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Seismotectonic Position of the Kaliningrad September 21, 2004, Earthquake

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Abstract—The paper presents an alternative consistent seismotectonic model of the Kaliningrad (Russia) September 21, 2004, earthquake according to which source zones of the two strongest shocks were confined to a N–S fault off the Sambiiskii Peninsula in the Kaliningrad region. A left-lateral deformation fractured a local crustal zone between the town of Yantarnyi and the settlement of Bakalino. The model was constructed with the use of a method developed by the authors for structural analysis of gravity and magnetic data. Initial materials are revised in terms of the EMS-98 macroseismic scale, and modified maps showing the shaking intensity in the NW part of the Sambiiskii Peninsula are compiled.

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INTRODUCTION

The Kaliningrad September 21, 2004, earthquake with $M_w \sim 5$ directly corroborated the ideas underlying modern seismic zoning [Ulomov, 1999] and pointing to the possibility of ubiquitous occurrence of weak and even moderate earthquakes with a low recurrence frequency.

Some researchers identified prognostic zones of probable sources of earthquakes as strong as $M_{\max} \sim 6.0$ in the Kaliningrad region [Garetskii et al., 1997; Reisner and Rogozhin, 2005]. Some sources are confined to the Pregolskii fault zone or to a NW trending fault in the Zelenogradsk area. No potential seismogenic zones have been discovered in the adjacent water area of the Baltic Sea.

Together with the Oslo graben (1904) and Osmussaar (1976) earthquakes, the Kaliningrad earthquake was the strongest in the Baltic region over the past century. However, unlike southern areas of Norway and Sweden and western Estonia, even very weak earthquakes have not been noted in the last century in the Kaliningrad region.

The earthquake of September 21, 2004, consisted of a series of shocks; however, for technical reasons, seismic stations recorded only three of them, and the first two of these three shocks were the strongest and occurred at 11:05 ($M_w = 5.0$, $m_b = 4.7$, $M_L = 4.8$) and 13:32 GMT ($M_w = 5.2$, $m_b = 4.8$, $M_L = 5.0$). These events have been studied as comprehensively as possible, but no researchers could obtain consistent results as regards both the location of the shocks and the determination of the seismotectonic position of the source zone. In their exhaustive study analyzing seismic records obtained at regional distances and generalizing all (in particular teleseismic) data available for the localization of the events, Gregersen et al. [2007] placed the epicenters of the two strongest shocks at the center of the Sambiiskii Peninsula. Their sources were fixed at a depth of 10 km. In some other publications, the source depth is estimated at 6–8 km [*International* ..., 2001; Assinovskaya and Karpinsky, 2005]. Gregersen et al. [2007] also described the focal mechanisms of the two earthquakes determined from the centroid moment tensor. The focal mechanism parameters were found to be absolutely identical and indicate strike-slip motions with a minor normal component in the sources on two possible fault planes trending E–W and N–S. The plane parallel to the Teisseyre-Tornquist zone, the junction zone of the Archean–Proterozoic East European and Phanerozoic West European platforms, was chosen as the main one. A more detailed seismotectonic position of the sources was not established. Moreover, Gregersen et al. [2007] presented results of processing of numerous macroseismic materials gathered at regional distances in the Baltic countries, Poland, Sweden, Denmark, Norway, Russia, and others; these results allowed the authors cited to construct macroseismic maps of the events, rather clearly displaying boundaries of zones of EMS-98 intensities of 3, 4, and 5 oriented NW–SE. In the Kaliningrad region proper, macroseismic manifestations have been studied only in the west of the region, on the Kurshskaya spit, and on the southern coast of the Kurshskii Bay [Nikonov et al., 2005; Aptikaev et al., 2005]. Maps of shaking intensity in the epicentral zone were constructed with the use of the MSK-64 scale. According to these data, the epicentral zone of the first shock is located in the northwest of

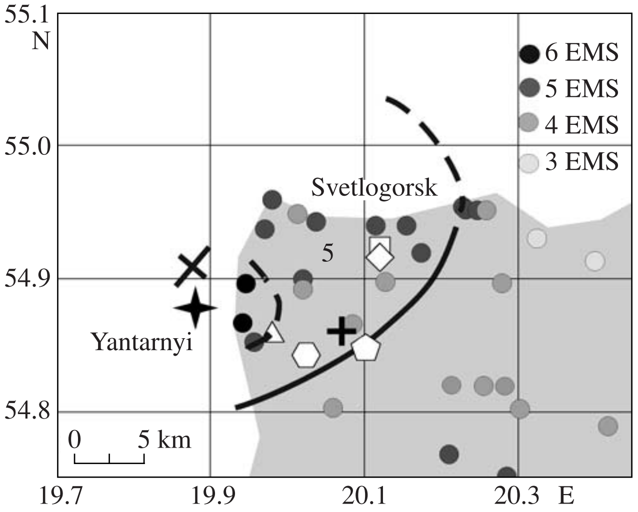

Fig. 1. Fragment of the shaking intensity map (the EMS-98 scale) for the first two shocks of the Kaliningrad earthquake. The macroseismic epicenter [Nikonov, 2005] is shown by a black diagonal cross; the instrumental epicenters are EMSC (white diamond), MOS (white hexagon), POL (white square), NEIS (white triangle), ISC_AKI (white pentagon), ISC_DB (straight cross), and our solution (black star).

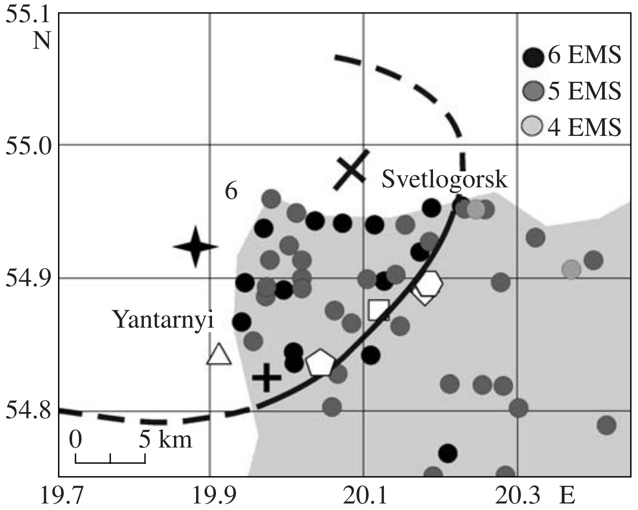

Fig. 2. The same as in Fig. 1.

the Sambiiskii Peninsula, with 5- and 5.5-intensity shakings being felt throughout the area, while 6-intensity manifestations were almost confined to the Yantarnyi area. For the second shock, the MSK-64 intensity in the northwest of the peninsula was estimated at 5.5 and 6.

According to [Nikonov et al., 2006], the macroseismic epicenter of the first shock was located in the west of the region, in the Bay of Gdansk near the town of Yantarnyi, and the macroseismic source of the second event formed near the northern shore of the Sambiiskii Peninsula, in the area of the settlement of Primorskii and the town of Pionerskii. The sources were determined to be 20 km deep. The first earthquake was related to a N–S fault located in the sea west of the peninsula, whereas the second event, following 2.5 h after the first, was attributed to an absolutely different fault trending E–W off the northern shore of the Sambiiskii Peninsula. Accordingly, different focal mechanisms were proposed for these shocks. In this case, the distance between their epicenters was estimated at ~20 km.

Thus, the lateral positions of the Kaliningrad earthquake sources as determined from instrumental and macroseismic data significantly diverge, which is unusual in the present epoch of intense development of instrumental observations (Figs. 1, 2). Contradictions are also evident in the determination of the seismotectonic position of source zones: the model constructed from macroseismic data is inconsistent with fault plane solutions for both shocks. We do not object to the position of the first source proposed in [Nikonov, 2006], particularly because it is corroborated by macroseismic manifestations in the Bay of Gdansk [Nikonov, 2005]; however, we believe that, since the sources had identical mechanisms, they should be confined to the same tectonic fault, probably striking NE–SW. Activation of precisely this strike-slip fault could have arisen due to its adequate position in the regional stress field with compressive stresses directed NW–SE. The sources of all earthquakes are associated with this fault, and the source of the second, strongest shock lay to the north of the first and was confined to its intersection with the blocking E–W fault bounding the Northern Sambiiskii block to the north. This will be substantiated by an additional analysis of the macroseismic field of the Kaliningrad earthquake and by use of available tectonic constraints from the epicentral area for the construction of an alternative model of the possible seismotectonic position of the source zones.

MACROSEISMIC FIELD

Figures 1 and 2 present fragments of macroseismic maps of the two main shocks of the Kaliningrad earthquake constructed using the EMS-98 scale [Grünthal, 1998]. All available data of observations were preliminarily reprocessed in accordance with the formal requirements of the scale and their statistical analysis was performed in order to eliminate partial, compound (double and triple), and approximate (unreliable) intensity estimates. As is known, only whole number intensities are admitted in the EMS-98 scale. Shaking intensity values in this approach seem to be less liable to the subjective factor.

As seen from Fig. 1, the first event is distinguished by the incompleteness of the 6-intensity isoseismal noted in [Nikonov, 2006] and the NE strike of the 5-intensity zone located in the northwesternmost part of the Sambiiskii Peninsula and farther in the sea. The land area of this zone is ~250 km^2. The zone of a maximum intensity of 6 was located mostly in the sea, and, therefore, the earthquake source lay to the west of the settlement of Yantarnyi.

In our new reconstructions, the second shock zone of an intensity of 6 locally fluctuating in some parts of the western and northern Baltic Sea coast and attenuating in the center strikes in the same direction as the 5-intensity zone of the first earthquake; i.e., the orientation of the epicentral zone is north-northeastern, orthogonal to the aforementioned general NW strike of the macroseismic field. The area of the zone is supposedly 750 km^2, ≈250 km^2 of which account for the land. The perceptibility ellipse is 35×27 km (in agreement with the usual ratio of 3/4), and its average radius is ~16 km. These reconstructions are quite consistent with the position of the second event a few kilometers north from the first.

The position of the sources in the Bay of Gdansk is additionally supported by previously unknown reports of seamen who were the first to inform local authorities about the earthquake [http://www.regnum.ru/news/328785.html]. We do not know where precisely they were, but it is likely that they were closer to the source of shaking than other eyewitnesses of the events. Moreover, an unusual phenomenon was observed on the coast: about 1 km from the shore, local inhabitants saw a funnel resembling a tornado [http://www.regnum.ru/news/331632.htm].

It is also noteworthy that, according to people living on coastal streets of the town of Yantarnyi (the western coast of the Sambiiskii Peninsula), both shocks were very hard, essentially horizontal, and directed from the seaside. It is sufficient to say that window panes facing the sea were instantaneously forced inward during both shocks. Changes in seawater and the sea bottom that took place near Yantarnyi during and after the events are described in detail in [Nikonov, 2005].

The intensity increase on the northern coast of the Sambiiskii Peninsula, where the second source is located according to [Nikonov, 2006], is accounted for in our approach by the propagation of shakings solely in the E–W direction along the strike of faults (Fig. 4). Moreover, the northern coast is distinguished by very complex inhomogeneous geological-engineering conditions: numerous aquifers, eolian deposits (e.g., moving sand dunes on the Gvardeiskii Cape in the Pionerskii area), and loose sands (e.g., in the Chistaya and Svetlogorka river valleys) ubiquitously alternate with denser siltstones, loams, and moraine deposits [*Geographic* …, 2002]. The presence of dense/loose sediment contacts at bases of buildings caused the wrenching effects described in [Aptikaev et al., 2005] (personal communication of M.A. Klyachko) that took place during the Kaliningrad earthquake.

For comparison, Figs. 1 and 2 also present results of the location of earthquakes by instrumental methods. Of all available determinations of the main parameters of the two Kaliningrad shocks by regional networks at epicentral distances of 230–1500 km, we chose the most reliable determinations, reported in [Wiejacz and Debski, 2005] and [Gabsatarova et al., 2005] and obtained by the European Mediterranean Seismological Centre [http://www.emsc-csem.org]. These solutions are in general mutually consistent: in all cases, the epicenters of both shocks are located in the NW part of the Sambiiskii Peninsula close to each other; however, it is remarkable that they are beyond or near the SE boundary of the zone of maximum shakings. Teleseismically located sources deviate significantly from epicenters determined at closer stations.

According to data of the National Earthquake Information Center (NEIC) [http://earthquake.usgs.gov/regional/neic/], the epicenters of both shocks lay south of the town of Yantarnyi, i.e., at the southern termination of the maximum shakings zone. The International Seismological Centre (ISC) sources [http://www.isc.ac.uk], 10 km apart, lie to the east and south of the shaking areas. The redetermination of source parameters based on the AK-135, rather than Jeffreys–Bullen, velocity model and performed in the framework of modernization of the ISC localization technique [http://www.isc.ac.uk/doc/analysis/2005p01/jb-ak_explanation.html] did not change significantly the position of the Kaliningrad earthquake sources (Figs. 1, 2). Thus, the divergence between source positions determined by different methods is evident. This fact can be naturally attributed to uncertainties in the instrumental localization due to the absence of seismic stations close to the epicenter and, accordingly, records of direct waves. Contrasting regional heterogeneities present in the crust prevent reliable determinations from refractions at distances of 200–1500 km. Very complex geological-engineering conditions locally increase the shaking intensity by an EMS-98 value of up to 2, thereby introducing a considerable uncertainty into macroseismic solutions.

In connection with the aforesaid, it is of interest to elucidate the agreement between data of macroseismic and instrumental localization (by different methods) of weak and moderate earthquakes in countries well provided with seismological observations.

COMPARATIVE ANALYSIS OF MACROSEISMIC AND INSTRUMENTAL DATA ON EARTHQUAKES WITH $M_w \sim 5$ IN OTHER SEISMICALLY ACTIVE REGIONS

Using the Internet's potential, we compared macroseismic, local instrumental, and teleseismic ISC and NEIC data on some earthquakes in Eurasia and North America. Ten events of the last decades comparable in magnitude (an M_w and M_L range of 4.5–5) with the Kaliningrad earthquake were selected. They occurred in Switzerland, the United States, and Great Britain. Dense local networks of instrumental seismic observations are functioning in these regions, and macroseis-

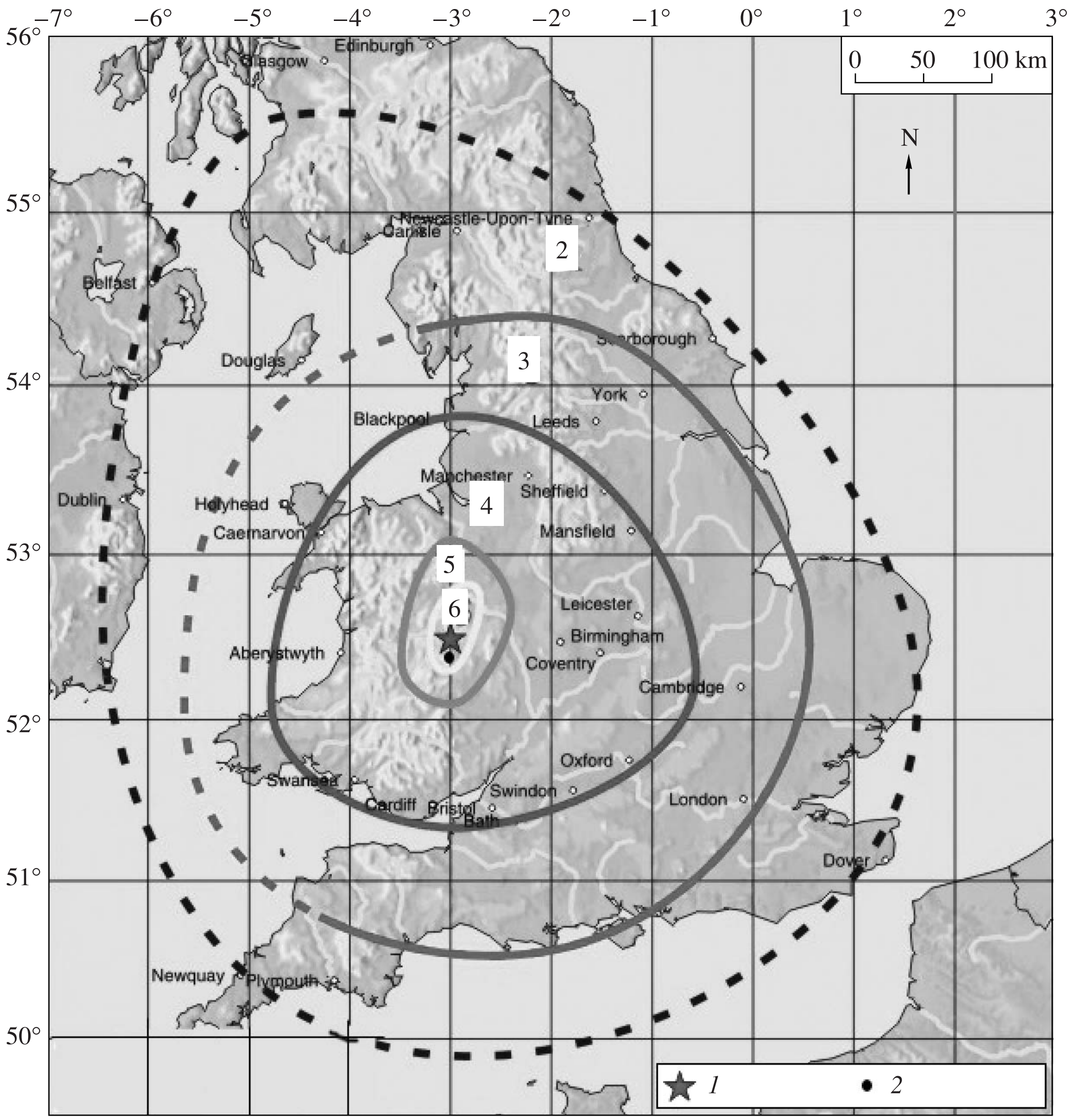

Fig. 3. Isoseismals of the Bishops Castle (Great Britain) earthquake of April 2, 1990 (13:46:43.2 UTC), with $M_L = 5.1$ and $H = 14$ km [http://www.earthquakes.bgs.ac.uk/macroseismics/bishopscastle_macro.htm]. The star is the instrumental epicenter according to data of the national network stations. The epicenter is seen to lie almost at the center of the 6-intensity isoseismal, whereas the teleseismic epicenter (black dot) is at a distance of ~10 km to the south. The ISC and NEIC locations virtually coincide in this case.

mic data are being constantly gathered (in particular, in a real-time mode via the Internet). It was found that, for example, three Swiss earthquakes of 1991–1996 with $M_w = 4.3$–4.6 and $H = 2$–12 km are localized with an error of ±5 km, and their instrumental (local network) epicenters were invariably located within maximum intensity zones, sometimes deviating from their centers [http://www.seismo.ethz.ch]. For the first two events, the ISC and NEIC determinations agree with solutions from local network data, while the divergence in the third case amounted to 12–13 km. The average isoseismal radius of an intensity of 6 (maximal in two cases) was 13–20 km.

In the case of four British earthquakes of 1979–2002 with $M_L = 4.7$–5.4 and source depths of 7–14 km, source positions instrumentally located from data of near stations are also within zones of maximum intensity, but teleseismic positions of the sources are shifted relative to macroseismic and local data by 10–16 km [http://www.earthquakes.bgs.ac.uk/macroseismics]. The earthquakes induced mainly shakings of intensities of 5–6 at epicenters; the mean radius of the 6-intensity zone is 16–25 km.

In the eastern United States, the instrumental NEIC epicenters of three earthquakes of 1996–2004 with magnitudes $M_w = 4.2$–4.6 and source depths of 5–18 km also lie mainly within zones of maximum intensity but are shifted relative to their centers [http://earthquake.usgs.gov/eqcenter/eqarchives/poster/]. The determination uncertainties lie within a range of 5–17 km. As an illustrative example, Fig. 3 presents a shaking intensity map for the Bishops Castle (Great Britain) earthquake of 1990.

Thus, the data analyzed above confirm the generally known fact that, given adequately configured local networks, macroseismic and instrumental parameters of weak and moderate earthquakes coincide within statistical errors of their determination. The errors of determinations from teleseismic data are systematic due to uncertainties of location methods and velocity models in use. However, NEIC and ISC epicenters lie within isoseismals of a maximum intensity for almost all of the earthquakes considered.

The above analysis of world data, first, raises doubts concerning the validity of the Kaliningrad earthquake localization by regional stations and, second, points once more to the inappropriateness of averaging regional and teleseismic determinations because in all cases the latter contain a significant systematic error.

TECTONICS

The determination of the tectonic position of the earthquake is a fairly complex and ambiguous problem because of inadequate and biased geological information about the region, studied solely in the framework of oil and gas exploration tasks. Only very general ideas exist about the structure of the crust as a whole in the NW Sambiiskii area. The nearest profile of deep seismic sounding lies at a distance of 80 km to the south of the epicentral zone and crosses the Kaliningrad region in the SW direction [Chekunov et al., 1993]. According to this model, the Moho in the south of the Kaliningrad region has a depth of 46 km and a velocity of V_p = 8.1–8.2 km/s; an intermediate reflector with V_p = 7.1–7.2 km/s has been recognized at shallower depths. The upper crust is 14–15 km thick, and the average velocity in the crust is 6.3 km/s. According to data of the NW segment of the EUROBRIDGE Lithuanian profile [EUROBRIDGE'95 Seismic Working Group et al., 2001], which are most significant for our study, a waveguide with a velocity drop from 6.3 to 6.15 km/s is identified at depths of 10–12 km. The waveguide, which is a subhorizontal fractured zone filled with mineralized solutions, is believed to have played a key role in the recent geodynamics of the Fennoscandian region and surrounding areas [*Deep Structure* …, 2004].

As regards its tectonic position, the Kaliningrad region is at the margin of the East European platform within the SE part of the Western Lithuanian granulitic massif between the Teisseyre-Tornquist suture zone and the Neman system of active faults [Bogdanova et al., 1994]. The NW orientation of the two aforementioned fault systems defined the regional pattern of the macroseismic field. It is established that the Archean–Proterozoic basement of the Kaliningrad block and the adjacent Gdansk trough is not homogeneous in the composition and age of its composing rocks [Zagorodnykh et al., 2001]. According to deep drilling data, the Rybachii–Pravdinsk N–S line separates the Archean basement rock complexes into western and eastern zones differing in metamorphism grade and composition. Intrusive rocks of the Lower Proterozoic form plagiogranite, granite, and gabbroid complexes composing ring structures in the northwesternmost part of the block. Karelian gabbroid intrusions cut rocks of the Archean Ashvaskii gneiss–schist complex, fixed in the south of the structure. Within the Gdansk trough, Lower Riphean intrusions of rapakivi (?) granites cut granite gneisses of the Lower Proterozoic Balnikanskii complex. The basement is overlain by a sedimentary cover thickening westward from 2.5 to 3 km.

The basement structure of the NW part of the Kaliningrad (Sambiiskii) block on land and its westward continuation into the sea is a system of E–W trending sunken and uplifted blocks broken by faults of NW and N–S strikes. The northern Sambiiskii block is most uplifted [*Tectonic* …, 2003; Zagorodnykh et al., 2001]. A few kilometers off the shore, researchers have distinguished a N–S fault zone marking the contact of Archean and Proterozoic basement blocks (Fig. 4). The NW part of the Sambiiskii block is bounded to the east (on land) by the Pionerskii-Grachevka fault, penetrating into the sedimentary cover [*Tectonic* …, 2003]. Several fractures trending E–W, N–S, and NW have been identified to the east of this fault (in the Taran Cape area) by P. Suveizdis [*Tectonic* …, 2003].

According to magnetic data [Banka et al., 2002] and tectonic reconstructions [*Tectonic* …, 2003], the tectonic structure of the northern offshore Sambiiskii zone is much simpler.

NEOTECTONICS

At the present time, the vast bulk of evidence points to recent tectonic activity in the Kaliningrad region. However, concrete data on active faults and their main parameters (morphology, fault motion amplitudes and velocities, and so on) are still unavailable.

The region under study includes a vast uplift of the surface of pre-Quaternary (Paleogene and Upper Cretaceous) deposits with an amplitude of 20–40 m and local subsidences of this surface below the sea level (Fig. 4) [Blazhchizhin, 1974; Dodonov, 1971; Orlenok, 2001; *Geographic* …, 2002]. The uplift of the surface of pre-Quaternary rocks is deformed, particularly at flanks, by numerous fractures, so-called paleoincisions, reaching elevations of –150 m below the sea level (Fig. 4) [*Buried* …, 1976]. Valleys of Quaternary age strike mainly N–S and E–W and vary in width and length; they have been discovered both on land (the settlement of Pri-

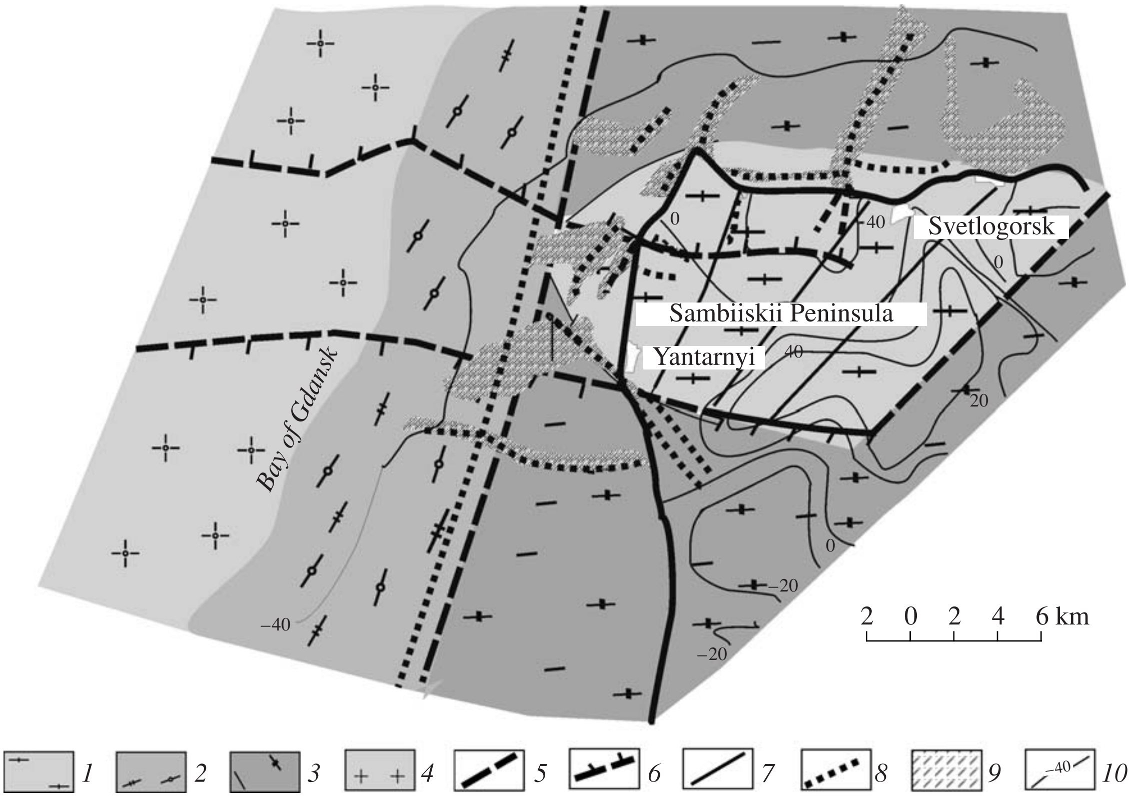

Fig. 4. Tectonic scheme of the NW part of the Sambiiskii Peninsula and offshore zone according to [*Tectonic Map* …, 2003; Blazhchizhin, 1974; *Geographic* …, 2006; Orlenok, 2001; personal communication of V. Zagorodnykh, A. Dovbnya, and V. Zhamoida]: (*1*) Lower–Upper Proterozoic, plagiomicrocline and microcline granites and granite migmatites; (*2*) Lower Proterozoic (Karelian), granite gneisses, migmatites, and sillimanite–cordierite–biotite gneisses of the Balnikanskii complex; (*3*) Archean, plagiomicrocline gneisses, microcline granite gneisses, and garnet–sillimanite–cordierite schists of the Ashvaskii complex; (*4*) Lower Riphean, rapakivi (?) granites; (*5*) interblock faults; (*6*) interblock normal faults; (*7*) interblock faults; (*8*) tentative Quaternary faults and neotectonically active linear zones; (*9*) Quaternary paleovalleys; (*10*) pre-Quaternary surface isohypses (m).

mor'e, the town of Pionerskii, and others) and off the Sambiiskii Peninsula shores. The majority of buried paleovalleys coincide in direction with deeper tectonic faults. Differences in the vertical position of segments of the same valley on the surface of pre-Quaternary rocks are attributed by V.K. Gudelis to neotectonic movements that have occurred up to recent time [*Geology of …,* 1976]. The uplift of the pre-Quaternary surface described above partially coincides in plan with the epicentral zone located in our study, and the Northern Sambiiskii block occurs in the zone of its abrupt dip to the north.

Numerous features indicating deformations of younger sediments (zones of their crumpling bounded by steep normal faults) and deeper horizons of the sedimentary cover have been revealed. Sedimentary rocks form two submarine structural–denudational benches on the western and northwestern submarine slopes of the Sambiiskii Peninsula at distances of about 5 and 7–10 km from the shore and at respective depths of 15–20 and 40 m [Blazhchizhin, 1974; *Geology and* …, 1991]. A neotectonically active zone was confined by P. Suveizdis [*Tectonic* …, 2003] to the first of these benches. This zone coincides in plan with the N–S fault in the basement described above (Fig. 4). It is worth noting that strong siliceous rocks are widespread on the submarine slope off the Taran Cape, which is direct evidence for a tectonic compression setting [*Geology of* …, 1976]. Because of the lack of data on the deep structure, we obtained detailed tectonic characteristics of the region by geophysical modeling of the deep structure of the crust.

MODELING

In accordance with the current concepts, the seismic process is due to both properties of the geological medium as a whole and its structural organization in the form of faults, contacts, structural boundaries, and anomalies [*Deep Structure* …, 2004].

To gain insights into the structure of at least the upper crust in the supposed area of the source zone, we used methods of structural analysis [Ovsov, 2004] and wavelet transforms [Shtokalenko and Alekseev, 2007] applied to available data (obtained by Zagorodnykh, Dovbnya, and Zhamoida in 2002) on gravitational and magnetic fields ~4000 km^2 in area. The study was

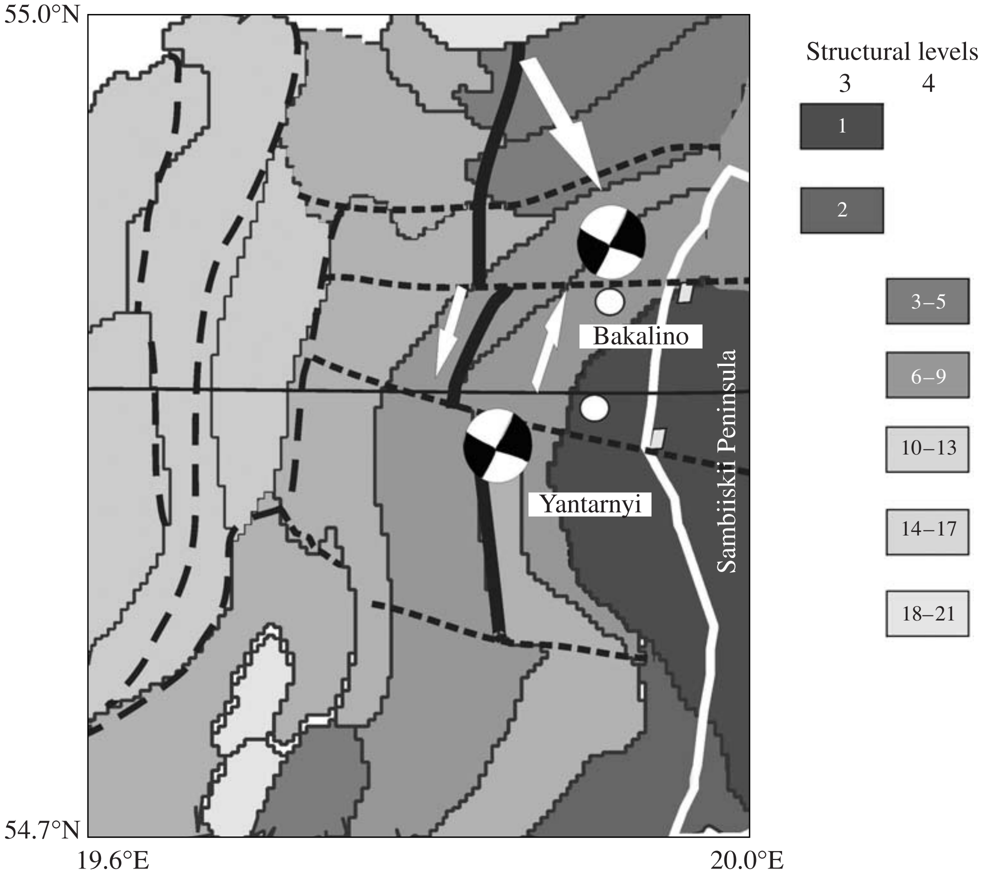

Fig. 5. Fragment of a map of classes obtained by geophysical modeling with the use of the structural analysis method. The darkest shade relates to the lower hierarchical level 3 and the smallest class 1. The map also shows the epicenters 11: 05 and 13 : 32 GMT (white circles), their focal mechanisms, the direction of the regional compressive stress (larger white arrow), and the fault slip sense (smaller white arrows). The thick broken lines are graben-forming faults and transverse faults, and the thick line is the seismogenic fault. The thin line shows the position of the section shown in Fig. 6. The broad white line is the shoreline.

divided into stages. At the first stage, structural analysis was applied to the entire data set.

This method, based on the use of correlation, cluster, factor, and dispersion analyses, allows one to construct a hierarchical (tree) structure of multivariate data represented at observation points by a set of numerical indicators. A main technique of specifying the structure is the examination of the dependence of the intercluster distance on the number of clusters. Division is performed by using a jump of the major rank alone, which ensures stable identification of the smallest number of most general, extensive clusters. The structural analysis of indicators converts observed indicators describing objects of study into the space of new generalized indicators, classes. In the space of new indicators, objects are divided into subsets related to the original set as species to a genus. The resulting classes represent the structure of the object at the first hierarchical level. The subsequent division of the species as genera of the lower level leads to the construction of a developed multilevel structure. The quality criteria of the structural solution are estimated in terms of a dual approach, statistical and cartographic. In the statistical aspect, the quality of the resulting structure is represented by the intergroup variability of initial indicators in end classes relative to the whole-group variability in the root class. The cartographic structure of the region studied is illustrated in Fig. 5 by a fragment of a map showing classes (subsets) of homogeneous data. A map of classes reveals images characteristic of complex buried geological objects.

At the second stage, we applied a method called by its authors "wavelet transforms with physical meaning" [Shtokalenko and Alekseev, 2007]. It is based on integral transformations of physical fields in which kernels are represented by functions describing an anomaly from an elementary source of the transformed field. As a result, the depth distribution of potential fields was calculated on the 54.87°N profile (Fig. 5).

At the third stage, the application of structural analysis to the inferred structure provided a detailed structure of the upper crust (to a depth of 8 km) in the supposed area of the source zone (Fig. 6). Unfortunately, due to the small volume of initial data, the study could

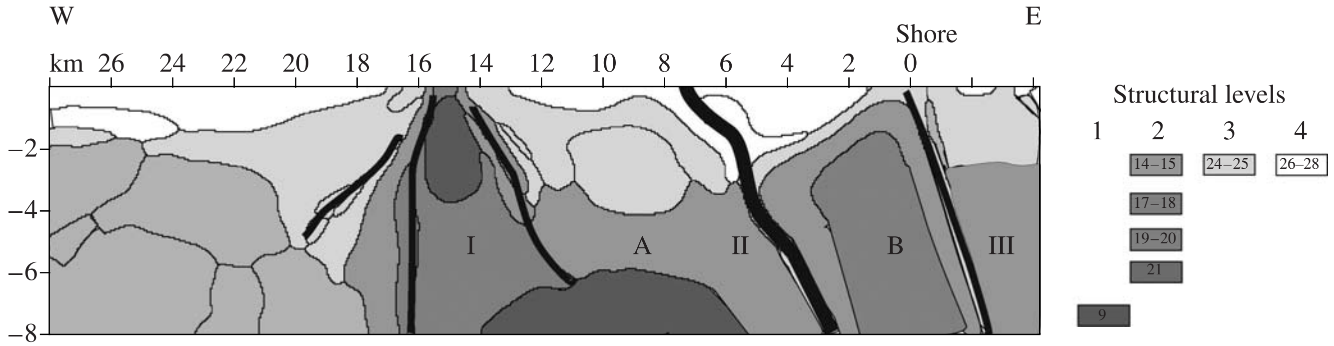

Fig. 6. Results of geophysical modeling by the methods of structural and wavelet analyses. The position of the section is shown in Fig. 5. The darkest shade relates to the lower hierarchical level 1 and the smallest class 9. The Roman numerals denote fault zones, and the capital letters denote basement blocks.

not be extended to greater depths or in the eastern direction.

The results of the analysis show that at least the upper 8 km of the crust in the region are divided into blocks (Figs. 5, 6). The section clearly displays a sedimentary cover and a complex basement surface broken into blocks. A linear grabenlike structure is seen to exist in the upper crust at a distance of 15–16 km from the western shore of the Sambiiskii Peninsula (Fig. 6); the eastern flank of this structure is a complex N–S trending fault zone of the strike-slip type up to 10 km wide (I in the section), crossed by the Northern Sambiiskii and Labsko-Sambiiskii E–W normal faults [Kanev and Lyarskaya, 1992], extending from land. The zone is complexly structured: its section displays numerous smaller fractures with fault planes dipping vertically or west- and eastward, as well as a great number of isometric structures, intrusive bodies of a basic composition (Fig. 6). The composition of these formations is constrained by large values of magnetization and density. Two faults (II and III in Fig. 6) parallel to zone I are located nearer to the shore; possibly, they are genetically related to zone I. These disturbances are most interesting because the neotectonically active zone of P. Suveizdis described above (Fig. 4) is confined to them.

The first of the aforementioned N–S trending strike-slip faults is at a distance of 7 km (5 km along the basement) from the Sambiiskii shore, with its strike-slip deformation being realized on an inclined, rather than vertical, plane. Moreover, the fault marks the contact of two basement blocks (A and B) differing in composition and age, and block B is uplifted relative to A. The fault plane dips eastward under the Sambiiskii block. The dip changes from 56° near the seafloor to 90° at the basement depth (3 km); the fault flattens out in the depth interval 4–7 km and becomes again subvertical at a depth of 8 km. In plan (Fig. 5), the Sambiiskii block is a monolithic rounded structure of the third and higher structural levels of possible intrusive origin and a granitoid composition. The western boundary of the block does not coincide with the shoreline, and its northern boundary marks the contact of the Northern Sambiiskii uplift with the Kurshskii trough. Another interblock contact with a subvertically dipping fault plane is identified at a distance of 1 km from the shoreline.

The source of the first shock might have been confined to a tectonic node, namely, the intersection area of an E–W fault disturbing the Sambiiskii block, a probable NW striking fault marked by the Pokrovskii incision, and one of the N–S trending faults revealed by the structural analysis that cross the Northern Sambiiskii block or bound it on the seaside (Fig. 5). Taking into account specific macroseismic features, this fault must coincide with inclined disturbance II in Fig. 5. If the source depth is accepted to be 8–10 km, the projection of the first event hypocenter will be 3 km west of Yantarnyi. Comparing the morphology of disturbance II and focal mechanism data pointing to a lateral slip on a vertical fault plane, we should suppose that the fault straightens with depth. On the other hand, the along-dip component of deformations is somewhat larger than is suggested by the fault plane solution [Gregersen et al., 2007], and the real focal mechanism is of the normal(reverse)–strike-slip type.

According to [Gregersen et al., 2007], the source radii of both shocks amounted to ~1 km. With a source zone width of ~0.5 km, its length will be ~6 km, which probably corresponds to the distance between the first and second hypocenters. Taking into account the same type of fault plane solutions for both shocks, the macroseismic field (Fig. 2), and the macroseismic intensity distribution pattern (an intensity increase at fault ends inherent in the strike-slip type of deformations), we may suggest that the source of the second event was located to the north of the first on the same tectonic fault. In maps of classes, this fault is distinctly observed south of Yantarnyi and north of Bakalino but is poorly resolved between these localities. In the geodynamic respect, this local rigid crustal zone is fractured due to a left-lateral deformation. In plan, the source position coincides with the center of the area of maximum shakings (Fig. 2). Taking into account the dip of the tentative seismotectonic fault, the hypocenter of the second shock was also located in the offshore zone near the shore. It is also seen that the source of the second shock is confined to a tectonic contact marked by a gradient zone on the pre-Quaternary surface (Fig. 4). As noted above, the distribution density of Quaternary deformations in this region is high.

However, it is also likely that the second earthquake occurred at a somewhat greater depth than 10 km (the determination uncertainty of this parameter makes such a suggestion possible) and was nearer to the first shock; in this case, its source zone should have been located directly beneath the Sambiiskii block to the northwest (or west) from the first source. The geographic coordinates of the shocks will then be close to the NEIC determinations, but the second shock epicenter will considerably deviate from the center of the maximum macroseismic intensity zone and the intensity distribution described above will need to be additionally explained.

Thus, the coordinates of the first shock are (54.9°N, 19.9°E) and the second epicenter lay at a distance of 6 km to the north. The depth of the sources was supposedly 8–15 km. The upper bound of this interval was obtained from the localization of the events using data of regional stations [Assinovskaya and Karpinsky, 2005]. The lower bound of the source depth interval could be established from the position of the lower boundary (15 km) of the brittle deformation zone calculated from heat flow data [Assinovskaya, 2006].

DISCUSSION

The focal mechanism type of the Kaliningrad earthquake source points to a setting of horizontal compression oriented NW–SE in accordance with the regional stress field. As is known, the major part of the Fennoscandian Shield is also under conditions of predominant horizontal compression of the same orientation. This orientation and deformation type are corroborated by numerous direct determinations of the stress state type [Reinecker et al., 2005]. The source of compressive stresses in this region is generally believed to be the nearby northern segment of the Mid-Atlantic Ridge. The stress transfer mechanism is related to the presence of a fluid-bearing waveguide in the upper crust, and the stresses are accommodated within the shield by deformations in its weakened zones.

According to other ideas, sources of recent geodynamic activity and higher seismicity are located not only in the lithosphere, where plates and blocks are moving, but also in deeper regions of the mantle [Rundquist et al., 2001]. The extended Central European rift system, presently identified in Western Europe, includes a number of tensile structures, for example, Rhine grabens and the Oslo graben near the Kaliningrad region. Developing rift systems a few hundred thousand years old include the Eastern Baltic system, consisting of the triple junction of the Bothnian, Finnish, and Gotland rifts [Garetskii, 1999]. The Kaliningrad earthquake occurred in the Gotland segment of this system.

There are different opinions concerning recent rifting processes in Western Europe. Some researchers relate them mainly to movements in the Alpine–Himalayan collisional belt [Meyer and Foulger, 2007, www.mantleplumes.org], while others believe them to be controlled by plume tectonics [Rundquist et al., 2001]. In any case, mantle convection, involving cold and hot mantle flows, gives rise to large heterogeneities in the sublithospheric mantle. Mantle motions increase the energy of geodynamic processes in the crust, stimulating the seismic process.

Thermal activity is noted ubiquitously in the Kaliningrad region, particularly in the north of the Sambiiskii Peninsula. Thus, the macroseismic inspection of the Kaliningrad earthquake of September 21, 2004, established that hot water appeared in the Lesnoi settlement well (the Kurshskaya spit) in winter 2002 [*Komsomol'skaya pravda*, Mar. 1, 2002] and vapor was observed in a shallow well in the settlement of Sosnovka after the events of September 21. Researchers also draw attention to local manifestations of mud volcanism on the seafloor off the northern coast. The higher heat flow is suggested to be of mantle origin in [Gordienko, 1993]. The water temperature in the Gdansk and Kurshskii bays abruptly rose in the spring of 2007; in our opinion, this rise could have been a precursor of the April 28, 2007, earthquake in the Bay of Dover with $M_L = 4.2$ and $H = 2$ km.

We should also note that detailed seismic tomography studies provide increasing evidence of a crucial significance of ancient weakened zones; thus, Variscan structures are shown to play a decisive role in the seismogenesis in the southern Rhine graben [Cardozo and Granet, 2003] and seismic activity in the Skagerrak area (southern Norway) is shown to relate to the ancient Langust fault system, which previously was not identified at all [Sorensen et al., 2006, http://bora.uib.no/bitstream].

CONCLUSIONS

The study resulted in the construction of a new map of the macroseismic field in the epicentral area of the Kaliningrad earthquake with the use of the EMS-98 scale; the map revealed similarity between the maximum intensity isoseismals of the two strongest shocks. This circumstance and the evidence for identical parameters of focal mechanisms determined from instrumental data indicate that the events occurred in the same tectonic fault zone off the western shore of the Sambiiskii Peninsula.

Based on the available geological and geophysical data and the structural analysis method developed in the paper, a seismotectonic model consistent with macroseismic and instrumental data was constructed. The position of hypocenters of the two main shocks of the Kaliningrad earthquake was determined.

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