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The M_w 3.1-4.7 earthquakes in the southern Baltic Sea and adjacent areas in 2000, 2001 and 2004

Gottfried Grünthal • Dietrich Stromeyer • Kurt Wylegalla • Rainer Kind • Rutger Wahlström • Xiaohui Yuan • Günter Bock

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Abstract The area south and east of the Baltic Sea has very minor seismic activity. However, occasional events occur as illustrated by four events in recent years, which are analysed in this study: near Wittenburg, Germany, on May 19, 2000, $M_w = 3.1$, near Rostock, Germany, on July 21, 2001, $M_w = 3.4$, and in the Kaliningrad area, Russia, two events on September 21, 2004 with $M_w = 4.6$ and 4.7. Locations, magnitudes (M_L and M_w) and focal mechanisms were determined for the two events in Germany. Synthetic modelling resulted in a well confined focal depth for the Kaliningrad events. The inversion of macroseismic observations provided simultaneous solutions of the location, focal depth and epicentral intensity. The maximum horizontal compressive stress orientations obtained from focal mechanism solutions, approximately N-S for the two German events and NNW-SSE for the Kaliningrad events, show a good agreement with the regionally oriented crustal stress field.

Keywords Seismicity • Southern Baltic Sea area • Focal mechanisms • Stress field • Synthetic seismograms • Macroseismics

G. Grünthal (✉) • D. Stromeyer • K. Wylegalla • R. Kind • R. Wahlström •X. Yuan • G. Bock
GeoForschungsZentrum Potsdam,
Telegrafenberg,
14473 Potsdam, Germany
e-mail: ggrue@gfz-potsdam.de

1 Introduction

The southern Baltic Sea and the adjacent areas of Germany, Poland, the Baltic states and the Kaliningrad enclave are characterized by very low seismicity. The earthquakes investigated in this study - near Wittenburg, Germany, on May 19, 2000, $M_w = 3.1$, near Rostock, Germany, on July 21, 2001, $M_w = 3.4$, and in the Kaliningrad area, Russia, on September 21, 2004, two events with $M_w = 4.6$ and 4.7 - are the largest ones in their regions in historical times. They are also manifestations of ongoing neotectonic processes in these parts of the continental crust. The Kaliningrad "double shock" has been the subject of several special studies (e.g., Jõeleht, 2005, Gregersen et al., 2007) treating various aspects of source and macroseismic parameters. In this study we concentrate on aspects which have not been addressed so far, i.e., the focal depth determination with instrumental and macroseismic methods, and an attempt to a seismotectonic interpretation of the events in the southern Baltic area, i.e., the southern Baltic Sea and its adjacent areas.

Historical forerunners of the Kaliningrad earthquakes, i.e., intensity 6-7 earthquakes in the area of the Kaliningrad exclave in the years 1303 and 1328 (Nikonov, 2006; Paèësa et al., 2005 and described in numerous earthquake catalogues of the 19th and 20th century), are proved to be fake (Grünthal and Riedel, 2007). The contemporary chronicler who described an event in 1303 has mixed it up with information on the $M = 8$ Crete/Rhodes earthquake on the same day. Both earthquakes were mentioned by the chronicler to underpin a historical upheaval situation and the political military will of the Teutonic Order the chronicler was belonging to.

To understand the recent, instrumental time seismicity in the investigated region, i.e., from Mecklenburg-Vorpommern, Germany in the west to Kaliningrad and neighbouring Lithuania in the east, we have to consider a larger geological environment as well as the historical seismicity record. Only in this way the general seismicity pattern can be understood in its seismotectonic and temporal context. With respect to the intensively discussed seismic event in 2004 between Bremen and Hamburg in NW Germany (marked in Fig. 1), which was induced in a gas field (Dahm et al., 2007), we can state that the earthquakes studied here can be classified as tectonic, i.e., causes like saline tectonics or dissolution processes with respect to the two German events or oil production in the Kaliningrad area can be excluded.

The objectives of this study are to present the seismicity of the area, give the results of the seismological investigations of the four recent events, pursue the question how the earthquake mechanisms agree with the regional crustal stress field, and discuss how the events can be associated with local faults or zones of weakness.

2 Seismicity

As demonstrated in Fig. 1, depicting the epicentre location and size of all known earthquakes in the period 1300-2004 (from Grünthal & Wahlström, 2003 with extensions for smaller earthquakes and for the time after 1993), the seismicity of the area of the southern Baltic Sea and its land area to the south is very low, also compared with the surrounding area in Fennoscandia and eastern parts of Germany (at about 12°E and S of 51.5°N). To put the most recent earthquakes in a correct historical context, we have to note that the historical and the instrumentally recorded events before the mid 1970s are not completely catalogued. In the Baltic states, there is still today insufficient seismic network coverage. We estimate the lower magnitude threshold for northern Germany since the mid 1980s at $M_w = 2$, for the northern part of Poland and the Kaliningrad area at about $M_w = 3$.

The four events of the present study are denoted with larger digits in Fig. 1. The parameters of the other specially marked events are given in Table 1. Seen in a large area perspective, which is important for low seismicity regions, Fig. 1 demonstrates that the four investigated events are not unique.

The denoted event in Denmark in 1997 was relocated in the frame of the present study (cf.

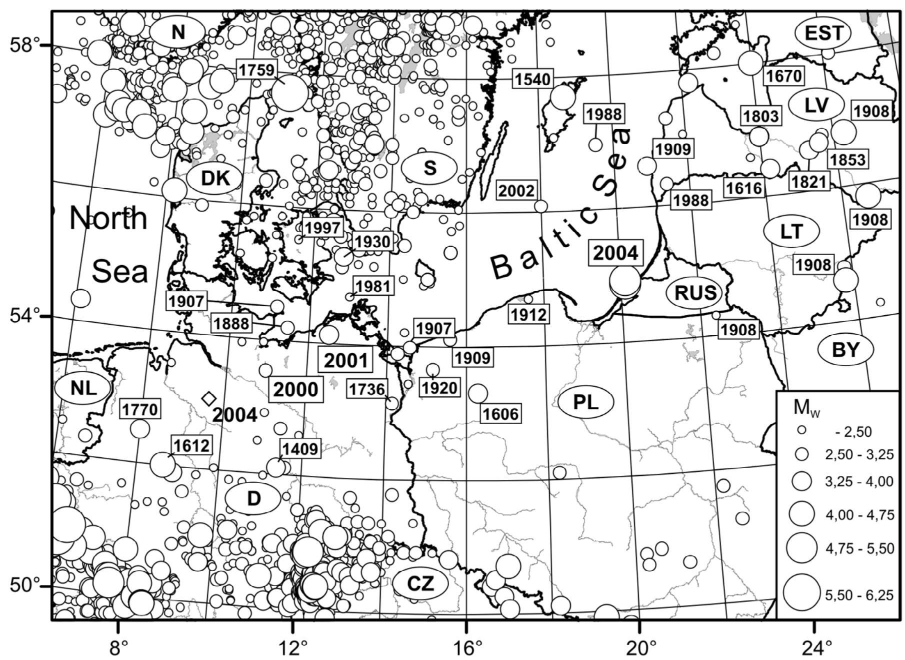


Figure 1. Seismicity of the study area according to the extended earthquake catalogue of Grünthal & Wahlström (2003). Selected events are denoted with their respective years of occurrence. The events in 2000, 2001 and 2004 treated in this study are highlighted in form of a *larger font*. The probably non-tectonic event in 2004 mentioned in the text is marked differently (*without frame*).

Table 1. Parameters of selected events from the epicentral map (Fig. 1).

Date	Coordinates Lat (°N)	Lon (°E)	Depth (km)	Int. I_0	M_w	Catalogue reference and/or source
1409 08 24	52.1	11.4		6	4	Grünthal & Wahlström, 2003; Grünthal & Meier, 1995
1540	57.7	18.7	5	7	4.2	Grünthal & Wahlström, 2003; FENCAT, 2006
1606	53.3	16.3		5	3.3	Pagaczewski, 1972
1612 11 07	52.0	8.65		6.5	4.3	Grünthal & Wahlström, 2003; Vogt & Grünthal, 1994
1616 06 30	56.4	24.2		6	3.6	Grünthal & Wahlström, 2003; FENCAT, 2006
1670 02 01	58.0	24.0	8	7	4.3	Grünthal & Wahlström, 2003; Nikonov, 1992
1736 11	53.13	14.17		4	2.7	Grünthal, 2006a
1759 12 22	57.7	11.1			5.6	Grünthal & Wahlström, 2003; FENCAT, 2006
1770 09 03	52.5	8.0		6	4	Grünthal & Wahlström, 2003; Meier & Grünthal, 1992
1803 02 23	56.9	24.0		3.5	2.1	Boborikin et al., 1993
1821 02 20	56.6	25.3		6.5	4	Grünthal & Wahlström, 2003; Boborikin et al., 1993
1853 02 05	56.7	25.6		6	3.6	Grünthal & Wahlström, 2003; Boborikin et al., 1993
1888 05 16	54.2	11.45		4	2.7	Grünthal, 1988
1907 04 30	54.45	11.17		3	2.1	Grünthal, 1988
1907 08 29	53.97	14.58		4	2.7	Grünthal, 1988
1908 12 29	56.8	26.3	12	7	4.4	Grünthal & Wahlström, 2003; Boborikin et al., 1993
1908 12 29	55.8	26.7		7	4.4	Grünthal & Wahlström, 2003; Boborikin et al., 1993
1908 12 30	54.3	22.4		3.5	2.4	Pagaczewski, 1972
1908 12 30	54.6	25.8		7	4.4	Grünthal & Wahlström, 2003; Boborikin et al., 1993
1909 02 11	54.1	15.6		4.5	3	Pagaczewski, 1972
1909 02 12	56.6	20.9		6	3.6	Grünthal & Wahlström, 2003; Boborikin et al., 1993
1912 12 01	54.7	17.6		3.5	2.4	Pagaczewski, 1972
1920 09 13	53.65	15.17		4	2.7	Grünthal, 1988
1930 10 31	55.3	12.8		5.5	3.4	Wahlström & Grünthal, 1994
1981 05 05	54.7	13.0			2.4	Grünthal, 1988
1988 04 29	56.97	19.53	1		2.8	FENCAT, 2006
1988 04 29	56.32	21.40	7		2.6	FENCAT, 2006
1997 08 19	55.53	11.60			2.3	Wylegalla, 2002 (pers. communication)
2000 05 19	53.54	10.97	17		3.1	this analysis
2001 07 21	54.11	12.50	9	4.5	3.4	this analysis
2002 12 18	56.08	18.00	10	5	2.9	FENCAT, 2006
2004 09 21	54.87	20.14	13	6	4.6	this analysis, M_w after ETHZ, 2004
2004 09 21	54.98	20.29	13	6	4.7	this analysis, M_w after ETHZ, 2004
2004 10 20	53.04	9.54	5		4.4	Dahm et al., 2006

Values as 6.5 denote uncertain intensity assessments like 6-7 etc. (cf. EMS-98, Grünthal, 1998). This convention is applied in the whole analysis.

Table 1). The event in 1930 just south of the Swedish coast was closer analysed by Wahlström & Grünthal (1994). To the southwest, the low seismicity area is limited by the events in 1409 (Grünthal & Meier, 1995), 1612 (Vogt & Grünthal, 1994) and 1770 (Meier & Grünthal, 1992).

There is some concentration of seismicity at the mouth of the river Oder (Grünthal 2006a, b). The seismic record of the northern part of Poland is, except for the 1606 event, limited to a few small events in the first quarter of the 20th century. There is reason to believe that the record might be incomplete in this area.

Whereas Lithuania, bordering the Kaliningrad enclave, is aseismic (according to the available sources) there is some activity in the border areas of Lithuania with Belarus and Latvia, respectively. The relatively high seismicity of Latvia is noticeable. So are the instrumentally documented events in the Baltic Sea in 1988 and 2002 north and northwest of Kaliningrad.

Therefore, even if the four investigated events are relatively strong and the Kaliningrad events even remarkable, they can be explained as parts of a large-scale background seismicity.

As we want to associate the seismicity as an expression for the ongoing tectonics with the large scale neotectonic characterization, Fig. 2 shows a neotectonic structural subdivision of the study area after Aizberg et al. (2001) extended with a schematic description of the graben system of the eastern Baltic Sea after Ludwig (2001). Since the concept of neotectonics is not uniformly defined with respect to the extent in time, we specify how it is applied here. In the region north of the Alpine area, the geological time period from the Badenian (15 Ma) to the present is generally named neotectonic (e.g., Květ, 1985, 1990; Pavlides, 1989). In large parts of the depression areas shown in Fig. 2 and in which the events investigated here took place, however, the distinct post-Eocene Rupelton horizon provides the fitting horizon to delimit the neotectonic time period (Garetsky et al., 2001), whereby the section since the beginning of the Oligocene (34 Ma) is outlined. Therefore, we here follow Garetsky et al. (2001) in the post-Eocene setting of the concept of neotectonics.

Comparing Fig. 2 with Fig. 1, we note a correlation of the areas of the lowest seismicity with those of depressions. The Kaliningrad events were located in the southwestern border area of the depicted graben system. The Tornquist-Teisseyre Zone (TTZ) and Sorgenfrei-Tornquist Zone (STZ) depicted in Fig. 2 play an inferior role neotectonically.

3 Instrumental analyses of the 2000, 2001 and 2004 earthquakes

3.1 Location and magnitude

For the localization of the Wittenburg 2000 and Rostock 2001 events, arrival times of P- and S-waves from the digital records of the stations of the German Regional Seismic Network (GRSN), the Danish stations BSD, COP and MUD, and the station GOR1 of the Bundesanstalt für Geowissenschaften und Rohstoffe Hannover were used. The locations of the stations are given in Table 2. The localizations were made with HYPO71 (Lee & Lahr, 1972) using a crustal model derived from the results of the seismic profile BASIN96 (Bayer et al., 1999), which represents the best currently available velocity-depth structure for the region of both sources. It has to be considered that the seis-

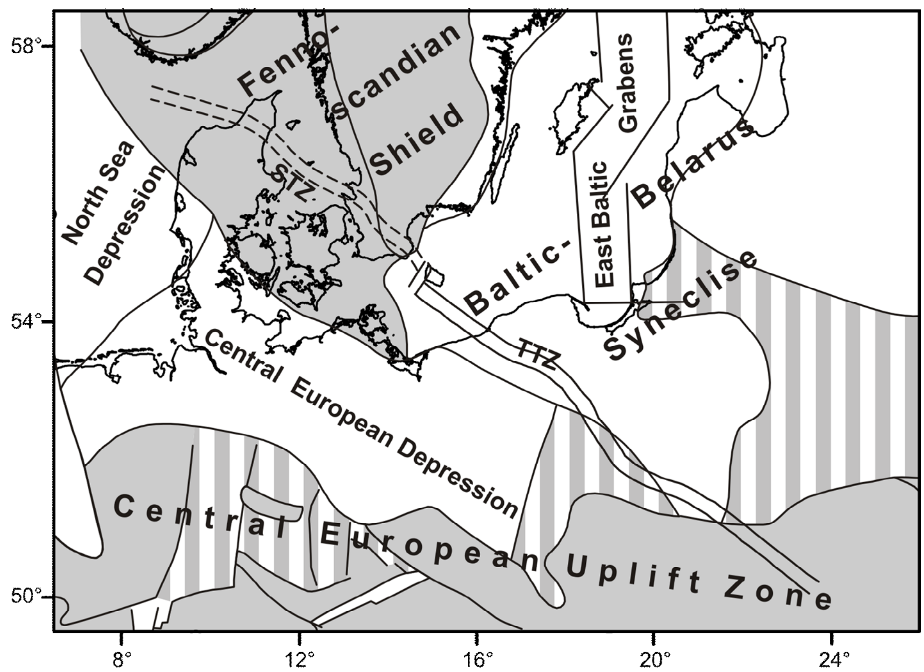


Figure 2. Post-Eocene (34 Ma) structural partition of the investigated area - simplified after Aizberg et al. (2001) - in depressed areas (*white*), depressed areas followed by uplift (*white-grey stripes*) and areas with predominant uplift (*grey*). In addition the extension of the STZ, the TTZ and parts of the east Baltic graben systems are schematically depicted (after Ludwig, 2001). The *lines* within the uplifted or depressed regions denote neotectonic structures of the second and third order.

Table 2. Instrumental source parameters of the Wittenburg and Rostock events.

	Wittenburg			Rostock		
Focal time	May 19, 2000 19:22:41,5 UTC			July 21, 2001 16:35:57,8 UTC		
Epicentre	53.54°N, 10.97°E ± 2 km			54.11°N, 12.50°E ± 3km		
Focal depth	17 km ± 3 km			9 km ± 1 km		
Seismic moment	4.2 x 10^{13} Nm			2.2 x 10^{14} Nm		
M_w	3.1			3.4		
M_L	3.4			3.4		
Focal mechanism solution	Strike	Dip	Rake	Strike	Dip	Rake
1. nodal axis	292°	87°	-138°	224°	77°	-49°
2. nodal axis	199°	48°	-4°	328°	43°	-161°
Main stress axes	Trend	Plunge		Trend	Plunge	
P-axis	164°	31°		173°	42°	
N-axis	295°	48°		33°	40°	
T-axis	58°	26°		284°	21°	

mological stations are located on different geological units, which have influence on the travel times of the crustal waves. Furthermore, the velocity ratio v_p/v_s is not known in the source regions nor along the travel paths. The ratio obviously changes significantly even within the North German Basin as shown by the arrival times of the Pg- and Sg-waves from the Wittenburg event at the closest stations BSEG and GOR1: Although both stations are equally far away, 62 km, from the epicentre, Pg arrives 0.24 s earlier at GOR1 than at BSEG, whereas Sg arrives 0.18 s later at GOR1. Although the obtained localizations still could not be much different from the true locations, different input sets were used: Only Pg, Pg + Sg, with and without station corrections. A station correction was obtained from the elevation and the sediment thickness at the station site. The solution with the smallest travel time residual (RMS) of the waves was preferred in each case.

3.2 Wittenburg 2000

The errors in the calculated epicentre location and the focal depth for the optimal solution according to the description above are about 2 km (epicentre) and 3 km (depth). The solutions from the different input data sets are similar and thus the hypocentre solution (Table 2) is well constrained. The relatively reliable determination of the depth can be credited the small distance to the closest stations.

Shortly after the occurrence of this event the first interpretation was a collapse at a salt deposit, since only clearly dilatational P-phases were recorded by the GRSN stations (Fig. 3a). Only the analysis of the BSD station record, with a clear compressive P-phase (Fig. 3b), and the determination of the focal depth, indicated that this was a tectonic earthquake. The lack of macroseismic observations was another indication of a relatively large focal depth.

A magnitude of $M_L = 3.4$ was obtained as a mean value based on readings from several stations.

3.3 Rostock 2001

The localizations gave a stable solution with a small RMS, 3 km, for the epicentre (Table 2), if arrival times of P- and S-waves up to a distance of 250 km were used. The corresponding six stations were well distributed around the epicentre. If more distant station data are included, the azimuthal coverage is only slightly improved but the error in the epicentre location increases to 4 km.

Fig. 4 shows the three components of the broadband seismograph records of the three

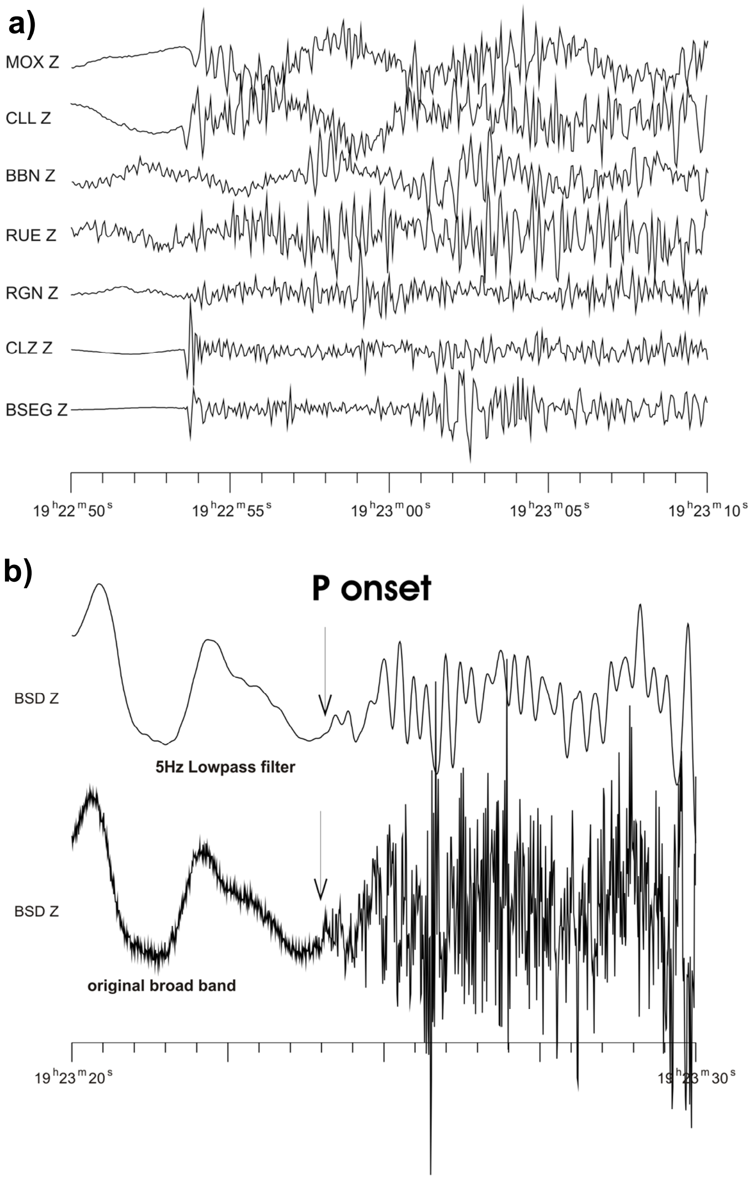


Figure 3. a) Broadband instrument records at the closest located GRSN stations of the Wittenburg event in 2000. The timescale refers to BSEG. The P-wave dilatation (downgoing first motion) is clearly observed for the traces BSEG, CLZ, CLL and MOX. **b)** Original and filtered records at the station BSD (Bornholm) of the Wittenburg event in 2000.

closest GRSN stations. The calculations of the focal depth show big differences. They give values of 11-24 km with a standard error of 2-9 km. A better depth determination is not possible with classical localization methods, since all epicentral distances are large, the closest being at 73 km (station RGN) and 145 km (BSEG). To get a more accurate determination of the focal depth, synthetic seismograms of the vertical component for the epicentral distance of 73 km, and depths between 2 and 26 km, were generated according to the reflectivity method of Kind (1979) and compared with the RGN record (Fig. 5). The best agreement of the wave fields with respect to the phase times of the secondary waves is obtained for a depth of 9 km with an error of about 1 km (Table 2).

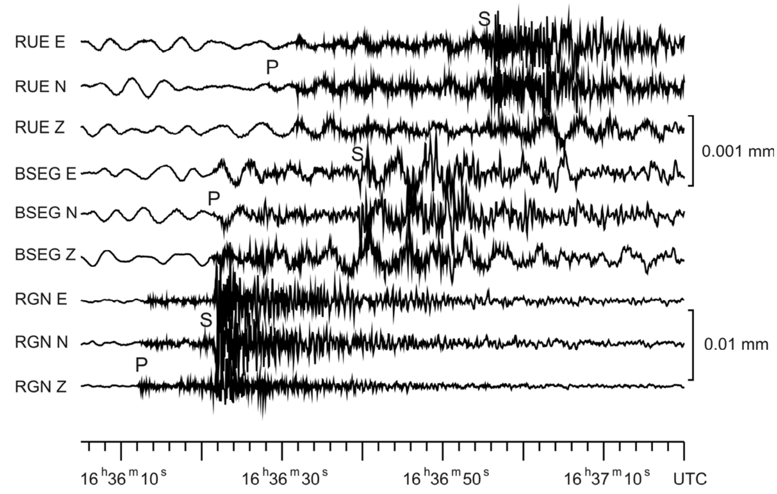
The mean value of M_L from the GRSN stations is 3.4. This is unusually small compared to M_w (see Table 2) according to the well established empirical relation by Grünthal & Wahlström (2003). M_L calculated from macroseismic data give the value 4.0 as we shall see in Section 4.

3.4 Kaliningrad 2004

The instrumental localization of the Kaliningrad events is poor (large errors) due to the far distances also to the closest stations and the scarce instrumental coverage of the Baltic states. For the location we use macroseismic data and compare with the results of ETHZ (2004) and Gregersen et al. (2007).

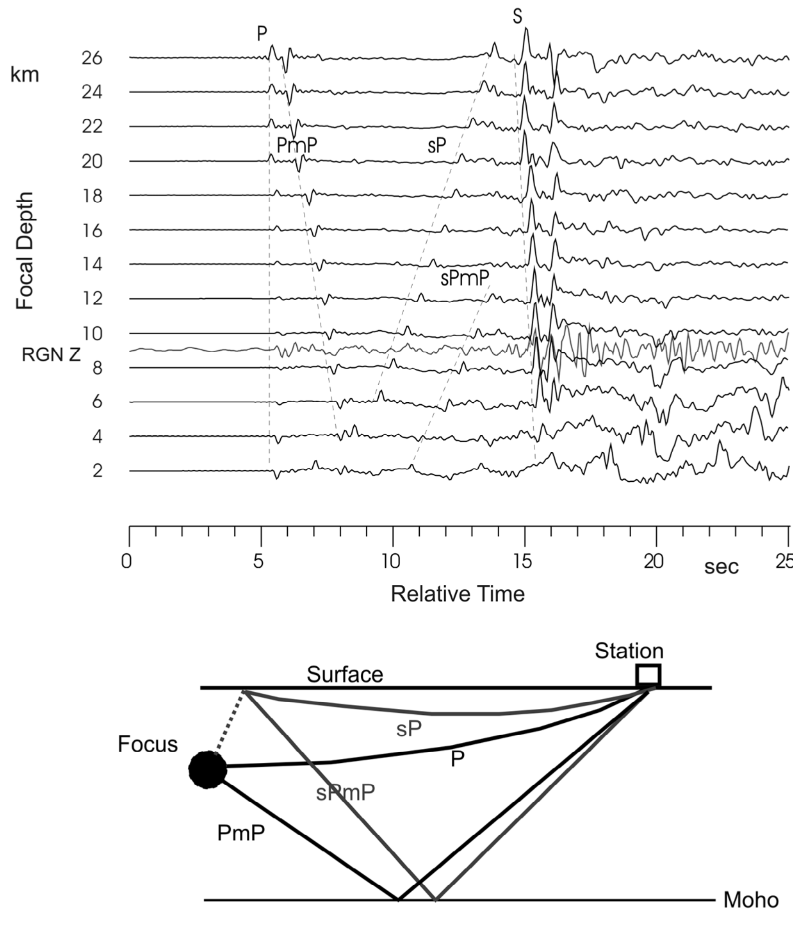
Here we concentrate on the calculation of the

Figure 4. Restituted displacement broad-band records of the closest located GRSN stations of the Rostock event in 2001.



focal depth with the use of depth phases, which can be well recorded at distant stations. This method is completely independent of the shortcomings of the local station data. Fig. 6a shows P-phases of the second, larger event (origin time 13:32 UTC) recorded at stations in Kyrgyzstan. The small differences between the stations with respect to epicentral distance (max. 0.7°) and back azimuth (max. 1.1°) facilitate the summation of the traces to improve the signal-to-noise ratio (top trace in Fig. 6a). A second phase (already denoted sP) about 5 s after the P-phase is obvious. Since this can be identified as a depth phase, a very accurate determination of the focal depth is possible. For this purpose, theoretical seismograms were calculated with the reflectivity method for a dislocation source in a layered half-space (Kind, 1978). Parameters of the source mechanism solution of the Swiss Seismological Service, Zurich (ETHZ, 2004) were used as input. The EUROBRIDGE (1999) model was used for the description of the struc-

Figure 5. Focal depth determinations from synthetic seismograms of the Rostock event in 2001. Observed and theoretical seismograms show the best agreement for a focal depth of 8-10 km. A 1/3-3 Hz bandpass filter was used for the RGN station record.



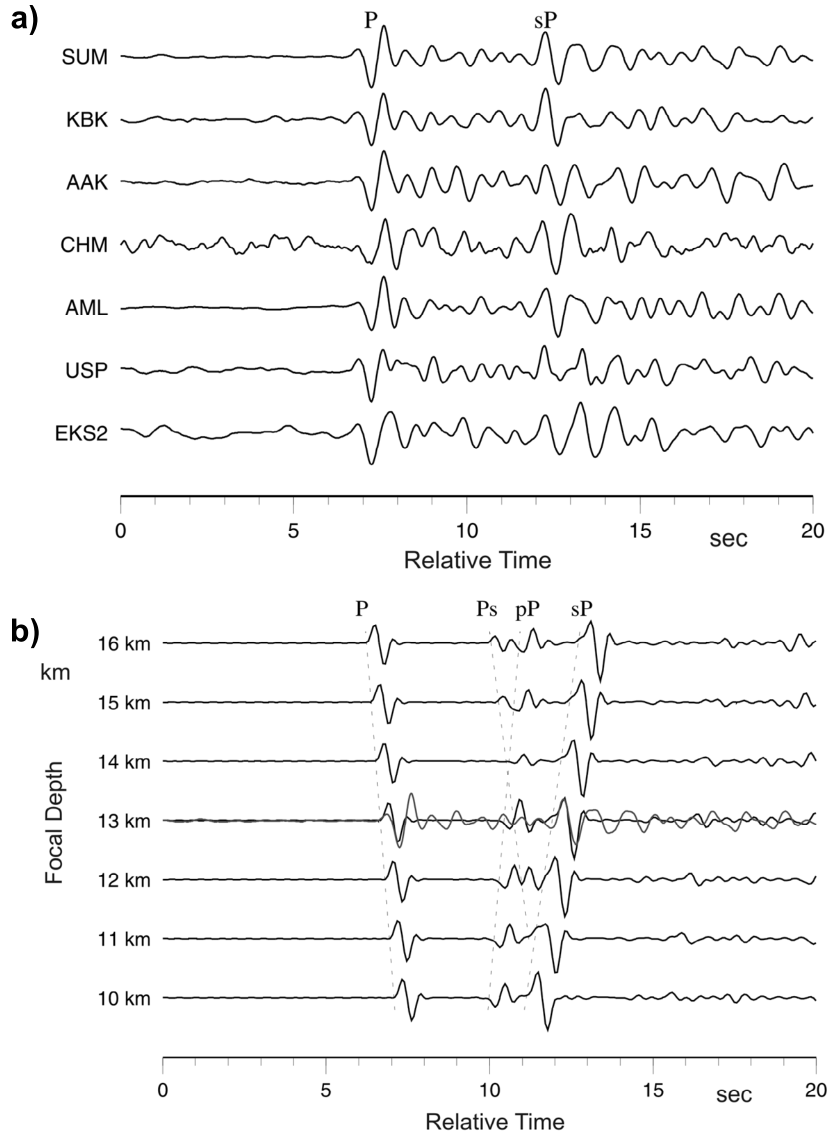


Figure 6. a) Seismic records of the Kaliningrad event on September 21, 2004 at 13:32 UTC at densely located stations in Kyrgyzstan (Kyrgyz Seismic Telemetry Network). After the first arriving P-wave, a second phase is clearly notable and interpreted as the sP phase. The amplitudes are individually scaled for each tree.
b) Comparison of theoretical seismograms for different focal depths with the beam trace of the Kyrgyz stations. Observed and theoretical seismograms show the best agreement for a focal depth of 13 km.

ture of the seismic source area. Above the source, a P-wave velocity of 6.2 km/s was applied, with an overlaying strata of 0.5 km thickness with velocity 5.0 km/s. A v_P/v_S ratio of 1.73 was assumed.

The derived theoretical seismograms as a function of the focal depth are shown in Fig. 6b. The strongest depth phase is sP. The pP-phase can also be detected but is much fainter than sP. This leads to the interpretation of the second phase in Figs. 6a, b as sP for the source orientation used (ETHZ, 2004). Other source orientation determinations are similar (see Gregersen et al., 2007). A further weak phase, Ps, is also observed in the theoretical seismograms. This phase corresponds to the vertical component of the Ps conversion at Moho below the station. This phase has a relatively constant time delay to P and is not dependent on the focal depth. For a depth of 13 km, the theoretical waveform data show the best agreement with those of the summed up trace from the recording stations (Fig. 6b). Seismic records from the Yellowknife array in northern Canada show a clear sP-phase confirming a similar depth. The first and slightly smaller Kaliningrad event at 11:05 UTC has very similar waveforms as the second and accordingly a similar depth.

Besides the phase identification, which in this case is correct beyond doubt, a second potential source of error is the inaccuracy of the seismic model in the source area. Since measurements have been made in the nearby area, the source area is relatively well known (EUROBRIDGE, 1999). Assuming an uncertainty in the used model (cited above) of 10%, a very conservative estimate, the error in the focal depth is about 1 km. For comparison, the routine moment tensor solution by Harvard (HMTS, 2004) gives a depth of 20 km for the 13:32 UTC event (no solution for the smaller 11:05 event), the corresponding solutions by the Swiss Seismological Service, Zurich (ETHZ, 2004) 15 km for both events, probabilistic locations referred by Gregersen et al. (2007) 16 ± 9 km for the 11:05 event and 20 ± 10 km for the 13:32 event, and estimations from macroseismic data by Nikonov (2006) are in the range 10-19 km.

Due to the large depths, any causal connection with the oil production in the near area (ENVOI, 2006) can be ruled out and the tectonic origin confirmed. Gregersen et al. (2007) came to the same conclusion with similar convincing arguments.

3.5 Source mechanism solutions and M_w magnitudes

The available P-wave polarities were not sufficient to make a unique classical determination of the source mechanism for the Wittenburg and Rostock events, respectively. Therefore, we utilize the inversion program FPFIT (Reasenberg & Oppenheimer, 1985) in which the P- and S-wave amplitudes are used beside the observed P-polarities. (Bock et al., 1994).

3.6 Wittenburg 2000

To improve the signal-to-noise ratio, the digital seismograms were filtered with a band pass between 0.3 and 2 Hz. No reliable amplitude analysis was possible below 0.3 Hz. From two stations, BSEG and GOR1, Pg- and Sg-amplitudes were used as input to the inversion, from four other stations only Sg. Due to the larger epicentral distance (> 185 km), these four stations were given lower weight. The parameters of the source mechanism solution are given in Table 2. The estimated errors in strike and dip are 10°-20°. The seismic moment calculated from the amplitude data of three stations corresponds to magnitude, $M_w = 3.1$ (Hanks & Kanamori, 1979 relation).

3.7 Rostock 2001

The inversion of P- and S-wave amplitudes was made from four station records. The increase in the signal-to-noise ratio was optimal with a band pass between 0.3 and 3 Hz. The weights set to the different stations were correlated to the epicentral distances (smaller distance, higher weight). The obtained mechanism parameters are shown in Table 2. The seismic moment corresponds to $M_w = 3.4$.

3.8 Kaliningrad 2004

No moment tensor solutions were made in the present study, since standard solutions from various seismological centres exist. We use the solution from the Swiss Seismological Service, Zurich (ETHZ, 2004): 11:05 UTC event with strike 29°, dip 86°, slip -5°, rake 23°, $M_w = 4.6$; 13:32 UTC event with strike 26°, dip 86°, slip 5°, rake 26°, $M_w = 4.7$.

4 Macroseismic analyses of the 2000, 2001 and 2004 earthquakes

Information of how an earthquake is felt and what damage it causes is valuable also for modern time events. In the present study, this is of special relevance in the case of the Kaliningrad events. The Wittenburg event was not reported felt and for the Rostock event a comparison between instrumentally and macroseismically obtained parameters were made.

4.1 Wittenburg 2000

There were no reports that this event was felt although the epicentral area is only slightly less populated than the surrounding regions. From the lack of reports on macroseismic observations it can be concluded that the focal depth must be at least 15-20 km.

4.2 Rostock 2001

The earthquake was clearly felt by a lot of people. Following requests from several local newspapers to report observations from the earthquake, over 80 useful observation from some 30 places were collected, most of them from the densely populated area of and near the town of Rostock. Unfortunately, no records were kept of the many incoming reports to the fire brigade or police. However, some 20 additional eyewitness reports to a local radio station gave sufficiently detailed descriptions to be useful for intensity evaluation. The maximum obtained intensity according to EMS-98 (Grünthal, 1998) was IV. The intensity in Rostock was III.

Fig. 7 maps the macroseismic observations. It is notable that in the central part of the area with intensity IV, no observations were made, although the population density is not smaller there and no bias in reporting is obvious.

An empirical intensity attenuation relation is a condition for the determination of source parameters from macroseismic data. Such a relation is derived from macroseismically and instrumentally well studied earthquakes in the area with different size and focal depth. For northern Germany, too few data have until now prevented such a relation to be derived.

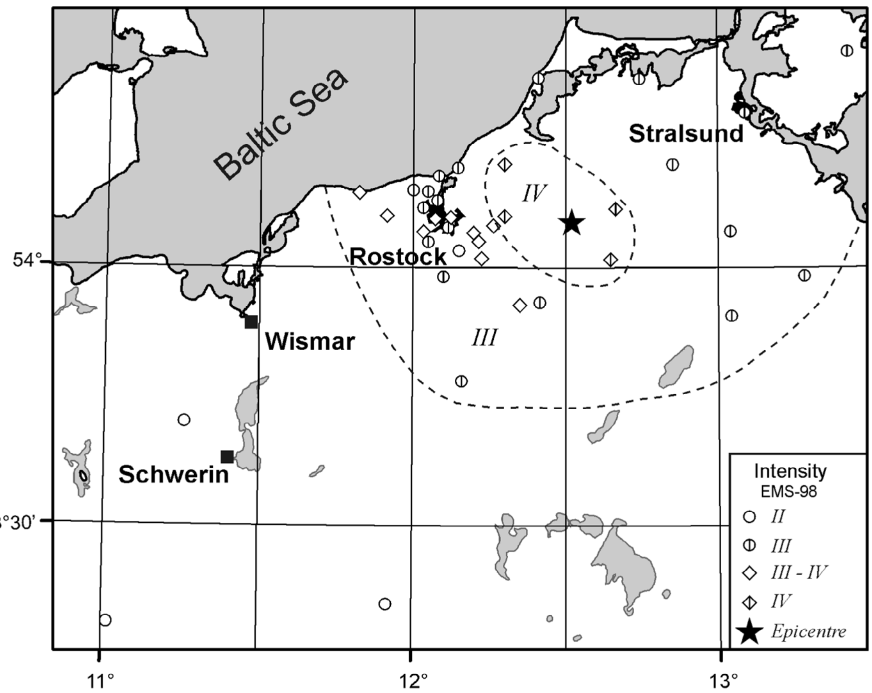
Using the inversion technique by Stromeyer & Grünthal (2007), the parameters a = 2.032 and b = 0.000 of the empirical attenuation model (Sponheuer, 1960)

$$I_0 - I = a \cdot \log \sqrt{\frac{R^2 + h^2}{h^2}} + b \cdot \left(\sqrt{R^2 + h^2} - h \right)$$

were estimated from the intensity data points (IDP) of the Rostock and Kaliningrad events simultaneously with their epicentre locations, source depths h and epicentral intensities I_0. The contribution of b characterizes the intensity attenuation at great epicentre distance R und can be sufficiently derived only from strong earthquakes. For the events investigated here, this contribution is without importance. The I_0 values calculated with this inversion algorithm are numerical quantities and no intensity grades in the true macroseismic sense.

To judge the accuracy of the calculated macroseismic parameters, it is not sufficient to give the formal confidence bounds. Thus, large standard deviations are obtained for I_0 (4.6 ± 5.4) and h (6.6 ± 4.6) for the Rostock event, which unambiguously can be referred to the missing observations in the epicentral area. A closer investigation of the common error range for I_0 and h (Fig. 8) facilitates a more distinct limitation of the possible range of values thanks to the

Figure 7. Macroseismic observations for the Rostock event in 2001.



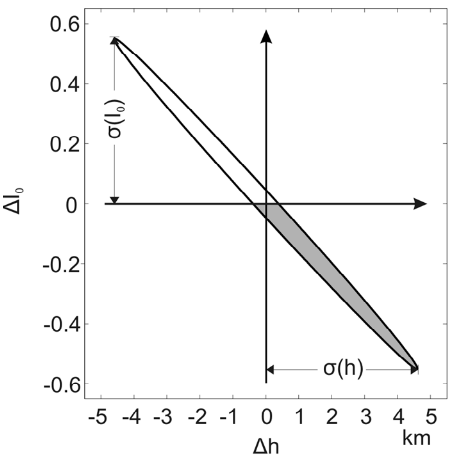


Figure 8. Formal error ellipse of focal depth *h* and numerical epicentral intensity I_0 for the Rostock event in 2001. The mean values of the inversion, $h = 6.6$ km and $I_0 = 4.6$, make up the centre of the error ellipse. The *grey area* marks the reduced range for $I_0 < 4.6$ which was used to estimate *h* and I_0 (Table3) due to lack of intensity observations in the immediate epicentral area.

good correlation between the two parameters. The missing intensity reports in the immediate source region leads to the assumption that the macroseismic epicentral intensity has not exceeded I_0 = IV-V. Otherwise, slight damages would have occurred which surely would have been reported. Since this is not the case our assumption seems to be well-founded. Therefore, the range of errors is reduced to the lower, grey-coloured part in Fig. 8. The error limits obtained for the numerical epicentral intensity are $4.1 \leq I_0 \leq 4.6$ and for the source depth 7 km $\leq h \leq$ 11 km. For the Rostock event, therefore, the macroseismically determined epicentre location and source depth (Table 3) are identical with the instrumental results.

Based on the area or radius of different isoseisms, the magnitude could be estimated. Empirical relations to calculate M_L are given by, e.g., Ahorner (1983) and Sponheuer (1962). The relation by Johnston (1996) gives M_w from macroseismic data. These relations are primarily valid for events in typical crustal layers at about 7-20 km depth. From the values corresponding to the isoseisms of Fig. 7, $M_L = 4.0$ (mean value) and $M_w = 3.5$ were calculated. The M_w value is in good agreement with the instrumental one.

4.3 Kaliningrad 2004

The full macroseismic data for both events are given by Gregersen et al. (2007). Fig. 9 shows the intensity data for the second somewhat larger at 13:32 UTC event. Model calculations with different arbitrarily chosen subsets (each 80% of the total data) give differences in epicentre location of up to 11 km. Therefore, a location error of 15 km in latitude and longitude should be a conservative estimate (Table 3). Yet the error is smaller than for the instrumental solutions, as can be judged from the different locations, up to 30 km, given by different sources. The lack of stations in the epicentral area is the main cause of this.

The magnitudes calculated from the macroseismic data (cf. Section 4) gave $M_L = 5.3$, $M_w = 4.5$ for the 11:05 UTC event and $M_L = 5.8$, $M_w = 4.8$ for the 13:32 UTC event. The agreement with the instrumentally determined M_w values is good (see Table 1), with M_L not so good.

5 Orientations of the compressional stress of the earthquakes and the recent crustal stress field

Information on the stress field in the seismogenic part of the central crust is obtained from earthquake focal mechanisms. It is there-

Table 3. Macroseismic inversion parameters of the Rostock and Kaliningrad events.

Date	Time (UTC)	Coordinates Lat (°N)	Lon (°E)	Depth (km)	Numerically determined epicentral intensity I_0
21/07/2001	16:35	54.12 ± 2 km	12.50 ± 3 km	7-11 km	4.1-4.6
23/09/2004	11:05	54.87 ± 15 km	20.14 ± 15 km	13-17 km	5.7-5.9
23/09/2004	13:32	54.98 ± 15 km	20.29 ± 15 km	15-19 km	6.1-6.3

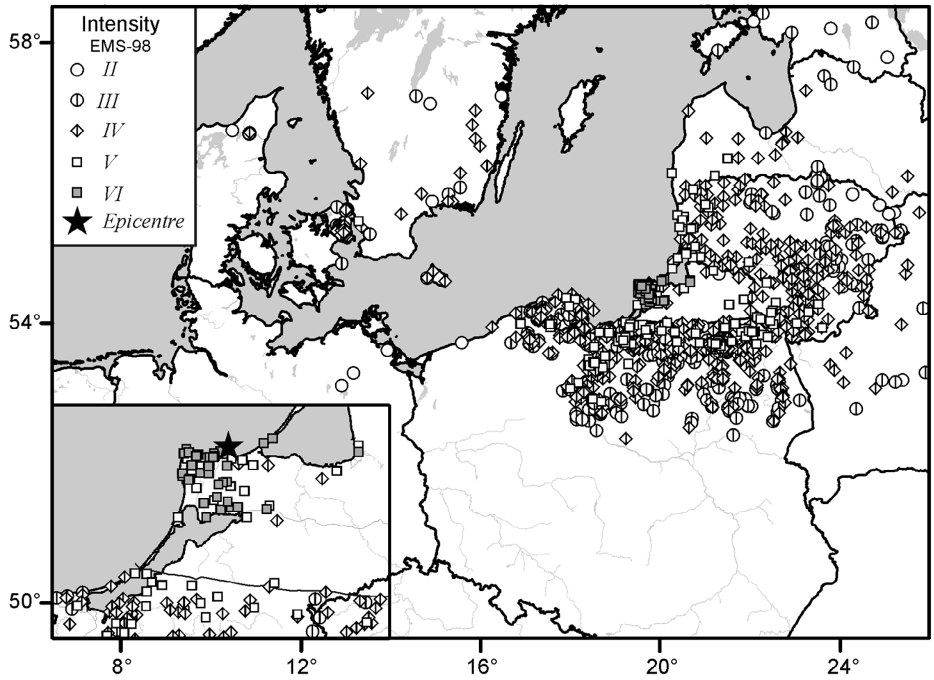


Figure 9. Macroseismic observations for the strongest Kaliningrad event on September 21, 2004 at 13:32 UTC (after Gregersen et al., 2005, 2007).

fore of importance if or to what extent the stress orientations obtained for the investigated events agree with the previously known stresses.

The orientation of the maximum horizontal compressive stress, S_{Hmax} (Fig.10), shows in the western part of the investigated area the NW-SE orientation which is well documented since many years. In northern Germany there is a change in the S_{Hmax} orientation east of about 10°E from N-S to NNE-SSW, which, supported by numerical modelling, has been described by Grünthal & Stromeyer (1986, 1992, 1994). A spatial increase of the area over which S_{Hmax} was investigated to include new data from the Baltic states and Belorussia was made by Grünthal & Stromeyer (2001). The map from this study is the basis for Fig. 10, in which also the mechanism solutions and S_{Hmax} orientations of the 2000, 2001 and 2004 events are depicted. As seen, the orientations of the most recent earthquakes show a good correlation to the already established stress picture. The two first events

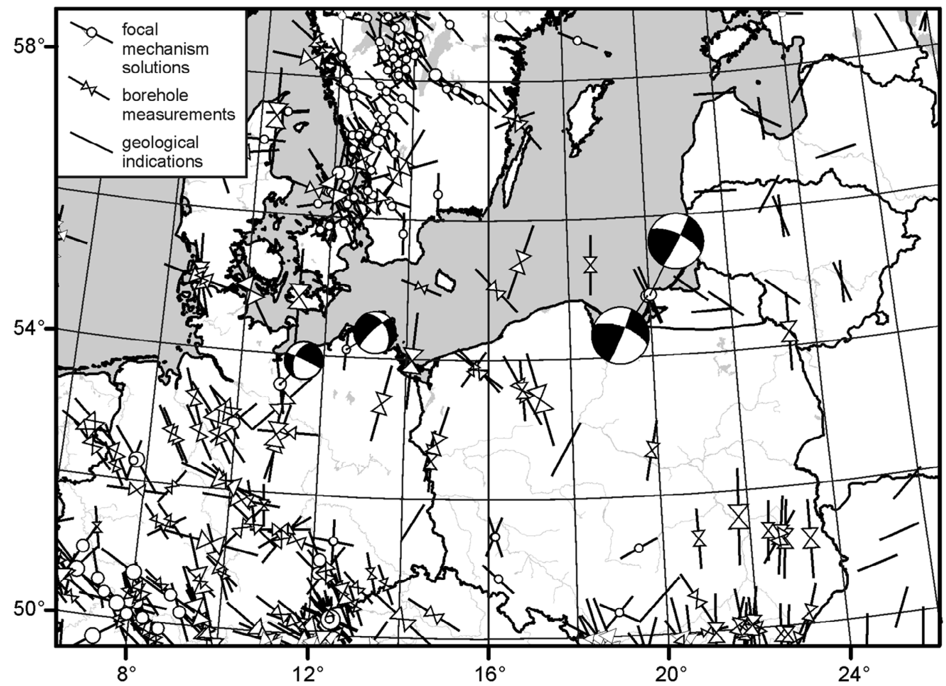


Figure 10. Directions of maximum horizontal compressional stresses, S_{Hmax}, in the Earth's crust implied from different kinds of measures (updated after Grünthal & Stromeyer, 2003). The focal mechanism solutions and the S_{Hmax} directions of the investigated events are specially indicated. The size of the symbols is a measure of the goodness of data. More explanations in the text.

have the N-S orientation of S_{Hmax} in NE Germany and the 2004 Kaliningrad events the NNW-SSE orientation expected in that area.

6 Correlation of the earthquakes to tectonic faults

In this Chapter, the possible correlation of the earthquakes to mapped faults is discussed, the characteristics of the obtained fault planes being the indicators. Common for all source mechanism solutions is an oblique displacement with a component of normal faulting. The normal faulting component is least pronounced for the Kaliningrad events.

6.1 Wittenburg 2000

One of the two possible fault planes agrees with a NNW-SSE oriented fault (Fig. 11; after Lange et al., 1990), which is documented near the surface as well as in the sub-saliniferous pre-Zechstein formation and lasts for about 30 km (Grünthal & Katzung, 2004). It is here crossing the SW-NE running Schwerin fault, which is gravimetrically and geomagnetically documented at depth. The second possible plane, which strikes hercynian, has no correspondence to mapped faults. Due to the focal depth of 15 to 20 km, it is questionable if this event can be associated with any known fault, although there is a coincidence with the Schwerin fault.

6.2 Rostock 2001

More seismotectonic interpretations are possible for this more shallow event. The possible fault planes are oriented NW-SE and NE-SW. The epicentre is located in the southwestern part of an approximately 75 km wide zone with NW-SE to NNW-SSE oriented faults (Fig. 12; after Lange et al., 1990). The source lies about 5 km underneath the base of the Zechstein formation, south of a 75 km long fault (the continuation of the Schwerin fault), which here is documented at the base of the sub-saliniferous pre-Zechstein formation. It can be assumed that a conjugate arranged set of NW-SE oriented faults associated with N-S running maximum compressive stresses, S_{Hmax}, increases the shear stress potential and so the possibility to trigger earthquakes.

6.3 Kaliningrad 2004

For the possible seismotectonic correlation of the potential fault planes of the two events, we first use a small-scale tectonic map of the Baltic states and Belorussia by Zui et al. (1995). In

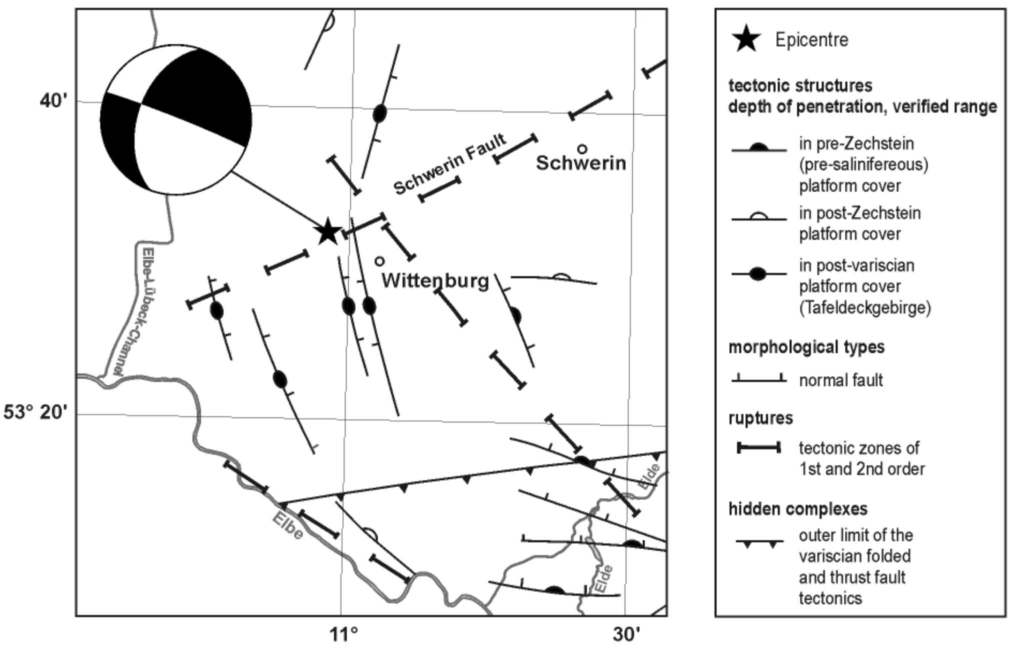


Figure 11. Epicentre and focal mechanism solution for the Wittenburg event in 2000 in the tectonic map after Lange et al. (1990). The possible focal planes of this event could correspond to the indicated NNE-oriented fault NNE of the epicentre. Further details in the text.

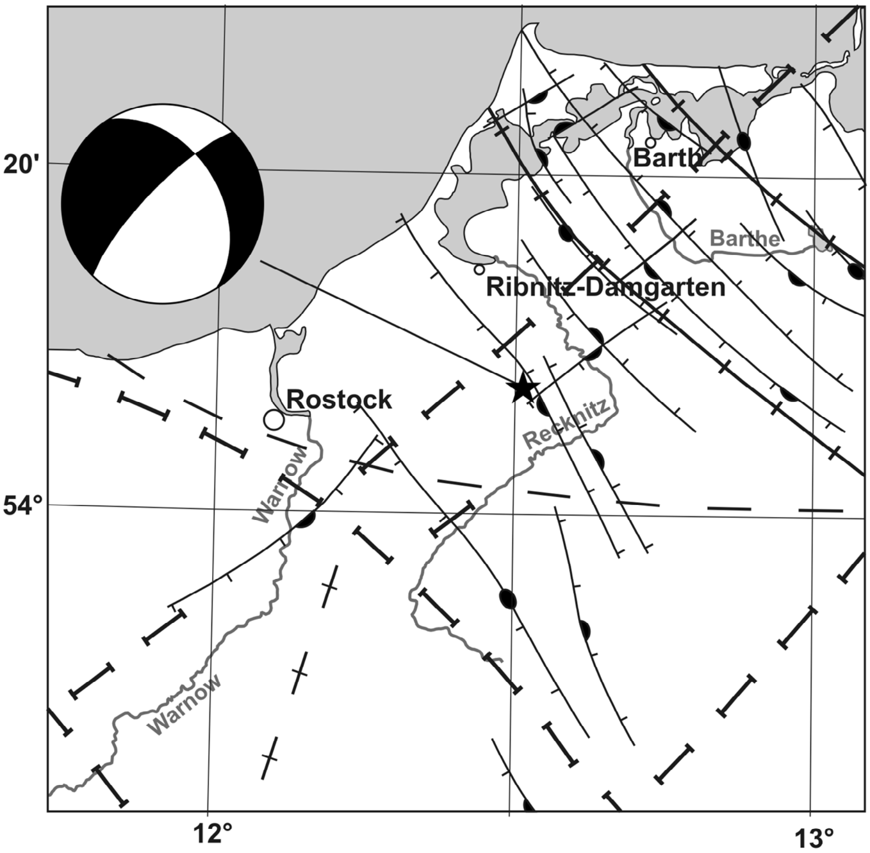


Figure 12. Epicentre and focal mechanism solution for the Rostock event in 2001 in the tectonic map after Lange et al. (1990; legend cf. Fig. 11). Both possible focal planes are consistent with the known fault directions. Further details in the text.

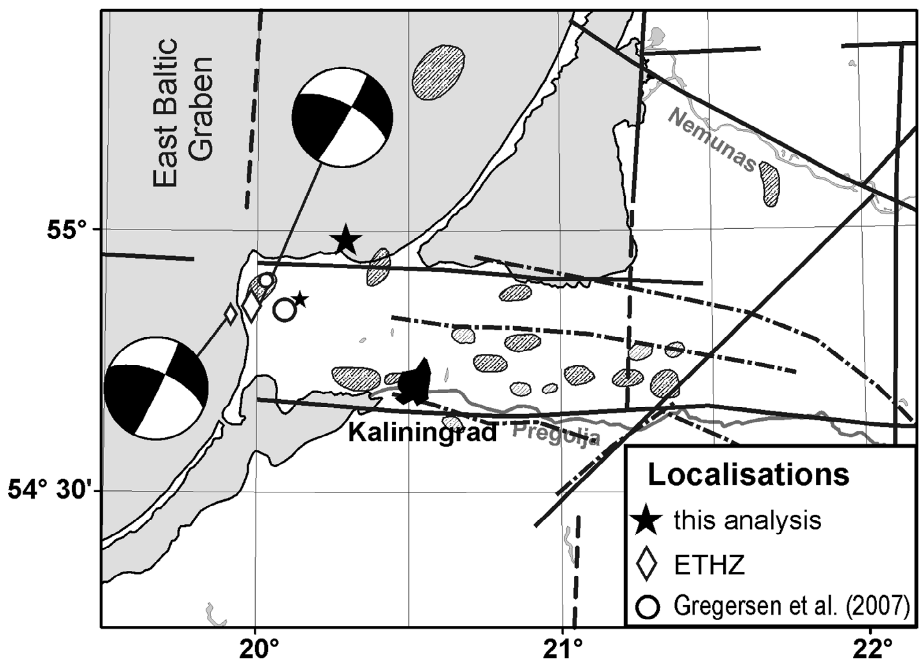


Figure 13. Focal mechanism solutions from ETHZ (2004), different location solutions for the two Kaliningrad events on September 21, 2004 and faults after Karabanov et al. (2001) as *full* and *dashed lines* and after Zui et al. (1995) as *dot-dashed lines*. The *small symbols* are related to the weaker foreshock at 11:05 UTC and the *large symbols* to the main shock at 13:32 UTC. Hatched areas denote oil fields (after ENVOI, 2006).

this, several ESE-WNW oriented faults pass through the Kaliningrad enclave (Fig. 13). Unfortunately, the map by Zui et al. (1995) ends just east of the source region of the two events. Yet it can be assumed that these faults are extended further to the west, to the west coast of Samland. At least there is a fair agreement between the orientation of the faults with one of the planes of the fault plane solutions.

In a map of the post-Eocene (Rupelian) vertical crustal movements and faults after Karabanov et al. (2001), based on data from Aizberg et al. (1997, 1999), and Garetsky et al. (1997), the Samland peninsula is framed by E-W to ESE-WNW oriented faults along the northern and southern coastal areas (Fig. 13). Aizberg et al. (1997, 1999) and Garetsky et al. (1997) predict these, following the method of Reisner and Johanson (1993), to be seismogenic zones - at that time without indications of actually occurring earthquakes. However, the maximum expected magnitude was predicted to 4.0, i.e., somewhat smaller than the recent earthquakes. Aronova (2006) picks up on this hypothesis. The E-W oriented tectonic units referred to above and the N-S running unit at the extension of the west coast of Samland at 20°E after all seem to be responsible for the special E-W orientation of the coast lines of the peninsula (cf. Fig. 13). The different, rather small-scale hydrocarbon deposits depicted in Fig. 13 after ENVOI (2006) give the impression of an E-W sequence. The E-W oriented faults, which are predominant on the peninsula, possibly constitute zones of weakness along which the deposits could have formed. Besides, the Kaliningrad area is located in a rather narrow zone in which the post-Eocene depression in the Belarus syneclise turned into an uplift (Fig. 2).

Gregersen et al. (2007) discuss the good agreement of the fault plane solutions derived by Harvard, the Polish Academy of Sciences (IGF) and the ETHZ. The latter of these are chosen for our Figs. 10 and 13. Gregersen et al. (2007) give preference to the about 300° striking nodal plane as the causative one, but do not try an association with any known fault pattern. Based on near-field macroseismic data, Nikonov (2006) associates the first event with a N-S oriented fault just west of the Samland peninsula (first shock) and the second and largest event with an E-W oriented fault just off the north coast of the peninsula. Nikonov's proposal agrees well with the fault traces discussed in the present study and which are depicted in Fig. 13. Also Nikonov's localisations, especially of the main shock, agree very well with the macroseismically determined epicentres of the present study.

7 Conclusions

The youngest earthquakes in 2000, 2001 and 2004 in the southern border region of the Baltic Sea show that significant events can occur also in this virtually aseismic area.

Improved localizations in comparison to routine analysis of the Wittenburg 2000 and Rostock 2001 events gave errors of 2 km and 3 km in epicentre locations, respectively.

From nearby stations, the focal depth of the Wittenburg event could be calculated to 17 ± 3 km, confirming a tectonic origin. Since the stations recording the Rostock event were less favourably located, the focal depth was calculated from numerical modelling of the wave field and a value of 9 ± 1 km was obtained.

The two Kaliningrad 2004 events were located at great distances from the closest stations, implying large errors in the epicentre locations. The focal depth could be accurately determined, however, from teleseismically recorded depth phases. Numerical modelling of the respective wave fields resulted in a value of 13 ± 1 km. Thus the Kaliningrad events like the other events of this study are tectonic beyond doubt.

With respect to the calculations of the fault planes and moment magnitudes, M_w, we concentrated on the Wittenburg and Rostock events, since reliable solutions from routine analysis at international seismological centres already exist for the Kaliningrad events. For all investigated events, including the Kaliningrad events, the directions of maximum horizontal compression derived from fault plane solutions using inversion analysis of P-polarities, and P- and S-wave amplitudes, agree very well with the regionally varying stress field. All mechanisms show oblique displacement with a normal component.

The possible fault planes for the Rostock event correlate very well with known faults. A similar correlation is principally difficult for the Wittenburg event due to its larger depth; a documented NNW-SSE running fault could possibly be associated with the event. It is also hard to correlate the planes of the mechanism solutions for the Kaliningrad events to the described E-W and N-S running faults in the area. At least could these demonstrate zones of weakness which are crossed by ESE-WNW oriented faults. The latter orientation agrees with one of the planes of the mechanism solution.

The moment magnitudes, M_w, obtained from inversion represent homogenous size measures: Wittenburg 3.1, Rostock 3.4, and Kaliningrad 4.6 (at 11:05 UTC) and 4.7 (at 13:32 UTC).

Macroseismic evaluations were made for the Rostock and Kaliningrad events. The Wittenburg event had no felt reports, indicating a depth of at least 15-20 km for this size an event. This is supported by the instrumentally determined depth of 17±3 km.

For the derivation of source parameters from macroseismic data, a newly developed technique could be applied, which does not, as is normal, use data from a few isoseisms, but uses all the individual intensity data points. The macroseismically founded epicentre location for the Rostock event is practically identical to the instrumental, in spite of the lack of intensity data in the epicentral region. The macroseismic focal depth determination with the new technique also agrees with the instrumental one, 9 km, although with an error of ± 2 km. The macroseismic epicentre locations and depths of the Kaliningrad events also show fair agreement with the obtained instrumental ones.

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