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# The exceptional earthquakes in Kaliningrad district, Russia on September 21, 2004

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**Abstract**

The earthquakes of magnitudes $M_w$ 5.0 and 5.2 in the Kaliningrad enclave of Russia on September 21, 2004 were unexpected in a low-seismicity area. The earthquakes caused moderate damage in the Kaliningrad enclave, and smaller damage in northern Poland and in southern and western Lithuania. The largest earthquake was the strongest ever recorded instrumentally in the region, and it was felt at distances up to 800 km. In directions towards the west and south the perceptibility area is abruptly cut off by the Tornquist-Teisseyre Zone, the south-west margin of the East European Craton. The earthquakes are instrumentally located at depths 16-20 km under the central-northern part of the Sambia Peninsula in the Kaliningrad enclave. For these events it is noted that the macroseismic calculations of 10-19 km depths are in reasonable agreement.

The source mechanism of the largest earthquake was determined to be a right lateral strike Slip on a WNW-ESE near-vertical fault of orientation almost parallel to the Tornquist-Teisseyre Zone and to the north coast of the Sambia Peninsula. Based on available stress information it is interpreted that the underlying cause of the earthquakes is the absolute plate motion. Historical information is scanty. It is searched in an attempt to evaluate past seismic activity in the region, and to evaluate vulnerable weakness zones in the geological structures.


Keywords: Intraplate earthquakes; Kaliningrad; Low-seismicity area; Intensity maps; Macroseismic effects; Baltic area

## 1. Introduction

The level of seismicity in the Baltic Sea region is low, with maximum earthquake magnitudes well below 6. Earthquakes that occur in the area have been attributed to ridge push forces originating from the MidAtlantic Ridge or to postglacial rebound (e.g. Lundqvist and Lagerbäck, 1976; Lagerbäck, 1979; Gregersen and Basham, 1989; Slunga, 1989; Arvidsson and Kulhánek, 1994; Nikonov, 2002; Uski et al., 2003; Husebye and Mäntyniemi, 2005). Seismic

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hazard in the area has been considered low. The map of seismic zoning in Russia (OSR-97) showed very low earthquake probability, although studies by Nikonov (2002, 2004) and other Russian authors recognized that earthquakes similar to that in Osmussaar, Estonia in 1976 could also occur in other parts of the eastern Baltic region. Studies by Schenk et al. (2001) and Guterch and Lewandowska-Marciniak (2002) show that the maximum historical intensities range from 3 in northern Poland to 5 in northeastern Poland, based on four earthquake reports in the catalogue of Pagaczewski (1972) within the last 1000 years. Another catalogue of the area (Avotinia et al., 1988; Boborykin et al., 1993) does not show any evidence of seismic activity in the present-day Kaliningrad enclave and Lithuania. However seismologists in Russia, Belarus, Latvia and Ukraine had earlier noted zones of possible earthquakes within the Kaliningrad-Lithuania area (Reisner and Ioganson, 1993; Garetsky et al., 1997). Forgotten historical descriptions of some past earthquakes in the broad area of interest have also been recognized after the recent events by Nikonov (2005a). He remarks that some earthquakes, such as that felt in the town of Torun in 1572, may have destroyed a few houses. One important issue is whether the rarity of earthquake reports between the 14th century and instrumental time indicates a genuine absente of seismic events or rather a lack of reports due to large population migrations in wars.

During the instrumental era only a few possible earthquakes have been recorded for the area of interest. Meyer and Kulhánek (1981) investigated a sequence of minor events in the Gulf of Gdańsk in the summer of 1980. The events occurred at a distance of about 50 km from Kaliningrad and were assigned magnitudes between 2.5 and 3.0. No felt observations were made. Meyer and Kulhánek (1981) were not able to conclude whether the sequence was composed of earthquakes or explosions. The above-mentioned Osmussaar, Estonia earthquake of magnitude $M_L$ 4.6, $M_S = 4.75$ in the Gulf of Finland in 1976 (Slunga, 1979; Nikonov, 2002) was regarded as distant from the Kaliningrad area. Thus, the occurrence of the earthquakes on September 21, 2004 was a surprise not only to the local population but to most seismologists as well.

The earthquakes on September 21, 2004 occurred in the territory of the Russian Kaliningrad enclave and were felt as far as Norway and Belarus (Gregersen et al., 2005) and also in high-rise buildings in St. Petersburg, Russia (Assinovskaya, 2005). They caused moderate damage in the Kaliningrad district (Nikonov, 2005b; Aptikaev et al., 2005; Nikonov et al., 2005, 2006) and smaller damage in northern Poland and in southern and western Lithuania. The first event occurred at 11:05 UTC, the second at 13:32 UTC, and a small aftershock followed the second event 4 min later. There were four felt reports during the following night, but they have not been confirmed instrumentally. The earthquakes were recorded at numerous seismic stations across the world. However, there was no seismograph station in the Kaliningrad enclave, and the closest station was Suwałki (SUW) in Poland 220 km away.

## 2. Macroseismic observations

The two first and largest Kaliningrad earthquakes on September 21, 2004 were widely felt in the Kaliningrad enclave, northern Poland, and southern and western Lithuania, and felt observations were made in all the countries surrounding the Baltic Sea and also in Belarus and Norway. The collection of macroseismic data was carried out country-wise within the perceptibility area, but intensity assessment was discussed and coordinated in a workshop in Tartu, Estonia in May 2005 (Jõeleht, 2005; Gregersen et al., 2005). This work was continued between representatives of Estonia, Latvia, Lithuania and Belarus under Russian leadership. As a result, maps for the two largest events have been compiled and isoseismals 2-6 contoured. The European Macroseismic Scale 1998 (EMS; Grünthal, 1998) was chosen for evaluation of the intensity observations. For this study, it was decided to attribute intensity 2 to observations "only felt by people in buildings higher than the second floor", i.e. not attribute intensity 3 ("felt indoors by a few") to observations made in high-rise buildings.

Preliminary intensity maps for the near-epicenter area for the two largest earthquakes were published soon after the earthquakes (Nikonov et al., 2005; Aptikaev et al., 2005). Personal contact to sources of information has supplemented questionnaires in many places. Many site reports are supported with photographs. The compilation of several regional maps of intermediate scale has been coordinated across the borders for separate publications. For the present publication two small-scale maps have been compiled with the total cross-boundary data set (Figs. 1 and 2). These maps are generalized intensity maps with smoothed and representative isoseismals.

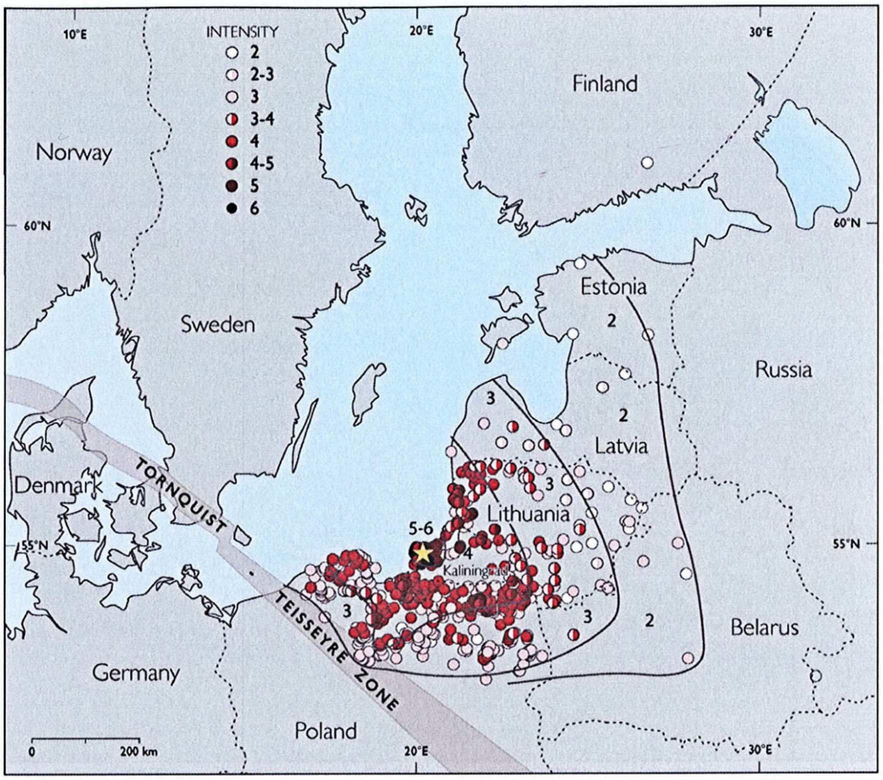


Fig. 1. A generalized intensity map for the $M_w$ 5.0 earthquake at 11:05 UTC on September 21, 2004 in the Kaliningrad enclave. Intensity values are given on the EMS-98 scale. The epicenter is denoted by a star.

The referred epicentral intensity of the larger earthquake was 6. In Kaliningrad 1 person died of a heart attack caused by fear, 20 people were seriously wounded by falling objects and about 2100 buildings suffered damages amounting to about $5,000,000 (Nikonov et al., 2005; Aptikaev et al., 2005). The earthquakes initially caused great anxiety and rumors that the events were human-induced, in particular some people feared an accidental nuclear explosion. These rumors were soon stopped when the felt reports started flowing in from a relatively wide area.

The earthquakes had some very spectacular effects (Nikonov, 2005b; Aptikaev et al., 2005; Nikonov et al., 2006). At a distance of 25 km from the epicenter to the south-east a ground crack occurred of about 20 cm vertical displacement, and 10 cm horizontal displacement. It was observed near Veselovka village along two perpendicular banks and several meters from a small artificial pond. It was seen during the first shock and was enlarged during the second shock. The loose sediments in which this happened were saturated with water. Also a railway line collapsed over a length of 30 m near Svetlogorsk town 40 min after the main shock, making this a delayed effect. This effect is attributed to failure of a nearby river embankment composed of soft sediments and of a railway bank made of mostly sand and clay. Both of the disturbances were surface effects due to local ground conditions. In Lithuania small sinkholes of a few meters size have been found in Sveksna cemetery. For both shocks local sea surface disturbances have been reported (Nikonov, 2005a) on the coasts of the area with intensities 5-6.

In northern Poland, the larger earthquake caused minor damage to buildings in about 100 localities. In Lithuania there were many reports of intensity 5 (Sliaupa and Pacesa, 2005; Pacesa et al., 2005), and a few dozen reports of cracked walls and broken window panes. Also in Lithuania a few people were frightened and ran out of buildings, and some schools stopped teaching, sending the children home. Further to the north in Latvia, the intensity in isolated points reached 5. There were cracks in walls of several buildings (Nikulin, 2005). In Estonia, the shaking was of intensity 3 or less and no damage was reported (Vall et al., 2005). The larger earthquake at 13:32 UTC was felt as far away as in Norway and Finland, at distances up to 800 km. In Landskrona, southwestern Sweden the shaking was so violent that the town hall was evacuated for sev-

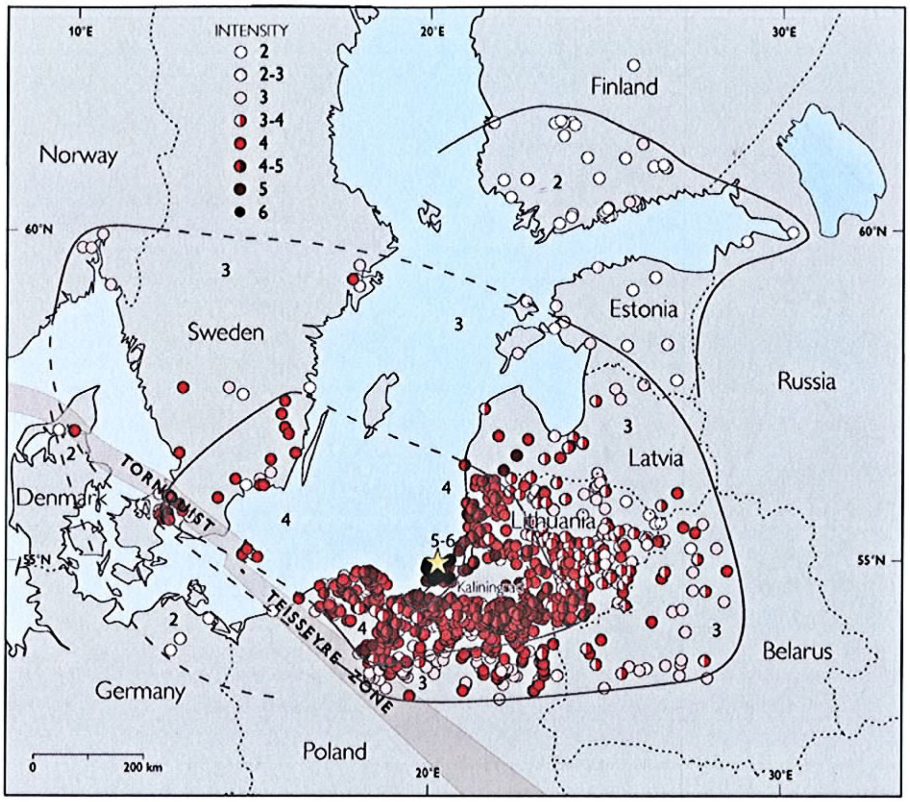


Fig. 2. A generalized intensity map for the $M_w$ 5.2 earthquake at 13:32 UTC on September 21, 2004 in the Kaliningrad enclave. Intensity values are given on the EMS-98 scale. The epicenter is denoted by a star.

eral hours. This is seen as an extreme high-building effect in connection with ground conditions.

Especially noteworthy in Fig. 2 is the large felt area in the East European Craton (north-east of the Tornquist-Teisseyre Zone, TTZ) in agreement with previous macroseismic observations (e.g. Harboe, 1912) and with seismological observations of wave propagation (Gregersen, 1984; Schweitzer, 1995). The second and largest earthquake of magnitude only 5.2 was felt at distances of up to 800 km towards the north-west. Another interesting feature in Fig. 2 is that the felt area is cut off towards south-west. The details of this are influenced by the focal mechanism of the earthquake as well as the regional geology. The broad-scale cause of this cut off is shown in Figs. 1 and 2 as the Tornquist-Teisseyre Zone, which constitutes the edge of cratonic, Proterozoic Europe towards Paleozoic areas with different, thinner crust in the south-west. Actually the distant observations in Denmark (500-700 km) and in Landskrona in Sweden (500 km) may well show some special edge effect since they are located close to the TTZ at particularly sensitive places due to specific local geological ground conditions. Concerning the Norwegian observations (800 km) of intensities 2-3 the interpretation is that the shaking propagated effectively in the craton and that topography and loose sediments magnified the shaking locally. The macroseismic observations show much similarity to the pattern of the Oslo earthquake in Norway in 1904 (Harboe, 1912): the intensity distribution is much elongated along the geological trend of the edge of the East European Craton marked by the TTZ. The intensity distribution shown in Fig. 1 is in many ways similar to that in Fig. 2.

All three recorded shocks were accompanied by strong sound effects (e.g. Nikonov et al., 2005). Hence the frequency of the ground vibration was very high, probably above 20 Hz. Those high frequencies are not observed at the seismograph stations. They have been attenuated already at the distance of the closest station.

## 3. Instrumental recordings

The earthquakes were recorded at numerous seismic stations, also at teleseismic distances. However the nearest station was surprisingly far away, considering the relatively dense distribution of seismic stations in Europe. In the Kaliningrad enclave there was no seismic station at the time of the earthquakes. The nearest station was Suwałki (SUW) in northern Poland some 220 km away. Two other stations were within 300 km distance (Gorka Klasztorna, GKP - at 259 km and Warsaw, WAR - at 299 km), five other stations were within a 400 km radius from the epicenters. Above 400 km distance there is a plenitude of stations. The azimuth distribution of the seismograph stations is also non-uniform, with much more stations to the west than to the east. This azimuthal bias, as well as the inhomogeneous crustal and upper mantle structure of the TTZ located immediately southwest of the source area, have to be accounted for in the study. Therefore, the data from one of the seismic stations of Ignalina Nuclear Power Plant (IIGN) in Lithuania, even though only short period single vertical component, proved very valuable. Fig. 3 shows a map of the area of interest with the locations of the seismic stations and the TTZ marked schematically.

## 4. Ground motion

The lack of near-epicenter stations causes limitations to the study of ground motions. The proximity of some of the nearest stations (GKP, WAR, BSD) to the border of the TTZ complicates the matter because of different geological structures. The TTZ is known for its special attenuation of earthquake waves (Schweitzer, 1995).

The peak ground velocities (PGV) and peak ground acceleration (PGA) at the six nearest seismic stations are given in Table 1. It is interesting that these values - especially the PGA - do not seem to be related directly with distance. The epicentral distance of WAR and BLEU is similar but the difference between the ob-


Fig. 3 Kaliningrad enclave and adjacent areas. The yellow star denotes the epicenters of the two largest events that overlap. Seismograph stations providing waveform data are shown as red triangles, other stations as white triangles. The IIGN station is actually a small network of four stations. The Tornquist-Teisseyre Zone (TTZ) with the East and West European Platform and the Carpathian orogen are also outlined.

Table 1
Peak ground velocities (PGV) and peak ground accelerations (PGA) observed at the six seismograph stations nearest to the epicenters of the September 21, 2004 Kaliningrad earthquakes

| | Distance (km) | Azimuth (°) | Event 1 | | Event 2 | |
|---|---|---|---|---|---|---|
| | | | PGV (mm/s) | PGA (mm/s$^2$) | PGV (mm/s) | PGA (mm/s$^2$) |
| SUW | 220 | 114.6 | 2.0 | 47.1 | 4.9 | 93.1 |
| GKP | 259 | 227.7 | 0.2 | 3.2 | 0.4 | 5.1 |
| WAR | 299 | 168.1 | 0.2 | 2.6 | 0.4 | 4.9 |
| BLEU | 313 | 302.2 | 0.8 | 34.5 | 2.4 | 62.2 |
| GOTU | 326 | 343.6 | 0.6 | 13.7 | 1.5 | 32.2 |
| BSD | 332 | 276.7 | 0.2 | 3.2 | 0.3 | 7.4 |

served PGA values is enormous. The highest values are observed at SUW. These values are extraordinarily high considering the small size of the earthquakes. High values are also observed at BLEU which is located in azimuth nearly opposite that of SUW. The station GKP is located in an azimuth perpendicular to that of SUW and shows low PGA/PGV. It therefore seems like a strong dependence of PGA/PGV on direction. Small values on stations southwest of the TTZ confirm the attenuating property of the TTZ.

## 5. Source parameters

The source parameters were calculated by spectral analysis of 28 seismic station records within 600 km from the epicenter. The parameters were calculated on the basis of Pg and Sg/Lg wave pulses. The signals contain an unusually strong component of high frequencies. No damping correction has been used, since the spectra became unstable. Unfortunately SUW, the closest station to the epicenter, exhibits an irregular spectrum and gives an exceptionally high seismic moment value. Therefore, SUW was removed from further consideration on source parameters.

The spectral parameters have been calculated using the method of Snoke (1987), i.e. approximating the spectra by the pulse model of Brune (1970). Irregular spectra that did not resemble the Brune spectra have been rejected. The source parameters have been calculated as an average of the accepted station data. The source radius was calculated using the coefficient of Madariaga (1976) while the seismic moment and spectral magnitude were calculated using the relations given by Gibowicz and Kijko (1994). The source parameters were calculated for P wave velocity at source 6800 m/s, density of medium 2900 kg/m3 and shear modulus 4.5 x 1010 kg/(m s2), which are estimated from the local structure model and the source depth (Grad et al., 1999, 2003). Stress drop, apparent stress and average displacement are based on formulae of Snoke et al. (1983). The results are given in Table 2.

Both of the main Kaliningrad events have unexpectedly small and nearly identical source radius of about 1 km despite the difference in magnitude. The corner frequencies are also almost identical. The difference in size of the two quakes seems to be attributed simply to the difference in stress drop, and hence the average displacement and radiated energy. The stress drops and average displacements for both events are relatively high. In other words we claim that the unexpected high stress drops and displacements make up for the unexpectedly small source radii. The two quakes are on this account unique.

## 6. Locations

Quick epicenter locations of the earthquakes have been readily provided by services of seismological datacenters such as the National Earthquake Information Center (NEIC) of the U.S. Geological Survey and the European-Mediterranean Seismological Centre (EMSC). However, many of these solutions are preliminary. In this study the nearest six seismic stations, which did not report on-line, were included

Table 2
Source parameters of the September 21, 2004 Kaliningrad earthquakes

| | Event 1 | Event 2 |
|---|---|---|
| Seismic moment (N m) | $5.0 \times 10^{16}$ | $7.2 \times 10^{16}$ |
| Magnitude $M_w$ | $5.04 \pm 0.15$ | $5.22 \pm 0.15$ |
| P wave corner frequency (Hz) | $1.3 \pm 0.4$ | $1.3 \pm 0.5$ |
| S wave corner frequency (Hz) | $1.1 \pm 0.4$ | $1.1 \pm 0.5$ |
| Source radius (m) | $962 \pm 360$ | $9945 \pm 336$ |
| Stress drop (MPa) | 24.6 | 37.4 |
| Apparent stress (MPa) | 4.2 | 11.9 |
| Average displacement (cm) | 38.0 | 57.1 |
| Seismic energy (J) | $4.3 \times 10^{12}$ | $2.2 \times 10^{13}$ |

in the location attempts. Uncertainties in the local geological model and its complexity due to the near border of the East European Platform in the TTZ combined with lack of seismic stations at distances within 100 km have resulted in uncertainties of the locations. Numerical locations are based primarily on the Moho-refracted Pn phases for which travel times vary with azimuth. Different teams of scientists (e.g. Wiejacz, 2004; Nikonov et al., 2006) have obtained different locations of the events, depending on velocity models, type of location algorithm, selection of data and assignment of weights to the data. Final locations for the two earthquakes have been calculated as averages of the instrumental solutions excluding the preliminary locations and the Harvard location that points to the moment tensor centroid rather than to the beginning of the rupture. Nine location results go into the mean. The standard errors of these solutions are less than 10 km. A list of the locations along with their average is given in Table 3. Unfortunately most of the instrumental locations are obtained for a fixed depth of 10 km, so it makes no sense to extract the mean estimate for depth.

Another possible approach is the probabilistic location method used by Wiejacz and Dębski (2005) as well as by Wiejacz (2006). The probabilistic solution is the most probable solution from among a whole range of velocity models, taking into account possible grave errors of phase picks at individual stations. The probabilistic location results are also shown in Table 3. The results of the probabilistic locations and the instrumental averages are similar. For the larger, second earthquake the origin times are equal while latitude and longitude are within error ranges of both methods. For the first event the locations differ slightly, by about 5 km in longitude. The difference is most likely a result of the earthquake being smaller, i.e. slightly fewer seismic stations have recorded it and phase picks at those that did are not as accurate as for the second earthquake. The probabilistic locations give interesting insight concerning the depths of the events, which were found to be 16 and 20 km. Although these results are burdened with high maximum errors, they confirm the macroseismic perception of the quakes over a large area and macroseismic depth estimation of 10-19 km (Nikonov, 2006).

Thus the results of the probabilistic location confirm the mean instrumental locations of the first quake at 54.908N, 20.029E and of the second quake at 54.849N, 20.088E. The standard errors of these locations are 4 km for the first event and 3 km for

Table 3
Instrumental location results for the two main Kaliningrad earthquakes of September 21, 2004

| ID | Source | Event 1 | | | | Event 2 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Time | Latitude | Longitude | Depth | Time | Latitude | Longitude | Depth |
| 1 | IGF IASP | 11:05:01.8 | 55.14N | 19.88E | 10 km fix | 13:32:33.6 | 54.79N | 20.14E | 10 km fix |
| 2 | IGF AK135 | 11:05:04.5 | 55.OON | 20.05E | 10 km fix | 13:32:32.5 | 54.86N | 20.13E | 10 km fix |
| 3 | EMSC | 11:05:04.3 | 54.91 N | 20.08E | 10 km fix | 13:32:30.8 | 54.89N | 20.18E | 10 km fix |
| 4 | ORFEUS | 11:05:08.7 | 54.8N | 19.7E | 10 km fix | 13:32:29.2 | 54.8N | 19.9E | 10 km fix |
| 5 | NEIC | 11:05:03.2 | 54.858N | 19.980E | 4.1 km | 13:32:30.8 | 54.841 N | 19.912E | 10.0 km |
| 6 | ASS | 11:05:04.6 | 54.85N | 20.04E | 6.6 km | 13:32:30.8 | 54.88N | 20.05E | 8.4 km |
| 7 | GSRAS | 11:05:05.0 | 54.84N | 20.13E | 21 km | 13:32:31.3 | 54.84N | 20.17E | 17 km |
| 8 | MOS | 11:05:02.0 | 54.843N | 20.024E | 10 km fix | 13:32:28.3 | 54.896N | 20.185E | 10 km fix |
| 9 | ISC | 11:05:03.0 | 54.83N | 20.04E | 10 km fix | 13:32:28.58 | 54.82N | 19.96E | 10 km fix |
| 0 | IGF PROB | 11:05:01.6 ± 1.4 | 54.924N ± 0.021 | 20.120E ± 0.050 | 16.0 km ± 9.3 | 13:32:31.0 ± 1.3 | 54.876N ± 0.021 | 20.120E ± 0.055 | 20.0 km ± 10.1 |
| * | Mean instr. | 11:05:03.6 ± 0.4 | 54.908N ± 0.036 | 20.029E ± 0.026 | n/a | 13:32:30.7 ± 0.5 | 54.849N ± 0.016 | 20.088E ± 0.031 | n/a |

IGF is the Polish Institute of Geophysics, using the IASPEI, AK135 models or probabilistic location, EMSC, ORFEUS and NEIC are self-explanatory, ASS is the Assinovskaya location, GSRAS is the Geophysical Survey of Russian Academy of Sciences, MOS is Moscow datacenter, ISC is the International Seismological Centre.

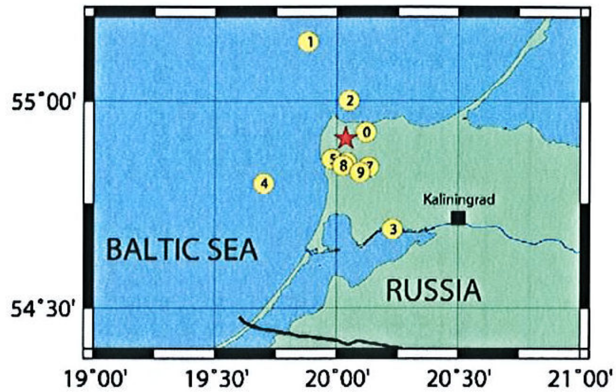


Fig. 4 Instrumental locations of the 11:05 UTC Kaliningrad earthquake according to agencies/scientific teams in Table 3.

the second event, which must be considered good in view of the fairly large distances to the seismic stations and the source size comparable to the accuracy. The nine instrumental locations, their means and the probabilistic locations are shown on maps in Figs. 4 and 5.

The Geophysical Survey of the Russian Academy of Sciences (GSRAS) has additionally calculated the instrumental location of the greatest aftershock that has taken place on 13:36:33.8 UTC - at 54.87N, 19.99E, with a depth of 0.5 ± 3 km. The location of this event by the probabilistic method is impossible due to an insufficient amount of data.

## 7. Magnitudes

Magnitudes determined by different seismological agencies vary. EMSC determined mb = 4.4 and mb = 5.0 for the two events while NEIC gave the

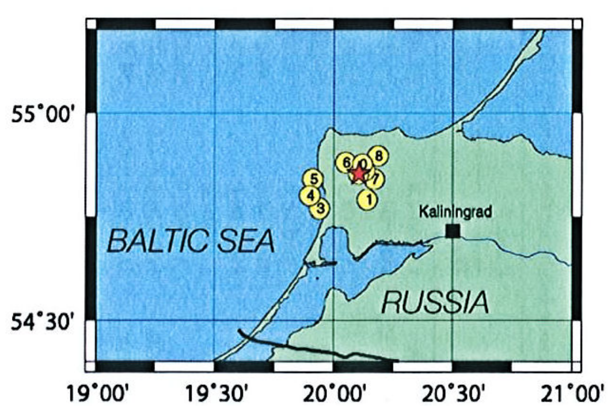


Fig. 5 Instrumental locations of the 13:32 UTC Kaliningrad earthquake according to agencies/scientific teams in Table 3.

values mb = 4.8 and mb = 4.9. Harvard moment magnitude for the second event is $M_w = 4.7$. GSRAS obtained the values $M_S = 4.1$ for the first shock, $M_S = 4.3$ for the second shock and $M_S = 3.0$ for the third shock, and $M_w = 4.8$ for the second shock. $M_w$ obtained from spectral analysis in this study are 5.0 and 5.2 (Table 2 after rounding).

Single station local magnitudes ML can be calculated from Sg/Lg wave amplitude on simulated Wood-Anderson display using the Seismic Handler program (Stammler, 1993). It must be regionally corrected depending on period, by 0.2-0.4 units down, following Bormann et al. (2002) and Wahlstrom and Strauch (1984). These $M_L$ values range between 4.7 and 5.1 for the first event and from 4.9 to 5.4 for the second, with the exception of station SUW where the values are especially high at 5.3 and 5.9, respectively. Except for SUW, the individual station magnitudes in Poland are by 0.1-0.2 magnitude units higher than those reported by datacenters and this result is confirmed by the value from VSU in Estonia. Husebye and Mäntyniemi (2005) quote a similar scatter of single-station magnitudes, ranging from 4.3 to 6.0 for the first and from 4.8 to 6.0 for the second earthquake. $M_L$ averaged over all stations within the 600 km applicability limit of the Gutenberg-Richter definition results in 5.0 for the first and 5.2 for the second event.

The differences in reported magnitudes are the result of a combination of local conditions in the propagation paths and at the stations and the directional radiation pattern. For the seismological datacenters the averaging among a selection of stations is critical. Most of the stations reporting on-line to the EMSC datacenter were in the southwestern direction where the seismic waves should be systematically weakened by the TTZ along the way (Schweitzer, 1995). However both large and weak Lg waves, on which the ML magnitude is based, were found south west of TTZ (Husebye and Mäntyniemi, 2005). Also in Norway, which is on the same side of TTZ as the earthquakes, observations show both large and small Lg amplitudes (Husebye and Mäntyniemi, 2005). In previous investigations by Kennett et al. (1985) and by Kvaerna and Mykkeltveit (1985) it was shown that TTZ north of Poland is only marginally a barrier for the Lg waves, and that the influence is frequency dependent. TTZ is a barrier for the human perception of the shaking as seen in Figs. 1 and 2, while the picture is more complicated for the Lg waves on which local magnitude calculations are based.

We note that the averaged $M_L$ magnitudes are in

Table 4
Source mechanism parameters of the Kaliningrad earthquakes resulting from IGF fault plane (f.p.) solution and moment tensor inversion

| | IGF f.p. | IGF Event 1 | IGF Event 2 | Harvard | INGV | ETHZ |
|---|---|---|---|---|---|---|
| Seismic moment 1016 N m | - | 0.57 | 2.13 | 1.40 | 1.20 | 1.38 |
| Nodal plane A strike | 211 | 202.0 | 204.7 | 205 | 211 | 206 |
| Nodal plane A dip | 88 | 89.2 | 84.3 | 78 | 81 | 86 |
| Nodal plane B strike | 301 | 111.7 | 113.4 | 297 | 300 | 294 |
| Nodal plane B dip | 82 | 73.7 | 77.3 | 80 | 81 | 64 |

Except for IGF Event 1 all data pertain to the second, larger event. In spite of the apparent differences in the azimuth of nodal plane B all these solutions are similar, in case of the IGF moment tensor solutions the nodal plane B azimuth is complementary because of opposite direction of dipping of the nodal plane. Non-shear component of all moment tensor solutions is below 5%.

accord with the $M_w$ values obtained from spectral analysis, both methods giving magnitudes of the two main Kaliningrad earthquakes on September 21, 2004 of 5.0 and 5.2, respectively.

## 8. Focal mechanism

The focal mechanism has been routinely calculated by moment tensor inversion at three seismological centers: Harvard University, INGV Mednet and the Swiss Seismological Service (ETHZ). The Institute of Geophysics, Polish Academy of Sciences (IGF) calculated a fault plane solution (Wiejacz, 2004) similar to earlier calculations for the 1992-1993 Krynica earthquakes (Dębski et al., 1997) and later has made a seismic moment tensor inversion using all available waveform data. The method was basically the same as the one used in studying the 1995 Egion, Greece, aftershock sequence (Gibowicz et al., 1999).

Despite the methodological differences and the IGF using more data from relatively near stations all the focal mechanisms are similar with dominating strike slip. The source mechanisms of the two events, as determined by IGF differ only in their size, while the angular parameters vary less than 5° - an effect that can easily be attributed to numerical stability. The INGV Mednet, ETHZ and Harvard University only determined a solution for the largest earthquake. The basic parameters of the solutions are given in Table 4 and the mechanism plots according to Harvard and IGF solutions are shown in Fig. 6.

Of the two nodal planes, plane B looks like the better candidate to be the plane of rupture whereas plane A is rather the auxiliary plane. One indication of this is tectonic as plane B is almost parallel to the TTZ. Another indication is the lack of evidence of earthquakes along the direction of plane A, relatively densely populated in comparison to the direction of plane B. A third indication is found in the extremely high S-wave amplitudes southeasterly towards SUW and northwesterly towards BLEU, which could be caused by rupture along a fault in this direction.

In contrast to the mechanism type itself and its angular parameters, the IGF moment tensor solution yields somewhat larger seismic moment. The resultant moment magnitude for the second event is 4.9, whereas it is 4.7 for the Harvard, INGV and ETHZ solutions. This difference can be attributed to the same causes as mentioned above in the discussion of magnitudes. Our calculation of the moment magnitude for the first earthquake is 4.5.

A source mechanism derivation by non-instrumental data has been made independently by our Russian colleagues. It is reported separately by Nikonov (2005b) and by Nikonov et al. (2005, 2006). The data were gathered and analyzed separately for each of the first three shocks. Those investigations have focused on the character of the oscillations, the direction of the rumble, and oscillations in the proximal zone during each of the shocks.

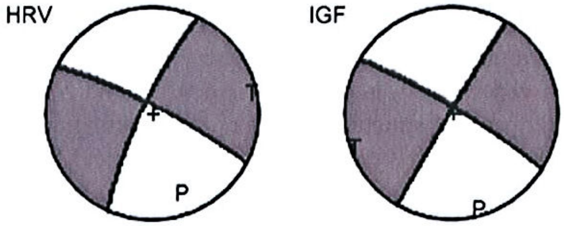


Fig. 6 Source mechanism diagrams according to the Harvard University (HRV) and Institute of Geophysics, Polish Academy of Sciences (IGF) moment tensor solutions of the second, bigger Kaliningrad earthquake of September 21, 2004.

## 9. Discussion and conclusion

The Kaliningrad earthquakes of September 21, 2004 occurred in an area previously considered aseismic and were so unexpected that at first they were suspected of being human-induced. Seismology provides evidence that the earthquakes were natural. The earthquake sources were located at 16-20 km depth, and focal mechanisms of clear strike-slip type rule out blast as the cause of the events.

The earthquake sources have been located under the Sambia Penninsula, about 20 km northwest of Kaliningrad city. The calculated instrumental locations are in accord with the macroseismic indications of depth of the events. Variations in the intensities close to the epicenters are interpreted to be caused mainly by differences in local geological structures. The focal mechanisms are right-lateral strike slip-most likely on a fault almost parallel to the TTZ. The instrumental focal mechanisms are in disaccord with the macroseismic source mechanisms determined by Nikonov (2006).

Magnitudes of the quakes have been established at 5.0 and 5.2 ($M_L$ and $M_w$ equal). For quakes of this size, the source radii are small-of the order of 1 km. In contrast to the small source size, the average displacements and stress drops are relatively large. The small source size and large stress drop result in the seismic signal having considerable high frequency component, causing serious macroseismic effects at relatively large distances, e.g. in the City of Suwałki, Poland about 200 km from the epicenter.

After evaluation of all the observations the discussion is still going on concerning the tectonic origin of the events. The Kaliningrad region is far from tectonic plate boundaries and there is no known seismically active fault. The TTZ 200 km south-west of the earthquakes has been a tectonic plate boundary between geological terranes known as Baltica and Avalonia in late Paleozoic times, but it appears to be inactive in the current geological epoch (Gregersen, 1995). Northeast of the TTZ, the Baltic area is known for weak seismic activity caused mainly by plate motion and influenced by post-glacial rebound (Gregersen, 2002). At this stage of investigations the Russian macroseismic evaluations (Nikonov, 2006) point to local faults along or parallel to the coasts of the Sambia Peninsula. The strike-slip mechanism on the other hand shows release of horizontal compressional stress oriented NNW-SSE and is in agreement with the regional stress field. This is dominated by nearly horizontal NW-SE compression in the major part of the Fennoscandian Shield (Slunga, 1989). Breakout studies in oil exploration wells in the southern part of the Baltic Sea (Polish offshore area) indicate dominance of NNW-SSE orientation of the maximum horizontal compressive stress (Jarosinski, 2005). NW-SE orientation is again identified in west Lithuania (Sliaupa and Zakarevicius, 2000). Strike slip faulting is not too common in the vast Fennoscandian area. The predominant faulting is thrust-type (Lundqvist and Lagerbäck, 1976; Lagerbäck, 1979). Gregersen and Basham (1989) and Stewart et al. (2000) investigated this and found that post-glacial rebound does not rule out strike slip mechanism. Mixtures of normal, thrust and strike slip faulting have been found in Norway (Hicks, 1996), Sweden (Slunga, 1989), Great Britain (Main et al., 1999), Greenland (Gregersen, 1989; Johnston, 1989), and in the Gulf of Finland (Slunga, 1989; Nikonov, 2002) with mechanisms indicating release of compression. A recent example of such strike slip faulting is the Dudley, UK, earthquake on September 22, 2002, of magnitude 4.7 (Baptie et al., 2005). The strike slip motion must be seen as release of regional stress on local faults. The tectonic stresses most likely come from ridge push forces from the MidAtlantic Ridge (Gregersen, 2002; Nikonov, 2005a, 2006; Husebye and Mäntyniemi, 2005) and forces inflicted on the Eurasian Plate by the African Plate pushing from the south.

The occurrence of the September 2004 earthquakes indicated that the seismic potential of the area may be larger than previously thought. A thorough investigation of historical documents reveals remarks and observations that must be historically studied and analyzed to construct a seismicity record of the region. These studies are difficult because of large population migration through history.

One of the most exciting results of this investigation is that concerning the wave propagation from the Kaliningrad earthquakes. The seismic waves, exemplified by the Sg/Lg waves, propagate extremely far in the Fennoscandian Shield, and the macroseismic area shows the same. The TTZ has some attenuating effect on the seismic waves recorded on the seismograph stations. This is seen beyond any doubt in the macroseismic intensity maps. These maps and the corresponding instrumental information on the source parameters open a fantastic possibility of comparison with older earthquakes in 1759, 1819, 1904 and possibly others in the East European Craton/Fennoscandian Shield.

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## References

Aptikaev, F.F., Nikonov, A.A., Alyoshin, A.S., Assinovskaya, B.A., Pogrebchenko, V.V., Erteleva, O.O., 2005. Kaliningrad earthquake of September 21, 2004 damage. In: International Conference on Earthquake Engineering Skopje EE-21C. CD: Topic 1: Lessons from Past Earthquakes, pp. 1-8.

Arvidsson, R., Kulhánek, 0., 1994. Seismodynamics of Sweden deduced from earthquake focal mechanisms. Geophys. J. Int. 116, 377-392.

Assinovskaya, B.A., 2005. Macroseismic effect of September 21, 2004 Kaliningrad earthquakes around the Saint-Petersburg Region. In: Jõeleht, A. (Ed.), The Kaliningrad Earthquake September 21, 2004 Workshop Materials. Institute of Geology, University of Tartu, p. 9.

Avotinia, I.J., Boborykin, A.M., Emelianov, A.P., Sildvee, H.H., 1988. Catalogue of Historical Earthquakes of Belarus and Baltic. Seismological Bulletin of Seismic Stations Minsk (Pleshenici) and Naroch for Year 1984. Institute of Geochemistry and Geophysics, Academy of Science of Belarus, pp. 126-137 (in Russian).

Baptie, B., Ottemoller, L., Sargeant, S., Ford, G., O'Mongain, A., 2005. The Dudley earthquake of 2002: a moderate sized earthquake in the UK. Tectonophysics 401, 1-22.

Boborykin, A.M., Garetsky, R.G., Emelianov, A.P., Sildvee, H.H., Suveizdis, P.I., 1993. Earthquakes of Belarus and Baltic region. Current state of seismological observations and their generalization. In: Methodological Proceedings of Unified System of Seismological Observations N 4. Academy of Sciences Belarus, pp. 29-39 (in Russian).

Bormann, P., Baumbach, M., Bock, G., Grosser, H., Choy, G.L., Boatwright, J., 2002. In: Bormann, P. (Ed.), Seismic Sources and Source Parameters, New Manual of Seismological Observatory Practice. GeoforschungsZentrum Potsdam (Chapter 3).

Brune, J.N., 1970. Tectonic stress and the spectra of seismic shear waves from earthquakes. J. Geophys. Res. 75, 4997-5009.

Dębski, W., Guterch, B., Lewandowska-Marciniak, H., Labak, P., 1997. Earthquake sequences in the Krynica region, western Carpathians 1992-1993. Acta Geophys. Polonica 40, 255-290.

Garetsky, R.G., Aizberg, R.E., Aronov, A.G., Karabanov, A.K., Safronov, 0.N., 1997. General seismic zoning of Belarus and of the Baltic region. Acad. Sci. Belarus 41 (4), 98-102 (in Russian).

Gibowicz, S.J., Kijko, A., 1994. An Introduction to Mining Seismology. Academic Press, San Diego.

Gibowicz, S.J., Domanski, B., Wiejacz, P., 1999. Focal mechanism and source time function of selected aftershocks of the Egion 1995 earthquake, Gulf of Corinth, Greece. Acta Geophys. Polonica 47, 1-26.

Grad, M., Janik, T., Yliniemi, A., Guterch, A., Luosto, U., Türa, T., Komminakho, K., Sroda, P., Honig, K., Makris, J., Lund, C.E., 1999. Crustal structure of the mid-Polish Trough beneath the Teisseyre-Tornquist zone seismic profile. Tectonophysics 314, 145-160.

Grad, M., Jensen, S.L., Keller, G.R., Guterch, A., Thybo, H., Janik, T., Türa, T., Yliniemi, J., Luosto, U., Motuza, G., Nasedkin, V., Czuba, W., Gaczynski, E., Sroda, P., Miller, K.C., Wilde-Piorko, M., Komminakho, H., Jacyna, J., Korabiova, L., 2003. Crustal structure of the Trans-European Suture Zone region along POLONAISE'97 seismic profile P4. J. Geophys. Res. 108 (B 11), 2541.

Gregersen, S., 1984. Lg-wave propagation and crustal structure differences near Denmark and the North Sea. Geophys. J. R. Astron. Soc. 79, 217-234.

Gregersen, S., 1989. The seismicity of Greenland. In: Gregersen, S., Basham, P.W. (Eds.), Earthquakes at North-Atlantic Passive Margins: Neotectonics and Postglacial Rebound. Kluwer, Dordrecht, pp. 345-353.

Gregersen, S., 2002. Earthquakes and change of stress since the ice age in Scandinavia. Bull. Geol. Soc. Denmark 49, 73-78.

Gregersen, S., Basham, P.W. (Eds.), 1989. Earthquakes at NorthAtlantic Passive Margins: Neotectonics and Postglacial Rebound. Kluwer Academic Publishers, Dordrecht, Netherlands, 716 pp.

Gregersen, S., the working group on recent crustal movements around the Tornquist Zone, 1995. Recent crustal movements and earthquakes in the area of the Tornquist Zone. Stud. Geophys. et Geodaetica 39, 257-261.

Gregersen, S., Mäntyniemi, P., Nikonov, A.A., Aptikaev, F.F., Aleshin, A.S., Assinovskaya, B.A., Pogrebchenko, V.V., Guterch, B., Nikulin, V., Pacesa, A., Wahlström, R., Schweitzer, J., Kulhänek, O., Holmquist, C., Heinloo, O., Puura, V., 2005. Felt reports at large distances of the earthquakes in non-seismic Kaliningrad in West Russia. In: Jöeleht, A. (Ed.), The Kaliningrad Earthquake September 21, 2004 Workshop Materials. Institute of Geology, University of Tartu, pp. 11-12.

Grünthal, G. (Ed.), 1998. European Macroseismic Scale 1998. Cahiers du Centre Européen de Géodynamique et de Séismologie 15, Luxembourg, Imprimerie Joseph Beffort, Helfent-Bertrange, 99 pp.

Guterch, B., Lewandowska-Marciniak, H., 2002. Seismicity and seismic hazard in Poland. Folia Quaternaria 73, 85-99.

Harboe, E.G., 1912. Das Skandinavische Erdbeben am 23 Oktober 1904, Gerlands Beitragen zur Geophysik, Band XI, pp. 470-500 (in German).

Hicks, E.C., 1996, Crustal stresses in Norway and surrounding areas as derived from earthquake focal mechanism solutions and insitu stress measurements, M.Sc. thesis, Department of Geology, University of Oslo, 164 pp.

Husebye, E., Mäntyniemi, P., 2005. The Kaliningrad, west Russia earthquakes on the 21st of September 2004-surprise events in a very low-seismicity area. Phys. Earth Planet. Interiors 153, 227-236.

Jarosinski, M., 2005. Ongoing tectonic reactiviation of the outher Carpathians and its impact on the foreland: results of borehole breakout measurements in Poland. Tectonophysics 410, 189-216.

Jõeleht, A. (Ed.), 2004. The Kaliningrad Earthquake September 21, 2004 Workshop Materials. Institute of Geology, University of Tartu, Estonia, 52 pp.

Johnston, A.C., 1989. The effect of large ice sheets on earthquake genesis. In: Gregersen, S., Basham, P.W. (Eds.), Earthquakes at North-Atlantic Passive Margins: Neotectonics and Postglacial Rebound. Kluwer, Dordrecht, pp. 345-353.

Kennett, B.L.N., Gregersen, S., Mykkeltveit, S., Newmark, R., 1985. Mapping of crustal heterogeneity in the North Sea basin via the propagation of Lg-waves. Geophys. J. R. Astron. Soc. 83,299-306.

Kvaerna, T., Mykkeltveit, S., 1985. Propagation characteristics of regional phases recorded at NORSAR. NORSAR Scientific Report no. 1-85/86, Final Technical Summary, 1 APR-30 SEP 1985.

Lagerbäck, R., 1979. Neotectonic structures in Northern Sweden. Geologiska Föreningens Stockholm Förhandlingar 100, 263-269.

Lundqvist, J., Lagerbäck, R., 1976. The Parvie fault: A late glacial fault in the Precambrian of Swedish Lapland. Geologiska Föreningens Stockholm Förhandlingar 98, 45-5 1.

Madariaga, R., 1976. Dynamics of an expanding circular fault. Bull.

Seism. Soc. Am. 66, 639-666.
Main, 1., Irving, D., Musson, R., Reading, A., 1999. Constraints on the frequency-magnitude relation and maximum magnitudes in the UK from observed seismicity and glacio-isostatic recovery rates. Geophys. J. Int. 137, 535-550.
Meyer, K., Kulhánek, 0., 1981. The Gulf of Gdatisk seismic event sequence of June 25-July 3,1980. Acta Geophys. Pol. 29,315-320.
Nikonov, A.A., 2002. The Osmussaar earthquake of October 25, 1976: macroseismic analysis, seismotectonics, and focal mechanism, Izvestiya. Phys. Solid Earth 38 (8), 690-703.
Nikonov, A.A., 2004. The Narva, 28.01,1881 earthquake in the East Baltic area. In: Proceedings of the European Seismology Commission Assembly, GeoForschungsZentrum Potsdam, p. 45.
Nikonov, A.A., 2005a. Were there worthy of note earthquakes and tsunamis within the south-eastern Baltic area? In: Jõeleht, A. (Ed.), The Kaliningrad Earthquake September 21, 2004 Workshop Materials. Institute of Geology, University of Tartu, pp. 23-25.
Nikonov, A.A., 2005b. Po sledam Kaliningradskogo zemletriasenia (on the traces of the Kaliningrad earthquake). Priroda (3), 47-53 (In Russian).
Nikonov, A.A., 2006. On the Kaliningrad earthquake, September 21, 2004 source mechanism. Doklady Earth Sci. RAN 407 (12), 317-320 (in Russian).
Nikonov, A.A., Aptikaev, F.F., Aleshin, A.S., Assinovskaya, B.A., Pogrebchenko, V.V., Ponomareva, 0.N., 2005. Kaliningrad earthquake of September 21, 2004, macroseismic data for near and mesoseismal zones. In: Jõeleht, A. (Ed.), The Kaliningrad Earthquake September 21, 2004 Workshop Materials. Institute of Geology, University of Tartu, pp. 26-29.
Nikonov, A.A., Aptikaev, F.R, Aleshin, A.S., Assinovskaya, B.A., Pogrebchenko, V.V., 2006. Kaliningradskoye zemletriasenie 21 sentiabria 2004 goda kak model'noe dlia Vostochno-Evropeiskoi platformy. In: 21 Century Geophysics: 2005. Papers of the 7th V.V. Fedynsky Geophysical Conference (3-5 March 2005), Moscow, Nauchny Mir, Moscow, pp. 282-289 (in Russian).
Nikulin, V., 2005. Estimations of Seismic effects in Latvia from the Kaliningrad earthquake of September 21, 2004. In: Jõeleht, A. (Ed.), The Kaliningrad Earthquake September 21, 2004 Workshop Materials. Institute of Geology, University of Tartu, pp. 30-31.
OSR-97. Komplekt kart obshchego seismicheskogo rayonirovania territorii Rossiyskoy Federazii OSR-97, 1:8,000,000. Ob'yasnitelnaya zapiska (set of maps general seismic zoning for the territory of Russian Federation. Explanatory comments). OIFZ RAN. Moskva, 1999, 56 pp. (in Russian).
Pacesa, A., Sliaupa, S., Lazauskiene, J., 2005. Compilation of macroseismic data of Kaliningrad earthquakes and perspectives of seismological investigation in Lithuania. Geologijos Akiraciai 2 (58), 46-53 (in Lithuanian).
Pagaczewski, J., 1972. Catalogue of earthquakes in Poland in 1000-1970 years. Publs. Inst. Geophys. Pol. Acad. Sci. 51, 3-36.
Reisner, G.I., Ioganson, L.I., 1993. Seismicheskij potenzial Zapadnoi Rossii, drugikh stran SNG 1 Baltii (about seismic potential of the Western Russia, other countries of UIC and Baltic countries). In: Ulomov, V.I. (Ed.), Seismicity and Seismic Zoning of the North Eurasia. M.: IFZ RAN. Vyp 1, pp. 186-195 (in Russian).
Schenk, V., Schenková, Z., Kottnauer, P., Guterch, B., Labak, P., 2001. Earthquake hazard maps for the Czech Republic, Poland and Slovakia. Acta Geophys. Pol. 49, 287-302.
Schweitzer, J., 1995. Blockage of regional seismic waves by the Teisseyre-Tornquist Zone. Geophys. J. Int. 123, 260276.
Sliaupa, S., Zakarevicius, A., 2000. Recent stress pattern in eastern part of the Baltic Basin, Lithuania. In: Europrobe (TESZ) and PACE Workshop Abstracts Volume, Warsaw, p. 79.
Sliaupa, S., Pacesa, A., 2005. Macroseismic observations and instrumental recording of Kaliningrad earthquakes 2004.09.21 in Lithuania. In: Jöeleht, A. (Ed.), The Kaliningrad Earthquake September 21, 2004 Workshop Materials. Institute of Geology, University of Tartu, pp. 11-12.
Slunga, R., 1979. Source mechanism of a Baltic earthquake inferred from surface wave recordings. Bull. Seism. Soc. Am. 69, 1931-1964.
Slunga, R., 1989. Focal mechanisms and crustal stresses in the Baltic Shield. In: Gregersen, S., Basham, P.W. (Eds.), Earthquakes at North-Atlantic Passive Margins: Neotectonics and Postglacial Rebound. Kluwer, Dordrecht, pp. 261-276.
Snoke, J.A., 1987. Stable determination of Brune stress drops. Bull. Seism. Soc. Am. 77, 530-538.
Snoke, J.A., Linde, A.T., Sacks, I.S., 1983. Apparent stress: an estimate of the stress drop. Bull. Seism. Soc. Am. 73, 339348.
Stammler, K., 1993. Seismic Handler-programmable multichannel data handler for interactive and automatic processing of seismological analyses. Comput. Geosci. 19, 135-140.
Stewart, I.S., Sauber, J., Rose, J., 2000. Glacio-seismotectonics: ice sheets, crustal deformation and seismicity. Q. Sci. Rev. 19, 1367-1389.
Uski, M., Hyvönen, T., Korja, A., Airo, M.-L., 2003. Focal mechanisms of three earthquakes in Finland and their relation to surface faults. Tectonophysics 363, 141-157.
Vall, T., Kalle, A., Talts, K., Veske, A., Kestlane, U., Heinloo, 0., Puura, V., 2005. Kaliningrad earthquakes, September 21, 2004: macroseismic effects in Estonia. In: Jõeleht, A. (Ed.), The Kaliningrad Earthquake September 21, 2004 Workshop Materials. Institute of Geology, University of Tartu, pp. 39-43.
Wahlstrom, R., Strauch, W., 1984. A regional magnitude scale for Central Europe based on crustal wave attenuation. Seism. Dep. Univ. Uppsala Report 3-84, 16 pp.
Wiejacz, P., 2004. Preliminary investigation of the September 21, 2004 earthquakes of the Kaliningrad Region, Russia. Acta Geophys. Pol. 52,415-441.
Wiejacz, P., Dębski, W., 2005. Kaliningrad earthquakes of September 21, 2004. In: Jõeleht, A. (Ed.), The Kaliningrad Earthquake September 21, 2004 Workshop Materials. Institute of Geology, University of Tartu, pp. 44-52.
Wiejacz, P., 2006. The Kaliningrad earthquakes of September 21, 2004. Acta Geodyn. Geomater 3, 7-16.