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The Interrelation of Morphometric Parameters of Relief and Seismicity of Sakhalin Island

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Abstract—Our structural-geomorphologic and morphometric studies have shown that seismically active areas of Sakhalin Island are distinguished by positive anomalies of nine morphometric parameters of the relief where their values exceed the median. These parameters include the difference between the hypsometric surface and the third order base surface; differences between the first and the second order and between the second and the third order base surfaces; the depth of vertical dissection; the standard deviation of slope aspect; density of weak zones; the height asymmetry, the standard deviation of the Gaussian curvature of the relief taken by the module, and the standard deviation of heights. It is shown that seismically active areas may also be delineated by the values of the seven mentioned parameters (excluding the last two), exceeding the third quartile. The density of weak zones is the most informative: 45% of all earthquake epicenters and 71% of earthquake epicenters with the magnitude of surface waves of ≥5.5 are allocated to small areas (25% of the island area), where the density of weak zones is ≥36 km^{-1}. Thus, the example of a well-studied seismotectonic territory shows the possibilities of identifying seismically active areas based on a set of geomorphologic characteristics. This result may be in demand when assessing the seismic hazard of areas with mid-mountain relief, where detailed seismological studies have not previously been performed.

Keywords: Sakhalin, seismicity, morphometric analysis of relief

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INTRODUCTION

The seismotectonic conditions of Sakhalin Island have been well studied: more than 300 earthquake epicenters with the maximum surface wave magnitude (*Ms*) of 7.5 were recorded here from 1924 to 2023 (International..., 2023; United..., 2023; *Seismologicheskii*..., 2023), detailed seismic zoning was performed (Saprygin, 2008), several lineament-domain models were elaborated (Levin et al., 2012), the seismic hazard of the territories of responsible structures was assessed (Ulomov, 2003), and active faults were identified (Voeikova et al., 2007; Zelenin, et al., 2022). Data on their configuration and the location of the epicenters of modern earthquakes are compared in our work with the results of a comprehensive morphometric analysis of the relief in order to show the possibilities of use of geomorphologic methods for identifying seismically active areas by the example of Sakhalin Island. This task is urgent and interesting due to the insufficient knowledge of the seismicity of a significant part of our country based on the results of instrumental seismological monitoring.

THE GEOLOGICAL AND GEOMORPHOLOGIC STRUCTURE OF SAKHALIN ISLAND

Sakhalin Island is located in the zone of interaction of three lithospheric plates: the Kuril, the Amur, and the Okhotsk ones (Fig. 1). The boundary between the latter two plates passes along the Tym'-Poronai (Central Sakhalin) deep fault of the upthrow-overthrust type. There is more than one opinion about the location of the boundary between the plates because the geological-geophysical data are contradictory (Rogozhin, 1996; Sim et al., 2017; Voeikova et al., 2007).

The alpine structure of Sakhalin is divided into Western and Eastern zones separated by the Central Sakhalin graben filled with Cenozoic deposits. The western zone is a monocline mainly composed of terrigenous-siliceous deposits of the Cretaceous and the Neogene ages. The eastern zone is composed by rocks of the ophiolite association and by volcanogenic-siliceous and terrigenous formations of the Triassic–Cretaceous Period metamorphosed under conditions of the greenschist and blueschist facies (Koronovskii, 2011).

The neotectonics (the second half of the Alpine tectonic-magmatic cycle) of the structures of Sakhalin are closely related to the island structure of Hokkaido. The two islands are assigned to the Hokkaido-Sakhalin island arc. The accumulation of sediments of the Tortonian stage of the Miocene (11 million years) is taken as the beginning of the recent stage. It is divided into the early and the late orogenic stages by the structural features of marine and subcontinental deposits. The boundary between them corresponds to the unconformity at the base of the upper sub-formation of the Maruyama formation (N_2–Q). The Sakhalin stage of folding and the stage of arched uplifts, which continue up to now, begin from the uncoformity. The structures of this phase are represented by deformations of the pre-orogenic erosion-denudation planation surface (N_{1-2}) (Voeikova et al., 2007). The late orogenic stage is associated with the formation of the main features of the modern topography and of seismic activity in the region (Mel'nikov, 1987, 2010).

The main relief forms of Sakhalin include the meridional elongated Western and Eastern Sakhalin ridge-mountain systems separated by the Tym'-Poronai Lowland. The North Sakhalin Plain and the Schmidt Peninsula are located to the north of it.

The main watershed between the basins of the rivers of the Sea of Okhotsk and of the Tatar Strait is formed by the West Sakhalin Mountains, the height of which reaches 1325 m (the Vozvrashcheniya Mountain). The highest peaks of the island, the Lopatina Mountain (1609 m) and the Nevel'skogo Mountain (1397 m), are located in the center of the East Sakhalin Mountains (Mel'nikov, 2010; *Resurcy*..., 1973).

The Western and Eastern Sakhalin Mountains are strongly dissected by blocky (arch) uplifts. There are well-pronounced planation surfaces with fault scarps, which enables their assignment to horsts. The uplifts are of different ages and asymmetric. The West Sakhalin Uplift was formed at the site of the Neogene trough, the sediments of which were folded at the end of the Pliocene and uplifted during the Quaternary Period. The older East Sakhalin Uplift began to form prior to the beginning of the recent stage and is now strongly differentiated into local structures.

The Tym'-Poronai Lowland is covered by very thick Cenozoic alluvial-marine deposits. The disturbance of the sediments indicates the formation of a graben or graben-shaped trough here. Echelon ruptures of the fault type are determined at its contact with the East Sakhalin Uplift (Rogozhin, 1996). The Central Sakhalin Cenozoic graben is allocated to the deep Tym'-Poronai upthrow-overthrust fault seen in the structures of the pre-Cenozoic basement.

The North Sakhalin hilly plain (200–400 m above sea level) is composed of marine Miocene and continental Pliocene sediments. At the early orogenic stage in the Miocene and the Early Pliocene it was located within a deep trough, which was closed at the end of the Pliocene as a result of the formation of folds and ruptures. The inversion uplift was formed in it at the late orogenic stage during the Quaternary Period. It was differentiated into ridges-uplifts that alternate with relatively narrow depressions. These structures are mainly characterized by nonconformity with the folded structures of the Miocene–Pliocene, but some ruptures are activated and orographically pronounced. The structure of the ruptures is echelon-like, and they are branched. This is important, because the epicenter of the Neftegorsk catastrophic earthquake of 1995 was

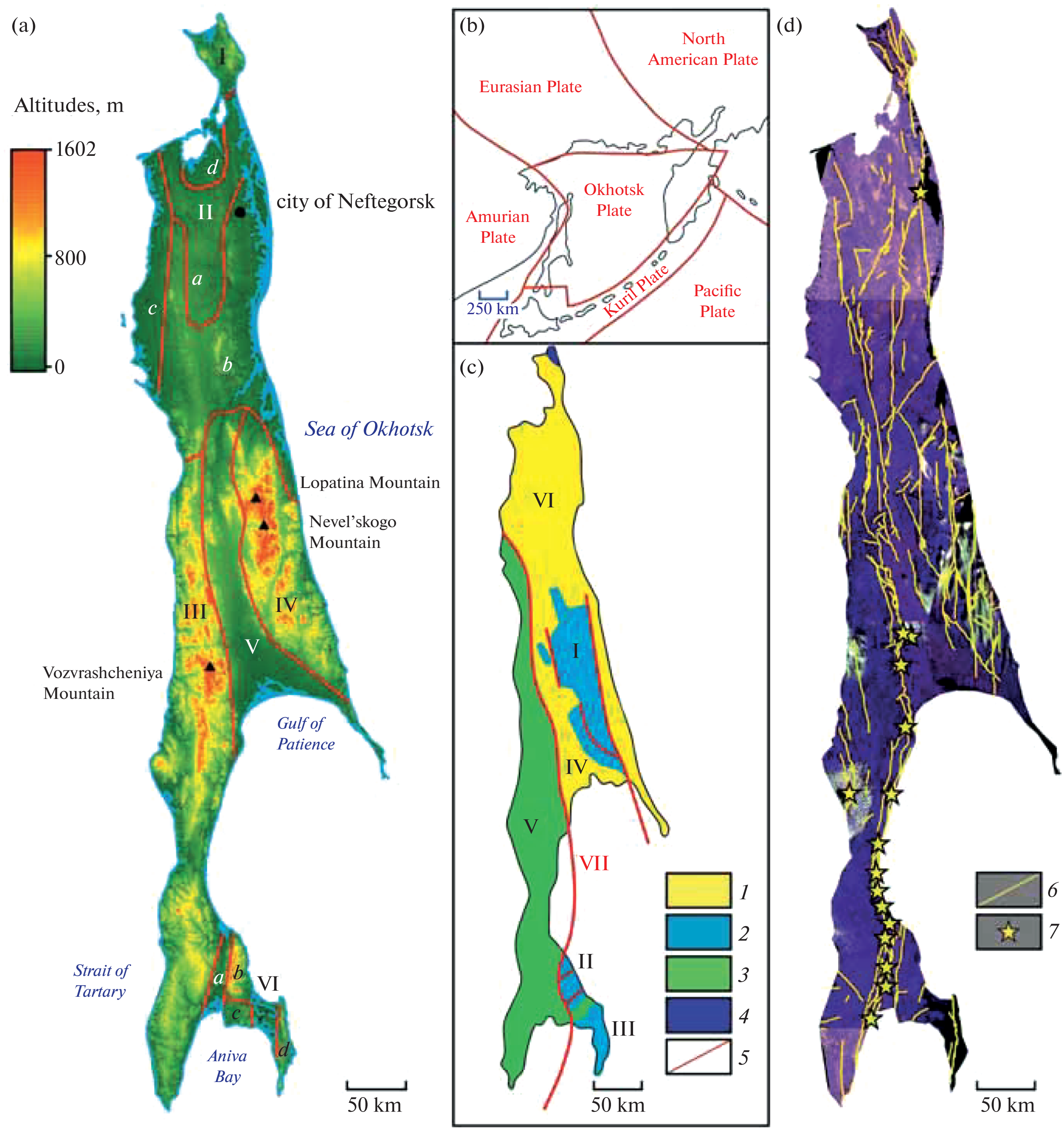

Fig. 1. Geological-geomorphologic schemes of Sakhalin Island. (a) Scheme of geomorphologic zoning according to (*Resursy*..., 1973): I—the Schmidt Peninsula with plain-ridge topography and coastal low mountains; II—North Sakhalin plain: (a) accumulative-denudation plain, (b) denudation plateau with separate monadnocks and ridges, (c) accumulative-marine terraced lowland, and (d) accumulative-marine lowland with lagoons and spits; III—West Sakhalin strongly dissected mountains; IV—East Sakhalin blocky strongly dissected mountains (with pronounced fault scarps); V—Tym'-Poronai Lowland composed of alluvial-marine sediments; and VI—Southeastern Sakhalin with a complex relief: (a) the Susunai Depression composed of marine and alluvial deposits, (b) the Susunai fold-horst ridge, (c) the Korsakovsk abrasion-denudation plateau, (d) the Murav'evsk accumulative lowland, and (e) the Anivsk fold-block low mountains. (b) Boundaries of the lithospheric plates of the Okhotomorsk region according to (Zlobin, 2006; Sim et al., 2017). (c) Scheme of tectonic zoning of Sakhalin Island according to (Koronovskii, 2011): (*1*) Neogene-Quaternary deposits, (*2*) Cretaceous and Cenozoic terrigenous deposits, (*3*) siliceous-terrigenous-volcanogenic deposits of the Triassic–Upper Cretaceous, (*4*) ophiolite mantle of Cape Schmidt, (*5*) ruptures. Roman numbers indicate the main structures: I, Eastern zone; II, uplift of the Susunai Ridge; III, uplift of the Tonino-Anivsk Peninsula; IV, Central Sakhalin graben; V, Western zone; VI, North Sakhalin trough; and VII, Tym'-Poronai (Central Sakhalin) fault. (d) Scheme of active faults according to (Zelenin et al., 2022): (*6*) active faults, (*7*) paleoseismodisocations (according to (Bulgakov et al., 2002; Lobodenko, 2010)). Landsat 8–9 satellite images taken in the near infrared spectral range (a combination of channels 6-7-5) are used as the background.

located within the plain. Many seismotectonic dislocations were formed during it (Rogozhin, 1996).

The Schmidt uplift is arch-like. The trough considered as an axial depression of the arch is composed of recent sediments of about 1-km thick. These are mainly analogues of the Maruyam formation of Southern Sakhalin. Flexural bending is seen along the boundaries of the trough with uplifts.

The Susunai Depression, the Susunai Range, the Korsakovsk Plateau, the Murav'evsk Lowland, and the Anivsk Low Mountains are identified on southeastern Sakhalin from west to east.

The Susunai submeridional depression composed of marine and alluvial deposits is opened to the south towards the Aniva Bay. There is a structural bench at the contact of the depression with the West Sakhalin uplift, which is formed in the zone of gentle thrust. It is seen as echelons in the topography. The Susunai Range is horst-like and is disturbed by faults from the west and the east. These are reflected in topography as benches of break off. The Korsakov Plateau is abrasive-denudation. There is a gentle uplift in it; to the west, it gives way to a bench formed within the fault displacements. The Murav'evsk Lowland with large lakes is assigned to the accumulative type formed in conditions of a graben-like trough. The Anivsk Low Mountains are folded-blocky.

Thus, the comparison of the schemes of geomorphologic (Fig. 1a) and tectonic zoning (Fig. 1b) shows that the main relief forms correspond to large tectonic structures. This is related not only to the importance of the tectonic factor in relief formation, but also to the effect of the composition and age of rocks on the topography. The youngest and least weathering-resistant Miocene–Quaternary sediments, including molasse strata, were formed in areas with plain topography: within the North Sakhalin Plain and the Tym'-Poronai Lowland. The older Cretaceous and Cenozoic terrigenous rocks form the Western Sakhalin Mountains, and the oldest rocky siliceous-terrigenous-volcanogenic formations of the Triassic–Upper Cretaceous comprise the East Sakhalin Mountains with the highest altitudes. They are more dissected by erosion processes compared to younger western orogens (Kuptsova, 2021).

MATERIALS AND METHODS

A digital elevation model (DEM) by SRTM with a resolution of 1 arc second (~30 m) (*Tsifrovaya*..., 2023), seismological catalogs (International..., 2023; United..., 2023; *Seismologicheskii*..., 2023), satellite images of Landsat 8–9 (*Baza*..., 2024], and databases of active faults (Zelenin, et al., 2022) and watercourses (Lehner and Grill, 2013) were used as source materials.

The schemes of the difference between the basic surfaces and the residual relief obtained by subtracting the basic surface of the third order from the hypsometric one have been constructed by the DEM and the scheme of watercourses in the ArcGIS environment. The order of valleys in the watercourse database we used is determined according to the methodology of V.P. Filosofov (1960). The valleys of the higher (the fourth and the fifth) orders are excluded from the analysis, because they are not represented throughout the island. The schemes of the residual relief and of the difference of the basic surfaces of the first and the second and of the second and the third orders reflect the direction of the neotectonic movements, determining the seismicity; therefore, they are used in our work.

The depth of vertical dissection of the relief is one of the morphometric characteristics that is informative for understanding the features of recent deformations: its positive anomalies often mark uplift areas and zones of increased fracturing that violate the latest morphostructural pattern (Netrebin, 2012; Filosofov, 1967). The depth of vertical dissection is calculated as the difference between the maximum and the minimum height in cells of 15 × 15 km (Simonov, 1999).

We used the example of Kamchatka (Agibalov et al., 2023) to show that high values of the standard deviation of slope aspect are often allocated to the zones of tectonic fragmentation of the upper part of the Earth crust. They are characterized by an increased density of lineaments distinguished by the sharp linear bends of the relief, separating the slopes of different directions. The values of the standard deviation of slope aspect are determined in cells of 15 × 15 km, using the Aspect tool of the ArcMap program.

Various authors have performed structural-geomorphologic interpretation by the method by N.P. Kostenko (1999) for many years to assess the fracturing of the area and to map active faults. The method is based on the identification of weak zones, that is, linear relief elements that form blocky structure, by a combination of geomorphologic features, primarily by the pattern of the hydrographic network. We have identified these zones on a scale of 1 : 200000, and a diagram of their density has been constructed.

Areas that are active in recent times often have steep slopes and are distinguished by anomalies of the Gaussian relief curvature (Agibalov et al., 2021). These parameters are determined by DEM, using the Slope and Curvature tools. Since the sign (positive or negative) of the relief curvature anomalies is not important in this work, the corresponding values are taken in absolute magnitude and the standard deviation is calculated in the above-mentioned cells. In addition, the steepness of the differences of the base surfaces of the second and the third orders is determined.

The results of the analysis of stochastic relief models are actively used in recent years to study the features of the morphostructural pattern. These models are represented by the central moments of distribu-

Table 1. Comparison of medians of morphometric parameters of relief of Sakhalin

Parameter		Median and its confidence interval (α = 0.90)			
		for the entire island	for raptures	for all earthquakes	for earthquakes with $Ms \geq 5.5$
1	Difference between the hypsometric surface and the base surface of the third order, m	83 [82...84]	108 [101...116]	91 [82...101]	141 [79...269]
2	Difference between the basic surfaces of the first and the second order, m	12 [12...13]	16 [13...18]	16 [14...19]	27 [15...52]
3	Difference between the basic surfaces of the second and the third order, m	14 [14...14]	17 [15...20]	17 [14...22]	21 [14...30]
4	Depth of vertical dissection of the relief, m	198 [186...211]	353 [318...342]	326 [334...370]	345 [118...530]
5	Standard deviation of slope aspect, deg	100 [100...100]		102 [101...102]	104 [101...105]
6	Density of weak zones, km^{-1}	31 [31...31]		34 [33...34]	36 [32...37]
7	Standard deviation of the curvature of relief taken by the module, $\times 10^3\ m^{-1}$	56 [51...62]	83 [81...88]	83 [79...95]	97 [47...127]
8	Standard deviation of heights, m	60 [60...62]	85 [80...87]	68 [61...77]	
9	Asymmetry of heights	0.512 [0.509...0.517]	0.720 [0.690...0.751]	0.562 [0.507...0.594]	
10	Steepness of slopes, deg	3.6 [3.5...3.6]	4.9 [4.6...5.3]		
11	Curvature of the relief taken by the module, $\times 10^3\ m^{-1}$	82 [81...83]	93 [87...99]		
12	Steepness of the difference between the base surfaces of the second and the third order $\times(10^{-3})°$	79 [78...80]	105 [96...13]		

Confidence intervals of the medians for α = 0.90 are given in square brackets. The empty cells in the table correspond to the values of morphometric parameters, which are less than or equal to the median (taking into account the confidence interval) calculated for the entire island.

tions of the heights of the earth surface in sliding averaging windows (Zhavoronkin and Tregub, 2019). Thus, we calculated the values of two parameters: the standard deviation and the asymmetry of relief heights. These are determined using the Focal Statistics module of the ArcMap program (the first) and the software that we developed (the second).

According to (*GOST*..., 2004), the median values and 90% confidence intervals of the listed morphometric parameters were calculated for the entire island, as well as for the sites corresponding to earthquake epicenters, and for a small sample ($N = 14$) consisted of epicenter points of strong earthquakes with $Ms \geq 5.5$ (Table 1).

These calculations were performed to show at the quantitative level the geomorphologic characteristics by which the areas where seismic events occur are distinguished. The seismically active regions are outlined by isolines, corresponding to the median values and the third quartile. The tables show the percentage of earthquake epicenters that fall within these contours, occupying 50 and 25% of the island area, respectively. Active faults are divided into many short segments, the ends of which are characterized by morphometric values, in order to reveal the relationship between the relief and active faults. Medians and their confidence intervals are also calculated for this set of points ($N = 971$) (Table 1). In addition, the pronouncement rate of active faults in the relief is shown, using Landsat 8–9 satellite images taken in the near infrared spectral range (channels 5–7). In our opinion, the combination of channels 6–7–5 is optimal for Sakhalin Island. A large number of works on its faults have recently been published in addition to the database (Zelenin, et al., 2022). One of the most detailed schemes, which, besides the configuration of faults, shows their kinematics and provides solutions of the focal mechanisms of earthquake centers, was analyzed in (Kamenev et al., 2024). However, the analysis of this scheme by geomorphologic methods requires detailed studies and it is reasonable to use data on the most well-known and extensive faults for regional-scale works.

Information about the locations of paleoseismological dislocations (Bulgakov et al., 2002; Lobodenko, 2010) is also used as the source data. It is compared with the results of our previous studies: the configuration of seismodomains and areas of increased neotectonic activity identified by fuzzy logic tools (Sobisevich, et al., 2024).

RESULTS AND DISCUSSION

The comparison of the hypsometric surface and the distribution of earthquake epicenters testifies to the complexity of the relationship between the seismicity and the relief: most epicenters are located in the Western Sakhalin Mountains and the North Sakhalin Plain, while the Eastern Sakhalin Mountains, where the site of the island with the highest altitude is located, have lower seismotectonic activity. Nevertheless, calculations of medians and confidence intervals of morphometric parameters for the entire island and for many earthquake epicenters have shown that the seismically active regions have positive anomalies of nine parameters: (1) differences between the hypsometric surface and the base surface of the third order; (2) differences between the base surfaces of the first and the second orders; (3) differences between the base surfaces of the second and the third orders; (4) the depth of vertical dissection; (5) the standard deviation of slope aspect; (6) the density of weak zones; (7) the standard deviation of the Gaussian curvature of the relief, taken in absolute magnitude; (8) the standard deviation of heights; and (9) the asymmetry of heights. Active faults are located in the region of higher values of the listed morphometric parameters, excluding the density of weak zones and the standard deviation of slope aspect, and are characterized by high slope steepness, Gaussian curvature of the relief (the absolute value), and the steepness of the difference between the base surfaces of the second and the third order (Table 1). The data in Table 2 show that seismically active regions may be delineated by the values of the nine mentioned morphometric parameters, exceeding the median. Such areas occupy 50% of the island area, while 53–62% of the epicenters of all earthquakes and 33–86% of the epicenters of earthquakes with $Ms \geq 5.5$ are located within their contours (Figs. 2 and 3, Table 2).

In addition, seismically active sites may be identified on the basis of morphometric characteristics, exceeding the third quartile. In this case, they occupy 25% of Sakhalin area, and 28–45% of the epicenters of all earthquakes and 21–71% of the epicenters of earthquakes with $Ms \geq 5.5$ are located in them (Table 3). The best result (45% of all epicenters and 71% of the epicenters of strong earthquakes) is achieved when the density scheme of weak zones is used. The high seismicity of the island is related to the development of active faults. According to Table 1, they are located within the positive anomalies of most of the listed morphometric parameters (excluding the density of weak zones and the standard deviation of slope steepness) and also have increased values of slope steepness, steepness of the difference of the base surfaces of the second and the third order, and the absolute value of the Gaussian curvature of the relief. Most of the faults are distinguished in cosmic images taken in the near-infrared spectral range (Fig. 1d).

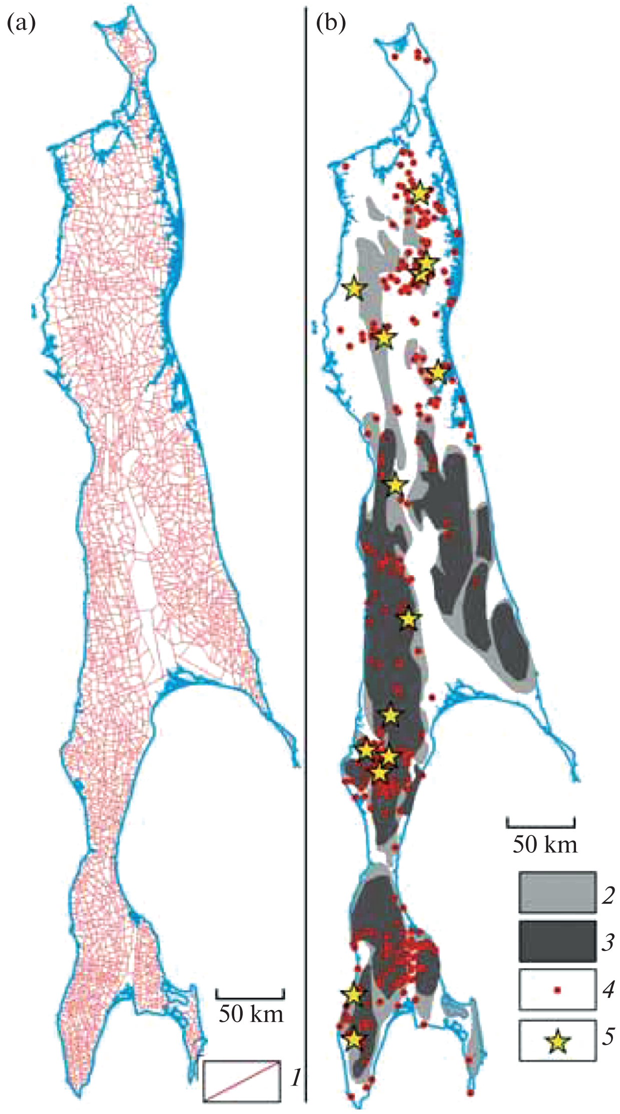

Fig. 2. Schemes of weak zones (a) and seismically active regions of Sakhalin Island delineated by the difference between the hypsometric surface and the base surface of the third order (b): (*1*) weak zones; (*2–3*) areas, where the difference between the hypsometric surface and the base surface of the third order exceeds: (*2*) median (≥83 m) and (*3*) the third quartile (≥220 m); (*4*) earthquake epicenters, (*5*) epicenters of earthquakes with $Ms \geq 5.5$.

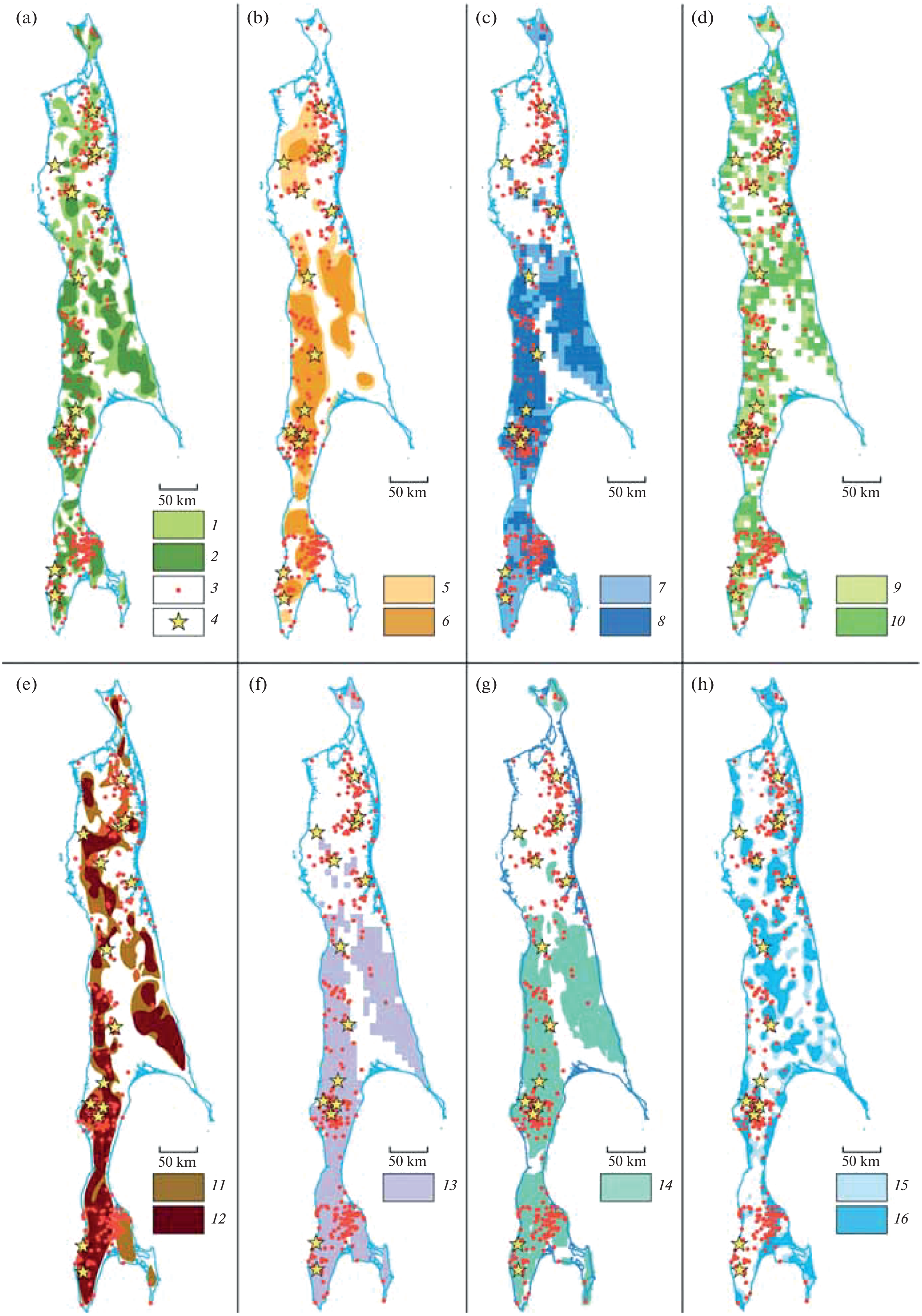
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Fig. 3. Scheme of seismically active regions of Sakhalin Island identified (delineated) by anomalies of morphometric relief parameters: (a) by the difference of the base surfaces of the first and the second order: (*1*) exceeding the median (≥12 m), (*2*) exceeding the third quartile (≥46 m), (*3*) earthquake epicenters, (*4*) epicenters of earthquake with $Ms \geq 5.5$; (b) by the difference of the base surfaces of the second and the third order: (*5*) exceeding the median (≥14 m), (*6*) exceeding the third quartile (≥50 m); (c) according to the values of the depth of vertical dissection of the relief: (*7*) exceeding the median (≥198 m), (*8*) exceeding the third quartile (≥462 m); (d) according to the standard deviation of slope aspect: (*9*) exceeding the median (≥100°), (*10*) exceeding the third quartile (≥105°); (e) according to the density of weak zones: (*11*) exceeding the median (≥31 km^{-1}), (*12*) exceeding the third quartile (≥36 km^{-1}); (f) by the standard deviation of the Gaussian curvature of the relief (absolute values): (*13*) exceeding the median (≥56 × 10^{3} m^{-1}); (g) by the standard deviation of heights: (*14*) exceeding the median (60 m); (h) by values of relief asymmetry: (*15*) exceeding the median (≥0.512), (*16*) exceeding the third quartile (≥0.874).

The comparison of the sites of 17 paleoseismodislocations (Fig. 1d) with the configuration of seismodomains (Sobisevich et al., 2024) shows that they occur at the boundaries of seismodomains (nine sites), to the zones of increased compressive stresses (11), and to areas of high neotectonic activity isolated by γ-operator of fuzzy logic (12).

Table 2. The proportion of epicenters of earthquakes located within the areas where the values of morphometric parameters exceed the medians

Parameter	Proportion of epicenters of all earthquakes	Proportion of epicenters of earthquakes with $Ms \geq 5.5$
1	0.62	0.78
2	0.60	0.78
3	0.56	0.71
4	0.61	0.64
5	0.62	0.86
6	0.62	0.79
7	0.59	0.57
8	0.55	0.40
9	0.53	0.33

The numbers in the first column correspond to the numbers of morphometric parameters of relief in Table 1.

CONCLUSIONS

We have revealed the relationship between the modern seismicity of Sakhalin Island and positive anomalies of nine morphometric relief parameters: (1) differences between the hypsometric surface and the base surface of the third order, (2) differences between the base surfaces of the first and the second orders, (3) differences between the base surfaces of the second and the third orders; (4) the depth of vertical dissection, (5) the standard deviation of slope aspect, (6) the density of weak zones, (7) the standard deviation of the absolute value of the Gaussian curvature of the relief (8) the standard deviation of heights, and (9) the asymmetry of heights.

The possibility of delineating the seismically active areas of Sakhalin by the values of the nine mentioned morphometric parameters, exceeding the median, is substantiated. The identification of seismically active regions by the values of seven parameters (excluding the standard deviation of the Gaussian curvature of the relief and the standard deviation of heights), exceeding the third quartile, is also informative. The result is best with the use of the scheme of the density of weak zones. The areas where the values of this parameter are ≥36 km^{-1} occupy 25% of the islands area and include 45% of all earthquake epicenters and 71% of earthquake epicenters with $Ms \geq 5.5$. In our opinion, this result is methodically significant and may be used for assessing the seismic hazard of areas with poorly studied seismotectonic conditions.

Table 3. The proportion of epicenters of earthquakes located within the areas, where the values of morphometric parameters exceed the third quartile

Parameter	The third quartile	Proportion of all earthquake epicenters	Proportion of epicenters of earthquakes with $Ms \geq 5.5$
1	220 m	0.37	0.43
2	46 m	0.28	0.36
3	50 m	0.28	0.21
4	462 m	0.33	0.36
5	105°	0.29	0.36
6	36 km^{-1}	0.45	0.71
9	0.874	0.31	0.27

Numbers in the first column correspond to the numbers of morphometric relief parameters in Table 1.

It is shown at the quantitative level that active faults are related to positive anomalies of ten morphometric characteristics: the difference between the hypsometric surface and the base surface of the third order; the difference between the base surfaces of the first and the second and of the second and the third orders; the depth of vertical dissection; the steepness of the slopes; the steepness of the difference of the base surfaces of the second and the third orders; the absolute value of the curvature of the relief and its standard deviation; and the standard deviation of heights and their asymmetry.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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