Earthquakes in Denmark

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Within the last two decades the sensitivity to small earthquakes has been much improved in Denmark. Two to ten earthquakes are recorded each year of magnitudes 1½ to 4½. The seismicity pattern seen in recent data basically confirms the patterns noted from previous instrumental locations, as well as from felt areas of older dates. This means earthquake activity cutting off the earthquake zones of western Norway and of southern Sweden: (1) In north-western Jylland, and in the Skagerrak Sea the earthquake zone cuts off a zone of earthquakes along the western coast of Norway. At least some of these earthquakes in Jylland and Skagerrak occur at depths 30–40 km, close to Moho. (2) In north-eastern Sjaelland and in the Kattegat Sea, as well as around Bornholm the earthquake activity occurs in the upper crust, at depths shallower than 15 km. This appears as the south-western boundary of the scattered activity in south-western Sweden.

In general terms this can be considered the south-western rheological edge of the Fennoscandian Shield. The north-western earthquake zone is along the middle axis of the Norwegian-Danish Basin, and the eastern earthquake zone is in the Tornquist Zone. The two earthquake zones are not connected. This can not be ascribed to lack of sensitivity, so the Fennoscandian Border Zone can not be termed active as such. The central part of Denmark is aseismic; and the same is true for the south-western part of Denmark and northern Germany.

In the North Sea the graben area is the most active. The Viking Graben in the north has a significant earthquake activity, and the Central Graben, which goes through the Danish sector of the North Sea has small, but noticeable activity. On the British side of the graben there are additional active areas.

The stress field responsible for these earthquakes is rather uniform across the Fennoscandian Border Zone, with scattered exceptions. It reflects the general NW–SE compression of northern Europe between the North Atlantic spreading ridge and the Alpine collision between Europe and Africa.

Key words: Earthquakes, Denmark, seismicity, stress field.

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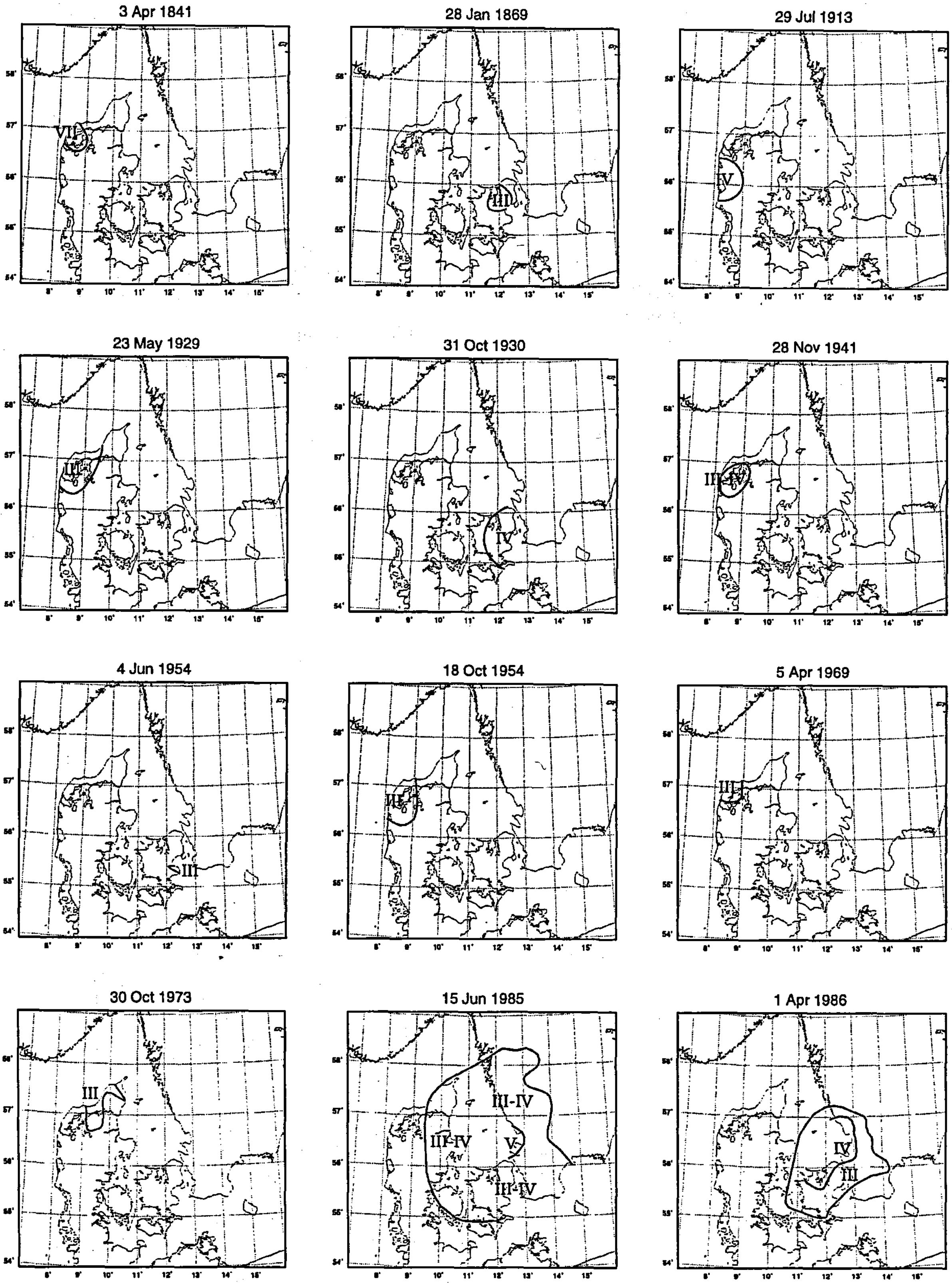
A comprehensive treatment of earthquakes in Denmark was made by Inge Lehmann many years ago (Lehmann 1956). She collected all the available historical and instrumental information on earthquakes on land in Denmark as well as in the surrounding seas. In those lists are 50 seismic events classified as earthquakes and 13 others, which Lehmann (1956) did not consider to be earthquakes. All of the latter are before the year 1830, quoted from Johnstrup (1870), and taken by him to be uncertain. For most of these the only existing remark is that an earthquake happened in Denmark, and no more. Lehmann mentions that bad weather, thunder and lightning occasionally go into these accounts.

The seismicity zones of Denmark are already broadly delineated in Lehmann's paper. This is largely based on the above-mentioned felt reports, but she also located earthquakes based on instrumental records in Skagerrak in 1929 (23 and 30 MAY) (Lehmann 1929) and in Oeresund 1930 (30 OCT) (Lehmann 1931) (see


3 Apr 1841
VII
28 Jan 1869
III
29 Jul 1913
V
23 May 1929
III
31 Oct 1930
IV
28 Nov 1941
III-IV
4 Jun 1954
III
18 Oct 1954
III
5 Apr 1969
III
30 Oct 1973
III
V
15 Jun 1985
III-IV
III-IV
V
III-IV
1 Apr 1986
IV
III

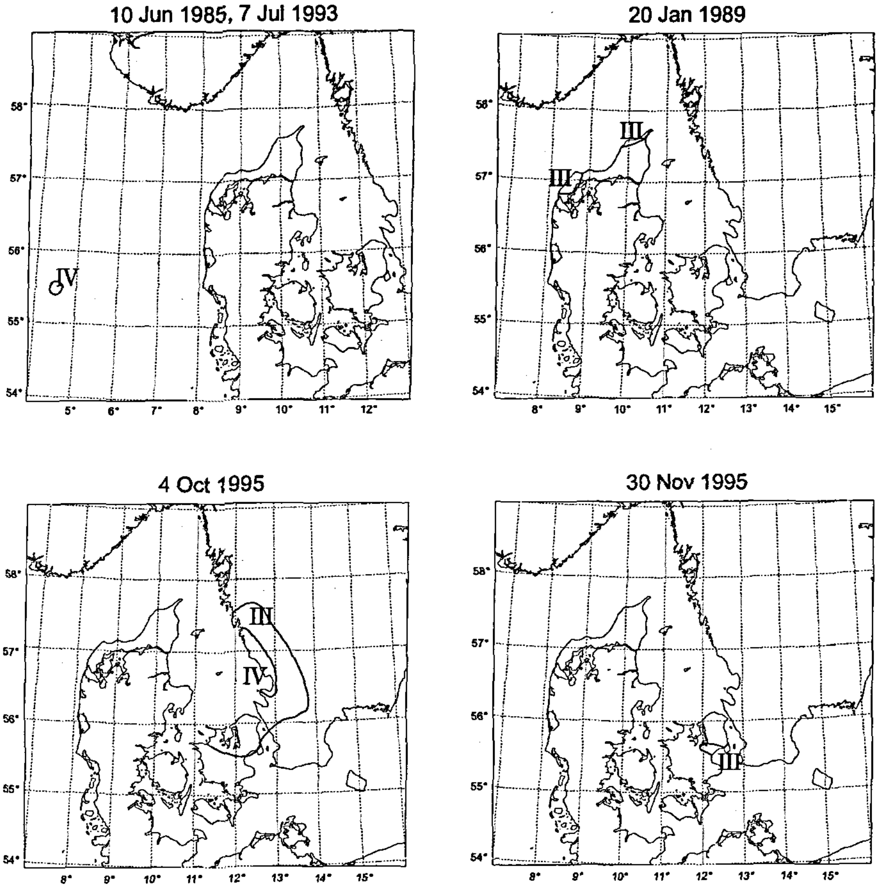


Fig. 1 a & b. Maps of the felt areas of the earthquakes in Denmark until the end of 1995. The Roman numbers are intensities in the Modified Mercalli scale, and the curves are limiting curves of the intensity areas. Until 1954 the curves are quoted from Lehmann (1956). The curves for the 1985 and 1986 earthquakes are quoted from Arvidsson et al. (1991). The curves for the 4 OCT 1995 earthquake are quoted from Kulhanek and Wahlström (1996).

Fig.2 for geographic names). And she included in her account two earthquakes happening in 1954: the first felt in the southeastern part of Sjaelland and investigated by Jensen (1954), and the second felt in northwestern Jylland and investigated by Saxov (1956).

In 1969 an earthquake was felt in the same area of Jylland as that investigated by Saxov (1956), and on this occasion the detailed felt reports were collected by Erik Hjortenberg, while the earthquake was large enough to be located by the new and improved, computer-based International Seismological Centre (ISC). The earthquake was located in the same area of the Skagerrak as the 1929 events, and this Skagerrak earthquake cluster was made the topic of a more detailed, but also time limited, investigation by Gregersen (1979). With 3 seismographs in northern Jylland it was possible to locate smaller earthquakes than previously, and it was possible to define some lineations. The suspected cluster of earthquakes was confirmed, at distances close to 100 km from both the Danish and the Norwegian coasts. It was stated that some earthquakes lined up with the cluster in a northeasterly direction, along the Norwegian Channel in the Skagerrak, but also that the earthquake APR 26 1978 did definitely not belong to the cluster, lying between the cluster and the coastal location of the 1954 earthquake (Saxov 1956). This was the first indication of a zone of earthquakes perpendicular to the coast near the felt areas delineated in Lehmann's (1956) paper.

From 1979 to 1985 a special investigation of Danish earthquake activity was carried out in cooperation with the Danish electricity companies and the Swedish nuclear power authority. The aim was to produce estimates of seismic hazard to existing nuclear power plants in Sweden and to the sites of proposed nuclear power plants in Denmark. The authors of the present paper wrote a series of reports, developed a local magnitude scale, and located earthquakes as small as magnitude 1 in special cases. Those reports (Geodætisk Institut 1983, 1985, 1986a, b) gave the first good mapping of the earthquake zone perpendicular to the coast in north-western Jylland, and they emphasized the less active but still significant zone just north of Sjaelland, in the Kattegat Sea.

Near the end of the special investigation period, in 1985, an earthquake, larger than any other in the Kattegat region since the famous 1904 Oslo Fjord earthquake, occurred in the zone north of Sjaelland, and fortunately Geodætisk Institut had continued recording with the installed seismographs, so that also an aftershock in 1986 and a smaller shock in 1990, were well recorded. These three events were made the topic of a special investigation between Swedish and Danish seismologists (Arvidsson et al. 1991), which determined locations and origin times, focal mechanisms, stress drops and moments.

Before these only few crustal stress determinations were made in the Danish region. Slunga (1982), in connection with the special earthquake studies for nuclear power plant sites, had determined several earthquake focal mechanisms from common Swedish-Danish data processing. These were discussed in connection with the common Scandinavian stress field by Gregersen (1992). In these papers it is noted that the dominating stress field is compression NW-SE in connection with the lithospheric plate motion, but also that several small earthquakes do not fit into the common stress field, in Scandinavia as well as especially in Denmark. Via in-situ measurements in bore holes new details have been added to this picture by Ask et al. (1993, 1996). And this has also reopened the discussion on the influence of the Tornquist Zone on the stress field.

The seismograph coverage of the Danish region has improved in several steps (Hjelme 1996), starting with the introduction of a Benioff seismograph in 1936 with its improved sensitivity to short period signals from local and regional earthquakes. Further improvements have been rather more recent. In the late 1970s portable short period seismographs were brought into operation mainly in Jylland. And the project of seismic hazard evaluation for the sites of planned nuclear power plants has instigated a significant improvement, which has brought forward the studies of the local earthquakes in Denmark. Since most of the seismograph stations are still in operation, more data has been gathered over the years. The present paper will report on this data collection and bring together unpublished and published material to present the state of knowledge about earthquakes in Denmark, including the surrounding seas, northwards toward Norway, eastwards toward Sweden and westwards toward Great Britain. To the south there is absolutely no earthquake activity.

Earthquakes located in Denmark

Felt earthquakes

The first earthquakes felt in Denmark, in year 1073 and also much later were mentioned only as earthquakes in Denmark, some of them in Latin texts, and no felt area is mentioned. The first documented earthquake is in 1841 in north-western Jylland. It may actually have been the largest earthquake ever in the Danish area. Based on the rather scattered reports of this and other earthquakes, Lehmann (1956) published a map with the felt area of this event, which we have included now in an overview figure of felt areas (Fig. 1). The reports of the 1841 earthquake contain mention of a crack in the ground. The phenomenon was at that time so poorly known, that nobody questioned whether this was really an earthquake crack or just some secondary slumping of the ground, or possibly even a phenomenon unconnected to the earthquake. We have written into the figure the intensity of 7 (VII) of the Modified Mercalli scale, because of this crack. But actually we are very doubtful.

Figure 1 contains sketches of felt areas of 15 later earthquakes. The earthquakes have had somewhat different magnitudes, and the investigators at various times have put different emphasis on delineating various intensity curves. Hence the curves in Figure 1 are not standardized. For most earthquakes the outer border of the intensity 3 (III) area is delineated, for others it is the intensity 4 (IV) area, and for a few earthquakes more than one curve, marked with intensity values, is included.

The first eight of these earthquakes, i.e. including two in 1954, were described by Lehmann (1956). We have quoted the intensities as we best interpret them from Inge Lehmann's description. As seen, all of these were felt with maximum intensities 3–4, except that in 1841 as discussed earlier.

The intensity values are chosen as representative for the delineated areas, which are separated by the curves, but there may well be peak values in single points that exceed the mapped values (e.g. in 1913 and in 1985). The date of the 1930 earthquake is here given as 31 OCT, in Greenwich Mean Time. The earthquake happened near midnight, so in Danish local time it was 1 NOV.

It is seen in Figure 1 that the earthquakes are felt typically in two areas of Denmark: (1) north-western Jylland and (2) Sjaelland-Sweden, but it may very well be that the earthquakes causing these felt areas are located offshore between Norway and Denmark, or between Sweden and Denmark (see Fig. 2 for location names). The larger of the recent of these earthquakes, 1929 and 1930 (Lehmann 1929, 1931) as well as those in 1954 (Jensen 1954, Saxov 1956) have been instrumentally located to the Skagerrak Sea/northwestern Jylland and the Oeresund region.

Not all events are within these typical areas. The earthquake in western Jylland in 1913 has a felt area different from the usual one around the north-western shoulder of Jylland. It appears that the earthquake happened in the North Sea, and we have asked our British colleagues, whether they were able to find reports of this earthquake. A special search was made in British newspapers (Graham Neilsson, personal communication 1985), but no British accounts were found. So the indication is that the earthquake occurred closer to the Danish coast than to the British.

Two earthquakes, felt widely in Denmark, have not been included in Figure 1, because their epicenters are known to be outside Denmark. In 1904 an earthquake happened in Oslo Fjord, large enough to be felt in vast areas of Sweden and Norway, as well as in the northern parts of Denmark. This earthquake is considered to be the largest known event of the Kattegat area, of a magnitude between 5½ and 6. Another large event, which was felt widely in Denmark occurred in 1931. This was an earthquake just off the coast of southern Britain, in the North Sea. It was felt in large parts of Britain, north-western continental Europe as well as in Jylland and Fyn.

The 1969 earthquake is sometimes referred to as the Easter earthquake, because of the holidays, April 5 that year. The Geodetic Institute was alerted by a telephone call and soon Erik Hjortenberg toured the shoulder of Jylland and found many people, who had felt the earthquake with intensities 3 and 4, extending to 5 or 6 in singular locations. Some people did report small cracks in walls, or fallen plaster. But just next door, many neighbors did not feel any shaking. On the southern coast of Norway, in the small town of Farsund, the earthquake is reported to have been felt as well.The strongest shaking was close to the coast of Jylland, toward the Skagerrak Sea. Comparison with the felt areas of the earthquakes in 1954 (Saxov 1956) and in 1929 (Lehmann 1929) soon showed that the areas were similar. The instrumental location later determined by the International Seismological Center (ISC) was also the same, lying in the cluster of earthquakes near 57 deg. North, 7 deg. East, which will be mentioned later. This earthquake was well recorded by 24 seismograph stations. Its magnitude is estimated close to 4½. Together with the largest of the 1929 earthquakes this shows that the earthquakes with open intensity curves in northwestern Jylland have their epicenters in the Skagerrak Sea. The documentation of this earthquake (a total of 37 questionaires, including statements from 57 persons) is in an unpublished report by Erik Hjortenberg in the archives in Kort & Matrikelstyrelsen.

The 1973 earthquake was nearly missed. Only because one curious person phoned the Geodetic Institute asking what had happened, was an investigation initiated, and only when the local newspapers asked their readers to inform the Geodetic Institute, did felt reports begin to come in. A total of 34 letters and 8 phone calls were received. The descriptions indicated that the event was an earthquake. No damage was reported. The elongated felt area was unexpectedly different from that of other earthquakes in northern Jylland. Although the intensity of the whole area was only 3, the reports said that the earthquake was felt strongest in the north, indicating an epicenter in the Skagerrak Sea. No felt reports were received from Norway. The reason for the irregular pattern of the felt area could as well be the distribution of the local newspaper as local geology.

The earthquake was recorded at one nearby seismograph in central Jylland (MUD), which had recently been installed. The records contain noise at a critical time for the signal interpretation. The distance indicated is approx. 50 km, which would put the epicenter close to the Danish coast of Skagerrak. No signals could be detected, neither at the very sensitive Norwegian seismograph stations nor at the Copenhagen station, 250 km away, even if this had noticeably low noise that day. So the earthquake has not been instrumentally located.

The earthquake in 1985 was the largest in the era of the present authors. In a cooperation with Swedish colleagues this, and the following events in 1986 and 1990, were described in a paper (Arvidsson et al. 1991). It was felt with intensity 6 in several separate locations in Sweden, with intensity 5 in an area near the Swedish coast and with intensities 3–4 in a wide area of south-western Sweden and eastern-central Denmark. The earthquake was located in the Tornquist zone with a magnitude of 4.7. Since radio, newspapers and television mentioned this event, the coverage of felt reports was very good for delineating the felt area and intensity zones. Many people in Denmark had heard squeaking of the wood in their house, and rattling sounds from shelves with small objects, as well as from things hanging on the walls.

The 1986 earthquake is considered to be an aftershock to the 1985 event, since it happened within 5 kilometers of that previous event. Fewer people felt it, but also here our observations were helped by radio, newspapers and television.

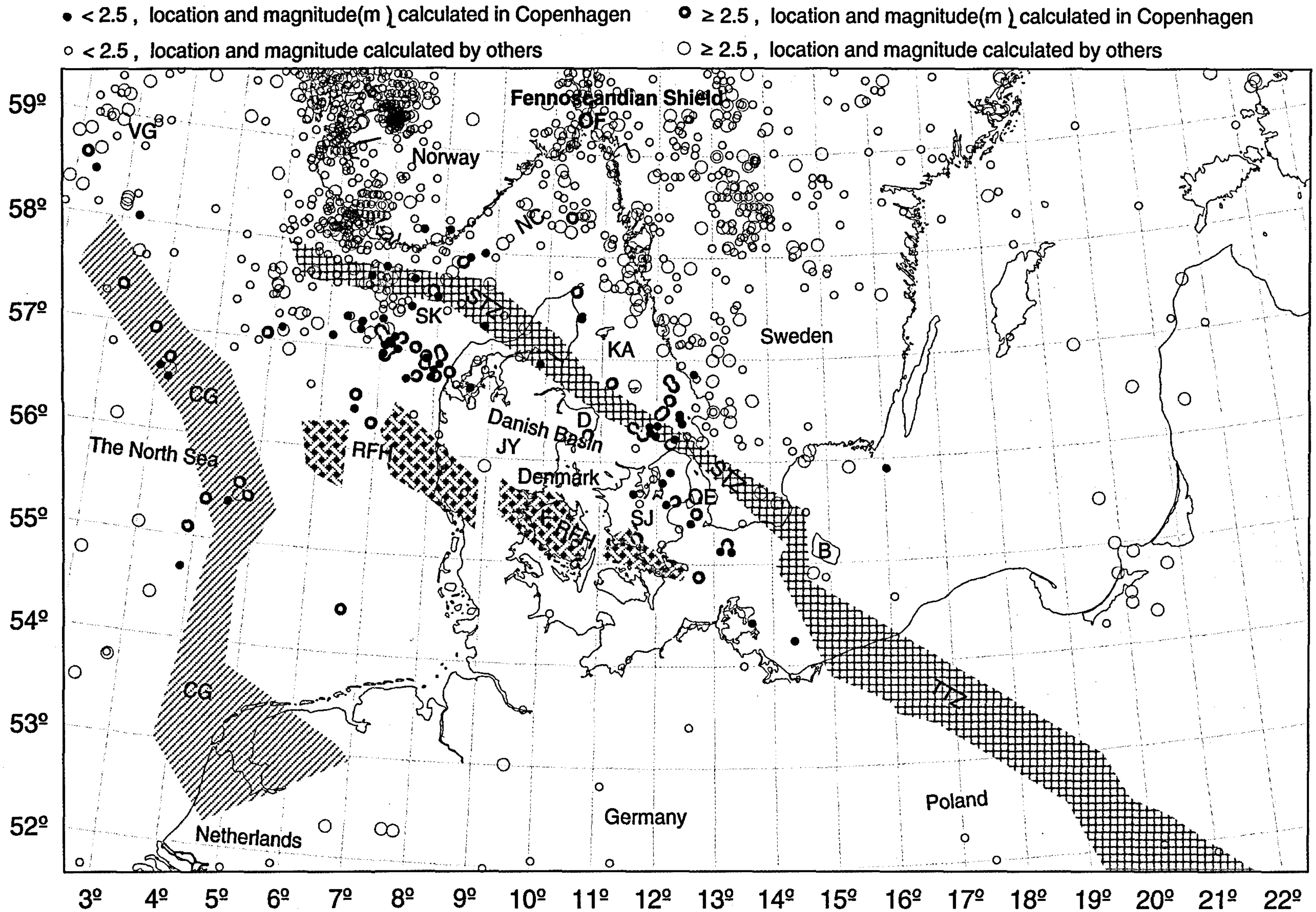
In 1989 an earthquake was felt weakly in 13 points close to the coast in the far northern and northwestern Jylland. The reports all mention shaking, which is best classified as intensity III. The earthquake, of magnitude 4.3, was located in the zone of earthquakes in the Norwegian Channel of the Skagerrak Sea (Figure 2).

At the time of writing, in 1996, three more shaking events have just been felt. The first has not been conclusively interpreted. It is in an abnormal location in the middle of Denmark, in Djursland. It is suspected to be an explosion, possibly in old ammunition from the Second World War. And consequently it has not been included in Figure 1. The second is less exciting, very close to the location of the earthquakes in 1985 and 1986. The evaluation of the felt area has been made together with Swedish colleagues (Kulhanek & Wahlström 1996). Both of these events have been located through instrumental observations, and they are

Table 1. Earthquakes, instrumentally located in Denmark, 1929–1995. Times are in Greenwich Mean Time. Year, month, day, hour, minute, second of origin time; latitude and longitude in degrees and decimal minutes, depth in km, local magnitude ML, and several computational results giving indication of accuracy: root mean square RMS, number of seismic time readings used for the location, largest gap between observing stations in degrees, distance to closest seismograph Dmin. Three earthquakes marked BGS have been quoted from the agency British Geological Survey.

y m d	h m s	dec. deg min N	dec. deg min E	km depth	ML	RMS	No	deg gap	km Dmin	
29 05 23	18 36 24.6	57 10.95	6 36.83	0.0	–	5.63	18	156	363	
29 05 29	23 31 11.3	57 17.99	6 20.77	11.4	–	2.76	12	236	347	
30 10 31	23 16 00.0	55 30.00	12 42.00	–	4.5	–	6	–	50	
54 06 04	21 03 00.0	55 24.00	12 36.00	–	–	–	–	–	–	
54 10 18	16 44 34.3	56 49.08	8 15.71	44.0	4.6	1.25	7	212	288	
63 06 19	17 00 19.8	56 16.20	11 44.40	–	3.0	–	–	–	–	
64 07 14	05 33 56.7	57 01.80	7 12.00	36.0	4.0	5.43	40	–	294	
67 08 21	13 41 48.5	57 03.60	4 55.20	33.0	4.5	1.68	44	–	367	
68 04 29	21 59 21.0	58 00.00	8 48.00	0.0	–	2.96	8	–	188	
69 04 05	19 09 48.3	57 07.80	7 02.40	33.0	4.3	1.68	24	–	315	
69 10 21	19 58 40.0	57 18.00	7 00.00	0.0	–	4.54	7	–	308	
71 02 21	00 03 50.0	55 47.12	12 06.33	30.0	–	1.76	9	222	24	
72 11 30	10 33 25.0	57 06.00	7 12.00	0.0	–	1.67	5	–	319	
74 05 19	15 56 50.0	56 24.00	6 36.00	0.0	–	2.25	5	–	395	
74 10 16	08 13 21.0	57 06.00	7 12.00	0.0	–	7.08	5	–	309	
75 11 12	00 06 16.0	57 00.60	7 10.20	95.0	3.7	0.96	34	–	323	
76 03 27	09 24 47.5	56 43.80	7 29.40	0.0	–	0.90	10	–	344	
77 04 15	00 27 36.9	57 06.00	6 06.60	33.0	–	1.07	11	–	347	
78 01 13	15 53 24.1	57 56.83	8 31.62	27.0	–	2.55	18	160	110	
78 03 07	02 31 55.2	56 45.60	7 55.80	33.0	–	0.81	17	–	333	
78 04 26	12 32 38.0	56 52.80	7 48.00	40.0	3.5	1.57	25	144	89	
78 10 02	08 49 50.0	57 42.46	6 43.93	5.0	–	1.64	13	139	168	
79 02 20	09 59 52.6	56 46.28	8 01.45	20.0	3.3	4.28	11	221	80	
79 12 25	02 41 11.8	56 40.82	8 39.41	39.2	2.4	0.86	19	265	41	
80 01 21	07 41 33.7	56 10.60	12 14.20	10.6	2.5	1.83	32	77	57	
80 12 12	21 53 32.2	56 56.60	9 53.10	59.9	1.7	0.68	14	170	41	
81 04 17	18 57 26.2	57 48.88	7 00.10	15.0	2.2	1.39	20	272	201	
81 04 29	10 29 29.2	57 23.94	10 37.07	0.0	1.6	0.99	12	282	138	
81 04 29	11 08 31.4	57 25.02	10 37.32	0.0	1.4	0.26	8	282	137	
81 09 06	04 12 01.8	57 10.73	6 57.83	40.0	3.9	2.15	50	140	138	
81 09 07	14 03 09.0	57 02.67	7 04.05	33.8	2.1	1.05	27	299	145	
82 02 15	14 10 55.6	55 54.13	12 14.69	3.4	2.0	0.83	16	97	63	
82 03 24	01 39 16.9	56 13.70	12 18.39	0.0	1.1	0.88	10	239	59	
82 05 24	03 10 20.3	56 50.06	7 58.37	40.0	2.3	1.20	39	273	79	
82 07 07	13 48 42.5	55 22.80	4 31.80	10.0	–	1.45	11	–	311	
82 09 17	11 19 55.2	55 41.60	11 35.56	0.0	1.5	1.75	7	286	120	
82 11 01	02 48 11.5	56 21.23	11 51.83	0.0	2.1	0.91	22	84	87	
83 03 12	16 19 33.6	56 57.62	7 02.61	0.0	1.9	0.49	9	308	133	
83 04 12	16 23 40.3	57 05.10	7 08.67	40.0	1.9	1.02	12	290	126	
83 05 19	03 18 56.3	56 53.55	8 04.49	35.1	2.2	0.63	35	266	72	
83 08 23	21 03 45.4	56 28.29	12 24.21	4.9	–	0.17	11	226	58	
83 12 18	21 25 20.1	56 15.70	11 58.34	0.0	2.0	0.30	9	289	115	
83 12 19	02 44 07.1	56 17.74	11 52.52	1.8	1.5	0.17	6	290	116	
84 01 07	09 08 14.0	57 07.30	7 22.10	20.0	2.9	1.47	56	215	113	
84 04 05	09 10 14.8	55 11.89	13 13.49	16.1	2.5	0.59	16	189	55	
84 04 16	01 47 13.7	55 35.34	12 10.36	40.5	1.9	0.37	21	111	19	
84 04 30	08 55 08.4	56 25.88	12 24.18	0.0	1.5	0.35	6	313	56	
84 04 30	08 57 33.6	56 22.50	12 26.40	0.0	1.6	0.40	6	312	52	
84 12 19	23 31 24.6	58 22.65	10 22.95	1.0	2.6	0.44	13	147	87	
85 01 07	04 45 50.1	57 08.01	5 10.90	15.0	–	1.21	10	213	255	
85 04 08	14 44 30.3	56 36.90	3 03.84	12.2	2.2	0.56	13	234	317	BGS
85 05 22	05 53 20.9	57 36.56	7 52.68	40.0	2.5	2.32	29	172	103	
85 06 10	15 28 43.8	55 34.00	4 41.76	22.7	3.5	2.35	53	80	256	
85 06 15	00 40 20.7	56 36.41	12 14.08	9.0	4.7	1.39	59	53	74	
85 07 16	05 10 46.3	57 21.36	2 11.76	15.0	2.5	0.99	20	200	273	BGS
85 08 22	19 02 20.8	58 02.34	2 18.54	15.0	2.4	0.87	9	265	215	BGS

y m d	h m s	dec. deg min N	dec. deg min E	km depth	ML	RMS	No	deg gap	km Dmin
85 09 21	22 50 38.6	54 41.51	3 50.57	0.0	–	0.66	11	165	268
85 09 28	20 55 13.8	56 42.64	3 13.45	15.8	2.9	0.42	10	167	303
86 02 01	18 47 52.6	57 42.63	7 31.96	5.3	2.0	1.43	8	179	172
86 04 01	09 56 53.2	56 29.96	12 06.75	2.1	4.2	2.47	53	93	93
86 10 15	19 15 12.8	56 56.36	7 50.01	15.0	2.0	0.69	8	207	98
86 11 13	08 00 35.8	58 12.83	8 07.15	17.4	2.2	1.05	12	274	139
87 01 19	04 07 22.1	55 22.83	4 08.67	13.6	3.2	1.97	9	275	336
87 02 01	12 36 40.9	56 57.53	7 49.39	15.0	2.9	0.77	16	206	100
87 03 01	06 42 03.8	56 56.26	7 04.44	40.0	3.8	1.43	53	146	139
87 03 10	10 55 45.8	57 15.85	6 37.69	40.0	2.0	1.16	18	221	159
87 04 19	22 16 18.6	56 45.33	7 40.20	37.3	3.0	1.41	39	216	98
87 05 13	07 22 21.3	57 39.60	10 30.41	14.1	2.6	1.80	12	242	157
87 08 19	01 15 36.8	56 58.52	8 06.17	23.3	2.6	1.06	10	207	88
87 10 04	02 25 05.7	58 26.44	1 21.97	17.7	–	1.17	11	157	230
88 01 21	15 28 09.1	58 35.20	1 10.02	37.0	2.6	0.80	27	161	245
88 03 02	07 38 35.0	57 00.30	7 18.24	15.1	2.0	0.49	9	217	130
88 03 31	02 56 09.4	56 58.52	2 53.71	15.0	3.4	2.70	18	156	285
88 04 15	10 49 33.1	54 25.72	6 38.78	14.5	2.7	0.16	7	286	277
88 05 03	06 34 12.2	57 14.78	6 37.23	40.0	–	0.73	14	141	179
88 06 06	15 55 56.3	57 03.50	7 05.18	45.0	2.7	0.69	11	220	144
88 06 27	07 55 08.1	56 46.07	11 11.54	3.8	2.6	1.93	15	128	129
88 07 17	12 51 46.2	57 02.46	7 37.37	0.0	2.8	1.03	10	207	97
88 07 17	15 58 54.3	57 04.96	7 10.45	17.6	2.1	0.73	9	216	141
89 01 20	09 33 48.3	57 53.75	8 23.55	21.8	4.3	0.68	18	94	167
89 02 26	19 02 27.3	55 15.71	11 39.31	30.7	2.5	0.72	9	263	36
89 11 23	14 12 40.0	58 11.97	7 37.98	22.2	1.8	1.10	9	274	141
90 01 08	16 41 07.4	57 33.15	7 58.16	0.0	–	1.06	9	323	215
90 02 23	12 28 53.0	54 14.25	14 21.39	0.0	2.0	1.42	6	303	104
90 03 28	22 21 06.4	54 25.35	13 38.12	3.9	2.3	2.43	14	141	113
90 05 09	16 47 13.6	57 17.50	8 51.59	8.8	2.0	0.91	5	253	284
90 05 24	09 51 56.8	56 28.03	12 03.06	3.6	3.3	1.20	14	147	91
90 05 28	08 43 51.2	55 07.59	13 06.67	20.5	1.2	1.72	7	202	62
90 08 30	21 44 01.0	57 26.12	7 30.07	21.0	2.0	1.41	8	297	210
90 10 16	08 32 59.2	55 54.22	16 02.22	11.7	1.9	1.00	6	206	113
91 03 11	21 09 05.1	57 18.75	09 32.39	10.7	3.5	1.07	23	119	98
91 10 20	02 42 10.9	56 31.23	3 13.59	33.3	–	1.05	12	165	323
92 05 18	05 28 34.1	56 32.65	6 36.65	0.0	4.0	1.29	17	178	158
92 08 11	22 00 40.3	56 20.42	11 34.47	0.0	3.2	0.75	8	206	91
92 08 31	18 25 50.8	55 05.15	3 53.55	17.1	3.3	0.78	15	198	365
92 09 17	00 16 15.8	56 16.03	6 54.63	5.0	3.3	2.22	11	178	141
92 09 28	13 30 49.6	54 52.77	12 44.16	11.3	3.5	0.68	11	231	61
92 12 14	11 42 19.7	55 08.00	13 11.52	1.4	2.7	0.97	6	200	66
93 05 02	19 08 24.8	58 55.34	1 07.11	40.0	–	0.62	24	155	181
93 07 07	11 48 10.8	55 33.06	4 30.01	15.0	4.3	4.31	20	83	308
93 12 07	12 27 31.3	56 49.21	12 42.63	20.3	2.4	1.16	7	242	128
94 10 18	18 38 20.4	55 27.99	4 53.49	0.0	4.2	1.50	66	84	408
94 11 02	14 57 35.5	57 00.34	8 03.59	0.0	3.4	1.45	19	203	296
95 05 30	04 00 16.5	56 25.79	10 48.37	5.00	3.5	1.28	6	129	101
95 10 04	20 49 43.6	56 44.90	12 09.45	26.37	4.1	2.16	16	95	120
95 11 30	05 23 52.4	55 38.55	12 15.62	25.00	2.5	0.69	8	132	12


• < 2.5 , location and magnitude(m L) calculated in Copenhagen
○ < 2.5 , location and magnitude calculated by others
● ≥ 2.5 , location and magnitude(m L) calculated in Copenhagen
○ ≥ 2.5 , location and magnitude calculated by others
Fennoscandian Shield
OF
VG
Norway
NC
STZ
SK
KA
Sweden
CG
Danish Basin
D
JY
RFH
The North Sea
Denmark
STZ
OE
SJ
RFH
B
TTZ
Germany
Poland
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included in the earthquake list (Table 1) and in Figure 2. The third is a very small event of magnitude 2.5, which was felt by 10–20 persons in eastern Sjaelland. One person wondered about the unusual shaking, and the rest reacted to a plea in the local newspaper immediately after. This earthquake happened 12 km from the Copenhagen seismograph.

Two earthquakes, in 1985 and 1993, have been felt on drilling rigs in the North Sea. No real damage has been reported, but the oil production was disturbed for several hours.

Earthquakes located instrumentally

The first seismographs were installed in Denmark in 1926. It only took 3 years until the first local earthquake was recorded as well as felt, on May 23 1929. This earthquake even had an aftershock 6 days later, which was smaller, and for which no felt reports were recorded. The main shock was mentioned above, and it is chronologically the first one included in Table 1 and in Figure 2, which shows the instrumentally determined earthquakes in Denmark from 1929 to the end of 1995.

Since the network sensitivity has improved mainly in the last 2 decades, because of new and better seismographs (Fig. 3), the number of earthquakes per year is not the same over the years (Fig. 4). In the first years only very few earthquakes were detected. Some were recognized as earthquakes in the area of Denmark, but no instrumental location can be determined (e.g. the earthquake in 1941 of Fig. 1). This means that the uncertainty is so large that the location does not carry much geographical information on earthquake zones, and these earthquakes have not been included in Figure 2.

It is seen in Figure 2 that the earthquakes occur in distinguishable zones. We have presented the earthquakes for which it has been possible for us to compute locations in the Danish area, as full circles, small and large according to the local magnitude scale (included were 3 locations in 1985 in the North Sea from the British Geological Survey, too small to be confirmed by Danish seismographs). In this study we have exhausted all the available seismograms from Danish seismographs (Fig. 3) as well as from seismographs in the neighboring countries.

The earthquake activity is in Figure 2 presented together with the activity of the surrounding areas, taken from local and regional earthquake catalogues. When these foreign catalogues contain events in Denmark, we have especially checked the Danish seismograms, and the events have either been confirmed, in some cases by very weak Danish records, or they have been left as very doubtful, given as open circles in the Danish area. Those events are believed to have happened somewhere in or close to Denmark, but we do not recognize any significance in their exact location. These events may well be seriously mislocated, or they may be unrecognized explosions.

The chief zones of earthquake activity in Denmark are two, which are in agreement with those indicated by the felt areas in Figure 1, and one emerging in the later years in the Central Graben in the North Sea. The first is in north-western Jylland and in the Skagerrak Sea. This acts as the southern boundary of the zone of earthquakes along the west coast of Norway, and it includes a significant cluster of earthquakes around 57 deg. North and 7 deg. East plus a trend from there extending towards the Danish coast and another trend from there northeastwards in the Norwegian Channel of the Skagerrak Sea (Gregersen 1979). The other earthquake zone in Denmark is just north of Sjaelland, with some scattered activity in Oeresund

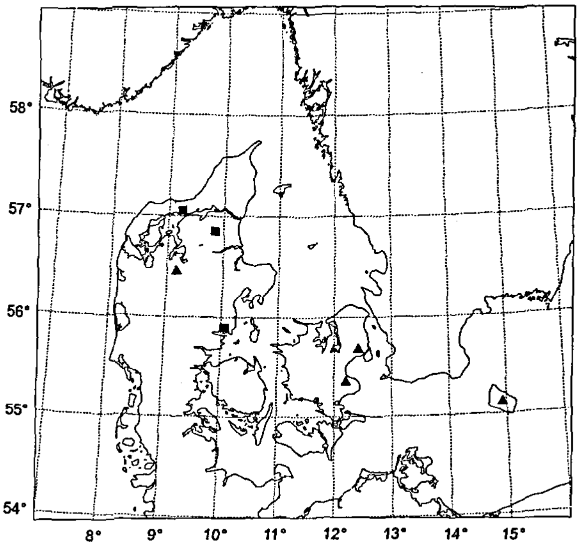

Fig. 3. Map of the Danish seismograph stations. Triangles are the present permanent stations, named from the north Moensted, Copenhagen, Stevns and Bornholm, while squares are long-lasting previous stations, named from the north Goettrup 1977–1989, Thingbaek 1977–1978 and Sondrup 1979–1985.

←
Fig. 2. Earthquakes. Full circles – instrumentally located by Kort & Matrikelstyrelsen in Copenhagen 1929–1995. Open circles – Scandinavian file from Helsinki, Finland 1929–1991, and locations by other agencies 1929–1987. CG – Central Graben. RFH – Ringkøbing-Fyn basement High. STZ – Sorgenfrei-Tornquist Zone. TTZ – Teisseyre-Tornquist Zone. JY – Jylland, SK – Skagerrak Sea, SJ – Sjaelland, KA – Kattegat Sea, OE – Oeresund, VG – Viking Graben, B – Bornholm, OF – Oslo Fjord, NC – Norwegian Channel, F – Fyn, D – Djursland.

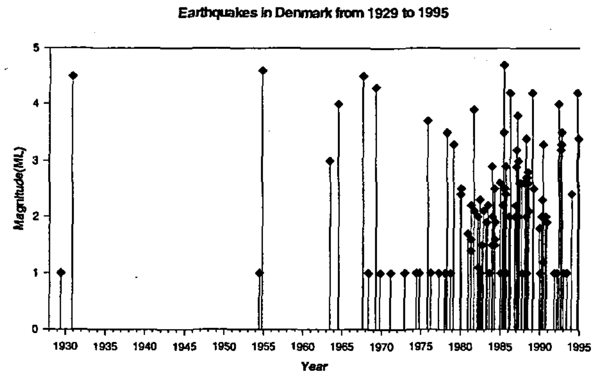

Fig. 4. Time sequence of the well-determined earthquakes in Denmark in the time period from the beginning of 1929 to the end of 1995.

and under Sjaelland. This acts as the southern boundary of the scattered activity in south-western Sweden. Recently the southern part of this seismicity, together with that around Bornholm was confirmed as scattered and extremely small by Wahlström and Grünthal (1994).

The earthquake activity in the North Sea, close to Denmark is mainly concentrated in the Central Graben. This activity has only been recognized in the last decade, as the sensitivity to offshore earthquakes was naturally lower in earlier years. But still, this is a manifestation of increased seismicity. We could have missed magnitude 3 events earlier, but we would have found earthquakes of magnitudes close to 4, if they had occurred. At the same time the activity in the Viking Graben was known much earlier. It can naturally not be distinguished whether the increased earthquake activity in the Central Graben is caused by the pumping activities of the oil companies, or whether this is just one of nature's time oscillations, which is very likely, according to seismological experience.

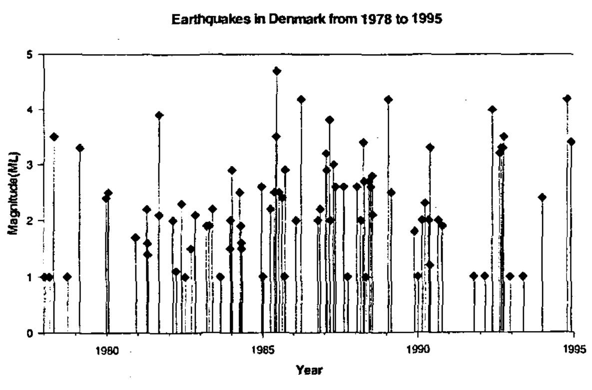

Fig. 5. Time sequence of the well-determined earthquakes in Denmark in the time period from the beginning of 1978 to the end of 1995.

In a new paper Gregersen et al. (1996) have looked for evidence of recent geological motion, and for correlation of the earthquakes with geological zones. In that paper it is argued that the earthquakes in the Kattegat Sea between Sweden and Denmark occur in the Sorgenfrei-Tornquist Zone, and those authors even document that recent geological motion has occurred there. The zone sketched in Figure 2 as the Sorgenfrei-Tornquist Zone has the extent as defined by the EUGENO-S group (EUGENO-S Working Group 1988; Gregersen 1991). Around this zone is a somewhat wider area with geological boundary effects (Gregersen et al. 1996). The earthquakes occur in the upper crust and seem to be connected to recent geological motion there.

It is more doubtful how the correlation is between the earthquakes and the faults in north-western Jylland and the Skagerrak Sea. The active trend is parallel to the Sorgenfrei-Tornquist Zone, which is here a part of the Danish Basin (Fig. 2). At least some of the earthquakes occur deep in the crust or in the upper mantle at depths of 30–40 kilometers (Gregersen 1979). The deepest faults mapped here are at depths approx. 10 km. They are not well correlated with the earthquake zone. Nearer the surface there are mapped faults overlying the earthquakes, but it is hard to imagine how the deep earthquakes can be related to the shallow faults.

No special investigation has been made of the correlation of the few earthquakes in the North Sea with known recent geological faulting. And this is not necessary given that Figure 2 shows that the largest activity is in the Central Graben, and a few earthquakes have occurred in the break in the Ringkoebing-Fyn High called the Horn Graben, closer to the Danish coast.

The time sequence of the earthquake activity is further described in Figure 4. It may look as if the earthquake activity in Denmark has increased tremendously within the last two decades. But it is known to the seismologists that the sensitivity of the seismograph network has increased through a field campaign in the late 1970s (Gregersen 1979), a special investigation in the early 1980s (Geodætisk Institut 1983 and following), and continuing operation of several seismographs in Denmark since then. So a better impression of the earthquake activity with time is seen in Figure 5, zoomed-in from Figure 4, covering only the period of improved sensitivity. The local magnitude scale was developed in the early 1980s to be consistent with the Swedish magnitude scale (Geodætisk Institut 1983), and also older earthquakes have had magnitudes assigned to them according to their seismogram records. In several cases though, no local magnitude has been assigned, because of uncertainty in the data with respect to the local scale. These earthquakes are in Figures 4 and 5 given with magnitude 1, even if there is no doubt that the magnitude was larger than this, since the earthquake was recorded at several seismographs and has been located. The estimate from Figures 4 and 5 is that the sensitivity now of the network of seismographs in and around Denmark is almost complete to magnitudes around 2½, rather good to magnitudes 2, and a few earthquakes are recorded to magnitudes 1½. The Figure 5 shows that the earthquakes of the detectable magnitudes happen quite irregularly, with 2–10 earthquakes in any given year, and with an average of 5 per year.

The earthquake locations have been computed with a modified version of the much used HYPO71 program of the U.S. Geological Survey (Gregersen 1979, Geodætisk Institut 1983). The crustal model used is not special for Denmark, but rather chosen to be identical to that used in the Finnish bulletin Earthquakes in Northern Europe (e.g. Uski & Pelkonen 1996). It has been tested that the crustal model has only minor influence with the stations available (Geodætisk Institut 1983), and therefore the choice of model has been that of the Finnish bulletin, so that the computations of travel times for stations north-east of the earthquakes, i.e. in Scandinavia, are identical.

Stress release in earthquakes

In the Danish area only few stress measurements have been made. Into the World Stress Map Project (Zoback et al. 1989) went the few available Danish stress orientation measurements based on earthquake focal mechanisms (Slunga 1982). These were evaluated together with those of Scandinavia (Gregersen 1992; Gregersen and Arvidsson 1992) and of Europe (Mueller et al. 1992). The general pattern of stress orientation is shown in Figure 6, taken from Gregersen (1992), which is still the valid representation of the stress field. It is seen that the dominating compressive stresses are aligned NW-SE, which is the orientation of the lithospheric plate motions as expressed in the result of the World Stress Map Project (Zoback et al. 1989). Denmark is part of the stress field of northern Europe, and has its special characteristics as the southern limit of the Scandinavian earthquake province (Gregersen et al. 1991).

The basic evidence concerning stress in the Danish region comes from earthquake focal mechanisms. In the rest of Scandinavia also many in-situ measurements are available. Those measurements as well as the focal mechanisms of very small earthquakes have large uncertainties, but can on average be associated with the regional stress field (e.g. Mueller et al. 1992, Zoback et al. 1992). Until very recently no in-situ stress measurements had been carried out in Denmark. This has been remedied by Ask et al. (1993, 1996), who give 20 new bore hole breakout measurements in Denmark. These have added detail to the pattern in the Danish area, showing the same orientations as well as local deviations. Where Gregersen (1992) claims that the large geological features, for instance the Tornquist Zone, do not influence the stress field, Ask et al. (1993, 1996) come to the opposite conclusion. Actually the data is presently not detailed and accurate enough to make a local regionalisation except in one region, where a certain alignment perpendicular to the graben in the North Sea (Spann et al. 1994) is a convincing regional deviation from the NW-SE compression. All of the existing measurements amount to a stress field dominated by ridge push from the North Atlantic and compression across the Alps in southern Europe.

Discussion of earthquake zones and geology

It is the experience from other parts of the world, for instance California, that the earthquake zones are stable as the general pattern, but that sometimes exceptions occur, and the activity is fluctuating. One can not confirm the same from the short historical sequence of earthquakes in Denmark, but at least the Danish earthquake activity so far does not contradict it. One example worth noting is that the Central Graben in the North Sea seemed completely inactive until the significant earthquake in 1985, which was felt on a drilling rig. And after that time several earthquakes have been observed there (Fig. 2). We judge this to be a combination of increased earthquake activity, and better sensitivity, and not of one of these effects alone. Whether this is a long-term increase or just one of nature's oscillations can not be judged on the short time sample available. It is also impossible to answer the question, whether this increased earthquake activity is influenced by the oil and gas drilling and pumping in the Central Graben.

As mentioned earlier, Gregersen et al. (1996) have argued that the earthquakes in the Kattegat Sea, occurring in the upper crust, are connected to faults limiting the Sorgenfrei-Tornquist Zone, and that the earthquakes in north-western Jylland and the Skagerrak Sea, of which at least some occur close to the bottom of the crust, do not correlate with known faulting in the Danish Basin. These conclusions can only be applauded by the present authors.

The recording of earthquakes in Denmark continues, and further questions and answers on the correlation with structures in the Danish deep underground will come with further data gathering, nationally as well as internationally.

Acknowledgment

During many years of locating and discussing local earthquakes in Denmark we have had tremendous help by the seismograph manager in Copenhagen, Hans Peter Rasmussen, as well as by many students, who have taken part in locating the earthquakes, and who have prepared the material for the plots: Helle Wagner,

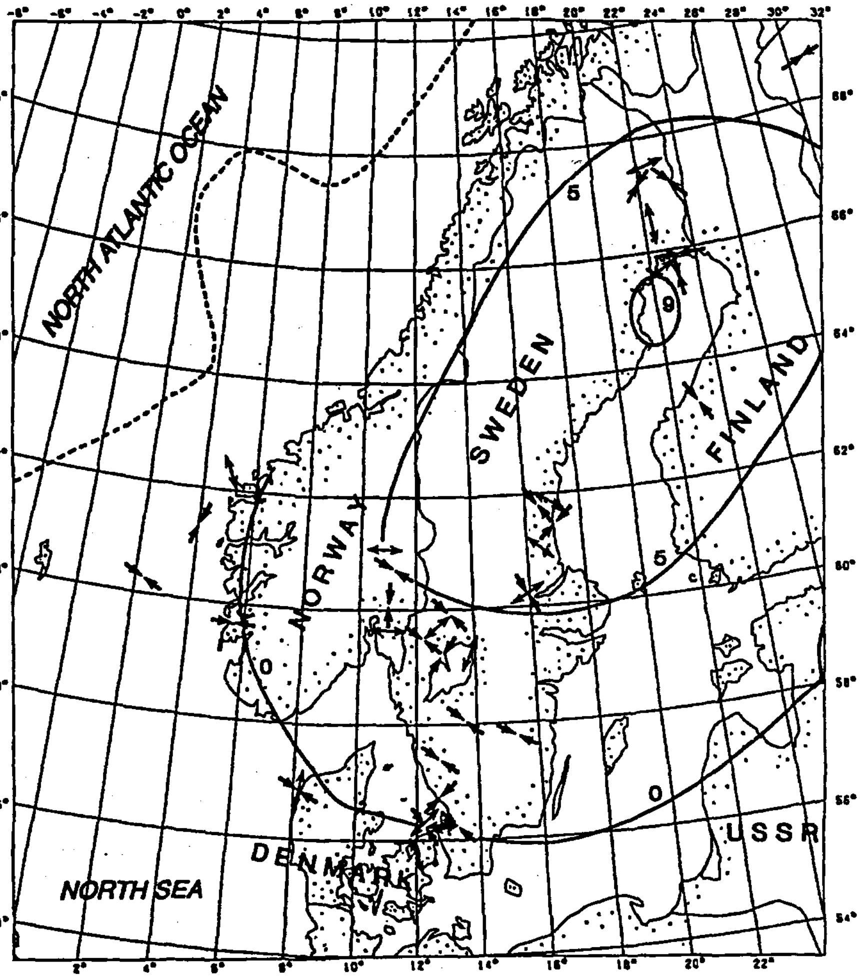

Fig. 6. Generalized pattern of the horizontal compression field, shown through thick arrow pairs pointing inwards. Thin lines are coast lines and national boundaries. Thick dashed line is continental margin. Thick solid lines are geodetic uplift curves with numbers in millimeters per year. Thin arrow pairs pointing outward are representative tensional orientations of focal mechanisms of normal faulting. From Gregersen (1992).

Helle Petersen, Birgitte Christensen, Karsten Korre, Stig Syndergaard and Trine Pedersen. John Adams helped with the English language. We thank all of them for their efforts.

Dansk sammendrag

Inden for de seneste 2 tiår er følsomheden over for små jordskælv blevet meget forbedret i Danmark. Fra 2 til 10 jordskælv bliver registreret hvert år med Richtertal mellem 1½ og 4½. Det mønster, der iagttages i jordskælvsaktiviteten ud fra moderne data, er i overensstemmelse med de mønstre, man tidligere har kunnet skimte i instrumentelle data såvel som i oplysninger om jordskælv, der er blevet følt af mennesker. Vi ser jordskælvsaktiviteten som afskæringer af jordskælvszoner i det vestlige Norge og i det sydlige Sverige: (1) I det nordvestlige Jylland, og i Skagerrak skærer de danske jordskælv en jordskælvszone langs Norges vestkyst af mod syd. I det mindste nogle af disse jordskælv i Jylland og Skagerrak optræder i dybder på 30-40 km, tæt ved Moho-diskontinuiteten. (2) I det nordøstlige Sjælland og i Kattegat, såvel som nede ved Bornholm, sker jordskælvene i den øvre del af jordskorpen, i dybder på mindre end 15 km. Denne zone skærer den spredte jordskælvsaktivitet i Sydsverige af mod sydvest.

I generelle vendinger kan dette ses som den sydvestlige deformations-kant af det Fennoskandiske Skjold. Den nordvestlige jordskælvszone ligger langs med midteraksen af det Norsk-Danske Bassin, og den østlige jordskælvszone er i Tornquist-zonen. De to jordskælvszoner er ikke forbundne. Dette kan ikke skyldes mangel på følsomhed overfor små jordskælv, så den Fennoskandiske Randzone kan ikke betegnes som jordskælvsaktiv. Den centrale del af Danmark er aseismisk, og det samme gælder for den sydvestlige del af Danmark, ganske som det nordlige Tyskland. Der sker ikke jordskælv der.

I Nordsøen er gravsænkningerne de mest aktive.

Viking-graven mod nord har signifikant jordskælvsaktivitet, og Central-graven, som går gennem den danske sektor af Nordsøen, har lille, men tydelig aktivitet. På den britiske side af gravsænkningen er der yderligere jordskælvsområder.

Spændingsfeltet, der forårsager disse jordskælv er temmelig homogent hen over den Fennoskandiske Randzone, med spredte undtagelser. Feltet reflekterer den generelle NV-SØ sammenpresning af det nordlige Europas lithosfæreplade mellem den Nordatlantiske spredningsryg og den Alpine kollision.

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