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Deep Structures in the Maritime Territory–Sea of Japan Continental Margin from Seismic Data

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Abstract—This paper discusses the results of interpreting seismic profiles on the Earth's crust of the Maritime Territory and Sea of Japan performed during the 20th century by the Sakhalin Integrated Research Institute and by the Schmidt Joint Institute of Physics of the Earth, Russian Academy of Sciences. The seismic profiles confirmed the presence of structural features under the Maritime Territory and the Sea of Japan that were revealed previously from geological data, such as spreading zones, rifts, deep-seated faults, overthrusts, and subduction zones, suggesting an active type of continental margin in the Far East region. We assumed that a high occurrence of the asthenospheric layer enclosing magmatic chambers explains the high activity of tectonic processes in the Far Eastern continental margin. The identified system of rifts and spreading centers supports this assumption.

Key words: seismic interpretation, DSS (deep seismic sounding), Maritime Territory, Sea of Japan, tectonics, spreading.

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INTRODUCTION

Examination of continental margins is of a particular importance currently, since these are regions of high seismic activity, volcanism, and natural catastrophes, which are very hazardous for their inhabitants. Active continental margins are also regions of active tectonic movements and hydrothermal processes and areas of accumulation of various minerals. The special Inter-Margins International Program, in which scientists of over 20 countries participate, was devoted to the examination of the deep structure of continental margins [Rodnikov et al., 2007]. We performed interpretation of seismic profiles run during the 1960s according to new methods worked out at the Faculty of Geology of MSU [Piip, 1991, 2001] with the purpose of revealing the deep structure of the Maritime continental margin.

During the 1960s, researchers from the Sakhalin Integrated Research Institute and from the Schmidt Joint Institute of Physics of the Earth, RAN performed deep seismic sounding of the Earth's crust under the Far Eastern seas. Two profiles (25 and 26) were run in the Sea of Japan. The profiles were 350 and 280 km long, respectively. The profiles had a common land part where four seismic receiving stations were located. Shots were performed only in the sea (Fig. 1) and the distance between shots was 5–10 km. The results of the operations were published in *Glubinnoe…*, [1971]. Profile 26 had an extension on land as Profile 1 (Spassk-Dal'nii–Tadushi) [Argentov et al., 1976]. These two profiles were interpreted as one continuous profile.

GEOLOGICAL INFORMATION ON THE STUDY AREA

The study area includes Sikhote Alin in the Maritime Territory, the continental slope, and the Sea of Japan, along which two profiles of deep seismic sound-

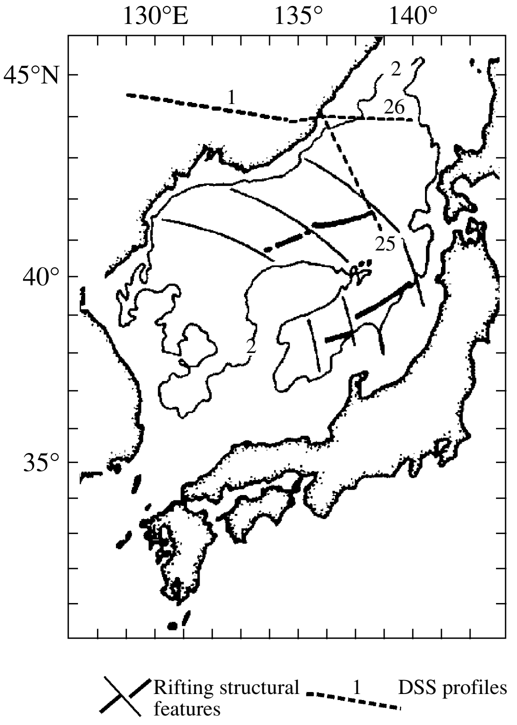

Fig. 1. Map of profiles layout.

ing (DSS) were run. The Sikhote Alin region rims the ancient continental margin of Asia that is currently presented by the Khanka Massif consisting of rocks of different ages (from Paleozoic through Neocomian) and origin (oceanic, continental-marginal, and island-arc complexes) [*Ob"yasnitel'naya*..., 2000; Khanchuk, 2000]. The Middle Cretaceous orogeny in Sikhote Alin resulted in the formation of imbricate thrusts, metamorphism, and granitization, as well as in the occurrence of syn-strike-slip sedimentary basins and magmatism. Middle Cretaceous accretion considerably increased the continental margin and increased its thickness to 40 km [Filatova, 1998]. All these structural features were subsequently overlain by volcano-plutonic rock complexes of the East Sikhote Alin supra-subduction belt. Cenozoic extensional structural features (including the Tatar Strait rift) distort all the previously formed structural features of the continental margin and the adjacent oceanic region [Filatova, 2004], which is locally accompanied by strong magmatic events.

The magmatic activity continued within the East Sikhote Alin belt from the Cretaceous to Early Quaternary time. Paleogene–Quaternary basalts are products of fissure eruptions; the thickness of basalt sheets reaches 1000 m. These basalts include tholeiites, subalkaline basalts, and rocks of the alkaline olivine-basalt series. The tholeiites are similar to MORB-type basalts and are, probably, related to asthenospheric magmatic sources [Rodnikov et al., 2005; Filatova and Rodnikov, 2006]. The crust thickness varies from 30 km under the volcanic belt to 38 km under the Sikhote Alin [*Structura*..., 1996]. The results of magnetotelluric sounding within Sikhote Alin [Nikiforova et al., 1980; Kaplun, 2002] demonstrated that the electrically conductive layer regarded as the asthenosphere is located in the upper mantle at a depth of approximately 100–120 km. Most of the Maritime Territory lies within a 5–6-point seismicity zone [Ulomov and Shumilina, 1999].

The floor of the Sea of Japan consists of rocks variable in their origin, composition, and age; they are subdivided into two complexes: pre-Cenozoic consolidated basement, Cenozoic sedimentary rocks, and volcanic rocks [Bersenev et al., 1976]. The pre-Cenozoic basement consists of Archean–Paleoproterozoic, Paleozoic, and Mesozoic rocks making up the margins of the continent, its shelf, and large elevations in the Sea of Japan, for example, the Yamato Rise. The Cenozoic rocks include sedimentary and volcanic complexes consisting largely of basalt.

The Earth's crust consists in the Sea of Japan of three major layers. The upper layer 1.0–2.0 km thick has a seismic velocity ranging from 1.5 to 3.5 km/s with a relatively constant gradient of velocity growth with depth. An intermediate layer 2.0–2.5 km thick and with velocities of 4.8–5.6 km/s is lying below. It is underlain by the main layer 8.0–10.0 km thick and with seismic velocities of 6.4–7.0 km/s. The velocity values range in the upper mantle along the Mohorovichich discontinuity from 7.8 to 8.2 km/s. It has been assumed from geophysical data that the floor in deep-sea basins in the Sea of Japan has an oceanic structure [Rodnikov et al., 1982]. The crust in them is 12–15 km thick. The structure of the sedimentary layer in the Sea of Japan is known from dredging [Bersenev et al., 1987] and from drilling data from research vessels *Glomar Challenger* and *JOIDES Resolution* [Karig, Ingle, Jr., et al., 1975; Tamaki and Honza, 1985; Tamaki, Suyehiro et al., 1985]. Drilling data in the Earth's crust of the Sea of Japan revealed that to the depth of 500–600 m the sedimentary layer consists of clayey, diatomaceous ooze, sand, sandy–silty sediments, and clay with ash interlayers. Compact dark green siltstone, sandstone, and green tuff consisting largely of devitrified glass and feldspar lie at the base of the sedimentary succession. Borehole 798 in the southern part of the sea penetrated Middle Pliocene–Holocene rocks consisting of alternating diatomaceous and terrigenous clay, argillite, and ooze containing organic matter. A considerable methane emanation was recorded. Boreholes 794, 795, and 797 reached basalts 25 million years old. This fact allowed drawing the conclusion that the Sea of Japan opened during the Miocene as a back-arc basin. This involved formation of a spreading zone located in the central part of the sea. Results of geomagnetic anomalies analyzing by Japanese researchers [Isezaki et al., 1976] allowed the identification of two spreading centers in the Sea of Japan; one of them is located in the Japanese Basin and the other, in the Yamato Basin.

One of the most important specific features in the structure of the Sea of Japan region is the occurrence of an asthenospheric layer in the upper mantle [Rodnikov et al., 1982; Rodnikov, Sergeeva, et al., 2001]. The asthenospheric layer is located at a depth of approximately 50 km in the transition zone, which is remarkable (compared to adjacent regions) for a high heat flow. The asthenospheric layer is located under the Maritime Territory and the Pacific Ocean at a depth of approximately 100 km. Seismic tomography data revealed an asthenospheric diapir in the upper mantle at a depth of 40–50 km under the Sea of Japan and in the western part of the Honshu Island; that diapir determined the magmatic activity during the Cenozoic [Hasegawa, Zhao, et al., 1991].

The Japanese Archipelago is located in a seismically active region, viz., in the transition zone between the Asian Continent and the Pacific Ocean and in the junction zone between three lithospheric plates: Eurasian (Amur River Plate), Sea of Okhotsk, Pacific, and Philippine, which determined its tectonic activity, seismicity, and volcanism. An overwhelming majority of earthquakes are confined to the eastern margin of the Japanese islands, where the Pacific Plate is downgoing under the Japanese island arc with a velocity of 2–8 cm/year and forms a subduction zone up to 600 km deep. The Philippine Sea Plate is descending below the Japanese islands in the Nankai Trough area with a velocity of 2 cm/year [Kiratzi and Papazachos, 1996].

A network of shallow-source earthquakes was traced in the Sea of Japan along the Hokkaido and northern Honshu islands; the sources mark a focal zone dipping under the islands to a depth of approximately 60 km. This focal zone is distinctly pronounced in its submarine topography by the Okushiri and Sado ridges and by a system of troughs, the largest of which is the Okushiri Trough, where the Pliocene–Quaternary sediments are up to 2–3 km thick [Honza, 1979]. The Okushiri Ridge extends along the eastern margin of the Japanese deep-sea basin and consists of separate en-echelon arranged small ridges up to 450 km long, up to 50 km wide, and with a relative elevation ranging from 1000 to 3500 m. The Okushiri Island where Cretaceous granite crops out is located in the middle part of the ridge. The basement in the northern part of the Okushiri Ridge consists of rocks of the continental and oceanic crust. The middle part of the ridge consists of oceanic crust, and the southern, of continental crust. The sedimentary cover consists of Miocene and Pliocene rocks.

K. Nakamura [Nakamura, 1873] and Ya. Kobayashi [Kobayashi, 1983] assumed that the eastern margin of the Sea of Japan is a convergent zone that originated during the Pliocene. Subduction of the oceanic crust of the Sea of Japan under the Japanese island arc was accompanied by the formation of troughs and ridges, whose structure distinctly displays itself in seismic profiles. In addition, the identified subduction zone reveals itself in a free-air anomalous gravity field, for example, the free-air gravity anomaly along the Okushiri Ridge is ~57 mGal, which, in the authors' opinion, [Tamaki and Honza, 1985], indicates a subduction of the oceanic crust under the Japanese island arc. Farther southward, Japanese researchers identified an obduction zone where the oceanic crust of the Sea of Japan overthrusts the continental slope of the Japanese island arc. The occurrence of a convergent zone at the boundary between the Sea of Japan and the Japanese islands is related to opening of the Baikal Rift, which actively proceeded during the Pliocene and which causes eastward motion of the Amur microplate, making up a portion of the Eurasian Plate [Tamaki and Honza, 1985].

Japanese researchers assumed that the subduction of the Sea of Japan plate began during the Pliocene and that this resulted in the formation of ridges and troughs at the eastern coast of the Japanese islands. Seismologic data indicate that subduction under these island was approximately 60 km during 1.8 million years. The displacement velocity of the Sea of Japan plate was 2 cm/year [Kiratzi and Papazachos, 1996]. GPS data indicate that the vertical component of displacement was 6 mm/year at the convergent boundary [Aoki and Shotz, 2003].

The new interpretation of seismic profiles allowed the refinement of the deep structure of the Earth's crust along the continental margin between the Maritime Territory and the Sea of Japan.

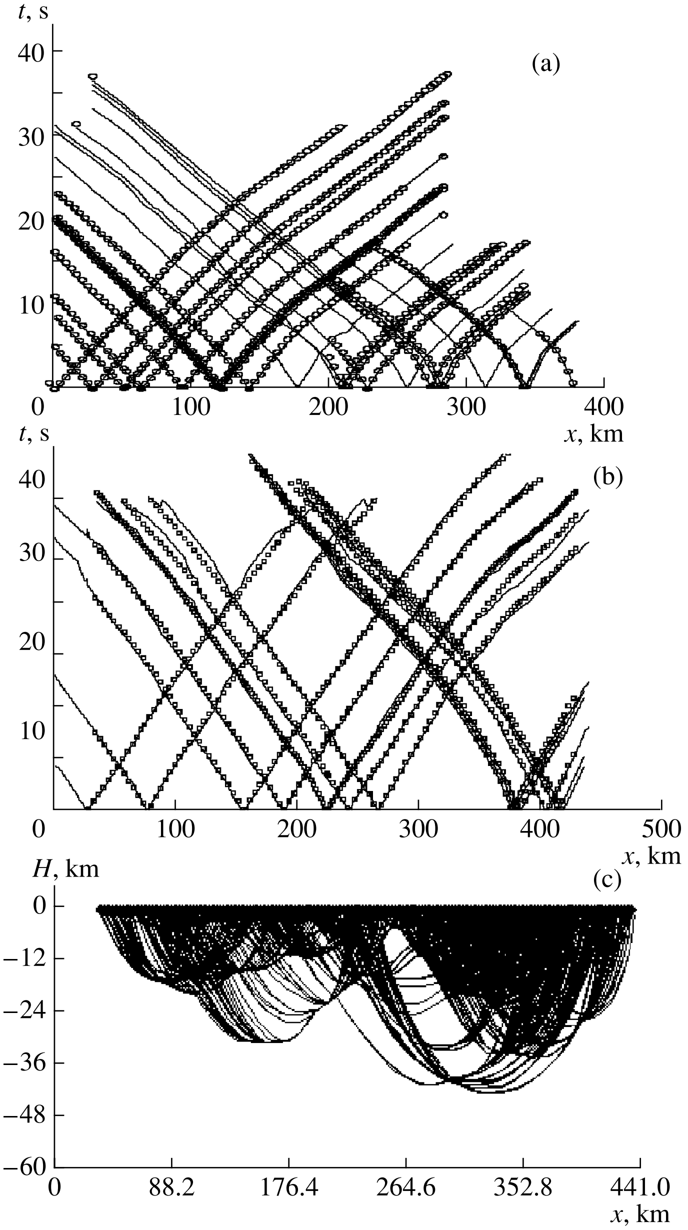

Fig. 2. Comparison between interpolated traveltime curves (thin lines) and calculated travel times (circles) in profiles 25 (a) and 1+26 (b). Mean square deviation in profile 25 is 0.26 s, and in profile 1+26 it is 0.47 s; raypaths corresponding to the calculated travel times in profile 1+26 (c).

Interpretation Method

We processed and interpreted the travel-time curves of refracted waves along profiles 25, 26, and 1 (Fig. 2) published in [Argentov et al., 1976; *Glubinnoe…*, 1971] applying the method of homogeneous functions. The fundamentals of the method were published in [Piip, 1991, 2001, and 2004]. The GODOGRAPH software packet performs automatic interpretation of traveltime curves of refracted waves in complex media and under conditions when horizontal and vertical velocity

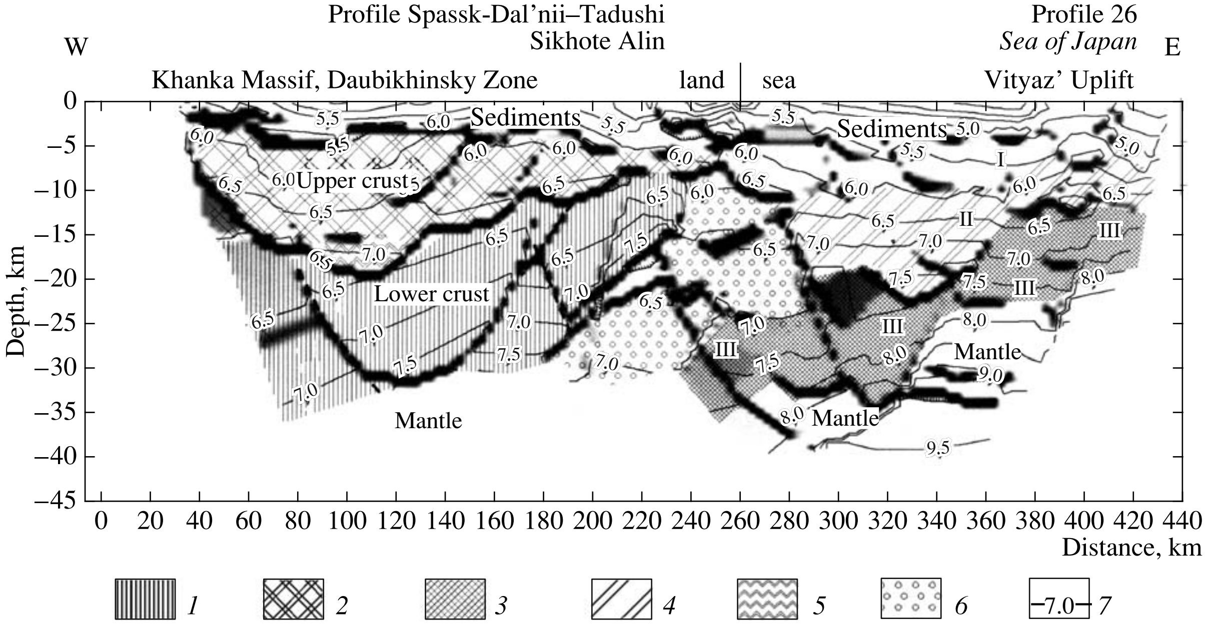

Fig. 3. Seismic section along profile 1 + 26 with geological interpretation. The sections are shown as surfaces with shaded relief. At such imaging, interfaces and faults are automatically visualized. Thin black lines show velocity contours, the contour interval is 0.5 km/s: (*1*) lower continental crust; (*2*) upper continental crust; (*3*) third layer of the oceanic crust (III); (*4*) second layer of the oceanic crust; (*5*) regions of increased velocity values; (*6*) regions of lowered velocity values; (*7*) velocity contours.

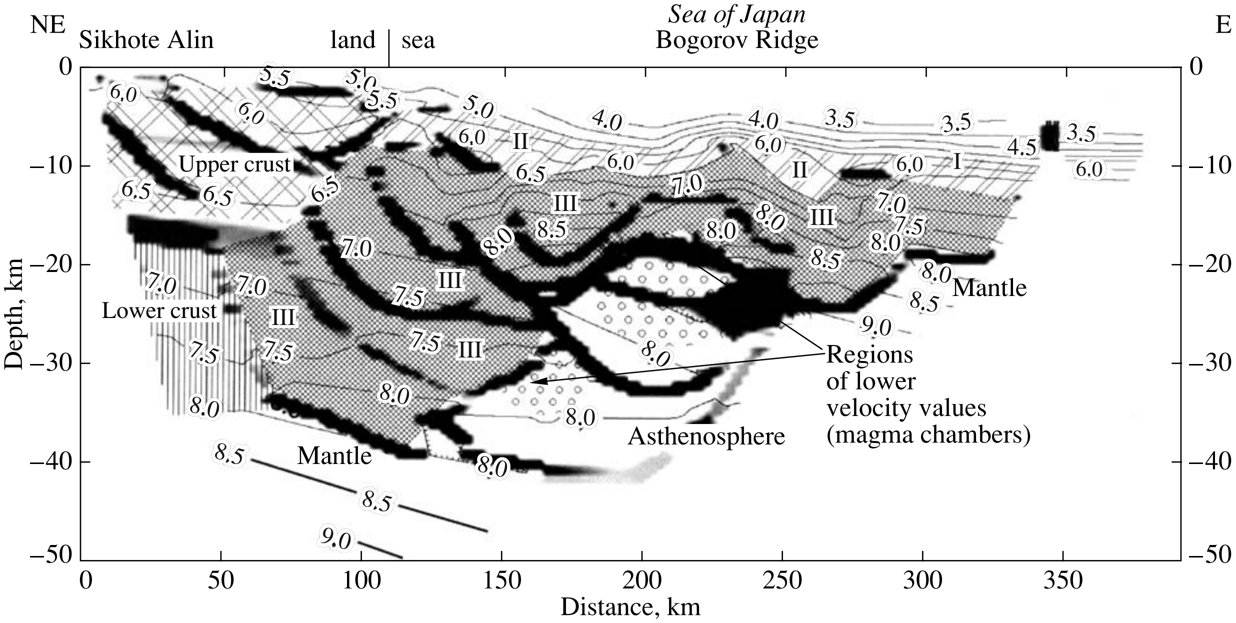

Fig. 4. Seismic section along profile 25 with its geological interpretation. The sections are shown as surfaces with shaded relief. Thin black lines show velocity contours; the contour interval is 0.5 km/s. See Fig. 3 for other symbols.

changes can be very significant. In this case, no a priory is required. Identification of the first arrivals in the travel-time curves is performed automatically.

The automatically calculated depth sections are a velocity field assigned in nodes of a rectangular network. This velocity field contains within it information on interfaces and tectonic distortions. The velocity field is presented as a surface with shaded topography (Figs. 3 and 4) in order to better reveal the interfaces and tectonic disturbances in vertical sections. Modern computer environments for imaging surfaces make this possible.

With lighting from above, the first-type interfaces (the velocity increases stepwise top-down at the interface) look like light lines. Inversion boundaries at the interface (the velocity decreases stepwise top-down) look like dark lines. Second-type interfaces, at which the velocity gradient changes stepwise, are identified as interfaces between layers of different lighting degree. Under conditions of the two-dimensional heterogeneity of the medium, the same interface can change its type along its extent, i.e., it can be a first-type interface, a second-type interface, and finally, an inversion interface. Tectonic faults occur in seismic sections as dark or light lines depending on their dip angle and the displacement direction. The authors combined imaging the velocity field as a surface with lighted relief with a field of velocity contours (thin lines in Figs. 3 and 4). This provided visualization of the velocity changes in individual layers of the section. Velocity values within layers in a section always grow downward. The velocity contour interval is a constant and is 0.5 km/s. Sections in profiles 25 and 26 were constructed from the seafloor topography.

The seismic profiles were checked by solving a direct kinematic problem in the seismic exploration. Theoretical traveltime curves in profiles 25 and 26 were calculated using the FIRSTOMO software [Ditmar, Roslov, et al., 1993]. Figure 2 shows a comparison between measured and theoretical traveltime curves in profiles 25 and 1 + 26 and raypaths calculated for a section along profile 1 + 26. The rays penetrate through the whole depth of the section. The coincidence between the calculated and measured traveltime curves is satisfactory. The mean square deviation of theoretical traveltime curves measured along profile 25 is 0.27 s and that along profile 1 + 26 is 0.47 s.

Lithosphere Structure along Seismic Profiles 25 and 1 + 26

Figures 3 and 4 show the measured profiles and their geological interpretation.

Profile 1 Spassk-Dal'nii–Tadushi and profile 1 + 26 in the Sea of Japan. A detailed land–sea section to a depth of 40 km was constructed along a common profile and this shows the junction between the oceanic crust of the Sea of Japan and the continental crust of Sikhote Alin (Fig. 3).

Structural features separating the oceanic and continental crust are located within a zone consisting of faults that dip on both sides at angles of 15–25° in the coastal area (distances 240–280 km). Regions of lower velocity values and lower velocity gradient were outlined here. Oceanic crust and mantle remarkable for their high velocity values and high velocity gradients occur in the section from the side of the Sea of Japan. The thickness of the consolidated crust is 20 km in the eastern part of the profile. The velocity in the upper mantle, which lies here at a depth of 20–35 km, varies from 7.5 to 9.5 km/s. The third layer of the crust 8–10 km thick (the velocity is 7–8 km/s and low gradient) plunges stepwise landward from 12 km in the east to 30 km in the central part of the profile. The thickness of the second layer of the oceanic crust (velocity from 5.2 to 7.5 km/s and increased gradient) increases within the profile interval of 390–330 km from 9 km in the west to 22 km in the west. This may indicate accretion of crust layers during subduction of the oceanic lithosphere.

Continental crust was found within the western part of the profile. The thickness of the two-layer continental crust decreases from 35 km in the west to 16 km near the coast. The lower crust was determined based on the constant velocity gradient and common incline of the velocity contours (the velocities change from 6.6 to 7.8 km/s). The lower crust is cut by faults into blocks and, consequently, is brittle. The base of the lower crust (sharp inversion interface) rose along faults to a depth of 15 km in the junction zone between the oceanic and continental crust.

The base of the upper crust is an inversion continuous interface lying at a depth of 15 km in the west and 8 km near the coast. The upper crust (velocities in it vary from 6 to 7 km/s) is remarkable for numerous deformations. Gently dipping faults cut the crust into blocks. A rifting structural feature is traceable in the area of the Dubikhinsky zone and at the margin of the Khanka Massif. A large body (magmatic?) with anomalously high seismic velocity from 6.8 to 7.5 km/s lies at the base of this rift. The basement was recorded at a depth ranging from 3 to 5.5 km.

Profile 25. A major portion of the profile is confined to the deep-sea basin of the Sea of Japan and crosses the Bogorov Ridge. In the section along Profile 25 (Fig. 4), a distinctly displayed rifting structural feature with its center located in the area of the Bogorov Ridge occurs. Three layers of the oceanic crust designated in the figure in Latin numerals are distinctly traceable immediately under the seafloor: I (v = 3–6 m/s), II (v = 6–6.5 km/s), and III (v = 6.5–8 km/s). The crust thickness under the Bogorov Ridge (from the seafloor to the level of v = 8 km/s) is approximately 13 km. The second layer shows a lowered velocity gradient.

Faults cut the second and third layers into blocks measuring approximately 40 km, which are typical of spreading zones. A sharp rise of the asthenosphere (a zone of anomalously low seismic velocity) occurs in the central part of the spreading zone. The velocity is lowered in certain parts of the asthenosphere by 0.5 km/s relative to enclosing rocks. Blocks of the third oceanic layer (seismic velocity is 6.5–8.2 km/s) steeply subside under the continent to a depth of 35–40 km from the center of the spreading zone toward Sikhote Alin. These blocks form large overthrusts along listric faults with dip angles of approximately 15°. The automatic section calculated by the present authors corresponds to the spreading scheme by I. Gibson and A. Gibbs (1987). The spreading is accomplished "by means of dike intrusions and surface basalt eruptions: the wedging action of the dikes caused opening and subsidence under basalt load and formed fan-like monoclines both sides of the axial zone [Khain and Lomize, 2005].

In the west of the profile, near the Maritime Territory, continental crust with low seismic velocity values up to 35 km thick was recorded. The upper mantle showed seismic velocities from 8 km/s to 9 km/s at depths from 35 to 40 km.

Thus, the constructed seismic sections agree well with the geological notions on the structure of the region and at the same time present concrete forms and digital parameters of the identified structural features.

CONCLUSIONS

The Earth's crust in the Maritime Territory shows blocky discontinuity, which is apparent in the lateral variability of its geologic–geophysical parameters. Faults of different ranks, rifting structural features, fold-and-thrust system, and ancient subduction zones separate these blocks.

The constructed seismic sections support the presence in the Sea of Japan of structural features that were identified from geological data, such as spreading zones, rifts, deep-seated faults, overthrusts, and subduction zones that characterize an active type of the continental margin in the Far East. In addition, the seismic sections indicate that sharp displacements of lithospheric blocks occur along deep-seated faults.

The activity of tectonic processes in the Far Eastern continental margin can probably be explained by the high position of the lithospheric layer enclosing magmatic chambers. The identified system of rifts and spreading centers along seismic profiles in the Earth's crust supports this assumption.

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