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Seismicity and seismotectonic implications in the southern Baltic Sea area

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ABSTRACT

An updated list of earthquakes and earthquake parameters (location, homogenized magnitude, macroseismic data) for the southern Baltic Sea area reveals activity north of the sea, whereas there are very few epicentres in the sea itself and in the region south of it. This is the first study to combine seismological data for the whole region to cover also the sea. Macroseismic data for the 1930 earthquake were reinvestigated leading to an intensity of V–VI (MM or MSK scale), a radius of perceptibility of 135 km and an unusually big focal depth of about 40 km. It is difficult to correlate individual earthquakes with specific faults, but some seismotectonic relations are suggested, e.g. for the Tornquist zone, the predominant structure of the region. Only few reliable focal-mechanism solutions exist. Possible seismogenic processes (ridge push, isostasy, etc) are discussed.

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INTRODUCTION

The southern Baltic Sea is an area of low seismicity. It is transected by the Teisseyre–Tornquist tectonic zone, part of which is the border between the Baltic Shield and the North German–Polish Depression with younger sedimentary structure. The shield border continues, with increased seismic activity, to the north-west as the Tornquist zone, in southern Sweden.

The purpose of this study is primarily to compile and systematize earthquake data – historical and instrumental – in the southern Baltic Sea area and to test various seismotectonic and seismogenic models with respect to the obtained catalogue. Previous seismicity studies of the southern Baltic Sea region were made either for Scandinavia or for the German–Polish area. In this study data from the whole region are combined. A general difficulty has been the limited seismograph monitoring in the area around the southern Baltic Sea (Table 1; Fig. 1). However, special emphasis is put on a reinvestigation of the 1930

earthquake – the largest known in the southern Baltic Sea.

SEISMICITY, SEISMOGRAPH STATIONS AND EVENT DETECTION

The compiled earthquake catalogue for the area 53.5°N–56.5°N, 11.0°E–16.0°E is given as Table 2. Epicentres are plotted in Fig. 2. The main databases are the catalogues by Grünthal (1988) for north-eastern Germany and northwestern Poland, and by Arvidsson *et al.* (1987), Wahlström (1990) and Ahjos and Uski (1992) for southern Fennoscandia. Each of the catalogues has homogenized magnitudes or such can be computed easily. Adjacent areas of the Baltic Sea are also covered by some of these catalogues. Additional information was obtained from other catalogues and special studies, mentioned in Table 2. In many cases, a new evaluation of macroseismic parameters and magnitude resulted from the present study (Table 2).

Although the catalogue of Table 2 is as complete as possible, the large time-span and the varying spatial and temporal seismograph monitoring make it inhomogeneous in a variety of respects. There has been a rather limited seismograph surveillance of the area (Table 1; Fig. 1). Due to poor ground conditions hardly any stations have been located in northeastern Germany. An upgrade has taken place only in the past few years with two stations installed near the coast. However, these were closed in 1992. Besides three stations of the SKI network in southern Sweden operating in the period 1979–1986 only a few stations have been and are operating in Denmark and southern Sweden. A strategic station for earthquake detection in the Baltic Sea, Akirkeby (BSD) on Bornholm, has been operating since 1981.

Kijko *et al.* (1993) estimate threshold magnitudes for southern Sweden (south of 60°N) at $M_L(UPP) = 3.4$ for the period 1659–1879, 3.3 for 1880–1919, 2.7 for 1935–1950 and 2.4 for 1951–1989. (The period 1920–1934 had anomalously high seismicity and was excluded by Kijko *et al.*) These values can be taken as realistic estimates also for the southernmost part of Sweden and its surrounding area. However, as can be seen in Table 2, a large number of low-amplitude earthquakes was recorded in the 1980s. This is thanks to the operation of the aforementioned SKI network stations.

The near total absence of epicentres in the southern Baltic Sea is striking in comparison with the activity in the land areas to the north. The Baltic Sea as a whole has very little seismicity. The poor seismograph coverage south of the Baltic Sea certainly makes detection poorer here and also in the sea. The almost total lack of events makes it hard to assign a quantitative measure of the detection capability for the area south of Fennoscandia. However, the seismicity

Table 1. Seismograph stations near southern Baltic Sea

Station	Code	Location		Time of operation
		°N	°E	
Åkirkeby	BSD	55.11	14.91	1981–
Copenhagen	COP	55.69	12.43	1927–
Delary	DEL	56.47	13.87	1967–
Karlskrona	KLS	56.17	15.59	1961–1968
Linde/Stevns	SVS	55.33	12.22	1979–
Lodmannshagen	LMH	54.09	13.65	1985–1992
Lund	LUN	55.70	13.19	1917–1953
Olofström	OLO	56.31	14.47	1979–1986
Örkelljunga	ORK	56.27	13.26	1979–1986
Roggendorf	RDF	53.68	11.01	1984–1992
Veberöd	VEB	55.60	13.52	1979–1986

rate is no doubt smaller than in the area north of the sea and seismogenic explanations for this are discussed below.

The largest earthquakes in the southern Baltic Sea, at least in this century, are the two shocks near Bornholm in August 1921, the earthquake of 31 October, 1930, discussed below, and the sequences NE of Bornholm in April 1946 and July 1948 (Table 2; Fig. 2). Note the remark above about anomalously high seismicity in southern Sweden in the period 1920–1934.

SEISMOTECTONIC DISCUSSION

Tectonics and seismicity (Figs 2 and 3)

The southern Baltic Sea area is characterized by an intense block structure. The Tornquist zone, with a NW–SE to WNW–ESE trend and a width of 20–50 km, is a complex and much faulted zone (dip-slip and strike-slip), often rejuvenated and frequently characterized by late Cretaceous to early Tertiary wrench movements and tectonic inversion.

The southern extension, the Teisseyre–Tornquist zone, is traced through Poland and further south down to its plunge at the Carpathian Mountains. The fundamental structural lineation represents the SW margin of the East European Platform. No enhanced seismic activity is associated with this major tectonic feature. The northern extension, the Sorgenfrei–Tornquist zone, continues under southern Kattegat and Skagerrak, possibly all the way to the North Sea (Pegrum, 1984). The two segments are linked with a bayonet-shaped joint, of

which the Rønne Graben seems to be a northerly part.

Other notable tectonic lines in the area are oriented WNW–ESE and connected with the Ringkøbing–Fyn High, or run approximately N–S.

The seismicity near Bornholm is possibly associated with the Rønne Graben and other sea-bottom exposed faults in the area. However, no earthquake focal-mechanism solutions exist to make a conclusive seismotectonic correlation.

Both historical and instrumental data show that the southern Baltic Sea west of Bornholm is virtually aseismic. The same is the case in the adjacent areas of southern Sjaelland and the areas south of it, northern Germany and northern Poland, whereas there is manifest activity to the north, i.e. in Skåne and northern Sjaelland. There seems to be no current activity associated with the Ringkøbing–Fyn High.

The concentration of seismicity along the SW coast of Skåne cannot be related to one tectonic zone. The events are from the historical record and location errors may be significant. It is not improbable that some historical events refer to faults making up the southern

Fig. 1. Locations of stations in the southern Baltic Sea region. Table 1 gives periods of operation.

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Table 2. Earthquakes in the southern Baltic Sea and surrounding areas, 53.5°N–56.5°N, 11.0°E–16.0°E, in the years 1600–1985. (Codes are explained below)

Time		Location		Magnitude		Maximum intensity (MM or MSK) and radius of felt area (km)				Remark
y/m/d	h m	°N	°E	M1	M2	LE	AR/WM	GL	NEW	
1629/09/06		55.0	15.0 B			X				
1632/02/29	23	55.8	12.5 D			X	6.0			
1691/02/17	03	56.2	14.0 S	3.0			5.0/20			
1709/02/11		55.6	12.3 D	2.8		X			4.0/20	
1752/01/03	11	56.5	13.0 S	3.0			5.0/20			
1766/01/28	0230	56.4	13.0 S	2.4			4.0/10			27? Jan. [WM]
1784/04/06	20	55.8	12.0 D	2.8		X			4.0/20	
1809/11/23	13	56.0	12.5 D			X			4.0	
1829/08/18	1415	55.8	12.5 D	4.2		X	4.0/80		5.0/200	[based on HI and KJ]
1850s		56.2	14.8 S	2.7			5.0/10			several shocks? [WM]
1860/08/12	2130	56.1	14.2 S	3.0			5.0/20			
1861/12/15	01	55.9	13.4 S	2.8			4.0/20			
1862/02/07		56.2	14.8 S	3.0			5.0/20			several shocks in the period 7 Feb. 18.00 h to 19 Feb. 03.00 h [WM]
1869		55.4	13.4 S	2.7			5.0/10			1870? [WM]
1869/01/28	11	55.7	12.1 D	3.1			4.5/30			
1869/07/19	20	55.4	13.2 S	3.2			5.0/30			
1875/08/13	17	55.0	15.0 B			4.5				
1881/05/21	22	55.6	12.7 D	3.2		4.0	4.0/30		4.0/50	
1882		55.5	13.7 S	2.7			5.0/10			year doubtful [WM]
1886/12/23	14	55.4	13.4 S	2.4			4.0/10			
1886/12/23	2210	56.4	12.5 S	2.7			5.0/10			
1888/05/16		54.2	11.5 G		2.5			4.0		
1888/05/29	00	55.4	13.5 S	2.2			3.0/10			multiple shocks? several shocks in earlier years [WM]
1888/08/17	18	55.4	13.7 S	2.7			5.0/10			not seismic? [WM]
1888/08/18	06	55.4	13.7 S	2.4			4.0/10			not seismic? [WM]
1890/10/08	07	55.0	15.1 B	2.4					4.0/10	[based on SV]
1894/04/22	2132	55.5	14.4 S	3.7			5.0/80			one foreshock and a few aftershocks [BÅ]
1894/04/30	1907	55.5	13.2 S	2.2			3.0/10			
1895/01/12	0930	56.4	13.0 S	2.6			3.5/18			
1896/10/21	1625	56.5	14.5 S	2.2			3.0/10			
1896/10/21	1700	56.5	14.5 S	2.2			3.0/10			
1897/01/09	0104	56.0	14.0 S	2.2			3.0/10			
1897/01/09	0115	56.0	14.0 S	3.3			4.5/45			
1897/01/09	0145	56.0	14.0 S	2.2			3.0/10			
1898/05/02	0930	56.1	12.9 S	2.3			3.5/10			3 shocks [BÅ]
1902/10		55.5	13.9 S	2.2			3.0/10			2 shocks in the period 12–18 Oct. [BÅ]
1904/10/26	0100	55.8	13.3 S	2.4			4.0/10			
1904/10/26	0246	56.2	12.9 S	2.4			4.0/10			
1905/01/15	1035	56.5	13.1 S	2.9			3.5/32			
1906/03/24	0330	56.5	13.0 S	2.7			4.0/17			
1906/09/14		54.5	11.2 G		2.5			4.0		
1907/04/30		54.5	11.2 G		1.9			3.0		
1907/08/29		54.0	14.6 P		2.5			4.0		
1909/03/14		56.5	15.9 S	2.2			3.0/10			
1909/07/27		56.0	14.0 S	2.8			4.5/15			
1910/03/15		56.3	14.7 S	2.4			3.5/12			
1911/01/09	0500	55.5	14.3 S	2.4			4.0/10			
1911/08/08	1000	56.5	13.1 S	2.3			3.5/10			
1913/02/27	0300	56.2	15.3 S	2.3			3.5/10			
1914/07/22	0130	55.5	13.0 S	2.2			3.0/10			
1921/08/23	2200	55.0	15.0 B	3.6		X	5.0/65			
1921/08/23	2345	55.0	15.0 B	3.6		X	5.0/65			
1924/12/15	2245	53.9	14.3 P		2.5			4.0		

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1929/07/19		55.7	11.7 D	2.8	X		4.0/20	possibly one foreshock [BÅ]
1930/05		55.4	13.5 S	2.2		3.0/10		
1930/10/31	2317	55.3	12.8 S	4.1	4.5/175	5.0/135	5.5/135	MS = 4.1 [BÅ]; possibly one foreshock 3 weeks earlier [BÅ]
1932/02/11	1633	56.0	14.6 S	3.3		4.0/52		
1932/04/12	0655	56.2	14.3 S	2.2		3.0/10		
1932/04/12	2009	56.2	14.3 S	2.2		3.0/10		
1937/03/05	1655	56.5	13.0 S	2.8		4.0/20		one aftershock [BÅ]
1945/04/26	1930	56.1	14.4 S	2.2		3.0/10		
1945/04/27	0200	56.1	14.7 S	2.7		4.0/16		foreshocks [BÅ]
1945/04/27	1900	56.1	14.7 S	2.7		4.0/16		
1945/08/17	01	56.5	11.5 D			4.5/3.7	4.5/100	explosion? [LE]
1946/04/24	1745	55.4	15.6 B	3.2		4.0/50		
1946/04/24	1830	55.4	15.6 B	3.8		5.0/100		MS = 4.4 [BÅ]; several fore- shocks and aftershocks [BÅ]
1946/04/24	1910	55.4	15.6 B	3.8		5.0/100		
1948/07/22	1915	55.4	15.6 B	2.2		3.0/10		
1948/07/22	2015	55.4	15.6 B	3.6		4.5/75		
1949/11/04	07	55.4	12.6 D	2.4	X		4.0/10	
1954/06/04	2103	55.4	12.6 D	2.8	4.0		4.0/20	
1960/10/20	1150	56.4	13.3 S	3.2		4.0/44		
1963/06/19	1700	56.3	11.7 D	3.1				
1971/02/21	0003	55.8	12.1 D	1.7				
1973/07/02	0407	56.2	12.8 S	2.5				
1977/04/20	2220	55.6	14.1 S	2.5				
1980/01/21	0741	56.2	12.2 D	2.5				
1980/07/05	0324	56.1	13.5 S	1.7				
1980/11/16	0605	56.3	12.5 S	1.9				
1981/04/06	2225	56.3	13.0 S	0.9				
1981/05/05	0300	54.7	13.0 G	2.8				M1 from Swedish stations; M _L = 2.6 from GDR stations [WS]
1981/10/30	0952	55.7	13.9 S	2.8				
1982/01/02	1720	55.8	11.9 D	1.0				[AR]
1982/02/15	1410	55.9	12.2 D	2.0				
1982/03/24	0139	56.2	12.3 D	1.1				
1982/06/30	1715	55.9	15.4 S	2.8				
1982/09/17	1119	55.7	11.6 D	1.5				
1982/10/06	2203	56.4	12.9 S	0.7				
1982/10/09	2337	56.1	11.6 D	0.9				
1982/10/17	0638	56.3	14.7 S	1.0				
1982/11/01	0248	56.4	11.9 D	2.1				
1983/06/22	1021	54.9	14.9 B	1.9				[GN]; explosion? [GN]
1983/07/04	2133	56.2	13.5 S	1.5				
1983/08/23	2103	56.4	12.3 S	1.6				
1983/12/18	2125	56.3	12.0 D	2.0				
1983/12/19	0244	56.3	11.9 D	1.5				
1984/04/05	0910	55.2	13.2 S	2.8				
1984/04/16	0147	55.6	12.2 D	1.9				
1984/04/30	0855	56.3	12.3 S	1.4				
1984/04/30	0857	56.3	12.3 S	1.6				

The Gregorian calendar is used for all events. Times are given in GMT; however, for many historical events it is unclear which time-frame is used in the original reference. Location regions (including surrounding waters): B, Bornholm; D, Denmark (except Bornholm); G, Germany; P, Poland; S, Sweden.

M1: M_L (UPP) magnitude [WA] or value compatible with this scale computed from either macroseismic data [M_M (UPP)] in WA or Danish seismograms [GI, GN]. M2: macroseismic magnitude [GL].

'X' marks that the event is reported felt without quantifying macroseismic parameters. Unless otherwise remarked, the references of data for various time periods and regions are: Before 1891–B[LE], D[AU] or [LE], G and P[GL], S[WM]; from 1891–B and S[AR], with intensities assessed in the present study, D[GI] or [GN], G and P[GL]. Assessments made in this study are listed in the column 'NEW'.

[AR] is based on [AU], except that magnitudes are consistently M1. [AU] gives intensities in steps of units, whereas in our catalogue half steps of units are given. This and the consistent use of M1, except for most region G and P events, sometimes produce a magnitude different from that in the reference list. Parameters have sometimes been slightly revised without a remark being given.

References: [AR] Arvidsson *et al.* (1987), Appendix I; [AU] Ahjos and Uski (1992); [BÅ]: Båth (1956); [GI] Geodætisk Institut (1983); [GL] Grünthal (1988); [GN] S. Gregersen, Copenhagen, pers. comm.; [HI] Hintze (1896); [KJ] Kjellén (1910); [LE] Lehmann (1956); [SV] Svedmark (1891); [WA] Wahlström and Ahjos (1984); [WM] Wahlström (1990); [WS] Wahlström and Strauch (1984).

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Fig. 2. Epicentres in the area 53.5°N–56.5°N, 11.0°E–16.0°E until 1985, inclusive. For size of symbols, intensities are referred to before 1961 and magnitudes from 1961 and on.

border of the Tornquist zone, whereas others refer to the offshore crotch-like fault pattern, which may have been the locus of the 1930 earthquake. Generally, though, since earthquakes in the region take place at several km down to several tens of km depth (as is probable for the 1930 event), the spatial correlation of foci with less prominent faults of which only the surface-exposure has been mapped is highly uncertain.

The activity in north-west Skåne and southern Kattegat does not appear to be higher than that in north-east Skåne and northern Sjælland, so there is no obvious association of the current seismicity with the Tornquist zone. Such an association has been proposed

for the Kattegat area by, for example, Gregersen and Lykke-Andersen (1993).

To improve our knowledge on seismotectonic relations more seismic data are needed, especially more precise hypocentre locations and better constrained fault-plane solutions. Improved and extended seismograph recording facilities are essential in this context.

Crustal stress field (Fig. 3)

Available data show that the crustal stress field of Fennoscandia as a whole has an approximate WNW–ESE mean orientation of compression. However, the scatter in the data is large compared to continental western Europe, for example.

In his mass production of focal-mechanism solutions for microearthquakes in southern Sweden, Slunga (1985) reports a strong horizontal component oriented roughly NW–SE for the deviatoric compressive-stress (P-) axis for two earthquakes in the southern Baltic Sea, both with a magnitude, $M_L(\text{UPP})$, of 2.8. Several focal mechanisms in southern Kattegat have similar P-axis type and orientation (Slunga, 1985). This is concordant with models of stress propagation generated by ridge push at the nearest plate boundary, a section of the North Atlantic Ridge near Iceland. On the other hand, Arvidsson *et al.* (1991a) obtained a well-constrained mechanism with an almost due N–S oriented P-axis, i.e. not easily reconcilable with the plate tectonics explanation, for the largest earthquake in southern Scandinavia in the past several decades, on 15 June, 1985, $M_L(\text{UPP})=4.6$, located in southern Kattegat just north of the seismicity area depicted in Fig. 2. A large, late aftershock on 1 April, 1986, $M_L(\text{UPP})=4.2$, had a similar mechanism. These two mechanism solutions are much better constrained than the ones for the microearthquakes derived by Slunga (1985). Local 'disturbances' in the principal stress pattern are thus obvious and complicate the seismotectonic interpretation.

P-axes of reliable focal-mechanism solutions are depicted in the figure and include some of the earthquakes just mentioned. The reliability criteria are specified by Arvidsson and Wahlström (1993). Most of the Slunga (1985) mechanisms do not fulfil the reliability criteria. The two mechanisms south of 56°N belong to the lowest quality rank of reliable solutions and we refrain from more detailed seismotectonic speculation based on these.

Well-established *in situ* hydrofracturing measurements for southern Sweden show NE–SW oriented compression. This is the same direction of maximum horizontal compression found south of the Baltic Sea (Grünthal and Stromeyer, 1992).

Ask *et al.* (1993) investigated several borehole breakouts near the Tornquist and Tornquist–Sorgenfrei zones and in the area to the south. Their first results indicate that the fault zones have a regional influence on the orientation of maximum horizontal

compressive stress, whereas the stress to the south behaves according to expectations from plate tectonics (ridge push; M. Ask and O. Stephansson, Stockholm, pers. comm.). Some recent borehole breakout data under the sea north of Poland show NNE–SSW to N–S oriented maximum compression (Jarosinski, pers. comm. to the World Stress Map Project).

Possible seismogenic mechanisms

Various models exist to explain the occurrence of earthquakes in Fennoscandia and adjacent areas: plate tectonics, isostatic postglacial rebound, more long-term isostatic processes, sedimentary loading, orogeny of earlier tectonic eras, etc. Whatever the process(es) of stress accumulation and

distribution may be, the stress release is connected to zones of weakness. The two main hypotheses – ridge push and postglacial land uplift – are discussed by Wahlström (1993).

A model that explains the generally high seismic activity in the Fennoscandian shield and the absence of earthquakes in surrounding areas, e.g. the Baltic Sea and the northern part of Germany and Poland, has recently been suggested by Muir Wood (1993). According to this model, isostasy due to the latest era of glaciation–deglaciation is the only significant seismogenic contributor in Fennoscandia and its surroundings, and provides sufficient (extensional) strain in the shield for earthquake occurrence. Muir Wood's (1993) main argument is that the extensional strain generated by the uplift is

several orders higher than the compressional strain caused by ridge push. Muir Wood's conclusion is controversial and most of his arguments, like the strain rate calculations, can be debated (see, e.g. Wahlström, 1993).

Ekman (1985) and Skordas and Kulhánek (1992), using different arguments, suggest uplift as the predominant mechanism for the seismicity in northern Fennoscandia and ridge push in southern Fennoscandia. The total picture given by various stress orientation data for the southernmost part of Fennoscandia (previous section) is unexpected in the plate tectonics framework. Perhaps local structural 'anomalies' guide the stress pattern or we have to search for other explanations for the contemporary seismicity.

Anderson (1980) has proposed an earthquake-generating mechanism related to long-term isostasy where differential strain is built up along the Swedish coastline of the Gulf of Bothnia, an area of enhanced seismicity. It is doubtful if such an explanation is relevant for the activity in southern Skåne and Bornholm, where there is practically no current uplift. Further north, not only the Baltic Sea but also the adjacent land areas, i.e. southeastern Sweden and the Baltic states, have hardly any seismic activity. The small activity in the Baltic Sea indicates that sedimentary loading is not a significant seismogenic contributor here.

THE 31 OCTOBER 1930 EARTHQUAKE

Instrumental data

A reinvestigation was made of the largest known earthquake in the southern Baltic Sea, occurring shortly after midnight, local time, on the night between 31 October and 1 November, 1930. The location of the epicentre, 55°17'N, 12°46'E, was determined from arrival-time and relative-amplitude data of waves recorded by the Wiechert seismographs in Copenhagen and Lund (Lehmann, 1931). Instrumental data give an approximate origin time at 23h16m40s GMT (31 October; Båth, 1956). The earthquake was also recorded in Uppsala, by several stations in Germany, and in Vienna (International

Fig. 3. Tectonic framework of the southern Baltic Sea and its surroundings (after Kraus and Möbus, 1981, Beutler and Schüler, 1981, Flodén, 1984, Pegrum, 1984, EUGENO-S Working Group, 1988). Notation: RFH = Ringkøbing-Fyn High; RG = Rønne Graben; STZ = Sorgenfrei-Tornquist zone; TTZ = Teisseyre-Tornquist zone. Open arrows indicate maximum compression obtained from in-situ hydrofracturing data (Zoback, 1992). Filled arrows indicate maximum compression obtained from reliable earthquake focal-mechanism solutions (from Arvidsson and Wahlström, 1993).

Seismological Summary). The instrumental data indicate an unusually large focal depth for the Scandinavian area.

Macroseismic data (Fig. 4)

The earthquake was felt in parts of Denmark, southern Sweden and northern Germany: Bornholm to the east, Skåne, western Blekinge and south-western Småland to the north-east and north, and Sjaelland, Fyn and eastern Jylland to the west; to the south-west there is one reported observation that the earthquake was felt in Kiel (Kieler Zeitung) and from the south the Greifswalder Zeitung reports that it was felt on Rügen. Plenty of macroseismic information, obtained from newspaper reports, questionnaires, direct interviews and other sources, was analysed at the Geodetic Institute, Copenhagen and Geological Survey of Sweden, resulting in detailed descriptions of how the earthquake was felt at various localities in Denmark (Lehmann, 1931) and Sweden (Sahlström, 1931). The area from which the strongest effects and experiences were reported encompasses eastern and southern Sjaelland, Møn, northern Falster and southwestern Skåne. Both Lehmann (1931) and Sahlström (1931) estimate the maximum felt intensity at IV–V. Lehmann used the Mercalli–Sieberg scale and Sahlström the Rossi–Forel scale. The two scales are compatible up to intensity V. Amongst the strongest effects can be mentioned cracks in walls, tiled stove pipes, woodpiles, bottles, pictures and flower pots falling down, furniture moving, doors and windows rattling, candelabers swinging and pendulum clocks stopping (see Lehmann, 1931, and Sahlström, 1931, for details). Such effects relate to intensity V–VI on the Modified Mercalli (MM) and Medvedev–Sponheuer–Karnik (MSK) scales. The sound is often described as similar to, but still not quite the same as, that of a heavily loaded truck driving by; occasionally people thought that the furnace in the basement had exploded. Many people were woken and frightened. At greater distances there were just faint experiences of shaking or just a sound.

There are several reports both from Denmark and Sweden that two shocks

Fig. 4. Intensity data and isoseismals for the 31 October, 1930 earthquake, $M_M(\text{UPP}) = 4.1$. The map with the new evaluation introduced is redrawn after Lehmann (1931) and Sahlström (1931). Lehmann (1931) did not assign intensities to many Danish localities but used a three-graded scale for larger towns (strongly, less strongly and weakly felt). This scale is here assumed to correspond to the three intensity classes used by Sahlström (1931) for Swedish data. For smaller villages Lehmann only assigned felt or not felt.

were felt within an interval of a few s. Since there is no indication on the seismograms of a double shock, the experiences can be referred to as the arrivals of P and S waves, respectively. There is a report of a weak foreshock during the night of 8–9 October (Sahlström, 1931) and of a weak aftershock about one hour after the main earthquake (Lehmann, 1931).

The mapped intensities and isoseismals are based on the data given by Lehmann (1931), Sahlström (1931) and the German newspapers mentioned above. Some minor assumption was made in order to homogenize the intensities (see caption of Fig. 4). Three isoseismals have been drawn, the

outermost depicting the limit of the area of perceptibility. The corresponding circular area has a radius of approximately 135 km (the uncertain Kiel observation excluded). The isoseismals separating intensity IV–V from IV, and IV from III, are drawn only for the landward portion of Denmark and Sweden. Whereas Lehmann (1931) suggests some correlation between the distribution of intensities and the local geology, Sahlström (1931) does not find any corresponding relationship. The obtained values for the intensities and the radius of perceptibility correspond to a magnitude, $M_M(\text{UPP})$, of 4.1 and a focal depth of about 40 km (based on formulae in Kulhánek and Wahlström, 1992).

Focal depth

Both instrumental and macroseismic data indicate a large focal depth. Although a depth of about 40 km, estimated from the macroseismic data, is considerably smaller than that calculated by Lehmann (1956), 58 km, it is larger than expected in this shallow-crust region (Moho depth slightly more than 30 km). Even if the intensities would be slightly underestimated (as also suggested by K. Arhe, Helsinki, pers. comm.), the depth remains large. It is probable that the focus is near the bottom of the crust. Slunga (1985) lists a nearby instrumentally located earthquake at 36 km depth. The existence of a local active zone near Moho is thus indicated. Such a zone may be explained by low ductility in the lower crust associated with low heat flow. Deep-crust earthquakes are not common in Fennoscandia, but they have been recorded also in other areas (see, e.g., Kim *et al.*, 1985, and Arvidsson *et al.*, 1991b).

CONCLUSIONS

A homogenized earthquake catalogue was compiled for the southern Baltic Sea area. The largest known offshore earthquake in the region, on 31 October, 1930, was reinvestigated. The regional magnitude was 4.1, radius of perceptibility 135 km, maximum intensity V–VI (MM or MSK) and focal depth 40 km. The unusually large focal depth, although an approximate estimate from macroseismic data, indicates a low-ductility, low heat flow lower crust.

Correlation of seismicity with fault zones is difficult to find. The seismicity near Bornholm may be associated with sea-bottom structures like the Rønne Graben. The sea itself is practically aseismic, as is the area south of it. There is more activity in Skåne, northern Sjaelland and nearby Kattegat, but correlation with the Tornquist zone, the predominant structural feature of the area, is not obvious.

Stress field data (focal mechanisms, *in situ* measurements) indicate roughly N–S to NE–SW orientations of maximum horizontal compression. This is not in accordance with the hypothesis of influence from ridge push at the

North Atlantic Ridge. There are problems also with possible seismogenic mechanisms like isostatic rebound and sedimentary loading.

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