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THE KALININGRAD EARTHQUAKES OF SEPTEMBER 21, 2004

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ABSTRACT
The earthquakes of magnitudes M_L=5.0 and 5.3 in the Kaliningrad enclave of Russia on September 21, 2004 were unexpected in a very low-seismicity area. The earthquakes caused minor damage in the Kaliningrad enclave, in northern Poland and in southwestern Lithuania, and macroseismic intensities of 6-7 (EMS) close to the epicenters. The earthquakes were felt up to 800 km distance. The events have been located under the central-northern part of the Sambia Penninsula at 16 and 20 km depth. Their source mechanism has been found to be a right lateral strike slip on a direction parallel to the edge of the Fennoscandian Shield and the East European Craton. The possible cause of the earthquakes is discussed. With the glaciotectonic cause unlikely, it seems the earthquakes evidence tectonic patterns, possibly resulting from stress propagating all across Europe from the Mediterranean region. Historical information seems to evidence past seismic activity in the region, which together with the 2004 earthquakes show the need to reassess seismic hazard in the area.

KEYWORDS: local seismicity; baltic region; hypocenter location, source mechanism

1. INTRODUCTION

Seismic activity in the Baltic Sea area is generally considered low, with maximum observed earthquake magnitudes well below 6. Earthquakes that occur in the area are attributed to ridge push forces originating from the Mid-Atlantic Ridge or to postglacial rebound (e.g., Husebye and Mäntyniemi, 2005; Gregersen and Basham, 1989; Lundqvist and Lagerbäck, 1976; Lagerbäck, 1979; Slunga, 1989; Arvidsson and Kulhánek, 1994; Uski et al., 2003). Seismic hazard in the area has been considered low, and studies by Schenk et al. (2001) and Guterch and Lewandowska-Marciniak (2002) show that the maximum historical intensity ranges from 3 in northern Poland to 5 in northeastern Poland, this due to four reports of earthquakes in the catalogue of Pagaczewski (1972). Thus, the occurrence of two earthquakes on September 21, 2004 was a big surprise not only to the local population but to most of the seismological community as well.

The earthquakes September 21, 2004 occurred in the territory of the Kaliningrad enclave and were felt as far as Norway and Belarus (Gregersen et al., 2005) and even in St. Petersburg (Assinovskaya, 2005). They caused minor damage in Kaliningrad Region of Russia, in northern Poland and in southwestern Lithuania. The first event occurred at 11:05 UTC, the second at 13:32 UTC, and a small aftershock followed the second event four minutes later. There were four felt reports during the following night, not confirmed instrumentally. The earthquakes were recorded at numerous seismic stations across the world. However, there was no seismic station in the Kaliningrad enclave itself but the closest station was Suwałki (SUW) in Poland, at a distance of 220 km.

2. MACROSEISMIC OBSERVATIONS

The Kaliningrad earthquakes on September 21, 2004 were widely felt in the Kaliningrad enclave, northern Poland, and southwestern Lithuania, and felt observations were made in all the countries surrounding the Baltic Sea and also in Belarus and Norway. Detailed intensity maps of the very central region have been prepared by the Geophysical Survey of Russia and are subject for a separate publication. The epicentral intensity of the larger earthquake was assessed at 6 in EMS-98 scale (Gruenthal,1998). In Kaliningrad one person died of a heart attack caused by fear, 20 people were seriously wounded by falling objects and about 2100 buildings suffered damage amounting to about $5,000,000 (Nikonov et al., 2005). The earthquakes caused great anxiety and rumors that the events were human-induced, in particular people feared an accidental nuclear explosion. The tectonic cause became clear once the felt reports started flowing in from a relatively wide area, indicating a considerable source depth of the events. Rumors and fear caused temporary problems in the telecommunications system in the area, thus contributing to further havoc. The earthquake had also surprising co-seismic aftereffects, namely vertical ground displacements of up to 40 cm over about 150 m distance (Wiejacz and Dębski, 2005) and local railway line collapse over about 100 m. These effects may be

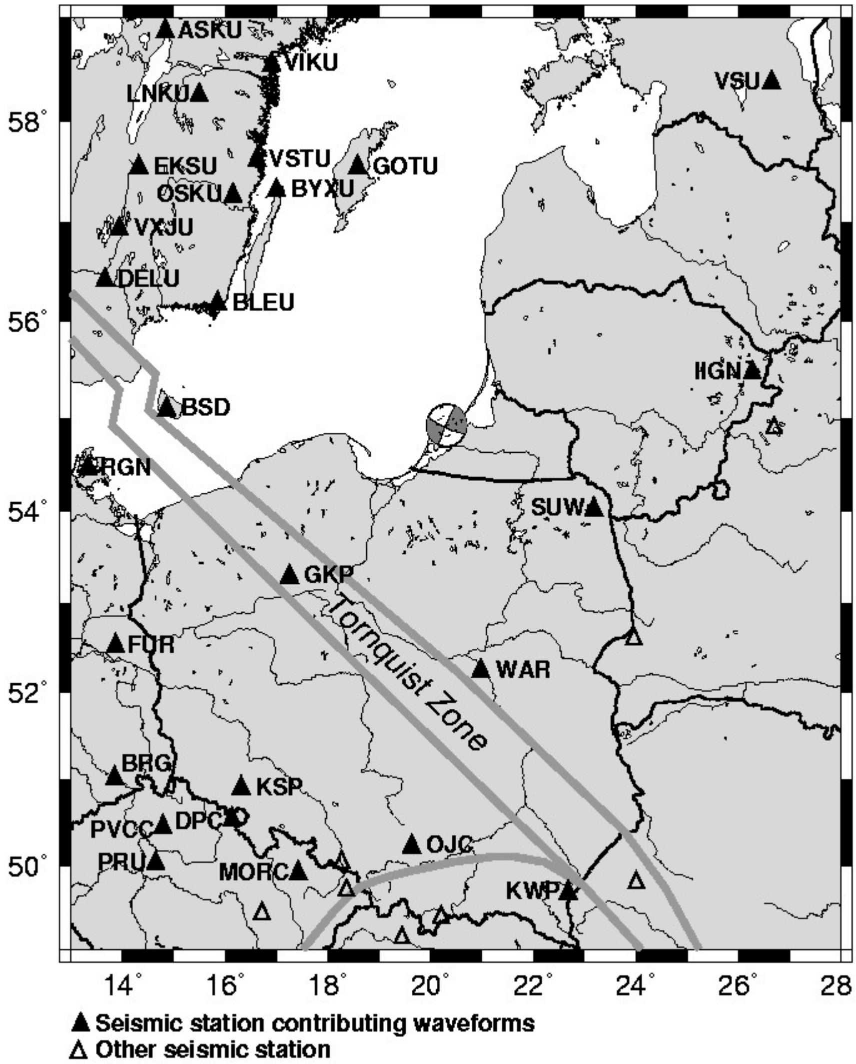

Fig. 1 Map of the region around the sources of the Kaliningrad earthquakes, showing the locations of seismic stations. Stations providing waveform data are shown as black triangles, while other stations are shown as open triangles. The IIGN station is actually a small network of four stations. Map also shows the Tornquist-Teisseyre Zone with the East and West European Platforms and the Carpathian orogen along the southern edge of the map. The epicenter is marked by source mechanism.

attributed to failure of nearby river embankment composed of soft sediments and of a railway bank made of mostly sand and clay that in addition was saturated with water due to prolonged rain. As is discussed later, the observed vertical displacement does not accord with the strike slip source mechanism but is in accord with direction of nearby river embankment. The considerable source depth should not result in faulting observed at the surface in case of earthquakes of this size.

In northern Poland, the larger earthquake caused minor damage to buildings at about 100 localities (Zembaty et al., 2005). In Lithuania there were many reports of intensity 5 (Sliaupa and Pacesa, 2005), and a few dozens reports of cracked walls and broken window frames. A few people were frightened and ran out of buildings. Further to the north in Latvia, the intensity barely reached 5 and caused cracks in walls of several buildings (Nikulin, 2005). In Estonia, the shaking was of intensity 4 and below 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 of up to 800 km. In Landskrona, southwestern Sweden the shaking was so violent that the town hall was evacuated for a moment (Gregersen et al., 2005). Especially noteworthy is the large felt area in the Baltic and East European cratons in agreement with previous observations (e.g. Harboe, 1912) and with common seismological observations demonstrated in the magnitude scales for small earthquakes in Scandinavia.

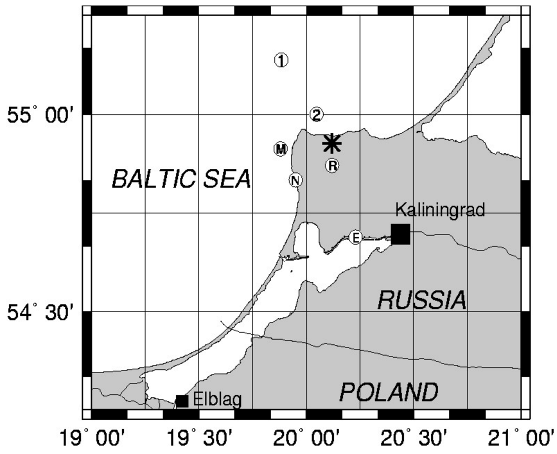

Fig. 2 Locations of the 11:05 UTC Kaliningrad earthquake. Asterisk shows the final probabilistic location. Hyposat locations are denoted by (1) and (2), EMSC location is denoted by (E), and NEIC location is denoted by (N). The GSRAS locations are (R) for the instrumental and (M) for macroseismic data. Harvard location is not available for this event.

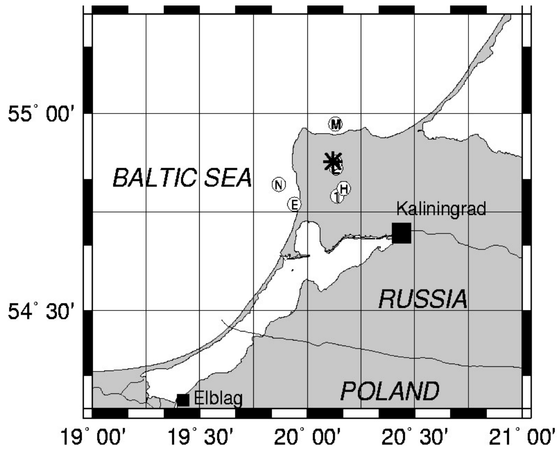

Fig. 3 Locations of the 13:32 UTC Kaliningrad earthquake. Asterisk shows the final probabilistic location. Hyposat IASPEI-91 location is denoted by (1), EMSC location by (E), NEIC location by (N) and Harvard location by (H). The GSRAS macroseismic location is denoted by (M). The Hyposat locations using AK135 and GSRAS instrumental location fall in almost the same place as the probabilistic location.

3. INSTRUMENTAL RECORDINGS AND SOURCE LOCATION

The earthquakes occurred relatively far from seismic stations, considering the number of seismic stations installed in Europe (Figure 1). In the Kaliningrad enclave not a single seismic station existed at the time of the earthquakes. It may be interesting to note that a seismological observatory of the Königsberg University existed in the very epicentral area but was destroyed during World War II. The stations closest to the epicenter were those in Poland: Suwałki (SUW) at a 220-km epicentral distance was the nearest, somewhat more distant were Górka Klasztorna (GKP) and Warsaw (WAR). Important data came also from the local Ignalina Nuclear Power Plant network (INPP) in Lithuania and from the BSD station on the Island of Bornholm in Denmark. Numerous other stations were located at distances exceeding 400 km and, for the most part, on the other side, i.e. the SW side of the Tornquist zone. The earthquakes were large enough to be detected by a few stations as far as the southwestern United States.

The location of the events posed some problems. Since there are no seismic stations at local distances – understood as such that yield first wave arrivals of Pg type – instrumental location had to be conducted using more distant stations and constituted a regional problem in a quite complicated geological setup. The source area is located on the East European Platform about 100-150 km of its margin, while most of the seismic stations are located on the West European Platform on the other side of the Tornquist-Teisseyre Zone. Each of the two platforms and the Tornquist-Teisseyre Zone are characterized by their own velocity models. Due to the lack of sizable earthquakes in the area very little is known about these models. Deep Seismic Sounding experiments carried out in the 1990s (Guterch et al., 1991; 1999, Grad et al., 1991; 1999; 2003, Czuba et al., 2002, Janik et al., 2002; Środa et al., 1999; Yliniemi et al., 2001) and in 2000 have given insight into the geological structure but have also revealed much complexity. It is difficult to build a velocity model for the whole area, especially if it is to be a horizontal layer model as required by most location procedures.

Preliminary location was performed using the Hyposat program (Schweitzer, 2001) making use of the standard travel time models IASPEI91 (Kennett and Engdahl, 1991) and AK135 (Kennett et al., 1995). Final location was performed after verifying all possible data, using the probabilistic approach that has been used earlier in studying a series of apparently induced events in the Gulf of Gdansk (Wiejacz and Dębski, 2001). The location results are given in Table 1. The depth values are somewhat uncertain, since the closest seismograph station is at a distance of 220 km, and the local velocity model is not well known. The depths quoted are medians of the allowed depth range.

Location of the third event (greatest aftershock) by the probabilistic method was not possible due to too few stations that recorded the event. Location of

Table 1 Instrumental location results for the two main Kaliningrad earthquakes of September 21, 2004 obtained by the probabilistic method.

	Time (UTC)	Latitude N	Longitude E	Depth km
Event 1	11:05:01.6±1.4	54.924±0.021	20.120±0.050	16.0±9.3
Event 2	13:32:31.0±1.3	54.876±0.021	20.120±0.055	20.0±10.1

that event has been performed by GSRAS (Husebye and Mantyniemi, 2005), however neither information on location error nor location method is provided.

The two main earthquakes were also located by several seismological centers, namely the European-Mediterranean Seismological Centre (EMSC), National Earthquake Information Center of the United States Geological Survey (NEIC) and Harvard University as part of their seismological routine. All these locations fall inside the Sambia Peninsula in Kaliningrad or offshore. It should be noted that all these agencies have reported the second earthquake to the south of the first one.

The scatter of the locations is smaller in case of the second event. This seems to result primarily from the event size: the larger event was recorded at more stations and at larger distances where using a global velocity model introduces smaller errors than if used at closer distances. Location was also performed by the Geophysical Survey of Russia (GSRAS; Nikonov et al., 2005) using two methods of instrumental data as well as a macroseismic location. The differences between the calculated GSRAS locations are negligible, while the difference between the calculated and macroseismic GSRAS locations are small. The distribution of the various location results is shown in Figures 2 and 3.

4. AMPLITUDES AND MAGNITUDES

A selection of seismograms recorded at eleven stations at various distances and azimuths is shown for the second (bigger) earthquake in Figure 4. Records of the first event look very similar, only the amplitudes are somewhat smaller and also the main aftershock seems to look similar at those stations that have recorded it.

Magnitudes determined by different seismological centers vary. In particular, EMSC has determined mb=4.4 and mb=5.0 for the two events while NEIC has determined mb=4.8 and mb=4.9. Harvard's moment magnitude for the second event M_w=4.7. Single station local magnitudes M_L calculated from Sg amplitude on simulated Wood-Anderson record using the Seismic Handler program (Stammler, 1993), regionally corrected (Bormann et al., 2002) depending on period by 0.2 to 0.4 unit down (Wahlstrom and Strauch, 1984) come out from 4.7 to 5.1 for the first event and from 4.9 to 5.4 for the second, with the exception of station SUW where they come out unprecedently 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. 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 5.3 for the second event. There seem to be two main reasons for this difference. The datacenters mainly give priority to the records of selected high quality observatories providing data in real time. Most of such stations in the region are located in western Europe and mostly in azimuth similar to that of GKP (the numerous Swedish stations were not providing their data in real time). This azimuth happens to be the direction of relatively weak S wave and together with the number of stations in this azimuth results in underestimation of the magnitude. The second reason is that most of the seismic stations are located on the other side, i.e. the SW side of the Tornquist Zone that is known for its attenuating properties for shallow travelling (100-200 km) seismic waves (Schweitzer, 1995).

With respect to SUW, as will be discussed later, SUW happened to be located close to the nodal plane of P waves and in the direction of maximum Sg waves (compare seismograms in Figure 4). A similar situation exists at a station in complementary azimuth in respect to the source, namely DELU. Local geological conditions – 150 meters of soft sediments on top of hard rock (Bock et al., 1997) have further contributed to the amplification of the signal. The earthquakes were also strongly felt in the city of Suwałki, 20 km away (and towards the epicenter with respect to the seismic station) where damage to buildings was sustained.

The maximum ground acceleration observed at the station SUW was 47.1 mm/s^2 for the first event and 93.1 mm/s^2 for the second event. The maximum ground acceleration at GKP was just above while for WAR just below 5 mm/s^2, and acceleration values observed at other stations are still lower. The currently authorized EMS-98 intensity scale does not make a direct relation between ground acceleration and the observed macroseismic effects (Grünthal, 1998), although according to other authors (Trifunac and Brady, 1975) the values observed at SUW correspond to intensity 4 while those at GKP and WAR – to intensity 1.

5. SOURCE MECHANISM

The source mechanism has been routinely calculated by moment tensor inversion at three

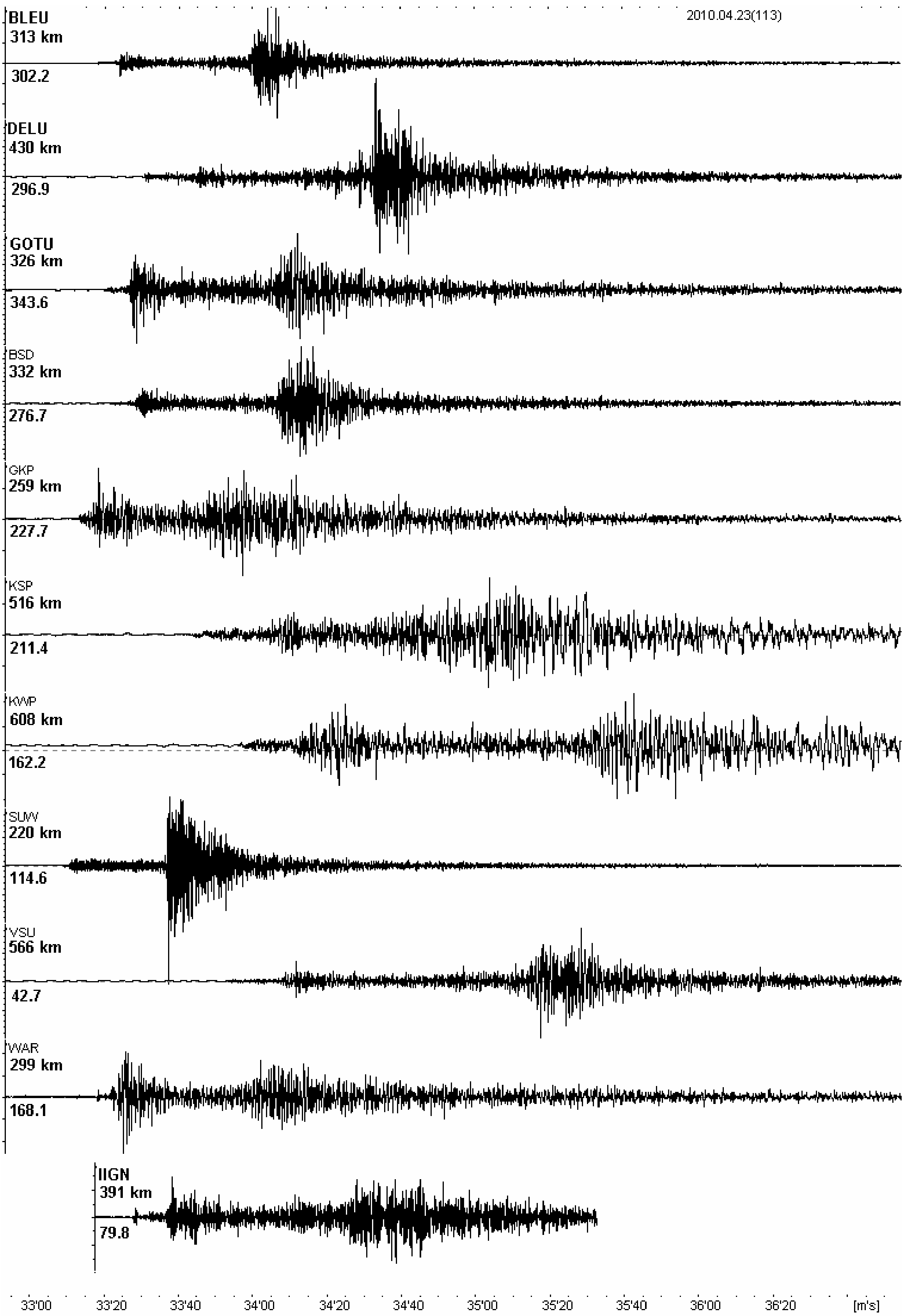

Fig. 4 A selection of seismograms of the second (13:32 UTC) Kaliningrad earthquake, recorded at various seismic stations of the region, vertical component. Vertical axes are scaled individually for each station as in physical units the maximum amplitudes may differ by over two order of times.

Table 2 Source mechanism parameters of the Kaliningrad earthquakes resulting from IGF fault plane solution and moment tensor inversion. 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%.

	IGF f.p.	IGF Event 1	IGF Event 2	Harvard	INGV	ETHZ
Seismic moment 10^{16} Nm	-	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

seismological centers: Harvard University, INGV-Mednet and the Swiss Seismological Service (ETHZ). The Institute of Geophysics, Polish Academy of Sciences (IGF) at first calculated the mechanism by classical fault plane solution (Wiejacz, 2004) used earlier in case of the 1992-1993 Krynica earthquakes (Debski et al., 1997). The moment tensor inversion has been performed later when waveform data has been retrieved from Sweden and IIGN. The method was basically the same as the one used in studying the 1995 Egion, Greece, aftershock sequence (Gibowicz et al., 1999).

All mechanisms are very much alike, presenting a right-lateral strike slip. The source mechanisms of the two events, as determined by IGF differ only in their size, while the angular parameters vary only by less than 5 degrees – an effect that can easily be attributed to numerical stability, especially considering that only 16 stations could have been used for the larger second event and still less – 11 stations for the smaller first quake. The source mechanism plot is shown on the map of the region in Figure 1, while the basic parameters of the solutions are given in Table 2.

Of the two nodal planes, the plane B looks the better candidate to be the plane of rupture whereas the plane A is rather the auxillary plane. This selection seems justified in view of the geological setup (parallel to the Tornquist-Teisseyre Zone) and past historical information (lack of evidence of earthquakes along the direction of plane A, relatively densely populated in respect to other directions of the source). Also the very high observed S wave amplitudes at SUW may indirectly support this selection. One of the possible explanation of the very high amplitudes at SUW may be that the rupture was not symmetrical and that it propagated unilaterally from the source in one direction along the rupture plane (Haskell, 1964) similarly to the findings of Yagi and Kikuchi (2000) in respect to the big earthquake in Turkey in 1999. A rupture velocity not much less than the S wave velocity could explain the very high amplitudes in that direction. Assuming SUW happened to be in that direction, this could explain the high amplitudes that have been observed there. Contrarily to the mechanism type itself and its angular parameters, the IGF moment tensor solution yields somewhat bigger 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. It seems this difference can be attributed to the same causes as mentioned above in the discussion of magnitudes. The moment magnitude for the first earthquake is 4.5.

6. HISTORICAL SEISMICITY

The occurrence of the Kaliningrad earthquakes on September 21, 2004 was very astonishing to the local population and to most seismologists as well. This follows from the almost total absence of known seismicity in the area according to previous literature. Wiejacz and Wojdynska (1997) speculated some weak seismic activity related to post-glacial isostasy.

During the instrumental era only a few cases of possible earthquakes have been reported 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 assessed magnitudes between M_L=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. Wiejacz and Debski (2001) studied human-induced activity in the Gulf of Gdańsk. The Osmussaar, Estonia earthquake of magnitude M_L 4.6 in the Gulf of Finland in 1976 (Nikonov, 2002) was regarded as too distant from the Kaliningrad area to have any influence on the seismic hazard there.

Relevant earthquake catalogues include those of Pagaczewski (1972), Boborikin et al. (1988) and Laska (1902). The historical catalogue for the Baltic region (Boborikin et al., 1988) was published as an internal seismic station report of very limited circulation and is not well known. It does not include evidence of seismic activity in the present-day Kaliningrad and Lithuania. The Polish historical earthquake catalogue of Pagaczewski (1972) lists only four occurrences of seismic events in the region over the 1000-year span of the record. Laska (1902) evidences two 14th century earthquakes reported by the chronicler Peter von Dusburg.

Recently, Nikonov (2005) after investigating documentary materials gives a list of 17 past earthquakes, six of them the same as in the Laska (1902) or Pagaczewski (1972) catalogues. Perplexing are the reports of tsunami-like events. The best documented of these took place in 1822 when on August 27 the water in the mouth of Pregola River has suddenly disappeared and when it came back, it came from the sea as a 2 meter high wave, causing the river to flow upstream. We may wonder how this can be, as tsunamis result from sea bottom movements under deep sea, when the water wave reaches the shallows of the oceanic shelf. The Baltic Sea is a shelf sea as a whole, there is no deep sea bottom. The phenomenon may be explained by sea bottom movement under the Baltic Sea where the typical depth is 80 to 100 meters. The water wave travels outwards from the source and travelling towards Kaliningrad it reaches the shallows of the Vistula Lagoon where depth falls to merely 6 – 7 meters. In addition, the Lagoon extends east gradually narrowing in to form the mouth of Pregola River – a configuration of the shore resembling that near Lisbon that was hit by a tsunami in 1755. Of the eight documented tsunami-like events four are connected with historical earthquakes, including the earthquake in 1572, and four are not, including the 1822 event. Unfortunately Nikonov (2005) does not cite references to sources of relevant information, making it impossible to verify his findings.

Another important issue is whether the rarity of earthquake reports indicates a genuine lack of seismic events or rather a lack of reports. In the twentieth century the population changes that resulted from World War II have broken the cultural continuity of the region. Newcomers of Russian or Polish origin who settled there after 1945 could not have been informed by their parents or grandparents about ground shaking noted in the past. Also, many local documents may have been lost during the war.

7. DISCUSSION

The Kaliningrad earthquakes occurred in a region previously considered aseismic and were so unexpected that they were at first taken to be human-induced. This idea has to be rejected due to three reasons at least. First, there were two main events, a clear aftershock and four other smaller events rather than a single blast. Secondly, the source depth of over 15 km indicates no human intervention. Thirdly, the source mechanism is clearly shear type and does not indicate a blast.

The source mechanism shows right-lateral strike slip in a direction parallel to the Tornquist-Teisseyre Zone, which is the boundary between the East- and West European Platforms. The zone is about 100 km wide but it runs at about a 200-km distance of the source of the Kaliningrad earthquakes. Explosion studies of the crustal structure have not evidenced any fault that could be associated with the earthquakes. Grad et al. (2003) mention a small high velocity body on a profile perpendicular to the hypothetical fault on a profile about 200 km from the earthquakes. The Neotectonic map of Soviet Baltic republics (Sliaupa et al., 1981) notes two neotectonic active linear zones in the northern and southern part of Sambia Peninsula, coinciding partially with tectonic faults.

The earthquakes have caused several injuries and some damage that has to be considered spectacular as for earthquakes of this size. The observed surface effects are not in accord with the strike slip source mechanism. Since the source depth is over 15 km and source radius estimated at about 2 km, the ground displacements of the source cannot show up at surface and even if they did, they are estimated to be only several millimeters. What is more likely to be observed are coseismic or postseismic effects of liquefaction and ground instability.

What is most perplexing is the actual cause of the events. Kaliningrad region is far from tectonic plate boundaries – the nearest are in the Mediterranean; neither there is known any seismic active fault running through the region. The Tornquist-Teisseyre Zone has possibly been a tectonic plate boundary between geological units known as Baltica and Avalonia but it appears to be inactive in recent geological times (Gregersen et al., 1995). In addition, the Zone does not cross the source area of the September 21, 2004 earthquakes but is located at a distance approximately 200 km from it. Therefore, the Zone cannot be considered the fault. The earthquakes may have occurred on some fault structure parallel to the zone. Whatever this structure could be, what are the mechanisms that cause horizontal stress buildup? The Baltic area is known for weak seismic activity caused by plate motion and/or post-glacial rebound (Gregersen, 2002). Strike slip faulting is not too common. The predominant faulting is thrust-type (Lundqvist and Lagerbäck, 1976, Lagerbäck, 1979). Gregersen and Basham (1989) and Stewart et al. (2000) investigated more deeply on this issue 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), or Greenland (Gregersen, 1989, Johnston, 1989). A recent example of such strike slip faulting is the Dudley, Great Britain, earthquake on September 22, 2002, of magnitude 4.7 (Baptie et al., 2005). The strike slip must be seen as release of stress on a fault parallel to the Tornquist-Teisseyre Zone. In case of Norway, Great Britain or Greenland the tectonic stress most likely comes from ridge push forces from the Mid-Atlantic Ridge (Gregersen, 2002; Husebye and Mäntyniemi, 2005) and forces inflicted on the European Plate by the African Plate pushing from the south.

The seismicity in the Baltic region is low and the available data is insufficient to establish a reliable Gutenberg-Richter relationship, so it is not possible to estimate the maximum earthquake size. Sedimentary cover of the area does not allow for mapping of major fault lines and the ambient stress is not well known.

Appearance of the earthquakes evidences the need of further geophysical investigation of the region focused on an attempt to discover the hypothetical active faults. Explosion studies of crustal structure carried out in 1995, 1996, 1997 and 2000 (projects EUROBRIDGE, POLONAISE and CELEBRATION) have not covered the Kaliningrad Region and in the adjacent areas the crustal structure is determined only to a limited depth or with limited accuracy.

8. CONCLUSION

The Kaliningrad earthquakes of September 21, 2004 are rare examples of intraplate seismic activity in a region previously considered aseismic. A total of seven shocks were observed, three of them recorded instrumentally, one of them much smaller than the main two events. The two main events have been located at 16 and 20 km depths in the Sambia Peninsula, about 30 km northwest of the Kaliningrad city. The source mechanism of both events is a right-lateral strike slip along the overall direction parallel to the Tornquist-Teisseyre Zone.

The occurrence of the September 2004 earthquakes showed that the seismic potential of the area is much larger than previously thought. A thorough investigation of historical documents reveals observations that previously were not taken into account.

The Kaliningrad earthquakes of September 21, 2004 occurred so unexpectedly mainly because this seismic region is relatively weakly active and due to the various social and demographic reasons it was simply overlooked and forgotten. In fact, Immanuel Kant, the famous philosopher and inhabitant of Königsberg – today Kaliningrad – wrote (Nikonov, 2005): *"The earthquakes occur relatively seldom and weak on a flat area where mountains are absent (...) If one was asked whether our mother country has reasons to fear such a kind of calamities, one cannot deny that they are generally possible."* Immanuel Kant has written these words after the devastating earthquake of Lisbon of 1755 but was he aware that himself he was also living in an area where earthquakes sometimes occur?

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