcrustal and asthenospheric) layers. The former are expressed by elevated and high density contrast values, while the latter are expressed by low values (less than \(10^{-2}\) kg m\(^{-2}\) km\(^{-1}\)). Sometimes, the sections contain a fifth, subasthenospheric rigid layer. The study of the spatial relationships between the layers makes it possible to predict deep extensional, thrust, and subduction structures in the crust and upper mantle. Deep rupture zones in crust and the lower layer of the lithosphere often coincide with rift structures on the Earth’s surface and, as a rule, are accompanied by linear heat flow maxima and reduced crustal thickness [36, 38]. These features are fully manifested in the Sea of Japan tectonosphere.

In the slice at a depth of 10 km (Fig. 2a), the maximum density contrast is observed in the Yamato
block, the vertical thickness of which, according to the data obtained (Fig. 2c), does not exceed 15 km. This block is in no way related to the continental crust or crust of Honshu and has clearly been displaced, just like the Sergeevsky and Anyui massifs in Sikhote-Alin. Thus, the statistical gravity model, regardless of existing data, has confirmed the conclusions of its predecessors about the allochthonous nature of the Yamato Rise [15, 16].

The layer at depths of 16–25 km (Fig. 2b) is characterized by a low density contrast \( \left( u_z < 15 \times 10^{-2} \text{ kg m}^{-2} \text{ km}^{-1} \right) \), which agrees with the small crustal thickness, 12–18 km [25], underlain by a subcrustal low-viscosity layer. Local low-viscosity zones in this layer \( \left( u_z < 5 \times 10^{-2} \text{ kg m}^{-2} \text{ km}^{-1} \right) \) are oriented transversely to the long axis of the Sea of Japan Basin, which can be considered a sign of extension in a strike-slip duplex, which is characteristic of pull-apart structures [57]. Likewise, linear zones of increased seismicity in the lithospheric and subasthenospheric slices [6], transverse to the strike of the seismic focal zone, are oriented NW–SE.

Increased density contrast is observed under the continental part of the studied region and under the Precambrian Hida and Abukuma–Hitikami blocks (Figs 1, 2b), where they correspond to thickening of the crust [8, 56].

Features of the structural relationships of rigid layers have been identified in sections of the \( \mu_z(x, y, H_c) \)-model (Fig. 2c). In both sections, subduction of the middle (granite-metamorphic) layer of the crust is expressed. Honshu is under the Yamato block, and in section 6–6, the crust of the Sea of Japan is subducted under the continental margin. In section 1–1, the lower crustal layer of the North China Craton continues in the lithosphere of the Sea of Japan to a distance of 800 km (Fig. 2c). The inclined ridge plane in the western half of section 6–6 (Fig. 2c) is probably related to Late Mesozoic subduction of the Pacific Plate [30]. In the same section, the lower layer of the Pacific lithosphere is subducting beneath the Japanese island arc and the lithosphere of the Sea of Japan (Fig. 3c), which in the Late Mesozoic represented the continental margin. The same relationships between rigid layers are observed in section 5–5 (Fig. 4c). In both sections (5–5 and 6–6)), the subducting slab is ruptured beneath the western margin of Honshu. Such ruptures are usually called “slab-windows” and are associated with transform displacements at the western margin of the Pacific Plate [29, 47].

In subcrustal sections, the tectonosphere of the Sea of Japan region (Figs. 3a, 3b) is characterized by broad density contrast minima, the size of which increases with depth. The island arc in the east of the region is accompanied by maxima of the \( \mu_z \)-parameter, and in its continental part, the maximum density contrast contours the Bureya–Jiamusi–Khanka block with a cratonic basement [11, 15], which corresponds to increased crustal thickness in this block up to 40–45 km. The lower crustal section of this block hosts the Tanlu transtension zone, along which, possibly, the Khanka Massif was detached from the Jiamusi massif and moved to the northeast. Transtension zones are expressed as ruptures of rigid layers in sections of the \( \mu_z(x, y, H_c) \)-model (Figs. 2c, 3c, 4c). The same ruptures accompany the Central and Yamato deep-water basins of the Sea of Japan, under which the crustal thickness is reduced to 12–16 km [25]. According to seismic data [21], in the east of the Central Basin, the thickness of the consolidated crust (without the sedimentary layer) is 6 km, which corresponds to newly formed oceanic crust. The absence or ruptures of the continental granite-metamorphic layer under the Central Basin is confirmed by sections of the \( \mu_z(x, y, H_c) \)-model (Figs. 2c, 3c, 4c).

Ruptures and sharp reductions in crustal thickness of are typical rift features [36, 38]; therefore, extension zones under the deep-water basins of the Sea of Japan can be identified with the rift structures of the same name. The extension zones in the Sea of Japan region are associated with strike-slip faults [30, 32, 46], while the Central and Yamato transtension zones form a strike-slip duplex, the zone of which contains second-order extension zones transverse to the duplex axis (Fig. 2b). The existence of transverse (northwestern) faults in the crust of the Sea of Japan is also indicated by magnetic anomalies [1], and the same orientation is characteristic of linear zones of earthquake hypocenter clusters in the lower lithosphere (depth 60–80 km) and in the subasthenospheric layer of the upper mantle (depth interval 200–450 km) [6]. All these data are obvious signs of a strike-slip duplex.

The vertical extent of extension structures is different. The Tanlu and Central Zones (in the Sea of Japan) penetrate deep into the upper mantle, and the rift beneath the Yamato Basin is limited to the crustal range (section 3–3 in Figs. 2c, 3c) and is therefore less pronounced in heat flow anomalies (Fig. 4a).

In sections \( \mu_z(x, y, H_c) \)-model (Figs. 3c, 4c), a layer of low viscosity corresponding to the asthenosphere is mapped. The spatial position of asthenospheric lenses coincides with the heat flow anomalies (Figs. 3c, 4c). An exception is the continental part of the Sea of Japan, where the asthenosphere in the Tanlu zone approaches a depth of 50–75 km [8]; however, the data on the heat flow in the Tanlu zone [8, 10] are much less representative than those for the Sea of Japan [5]. Another reason for the reduced heat flow in the Tanlu zone may be the shielding of asthenospheric heat by a thick layer of continental crust.

The subcrustal viscous layer, which can also be partially or completely melted, also contributes to the heat flow anomalies [34]. Beneath the Sea of Japan, the subcrustal viscous layer is thickened to 20–30 km (section 3–3 in Fig. 3c) and often merges with the asthenosphere (section 5–5 in Fig. 4c). The astheno-
spheric lens under the Sea of Japan has a mushroom shape (sections 1–1 and 5–5 in Fig. 4c and 6–6 in Fig. 3c), which is typical of central plume structures [50]. In section 3–3 (Fig. 3c), under the asthenospheric lens, there is a narrow protrusion of the subasthenospheric mantle, which, to some extent, confirms the hypothesis of the diapiric nature of the Sea of Japan [3, 30].

The distribution of the heat flow (Fig. 4a, b) is consistent with the riftogenic (spreading) origin of the Sea of Japan. In the diagram of the averaged heat flux within a radius of 50 km (Fig. 4a), two band maxima of the heat flux are observed \( Q > 90 \text{ mW/m}^2 \). The northwestern maximum (C) coincides with the deep-water Central Basin and the corresponding rupture of the lithosphere in the sections of the \( \mu(x, y, Hc) \)-model (Figs. 2c, 3c, 4c). Its location corresponds approximately to the most ancient (Eocene) Tsushima strike-slip zone [30], traces of which are preserved in the upper mantle. The southeastern high heat flow zone (Y) is manifested by a chain of local heat flow maxima near the western flank of the Japanese island arc and coincides with the deep-water Yamato Basin. This zone is accompanied by ruptures of crust (sections 6–6 in Fig. 2c, 3–3 in Fig. 3c, and 1–1 in Fig. 4c) and roughly corresponds to the pull-apart that occurred 1.5–2 Ma ago [30]. The wide maximum of the heat flux averaged over a radius of 100 km (Fig. 4b) corresponds to the protrusion of the asthenospheric lens, combined with the subcrustal viscos layer, in the slice at a depth of 35 km (Fig. 3a).

Determinations of the age of volcanic rocks dredged from the floor of the Sea of Japan show that in the Yamato Basin, their upper age limit is 0.8 Ma younger than the youngest volcanic rocks in the Central Basin; however, the oldest volcanic rocks in the

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**Fig. 3.** Density contrast distributions in subcrustal mantle (a) and lower lithosphere (b) with sections (c). (1) Pre-Paleozoic blocks; (2) Mesozoic and Cenozoic complexes; (3) Tanlu transension zone; (4) density contrast isolines (1 unit = 10^{-2} \text{ kg/m}^2/\text{km}); (5) graphs of heat flow above sections; (6) rigid plates in sections; (7) asthenosphere. Notation: blocks with continental type crust: B, Bureinsky; J, Jiamusi; H, Hangkai. SA = Sikhote-Alin accretion-fold system; CSA, Central Sikhote-Alin fault. For other notation, see Fig. 2.
Central Basin are 5 Ma younger than the oldest volcanic rocks in the Yamato depression. This indicates that volcanic processes in the crust of the Sea of Japan were initiated not only (and not so much) by rifting, but also by other processes related to the influence of the mantle plume and subduction of the Pacific Plate.

Opposite displacements of tectonic masses in Central and Yamato extension zones of (Fig. 4) form a duplex typical of strike-slip zones, which is reflected in paleotectonic schemes [30] and may be accompanied by vortex processes in rheologically weakened layers of the tectonosphere [18, 20, 49]. In the near-surface layer of the crust, a vortex structure is expressed by ring and arc lineaments, identified from space altimetry data (ETOPO 1) (Fig. 5a). It is also expressed on the maps of the free-air gravity field anomaly [43] (Fig. 5b) and the anomalous magnetic field [31] (Fig. 5c). In the lower crustal slice (Fig. 6a), the central-type structure (CTS) is expressed as a concentric distribution of earthquake magnitudes, and in the asthenosphere (Fig. 6b), as the distribution of the magnitude variability vectors.

Displacement of the lower crustal contour of the CTS to the southwest of the asthenospheric contour...
agrees with the geodynamics of the transform fault at the western margin of the Pacific Plate [30]. In turn, the center of the concentrically zoned upper crustal structure (Fig. 5a) is displaced west of the lower crustal CTS (Fig. 6a), which is explained by the displacement of the upper crustal layer towards the continent. This is consistent with GPS data from stations on Honshu [54, 65], where the rate of northwestern horizontal displacements of the Earth’s surface varies ranges from 30–40 mm/year. Similarly, the CTS contour, identified by magnetic anomalies (Fig. 5c), is displaced to the west relative to the CTS expressed in gravity anomalies (Fig. 5b). The observed displacements lead to the conclusion about layer-by-layer displacements of tectonic masses in the zone of the global transform fault, combined with directed imbricated thrusting of crustal structures from east to west, associated with subduction of the Pacific Plate. Thus, the structure of the upper crustal layer of the earth’s crust in the Sea of Japan resembles the structure of this layer in the Sikhote-Alin [9].

The thrust of crustal masses of island-arc and oceanic origin onto the continent, combined with subduction of the lower lithosphere, is a characteristic feature of the two-level collision of the Asian continental margin with the Pacific Plate [35, 36]. From sections 5–5 (Fig. 4) and 6–6 (Fig. 3), it follows that the lower layer of the lithosphere of the Pacific Plate is subducting beneath the asthenosphere of the Sea of Japan, while the upper layer is thrust over it.

In the Sea of Japan tectonosphere, several stages of rifting, spreading, and postspreading volcanic processes have occurred. [2, 14, 27, 47]. Rift-related volcanism spans from the Oligocene to the Early Miocene, followed by marginal spreading, which was accompanied by an outbreak of volcanism with geochemical properties characteristic of mid-ocean ridge volcanism (N-MORB). It ended with a powerful man-

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**Fig. 5.** Diagrams of arc and ring lineaments, indentified from satellite altimetry data (a), interpretation of gravitational (b) and magnetic (c) anomalies after [17, 19, 28] with changes.
ifestation of postspreading volcanism with geochemical specifics typical of oceanic islands alkaline-basaltoid volcanism (OIB). Rift-related Late Oligocene–Early Miocene calc-alkaline volcanism is well studied in the Yamato Upland. Here, volcanic rocks are characterized by alternating, often positive Sr anomalies, as well as negative Ta–Nb, Zr, and Ti anomalies (Fig. 7a), which is typical of rocks of active continental margins (ACMB; Fig. 8). The enrichment of magmatic melts in continental crust is indicated by the high andesitoid assimilation rate [52].

In the Late Oligocene–Early Miocene, a transform margin regime existed on the continental margin [30, 48], which caused widespread strike-slip processes, as a result of which the Late Cretaceous subducting plate was destroyed. However, the screening of the asthenosphere by a rigid plate in the lower lithosphere (sections 1–1 and 5–5 in Fig. 4d) did not lead to an outbreak of tholeiitic basaltic volcanism in the Yamato Rise. The manifestation of calc-alkaline volcanism here is associated with enrichment of melts in aqueous fluids containing elevated concentrations of Al, K, Na; LILE—Rb, Ba, Sr, etc.; and LREE, which was also typical of magmatic melts of some near-continental regions in the western Sea of Japan (section 1–1 in Fig. 2).

The geochemical properties of volcanic rocks in borehole 794 confirm the presence of spreading in the Sea of Japan, which manifested itself at the end of the Early—beginning of the Middle Miocene (about 15 Ma ago) [46, 63]. On the multicomponent diagram, volcanic rocks of this age form a spectrum of trace elements similar to that of tholeiitic basalts of mid-oceanic ridges (N-MORB) (Fig. 7b). And on the Nd and Sr isotope diagram, they are located near a depleted source (DM) (Fig. 9). Tholeiitic basalts with the described geochemical characteristics are derivatives of an asthenospheric source, the products of which are among the most depleted volcanic formations, which testifies in favor of domelike uplift of the asthenosphere, expressed in the gravity rheological model (Fig. 3, 4). The heat required to raise the asthenosphere is illustrated in Fig. 4b.

The protrusion of the high-temperature asthenospheric mantle, which rose to a depth of 100 km (Fig. 3c) in combination with a thick subcrustal viscous layer at depths of 60–80 km (Figs. 3b, 3c) in the central Sea of Japan in the Middle Miocene–Pliocene, contributed in marine basins to the manifestation of plume alkaline-basaltoid marginal-sea (MS) volcanism, which is similar in isotope-geochemical parameters to OIB. This is clearly illustrated by the multicomponent diagram of trace elements (Fig. 7b) with a positive Ta-Nb anomaly characteristic of hot spots, as well as by the (Zr/Y)–(Nb/Y) discriminant diagram and Nd and Sr isotope diagram (Figs. 8, 9). The OIB nature of MS basaltoids is also indicated by the inverse correlation between the Nb/Ta and Zr/Hf ratios from alkaline to tholeiitic varieties and the Nb/Ta values in the narrow range of 15.71–16.26, which is typical of rocks of within-plate settings, which, according to [58] range from 15 to 17. According to one point of view, the formation of Middle Miocene–Pliocene MS alkaline-basaltoid OIB-type rocks occurred as a result of melt-

![Fig. 6. Distribution of average (in 100 \( \times \) 100 km cell) earthquake magnitudes in 33–40 km layer (a) and magnitude gradients in 180–200 km layer (b) [6]. (1) Isolines of average earthquake magnitudes; (2, 3) trends of changes in magnitudes in cells (2) and on flanks of central-type structure (3); (4) contours of vortex structure.](image-url)
The uplift of the asthenospheric layer is controlled by a mantle diapir—the column of the Sea of Japan plume running deep into the mantle.

**DISCUSSION**

According to the obtained and analyzed data of predecessors, in the crust and upper mantle of the Sea of Japan, traces of at least six tectonic processes that have taken place here from the end of the Upper Cretaceous (67 million years) to the present have been recorded:

1. Late Cretaceous subduction of the Pacific Plate.
2. The post-subduction stage in the western regions of the Sea of Japan, spanning from the Oligocene to the Early Miocene,
3. Marginal-seas spreading from the end of the Early to the beginning of the Middle Miocene, which manifested itself to the maximum extent under the Central Basin of the Sea of Japan (4–13 Ma). It is marked by high heat flow, reduced crustal thickness, and rupture of the lithosphere.
4. The postspreading stage (Middle Miocene–Pliocene), during which (or slightly earlier) the asthe-
Fig. 8. (Zr/Y)–(Nb/Y) [51] diagram for Late Oligocene–Early Miocene andesitoids (squares) and Middle Miocene–Pliocene OIB OM basaltoids (filled squares) [2, 14] with additions after [27] and tholeiitic basalts from borehole 794 (circles) [63]. Mantle sources: PM, primitive mantle; DM, shallow depleted mantle; DEP, deep depleted (plume) mantle. Volcanic rock settings: N-MORB, mid-ocean ridge basalts; OIB, oceanic island basalts; OPB, oceanic plateau basalts; IAB, ACMB, island arc and active continental margin basalts. Dotted line separates plume and nonplume source regions.

Fig. 9. (87Sr/86Sr)–(143Nd/144Nd) isotope correlation diagram for Middle Miocene–Pliocene OM basaltoids [14] with additions after [27] and tholeiitic basalts of borehole no. 794 [46, 63]. Sources: DM, depleted mantle; BSE, bulk composition of silicate part of Earth; PREMA, predominant mantle; HIMU, high μ-enriched mantle; EM1 and EM2, mantle enriched in within-plate and subduction components, respectively. Mantle array.
nosphere was uplifted and the head of the Sea of Japan plume was formed.

(5) Cenozoic torsion and rotation of tectonic masses associated with a central-type structure in the upper mantle and a strike-slip duplex in the crust.

(6) Eocene–Oligocene subduction of the Pacific Plate beneath the Japanese island arc, accompanied by western movement of upper crustal masses.

Traces of these processes are expressed in rheological gravity models, constructed without external, i.e., gravimetric, information, which, on the one hand, strengthens confidence in the developed method for statistical processing of gravitational anomalies, and on the other hand, makes it possible to link disparate geomorphological, geophysical, petrological, and seismological data on a three-dimensional structural basis.

The Sea of Japan formed mainly in the Oligocene–Miocene and was associated with stages of powerful tectogenesis and manifestations of rift-related, spreading and postspreading volcanism. Changes in geodynamic settings altered the character of volcanism—from continental marginal calc-alkaline (rift-related) to tholeiitic N-MORB type (spreading) and alkaline-basaltoid OIB (postspreading). Calc-alkaline volcanism retains its “suprasubduction” chemical specificity after the Late Cretaceous subduction of the Pacific Plate under Eurasia. Tholeiitic volcanism (N-MORB) is evidence of an asthenospheric lens under the Sea of Japan, and OIB alkaline-basaltoid volcanism indicates the formation of a hot spot within the Sea of Japan—a lower mantle plume source of magmatic melts.

The tectonosphere of the marginal Sea of Japan is a complex tectonic–magmatic structure that formed from the lateral interaction of the Eurasian and Pacific lithospheric plates moving relative to each other with the participation of extension processes, vortex movements in the tectonosphere, and intense magmatism.

Convergence of the Eurasian and rotating Pacific lithospheric plates was accompanied by regional and vortex structures found in lineament analysis [55] of the surface of the solid Earth (Fig. 5). Apparently, plume and associated vortex geodynamics, along with transform faults, form the main features of the deep structure of the Sea of Japan tectonosphere.

Four structure-forming layers are involved in the structure of the Sea of Japan tectonosphere: crustal, lower lithospheric, asthenospheric, and subasthenospheric. In the stratified tectonosphere, movements of tectonic masses can occur independently, or semi-independently, in each of the layers [39, 44]. Not so long ago [24], a model of layer-by-layer displacements and transformations of tectonic masses found mathematical confirmation. As a result of layer-by-layer displacements, the contours of deep structures observed in gravity, seismological, and topometric models in different depth sections may not exactly coincide with each other.

Based on the data obtained, ancient rigid blocks in the crust and lower lithosphere could have been the centers of rotation structures: the Yamato in the upper crustal layer (Figs. 2a, 5a), Hida in the lower crustal layer (Fig. 6a), and Abakuma–Hitikami in the lower lithosphere (Fig. 6b).

Gravity models preserve traces of the Eocene, or earlier, subduction of the Pacific Plate under the continental margin in the western regions of the Sea of Japan (section 6–6 in Fig. 3) and the modern subduction of this plate under the island arc in the east of the region (section 6–6 in Fig. 4; section 5–5 in Fig. 5).

Two stages of Miocene rifting processes associated with transform faults on the continental margin are expressed in ruptures of crustal and rigid mantle layers and heat flow anomalies. As a result of these processes, traces of earlier (Late Cretaceous–Eocene) subduction were destroyed and horizontal displacements of tectonic blocks occurred, one of which is the Yamato. The spatial position of the transtension zones coincides with the deep-water basins of the Central and Yamato basins, under which the crustal thickness decreases to 12–17 km.

At the convergent boundary of the Pacific and Eurasian plates, a tectonic–magmatic central-type structure of plume nature formed, which has broken through the subducting Pacific lithosphere, and the asthenosphere is spreading outward from the magma center under the foot of the Sea of Japan lithosphere. A viscous or fluid asthenosphere is characterized by signs of a vortex structure expressed in the distributions of earthquake magnitude vectors (Fig. 6b). Vortex processes in the sublithospheric mantle may be associated with convective currents [45, 67], since it is difficult to imagine that convection cells rotate only in the vertical plane, setting lithospheric segments in motion. The horizontal components of cell rotation are none other than vortex structures.

**CONCLUSIONS**

As a result of comprehensive analysis of gravity, tectonic, geomorphological, seismological, thermometric, and petrological data, a consistent generalized model of the deep structure and evolution of the Sea of Japan tectonosphere has been constructed, combining the features of rift-related, shear, vortex, subduction, and plume processes that manifested themselves in the Sea of Japan at different times.

Rift structures are expressed in ruptures (or reduced thickness) of the hard crystalline layer of the crust in gravity (Figs. 2c, 3c), seismic (Fig. 4c), and thermophysical (Fig. 4a) models. The strike-slip duplex like pull-apart structures is expressed in the transverse orientation of extension structures in the middle layer of the crust (Fig. 2a), and syn-shear vortex processes, in the circular orientation of lineaments of the satellite-geological model (Fig. 5a), and in the
existence of central type structures in the seismological model (Fig. 6). Late Cretaceous subduction of the Pacific Plate is expressed in subduction of oceanic crust under the continent (Fig. 2c), and Cenozoic subduction is expressed in subduction of the Pacific lithosphere under the Japanese island arc (Fig. 4d). The structural and geophysical features of the abovementioned processes have been confirmed by petrological data (Figs. 7–9), and absolute age determination for rocks dredged from the floor of the Sea of Japan makes it possible to temporally separate these processes. The following age series of tectonic structures and processes have been constructed: Early Cretaceous (prerift) subduction of the Pacific Plate—occurrence of a strike-slip duplex in the Miocene extension zone in the western and eastern regions of the Sea of Japan with the formation of vortex structures—Pliocene uplift of the asthenosphere in a transtension zone, which intensified the rotation processes of tectonic masses—Eocene–Oligocene subduction of the Pacific Plate beneath the Japanese island arc.

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