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Shallow Seismicity of the Sea of Okhotsk and Its Probable Tectonic Nature

I. N. Tikhonov and V. L. Lomtev

Institute of Marine Geology and Geophysics, Far East Branch of the Russian Academy of Sciences, Yuzhno-Sakhalinsk, ul. Nauki 1b, 693022 Russia

e-mails: tikhonov@imgg.ru, lomtev@imgg.ru

Abstract—Based on the analysis of different seismological data on the Sea of Okhotsk, two of the fullest catalogs of shallow-focus earthquakes are made for the historical (1735–2010; $M \geq 5.0$) and instrumental (1962–2010; $M \geq 4.0$) periods. The peculiarities of the lateral and depth distributions of seismicity are considered, and earthquake recurrence on three shelf zones of the Sea of Okhotsk is estimated. Maps of earthquake hypocenters are compared with the Moho depth scheme. With the data of seismic continuous profiling (SCP) and common depth point studies (CDP) taken into account, the probable relationship between the tectonic nature of seismicity in the Sea of Okhotsk and the mobility and allochthonous occurrence of the crust (divergent glide on the Okhotsk Swell, regional thrusts along the island arc margins, subsidence of the Kuril Basin's bottom) is examined.

Keywords: Sea of Okhotsk, earthquake catalog, shallow seismicity, Earth's crust, basement, cover, swell, basin, shelf, active fault

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INTRODUCTION

The Sea of Okhotsk is a marginal sea located within the limits of the Pacific seismic belt which, in its order, hosts more than 80% of earthquakes on Earth, including most catastrophic events. Strong and major earthquakes occurring east of the Kuril Islands are accompanied by great destruction and human death. The most striking examples are the Kamchatka earthquake of November 04, 1952 ($M_w = 9.0$) (MacInnes et al., 2010) and the Shikotan one of October 4, 1994 ($M_w = 8.3$) (*Shikotanskoe*..., 1994; Aleksin et al., 1995). Considerable damage is related to the fact that most seismic events in the region of the Kuril–Kamchatka arc occur in the Benioff focal zone dipping beneath the continent (Tarakanov, 2006). The existence of this zone is attributed to either subduction of the Pacific Plate beneath the Okhotsk Plate (Le Pichon et al., 1973; Wei and Seno, 1998) or deep thrust of Eurasia onto the bottom of the Nortthwest Pacific (Sergeev, 1976; Lomtev et al., 2012). The Benioff zone reaches the Earth's surface on the continental slope of the Kuril–Kamchatka deep trench. An additional, although almost not studied, contribution to the seismicity of the island arc is made by the shallow opposite focal zone discovered south of here and named (Kropotkin, 1978) "Tarakanov zone." North of Honshu Island, the focal zone is exposed on the surface near the volcanic front (line of Quaternary volcanoes) (Tarakanov et al., 1977; Hasegawa et al., 1978).

However, the present work's object of study is the shallow-focus (crustal) seismicity of the Sea of Okhotsk related to the tectonics of crust of up to ~20–40 km thick (Poplavskii and Bobkov, 2001; *Tektonika*..., 2004). The investigation of the seismicity of marginal seas and open ocean differs from that of land. The seafloor is reachable by seismological study only with difficulty; therefore, marine seismic catalogs are less full, and the accuracy of hypocenter localization is lower. The seismicity level in the central parts of marginal seas is usually lower than that in the peripheries (Gordeev et al., 2006). Some segments of the peripheries can considerably differ in seismicity level both within the limits of any given sea and for different seas, at that. Seismic activity east of the Kuril Islands is nearly maximal for the entire Earth, while west of it, in the Sea of Okhotsk, it is of a moderate character (*Novyi*..., 1977; Ivashchenko et al., 1990).

INITIAL DATA

Data on seismicity in the Sea of Okhotsk are available from a number of articles and chapters of some monographs (Soloviev et al., 1967; *Novyi*..., 1977; *Seismicheskoe*..., 1980; *Seismichnost'*..., 1993, 1995). Additionally, there are particular data in various catalogs and bulletins (JMA..., 1926–2000; Bulletin..., 1974–2005; JNEC, 1985–1990; *Unifitsirovannyi*..., 1996; *Operativnyi*..., 2005–2010; *Katalog zemletryasenii*..., 2001) and in the yearbooks *Zemletryaseniya v* 2
SSSR (Earthquakes in USSR) and *Zemletryaseniya* 2

Severnoi Evrazii (Earthquakes in Northern Eurasia) as well. The data of instrumental seismological observations in 1913–1975 for the Sea of Okhotsk region were considered in (Poplavskaya and Oskorbin, 1977): these authors concluded that the data from 1913–1958 are heterogeneous and often unreliable; in the following period (1959–1975), when the network of seismic stations was developed and their equipment was enhanced, more high-quality data began to be obtained. The next generalizing analysis of seismicity in the Sea of Okhotsk was made in (Ivashchenko et al., 1990).

The study of shallow seismicity in the Sea of Okhotsk is topical for several reasons. First, the strongest earthquakes near the coasts can be significant hazard for harbor facilities and coastal settlements. Second, the intensive industrial development of oil and gas fields (in particular, on the northeastern shelf of Sakhalin) also requires a degree of seismic risk and hazard to be taken into account. In its order, the informational basis for any seismic zoning is a unified catalog of earthquakes representative for the studied area. Third, the underestimation of seismic hazard may lead to the underestimation of possible tsunami hazards associated with strong underwater earthquakes, and hence to human death and considerable economic loss.

In the present work, we addressed the following problems:

(1) preparation of a catalog of strong (Ì ≥ 5.0) shallow earthquakes ($h \leq 60$ km), both historical and contemporary, for the water area of the Sea of Okhotsk;

(2) compilation of a more detailed catalog for this region (earthquakes with *Ì* ≥ 4.0) for the last half-century;

3) description of the seismic regime in the areas of highest activity;

4) analysis of the relationship between seismicity and thickness and tectonics of the Earth's crust.

When compiling cumulative earthquake catalogs, we took into consideration the peculiarities of initial data published by different agencies in order to choose the most full and reliable estimates of earthquake parameters. The problem regarding seismic-regime description was solved using standard seismological approaches. The fourth problem mentioned above was solved using geological–geophysical data (mainly CDP and SCP, with the elements of new geological interpretation). Considering the new character of some conclusions obtained, we consider the present work to be posing a problem.

The investigation of the crustal structure of the Sea of Okhotsk, Kuril arc, and the adjacent seafloor of the Northwestern Pacific began under the auspices of the International Geophysical Year, when the Institute of Physics of the Earth, Academy of Sciences of USSR, made a network of deep seismic sounding profiles (*Stroenie*..., 1976). In the 1970–1980s, the Institute of Marine Geology and Geophysics (IMGG, Far East Branch of Academy of Sciences of USSR), *Dal'morneftegeofizika* geophysical enterprise, the Far East Office of Marine Survey Drilling (FEOMSD), and the Far East Marine Geological Engineering Expedition (FEMGEE) carried out geological–geophysical studies of various scales and depths, including depth measurements, SCP, CDP, and refracted wave correlation (RWC); gravimetry, magnetometry, and thermometry; dredging, core sampling, prospecting, and stratigraphic drillings. The densest survey was implemented on the shelves of Northeastern Sakhalin, Western Kamchatka, the Cis-Magadan Region, shallow-water northwestern Sea of Okhotsk (Okhotsk-Shantar sedimentary basin), and in southern Middle Kuril trough and its adjacent areas (Chuiko et al., 1988; *Geologiya*..., 2002; *Tektonika*..., 2004). In this period, a regional geological–geophysical survey was also implemented for the submarine margins of the Japan Islands (Geological..., 1978, and others) and almost all marginal seas of the Pacific, primarily for the purposes of petroleum geology (Gnibidenko, 1979).

As a result of this work, the bathymetry was specified; maps of the Cenozoic cover isopachs and those of the acoustic basement depths (composed of volcanogenic–sedimentary rocks of the Cretaceous, or the Paleozoic in the northwestern Sea of Okhotsk) were published; the composition, age (in part), and petrophysics (in part) of the recovered rocks of the basement and sedimentary cover were found; the main features of stratigraphy, tectonics, magmatism, and geological evolution of the Sea of Okhotsk basin and other marginal seas of the Pacific were outlined. In earlier publications it was believed there had been an Okhotsk rigid block, or a middle massif with continental (subcontinental) crust, surrounded by Cenozoic folding zones. Later, as plate tectonics were developed, the range of ideas significantly expanded: mantle diapirism, backarc spreading (Karig, 1971; Zlobin, 2006); gapping in the zone of left-lateral mega-strike–slip between Eurasia and the Pacific (Utkin, 1980), and other hypotheses. Nevertheless, almost all researchers thought that Cenozoic riftogenesis played a leading role in the Sea of Okhotsk and other marginal seas of the Pacific (Gnibidenko, 1979; *Stroenie*..., 1976, 1981; *Tektonika*..., 2004). It is attributed to in situ tension and tectonic subsidence of continental crust on a system of normal faults confining horsts and grabens of the Meso-Paleozoic acoustic basement (Emelyanova, 2004). Grabens are filled with Cenozoic marine and coastal-marine deposits (Bol'shakov et al., 1989). Commonly accepted ideas are (i) the stratified, without detachment, occurrence of the crust upon the mantle; (ii) large crustal protrusion in the Kuril Basin (*Stroenie* ..., 1976; Prokudin and Medvedev, 2011); and (iii) relationship between the crustal seismicity of coasts of the Sea of Okhotsk and the active faults exposed in part in the water area (Vashchilov et al., 2004; Voeikova et al., 2007; Trifonov and Kozhurin, 2010; Kharakhinov, 2010).

In the last decades, seismologists have considerably enhanced the accuracy of the determination of hypocenter location for both land and offshore earthquakes. E.g., on Sakhalin Island and in its submarine margins, strong earthquakes occurred in the lithosphere at depths of 50–150 km and, as determined in (Soloviev et al., 1968), received a crustal status (Nagornykh et al., 2003). The main problem in the seismotectonics of the Sea of Okhotsk is the mobility of the crust and the aseismicity of the subcrustal mantle. Apart from the seismicity, crustal mobility is proved by other evidence: (i) the considerable (5–12 km) amplitude of the acoustic basement relief, which is typical for continental mountain regions (akin to the so-called Okhotia (Lomtev et al., 2002; *Tektonika*..., 2004)); (ii) discordance between the Japan–Sakhalin arc and the seismoisobaths of the Benioff zone (*Geologo-geofizicheskii*..., 1987; Tarakanov et al., 1977); and (iii) the regional thrust (up to 30–70 km long) of the Kuril and Tohoku arcs upon the bottom of the Northwestern Pacific in the Middle Pleistocene to the Holocene (Tihonov and Lomtev, 2011; Lomtev et al., 2012). Since there are no young longitudinal openings of comparable width in the seas of Okhotsk and Japan (*Osnovnye*..., 1978; *Tektonika*..., 2004)—openings that could compensate thrusting of the mentioned arcs—we have to state an allochthonous occurrence of the crust in these marginal seas. To investigate the signs of mobility of the crust in the Sea of Okhotsk, we used SCP and CDP data with a new geological interpretation, which had been tested earlier in the Kuril and Japan trenches, on the seafloor of Northwestern Pacific, and in some other areas (Lomtev, 2000, 2008, 2009, 2012; Lomtev and Patrikeev, 1985). In the Cenozoic, coal accumulation, abrasion of escarpments, and marine bioterrigenous sedimentation had considerably leveled the mountain relief of Okhotia and formed the plains in the shelf, avant-shelf, and seafloors of three bathyal basins of Sea of Okhotsk (Bol'shakov et al., 1989; *Tektonika*..., 2004).

PREPARATION OF CATALOGS OF SHALLOW-FOCUS EVENTS FOR 1735–2010 (*M* ″ 5.0) AND 1962–2010 (*M* ″ 4.0). PECULIARITIES OF REGIONAL SEISMICITY AND SEISMIC REGIME

The low population of the coastal areas of the Sea of Okhotsk during the historical period is the main cause of the scarce earthquake records for this time interval. Historical earthquakes in the Sea of Okhotsk Region, starting from 1735, are available in the catalog compiled by I.V. Mushketov and A.P. Orlov (1893). This catalog contains the data on earthquakes for the period of 1700–1888. The data for the period of 1889–1897 were given in additional issues published by I.V. Mushketov, and—from 1902 to 1907—in the bulletins of Permanent Central Seismic Commission.

In 1961, the *Atlas zemletryasenii v SSSR* (Atlas of Earthquakes in USSR) was published; it contained, in particular, an earthquake catalog for the Russian Far East for 1911–1953. In addition to the main earthquake parameters, it provided accuracy classes for the determination of the seismic event location. In 1977 another fundamental work had been finished and (*Novyi*..., 1977) (hereinafter, the New Catalog) had been published: this catalog generalized all the data available that time on the strong earthquakes in the territory of USSR. This catalog included all known historical events, and strong contemporary ones until 1974 inclusively. For every particular earthquake, the most probable value of each parameter was chosen on the basis of the entire set of available data. Estimates of each parameter's value were accompanied by estimates of determination accuracy.

In addition to the New Catalog, the present work drew on other sources of information (see the references).

Different estimates of the same parameters for the same events, based on the data from different seismological sources, complicated the work of compiling a unified catalog of seismic events. In the studied area, an additional complexity is the subdivision of the water area of the Sea of Okhotsk into six parts, with different divisions of the Geophysical Survey of the Russian Academy of Sciences (GS RAS) being responsible for their study. As a result, data on earthquakes in the Sea of Okhotsk Region can be found in the catalogs of the following regions: Northeastern Russia (Magadan Division of the GS RAS); Yakutia (Yakutian Division of the GS RAS); Kamchatka and the Komandor Islands (Kamchatkan Division of the GS RAS); Kuril–Okhotsk Region, Sakhalin, Cis-Amurian Region, and Primorye (Sakhalin Division of the GS RAS).

When compiling the catalog of strong shallow earthquakes in the Sea of Okhotsk Region, we imposed the following restrictions upon the values of earthquake parameters. Data on historical earthquakes were selected for all magnitudes (with the minimal value being 4.0), while for modern events the chosen magnitudes were $M \geq 5.0$. The range of hypocentral depths for surface quakes was assumed to be 0–60 km. This choice was based on the fact that the majority of earthquakes occur at depths from 0 to 30–40 km (Poplavskii and Bobkov, 2001). The compiled catalog included data from sources containing the most reliable estimates of earthquake parameters. Preferred data on earthquakes occurring in any of six sectors were usually those from the GS RAS division responsible for the given sector. Data from international earthquake catalogs were used mainly to provide for the completeness of the complied catalog.

When sampling data from the regional earthquake catalogs of the Kamchatkan Division of the GS RAS,

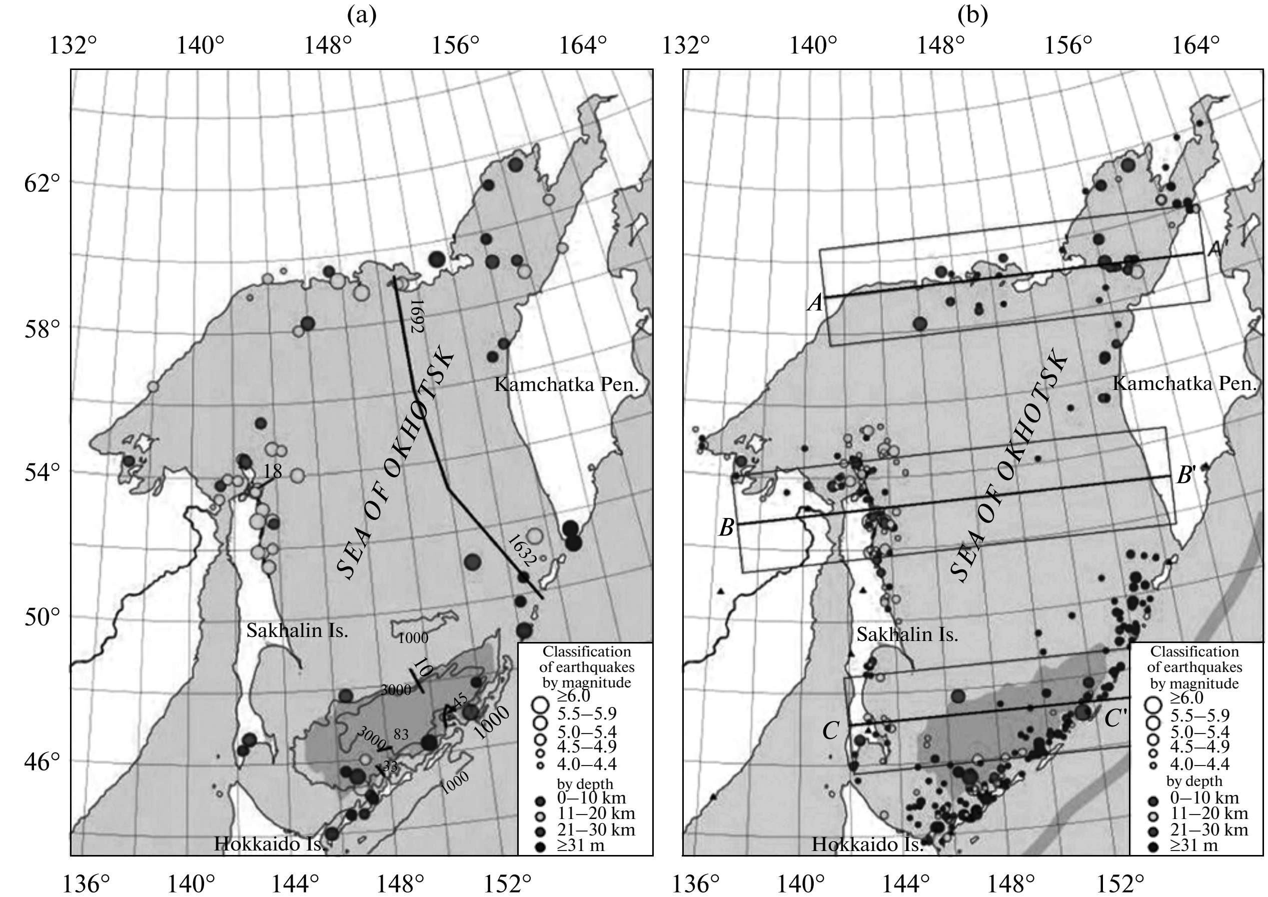

Fig. 1. (*a*) The map showing epicenters of all historical and contemporary earthquakes ($M \geq 5.0$, $h \leq 60$ km) in the Sea of Okhotsk for the period of 1735–2010, with the positions of the SCP and CDP profiles denoted. Isobaths, in meters, are shown fragmentarily, after (Krasnyi et al., 1981); (*b*) the map showing epicenters of shallow ($h \leq 60$ km) earthquakes with $M \geq 4.0$ in the Sea of Okhotsk for the period of 1962–2010, with the profiles A–A', B–B', and C–C' denoted (axial lines of vertical sublatitudinal section of the seismoactive zones of ±150 km wide). Triangles indicate locations of seismic stations.

values of energy class K_S, after S.A. Fedotov, were recalculated into magnitudes Ì based on the relation (Fedotov, 1972) $K_S = 4.6 + 1.5Ì$.

Analogously, values of energy class K_C, after S.L. Soloviev, for the Kuril–Okhotsk Region, were recalculated into magnitudes M based on the relation (Soloviev and Solovieva, 1967) $K_{\tilde{N}} = 1.2 + 2.0Ì$.

After processing the data, a catalog of historical ($M \geq 4.0$) and contemporary ($M \geq 5.0$, $h \leq 60$ km) earthquakes for the Sea of Okhotsk Region during the period of 1735–2010, including 81 event, was compiled. The map of the epicenters of these earthquakes is shown in Fig. 1a. Each line in the catalog contains a list of the estimates of main parameters for each particular earthquake (date and time in source, epicentral coordinates, focal depth, and magnitude), and the errors of these estimates as well. Each line also contains the source of information for the given earthquake.

The described scheme of data processing was also used when preparing the more detailed earthquake catalog for the Sea of Okhotsk Region during the period of 1962–2010 ($M \geq 4.0$, $h \leq 60$ km). This catalog includes 356 events. The map of the epicenters of these earthquakes is shown in Fig. 1b and the sublatitudinal vertical sections of seismoactive zones for the northern, middle, and southern parts of the Sea of Okhotsk are given in Fig. 2.

According to Fig. 1, almost all sources of crustal earthquakes with $M \geq 4.0$ are clustered near the coast of the Sea of Okhotsk. The highest seismicity level is observed in three areas: near the northwestern coast of Sakhalin Island, at one segment of the near-Kuril shelf, and in the northern Sea of Okhotsk (from the vicinity of Magadan to 56° N on the western coast of Kamchatka Peninsula).

The lowest seismicity level is observed in the central Sea of Okhotsk, and also within several aseismic "windows" of the first and second orders (northwestern Sea of Okhotsk, southwestern Kamchatka Peninsula for the first order; along the middle and southern Sakha-

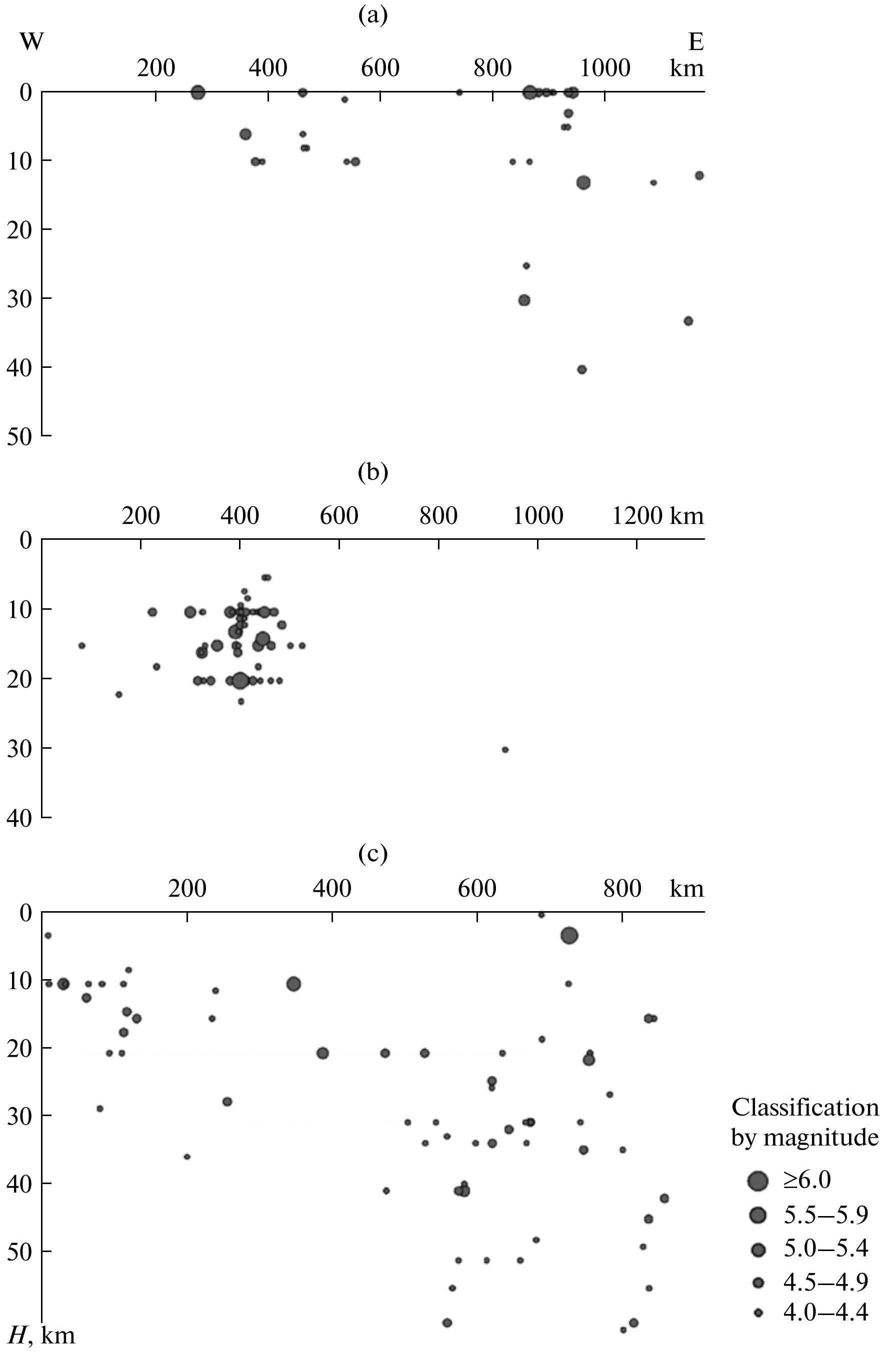

Fig. 2. Vertical sublatitudinal sections of the seismoactive zones along the A–A' (*a*), B–B' (*b*), C–C' (C) profiles, within the limits of ±150 km relative to these lines. Coordinates of end points: A (59.0° N; 141.0° E), À' (58.65° N; 161.40° E); B (52.65° N; 137.0° E), B'; (53.0° N; 157.0° E); C (47.1° N; 142.0° E), C'; (47.2° N; 154.0° E).

lin, and along Hokkaido, in the South Okhotsk (Kuril) bathyal basin for the second).

The assessment of the seismic regime using the earthquake recurrence graphs is feasible only for three areas with high seismicity, located at a great distance from each other and characterized by different seismotectonic settings. Let us construct the recurrence graphs for each of these areas on the basis of the catalog of earthquakes with $M \geq 4.0$ for the period of 1962–2010.

(1) The area near the northwestern coast of Sakhalin Island. Sakhalin Island is where the boundary between the North American and Eurasian plates is located; the system of main submeridional faults of the island is identified with this boundary (Prytkov and Vasilenko, 2011). Based on GPS observations, the

island is moving westward relative to Eurasia at the rate of from 2.5 mm/yr in the north to 7.6 mm/yr in the south. Over the entire extent of the island, the dominating deformations are those of sublatitudinal compression accompanied by right-lateral strike–slip.

Let us consider the sampling of earthquakes with $M \geq 4.0$ for this area confined between 50.0° and 55.7° N. The cumulative earthquake recurrence graph normalized to a one-year time interval, in the magnitude range of 4.0–6.7, is of the following form:

$$\log N = (3.65 \pm 0.13) - (0.82 \pm 0.03)M.$$

According to this graph, earthquakes with $M \geq 6.0$ near the northwestern coast of Sakhalin Island may occur approximately once every 23 years. Note that the recurrence period of the same events in the northern land part of the island is much smaller due to the fact that it is here that the main submeridional fault systems of high seismicity are located.

(2) Near-Kuril shelf. Here, epicenters of earthquakes with $M \geq 4.0$ occupy the band which is widest (up to 150 km and more) on the flanks of the Kuril arc, while the narrowest (~40 km) are in the central part. The cumulative earthquake recurrence graph on the western shelf of Kuril Islands is of the following form:

$$\log N = (3.83 \pm 0.21) - (0.83 \pm 0.04)M.$$

The resultant graph suggests that earthquakes with $M \geq 6.0$ may occur here approximately once every 16 years.

(3) Northern Sea of Okhotsk. The seismicity of this shelf zone is likely related to the tectonic activity of the Okhotsk–Chukotka volcanogenic belt which stretches along the northern coast of the Sea of Okhotsk (Êîçüìèí, 1984). Earthquake recurrence for this area is determined by the following equation:

$$\log N = (3.36 \pm 0.32) - (0.77 \pm 0.07)M.$$

This implies that earthquakes with $M \geq 6.0$ in the area can be expected approximately once every18 years.

When considering the three sublatitudinal sections shown in Fig. 2, we revealed a significant difference between depths of crustal earthquakes. E.g., in the northern profile, in the Cis-Magadan Region (see Fig. 2a), focal depths do not exceed 10 km (upper crust) with some deepening to 30–40 km (lower crust) in Gulf of Shelikhov and northwestern Kamchatka. The seismicity of Eastern Sakhalin and the adjacent water area of the sea of Okhotsk (Fig. 2b) is located over the entire continental crust in a range of ~20–40 km (*Tektonika*..., 2004). When comparing the central and southern profiles, it can be noticed that hypocentral depth increases towards Southern Sakhalin, from 22 (upper crust) to 35 km (lower crust). Thus, with the upper crustal earthquakes in the Cis-Magadan Region of the western Sea of Okhotsk taken into account, we can infer a meridional trend of deepening shallow (crustal) seismicity towards the south.

POSSIBLE TECTONIC NATURE OF SHALLOW-FOCUS SEISMICITY

Generally, shallow marginal seismicity is reported in the considered region, with a vast asesimic zone in the central part of the sea (Okhotsk swell), opening towards the Southwestern Kamchatka (Sobolevo basement high) and northwestward (Okhotsk–Shantar sedimentary basin with a system of submeridional horsts and grabens compensated by sediment transport of the Amur River (*Geologiya*..., 2002)) (see Figs. 1–3). Seismic zones tend to the Kuril Islands, Sakhlain, Hokkaido, Northwestern Kamchatka, and the Cis-Magadan Region, including the Gulf of Shelikhov. Comparing the maps in Fig. 1 with the existing schemes of the Okhotsk Plate boundaries, we found that the northwestern plate boundary along the line Sakhalin–Okhotsk (or probably between Schmidt Peninsula and Shantar Archipelago, with the latter being the submarine termination of the Mongol–Okhotsk folded belt (Wei and Seno, 1998; Zlobin, 2006; Trifonov and Kozhurin, 2010)) is not identified because it is an aseismic zone. Note that regional geophysical studies revealed that the aseismic spreading zone supposed to be in the Kuril Basin (Zlobin, 2006) is not manifested on the seafloor relief as a large spreading ridge with apical rift and associated zones of linear magnetic anomalies (Gnibidenko, 1979; Chuiko et al., 1988; *Tektonika*..., 2004).

The Okhotsk Swell (Middle Massif)

According to the earlier conception, this is the main structure in the basin of the Sea of Okhotsk. Its contrasting mountainous relief with flattened abraded highs of the Meso-Paleozoic acoustic basement were traditionally attributed to riftogenesis and, in part, to taphrogenesis under the settings of in situ tension and subsidence of the rigid continental crust (Gnibidenko, 1979; *Stroenie*..., 1981; *Tektonika*..., 2004). However, the recent discovery of young Late Quaternary units of lateral compression in the structure of Nagaevo stratum at the southern margin of Magadan (Pahomov Lyamin, 2003) required the revision of the interpretation of the close CDP regional profile 1632 made by *OAO Dal'morneftegeofizika* (*Tektonika*..., 2004; Lomtev, 2009) between the shelf of the Cis-Magadan Region and the North Kuril Islands (Fig. 4). The traveltime section along the profile was published in (*Mezhdunarodnyi*..., 2003), but without a geological interpretation.

A noticeable feature in Fig. 4 is the monoclinal appearance of ranges in acoustic basement due to their slopes, which are of different angles and up to 5–6 km high. E.g., near the Central Okhotsk Range (megamonocline) bordering the North Okhotsk trough to the north, the frontal and rear faces are of 45° and 16°, respectively. The width of the ranges exceeds 10–20 km. According to (Lomtev, 2008), monoclines are formed from bed detachment within the crust, and in

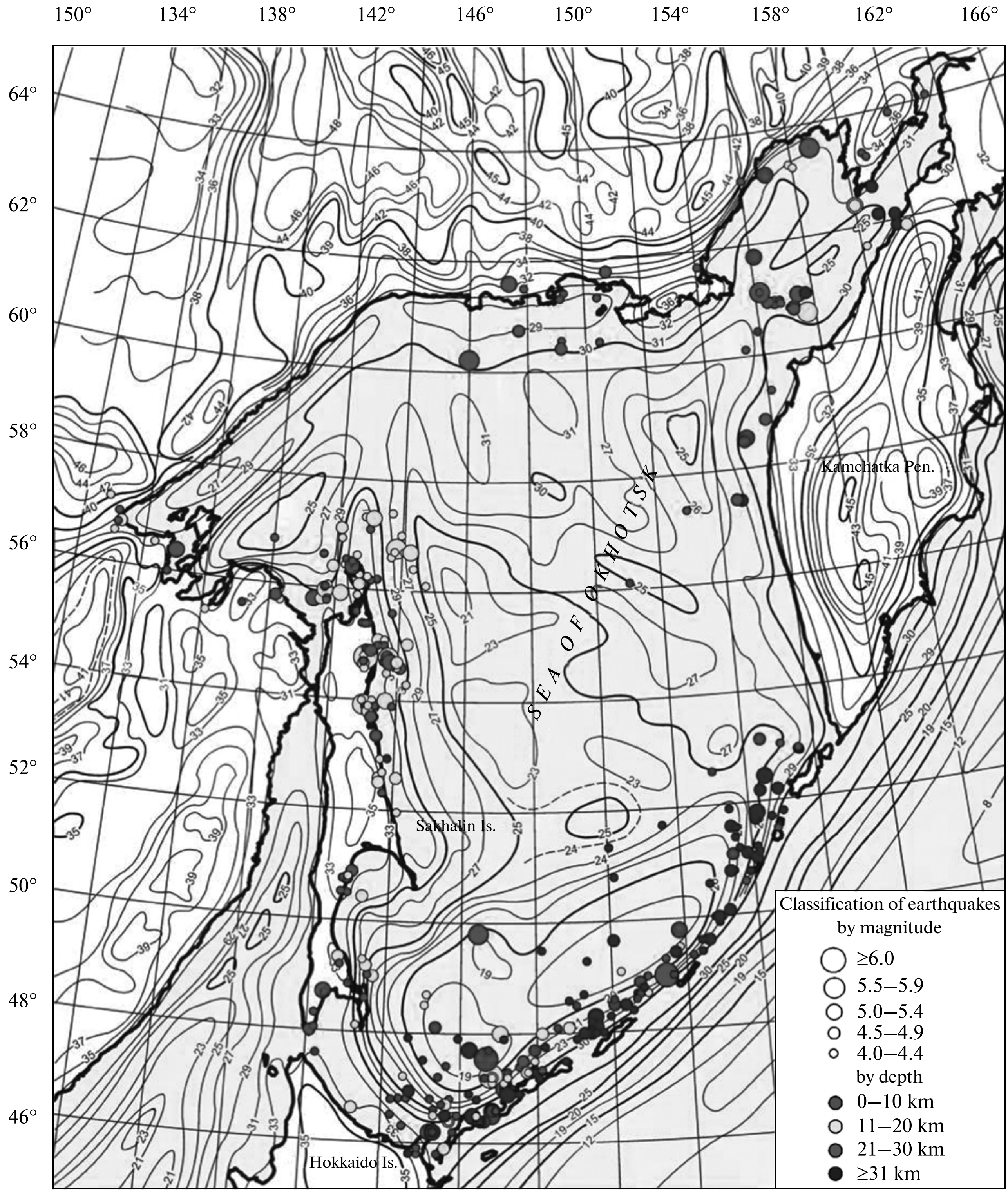

Fig. 3. Map showing epicenters of shallow earthquakes with $M \geq 4.0$ in the Sea of Okhotsk $M \geq 4.0$ for the period of 1962–2010, combined with the scheme of Moho depth, in km, after (*Tektonika*..., 2004).

section they are limited by overthrust faults. In their order, overthrust faults near surface exposure are often complicated by folding and turn into reverse faults. Their positions are marked by analogy with the structural interpretation of CDP and SCP profiles in (Lomtev and Patrikeev, 1985; Lomtev, 2010). In par-

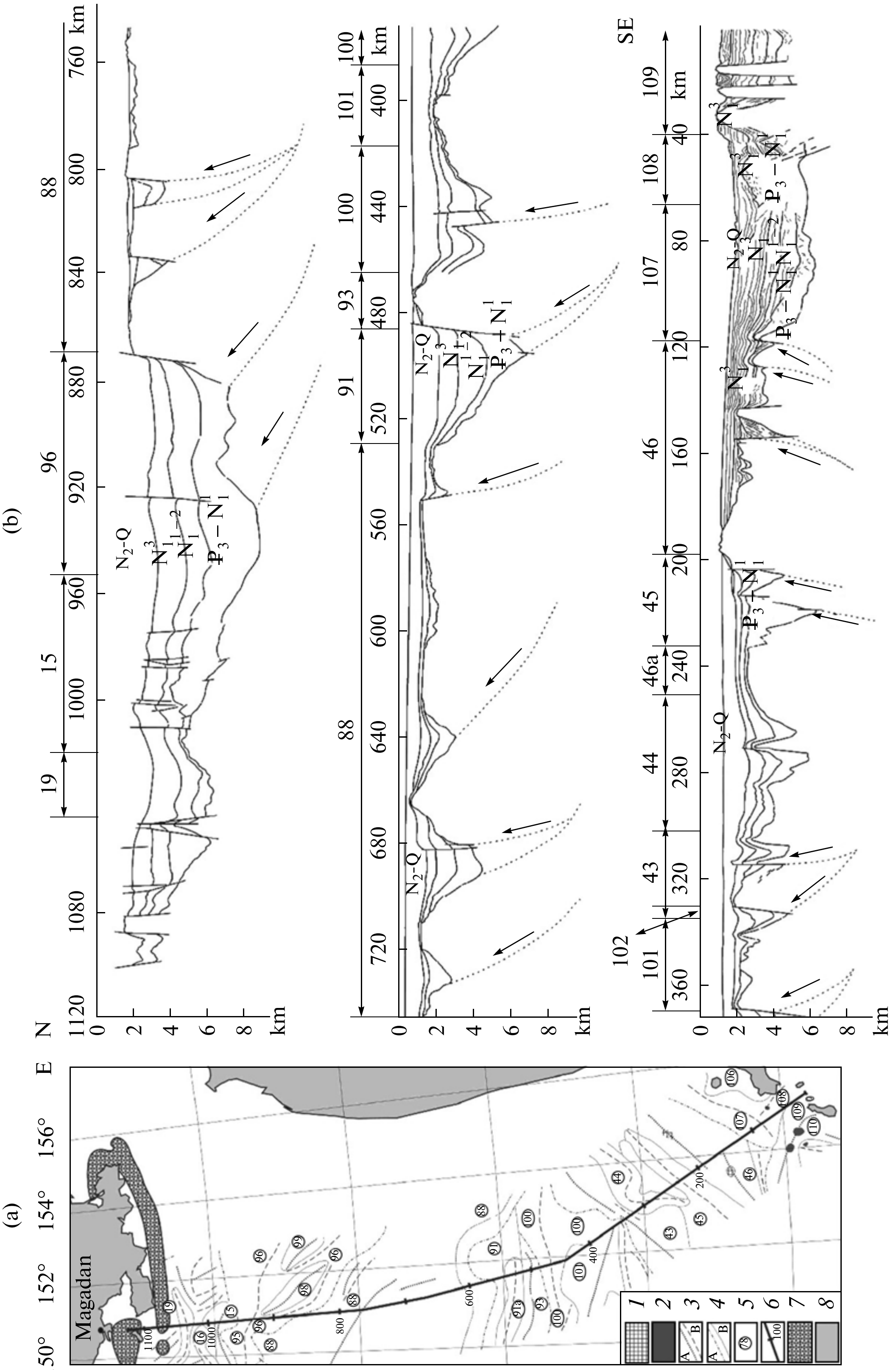
(a)
(b)
Magadan
150°
152°
154°
156°
58°
56°
54°
52°
50°
N
E
SE
km

Fig. 4. Fragment of the map of structural elements in the sedimentary cover of the Sea of Okhotsk (*a*) and the interpretation of CDP profile 1632 (*b*), after (*Tektonika*..., 2004; Lomtev, 2009) with modifications: (*1*) exposures acoustic basement of the seafloor; (*2*) Pliocene–Quaternary volcanoes; (*3*) axes of relative rises (A) and troughs (B); (*4*) boundaries of tectonic elements and zones (A) and structures within zones (B); (*5*) numbers of structural elements; (*6*) position of the CDP profile 1632; (*7*) positive magnetic anomalies, after L.M. Lyutaya with modifications (see (Lomtev, 2009)), above the Koni-P'yaga (right) and Magadan mega-dikes; (*8*) shore of the Sea of Okhotsk. Nonitalicized digits denote rises (15, North Okhotsk; 98, West Tinro; 99, East Tinro; 88, Central Okhotsk; 93, Lebed'; 101, Atlasov; 43, Sobolevo; 46, Bol'sheretskoe; 106, Alaid-Paramushir; 109, Onekotan; 110, Ekarma-Simushir) and troughs (19, Koni; 16, Motyklei; 95, Northwestern Tinro; 96, Central Tinro; 91, Lebed'; 91a, Lineinyi; 100, Central Pkhotsk; 44, Kol'; 45, Bol'sheretskii; 107, Golygina; 8, Fourth Kuril Strait. The turn of the CDP profile 1632 from NW to submeridional direction towards Magadan is at its 445th km. In the section, arrows with points denote compression faults with active hanging wall. Position of the profile is also shown in Fig. 1a.

ticular, the frontal (base) overthrust of each slab seems to continue a gentle outer side of the adjacent trough into depth, where the allochthonous and autochthonous basement blocks are divided. Fault types were determined by using the Lagrangian prionciple when determining their active walls.

As a result, on both sides of the Kola trough (opening zone with a young diapir) the opposite dips of thrust and reverse faults is outlined—this is typical for zones of divergent gravity detachment. In other words, the opening divided the Okhotsk swell into two allochthonous megablocks, which are slowly diverging northwards and southwards. The largest slab of the northern megablock is the Central Okhotsk megamonocline, 180 km wide, consisting of several sheets. Judging by the relief of the acoustic basement top, some sheets can be categorized as bed monoclines, while others are folded ones; however, the former have fine fold-related bends in places. Thus, judging by dislocation types in the part of the CDP profile 1632 corresponding to the Sea of Okhotsk, the compression of the crust dominates, excluding the narrow opening zone. Compression also resulted in the Quaternary rising of some ranges, for example, the Lebed' one, by 1.0–1.5 km and the formation of overthrusts in the northern megablock of swell on regional high the bottom and basement top, analogous to regional nappes of basement in the Pacific trenches (Lomtev and Patrikeev, 1985).

Another characteristic feature of the Okhotsk swell structure is ramp semigrabens. E.g., North Okhotsk and smaller troughs filled with Cenozoic deposits are asymmetric in cross-section (semigrabens, or so called unilateral grabens) (Bol'shakov et al., 1989). Their sides are weakly terraced with faults, especially steep ones (of up to 45°), to which trough depocenters tend. Semigrabens are joined with monoclinic ranges in the basement, forming sheet tectonocouples of overthrust monocline–ramp semigraben. The formation of tectonocouples, analogous to the Pacific trenches (Lomtev and Patrikeev, 1985) is caused by thrusting of allochthonous masses of acoustic basement and subsidence of autochthon under their pressure (such a mechanism was proposed as early as 1920s by A. Wegener (1922) for the Peru-Chile Trench), and, in part, by the presence of plastic strata in the underlying section. Some authors attribute the production of grabens to crustal tension in shear zones, in the framework of the pull-apart basin concept ("hanging basins," after (Ioganson, 2005)). However, this contradicts such facts as (i) the areal development of the mentioned cover tectonocouples (instead of linear development, as in the case of strike–slips; see Fig. 4 and (*Tektonika*..., 2004)); (ii) signs of young (Quaternary) rising of some monoclinic ranges and those of lateral compression in the vicinity of Magadan (Pahomov and Lyamin, 2003); and (iii) opposite dipping of sheet overthrusts of acoustic basement along the CDP profile 1632.

An important sign of crustal detachment in the Sea of Okhotsk is velocity inversion (up to 0.5 km/s) based on deep seismic sounding data (*Tektonika*..., 2004; Lomtev, 2008, 2009) that was revealed in the 4-km layer occurring in the bottoms of allochthon immediately above Moho (decollement, or detachment surface). The regional slope of the decollement towards the mountain–plain framing of the Sea of Okhotsk basin provides the development of gravity intracrustal detachment in the Cenozoic (Lomtev, 2008, 2009).

Kuril (South Okhotsk) Bathyal Basin

In early publications this basin was believed to be the deepest part of the Okhotsk middle massif; then it was thought to be part of the Pacific basin divided from the main part by the Kuril arc in the Cenozoic, or to be produced by magmatic diapirism (Karig, 1971; Rodnikov et al., 2005), backarc spreading, and formation of thin suboceanic crust (Zlobin, 2006; Prokudin and Medvedev, 2011). From the viewpoint of currently accepted concepts of Cenozoic riftogenesis, the origin of this basin is unclear because there is no developed system of rift-related grabens and horsts limited by normal faults (*Stroenie*..., 1976, 1981; Gnibidenko, 1979; *Geologiya*..., 2002). Let us briefly consider the structural peculiarities of the northern and eastern sides of the Kuril Basin based on SCP and depth-measurement data (Fig. 5).

The structure of the northern side can be seen from the fathogram containing stepwise (normal) faults (Baranov and Vol'nev, 1982) and the SCP section along the profile 10 shown in Fig. 5 as interpreted by one of the authors (V.L. Lomtev). The identification of normal faults on this side of the Kuril Basin agrees with the ideas about tension and subsidence of the Earth's crust in the Sea of Okhotsk (Gnibidenko,

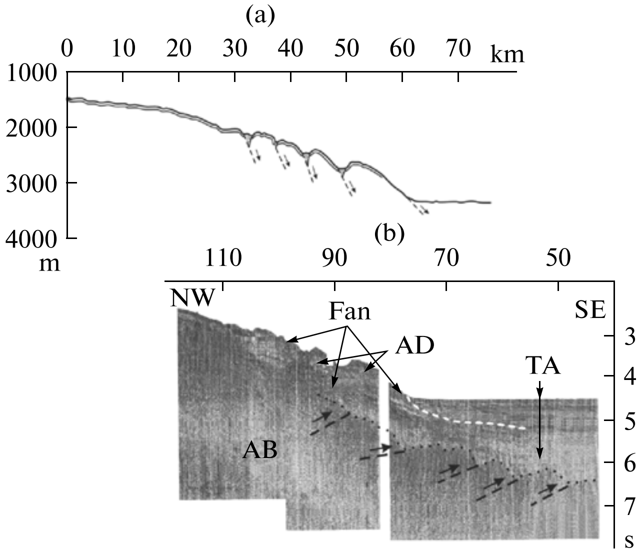

Fig. 5. Fragments of the SCP profile 10 (21st cruise of R/V *Pegas-1980*) across the northern side of the Kuril (South Okhotsk) Basin (*a*) and those of echogram showing stepwise normal faults, after (Baranov and Vol'nev, 1982) (*b*). AB means acoustic basement (top is indicated with dotted line); AD, alluvial dams of channels within the limits of submarine fan; TA, through anticline in the Cenozoic cover; dashed arrows, small-amplitude overthrusts of the basement, which form stepwise profile of the basement top, and displacements on these faults. Position of the profile is shown in Fig. 1a. Vertical scale of the profile is in double travel seconds.

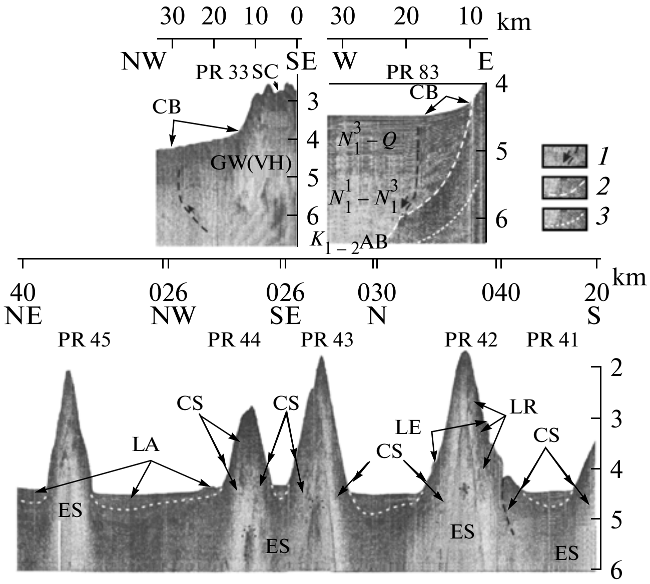

Fig. 6. The SCP profiles made during the 21st cruise of R/V *Pegas*-1980 on the Okhotsk submarine margin of the Kuril Kuril arc. CB means continental slope base; GW(VH), gas window (vapor hydrothermals); L, laccolith; SC, summit crater; ES, extrusive swell with sedimentary cap; CS, covers of slopes; LA, landslides; LE, lateral cone-shaped edifices; LR, lateral reflections. Dashed arrows denote faults and slips on them; empty dashes, unconformity; empty points, top of extrusion-piercing core. Positions of the profiles are shown in Fig. 1a.

1979). This is how stepwise slopes were interpreted in fathograms, from the viewpoint of tectonics, by marine geologists and geomorphologists before the SCP and CDP methods appeared (Menard, 1964). However, in this case, such an interpretation is erroneous for at least two reasons. First, the SCP profile reliably detects seismofacies of relic (extinct) submarine fan in the lower part of the basin side, with channels framed by alluvial dams—it is these dams that formed the "steps" on the slope. Second, tectonic steps on slopes form both tension and compression faults (overthrust and reverse faults), as follows from the SCP and CDP data of tectonic simulation (Lomtev and Patrikeev, 1985). E.g., the stepwise outline of the basement top in the same profile is formed by gentle small-amplitude overthrusts. The slow southward shift of basement sheets on them has been continuing and is marked in part by the through, almost reaching the bottom, anticline of the Cenozoic cover (Fig. 5).

Larger-scale gravity tectonics is presumed to be on the eastern side of the basin, or, in other words, at the Okhotsk submarine margin of the Kuril arc. One example illustrating this is the asymmetric overthrust anticline more than 15 km wide near Iturup Island in the SCP profile (Fig. 6). This anticline is a side pressure fold related to the slow slide of the Cenozoic cover and probably the acoustic basement.

Another example is a large overthrust (retro-overthrust) in the regional CDP profile 1620 crossing the Friz Strait between Iturup and Urup islands. Under the pressure of allochthonous masses at its hanging wall, acoustic basement (autochthon) is submerged by 2 km relative to the adjacent bottom of the basin (Chuiko et al., 1988; *Tektonika*..., 2004). In other SCP and CDP profiles, this retro-overthrust is not distinguished (hidden fault) due to the saturation of the Cenozoic cover with gas (see the profile 33 in Fig. 6) and near-bottom gas hydrates (Bondarenko and Rashidov, 2011). The existence of the retro-overthrust is also proved by bathyal mud volcanoes near Bussol' Strait (Bondarenko and Rashidov, 2011), if their genesis is compared with the South Skhalin and Pugachevo mud volcanoes exposed at the Central Sakhalin regional upthrust–overthrust (Veselov et al., 2004).

Gravity tectonics is probably related to the en-echelon arrangement of diagonal ranges in the eastern side of the Kuril Basin (*Geologo-geofizicheskii* ..., 1987)—similarly to the diagonal anticlines of the sliding Cenozoic cover in the rear part of the Kamyshevo monoclinorium on Sakhalin (Chuiko et al., 1988; Lomtev, 2010b)—and to the complex cover-and-folded structure of the basement and Cenozoic sedimentary filling of the oil-and-gas-bearing West Kamchatka marginal trough with multiple predepositional, syndepositional, and postdepositional faults (Chuiko et al., 1988; Kim, 2010).

However, the seismicity of the eastern and southern Kuril Basin is mainly deeper (30–60 km) than that of Western Kamchatka (Figs. 1–3). This may indicate the subsidence of the basin under the pressure of sliding masses on the slopes of the Kuril and Japan–Sakhalin arcs, due to the outflow of magmatic masses towards the surface and associated weighing of the crust. Let us consider the last point with the help of Fig. 6, where a structure of several cone-shaped mountains near the base of the Okhotsk margin, near the Brouton Island, is seen (SCP profiles 41–45; Fig. 1a). The heights of the seamounts are more than 2 km in most cases, the base diameter is 15–30 km, the angles of slopes are ~15°. These and other cone-shaped seamounts with their hills have been traditionally considered submarine volcanoes, i.e., mound edifices consisting mainly of lava and ash (Tuezov, 1977; *Geologo-geofizicheskii*..., 1987; *Podvodnyi*..., 1992; Emelyanova and Lelikov, 2010). However, SCP profiles 41–45 show that the tops and slopes of the area of seamounts are composed by a Cenozoic sedimentary cover, traceable through the adjacent saddles. Hence these seamounts formed when viscous magma penetrated into the sedimentary cover (magma diapirs or extrusive swells with thick sedimentary caps). In saddles, bottom sediments of ~0.2–0.4 km thick occur horizontally indicating that their accumulation stopped (relics). The relative age of the seamounts can be inferred from the average rate of magmatic edifice growth, 1–2 mm/yr (Kukal, 1983), and sedimentation rate (~100–200 m/Ma) for contrast sediments in intermontane lenses (Lomtev, 2010a). In the first case, it will be 0.5–3 Ma, while 1–4 Ma in the second case; nevertheless, both estimates are close to radiocarbon isotope datings of volcanic rocks (0.9–4.1 Ma) dredged at the seamounts of the Kuril Basin (Emelyanova and Lelikov, 2010).

However, according to the SCP profile 83 (Fig. 6), the slope of the more ancient, pre-Miocene extrusive seamount (paleorelief) is composed by Oligocene marine (?) deposits, which are absent on the bottom of the Kuril Basin. Therefore the acoustic basement top with rough seismofacies (trappean eluvium) is composed here by subaerial Cretaceous trapps of Okhotia paleoland (Lomtev et al., 2002) and this agrees with the parametric drilling data on the North Okhotsk Trough (Bol'shakov et al., 1989). Thus, the Kuril Basin is the deepest (4–5 km) part of the Okhotsk Swell (middle massif) whose subsidence is probably related to the deepening of shallow seismicity (Figs. 1 and 2).

Okhotsk submarine margin of Sakhalin

Judging by Figs. 1 and 2, shallow seismicity is distributed on the coasts and submarine margins of northern and southwestern Sakhalin (East Sakhalin upthrust–overthrust (Margulis et al., 1979; *Geologo-geofizicheskii*..., 1987)) and, locally, at the head of Terpeniya Bay (Makarov compensated trough limited with the Central Sakhalin upthrust–overthrust on west (Mel'nikov, 1987; Chuiko et al., 1988)). The depths of the hypocenters increase from 20–25 km in the north to 30–35 km in the south. Crustal seismicity is characteristic for the island proper as well (Poplavskaya et al., 2006), except the southern part where deep earthquakes of the Benioff zone are also reported (Tarakanov, 2006; Lomtev et al., 2012).

The shallow seismicity of Sakhalin Island is traditionally attributed to its main meridional thrust faults (Smekhov, 1953; Mel'nikov, 1987; Voeikova et al., 2007). However, in recent years the island has been interpreted as the boundary between the Mesozoic plates, with different versions of the boundary proper being drawn along the West and Central Sakhalin regional faults (Wei and Seno, 1998; Zlobin, 2006; Trifonov and Kozhurin, 2010; Prytkov and Vasilenko, 2011); the shear component of displacements along active faults is also emphasized (Mel'nikov, 1987; Kharakhinov, 2010). Nevertheless, the geological youth of Sakhalin Island, which was formed in the Sakhalin folding and orogenic stage (Pliocen or the end of Late Pliocene until Quaternary), and the aseismicity of the subcrustal mantle, contrasting with the seismicity of the continental crust, 35–40 km thick, reliably shows the continental crust's tectonic mobility (Fig. 3).

With the regional overthrusts and asymmetric, monoclinorium-type structure of anticlinoria in Sakhalin Island, V.L. Lomtev and his coauthors (2007) came to the conclusion of an eastward amagmatic detachment of the continental crust in different time periods (detachments of different ages). The amplitudes of horizontal displacement of its eastern and western allochthonous slabs forming mountain systems of East and West Sakhalin, respectively, are probably small (up to 5–10 km). Vertical deformations are more noticeable: in the Chaivo syncline of the oil-and-gas-bearing shelf of Northeastern Sakhalin (North Sakhalin sedimentary basin) they are more than 12 km, if measured based on the acoustic basement's top (Chuiko et al., 1988; Kharakhinov, 2010). The study of crustal seismicity on this shelf is currently being implemented with the use of land digital seismic stations and bottom seismographs, in order to provide seismic safety and diminish the risk of prospecting and production drilling, and to do the same for the system of oil and gas pipes between the fields and shores.

In the context of the present work, let us pay attention to the Trekhbratskaya (Tri Brata, or East Odoptu) mega-anticline, 360 km long, on the northeastern shelf of Sakhalin Island, in whose vicinity the epicenters of shallow earthquakes have been recorded (Figs. 1 and 2). It was traditionally thought to be a marginal rise of the North Sakhalin sedimentary basin, the east-

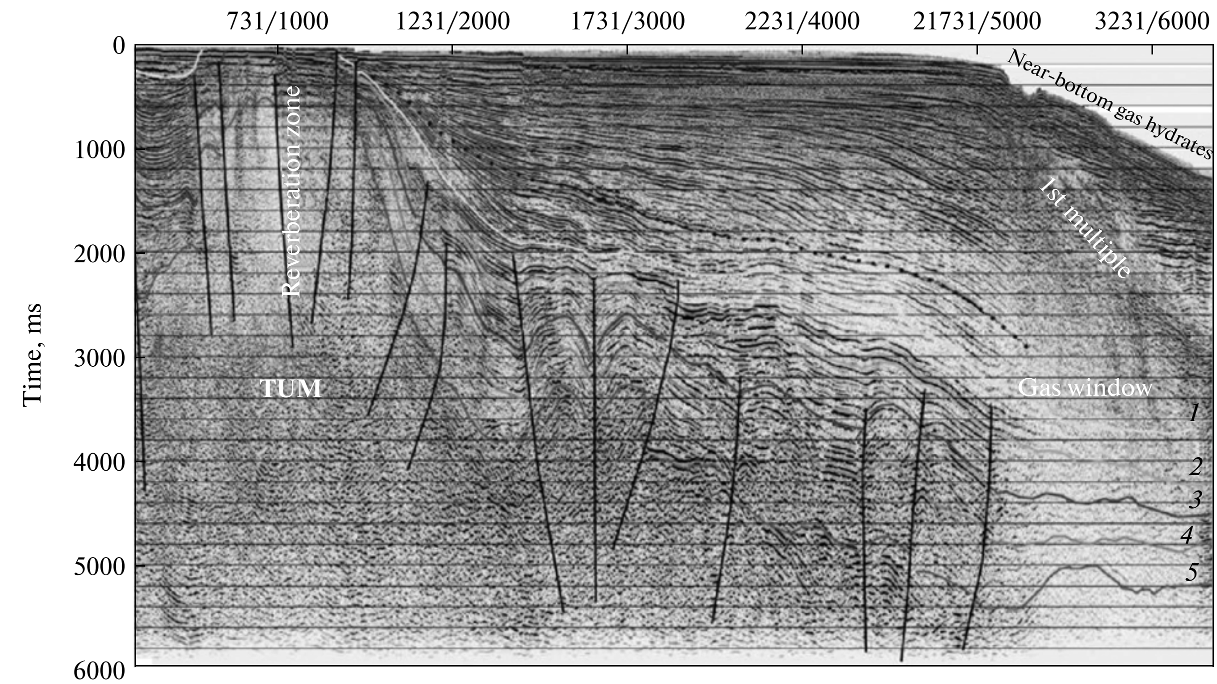

Fig. 7. Fragment of the CDP profile 18 across the submarine margin of Northern Sakhalin, after (Litvinova and Lomtev, 2010): (*1*)–(*5*) faults and boundaries of sedimentary seismic complexes, based on the data of geological department of *OAO Dal'morneftegeofizika*: (*1*) top of the Nut complex, Late Miocene–Early Pliocene; (*2*) top of the Okobykai complex, Middle–Late Miocene; (*3*) top of the Dagi-Uinin complex, Early–Middle Miocene; (*4*) top of the Daekhuriin-Lyukamin complex, Paleogene; (*5*) the acoustic basement's top composed by Late Cretaceous rocks. Horizontal scale is determined between the SP/CDP points and is 25 and 12.5 m, respectively. The points mark local unconformity dividing the the Pomur and Deryugin sediments and appeared after penetration of the Trekhbratskaya ultrabasite mega-dike (TUM) (Lomtev and Litvinova, 2012).

ern limit of the basin (Lopatnev et al., 1989). The mega-anticline is marked with linear positive anomalies of magnetic and gravity fields, including those of the Eastern Range on the Schmidt Peninsula corresponding to the massif of Early Mesozoic serpentinites (Margulis et al., 1979). The authors of the just-cited work identified here a zone of the East Sakhalin deep fault with ultrabasic bodies. Later, CDP profiles revealed through postdepositional anticlines in the Late Cenozoic cover above the zone, with arches abraded in the Late Quaternary (Fig. 7; (Lomtev and Litvinova, 2012)). Hence, these folds formed in the Early–Middle Quaternary, and this formation was related to repeated intrusion of ultrabasites along the zone of East Sakhalin deep fault which has existed since the Mesozoic (Trekhbratskaya mega-dike). This intrusion can be seen in Fig. 7 from the local angular unconformity, which divides the Pomyr and cross-bedded Deryugin deposits (end of Late Pliocene–Quarternary, after V.O. Savitskii (Chuiko et al., 1988)) and is located seaward. The formation of this unconformity and the cross-bedded series of bottom sediments is related to the appearance of the topographic barrier (intrusive mega-anticline) before the front of the paleo-Amur avant-delta (Lomtev and Litvinova, 2012).

V.V. Kharakhinov (2010) considered the Trekhbratskaya structure to be a clod protrusion of Mesozoic serpentinites. However, the development of near-bottom gas hydrates in the margins of shelf as permafrost relic, due to shelf dewatering in Late Quaternary (i.e., at some distance from the mega-dike), indicates a higher heat flow from this megadike; this heat might promote the thermal generation of hydrocarbons in the North Sakhalin sedimentary basin (Lomtev and Litvinova, 2012). The apophysis (tongue) of a hot mega-dike is probably related to the Dagi hot springs on the coast.

Thus, the weighting of the crust in Northern Sakhalin due to the recent penetration of ultrabasite of Trekhbratskaya mega-dike and, in part, the at least occasional manifestations of crustal and/or intracrustal detachment eastwards (Figs. 1 and 2), generates shallow seismicity in both allochthon and autochthon, with the latter being subsided under the pressure of the allochthon load. A similar, in the seismotectonic sense, situation is observed south of here, at the submarine margin of the East Sakhalin Mountains of Middle Sakhalin, where geophysical data suggest presence of young Pogranichnaya ultrabasite megadike (Mel'nikov, 1987; Lomtev et al., 2007).

The anomalous feature in the structure of the Okhotsk margin of Sakhalin Island is the almost aseismic shelf block of Terpeniya Bay and its adjacent areas. In terms of the structure shown in the SCP and CDP, it is a typical plain tableland (platform) with Cretaceous marine sedimentary basement, gentle regional slope westwards, and with a developed tree-like river network of paleo-Poronai with avant-delta near the town of Makarov (Chuiko et al., 1988). In Early Cenozoic it was probably still a part of the Okhotsk middle massif, but later was isolated from the massif with the development of eastward crustal detachment.

DISCUSSION

Thus, based on the data from new catalogs, the peripheral character of shallow earthquakes in the Sea of Okhotsk is identified. A large aseismic zone is observed, however, in the central part of the sea (Okhotsk Swell): it expands northwestwards (grabens and horsts of the Okhotsk–Shantar sedimentary basin) and towards Southwestern Kamchatka (Sobolevo high). Such a distribution of earthquakes indicates the leading role played by orogeny in formation of mountain-and-plain framing of the Sea of Okhotsk (Kuril-Kamchatka and Japan-Sakhalin island arcs). Among them, the deep overthrust on the Benioff zone is traditionally distinguished (Sergeev, 1976); plate tectonics suggests an underthrust here (Le Pichon et al., 1973). The deep overthrust during the global Pasadenian orogeny (Stille, 1924) led to the formation of the Kuril–Kamchatka Trench, and the middle and lower (tectonocouple of basement nappe–accretionary prism) parts of the Pacific slope of the Kuril—Kamchatka from the Middle Quaternary to the Holocene (Lomtev and Patrikeev, 1985; Tihonov and Lomtev, 2011; Lomtev et al., 2012); it also caused an intensive magmogenesis (volcanic arc and submarine, predominantly extrusive, volcanism), seismogenesis (opposite focal zones and allochthonous seismic crust), and tsunamigenesis (regional tectonic tsunamis of focal rhombus and landslide-caused local tsunamis in canyons and on steep open slopes). The horizontal displacement of the Kuril arc to the bottom of the Northwestern Pacific for the last 0.5–1 Ma is from 30 km in the central part to 50–70 km in the flanks, at thickness of basement nappe (Pegas) of 10–20 km at the base.

The absence of a young longitudinal opening in the Kuril Basin parallel to the island arc and compensating the eastward overthrust of the basin suggests an allochthonous occurrence of the continental crust and probably upper mantle (up to the asthenosphere level (Rodnikov et al., 2005)) in the Sea of Okhotsk. From the velocity inversion above the Moho in deep seismic sounding profiles, we can conclude presence of a crustal, not an upper-mantle, gravity detachment (Lomtev, 2009). In the CDP profile 1632 (Fig. 6), opposite overthrusts of acoustic basement mark the submeridional direction of the megablocks in the Okhotsk Swell relative to the Kol' Trough (opening zone). However, the relief of Moho in Fig. 3 and the conclusions of some researchers regarding the thin (~14 km) suboceanic crust in the probably newly formed Kuril Basin (Prokudin and Medvedev, 2011) contradict the supposed southward gravity detachment of the southern megablock of the Okhotsk Swell. In contrast, such a detachment agrees with the direction of basement shift on small-amplitude overthrusts in the northern side of the basin in profile 10 (Fig. 5). The key to solving this ambiguity can be found in the work by E.A. Starshinova (1980): based on this publication, the depth of Moho in the Kuril Basin is up to 28 km.

With the SCP and CDP data taken into account, the seismicity of the Okhotsk margins of the Kuril arc and Kamchatka, including the Gulf of Shelikhov (Fig. 1), may be related to the development of regional retro-overthrust and subsequent subsidence of its autochthon with the adjacent seafloor of the Sea of Okhotsk in the back part of the deep overthrust of Benioff zone. The latter statement is verified by results from (Gordeev et al., 2006) on the crustal (0–55 km) seismicity of Kamchatka: the latitudinal trend of intensifying seismicity is revealed towards the exposure of Benioff zone on the Pacific slope of the peninsula (see also (*Tektonika*..., 1980; *Geologo-geofizicheskii*..., 1987)). A similar trend can be traced in the crustal seismicity of the Kuril and Japan (Tohoku) arcs (Asano et al., 1979; Hasegawa et al., 1978; *Tektonika*..., 1980), and the Kamyshevo monoclinorium (Sakhalin), with the Central Sakhalin upthrust–overthrust in the frontal and West Sakhalin upthrow in the rear part (Lomtev, 2010b; Tihonov and Lomtev, 2012).

The shallowest seismicity (0–10 km) is observed on the shelf of Cis-Magadan Region (Figs. 1 and 2). It is important to emphasize the slow displacement of the northern megablock in the Okhotsk Swell, and the Koni-P'yagina and Magadan young (Early–Middle Quaternary) ultrabasite megadikes in the CDP profile 1632 (Fig. 6; (Lomtev, 2009)) marking the southern flank of the Cretaceous Okhotsk-Chukotka volcanic belt and the considerable increase in thickness (up to 55 km) of the continental crust on the coast of the Cis-Magadan Region (Surkov et al., 2003). The increase in thickness and weighting of the crust likely impeded gravity detachment along the Moho northwards, and this might have promoted the regional rising of decollement into the upper crust i.e., crustal detachment became intracrustal.

Deepening of shallow earthquakes in S–N direction is observed in the Sakhalin and Kuril sides of the Sea of Okhotsk basin (Figs. 1 and 2). In the former case, it is reliably shown (Nagornykh et al., 2003) and is related to eastward crustal and/or intracrustal detachment, which is complicated in places with large ultrabasite intrusions (Lomtev et al., 2007). In the latter case, it likely reflects the regional subsidence of the Kuril Basin seafloor as the deepest part of the southern Okhotsk Swell (middle massif). Subsidence can be compensatory, due to the outflow of magma masses from the top of the Benioff zone towards the surface and the accompanying weighting of the continental crust and increased load on the underlying mantle. Tectonic subsidence might also affect the rear zones of regional thrusts, as was manifested, for example, in the Tohoku megaearthquake (Rogozhin, 2012). However, this problem requires detailed consideration, as well as does the aseismicity in the zone of elongated regional grabens and horsts in the Meso-Paleozoic basement in the shallow water of the northeastern Sea of Okhotsk (Okhotsk–Shantar sedimentary basin)—jointly with the structures of the Okhotsk Swell and North Okhotsk Trough, these horsts and grabens form a reentrant structural corner near the town of Okhotsk (Chuiko et al., 1988; *Geologiya*..., 2002; *Tektonika*..., 2004). One of the most reliable ways to study shallow seismicity of oil-and-gas-bearing shelves and avant-shelf in the Sea of Okhotsk is the application of bottom seismographs.

CONCLUSIONS

The present work resulted in the compilation of two catalogs of the shallow earthquakes ($h \leq 60$ km) that occurring during the historical and contemporary observation periods within the limits of the Sea of Okhotsk: a catalog of strong ($M \geq 5.0$) earthquakes for 1735–2010 and a more detailed one ($M \geq 4.0$) for 1962–2010. The maps of earthquake epicenters and the vertical sublatitudinal sections of seismoactive zones constructed on the basis of these catalogs allow us to obtain a more objective view of the spatiotemporal distribution of regional seismicity and to find the relationship between seismicity and crustal tectonics. It is found that historical and contemporary (1735–2010) shallow earthquakes in the Sea of Okhotsk are clustered at the Kuril, North Sakhalin, Cis-Magadan (including Gulf of Shelikhov), and North and South Kamchatka submarine margins.

The central part of the sea is generally aseismic (Okhotsk rigid block, or middle massif framed by the Cenozoic folded zones). Vast aseismic areas (“windows”) are revealed in the northwestern Sea of Okhotsk and at the southwestern submarine margin of Kamchatka. Small “windows” are detected along the Middle and Southern Sakhalin, Hokkaido Island, and in the Kuril bathyal basin. Comparison between the seismicity distribution and schemes of the Okhotsk Plate has not revealed the northwestern plate boundary due to presence of an aseismic zone here.

Shallow (crustal) seismicity in the Sea of Okhotsk is characterized by different depths depending on location: it ranges from 0–10 km on the shelf of Cis-Magadan Region to 20–30 km on the Sakhalin one; its range is 0–40 km on the North Kamchatka shelf (including the Gulf of Shelikhov) and mainly 30–60 km at the Okhotsk side of the Kuril arc and the Kuril basin. Shallow seismicity reliably marks the mobility of the continental crust in the region and its allochthonous occurrence on the aseismic mantle, and this is verified by seismic survey data from deep seismic sounding, CDP, CDP, and SCP. On the Okhotsk side of the Kuril–Kamchatka arc, gravity sliding of the sedimentary cover (and probably that of the basement) in the rear part of the deep overthrust of Benioff zone dominates. The deepening of the shallow seismicity in the Kuril Basin (which is the deepest part of the Okhotsk Swell) is likely caused by compensatory subsidence of the basin’s seafloor due to the outflow of magma masses towards the surface (extrusive submarine volcanism) and weighting of the crust.

At the Okhotsk margin of Sakhalin Island, the rigid platform block of Terprniya Bay is nearly aseismic, while the shallow seismicity north and south of it is related to the long-term active East Sakhalin marginal fault, the penetration of large volumes of ultrabasites (mega-dikes), and to the at least occasional manifestations of crustal and intracrustal (on north) detachment eastwards. The aseismic Okhotsk Swell (middle massif), which is the main structure in the Sea of Okhotsk and characterized by the developed system of covering tectonocouples “monocline range–ramp semigraben,” is the zone of slow divergent detachment of the continental crust (opening zone) in the areas north and south of the Kol’ Trough (based on the CDP profile 1632). In the northern megablock of the swell, decollement (detachment surface) probably rises from the crustal base to the upper crust due to thickening (up to 55 km) and weighing (mega-dikes) of the allochthonous crust.

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