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Estimation of Seismic Hazard in the Kaliningrad Region

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Abstract—The paper discusses problems of seismic zoning of the Kaliningrad region, where a series of perceptible earthquakes occurred in 2004; the strongest event had a magnitude of $M_s = 4.3$ and produced shakings of an intensity of 6 in the coastal zone of the Sambiiskii Peninsula, classified as a 5-intensity zone. The enhanced seismic effect is shown to be caused by bad ground conditions, long-term action of seismic effects, resonance phenomena, and other factors. To gain additional constraints on the seismic hazard degree in the Kaliningrad region, the paper discusses an improved version of the model of earthquake sources underlying the compilation of normative maps of seismic zoning (OSR-97). Modified fragments of OSR-97 probability maps of the Kaliningrad region are constructed at different levels of probability that the seismic effect indicated in the maps will be exceeded over 50 yr. It is shown that additional seismological investigations should be conducted in this region.

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1. INTRODUCTION

A series of earthquakes of September 21, 2004, off the NW coast of the Kaliningrad region in the Gulf of Gdansk of the Baltic Sea attracted the attention of both the general public and seismologists. Shakings of at least nine of them were perceptible. The strongest shock occurred at 13:32 GT and had a magnitude of $M_s = 4.3$ determined by the RAS Geophysical Service (GS) [Malovichko et al., 2007]. It was preceded by an $M_s = 4.1$ earthquake that occurred at 11:05 GT. A third, weaker shock with a magnitude $M_s < 4.0$ occurred at 13:36 GT. According to data of many seismological services, the generalized coordinates of these earthquakes are 54.9°N and 19.9°E and their source depths are no less than 20 km. The source area is confined to the seismically active zone located to the west of the Sambiiskii Peninsula. According to data of the Harvard Center (United States), the moment magnitude of the main earthquake was $M_w = 4.7$ and the source slip was of the left-lateral type.

In spite of the moderate magnitudes, the macroseismic effects of these seismic events were quite impressive. Large ground deformations (landslides, collapses, etc.) that are typical of stronger earthquakes arose in the Kaliningrad region. Surface vibrations from the strong shock were felt throughout the vast territory of the Kaliningrad region, Baltic states (Lithuania, Estonia, Latvia, and Finland), Belarus, Poland, and eastern Denmark and in St. Petersburg. The seismic activation was also manifested as a series of other, less perceptible events. Two areas of a shaking intensity of 6 due to the main shock of September 21 were localized on the NW coast of the Kaliningrad region. One area is located to the west of the city of Kaliningrad, and the other, in the NW part of the Sambiiskii Peninsula. However, other estimates of the observed seismic effect are also available. Investigations continue, and their diverse results require a comprehensive analysis.

An extensive review of publications on this subject is given in [Assinovskaya and Ovsov, 2008], where a tectonic model is also proposed according to which the source area of the strongest shocks of the Kaliningrad series is confined to a N–S fault crossing the offshore zone of the Sambiiskii Peninsula, the Bay of Gdansk, and the area of the settlements of Yantarnyi and Bakalino. Using the macroseismic EMS-98 scale, Assinovskaya and Ovsov [2008] revised original material and compiled modified maps of shaking intensity for the NW part of the Kaliningrad region.

The Kaliningrad earthquakes occurred in a 5-intensity zone of the OSR-97 general seismic zoning maps of the Russian Federation. In accordance with the concept adopted for the creation of the OSR-97 set of maps, the rated values of seismic intensity in each seismic zone, including 5-intensity zones, can be exceeded at a specified probability [Ulomov and Shumilina, 1999; *Seismic Zoning* …, 2000]. For the Kaliningrad region, the normative OSR-97 maps estimate at less than 1% the probability that an intensity of 5 will be exceeded during a 50-yr interval.

The main reason why the observed seismic effect exceeded the expected value is unfavorable ground conditions that are worse as compared with mean grounds (of category 2 according to [*SNiP II-7-81**. *Construction* …, 2000]) used for the classification of the seismic intensity indicated in the OSR-97 maps. Very old buildings were damaged. Relatively insignificant but long seismic vibrations served as a trigger for the loss of stability in the railway fill near the town of Svetlogorsk. Because of heavy rains falling before the earthquake, the fill material was ultimately saturated with water. If these had not occurred, the fill could have been fractured due to critical shakings produced by passing trains. In this case, one may state that the Kaliningrad series of earthquakes prevented a railway catastrophe.

Opinions of professional seismologists were so diverse that some of them consider the Kaliningrad earthquake of September 21, 2004, as a unique phenomenon, while others believe that it was predictable in relation to both its position and magnitude. The latter usually refer to the work [Reisner and Ioganson, 1993]. In fact, these authors classify as aseismic not only the Kaliningrad region but also its surrounding area within a radius of up to 80 km, as is seen from their schematic map showing the distribution of the estimated seismic potential (M_{max}). A small area with $M_{max} \leq 3.9$ closest to the epicenter of the earthquakes in question is much smaller in magnitude than the observed value. A smaller zone of $4.0 \leq M_{max} \leq 4.9$ is at a distance of about 300 km from the epicenter [Reisner and Ioganson, 1993, p. 192].

In this respect, a more realistic model of geodynamic zoning of the East European platform (EEP) is the model developed by Grachev et al. [1996] during the work on the construction of the OSR-97 maps. According to this prognostic model, the entire Kaliningrad region is located in a large zone of possible earthquakes with $M_{max} = 4.0$ and the zone of $M_{max} = 5.0$ is at a distance of more than 160 km from the real epicenter.

Another extreme in the discussion on the seismic hazard is encountered in the work by Nikonov et al. [2005], who state that "… the existing normative documents (first of all, the OSR-97 map) are at variance with reality and can no longer serve as a basis for design, construction, and safety measures."

Because we face not only misunderstanding but also misrepresentation of principles underlying the probabilistic estimation of seismic hazard during the creation of the OSR-97 set of maps, the methodological basis of the construction of these normative maps and the technology of their use are briefly described in the next section.

The main goal of the present paper is the revision of the seismic situation in the Kaliningrad region using the newest data on the weak seismicity of the region, which were absent before 2000. This study is based on catalogs of $M > 3$ earthquakes that have been published relatively recently by the European Mediterranean Seismological Centre (EMSC, France) and catalogs of seismic events with $M > 2$ over the period 2000–2006 published in the Reviewed Event Bulletin (REB, Austria) of the seismic service functioning within the framework of the Comprehensive Nuclear Test Ban Treaty (CTBT) and publishing bulletins with data on natural and artificial seismic sources.

2. PRINCIPLES OF THE PROBABILISTIC ESTIMATION OF SEISMIC HAZARD

Because of uncertainties inevitably involved in nature, the probabilistic approach to seismic zoning is most effective. Although assessment of seismic hazard always entails a certain risk, it can be quantified, minimized, and taken as acceptable socially and economically. Since the majority of the used physical parameters characterizing geodynamics, seismicity, and seismic effects are, in essence, probabilistic, in 1991–1997 we constructed not one deterministic map (as before) but the OSR-97 set of probabilistic maps reflecting different degrees of seismic hazard within given time intervals. For the first time, seismic zoning encompassed plain territories and shelves of marginal and inner seas. Instead of traditional ideas of pointlike seismic sources, earthquake sources were considered as finite. Other novel concepts were also introduced; in particular, nonlinear manifestations of seismogeodynamic processes and seismic influence were taken into account.

Seismic hazard assessment and seismic zoning of Northern Eurasia were implemented by developing two basic interrelated models: (1) a 3-D model of earthquake source zones in the crust and the entire lithosphere and (2) a model of the seismic effect produced by model (1) at the Earth's surface. Each of the models is based on probabilistic estimates of nearly all parameters used for calculations and reconstructions and is characterized by a degree of indeterminacy, dispersion, and possible uncertainties (errors in the determination of source positions and earthquake magnitudes, a scatter in seismic effect estimates, and so on). The most complicated and critical aspect of seismic zoning is the identification of zones of earthquake sources occurrence (ESO) and the determination of parameters of their seismic regime because the reliability of all subsequent reconstructions depends on this model.

LDF Model of Earthquake Sources

The creation of a model of ESO zones for Northern Eurasia is based on the lineament–domain focal (LDF) model, developing fractal ideas of the geophysical medium and its seismogeodynamic processes [Ulomov, 1998].

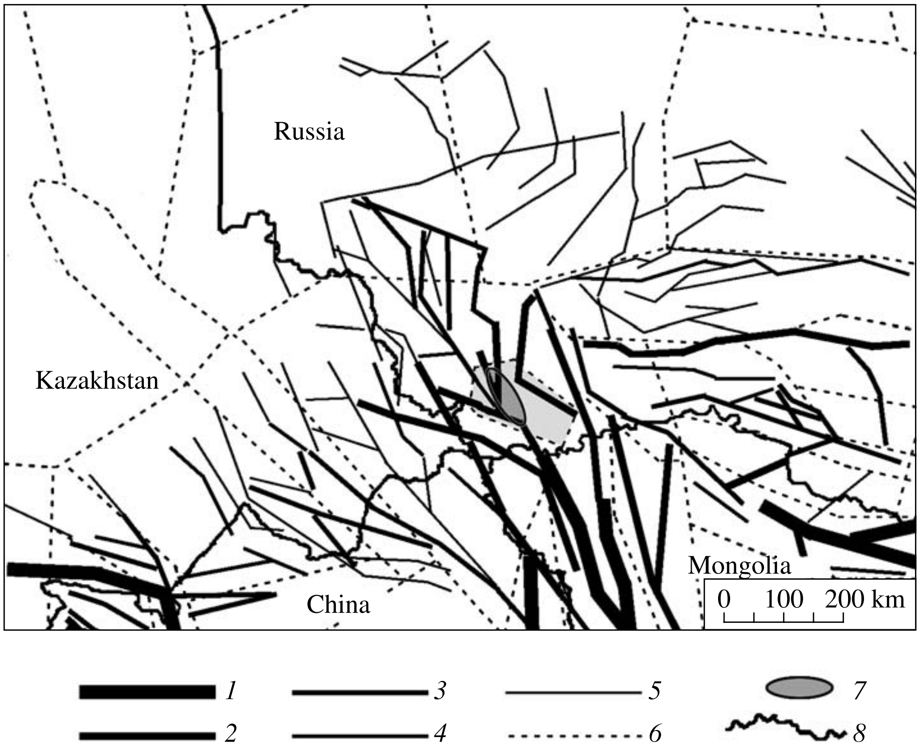

Fig. 1. Typical fragment of the LDF model of ESO zones in the Gornyi Altai and adjacent areas: (*1–5*) lineaments with magnitudes *M* of (*1*) 8.0 ± 0.2, (*2*) 7.5 ± 0.2, (*3*) 7.0 ± 0.2, (*4*) 6.5 ± 0.2, and (*5*) 6.0 ± 0.2; (*6*) domain boundaries; (*7*) source of the September 27, 2003, earthquake (*M* = 7.3); (*8*) state borders. Other explanations are given in the text.

In accordance with the accepted concept, the LDF model includes four scale levels of earthquake sources, namely, a large, genetically and seismogeodynamically coherent region with a general characterization of its seismic regime and the following three main structural seismogenic elements of the region: *lineaments,* generally representing axes of 3-D seismically active fault zones or shear structures and reflecting structured seismicity; *domains,* encompassing geodynamically quasi-homogeneous volumes of the geological medium and characterized by scattered seismicity; and *potential earthquake sources,* delineating the most hazardous parts (foci) of seismogenic structures.

A parameterized LDF model specifying how yearly averaged flows of seismic events of an entire region are distributed among the main structural elements (lineaments, domains, and potential earthquake sources) and a model of the seismic effect describing the attenuation of the seismic intensity with distance are used for the numerical modeling of predicted (virtual) seismicity and for the subsequent calculation of seismic shaking potential and seismic zoning [Ulomov and Shumilina, 1999]. A synthetic seismicity scenario is realized on the basis of a model catalog of earthquakes compiled for very long time intervals from which the required interval depending on the admissible seismic hazard is chosen.

For general seismic zoning of federal significance (OSR-97), it is accepted that sufficiently large events ($M = 6.0 \pm 0.2$ or more) belong to lineaments and potential earthquake sources, whereas earthquakes with $M = 5.5 \pm 0.2$ or less belong to domains. In detailed seismic zoning (DSZ) and seismic microzoning (SMZ), possessing, respectively, regional (territorial) and local (municipal) status, the maximum magnitude threshold can be lowered in accordance with the detail degree of seismological studies. Henceforward, by the magnitude M we mean, except if otherwise indicated, the magnitude M_s determined from surface waves. Magnitudes of all types are converted to M_s values in the special catalog of earthquakes used for the creation of the OSR-97 maps.

As an example clearly illustrating the LDF model used for the creation of the OSR-97 maps, Fig. 1 presents a fragment of Northern Eurasia ESO zones in a fairly well studied area of the Gornyi Altai. As seen from the figure, the width of lineaments, reflecting their fractal properties, decreases away from the mountains in the south, distinguished by the largest seismogenic faults. Correspondingly, the magnitudes of maximum possible earthquakes decrease in the same direction. Domains alone are present in the north, where seismicity is weak. Lineaments are seismologically parameterized with the help of the entire yearly averaged flow of regional seismic events distributed among them in proportion to the length of each of these structural elements and in accordance with their rank, decreasing from the maximum magnitude M_{max} at a step of 0.5 ± 0.2. Domains are parameterized according to generalized recurrence plots of $M \leq 5.5$ earthquakes within their limits.

A high reliability of the LDF model of ESO zones and the maps of general seismic zoning of the Russian Federation is objectively demonstrated by the large ($M = 7.3$) earthquake that occurred in the Gornyi Altai in 2003, i.e., six years after the publication of the OSR-97 maps (Fig. 1). Its extended source coincided perfectly well with lineaments having the expected magnitude $M_{max} = 7.5 \pm 0.2$ and was located within a local domain (D0295 in the OSR-97 database) identified from the LDF model of ESO zones as a source area of a potential earthquake [Shebalin et al., 2000]. The D0295 domain, which is relatively small compared to other structural elements of this type, was delineated on the basis of a high concentration of active faults and their junctures. In the figure it is shown as a shaded area. According to several criteria described in [Shebalin et al., 2000], the maximum magnitude of the earthquake expected in this domain was estimated as M_{max} = 7.2, which is very close to the observed value of M = 7.3. Along with the Gornyi Altai earthquake of 2003, the long-term seismological prediction was corroborated by other large seismic events that occurred after the publication of the OSR-97 maps (earthquakes in the Koryak, Sakhalin, and Kuril regions).

Probabilistic Estimation of Seismic Hazard

As noted above, the OSR-97 method of estimating seismic hazard is based on a set of maps characterized by an average recurrence of an event of an intensity I once in T years in a given area (denoted as I_T). The probability P that the intensity I_T will be exceeded during t years (i.e., that at least one such event will occur during this time) is

$$P = 1 - \exp(-t/T).$$

Given $t \ll T$, the probability is $P = t/T$. For example, P is ~10% (more specifically, 9.52%) for T = 500 yr and t = 50 yr, ~5% (4.88%) for T = 1000 yr and t = 50 yr, and so on. The degree of seismic hazard can be estimated by calculating a set of I_T maps differing in T values, i.e., in the probability of an event whose intensity will exceed (or will not exceed) the prescribed value in a given time interval; and vice versa, the required map of the prescribed intensity I_T can be chosen by specifying the admissible value of seismic hazard for a construction site.

A map of prescribed intensity I_T (a map of shaking intensity) is calculated from a model catalog of earthquakes with the use of a regional intensity dependence on magnitude and distance for an extended seismic source of natural sizes. The model catalog is compiled from long-term characteristics of seismicity in a region studied.

An important distinction of the OSR-97 method from traditional approaches is that it takes into account the nonlinearity of the plot $\log N(M)$ characterizing the interrelation between the number of earthquakes N and their magnitude in the range of large seismic events (up to M_{max}). Moreover, this method allows for factors of possible overestimation of the seismic activity level (for example, due to the contribution of aftershocks of large earthquakes) or its underestimation (a short time interval of detailed observations and a limited amount of data for periods of weak seismicity).

In preparing the OSR-97 maps, the entire territory was covered by a rectangular grid of 25 × 25-km cells in order to calculate the shaking intensity. (In principle, the grid step may have an arbitrary value and depends on the reasonable degree of model detail.) Each node interrogates all virtual sources arising in the process of the computer modeling of prognostic seismicity and accumulates information on the year-normalized number of seismic events N in the form of distribution histograms of the seismic intensity I or peak accelerations PGA (cm/s^2) of seismic ground motions. In this procedure, the sizes and orientation of virtual earthquake source planes are taken into account.

Specifying fixed time intervals (500, 1000, and 5000 yr in the OSR-97 case), the OSR-97A, OSR-97B, and OSR-97C maps of seismic intensity with probabilities P = 10, 5, and 1% of intensities exceeding the mapped values during 50 yr were created. Vice versa, fixing a value of the seismic intensity I (6, 7, 8, and 9 in the OSR-97 case), maps of recurrence intervals T of a given seismic event were created [*Seismic Zoning* …, 2000].

In 1991–1997, the OSR-97D map was created, which characterizes a 0.5% risk that the indicated intensity will be exceeded during 50 yr; i.e., it characterizes the average recurrence of a seismic effect once over 10 000 yr. This map is intended for estimating seismic hazard at sites of nuclear power plants and other objects of the nuclear-radiation complex.

The method and principles developed by the authors for constructing new maps of seismic zoning have been acknowledged worldwide, and the OSR-97A map, represented in terms of peak accelerations, was incorporated in 1999 in the world map of global seismic hazard published in the United States in the framework of the GLOBAL SEISMIC HAZARD ASSESSMENT PROGRAM implemented over 1993–1998 under the auspices of the UN and the international program, "Lithosphere" ["The Global …," 1999; *International* …, 2003]. The OSR-97 maps have been repeatedly published in Russia.

Objectives of the OSR-97 Set of Maps

The new methodology of the development and practical use of the set of new, OSR-97 maps was approved by a resolution passed at an expanded session of the Scientific Council of the IPE RAS (February 12, 1998); was authorized by the governing board of the RAS (March 23, 1998), Federal Agency of Construction and Housing and Communal Facilities (FACHC) (March 28, 1998), Science and Technology Council of the Ministry of Construction of the Russian Federation (April 21, 1998), and Bureau of the RAS Division of Geology, Geophysics, Geochemistry, and Mining (May 20, 1998); and was recommended as a basis of normative documents. The OSR-97 maps, together with inset maps of ESO zones, seismicity, and recurrence intervals of shakings of different intensities, were published as wall maps on a scale of 1 : 8000000 [*Seismic Zoning …*, 2000]. In the same year, the FACHC incorporated the OSR-97 set of maps into the SNiP II-7-81* Code of Norms and Regulations for Construction in Seismic Regions [*SNiP II-7-81*. Construction …*, 2000].

The main SNiP II-7-81* regulations concerning the OSR-97 maps should be followed in designing buildings and structures to be constructed at sites characterized by a seismic intensity of 7, 8, or 9 (SNiP II-7-81* point 1.1). The OSR-97 set of maps provides for antiseismic measures that should be taken in construction and reflects 10% (map A), 5% (map B), and 1% (map C) probabilities that the seismic intensities indicated in the maps will be exceeded (or 90, 95, and 99% probabilities that they will not be exceeded) during 50 yr (point 1.3).

The seismic intensities in the maps were specified for grounds with mean seismic properties (category 2). The OSR-97 set of maps (A, B, and C) allows one to assess seismic hazard at three levels and provides for antiseismic measures that should be taken in constructing objects of three categories in accordance with their significance: the A map is designed for repetitive construction, and the B and C maps, for works of increased and critical significance. The seismicity of a specific construction site should be assessed on the SMZ basis (point 1.4).

The latter statement, pointing to the necessity of SMZ studies, is of crucial importance because it requires that the seismic hazard degree indicated in the OSR-97 maps for grounds with mean properties must be refined with regard for real ground conditions of construction sites and their response to seismic effects. Unfortunately, SMZ is not always performed, and this leads to consequences observed during the Kaliningrad earthquakes of 2004.

In civil engineering practice, deterministic, rather than probabilistic, methods are also often used for calculating expected seismic effects from so-called scenario earthquakes regardless of their occurrence time. In this approach, spectral responses of specific buildings and structures to seismic effects are calculated from theoretical seismograms determined with regard to geological, geophysical, and dynamic parameters of a seismic source and a medium in which seismic waves propagate, as well as with regard to the effect of real grounds including their resonance properties. However, in these cases as well, deterministic estimates should often be converted to their probabilistic analogues in accordance with the normative requirements of the OSR-97 maps and SNiP II-6-81* code [Ulomov, 2005, 2006].

3. SOME ASPECTS OF SEISMICITY OF THE KALININGRAD REGION

The EEP, in the NW part of which the Kaliningrad region is located, is characterized by relatively weak seismicity and rare local earthquakes with magnitudes $M \leq 5.5$ and an intensity at the epicenter of up to $I_0 = 6$–7. Seismicity in NW Russia is mainly due to continuing postglacial isostatic vertical movements of the Fennoscandia lithosphere. The territory of the Kaliningrad region is subject to shakings from earthquakes in Scandinavia (e.g., an event of 1817 in Norway) and the largest seismic events originating at depths of 100–200 km in the Eastern Carpathians, particularly in the Vrancea zone of Romania (events of 1802, 1940, 1977, and others). Stronger earthquakes are known to have occurred on the Kola Peninsula and adjacent areas (e.g., the M = 6.3 Kandalaksha, White Sea, event of 1626). Earthquakes in Poland (1803) and Sweden (1904) were felt in Koenigsberg and throughout Prussia. Weak shakings of an intensity of up to 5–6 are possible nearly all over the EEP territory. Seismic activity is often induced by anthropogenic impact on the lithosphere (production of oil, gas, and other minerals; injection of fluids into faults; and so on).

Analysis of Catalogs of Weak Earthquakes in the Kaliningrad Region

The analysis of seismological bulletins published by the GS RAS in 1980–2006; the International Seismological Centre (ISC), Great Britain, in 1948–2003; and the REB, Austria, in 2000–2007 have shown that the earthquakes nearest in occurrence time and distance to the Kaliningrad earthquakes of September 21, 2004, were 14 weak seismic events that occurred from February 18 to May 25, 2004, and 3 events that occurred in October, i.e., after the Kaliningrad series of earthquakes. According to GS RAS data, the Baltic Sea earthquake ($M_b = 4.4$) of December 18, 2002, was nearest to their source.

In recent years, fairly detailed information on seismicity in the study territory has been published at the EMSC Internet site. A fragment of one of its maps is presented in Fig. 2a. The abundance of seismic events in the Bay of Gdansk west of the Kaliningrad region raises doubts concerning the tectonic origin of most of these earthquakes. This is particularly true of a map of epicenters that we constructed from data of the REB catalog, undoubtedly dominated by records of explosions, rather than earthquakes, because this service is conducting seismic monitoring of explosions in the CTBT framework.

Ordered linear clusters of epicenters are clearly seen in Fig. 2b (within rectangular contours). It is noteworthy that the N–S strike of the southern cluster differs

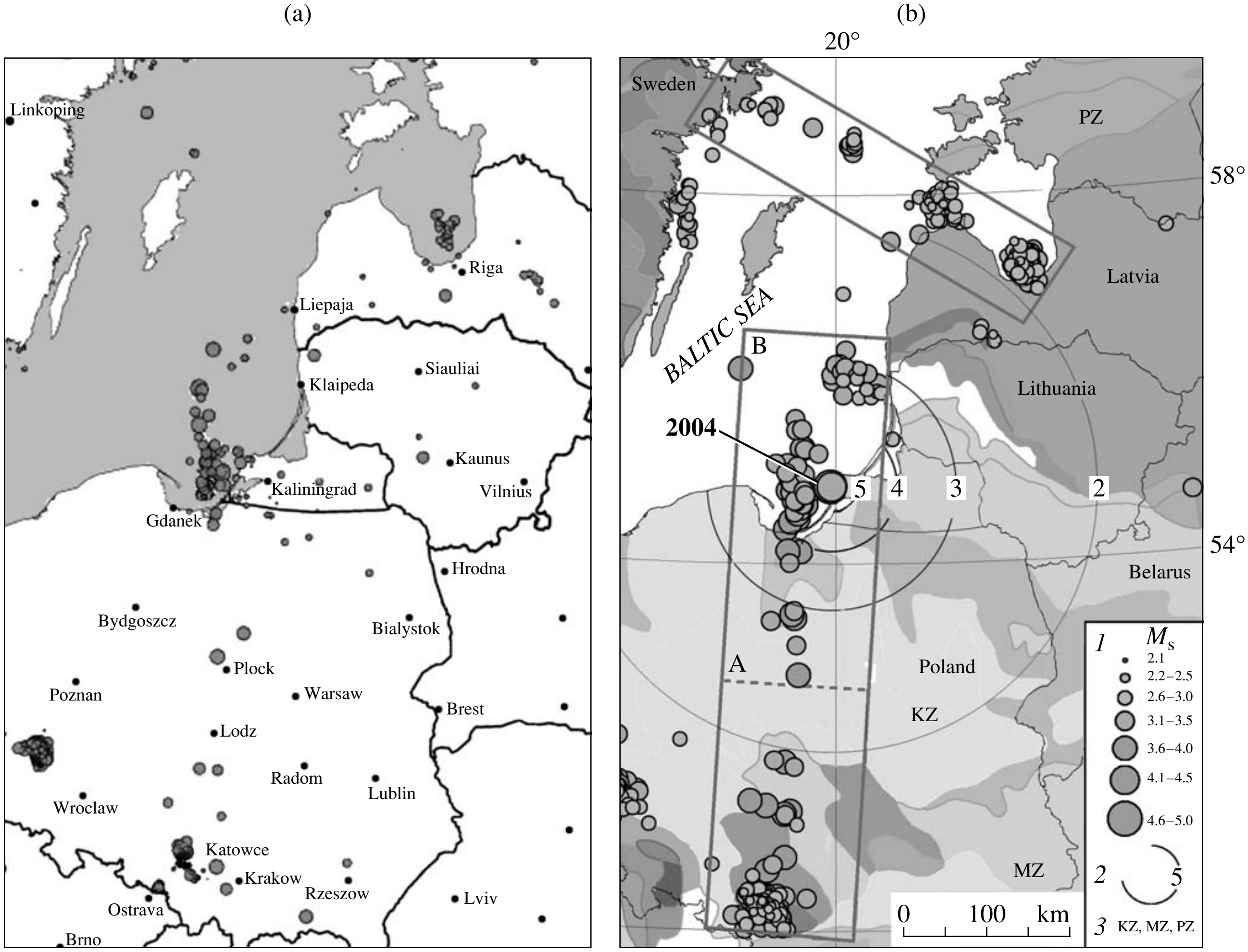

Fig. 2. (a) Fragment of the EMSC map showing epicenters of earthquakes with magnitudes $M > 3$ and (b) geological map showing epicenters of seismic events with $M > 2$ from the REB catalog over 2000–2006: (*1*) epicenters of seismic events of various magnitudes M_s; (*2*) theoretical isoseismals (MSK-64 intensity) of the Kaliningrad earthquake of 13:32 on September 21, 2004 (the epicenter is shown by an arrow); (*3*) age of geological structures.

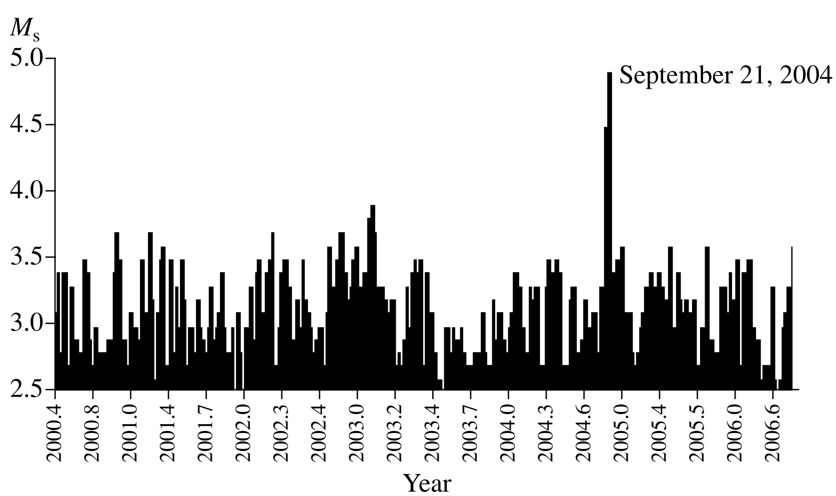

Fig. 3. Succession of the seismic event occurrence in the magnitude interval $2.3 < M \leq 4.9$ in the period 2000–2006 according to the REB catalog. The date of the Kaliningrad earthquakes is given.

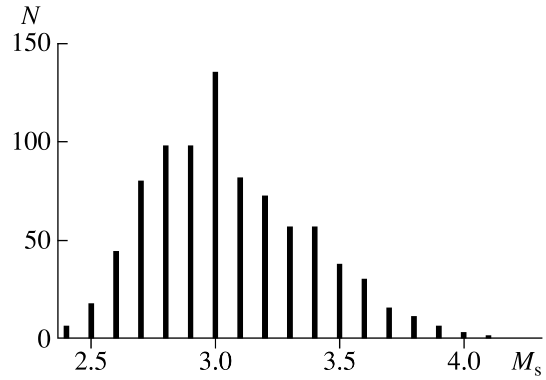

Fig. 4. The number of REB seismic events *N* of the southern band as a function of M_s.

from the general SE strike of geological structures. Circular theoretical isoseismals that we calculated for mean grounds are also shown in the figure. For hypocentral depths of about 15 km, seismic shakings in the region should have had an intensity of no more than 5. However, as noted above, the real seismic effect exceeded the predicted intensity by ~1 due to unfavorable ground conditions. A long duration of seismic effects (no less than nine perceptible shocks) also played a certain role.

We analyzed all of the REB seismic events in the range $2.3 < M \leq 4.9$ located in the southern Baltic Sea and in Poland (the southern cluster) in order to gain constraints on their possible use for assessing seismic hazard in the Kaliningrad region. Figure 3 plots the time succession of these seismic events. The enormous number of such events over a 7-yr interval is untypical of even highly seismic regions and is evidence for their predominantly anthropogenic origin. In all, 276 events of the catalog belong to the southern cluster (band), and four of them with respective magnitudes of 4.9, 4.5, 3.9, and 3.8 may be regarded as tectonic. The distribution of the remaining events of various origins over magnitude intervals of 0.1 is shown in Fig. 4. Events with $M < 3.0$ are obviously nonrepresentative, and those with $M = 3.0$ decrease rather naturally by an exponential law. The slope of their logarithmic recurrence plot is close to $b = -0.8$.

The hourly distribution of seismic events during a day over the period 2000–2007 is presented in Fig. 5, clearly displaying the predominance of their number in morning hours of a working day (they are marked by a rectangular contour). These events are most likely of anthropogenic origin. There is no doubt that such events are also present in other 1-h intervals. As noted above, it is of interest to inspect the spatiotemporal development of the entire flow of seismic events.

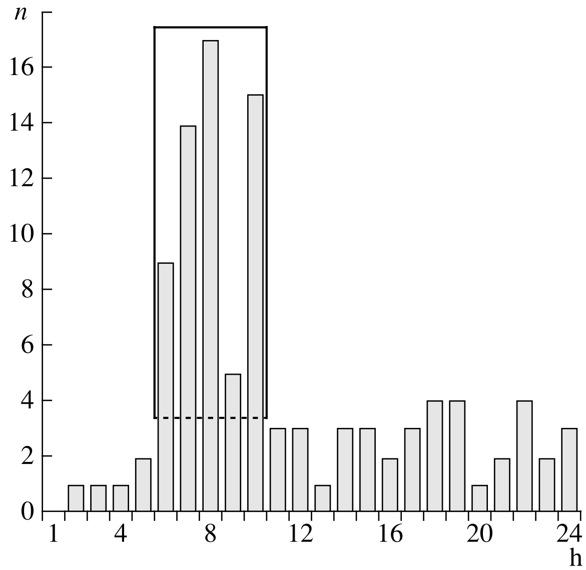

Fig. 5. Hourly distribution of the number of seismic events *n* within a day over the period 2000–2007. The rectangular contour encloses events of obviously nontectonic origin.

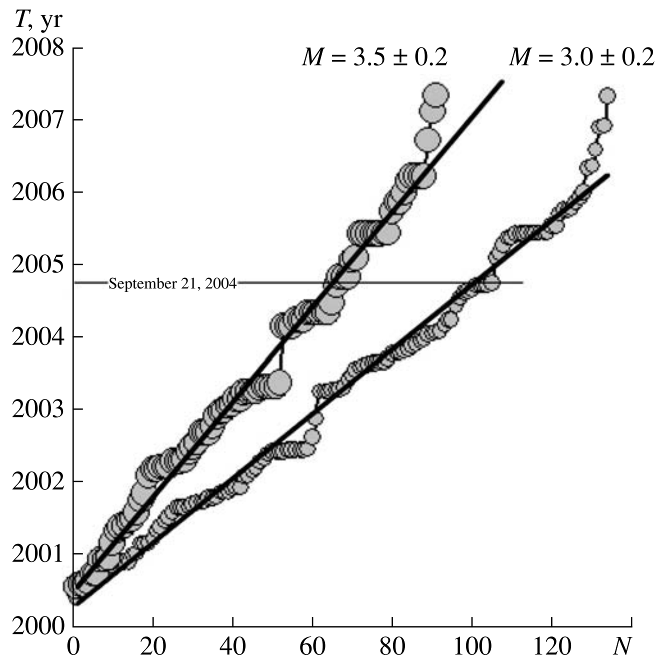

Fig. 6. Accumulation plots of REB seismic events within the southern band (Fig. 2b). *N* is the ordinal number in the succession of events with $M = 3.0 \pm 0.2$ and 3.5 ± 0.2. The date of the strongest Kaliningrad earthquake is shown.

Some Features of the Development of Seismogeodynamic Processes

Figure 6 presents accumulation plots for REB seismic events with the magnitudes $M = 3.0 \pm 0.2$ and 3.5 ± 0.2 within the southern band (Fig. 2b) during the period from 2000 to the middle of 2007. Each sequence can be linearly approximated with a fairly high correlation coefficient ($R^2 = 0.98$). Appreciable deviations of the event flow rate from the approximating lines are note-

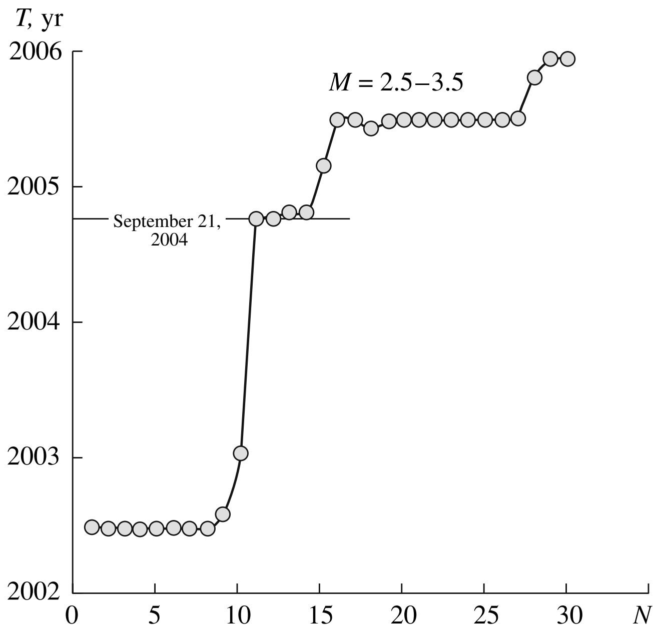

Fig. 7. Accumulation plot of seismic events in the magnitude range M = 2.5–3.5 within the southern band (Fig. 2b), with explosive sources being partially removed. The date of the strongest Kaliningrad earthquake is shown.

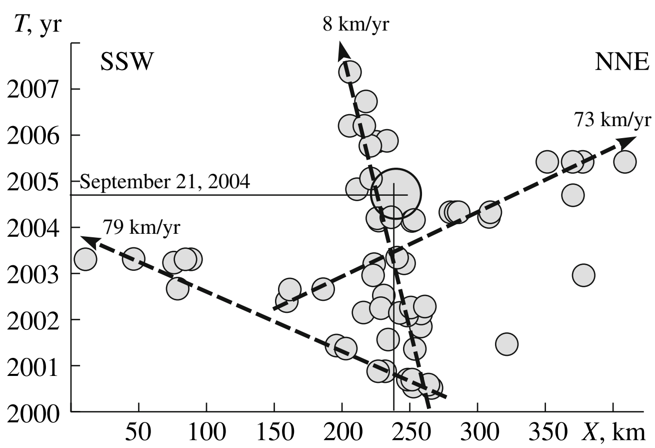

Fig. 8. Migration of REB seismic events within segment AB of the southern band (Fig. 2b) in the period 2000–2007. The dashed arrows with numbers show the migration direction and rate.

worthy. First of all, these are quiescence periods nearly one year long. It is seen that an abrupt drop in the occurrence rate of events with $M = 3.0 \pm 0.2$ took place in the middle of 2002. Beginning from the middle of 2003, events with $M = 3.5 \pm 0.2$ were completely absent for nearly one year. Both anomalies in the sequences of seismic events preceded the series of Kaliningrad earthquakes, the occurrence time of which is marked in Fig. 6 by a horizontal line. Another anomalous period of a significant drop in the event flow rate started at the beginning of 2006 for events with $M = 3.0 \pm 0.2$ and in spring of 2006 for $M = 3.5 \pm 0.2$. These quiescence periods remained uninterrupted until the end of 2007.

Figure 7 presents an analogous plot for 30 events in the magnitude range M = 2.5–3.5 that occurred from the middle of 2002 to the end of 2006. In this case, the supposed anthropogenic events of the morning time (Fig. 5) were removed from the catalog. As in the preceding case, quiescence abruptly started in the middle of 2002, but this time it lasted for nearly 2.5 yr, up to the series of Kaliningrad earthquakes of September 21, 2004, after which the quiescence still continued for about half a year.

Some features of migration of seismic sources within the southern band are also noticeable. Figure 8 illustrates the spatiotemporal distribution of seismic events that occurred within the upper part of the band (segment AB), which is nearest to the Kaliningrad region. The distance from the dashed line in Fig. 2b is plotted on the abscissa axis, and the occurrence time (years) of a seismic event is plotted on the ordinate axis.

Three epicenter migration branches are noticeable in the AB segment of the southern band. The main is the central branch, including the epicenter of the main Kaliningrad earthquake of September 21, 2004. The majority of events occurred along this branch, which is characterized by a relatively low migration rate (~8 km/yr). The migration rate along the other two branches is nearly an order of magnitude higher (79 and 73 km/yr). The branching took place near the epicentral area of the Kaliningrad earthquake a few years before its occurrence, after which events migrated in opposite directions, toward the south-southwest and north-northeast.

It is also possible that tectonic earthquakes in the western Kaliningrad region were initiated by numerous anthropogenic impacts (explosions, well operations, etc.), as was noted by Kovachev [2008] on the basis of the analysis of seismic data he obtained on the shelf of the Bay of Gdansk.

It is also appropriate to mention here another natural phenomenon observed by researchers of Kaliningrad State University (KSU) during a few years before the Kaliningrad earthquakes. Anomalous rises in the temperature of groundwater were recorded in some areas of the region. The last significant rise in the groundwater temperature (up to 50°C) was observed in wells at the end of December 2002 [Krivosheev, 2003]. This took place intermittently in different areas of the region. Only in 2002, three events of hot water inflows in deep wells accompanied by evaporation were revealed. For the first time, hot water was discovered in the well of the settlement of Lesnoe near the Kurshskaya Kosa national park, and in summer hot water was noted in a well in the Vishtynetskii Lake area. Both times, a high temperature of water persisted for two weeks, after which it dropped to the normal value over one day. It is likely that all these anomalous phenomena and concur-

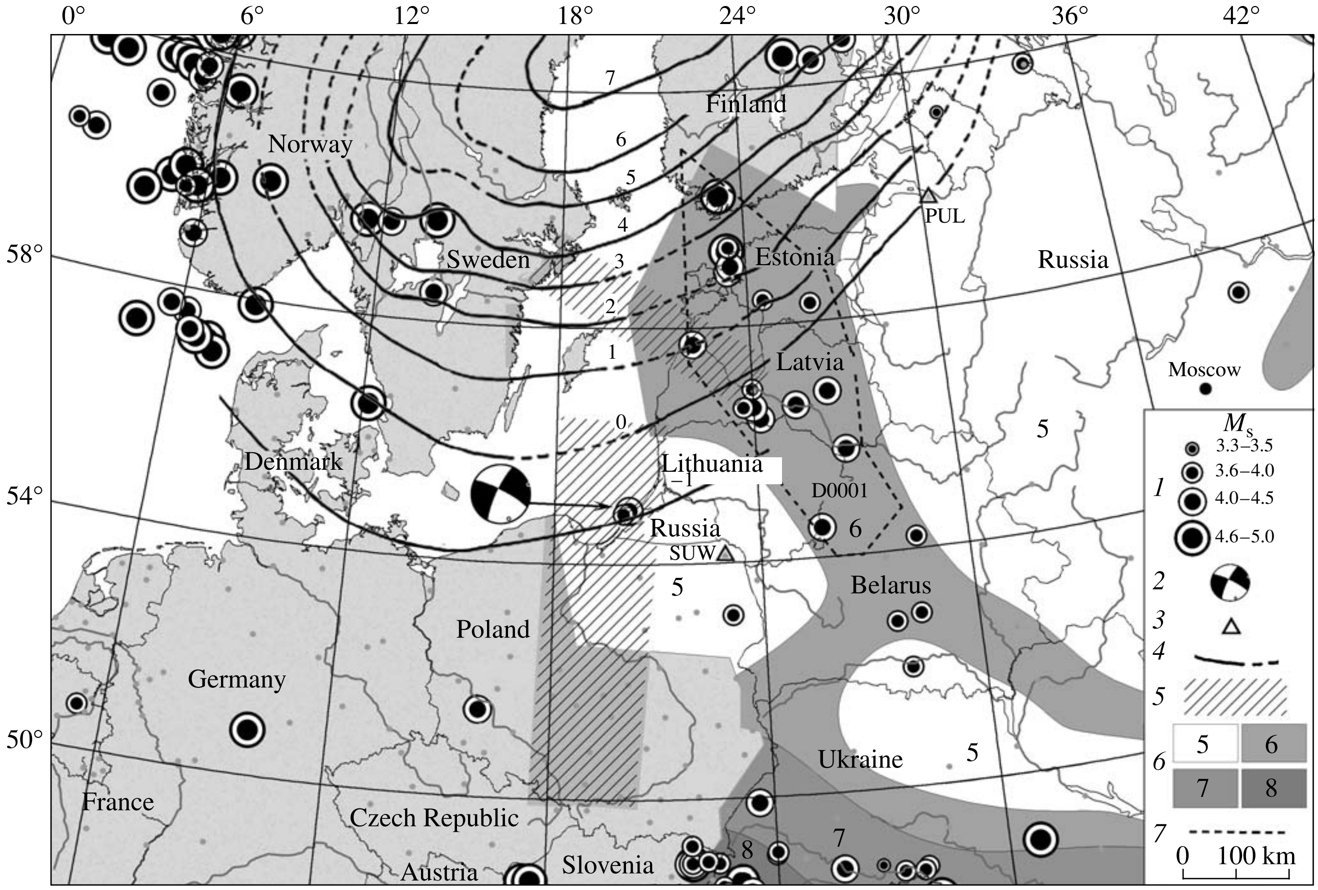

Fig. 9. Seismogeodynamics of the Baltic region: (*1*) earthquake epicenters from the SECNE specialized catalog complemented up to 2007; (*2*) focal mechanism of the earthquake of September 21, 2004 (13:32); (*3*) seismic stations SUW and PUL; (*4*) velocity contours (mm/yr) of recent postglacial crustal movements in Fennoscandia after [Ekman, 1996]; (*5*) bands of ordered quasi-linear distribution of REB epicenters; (*6*) seismic intensity zones of the OSR-97C map; (*7*) D0001 of the ESO model.

rent seismicity manifestations had the same deep geodynamic origin.

In this respect, we remind the reader that changes in the groundwater regime associated with earthquakes were noted long ago. In our country, the first seismohydrodynamic studies were conducted in the Caucasus in 1901–1902 by F. Moldengauer; systematically observing a hot spring in the Borzhomi area, he inferred that disturbances in the periodicity of the spring correlate with local seismic events. Later, seismohydrodynamic methods were applied to the study of the origin of the Tashkent 1966 (M = 5.2) earthquake [Ulomov and Mavashev, 1967]. A crustal deformation preceding this earthquake was revealed from the analysis of the radon concentration in thermomineral water of the Tashkent artesian reservoir. The radon method of the search for earthquake precursors immediately received wide recognition in many countries. Inspections of epicentral areas of other earthquakes revealed a relation between changes in the hot water temperature and head preceding and accompanying earthquakes. It was shown that this and other anomalous phenomena provide useful information on deep tectonic processes. On the other hand, water itself can promote earthquake occurrence (so-called induced seismicity).

The geophysicist V.V. Orlenok (the dean of the KSU Faculty of Geography and Geoecology) and his colleagues believe that local and near earthquakes can be precursors of water "boiling" in wells. Three recently observed wells were in a zone above deep-seated faults near which large oil deposits are known to exist, and a rise in temperature to 80°C was recorded in water of an oil-bearing bed at a depth of about 2000 m (the normal value at such a depth is ~20°C).

4. SEISMICITY AND ASSESSMENT OF SEISMIC HAZARD IN THE KALININGRAD REGION

It is known that seismicity of Fennoscandia is closely related to postglacial recent movements of the crust and the entire lithosphere in this region, whose peripheral parts are subsiding in the process of the isostatic adjustment of the general uplift that arose in the glaciation period. Thus, the Kaliningrad region is located within the Polish-Lithuanian syneclise, developing for a long time and still downwarping at a rate of ~1 mm/yr. The most recent tectonic movements involving some parts of the platform cover divided into blocks have resulted in their insignificant uplift against the general downwarping background. Such blocks include the Sambiiskii Peninsula, particularly its western part, facing the Baltic Sea, where the seismicity of 2004 was observed.

We compiled a seismogeodynamic map of the Baltic region (Fig. 9) characterizing seismicity from data of the specialized catalog of earthquakes used for creation of the OSR-97 maps and extended to 2007 by supplementing GS RAS data. Contours of recent postglacial vertical crustal movements of Fennoscandia are also shown in this figure on the basis of data reported in [Ekman, 1996]. Zones of the highest density of seismic event epicenters according to the REB catalog over the period 2000–2006 (Fig. 2b) are shown by oblique hatching. Different shades of gray depict a fragment of the OSR-97C map, which is the most "rigorous" of the set of normative maps and corresponds to an average recurrence interval of a seismic effect of 5000 yr and to a 1% probability that a given intensity will be exceeded during 50 yr. The polygon outlined by a broken line illustrates the D0001 domain, which is a structural element of the model of ESO zones that includes earthquake epicenters in the northwest EEP and was used for constructing the OSR-97 maps. The main parameters of the corresponding earthquakes are presented in Table 1.

Table 1. Main parameters of earthquakes in the D0001 domain

Year	Month	Day	Hour	Depth, km	M_s
1616	June	30	7	5	4.1
1670	Feb.	1	22	8	3.9
1821	Feb.	20	23	3	4.0
1821	Feb.	21	4	13	4.5
1827	Sept.	28	9	14	4.0
1857	May	18	11	10	4.5
1877	Oct.	16	5	10	4.2
1896	Sept.	20	15	5	3.5
1907	Jan.	22	23	7	3.5
1908	Dec.	28	22	10	4.5
1908	Dec.	29	19	10	4.5
1908	Dec.	30	2	10	4.5
1909	Jan.	31	7	6	3.5
1910	May	21	3	10	4.0
1934	Dec.	12	20	25	4.9
1976	Oct.	25	8	10	4.7
1976	Oct.	25	8	10	3.5
1976	Nov.	8	10	10	3.5
1987	Apr.	8	20	18	3.5

Quantitative Parameters of the Kaliningrad Earthquake Sources

The epicenter of the main earthquake, which occurred at 13:32 GT on September 21, 2004, in the offshore zone of the Kaliningrad region, is shown by an arrow in Fig. 9, where the stereographic projection of its focal mechanism onto the lower hemisphere (data of the Harvard center) is also depicted. The fault slip in the seismic source took place under the conditions of compressive stresses oriented SE–NW and tensile stresses oriented NE–SW. Both nodal planes are rather steep. According to Harvard data, the moment magnitude is $M_w = 4.7$.

Figure 10 illustrates instrumental records of the three strongest Kaliningrad earthquakes obtained at the Pulkovo (PUL) station (Russia) at an epicentral distance of 826 km. Ground accelerations in Pulkovo are seen to have reached 5 cm/s^2, which corresponds to a 2–3-intensity shaking felt in St. Petersburg. The station that recorded this earthquake at the smallest epicentral distance (234 km) was the Suwalki (SUW) station (Poland).

The main parameters of the three earthquakes of September 21, 2004, determined by the GS RAS and EMSC are presented in Table 2. Thus, the maximum magnitude M_s of the strongest Kaliningrad earthquake has a value of 4.3 and the seismic effect at the epicenter in the offshore area is I_0 = 6–7.

Model of Seismic Sources in the Kaliningrad Region

As noted above, the Kaliningrad region belongs to a 5-intensity zone of seismicity in all maps of the OSR-97 set. A zone characterized by an intensity of 6 and displayed in the OSR-97C map alone is at a distance of about 100 km to the east from the Kaliningrad region. This zone contains earthquake epicenters that are rather numerous for platform territories and form the D0001 domain in the OSR-97 maps, one of the 458 domains of the LDF model of ESO zones in Northern Eurasia.

Figure 11 depicts boundary contours of seismotectonically quasi-homogeneous zones (domains) of seismic sources whose seismogeodynamic parameters were used for quantifying seismic hazard in the OSR-97 maps of the territory considered and fragments of the world map of seismic hazard ["The Global ...," 1999; Grünthal et al., 1999]. The world map shows ground accelerations and estimates the expected seismic effect at a value of 0 to 20 cm/s^2 for a vast territory encompassing without any differentiation the entire Kaliningrad region and adjacent areas of Baltic countries. This estimate of the seismic effect corresponds to an MSK-64 intensity significantly smaller than 5.

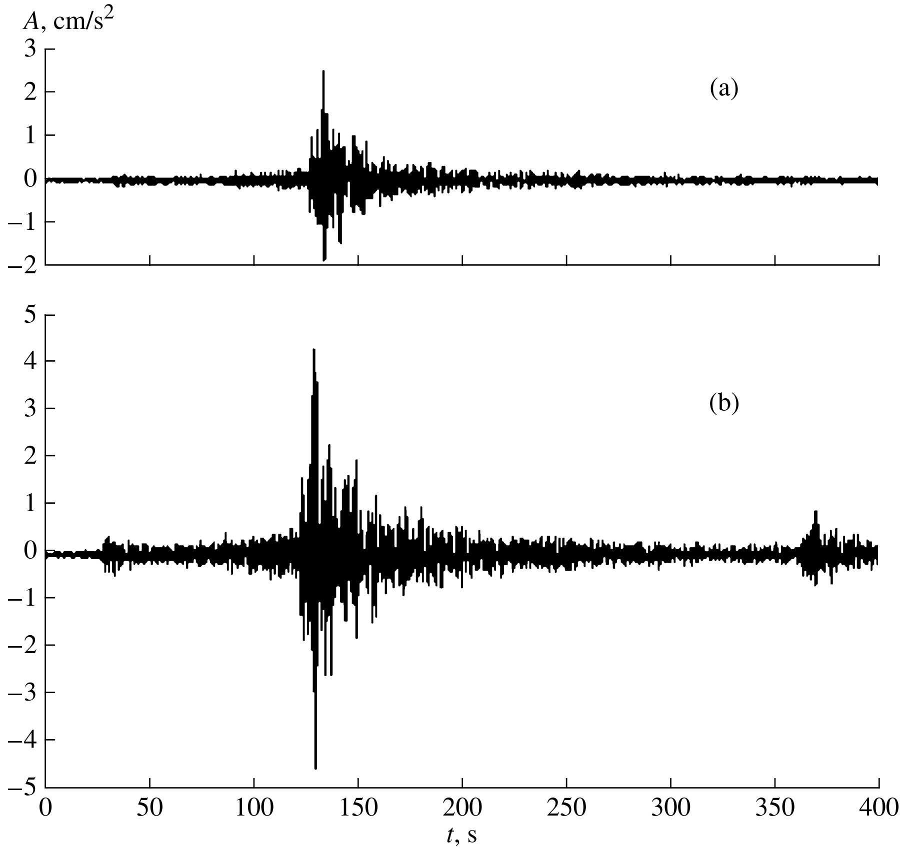

Fig. 10. Ground acceleration records obtained at the Pulkovo seismic station during three shocks of the Kaliningrad earthquake of September 21, 2004: (a) 11:05 ($M_s = 4.1$); (b) 13:32 ($M_s = 4.3$) and 13:36 ($M_s < 4.0$).

As seen from Fig. 11, the OSR-97 domains D0002, D0001, and D0015 are nearest to the Kaliningrad region, and their maximum magnitude and seismic regime parameters were mainly used for the assessment of seismic hazard in this region. However, because any evidence on local seismicity manifestations in the Kaliningrad region and adjacent areas was absent at the time of the OSR-97 investigations, the OSR-97 domains were bounded to the west by the 22°E meridian [Shebalin et al., 2000]. Although the nearest domain D0002 included only the eastern part of the Kaliningrad region, the seismic effect calculated for this and two other (D0001 and D0015) domains was extended to the entire territory of the region [Ulomov and Shumilina, 1999]; as noted above, this effect corresponds to an intensity of 5 and is distinguished by a very low probability (<1%) that this value will be exceeded during 50 yr.

After the occurrence of the Kaliningrad 2004 earthquake with $M_s = 4.3$ and the publication of the REB and EMSC catalogs providing information on weak seismic events, we performed the aforedescribed comprehensive analysis of the seismic setting in this region. As a

Table 2. Main parameters of the Kaliningrad earthquakes

Service	GT	Lat, N	Lon, E	H, km	M_s	M_b	I_0
GS RAS	11:05:05	54.84	20.13	21	4.1	4.9	4–5
	13:32:31	54.84	20.17	17	4.3	5.1	5–6
	13:36:24	54.87	19.99	1	3.0	–	3–3.5
EMSC	11:05:04	54.69	20.23	10	–	4.4	–
	13:32:29	54.77	19.94	10	–	5.0	–

Note: Lat and Lon are, respectively, latitude and longitude; H is the hypocentral depth; M_s and M_b are, respectively, the surface and body wave magnitudes; I_0 is the shaking intensity in the epicentral zone [Malovichko et al., 2007].

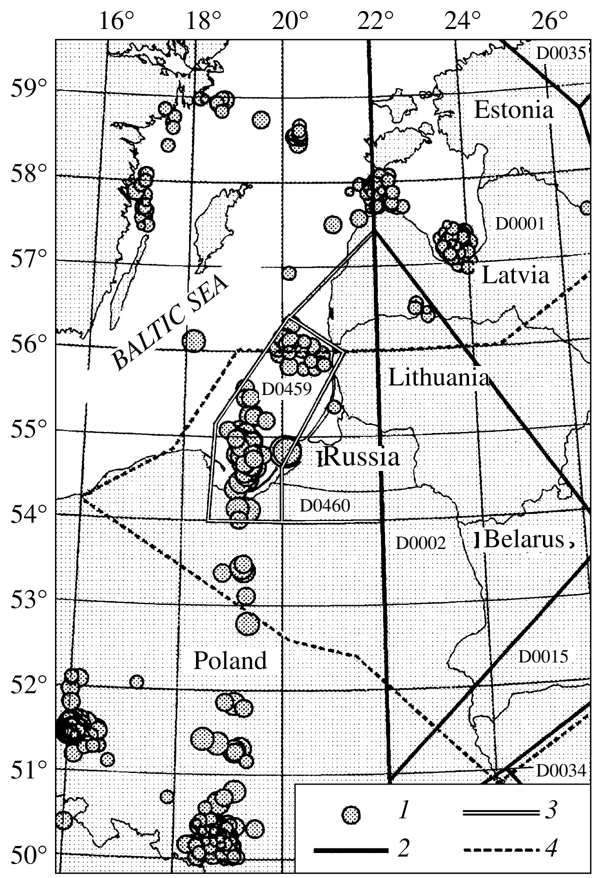

Fig. 11. Outlines of seismic domains in the Kaliningrad region: (*1*) earthquake epicenters after the REB catalog; (*2*) boundaries of the OSR-97 domains; (*3*) boundaries of domains added to account for the new catalog of earthquakes published in 2000; (*4*) boundary fragment of the zone of seismic sources used for mapping seismic hazard in the European–Mediterranean region after GSHAP data [Grünthal et al., 1999].

result, we complemented the main OSR-97 LDF model of ESO zones with the domains D0459 and D0460 shown in Fig. 11 and performed the cycle of calculations for the seismic zoning of the Kaliningrad region and adjacent territories. However, due to a low reliability of the aforementioned catalogs, dominated, as shown above, by anthropogenic events rather than tectonic earthquakes, the D0459 domain, including the epicenters of the Kaliningrad earthquakes of 2004, was parameterized on the basis of the seismic regime of the D0001 domain, lying to the east (Fig. 9) and most active in this part of the EEP. We accepted the value $M_s = 5.0$ as the maximum possible magnitude of a potential earthquake in the D0459 domain, which exceeds the magnitude of the strongest Kaliningrad earthquake of 2004 by a value of about 0.5.

Table 3. Seismic regime in the D0001 and D0459 domains

M_s	D0001 160000 km^2 $\log N = 1.796 - 0.8M_s$		D0459 25000 km^2 $\log N = 0.989 - 0.8M_s$	
	$V = 1/N$	$T = 1/V$	$V = 1/N$	$T = 1/V$
3.50	0.09901	10	0.01547	65
4.00	0.03942	25	0.00616	162
4.50	0.01569	64	0.00245	408
5.00	0.00625	160	0.00098	1024

Table 3 presents, for the magnitudes of the domains under consideration, values of the year-averaged rate of the seismic event flow V and the recurrence interval T (in years) for earthquakes of the D0459 domain calculated from the recurrence plot of such events in the D0001 domain with due regard for the relation between the areas of these domains, given in the upper part of the table. The area effect decreased the seismic event flow rate and increased the recurrence intervals in the D0459 domain by a factor of 6.4. The slope $b = -0.8$ of the earthquake recurrence equations shown in the table is typical of platform areas.

The D0460 domain, for which the seismic event flows of the adjacent domain D0002 are accepted with regard for the relative areas of the domains, was parameterized in a similar way.

Assessment of Seismic Hazard in the Kaliningrad Region with Regard for the Activation of 2004

Based on the ESO model complemented with the D0459 and D0460 domains, we calculated the seismic hazard effect for the territory of the Kaliningrad region. In accordance with the OSR-97 normative requirements, the results are represented in Fig. 12 in the form of OSR-97 maps (A, B, and C) with probabilities (risks) of 10, 5, and 1% that the mapped seismic intensity will be exceeded during a 50-yr interval. As distinct from the typical normative OSR-97 maps, with an isoseismal step of 0.5, the isoseismals in these maps are drawn at a step of 0.2.

As seen from the OSR-97A map, the majority of the territory of the Kaliningrad region lies in the zone of weak seismicity (an intensity of no more than 3) and a 4-intensity zone is located only to the west of the isoseismal between the settlements of Svetlogorsk and Ladushkin. The narrow 5-intensity zone in the OSR-97B map includes only coastal towns (Yantarnyi, Primorsk, and others). Finally, in the OSR-97C map, the model seismic intensity exceeded a value of 5.5 in the westernmost part of the Kaliningrad region, and this gave rise here to a 6-intensity zone. Its eastern boundary lies between the following pairs of settlements: Svetlogorsk–Yantarnyi, Svetlyi–Primorsk, and

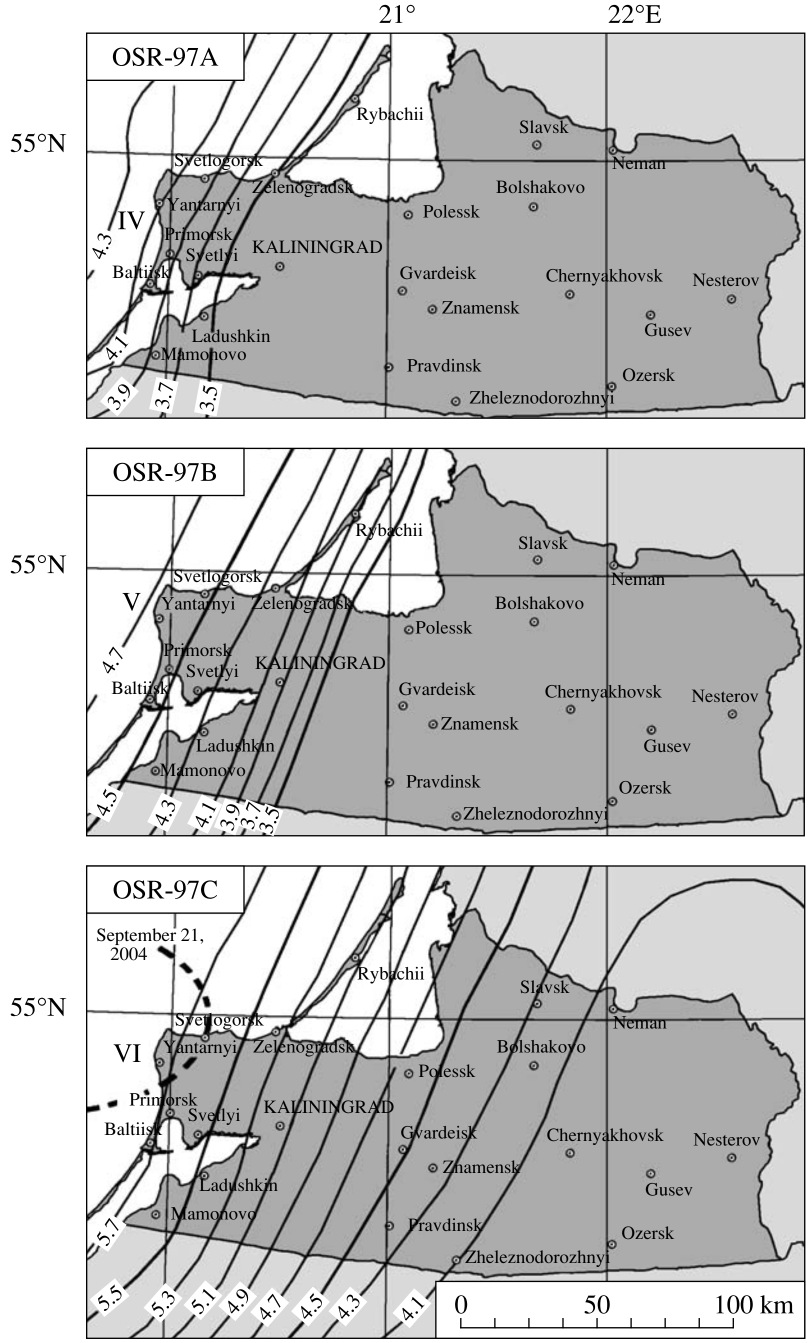

Fig. 12. Results of calculating the probable seismic effect in the Kaliningrad region using parameters of the additional domains D0459 and D0460 of the ESO model. As distinct from the typical normative OSR-97 maps, isoseismals are plotted at a step of 0.2. The thick dashed line is the eastern boundary of the 6-intensity territory after [Assinovskaya and Ovsov, 2008].

Ladushkin–Mamonovo. The thick dashed line in the same map shows the boundary of the 6-intensity shaking effect due to the Kaliningrad 2004 earthquake according to [Assinovskaya and Ovsov, 2008]. Naturally, it encompasses a smaller area as compared with the prognostic zone because it is associated with an $M_s = 4.3$ earthquake, whereas our calculations were performed for a maximum possible magnitude of $M_{max} = 5.0$.

5. DISCUSSION

The seismic activation in the second half of September and in October 2004 was noticeable not only in the Kaliningrad region but also in Poland and northern Germany, indicating a large scale of regional geodynamic processes active in this period. The Kaliningrad earthquake with $M_s = 4.3$ was the strongest event of this series. In spite of the moderate magnitude, perceptible shakings covered an unusually large area in the Baltic region and, propagating into adjoining Lithuania, Belarus, Latvia, Estonia, and Poland, reached southwestern Finland, southern Sweden, and eastern Denmark.

It is interesting to note that the year 2004 was very active with respect to global seismic manifestations. One of the largest earthquakes of the world ($M = 9.0$) occurred in December near Sumatra and the Andaman Islands. It is noteworthy that seismic events with magnitudes $M = 8.5 \pm 0.2$ or more were completely absent for nearly 40 yr and beginning from 2001 started to occur in various regions of the world almost every year; moreover, our studies of global seismogeodynamic and hydrogeodynamic processes revealed synchronism in variations of the Earth's seismic regime and ocean water level [Ulomov, 2007a, 2007b]. The earthquake of October 27, 2004, in the Vrancea zone, Eastern Carpathians, was the largest in Europe over the last 14 years; it had a moment magnitude of $M_w = 5.9$ and its source was located at a depth of about 100 km. The earthquake was felt at great distances from its epicenter.

Returning to the problem of assessment of seismic hazard in the Kaliningrad region, we remind the reader that, in all official OSR-97 maps (A, B, and C) the entire territory of the region belongs to a 5-intensity zone. These estimates are consistent with all values presented in Fig. 12 and obtained by calculations taking into account the Kaliningrad earthquakes of 2004; the only exception is the western part of the region, which was virtually unexplored until 2004. Therefore, we estimated the potential seismicity of the Kaliningrad region for the normative OSR-97 maps by extrapolating the seismic effect expected in the east, on the territory of Lithuania, Latvia, and Estonia, and characterized by a fairly large number of epicenters of earthquakes with magnitudes in the range $3.5 \le M_s \le 4.9$ united into the D0001 domain in the OSR-97 model of ESO zones (Table 1, Fig. 9).

Since the EMSC and REB catalogs contain no information on the identification of seismic events, they were found unsuitable for the estimation of seismic regime parameters in the D0459 domain, including the epicenters of the Kaliningrad earthquakes of 2004; for this reason, to parameterize the D0459 domain, we used D0001, which is the most active domain closest to the Kaliningrad region. Nineteen epicenters of earthquakes are located in its area of 160 000 km^2, approximately one epicenter per 8000 km^2. The same surface density characterizes the three Kaliningrad earthquakes in the same magnitude range because the area of the D0459 domain is ~25 000 km^2.

Another important factor is that the seismic effect in less dense water-saturated unstable grounds, classified as grounds of the third category according to their seismic properties, can exceed by unity or more the normative intensities indicated in the OSR-97 maps and related to mean ground conditions (grounds of the second category according to the SNiP II-7-81* code).

As is known from practice, a longer duration of ground motions can enhance the seismic effect even in the case of moderate magnitudes of earthquakes and insignificant values of ground accelerations. It is possible that this phenomenon can account for the very large territory covered by perceptible vibrations from the 2004 swarm of Kaliningrad earthquakes. For example, during the strong ($M = 7.4$) earthquake of March 3, 1977, the real seismic effect in Moscow was quantified by an intensity of 4 or more (6–7 on upper floors of buildings) due to prolonged low-frequency vibrations whose accelerations in Moscow, at an epicentral distance of about 1400 km, did not exceed 2 cm/s^2 in the frequency range 0.3–1.0 Hz (such an acceleration corresponds to an MSK-64 intensity of 1–2). Moscow ground motions from the Vrancea earthquake of 2004 lasted for 200–300 s, which was one order longer than the duration of the source process (20–30 s) [Ulomov, 2008].

6. MAIN CONCLUSIONS

The earthquake that occurred at 13:32 on September 21, 2004, in the Kaliningrad region had a magnitude ($M_s = 4.3$) consistent with the OSR-97 concept, according to which rarely recurring weak and moderate seismic events can occur almost ubiquitously. Therefore, 5-intensity OSR-97 zones even in platform regions should be regarded as seismic although not as seismically hazardous from the practical standpoint (antiseismic measures in civil engineering are taken beginning from a seismic intensity of 7).

Since the OSR-97 map estimates of the expected seismic effect refer to mean ground conditions, detailed geological-engineering and seismic microzoning investigations must be conducted in all inhabited areas and at construction sites of particularly significant objects. For example, investigations refining the seismic hazard are carried out in designing high buildings and structures on the territory of Moscow, which, like the Kaliningrad region, is located in a 5-intensity zone of the OSR-97 maps.

We should also note that seismic hazard estimates corresponding to the most "stringent," OSR-97C map, with a very long recurrence interval of seismic impacts (once per 5000 yr), are actually close to deterministic estimates calculated for individual scenario earthquakes regardless of their recurrence frequency [Ulomov, 2005, 2006]. Therefore, the observed 6-intensity isoseismal in the west of the Kaliningrad region agrees fairly well with the value that we calculated in accordance with the normative requirements of the OSR-97C map. The larger area of the calculated 6-intensity zone is due to the higher magnitude ($M_s = 5.0$) taken as a maximum value for the D0459 domain, where earthquakes of such magnitudes have not been observed as yet.

It is possible that the new probabilistic estimates of seismic hazard obtained in this work are overestimated and they cannot be considered at present as normative values. Seismological, seismotectonic, and seismogeodynamic investigations need to be continued in the Kaliningrad region, whose seismic characteristics are poorly studied, and seismic microzoning of inhabited localities and industrial centers of the region is required. Geodynamic monitoring should be conducted in areas, subject to intense anthropogenic impacts.

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