The earthquake that shook central Sjælland, Denmark, November 6, 2001

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Earthquakes on Sjælland are in general small and seldom felt. The largest earthquakes in the Danish region occur in Skagerrak and Kattegat, and they are felt in NW Jylland (Thy) and in North Sjælland on average several years apart. A small earthquake measuring just 2.8 on the Richter Scale was felt and heard over a surprisingly large area of Sjælland, Denmark on November 6, 2001. The earthquake caused people to abruptly leave their houses near the epicenter, and minor damage to several build-ings was observed. The felt area is oriented strongly asymmetrically with respect to the epicenter, but it correlates well with the local geology. Specifically the shaking was felt in a region where the depth to the Top Chalk surface is small, and the thickness of the Quaternary sediments is less than 50 m. In 1869 an earthquake was felt strongly in the exact same area, and contours separating the felt area from the area where nothing was felt coincide almost exactly for the two earthquakes. This supports that geology and not human subjectivity is the determining factor in delineating the felt area for this earthquake.

Keywords: Earthquake; macroseismic data; seismicity.

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On November 6, 2001 at 18:05 UTC a small, $M_L = 2.8$ earthquake struck central Sjælland (Fig. 2a). It was a time of day when most people were at home quietly relaxing, and thus conditions for feeling the small bumps from the earthquake were favorable for many. Felt reports were received from several hundred peo-

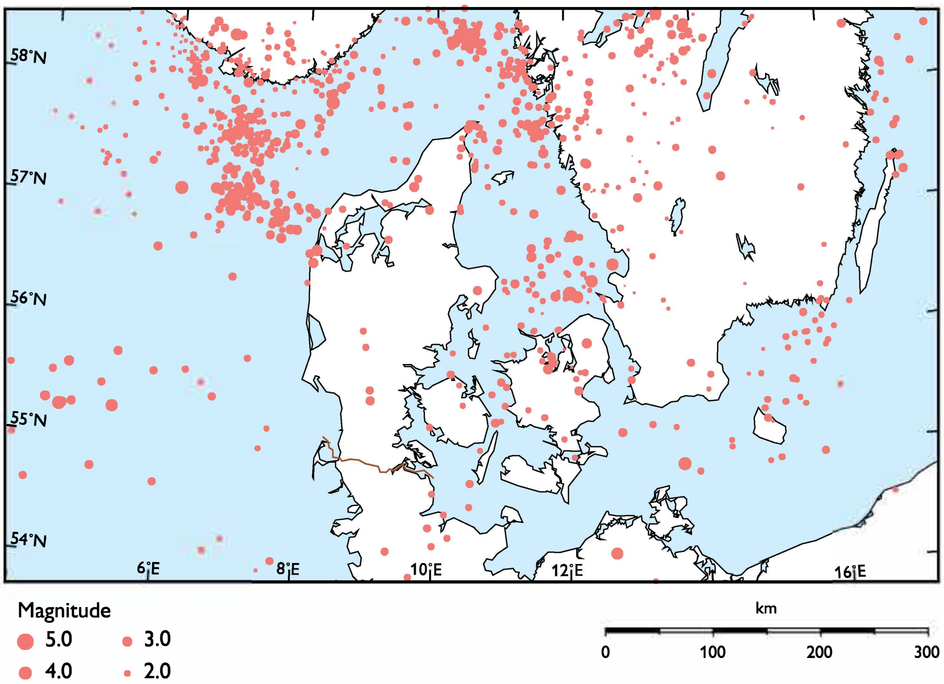

Fig. 1: Seismicity in Denmark and adjacent areas 1970 to 2008. Epicenters are from the GEUS earthquake catalogue and Catalogue of earthquakes in Northern Europe by University of Helsinki. All epicenteres are determined using a minimum of three stations.

ple, which is very unusual for a Danish earthquake. In some areas the earthquake was felt strongly, and minor damage to four houses was reported. Both humming and cracking sounds were associated with the earthquake even at significant distance from the epicenter.

Central Sjælland is seldom seismically active (Lehmann, 1956; Gregersen et al., 1998), compared to the Skagerrak and Kattegat regions where small earthquakes are registered several times a year (Fig. 1). However over the last 300 years a few widely felt earthquakes are believed to have occurred in the same region as the November 6, 2001 earthquake. Additionally, a smaller earthquake in the area has been detected instrumentally, but not felt. No instrumental recordings exist for Danish earthquakes occurring before 1929, and the determination of epicenters for the older earthquakes is therefore highly uncertain.

The oldest known earthquake we can attribute to the area occurred on February 11, 1709. The only available information about this earthquake describes that it was felt in Copenhagen, Roskilde, and Køge.

Fig. 2a: Map showing the epicenter and the seismograph stations that recorded the earthquake.

The event is mentioned in Lehmann (1956), where it is no. 12 on her list of Danish earthquakes. Significantly more information exists about an earthquake that occurred shortly after noon on January 28, 1869. Johnstrup (1870) collected 127 felt reports, both from regions where the earthquake was felt and from the adjacent area, where nothing was felt. Later in this paper Johnstrup's findings will be compared in detail to the November 2001 earthquake.

Lehmann (1956) lists an earthquake (no. 41) in July 1929, which was felt in the Holbæk and Sjællands Odde area. However, close inspection of the felt reports show that a series of three to four bumps were felt by at least two different observers. This information reduces the likelihood that the source of the observed phenomenon was an earthquake. Indeed, Gregersen et al. (1998) have omitted the event from the Danish earthquake catalogue.

A small M_L 1.5 tremor was detected instrumentally on September 17, 1982 (Gregersen et al., 1998). The epicenter was located at 55 41′.60 N, 11 35′.56 E which is nearly in the same location as the November 6, 2001 earthquake, given the uncertainties in the hypocenter determination process. The 1982 earthquake was too small to be felt by anyone, but it confirms that the area is mildly seismically active. With the improved instrumentation in recent years the chance of registering more earthquakes in the future has increased.

It is the objective of this paper to investigate and describe in detail the November 6, 2001 earthquake, and attempt to shed light on why the earthquake was felt strongly over a large area. The vast macroseismic material collected from this earthquake enables us to study the variations in site response and possible correlations with the geology. This information can prove useful for future assessments of seismic hazard in the area.

Description of the earthquake

The earthquake is peculiar in that we have a significantly better macroseismic record than instrumental recordings. It was a small magnitude earthquake causing a low signal to noise ratio on the seismographs, but as it was felt strongly over a large and densely populated area, we were able to collect several hundred felt reports. The unique macroseismic data set enables us to understand better the connection between local geology and ground shaking, something that cannot be obtained by the seismographs alone.

Hypocenter and magnitude determination

The 2001 earthquake was recorded by the Danish seismograph network, as well as by the seismograph networks in our neighboring countries (Fig. 2a). As the earthquake was small, the overall data quality is rather poor although the records are abundant. In order to determine the epicenter, a few spatially well-distributed P and S-wave arrival times are sufficient, whereas both determination of magnitude and focal mechanism require reliable amplitude readings as well. The latter can only be achieved on a few of the stations (Fig. 2b).

The earthquake location has been determined using the SeisAn seismological analysis software (Havskov & Ottemöller, 1999) as well as an older Danish location program (Gregersen, 1979), which is an extension of the HYPO71 program (Lee & Lahr, 1971) to include also Lg waves. The Lg wave is the phase with the largest amplitude on a regional seismogram, and it constitutes an important supplement to the P and S readings when few recordings are available. The Lg wave is, however, very sensitive to variations in crustal structure as it is a superposition of S-wave multiples trapped in the crust. The Lg wave train is fully developed at a distance of approximately 100-200 km from the source. At closer range the amplitude cannot be used.

The search for the best fit of latitude, longitude, depth and zero time for the earthquake is done in a least squares sense. Travel times are calculated in a layered model. The two different location programs yield epicenters just a few km apart and with overlapping uncertainty ellipses. The closely overlapping results emphasize the credibility of both localisation procedures. The final location is based on 57 arrival readings from 25 different seismograph stations (Fig. 2a). The result of the location calculation can be found in Table 1.

Table 1. Hypocenter and zero time for the earthquake

Date	Time (UTC)	Latitude (deg N)	Longitude (deg E)	Depth (km)
6 Nov 2001	18:05:27	55,677	11,701	20

The earthquake was reasonably well surrounded by seismographs in Denmark, Germany, Norway, Sweden and Finland, and the largest azimuthal gap in coverage is 93 degrees. Thus the epicenter of the earthquake is well determined. However, the location programs use a travel-time curve based on a one-dimensional model without inclusion of local crustal inhomogeneities, so we estimate that the real uncertainty can be as much as 10 km. The distance from the epicenter to the closest seismograph station is approximately 50 km which is too far away to obtain an accurate hypocentral depth based on crustal phases. The standard error of the least squares solution is 10 km for the depth, but the real uncertainty could be as much as 15-20 km.

The magnitude has been determined to 2.8 ML using a calibration of the local magnitude scale to Danish conditions (Geodætisk Institut, 1983). The magnitude is based on only one reading from the MUD station in central Jylland, as the other Danish stations COP and LLD are too close for reliable amplitude reading of the Lg wave. The rest of the seismograms do not contain measurable Lg wave amplitude.

An attempt was made to determine the focal mechanism for the earthquake. The focal mechanisms derived from earthquake data are often used to investigate the regional stress pattern (e.g., Zoback et al, 1989). However, very weak events with a magnitude of less than three are generally assumed to express local conditions, which are not necessarily in line with the regional stress pattern (Gregersen, 1992). The focal mechanisms on the larger earthquakes in Denmark are consistent with ridge push from the Midatlantic Ridge.

Several different methods were applied to the data to obtain a focal mechanism for the earthquake. Between 8 and 10 stations, including a few in Norway and Germany have sufficiently clear signals for the procedure. Unfortunately the stations are mainly concentrated to the north and south on the focal sphere. This causes the problem to be poorly constrained, and the solution is therefore not unique. The many possible solutions range from pure strike-slip to pure normal faulting on a vertical plane, so we are unfortunately not able to suggest a reliable focal mechanism.

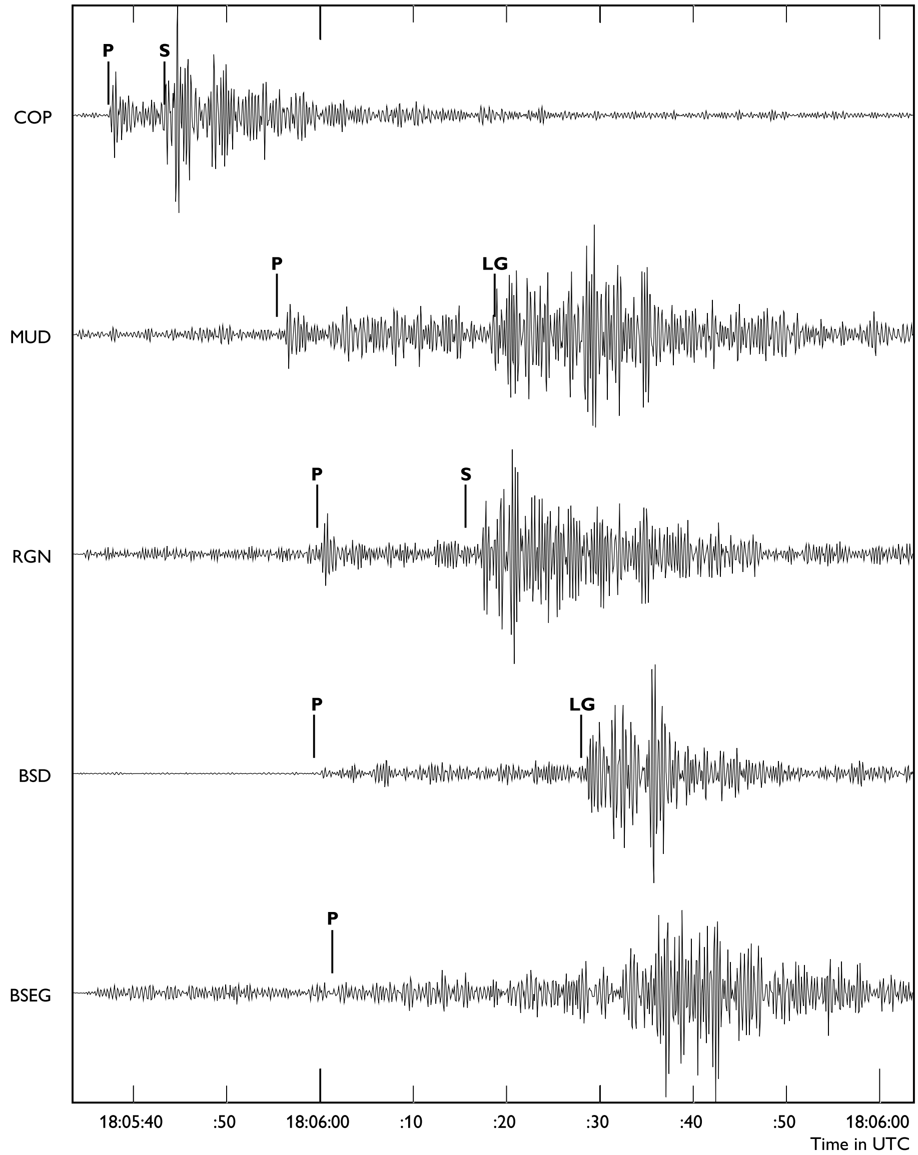

Fig. 2b: A selection of the best vertical component seismograms for the earthquake. Even for the clearest recordings the signal to noise ratio is rather low. The phases picked on these vertical component seismograms are marked on the figure. The location of the seismograph stations can be found in Fig. 2a.

Macroseismic description – shaking and sound

Following the 6th of November, people who had felt the earthquake were encouraged to fill in a questionnaire. This call, which went out through TV, radio as well as newspapers, resulted in over 400 contacts and a total of 308 useable felt reports. This is a remarkable number given the modest magnitude of the earthquake. In the past Danish earthquakes of similar magnitude have seldom resulted in more than 20 felt reports.

The data coverage is incomplete in that only those observers who actively came forward received a questionnaire. In order to assess the effect of the tremor more accurately, it could have been beneficial to send a questionnaire to everyone in the affected area. In this way the borders of the felt area could be delineated more accurately. However this would be too costly to carry out, as the earthquake was widely felt over a heavily populated area, including Greater Copenhagen. Recently a web-based version of the earthquake questionnaire has been set up with the hope of reaching a larger number of people following the next earthquake.

The earthquake affected a wide area as seen in Fig. 3, where shaking intensities from the felt reports are plotted. Each felt report was assigned an intensity according to the European Macroseismic Scale (Grünthal, 1993). The value 6 represents modest damage to weak buildings, such as cracks in houses with poor foundation, and 5 is assigned to locations where loose objects moved during the earthquake, e.g. a cup or a plate that shifted on a table, or a lamp or a door that started swinging. Intensity 4 is assigned where windows rattled or the frame of the house gave off clear sound, and intensity 3 is assigned where the earthquake was felt, but nothing moved or rattled. A geographical coordinate, necessary for plotting the data, was assigned to

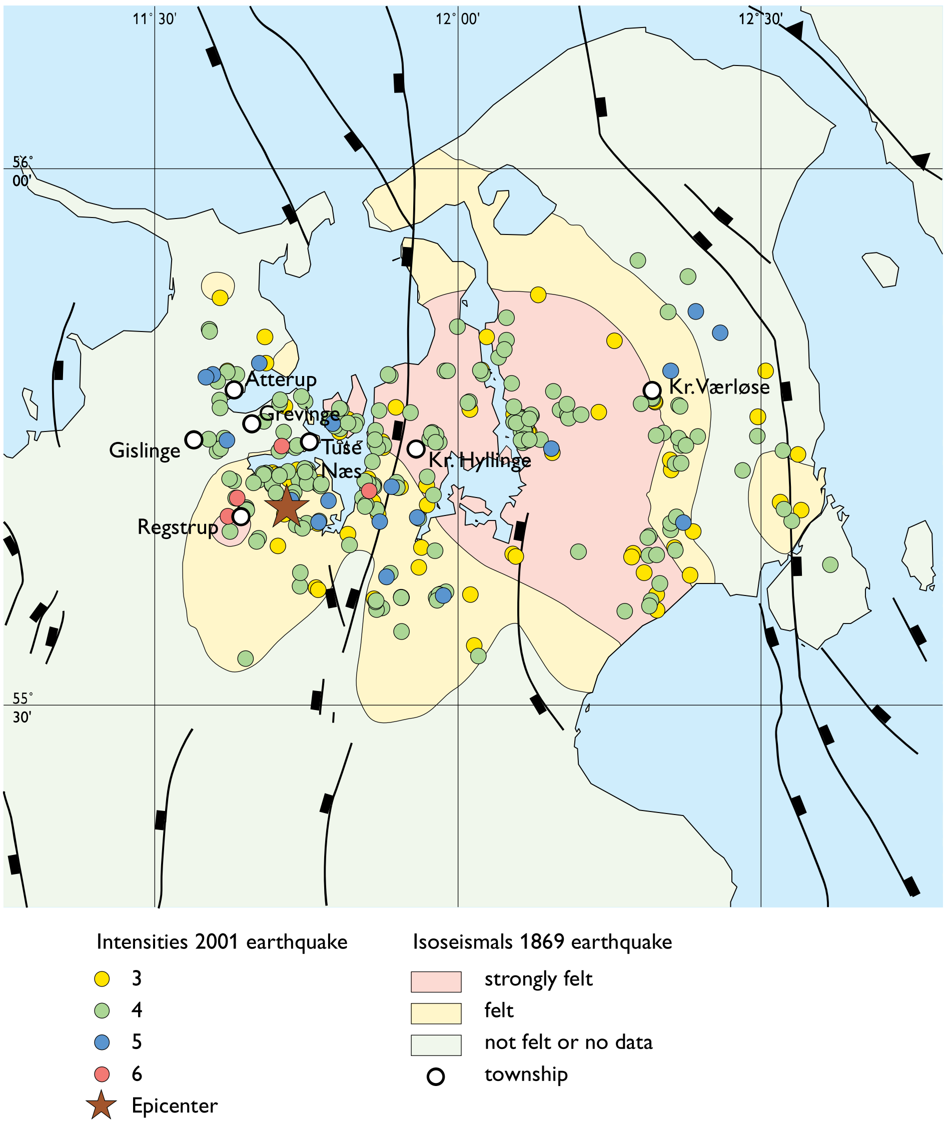

Fig. 3: Map showing where the November 2001 earthquake (colored dots) and the January 1869 earthquake (shaded areas) were felt. Each dot represents one observer, and the dots are color coded according to the intensity on the European Macroseismic Scale. 6: modest damage to weak structures, 5: loose objects moved, 4: houses rattle, 3: the earthquake was felt. The shaded areas from the 1869 earthquake are redrawn from Johnstrup (1870). Faults are redrawn from Vejbæk & Britze (1994).

each report based on the National Survey and Cadastre (KMS) address-coordinate register.

Many of the observers describe that they have found minor cracks in wallpaper or poor quality brick walls. When there is any doubt weather a crack has been caused by the earthquake or if it was previously there, this information has been ignored when determining the intensity for an observation point.

In the ideal case, the highest intensities are located near the epicenter, with the intensity tapering off with distance in a regular form. In the past isoseismals drawn on intensity maps were used to determine the epicenter of an earthquake, when only macroseismic information was available. However, this method cannot be used for the November 6, 2001 earthquake. The instrumentally determined epicenter is located at the western edge of the felt area, and the different intensity levels do not form anything that resembles a regular form (Fig. 3). While it can be somewhat subjective whether a report is assigned an intensity of 3 or 4, the distinction between 4 and 5, and between 5 and 6 is quite clear. The intensity pattern in Fig. 3 is therefore stable and reliable. However, given the uncertainty in the epicenter location it is possible that the epicenter is located closer to the center of the intensity 6 region.

The felt effects are sensitive to the local geology and soil conditions, as well as the condition, geometry and material of the buildings in which each observer is located. The surface shaking is also influenced by the source mechanism of the earthquake through the directionality of the radiation of energy. Cultural factors such as population density can also influence the observed intensities. The area west of the 2001-epicenter is thinly populated with summer houses making up a significant percentage of the inhabited areas. However, this alone cannot explain the almost total lack of felt reports just a few km vest of the epicenter.

The earthquake was felt very strongly over a large area, and frightened many people. Many, even among those who felt the earthquake at intensity 4, describe that they initially thought that a car or a truck had hit their house. Many feared that their furnace had exploded, and others thought that the roof of their house had suffered serious damage by an unknown cause. The earthquake was felt particularly dramatically in the Tuse Næs and Regstrup areas not far from the epicenter. In those areas many observers report that it felt as though their houses settled. One family in Kr. Hyllinge saw the plaster wall behind their television crack, as they were watching the evening

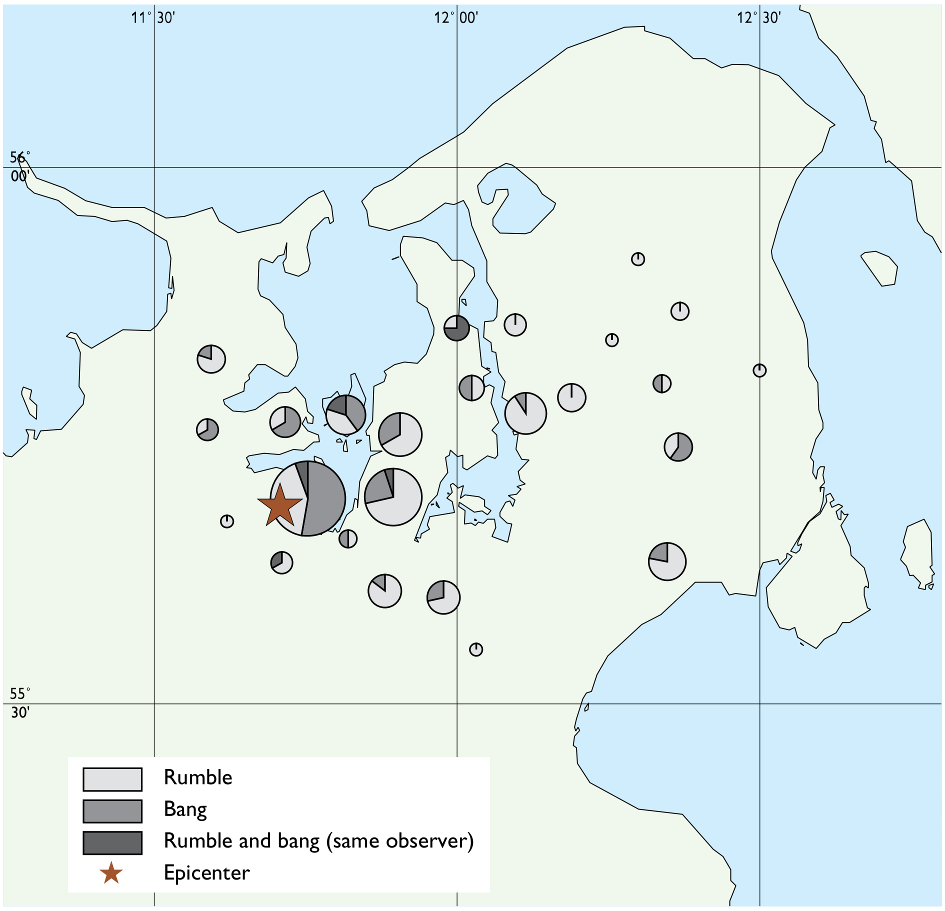

Fig. 4: Distribution of observations of sounds from the earthquake. The observations are grouped geographically where appropriate, and the circles are scaled according to the number of observations. The smallest circles are equivalent to just one observer, and the largest circle represents 28 observations of sound from one geographical location (the city of Holbæk).

news. In Gislinge an observer describes that it felt as though her house was pulled over an old-fashioned washboard, and in Grevinge another observer looked up and saw the ceiling was in motion.

What scared the majority of people the most, however, appears to be the sounds associated with the earthquake. 171, or more than half of the felt reports describe hearing various sounds from the earthquake. The observations of sound are scattered throughout the felt area, and not just close to the epicenter (Fig. 4). The sounds appear to have the highest dB levels closest to the epicenter, but apart from that there is no clear geographical pattern in how the earthquake was heard. A few observers, including one in Atterup, which is at or very near the epicenter, describe hearing a cracking sound (as in cracking a whip), and the same is observed by one person in Kr. Værløse. All over the affected area people describe hearing a deep humming sound or distant rumbling not quite like thunder or anything else they have ever heard. Within approximately 30 km of the epicenter many heard a loud bang, not quite like an explosion. Then there is a 20 km wide band from a distance of 30 to 50 km, where only rumbling is heard, and then again a little less than 50 km away some hear rumble and some hear a bang. We interpret a bang to be a higher frequency sound than a rumble, and it is therefore not surprising that the majority of the observations of a bang is relatively close to the epicenter, as the higher frequencies are dampened quicker than the low frequencies.

It is common that sounds are heard in connection with an earthquake, but the literature on the subject is very sparse. Audible sound is not picked up by seismographs, and in most earthquake studies the macroseismic analysis focuses on the permanent damage caused by the earthquake. However, sound is important for the perception of a weak earthquake. With very weak earthquakes it can be difficult for observers to distinguish if they heard or felt the earthquake. In some cases low frequency rumble is heard from tremors too weak to be felt (Davison, 1938).

The physics behind earthquake sounds is quite well described. Incident P- and SV-waves are converted to acoustic waves at the soil-air interface, with the soil acting as a giant loudspeaker directly under the observer. Hill et al. (1976) have treated the phenomenon in great detail and find that theoretical transmission coefficients fit well with the observations of sound. Sound from P-waves is far more common than sound from SV-waves, a fact that explains why sound from small earthquakes often is heard before shaking is felt. In these cases no shaking is felt before the arrival of the S-wave, as the P-wave shaking is too weak.

The sound observations from the Nov. 6, 2001 earthquake fit well with an empirical relationship for sound, distance and local magnitude developed by Sylvander and Mogos (2005). Their study is based on 184 weak earthquakes occurring in the French Pyrenees. According to the relationship it should be possible to hear an earthquake with ML = 2.8 loudly to a distance of about 30 km and faintly to a distance of about 50 km. The geology is of course significantly different in the Pyrenees than on Sjælland, but the predictions of sound loudness fit nonetheless very well with our observations east of the epicenter.

As the sound primarily comes from converted P-waves, the audibility of an earthquake can reflect the P-wave radiation pattern, as demonstrated for moderate earthquakes by Tosi et al. (2000). In our case there is clear directionality on the felt and heard area (Figs 3 & 4). However, the macroseismic observations correlate very closely with the geology of the region, so we are not prepared to suggest a focal mechanism based on the observations of sound.

Discussion

Very local conditions can influence how an observer perceives an earthquake, but with the large number of macroseismic reports we are able to detect trends and correlations with geology. The earthquake in 1869 also generated a large number of reports, and the old observations coincide almost exactly with observations from 2001.

Geological setting

The earthquake occurred on Sjælland in an area where sharp lateral changes in geology dominate to a significant depth. The island of Sjælland is located within the Danish Basin which has been subsiding for several hundred million years (e.g., Sørensen, 1986). An interpretation of seismic, gravimetric and magnetic models given in Thybo (2001) shows that the Danish Basin extends down to about 9 km on a profile near the epicenter. The Danish Basin overlays crystalline rocks, but even within the basin the sedimentary rocks are likely to be strong enough to support an earthquake. The earthquake occurred at an estimated depth of 20 km, but there is significant uncertainty in this depth estimate, as described in section 2.1.

The knowledge of the geological conditions near the hypocenter is not very detailed. The deepest published mapping of geological layers and faults in the area stops at the Top Pre-Zechstein level (Vejbæk & Britze, 1994). It is not known how far down the faults extend, and near the hypocenter the data coverage is sparse and could easily have missed a fault. At Top Pre-Zechstein there are no known faults near the epicenter, but in general there are many faults cutting through Sjælland in the N-S direction. Near the hypocenter the bottom of Zechstein is at a depth of more than 5 km, but the horizon rises steadily up to a depth of about 2 km by the east coast of Sjælland.

The shaking at the surface is strongly influenced by the softer Quaternary sediments in the affected area, and the underlying tertiary clay towards the west. The Pre-Quaternary surface (Fig. 5) is located at a depth exceeding 50 m at the epicenter and to the west, whereas it rises up close to surface level just 10 km to the east. The depth to the bottom of the Quaternary sediments does not exceed approximately 50 m in the areas where the earthquake was felt, with very few exceptions close to the epicenter.

The depth to the Top Chalk Group (Ter-Borch, 1991) could also affect the surface shaking. As with the depth to the Pre-Quaternary surface, a NW-SE trending line through the epicenter separates deep lying layers to the west from shallow layers to the east. Right by the epicenter the chalk surface is at a depth of approximately 100 m, whereas 10 km to the east, chalk is found at a depth of just 10 m. All the way to Copenhagen in the east, chalk is consistently found at depths of less than 25 m where the earthquake is felt. With the available data, it is not possible to determine if a shallow depth to the top chalk or thin Quaternary sedimentary layers are most important for transmitting the shaking to the surface.

The 1869 earthquake

In January 1869 a large part of Sjælland was affected by an earthquake which is peculiarly similar to the 2001 earthquake. Johnstrup (1870) made a consider-

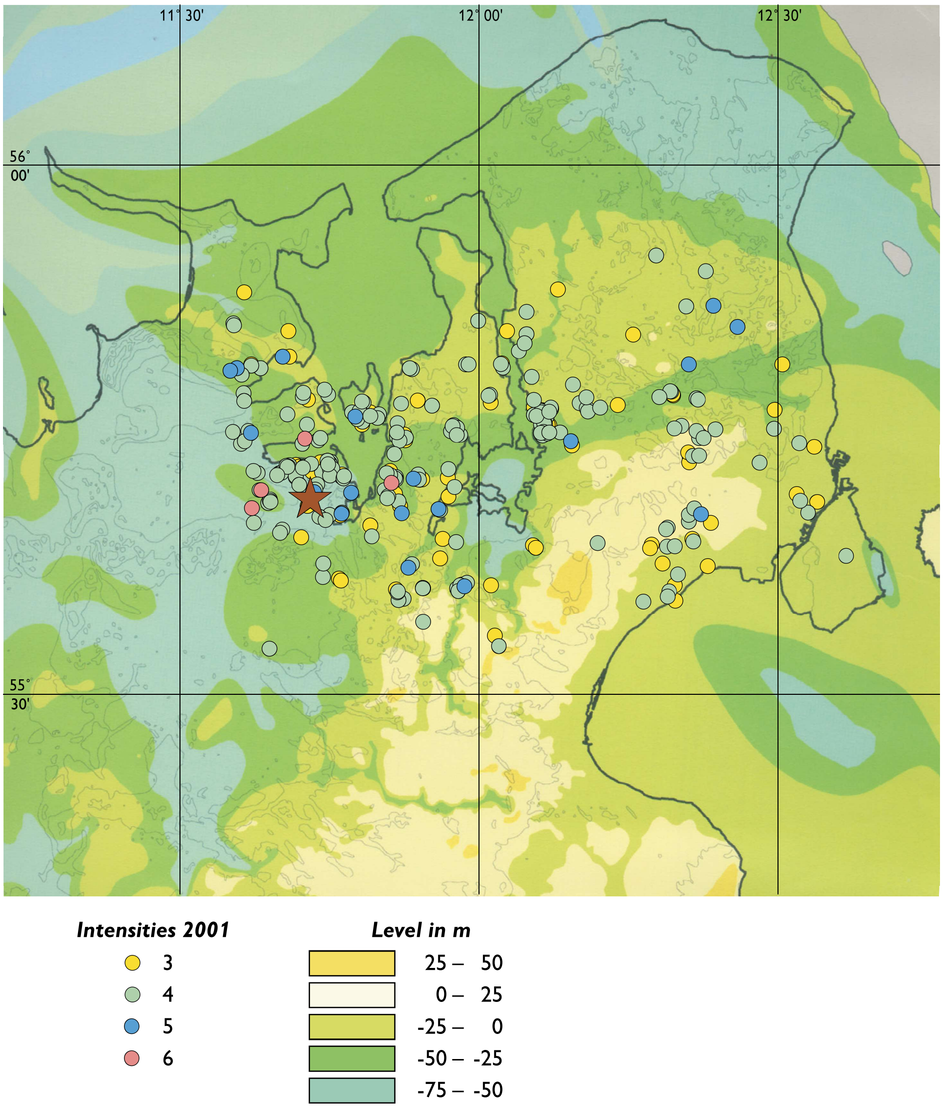

Fig. 5: A small section of the geological map showing the depths to the Pre-Quaternary surface (Binzer & Stockmarr, 1994) with the earthquake intensities from Fig. 3 overlaid.

able effort to map where and how the earthquake was felt in an attempt to understand the phenomenon. He collected and analysed 127 reports, and was able to determine two isoseismals for the earthquake.

The isoseismals from Johnstrup (1870) are reproduced in yellow and pink on Figs. 3 and 6. Note how closely Johnstrup's isoseismals correlate with the area where the 2001 earthquake was felt (Fig. 3). The yellow lobes on the map south of the fjords perfectly encompass the point observations from 2001. In other areas the correlation is not quite as perfect but still good.

In order to make a more accurate comparison of the two earthquakes, we revisited the original felt reports from 1869, and Johnstrup's notes regarding the reports. Both are kept at the Geological Museum in Copenhagen. The reports are in essay form whereas we nowadays use a preprinted questionnaire. We assigned an intensity to each report following the same European scale (Grünthal, 1993) as we used for the 2001-earthquake. Finding a coordinate for each observer was less straight-forward, as street addresses were not yet in use in rural Denmark in 1869. The location information was instead given as the name of the town/village and in some cases the name of a farm. In other cases the report was written by a vicar, providing the name of his church.

Geodetic software, Geodisp, was used to obtain coordinates for the observation points on a map. All the churches mentioned in the felt reports could easily be found on the map, and some of the larger farms as well. When a particular farm house could not be identified on the map, or when no detailed information was available, the point was placed in the center of the village. The resulting intensity map is shown as Fig. 6.

When comparing Figs. 3 and 6 it is clear that the intensity 3 and 4 observations correlate very well, whereas the intensity 6 observations do not correlate

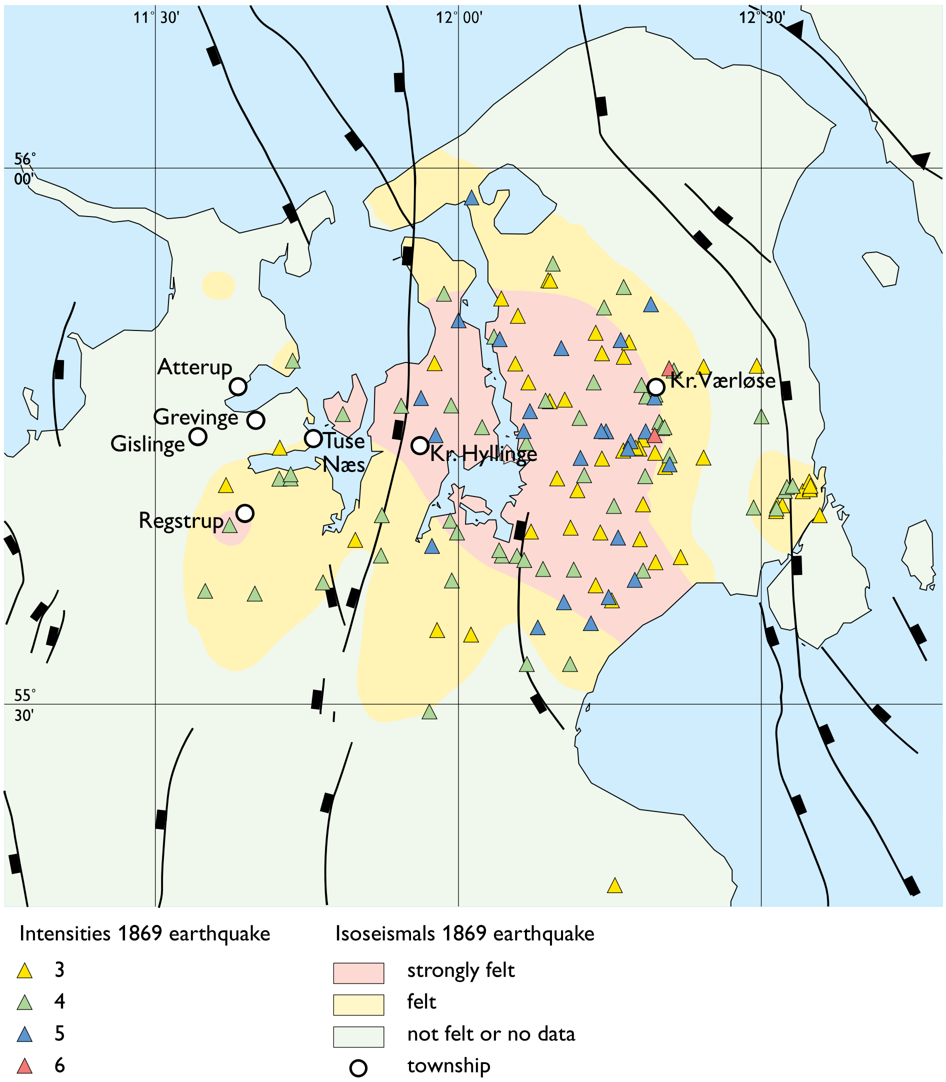

Fig. 6: Map of felt intensities for the January 1869 earthquake with the original isoseismals from Johnstrup (1870) redrawn as shaded areas. Each triangle represents one observer, and the triangles are color coded similarly to the intensities in Fig. 3. Faults are redrawn from Vejbæk & Britze (1994).

at all. There are, however, very few intensity 6 observations (minor cracks in weak buildings), and they occur only where vulnerable structures are found. It is therefor difficult to make any geological conclusions based on those. The field of intensity 5 observations (blue symbols) is located further to the west for the 2001 earthquake than for the 1869 earthquake. This could indicate that the two earthquakes do not have exactly the same epicenter location, although the epicenters must be very close. Since a large number of felt reports are available for both earthquakes, it is not very likely that the discrepancy is caused by random errors.

Conclusions

The large macroseismic data set collected from the November 6, 2001 earthquake made it possible to study local variations in site response and correlations with geology. The most remarkable feature of the earthquake is that it was felt very strongly and heard very loudly out to a significant distance east of the epicentre, whereas nothing was felt or heard more than a few km west of the epicentre. The earthquake happened in an area where sharp lateral changes in geology dominate to a significant depth, and it is clear that the local geology plays an important role in damping or amplifying the vibrations from the earthquake. West of the epicenter the chalk is overlaid by a thick layer of Quaternary sediments and tertiary clay that dampen the effects from the earthquake almost completely, whereas to the east the thin Quaternary sediments and the proximity of the chalk to the surface easily conducts or even amplify the shaking. The same area has been hit by two widely felt earthquakes about 150 years apart, and it is not unlikely that it could happen again, although Sjælland is not among the seismically most active areas in Denmark.

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Dansk sammendrag

Rystelserne fra et mindre jordskælv 6. november 2001, som målte blot 2.8 på Richterskalaen, kunne mærkes kraftigt over en overraskende stor del af Sjælland. Efter jordskælvet blev der indsamlet mere end 300 rapporter fra borgere som havde mærket jordskælvet. Dette omfattende makroseismiske datasæt gjorde det muligt at afdække en sammenhæng mellem lokale geologiske forhold og de følte rystelser. Jordskælvet fandt sted i et område der domineres af skarpe laterale ændringer i geologien, og det afspejles i de indsamlede rapporter. Vest for epicentret er kalken dækket af et tykt lag kvartære sedimenter og tertiært ler, som næsten fuldstændig dæmper rystelserne fra jordskælvet. Øst for epicentret findes kalken tæt ved jordoverfladen og er kun dækket af et tyndt lag kvartære sedimenter. Her transmitteres rystelserne over store afstande. Samme område blev for ca. 150 år siden rystet af et tilsvarende jordskælv, og det kan ikke udelukkes at der vil komme flere jordskælv i fremtiden, selvom Sjælland ikke er blandt de seismisk mest aktive områder i Danmark.

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