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Refinement of Background Seismicity on the Survey Plot of Sakhalinskaya GRES-2 (Sakhalin Island)

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Abstract—The background seismicity of the territory in the vicinity of the site of the planned construction of the Sakhalinskaya GRES-2 power plant, in the region of the Poyasok Isthmus, is refined. The interpretation of aerial photos of the territory under study is performed including the survey plot. Five active faults, previously unknown, are discovered, four of which are identified with a high degree of reliability. All of them are located beyond the survey plot limits. Within the survey plot, no indications of active faults are found. Design response spectra are calculated for return periods of 500, 1000, and 5000 years, and accelerogram analogues are selected. Maps of detailed seismic zoning (DSZ) are developed in parameters of the macroseismic intensity (I_{MSK}) and the peak ground acceleration (*PGA*, *g*) with 5% damping for the return periods of 500, 1000, and 5000 years. The I_{MSK} assessments of DSZ maps at the central survey point for mean grounds of category II appeared to be lower in comparison with the similar GSZ-97 data by 0.4 (for map A), 1.0 (for map B), and 0.3 (for map C).

Keywords: Sakhalin Island, shallow seismicity, active faults, models of seismicity, probabilistic analysis, seismic hazard assessment, detailed seismic zoning

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INTRODUCTION

The official documents determining a level of background seismicity and influence of ground conditions for the Russian Federation territory are SNIP II-7-81* (2000) and a set of maps of general seismic zoning (GSZ) GSZ-97 (Ulomov and Shumilina, 1999). The GSZ-97 maps reflect the calculated intensity of seismic shaking in numbers of the MSK-64 scale expected on the given area with the given probability p (%) during the certain time interval t on mean grounds corresponding to the grounds of category II according to SNIP II-7-81*.

The set of GSZ-97 maps consists of three maps: GSZ-97A (map A), GSZ-97B (map B), and GSZ-97C (map C), which correspond to probabilities of 10, 5, and 1%, respectively, of possible exceedance (or 90, 95, and 99%, respectively, of nonexceedance) of the design seismic intensity over 50-year intervals of time, which is appropriate to the recurrence of the seismic effect on the Earth's surface on the average of once every 500, 1000, and 5000 years.

Thus, the maps display the numbers that (with correction for ground conditions) are initial data for the calculation of a seismic load on a building. The GSZ-97 map set allows the seismic hazard degree to be assessed at three levels when constructing objects of different responsibility. Map A is intended for objects of normal (large-scale construction) and reduced responsibility; maps B and C are destined for objects of increased liability (especially dangerous, technically complicated or unique buildings).

The fact that, according to map A, North Sakhalin and the western part of Middle Sakhalin are related to the 9-point zone indicates a high level of seismicity of Sakhalin Island. The survey object (Sakhalinskaya GRES-2) is situated in Tomari borough of Sakhalin Oblast, north of Il'inskii village, in the region of the Poyasok Isthmus. For Il'inskii village, a level of seismic hazard is determined by the GSZ-97 data as 8 (map A), 9 (map B), and 9 (map C) (Ulomov and Shumilina, 1999).

The GSZ maps are made on a scale from 1 : 8000000 to 1 : 2500000. When a background level of seismic hazard is assessed, calculations are performed taking into account regional (generalized) seismotectonic models. In this connection, the transfer from GSZ maps to those of larger scale (1 : 500000–1 : 100000 and larger) is an urgent problem. These studies are conventionally called the refinement of initial seismicity or refinement of GSZ maps. The problem is resolved by the conduction of detailed seismic zoning (DSZ), taking into account local features of a seismotectonic model of one or other region. In this case, the separation of zones of earthquake source occurrence (ESO) is performed using larger-scale maps (in comparison to GSZ-97 maps) on the basis of data on geological structure, tectonics, geophysical fields, seismic statistics, and other materials available.

In this work, the results are described of the interpretation of aerial photos that was performed for the purpose of discovering active faults on the territory under study, including the survey plot, whose position is shown in Fig. 1. Calculations for the DSZ of the territory in the vicinity of the Sakhalinskaya GRES-2 survey plot have been carried out. Materials of multiyear investigations of the fault tectonics of the earth's crust of the region, the historical and instrumental data on the seismicity and seismic regime, the existing seismotectonic models of the region, as well as modern technology of probabilistic seismic-hazard analysis (PSHA) with identification and quantitative estimation of the arising uncertainty on a logic tree basis were involved during the work-execution phase.

ACTIVE FAULTS OF SAKHALIN ISLAND

Active faults within Sakhalin Island form two zones of meridional stretch, which correspond to island elongation (see Fig. 1). The first zone (I, see Fig. 1) is located in the southern and central parts of the island, displaced westward from its axis, and separates the uplift of the Western Sakhalin Mountains from the late Cenozoic Susunai and Tym-Poronai depressions situated to the east. There has been no confirmation so far that this zone stretches within the limits of North Sakhalin, though it seems to be quite possible. The zone is known as Tsentral'no-Sakhalinskaya (Central Sakhalin), or Tym-Poronaiskaya (Rozhdestvenskii, 1982; 1984), and Klyuchevskaya (Kuchai, 1987). The kinematics of active movements along the zone's faults is of the thrust-fault type (Kuchai, 1987; Bulgakov et al., 2002; Tsutsumi et al., 2005); the revealed recurrence periods (return periods) for the zone's individual faults reach 3000–5000 years, while the detected values of the one-event net displacement are up to 4 m (Strel'tsov and Kozhurin, 2002; Tsutsumi et al., 2005). Strike-slip displacements in the relief's young forms are detected for none of the zone's faults, though echelon elements in the plan view created by them allow the presence of a right-lateral shear component to be supposed.

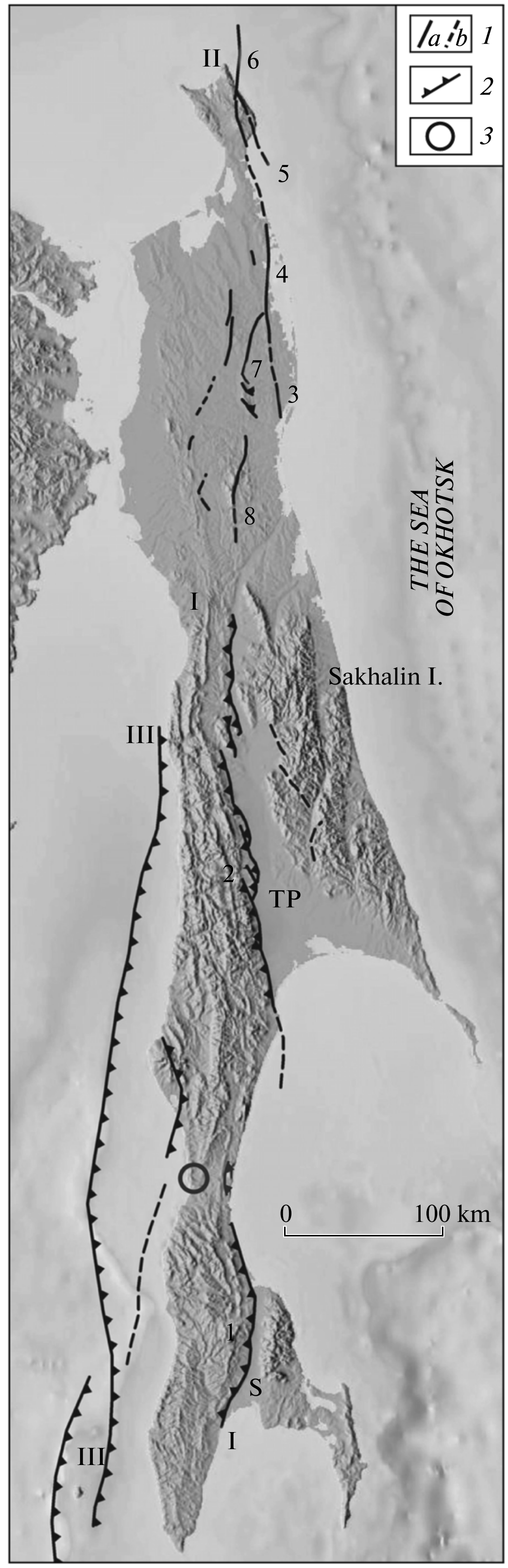


Fig. 1. Main active faults and fault zones of Sakhalin Island (based on SRTM30_PLUS (Becker et al., 2009)): (*1*) (a) active and (b) supposed faults; (*2*) thrust faults and reverse faults; (*3*) survey plot Sakhalinskaya GRES-2. On the map: Roman numerals denote (I) Central Sakhalin (Tym-Poronai), (II) Northern Sakhalin, and (III) Western Sakhaline fault zones; Arabic numerals denote: (*1*) Aprelovskii, (*2*) Klyuchevskoi, (*3*) Goromai, (*4*) Piltun, (*5*) Longri, (*6*) Kheiton, (*7*) Upper Piltun (Neftegorsk), and (*8*) Dagi faults. Letters S and TP denote Susunai and Tym-Poronai central depressions, respectively.

Faults of the second, Severo-Sakhalinskaya (Northern Sakhalin), zone (the name is taken from (Rozhdestvenskii, 1982)) (II, see Fig. 1) stretch closer to the eastern edge of the island, in its northern lowland part and on the Schmidt Peninsula. These are (from south to north) the Goromai, Piltun, Longri, and Kheiton faults. The first two faults are sometimes combined into a single fault: Piltun-Ekhabinskii (name after (Rozhdestvenskii, 1982)). In addition to them, this zone, obviously, includes also (i) the Upper Piltun fault, the movement along which in 1995 caused the Neftegorsk earthquake and the occurrence of the Neftegorsk seismic rupture, (ii) the Dagi fault (in the axial part of the Dagi uplift–anticline, see Fig. 1), and (iii) other relatively nonextended faults discovered during the interpretation of satellite photos.

Apart from the two zones above considered, the third zone stands out, the Zapadno-Sakhalinskaya (Western Sakhalin), which stretches, as supposed, in the foot of the western continental slope of the island (III, see Fig. 1). The zone is known for a sequence of strong earthquakes of the past and present centuries: Lesogorsk–Uglegorsk (1924, M_S = 6.2), Moneron (1971, M_S = 7.5), Uglegorsk (2000, M_S = 7.2), Nevelsk (2007, M_w = 6.2), etc. The short parts of the zone or its splays only outcrop on the land (Ivashchenko et al., 2003). Separating the island uplift and the Tatar Strait trough, this zone is undoubtedly the main zone, whereas the first two zones are elements of the inner deformation of the island.

BRIEF CHARACTERISTIC OF SEISMICITY OF SAKHALIN REGION

The territory of Sakhalin Oblast is situated within the Pacific Ocean seismic belt, which determines the high seismic activity of the territory. In the area of the Kuril Islands and the Sea of Okhotsk, earthquake hypocenters are concentrated mainly in the seismofocal zone, about 70 km thick, which stretches below the mainland down to depths of 650 km (*Seismicheskoe raionirovanie*..., 1980; Tarakanov, 2006). This zone projects onto the day surface 60–70 km eastwards of the Kuril Islands near the deep-water Kuril Trench. Here seismic activity reaches almost the maximal level on earth. More than half the earthquakes of the zone occur at depths of 30–50 km. On the average, a single earthquake with $M \geq 8$ and around 10 events with $M \geq 7$ are recorded each decade near the Kuril Islands. The most devastating earthquakes on the Kuril Islands were those of: Kamchatka (1952, M_w = 9.0), Iturup (1958, M_w = 8.4), Shikotan (1994, M_w = 8.3), Iturup (1995, M_w = 7.9), Simushir (2006, M_w = 8.3 and 2007, M_w = 8.1).

Seismic activity in the Sakhalin region is of a more moderate nature: it is distributed extremely unevenly and is divided into the crustal and mantle (h = 250–650 km; mainly 280–350 km) activities. Deep-focus (mantle) earthquakes are connected with the inclined seismofocal zone passing under the island. It appears that the mode of crustal seismicity does not depend substantially on the regime of mantle seismicity and deep earthquakes do not present a significant seismic hazard. In this connection, only crustal earthquakes are considered below (Fig. 2), the majority of foci of which are located in the upper part of the earth's crust at depths to 30 km, while the distribution maximum corresponds to the depth ~10 km.

Strong (M ~ 5.0 and stronger (larger)) earthquakes are associated with the Western Sakhalin, Central Sakhalin, and Northern Sakhalin faults or with their splays. On the average, a single earthquake with $M \geq 6$ and around 10 events with $M \geq 5$ are recorded on Sakhalin Island every 10 years. For the period of instrumental observations, the most significant seismic events on Sakhalin Island were the Lesogorsk–Uglegorsk (1924, M_S = 6.8), Onori (1909, M_S = 6.1), Moneron (1971, M_S = 7.5), Neftegorsk (1995, M_S = 7.2), Uglegorsk (2000, M_S = 7.2), and Nevelsk (2007, M_w = 6/2) earthquakes.

On the map given in Fig. 2, it can be seen that the region of the Poyasok Isthmus, where the survey object is situated, is characterized by a small level of seismicity.

METHODOLOGY OF REFINEMENT OF BACKGROUND SEISMICITY

The refinement of background seismicity is based on PSHA (Cornell, 1968; Kramer, 1996; Levin et al., 2012). This approach is the analytical method, which estimates the probability of exceedance of the (specified) level of ground motion induced by earthquakes at the given point during the specified future period of time. A goal of this analysis is to assess the annual rate of motion level exceedance, while a main result is the determination of the dependence of the annual rate of exceedance upon the motion level (hazard curve). Most frequently, and in many cases necessarily, the spectral acceleration $S_a(f, \xi)$, depending on the frequency f and damping ξ of the oscillator, is used as a parameter of ground motion because the response spectrum adequately describes the dynamical load and is useful in the selection of design (empirical or synthetic) accelerograms.

Two main components of the PSHA model are as follows:

(1) seismicity characterization in the vicinity of the point under study;

(2) prediction of ground motion at the point induced by the earthquake of the specified measure (magnitude) and occurring at the specified distance from the point.

We emphasize that both components are expert estimates, i.e., not unique ones.

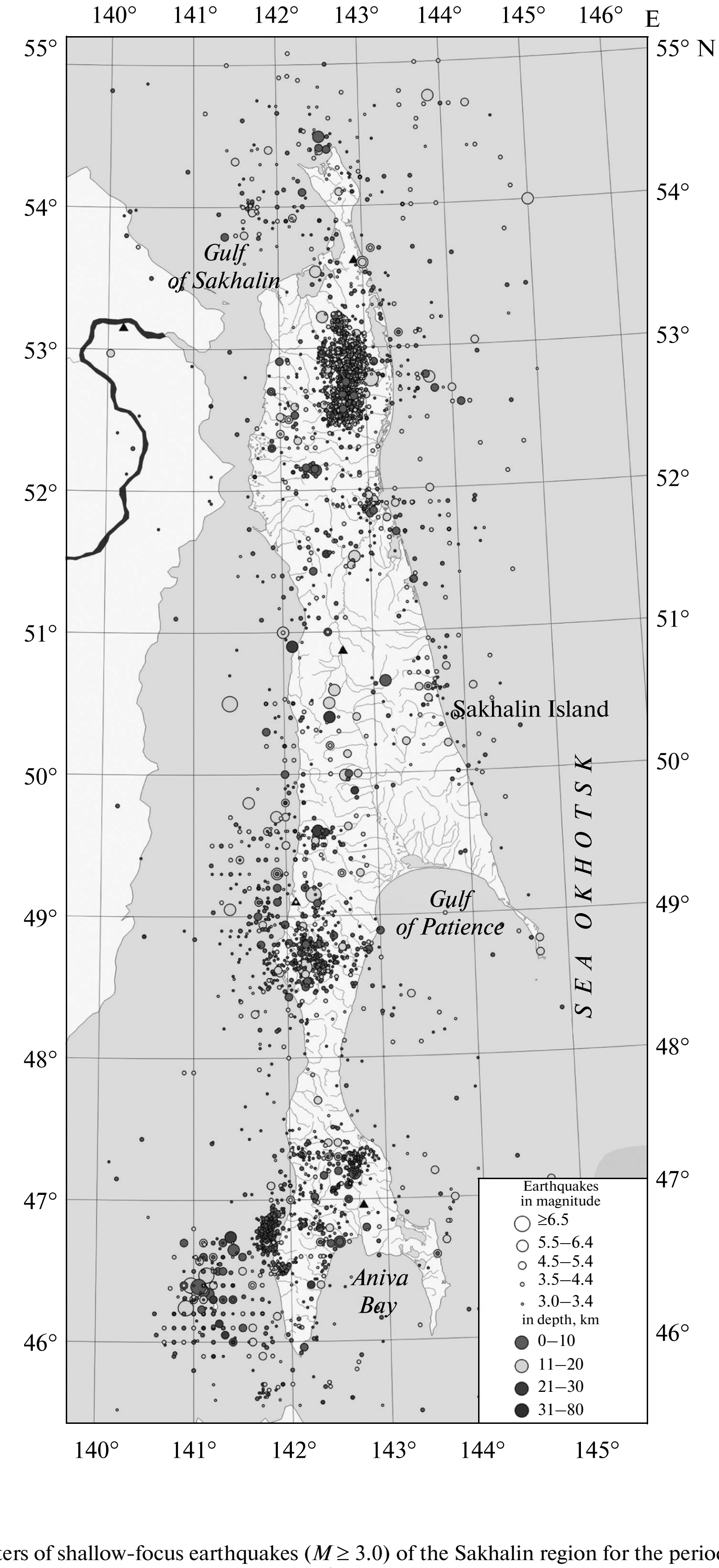


Fig. 2. Map of epicenters of shallow-focus earthquakes ($M \geq 3.0$) of the Sakhalin region for the period 1906–2012 according to the data of the regional catalogue (Poplavskaya et al., 2006) added since 2005 by the data of the catalogue of earthquakes of the southern part of Sakhalin Island (Kim et al., 2011) and the Operative Seismological Catalogue of the Sakhalin Branch of the Geophysical Survey of the Russian Academy of Sciences.

Results of DSZ for a center of the survey plot Sakhalinskaya GRES-2 (circular domain *1* in Fig. 4)

Return period, years	Shear-wave velocity of the upper 30-m layer of the ground V_{S30}, m/s											
	160		230		350		430		540		760	
	PGA	I_{MSK}	*PGA*	I_{MSK}	*PGA*	I_{MSK}	*PGA*	I_{MSK}	*PGA*	I_{MSK}	*PGA*	I_{MSK}
500	0.194	8.0	0.178	7.8	0.166	7.7	0.155	7.6	0.147	7.6	0.129	7.4
1000	0.243	8.3	0.226	8.2	0.213	8.1	0.200	8.0	0.191	7.9	0.168	7.8
5000	0.378	8.9	0.360	8.8	0.349	8.8	0.333	8.7	0.320	8.7	0.286	8.5

Values of horizontal peak accelerations (*PGA*) are given in fractions of *g*, while macroseismic intensity values (I_{MSK}) are presented in numbers.

Initial data for performing PSHA are as follows:

—models of zones of potential earthquake sources (ESO zones);

—models of recurrence of different-magnitude earthquakes;

—models of attenuation of ground motion parameters depending on earthquake magnitude and distance from the observation point.

A seismotectonic model of the region is described by a set of *s* independent "sources": linear (faults or zones of faults) and areal (scattered seismicity without explicit relation to the identified faults) sources.

The ground-motion prediction is performed by the means of the function $g(M, R)$, defining the dependence of the mean value of the (natural) logarithm of the ground-motion parameter $\ln S_a$ upon the event with a magnitude *M* and at the distance *R*. This function, called the attenuation relation (or engineering model of attenuation), is represented by the regression relation constructed on the basis of a regional database for strong motions of the ground.

The PSHA output results typically are estimates of peak amplitudes of ground motion accelerations (*PGA*) in the given time period *T* and/or assessments of uniform response spectra for the acceleration (*SA*), which simulate a response of simple vibrating systems to an external seismic impact. In the context of this work, according to Russian practice, the magnitude scale M_{LH} is used, while the macroseismic intensity by the MSK-64 scale is presented as a final output parameter.

Generally PSHA is conducted for one or several classes of grounds defined as reference grounds. The grounds for category II are typically selected from the SNIP II-7-81* table. PSHA results obtained for a reference ground are in turn the initial data for the detailed estimation of the parameters of seismic effects on that or another area, taking into account the seismic properties of a local ground and engineering–geological conditions of the area. In this work, calculations were carried out for six ground types (with shear-wave velocities in the upper 30-m layer) V_{S30} = 760, 540, 430, 350, 230, and 160 m/s. The calculation results are given in the table, while illustrations are presented only for one type of grounds with velocity V_{S30} = 430 m/s.

For the implementation of PSHA procedures, one of the authors of this work (V.N. Solovjev) has prepared a package of computational programs:

—TR4RISK3 for PSHA using logic trees;

—DMR3RISK for determining parameters (*M*, *R*) of the most probable earthquake from specified levels of seismic hazard (deaggregation);

—SEIS_SELECT for choosing accelerogram analogs from deaggregation results and uniform response spectra.

The first two programs enumerated are based on the program SEISRISK III (Bender and Perkins, 1987) and completely retain its ideology. For random number generation, a subprogram from the known library IMSL was used.

Since the spectral accelerations of the ground (*PSA*) are distributed according to the lognormal law, computation in the program is performed for mean values of ln(*PSA*), while a spread of the peak acceleration (*PGA*) with respect to the mean value is taken into account as a value of the standard deviation $\sigma_{\ln(PGA)}$ for the quantity ln(*PSA*). The peak acceleration is the spectral acceleration *PSA* in the zeroth period (or at the infinite frequency).

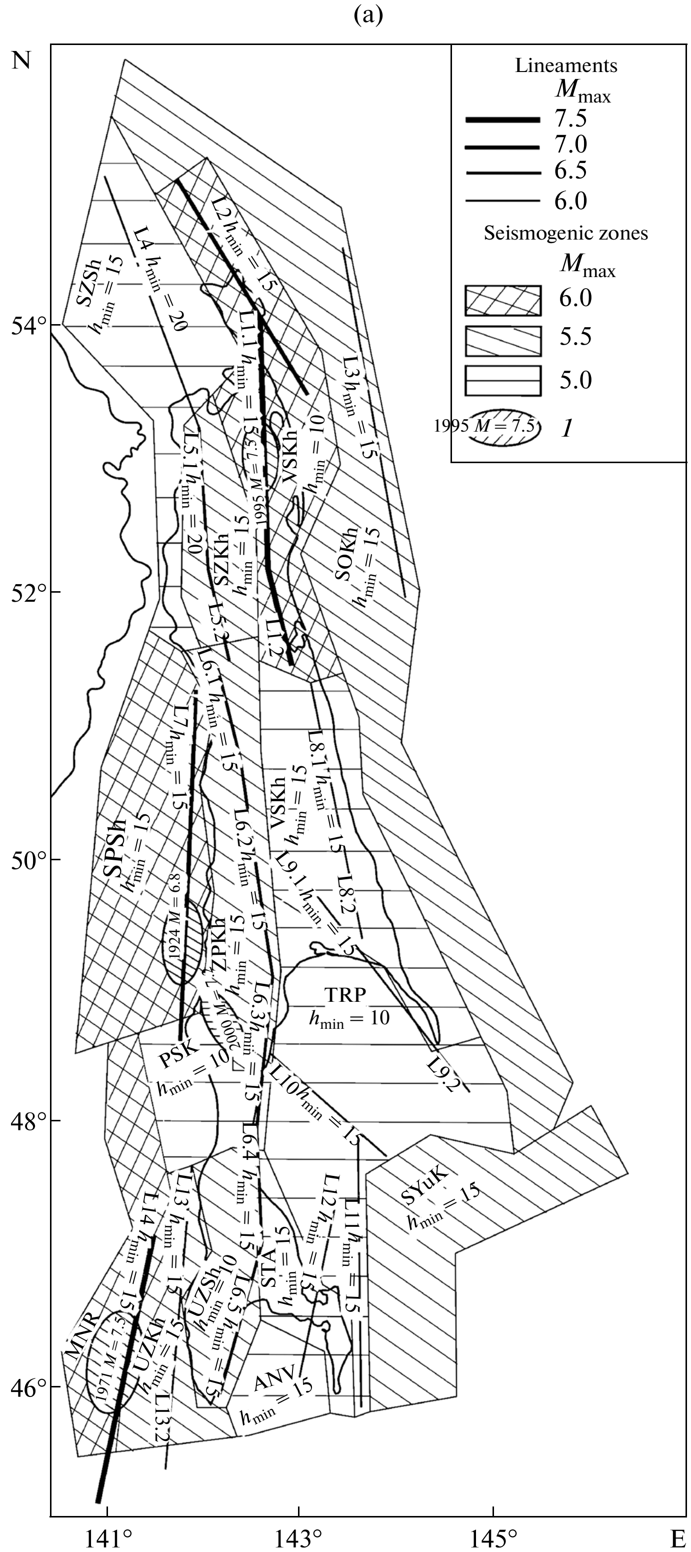
In accordance with requirements of SNIP II-7-81*, in this work, the probabilistic computation of the *PGA* and *PSA* values (for T = 0.2 s and T = 1.0 s) was performed for three values of mean return period: 500, 1000, and 5000 years. Recalculation of the *PGA* and *PSA* values to the appropriate values of macroseismic intensity in numbers of the MSK-64 scale was carried out by the formula recommended in SNIP II-7-81*:

$$I_{MSK} = 7 + \log(10PGA)/\log(2).$$

The PSHA methodology that we have used is set forth in more detail in (Levin et al., 2012).

MODELS OF EARTHQUAKE SOURCES

In 1995–1996, a model of the seismic sources of Sakhalin Island was constructed by L.S. Oskorbin (1997) on the basis of the method of qualitative seismotectonic analysis. The essence of the method is the



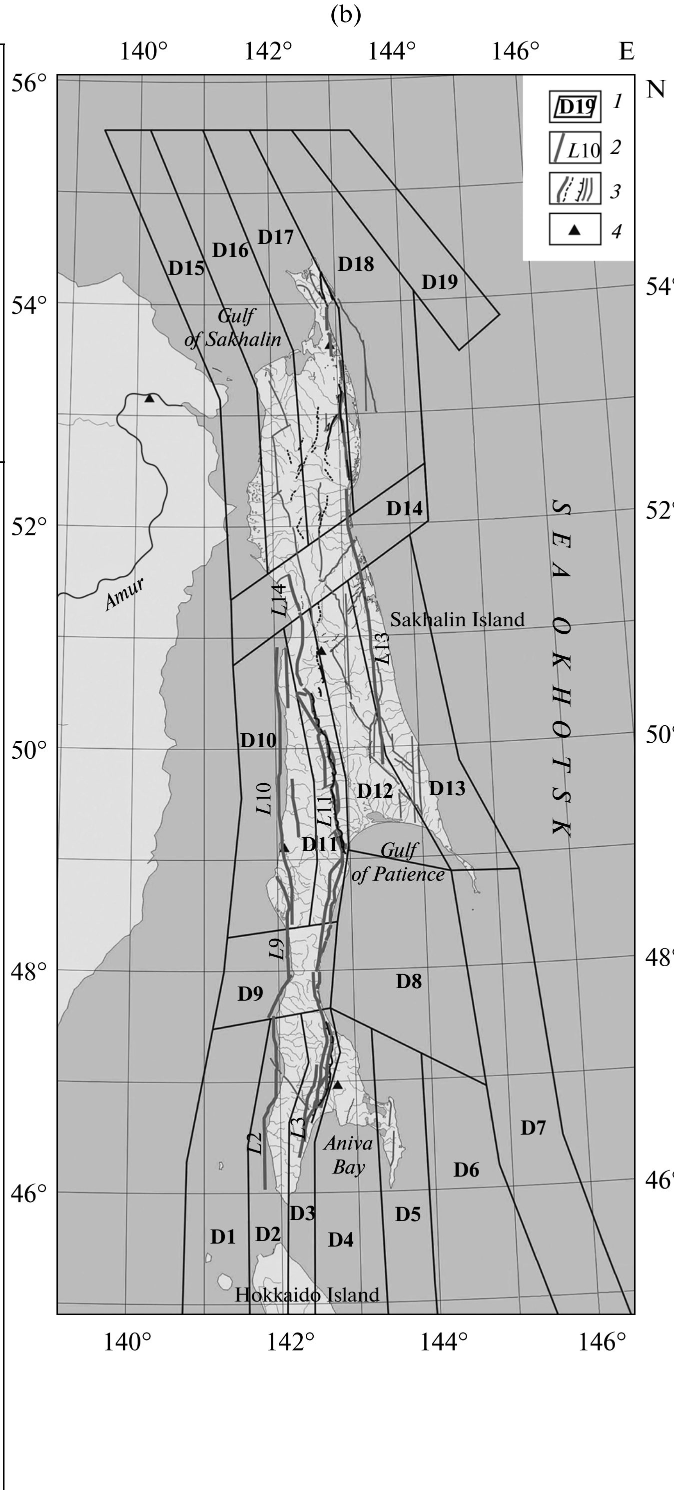


Fig. 3. Configuration and parameters of seismic-source zones of Sakhalin Island according to the lineament-domain models (a) IMGiG-97 and (b) IMGiG-07. (a) (*1*) focal zones of the strongest earthquakes with indication of magnitude and year of event. Letter designations of seismogenic zones on the chart: (SZSh) North-west Sakhalin shelf; (SZKh) North-west Sakhalin; (SVKh) North-east Sakhalin; (SOKh) Sakhalin Okhotsk-Sea; (VSKh) Eastern Sakhalin; (ZPKh) Western Sakhalin; (ZPSh) Western Sakhalin shelf; PSK Poyasok Sakhalin; (TRP) Terpeniya; (MNR) Moneron; (UZSh) South-west Sakhalin shelf; (UZKh) South-west Sakhalin; (STA) Susunai-Tonino-Aniva; (ANV) Aniva; (SYuK) Sakhalin-South-Kuril. (b) (*1*) Numbers and boundaries of ESO zones; (*2*) linear sources (seismolineaments) and their numbers; (*3*) faults of different genesis; (*4*) seismic stations.

extrapolation of seismotectonic information in space based on general and partial seismicity criteria (Kirillova and Sorskii, 1970; Reisner, 1980):

(1) determination the seismotectonic situation at the sites of the observed seismicity;

(2) finding and merging the areas with similar seismotectonic conditions;

(3) estimating parameters of maximal earthquake in these zones.

The model developed by L.S. Oskorbin served a basis for construction of the GSZ-97 map for Sakhalin Island and adjacent regions. In the model, the sources of earthquakes with magnitudes $M_{LH} \geq 6$ are presented by the generalized lines of main fault zones of Sakhalin Island. For a detailed analysis of the seismic situation, the model, called the IMGiG-97 model, was developed, in which only the original geometry of seismic sources (Fig. 3a) was borrowed from the model by L.S. Oskorbin. For all sources of the IMGiG-97 model, the exponential distribution of magnitude is assumed.

The need for a new seismotectonic model (*Nevel'skoe zemletryasenie*..., 2009) (below, IMGiG-07, Fig. 3b) was connected with the new information that recently has appeared, namely:

(1) in paleoseismic studies, measures of characteristic earthquakes have been found on large segments of active faults;

(2) positions of hypercenters are substantially refined and thus variations in the depth of the seismoactive layer are established;

(3) average slip rates are measured for a number of large faults.

The domain-lineament model IMGiG-07 comprises 19 areal zones of sources, which correspond to structural elements of Sakhalin Island and the adjacent water area. Additionally, a number of linear sources are separated (seismolineaments), which correspond to reliably established or probable (by indirect signs) faults.

ASSESSMENT OF PARAMETERS OF GRAPHS OF EARTHQUAKE RECURRENCE AND MAXIMUM MAGNITUDES

From the earthquake recurrence model, the average annual number of earthquakes of different magnitudes $n(M_{LH})$ is determined for each areal zone of sources. The model of recurrence of maximal-magnitude earthquakes for three zones located in the close proximity to the object of survey exerts a decisive influence on seismic hazard assessment for the territory under study; these are (see Fig. 3a): (1) ZPKh (Western Sakhalin); (2) YuZKh (South-west Sakhalin); (3) PSK (Poyasok Sakhalin) and TRP (Terpeniya).

In this work, recurrence graphs from (Oskorbin and Bobkov, 1997) constructed for the whole of Sakhalin Island and individually for different areal ESO zones were taken as a basis. Recurrence graphs in the mentioned work were determined only from the representative earthquakes, i.e., for time intervals during which the earthquakes of some magnitude were recorded without gaps. After 1980, almost all earthquake shocks with $M_{LH} \geq 3.0$ are recorded without gaps on Sakhalin Island; and this magnitude value has been assumed to be $M_{\min}$ in calculations of recurrence graphs for all ESO zones.

For recurrence determination, the maximal magnitudes $M_{\max}$ of the observed events are considered. The number of events for magnitudes from $M_{\min} = 3.0$ to $M_{\max}$ with the step $M_{LH} = 0.5$ was calculated in the magnitude ranges $M_{LH} - 0.25 < M_{LH} \leq M_{LH} + 0.25$ and referred to the center of the range. To obtain comparable estimates of recurrence (taking into account the representativeness of different-magnitude earthquakes), the number of earthquakes was normalized to the unit time (1 year) and related to an area of 10000 km^2. For the same magnitude range and with the same step in magnitude, the cumulative number $N(M_{LH})$ of earthquakes with the magnitude $M \geq M_{LH}$ was determined. Parameters of recurrence graphs for ESO zones were calculated according to the catalogue of main shocks after removing aftershocks of strong events using two methods described in (Gardner and Knopoff, 1974; Reasenberg, 1985).

For seismolineaments, the recurrence was not determined separately because of insufficient data on the strongest earthquakes. With the subsequent seismic-hazard calculations, earthquake recurrence in the vicinity of the lineament was calculated from the same recurrence graph as for the areal ESO zone in which it is included but only for a magnitude range of $M > M_{\max 1}$, where $M_{\max 1}$ is the maximum possible magnitude for the given areal ESO zone. With $M \leq M_{\max 1}$, the recurrence graphs determine the average annual number of earthquakes within the entire areal ESO zone, including, of course, also the vicinity of the seismolineament as a certain part of this zone.

Assessment of the maximum possible earthquakes for the zones of sources and lineaments is very difficult. Paleoseismological studies call into question the possibility of parameterization of individual ESO zones using the Gutenberg–Richter law. It is obvious that strong earthquakes on the majority of faults on Sakhalin Island have not revealed themselves yet for the period of instrumental observations. Traces of ancient strong earthquakes are detected within the limits of the Piltun and Garomai faults on the north of Sakhalin Island, as well as in the region of the Central Sakhalin fault (the village Smirnykh and the Lira River) (Strel'tsov and Kozhurin, 2002).

Data of paleoseismological studies show that sequential displacements along faults or their segments have roughly the same amplitude. In other words, individual faults generate earthquakes of approximately the same (within the limits of ±0.5) magnitude, which are known as characteristic earthquakes, close to their maximal magnitude. Through dating these characteristic events, their return period can be estimated. Geological data show that these earthquakes occur more frequently than can be believed from the extrapolation of the Gutenberg–Richter law. A model of characteristic earthquakes predicts the higher recurrence near the magnitude of characteristic events and the lower recurrence with lower values of magnitude.

To estimate which model is most suitable for the given ESO zone is difficult due to the paucity of historical and/or instrumental observations. However it is clear that in comparison with the Gutenberg–Richter law of recurrence, the model of characteristic earthquakes describes the observed distribution of earthquake magnitudes better. Using paleoseismological data obtained on the faults of Sakhalin Island, the attempt was made in 2009 to assess the parameters of the characteristic earthquake. This issue is set forth in detail in the scientific–technical report "Detailed Seismic Zoning of the Sakhalin Oblast Territory: DSZ-07 Maps of the Territory of Cities of Yuzhno-Sakhalinsk, Dolinsk, Korsakov, Aniva, Kholmsk, Aleksandrovsk-Sakhalinskii, Nogliki, Okha, and Nevelsk" (Fondy IMGiG DVO RAN, Yuzhno-Sakhalinsk, 2007). In this case the $M_{\max}$ assessment was performed according to the correlation relations (Wells and Coppersmith, 1994) based either on fault length or on the value of one-event displacement along the fault (taking into account the sense of displacement or neglecting it).

In this connection, the problem of the segmentation of the zone of faults arises. Geometrical parameters of the fault zones in plane-view allow the zone to be divided into segments with lengths of the order of 35–45 km. These data do not contradict the studies by V.V. Kharakhinov and coauthors (Kharakhinov et al., 1984), who noted that main meridional faults of Sakhalin Island are partitioned by sublatitude faults into segments around 40 km long. The value of one-event net displacement along thrust-faults reaches 4.6 m (the region of the village Smirnykh and the Lira River). Thus, the assessment of maximal magnitude of earthquake appeared to be roughly the value ~7–7.2.

MODELS OF GROUND-MOTION ATTENUATION

For Sakhalin Island, the amount of instrumental records of strong ground motions, for which $I_{MSK} > 5$, is insignificant; therefore to construct the regional attenuation relationships for the peak and spectral ground motions is very difficult. A satisfactory solution to this problem has appeared rather recently, when in 2008 in the USA, a project was implemented under the name of Next Generation Attenuation (NGA). In (Abrahamson and Silva, 2008; Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008; Chiou and Youngs, 2008; Idriss, 2008), five different models of attenuation were constructed for a wide (0–10 s) range of spectral accelerations and $\xi = 5\%$. These models were developed on the basis of a single global database (records of a number of Turkish, Italian, Chinese, Taiwanese, and California earthquakes with the natural prevalence of records of the latter). In a number of works, e.g., (Stafford et al., 2008), their applicability to many seismically active world regions was established. In other words, reasonable agreement was found between the NGA attenuation relationships and local databases for strong motions.

For Sakhalin Island, this agreement is established only for records of events with small (in the engineering sense) magnitudes. However, the available representative database on macroseismic observations allows the coefficients of regional attenuation equation for macroseismic intensity I_{MSK} to be determined quite reliably. The attenuation of the peak and some spectral accelerations, calculated by known empirical formulas (in particular, (Atkinson and Sonley, 2000)) from the I_{MSK} attenuation on Sakhalin Island, are quite consistent with attenuation of the same accelerations in NGA models for the magnitudes M_{LH} within a range of 5.0–6.5. Therefore it is reasonable to suggest that without noticeable error, this correspondence may be transferred also to the entire range of spectral periods, magnitudes, and distances.

Nevertheless, the development of attenuation relationships on the basis of the hybrid method (Campbell, 2003b) for Sakhalin Island remains an urgent task. It should be also noted that response spectra calculated using records from the Japanese databases often sharply differ in shape from the response spectra in the records of Sakhalin earthquakes; therefore we did not use Japanese models of attenuation.

RESULTS OF REFINEMENT OF BACKGROUND SEISMICITY OF THE TERRITORY UNDER STUDY

The refinement of background seismicity was performed for the rectangular area sized 150 × 150 km with a center coinciding with the center of circular domain *1* in Fig. 4, i.e., at the site where construction of Sakhalinskaya GRES-2 is planned. This object will be situated in Tomari borough of the Sakhalin Oblast, north of the village Il'inskii. As has been said above, the seismic hazard level for the village Il'inskii according to the GSZ-97 data is determined as 8 (map A) and 9 (maps B and C).

DISCOVERING AND MAPPING THE PROBABLE ACTIVE FAULTS ON THE TERRITORY UNDER STUDY

While finding (discovering) and mapping active faults, we relied on their feature such as expressiveness in deformations of young relief forms. The expressive-

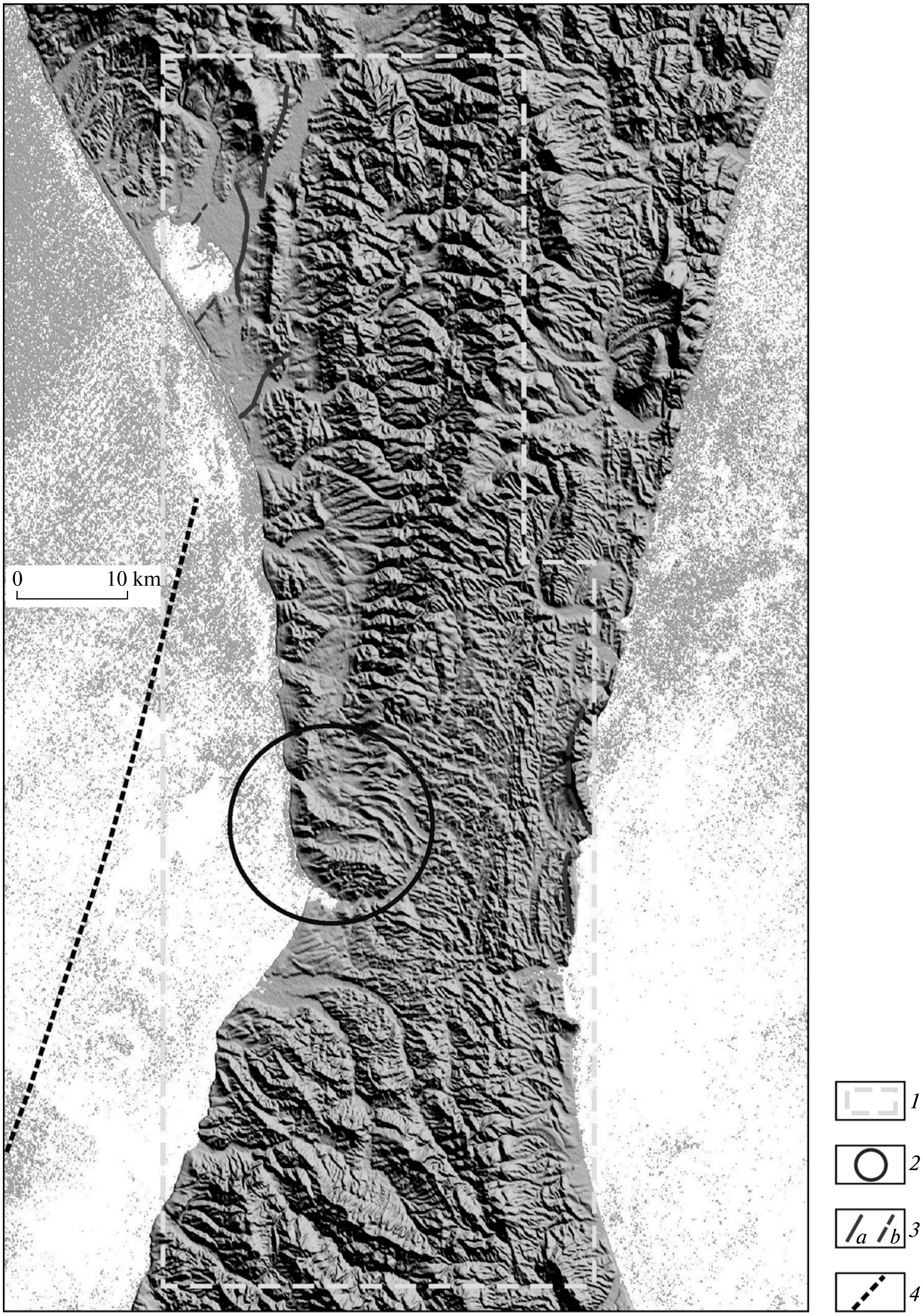


Fig. 4. Results of analysis of aerial photos: (*1*) territory covered by aerial photos; (*2*) survey plot Sakhalinskaya GRES-2; (*3*) (*a*) active and (*b*) supposed faults detected during the interpretation; (*4*) the approximate position of the splay fault, of the regional Western Sakhalin fault.

ness of active faults in the relief, as a rule, in the form of scarps of different height, which frequently vary along the strike of the fault, presents a practically effective and (due to the fact that a relief is everywhere) a universal indication for discovering and mapping active faults.

The particular morphological expression of displacement in the relief is a result of the combination of many factors, the main of which are the type (genetic) of the displaced form and kinematic parameters of an individual rupture. The ledges express not only faults with predominantly vertical motion, but also faults the motions along which are almost purely strike-slip: the displaced surfaces are never perfectly even and horizontal; therefore, the primarily unequal-height parts of the displaced surface can be superposed by horizontal movements at one point of the fault. In this case, the vertical displacement is only visible; here a vertical component of displacements may be absent. As a whole, when distant images of the Earth's surface (in our case, aerial photos) are interpreted, it appears possible to determine (often to high accuracy) the main parameters of active faults: the kinematics of motions (sense of displacements), their values and ratios between vertical and horizontal components, as well as the mean rates of motions when the displaced forms can be dated.

The results of interpretation provide the basis for detailed paleoseismological studies aimed at retrieving the data on the recurrence of movement along the fault and the age of the last movement. Now, as a rule, this occurs in the course of trenching (laying trenches across faults) and studying sediments deformed by motions along the fault.

We performed an interpretation of aerial photos of the territory with an area of 1200 km^2, including the survey plot (*2*, see Fig. 4). Aerial photos from 1952 and 1966, on a scale of 1 : 30000–1 : 35000, were interpreted. The interpretation was carried out in the stereo mode with the application of both a standard desk stereoscope and (for the selected stereo pairs) the ad hoc software Photomod Light 5.0 of the Russian company Rakurs. In total, five faults are revealed, four of which are identified with a high degree of certainty.

In particular, westward of the Ainu River, two faults are detected, probably splaying off the Western-Sakhalin zone. It might be suggested that the Uglegorsk seismic rupture of 2000 could proceed southward along strike of one of these faults. Unfortunately, at the time of studying the seismic rupture, the faults identified in this work were not known. One more interpreted fault, south of the Tikhaya River, was found to be closest (roughly, 12–15 km) to the eastern edge of the survey plot. This fault, probably, is a reverse fault in the hanging wall of the Tym-Poronai fault. Within the limits of the survey plot itself, no indications of active faults were detected.

Thus, there are no seismogenerating fault structures on the survey plot. The supposed branch of the underwater Western Sakhalin fault (line *4*, see Fig. 4) may be a seismogenerating structure nearest on the west (roughly 10 km from the western edge of the survey plot). The active fault, southward of the Tikhaya River identified during the interpretation, is a seismogenerating structure nearest to the east (approximately 12–13 km from the eastern edge of the survey plot).

MAPS OF DETAILED SEISMIC ZONING

Figures 5 and 6 present DSZ maps of the territory under study in parameters of peak acceleration (*PGA*) and macroseismic intensity of shaking (I_{MSK}) for return periods of 500 (see Fig. 5) and 1000 years (see Fig. 6) and grounds of category II (V_{S30} = 430 m/s). In the construction of DSZ maps in the macroseismic intensity parameters on the basis of the calculated spectral acceleration, the formula given above was used.

DSZ map calculations are performed for a rectangular area with a size of 150 × 150 km in the nodes of a grid with a step of 8.3 km in the X coordinate and 8.5 km in the Y coordinate and with a center coinciding with the center of the circular domain *1* in Fig. 4. Assessments of peak accelerations of the ground and macroseismic intensity of shaking by the MSK-64 scale for return periods of 500, 1000, and 5000 years for the given point with account for ground conditions are summarized in table.

CONCLUSIONS

The refinement of background seismicity at the survey plot allocated for the construction of the Sakhalinskaya GRES-2 has been performed on the basis of input data (characteristics of active faults, ESO zones, seismic regime, seismotectonic models, etc.) using computational programs developed at the Institute of Marine Geology and Geophysics of Far Eastern Branch of the Russian Academy of Sciences. The construction of this object is planned in the region of the Poyasok Isthmus (Tomari district of Sakhalin Oblast, north of the village Il'inskii). The background seismicity for the village Il'inskii according to general seismic zoning data GSZ-97 is determined as 8 (map A) and 9 (maps B and C). In the course of the work, the following results are obtained.

The interpretation of aerial photos of a scale 1 : 30000–1 : 35 000 is performed for a territory with an area of roughly 1200 km^2, including the survey plot. In total, five faults are discovered; four of them are identified with a high degree of reliability. In particular, two faults westward of the Ainu River are detected that probably represent the southern continuation of the Uglegorsk seismic rupture, which is the subsidiary fault of the Western Sakhalin zone of active faults. One more interpreted fault southward of the Tikhaya River

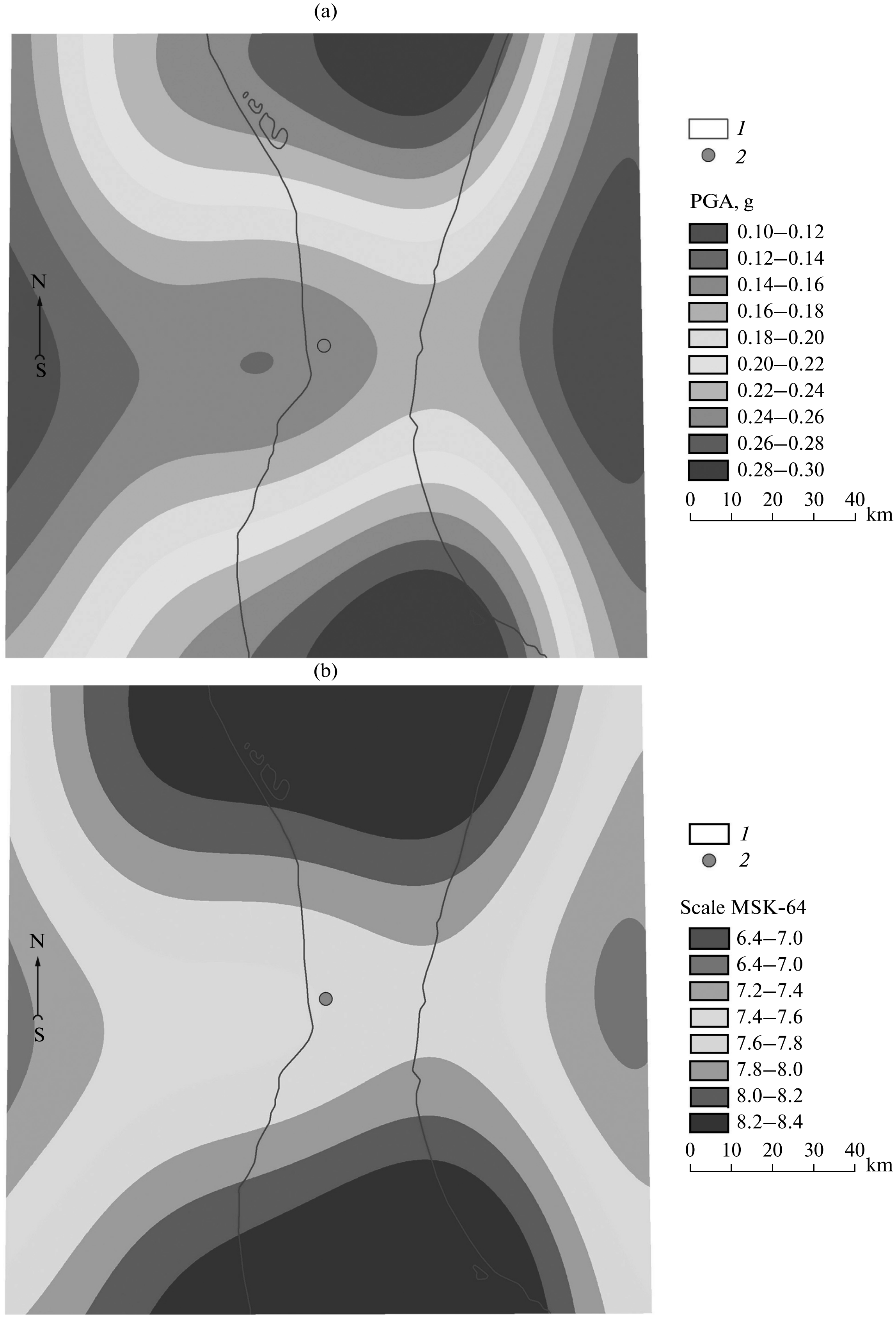


Fig. 5. Map of DSZ of the territory under study and its surroundings in parameters of (a) peak ground accelerations and (b) macroseismic intensity of shaking for the return period $T = 500$ years and the grounds of category II ($V_{S30} = 430$ m/s): (*1*) coastline; (*2*) village of Il'inskii.

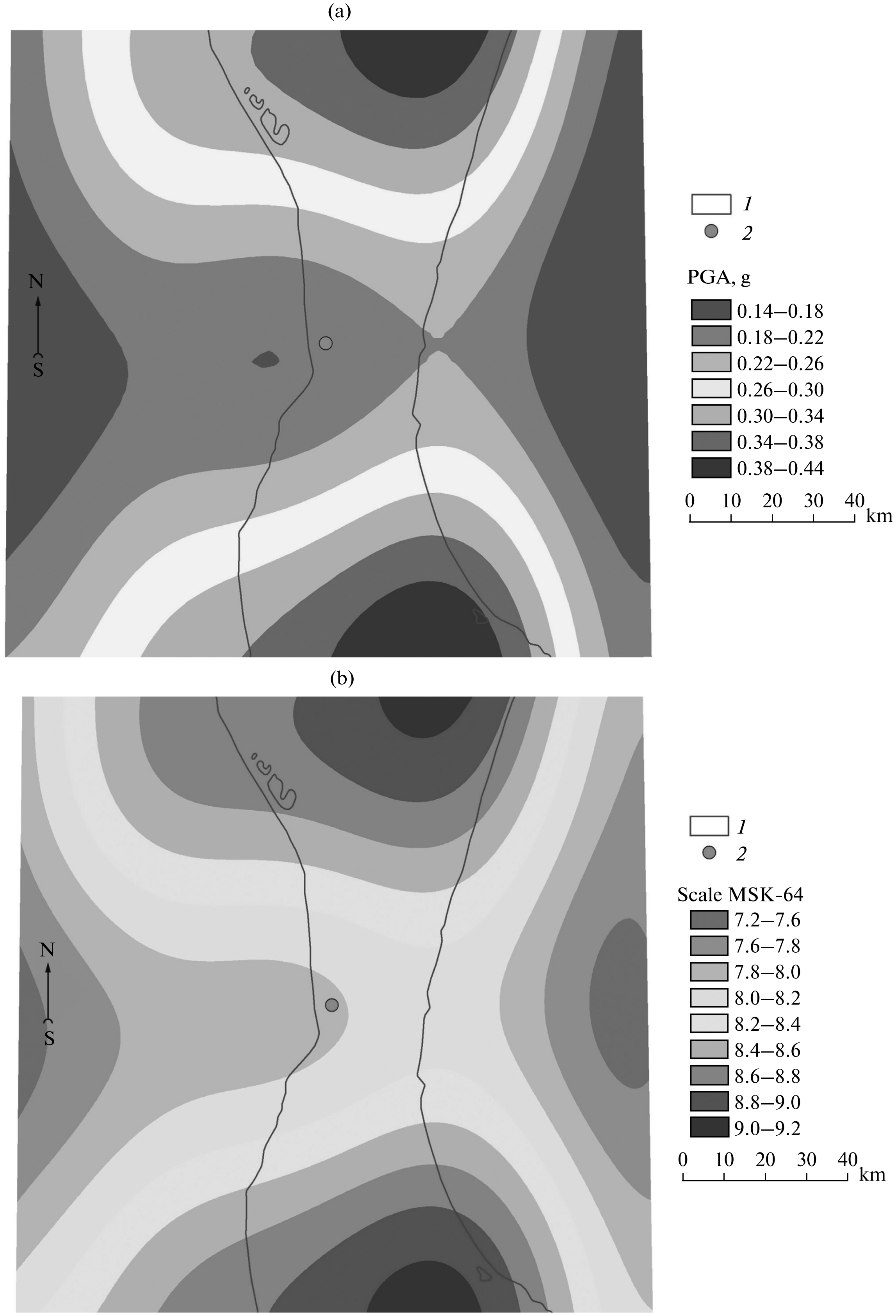


Fig. 6. Map of DSZ of the territory under study and its surroundings in parameters of (a) peak ground accelerations and (b) macroseismic intensity of shaking for the return period $T = 1000$ years and the grounds of category II ($V_{S30} = 430$ m/s): (*1*) coastline; (*2*) village of Il'inskii.

was found to be the nearest one (approximately 12–13 km) to the eastern edge of the survey plot. This fault, probably, is a secondary one with regard to the Tym-Poronai zone of active faults. Within the limits of the survey plot itself, indications of active faults were not found.

For the region under study, the probabilistic assessments of seismic hazard in parameters of macroseismic intensity (I_{MSK}) are refined in comparison to the GSZ-97 maps. The average horizontal peak accelerations (*PGA*, *g*) and horizontal pseudo-spectral accelerations (*PSA*, *g*) are calculated for periods of 0.2 and 1.0 s with 5% damping for three return periods (500, 1000, and 5000 years).

Based on the calculated parameters of strong motions of the ground, the DSZ maps are constructed for the territory under study in parameters of peak ground accelerations and macroseismic intensity of shaking by the MSK-64 scale for the return periods 500, 1000, and 5000 years with account for the grounds of categories I, II, and III. The I_{MSK} assessments on the DSZ maps at the central point of survey for the grounds of category II appeared to be lower than similar GSZ-97 data by 0.4 (map A), 1.0 (map B), and 0.3 (map C).

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