ISSN 0747-9239, Seismic Instruments, 2013, Vol. 49, No. 4, pp. 327–342. © Allerton Press, Inc., 2013.
Original Russian Text © V.L. Lomtev, T.V. Nagornykh, D.A. Safonov, 2013, published in Voprosy Ingenernoy Seismologii, 2012, Vol. 39, No. 4, pp. 19–38.

On the Structure and Seismotectonics of the Kuril Arc-Trench System

V. L. Lomtev, T. V. Nagornykh, and D. A. Safonov

Institute of Marine Geology and Geophysics, Far East Branch, Russian Academy of Sciences, Yuzhno-Sakhalinsk, Russia
e-mail: lomtev@imgg.ru

Abstract—Based on the new regional catalog of focal mechanisms for 396 strong ($M \geq 6.0$) earthquakes in the Kuril-Okhotsk region and Japanese one in part for the period of 1964–2009 and with the data of seismic continuous profiling and multichannel common-depth point sounding by reflection method used, the peculiarities of the structure and seismotectonics of the Kuril arc-trench system have been analyzed. Additionally, the features of the Benioff and Tarakanov opposite seismofocal zones, associated with the Kuril arc-trench system, are studied. It is shown that the Benioff zone is a deep thrust through which the Kuril Arc (or Eurasian tectonic forefront) has thrust on the Pacific Plate by up to 50–70 km for the last 0.5–1.0 Ma (Pasadenian global phase of folding and orogeny). The thrusting process formed the middle and lower parts of the Pacific Ocean slope, the tectonic couple of Pegasus regional nappe and accretionary prism, the ramp structure of the Kuril Trench, and probably the opposite seismofocal zones.

Keywords: Kuril arc-trench system, Benioff and Tarakanov opposite seismofocal zones, focal mechanism, deep thrust, Pegasus nappe, accretionary prism, acoustical basement, Cenozoic sedimentary cover, seismodislocation types

DOI: 10.3103/S074792391304004X

INTRODUCTION

The geological structure of the Kuril arc-trench system has been studied for about 100 years. The first investigations were carried out primarily by Japanese researchers; the studies by Russian ones began after World War II (Sergeev, 1976; *Tektonika*..., 1980, 2004; *Geologo-geofizicheskii*..., 1987). The major contribution into the study of the Kuril-Okhotsk region was made during the research carried out in the framework of the International Geophysical Year. In this period, deep seismic sounding was carried out by the Institute of Physics of the Earth, Academy of Sciences of the USSR, in the Sea of Okhotsk and near-Kuril part of the Pacific Ocean; in addition, the research vessel Pegas of the Sakhalin Complex Research Institute that carried out the regional geological geophysical survey included measurement, one-channel seismic continuous profiling (SCP) using the reflection method (RM), onboard gravimetric and magnetometric works, and dredging in the same region (Vasil'ev et al., 1979; *Tektonika*..., 1980, 2004). Later, the Dal'morneftegeofizrazvedka trust explored several regional profiles of multichannel RM- common depth point (CDP) sounding (Lomtev and Petrikeev, 1985; Gnibidenko, 1987; *Tektonika*..., 2004). As a result, the regional features of the geological structure and evolution of the external, not volcanic arc (at present, it includes the Lesser Kuril Ridge and its submarine continuation, the Vityaz Ridge) and internal, volcanic one (Greater Kuril Ridge), and the Kuril Trench as well. However, there are significant contradictions in viewpoints and interpretations of the seismotectonics and structure of the Kuril arc-trench system; this contradiction especially sharpened after the discovery of the coastal and shelf regional facies of Late Mesozoic–Early Cenozoic and the subsequent facies of Late Cenozoic fans (alluvial fan) associated to canyons in the Japan–Kuril–Kamchatka continental margin on the Zenkevich Swell and in the Tuscarora Basin, which is located more in the ocean relative to the Kamchatka contour megafan, resulting from drilling and SCP on the NW Pacific bottom (Lomtev et al., 1997; Patrikeev, 2009).

Seimotectonics of the region has been being studied for a long time period (primarily by seismologists of the Institute of Marine Geology and Geophysics, Far East Branch, Russian Academy of Sciences, and the Geophysical Survey, Sakhalin Branch, Russian Academy of Sciences) based on the stationary observation data (epicentral and hypocentral parameters, focal mechanisms, velocity heterogeneities in the crust and upper mantle, geostatistics) collected at seismic stations of the region and worldwide network, and on the basis of field studies of seismodislocations on islands in source zones of strong earthquakes (Aver'yanova, 1968; Simbireva et al., 1976; Tarakanov et al., 1977; Rudik and Poplavskaya, 1987; Balakina, 1995; Tarakanov, 2004; Tikhonov et al., 2008). It has been found that the main contribution into the regional seismicity is made by the Benioff or Wadati–Zavaritsky–Benioff (Lomtev and Patrikeev, 1985) and Tarakanov ones (Kropotkin, 1978), which outcrop on the bottom in the vicinity of the external arc and within the trench limits (Tarakanov et al., 1977; Tarakanov, 2004); also, the significant contribution is made by autonomous shallow focus seismicity probably within the allochonous crust, located in part in young orogenic morphostructures and active fault zones (*Tektonika*..., 1980; Lomtev et al., 2007).

In addition, the tectonic aspects of seismicity, as well as the structure and geological evolution of the discussed region, are still arguable. E.g., fixism theory implies the normal faulting or normal faulting–landsliding structure for the Kuril Trench (so called rift-graben, see (Vasil'ev et al., 1979; *Tektonika*..., 1980; Gnibidenko, 1987; Verba et al., 2011)) which is a structure produced by tension and sinking of the crust and underlying mantle. Such an approach is based on the direct geological interpretation of the SCP time sections showing a complex wave field and numerous noises; the latter requires noise minimization or elimination when constructing the real-scale (1 : 1) deep sections (Lomtev and Patrikeev, 1985, 2006). However, this approach does not explain such features as asymmetry of the transverse and longitudinal profiles for this and other trenches of the Pacific Ocean; formation accretionary prism and regional nappe in acoustical basement and the highs adjacent to the Zenkevich Swell (Hokkaido) and the double Kuril Arc of 5 and 10 km height, respectively; curvature of the arc-trench system and the Kuril segment of the Benioff zone towards the ocean. In terms of the mobilism theory (or plate tectonics), tension and sinking of blocks is implied for the external slope of the Kuril Trench (the Pacific Plate subducts since the Createous along the system of normal faults); on the internal slope, the landslides, normal faults, accretion of the Cenozoic sedimentary cover with west-verging flake-type thrusts (Lomtev and Patrikeev, 1985)—or subduction of this cover in tectonic pockets of the acoustical basement (Pichon, Francheteu, and Bonnin, 1973; Ueda, 1974)—are implied. Thus, different researchers attribute different deformation types, and hence different tectonic structure, for the slopes of the Kuril and other frontal trenches of the Pacific Ocean. Finally, there also are discrepancies in terms of the foundation age for trenches within the Pacific: from Jurassic–Cretaceous to Pleistocene–Holocene (see a review in (Lomtev, 1989)).

With the recent catastrophic Simushir earthquakes (2006–2007) and the Tohoku-Oki one (March 2011), accompanied by tsunamis of more than 10–30 m in height (Tikhonov et al., 2008; Tikhonov and Lomtev, 2011), taken into account, the emphasis of the present work is put to specification of the structure and seismotectonics of the Benioff seismofocal zone, which is the largest arc fault on the earth, and the zone of its outcrop on the Pacific Ocean slope of the Kuril arc and trench (Tarakanov et al., 1977; Tarakanov, 2004).

The factual basis of the work is the data of new regional focal mechanism catalog for strong ($M \geq 6.0$) earthquakes in the Kuril-Okhotsk region for the period of 1964–2009, made with respect to the modern international standards (*Katalog*..., 2011); another basis is the SCP–CDP deep sections built by the aplanatic surface method (wave front envelopes) in scale 1 : 1 within the accuracy of 50–100 m for the locations of reflectors in the top of the acoustical basement, in the accretionary prism, and the Cenozoic sedimentary cover; finally, we used the model of the Kuril arc-trench system's south flank, based in part on the previously mentioned SCP–CDP deep sections. Note that the mentioned above method for interpreting the complex wave fields has no analogs among the published materials on the one- and multichannel RM exploration of the Pacific, Atlantic, and Indian oceans.

In the recent years, intensive funding of the Kuril Islands' infrastructure is made in order to increase the region's investment attractiveness. Undoubtedly, capital development in the shaking intensity zone denoted X (based on the OSR-97 map) is of a high risk. To diminish possible damage, the comprehensive investigation of geological structure and tectonic processes in the crust and upper mantle in the one of the most seismically active regions of the world is necessary. The present study can provide a sound tectonic and seismotectonic framework for solution of many engineering seismological problems. In particular, domination of upthrows and thrusts (>75%) in the outcrop of the Benioff zone (down to 80 km depth) predetermines the higher degree of the earthquake effect on the objects of industrial and transport infrastructure in the North and South Kurils and higher tectonic cracking and fragmentation of the crust. Therefore, mapping of seismogenic cracks, clastic dikes, active main and feathering faults (seismic ruptures), and their active (mobile) wings remains the main objective of practical seismology; implementing this task involves application of portable digital seismic stations, shallow depth seismic exploration utilizing P and S waves, georadars, geophones, geodetic, and GPS observations. The data discussed in the present work indicate the young geological age of the Kuril arc-trench system located in the hanging wall of the Benoiff zone's deep thrust. Hence, the seismic gap (for example that in the northern flank of the Kuril arc-trench system) does not mean the finish of crustal-mantle thrusting of Eurasia onto the Pacific Plate in the epoch of the global Pasadenian orogeny (Middle Pleistocene–present), but reflect the peculiarities of stress accumulation and preparation of new strong earthquakes, usually accompanied by tectonic (upthrow–thrust) tsunamis. This viewpoint is verified by investigation of the Tohoku-Oki earthquake off the coast of Japan, which occurred on March 11, 2011 (Kossobokov, 2011;

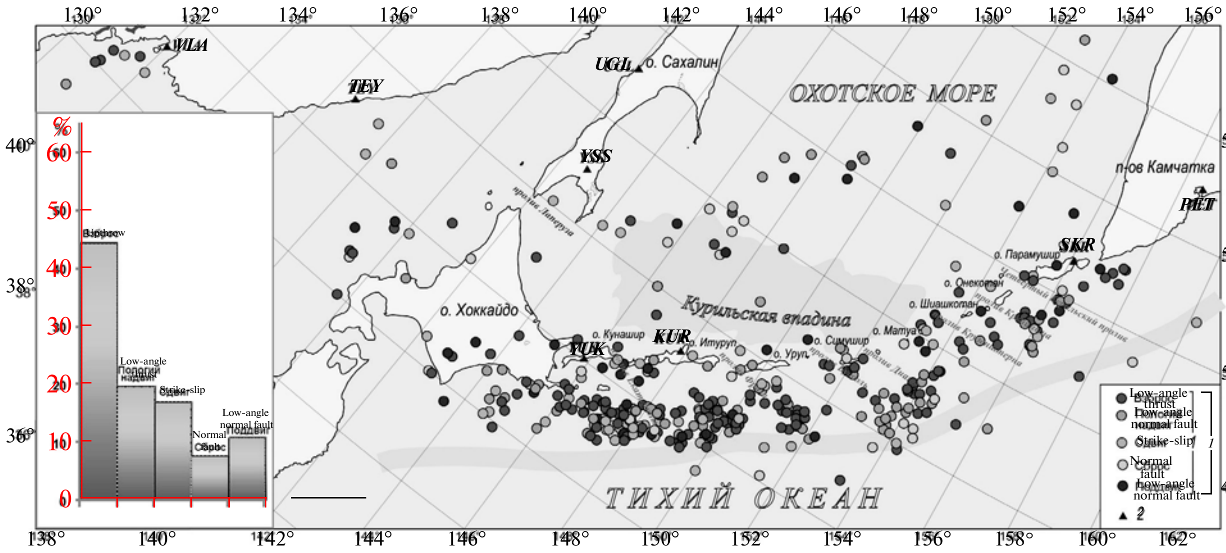

Fig. 1. The map of seismodislocations in the Kuril-Okhotsk region for the period of 1964–1999. In the inset, the histogram of seismodislocation types' distribution is shown. *1*, seismodislocation types; *2* seismic stations.

Levchenko et al., 2011; Lutikov, 2011; Lyubushin, 2011a, 2011b; Malovichko et al., 2011; Rogozhin, 2011; Rogozhin et al., 2011; Rodkin and Tikhonov, 2011; Sidorin, 2011a, 2011b; Trubitsyn, 2011; Shebalin, 2011; Yunga, 2011). In the distant prospect, we can expect the Benioff zone "healing" (i.e., disappearance of seismicity) and transition to a more quiet and amagmatic phase of tectonic evolution, when processes of gravity creeping of the Kuril mountain structure will dominate, crustal seismicity will be less intensive, and tension seismodislocations (normal faults and strike-slips) will be more common. However, in the nearest future the most topical problem is practical studying of the seismicity, especially a shallow focus one and including the problems of strong earthquakes prediction, in the discussed region of the Pacific Ocean and adjacent ones.

RELATIONSHIP BETWEEN SEISMODISLOCATIONS AND TECTONIC STRUCTURE OF THE KURIL-OKHOTSK REGION (BASED ON *KATALOG*..., 2011)

Based on the new regional focal mechanism catalog for $M \geq 6.0$ earthquakes in the Kuril-Okhotsk region and, in part, the Japanese region for the period of 1964–2009 (*Katalog*..., 2011), we considered the relationships between seismodislocations and the structure of the Kuril segment of Benioff and Tarakanov zones, where these relationships manifest, via statistical interpretation of the results of focal mechanisms determination and using consideration of individual stress orientation patterns and other characteristics within the zones. The study of specific stress orientation patterns allows us to subdivide seismodislocations in terms of their significance, which is very important to define the role played by particular dislocation types in formation of the zonal structures. The methodical basis was basic algorithms of the Mekhanizm program (*Massovoe*..., 1979). This program does not define the one "best" solution, but all solutions fitting the observed data (within the 85% confidence interval) in order to characterize in full the accuracy and degree of uncertainty of the sought model in every individual case. This program has been tested in the Kuril-Okhotsk region in 1964–1999 (*Katalog*..., 2011).

Figure 1 presents the focal mechanisms of strong ($M \geq 6.0$) earthquakes based on their seismodislocation types for the period of 1964–2009. In terms of lateral and depth extent, the earthquake sources are distributed nonuniformly (*Katalog*..., 2011, Figs. 1, 2). E.g., in terms of depth distribution, there are three groups of earthquake sources (Fig. 2). Most of them (65.1%) occur at depths ~80 km. The second cluster includes the depth interval 81–300 km (22.6%). The third group consists of the deep focus events of H = 301–700 km (12.3%).

Analysis of the distribution of seismodislocation types (inset in Fig. 1) shows that the predominant part of strong ($M \geq 6.0$) earthquake sources in the Kuril-Okhotsk region were in the background of compression that caused upthrow slips (45%), low-angle thrust ones (20%), and strike-slips (17%). Of the sources 18% were under tension stresses, which produce normal faults (7%) and low-angle normal faults (11%).

For the detailed analysis of seismodislocations in terms of depth intervals, the additional histograms were plotted (Fig. 3); these graphs showed that, as an analog to the entire catalog (inset of Fig. 1), the dominating focal mechanisms in the depth interval of 0–40 km were upthrows (48.9%). For the same depth inter-

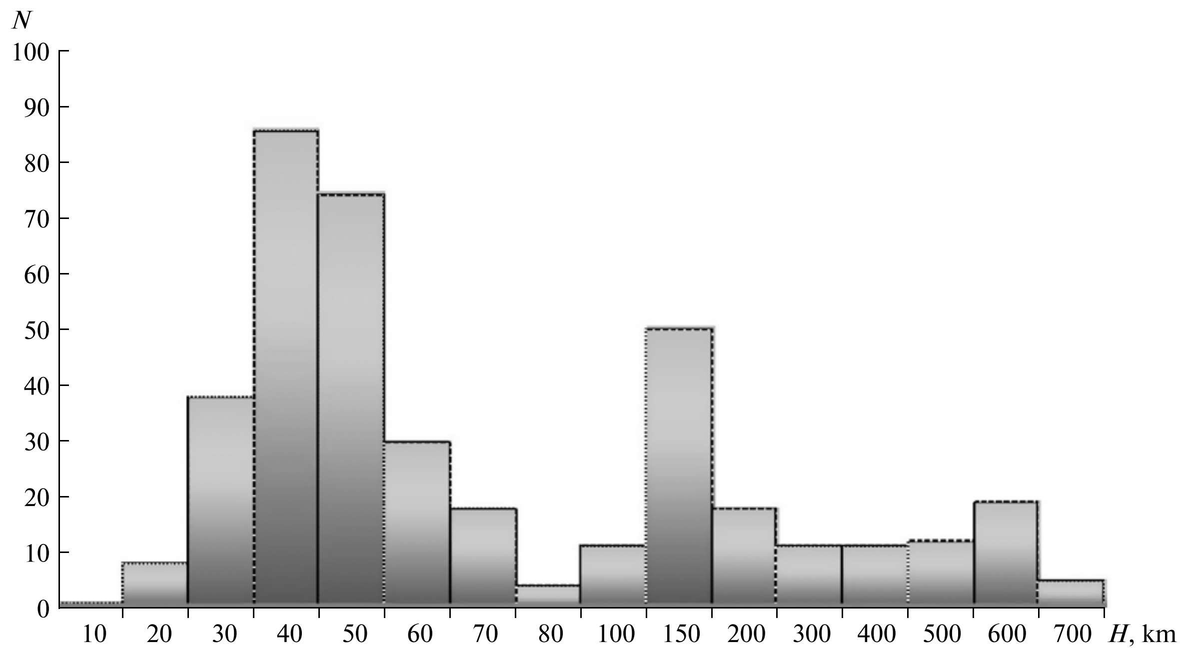

Fig. 2. The histogram of the depth distribution for earthquakes in the Kuril-Okhotsk region.

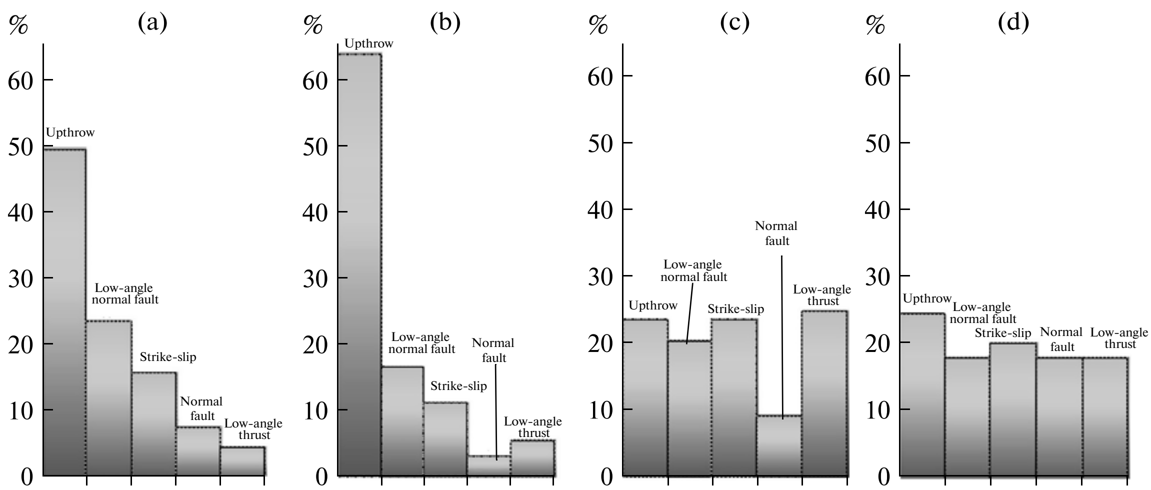

Fig. 3. Depth distribution for seismodislocations in the Kuril-Okhotsk region. (a) 0–40 km, (b) 41–80 km, (c) 81–300 km, and (d) 301–700 km.

val, the percentage of gentle low-angle thrusts was 23.3%; that of strike slips, 16%; and that of normal faults, 10%; notably, the percentage of low-angle normal faults was less than in the entire catalog by 50%. For the earthquakes at depths 41–80 km, the number of upthrows increased by 32% in comparison to the previous group, while those of other seismodislocations reduced by 25–41% (Fig. 3b). As the earthquake source depth grows further, the numbers of seismodislocation types becomes equalized, e.g., for the interval $H = 81–300$, upthrows made up 23.3%; low-angle thrusts, 20%; strike-slips, 23.3%; and low-angle normal faults, 21.4%. The only exclusion is for normal faults that made up 8.9% (see Fig. 3c and the inset in Fig. 1). For the depth interval of 301–700 km, the numbers of all seismodislocation types are from 18 to 23%.

Despite the diverse earthquake source mechanisms, the general properties of most sources can be defined. This is well illustrated through construction of vector diagrams for the repetition rate of some spatial parameters characterizing the source mechanism (averaged interval is 10%). Figure 4 presents the vector diagrams of all source parameters for the studied

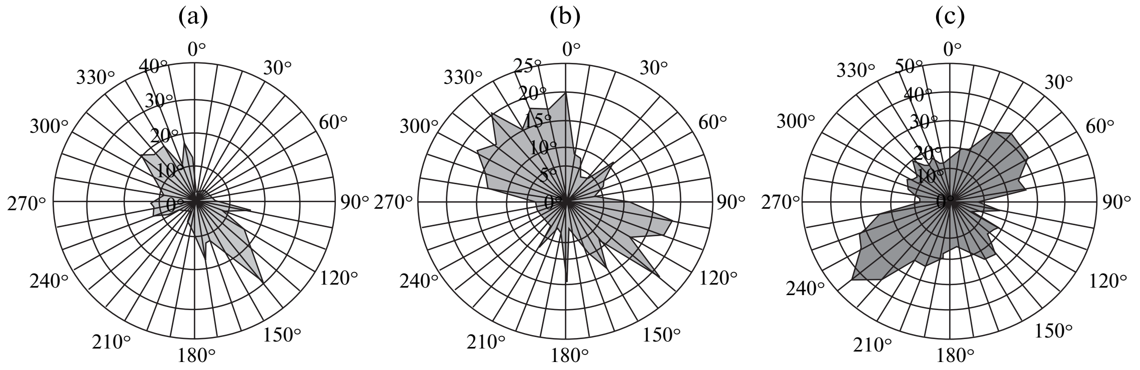

Fig. 4. The vector diagrams of source parameters for the earthquakes that occurred in the Kuril-Okhotsk region: (a) compression stresses, (b) tension stresses, and (c) strike azimuths of nodal planes (NP1, NP2).

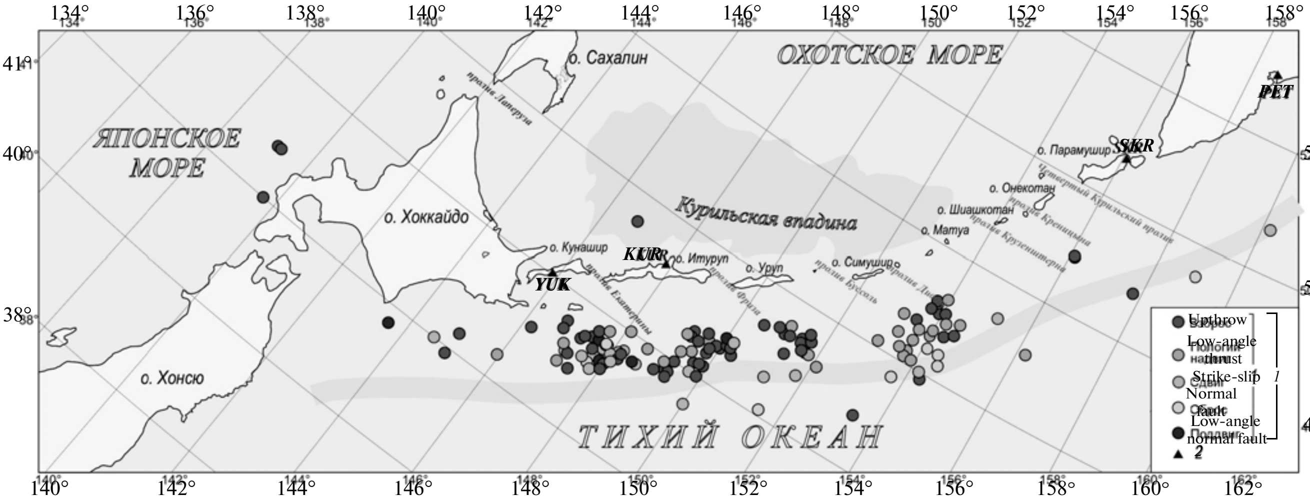

Fig. 5. The map of seismodislocations in the Kuril-Okhotsk region for the depths of 0–40 km. *1*, seismodislocation types; *2* seismic stations.

earthquakes. Horizontal projections of source mechanism parameters have two equivalent directions that differ by 180° in azimuth.

The vector diagram showing distribution of compression stress axes relative to the zenith direction (Fig. 4a) has two clear maxima in the intervals of 120°–150° and 300°–330°. The tension stresses demonstrate almost the same predominant directions as compression stresses; however, their general distribution in terms of azimuths has less sharp maxima in the intervals of 100°–150° and 280°–360° (Fig. 4b). We emphasize that the horizontal projection of compression stresses is oriented primarily perpendicularly to the Kuril arc and trench. This feature was also noted in (Balakina, 1995).

It can be seen in Fig. 4c that strike azimuths of nodal planes also have two dominating directions. The one maximum is oriented at 220°–260° relative to the northward direction and most nodal planes are oriented along the strike of the Kuril Arc, at average dipping angle of ~50° westwards. In the second possible version, rupture planes are oriented in the interval of 30°–80° and also reveal a good consistency with the strike of the arc, but with eastward dipping, that, however, does not contradict the data by V.N. Aver'yanova (1968). The less clear maximum is identified in the interval of 290°–340°, but the number of earthquakes here is significantly less than in the previous one.

MAIN TYPES OF CRUSTAL SEISMODISLOCATIONS IN THE KURIL-OKHOTSK REGION IN THE DEPTH INTERVAL OF 0–40 KM

It can be seen in Fig. 5 that shallow focus earthquakes are confined by the Kuril Islands and the Kuril Trench axis, forming several spatially isolated groups with different dominating seismodislocation types in every group. Despite that most crustal earthquakes are located under the conditions of subhorizontal com-

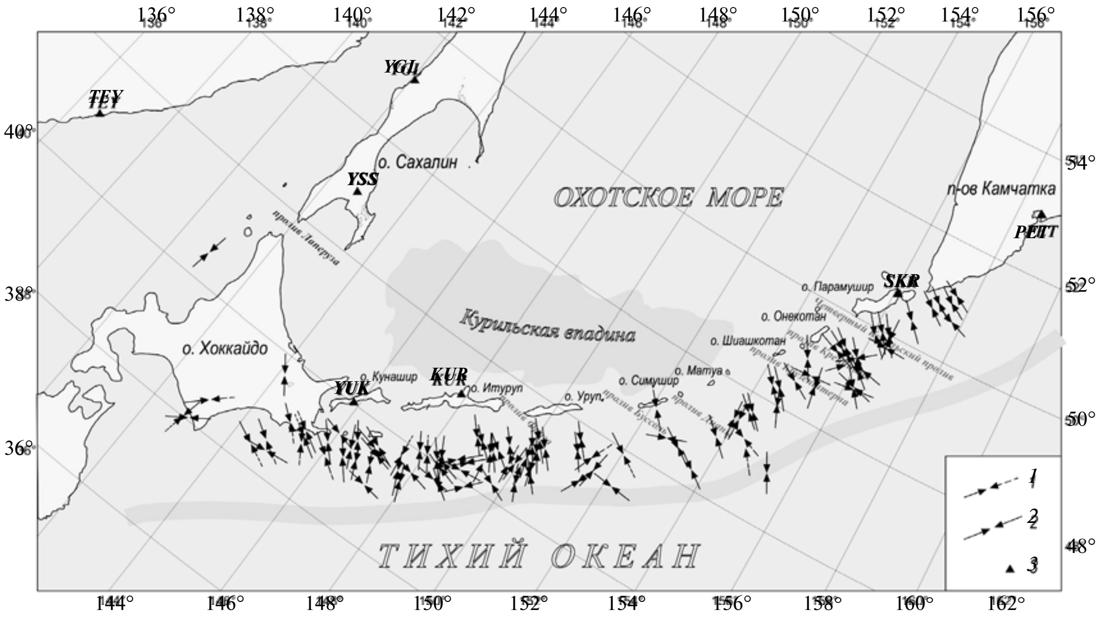

Fig. 6. Orientation of compression axes for the crustal ($H = 0–40$ km) earthquakes in the Kuril-Okhotsk region. *1*, subhorizontal compression; *2* high inclination of compression axis (the number of arrow dashes corresponds to 20°); and *3* seismic stations.

pression stresses, orthogonally to the strike of the Kuril Arc, the main seismodislocation types can be different.

The first, quite compact group (37 events) is located in front of the Yekaterina Strait. Its sources demonstrate primarily upthrow slips (40.5%) and strike-slips (32.5%).

The second and third groups of earthquakes are located in the area oceanward from the Iturup and Urup islands, closer to the Kuril Trench axis. The dominating slips in their sources are upthrows (67%) and low-angle thrusts (20–27%).

The fourth group of hypocenters is located closer to the trench, oceanward from Simushir Island. Here, low-angle thrusts (50%) and upthrows (32%) dominated. This group includes the recent, strongest Simushir earthquakes (Tikhonov et al., 2008): the first was a low-angle thrust and the second was a normal fault.

Additionally, the series of individual events can be distinguished off the coast of Hokkaido Island, where a low-angle normal fault, strike-slip, and two upthrow seismodislocations alternate. Another series of seismic events surrounds the Kuril Trench axis. Here, 50% of earthquakes occurred under subhorizontal compression and 50% under subhorizontal tension.

We emphasize the absence of strong crustal earthquakes with the mentioned mechanisms in the zones at southern and—what is more important—northern flanks of the Kuril arc-trench system, probably including the South Kamchatka region; these are the zones of probable strong earthquakes occurrence in future.

We compared the compression stresses orientations in the sources of crustal earthquakes with the strikes of surface tectonic structures (Fig. 6). It was noted that subhorizontal compression stresses perpendicular to the island arc dominate for the first and the fourth groups of earthquakes. In the rest of the groups, horizontal compression stresses with submeridional orientation dominate, however, individual events with a sublatitudinal one can be found.

MAIN TYPES OF CRUSTAL SEISMODISLOCATIONS IN THE KURIL-OKHOTSK REGION IN THE DEPTH INTERVAL OF 41–80 KM

Figure 7 presents the main seismodislocation types with source depths of 41–80 km. Earthquake hypocenters of this interval are located between the Greater Kuril Islands and the trench axis, forming a wide chain that turns to small groups or individual events as progressing SE of the Middle Kuril Islands.

In the region of the North Kuril Islands, the number of earthquakes increases and the groups become more compact and epicenters are clustered in straits. Most earthquakes occurred under subhorizontal compression stresses oriented orthogonally or submeridionally to the strike of the Kuril Arc (the characteristic slip types are upthrows (63.9%), low-angle thrusts (16.7%), strike-slips (11%)). In the SE part of the zone, steeper submeridional and sublatitudinal compression stresses can be found (Fig. 8).

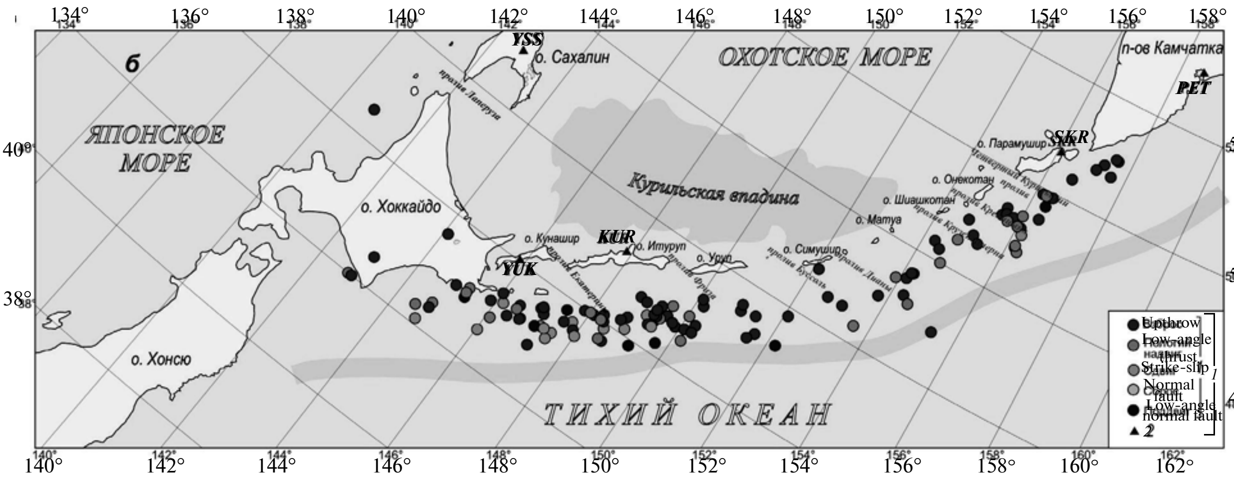

Fig. 7. The map of seismodislocations in the Kuril-Okhotsk region for the depths of 41–80 km. *1*, seismodislocation types; *2* seismic stations.

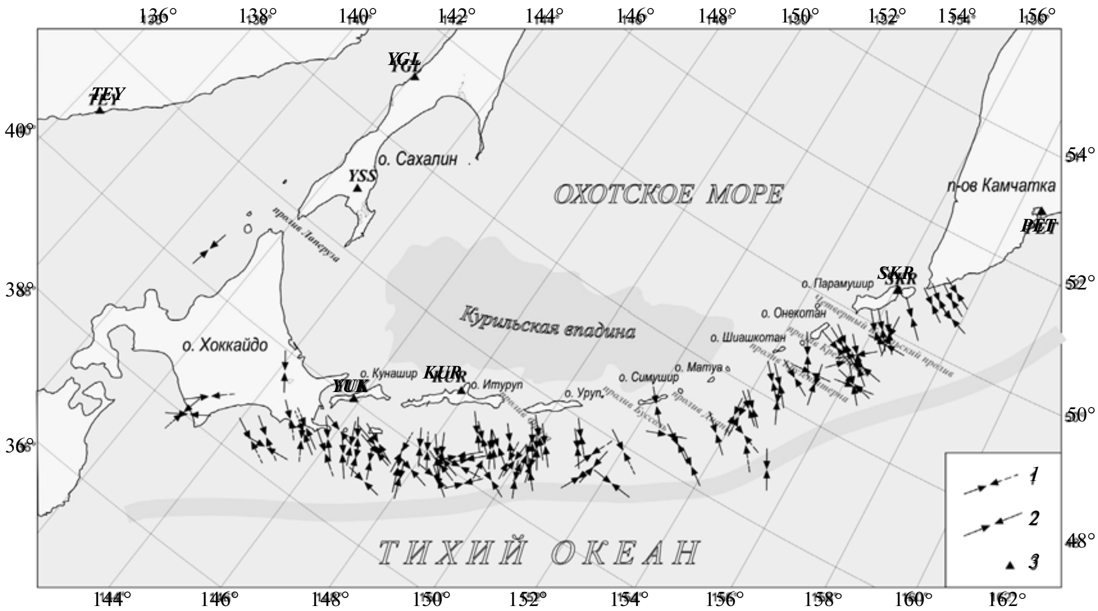

Fig. 8. Orientation of compression axes for the earthquakes of $H = 41–80$ km in the Kuril-Okhotsk region. *1*, subhorizontal compression; *2* high inclination of compression axis (the number of arrow dashes corresponds to 20°); and *3* seismic stations.

MAIN TYPES OF CRUSTAL SEISMODISLOCATIONS IN THE KURIL-OKHOTSK REGION IN THE DEPTH INTERVAL OF 81–300 KM

The group of earthquakes with sources in the depth interval of 81–300 km (22.6% from the total number of the studied events) is a narrow band of events, with hypocenters located immediately beneath the Kuril Islands (Fig. 9). Spatially, small clusters can be distinguished.

Most earthquakes of this hypocentral depth occurred under dominating compression stresses; however, this is not a significant feature. Also dominating are quite steep submeridional and rarely sublatitudinal orientations (Fig. 10). For tension axes, steep submeridional and sublatitudinal orientations are also typical.

Among all cases of compression stresses, those oriented perpendicularly to the strike of the Kuril Arc and nearly horizontal ones are singular. The percentages of seismodislocation types are as follows: 25% of strike-slips, 24% of upthrows, 25% of low-angle normal faults, 16% of low-angle thrusts, and 10% of normal faults.

The small group of earthquakes is distinguished in the area between Hokkaido Island and the Primorye

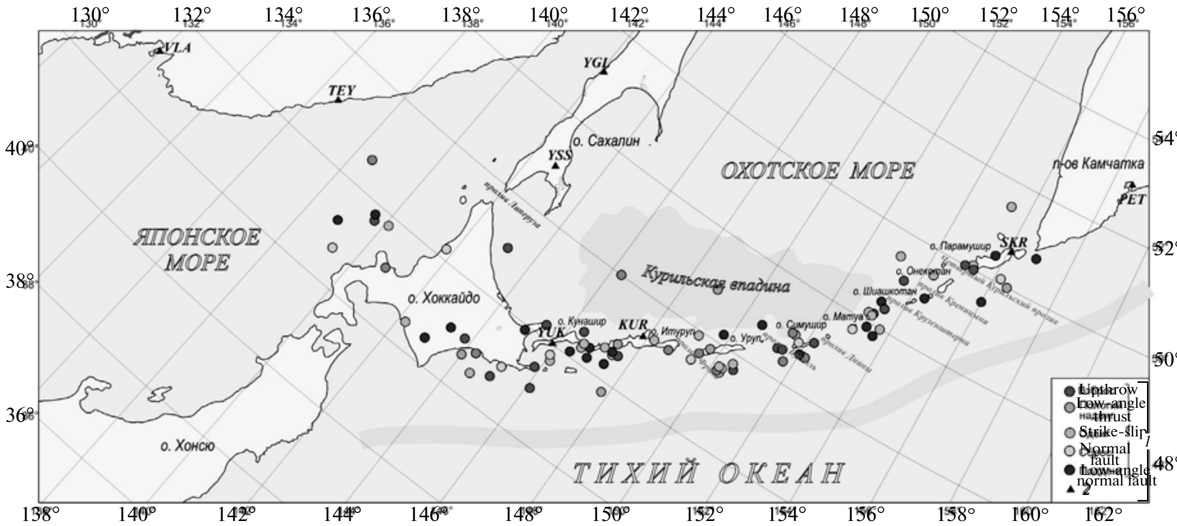

Fig. 9. The map of seismodislocations in the Kuril-Okhotsk region for the depths of 81–300 km. *1*, seismodislocation types; *2* seismic stations.

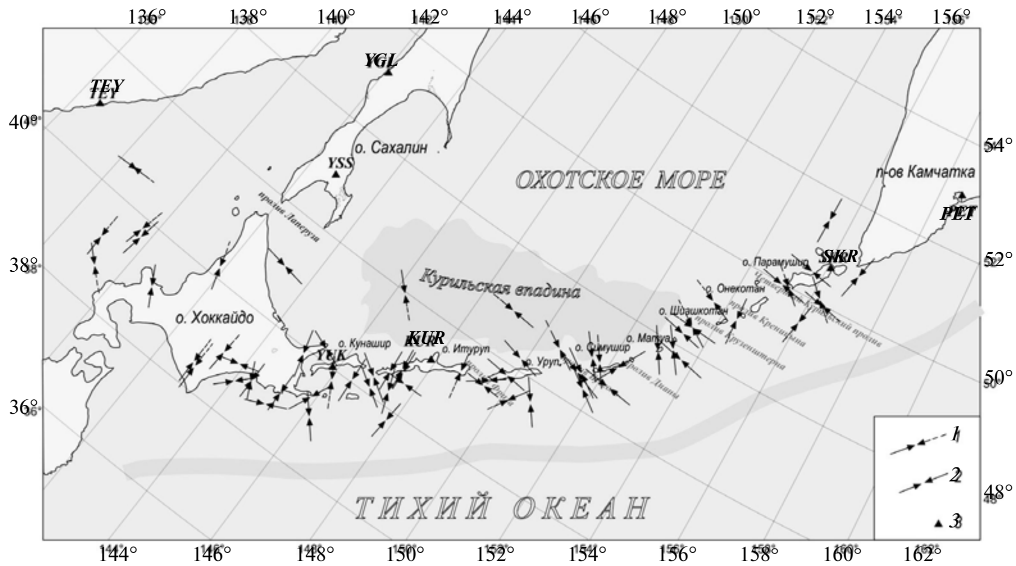

Fig. 10. Orientation of compression axes for the earthquakes of $H = 81–300$ km in the Kuril-Okhotsk region. *1*, subhorizontal compression; *2* high inclination of compression axis (the number of arrow dashes corresponds to 20°); and *3* seismic stations.

coast. Here, earthquakes occur under both tension (32% of low-angle normal faults and 17% of normal faults) and compression conditions (17% of upthrows, 17% of low-angle thrusts, and 17% of strike-slips), with stresses oriented diagonally to the island arc.

MAIN TYPES OF CRUSTAL SEISMODISLOCATIONS IN THE KURIL-OKHOTSK REGION IN THE DEPTH INTERVAL OF 301–700 KM

This group includes the deep focus events (301–700 km), which make up 12.3% of the total number of the considered catalog (*Katalog*..., 2011). These hypocenters form a wide zone extending from the western coast of Kamchatka through the Kuril Basin to Petra Velikogo Bay in Primorye. The earthquakes within this zone form spatially isolated groups (Fig. 11), which are characterized by certain dominating stresses and seismodislocation types.

The first group of earthquake epicenters, characterized by dominating sublatitudinal subhorizontal tension stresses, forms a wide zone located nearly in parallel to the Kamchatka Peninsula coast. Seismodislocation types are: 25% of normal faults, 25% of low-

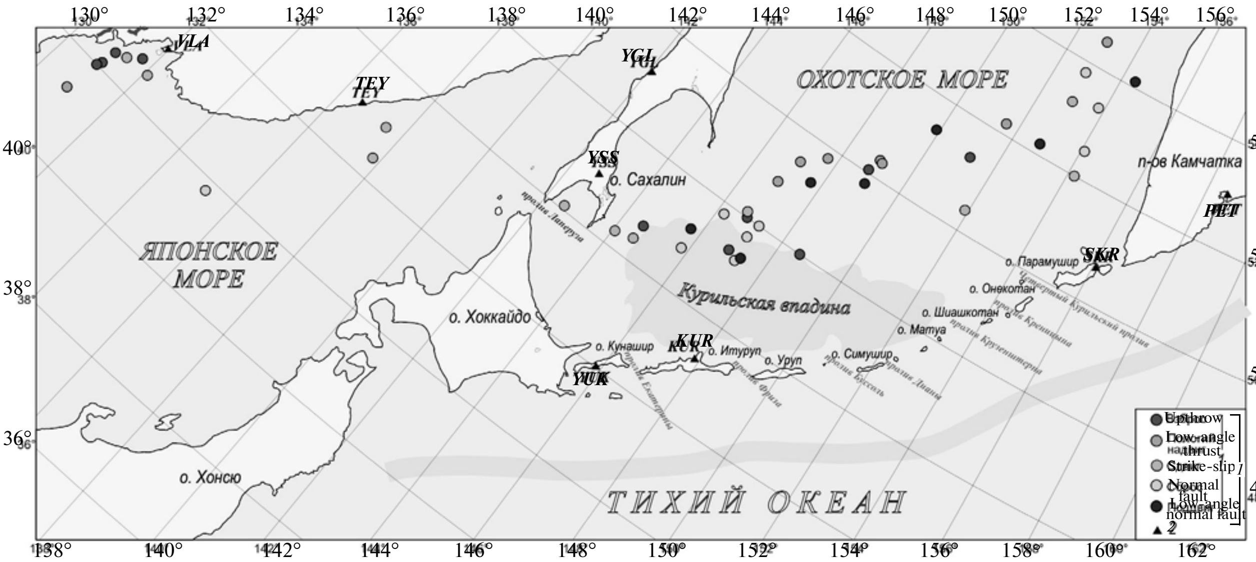

Fig. 11. The map of seismodislocations in the Kuril-Okhotsk region for the depths of 301–700 km. *1*, seismodislocation types; *2* seismic stations.

angle normal faults, 25% of strike-slips, 17% of low-angle thrusts, and 8% of upthrows.

The second group of earthquake epicenters is located north of the Kuril (South Okhotsk) Basin. The main seismodislocation types are low-angle thrusts (62%), upthrows (13%), and low-angle normal faults (25%). Quite steep compression stresses, oriented orthogonally to the island arc structures, or submeridionally, dominate here.

The third group of earthquake epicenters is located in the NW Kuril Basin. Earthquakes occurred under the predominant conditions of subhorizontal tension stresses oriented diagonally to the island arc. The main seismodislocation types are normal faults (37%), upthrows (28%), low-angle normal faults (21%), and strike-slips (14%).

The fourth group of deep focus earthquakes is clustered in the Sea of Japan, close to the Vladivostok seismic station. The main seismodislocation types are upthrows (57%) and strike-slips (29%). In this group, the dominating stresses were those of sublatitudinal subhorizontal compression.

Thus, analysis of the source mechanism catalog of 396 strong earthquakes that occurred in the Kuril-Okhotsk region for the period of 1964–2009 has shown that most earthquake sources with ~80 km depth predominantly were located under conditions of subhorizontal compression oriented orthogonally to the structures of the island arc and having steep orientations of tension axes. The characteristic dislocation type is upthrows (56.3%).

For the earthquake sources of >81 km depth, this regularity has not been found; the number of earthquakes of this source depth sharply reduces and the characteristic dislocation type is not distinguished.

TECTONIC STRUCTURE OF THE KURIL ARC

Traditionally, the Kuril Arc is subdivided into the inner (volcanic) and outer (currently nonvolcanic) arcs divided by the Middle Kuril Trough; also, the wide Pacific and the narrow Okhotsk submarine continental margins are distinguished (Svarichevskii et al., 1979; *Tektonika*..., 1980; *Geologo-geofizicheskii*..., 1987). The external arc is located beyond the edge, or outer edge, of the Pacific Ocean's shelf zone off the Lesser Kuril Islands and beyond the top foreshelf of submarine continuation of Lesser Kuril Islands (South and North Vityaz ridges and deep water bench seaward of Simushir Island). The internal arc is located beyond the shelf edge of Greater Kuril Islands on the side of the Sea of Okhotsk (Figs. 12–15).

The Pacific Ocean slope of the Kuril Arc is subdivided into the upper, middle, and lower parts. The first and the third ones are the steep (up to ~10°) scarps divided by the middle, step-wise part of the slope, containing large (upper and lower) steps, or terraces. The lower step of 1–2 km high and 10–12 km wide is also the internal slope of the Kuril Trench; some authors considered this slope as a part of the entire Pacific continental slope. The external gentle (3°–5°) slope of the trench is 3–4 km high and 40–50 km wide; it has the step-wise (key-step in places) structure, which is typical for trenches in the Pacific. This slope confines the flattened top of the marginal Zenkevich Swell on the west and rests on the trench bottom (trench width here is 5–15 km). In the RM section in 1 : 1 scale, the trench is a valley of 500 m depth with step-wise (terraced) sides and flattened accumulative bottom of 1–3 km width at depths of 9550–9600 m, or up to 9717 m, taking the sonic speed change with depth into consideration (*Tektonika*..., 1980).

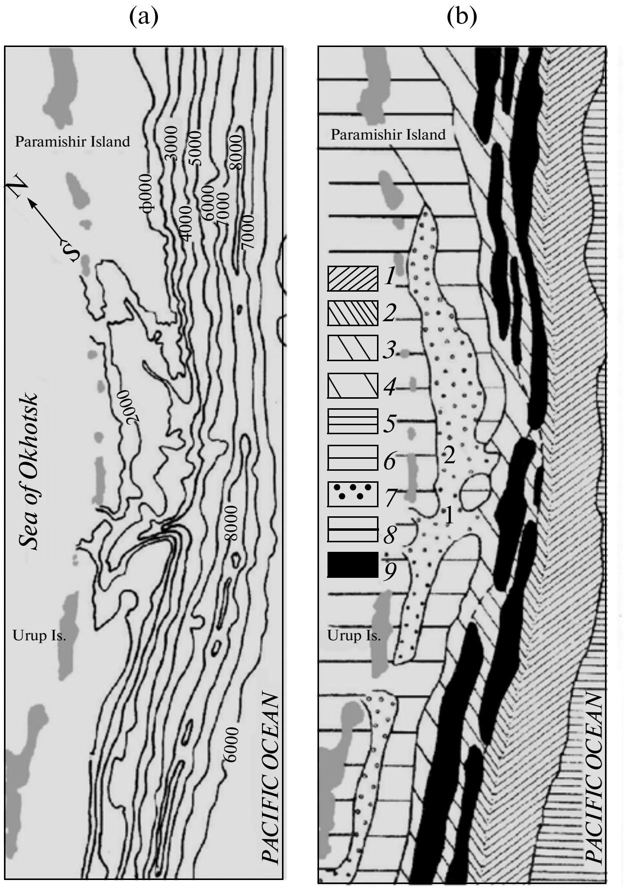

Fig. 12. The bathymetric map after (*Tektonika*..., 1980) (a) and morphographic scheme (b) of the Kuril arc-trench system. (*1*), (*2*) outer and inner slopes of the trench, respectively; (*3*), (*4*) middle (step-wise) and upper parts of the Pacific Ocean slope, respectively; (*5*) top of the marginal swell; (*6*) top of the outer (currently nonvolcanic) arc; (*7*) Middle Kuril Trough; (*8*) inner (volcanic) arc of Greater Kuril range; and (*9*) tectonic steps (terraces) of the Pacific Ocean slope. Digits denote (1) Bussol canyon and graben; (2) deep water bench. Isobaths are drawn for every 1000 m.

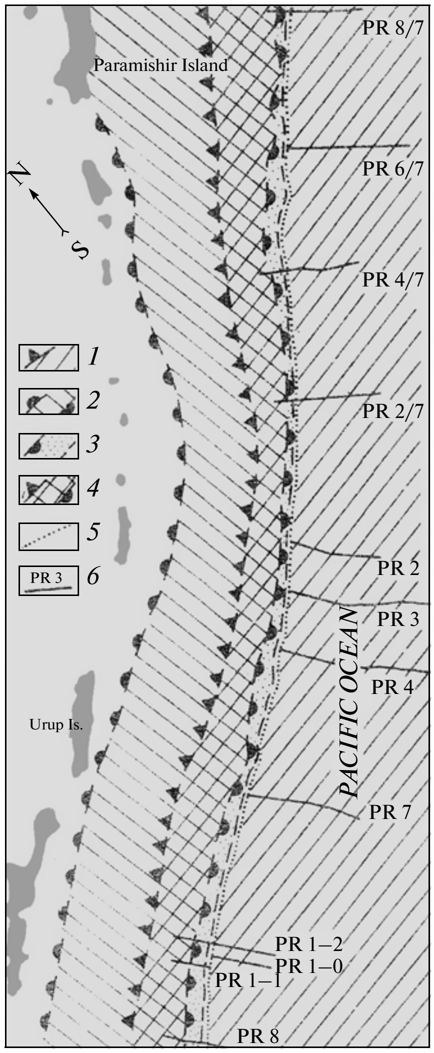

Fig. 13. Structural scheme of the Kuril arc-trench system with the positions of RM deep sections (see Fig. 14). (*1*) acoustical basement high on the trench's outer slope (A); (*2*) acoustical basement high on the Pacific continental slope (B); (*3*) accretionary prism on the trench's internal side; (*4*) Pegasus regional nappe; (*5*) thalweg of the Kuril Trench; and (*6*) SCP and RM profiles.

Describing the tectonic structure of the Kuril arc-trench system, it is important to take into account its model (see Fig. 15) constructed on the basis of the RM data (see Fig. 14). The key elements of the model are two highs of the acoustical basement (A and B), and the accretionary prism on the internal slope of the trench.

High A is the periphery of the NW Pacific Plate, gently sloped towards the Kuril Arc and buried in the middle part of the plate's continental slope beneath the sediments of the accretionary prism and Pegas regional nappe. The western edge of this high is sunken by 10–15 km, or slightly more, into the upper submarine terrace. Its location is identified based on the conductive heat flow minimum, on the position of the Meinetz zone (according to H. Stille (1957), this is a linear negative gravity anomaly in trenches), on the sources of regional tsunamis, and on the seismological data of Benioff and Tarakanov zones' outcrops (Tarakanov et al., 1977; Tarakanov, 2004). South of here, on the Pacific Ocean slope of Honshu Arc, the western edge of the plate is also sunken to a significant (10–20 km) depth and is likely cut by the Benioff zone, as is found from the seismological data (Hasegawa, Umino, and Takagi, 1978).

Analyzing the SCP and RM sections (Fig. 14), one should note the tectonic fragmentation of high A, especially in RM profiles; this fragmentation increases from the edge to the foot of the external slope of the trench. The width of the steps varies from a few tens and few hundreds of meters to few tens of kilometers (compare the RM profiles 1–1 and 1–0 with SCP pro-

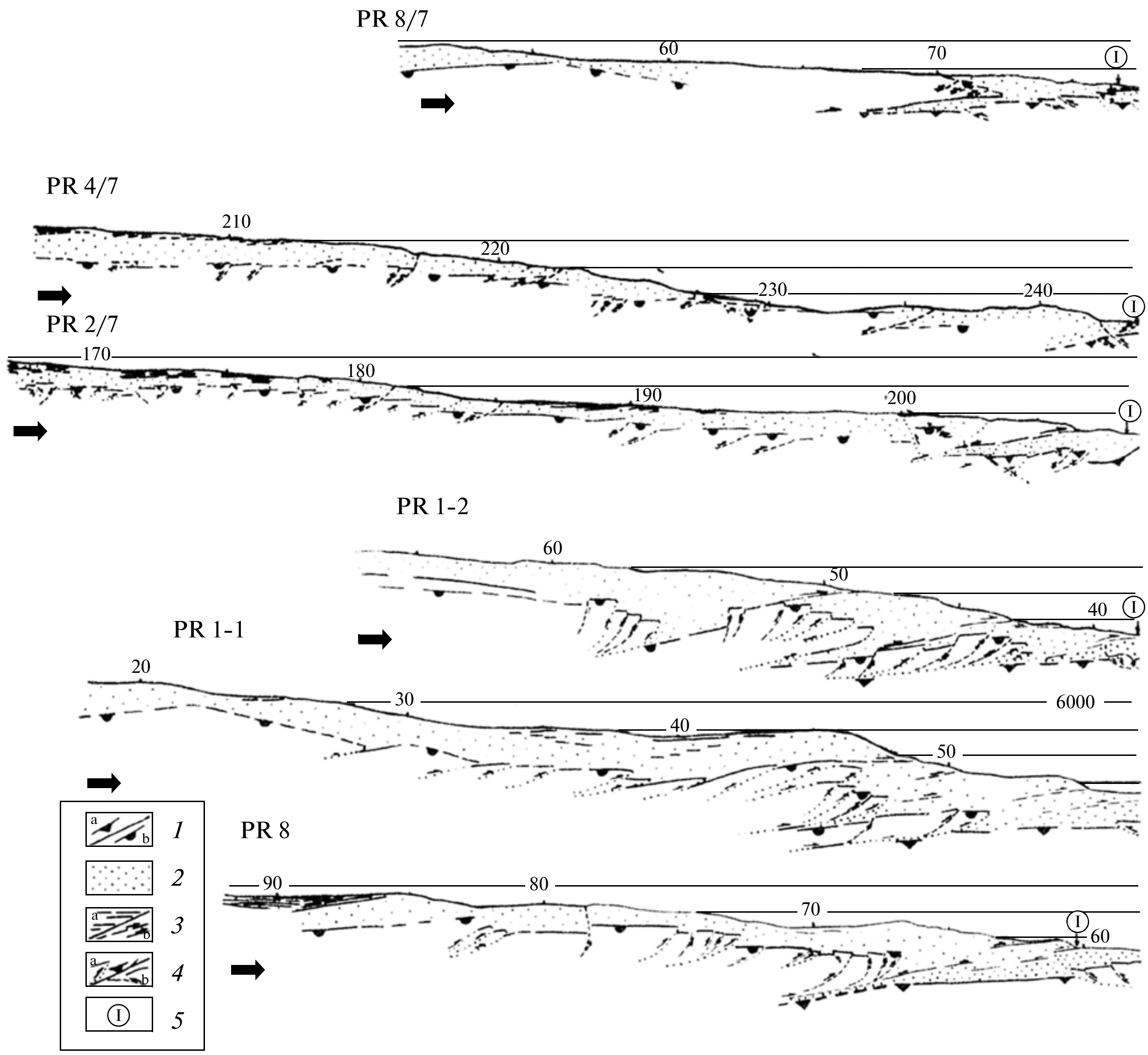

Fig. 14. The deep sections interpreted on the basis of SCP (PR 8/7, 6/7, 4/7, 2/7, 2–4, 7, 8) and RM profiles (PR 1–1, 1–0, 1–2) within the limits of the Kuril arc-trench system. (*1*) top of the Cretaceous acoustical basement in the external side of the trench, or layer 2 S3 of the Pacific Plate (a) and the Pacific Ocean slope (b); (*2*) Cenozoic cover of the Pacific Ocean slope and accretionary prism (rarefied points); (*3*) reflectors in the sedimentary cover: (a) turbidite lenses, (b), thrust fault planes in accretionary prism; (*4*) faults in acoustical basement: (a) found, (b) supposed; and (*5*) accretionary front and the basement of inner slope of the trench and the Pacific Ocean slope. Positions of the sections are indicated in Fig. 13.

files 4 and 4/7). Correlation between the scarps in the top of the acoustical basement and in the bottom relief reveals in most cases a clear inclination of fault planes to the east, beneath the Zenkevich marginal swell, in accord with the dip of the Tarakanov seismofocal zone. Considering the hanging walls of faults being active, we can conclude that most of the faults on the external slope of the Kuril Trench are thrusts and upthrows with horizontal and vertical displacement amplitudes of up to 0.5–1.5 km. The structures of large steps often reveal vergence of faults, at that: from gentle in the frontal part to high-angle and subvertical reverse-dip ones in the rear part (fold thrusts, according to G.D. Azhgirei (1956)).

Thus, the regional bulging of the crust, with formation of a megaduplex of mostly east-dipping compression faults, is observed on the foreslope of the Kuril Trench. Formation of such a megaduplex is attributed (Lomtev, 2008) to Late Cenozoic gravity sliding of 1–4 layers down the foreslope; based on the bottom seismometry data, this process could be accompanied by seismic activity, which was significant in places (*Tektonika*..., 1980). However, the fault types traditionally identified here are normal faults dipping mostly towards the trench axis (Pichon, Francheteu, and Bonnin, 1973; *Tektonika*..., 1980; Verba et al., 2011).

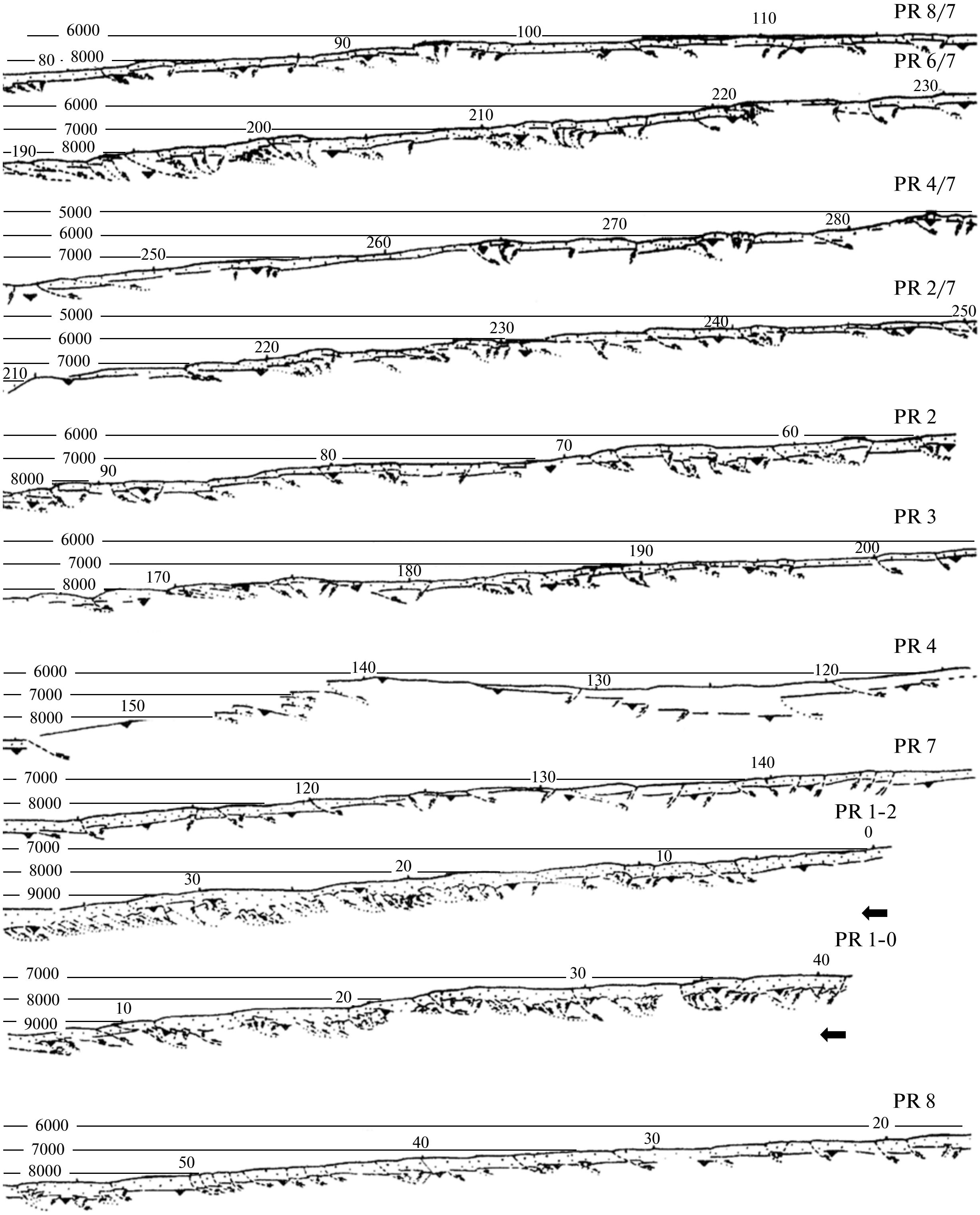

Fig. 14. Contd.

High B, judging by Fig. 14, includes the outer arc and upper–middle pars of the Pacific Ocean slope. The middle part is important for decoding the modern structure and tectonic evolution of the Kuril arc-trench system, because it is formed by the mid-slope basement high (according to D.E. Karig (1971)). The outcrop of the upper focal plane of the Benioff zone is also outlined here. SCP and RM deep sections (PR 1–

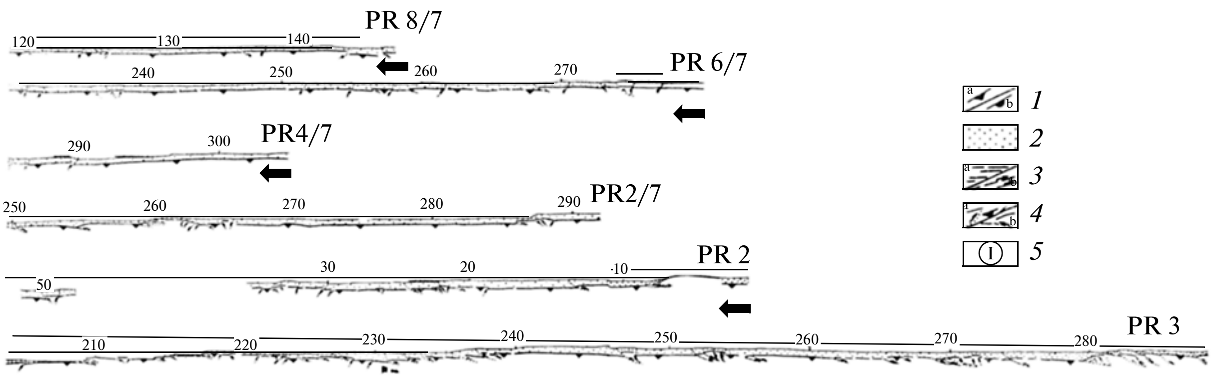

Fig. 14. Contd.

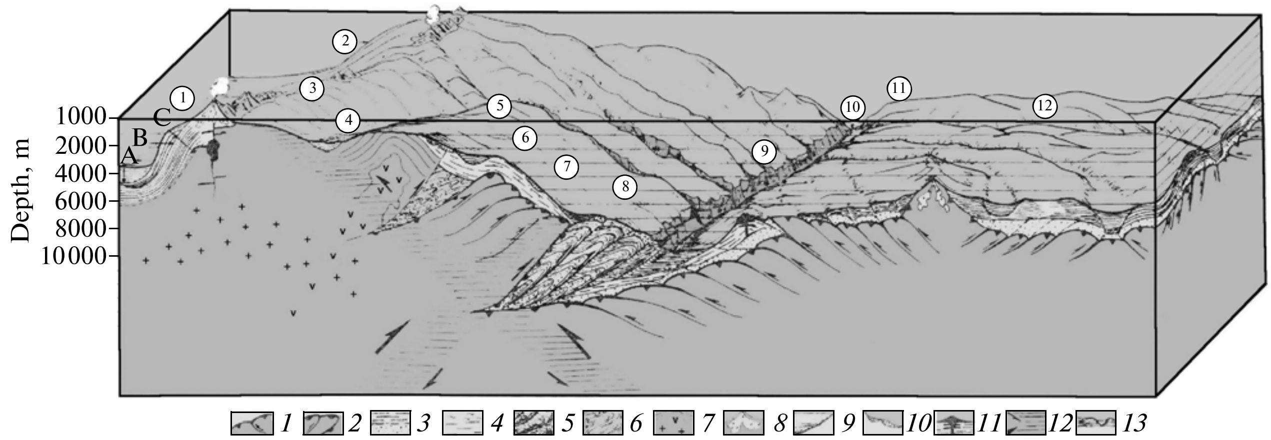

Fig. 15. The model of the Kuril arc-trench system's south flank. (*1*), (*2*) tops of the Cretaceous acoustical basement in the outer side and the middle part of the Pacific Ocean slope (Pegasus nappe), respectively; (*3*) Cenozoic oceanic cover with Pacifides loesses and overlying hemiterrigenous sediments (fans); (*4*) Cenozoic cover of the Pacific Ocean slope; (*5*) accretionary prism; (*6*) ancient accretionary prism of the Miocene(?) trench, upper terrace; (*7*) Miocene(?) nappe of the outer arc, composed by Mesozoic sedimentary-volcanic and Paleozoic granitoids, pierced by the young Kuril megadike (Lomtev and Patrikeev, 2006); (*8*) volcanoes (of different age); (*9*) angular unconformity in the basement of the turbidite complex of trench; (*10*) landslides; (*11*) mud volcano; (*12*) Benioff and Tarakanov seismofocal zones; and (*13*) abyssal valleys formed by embanked washed in dams. Digits in circles: (1) foot of the back-arc Kuril (South Okhotsk) bathial basin; (2) Okhotsk continental slope; (3) top of the inner volcanic arc; (4) Middle Kuril Trough; (5) top of the external arc; (6) upper part of the slope and upper deep water terrace; (7) middle part to the slope; (8) lower deep water terrace; (9) lower part (inner slope) of the Kuril Trench; (10) thalweg of the Kuril Trench; (11) outer slope of the Kuril Trench; and (12) Zenkevich marginal swell. Letters denote (A) young filling complex of the Kuril Basin; (B) filling complex of the back-arc paleo-trench; and (C) ancient filling complex of the basin.

1, 1–2) show the structure of the 20–40-km wide outer part of the rise. Here, the rise consists of few wedge-like tectonic slabs limited by west-dipping low-angle thrusts. In place, structure of the slabs reveal particular, finer tectonic flakes of the basement (for example, in PR 1–2 and 1–1). The visible horizontal displacement of the slabs is small, 3–8 km, which is explained likely by an insufficient radiating power (compare with the RM profiles 1639 and 1700 made by OAO Dal'morneftegeofizika in *Tektonika...*, 2004) or with the RM study data acquired in the Japan Trench (Gnibidenko, 1987; *Initial Reports...*, 1980; Lomtev and Patrikeev, 1985)).

With all the said above, we can interpret the acoustical basement's rise in the middle part of the Kuril Arc as the Pegasus regional nappe of the acoustical basement with the horizontal displacement of 30–40 km in the center and 50–70 km in the flanks (see Figs. 14 and 15). Since this nappe is a part of the Kuril Arc, we can deduce the nappe of the arc on the adjacent bottom of the Pacific Plate or its northwestern minor plate. In the plan, the Pegasus nappe is located at the Benioff zone's outcrop, or saying it more precisely, in its upper foal plane (analogous to the Oyashio nappe on the Pacific Ocean slope of the Honshu Arc (Tikhonov and Lomtev, 2011)). Hence, we can think of it as a near-surface structural salient of this seismofocal zone and the zone proper is a deep thrust—this agrees with the classical tectonic interpretation for this zone (Sergeev, 1976).

The outer edge of high B is located along the lower deep water terrace beyond which the internal side and accretionary prism of the trench begin (see Figs. 12b, 13–15). The accretionary prism is usually semitransparent in seismic sections, as well as the Cenozoic sedimentary cover, but it contains numerous diffractions related mostly to thrusts and folding. Thickness of the prism is maximal (1–2 km) near the front of the Pegasus nappe, while eastwards (accretionary front) and westwards (beneath the nappe), its thickness reduces to 50–10 m and less. At the distance of 1–8 km from the slope's foot, the prism is thrusted at a low angle upon the Cenozoic oceanic cover, whose thickness beneath the prism significantly reduces westwards (see PR 8, 2/7 and others in Fig. 14). Hence, the accretionary prism is a packet of tectonic flakes of the Cenozoic sedimentary cover, which were torn off by the Pegasus nappe with its eastward motion; the accretionary prism and the Pegasus nappe can be considered as a nappe–prism (allochthon) tectonic couple. The prism provides a significant lithostatic pressure that determines a large asymmetric sinking of the autochthon and adjacent ocean floor (marginal part of the NW Pacific Plate).

Note that thrusts and upthrows in the sides of the Kuril Trench (Figs. 14, 15) are generally of opposite dips, hence the trench can be considered as the ramp graben structure produced by lateral compression of the crust and, probably, upper mantle. Judging by the rupture of the unioted Neogene–Early Quaternary valley network of canyons and abyssal fan channels, and by the other features as well, foundation of the graben took place in the Middle Pleistocene, around 0.5–1.0 Ma BP (Lomtev et al., 1997; Patrikeev, 2009). H. Stille (1945) refers to this period as the beginning of the Pasadenian global phase of folding and orogeny (Lomtev, 1989). Therefore, the middle and lower parts of the Pacific Ocean's slope within the Kuril Arc, the tectonic couple (regional nappe–accretionary prism) that shapes these slope parts, and likely the opposite Benioff and Tarakanov seismofocal zones are to be of the same age as well.

DISCUSSION

Discussing the data from the new regional focal mechanism catalog for strong earthquakes in the Kuril-Okhotsk region (*Katalog*..., 2011) and their relationship wit the SCP and RM data on the structure of the Pacific Ocean slope of the Kuril arc and trench, we can point out the common distribution of compression-type seismodislocations (upthrows and low-angle thrusts) along the entire Kuril segment of the Benioff zone, and their domination in the depth interval <80 km within the zone's outcrop. From the viewpoint of seismotectonics and classical tectonics, the Benioff zone is a deep thrust along which the eastern edge of Eurasia overrides the Pacific Ocean floor. This verifies the old hypothesis of continental thrusting upon the ocean floor (Sergeev, 1976) and correlates with the vector diagrams in Fig. 4, showing the summarized orientations of tectonic stresses in the crust and upper mantle—orthogonally to the Kuril arc-trench system with its curvature oceanward. Nevertheless, definition of the seismodislocation type based on either the nodal plane (dipping towards either ocean or continent), as well as that of an active wall of the fault in tectonics, is still carried out by a researcher. The independent evidence of Eurasia thrusting on the Pacific ocean floor by deep thrusts of the Kuril and Japan Benioff zones is the SCP and RM data given in Fig. 14 and in (*Tektonika*..., 2004; Tikhonov and Lomtev, 2011).

Compression seismodislocations also indicate compression setting, especially in the crust and underlying mantle; the RM data indicate the same (tectonic couple regional nappe–accretionary prism and ramp structure of the Kuril Trench in Figs. 14 and 15). At these conditions, tension seismodislocations (normal faults and low-angle normal faults), especially at depths >80 km, are hardly explainable at first sight. In our opinion, they are related to the bend of the deep thrust zone (Tarakanov et al., 1977), which produces relative lateral tension in the foot of deep thrust and compression in its top. The aseismic layer, where these strains are compensated (neutral plane in the bend models), lies between them. Such an interpretation is based on the discovery of a two-layer structure of the Benioff zone's Japanese segment, revealed from microearthquakes demonstrating compression seismodislocations in the upper focal plane and tension seismodislocations in the lower one (Hasegawa, Umino, and Takagi, 1978). This interpretation allows one to make a more founded insight into the nature of coupled strong tsunamigenic Simushir earthquakes in 2006 and 2007 (Tikhonov et al., 2008): the first one was related to the upper focal plane of the Benioff zone (eastward low-angle thrust), while the second one was caused by normal faulting in the Benioff zone's lower plane.

Strike-slips in the sources of strong earthquakes occurring within the Kuril segment of the Benioff zone are distributed almost uniformly (10–20%). In the models of deep thrust of Eurasia, or low-angle normal fault of the Pacific Plate, the tectonic origin of these faults is not clearly explained. However, from the viewpoint of gravity tectonics that can be seen, for example, in crustal, monovergence, and divergence detachments on the decollement dipping angles of up to 0.1° (Lomtev et al., 2007; Lomtev, 2008), or eastward thrust of Eurasia, the notable is the known gentle uplift of the Benioff zone northwards, towards Kamchatka Peninsula, from 600–700 to 200–300 km depth (Tarakanov et al., 1977). This uplift suggests gravity sliding of the deep hanging wall southwards, hence producing the orogenic bridge between Sakhalin and the South Kuril Islands (mountains of Hokkaido Island); the reentrant structural corner formed by the Kuril–Kamchatka and Izu–Mariana deep thrusts (see isobath maps of the Benioff zones in

(Hamada et al., 1977; Tarakanov et al., 1977)); the small Honshu arc-trench system between them; and probably the back-arc Kuril Basin in the Sea of Okhotsk.

Note also the bimodal distribution pattern for the studied 396 strong earthquakes in terms of depth, with the maxima in the depth intervals of 30–50 and 150–200 km (see Fig. 2). The former one is more significant and probably located in the zone of crossing between the oppositely directed Benioff and Tarakanov seismofocal zones, according to the data on geometrically oppositely directed seismofocal zones in the Pacific margin of the Honshu Arc (Hasegawa et al., 1978; Tarakanov, 2004). The latter seismicity maximum is less significant; it is located in the magma generation zone beneath the orogenic volcanic arc (Greater Kuril Islands and its Okhotsk submarine margin), supposed by many researchers in the top of the Benioff zone (*Tektonika...*, 2004; *Podvodnyi...*, 1992; Tarakanov, 2004).

The special emphasis should be put on geography, or epicentral location, of strong crustal earthquakes in the depth interval of 0–40 km (Fig. 5), which marks the seismic gaps in the flanks of the Kuril arc-trench system as the areas of upcoming strong earthquakes (according to S.A. Fedotov (1965)). In particular, the northern flank is remarkable for the catastrophic tsunamigenic earthquake in 1952 when the town of Severo-Kuril'sk was destroyed.

The strong earthquake sequences clustered and/or subperpendicular to the Kuril arc-trench system, seen in the maps of epicenters distribution, for example, in the area of the Bussol graben and canyon (Figs. 1, 5, 7, 9) likely outline the active faults of hanging wall of the deep thrust of the same name (Sergeev et al., 1982).

CONCLUSIONS

Thus, judging by the new focal mechanism catalog for 396 strong ($M \geq 6.0$) earthquakes in the Kuril-Okhotsk and, in part, Japan region (*Katalog...*, 2011), the key role in the structure and seismotectonics of the Kuril arc-trench system is played by the deep thrust of the same name located in the Benioff seismofocal zone. Based on the SCP and RM data, the structural salient of this thrust—Pegasus nappe in the frontal part of Kuril Arc—has thrusted upon the Pacific Ocean floor as long as up to 50–70 km for the last 0.5–1.0 Ma. Thrusting was accompanied by accretion of the Cenozoic sedimentary cover, formation of accretionary prism, middle and lower part of the Pacific Ocean slope, and significant sinking of the NW marginal part of the Pacific Plate under the lithostatic load of allochthon (tectonic couple regional nappe–accretionary prism).

REFERENCES

Aver'yanova, V.N., *Glubinnaya seismotektonika ostrovnyh dug* (Deep seismotectonics of island arcs), Moscow: Nauka, 1968.

Azhgirei, G.D., *Strukturnaya geologiya* (Structural geology), Ìoscow: Moscow Gos. Univ., 1956.

Balakina, L.M., Kuril-Kamchantka seismogenic zone: structure and earthquake generation order, *Fiz. Zemli*, 1995, no. 12, pp. 48–57.

Fedotov, S.A., Regularities of strong earthquakes distribution in Kamchatka, Kuril Islands, and NE Japan, in *Tr. IFZ AN SSSR* (Proc. Inst. Phys. Earth Akad. Nauk. USSR), 1965, vol. 36, pp. 66–93.

Geologo-geofizicheskii atlas Kurilo-Kamchatskoi ostrovnoi sistemy (Geological-geophysical atlas of the Kuril-Kamchatka island system), Ed. by Sergeev, K.F. and Krasny, M.L., Leningrad: VSEGEI, 1987.

Gnibidenko, G.S., *Struktura glubokovodnykh zhelobov Tikhogo okeana (po dannym MOV–OGT)* (Structure of deep trenches of the Pacific Ocean based on the RM–CDP data), Vladivostok: Dal'nevost. Otd. Akad. Nauk SSSR, 1987.

Hamada, K., P-traveltime anomalies and upper mantle structures beneath Japan: review of Japanese seismological investigations, in *Rep. Nat. Res. Center for Disaster Prevention*, 1975, vol. 12, pp. 53–70.

Hasegawa, A., Umino, N., and Takagi A., Double-planed structure of the deep seismic zone in the northeastern Japan arc, *Tectonophysics*, 1978, vol. 48, pp. 43–58.

Initial reports of the deep-sea drilling project, Washington, DC: U.S. Govern. Printing Office, 1980, vols. 56–57, Pt. 1.

Karig, D.E., Structural history of the Mariana island arc system, *Geol. Soc. Am. Bull.*, 1971, vol. 82, no. 2, pp. 323–344.

Katalog mekhanizmov ochagov sil'nykh ($M \geq 6.0$) zemletryasenii Kurilo-Okhotskogo regiona 1964–2009 gg. (Catalog of focal mechanisms of strong ($M \geq 6.0$) earthquakes in the Kuril-Okhotsk Region for 1964–2009), Vladivostok: Dal'nauka, 2011.

Kossobokov, V.G., Are mega earthquakes predictable?, *Izv., Atmos. Ocean. Phys.*, 2011, vol. 47, no. 8, pp. 951–961.

Kropotkin, P.N., Seismicity related to the fracture of the dipping plate (subduction), *Geotektonika*, 1978, no. 5, pp. 3–6.

Levchenko, D.G., Kuzin, I.P., Zubko, Yu.N., and Chervinchuk, S.Yu., The Japan earthquake: problems of forecast, *Seism. Instrum.*, 2011, vol. 48, no 1, pp. 10–15.

Lomtev, V.L., Methods of age determination for deep trenches, in *Geologiya dna Tikhogo okeana i zony perekhoda k Aziatskomu kontinentu* (Geology of the Pacific Ocean floor when transition to the Asian continent), Vladivostok: Dal'nevost. Otd. Akad. Nauk SSSR, 1989, pp. 105–111.

Lomtev, V.L., New data on the tectonics and magmatism of the northwestern Pacific Ocean, *Geol. Polezn. Iskop. Mirovogo Okeana*, 2008, no. 4, pp. 93–105.

Lomtev, V.L. and Patrikeev, V.N., *Struktury szhatiya v Kuril'skom i Yaponskom zhelobakh* (Compression structures in the Kuril and Japan trenches), Vladivostok: Dal'nevost. Nauchn. Tsentr, Akad. Nauk SSSR, 1985.

Lomtev, V.L. and Patrikeev, V.N., Seismic studies of the Institute of Marine Geology and Geophysics, Far East Branch of the Russian Academy of Sciences, in the northwestern Pacific Ocean in 1980–2005, *Vestn. Dal'nevost. Otd. Ross. Akad. Nauk*, 2006, no 1, pp. 59–66.

Lomtev, V.L., Patrikeev, V.N., and Nemchenko, G.S., Seismostratigraphy of the Cenozoic sedimentary cover in the Northwestern Plate, Pacific Ocean, *Struktura i veshchestvennyi sostav osadochnogo chekhla severo-zapada Tikhogo okeana* (Structure and material composition of the sedimentary cover in the northwestern Pacific Ocean), Yuzhno-Sakhalinsk: IMGiG DVO RAN, 1997. Ñ. 21–41.

Lomtev, V.L., Nikiforov, S.P., and Kim, Ch.U., Tectonic aspects of crustal seismicity in Sakhalin, *Vestn. Dal'nevost. Otd. Ross. Akad. Nauk*, 2007, no. 4, pp. 64–71.

Lutikov, A.I., Great Tohoku earthquake of March 11, 2011: preliminary seismological analysis, *Izv., Atmos. Ocean. Phys.*, 2011, vol. 47, no. 8, pp. 971–977.

Lyubushin, A.A., Seismic catastrophe in Japan on March 11, 2011: long-term prediction on the basis of low-frequency microseisms, *Izv., Atmos. Ocean. Phys.*, 2011, vol. 47, no. 8, pp. 904–921.

Lyubushin, A.A., Microseisms noise analysis proved prediction of Japan earthquake of March 11, 2011, *Nauka Tekhnol. Razrab.*, 2011b, vol. 90, no 1, pp. 3–12.

Malovichko, A.A., Starovoit, O.E., Gabsatarova, I.P., Kolomiets, M.V., and Chepkunas, L.S., Catastrophic Tohoku earthquake of March 11, 2011, in Japan, *Seism. Instrum.*, 2012, vol. 48, no. 1, pp. 1–9.

Mass determination of earthquake source mechanisms
1 using electronic computers, in *Teoriya i analiz seismicheskikh nablyudenii* (Theory and analysis of seismic observations), Moscow: Nauka, 1979, pp. 45–58.

1 Patrikeev, V.N., *Atlas seismicheskikh razrezov Severo-Zapadnoi plity Tikhogo okeana* (Atlas of seismic sections in the Northwestern Plate, Pacific Ocean), Moscow: GEOS, 2009.

Pichon, X. Le, Francheteu, J., and Bonnin, J., *Plate tectonics* (Amsterdam: Elsevier, 1973).

Podvodnyi vulkanizm i zonal'nost' Kuril'skoi ostrovnoi dugi (Submarine volcanism and zonation of the Kuril island arc), Moscow: Nauka, 1992.

Rogozhin, E.A., Japan Tohoku March 11, 2011 ($M = 9.0$) earthquake source structure, its macroseismic, seismological, and geodynamic manifestations, *Seism. Instrum.*, 2012, vol. 48, no. 2, pp. 93–104.

Rogozhin, E.A., Yunga, S.L., and Rodina, S.N., Specific features of the appearance of seismotectonic deformations during the genesis of March 11, 2011, Tohoku earthquake source, *Izv., Atmos. Ocean. Phys.*, 2011, vol. 47, no. 8, pp. 962–970.

Rodkin, M.V. and Tikhonov, I.N., Megaearthquake of March 11, 2011, in Japan: the event magnitude and the character of the aftershock sequence, *Izv., Atmos. Ocean. Phys.*, 2011, vol. 47, no. 8, pp. 941–950.

Rudik, M.I. and Poplavskaya, L.N., *Katalog mekhanizmov ochagov sil'nykh ($M \geq 6.0$) zemletryasenii Kurilo-Okhotskogo regiona (1964–1982 gg.)* (Catalog of source mechanisms of strong ($M \geq 6.0$) earthquakes in the Kuril-Okhotsk Region in 1964–1982), Yuzhno-Sakhalinsk: IMGiG DVO RAN, 1987.

Sergeev, K.F., *Tektonika Kuril'skoi ostrovnoi sistemy* (Tectonics of the Kuril island arc system), Moscow: Nauka, 1976.

Sergeev, K.F., Kim, Ch.U., and Kochergin, E.V., Transversal deep faults in the Kuril island arc system, *Dokl. Akad. Nauk SSSR*, 1982, vol. 264, no 2, pp. 412–417.

Sidorin, A.Ya., An outstanding achievement of the Russian Academy of Sciences: the successful forecast of the earthquake of March 11, 2011, in Japan, *Izv., Atmos. Ocean. Phys.*, 2011a, vol. 47, no. 8, pp. 901–903.

Sidorin, A.Ya., Mega earthquakes are predictable!, *Nauka Tekhnol. Razrab.*, 2011b, vol. 90, no 1, pp. 45–48.

Simbireva I.G., Fedotov S.A., and Feofilaktov V.D., Inhomogeneity of the stress field in the Kuril-Kamchatka arc based on the seismic data, *Geol. Geofiz.*, 1976, no. 1, pp. 70–85.

Shebalin, P.N., Large-scale short-term seismicity activation prior to the strongest earthquakes of Japan and the Kurile Islands, *Izv., Atmos. Ocean. Phys.*, 2011, vol. 47, no. 8, pp. 922–928.

Stille, H., Die zirkumpazifischen Faltungen in Raum and und Zeit, *Geotekt. Forsch.*, 1945, nos. 7–8, pp. 261–323.

Stille, H., "Atlantische" und "Pazifische" Tektonik, *Geol. Jb.*, 1957, vol. 74, pp. 677–686.

Svarichevskii, A.S., Lomtev, V.L., and Patrikeev, V.N., New data on the geomorphometry of southern Kuril deep trench, in *Struktura osadochnykh otlozhenii Kurilo-Kamchatskogo zheloba* (Structure of sedimentary deposits in the Kuril-Kamchatka trench), Yuzhno-Sakhalinsk: SakhKNII DVO AN SSSR, 1979, pp. 37–50.

Tarakanov, R.Z., New approach to the nature of seismofocal zone, *Geodinamika, geologiya i neftegazonosnost' osadochnyh basseinov Dal'nego Vostoka Rossii* (Geodynamics, geology, and oil- and gas-bearing potential of sedimentary basins in the Russian Far East), Yuzhno-Sakhalinsk: IMGiG DVO RAN, 2004, vol. 1, pp. 157–175.

Tarakanov, R.Z., Kim, Ch.U., and Sukhomlinova, R.I. Regularities of spatial distribution of earthquake hypocenters in the Kuril-Kamchatka and Japan regions, and their relationship with the peculiarities of geophysical fields, in *Geofizicheskie issledovaniya zony perekhoda ot Aziatskogo kontinenta k Tikhomu okeanu* (Geophysical studies of transitional zone from the Asian continent to the Pacific Ocean), Moscow: Nauka, 1977, pp. 67–77.

Tektonika i uglevodorodnyi potencial Ohotskogo morya (Tectonics and hydrocarbon potential of the Sea of Okhotsk), Vladivostok: Dal'nevost. Otd. Ross. Akad. Nauk, 2004.

Tektonika Kurilo-Kamchatskogo glubokovodnogo zheloba (Tectoncis of the Kuril-Kamchatka deep trench), Moscow: Nauka, 1980.

Tikhonov, I.N. and Lomtev, V.L., Great Japan earthquake of March 11, 2011: tectonic and seismological aspects, *Izv., Atmos. Ocean. Phys.*, 2011, vol. 47, no. 8, pp. 978–991.

Tikhonov, I.N., Vasilenko, N.F., Zolotukhin, D.E., Ivelskaya, T.N., Poplavskii, A.A., Prytkov, A.S., and Spirin, A.I., Simushir earthquakes and tsunami of November 15, 2006, and January 13, 2007, *Rus. J. Pac. Geol.*, 2008, vol. 2, no. 1, pp. 1–14.

Trubitsyn, V.P., Model of the 2011 Great East Japan earthquake ($M = 9.0$), *Izv., Atmos. Ocean. Phys.*, 2012, vol. 48, no. 3, pp. 673–682.

Uyeda, S., Northwest Pacific trench margins, in *The geology of continental margins*, Burk, C.A. and Drake, C.L., Eds., (Berlin: Springer-Verlag, 1974), pp. 473–491.

Vasil'ev, B.I., Zhil'tsov, E.G., and Suvorov, A.A., *Geologicheskoe stroenie yugo-zapadnoi chasti Kuril'skoi sistemy duga–zhelob* (Geological structure of the southwestern part of the Kuril arc-trench system), Moscow: Nauka, 1979.

Verba, M.L., Ivanov, G.I., and Tikhonova, I.M., Absence of subduction signs in the structure of the Kuril deep trench (based on the RM–CDP data aquired on the 1-OM reference section), *Sovremennoe sostoyanie nauk o Zemle: Materialy Mezhdunarodnoi konferentsii, posvyashchennoi pamyati V.E. Khaina, Moscow, 2011* (Proc. Int. Conf. "Modern state-of-art in the Earth sciences" in memory of V.E. Khain, Moscow, 2011), Moscow: Moscow Gos. Univ., 2011, pp. 318–323.

Yunga, S.L., Analysis of temporal variations of seismic strain release in source zones of large earthquakes, *Nauka Tekhnol. Razrab.*, 2011, vol. 90, no. 1, pp. 27–34.

Translated by N. Astafiev

SPELL: 1. seismicheskikh