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An M_w based earthquake catalogue for central, northern and northwestern Europe using a hierarchy of magnitude conversions

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Abstract

Data from 25 local catalogues and 30 special studies of earthquakes in central, northern and northwestern Europe have been incorporated into a Databank. The data processing includes discriminating event types, eliminating fake events and duplets and converting different magnitudes and intensities to M_w if this is not given by the original source. The magnitude conversion is a key task of the study and implies establishment of regression equations where no local relations exist. The Catalogue contains tectonic events from the Databank within the area 44°N-72°N, 25°W-32°E and the time period 1300-1993. The lower magnitude level for the Catalogue entries is set at M_w = 3.50. The area covered by the different catalogues are associated with polygons. Within each polygon only data from one or a small number of the local catalogues, supplemented by data from special studies, enter the Catalogue. If there are two or more such catalogues or studies providing a solution for an event, a priority algorithm selects one entry for the Catalogue. Then M_w is calculated from one of the magnitude types, or from macroseismic data, given by the selected entry according to another priority scheme. The origin time, location, M_w magnitude and reference are specified for each entry of the Catalogue. So is the epicentral intensity, I_0, if provided by the original source. Following these criteria, a total of about 5,000 earthquakes constitute the Catalogue. Although originally derived for the purpose of seismic hazard calculation within GSHAP, the Catalogue provides a data base for many types of seismicity and seismic hazard studies.

Introduction

The basis for numerous kinds of studies in seismology are reliable and homogeneous seismicity data. Historical and instrumental data are available for separate countries or areas in Europe. However, homogeneous catalogues with high-quality data covering large territories and long historical time spans have been lacking. The catalogues from the international seismological data centres, such as the International Seismological Centre (ISC), U.S. National Earthquake Information Service (NEIS) / Center (NEIC), Bureau Central International Seismologique (BCIS) and European Mediterranean Seismological Centre (EMSC), cover short time periods and use high magnitude thresholds with respect to the needs of long term seismicity studies and seismic hazard assessment in areas of relatively low seismic activity. The same is the case with the catalogue for European and Mediterranean earthquakes by Kárník (1996), where the general limits are intensity 7 for the period 1800-1900, M_S = 4.5 for 1901-1950 and

Table 1a. Areas, local catalogues and associated polygons (cf. Figure 2)

Country/area	Main local catalogue /year of last entry in the Databank, if before 1993/	Catalogue notation	Polygons associated with the local catalogue (with notation)
Austria	Lenhardt (1996)	**ZAMG**	Austria (A) adjacent parts of Germany (D) Switzerland (CH)
Belgium	Verbeiren et al. (1995)	**ORB**	Belgium and Luxemburg (BL) Germany, United Kingdom, Ireland and adjacent waters (UK), France (F)
Belorussia	Boborikin et al. (1993) /1988/	**Bob**	Belorussia (BY), Fennoscandia, Balticum, Kola Peninsula and adjacent waters (FEN)
Croatia	Živčić (1994) /1981/	**ZivC**	Croatia (CRO) Slovenia (SLO), Bosnia and Serbia (BS)
Estonia	Nikonov (1992) /1987/	**Nik**	Fennoscandia etc.
Fennoscandia	Ahjos and Uski (1992) /1991/	**FEN**	Fennoscandia etc. North Atlantic Ocean and Iceland (AOI)
France	Lambert and Levret-Albaret (1996)	**LLA**	France United Kingdom etc.
Germany	Leydecker (1986) /1981/, (1996)	**Ley, Ley96**[1]	Germany outside 49.6°N–54.8°N, 9.5°E–15.5°E adjacent parts of Switzerland, Austria and France
Germany, central part	Grünthal (1988) /1984/, (1991) /1991/	**Gru, Gru91**	catalogued area 49.6°N–54.8°N, 9.5°E–15.5°E, i.e., including parts of Germany, the Czech Republic (CZ) and Poland (PL)
Hungary	Zsíros et al. (1990) /1986/, Zsíros (1994)	**Zsi, Zsi94**	Hungary (H) The Czech Republic, Poland, Ukraine (UA), Bosnia and Serbia
Iceland	Halldorsson (1997) /1990/	**IMO**	North Atlantic Ocean and Iceland
Italy	Camassi and Stucchi (1996) /1980/	**NT4.1**	Italy (I), France
The Netherlands	Houtgast (1995) /1992/	**Hou**	The Netherlands (NL)
North Atlantic Ocean (selection from world-wide data base)	Global Hypocenter Data Base, CD version 2.0 (1996) /1990/	**NEIC**	North Atlantic Ocean and Iceland
Poland	Pagaczewski (1972) /1966/	**Pag**	Poland The Czech Republic
Romania	Oncescu et al. (1999)	**Onc**	Romania (RO) Ukraine, Bosnia and Serbia, Moldavia (MD)
Slovakia	Labak (1998)	**Lab**	Slovakia (SK) The Czech Republic, Poland
Slovenia	Živčić (1993) /1981/	**ZivS**	Slovenia Croatia
Southern Baltic Sea	Wahlström and Grünthal (1994) /1984/	**WG**	Fennoscandia etc.
Switzerland	Mayer-Rosa and Baer (1992) /1992/	**SED**	Switzerland adjacent parts of Germany, Austria, France
United Kingdom	Musson (1994)	**Mus**	United Kingdom etc. Belgium and Luxemburg
The former USSR	Kondorskaya and Shebalin (1982) /1974/	**KSh**	Ukraine, Moldavia

[1] Before 1982 **Ley96** is given when the corresponding **Ley** entry is revised.

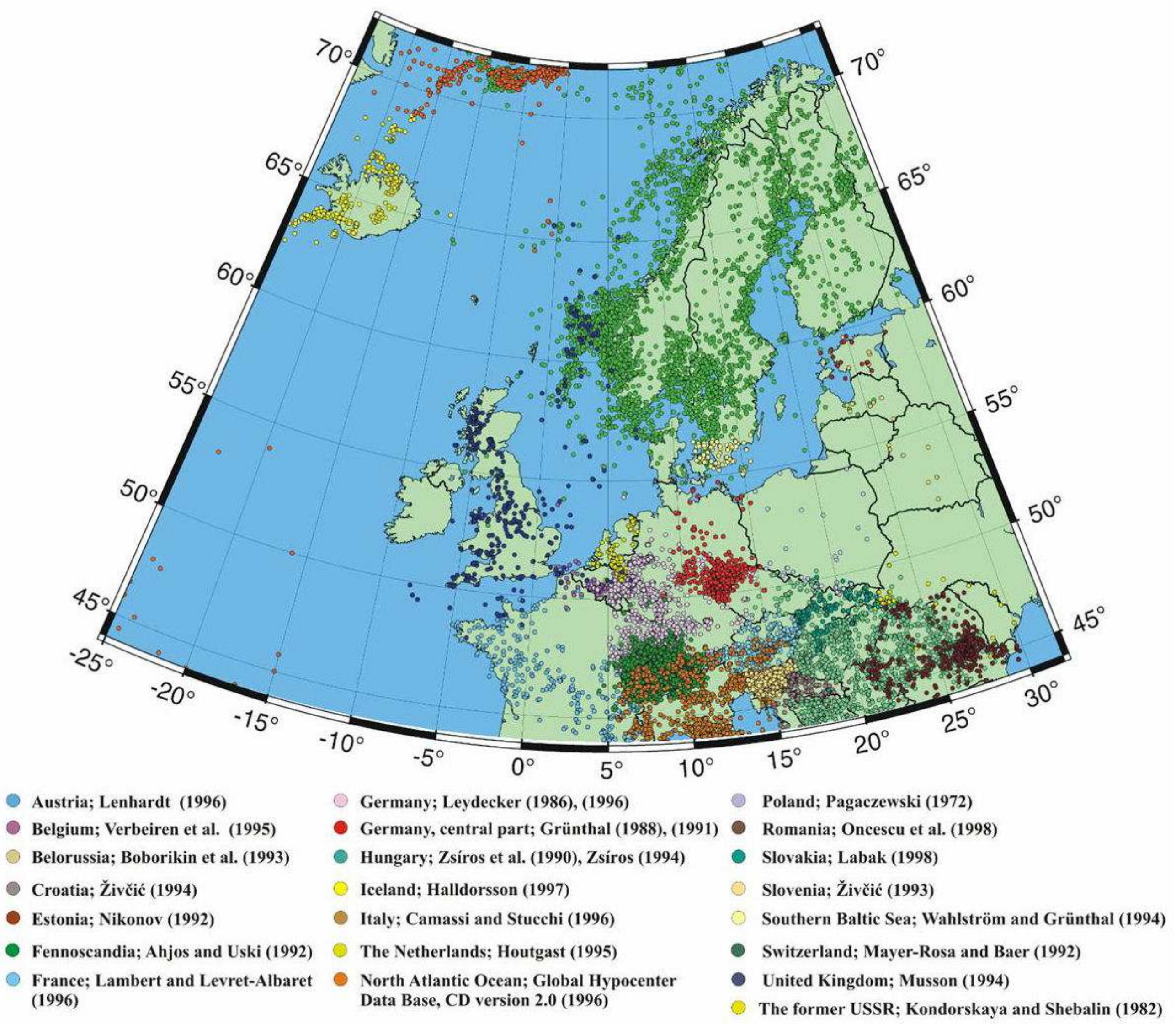

Figure 1. Original epicentres from the 25 local catalogues used in this study. There are about 37,000 points plotted in the selected area, but one event can be represented by more than one point (i.e., be listed by more than one catalogue). No discrimination has been been done as to event type or size.

M_S = 3.8 for 1951-1990, with few, scattered events below the thresholds. The restrictions make the use of this catalogue north of the Alps insufficient. The different national catalogues together contain much more information and are in many cases remarkably complete back to historical times.

The present Catalogue covers central, northern and northwestern Europe, more precisely the area 44°N-72°N and 25°W-32°E°. This corresponds to the GSHAP Region 3 defined within the Global Seismic Hazard Assessment Program (GSHAP - *Giardini and Basham*, 1993; *Giardini*, 1999), where certain institutions were co-ordinators to specify and obtain seismic hazard maps for various regions. A requirement for GSHAP was to derive such maps from homogeneously compiled data. The GeoForschungsZentrum Potsdam was responsible for GSHAP Region 3 (*Grünthal et al.*, 1999a) and the purpose of the current paper is to present a uniform earthquake catalogue for this region and describe the details of its contents and how it was developed. The work implied a major challenge due to the large number of national and regional catalogues and their different types of data. A major task was to convert the occurring size measures, i.e., different magnitudes and intensi-

Table 1b. Special studies

Special study	Catalogue notation
Ahorner, L., pers. communication	*Aho*
Alexandre (1994)	*Alx94*
Ahorner and Pelzing (1983)	*AP83*
Arvidsson et al. (1991)	*Arv91*
Arvidsson et al. (1992)	*AWK92*
Bonjer et al. (1990)	*BFA90*
Bonamassa et al. (1984)	*Bon84*
Brüstle (1985)	*Bru85*
Bachmann and Schmedes (1993)	*BS93*
Camelbeeck et al. (1994)	*Cam94*
Console and Rovelli (1985)	*CR85*
Fischer and Grünthal (1996)	*FG96*
Fischer et al. (2001)	*FGS01*
Grosser et al. (1986)	*GBK86*
Gutdeutsch et al. (1987)	*Gdt87*
Grünthal and Fischer (1998)	*GF98*
Grünthal and Fischer (1999)	*GF99*
Grünthal and Fischer (2001)	*GF01*
Grünthal and Fischer (2002)	*GF02*
Grünthal et al. (1999b)	*GFV99*
Grässl et al. (1984)	*GGG84*
Gutdeutsch et al. (1999)	*GHK99*
Grünthal and Meier (1995)	*GM95*
Grünthal et al. (1998)	*GML98*
Grünthal, G., renewed analysis	*GruRA*
Grünthal (1988)	*Gru88*
Grünthal (1989)	*Gru89*
Grünthal and Schwarz (2001)	*GS01*
Haessler et al. (1980)	*Hae80*
Hammerl and Lenhardt (1997); Lenhardt, W., pers. communication	*HL97*
Kunze (1986)	*Kun86*
Langer (1986)	*Lan86*
Lenhardt, W., pers. communication	*Len*
Leydecker, G., pers. communication	*LeyP*
Meidow (1995)	*Mei95*
Meidow (2001)	*Mei01*
Meier and Grünthal (1992)	*MG92*
Neunhöfer and Grünthal (1995)	*NG95*
Oncescu et al. (1994)	*OCM94*
Prinz et al. (1994)	*PHW94*
Schneider, G., pers. communication	*Sch*
Scherbaum and Stoll (1983)	*SS83*
Strauch (1989)	*Str89*
Vogt and Grünthal (1994)	*VG94*
Vogt (1984)	*Vog84*
Vogt (1991)	*Vog91*
Vogt (1993a)	*Vog93a*
Vogt (1993b)	*Vog93b*

ty, to one concept. M_w was chosen for reasons explained below.

The Catalogue contains tectonic earthquakes with $M_w > 3.50$ in the years 1300–1993 in the area specified above. The starting year 1300 is chosen because in many parts of the study area the highest magnitude classes reach a certain degree of completeness since that time. 1993 is the last year of data in about half of the domestic catalogues provided for the project.

Some 30 countries or parts of them belong to the selected region and difficulties in preparing a unified catalogue arise already in accessing data from several of these catalogues (see below). Other difficulties to overcome are due to the different structures of the various catalogues, e.g., earthquake strength parameters and error measures, and the identification of duplications of events appearing in more than one catalogue, often with slightly different parameters.

All original data from the different sources are incorporated into a Databank, including not only tectonic earthquakes but also rockbursts, explosions and suspected non-seismic events of different kinds. The entries from the many sources are given a uniform form in the Databank, which is passed on to the Catalogue. The Catalogue is an excerpt from the Databank giving a selected set of parameters for tectonic events, with improvements and supplements made in different respects (see below). The parameters are: Origin time, location, M_w magnitude, epicentral intensity (if given) and a reference. These are the data needed to perform seismic hazard studies, a main purpose of the Catalogue, and various types of seismicity studies.

The general limited access to detailed macroseismic information for historical earthquakes prevents the application of modern macroseismic methods to determine M_w (see below). Other restrictions are caused by the inaccessibility of later possible improvements of national catalogues and of special studies on new interpretations of historical earthquakes. It is beyond the scope of our analysis to penetrate such data in detail in order to upgrade the Catalogue.

Seismicity data sources for the catalogue

Most European countries have advanced and elaborated local catalogues starting in the late 1970s and early 1980s connected with the advent of appropriate computer techniques. They are supplied as printed earthquake lists and/or computer files. At the start of the GSHAP pro-

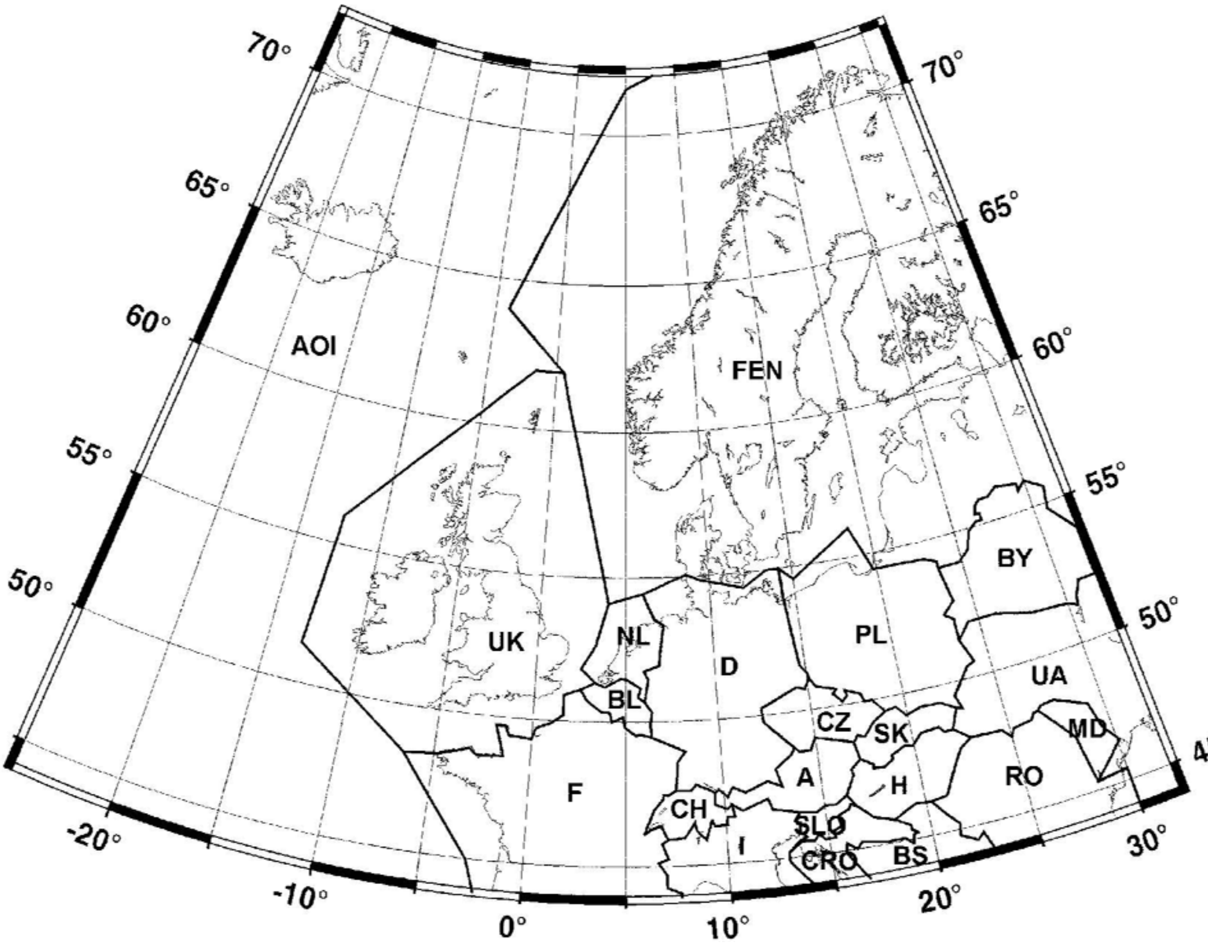

Figure 2. The polygons.

ject, many catalogues were made available to us only for this study, i.e., for the seismic hazard assessment, but they have later become fully accessible. In a few cases, the data remain classified and cannot be published in the Catalogue. In these exceptional cases, entries from other catalogues covering the same area are used and the total loss of data is minor. The 25 local catalogues contributing data to the Catalogue are listed in Table 1a. Epicentres of events from the catalogues are plotted in Figure 1. In the course of the GSHAP project, upgraded data from several of them were submitted and incorporated in the Databank. Even so, about half of the local catalogues terminate before 1993 (see Table 1a), implying a slight temporal inconsistency of different geographical parts of the Catalogue. However, this can be considered (or would else be insignificant) for hazard calculations.

The Italian catalogue (*Camassi and Stucchi*, 1996) is special in that dependent earthquakes (in time and space) are excluded. Therefore, fore- and aftershocks in Italy are not included in the Catalogue.

Besides local catalogues, 30 special studies contribute seismicity data to the Catalogue. These studies, the majority of which apply to events in Germany, yield new information on source parameters compared to the local catalogues. Many more special studies contribute data to the Databank. Future updates of the Databank should include not only the prolongation in time of the local catalogues but also information from further special studies. Table 1b lists special studies used, including the 30 contributing data to the Catalogue, those identifying fake events and those from which data for some of the regressions are taken (see below).

Table 2. Polygons and the hierarchy of local catalogues to which they are associated

Polygon	Country/area	Original sources
A	Austria	**ZAMG**
AOI	North Atlantic Ocean and Iceland	**IMO ⇒ NEIC ⇒ FEN**
BL	Belgium and Luxemburg	**ORB ⇒ Mus**
BS	Bosnia and Serbia	**ZivC ⇒ Onc ⇒ Zsi, Zsi94**
BY	Belorussia	**Bob**
CH	Switzerland	**SED**
CRO	Croatia	**ZivC ⇒ ZivS**
CZ	Czech Republic	**Lab ⇒ Gru, Gru91 ⇒ Zsi, Zsi94 ⇒ Pag**
D	Germany	**(Ley96 ⇒ Ley, Gru, Gru91 ⇒ ORB**
F	France	**LLA ⇒ SED ⇒ Ley96 ⇒ Ley ⇒ ORB ⇒ NT4.1 ⇒ Mus**
FEN	Fennoscandia, Balticum, Kola Peninsula and adjacent waters	**FEN ⇒ Nik ⇒ Bobs WG**
H	Hungary	**Zsi, Zsi94**
I	Italy	**NT4.1**
MD	Moldavia	**Onc ⇒ KSh**
NL	The Netherlands	**Hou, Hou01**
PL	Poland	**Pag ⇒ Gru, Gru91 ⇒ Lab ⇒ Zsi, Zsi94**
RO	Romania	**Onc**
SK	Slovakia	**Lab**
SLO	Slovenia	**ZivS ⇒ ZivC**
UA	Ukraine	**KSh ⇒ Zsi, Zsi94 ⇒ Onc**
UK	United Kingdom, Ireland and adjacent waters	**Mus ⇒ LLA ⇒ ORB**

Falling order in the hierarchy is indicated with ‘-’ and similar order with ‘,’.

Areal data selection

The investigated area is subdivided into 21 polygons, geographical regions in general following national borders (Table 2; Figure 2). One or a few local catalogues are associated with a given polygon, i.e., only entries in the Databank with certain local catalogue – polygon combinations, specified in Tables 1a and 2, qualify for the Catalogue. If more than one local catalogue contributes entries to the Databank for an earthquake, the priority scheme in Table 2 decides which one should be included in the Catalogue. Sometimes, this selection can be complicated - see below. Special studies are usually given higher priority than local catalogues. If only non-associated original sources list an earthquake, e.g., an event in the Italian polygon (I) is given only in catalogues (one or more) other than the Italian, then this event does not at all enter the Catalogue.

In the border regions of the polygons of Germany, Austria and Switzerland - the so-called D-A-CH countries - the priority schedule is not strictly followed. Here, entries from the catalogues of *Leydecker* (1986, 1996), *Lenhardt* (1996) and *Mayer-Rosa and Baer* (1992) were selected for the Catalogue irrespective of which polygon they are located in. D-A-CH was a test area introduced in the GSHAP study (*Grünthal et al.*, 1998).

The catalogue for France (*Lambert and Levret-Albaret*, 1996) lists only earthquakes with well constrained solutions. This makes it rather incomplete compared to the catalogues from the neighbouring countries and since these have some overlap in France they are also associated with the French polygon, in the order given in Table 2. The incompleteness of the French catalogue is the reason why the British catalogue of *Musson* (1994) is preferred for the English Channel. The British polygon is thus extended to cover the area of the whole Channel (see Figure 2). However, the French and the Belgian (*Verbeiren et al.*, 1995) catalogues remain as associated references of lower priority for the British polygon (see Table 2) and are used for a few events for which the British cata-

Table 3. Revealed fake events according to special studies

Time of event					Special study	Event classification
year	mo	day	h	min		
1323					GruRA	mixture with other event
1346					GruRA	mixture with other event
1348					GML98	mixture with other event
1410	08	23	22		GM95	wrong time, place and size
1412	11	28			GM95	storm
1445	02	15			GFV99	non-seismic collapse of houses
1471	05				GF01	non-seismic collapse of houses
1558	05	17			FG96	storm
1591					GF01	mixture with other event
1593	02	06			GF01	storm
1595	06				GF99	wrong time & place
1670	04	12	02	30	GF01	non-seismic collapse of houses
1690	11	24	15	15	GF01	mixture with other event
1693	12	26	13		Gru88	mixture with other event
1755	12	09	09	30	GF01	mixture with other event
1789	05	17			GruRA	mixture with other event
1822	02	07	23		BS93	hoax
1838	03	16			FG96	hoax
1871	02	16			GHK99	mixture with other event
1876	10	31	11	50	GruRA	hoax
1904	02	11	20	30	LeyP	hoax

logue has no data.

In an analogous way to the French data, several catalogues are associated and ranked for Poland and the Czech Republic, since modern domestic earthquake lists for these countries could not be used in the present study.

Data cleaning

The Catalogue contains parameter values from the original catalogues to the greatest possible extent. Only events with a location and a measure of the strength (intensity or magnitude) corresponding to $M_w > 3.50$ enter the Catalogue. Several suspected erroneous entries have been rejected. Obvious errors, e.g., in the dates or locations, detected in several catalogues have been corrected. Inadequacies like 'February 29' in non-leap years, 'April 31', etc. have been adjusted to 'February 28', 'April 30', etc. The hour '24' has been consistently changed to '00' of the next day and the minute or second '60' to '00' of the next hour or minute, respectively. Some important 'cleaning' procedures are described below.

Non-tectonic and fake events

Entries of the Databank identified as belonging to other types of events than tectonic earthquakes are not included in the Catalogue. The non-tectonic character (rockburst, collapse, explosion, etc.) is normally identified in the respective local catalogues. A number of events are reinterpreted as fake 'earthquakes'. These are events which have either been moved both in time by more than one year and location by more than 100 km and/or where the intensity has changed by at least one degree. The corrected solutions for these events are given in the Catalogue. Events for which single parameters have been only slightly changed are not classified as fake. Events whose origin is classified as non-seismic do not enter the Catalogue. The authors notably came across studies revealing fake events for German 'earthquakes'. The detected fake events and the sources revealing them are listed in Table 3. Events identified as fake already in an original local catalogue are not included in the table. The different types of fake events, i.e., hoax, storm, collapse, mixture with other event or large deviation in

Table 4. Duplicates in the Databank with respect to Julian vs Gregorian times. Only sources referred to in the Catalogue are included. Entries to the Catalogue have the dates marked in bold.

Origin time					Local catalogue
year	mo	day	h	min	or special study
1590	09	05			**ZivC**
1590	09	15			**Ley**
1590	09	15			**Lab**
1590	**09**	**15**	**17**		**ZAMG**
1590	09	15	17		*Gdt87*
1642	06	03	21	30	**SED**
1642	**06**	**13**	**22**		**NT4.1**
1669	09	30	12	45	**Ley**[1]
1669	**10**	**10**	**00**	**45**	**Ley**[1]
1670	07	06	01		**SED**
1670	**07**	**17**	**01**	**15**	**ZAMG**
1670	07	17	02		**Ley**
1670	07	17	02		**NT4.1**
1695	02	15	05		**SED**
1695	**02**	**25**	**05**	**30**	**NT4.1**
1714	**01**	**13**	**21**	**30**	**ORB**
1714	01	13	22		**Hou**
1714	01	23	22		**Ley**
1714	01	31	22[2]		*Mei95*
1732	**08**	**09**			**NT4.1**
1732	08	19			**SED**

[1] Ley reference is made to different sources.
[2] Date error.

time/distance/intensity, are specified in Table 3.

Duplicates

As mentioned above, the scheme in Table 2 decides which entry should enter the Catalogue if more than one source in the Databank lists an event. In general, the polygons follow national borders and the top priority is given to a domestic catalogue. An entry in a special study published later than a local catalogue has higher priority than the catalogue entry.

The selection of an entry for the Catalogue must be preceded by an identification of what entries in the Databank are associated with this event. This is not always trivial, since the precision of time and location is low for many historical earthquakes. As examples, (1) only the year is given in one catalogue but the exact date (or any other closer specification) in another catalogue, (2) entries have different local times (hours) and there are mixtures between local time and GMT, (3) the locations for two or more simultaneous entries show a significant difference, sometimes matched by a difference in intensity. In such and similar cases, it may be hard to conclude if one or more earthquakes have taken place. The large number of local catalogues used in the present study makes the introduction of a deterministic schedule for the identification of duplicates based on deviations in time and location inexpedient. Instead, a thorough manual inspection was made for the identification and for the selection of the proper entries to the Catalogue in a consistent way.

Different calendars

A special type of duplicate for historical earthquakes is due to the mixed use of the Julian and Gregorian calendars by different sources, sometimes even within the same catalogue. The new calendar was introduced by Pope Gregor XIII in October 1582 and was adopted in this year in Italy (with some exceptions) and on the Iberian peninsula. The other countries concerned in this study switched to the Gregorian calendar in quite different years and the period over which the changes were made is stretched out over many centuries up to 1924 (Romania). No detailed investigation is made in this study of what catalogue uses what time frame over what period. If entries separated by some 10 days in time can be identified as probably referring to one and the same event, then the priority scheme in Table 2 decides which one should enter the Catalogue and this is listed with Julian or Gregorian time as given by the local catalogue. Duplicates of this kind in the Databank are listed in Table 4.

Magnitude assessment and conversion

Hierarchy for calculating M_w

Seismic hazard calculations are currently based mostly on M_w magnitudes, which, unlike other magnitude concepts, do not saturate for strong

Table 5. Hierarchy of calculation of M_w for the different local catalogues and special studies. The default value for h is 10 km, if not specified otherwise. Equation notations (1)-(7) are from Chapter 5

Local catalogue or special study

Priority / Original concept / Algorithm[1] / (Eq. notation)[2]

Local catalogues

Ahjos and Uski (1992)

1. M_L: Eq. (3)
2. M_S: Eq. (4)
3. m_b: Equations (7) & (2)
4. Macroseismic data: $M_L = 0.88(\pm 0.09)\ I_0 + 0.64(\pm 0.25) \log h - 1.52(\pm 0.45)$ /GFZ; N = 101; σ = 0.33/ (*FEN*) *Figure 8c*
   + Eq. (3)
5. M_c: $M_L = M_c$ + Eq. (3)

Boborikin et al. (1993)

1. Macroseismic data: Equations (*FEN*) & (3)

Camassi and Stucchi (1996)

1. M_S: Equations (5.1) / (5.2)
   where M_S is M_S, M_S0100, M_S0110 or M_S0120, corresponding to O, C, M and G, respectively, in *Camassi and Stucchi* (1996), p. IX

Global Hypocenter Data Base, CD version 2.0 (1996)

1. M_S: Eq. (4)
2. m_b: Equations (6.2) / (6.3) *Figure 5* + Eq. (4)

Grünthal (1988, 1991), *Leydecker* (1986, 1996)

1. M_L: Eq. (1)
2. Macroseismic data: $M_L = 0.74(\pm 0.05)\ I_0 + 0.78(\pm 0.23) \log h - 0.87(\pm 0.36)$ /GFZ; N = 145; σ = 0.39/ (*GER*) *Figure 8d*
   + Eq. (1)
3. M_{Ii}: $M_L = M_{Ii} + 0.65$ (*Grünthal*, 1988)
   + Eq. (1)

Halldorsson (1997)

1. M_L: $\log(M_0) = 1.3M_L + 10.5$ (K. Agustsson, personal communication)
   + Eq. (2) with $\log M_0 + 7$ (conversion from Nm to dyn cm)

Houtgast (1995)

1. M_L: Eq. (1)
2. Macroseismic data: $M_L = 0.77(\pm 0.07)\ I_0 + 0.43(\pm 0.32)$ /GFZ; N = 12; σ = 0.21/ *Figure 8e*
   + Eq. (1)

Kondorskaya and Shebalin (1982)

1. Macroseismic data: Equations (*FEN*) & (3)

Labak (1998)

1a. M_L: Eq. (1); beside the original M_L, the MM type 5 is considered original M_L, i.e., M_L = MM is set
[All events with NMAG = 4 are located outside Slovakia]

1b. M_S: M_S = MM is set for NMAG = 1, 2 and 3 (*Labak*, personal communication), these are to be considered original M_S
+ Eq. (4)

2. Macroseismic data: $M_S = 0.55\ I_0 + 0.95$, which is the most frequently used MM formula by *Labak* (1998), corresponding to NMAG = 1
   + Eq. (4)

Lambert and Levret-Albaret (1996)

1. Macroseismic data: $M_L = 0.44\ I_0 + 1.48 \log h + 0.48$ (*Levret et al.*, 1994), region-specific h used when no depth given
   + Eq. (1)

Lenhardt (1996)

1a. M_S: Eq. (4)

1b. M_L: Eq. (1)

Table 5. Continued

Mayer-Rosa and Baer (1992)	
1.	M_L: Eq. (1)
2.	Macroseismic data: M_L = 0.74(±0.09) I_0 + 0.14(±0.42) /GFZ; N = 53; σ = 0.39/ *Figure 8f* + Eq. (1)
Musson (1994)	
1.	M_L: Eq. (1)
Nikonov (1992)	
1.	Macroseismic data: Equations (*FEN*) & (3)
Oncescu et al. (1998)	
1.	M_w given for all events
Pagaczewski (1972)	
1.	Macroseismic data: Equations (*GER*) & (1)
Verbeiren et al. (1995)	
1.	M_L: Eq. (1)
2.	Macroseismic data: M_L = 0.77(±0.07) I_0 + 2.02(±0.48) log h – 2.25(±0.67) /GFZ; N = 15; σ = 0.24/ *Figure 8*^{a} + Eq. (1)
Wahlström and Grünthal (1994)	
1.	M_L: Eq. (3)
2.	Macroseimic data: Equations (*FEN*) & (3)
Živčić (1993)	
1.	M_L: Eq. (1)
2.	Macroseismic data: M_L = 0.494 I_0 + 1.27 log h + 0.09 (*Živčić et al.*, 2000) + Eq. (1)
Živčić (1994)	
1.	M_L: Eq. (1)
2.	Macroseimic data: M_L = 0.70(±0.07) I_0 + 1.09(±0.28) log h – 1.14(±0.56) /GFZ; N = 39; σ = 0.33/ *Figure 8b* + Eq. (1)
Zsíros et al. (1990), *Zsíros* (1994)	
1.	M_L: Eq. (1), with M_L = MM set
2.	Macroseimic data: M_L = 0.6 I_0 + 1.8 log h – 1.0 (*Zsíros*, 1983 – after Gutenberg and Richter, 1942 on recommendation from T. Zsíros) + Eq. (1)
Special studies	
Where M_w does not exist, it is calculated from available formulae for the polygon in which the event is located.	

[1] GFZ denotes that a M_L vs. I_0 regression has been performed in the present study, with *N* number of data points and σ standard deviation.
[2] Introduced for equations with repeated occurrence in the table.

events. Most strong motion relations refer to M_w. Therefore, M_w is also used by the present Catalogue. Where M_w or the seismic moment, M_0, is provided by the original source, these concepts are used, M_0 being converted to M_w using the *Hanks and Kanamori* (1979) relation (p. 518). Where M_w or M_0 is not given, an algorithm is followed to select the magnitude type or macroseismic data from which M_w should be calculated. A detailed hierarchy scheme specifying which strength concept(s) to base the calculations on for the different catalogues is given as Table 5. For the special studies, M_w is calculated according to Table 5 based on the location of the event. In the special studies giving M_w, this has been computed from formulae given by *Ahorner* (1983) or *Johnston* (1996b).

For the majority of the catalogues, M_L and/or

I_0 are the only original strength concepts given. Where both occur, M_L is given priority. For the historical time, many catalogues give only macroseismic data. Therefore, we are confined to this type of data for the M_w calculations of a lot of earthquakes. Special attention is paid to these calculations (see below).

For Fennoscandia, several original concepts exist (*Ahjos and Uski*, 1992) and we rank them in the order M_L, M_S, b_b, I_0 and M_c. The coda magnitude, M_c, has been calibrated with M_L. Other catalogues providing other magnitudes than M_L are the *Global Hypocenter Data Base*, CD version 2.0 (1996) for the North Atlantic Ridge and Ocean, with M_S and/or m_b, *Camassi and Stucchi* (1996) for Italy, M_S, *Labak* (1998) for Slovakia and *Lenhardt* (1996) for Austria, both of which give M_S or M_L, and *Verbeiren et al.* (1995) for Belgium, M_S and/or M_L.

Details of the priority settings are given in Table 5. Since the hierarchy of the strength concepts, i.e., magnitude types and/or epicentral intensity, is subordinated to that of selecting the original source for the Catalogue (Table 2), only concepts occurring in the associated local catalogue - polygon combinations are listed in Table 5.

Original and calculated M_w

Although M_w is given for each entry of the Catalogue, the vast majority of the values are not from the original catalogues but had to be derived from other magnitude concepts or from macroseismic parameters. Exceptions are the M_w based Romanian catalogue (*Oncescu et al.*, 1999) and many special studies giving M_w or M_0 values. Different measures of the event strength are given by different sources. Existing local formulae for the conversions to M_w are used in the first place. Lacking such formulae, the conversion routines below are followed. The full algorithm for the calculation of M_w for various catalogues and from various magnitude types and/or macroseismic parameters is given in Table 5.

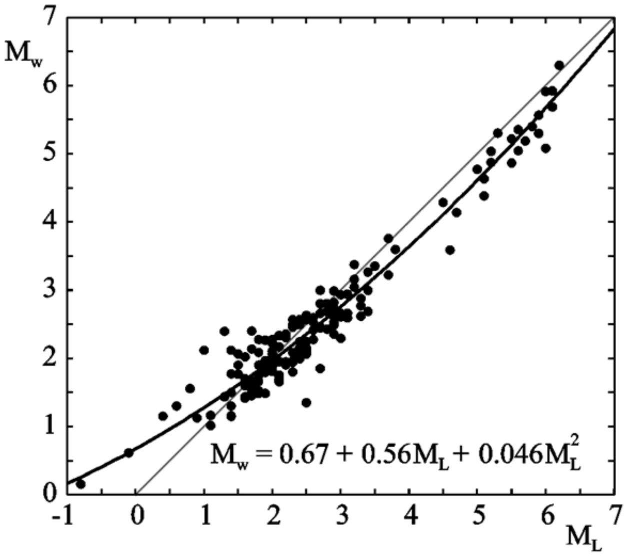

Figure 3. Input data and M_w vs. M_L chi-square maximum likelihood regression curve for central Europe, eq. (1). Data from 164 events (Table 6). The M_w = M_L line is drawn for comparison.

M_w from instrumentally determined magnitudes

M_L M_L is by far the most frequent magnitude concept in the Databank. For many earthquakes, it is the only magnitude given. The well constrained relation

$$M_w = 0.67(\pm 0.11) + 0.56(\pm 0.08)\, M_L + 0.046\left(\pm 0.013\, {M_L}^2\right) \quad (1)$$

derived in this study by chi-square maximum likelihood regression is based on 164 earthquakes in central Europe with original seismic moment data (Table 6; Figure 3). The second order structure gives an improved fit for small and large magnitudes compared to a linear fit. The technique to fit measured data with known or assumed statistical errors to a given model is described in detail by *Stromeyer et al.* (2004). The chi-square maximum likelihood regression is preferred over the frequently used orthogonal maximum likelihood procedure since the data points can have their own error distribution in the former method. This method is also useful when the measurement errors are not normally distributed. Eq. (1) is applied to many catalogues in the present study (Table 5).

Table 6. Events with original M_0 data in the study area used for the derivation of eq. (1)

year	note	mo	day	h	min	lat °N	lon °E	ref	M_0 dyn cm	ref	M_L	ref	A_{III} km^2	ref	I_0	ref
1911		11	16	21	25	48.22	9.00	**Ley**	3.8e+24	*Kun86*	6.1	*Kun86*	7.9e+05	**Ley**	8.0	**Ley**
1913		7	20	12	6	48.23	9.01	**Ley**	4.1e+23	*Kun86*	5.6	*Kun86*	2.0e+05	**Ley**	7.0	**Ley**
1935		6	27	17	19	48.04	9.47	**Ley**	1.4e+24	*Kun86*	5.8	*Kun86*	7.9e+05	*Kun86*	7.5	**Ley**
1943		5	2	1	8	48.27	8.98	**Ley**	2.2e+23	*Kun86*	5.5	*Kun86*	4.4e+05	**Ley**	7.0	**Ley**
1943		5	28	1	24	48.27	8.98	**Ley**	1.2e+24	*Kun86*	5.6	*Kun86*	7.4e+05	**Ley**	8.0	**Ley**
1951		3	14	9	46	50.63	6.72	**Ley**	4.7e+23	*Kun86*	6.0	*Kun86*	2.1e+05	**Ley**	7.5	**Ley**
1955		5	22	4	57	47.30	11.40	**Ley**	9.1e+22	*Sch*			3.1e+04	**Ley**	6.5	**Ley**
1967		1	29	0	12	47.90	14.30	**ZAMG**	5.2e+22	*Sch*			8.6e+04	*Sch*	6.5	**Sch**
1969		2	26	1	28	48.29	9.01	**Ley**	4.2e+22	*Kun86*	5.1	*Kun86*	9.6e+04	**Ley**	7.0	**Ley**
1970		1	22	15	25	48.28	9.03	**Ley**	2.3e+23	*Kun86*	5.2	*Kun86*	1.7e+05	**Ley**	7.0	**Ley**
1971		9	29	7	18	47.10	9.00	**Ley**	3.0e+22	*Sch*	4.5	**Ley**	9.1e+04	**Ley**	7.0	**Ley**
1976		5	6	20	0	46.23	13.07	**NT4.1**	3.1e+25	*Bon84*	6.2	*Bon84*	1.5e+06	*Sch*	9.5	**NT4.1**
1976		5	11	22	44	46.29	12.99	*CR85*	1.0e+24	*Bon84*	5.3	*Bon84*				
1976		9	11	16	31	46.29	13.18	*CR85*	7.5e+23	*Bon84*	5.5	*Bon84*				
1976		9	11	16	35	46.30	13.19	*CR85*	2.5e+24	*Bon84*	5.9	*Bon84*				
1976		9	15	3	15	46.30	13.19	*CR85*	8.5e+24	*Bon84*	6.1	*CR85*				
1976		9	15	4	38	46.29	13.13	*CR85*	1.6e+23	*Bon84*	5.0	*Bon84*				
1976		9	15	9	21	46.34	13.12	*CR85*	8.3e+24	*Bon84*	6.0	*Bon84*				
1977		9	16	23	48	46.28	12.98	*CR85*	4.0e+23	*Bon84*	5.2	*Bon84*				
1978	[1]	9	3	5	8	48.28	9.03	**Ley**	6.8e+23	[1]	5.7	**Ley**	3.4e+05	**Ley**	7.5	**Ley**
1978	[2]								[2]	*SS83*	[2]	*SS83*				
1980		7	15	12	17	47.67	7.48	**Ley**	1.8e+22	*Sch*	4.7	**Ley**			6.5	**Ley**
1981		12	20	10	38	50.86	5.84	**Hou**	3.5e+20	*AP83*	2.7	**Hou**				
1982		2	20	4	35	51.35	12.44	**Gru**	2.0e+20	*GGG84*					5.0	**Gru**
1982		2	24	5	15	51.35	12.44	**Gru**	1.7e+19	*GGG84*	1.4	**Gru**				
1982		3	2	1	27	51.02	5.83	**Hou**	1.2e+21	*AP83*	3.5	**Hou**	3.8e+03	**Hou**	4.0	**Hou**
1982		5	22	6	0	51.02	6.00	**Hou**	4.9e+21	*AP83*	3.7	**Hou**	3.1e+04	**Hou**	4.5	**Hou**
1982		11	28	4	34	48.30	9.04	*Lan86*	7.6e+20	*Lan86*	3.7	*Lan86*				
1982		11	28	4	36	48.30	9.04	*Lan86*	4.7e+19	*Lan86*	2.6	*Lan86*				
1983		2	19	18	42	48.34	8.96	*Lan86*	9.5e+18	*Lan86*	2.1	*Lan86*				
1983		2	19	18	43	48.34	8.96	*Lan86*	2.0e+18	*Lan86*	1.4	*Lan86*				
1983		3	23	22	27	48.34	8.95	*Lan86*	6.9e+19	*Lan86*	2.9	*Lan86*				
1983		3	27	5	8	48.34	8.95	*Lan86*	9.3e+19	*Lan86*	2.9	*Lan86*				
1983		5	5	14	28	48.34	8.96	*Lan86*	4.9e+19	*Lan86*	2.8	*Lan86*				
1983		5	11	13	11	48.34	8.96	*Lan86*	9.9e+18	*Lan86*	1.9	*Lan86*				
1983		5	11	14	14	48.34	8.96	*Lan86*	5.2e+19	*Lan86*	2.7	*Lan86*				
1983		9	11	11	48	48.32	9.04	*Lan86*	3.5e+20	*Lan86*	3.4	*Lan86*				
1983		9	14	9	13	48.32	9.04	*Lan86*	8.7e+18	*Lan86*	1.9	*Lan86*				
1983		9	14	10	52	48.32	9.04	*Lan86*	6.8e+18	*Lan86*	1.9	*Lan86*				
1983		9	14	18	25	48.32	9.04	*Lan86*	1.5e+19	*Lan86*	2.3	*Lan86*				
1983		9	15	6	26	48.32	9.04	*Lan86*	1.4e+20	*Lan86*	2.9	*Lan86*				
1983		9	15	13	59	48.34	9.04	*Lan86*	7.0e+18	*Lan86*	1.9	*Lan86*				
1983		10	11	16	49	48.31	9.04	*Lan86*	9.2e+19	*Lan86*	3.0	*Lan86*				
1983		11	5	14	13	50.81	12.68	**Gru**	4.5e+19	**Gru**	1.7	**Gru**	2.5e+02	**Gru**	4.5	**Gru**
1983		11	8	0	50	50.63	5.50	**Hou**	1.0e+23	*Kun86*	5.1	*Sch*	2.3e+05	**Hou**	7.0	**Hou**
1983		12	12	11	32	48.36	9.19	*Lan86*	1.1e+20	*Lan86*	3.1	*Lan86*				
1984		1	3	15	28	48.25	9.05	*Lan86*	2.6e+19	*Lan86*	2.5	*Lan86*				
1984		1	26	17	15	48.37	9.02	*Lan86*	1.1e+20	*Lan86*	3.0	*Lan86*				
1984		2	25	19	5	48.29	9.04	*Lan86*	1.6e+19	*Lan86*	2.4	*Lan86*				
1984		3	21	1	7	48.34	9.20	*Lan86*	1.4e+19	*Lan86*	2.0	*Lan86*				
1985	3	12	14	9	50	[3]	[3]	*GBK86*	8.0e+18	*GBK86*	1.8	*GBK86*				
1985		12	16	15	26				1.4e+19	*GBK86*	1.5	*GBK86*				
1985		12	22	5	6				1.2e+19	*GBK86*	1.6	*GBK86*				
1985		12	22	5	51				2.0e+19	*GBK86*	2.1	*GBK86*				
1985		12	22	6	23				1.2e+19	*GBK86*	1.6	*GBK86*				
1985		12	22	8	2				5.1e+18	*GBK86*	1.4	*GBK86*				

Table 6. Continued

year	note	mo	day	h	min	lat °N	lon °E	ref	M_0 dyn cm	ref	M_L	ref	A_{III} km^2	ref	I_0	ref
1985		12	22	9	11				8.0e+19	*GBK86*	2.3	*GBK86*				
1985		12	22	17	31				3.5e+19	*GBK86*	2.1	*GBK86*				
1985		12	23	3	25				2.9e+20	*GBK86*	3.1	*GBK86*				
1985		12	23	4	5				8.7e+19	*GBK86*	2.6	*GBK86*				
1985		12	23	4	27				1.3e+21	*GBK86*	3.2	*GBK86*				
1985		12	23	4	47				1.4e+19	*GBK86*	1.5	*GBK86*				
1985		12	29	15	30				1.0e+20	*GBK86*	2.5	*GBK86*				
1985		12	30	18	40				2.9e+19	*GBK86*	1.8	*GBK86*				
1985		12	30	21	50				3.8e+19	*GBK86*	2.2	*GBK86*				
1985		12	31	1	0				1.2e+19	*GBK86*	1.6	*GBK86*				
1988		8	26	0	30	47.80	7.69	*BFA90*	2.3e+20	*BFA90*	3.3	*BFA90*				
1988	[4]	8	26	4	59	[4]	[4]	*BFA90*	1.9e+16	*BFA90*	-0.8	*BFA90*				
1988	[4]	8	26	9	44	[4]	[4]	*BFA90*	9.5e+16	*BFA90*	-0.1	*BFA90*				
1988		8	28	20	45	47.00	7.00	*BFA90*	8.0e+18	*BFA90*	1.5	*BFA90*				
1992	[5]	4	13	1	20	51.16	5.95	*Cam94*	1.0e+24	[5]	5.9	[5]	5.5e+05	*Sch*	7.0	[5]
1992	[6]	4	13	2	8	51.17	5.95	*OCM94*	6.2e+19	*OCM94*	2.4	*OCM94*				
1992		4	13	3	3	51.18	5.92	*OCM94*	9.0e+19	*OCM94*	2.5	*OCM94*				
1992		4	13	3	41	51.16	5.98	*OCM94*	8.3e+19	*OCM94*	2.5	*OCM94*				
1992		4	13	3	49	51.17	5.97	*OCM94*	8.8e+20	*OCM94*	3.4	*OCM94*				
1992		4	13	4	37	51.07	6.06	*OCM94*	7.0e+19	*OCM94*	2.6	*OCM94*				
1992		4	13	5	20	51.10	5.99	*OCM94*	2.8e+20	*OCM94*	3.0	*OCM94*				
1992		4	13	6	2	51.15	5.99	*OCM94*	4.1e+20	*OCM94*	3.2	*OCM94*				
1992		4	13	6	16	51.16	5.99	*OCM94*	1.1e+20	*OCM94*	2.7	*OCM94*				
1992		4	13	6	33	51.16	5.99	*OCM94*	1.8e+20	*OCM94*	2.7	*OCM94*				
1992		4	13	18	34	50.81	6.23	*PHW94*	1.7e+19	*PHW94*	1.0	*PHW94*				
1992		4	13	18	46	50.84	6.20	*PHW94*	5.5e+17	*PHW94*	0.9	*PHW94*				
1992		4	13	21	50	51.17	6.00	*OCM94*	3.2e+19	*OCM94*	2.2	*OCM94*				
1992		4	13	22	59	51.15	6.01	*OCM94*	2.4e+19	*OCM94*	2.0	*OCM94*				
1992		4	14	1	6	50.94	6.17	*PHW94*	2.8e+21	*PHW94*	3.8	*PHW94*				
1992		4	14	1	36	50.82	6.22	*PHW94*	3.4e+20	*PHW94*	2.9	*PHW94*				
1992		4	14	2	31	51.16	6.00	*OCM94*	6.3e+19	*OCM94*	2.3	*OCM94*				
1992		4	14	12	41	51.17	5.92	*OCM94*	1.8e+20	*OCM94*	2.8	*OCM94*				
1992		4	14	12	56	51.17	5.99	*OCM94*	1.9e+20	*OCM94*	2.9	*OCM94*				
1992		4	15	22	5	50.82	6.23	*PHW94*	5.0e+18	*PHW94*	1.5	*PHW94*				
1992		4	16	0	5	50.83	6.24	*PHW94*	2.4e+18	*PHW94*	0.8	*PHW94*				
1992		4	17	23	56	50.81	6.26	*PHW94*	3.7e+17	*PHW94*	1.1	*PHW94*				
1992		4	20	4	41	51.18	5.97	*OCM94*	2.8e+19	*OCM94*	1.9	*OCM94*				
1992		4	20	7	27	51.15	6.00	*OCM94*	2.9e+19	*OCM94*	2.0	*OCM94*				
1992		4	20	16	50	50.81	6.22	*PHW94*	2.5e+19	*PHW94*	2.0	*PHW94*				
1992		4	24	10	35	51.16	6.00	*OCM94*	5.4e+19	*OCM94*	2.3	*OCM94*				
1992		4	26	1	45	50.82	6.21	*PHW94*	4.4E+19	*PHW94*	1.3	*PHW94*				
1992		5	2	8	50	51.18	6.01	*OCM94*	8.0e+19	*OCM94*	2.5	*OCM94*				
1992		5	17	9	26	50.89	6.32	*PHW94*	1.4e+19	*PHW94*	2.0	*PHW94*				
1992		6	8	2	17	50.85	6.22	*PHW94*	1.0e+18	*PHW94*	0.6	*PHW94*				
1992		6	25	16	48	50.97	6.10	*PHW94*	1.2e+18	*PHW94*	2.5	*PHW94*				
1992		8	22	2	46	50.81	6.24	*PHW94*	6.0e+17	*PHW94*	0.4	*PHW94*				

[1] Seismic moment is the average of *Bru85*, *Hae80* and *Kun86*.

[2] Data from 58 aftershocks in September-October 1978, M_L = 1.1–3.4, to the Swabian Jura earthquake 1978-09-03 are included in the M_0-M_L regression. Only data from two of the field stations, NHS (first priority) or BHB, are used, since the other three stations give unreliable spectral data (*SS83*).

[3] The Vogtland earthquake sequence was limited to a small area – the coordinates for the largest shock, on December 21 at 10:16, apply with good approximation to all listed events in December 1985.

[4] Location is similar to the other events on this date.

[5] Seismic moment is the average of the values given in *Cam94*.

[6] Several of the Roermond aftershocks with seismic moments from *OCM94* and *PHW94* have similar determinations by Ahorner (1994).

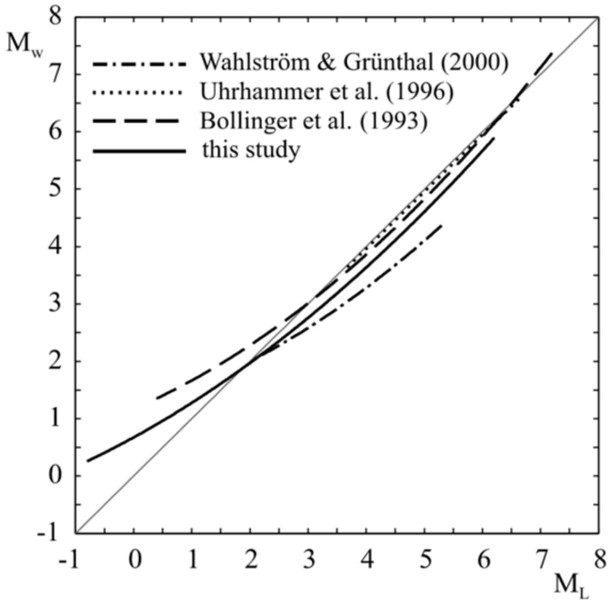

Figure 4. Comparison of M_w-M_L curves for different data sets: *Bollinger et al.* (1993) for western United States: $M_w = 1.17{+}0.436\ M_L + 0.059\ {M_L}^2$; the original *Bollinger et al.* (1993) curve is a log(moment) vs. M_L plot which we have converted using eq. (2) *Uhrhammer et al.* (1996) for California: $M_w = -0.050 + 0.997\ M_L$. Present study for central Europe, eq. (1). *Wahlström and Grünthal* (2000) for Fennoscandia, eq. (3). Each curve is plotted within its respective range of input M_L data and the $M_w = M_L$ line is drawn for comparison.

The M_w values used for derivation of eq. (1) are calculated from the seismic moment (in dyn cm) using the relation of *Hanks and Kanamori* (1979)

$$M_w = 2/3\ log(M_0) - 10.7 \qquad (2)$$

As a local magnitude scale, the M_L-scale is different for different catalogues and this is a factor of uncertainty in the applicability of eq. (1). However, the errors of the coefficients of the equation are small, although derived from data from many sources, and equations (1) and (2) are applied for all events with original or calculated M_L, where no local formulae are available.

Modifying a linear relation by *Kim et al.* (1989), *Wahlström and Grünthal* (2000) derived a quadratic M_w-M_L relation for Fennoscandia

$$M_w = 1.2 + 0.28\ M_L + 0.06\ {M_L}^2 \qquad (3)$$

Eq. (3) is used also for the structurally similar parts of eastern Europe east of the Tornqvist-Teisseyre zone (*Nikonov*, 1992, *Boborikin et al.*, 1993 and *Kondorskaya and Shebalin*, 1982 catalogues and eastern Poland).

The non-linear behaviour of equations (1) and (3) has been discovered also in several studies for North America, e.g., by *Bollinger et al.* (1993), *Hasegawa* (1983), *Nuttli* (1983), *Street et al.* (1975) and *Uhrhammer et al.* (1996) and is ascribed to the intrinsic character of M_L. Figure 4 shows a comparison of eq. (1), eq. (3) and two of the North American relations. There is fair agreement between the M_w-M_L relations for central Europe (this study), Fennoscandia and North America, although the relation for Fennoscandia gives lower M_w values than the others for $M_L < 4$. A formula by K. Agustsson (personal communication) to calculate M_0 from M_L is used for events in the Icelandic catalogue (Table 5; *Halldorsson*, 1997).

M_S Only 19 of the earthquakes with original M_0 data (Table 6) have M_S magnitudes, preventing a meaningful regression with the two concepts. M_S magnitudes need to be converted to M_w in the catalogues for Fennoscandia (*Ahjos and Uski*, 1992), the North Atlantic Ocean (*Global Hypocenter Data Base*, CD version 2.0, 1996), Austria (*Lenhardt*, 1996), Italy (*Camassi and Stucchi*, 1996) and Slovakia (*Labak*, 1998). For all but *Camassi and Stucchi* (1996), we found the equality

$$M_w = M_S \qquad (4)$$

reflecting the original intention with the M_w concept to be a good approximation. This equality has recently been confirmed empirically for central and northern Europe by *Bungum et al.* (2003). For the more southern part of Europe, transformation formulae proposed by *Bungum et al.* (2003)

$$M_w = 0.769\ M_S + 1.280 \text{ for } M_S \geq 5.4 \qquad (5.1)$$
$$M_w = 0.585\ M_S + 2.422 \text{ for } M_S < 5.4 \qquad (5.2)$$

are applied to the *Camassi and Stucchi* (1996)

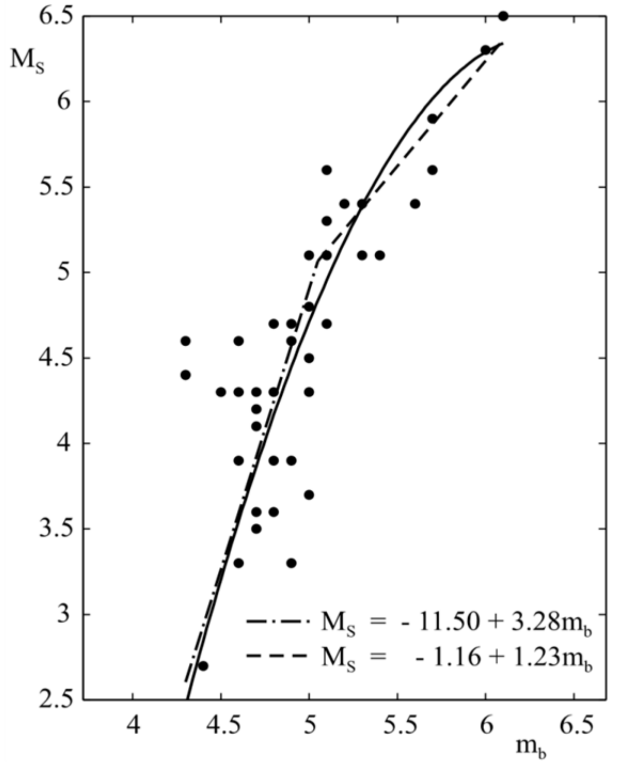

Figure 5. Input data and M_S vs. m_b chi-square maximum likelihood regression curve, eq. (6.1), and bilinear fit, equations (6.2) and (6.3), for events in *Global Hypocenter Data Base*, CD version 2.0 (1996) located in the polygon North Atlantic Ocean and Iceland. Eq. (6.2) is used in the interval for 4.5 < m_b < 5.04 and eq. (6.3) for m_b > 5.04.

catalogue (see Table 5). There is then no need first to use a local formula given by *Camassi and Stucchi* (1996) to convert M_S to M_L and then to use equations (1) and (2) to calculate M_w.

Also *Verbeiren et al.* (1995) give M_S for a few events. First priority M_L magnitudes are given for four of these. For the fifth event, M_w calculated from I_0 differs by only 0.1 from M_w calculated from M_S using eq. (4). Therefore, M_S magnitudes are not included in the priority scheme for the *Verbeiren et al.* (1995) catalogue.

$\boldsymbol{m_b}$ The *Global Hypocenter Data Base*, CD version 2.0 (1996) contains M_S and m_b magnitudes and we give priority to the former. A linear relation between M_S and m_b based on 42 data points in this catalogue located in the polygon North Atlantic Ocean and Iceland (AOI in Figure 2) gives an acceptable mean fitting error of 0.26 for both magnitudes (see *Stromeyer et al.*, 2004), but there are systematic deviations in the lower and upper parts of the data range. With a second order chi-square maximum likelihood regression

$$M_S = -31.95(\pm 8.63) + 12.13(\pm 3.18)\, m_b \\ -0.96(\pm 0.29)\, {m_b}^2 \qquad (6.1)$$

where the fitting error is reduced to 0.23, a good approximation within the whole range of data (4.4 < m_b < 6.1) is obtained, but the relation is in this case inadequate for small and large events outside the range, where the calculated m_b values may even be imaginary. Therefore, to calculate M_w for North Atlantic Ridge and Ocean earthquakes which only have m_b, formulae for the bilinear fit with optimized intersection (at m_b = 5.04)

$$M_S = -11.50(\pm 2.70) + 3.28(\pm 0.54)\, m_b \\ \text{for } 4.5 \leq m_b \leq 5.04 \qquad (6.2)$$

$$M_S = -1.16(\pm 1.36) + 1.23(\pm 0.26)\, m_b \\ \text{for } m_b \leq 5.04 \qquad (6.3)$$

are used, together with eq. (4). The lower level, $m_b = 4.5$, is sufficient to obtain M_w for all Catalogue events, i.e., with $M_w = 3.50$ or larger. The relations (6.1) – (6.3) are plotted in Figure 5.

The Fennoscandian catalogue by *Ahjos and Uski* (1992) is the only other local catalogue where m_b magnitudes need to be converted to M_w, and this only for five events. Although the events in question have slightly offshore locations, the global relation for continental interiors by *Johnston* (1996a)

$$log(M_0) = 18.28 + 0.679\, m_b + 0.077\, {m_b}^2 \qquad (7)$$

is applied and combined with eq. (2) to give M_w.

$\boldsymbol{M_c}$ *Ahjos and Uski* (1992) is the only catalogue contributing coda magnitudes, M_c, which need to be converted to M_w. The M_c magnitudes are given mostly for small earthquakes in Finland and Norway and for offshore earthquakes. Since the M_c magnitudes have been calibrated

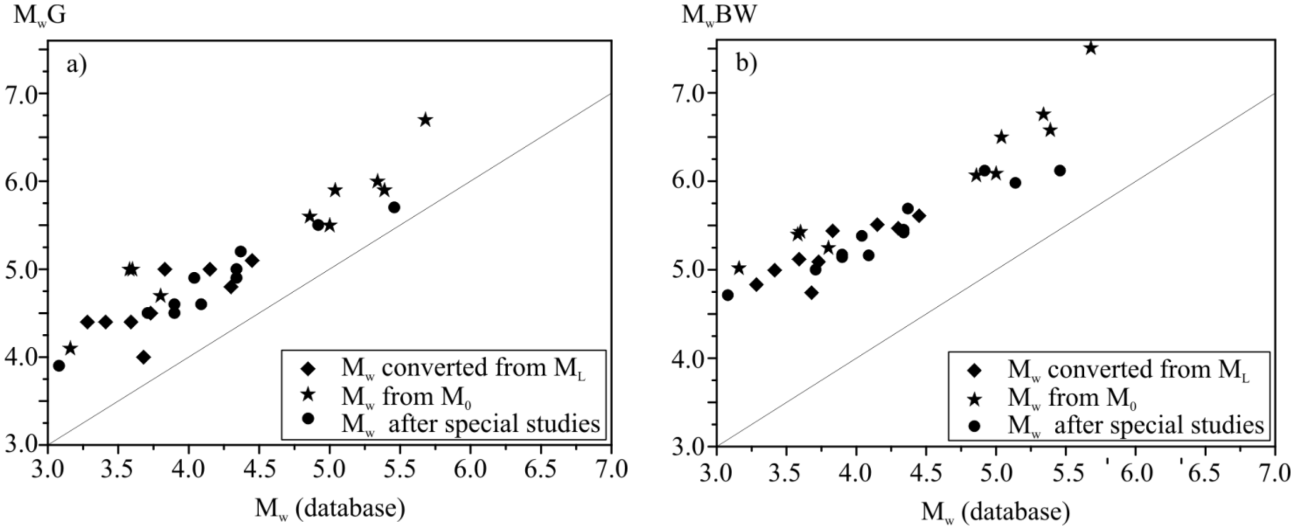

Figure 6. M_w magnitudes for earthquakes in central Europe using the formulae of the present study and those of a) *Gasperini et al.* (1999); b) *Bakun and Wentworth* (1997). Each of the 36 earthquakes compared have 15 or more data points with intensity 4 or larger. See the text for details of the methods. The line representing the equality of both M_w determinations is drawn in each case for comparison.

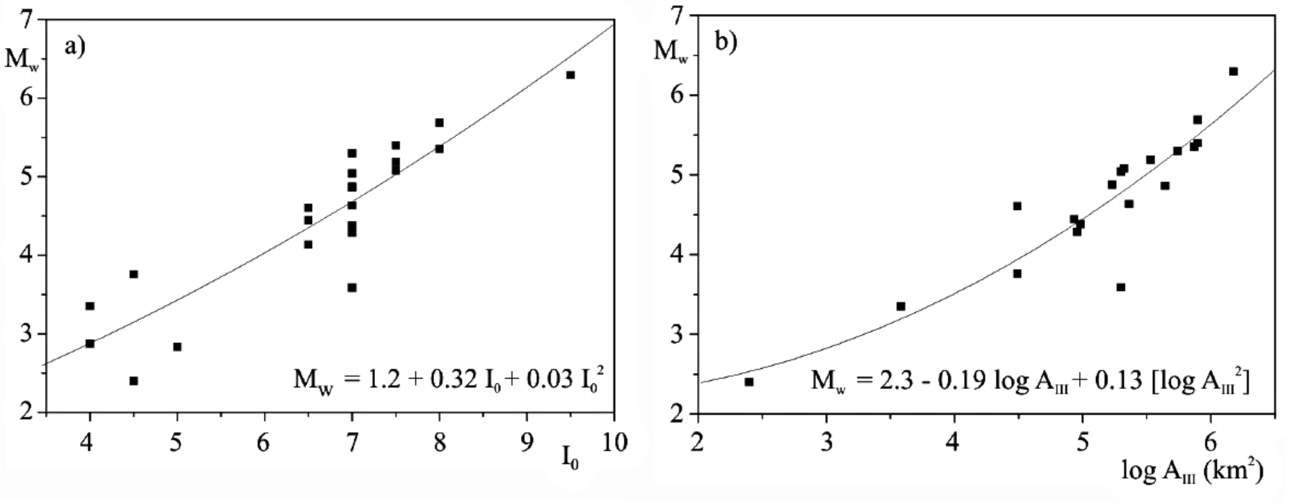

Figure 7. Input data and regression curves for central Europe based on data in Table 6: a) M_w-I_0, where I_0 is epicentral intensity; b) M_w-log(A_{III}), where A_{III} is area (km^2) of intensity 3 and larger. These relations are not used for M_w calculations in this study.

with the local M_L magnitudes, M_L is put equal to M_c and eq. (3) is applied. Coda based M_w values for the offshore events are often very small compared to M_S based M_w values and also to M_w obtained from data in other catalogues. M_c is therefore not used for offshore events and it is given the lowest priority for the other events (see Table 5).

M_w from macroseismic data

For historical earthquakes, M_w has to be calculated from macroseismic data in many catalogues. Similar to a local study (western Nevada) by *Toppozada* (1975), *Sibol et al.* (1987) found that the felt area is a better predictor than maximum intensity for calculation of the magnitude, in this case m_b for North American earthquakes. The combined use of I_0 and felt area was found even better. *Musson* (1994) used the area of intensity 3 to calculate M_L. *Bollinger et al.* (1993) used the area of higher intensities (damage) as a predictor of M_w in the United States.

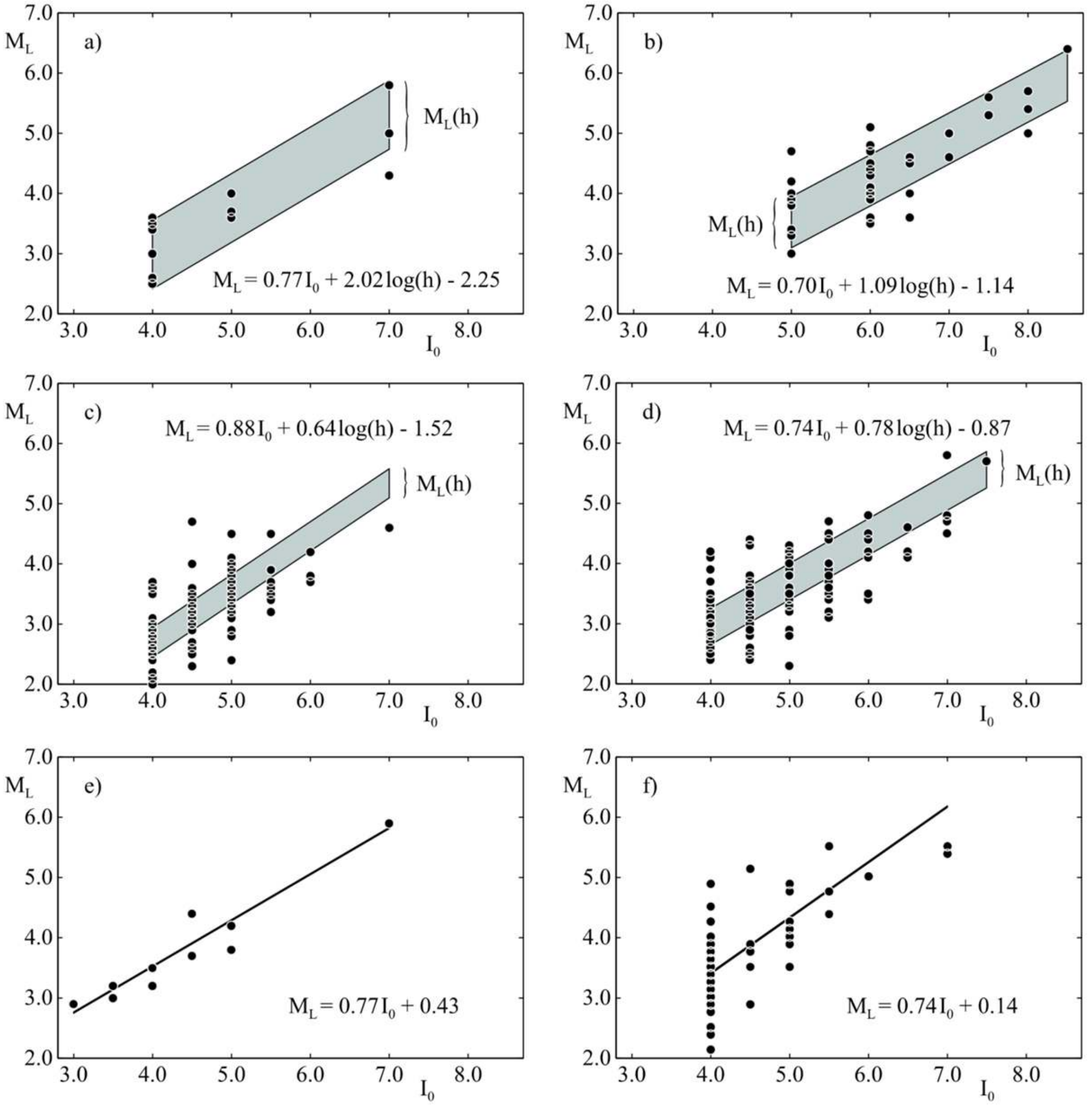

Figure 8. Graphs showing input data to and output sheets from M_L vs. I_0 chi-square maximum likelihood regressions for the local catalogues for: a) Belgium - *Verbeiren et al.* (1995); b) Croatia - *Živčić* (1994); c) Fennoscandia - *Ahjos and Uski* (1992); d) Germany - *Grünthal* (1988, 1991) and *Leydecker* (1986, 1996); e) The Netherlands - *Houtgast* (1995); f) Switzerland - *Mayer-Rosa and Baer* (1992). The full equations with error estimates are given in Table 5. The solutions a-d contain the focal depth as an independent parameter; for the solutions e and f the focal depth influence is insignificant.

Bakun and Wentworth (1997) and *Gasperini et al.* (1999) used individual intensity observation data to calculate M_w for earthquakes in Italy and California, respectively. *Bakun and Wentworth* (1997) calculate M_w for each intensity class and the final M_w is the mean of the values for the different classes. Figure 6 compares M_w magnitudes calculated with the algorithms of *Gasperini et al.* (1999) and *Bakun and Wentworth* (1997), respectively, with those of the present study. The comparisons are based on 36 earthquakes, each of which has 15 or more data points with intensity 4 or larger. Both the *Bakun and Wentworth* (1997) and *Gasperini et* *al.* (1999) M_w values, about one third of which were directly converted from M_0, fall significantly above those of our study (Figure 6). The highest values are obtained from the *Bakun and Wentworth* (1997) algorithm. *Bakun and Wentworth* (1997) point out that their method must be tested and perhaps modified and the empirical relations calibrated before they should be applied in other regions. The extent of the required calibrations are indicated in Figure 6. The discrepancy between our values and those of Gasperini's may be explained by the lower attenuation north of the Alps than south thereof. In summary, the macroseismic data available for the present study are insufficient for an application of these techniques to derive M_w.

Regressions of M_w on epicentral intensity, I_0, and felt area, A_{III} (km), respectively, have been performed based on the data in Table 6

$$M_w = 1.2(\pm 1.6) + 0.32(\pm 0.52)\, I_0 + 0.03(\pm 0.04)\, {I_0}^2 \tag{8.1}$$

$$M_w = 2.3(\pm 1.6) + 0.19(\pm 0.76)\, logA_{III} + 0.13(\pm 0.09)\, (logA_{III})^2 \tag{8.2}$$

The corresponding plots are shown in Figure 7. The quadratic structure was again applied, like, e.g., by *Johnston* (1996b). Due to the scarce data (22 data points for I_0 and 19 for A_{III}) and large errors, equations (8.1) and (8.2) are not used in this study.

An attempt to derive an M_L-I_0 relation from data from all local catalogues together showed an unsatisfactorily large scatter, probably mainly due to the heterogeneity in the macroseismic practice and between different M_L scales. Considerable improvement was achieved when each catalogue was treated separately. In several catalogues, magnitudes are given for all events, also the historical: The Austrian (*Lenhardt*, 1996), British (*Musson*, 1994), Icelandic (*Halldorsson*, 1997), Italian (*Camassi and Stucchi*, 1996), Romanian (*Oncescu et al.*, 1999) and that for the North Atlantic Ocean (*Global Hypocenter Data Base*, CD version 2.0). There is thus no need to convert macroseismic data from these catalogues. For France (*Levret et al.*, 1994), Hungary (*Zsíros*, 1983), Slovakia (*Labak*, 1998) and Slovenia (*Živčić et al.*, 2000), a local M_L vs. I_0 or M_S vs. I_0 formula exists (Table 5) and is combined with formulae given in the text above to give M_w.

For each remaining catalogue which has sets of M_L and I_0 data, a chi-square maximum likelihood regression was performed, with the focal depth as an additional parameter where this is significant (see *Stromeyer et al.*, 2004). With a few exceptions, only data from a more reliable period of instrumental recording, starting in 1963, were used in the regressions. No data from offshore located events were used (no epicentral intensity). The six obtained relations are given in Table 5 and the data and graphs are shown in Figure 8. The relations for the Belgian (*Verbeiren et al.*, 1995), Croatian (*Živčić*, 1994), Fennoscandian (*Ahjos and Uski*, 1992) and German (*Grünthal*, 1988, 1991 and *Leydecker*, 1986, 1996, combined) catalogues include the depth parameter, whereas the Dutch (*Houtgast*, 1995) and Swiss (*Mayer-Rosa and Baer*, 1992) catalogues do not. In general, there is a resemblance of the coefficient of the intensity term for all relations (see Table 5). The catalogues covering mostly the East European Platform or adjacent to Fennoscandia, i.e., Belorussia (*Boborikin et al.*, 1993), Estonia (*Nikonov*, 1992), the southern Baltic Sea (*Wahlström and Grünthal*, 1994) and Ukraine and Moldavia (*Kondorskaya and Shebalin*, 1982), use the relation for Fennoscandia.

Entries of the Catalogue

After the data selection and cleaning of the events, there are about 5,000 tectonic earthquakes entering the current Catalogue. The epicentres are plotted in Figure 9 and a histogram showing the magnitude distribution of all events except those in the polygon Atlantic Ocean and Iceland is given as Figure 10. The Catalogue is available at the home page of the Geo-

ForschungsZentrum Potsdam:

http://seismohazard.gfz-potsdam.de/projects/catalogues/EEC_CNNW.html

The following information is given in the Catalogue:

- *Origin Time.* Year, month, day, hour and minute, specified to the smallest unit given by the original source. Time period 1300–1993. Except for the adjustments mentioned above, original data have been kept. This means that no separation has been made between GMT and local times.
- *Location.* Latitude, longitude and focal depth. Events with quantified epicentral location within the area 44°N–72°N, 25°W–32°E.
- *Intensity,* I_0. The epicentral intensity, I_0, if quoted by the original source. There is no notable difference between the various intensity scales applied in the local catalogues, but experience tells that there may still be differences in the intensity assessment between and also within the different catalogues due to different routines in the compilation of macroseismic data and the subjectivity in their evaluation. Maximum observed intensities from offshore located earthquakes are sometimes listed by the local catalogues. They are not given in the Catalogue and also not used in the calculations of M_w.
- *Original magnitude and moment,* M_w. Events with $M_w \geq 3.50$. *Hanks and Kanamori*'s (1979) relation is used to calculate M_w from the seismic moment. If not given by the original source, M_w or the seismic moment is calculated from a magnitude concept – M_L, M_S, m_b or M_c – or from macroseismic data via M_L or M_S. Details of the calculation of M_w are given in previous text.
- *Reference.* The original reference, i.e., local catalogue (Table 1a) or special study (Table 1b), of each event. The Catalogue lists only one reference for each entry, although the parameters are sometimes taken from different sources, notably when only one or a few of the parameters have been reassessed in a special study.

Discussion and conclusions

Any earthquake catalogue should endeavour to homogenize the given parameters, especially the magnitude or any other strength measure. M_L is by far the dominant (and often the only) magnitude in most of the used catalogues and there is a heterogeneity between different local M_L scales, unknown to its extent, which only an analysis of basic seismogram data can possibly overcome. This has not been possible in the present study and the M_w values of the Catalogue are therefore not homogenized in a strict sense. The subjectivity in intensity assessments is another possible factor influencing the heterogeneity in the calculated M_w values. The approximate homogeneity of M_w can nonetheless be tested by comparison of values calculated for different catalogues, notably for events listed by more than one source. Although there is a good agreement in most cases, certain systematic discrepancies have been observed and are described below.

M_w values based on data from the Icelandic catalogue are usually 0.7–0.8 units larger than those from the *Global Hypocenter Data Base*, CD version 2.0 (1996). M_w based on Fennoscandian M_S magnitudes (*Ahjos and Uski*, 1992), which are reported primarily for large offshore events, agree well with those given by the *Global Hypocenter Data Base*, CD version 2.0 (1996) and with M_w values for offshore events based on *Musson*'s (1994) M_L magnitudes. As mentioned above, coda based M_w in this region (from *Ahjos and Uski*, 1992) give much lower values and are discarded. The Fennoscandian M_w values are generally low compared to the continental M_w values for similar intensities or M_L magnitudes. This is most likely an effect of the different local M_L scales.

The M_w values obtained for the Swiss catalogue (*Mayer-Rosa and Baer*, 1992) are slightly

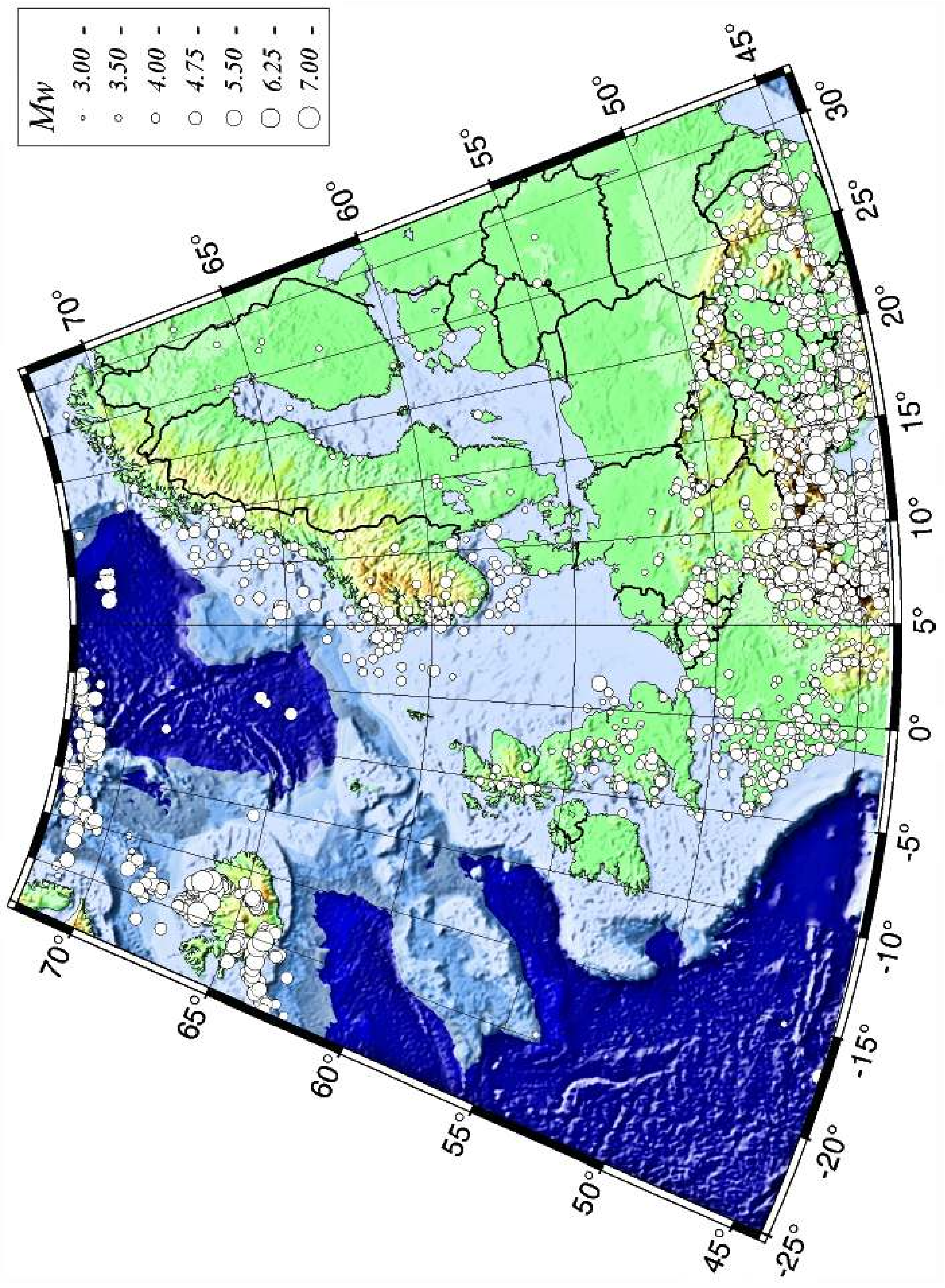

Figure 9. Epicentres of the Catalogue entries. Only tectonic earthquakes are plotted.

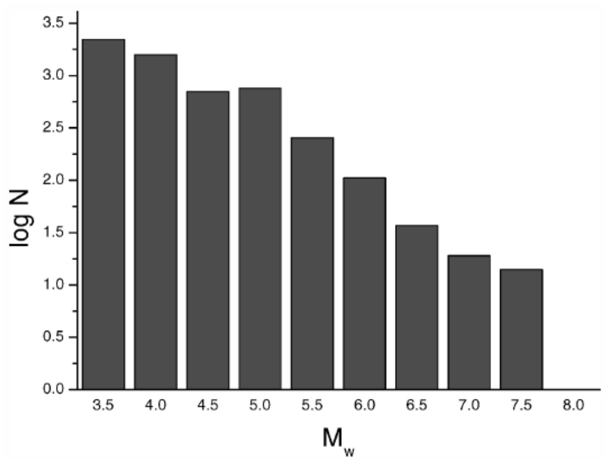

Figure 5. Input data and M_S vs. m_b chi-square maximum likelihood regression curve, eq. (6.1), and bilinear fit, equations (6.2) and (6.3), for events in *Global Hypocenter Data Base*, CD version 2.0 (1996) located in the polygon North Atlantic Ocean and Iceland. Eq. (6.2) is used in the interval for $4.5 < m_b < 5.04$ and eq. (6.3) for $m_b > 5.04$.

higher than the corresponding values from the catalogues of neighbouring countries, as are the M_w values calculated from intensity data in the Dutch catalogue (*Houtgast*, 1995) in comparison to neighbouring countries (*Levret et al.*, 1994; *Leydecker*, 1986, 1996; *Verbeiren et al.*, 1995).

The largest events for various geological areas with respect to the obtained M_w values are shown in Table 7. For simplicity, the geological regions are associated with the polygons (Figure 2): The Alpine region encompasses Italy, Switzerland, Austria, Slovenia, Croatia, Bosnia and Serbia, Hungary and Slovakia. Variscian Europe encompasses United Kingdom, the Netherlands, Belgium and Luxemburg, France, Germany, Poland and the Czech Republic. Fennoscandia, and the North Atlantic Ocean and Iceland, are represented by the single polygons with these names, with a modification for Fennoscandia mentioned below. For Vrançea, the earthquakes are easy to identify from their intermediate depth.

The two destructive Vrançea earthquakes in the past century, in 1940 ($M_w = 7.7$) and 1977 (M_w 7.4), are much larger than the strongest events in the complete record for central and northern Europe since 1300 outside Vrançea.

Two earthquakes in the mid 14th century are the dominant events in the Alpine region. The 1356 Basel earthquake was located at the border to the Variscian Europe region according to our definitions. Previous interpretations had lower magnitudes for this event. The historical Swiss earthquakes in general yield somewhat high M_w compared to events in neighbouring areas with similar intensities. The 1348 event ($I_0 = 10$, $M_S = 6.8$), formerly located in Villach (Austria), now falls inside the polygon Italy with $M_w = 6.5$.

Two earthquakes in Germany, in 1756 (Düren, $M_w = 5.8$) and 1911 (Ebingen, $M_w = 5.7$), and one in the North Sea in 1931 ($M_w = 5.8$) are topping the list in Variscian Europe. As a comparison, the 1992 Roermond, the Netherlands, earthquake has an M_w magnitude of 5.3.

While discrepancies in M_w obtained from different scales in Fennoscandia may bias the earthquake statistics for this region, the expected earthquakes are found in Table 7 (they are all based on M_S). The events without intensity have offshore locations. Whereas the Fennoscandian polygon is extended way offshore to give the catalogue of *Ahjos and Uski* (1992) priority (see Figure 2), only events in or near Fennoscandia are considered for Table 7.

The work to prepare the Databank from the many sources of different kinds and to establish selection criteria for the events entering the Catalogue has been lengthy and non-trivial. It is the hope of the authors that the Catalogue will be useful for broad applications in various fields of seismology and seismic hazard.

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