Seismic activity in Denmark: detection level and recent felt earthquakes

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The Geological Survey of Denmark and Greenland (GEUS) records seismological data at six locations in Denmark (Fig. 1) and all data from these stations are manually reviewed for events like earthquakes and explosions. The identified events are analysed and located, in many cases using supporting data from stations outside Denmark. Seismic events have been recorded instrumentally in Denmark since 1929, but earthquakes felt in Denmark have been reported as far back as 1515 (Lehmann 1956; Gregersen *et al.* 1998; GEUS 2012). This article reports on the developments in detection level of both man-made events and natural earthquakes within the Danish Exclusive Economic Zone (EEZ) from 2000 to 2012. Changes in detection level are mainly due to the availability of data from new seismic stations in Sweden and Norway as well as from a GEUS test station at Gøttrup in NW Jylland. As a case study, the list of events on and around Bornholm is reviewed. Also described here are the reported intensities at two recent felt events in Denmark (North Sea magnitude 4.3 on 19 February 2010 and Kattegat magnitude 4.1 on 6 August 2012).

Development in detection level and completeness from 2000 to 2012

The events from 2000 to 2012 located within the Danish EEZ (Fig. 1) are divided into known explosions (pink), events recorded only on one or two stations which are typically small events (yellow), events where a magnitude could not be calculated (grey) and events which possibly are earthquakes (red) and recorded on three or more stations. Many of the 'possibly earthquakes' events occur in areas where explosions are known to take place, and many of these events are suspected to have a man-made origin. Many explosions are reported to the Seismological Service at GEUS, and are tagged as such, but many more are not reported and only some are tagged as possible explosions. The North Sea is the only area with no explosions known to the Seismological Service but with many probable earthquakes. For example, the earthquake felt in February 2010, described below, is located in this area. However, earthquakes do occur in other areas of Denmark; for example the felt earthquake that occurred in August 2012 in Kattegat.

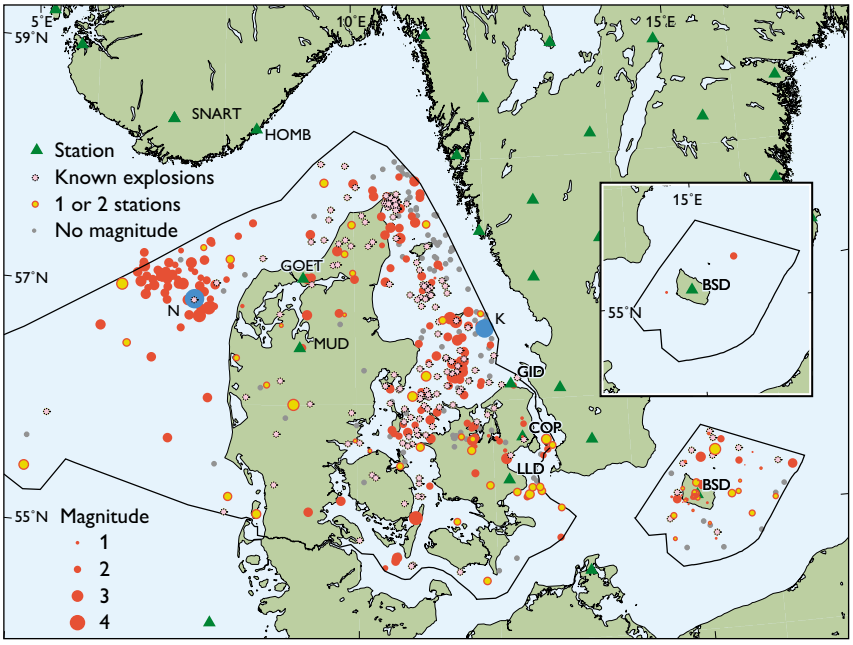

Fig. 1. Seismic events within the Danish Exclusive Economic Zone (EEZ). Among the recorded events are un-identified explosions, particularly in the area where many identified explosions are marked (in pink). The two felt events described in this paper are marked in blue. **K** = Kattegat on 6 August 2012 and **N** = North Sea on 19 February 2010. Seismological stations are green triangles. The events are divided into events seen on three or more stations with defined magnitude (red), events seen on only one or two stations with defined magnitude (yellow), events where no magnitude has been calculated (grey) and known (or probable) explosions (pink). Inset: The EEZ around Bornholm after revision of the database.

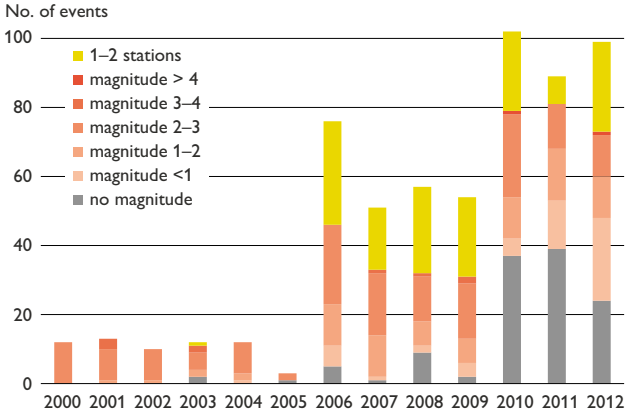

Fig. 2. Statistics on event detection from 2000–2012 within the Danish Exclusive Economic Zone. Known or probable explosions are not included.

In the years 2000–2005, fewer than 15 events (either earthquakes or non-reported explosions) observed on three or more stations were recorded each year, with an additional *c.* 20 known explosions. Only large events were seen outside the Danish network of stations (at the time BSD, COP, MUD, LLD and GID) (Fig. 1). The number of events rose dramatically in 2006 (Fig. 2), as a result of the installation of the Norwegian seismological station SNART (NNSN 2012). The addition of this station has aided in locating events, as it provides a much improved geometry of the station network (Fig. 1). The increase in the number of events recorded is also due to a change in policy in 2006; since then

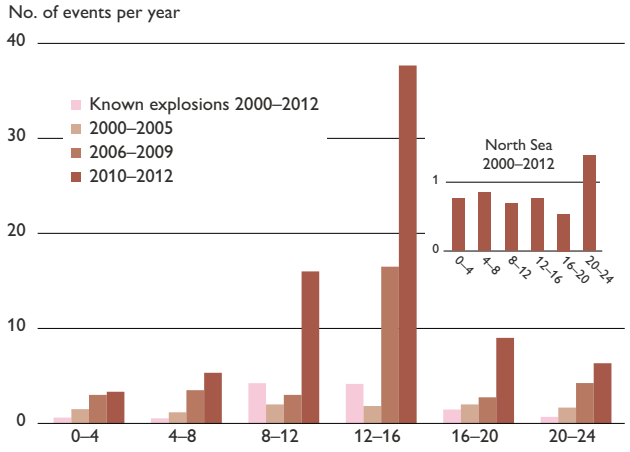

Fig. 3. Seismic events seen on three or more stations sorted by time of day. The events are sorted into 4 hour intervals in UTC time. Denmark is one hour ahead of UTC (two hours in summertime). For each series of years, the number of events within a 4 hour interval is calculated as per year, so the three periods (2000–2005; 2006–2009 and 2010–2012) can be compared. In addition the number of known explosions in the entire period (2000–2012) is sorted in the same manner for comparison. Inset: events in the area in the Danish North Sea with many events recorded but no known explosions.

events located by azimuthal analysis when only one or two stations have recorded the events (Fig. 2) are included. For events seen on three or more stations, the increase is most pronounced for the smaller events, under magnitude 2, but also events with magnitudes between 2 and 3 are more numerous. The next large step up in event detections occurred in 2010 (Fig. 2). This is due to data from the large Swedish network (SNSN 2012) becoming available, and also data from the new Norwegian station HOMB. Many of the additional events, only recorded on the SNSN stations, have no magnitude due to missing calibration information from the new SNSN. In 2012 the number of events with no magnitude declined, while the total number of events is fairly constant, as a result of SNSN becoming established and complete metadata becoming available. In Denmark we added GOET as a test station in 2012, and data came online in November 2012. Together with MUD and the Norwegian stations the azimuth coverage for the many events in the Danish North Sea is highly improved.

Explosions in the database

Far from all activity recorded within the Danish EEZ are natural earthquakes. The Seismological Service at GEUS is frequently notified by the Danish Navy of upcoming or recent blasts. Following World War II, numerous unexploded mines and ammunition are still present in Danish water; the largest neutralised in 2012 was equivalent to 800 kg TNT. The Navy searches for the mines and detonates them on site. Many are seen as signals on the seismic stations, and if known to be explosions they are logged as such in the database. On Fig. 1 the known explosions are marked with pink, and are present in large parts of Danish waters. Known explosions also occur on land – for example in controlled-source scientific projects (Thybo *et al.* 2006) and on rare occasions a house demolition. However, not all explosions are known by the Seismological Service. Natural earthquakes are distributed evenly throughout the 24 hours of the day, while man-made events such as explosions mainly take place during the daytime. The Navy usually blasts in the early afternoon. Figure 3 illustrates the distribution of recorded events sorted by of day, and it is clear that the distribution is heavily skewed towards events in daytime hours. The known explosions are, as expected, concentrated during daytime hours; the exception being urgent blasts when a find of undetonated explosives endangers the surroundings. Scientific blasts often take place during the quiet night hours. In the period 2000–2005 the events are evenly distributed through all 4 hour intervals, while the events in both the 2006–2009 and the 2010–2012 periods have a large overrepresentation in daytime. In total

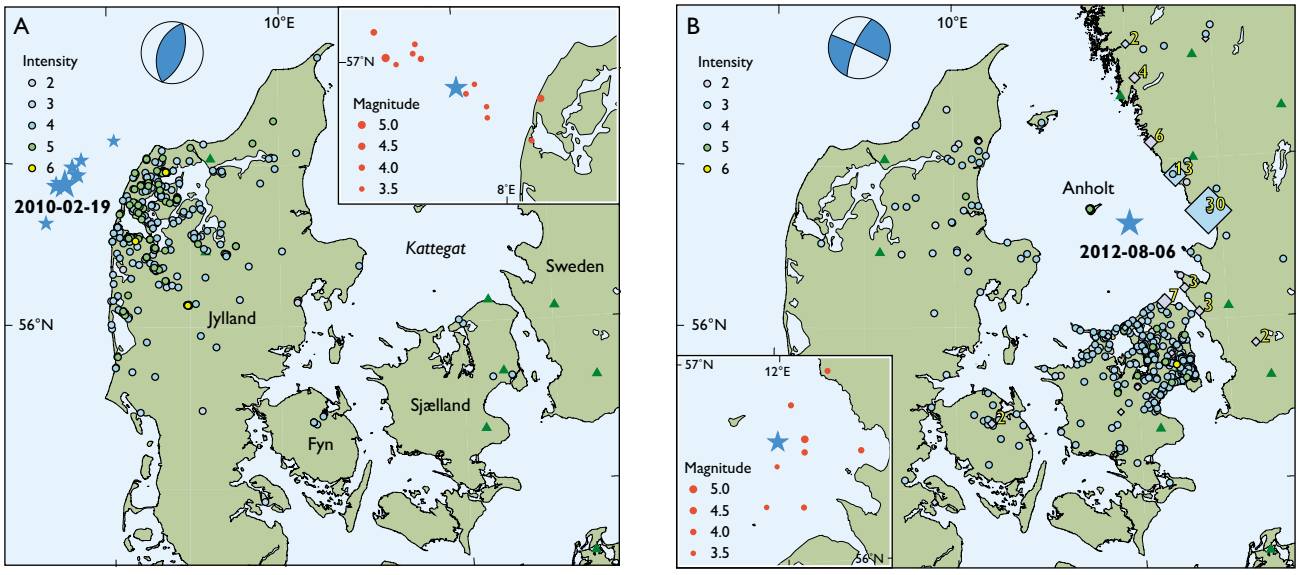

Fig. 4. Reports of observed intensity from the public. The earthquakes are marked by blue stars scaled by size. **A**: North Sea on 19 February 2010 magnitude 4.3. GEUS received 344 reports from people who felt the earthquake. Seven small aftershocks (magnitude 1.9 to 2.8) were observed during four weeks after the main event. **B**: Kattegat on 6 August 2012 magnitude 4.1. In addition to reports received by GEUS (441), we have reports from the United States Geological Survey (in all 76 reports of which more than half are from Sweden (30 in Halmstad and 13 in Falkenberg)) marked with diamonds scaled to the number of individual reports, and from The Swedish National Seismic network (SNSN) (16 reports) – marked with dots in Sweden – are included. The insets in both A and B are all known, instrumentally recorded events over magnitude 3.5 in the two areas.

426 events are included. Assuming that the night-time level of events is correct, and the natural earthquakes are evenly distributed, a simple calculation shows that at least half the events are probably not natural earthquakes. Not all explosions are reported to GEUS, for example explosions carried out by foreign naval vessels participating in exercises in Danish waters or mines or ammunition neutralised by our neighbouring countries but erroneously located into Danish waters. The only area where no known explosions are located is within the group of events in the Danish North Sea. For events in this area there is no concentration in daytime (Fig. 3 – inset), and they are assumed to be natural earthquakes.

Case study Bornholm

A revision of the entire database of seismic events is in its initial phase, and for 2000 to 2012 the revision has been carried out on Bornholm and within the EEZ around the island. Here quarry blasts add to the man-made events recorded, as Bornholm Granit blasts several times a week at set times (Paul Ebbesen, Rønne Granit, NCC, pers. communication). By logging all events known or strongly suspected to be explosions, excluding small events seen only on one or two stations (and with a large uncertainty in location) and events so small that no magnitude could be calculated in spite of all necessary station information, only two events remain as probable natural earthquakes. The original list contained 129 events within the EEZ around Bornholm, of which 25 were seen on three or more stations (of these three without magnitude). The remaining 104 events were seen only on one or two stations, and many with no magnitude. Seventy events are suspected quarry blasts. In all 23 events had a magnitude of 2 or higher. Ten previously known explosions make an original total of 139 events recorded. The two 'surviving' events are marked on the inset on Fig. 1 and are a magnitude 2.0 event in 2006 and a very small magnitude 0.8 event in 2011.

Recent felt earthquakes

It is rare for Denmark to experience an earthquake which can be felt. However, it does happen and the two most recent felt earthquakes are briefly described below.

North Sea, 19 February 2010, magnitude 4.3

At 21:08 UTC (22:08 local time) on 19 February 2010, a magnitude 4.3 earthquake occurred 45 km offshore the north-western Danish coast at a depth of 39 km (Fig. 4A). The focal mechanism indicates a reverse fault overthrusting to the west, in agreement with earlier earthquakes in the area. This is the most active area in Denmark, with many known earthquakes. From the instrumental era, Table 1 lists

Table 1. All instrumentally recorded events over 3.2 on the Richter scale in the areas around the North Sea and Kattegat earthquakes

Y/M/D-T (UTC)	Position (Degree)	Depth (km)	Stations	Magnitude (ML)
North Sea area				
1954/10/18 -16:44	56.85N 8.29E	25.5	4	4.6
1964/07/14 -05:33	57.03N 7.20E	36.0		4.0
1969/04/05 -19:09	57.16N 6.76E	0.1	23	4.2
1975/11/12 -06:00	57.10N 7.14E	40.0	37	3.7
1978/04/26 -12:32	56.75N 7.81E	40.0	18	3.4
1981/09/06 -04:11	57.03N 6.88E	40.0	84	5.2
1981/09/07 -14:03	57.06N 7.12E	30.3	13	3.6
1982/05/24 -03:10	56.64N 8.21E	41.4	25	3.7
1987/03/01 -06:42	57.00N 6.98E	40.1	26	3.5
1997/11/15 -16:11	56.86N 7.62E	6.6	56	3.6
1997/12/04 -22:03	56.91N 7.69E	8.5	48	3.4
2001/06/02 -00:44	56.80N 7.80E	59.3	39	3.5
2010/02/19 -21:08	56.89N 7.52E	22.0	111	4.3
Kattegat area				
1970/03/12 -16:05	56.54N 12.69E	0.0	12	4.0
1980/01/21 -07:41	56.27N 12.16E	10.2	29	3.9
1982/11/01 -02:48	56.28N 11.82E	3.4	17	3.5
1985/06/15 -00:40	56.61N 12.19E	9.1	44	4.7
1986/04/01 -09:56	56.54N 12.18E	7.2	37	4.1
1990/05/24 -09:51	56.48N 11.93E	10.0	15	3.2
1995/10/04 -20:49	56.78N 12.08E	9.9	31	3.8
1997/09/20 -14:21	56.94N 12.42E	15.0	4	3.8
2012/08/06 -02:57	56.60N 11.95E	22.1	31	4.1

earthquakes in the area over magnitude 3.5 (see also inset in Fig. 4 A). Earlier earthquakes are also known historically (Gregersen *et al.* 1991). GEUS received 344 macroseismic reports with observations of the 2010 earthquake from the public. The earthquake was mainly felt in north-western Denmark, with a few reports from northern Sjælland and Fyn. All observations were classified according to the European Macroseismic Scale (Grünthal 1993), and ranged from 2 to 6, including three instances of slight damage to houses in the form of cracks in walls.

Kattegat, 6 August 2012, magnitude 4.1

Early morning at 02:57 UTC (03:57 local time) on 6 August 2012, a magnitude 4.1 earthquake occurred in Kattegat, 26 km from the island of Anholt, at a depth of 22 km. The focal mechanism indicates a dextral strike-slip movement in a NW–SE direction, aligning with the general fault direction in the area including the Tornquist zone. Also in this area earthquakes are known, both historically (Gregersen *et al.* 1991) and instrumentally recorded (events over magnitude 3.5 in Table 1 and inset in Fig. 4B). GEUS received 441 macroseismic reports with observations of the 2012 earthquake from the public. The earthquake was felt mainly in northern Sjælland – where the population density is high, and where many people also experienced the magnitude 4.8 earthquake in southern Sweden in 2008 (Voss *et al.* 2009). But the earthquake was also felt in north-eastern Jylland and northern Fyn – and of course on Anholt. Furthermore, this event was widely felt in Sweden, and on Fig. 4B observations from SNSN (SNSN 2012) and USGS (USGS 2012) in USA are included. All observations were classified according the European Macroseismic Scale (Grünthal 1993), and ranged from 2 to a single occurrence of intensity 6 where small cracks had opened in the façade of a house.

Acknowledgement

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