ISSN 1028-334X, Doklady Earth Sciences, 2006, Vol. 407, No. 2, pp. 317–320. © Pleiades Publishing, Inc., 2006.
Original Russian Text © A.A. Nikonov, 2006, published in Doklady Akademii Nauk, 2006, Vol. 407, No. 1, pp. 102–105.

GEOPHYSICS

Source Mechanism of the Kaliningrad Earthquake on September 21, 2004

A. A. Nikonov

Presented by Academician V. V. Adushkin June 20, 2005

Received July 19, 2005

DOI: 10.1134/S1028334X06020371

The Kaliningrad earthquake on September 21, 2004 was a rare but very significant example of the potential of moderate earthquakes in the East European Platform. The following three shocks were instrumentally recorded with sequential magnitudes m_b: 4.1, 4.9, and 3.0 (Geophysical Service of Russia); 4.4 and 5.0 (EMSC); and 4.8 and 4.9 (NEIC). The location of their epicenters and the depths of the source measured by different services differ strongly [1, 2]. This earthquake was characterized by a vast area of the manifestation of noticeable shocks (radius up to 500–600 km). Before this event, two earthquakes of similar magnitude were instrumentally recorded in the East European Platform: the Sysol earthquake in 1939 ($M = 4.5 \pm 0.2$) and the Osmussaar earthquake in 1976 ($M = 4.75$). Both events had the epicenter intensity $I = 7$ and "normal" areas of perception [3, 4].

Analysis of the effects at the epicenter area suggests the following conclusions: (1) The event discussed here was a series of seven sensible shocks with intensity decreasing from 6–6.5 during the second shock to a threshold of perception in only 17 h.

(2) According to the entire macroseismic data, epicenters of all shocks were located under the sea bottom. Epicenters of the first and third shocks were located near the western coast of the Sambia Peninsula, while the epicenter of the second shock was located at its northern coast.

(3) Locations of the epicenters determined with instrumental data on land (Sambia Peninsula) are hardly more exact than locations based on macroseismic data, because of the absence of closely located stations, deviations in hodographs used in the calculations, poor correlation with known geological structures, and macroseismic manifestations.

(4) Amplification of oscillations during each of the three shocks over a sublatitudinal area in the southern part of the Sambia Peninsula (west of Kaliningrad), based on the sum of indicators, suggests that this feature was related to local geological conditions rather than real seismotectonic activation.

In order to pass judgement about the mechanisms of the sources, usually instrumental data along with seismotectonic data are used. In favorable situations, the effects at the surface are also taken into account. In our case, it is difficult to take into account the surface effect in full, because the epicenters and, consequently, the sources, are located under the sea bottom. Therefore, attention was focused on the following tasks: (a) consideration of the data on neotectonics and young tectonics of the proximal zone, in order to distinguish the active and seismogeneric fractures, and (b) gathering and evaluating macroseismic indicators, which are representative from the point of view of both the strength of shocks and the possible source mechanism. In accomplishing the latter task, the analysis was based on the collective works on land [2] and the author's data on the adjacent water media [5]. The data were gathered and analyzed separately for each of the first three shocks. Special attention was focused on the character of the oscillations, direction of the rumble, shocks, and oscillations in the proximal zone during each of the shocks. Thus, we obtained corresponding maps for each of the shocks (such maps are rarely prepared in the investigation of macroseismic activity). Joint processing of macroseismic characteristics of shocks on land and perturbations of water masses near the northern and western coasts of the Sambia Peninsula allowed us to determine the elongation of the epicenter zones and sources of the first and third shocks in the meridional direction along the western coast of the peninsula, and, for the second shock, in the sublatitudinal direction along the northern coast of the Sambia Peninsula [2].

Schmidt Institute of Physics of the Earth,
Russian Academy of Sciences, ul. Bol'shaya Gruzinskaya 10,
Moscow, 123995 Russia

Horizontal oscillations and distribution of vertical oscillations in the proximal zones suggest an upthrust–sinistral strike-slip rapture during the first shock and dextral strike-slip faulting during the second shock.

Here, we shall pay attention to the facts of macroseismic character that are most important for reconstructing the source. During the first shock (and only during this shock) along the northern coast of the peninsula (only within a band along the peninsula), the main motion was vertical, while the oscillations approached the western coast from the sea, i.e., from the west. During the second shock at the northern coast (Svetlogorsk and its vicinities), the direction of the rumble and the arrival of oscillations (based on the perception of the people, displacement of objects, and elements of constructions) was from the northwest. In the center of the city, several observers saw the waves running from the northwest to southeast along the tile parapet surface near the city administration building.

In the southwestern vicinity of the city, the rails were strongly damaged at the "49" of the railway distance. In addition, nearby a landslide occurred in the middle part of a high railroad embankment, 32 min after the third shock [5]. We shall pay attention to the documented wave-shaped vertical bending of the entire railway, together with the rails. This damage, which is not related to the landslide of the railroad embankment at a distance of tens of meters from the segment with wave-shaped bending of the railway, reflected the deformation of the railroad over a short interval in the highest (southeastern) part of the embankment, immediately at the right bank of the overlain creek valley. It is noteworthy that the railway is seamless over the entire studied segment of the railroad. As a result, residual vertical wavy deformations (with amplitudes not less than 1–1.5 m over a length of 3–4 m) can only be considered a result of strong longitudinal compression. Here, the railway is directed from the northwest to the southeast. Hence, the direction of the compression should be the same. The appearance of the deformation in exactly this place over a distance of only ≤10 m is explained by its location near the valley bank at the boundary between the stable native slope in the northwest and thick (up to 20–30 m) loose artificial substratum in the large (approximately 60 m long) embankment in the southeast. The deformation considered here could be related either to the influence of compression wave *P* propagating from the northwestern proximal source of the second shock or to the folding of loose sediments of the embankment in the course of its collision with the native slope of the valley, as a result of the general motion of the land block to the west (northwest).

Fractures that are active in the neotectonic stage and Quaternary are not shown in general maps [6–8] of the study region. However, some regional small- and middle-scale maps [9–11] show sublatitudinal (along the northern coast) and submeridional (along the western coast) tectonic fractures that crosscut the entire sedimentary cover (including Cenozoic sediments) along the frame of the Sambia Peninsula. Analysis of the neotectonics of the Sambia Peninsula and its underwater framing distinctly shows the existence of sublatitudinal flexure-fracture type of disturbances. Some of them, located on land along the northern coast, demonstrate clear indications of activity in the form of an upthrust up to the Late Pleistocene but not later [12]. It is noteworthy that the position of Paleogene clays in the shallow-water zone north of the peninsula is very low, as compared to their bedding on adjacent land. The height difference (from –2 to –12 m on land and from –30 to –44 m in the shallow water area) can be explained only by relative descent of the basin bottom in the alongshore fracture.

Linear alongshore fractures were revealed during underwater geophysical studies [13] near the western and northern coasts. They can be interpreted as indicators of young fractures at the bottom. This conclusion is consistent with the concept about the Sambia Massif as a uplifted during the neotectonic stage block bounded by young submeridional fractures in the west and by sublatitudinal fractures in the north. Special seismotectonic investigations were not carried out previously in the Kaliningrad region. Only in [14], we find reports of the sublatitudinal seismogenerating zones (with an estimate of the maximal possible magnitude of the earthquake equal to $M = 4$) located south of the northern coast of the Sambia Peninsula.

In general, comparison of the available macroseismic data (including those related to the activation of alongshore underwater zones [5]) with the available data on neotectonics and young tectonics along the coasts of the Sambia Peninsula reveals a consistent pattern: the existence of a submeridional zone in the west and sublatitudinal vertical alongshore zone in the north with signs of young activity. These zones are considered seismogenerating ones. On the basis of seismotectonic and macroseismic data, we can conclude that the source of the Kaliningrad earthquake of 2004 was a complex structure composed of two mutually perpendicular fractures, the activating of which was alternating in time. First, the meridional fracture was opened along the western coast, probably, as a sinistral strike-slip displacement. The main earthquake took place after 2.5 h, due to the opening of the sublatitudinal upthrust faulting in the north, which was probably accompanied by a dextral displacement. The third shock reflected the continuation of the western fracture activation, whereas weaker aftershocks that followed in 10–12 h were related exclusively to the northern sublatitudinal fracture.

Comparison of the obtained solutions with the solutions based on the instrumental data (Table 1) shows a satisfactory agreement.

The source was determined for the main shock at five seismic centers, located at Harvard (HRV, United

Solutions of the source mechanisms of Kaliningrad earthquake on September 21, 2004

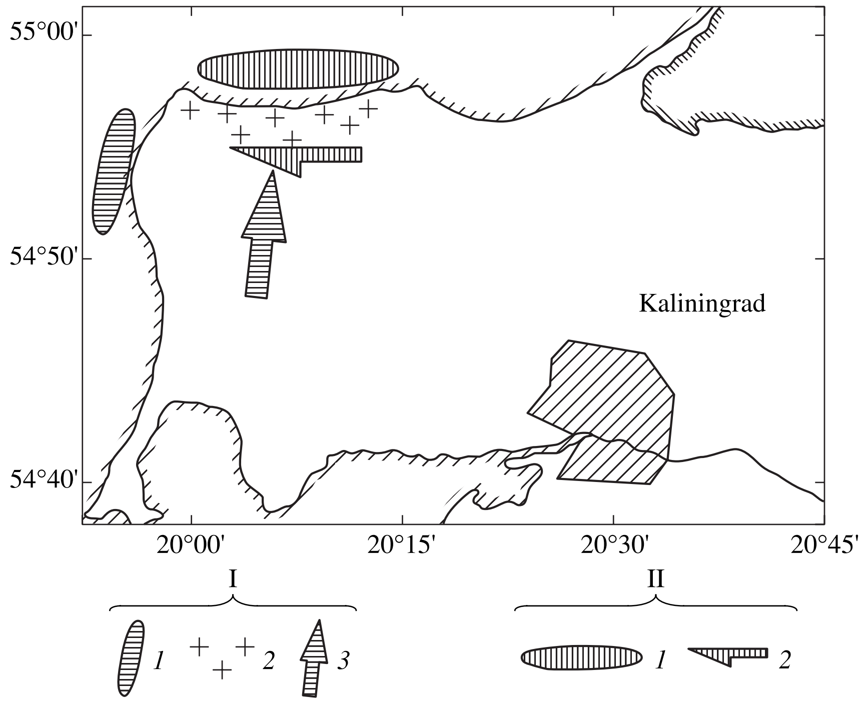
Shock	Based on macroseismic and seismotectonic data. Planes of activation (fractures)		Based on instrumental data. Nodal planes		
	azimuth, deg	inclination, deg	seismic center	azimuth, deg	inclination, deg
First	190 ± 10	90 ± 10	IGP		
			A	202	89.2
			B	111.7	73.7
Second	95 ± 10	(80) ± 10	Harvard		
			A	205	78
			B	117	80
			IGP		
			A	204.7	84.3
			B	113.4	71.3
			INGV		
			A	211	81
			B	120	81
			ETHZ		
			A	206	86
			B	114	64
Third	190 ± 10	90 ± 10			

States), Mediterranean (INGV, Italy), Switzerland (ETHZ), and Poland (IGR). Sufficiently similar solutions obtained indicate that both planes are very steep (~80°). One plane extends from the north-northeast to the south-southwest, while the other plane extends from the east-southeast to the west-northwest [1, 2] (table). Comparison of the data of independent determinations on the basis of macroseismic and seismotectonic data [1, 2] and those using the instrumental data indicates that the results are in a good agreement with respect to the inclination of displacement planes, while the directions of their strike diverge within 15°–20°, if solutions *A* and *B* are based on instrumental data (for the first and second shocks, respectively). Correspondingly, these solutions can be accepted as satisfying all data available at present. Relative to the solution based on macroseismic and structural tectonic data, the solution based on the instrumental data is distinguished by the following: (a) sources of the three shocks are located under the seafloor near the western and northern coasts of the Sambia Peninsula rather than on the adjacent land, and; (b) the source of the first shock is extended in the meridional rather than latitudinal direction. In the north of the Sambia Peninsula, where geophysicists assume the sources of the two main shocks [1, 2] exist, seismogeneric structures are absent and the intensity of oscillations is lower than along the coasts.

Estimates of the source depth (16 ± 9 and 20 ± 10 km for the first and second shocks, respectively [1]), do not apparently contradict the geological data. In any case, these values are more realistic than the assumption of the location of the hypocenters at a depth of a few kilometers (according to the data of the Geophysical Service of the Russian Federation).

The existence of a complex source at the junction of two fractures is not an exceptional phenomenon during earthquakes in general, particularly at the southeastern periphery of Fennoscandia. A similar case occurred during the Osmussaar earthquake in 1976, and, possibly, during the Narva earthquake in 1881 near the coast of Estonia [4, 15]. In all cases, there are grounds to assume that the earthquakes appeared under conditions of the domination of subhorizontal NW–SE compression, which is characteristic of the major part of the Fennoscandian Shield, according to independent data.

Both the instrumental data recorded at remote stations and macroseismic data indicate that the Kaliningrad earthquake was a valuable regional phenomenon, which provided new insights into the seismotectonic



Location of the projections of the sources of the first (I) and second (II) shocks of the Kaliningrad earthquake on September 21, 2004, based on macroseismic and seismotectonic data. (I) First shock: (*1*) projection of the source; (*2*) region with the first shock perceived as vertical; (*3*) direction of relative displacement of the continental block (Sambia Peninsula). (II) Second shock: (*1*) projection of the source; (*2*) direction of relative displacement of the continental block (Sambia Peninsula).

environment and seismic potential of the Eastern Baltic region.

ACKNOWLEDGMENTS

The author thanks F.F. Aptikaev, A.S. Aleshin, B.A. Assinovskaya, and V.V. Pogrebchenko for active cooperation and discussion of the obtained material. The author is grateful to V.V. Adushkin, F.F. Aptikaev, and Yu.K. Shchukin for useful remarks, and to L.E. Borisova for technical assistance.

REFERENCES

1. P. Wiejacz and W. Debski, in A. Joeleht (Ed.) *The Kaliningrad Earthquake on September 21, 2004*, *Workshop Materials* (Institute of Geology, Tartu, 2004), pp. 44–52.
2. A. A. Nikonov, F. F. Aptikaev, A. S. Aleshin, et al., in *The Kaliningrad Earthquake on September 21, 2004*, *Workshop Materials* (Institute of Geology, Tartu, 2004), pp. 26–29.
3. A. A. Nikonov, L. S. Chepkunas, and V. V. Udoragin, in *Geology of the European North Part of Russia* (Syktyvkar, 2001), Issue 108, pp. 29–43 [in Russian].
4. A. A. Nikonov, Izv. Ross. Akad. Nauk, Ser. Fizika Zemli, No. 8, 74–88 (2002) [Izv. Phys. Solid Earth, No. 8, 690 (2002).
5. A. A. Nikonov, Priroda, No. 3, 47 (2005).
6. *Map of Deep Fractures in the USSR Territory,* Scale 1 : 2 500 000, Ed. by A.V. Sidorenko (Leningrad, 1980).
7. *Map of Neotectonics in Northern Eurasia,* Scale 1 : 5000000, Ed. by A.F. Grachev (Moscow, 1997).
8. V. G. Trifonov, Tectonophysics **380**, 123 (2004).
9. V. N. Gurov, *Geology of the Crystal Basement and Sedimentary Cover in the Baltic Region* (Zinatne, Riga, 1975), pp. 223–230 [in Russian].
10. A. N. Lastochkin, *Methods of Marine Geomorphological Cartography* (Nedra, Leningrad, 1982) [in Russian].
11. *Tectonic Map of Lithuania,* Scale 1 : 500000 (Riga, 2003).
12. A. E. Dodonov, Vest. Mosk. Gos. Univ., Ser. 4: Geol., No. 6, 78 (1971).
13. V. V. Orlenok, *Geography at the Changeover of Centuries* (Kaliningrad, 2001), pp. 65–75 [in Russian].
14. R. G. Goretskii, R. A. Aizberg, A. G. Aronov, et al., Dokl. Akad. Nauk Belarusi **41** (4), 98 (1997).
15. A. A. Nikonov, *European Seismology Commiss. Assembly, September 11–17, 2004* (Potsdam, 2004) p. 45.