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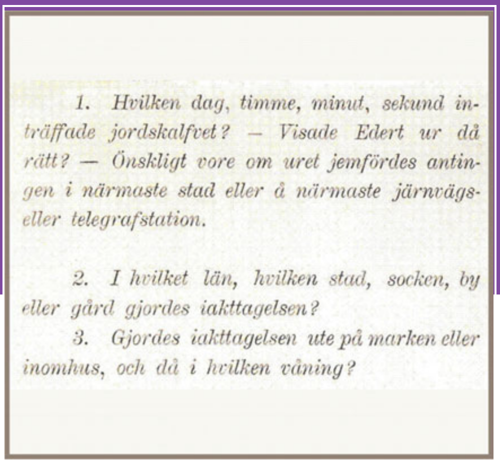

1. Hvilken dag, timme, minut, sekund inträffade jordskalfvet? — Visade Edert ur då rätt? — Önskligt vore om uret jemfördes antingen i närmaste stad eller å närmaste järnvägs- eller telegrafstation.

2. I hvilket län, hvilken stad, socken, by eller gård gjordes iakttagelsen?

3. Gjordes iakttagelsen ute på marken eller inomhus, och då i hvilken våning?

Macroseismology as a Component of Seismicity Assessments in an Intraplate Region: Studies of Northern Europe with Emphasis on Finland

Cover
A fragment of a Finnish circular used to collect felt observations of earthquakes in the late 1800s.

Report S - 47 of the Institute of Seismology

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Report S - 47

Macroseismology as a Component of Seismicity Assessments in an Intraplate Region: Studies of Northern Europe with Emphasis on Finland

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ACADEMIC DISSERTATION

To be presented, with the permission of the Faculty of Science of the University of Helsinki, for public examination in Auditorium XII, University Main Building, on 25 April 2008, at 12 o'clock noon.

Helsinki

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To my fellow colleagues Hjalmar Gylling and Henrik Renqvist

Abstract

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This work focuses on the role of macroseismology in the assessment of seismicity and probabilistic seismic hazard in Northern Europe. The main type of data under consideration is a set of macroseismic observations available for a given earthquake. The macroseismic questionnaires used to collect earthquake observations from local residents since the late 1800s constitute a special part of the seismological heritage in the region.

Information of the earthquakes felt on the coasts of the Gulf of Bothnia between 31 March and 2 April 1883 and on 28 July 1888 was retrieved from the contemporary Finnish and Swedish newspapers, while the earthquake of 4 November 1898 GMT is an example of an early systematic macroseismic survey in the region. A data set of more than 1200 macroseismic questionnaires is available for the earthquake in Central Finland on 16 November 1931. Basic macroseismic investigations including preparation of new intensity data point (IDP) maps were conducted for these earthquakes. Previously disregarded usable observations were found in the press. The improved collection of IDPs of the 1888 earthquake shows that this event was a rare occurrence in the area. In contrast to earlier notions it was felt on both sides of the Gulf of Bothnia.

The data on the earthquake of 4 November 1898 GMT were augmented with historical background information discovered in various archives and libraries. This earthquake was of some concern to the authorities, because extra fire inspections were conducted in three towns at least, i.e. Tornio, Haparanda and Piteå, located in the centre of the area of perceptibility. This event posed the indirect hazard of fire, although its magnitude around 4.6 was minor on the global scale. The distribution of slightly damaging intensities was larger than previously outlined. This may have resulted from the amplification of the ground shaking in the soft soil of the coast and river valleys where most of the population was found. The large data set of the 1931 earthquake provided an opportunity to apply statistical methods and assess methodologies that can be used when dealing with macroseismic intensity. It was evaluated using correspondence analysis. Different approaches such as gridding were tested to estimate the macroseismic field from the intensity values distributed irregularly in space. In general, the characteristics of intensity warrant careful consideration. A more pervasive perception of intensity as an ordinal quantity affected by uncertainties is advocated.

A parametric earthquake catalogue comprising entries from both the macroseismic and instrumental era was used for probabilistic seismic hazard assessment. The parametric-historic methodology was applied to estimate seismic *hazard at a given site in Finland and to prepare a seismic hazard map for Northern Europe. The interpretation of these results is an important issue, because the recurrence times of damaging earthquakes may well exceed thousands of years in an intraplate setting such as Northern Europe. This application may therefore be seen as an example of short-term hazard assessment.*

Keywords: macroseismology, macroseismic questionnaire, macroseismic intensity, intensity data point, probabilistic seismic hazard assessment, parametric-historic methodology; Northern Europe, intraplate regions

Contents

List of original articles

This thesis is based on the following original articles which are referred to in the text by their roman numerals:

I Mäntyniemi, P., Kijko, A., Retief, P., 2001. Parametric-historic procedure for seismic hazard assessment and its application to northern Europe, *Boll. Geof. Teor. Appl.* 42: 41-55.[1]

II Mäntyniemi, P., 2004. Pre-instrumental earthquakes in a low-seismicity region: A reinvestigation of the macroseismic data for the 16 November 1931 events in Central Finland using statistical analysis, *J. Seismology* 8: 71-90.[2]

III Mäntyniemi, P., 2005. A tale of two earthquakes in the Gulf of Bothnia, Northern Europe in the 1880s, *Geophysica* 41: 73-91.[3]

IV Mäntyniemi, P., 2007. Town of Tornio in November 1898: a rare survey of earthquake damage in Finland, *J. Seismology* 11: 177-185.[4]

V Mäntyniemi, P., 2008. The earthquake of 4 November 1898 in Northern Europe – new insights (*manuscript*).

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Figure 2 of Paper IV is reprinted with kind permission from the National Land Survey of Finland; base map data © National Land Survey of Finland, permission number 51/MML/08.

Paper I was prepared on the initiative of PM, who produced the results, plotted the figures and wrote the text that was actively commented by the co-authors.

Introduction

This work focuses on the role of macroseismology in the assessment of seismicity and probabilistic seismic hazard in Northern Europe, especially Finland, and on the macroseismic era between the 1880s and 1950s in particular. Northern Europe is defined as including the Nordic countries (Denmark, Finland, Norway, Sweden) and the Baltic countries (Estonia, Latvia, Lithuania) as well as the Russian enclave of Kaliningrad, the Kola Peninsula and Northwest Russia (Fig. 1). The term Fennoscandia refers to areas belonging to the Fennoscandian shield, namely Sweden, Finland, Russian Karelia and Northwest Russia.

The region of interest is located in a plate interior and is nearly devoid of earthquakes on global seismicity maps. On regional and local scales, however, ground shaking is felt from time to time and areas with enhanced seismic activity can be discerned. The existing instrumental earthquake catalogues are brief: short-period seismograph station installations commenced in the late 1950s, and the network remained sparse in some parts of the region until the 1980s. The need to expand the knowledge of seismicity in the region back in time using non-instrumental research methodologies is obvious. Several significant events are known to have occurred in the region in the past, which motivates investigations on pre-instrumental seismology.

In this study, emphasis is laid on macroseismology. The interest in macroseismic data is two-fold: to search for previously unknown macroseismic observations, i.e. written documentary records of past seismic events, and to pay due attention to methodologies suitable for these kinds of data. The search for primary earthquake documentation for the years prior to 1929 came to a halt in Finland when the descriptive earthquake catalogue of Renqvist (1930) was published, so the new findings included in the present work mark a revival in this field after a quiescence of several decades.

The main type of data under consideration is a set of macroseismic observations available for a given earthquake, collected either with the help of specific questionnaires or retrieved from other sources such as the press, or a combination of these. Understandably, the quantity and quality of the data increased when systematic macroseismic surveys were conducted. The collections of primary observations are essentially non-parametric in character. It is common practice to determine basic earthquake parameters such as the epicentre and magnitude on the basis of macroseismic data and add them to parametric catalogues. However, the entries may not be numerous in the non-instrumental era, and the threshold of completeness varies with time. When using macroseismic data, it is necessary to pay proper attention to such features. All observations are prone to errors, but the uncertainties associated with historical records may easily be of a different order of magnitude than those of high-quality instrumental data. The incompleteness and uncertainty of the data have to be taken into account. Moreover, the fundamental parameter of historical earthquake studies, macroseismic intensity, is an ordinal variable, which restricts the suite of methodologies allowed in the analyses.

Figure 1. *The geography and basic place names of the region of interest.*

Paper I deals with probabilistic seismic hazard assessment (PSHA) in Northern Europe. The parametric-historic methodology developed by Kijko and Graham (1998, 1999) is used to estimate seismic hazard at a given site in Finland and to prepare a seismic hazard map for Northern Europe. It is an interesting methodological contribution to PSHA. The main features are that the input data may consist of either historical or instrumental earthquake catalogues, or a combination of both and that magnitude errors are taken into account. No seismic zones and/or seismic sources are specified separately, but the level of seismicity is determined by the knowledge of the past activity.

Paper II investigates the largest earthquake known to have occurred in Central Finland. Stemming from the year 1931 it is a fairly recent event on the time scale of historical seismology but, nevertheless, has to be studied with the help of macroseismology. Almost 1200 macroseismic questionnaires were collected shortly after the earthquake. They were augmented with contemporary press reports in this study. The area of perceptibility is favourably located away from state borders and coastlines. Therefore, the data set offers an ideal opportunity to apply statistical methods. As preprocessing of the data, factor analysis was applied to the dichotomous classification items of intensity degrees to determine whether they can be represented on an underlying unidimensional scale. Tetrachoric correlations served as a starting point for factor analysis in the case of one factor. The asymptotic covariance matrix and the matrix of tetrachoric correlations were produced and the LISREL algorithm of Jöreskog and Sörbom (1989) was applied to analyse the data and compute some goodness-of-fit measures. Intensity was assessed using correspondence analysis. Different approaches such as gridding, Delauney triangulation and nearest-neighbour methods were used to estimate the macroseismic field from the intensity values distributed irregularly in space.

Paper III is a basic macroseismic analysis of two earthquakes that were felt along the shores of the Gulf of Bothnia in the 1880s. The data sets available for the earthquakes occurring between 31 March and 2 April 1883 and on 28 July 1888 were investigated in detail, and previously disregarded observations were retrieved from the contemporary Finnish and Swedish press. The new intensity data point (IDP) collections of the two main shocks were displayed on maps. The reassessment changed completely the area of perceptibility of the 1888 earthquake in particular: the other existing map prepared in the early 1900s outlined a mere strip along the coastline, while the improved set of IDPs is far more scattered and shows that this event was a rare occurrence in the central Gulf of Bothnia (defined to extend from latitude 62 to 64 °N). The earthquake of 28 July 1888 had also been doubly reported in the parametric earthquake catalogues for Northern Europe.

Paper IV focuses on the effects of the Fennoscandian earthquake of 4 November 1898 (GMT) on the town of Tornio located on the Finnish-Swedish border in Northern Finland. It constitutes a special case of macroseismic analysis in Finland, because damage resulting from the earthquake of macroseismic magnitude around 4.4 was reported in the town and the available data are quite plentiful in comparison with the conditions of Northern Europe on average. The useful reports extracted from contemporary Finnish and Swedish newspapers were augmented with documents discovered in the Tornio Town Archives. Also, a lot of background information about the town at the time of the earthquake was incorporated in the analysis. The intensity value assigned to Tornio is the first modern IDP for the earthquake in question.

Paper V continues the analysis of the earthquake of 4 November 1898. It provides complete lists of usable press reports and IDPs, totaling 74 localities in Northern Sweden and Finland. According to Paper IV, the area of the strongest ground-shaking defined by Moberg (1901) is not valid, so this contribution redetermines the epicentre and magnitude, using all available documents. The new epicentre is discussed in the light of the geophysical background information available for the area today. In addition, a discussion on the features of macroseismic intensity is included.

Scope of seismicity studies in plate interiors

The earthquakes of interest in this work are intraplate earthquakes: they occur far away from plate boundaries, within the plate interior. Although plate interiors constitute by far the largest part of the Earth's surface, their total seismic energy release only represents some 10% of the global value. Because of the slow rate of seismic activity and the ratio of large to small earthquakes, i.e. the *b*-value, few observations of strong earthquakes have accumulated in intraplate regions during the era of systematic monitoring. Studies of intraplate seismicity are thus characterised by inadequate information about the location and maximum size of earthquakes, which makes it difficult to construct reliable recurrence intervals. Besides long recurrence times, intraplate earthquakes are characterised by higher stress drops than seismic events at plate boundaries (Lay and Wallace, 1995). These two features may be connected: since faults fail frequently at plate boundaries, they appear weaker than those in plate interiors. One noteworthy aspect is that the attenuation of the ground motion as a function of the earthquake magnitude and distance is commonly held to be slower on average in intraplate than interplate regions. This is sometimes illustrated as maps of the areas affected by earthquakes of comparable magnitude in the two different seismo-tectonic settings. The repeat of known large historical intraplate earthquakes is therefore a matter of concern today.

Bungum and Fyen (1980) discerned three reasons for studying intraplate seismicity: i) it is a natural continuation of previous basic research on earthquakes occurring at plate boundaries and global tectonics; ii) knowledge of seismic risk is required for the construction of critical structures such as nuclear power plants, oil platforms and depositories for radioactive waste; and iii) destructive earthquakes have occurred within continental areas.

The input data required to control the earthquake recurrence at different time scales depends on the seismo-tectonic setting (Fig. 2, from Giardini, 1995). At a fast plate boundary, the duration of a characteristic seismic cycle is short, so the data accumulated during the instrumental era alone provide helpful information about the maximum size of earthquakes. In plate interior where the crustal deformation is extremely slow, the recurrence times of the largest earthquakes may exceed the time span of available data, even if different types of data (historical, palaeoseismic, geological) are combined. It is obvious from this that macroseismology alone is not sufficient to guarantee ultimate control of the largest earthquakes in Northern Europe; instead, the geologic and geomorphic expression of past earthquakes needs to be investigated in zones of slow continental deformation (e.g. Muir Wood, 1993). The benefit of macroseismology is that it augments and improves our knowledge of earthquake activity. For instance, Central Finland exhibits only infrequent, scattered microearthquakes according to the instrumental seismicity record. The contribution of macroseismology changes this notion completely, because the earthquake of 16 November 1931 was widely felt (Paper II) and clearly stands out from the other occurrences in the area. Similarly, in the discipline of PSHA, which aims at obtaining probabilities of the occurrence of seismic events of a specified size in the area of interest within a given time interval, studies based on the available macroseismic and instrumental observations such as Paper I do not provide any conclusive information of the repeat time of the largest magnitudes in an intraplate setting.

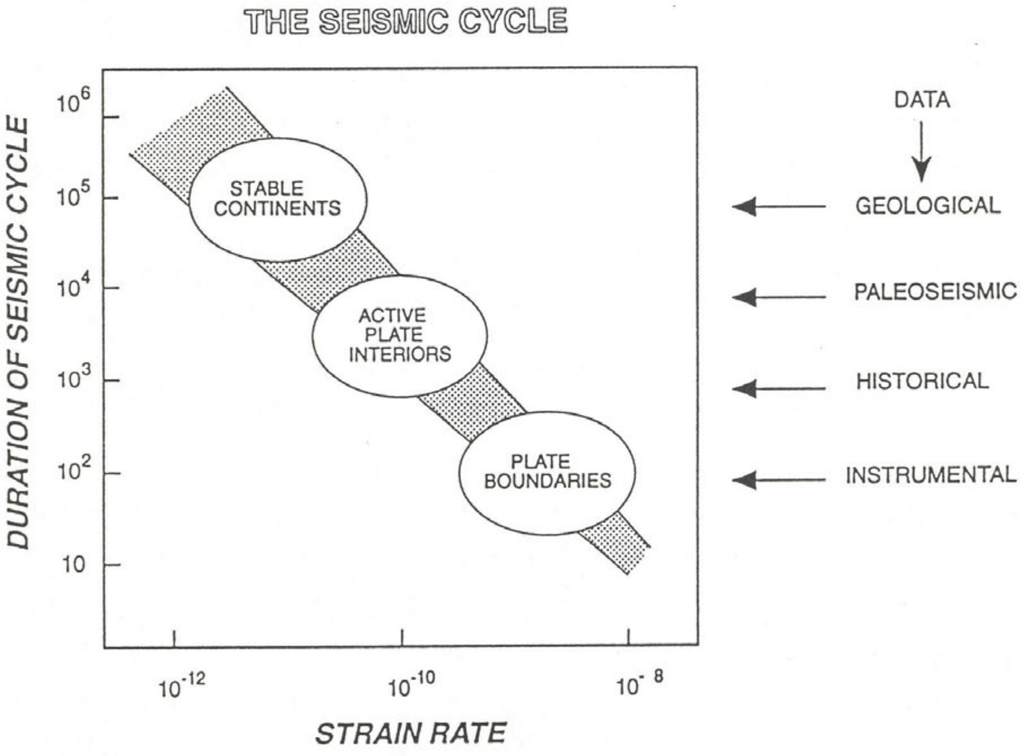

Figure 2. *Strain rate versus duration of characteristic seismic cycles for different seismo-tectonic provinces, and input data required to control the earthquake recurrence at different time scales (From Giardini, 1995).*

In practice, the assessment of seismic hazard involves some implicit time period of concern in the future. It naturally depends on the practical problem to be tackled: the lifetime of a nuclear power plant implies short-term hazard, while the construction of depositories for spent nuclear fuel is a problem for long-term hazard assessment. It can be reasoned on the basis of Figure 2 that the difference between the short-term and long-term hazard is largest in intraplate settings. This applies well to Finland, where the discipline of seismic hazard assessment has a very dual character. The short-time hazard analyses such as Paper I make use of the national or regional earthquake catalogue spanning four to six centuries, and deal with earthquakes of magnitude below 5 within the territory, while the long-term hazard is attributed to the glacio-rebound cycle. The traces left by large earthquakes in the past have been dated within a short time during and after the last deglaciation about 10 000 years BP. Kuivamäki et al. (1998) estimated the magnitudes of such palaeoearthquakes at the range of 5.5 – 7.0. This aspect is of relevance when planning disposal of nuclear waste (Saari, 1998). The probability of an earthquake of above magnitude 5 not related to the glacio-rebound cycle has not been subjected to consideration.

Probabilistic seismic hazard assessment

Much of the work expended in PSHA has been motivated by the needs of interplate regions where large earthquakes pose a high threat to life and infrastructure. Basically the same approaches are used in intraplate settings, even though the observed seismicity rates are different in these regions. A number of different seismic quantities such as the maximum expected macroseismic intensity, earthquake magnitude, peak ground acceleration (PGA) or peak ground velocity (PGV), or the duration of strong ground motion, can be used for the purpose of PSHA.

The practice of PSHA over the years has reflected different levels of understanding of seismic hazard, the amount of information available for the assessment and knowledge of the processes leading to earthquakes. Muir Wood (1993) discerned five methodological generations in the evolution of seismic hazard. The early attempts to map seismic hazard represented historical determinism, because they relied on the record of historical earthquakes in that the known sites of maximum intensity were regarded as the most hazardous. An uncertainty may have been added to the observed intensities to imply a more extreme hazard. The second generation is described as historical probabilism. It considers the duration of the available seismicity record to obtain probabilities for given time intervals. In the modified methodologies of this generation the hazard is estimated using some ground motion parameter derived from intensity, and the effect of distance is taken into account with the help of an attenuation relationship. Paper I falls into this category. Seismo-tectonic probabilism is the third generation and incorporates geological information such as the prehistoric record of palaeoseismic ground motion and neotectonic surface faulting. The different data sources are combined through a seismic source model. An example of the third generation seismic hazard for an intraplate region is the study by Main et al. (1999). They applied the Gutenberg-Richter frequency-magnitude distribution and the gamma distribution to seismic hazard in mainland United Kingdom and its immediate continental shelf, constrained by a combination of instrumental, historical and neotectonic data.

The fourth generation of seismic hazard according to Muir Wood (1993) is non-Poissonian probabilism. Time-dependent seismic hazard models have so far been developed and implemented in plate boundary regions such as California (WGCEP, 1995) and the North Anatolian fault zone in Turkey (Parsons et al., 2000). In the fifth phase knowledge of seismicity and impending earthquakes is available in such supreme abundance that seismic hazard assessment becomes earthquake prediction.

McGuire (1993) presented another classification of PSHA methodologies. The widely used Cornell (1968) approach represents deductive methodologies of PSHA. It involves defining (deducing) the seismic sources, seismicity parameters and the ground motion equation, and then using the consequent distributions to obtain the probability per unit time that a given ground motion value is exceeded. The non-parametric historic method (Veneziano et al., 1984) represents another main category of PSHA computations. The available earthquake catalogue is used to estimate the seismicity surrounding the site of interest and the rates at which different levels of ground motion are exceeded. Both the deductive and historic methods allow all available information on tectonics, seismicity and earthquake-related ground motions to be incorporated into the PSHA computations.

The PSHA methodology applied to Northern Europe in Paper I has been classified as parametric-historic, because it combines features of both the deductive and historic procedures. It is similar to the historic methods in that no interpretations of faults, seismic sources or seismicity parameters are used, but also parametric. The level of seismic hazard at a given site is essentially described by two parameters: the mean value of seismic activity rate λ and slope of seismic hazard curve $\gamma = b/a'$, where b is the parameter of the Gutenberg-Richter frequency-magnitude relation and a' is the coefficient related to earthquake magnitude in the ground motion attenuation relationship that includes what is known of the ground motion as a function of the earthquake magnitude and distance. Parameter λ refers to the mean activity rate of earthquakes that cause a ground motion value a at the given site exceeding the specified threshold value a_{min} of engineering interest. It is assumed that the occurrence of earthquakes producing ground motion parameter value a, where $a \geq a_{min}$, at the site, follows Poisson distribution with a mean seismic activity rate λ.

The parametric-historic approach has been described in detail in Kijko and Graham (1998, 1999). The first part of their work focuses on the development and presentation of statistical techniques that can be used for the evaluation of the maximum regional magnitude, m_{max}. The second part delineates the methodology for probabilistic seismic hazard assessment at a given site, which is of interest in Paper I. The map is prepared by applying the methodology repeatedly to grid points covering the area of interest.

The revival of non-instrumental seismology

The advent of seismological instrumentation around the world up to the 1970s meant that the interest in non-instrumental observations waned. This situation changed at the turn of the 1970s and 1980s, when seismic hazard assessments became mandatory in several countries because of the needs of modern societies. It was realised that comprehensive seismic records compiled on a multinational basis are essential for this purpose.

Since then a wealth of new studies has emerged, and new disciplines of non-instrumental seismology have been established. Archaeoseismology investigates the traces of past earthquakes in archaeological remains and strives towards a methodology of interpreting such evidence within a seismo-tectonic framework (Kovach, 2004; Galadini et al., 2006). Palaeoseismology inspects the geologic and geomorphic expression of past large-magnitude earthquakes ($M \geq 6.5$) and provides means to extend the historical seismicity record studied in macroseismology into prehistoric time (Pantosti and Yeats, 1993; McCalpin, 1996). Palaeo- and archaeoseismic investigations can reveal whether large historical earthquakes have been preceded by shocks of similar magnitude in a given seismic zone.

The palaeoseismic approach is of interest in Northern Fennoscandia, where several large-scale bedrock faults have been discovered and realised as evidence for large earthquakes (e.g., Lundqvist and Lagerbäck, 1976; Lagerbäck, 1979; Olesen, 1988). Since these faults post-date the last glaciation, they are attributed to the unloading of the Fennoscandian ice sheet, which would have changed the local stress regime. The investigations in the area include palaeoseismic trenching (Bäckblom and Stanfors, 1989; Dehls et al., 2000). Hutri (2007) investigated Holocene sediment faults in the Northern Baltic Sea near the Southwest coast of Finland. Their movement is suggested to have been caused by a single or several palaeoseismic events when the ice sheet was retreating from the site. Dating yielded an age estimate of 10650 to 10200 years BP to the event(s), which supports the notion that the main seismic activity occurred within a short time during and after the last deglaciation. No younger traces of seismic events were found.

Macroseismic intensity was the only means to quantify earthquakes until the introduction of instrumental magnitude in the 1930s, so the revival of macroseismology half a century later can be called a renaissance. Much effort has been devoted to developing methodologies suitable for the analysis of written documents testifying of past seismic activity. This involves strategies both for searching archives for unknown documentation and correct interpretation and analysis (Guidoboni and Stucchi, 1993; Guidoboni, 2000). Novel research has been carried out in the framework of multinational projects such as the Review of Historical Seismicity in Europe (RHISE) and Basic European Earthquake Catalogue and a Database for the evaluation of long term seismicity and seismic hazard (BEECD). They have resulted in numerous new studies on historical seismicity (see the respective websites given in the References).

An outcome of comprehensive and coordinated efforts among seismologists during a number of years is the European Macroseismic Scale (EMS; Grünthal, 1993, 1998). It is essentially an update of the MSK-64 intensity scale and draws from the vast experience obtained over the years of its use. The EMS provides detailed definitions of each intensity degree. The respective classification factors are divided into three groups according to the effect on people, objects and nature, and damage to buildings. The statistical nature of intensity is underlined. The EMS also includes classifications of damage to masonry buildings and those of reinforced concrete and a discussion on engineered structures.

Isoseismal maps are a traditional way to present the results of macroseismic investigations (e.g. Shebalin, 1974) and continue to be in use (e.g. Hough et al., 2000). The concept of an intensity data point (IDP) has been introduced more recently as a means to display the original data. An IDP contains at least the time of observation, location of a site and the respective intensity, and has been described as the elementary cell of a macroseismic archive (Stucchi et al., 2000). Each earthquake is constructed by IDPs having the same time.

A practical problem in historical seismology, both non-instrumental and seismometry, is how to archive observations and make them available to users. It has lately been subjected to considerable attention (e.g. http://storing.ingv.it/es_web/ - EuroSeismos). Several intensity databanks were released over the Internet in the late 1990s for various countries around the world (Rubbia, 2004). An online data bank is a convenient means to store, display and disseminate macroseismic data. The ultimate purpose is to make use of macroseismic information to a larger extent than parametric earthquake catalogues allow (Postpischl et al., 1991). This may be of value in seismic hazard assessments (Mucciarelli et al., 2000).

Macroseismology in Northern Europe

The rebirth of macroseismology described above extended to Northern Europe. Exploration of the rich North Sea oil and gas fields motivated seismic hazard assessment in this part of the region, and a multinational programme of historical earthquake information retrieval from libraries and record offices in Norway, Denmark, Sweden and Britain was launched. The outcome included several new publications (e.g. Ambraseys, 1985; Bungum et al., 1986; Muir Wood et al., 1988). The construction of nuclear power plants and plans for radioactive waste disposal in the bedrock of Sweden, Finland and Russia increased the need for seismic hazard assessments in these countries.

Much effort was expended on quantification and listing of historical data. Avotina et al. (1988) published an earthquake catalogue for Belarus and the Baltic countries between the years 1616 and 1987. Wahlström (1990) presented a historical earthquake catalogue for Sweden covering the period from 1375 to 1890. The seismicity of the Baltic area arrested scientists' attention after the surprising Osmussaar earthquake in the Gulf of Finland on 25 October 1976. Nikonov and

Sildvee (1991) investigated historical earthquakes in Estonia and published a parametric catalogue for many events occurring between 1670 and 1976. Another parametric catalogue for Estonia was published by Sildvee and Vaher (1995). Wahlström and Grünthal (1994) compiled and systemised earthquake data in the southern Baltic Sea area, which covered southern Sweden, Denmark and parts of northern Germany and Poland. The study included new evaluations of macroseismic parameters. The work included a reinvestigation of the macroseismic data of the 1930 earthquake, which is the largest known in the southern Baltic Sea. The area of perceptibility extended to Denmark, Southern Sweden and Northern Germany.

More recent studies focus on individual historical earthquakes in the region. Kebeasy and Husebye (2003) reinvestigated the Kattegat, Denmark earthquake of 1759. It is a unique case of the early use of macroseismic questionnaires in Northern Europe: Bishop C. Horrebow wrote to the vicars in his diocese in Zealand, asking how the earthquake was felt in different localities. The original material has been published together with newspaper reports from adjacent Norway, Sweden and Northern Germany (Bondesen and Wohlert, 1997). Similarly, Paper II is a reassessment of the earthquake of 1931 in Central Finland, and Papers IV and V reanalyse the earthquake of 1898 in Northern Fennoscandia. There are no separate earlier studies of the seismic events dealt with in Paper III.

The Lurøy, Northern Norway earthquake of 31 August 1819 has been subjected to several investigations (Ambraseys, 1985; Muir Wood and Woo, 1987; Muir Wood, 1989), and the magnitude values have been estimated in the range M_S = 5.8-6.2. Having long been rated as the largest observed earthquake in the region it has a direct bearing to PSHA studies such as Paper I. The study of Husebye and Kebeasy (2004) resulted in a significantly reduced value of M_S = 5.1. The debate following the readjustment of the magnitude was hectic, and no consensus about the matter emerged from it (Wahlström, 2004; Husebye and Kebeasy, 2005; Bungum and Olesen, 2005; Husebye, 2005).

The earthquakes of 21 September 2004 in the Russian enclave of Kaliningrad appeared in an area where little information is available about past earthquake activity and which has therefore been mapped as being of very low seismic hazard (e.g. Grünthal and the GSHAP Region 3 Working Group, 1999). They will likely be followed by reinvestigations of the historical seismicity record in the district.

Macroseismic observations and IDPs

The primary macroseismic documentation included in Papers III to V resulted from the first systematic search for historical Finnish earthquake data since the work of Renqvist (1930). The contemporary press was also thoroughly scanned in Paper II. Paper III revealed typical mistakes of macroseismic analyses such as a double reporting of the earthquake of 28 July 1888 in existing catalogues due to an erroneous date. Previously disregarded data points of the 1883 and 1888 events were also discovered. Papers IV and V constitute the first modern analysis of the

Fennoscandian earthquake of 4 November 1898 (GMT). They are based on first-hand macroseismic data supplemented by plenty of historical and geophysical background information. In addition, Mäntyniemi (2004) reported seven small Finnish earthquakes that occurred in the late 1800s and were missed in the earlier earthquake compilations of the area.

These studies show that there is some scope to improve the collections of primary observations of past earthquakes in Fennoscandia: there has clearly been negligence of the press as a potential source of earthquake reports. Early investigators such as Svedmark (1889a,b) and Moberg (1901) had access to the largest national newspapers, but many local titles from the areas adjacent to the epicentres remained unnoticed. Later, when microfilms of newspapers became available, no one was paying attention to historical Fennoscandian earthquakes. A renewed interest in the press as a source of macroseismic information displayed by seismologists followed later with the digital newspaper archives that have become available in many places. However, the present investigations concern the last quarter of the 1800s and more recent times when many newspapers existed and the use of macroseismic questionnaires had been initiated. It is not realistic to expect that large amounts of previously unknown macroseismic materials from earlier times can still be found.

The determination of IDPs by definition includes intensity assessment on the basis of the observations available for a given place. A typical problem associated with macroseismic analysis in Northern Europe is that the amount of written evidence on past seismic activity is limited, so critical text analysis including cross-examination of diverse documents and disregarding unreliable records is seldom possible. In other words, the epistemic uncertainty of intensity remains large (Paper V). The involvement of historians in the studies on earthquakes that occurred in earlier centuries could provide some help. Also, even if an archival search does not significantly improve the quantity of the data, a reanalysis of primary data is meaningful if the existing studies were prepared prior to the development of rigorous macroseismic methodologies. An example is the Fennoscandian earthquake of 1898 previously studied by Moberg (1901). The existing information on many interesting earthquakes in Northern Europe can still be found only in printed national publications, often in different languages and based on different intensity scales and data analysis practices. New studies are thus feasible for carefully selected events.

A practical issue is that Northern Europe still lacks an intensity databank on the Internet. It is strongly advocated that such a facility is prepared also for this region. A databank would be helpful in displaying available IDP collections and other macroseismic materials especially when debating related problems. An illustrative aspect is the possible damage, or harm, resulting from earthquakes. Parametric catalogues may be browsed at the maximum intensity, but will not reveal other information about the type of failures or damaging intensities. An IDP map provides a more complete picture about the distribution of the intensity as exemplified by the studies of the 1898 earthquake in Northern Fennoscandia (Papers IV and V).

Damage resulting from earthquakes

Descriptions of historical earthquakes in Northern Europe occasionally comprise casual references to damage such as cracks in the masonry components of dwellings, or chimney stacks being thrown down (e.g., Ambraseys, 1985). However, no detailed case study of any pre-instrumental earthquake-induced damage in Northern Europe existed prior to Paper IV. Although the intensity I=6 (EMS) assigned to Tornio, Finland in this work was not exceptionally high, the value, standing by definition for slightly damaging, was based on much more information than in the conditions of Finland on average. The investigation showed that the Fennoscandian earthquake of 4 November 1898 (GMT) was of some concern to the authorities: besides Tornio, extra fire inspections were carried out in the Swedish towns of Haparanda and Piteå to survey the failures sustained by the masonry stone components of timber houses. The information on the damage may not be complete, because no field work was conducted in the affected area; at least the spatial distribution of slightly damaging intensities was larger than previously outlined. The 1898 event stands out as a noteworthy example of earthquake-induced harm in the region: many residents had to have their heating units repaired at their own cost. The indirect hazard of fire posed by relatively small-magnitude earthquakes to timber houses may have been realised after the previous large earthquake in the Northern Gulf of Bothnia, i.e. that of 23 June 1882 (Paper V).

The relative abundance of macroseismic data available for the 1898 earthquake can be attributed to its being rather recent on the time scale of historical seismology. The absence of reports of earthquake-related problems in Northern Europe throughout the centuries tells us not only about the rarity of strong ground motion in an intraplate setting, but might also rarely tell us about the absence of reports. For instance, Ambraseys (1985, p. 368) mentioned that authorities collected an extra tax in Western Scandinavia in the 1630s to defray the repairs needed after damage resulting from earthquake activity. This incident could easily have been consigned to oblivion, because the sole evidence of it is a letter. Similar episodes may have occurred in Northern Europe at other times, although no documents are known to exist.

Earthquake-related problems in Northern Europe arose more recently in Kaliningrad on 21 September 2004. The two largest earthquakes there have been assigned magnitudes M_w5.2 and 5.0 (Gregersen et al., 2007). Moderate damage resulted from the events in the city of Kaliningrad, where one person died of a heart attack, 20 people were seriously wounded by falling objects and about 2100 buildings sustained damage amounting to more than 5 Million USD. Minor damage was sustained in Northern Poland and in Southern and Western Lithuania. The amount of damage can be attributed to the proximity of the epicentres to a large modern city. Thus, the Kaliningrad earthquakes of 2004 serve as a useful reminder of the fact that modern earthquakes may be more damaging than those in the past, even if their magnitudes do not exceed the largest observed, owing to the increase of population and building stock. Another example from intraplate Europe is the

Folkestone (Kent) earthquake in the United Kingdom on 28 April 2007. The magnitude measured only at M_L 4.2, but the maximum intensity was 7 (EMS), a value that is described as damaging.

The study by Wesson (2004) is an interesting loss assessment that uses information of a small-magnitude historical earthquake, the Colchester (Essex) earthquake in the United Kingdom on 22 April 1884. Its magnitude has been estimated at M_L 4.7 (Musson, 1994), but it is among the most damaging in the national seismic record of the country. Using tools based on Geographic Information Systems and many sources of information Weston (2004) showed that a repeat of the Colchester earthquake would be financially significant to the building stock and infrastructure existing in the 1884 area of perceptibility today. This is one way of reminding that there are more elements at risk today than in earlier times. The concern shared by the seismological communities worldwide is that the losses resulting from earthquakes may be on the increase.

Conclusions

The macroseismic studies included in the present work belong to the second era of macroseismology that commenced in the late 1970s and early 1980s. It is marked by an urge to return to the primary observations instead of repeating earlier interpretations of individual earthquakes. In Northern Europe, much of the effort expended on historical earthquakes has resulted in parametric catalogues covering separate countries or subregions, while the related macroseismic information remains insufficiently known and inadequately available. The comprehensive collections of IDPs and the related documentation given in this work therefore present new contributions to the study of historical earthquakes in Northern Europe. The new findings given mark a revival in the search for primary earthquake observations in Finland after a quiescence of several decades.

Besides previously unknown IDPs, reinvestigations that include a thorough search for original macroseismic reports bring to light facts that were not taken note of earlier or have been consigned to oblivion. An example is the indirect threat of fire that relatively small-magnitude may pose to timber dwellings (Papers IV and V). Macroseismic reassessments typically reveal mistakes in previous studies such as erroneous dates (Paper III). Another benefit of reinvestigations is that the phenomena related to earthquakes may be interpreted against the improved and more comprehensive understanding that exists today. An example is earthquake-related lights, which were mistaken for meteorites in a previous study, because the phenomenon had not yet become established at that time (Paper II).

Macroseismic studies are special in the field of natural sciences, because the fundamental parameter, intensity, is an ordinal variable. This calls for appropriate methods also in the case of a large data set associated with recent earthquakes (Paper II). A more pervasive understanding of the characteristics of intensity is advocated (Paper V).

It is recommended that selected historical earthquakes in the region of interest should be subjected to similar reassessments. A practical issue is that Northern Europe still lacks a digital intensity database which would be helpful in storing, displaying and disseminating macroseismic data.

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