Contents lists available at ScienceDirect

Tectonophysics

journal homepage: http://ees.elsevier.com

Geodynamic nature of the Okhotsk Sea lithosphere. An overview of seismic constraints

Nina I. Pavlenkova [a,*], Sergey N. Kashubin [b], Tamara S. Sakoulina [c], Galina A. Pavlenkova [a]

[a] *Institute of Physics of the Earth, Russian Academy of Sciences, 123995, B. Grusinskaya 10, Moscow, Russia*
[b] *Russian Geological Research Institute (VSEGEI), 199106, Srednii Prospect 74, St. Petersburg, Russia*
[c] *Earth's Science Institute of St. Petersburg State University, University Naberezhnaya 7, St. Petersburg, Russia*

ARTICLE INFO

Keywords
Earth's crust
Upper mantle
Continent
Ocean
Okhotsk Sea
Mantle faults
Geodynamics

ABSTRACT

A combined interpretation of the geological, seismological and active-source seismic data in the Okhotsk Sea (Sea of Okhotsk) region allows describing the structure and geodynamics of this transition zone between the continent and the ocean. The interpreted data on the crust and uppermost mantle structure of this region are based on the recent seismic profiles with detailed system of observation carried out during the last decades in the Okhotsk Sea. Large air guns and 119 ocean bottom stations were used to study the lithosphere structure of beneath the sea down to 70 km depth. Detailed P- and S-waves interpretation methods were applied for these profiles. The study shows the Okhotsk Sea crust to be of the continental type composed mainly of the felsic rocks. Only within the elongated basin along the Kuril island arc, the crust thickness is reduced and the velocities increased to the values typical for the oceanic crust. The new seismic data are also obtained on the upper mantle structure. The detailed mathematical modeling of the observed mantle waves revealed unusual type of the wide angle reflections recorded at the first arrivals which previously interpreted as refractions. As a result, two reflective boundaries M and M1 are revealed beneath the sea depression, with velocities of 7.9 and 8.0 km/s. Along the Sakhalin Island a deep mantle fault was traced down to the depth of 70 km. This deep fault is traced in the north-south direction far into the Pacific ocean and into the east Asia. The seismological data show the Okhotsk Sea to be surrounded by deep faults of global nature. In addition to the Kuril arc zone limiting the sea depression in the eastern part, the deep Magadan fault separates the depression from the continent. These data suggest the Okhotsk Sea region as a separate micro-plate of the continental type.

1. Introduction

The deep structure of the Okhotsk Sea (Sea of Okhotsk) region, as well as the entire transition zone from the Asian continent to the Pacific ocean, is of great interest for the study of the global geodynamics processes and formation of the continents and oceans. In this regard, detailed seismological and seismic studies of the crust and upper mantle have been carried out in this region since the middle of the 20th century.

The main objective of these studies was to define the type of the crust: whether it is of continental, oceanic or of some transition types. The type of the crust is determined mainly by the thickness of the crust and the composition of its consolidated rocks. These characteristics are now estimated by the seismic models. The continental crust is thick, from 25 to 30 km to 50–60 km, and its consolidated part consists of three layers with P-wave velocities (Vp) of 6.0–6.4 km/s (the upper crust), 6.5–6.7 km/s (the middle crust) and 6.8–7.2 km/s (the lower crust) (Beloussov and Pavlenkova, 1984). Deep drilling, xenoliths and laboratory studies of the rocks physical properties allow to distinguish the average composition and degree of metamorphism of these layers: they are the granite-gneiss upper crust, the granulite-gneiss middle crust and granulite-basitic lower crust (Kremenetskii and Ovchinnikov, 1983; Downes et al., 2002).

In contrast to the continental crust, the oceanic crust is thin (5–10 km) with Vp velocities of 6.7–7.0 km/s, it is the basitic crust composed of mafic rocks. There are also many transitional types of the crust of different thicknesses (10–30 km) and with different velocities (the subcontinental crust with a thin granite-gneiss layer and the suboceanic crust without such layer).

A number of detailed deep seismic studies were carried out in the Okhotsk Sea region to determine the crustal types and corresponding dynamic evolution of the transition zones between the continent and ocean (Fig. 1). These studies are briefly described in the following sections.

2. Deep seismic studies in the Okhotsk Sea region

The first seismic studies by the method of the refracted and wide angle reflected waves, or Deep Seismic Sounding (DSS), were car-

---

* Corresponding author.
E-mail address: ninapav@mail.ru (N.I. Pavlenkova)

https://doi.org/10.1016/j.tecto.2020.228320
Received 7 August 2019; Received in revised form 24 December 2019; Accepted 5 January 2020
Available online xxx

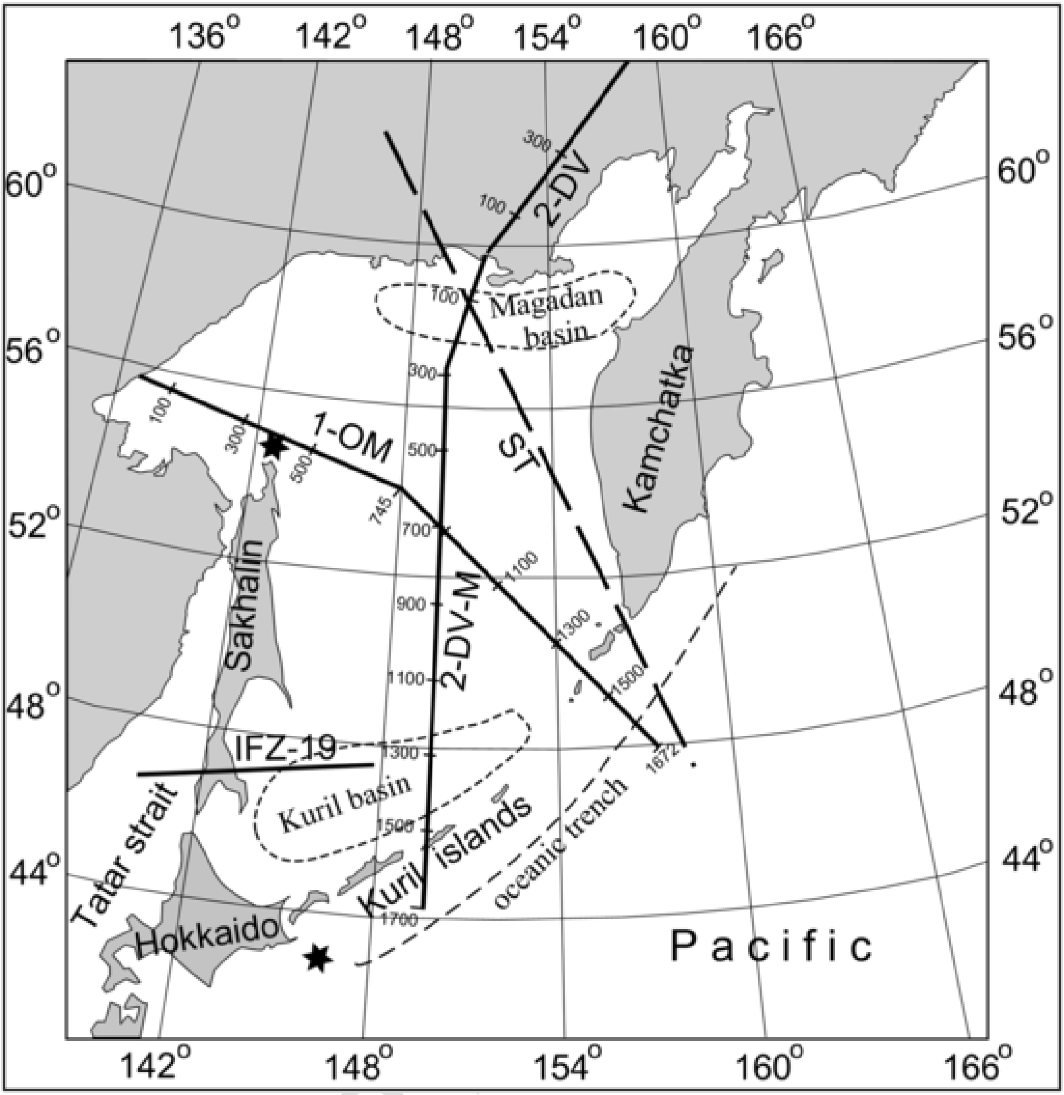

Fig. 1. Scheme of seismic profiles in the Okhotsk Sea (Sea of Okhotsk) region: the most recent profiles 1-OM, 2-DV-M of "Sevmorgeo" (Sakoulina et al., 2011) and the profile 2-DV of "SNIIGGIMS" institute (Salnikov, 2007); the older seismic profiles IFZ-19 and 9–0 carried out in the 1950s by the Institute of Physics of the Earth (IFZ) (Galperin and Kosminskaya, 1964). ST - profile of the seismo-tomography studies (Bijwaard et al., 1998). Stares are epicenters of the earthquakes in 1994–1995.

ried out in the Okhotsk Sea in the 1950s by the Institute of Physics of the Earth (IFZ) of the USSR Academy of Science (Galperin and Kosminskaya, 1964). Several profiles were acquired explosions and seismic stations attached to submarine bottoms (two of these profiles, IFZ-19 and 9-O, are shown in Fig. 1). The obtained seismic records have determined the crust of the sea as the continental type: thickness of 25–30 km and average P-wave velocities of granitogneiss rocks Vp = 6.0–6.7 km/s. Only in a small area of the Kuril basin (the South Okhotsk basin) the sub-oceanic crust was revealed: its consolidated crust thickness is only 5–7 km and the velocities Vp = 6.7–6.9 km/s.

Later re-processing of these data by using the established methods has confirmed the original interpretations (Pavlenkova et al., 2009). Nevertheless, the first DSS studies were not suitable for a reliable definition of the Okhotsk Sea crustal type, and by analogy with other sea depressions, it was often considered as the crust of the oceanic origin (Zonenshain et al., 1990; Bogdanov and Dobretsov, 2002).

In order to solve the above problem, in 2006–2009, detailed CDP and DSS seismic studies were carried out in the Okhotsk Sea along two profiles 1-OM and 2-DV-M by the Russian State Company "Sevmorgeo" (St-Petersburg) (Fig. 1). The profiles have a total length of more than 4000 km (Sakoulina et al., 2011, 2015). Prior to these studies, "Sevmorgeo" has been investigating the Arctic shelf for several years and developed an efficient survey methodology for marine deep seismic studies with the ocean bottom stations (OBS) and air guns (Roslov et al., 2009). This methodology was used on the Okhotsk Sea profiles. The observations were made by four-component OBS's each equipped with a three components geophone and hydrophone. A dense observation system was used. The bottom stations were spaced 10–20 km apart. The interval between the shots was 2 min, which provided an interval of 250 m spacing between seismic sources. Air guns with a chamber volume of 120 l ensured the wave recording at offsets of 250–300 km and a study depth of 40–50 km. The records were obtained with 119 OBS's.

The first data processing compiling the record sections from all OBS's and constructing the 2-D velocity models were carried out in "Sevmorgeo" (Sakoulina et al., 2011). Later these data were used for more detailed P-wave velocity models constructions and for processing of the shear (S) wave fields in St-Petersburg, in the Russian Geological Research Institute (VSEGEI) and also in Moscow, in the Institute of Physics of the Earth of Russian Academy of Science (IPE RAS) (Kashubin et al., 2013, 2017; Pavlenkova et al., 2018). The results of these interpretations are provided below.

3. The crustal structure in the Okhotsk Sea (Sea of Okhotsk) region

3.1. Profile 2-DV-M

A typical record, obtained along the profile 2-DV-M, is shown in reduced form in Fig. 2 (t - time, d – offset from the source).The record illustrates the main P-waves, characterizing the crustal structure. The refracted waves from the consolidated crust (Pg) are observed in the first arrivals at the offsets of up to 70–80 km with a strong change in the velocities where the refracted waves from the upper mantle (Pn) are recorded. In the secondary arrivals, the reflected waves from the crustal boundaries (PiP) from the Moho (M) (PmP), and the sea bottom related peg-leg multiples p_0P are dominant.

The ray tracing method of mathematical modeling (Červeny et al., 1977) was employed for analysis of the observed waves and construction of the seismic sections. This method is based on comparison of the observed travel times with those calculated from a set of starting models. In an iterative process of gradual model adjustments, the final velocity model is obtained and uncertainties of the model are estimated. Several ray tracing software packages (Červeny and Pšenčik, 1983; Zelt and Ellis, 1988) were used for the modeling of this dataset.

In Fig. 3a,b, the velocity cross-section along the 2-DV-M profile obtained with the ray tracing modeling is shown in comparison with the CDP data. The profile crosses all the main tectonic units of the Okhotsk Sea: the Magadan basin on the northern edge of the sea, the central parts of the sea depression, the Kuril basin on the southern margin of the sea and the Kuril island arc. The average thickness of the crust along the profile is 25–30 km, and the sediments thickness is 2–4 km. In the consolidated crust there are three main layers with velocities of 5.7–6.1, 6.2–6.3 and 6.5–6.8 km/s. This velocity structure is typical for a continental crust. However, this structure is somewhat different from the crust of the neighboring continent. On the profile 2-DV, which is a continuation of 2-DV-M in the continent (Fig. 1, Salnikov, 2017), the crustal thickness is more than 40 km (Fig. 3c), and it decreases to 30 km only within the narrow coastal zone. The sea velocity model is also somewhat differing from the crust of the adjacent continent. It lacks the lower layer with velocities exceeding 6.8 km/s, and in the upper crust, the velocity is slightly reduced.

The thickness of the upper crust (Vp = 5.7–6.2 km/s) along the profile 2-DV-M varies from continent to the Kuril basin, that is, perhaps, in this direction, the average composition of the crust changes too. In the northern part of the profile, the thickness of the upper granite-gneiss layers is 20–23 km, and the lower (mafic) crust is 5–7 km thick. In the southern part of the profile the thickness of the upper crust is reduced to 7–10 km and the lower crust thickness increases to 10–15 km. This change does not occur gradually, but mainly in the central part of the sea.

Legend: layers with different P velocities and rock composition: 1 – sediments (Vp = 2.0–5.3), 2 – granite-gneiss and granulite-gneiss rocks (5.8–6.6 km/s), 3 – mafic rocks (6.7–7.2 km/s), 4 – mantle materials (7.5–8.1 km/s). The thin lines are the refracting seismic boundaries; the thick lines - the reflecting boundaries of the crust.

In the elongated Kuril basin the structure of the crust changes dramatically: the crustal thickness is reduced to 10 km, and the average seismic velocities in the consolidated part increase to 6.5–6.6 km/s. On this basis, the crust of this basin was previously considered as an oceanic crust (Pavlenkova et al., 2009). To reveal the history of this basin formation the data along the profile 2-DV-M were studied thoroughly, including S-waves and P/S converted wave analysis (Kashubin et al., 2013) (Fig. 4).

As a result of this study, in the basin consolidated crust the two layers were revealed: a 2-km thick layer with seismic velocities of 5.8 km/s, which is characteristic of the upper continental crust, and a 6 km thick layer with velocities 6.6–6.7 km/s (the middle-lower continental crust). Only on the both sides of the basin in the middle crust the thin layers with velocity of 7.1 km/s were released, corresponding, perhaps, to the mantle intrusions. The P to S-velocity ratio in these layers is above 1.8, which is characteristic of mafite intrusive rocks.

The profile 2-DV-M crosses not only the Kuril basin but also the quite deep Magadan basin (Figs. 1 and 3). This basin is located near the transition zone from the continent to the sea depression and it was proposed the same crust transformation as in the Kuril basin. Nevertheless, the detailed seismic observations shows that the thick continental type of the crust is well preserved beneath this basin, being disturbed only by the narrow grabens and faults at the M (Moho).

The local Moho faults are observed also in the central part of the Okhotsk Sea, where the crust is sufficiently stable. They can be traced by sharp changing in the M boundary shape and by the inclined reflectors that cut the boundary. The clear disturbance is also seen in the basement structure. The major faults are observed along the all mar-

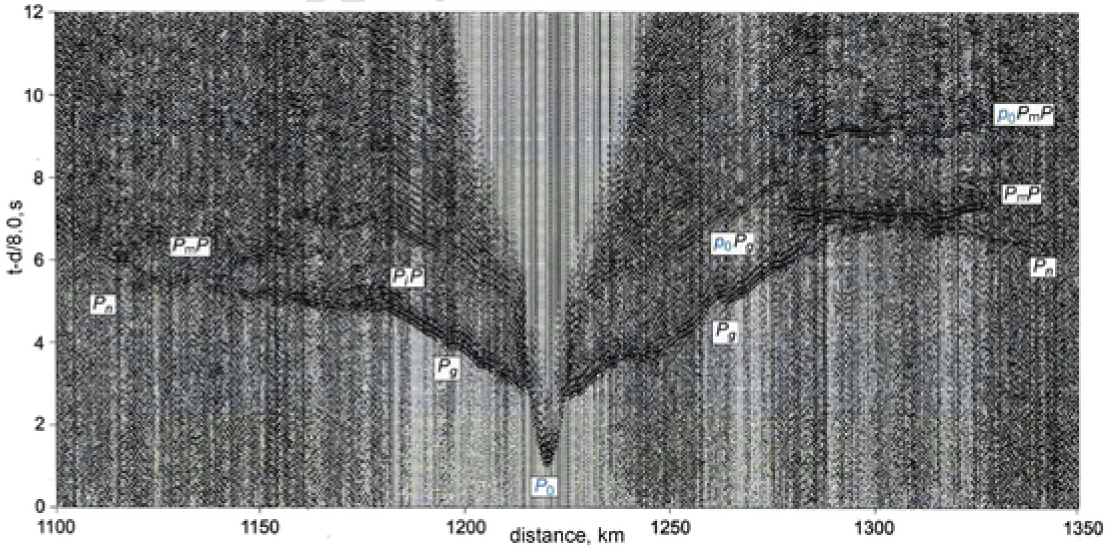

Fig. 2. Record section of the P- waves along the profile 2-DV-M (Kashubin et al., 2011, 2013). Pg – the refracted waves in the consolidated crust, Pn - in the mantle; PmP - reflections from the M boundary, PiP – reflection from the crustal boundary; p_0 – prefix for the sea bottom related waves in the consolidated crust, P_0 direct water wave.

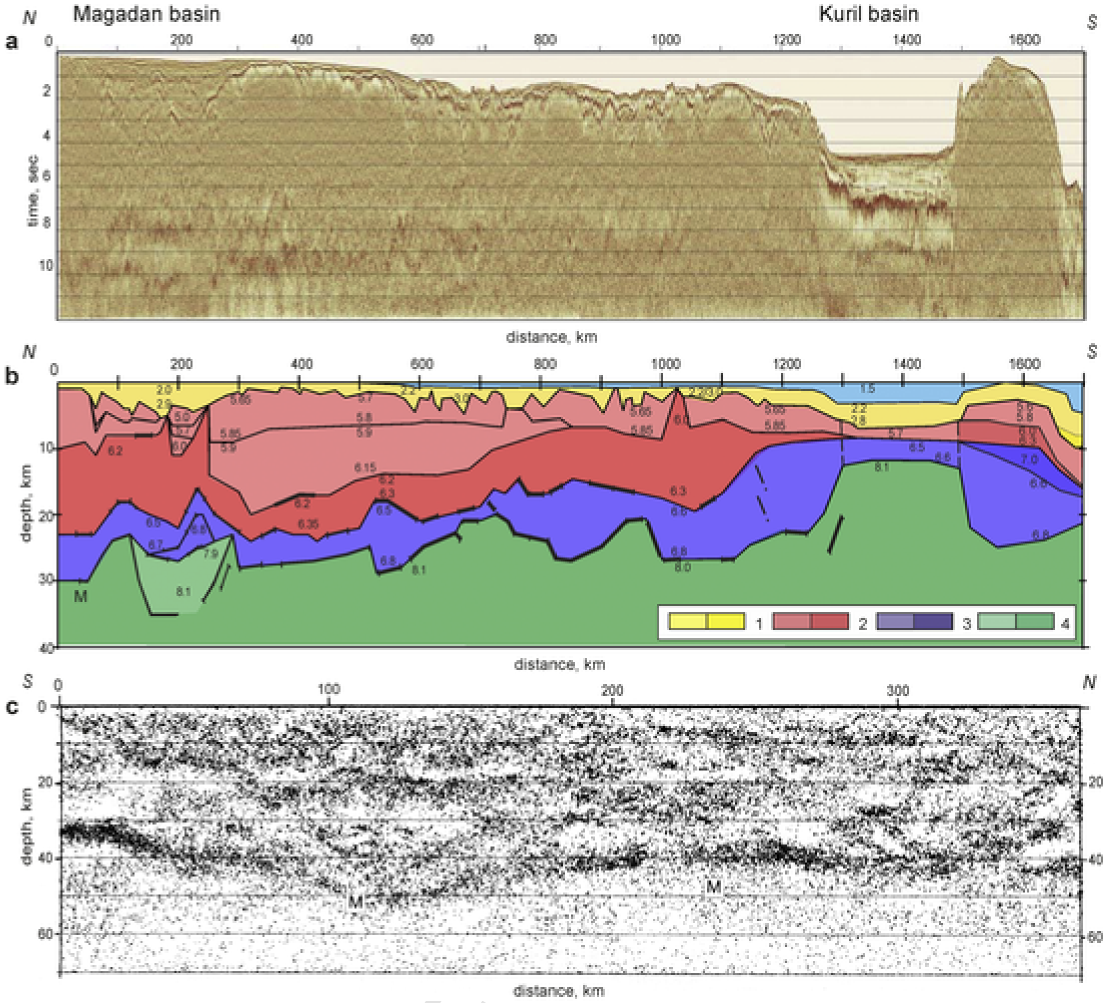

Fig. 3. Seismic cross-sections of the Okhotsk region crust (Fig. 1) obtained along the profiles: (a) 2-DV-M by CDP methods (Sakoulina et al., 2011), (b) 2-DV-M by the DSS method of refraction and wide angle reflection (Pavlenkova et al., 2018) and (c) by CDP method along the profile 2-DV (Suleimanov et al., 2007).

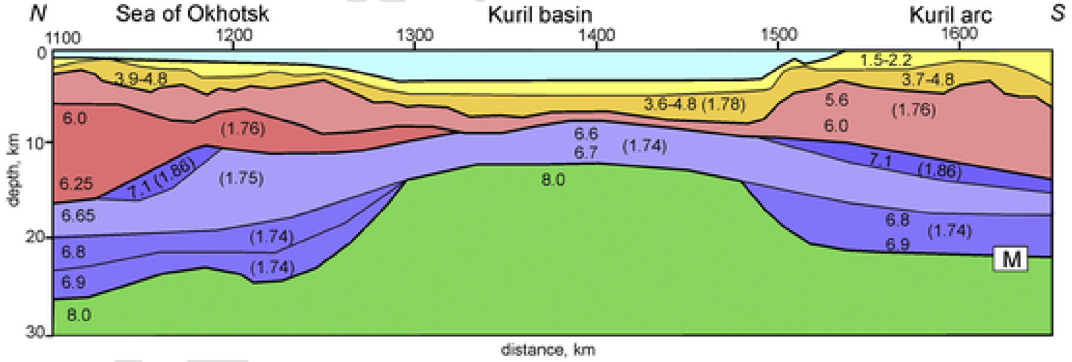

Fig. 4. Detailed velocity section of the Kuril basin crust on the PK 1100–1650 of the profile 2-DV-M, Fig. 1). Numbers are P-wave velocities; in the brackets they are Vp/Vs ratios (Kashubin et al., 2013).

gins of the sea where the crustal thickness changes and many local faults are formed.

3.2. Profile 1-OM

The profile 1-OM, as well as the profile 2-DV-M, crosses the Okhotsk Sea from the continent to the Kuril island arc (Fig. 1). The observation methodology on this profile was geared toward wave recording at the large distances from the sources, and as a result, the upper mantle structure was studied more detail than along the 2-DV-M profile.

The 1-OM profile does not cross the Magadan and Kuril basins, and the structure of the crust along this profile is more uniform (Fig. 5a). It is the crust of the continental type with thick granite-gneiss layer. Only some decrease of the crustal thickness from 25 to 20 km is observed in the central part of sea depression. The Kuril arc crust is thin along this profile, the crustal thickness is about 15 km.

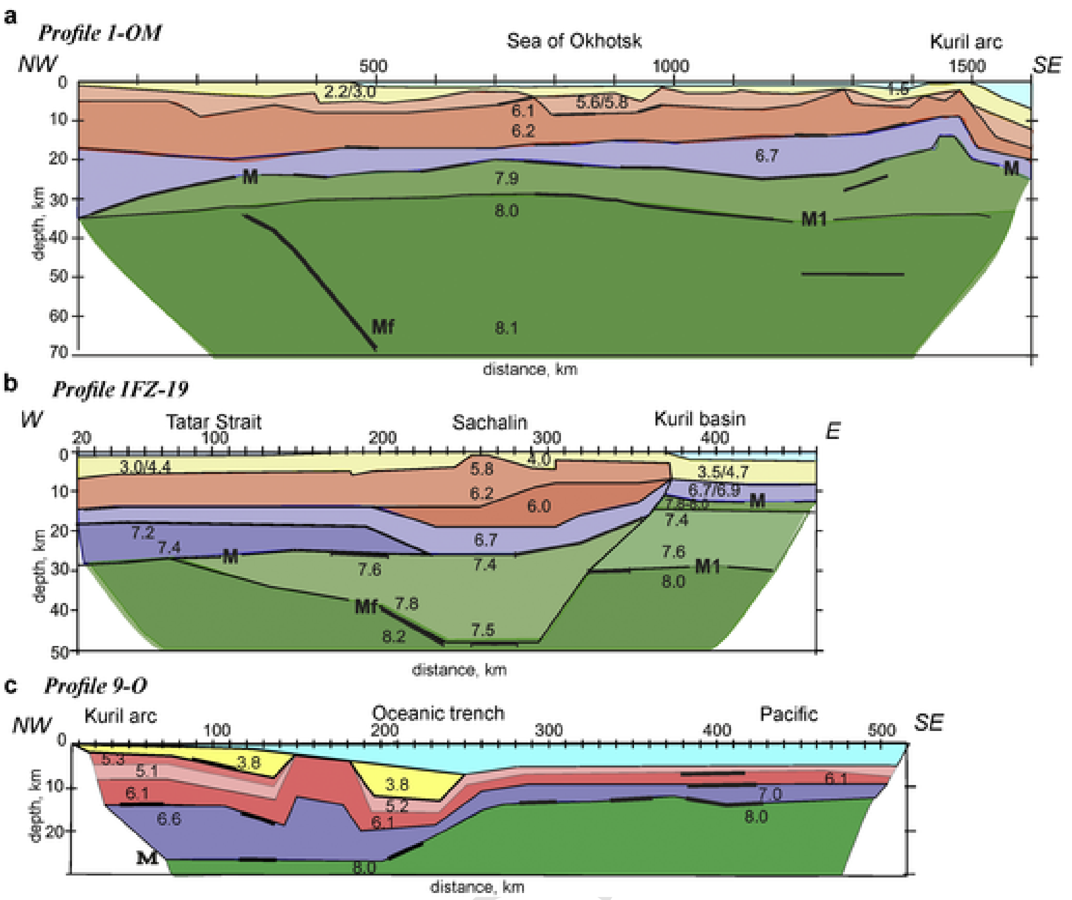

Fig. 5. Seismic cross-sections along the profiles: (a) 1-OM (Pavlenkova et al., 2018), (b) IFZ-19 (Pavlenkova et al., 2009), (c) 9-O (Galperin and Kosminskaya, 1964) (Fig. 1).Legend is in Fig. 3.

In Fig. 5 the 1-OM profile cross-section is compared with the older seismic profiles IFZ-19 and 9-O (Galperin and Kosminskaya, 1964) (Fig. 1). The IFZ-19 profile crosses three different tectonic units: the Tatar Strait, the Sakhalin Island and Kuril basin. The crustal thickness of the Tatar Strait and the Sakhalin Island is similar to the 30-km-thick crust of the Okhotsk Sea (Fig. 5b). However, these units differ in velocity and thickness of the lower crust: beneath the strait a 10-km-thick layer with velocity 7.2–7.4 km/s is observed, whereas beneath the Sakhalin Island and beneath the sea, the velocities do not exceed 6.7 km/s. The crust of the Kuril basin on the IFZ-19 profile in average is similar to the 2-DV-M crust, although it was not studied in detail on this older profile.

In Fig. 5c, the seismic cross-section is presented for the 9-O profile which crosses the transition zone from the Kuril arc to the Pacific ocean (Fig. 1). The sharp reduction in the crustal thickness from 25 to 7 km and two deep trenches are observed in this zone. The unusual data were obtained on this profile for the ocean crust. It is not a typical mafic crust, with two thin layers with the felsic rock velocities of 5.2 and 6.1 km/s identified along this profile. From deep-water drilling similar layers may be composed of pillow basalts (Vp = 2.5–3.8 km/s) and dike complex rocks (4.0–6.0 km/s) [Blyuman, 2011]. The third and the thickest layer (Vp = 6.6–7.0 km/s) has gabbro composition.

Thus, the described above seismic data have revealed the following main regularities in the crustal structure of this transition zone between the continent and the ocean: (1) the crust of the region is similar to the crust of the East Eurasia, only a decrease of its thickness and average crustal velocities are observed from the continent to the sea, (2) the crustal structure of the Okhotsk Sea depression is similar to the cratonic deep basins' structure, only the narrow Kuril basin has a thin suboceanic crust.

4. The upper mantle structure. The nature of the mantle waves

The most interesting results on the Okhotsk Sea upper mantle are obtained along the profile 1-OM, where unusual mantle waves were recorded (Fig. 6). At distances 70–100 km from the source the typical for the Moho low intensity Pn refractions are recorded. At larger distances, the M1 wave with the same velocities as Pn, 7.9–8.1 km/s, but of an unexpected high intensity is observed. It is almost continuously traced in the central part of the 1-OM profile between PK 700 and 1200 km.

The high magnitude first arrivals were also recorded by some OBS along the 2-DV-M profile. The ray tracing modeling has shown that it is necessary to assume the presence of another boundary, M1, under the Moho to explain such wave pattern. Due to the strong refraction of the wave at the M boundary, the critical reflections from M1 boundary are recorded at distances of 200–250 km from the source and have the linear travel-time curves with apparent velocities of Pn waves, 7.9–8.1 km/s (Fig. 7). The higher intensity of the critical reflections $P_{M1}P$ in comparison with the refracted waves Pn is confirmed by numerical modeling of these wave dynamics.

Thus, the observed first arrivals (Fig. 6) with the travel-time curve form, typical for the Moho refraction Pn, is a combination of two different waves: the Pn refraction and wide angle reflection from the boundary M1 in the upper mantle (Fig. 5a).

Large series of the mathematical modeling have shown that interpretation of such complicated mantle waves as ordinary refractions or reflections may give a wrong result in the upper mantle velocity deter-

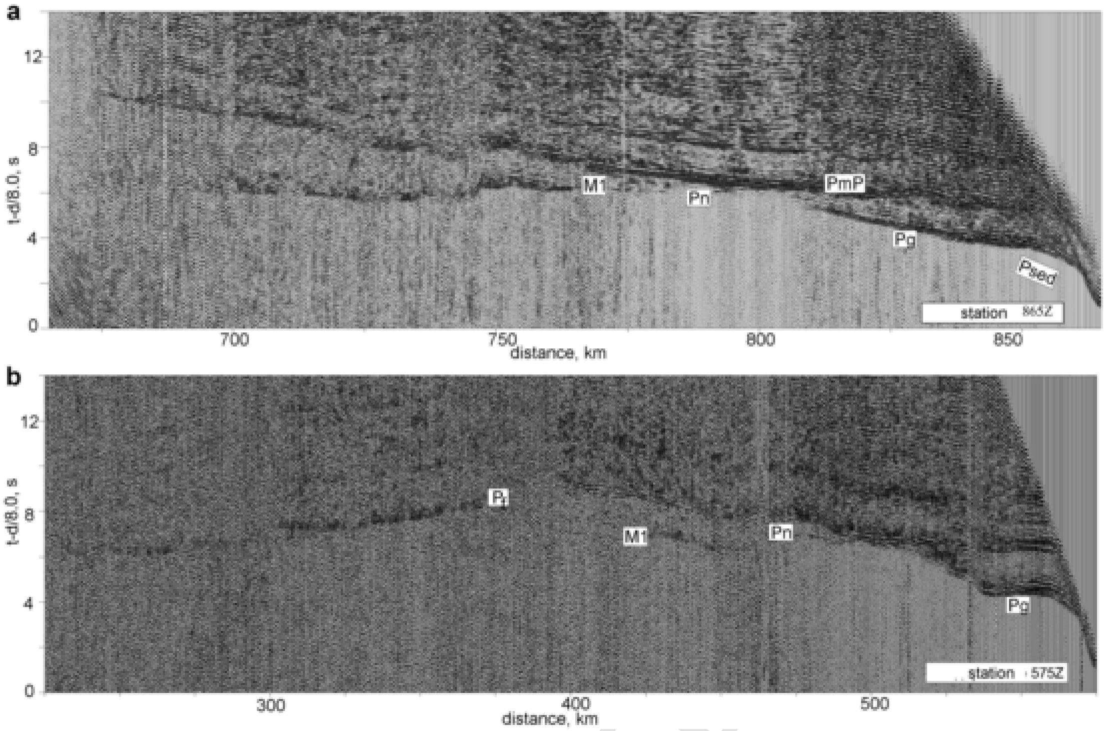

Fig. 6. Record sections of the P-waves at Z components along the profile 1-OM from the bottom stations 865 и 575 (Pavlenkova et al., 2018). The waves M1 and Pf are the reflections from the boundaries M1 and Mf (Fig. 5a).

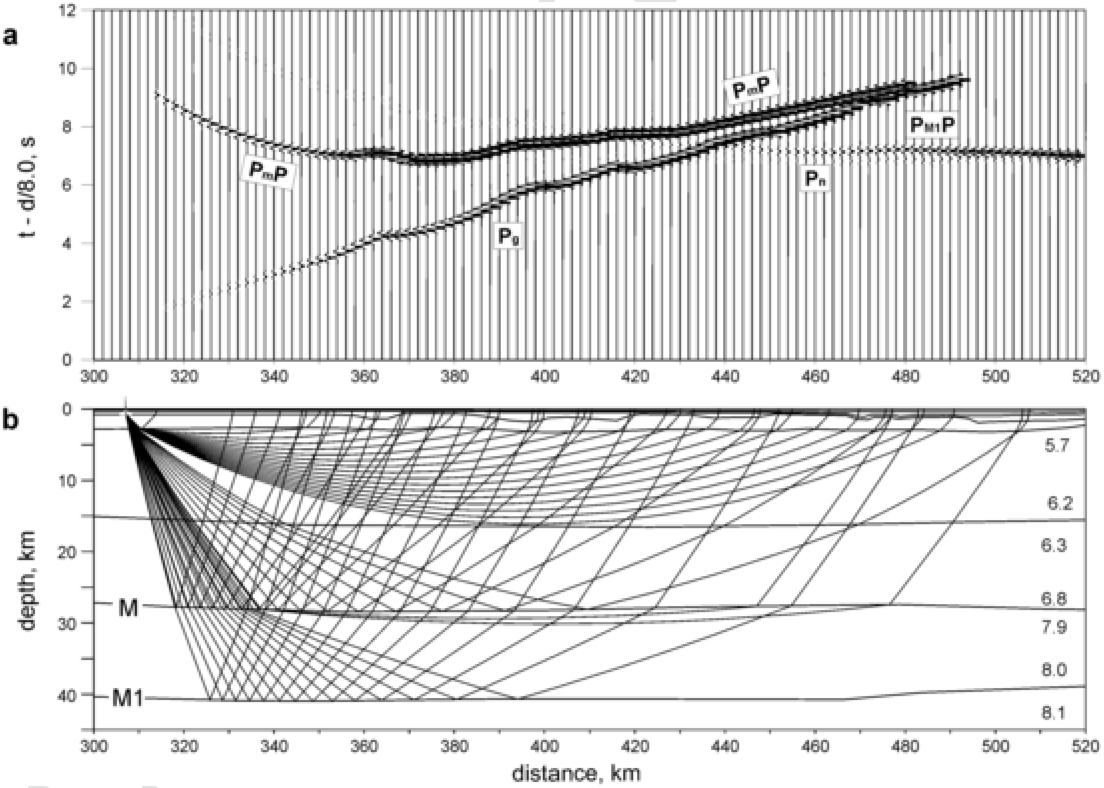

Fig. 7. Results of the ray tracing modeling for the mantle M1 boundary (Kashubin et al., 2011): (a) calculated synthetic seismograms of the refracted and reflected waves Pn and PmP from the Moho, PM1P - reflection from the M1 boundary, (b) calculated rays for the simplified velocity model of the 2-DV-M profile.

mination. The apparent velocities of wide angle reflections are usually a little bit higher than the boundary velocity and depend upon the inclination of the boundaries. Interpretation of such waves as the ordinary refractions gives the higher value of velocities beneath this boundary. Such mistakes were obtained on the 2-DV-M profile: the determined velocity beneath this boundary was 8.3 km/s (Kashubin et al., 2013). This velocity is unrealistically high for the uppermost mantle of this active tectonic region. The more reliable velocities were determined along the 1-OM profile where the reflection waves Pf were observed from the deep mantle boundary. The Pf waves with abnormally high apparent velocities are recorded at the secondary arrivals in the northern part of the profile at a distance from the source greater than 200 km. They are high-amplitude waves with the travel time shape corresponding to reflected waves (Fig. 6 b).

In Fig. 8, the results of Pf rays tracing and construction of the corresponding mantle boundary Mf are presented. The figure is presented in a simplified form, and the calculated travel times of the crustal reflections recorded at the secondary arrivals are not shown. From this modeling, the Mf boundary is a dipping boundary extending down to a depth of 70 km. The real inclination of this boundary is difficult to determine because it is not known how the profile crosses the boundary. However, the reliability of the boundary construction was proved by ray tracing for a number of the bottom stations with large distances between them. The large depth of this boundary extending down 600 km ensured also the reliable determination of the mantle velocity 8.0–8.1 km/s and the velocity value 8.3 km/s was removed from the Fig. 4.

The similar results on the mantle structure were obtained on the profile 19-OM, where the reflection boundaries M and Mf were revealed too. The inclined reflectors Mf, observed on profiles 1-OM and IFZ-19, are of great interest for studies of the Okhotsk Sea tectonics. Clearly, they correspond to the deep fault, extending along the Sakhalin Island and sinking under the sea.

The described ray tracing shows that the Pf waves are very informative for a reliable determination of the velocity in the upper mantle to a depth that is inaccessible to the refractions. The Pf waves cover long distances from the source, and they are recorded at several stations, that are up to 100 km from each other. The reflective boundaries constructed for all stations coincide well with each other in respect of their depth and slope. This correspondence indicates weak horizontal variations of the velocities and depths of the maximum ray penetration, with a small velocity increase from 8.0 to 8.1 km/s. The data on a small vertical velocity gradient in the upper mantle, agree well with the linear form of the Pn and M1 travel times to the large distances from the source (Fig. 6).

The velocity 8.0–8.1 km/s is typical for the upper mantle in the cratonic areas of the Northern Eurasia (Pavlenkova, 2011), and since the Okhotsk Sea region is characterized by high tectonic activity, it was assumed that the seismic velocities in the upper mantle of this region would be lower in comparison to the Eurasian continent. However, it is not observed: beneath the Okhotsk Sea down to 70 km (Fig. 8).

The relative stability of the velocities at the top of the mantle in the central part of the Okhotsk Sea significantly differs from the Kuril arc zone, where, according to seismological studies, the velocities of P waves are extremely variable with depth and are in average lower (7.7–7.8 km/s). Beneath the Sakhalin Island and Kuril basin the mantle velocities are also reduced to 7.4–7.6 km/s (Figs. 5b,c).

Thus, the DSS studies in the Okhotsk Sea (Sea of Okhotsk) result in the new interesting data on the upper mantle structure of this region.: (1) two reflecting boundaries M and M1 (Double Moho) are revealed beneath the sea depression, (2) the upper mantle velocities are similar to the velocities beneath the Northern Eurasia, (3) a deep upper mantle fault is observed along the Sakhalin Island.

5. The lithospheric structure of the Okhotsk Sea region

The deep upper mantle structure of the Okhotsk Sea region was studied by seismological methods. The tomographic method was used to determine the P-velocity models of the upper mantle and transition zone to the lower mantle (Fig. 9).

These studies show that in the sea lithosphere structure an important role belongs to the deep faults. The fault zones, bounding the Okhotsk Sea depression are traced in tomographic data as the higher velocity anomalies to a great depth (Fig. 9). The data on the deep earthquake hypocenters supply the information on the tectonically active faults, their depth, shape and the inner structure.

The deepest and the most seismically active zone stretched along the Kuril arc (Igarashi et al., 2001). This zone dips under the central part of the Okhotsk Sea down to 600 km depth (Fig. 9). The structure of this zone (so called "subduction zones") is well studied by 3-D seismic tomography (Kulakov et al., 2011). It was shown that this zone has a thickness of more than 200 km and on the surface it covers a wide area where a change in the type of the earth's crust from conti-

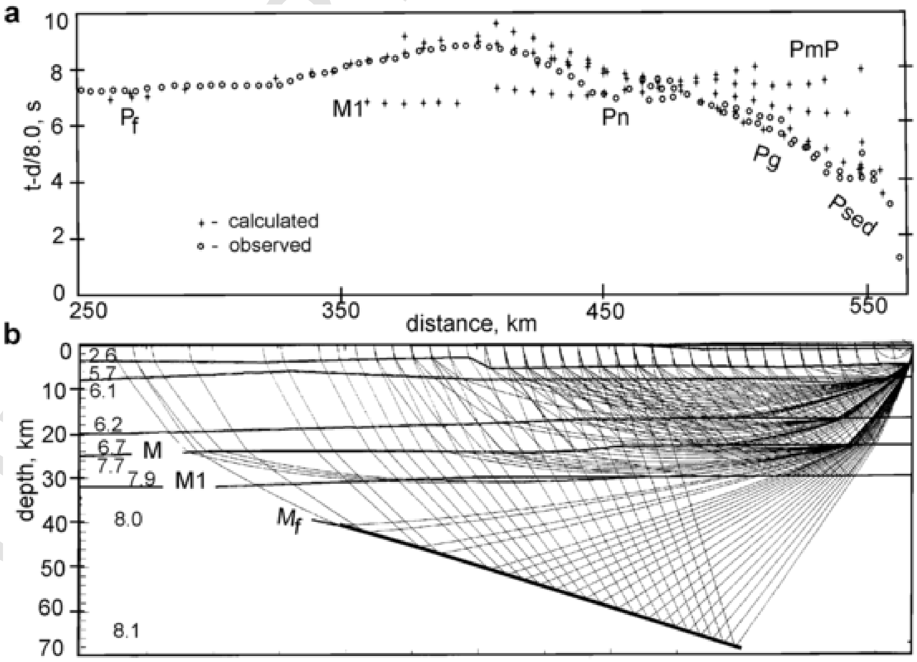

Fig. 8. Results of ray tracing for the Mf boundary along the 1-OM profile: calculated and observed travel-times of the refracted and reflected waves for the bottom station 575 (Pavlenkova et al., 2018). Pn and PmP are the refraction and reflection from the Moho, Pf is reflection from the M1 boundary.

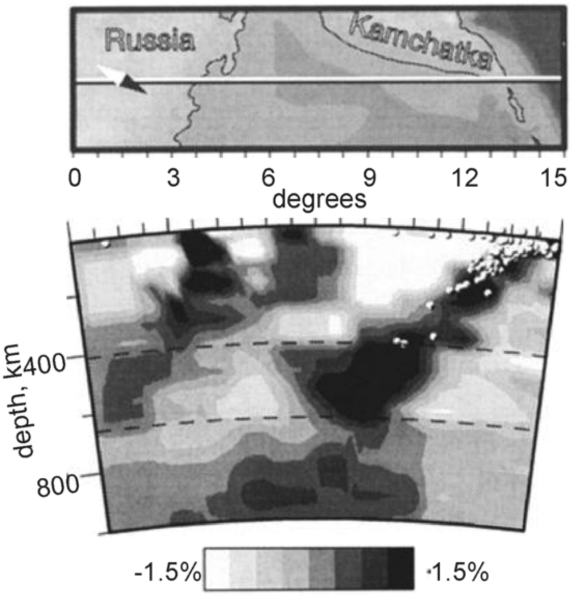

Fig. 9. Tomographic model of the upper mantle structure in the Okhotsk region (Bijwaard, 1998). Black zones are the high velocity anomalies, the dots show earthquake focus locations.

nental to oceanic type is observed (Fig. 5). Near this zone the extended Kuril basin of suboceanic type was formed.

In the north, the Okhotsk Sea is separated from the continent by a higher velocity anomaly that is traced beneath the continent also to the depth of 600 km (Fig. 9). The deep structure of this fault has not been studied in the same detail as the Kuril fault. It was unclear where it comes to the surface, on the northern edge of the sea (near Magadan), or in its central part (Fig. 9). But the structural features of the crust clearly show that this fault separates the Okhotsk Sea from the continent. It follows from comparison of seismic sections in the profiles 2-DV and 2-DV-M at their common points (Fig. 5c). Along the whole profile 2-DV the crustal thickness is about 40 km, but on the initial 100 km of the profile it sharply decreases to 30 km, to the Moho depth in the 2-DV-M profile.

Thus, two mantle faults determined by the seismic tomography (Fig. 9) are wide (100–200 km) destructed zones, where the crustal structure essentially changes: at the border between the sea and the continent, the Magadan basin was formed; the Kuril basin is observed along the Kuril arc fault (Fig. 1).

The western boundary of the Okhotsk depression is also limited by the deep fault extending along Sakhalin Island. This fault was interpreted in the seismic profiles 1-OM and IFZ-19 as the inclined mantle boundaries Mf that are sinking beneath the sea depression to the depth of 70 km (Fig. 5a, b) Seismological studies confirm the presence and the great depth of this fault: a sharp bend of the Kuril-Kamchatka slab is observed toward the Sakhalin Island (Kulakov et al., 2011). The presence of a deep fault along Sakhalin is confirmed also by the seismic activity in this region, which shows that two largest earthquakes recently occurred along this fault (Fig. 1).

Thus, the Okhotsk Sea is limited by deep fault zones from its three sides, and it is possible to propose an existence of a separate Okhotsk lithosphere micro plate. Only the eastern boundary of this plate is unclear, in particular whether it passes along the border with Kamchatka or includes this peninsula. According to the tectonic structure of this region, the later assumption (about a single Okhotsk-Kamchatka plate) looks more plausible. However, there are some seismological data that propose the existence of a deep fault zone along the eastern margin of the Kamchatka. In the central part of the sea close to Kamchatka peninsula several earthquake hypocenters are concentrated at the depth of 600 km. These data may be interpreted as an evidence of the deep fault separating the sea from the peninsula (Gordienko and Gordienko, 2018).

For determination of the Okhotsk micro-plate origin it is important to compare the lithosphere structure of this plate with structure of the adjacent regions. In Fig. 10a, the generalized velocity model of the upper mantle (the reference model IASP91 (Kennet and Engdahl, 1991) and the average model for the Northern Eurasia (Pavlenkova, 2011) are presented. These models characterize regions that are essentially different in their geodynamics: the IASP91 model based on seismological data mainly represents the upper mantle structure of tectonically active regions. The Northern Eurasia model, based on the Russian Peaceful Nuclear Explosion (PNE) seismic data, characterizes the platform areas with low heat flow. This model differs from the reference model by higher velocities to a depth of 200–250 km.

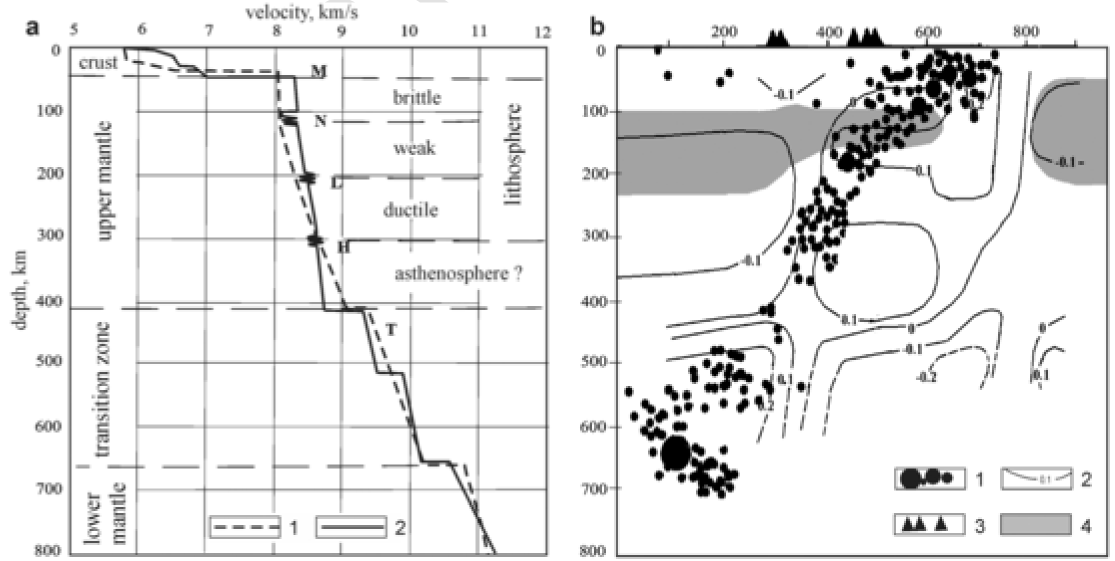

Fig. 10. (a) Generalized velocity models of the upper mantle and transition zone to the lower mantle: 1 - reference model IASP91 (Kennet and Engdahl, 1991), 2 – the model for the Northern Eurasia (Pavlenkova, 2011). (b) Structure of the Kuril-Kamchatka earthquake focal zone (Pavlenkova et al., 2018): 1 – earthquakes of various energy categories; 2 – P-wave velocity anomalies in km/s; 3 - Kamchatka volcanoes; 4 – area of mantle rocks partial melting (Gordienko and Gordienko, 2018).

As the Okhotsk region is characterized by high tectonic activity, it was assumed that the seismic velocities in the upper mantle of this region would be close to the IASP91 model and somewhat lower than in the central parts of the Eurasian continent. However, the seismic data from the 1-OM profile show that beneath the sea depression the P- velocities at the upper 70 km of the mantle are 8.0–8.1 km/s. That is comparable with the continental velocities.

The Eurasian continent is characterized by the large thickness of the lithosphere, about 300 km, and the lithosphere is divided by several seismic boundaries on layers with different rheological properties (Fig. 10a). The waves recorded from these mantle boundaries are multiphase interference oscillations with the first phases travel-time form which is characteristic to reflected waves. At the boundaries, there is no significant increase in the average mantle velocities, and the seismic modeling has shown that the large magnitude of these multiphase waves can be explained by the internal structure of these boundaries represented by чередование alternating thin layers with the higher and lower velocities (Pavlenkova, 2011).

Experimental data on petrophysical properties of the upper mantle matter at high pressure and temperature and the data on deep xenoliths have showed a large role of the energy-intensive deep fluids in the formation of these complicated seismic boundaries. The fluids change the physical properties of the mantle rocks, their porosity and mobility, sometimes their composition (Kern, 1993; Lebedev et al., 2017). The fluids decrease the seismic velocities but the matter flows produce the high velocity anisotropy. As a result, the complicate zones with alternation of the higher and lower velocities are created. The multiphase records from these zones (the mantle boundaries in Fig. 10a)) include the refracted, reflected and multiple waves from their thin laminas.

The Okhotsk plate lithosphere is studied by the seismological methods and its structure can be revealed from the data of the Kuril-Kamchatka earthquakes hypocenters (Fig. 10b). Generalization of these materials, carried out on a dense network of the Russian and Japanese seismological stations, allowed to reveal several particular features in the structure of this hypocenter zone (Igarashi et al., 2001; Gordienko and Gordienko, 2018). These features are correlated with the Eurasian upper mantle rheological stratification. At depths of about 100 km a change in the inclination of the focal zone is observed (Fig. 10b), that corresponds to the bottom of the lithosphere brittle part in the Eurasia continent, to the N1 and N2 boundaries (Fig. 10a). The latter can be interpreted as a zone of deep fluids concentration and gas fluxing (Pavlenkova, 2011). This is consistent with proposed area of the mantle rocks partial melting in the Kuril-Kamchatka region (Gordienko and Gordienko, 2018) (Fig. 10b).

At the depth of 200 km a gap in the focal zone coincides with the L boundary (Lehmann, 1959), observed in the continents by seismological methods and along the all PNE Russian profiles. At a depth of 300–400 km, in the proposed continental asthenosphere (Fig. 10a), the earthquake hypocenters are almost completely absent.

Thus, the upper mantle velocities beneath the Okhotsk Sea depression and the clear correlation of the Kuril-Kamchatka earthquake hypocenters with the Eurasia upper mantle structure suggests that not only the Earth's crust of the Okhotsk Sea, but also its entire lithosphere is close to the lithosphere of the neighboring continent. These data are very important for determination of the Okhotsk plate origin and its dynamic history. They are of great interest for studies of the whole transition zone between the Eurasia continent and the Pacific ocean.

6. Geodynamics of Okhotsk Sea region

Geodynamic interpretation of the described above geophysical data includes an explanation of the Okhotsk plate origin and of the petrophysical processes forming the structural features of its crust, the large sea depression and the local deep basins.

6.1. Origin of the Okhotsk plate

The combined geological and geophysical studies in the transition zone between Eurasia continent and the Pacific ocean show that the boundaries limiting the Okhotsk plate are related to the large deep faults of global significance (Fig. 11).

The eastern boundary of this plate is the fault along the Kuril island arc which is a part of the Pacific "subduction zone". The northern boundary of the plate is the Magadan fault. It is also very deep mantle fault (Fig. 9). It can be assumed that this fault is traced along the Eurasia continent margin from the Okhotsk Sea to Chukotka, as a part of the so-called "Ring of Fire", identified by geological data (Yano, 2014). This ring is characterized by a high level of volcanism and transformation of the crust by antle intrusion in the Cretaceous period (Fig. 11).

These data allow suggesting that the formation of the Okhotsk plate occurred in the Cretaceous times, when the tectonic active zones of the Pacific "Ring of Fire" were formed, and they separated the plate from the Asian continent. The relative displacement of this plate to the neighboring continent has not occurred along this zone.

The eastern boundary of the Okhotsk plate, the Sakhalin fault, is a part of the Pacific global disturbance zone extending hundreds of kilometers from the northeastern edge of the Japanese Islands to the Mariana Islands (Fig. 11). This fault zone is traced as an active seismicity zone in the Eurasian continent (Salnikov, 2007). The global character of this Mariana-Sakhalin-Siberia fault zone is confirmed by the data on the Earth degassing: it is an area of high hydrogen flows, which stretches from the Western Pacific to the Arctic oceans (Syvorotkin, 2002). In the plate-tectonic construction, this fault is considered as a boundary between the Eurasian and North American plates (Steblov et al., 2003).

The position of the Okhotsk plate between these large distraction zones results in development of many quite different conceptions on the origin of the plate. The most common and generally accepted state that the Okhotsk region is a part of the larger North American plate (Steblov et al., 2003; Bird, 2003 and others). However, in some publications the Okhotsk micro-plate, including Kamchatka Peninsula and the Sakhalin Island, was considered as a part of the Eurasia plate (Seno et al., 1996; Yano, 2014; Pavlenkova, 2019). There were also conceptions on the oceanic nature of the Okhotsk Sea crust which may be formed as a result of the lithosphere spreading between

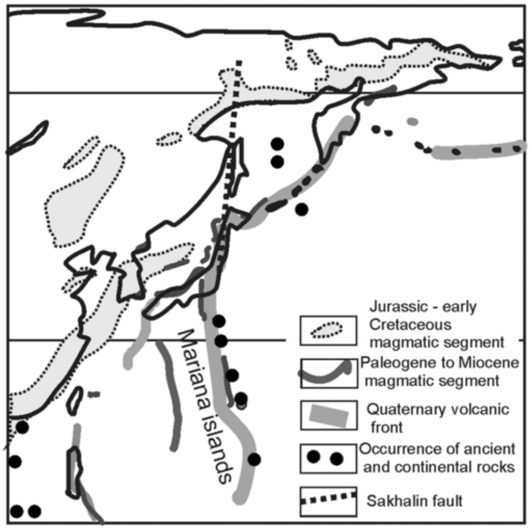

Fig. 11. The main tectonically active and deep destruction zones of the Okhotsk region (Yano, 2014).

the Sachalin and Kamchatka (Zonenshain et al., 1990). The less justified and unrealistic model of the Okhotsk Sea origin was proposed by (Bogdanov and Dobretsov, 2002): it was considered as a local oceanic plate intruded in the Asian continents.

The described above seismic data on the deep structure of the Okhotsk plate give grounds to an assumption that this plate is a part of the Eurasian continent. The main argument is the observed similarity of the Okhotsk and Eurasian lithosphere structure. The Okhotsk Sea is a tectonic active region however the velocities in the uppermost mantle are the same as beneath the continent, 8 km/s (Fig. 5a). In both regions, the lithosphere thickness is about 300 km and three main layers with different rheological properties are observed (Fig. 10). This similarity in the lithospheric structure of the Okhotsk micri-plate and the Eurasia continent cannot be occasional and it is the main proof to consider the micro-plate as a part of the continent. It is not an assumption but factual data.

The Okhotsk plate differs from the Eurasian continent only by the lower thickness of the crust. However, such change of crustal thickness is not a feature of this region alone; that is a general pattern for the continental margins of all continents (Mooney, 2007; Pavlenkova, 2019). In Eurasia, it is observed in the West Europe (Meissner, 1986; Grad et al., 2009), in the Barents-Kara shelf zone of the Arctic (Petrov et al., 2019) and in the eastern parts of the continent (Bing Xia et al., 2015).

The data on the age of the “Ring of Fire”, that is the northern boundary of the Okhotsk plate, allows to assume the time when the plate might be separated from the continent: it is Jurassic – early Crataceous (Fig. 11). No significant rearrangement of the plate lithosphere happened at that time.

6.2. Formation of the Okhotsk Sea depression and its local basins

Formation of the Okhotsk Sea depression may be described by the geodynamic processes, which are typical for the continental deep basins. The crustal thickness decreases beneath these basins with a reduction in thickness of the upper granite-gneiss layer. To explain such transformation the different processes were proposed. The most studied and the most reliable processes are the processes of the crust “basification” (Frolova et al., 1992), mechanical mobility of the weak middle crust (Pavlenkova et al., 2016), and “eclogitization” of lower crust (Artyushkov, 2010) .

The formation of the continental basins due to the crust basification means not only the intrusion of the mafic material into the crust but also the transformation of the crust as a result of the metamorphic and volcanic processes. Such processes are widely studied and are shown to take place in many deep basins (Frolova et al., 1992). The intensive mantle intrusions were not of great importance in the formation of the Okhotsk Sea depression because no high-velocity intrusion was identified in the consolidated crust of the central part of the depression (Figs. 3 and 5). The dominant processes of the crust basification were the increases of density and seismic velocity due to the crust immersion, changes in the pressure-temperature (PT) conditions and the corresponding rock transformation.

An important source of such transformation belongs to the deep fluid advection (plumes). Fluids facilitate the metasomatic processes, that significantly change the petrophysical properties of the rocks (Kern, 1983; Lebedev et al., 2017). Mantle fluids also bring into the crust the mantle material, increase the crust temperature and stimulate the changes in the mechanical properties of rocks, their plasticity and mobility. As a result, any crust deformation can move out the weak materials from the layers beneath the basins and produce the corresponding reduction in the crust thickness (Pavlenkova et al., 2016). In the Okhotsk region, the zones of the most intensive fluids advection may be the areas of high seismic velocities extending through the entire mantle and associated with hypocentral zones of deep earthquakes (Fig. 9). These zones are indeed characterized by intense flows of high-energy fluid; for instance, the Kuril arc zone are fixed by major changes in the composition and temperature of the ionosphere.

The process of “eclogitization” of the lower crust rocks led to an increase in their density and the seismic velocity to the upper mantle values of 8.0 km/s (Artyushkov and Baer, 1986; Artyushkov, 2010). As a result, the crustal thickness decreased and the Moho uplifted. It is a well-grounded process in the formation of the Okhotsk Sea depression, where the thickness of the crust reduces and the M boundary rises. This process may also explain the formation of the two boundaries M and M1, which are the young and the old Moho, with the eclogite layer located in between them (Fig. 5a).

The Kuril basin has a different nature. Such basins of elongated shapes with thin and high seismic velocity crust are often associated with rifting processes, which consist in stretching of the crust and formation of spreading zones filled with mantle material (Figs. 3 and 5b). However, as noted above, in the consolidated crust of the Kuril basin there are thin layers with the mafic velocity of 7.1 km/s but the ratio 1.86 is typical for the continental rocks (Fig. 4). This means that the Kuril basin have been formed by a combined process of rifting and continental crust destruction, so that at present the basin crust is composed from the remains of the continental rocks mixed with basalts.

Thus, during the formation of the Okhotsk Sea depression, several tectonic processes may be proposed with their effects gradually changing from the continent to the Kuril arc. In the central part of the depression, the main process was a quiet process of “eclogitization” of the lower crust, in the southern part there was some consolidation of the crust due to its “basification”, and in the Kuril zone, the rifting and the continental crust destruction were prevailed.

The different intensity of the dynamic processes involves variability in the area of the respective energy sources. In this case, the main source was obviously the Pacific focal zone of deep earthquakes. It is characterized by a high heat flow, active volcanism and high-temperature degassing. Apparently, this zone is a channel of intensive deep fluids advection. The intensity of thermal advection from the focal zone depends upon its depth. Near the centre of Okhotsk Sea, the focal zone depth reaches 600 km. The heat from this depth covers a large area and contributes to the uniform eclogitization of the crust. Near the Kuril arc, the depth to this high heat flow zone decreases, and the crust transformation due to basification and rifting becomes more intense.

The above is our summary of the general history of the Okhotsk plate formation which follows from the detailed seismic studies of this region.

7. Conclusion

The re-processing, interpretation and integration of the deep seismic studies in the Okhotsk Sea region allows us to describe the detailed structure of the Earth's crust and geodynamics of this transition zone from the continent to ocean while addressing a number of important scientific problems. The main results of this integration are as follows.

(1) The crust of the Okhotsk region belongs to the continental type with an average thickness of 25–30 km. The major part of the crust is composed of the felsic rocks with seismic velocities of 5.7–6.3 km/s. Only within the Kuril basin zone, the crust thickness is reduced to 12–14 km, and it is composed of the rocks of both the felsic and mafic composition.
(2) The structure of the Okhotsk Sea depression is similar to other deep sedimentary basins in the platform regions. A specific feature is only two reflected boundaries M and M1 (Double Moho) at the crust bottom of the sea.
(3) The lithosphere of the Okhotsk Sea region also contains the characteristic features of the lithosphere structure of the Northern Eura-

sia. The thickness of the lithosphere is about 300 km and it is divided by seismic boundaries on several layers. This means that this region is a part of the Eurasia continent.

(4) The Sea of Okhotsk is surrounded by deep faults of global nature. In addition to the Kuril subduction zone in the south, the sea is limited from the north by the Magadan zone of Jurassic-Cretaceous tectonic activation. A deep disturbance zone is also revealed along the Sakhalin Island. These faults allow us to identify the Okhotsk region as a separate lithosphere plate which was separated from the continent in the Cretaceous.

(5) The structural features of the Okhotsk plate suggest that the process of sea formation depended mainly upon the intensity of the heat and deep fluid flows. They triggered influx of the mantle material in the crust from a great depth and facilitated metamorphism of the rocks. The intensity of such transformation is increased from the north to south parts of the sea and that means that the most intense deep flows come from the Kuril subduction zone.

Credit author statement

Nina Pavlenkova: Conceptualization, Writing and Editing
Sergey Kashubin: Methodology, Data curation and interpretation
Tamara Sakoulina: Data interpretation
Galina Pavlenkova: Graphic preparation

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors thank the leading specialists of "Sevmorgeo" for the cooperation in working on the high-quality seismic data and all colleagues for proceeding the data and fruitful discussions of main results of these common studies.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The described studies were a part of the IFZ scientific program.

References

Artyushkov, E.V., 2010. Mechanism of formation of ultra-deep sedimentary basins. Stretching of the lithosphere or eclogitization? Russ. Geol. Geophys. 51 (12), 1675–1686.

Artyushkov, E.V., Baer, M.A., 1986. Mechanism of formation of hydrocarbon basins: the west Siberia, Volga–Urals, Timan–Pechora basins and the Permian Basin of Texas. Tectonophysics 122, 247–281.

Beloussov, V.V., Pavlenkova, N.I., 1984. Types of the earth's crust. J. Geodyn. 1, 167–183.

Bijwaard, H., Spakman, W., Engdahl, E.R., 1998. Closing the gap between regional and global travel time tomography. J. Geophys. Res. 103 (B12), 30055–30078.

Bird, P., 2003. An updated digital model of plate boundaries. Geochemistry, Geophys. Geosystems 4. doi:10.1029/2001GC000252.

Blyuman, B.A., 2011. The Earth's Crust of the Oceans. Data of the International Programs of the Deepwater Drilling in the World Ocean. VSEGEI, S.Peterburg. (344 pp. (in Russian).

Bogdanov, N.A., Dobretsov, N.L., 2002. Okhotsk oceanic volcanic plateau. Russ. Geol. Geophys. 43 (2), 101–104.

Červeny, V., Pšenčik, I., 1983. SEIS 83-numerical modeling of seismic wave fields in 2-D laterally varying layered structure by the ray method. In: Engdahl, E.R. (Ed.), Documentation of Earthquake Algorithms, World Data Cent. A. for Solid Earth Geophys. pp. 36–40. Boulder, Rep. SE-35.

Červeny, V., Molotkov, I.A., Psencik, I., 1977. Ray Method in Seismology. Univerzita Karlovo, Praha. (214 pp).

Downes, H., Pchtonen, P., N'Ianttari, I., Sharkov, E.V., 2002. Proterozoic zircon aces from lower crustal granuliie xenohiths, Kola Peninsula, Russia: evidence of crustal growth and reworking. International Geological Society 159, 485–488.

Frolova, T.I., Perchuk, L.L., Burjakova, I.A., 1992. Magmatism and Transformation of Active Areas of the Earth's Crust. Oxford & IBH Publishing CO.PVT.LTD, New Delhi. (271 pp).

Galperin, E.I., Kosminskaya, I.P. (Eds.), 1964. The Structure of the Earth's Crust in the Transition from the Asian Continent to the Pacific Ocean. Nauka, Moscow. (308 pp (In Russian).

Gordienko, V., Gordienko, L., 2018. Plate tectonics and earthquakes. New Concepts in Global Tectonics Journal 6 (4), 481–493.

Grad, M., Tiira, T., ESC Moho Working Group, 2009. The Moho depth of the European Plate. Geophysical Journal Intenational 176, 279–292.

Igarashi, T., Matsuzawa, T., Umino, N., Hasegawa, A., 2001. Spatial distribution of focal mechanisms for interplate and intraplate earthquakes associated with the subducting Pacific plate beneath the northeastern Japan arc: a tripled-planed deep seismic zone. J. Geophys. Res., 106. P. 2177–2191.

Kashubin, S.N., Sakoulina, T.S., Pavlenkova, N.I., Lukashin, Y., 2011. Characteristics of compressional and shear waves generated in marina deep seismic studies. Technology of Seismic Prospecting 4, 88–102. (in Russian with English abstract).

Kashubin, S.N., Lukashin, Y., Sakoulina, T.S., Pavlenkova, N.I., 2013. Modern methods of conducting and interpretation of deep seismic sounding in the marginal seas of Russia. In: Relevance of G. A. Gamburtsev's Ideas in the XXI Century. Nauka, Moscow, pp. 175–194. (In Russian).

Kashubin, S., Petrov, O., Rybalka, A., Milshtein, E., Shokalsky, S., Verba, M., Petrov, E., 2017. Earth's crust model of the South Okhotsk Basin by wide-angle OBS data. Tectonophysics 710–711, 37–55.

Kennet, B.L.N., Engdahl, E.R., 1991. Travel times for global earthquake location and phase identification. Geophys. J. Int. 105, 429–465.

Kern, H.M., 1993. Physical properties of crustal and upper mantle rocks with regards to lithosphere dynamics and high pressure mineralogy. Phys. Earth Planet. Inter. 79, 113–136.

Kremenetskii, A.A., Ovchinnikov, L.N., 1983. Model of the chemical composition of the initial crust of continents. DAN SSSR 270 (6), 1462–1467.

Kulakov, I.Y., Dobretsov, N.L., Bushenkova, N.A., Yakovlev, A.V., 2011. The shape of slabs in subduction zones under the Kurile-Kamchatka and Aleutian arcs according to the regional tomography. Russ. Geol. Geophys. 52 (6), 830–851.

Lebedev, E.B., Pavlenkova, N.I., Lukanin, O.A., 2017. Experimental studies of the water influence on the elastic wave velocity in dunite and serpentinite (on the nature of the low velocity zone in the upper mantle of the Earth). DAN RAS 472 (1), 1–4.

Lehmann, I., 1959. Velocities of longitudinal waves in the upper part of the Earth's mantle. Ann. Geophys. 15, 93–118.

Meissner, R., 1986. The Continental Crast: A Geophysical Approach. Academic Press, London. (426 pp).

Mooney, W.D., 2007. Crust and lithospheric structure - global crustal structure. In: Romanowicz, B., Dziewonski, A. (Eds.), Treatise on Geophysics, Vol. 1: Seismology and Structure of the Earth. Elsevier, pp. 361–417.

Pavlenkova, N.I., 2011. Seismic structure of the upper mantle along the long-range PNE profiles – rheological implication. Tectonophysics 2011 (508), 85–95.

Pavlenkova, N.I., 2019. Unsolved problems of the global tectonics and possibility of their solution. Geofizicheskii Zhurnal (Geophysical Journal) 41 (2), 1–57. (in Russian with English abstract). doi:10.24028/gzh.0203-3100.v41i2.2019.164448.

Pavlenkova, N.I., Pilipenko, V.N., Verpakhovskaja, A.O., Pavlenkova, G.A., Filonenko, V.P., 2009. Crustal structure in Chile and Okhotsk Sea regions. Tectonophysics 472, 28–38.

Pavlenkova, N.I., Kashubin, S.N., Pavlenkova, G.A., 2016. The Earth's crust of the deep platform basins in the Northern Eurasia and their origin. Izvestiya, Physics of the Solid Earth 52 (5), 770–784.

Pavlenkova, N.I., Kashubin, S.N., Gontovaya, L.I., Pavlenkova, G.A., 2018. Deep structure and geodynamics of the Sea of Okhotsk region. Regional geology and metallogenia 76, 69–82. (in Russian with English abstract).

Petrov, O.V., Kashubin, S.N., Milshtein, E.D., Androsov, E.A., Pavlenkova, N.I., Shokalsky, S.P., Erinchek, Y., 2019. Map of crustal types in the Arctic. In: Petrov, O.V., Pubellier, M. (Eds.), Sientific Contributions to the Tectonic Map of the Arctic (VSEGEI/CGMW). CGMW, Paris, pp. 26–32.

Roslov, Y., Sakoulina, T.S., Pavlenkova, N.I., 2009. Deep seismic investigations in the Barents and Kara Seas. Tectonophysics 472, 301–308.

Sakoulina, T.S., Kulenich, A.P., Atakov, A.I., Tichonova, I.M., Krupnva, N.A., Pizhyanova, T.M., 2011. The geological model of the Okhotsk sea region according to the reference profiles of the 1-OM and 2-DV-M. Prospecting and Protection of Mineral Resources 10, 11–17. (In Russian).

Sakoulina, T.S., Pavlenkova, G.A., Kashubin, S.N., 2015. Structure of the Earth's crust in the northern part of the Barents–Kara region along the 4-AR DSS profile. Russ. Geol. Geophys. 56, 1622–1633.

Salnikov, A.S.(red.), 2007. Structure of the Crust in the Magadan Region of the Pussia from Geophysical Data. Novosibirsk, "Nauka". (172 pp (in Russian).

Seno, T., Sakurai, T., Stein, S., 1996. Can the Okhotsk Plate be discriminated from the North American plate? J. Geophys. Res. Solid Earth 101, 11305–11315. doi:10.1029/96jb00532.

Steblov, G.M., Kogan, M.G., King, R.W., Scholz, C.H., Brgmann, R., Frolov, D.I., 2003. Imprint of the North American plate in Siberia revealed by GPS. Geophys. Res. Lett. 30 (18).

Suleimanov, A.K., Zamognaja, N.G., Andryuschenko, Y., Lipilin, A.V., 2007. Deep seismic studies with reflected waves red. In: Salnikov, A.S. (Ed.), Structure of the Crust in the Magadan Region of the Pussia from Geophysical Data. Nauka, Novosibirsk, pp. 23–26. (in Russian).

Syvorotkin, V.M., 2002. Deep Degassing of the Earth and Global Catastrophes. OOO Geoinformcentre, Moscow. (250 pp. (in Russian).

Xia, B., Thybo, H., Artemieva, I., 2015. Seismic crustal structure of the North China Craton and surrounding area: synthesis and analisis. Journal of Geophysical Research: Solid Earth 1–27. doi:10.1002/2016jB013848.

Yano, T., 2014. Tectonic development of the Pacific Ocean and its periphery: a constraint on large-scale rotations of lithospheric blocks. NCGT Journal 2 (2), 54–68.

Zelt, C.A., Ellis, R.M., 1988. Practical and efficient ray tracing in two-dimensional media for rapid traveltime and amplitude forward modeling. Can. J. Explor. Geophys. 24 (1), 16–31.

Zonenshain, L.P., Kuzmin, M.I., Natapov, L.M., 1990. Geology of the USSR: A Plate-Tectonic Synthesis. In: Geodynamics Series, 21. American Geophysical Union, Washington, D. C.