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State-of-the-art of historical earthquake research in Fennoscandia and the Baltic Republics

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Abstract
We review historical earthquake research in Northern Europe. 'Historical' is defined as being identical with seismic events occurring in the pre-instrumental and early instrumental periods between 1073 and the mid-1960s. The first seismographs in this region were installed in Uppsala, Sweden and Bergen, Norway in 1904-1905, but these mechanical pendulum instruments were broad band and amplification factors were modest at around 500. Until the 1960s few modern short period electromagnetic seismographs were deployed. Scientific earthquake studies in this region began during the first decades of the 1800s, while the systematic use of macroseismic questionnaires commenced at the end of that century. Basic research efforts have vigorously been pursued from the 1970s onwards because of the mandatory seismic risk studies for commissioning nuclear power plants in Sweden, Finland, NW Russia, Kola and installations of huge oil platforms in the North Sea. The most comprehensive earthquake database currently available for Northern Europe is the FENCAT catalogue covering about six centuries and representing the accumulation of work conducted by many scientists during the last 200 years. This catalogue is given in parametric form, while original macroseismic observations and intensity maps for the largest earthquakes can be found in various national publications, often in local languages. No database giving intensity data points exists in computerized form for the region. The FENCAT catalogue still contains some spurious events of various kinds but more serious are some recent claims that some of the presumed largest historical earthquakes have been assigned too large magnitude values, which would have implications for earthquake hazard levels implemented in national building codes. We discuss future cooperative measures such as establishing macroseismic data archives as a means for promoting further research on historical earthquakes in Northern Europe.

Key words *historical earthquakes – Fennoscandia and Baltic Republics*

1. Introduction

The region addressed here covers Fennoscandia, Denmark, the Baltic countries, Kola and NW Russia (fig. 1a,b). It comprises the adjacent sea areas of Norway out to the Eurasian and North American plate boundaries along the midoceanic ridges in the Norwegian and Greenland Seas. This region is situated in the NW Eurasian intraplate domain, which is nearly devoid of earthquake activity in global terms. However, earthquakes are felt occasionally and areas with enhanced seismic activity can be found, particularly in the coastal areas of Norway.

Assessing macroseismic observations in this region can be complicated, because off-

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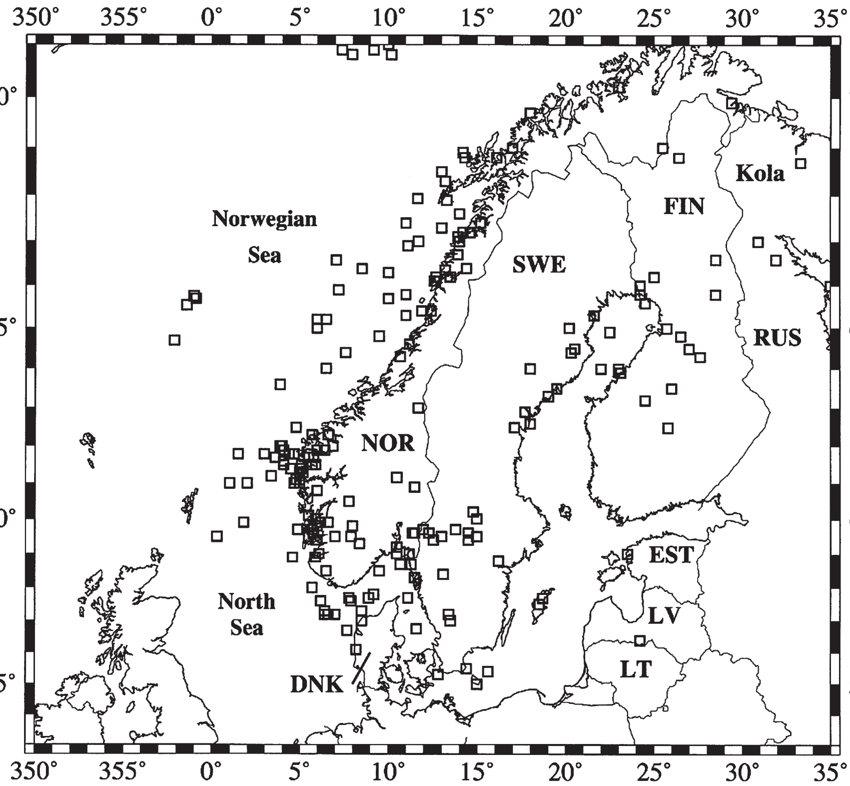

Fig. 1a. Region addressed in the present study. Letters denote present-day Denmark, Estonia, Finland, Latvia (LV), Lithuania (LT), Norway, Russia and Sweden. Squares show epicentres for earthquakes of magnitude 4 and above occurring between 1375 and 1964 as given in the FENCAT catalogue (Ahjos and Uski, 1992) and its updated version (http://www.seismo.helsinki.fi). The reported event magnitudes are of the ML type but stem from a variety of sources. Some events are located in offshore areas reflecting mechanical seismograph installations up to the mid-1960s.

shore events may be poorly sampled and sturdy timber houses were the predominant type of dwelling in the past. Also, macroseismic evidence for significant amounts of damage is very rare. When stone churches and some masonry buildings in Sweden were inspected for traces of permanent earthquake damage as part of a programme of seismic risk assessments for nuclear power plants, the outcome was negative. Many intensity estimates for the historical data have been given using the Modified Mercalli (MM) scale, which differs somewhat from the Medvedev-Sponheuer-Kárník scale (MSK 64) and the revised European Macroseismic Scale (EMS). This is not considered a severe drawback, since most events have an intensity value of V and below for which range these scales are similar. This would not constitute a serious problem even for the largest earthquakes with intensities up to VII, because magnitude estimates are tied to the perceptibility area as defined by intensity I = II-III observations.

Historical times are defined here as those beginning with the earliest written account in 1073 until the use of short period instruments. The latter is not clearly defined because short period

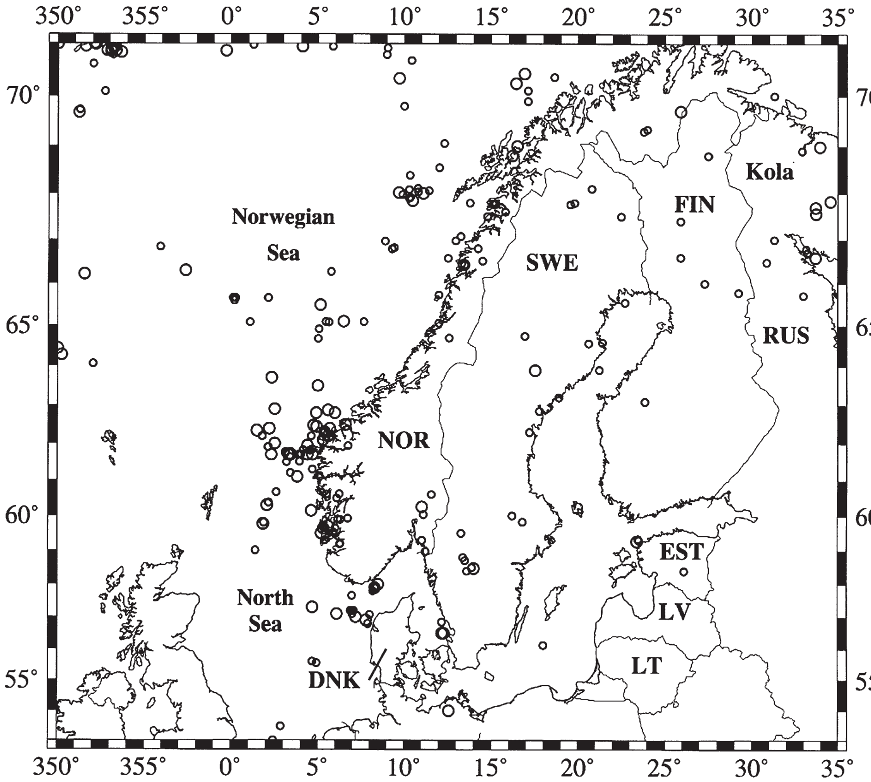

Fig. 1b. Region addressed in the present study. Letters denote present-day Denmark, Estonia, Finland, Latvia (LV), Lithuania (LT), Norway, Russia and Sweden. Circles show epicentres for earthquakes occurring between 1965 and 2002. The smaller symbols refer to magnitudes in the range of 3.5-3.9 and the larger symbols to magnitudes 4 or above as given in the FENCAT catalogue (Ahjos and Uski, 1992) and its updated version (http://www.seismo.helsinki.fi).

seismograph station installations commenced in most countries during the 1960s, while in the Russian part of Fennoscandia the network remained very sparse until the 1980s and in Norway the national network remained somewhat incomplete until 1990. Here we define historical records from the earliest available report up to the 1960s. The following section presents some background on the earthquake catalogues available for the region. The third section describes historical earthquake research in various parts of the region during the past 20 years, and the fourth section discusses today's situation and future plans.

2. A brief history of macroseismic studies in Northern Europe

Many studies have addressed the problem of compiling a homogeneous and comprehensive earthquake catalogue for Northern Europe. These activities date back to about the 1750s, coinciding with a growing interest in science and natural phenomena. Learned societies were established in the Nordic countries for the advancement of scientific thinking and debate. Earthquakes were well established as natural phenomena, but their origin was vigorously debated in theological, philosophical and natural science contexts.

Although a proper physical understanding of earthquakes developed slowly, descriptions of local events were written down. The oldest documentation was related to a Danish earthquake in 1073 (Lehmann, 1956), while the first attempt on a Swedish catalogue is credited to Hjärne (1706). The Kattegat, Denmark earthquake in 1759 is a unique example of the early use of macroseismic questionnaires. Bishop C. Horrebow wrote to all the priests in his Zealand diocese, asking how the earthquake was felt locally. The original material was rediscovered recently and has now been published together with newspaper clippings from adjacent Norway, Sweden and Northern Germany (Bondesen and Wohlert, 1997).

The flow of scientific earthquake studies began in the 1800s. The Swedish Academy of Sciences promoted interest in earthquakes, and these efforts resulted in many annual and biannual reports (Ehrenheim, 1824; Berzelius, 1823, 1824, 1826, 1827). Earthquakes were frequently reported in Norway as well, and the first compilation there was due to Keilhau (1836). The Finnish Society of Sciences and Letters collected information on natural phenomena, which led Moberg (1855) to give the first earthquake report in Finland. These activities inspired further investigations. A comprehensive listing of all known Norwegian earthquakes up to 1912, including the corresponding publications, was later published by Kolderup (1913). Svedmark (*e.g.,* 1886, 1902) published several papers on seismic events felt in Sweden, and Renqvist (1930) compiled the first descriptive earthquake catalogue in Finland.

Systematic interest in earthquakes was also shown in neighbouring areas and countries. Mushketov and Orlov (1893) compiled the first comprehensive earthquake catalogue for the Russian Empire and adjacent areas, comprising more than 2500 entries. Some of these events occurred in Russian Lapland and the Kola regions, which are parts of NW Russia. Only the Narva earthquake in 1881 was included for the SE Baltic area. More updated earthquake catalogues for NW Russia and Kola were later published by Gorshkov (1947), Panasenko (1969) and Kondorskaya and Shebalin (1977).

Doss (*e.g.,* 1898, 1909, 1910, 1911) began historical and contemporary earthquake research in what is today Latvia and Estonia. As usual, the main sources of information were ancient church chronicles, newspapers and eyewitness reports. He compiled an earthquake list that comprised 18 events occurring in Latvia and Estonia between 1616 and 1896 (Doss, 1909). No historical earthquake records are known for Lithuania, which is not surprising in light of the present-day very low seismic activity. Some large regional events were reportedly felt within Lithuanian territory (Gudelis, 1958).

An important milestone in studies of historical earthquakes was the systematic use of macroseismic questionnaires, which commenced in Fennoscandia in the 1880s. Initially the Rossi-Forel intensity scale ranging from I to X was used. Later the Mercalli, MM and MSK-64 scales and, most recently, the EMS (Grünthal, 1993, 1998) came into use. These scales are similar up to intensity I = V or even I = VI and thus comparable for the large majority of reported historical earthquakes.

Basically, the use of questionnaires has continued without interruption until now, although wars naturally hampered such activities. With the deployment of several modern seismograph stations in the 1960s and afterwards, the interest in macroseismic studies waned and returned questionnaires were often simply archived without much further analysis. This practice changed in the 1970s when seismic hazard studies became mandatory for nuclear power plant operations and later for commissioning oil production platforms in the North Sea.

Since it is not scientifically sound to restrict seismicity studies to events occurring only within national borders, it naturally followed that Fennoscandian catalogues began to be compiled. An important work was that of Båth (1956), whose catalogue comprised earthquakes occurring in Fennoscandia (without its Russian part) between 1891 and 1950. Ahjos and Korhonen (1984) extended Båth's work by compiling a Fennoscandian earthquake catalogue covering about 500 years. It can be seen as one step towards the FENCAT catalogue, which is the present regional catalogue available in parametric form (Ahjos and Uski, 1992). It is constantly updated and available over the Internet: http://www.seismo.helsinki.fi/

3. Historical earthquake studies during the past 20 years

Since the Fennoscandian Shield is characterized by the relatively infrequent occurrence of small rather than devastating earthquakes, the attention focused on these during the years of serious study was largely determined by the level of academic interest. Increased interest in Fennoscandian seismicity followed from the mandatory seismic risk analysis for nuclear power plants and plans for radioactive waste disposal in the bedrock of Sweden, Finland and Russia and large offshore oil installations in Norway commissioned over 20 years ago.

Exploration of the rich North Sea oil and gas resources motivated seismic hazard assessment in that area and greatly increased the need for a homogeneous seismic record compiled on a multinational basis. A comprehensive multinational programme of historical earthquake information retrieval from libraries and record offices in Norway, Denmark, Sweden and Britain was launched. It is rated very successful in terms of many new publications on this subject (*e.g.,* Ambraseys, 1985; Bungum *et al.*, 1986; Muir Wood *et al.*, 1988). During the search new information on several known events was found and event duplications, meteor-induced tremors and previously unknown events were identified. The new database was used to quantify the earthquakes in terms of MSK intensity and to prepare a collection of isoseismal maps following a standard method. A noteworthy outcome of these studies was also that magnitude estimates were given to most of the historical earthquakes. Among the largest events was the earthquake in the vicinity of Oslo on 23 October 1904 which was initially given a M_L magnitude of 6.4 mainly based on I = VII reporting near its epicentre. However, this appeared a bit excessive since no significant damage was reported, and later readjustments gave a ML value of 5.4 using the magnitude formula tied to felt area for I = III as given below.

Of particular interest are large recent earthquakes, for which both macroseismic and instrumental data are available. They are helpful in establishing formulas relating intensity and magnitude, thus enabling magnitude estimates for historical earthquakes as well. Initially, maximum intensity was used, as in the case of the 1904 earthquake near Oslo, but this proved far too unreliable for several reasons, not the least because many epicentres lie outside populated areas. More representative are log-linear relations comprising the entire area characterized by I = III observations such as

$$M_s = 0.69 \cdot \log(A_{\mathrm{III}}) + 0.0006 \cdot A_{\mathrm{III}}^{1/2} + 0.95 \quad (3.1)$$

$$M_L = 0.86 * \log(A_{\mathrm{III}}) + 0.21 \quad (3.2)$$

where the Ms formula is given by Muir Wood and Woo (1987) and the M_L formula by Almhjell *et al.* (2001). Many local magnitude formulas have been published (see Bungum *et al.*, 1998), but our preference is that of eq. (3.2) because it is calibrated against M_L magnitudes stemming from modern instrument recordings.

The above relationships should in principle be simple enough to apply but are not so in actual practice due to the presence of so-called outliers. An illustrative example here is the earthquake that occurred in Lurøy, northern Norway in 1819, which has generally been taken to be the largest in NW Europe in historical times. Muir Wood (1989) assigned it a magnitude value of M_s = 5.8, which was entirely due to his acceptance of reports from Stockholm more than 800 km away as genuine I = III observations, while Husebye and Kebeasy (2003) rated these observations as outliers. When the Stockholm observations are classified as belonging to category I = II, the radius of perceptibility reduces to only 350 km and the corresponding magnitude to only M_L = = 4.8 or, equivalently, M_s = 5.1.

Another interesting example is the Kattegat, Denmark earthquake of 23 December 1759. The peculiar feature here is that this event was felt as far (500 km) as Schleswig-Holstein (Northern Germany) to the south but at a far less distance to the north (Norway) and north-east (Sweden). A rational explanation is the strong wavefield amplification on the northern flanks of both the Danish and North German basins, causing persistent biases in intensity observations. Kebeasy and Husebye (2003) used 2D finite-difference waveform modelling to evaluate amplifications due to subsurface basin structures and reassessed intensity on the EMS, using original questionnaire data from Bishop Horrebow mentioned above. When correcting for the amplifications the shape of the perceptibility area became symmetric, but most significantly the revised Kattegat earthquake magnitude became $M_L = 4.9$ ($M_s = 5.1$) compared with $M_s = 5.6$ given by Muir Wood (1989).

Musson *et al.* (2001) conducted a study on the historical seismicity of the Faroe Islands, which today are a self-governing community within the Danish Realm. No previous search for historical earthquakes was ever performed there. The study involved a search for earthquake records, especially in the National Archives and the National Library of the Faroe Islands. The main conclusion was that the absence of reports of historical earthquakes was evidence that no events occurred there. No historical earthquakes are known for Greenland.

Wahlström (1990) presented a historical earthquake catalogue for Sweden covering the period between 1375 and 1890. The purpose was to investigate and quantify known historical earthquakes rather than perform a search for new data, although a few previously unknown events were found. The historical data were quantified on the macroseismic magnitude scale designed by Wahlström and Ahjos (1984), which has been calibrated against the instrumental local magnitude scale. Furthermore, Wahlström and Grünthal (1994) compiled and systemized earthquake data in the southern Baltic Sea area, which covered southern Sweden, Denmark and parts of northern Germany and Poland. Existing catalogues and special studies were made use of, but new evaluations of macroseismic parameters were also carried out. Intensities were given on the MM and MSK scales. Wahlström and Grünthal reinvestigated the macroseismic data of the 1930 earthquake, which is the largest known in the Southern Baltic Sea. It was felt in parts of Denmark, Southern Sweden and Northern Germany.

One conference to increase interest in historical earthquake catalogues was the 1988 meeting of former USSR scientists in Minsk, where seismotectonic zoning was planned for the Western USSR, including Estonia, Latvia, Lithuania, Belarus, Ukraine and Moldova. Avotina *et al.* (1988) published an earthquake catalogue for Belarus and the Baltic countries that covered the period between 1616 and 1987. It included the epicentral coordinates for 54 shocks, their intensities given on the MSK-64 scale and brief explanations of the macroseismic effects reported to accompany the tremors. Garetsky *et al.* (1989) and later Boborykin *et al.* (1995) provided improvements and additions to this catalogue, such as the determination of macroseismic magnitude and focal depth.

The seismicity of the SE Baltic became particularly interesting after the unexpected Osmussaar earthquake in the Gulf of Finland in 1976 (Klaamann, 1977; Slunga, 1979; Ananjin *et al.*, 1980; Kondorskaya *et al.*, 1988). Nikonov and Sildvee (1991) investigated historical earthquakes in Estonia and published a comprehensive earthquake catalogue including presumed seismotectonic settings for many events occurring from 1670 to 1976. The parametric catalogue was later enlarged and updated from 19 to 27 events occurring between 1602 and 1987, and a map of maximum observed shaking and seismogenic zones of the area was presented (Nikonov, 1992a). Another parametric catalogue for Estonia was published by Sildvee and Vaher (1995).

A reinvestigation of the 16 November 1931 earthquake in central Finland was carried out by Mäntyniemi (2004). Statistical methods such as correspondence analysis were used to reassess intensity on the EMS.

A more problematic data set on the earthquake of 18 August 1926 is currently being analyzed by Mäntyniemi and Nikonov. The felt observations were distributed between Finland and NW Russia in a very sparsely populated area.

Studies on historical earthquakes in the Russian part of Fennoscandia were conducted by Nikonov (1991, 1992b) and Assinovskaya and Nikonov (1998a,b). The most comprehensive of these was devoted to the felt effects of 37 earthquakes occurring in the 1900s and included known and previously unknown primary data, data analysis and intensity assessment as well as sources of information (Nikonov, 1991, 1992b). Later, also magnitude estimation was carried out (Assinovskaya and Nikonov, 2003).

When studying seismicity in NW Russia, a severe problem is the scarce information on historical events (Bungum and Lindholm, 1996). However, large industrial installations in Kola and NW Russia have been subjected to extensive seismic hazard studies as part of safety managements (Kuzmin, 1993). Assinovskaya and Nikonov (2003) have studied in detail certain large earthquakes there, one occurring in the White Sea area in 1627 and the others in the Lake Ladoga basin in 1861 and 1921. The epicentral intensity of the White Sea event may have been up to VIII degree, while the epicentral intensities of the others have been assessed at VII and VI, respectively**.**

An updated version of the FENCAT catalogue given by Ahjos and Uski (1992) served as the main input data for hazard computations in Fennoscandia during the Global Seismic Hazard Asssessment Programme (GSHAP) in the 1990s (Giardini and Basham, 1993; Grünthal *et al.*, 1999). This database is also frequently used for seismic zoning and national building codes in the respective Fennoscandian countries.

4. Today's situation and future plans

All historical events of magnitude 4 and above have been plotted in fig. 1a while, for comparison, the largest instrumental events have been plotted in fig. 1b. The seismicity features displayed in the two maps are similar except for offshore areas (Gregersen *et al.*, 1991). Differences can be noted especially in Southern-central Norway and Sweden, offshore Northern and Western Norway and in the West coast of Denmark. Some offshore events shown in Fig. 1a have obviously been located with the help of instrumental recordings and have been assigned magnitudes above 4.5.

Compilation of the historical part of the regional FENCAT catalogue (Ahjos and Uski, 1992) was based on existing literature and priority was given to the most recent solutions for macroseismic parameters. As Ambraseys (1985) stated, it is often problematic to reconcile earthquake listings given in various catalogues and therefore advocated the use of original sources. In other words, much work remains before we may have a uniform Northern Europe historical earthquake catalogue based on common analysis procedures.

Recent studies show that large historical events often warrant reinvestigation (*e.g.,* Husebye and Kebeasy, 2003; Kebeasy and Husebye, 2003), as depicted in the previous section. Another problem is that historical Fennoscandian earthquake data were more frequent during winter than summer, which has been attributed to frost shocks having been accepted as earthquakes (Renqvist, 1930; Wahlström, 1990). It was noted recently that the historical Norwegian events were more abundant in winter than in summer only in the 1880s, which was a very cold decade in Norway (Boulaenko and Husebye, personal communication). Winter events in the Latvian earthquake data are also more numerous than those of other seasons; Nikonov (1995) pointed out that this may be due to sharp changes in temperature.

4.1. *Future plans*

Seismic hazard analysis is critically dependent on the knowledge of historical seismicity. For real progress here we advocate cooperation in Northern Europe for realising research goals as tentatively listed below:

i) Refining the FENCAT catalogue:

– procedures for processing macroseismic data;

– reanalysis of the largest earthquakes;

– removal of spurious events such as explosions, etc.

ii) Establishing a macroseismic data base, comprising:

– an intensity map data base;

– intensity observation files for all major events;

– archives of written earthquake descriptions.

iii) Cooperative measures for establishing:

– a uniform magnitude-intensity scale for Northern Europe;

– intensity and acoustic (sound) decays with distance;

– a strategy for searching unknown earthquakes.

iv) Coordinating data centre bulletins in Northern Europe:

– clearly marked genuine earthquakes;

– report macroseismic material as well;

– coordinate efforts on earthquake location procedures.

In short, macroseismic observations may still be considered a research challenge and remain important for properly assessing past, present and future earthquake activity in Northern Europe.

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