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ORIGINAL ARTICLE

# The SHARE European Earthquake Catalogue (SHEEC) 1000–1899

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**Abstract** In the frame of the European Commission project “Seismic Hazard Harmonization in Europe” (SHARE), aiming at harmonizing seismic hazard at a European scale, the compilation of a homogeneous, European parametric earthquake catalogue was planned. The goal was to be achieved by considering the most updated historical dataset and assessing homogenous magnitudes, with support from several institutions. This paper describes the SHARE European Earthquake

Catalogue (SHEEC), which covers the time window 1000–1899. It strongly relies on the experience of the European Commission project “Network of Research Infrastructures for European Seismology” (NERIES), a module of which was dedicated to create the European “Archive of Historical Earthquake Data” (AHEAD) and to establish methodologies to homogeneously derive earthquake parameters from macroseismic data. AHEAD has supplied the final earthquake list, obtained after sorting

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duplications out and eliminating many fake events; in addition, it supplied the most updated historical dataset. Macroseismic data points (MDPs) provided by AHEAD have been processed with updated, repeatable procedures, regionally calibrated against a set of recent, instrumental earthquakes, to obtain earthquake parameters. From the same data, a set of epicentral intensity-to-magnitude relations has been derived, with the aim of providing another set of homogeneous  $M_w$  estimates. Then, a strategy focussed on maximizing the homogeneity of the final epicentral location and  $M_w$ , has been adopted. Special care has been devoted also to supply location and  $M_w$  uncertainty. The paper focuses on the procedure adopted for the compilation of SHEEC and briefly comments on the achieved results.

**Keywords** Earthquake catalogue · Europe · Earthquake parameters · Magnitude · Parameters uncertainty

## 1 Introduction

The need for an authoritative earthquake catalogue, covering the whole Europe and a sufficiently long time window, has been increasingly recognised in recent years, in connection with the issues of seismic hazard assessment for supporting building codes, insurance industry and land use planning.

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Actually, while the number of national catalogues rapidly increased, no catalogue covering the entire European area was available before 2010. Some catalogues covered limited time window and/or regions. The prominent European catalogue by Kárník (1969, 1971) covered the time window 1800–1958, then expanded to 1990 (Kárník 1996). The Unesco “Balkan Project” promoted a major project which led to, among other results, the “Catalogue of earthquakes of the Balkan region” (Shebalin et al. 1974) and the related atlas of isoseismals maps (Shebalin 1974). An effort to compile a European catalogue was initiated by Van Gils (1988), with the goal of preparing, for the first time in a digital form, a harmonised compilation of the historical and recent seismic data provided by national catalogues, with the specific object of producing “seismicity maps” for seismic hazard evaluation at nuclear power plants. The catalogue, published as Van Gils and Leydecker (1991), spanned a time window from the ancient times to 1981 and covered the 12 member countries of the European Community as of 1986. Shebalin and Leydecker (1998) compiled the “Earthquake Catalogue for Central and South-eastern Europe (342 BC–1990 AD)”, with the purpose of extending the “New catalogue of USSR” by Kondorskaya and Shebalin (1982). The catalogue was compiled in two versions: (1) an extended one,

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containing all the available determinations from the investigated data sources, and (2) a summary one, containing a unified estimate of the parameters with uncertainty assigned. The seismicity of Europe was included in global seismicity databases, such as those by Dunbar et al. (1992), Utsu (2002) and the “Centennial Catalog” (Engdahl and Villaseñor 2002). However, these compilations mostly relied on regional catalogues that were not up-to-date.

A catalogue for Central, Northern and Northwestern Europe (CENEC; lat,  $\geq 44^\circ$  N) was published by Grünthal and Wahlström (2003). The catalogue, covering the time window 1300–1993, was compiled assembling national catalogues supplemented with data from specific studies, with a geographical priority scheme.  $M_w$  was assessed for all the earthquakes, through the conversion of the magnitude or intensity of the source catalogue, with published or specifically derived regressions. In 2009, CENEC was expanded to the years 1000 and 2004 (Grünthal et al. 2009a); in addition, the list of input catalogues was updated to include more recently published ones.

In 2006, the European Commission project “Network of Research Infrastructures for European Seismology” (NERIES) promoted a module dedicated to establishing a distributed archive of historical earthquake data 1000–1899 and providing methodological experience for assessing earthquake parameters from macroseismic data points (MDPs).

In 2010, the compilation of a homogeneous, European earthquake catalogue was planned in the frame of the European Commission project SHARE (“Seismic Hazard Harmonisation in Europe”), to be built on the NERIES and CENEC experiences. It was then agreed that the time window 1000–1899 would be compiled under the coordination of Istituto Nazionale di Geofisica e Vulcanologia, Milan, while the time window 1900–on would be compiled by GeoForschungsZentrum, Potsdam, which later developed it into EMEC, the European Mediterranean Earthquake Catalogue (Grünthal and Wahlström 2012).

This paper describes the catalogue covering the time window 1000–1899, hereafter referred to as SHEEC, the SHARE European Earthquake Catalogue.

We first summarise how the earthquake list and the relevant background information have been compiled. Then we present the procedures adopted

for determining the earthquake parameters from MDPs or from regional parametric catalogues, the criteria for determining the final assessment and the relevant uncertainty. We then describe and comment on the results.

## 2 Compilation strategy

Earthquake catalogues are usually compiled assessing parameters from the background information, which consists of earthquake studies, intensity data points, previous catalogues, etc.; very often, this material is unpublished and available only to national compilers. An investigator wishing to compile a comprehensive European catalogue has little access to most of such material; therefore, in principle, he/she can only proceed recompiling regional catalogues.

This procedure, however, has advantages and limitations.

The first limitation is that regional catalogues are not always the best source of information for the respective area, because historical information is not always preserved “at home” and may not have been investigated by national investigators. Moreover, regional catalogues are not updated frequently; therefore, the results of the most recent investigations do not flow immediately into them. The second, main limitation is that the inhomogeneity of the parameters of the varied catalogues can be very large (see for instance the results of the survey performed by Stucchi and Bonnin 1995; Cecić et al. 1996, etc.).

Van Gils (1988) was aware of such limitations; he clearly stated that, in the future: (1) macroseismic data should be collected systematically, and (2) historical data should be gathered and treated homogeneously, with particular reference to earthquakes with effects crossing national borders.

Following these ideas, at the turn of the 1990s, the EC project “Review of Historical Seismicity in Europe” (RHISE, 1989–1993; Stucchi 1993; Albini and Moroni 1994) compiled some recommendations (Stucchi 1994; Camassi et al. 1994). In 1995–1998, the EC project “A Basic European Earthquake Catalogue and a Database” (BEECD) was funded with the aim of establishing and testing the methodologies for compiling a parametric

earthquake catalogue of Europe starting from the creation of a database of primary data (Stucchi and Camassi 1997; Albini and Stucchi 1997; Stucchi 1998). Boschi et al. (1995, 1997, 2000) compiled a database of the largest earthquakes in Italy, including short summaries.

In the same years, the main agencies of three European countries, Italy, France and Switzerland, started:

- Building up national archives of background information (Monachesi and Stucchi 1997; SisFrance 2001; Swiss Seismological Service 2002) and
- Compiling, from such material, homogeneous catalogues. This goal was achieved adopting formalised, transparent procedures for determining the earthquake parameters from MDPs.

These examples showed that an alternative strategy could allow the two abovementioned limitations to be overcome. Should the background information be available for all earthquakes, earthquake parameters would be determined from them and there would be no need to recompile regional catalogues.

SHEEC has been compiled following, as much as possible, the new strategy. At a European level, a distributed archive of background information 1000–1899, called Archive of Historical Earthquake Data (AHEAD; <http://www.emidius.eu/AHEAD/>), was built (Rovida et al. 2009; Albini and Locati 2009; Locati et al. 2010) in the frame of the already mentioned NERIES project. The same project addressed the tasks of (1) selecting procedures for assessing earthquake parameters from macroseismic data points and (2) testing them to determine the parameters of the largest historical events.

The working scheme of SHEEC compilation is presented in Fig. 1.

### 3 The earthquakes and the related background information

The main goal of AHEAD was to build up, at a European scale, what France, Switzerland and Italy had already started independently. In particular, AHEAD inventories and makes available the results of the historical investigations compiled in a format suitable for being used by seismologists: a report or a paper providing an overview of the investigation and the distribution of the effects; a map and/or a list of MDPs, etc. This is what we call background information, or a “root”. AHEAD considers:

1. The most recent online archives providing MDPs, such as: the Swiss ECOS-02 (Swiss Seismological Service 2002) and ECOS-09 (Fäh et al. 2011), the latest version of SisFrance (BRGM-EDF-IRSN/SisFrance 2010), DBMI04 (Stucchi et al. 2007), the macroseismic databases of UK (British Geological Survey 2010), Greece (University of Thessaloniki 2003; University of Athens 2010), Iberian region (Instituto Geográfico Nacional 2010) and Catalunya (Olivera et al. 2006);
2. The volumes by Alexandre (1990) and by Guidoboni and Comastri (2005), little exploited by the regional catalogues of Central Europe and Eastern Mediterranean, respectively;

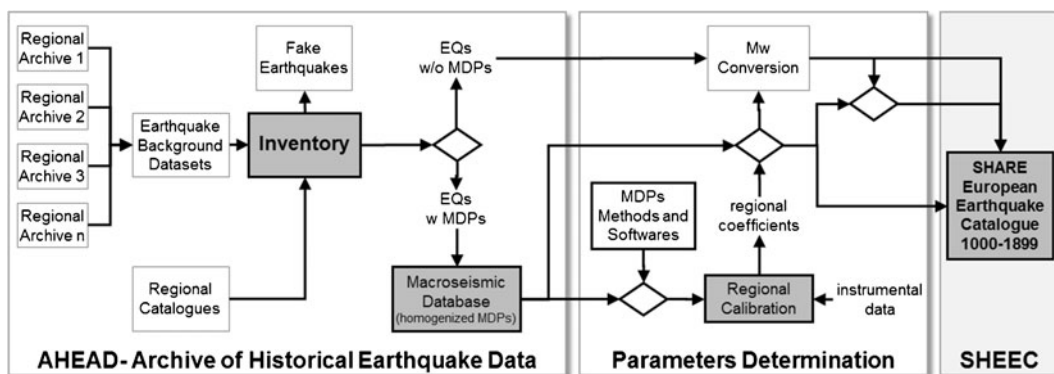


Fig. 1 Working scheme for compiling SHEEC

3. A number of new studies of Italian earthquakes, providing MDPs, now included in the new version of the Italian DBMI11 (Locati et al. 2011);
4. A number of recent historical studies on individual earthquakes; and
5. The main current catalogues and the relevant roots, when available.

The compilation of AHEAD required dealing with the fact that different roots may refer to the same earthquake; they can provide coinciding or conflicting information. The roots referring to the same earthquake have been clustered case by case, examining and comparing their content. This work has allowed us to critically solve, among others, the problems of:

- (a) Duplications, that are earthquakes with different origin time and/or location, due to conflicting interpretations of the historical record(s) provided by different studies but basically the same event;
- (b) Fake events, usually created by the incorrect interpretation of historical records referring to other natural phenomena, such as landslides or storms; and
- (c) Earthquakes missing in one or more catalogues.

As a result of this work, the AHEAD inventory provides a reliable earthquake list, which has been adopted by SHEEC.

It contains 4,722 earthquakes with approximately  $I_0 > 5$  and/or  $M > 3.5$ ; it covers the territories belonging to EU member states and neighbouring areas up to  $32^\circ$  E.

For about 51 % of them, the roots provide MDPs (42,358 data points), derived from databases or literature (Appendix 1). For 40 % of the earthquakes, we could retrieve a root without MDPs, while for the remaining 9 % we could not. For these events, only the entries from national or regional catalogues are available, without any possibility of tracking the relevant, supporting background information. Figure 2 shows the area covered by AHEAD and the earthquakes with and without MDPs.

It is worthwhile noticing that 306 earthquakes with roots providing MDPs, including some destructive ones, are new even to the most recent regional catalogues. These earthquakes are mostly located in Italy and the Eastern Mediterranean, plus some in Germany. Furthermore, for other 812 earthquakes the study providing MDPs is more recent than the regional catalogue.

## 4 Earthquake parameters

### 4.1 Strategy

For the purpose of harmonising seismic hazard across Europe, the SHARE project required a homogeneous catalogue based on the most updated knowledge, compiled in terms of  $M_w$ , with transparent and repeatable procedures, and with uncertainty estimates of the main parameters. Moreover, as a collaborative project, it also required to consider the regional knowledge supplied by the best, regional current catalogues.

To fulfil these requirements, for each earthquake two sets of main parameters (latitude, longitude and  $M_w$ ) have been determined, when possible, according to two approaches:

- Dataset (1) Parameters determined processing MDPs with homogeneous, repeatable procedures supplying location,  $M_w$  and uncertainty estimates;
- Dataset (2) Parameters derived from the most reliable regional catalogues. In particular,  $M_w$  has been assessed from the epicentral intensity ( $I_0$ ) provided by such catalogues, coherently with dataset (1).

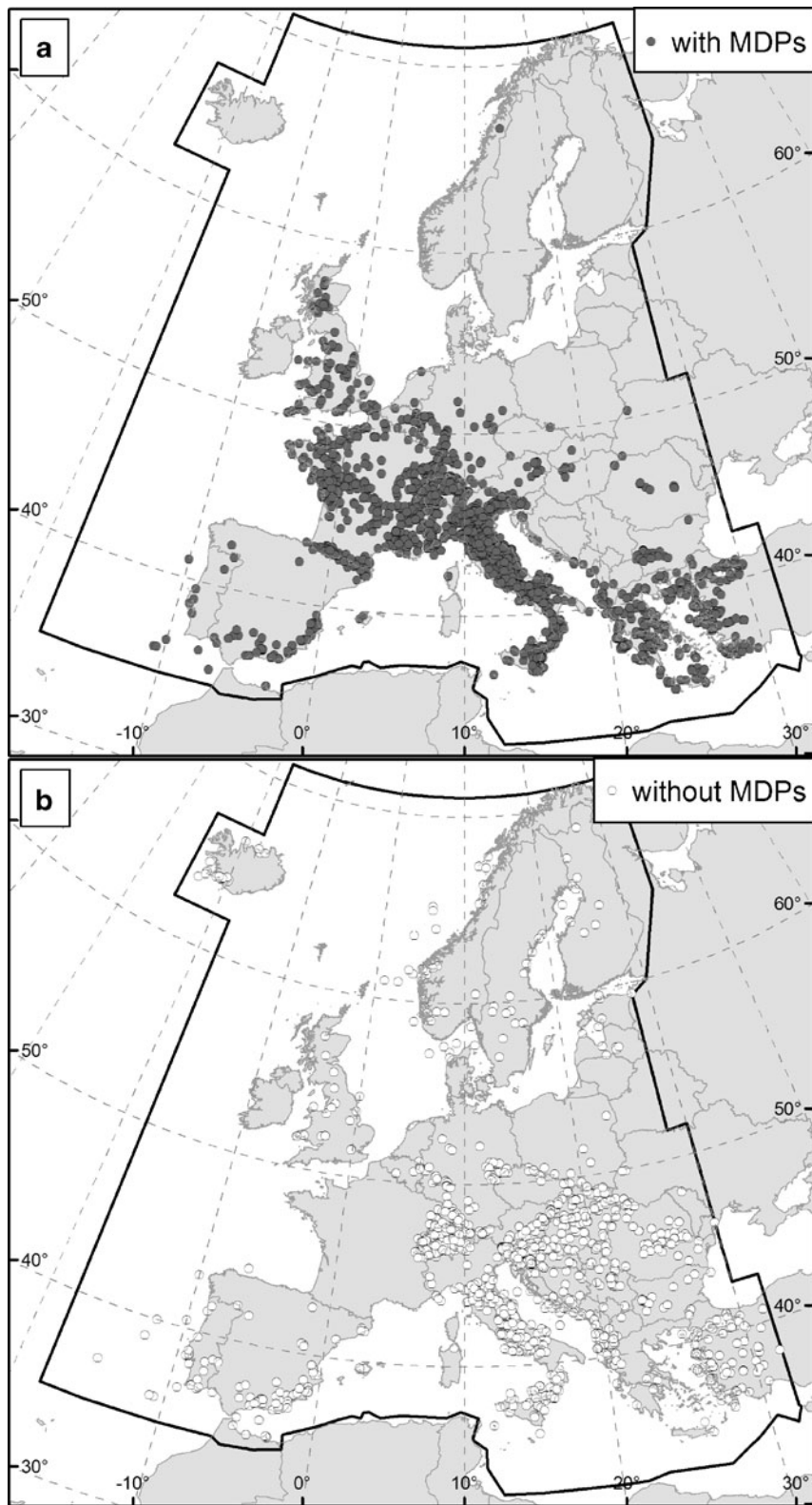
The details of how datasets (1) and (2) have been determined are given in Sections 4.2 and 4.3.

Once datasets (1) and (2) have been prepared, the SHEEC 1000–1899 parameters have been determined from them as follows:

- The epicentral parameters (latitude, longitude and uncertainty) have been selected from either dataset (1) or (2) according to a priority scheme; and
- The  $M_w$  value and related uncertainty has been:
  - (a) Determined as the weighted mean of datasets (1) and (2), when they are both available;
  - (b) Obtained from dataset (1), when it is the only available one;
  - (c) Obtained from dataset (2), when it is the only available one.

### 4.2 Parameters determined from MDPs: dataset (1)

Three methods which provide repeatable procedures for processing MDPs (from now on MDPs methods) were considered:



**Fig. 2** Area covered by AHEAD and distribution of earthquakes with MDPs (a) and without MDPs (b)

- (a) Boxer, version 4.0 (model 0; Gasperini et al. 2010, equivalent to version 3.3; Gasperini et al. 1999);
- (b) MEEP (Musson and Jiménez 2008); and
- (c) B&W (Bakun and Wentworth 1997).

A short comparison of these methods can be found in Bakun et al. (2011). They are based on the attenuation of macroseismic intensity as a function of the earthquake magnitude and the distance from the epicentre. They rely on different attenuation models that need to be calibrated with data from modern earthquakes, i.e. with reliable instrumental magnitude and MDPs distributions.

The calibration of the MDPs methods required the definition of different attenuation regions, accounting for a number of factors including:

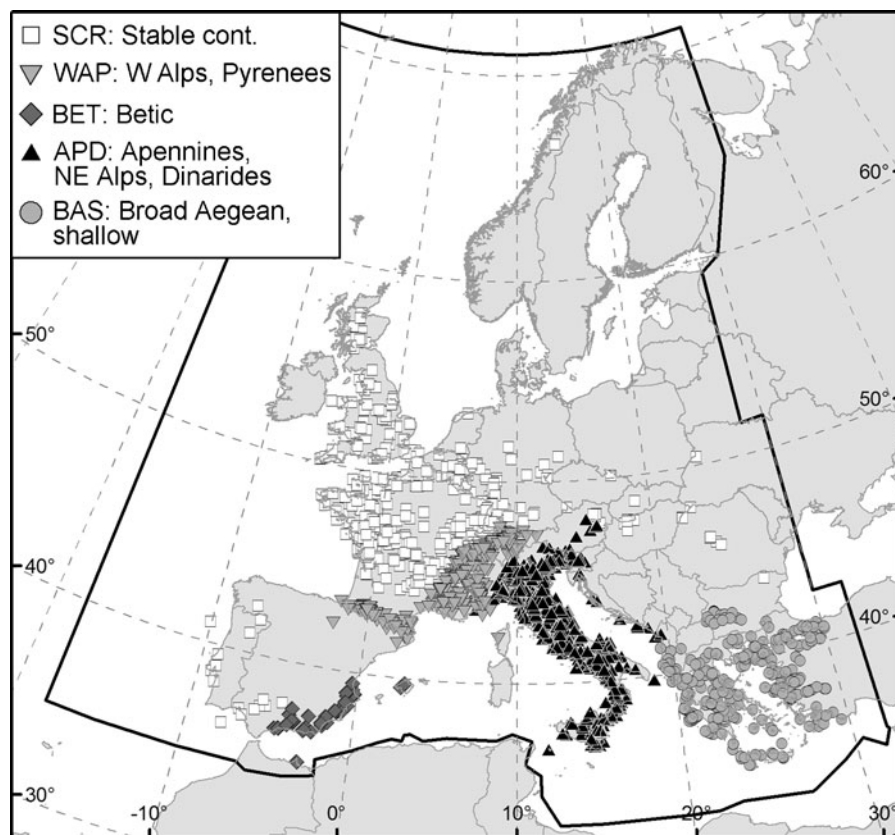
- Regional attenuation characteristics;
- Regional peculiarities of intensity assessment; and

- Availability of a good set of calibrating data, both instrumental and macroseismic.

For each of the three methods, the attenuation models have been derived with reference to the following, five regions (Fig. 3):

- Stable continental region (SCR)
- Western Alps and Pyrenees (WAP)
- Betic (BET)
- Apennines, North-Eastern Alps and Dinarides (APD)
- Broad Aegean, shallow (BAS)

To ensure homogeneity of the results, the attenuation models required by the three MDPs methods have been derived using, in each region, the same set of calibrating events. As a whole, 482 earthquakes of the twentieth century, with instrumental  $M_w$  ranging from 3.3 to 7.1, and supported by 70,752 MDPs, were considered.



**Fig. 3** Earthquakes for which parameter dataset (1) has been determined and their assignment to the five regions in which the MDPs methods have been calibrated

**Table 1** Main features of the datasets used for deriving the Mw (Io) relations for the calibration regions and relevant linear equation with its standard deviation. BET Betic, SCR stable continental region, WAP Western Alps and Pyrenees, APD

Region	No earthquakes	Io range	Mw range	Equation	$\sigma$
BET	32	4.0–8.0	3.3–6.2	$M_w = 1.487 + 0.552 * I_o$	0.38
SCR	26	4.5–8.0	3.6–5.6	$M_w = 0.528 + 0.655 * I_o$	0.25
WAP	17	5.0–8.5	3.5–5.8	$M_w = 1.441 + 0.502 * I_o$	0.31
APD	345	5.5–11.0	4.0–7.0	$M_w = 2.182 + 0.423 * I_o$	0.34
BAS	62	5.0–10.0	4.6–7.1	$M_w = 3.404 + 0.355 * I_o$	0.25
Central Europe	41	5.0–9.5	3.0–6.4	$M_w = 0.160 + 0.682 * I_o$	0.32

The relation for Central Europe by Grünthal et al. (2009b) is shown for comparison

*BET* Betic, *SCR* stable continental region, *WAP* Western Alps and Pyrenees, *APD* Apennines, North-Eastern Alps and Dinarides, *BAS* Broad Aegean, shallow

Several trials of calibration and validation all over Europe allowed for checking the stability of the methods and related regional coefficients. In the end, the choice was in favour of Boxer 4.0 (model 0) for most events of the five regions. MEEP was used for both onshore and offshore events in the UK area. B&W was used for a few, offshore events.

Altogether, we have processed the MDPs of 2,410 earthquakes (Appendix 1).

#### 4.3 Parameters derived from regional catalogues: dataset (2)

Dataset (2) builds on 30 main regional catalogues selected on the basis of their reliability, transparency and covered area; publicly available catalogues and those providing references have been preferred. They are listed in Appendix 2 together with the respective area, the type of size measure, the number of entries considered and whether they quote their references or not.

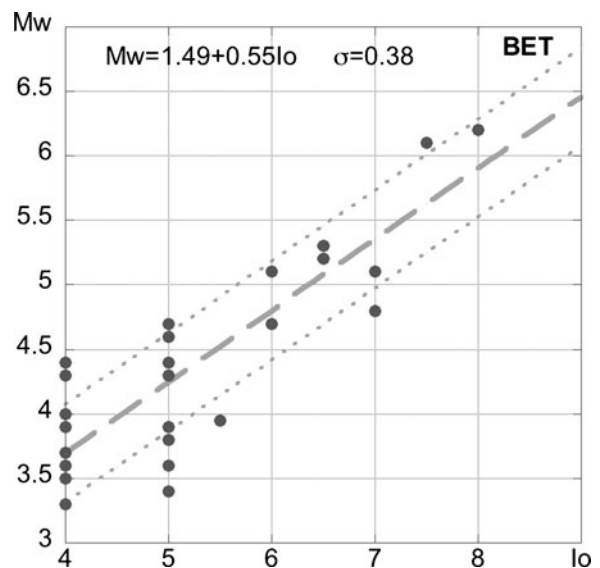
Although epicentral locations provided by the regional catalogues are determined according to varied criteria, we had no other alternative than to adopt them as they were.

As for the earthquake size, we have adopted the following criteria:

- (a) When the catalogues provide Mw values, we have adopted them without modifications;

Apennines, North-Eastern Alps and Dinarides, *BAS* Broad Aegean, shallow. The relation for Central Europe by Grünthal et al. (2009b) is shown for comparison

- (b) In the other cases, when Io was available we have preferred to calculate Mw from Io, considering that in time window before 1899 any magnitude value is obviously derived—in some way—from macroseismic data. For homogeneity with the Mw of dataset (1), we derived five Mw (Io) relations (Table 1) using, for each region, the same datasets used for calibrating the MDPs methods. Figure 4 shows the relation determined for the Betic region.



**Fig. 4** Mw (Io) relation (*dashed bold line*) determined for the Betic region. The standard deviation is represented with the *dashed lines*



**Table 2** Catalogues providing neither  $I_o$  nor  $M_w$  and adopted solution (with reference) for deriving SHEEC  $M_w$

Catalogue	Entries	Original M	SHEEC $M_w$	Reference
University of Helsinki (2007)	38	Ms	Ms	Bungum et al. (2003)
Icelandic Meteorological Office (2007)	13	Ms	Ms	Grünthal et al. (2009a)
Ambraseys and Sigbjörnsson (2000)	8	Ms	Ms	Grünthal et al. (2009a)
LNEC (1986)	4	Ms	Ms	Bungum et al. (2003)
Martins and Mendes Victor (2001)	11	M (not specified)	M	
Musson (1994)	16	ML	$0.0376 * ML^2 + 0.646 * ML + 0.53$	Grünthal et al. (2009a)

(c) In the very few cases when neither  $M_w$  nor  $I_o$  were available (Table 2), we used Ms values considered equivalent to  $M_w$  (Bungum et al. 2003; Grünthal et al. 2009a) or we converted the original ML using the relation by Grünthal et al. (2009a).

#### 4.4 The SHEEC parameters

After having datasets (1) and (2) ready, the main SHEEC parameters have been determined as follows:

*Time* It has been adopted as it is from the AHEAD inventory and, consequently, from the selected study.

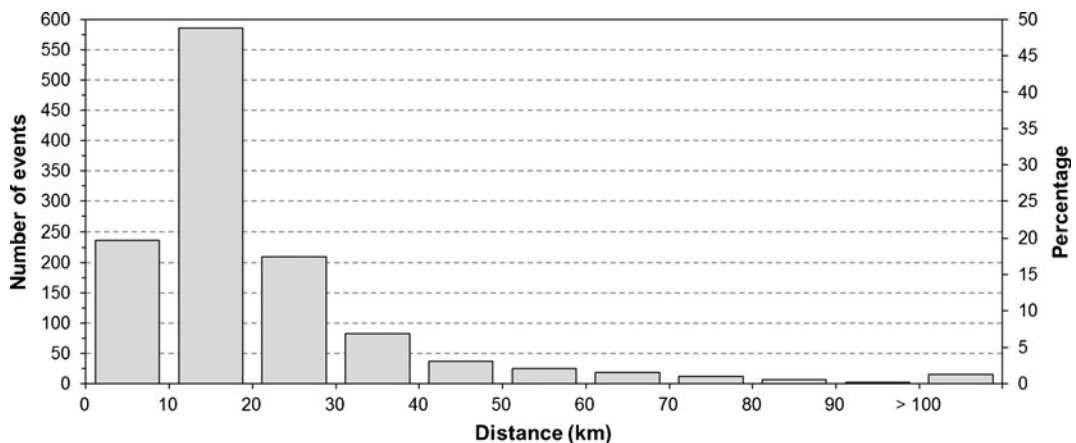
*Location* The epicentral location has been adopted from either dataset (1) or (2), according to the following criteria:

(a) When only dataset (1) or (2) is available, the relevant location has been adopted;  
 (b) When both datasets (1) and (2) are available, priority has been given to dataset (1), with the following, main exceptions:

1. All earthquakes in Baumont and Scotti (2011) since the relevant  $M_w$  values are said to be valid only in relation with the epicentres of that catalogue;
2. All earthquakes in Fäh et al. (2011) since the relevant epicentres derive from MDPs processing (Álvarez-Rubio et al. 2012);

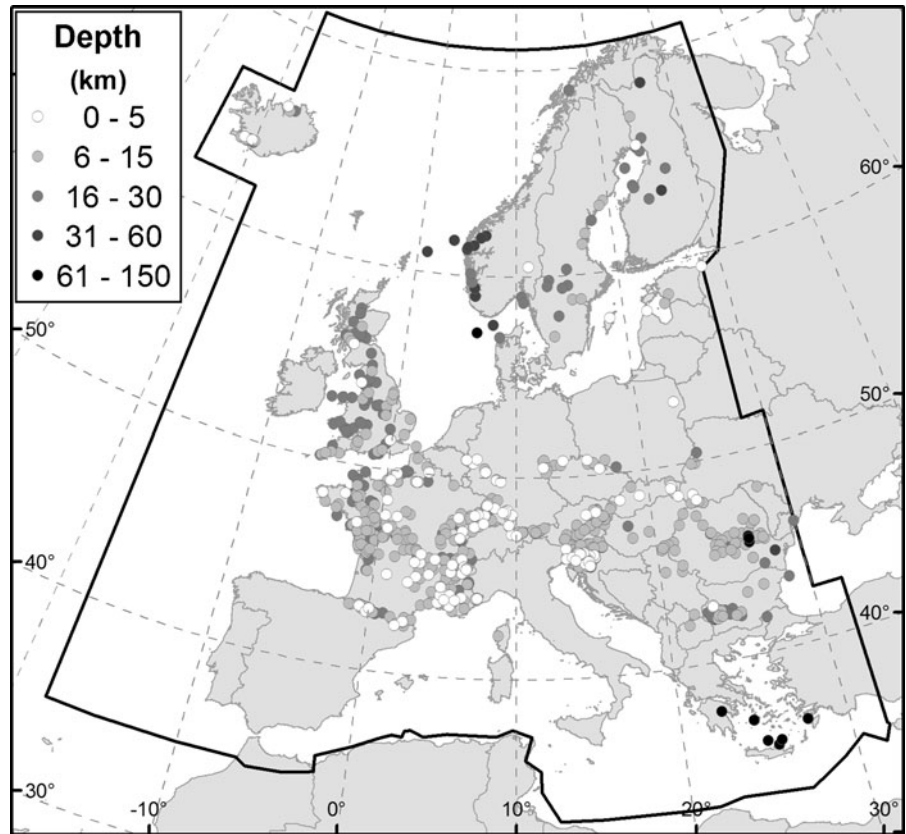
Summarising, SHEEC epicentres derive from dataset (1) for 37 % of the earthquakes; from dataset (2) for 63 %.

We evaluated the distances between the epicentres from datasets (1) and (2) when both are available



**Fig. 5** Frequency distribution of the distances between epicentres from datasets (1) and (2), when both are available

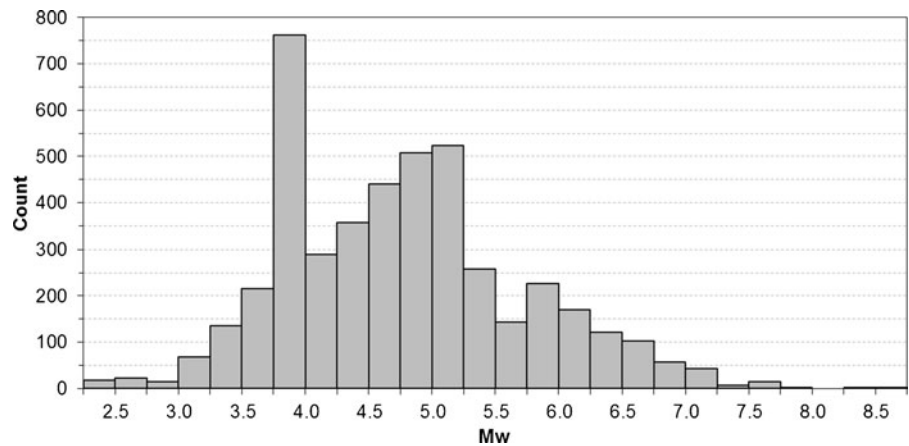
**Fig. 6** Depth distribution of earthquakes. For UK it comes from the MEEP determinations



(Fig. 5). Many of such distances are due to the adoption of MDPs method and updated roots with respect to the regional catalogues. For most of them, the distance is less than 50 km. Distances larger than 50 km are mostly observed in the Broad Aegean and in the UK areas.

*Depth* The assessment of depth is a controversial issue, even for modern instrumental earthquakes. Depth values of historical earthquakes seem to derive, in some cases, from circular thoughts (such as “since in this area there are a few events with such a depth value, all the events in the area may have the same

**Fig. 7** Distribution of  $M_w$  values in SHEEC



depth”). As for the MDPs methods, only MEEP provides a depth value between 0 and 20 km, and related uncertainty. The adoption of Boxer 4.0, model 0, implies that depth is not assessed for most earthquakes with MDPs. This choice is coherent with the above considerations concerning the poor reliability of many estimates. Therefore depth values, either from MEEP—for the UK—or from the regional catalogues, for a total of 1,079 earthquakes (Fig. 6), are provided in SHEEC as additional information, only.

*Magnitude*  $M_w$  has been determined according to one of the following rules:

- (a) When  $M_w$  from datasets (1) and (2) are both available, SHEEC  $M_w$  has been determined as their mean, weighted according to the following, main scheme (see also Appendix 2):
  - A weight of 0.75 has been given to  $M_w$  from dataset (1) and a weight of 0.25 to  $M_w$  from dataset (2) and
  - The opposite weighting scheme, i.e. 0.25 for  $M_w$  from dataset (1) and 0.75 for  $M_w$  from dataset (2), has been adopted for the entries from Baumont and Scotti (2011) and from Fäh et al. (2011) since these catalogues are compiled—in their turn—making use of MDPs;

- (b) When only dataset (1) is available, the relevant  $M_w$  has been adopted;
- (c) When only dataset (2) is available, the relevant  $M_w$  has been adopted.

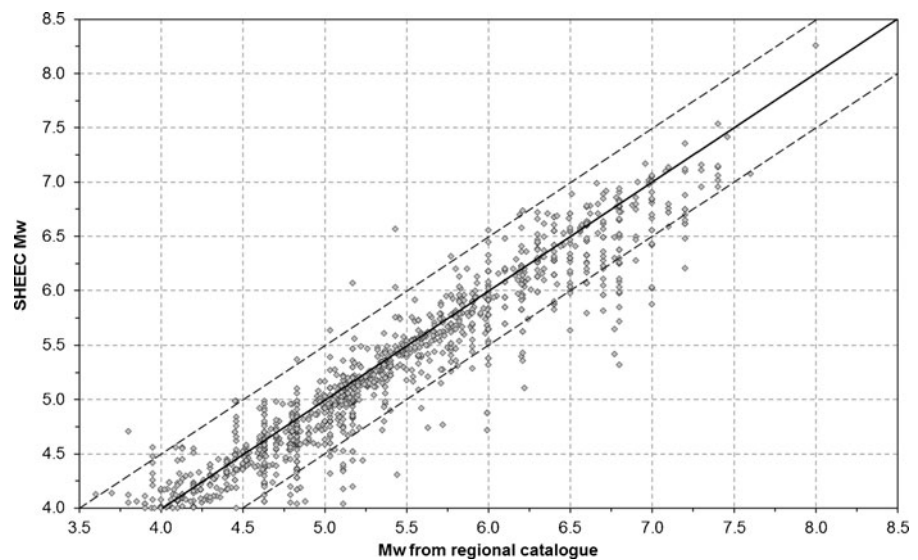
For 224 earthquakes whose background information is contradictory, no  $M_w$  has been determined; they are listed in the catalogue with time and location only.

The distribution of  $M_w$  values is presented in Fig. 7. A few earthquakes with  $M_w < 3.0$  are also included. The peak between  $M_w 3.75$  and 4.00 mainly derives from the conversion of  $I_0=5$  or 5–6, of a large number of non-damaging aftershocks from Fäh et al. (2011) and Živčić (2009).

Comparison between the SHEEC  $M_w$  and the values from the regional catalogues can be made for 1,829 earthquakes for which  $M_w$  has been assessed as the weighted mean (Fig. 8).

SHEEC  $M_w$  tend to be lower than those derived from the regional catalogues. The reason is to be found in: (a) the use of MDPs rather than maximum intensity, only and (b) the use of more recent studies which, as a general trend, provide less severe earthquake scenarios. About 50 % of  $M_w$  show a decrease of up to 0.3  $M_w$  unit.

**Fig. 8** Comparison of SHEEC  $M_w$  values ( $\geq 4$ ) with  $M_w$  values obtained or recalculated from a regional catalogue



Differences reach up to 1.0 Mw unit, either plus or minus, in a small percentage of cases.

## 5 Uncertainty

The issue of assessing of the parameters' uncertainty is another controversial one. On the one hand, users increasingly ask for it; on the other hand, the variety of rules, criteria and procedures used for assessing location uncertainty is large. Not supplying uncertainty may let the catalogue compilers feel better but it cannot avoid users to adopt arbitrary estimates. Therefore, the SHARE request for parameters uncertainty was accomplished with the understanding, and the warning, that the released estimates are preliminary.

### 5.1 Uncertainty: location

The variety of rules, criteria and procedures used for assessing location uncertainty is enormous.

Boxer 4.0 and MEEP provide uncertainty estimates for the epicentre, according to their own procedures. In general, the uncertainty depends on the number and spatial distribution of the input MDPs and it is not influenced by other factors such as the magnitude of the earthquake; Boxer provides asymmetrical uncertainty with respect to latitude and longitude. B&W supplies varied levels of confidence of the location as contour lines, difficult to be translated into catalogue parameters. When the number of MDPs is small, all MDPs methods do not supply uncertainty.

The uncertainty supplied by regional catalogues show a large variability of values, often derived from unclear or unrepeatable criteria. Baumont and

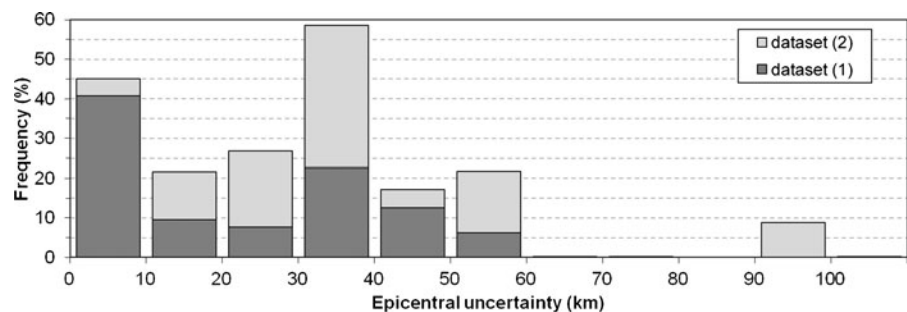
Scotti (2011), Fäh et al. (2011), Martinez Solares and Mezcuca Rodriguez (2002) assess uncertainty as classes ranging from a few kilometres to more than 50 km and over 100 km; University of Helsinki (2007), Kondorskaya and Shebalin (1982) and Shebalin and Leydecker (1998) up to 1°. On the other side, Grünthal (1988) allows a maximum of 6 km. Some catalogues such as LNEC (1986) and Soysal et al. (1981) provide only the “quality” of the assessed epicentre, rather than an uncertainty estimate. More than half of the considered catalogues do not provide epicentral uncertainty at all.

Consequently, we have adopted the following rules:

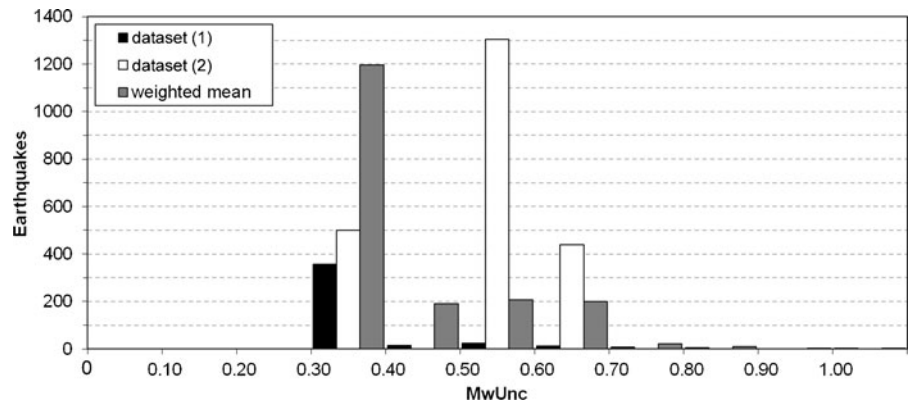
- When the location is determined by MEEP or Boxer 4, the uncertainty supplied by them is adopted;
- When the location is chosen from a catalogue providing uncertainty, it is adopted; values in degrees have been converted to kilometres;
- When the location is chosen from B&W, or when MDPs distributions do not allow Boxer or MEEP to assess it, default values ranging from 30 (onshore earthquakes) to 50 km (offshore earthquakes) are adopted;
- When the location is chosen from a catalogue not providing uncertainty, default values of 40 (onshore earthquakes), 50 (offshore earthquakes) or 100 km (when a catalogue assessed “undefined” uncertainty or values/classes such as >50 km) are adopted.

The distribution of location uncertainty is presented in Fig. 9.

**Fig. 9** Frequency distribution of location uncertainty values from datasets (1) and (2)



**Fig. 10** Distribution of the Mw uncertainty values in SHEEC



5.2 Uncertainty: magnitude

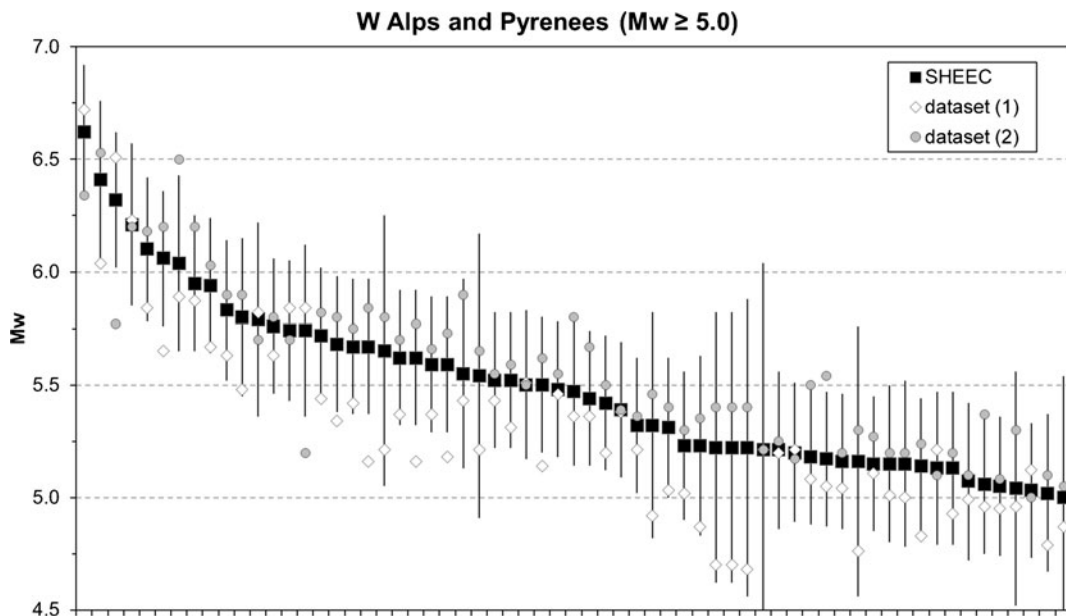
The MDPs methods provide Mw uncertainty according to their own procedures. B&W assesses it as a function of the number of MDPs used; MEEP uses a bootstrap resampling technique; Boxer 4.0 computes both formal and bootstrap uncertainties.

Among the considered regional catalogues, only Fäh et al. (2011), Baumont and Scotti (2011), Papazachos and Papazachou (2003) and CPTI

Working Group (2004) provide Mw uncertainties (see also Appendix 2).

We have adopted the following rules for the assessment of Mw uncertainty (MwUnc):

- (a) When Mw is determined from MDPs methods, the uncertainty provided by the selected method is adopted if larger than 0.3; otherwise, it has been fixed at 0.3. The same value has been adopted when the MDPs methods do not compute the uncertainty;



**Fig. 11** SHEEC Mw values ( $\geq 5.0$ ) determined as the weighted mean of the Mw from datasets (1) and (2) for the Western Alps and Pyrenees area. Bars indicate the uncertainty. The graph is ordered from left to right by decreasing Mw

- (b) When  $M_w$  is obtained from dataset (2), the uncertainty has been assessed as either:
1. The one provided by the relevant catalogue. In the case of Baumont and Scotti (2011), who supply asymmetrical uncertainty, the maximum of the two values has been used;
  2. A default value of 0.3 or 0.5, when no uncertainty is available or when  $M_w$  has been obtained from the conversion of  $I_0$ ; and
  3. The uncertainty associated to the regression from another type of magnitude;
- (c) When  $M_w$  is obtained as the weighted mean of the values from MDPs methods and from a regional catalogue, the relevant uncertainty  $M_wUnc$  is calculated as the square root of the sum of the squares of the uncertainties, each multiplied by its own assigned weight:

$$MwUnc = \sqrt{w_m * MMwUnc^2 + w_c * CMwUnc^2}$$

where  $MMwUnc$  and  $CMwUnc$  are the uncertainties of the magnitude values determined, respectively, from MDPs and from the regional catalogues, and  $w_m$  and  $w_c$  are the weights respectively assigned to them.

The rationale for this decision is that, as the averaged estimates are obtained with different methods, the average variance depends on the variance of all the estimates, proportionally to the weight assigned to each of them. In the calculation of the uncertainty associated to  $M_w$ , the weights are interpreted as the multiplicity of each magnitude value divided by the sum of the multiplicities.

For the whole of SHEEC, the  $M_w$  uncertainty ranges between 0.3 and 1.2, with a higher density around 0.3–0.4 and 0.5–0.6 (Fig. 10).

In conclusion, Fig. 11 shows, for the area of Western Alps and Pyrenees and for  $M_w \geq 5.0$ , the input  $M_w$  and the SHEEC  $M_w$  values, giving an idea of the “blending effect”. The uncertainties are also presented; they show that in most cases the differences between the  $M_w$  values related to each earthquake are within the uncertainty itself.

## 6 Conclusions

The main goal of SHEEC is to supply the SHARE project and a broad community of users with a European parametric earthquake catalogue, as much homogeneous as possible, for the time window 1000–

1899. To accomplish this goal, we used the best available data and the most updated methodologies.

The best available data come from AHEAD, the collaborative Archive of Historical Earthquake Data compiled in the frame of the NERIES project. The AHEAD compilation has allowed us:

- To inventory the most recent historical earthquake studies, including those not used for the compilation of the most recent national catalogues, yet;
- To sort the duplications out; and
- To remove a significant number of fake events.

The AHEAD inventory has supplied the SHEEC earthquake list. It contains 4,722 earthquakes, including 306 earthquakes so far unknown to regional catalogues.

The SHEEC earthquake parameters have been determined by blending, when possible, two sets of parameters homogeneously determined for each entry:

- Dataset (1) Obtained from MDPs processing  
 Dataset (2) Obtained from the parameters of the most reliable regional catalogues, assessing  $M_w$  according to homogeneous procedures

Dataset (1) has been determined for 2,253 earthquakes for which 41,425 MDPs were available. For the first time in Europe, a massive exercise of parameters determination by means of repeatable procedures, namely the methods Boxer (Gasperini et al. 1999, 2010), B&W (Bakun and Wentworth 1997) and MEEP (Musson and Jiménez 2008), with attenuation models homogeneously calibrated throughout Europe, was performed.

Dataset (2) has been determined for 4,221 earthquakes. We have assessed  $M_w$  from  $I_0$  for 1,579 earthquakes, using five ad hoc relations obtained with the same datasets used for calibrating the attenuation models mentioned above.

The final SHEEC parameters consist of a combination of datasets (1) and (2), when both are available (40 % of the earthquakes). In these cases, the SHEEC parameters have been determined according to the following rules:

1. Location—dataset (1) has been selected in the majority of the cases;
2. Magnitude—it has been calculated as the weighted mean of  $M_w$  from datasets (1) and dataset (2) giving higher weight to the values determined from MDPs methods.

The final SHEEC parameters derive entirely from dataset (1) for the 10 % of the earthquakes and from dataset (2) for 50 % of the cases.

An uncertainty estimate has been assessed for both location and Mw of all entries, using the values provided by either dataset (1) or (2). When Mw has been determined as weighted mean, the uncertainty has been assessed as the square root of the sum of the squares of the uncertainties, each multiplied by its own assigned weight.

The basic elements for the completeness assessment are described in Appendix 3.

In conclusion, we believe that SHEEC 1000–1899 represents a step forward from many points of view, which was made possible by the collaborative effort of many investigators and by the initiative of two European Commission projects, NERIES and SHARE.

Authors are aware that not all problems are solved yet; the main ones are the lack of background information for many events and the lack of data, including those of the twentieth century, for improving the attenuation models. We believe that the community of European investigators will be able to improve this situation in the future.

The catalogue is available at <http://emidius.eu/SHEEC/>.

**Acknowledgements** Earthquake catalogues are generally compiled by individual scientists or small teams. SHEEC 1000–1899 stems from the collaborative effort of several scientists— included in the authorship—either partners of the SHARE project or independent contributors. The catalogue owes much to other scientists, who contributed basic data to AHEAD, namely R. Camassi, I. Cecic, R. Glavcheva, G. Grünthal, Ch. Hammerl, C. S. Oliveira, A. Roca and R. Wahlström. We also acknowledge the contribution of R. Basili, F. Carrilho, V. D’Amico, J. Fonseca, B. Glavatovich, P. Mäntyniemi, C. Mirto, M. Pagani, G. Valensise and M. Zare. J. Wössner took care of the full use of the catalogue into the SHARE hazard computation. A special thank goes to Bill Bakun for his constant and precious assistance dealing with the earthquake parameters determination. This work has been supported by the EC-Research Framework programme FP7, Seismic Hazard Harmonization in Europe, Grant Agreement No. 226769.

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## Appendix 1

**Table 3** Databases, volumes and studies archived in AHEAD and providing MDPs to SHEEC. The area covered, the number of earthquakes, and the total number of MDPs are also shown

Type	Reference	Area	Number of earthquakes	Total MDPs number
Online databases	British Geological Survey (2010)	UK	70	4,438
	SisFrance (BRGM-EDF-IRSN 2010)	France	584	7,752
	ECOS-02 (Swiss Seismological Service 2002), ECOS-09 (Fäh et al. 2011)	Switzerland	214	2,195
	DBMI04 (Stucchi et al. 2007)	Italy	303	3,862
	Instituto Geografico Nacional (2010)	Iberia	66	794
	Olivera et al. (2006)	Catalunya	12	323
	University of Thessaloniki (2003)	Aegean	259	845
	University of Athens (2010)	Aegean	92	807
Volumes	Alexandre (1990)	France, Belgium, Germany	40	117
	Guidoboni and Comastri (2005)	Eastern Adriatic coast, Aegean	66	140
Studies on Italian earthquakes included in DBMI11 (Locati et al. 2011)	Many	Italy	617	15,894
Studies on individual earthquakes	Many	Many	84	5,191
	Total		2,410	42,358

## Appendix 2

**Table 4** Adopted, main regional catalogues with their principal features, assigned attenuation region, number of earthquakes considered in SHEEC, and weight assigned to their magnitude when averaged with Mw from MDPs (see Section 4.1). A few catalogues, published after SHEEC had been released to SHARE such as CPT111 (Rovida et al. 2011), Leydecker (2011), and EMEC (Grünthal and Wahlström 2012) will be considered for a next, updated version of SHEEC. SCR stable continental region, WAP Western Alps and Pyrenees, APD Apennines, North-Eastern Alps and Dinarides, BAS Broad Aegean, shallow, BET Betic

N	Catalogue reference	Code	References	Size measure	Epicentral uncertainty	Size measure uncertainty	Area	Attenuation region	Events considered in SHEEC	Weight
1	Icelandic Meteorological Office (2007)	IMC007	No	Ms	No	No	Iceland	–	13	0.25
2	Ambraseys and Sigbjörnsson (2000)	AMBSI000	Yes	Ms	No	No	Iceland	–	8	0.25
3	University of Helsinki, Institute of Seismology (2007)	FEN07	Yes	Ms and Io	4 classes (deg)	No	Fennoscandia	SCR	75	0.25
4	Musson and Sargeant (2007)	MUSA007	Yes	Mw	No	No	UK	SCR	64	0.25
5	Musson (1994)	MUSS994	Yes	ML	No	No	UK	SCR	29	0.25
6	Baumont and Scotti (2011)	BAUSC011	Yes	Mw	4 classes (km) as in SisFrance	Yes	France	SCR and WAP	333	0.75
7	Observatoire Royal de Belgique (2010)	ORB010	No	Io	No	No	Belgium	SCR	13	0.25
8	Grünthal et al. (2009a)	GRUAL009	Yes	Mw	No	No	Germany, Poland and Czech Republic	SCR	12	0.25
8	Grünthal (1988)	GRUE988	Yes	Io	5 classes (km)	No	Germany	SCR	39	0.25
10	Kondorskaya and Shebalin (1982)	KOSH982	Yes	Io	5 classes (degrees)	No	Poland, Ukraine and Moldavia	SCR	11	0.25
11	Labak and Broucek (1995)	LABR995	Yes	Io	5 classes (km)	No	Slovakia	SCR	76	0.25
12	Leydecker (1986)	LEYD986	Yes	Io	4 classes (km)	No	Germany and Switzerland	SCR and WAP	92	0.25
13	Meidow (1995)	MEID995	Yes	Io	No	No	Germany	SCR	21	0.25
14	Fäh et al. (2011)	ECOS009	Yes	Mw	7 classes (km)	Yes	Switzerland	SCR and WAP	717	0.75
15	Onescu et al. (1999)	ONAL999	Yes	Io, Mw	No	No	Hungary and Romania	SCR and VRD	125	0.25
16	Shebalin and Leydecker (1998)	SHELE998	Yes	Io	5 classes (degrees)	No	Bulgaria, Romania, Ukraine and Poland	SCR, BAS and APD	38	0.25
17	ZAMG (2010)	ZAMG010	No	Io	No	No	Austria	APD, WAP and SCR	74	0.25
18	Zsiros et al. (1988)	ZIAL988	Yes	Io	5 classes (km)	No	Hungary	SCR and APD	131	0.25
19	CPTI Working Group (2004)	CPTI004	Yes	Mw	No	Yes	Italy	WAP and APD	987	0.25
20	Živic (2009)	ZIVC009	No	Io	No	No	Slovenia	APD and SCR	317	0.25



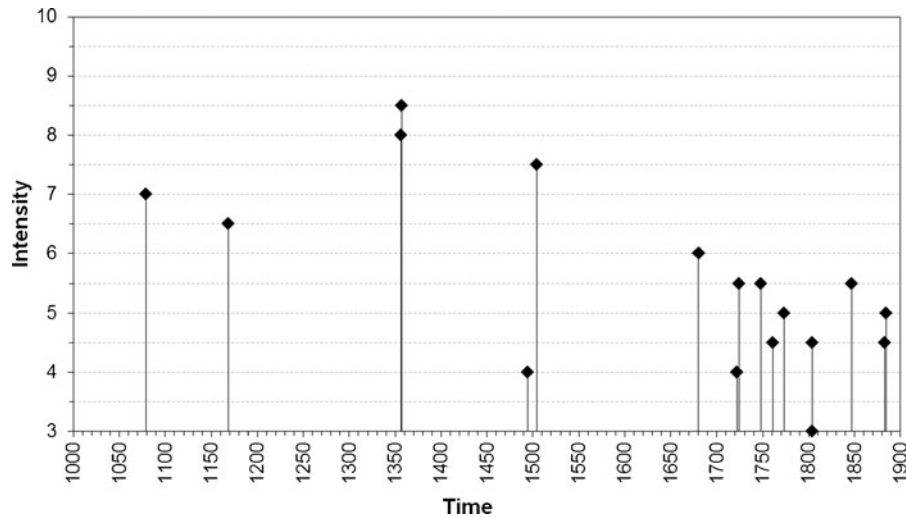
**Table 4** (continued)

N	Catalogue reference	Code	References	Size measure	Epicentral uncertainty	Size measure uncertainty	Area	Attenuation region	Events considered in SHEEC	Weight
21	Grigorova et al. (1978)	GRAL978	Yes	Io	No	No	Bulgaria	SCR and BAS	13	0.25
22	Herak (1995)	HERA995	Yes	Io	No	No	Croatia, Slovenia, Serbia, Bosnia and Heregovina and Montenegro	SCR, APD and BAS	174	0.25
23	LNEC (1986)	LNEC986	Yes	Io, M	3 quality codes	No	Portugal	SCR and TSZ	25	0.25
24	Martins and Mendes Victor (2001)	MAMV001	Yes	M	No	No	Portugal	SCR and TSZ	11	0.50
25	Vilanova and Fonseca (2007)	VILFO007	Yes	Mw	No	No	Portugal	SCR	5	0.50
26	Martinez Solares and Mezcuca Rodriguez (2002)	MAME002	Yes	Io, Mw	4 classes (km)	No	Iberia and Portugal	SCR, WAP, BET and TSZ	199	0.25
27	Olivera et al. (2006)	OLIAL006	Yes	Io, Mw	No	No	Iberia	WAP	12	0.25
28	Sulstarova and Kociu (1975)	SUKO975	Yes	Io	No	No	Albania	BAS and APD	56	0.25
29	Papazachos and Papazachou (2003)	PAPA003	Yes	Mw	2 classes (km)	Yes	Broad Aegean	BAS, BAI and APD	346	0.25
30	Soysal et al. (1981)	SOYAL981	Yes	Io	7 quality codes	No	Western Turkey and Aegean	BAS	220	0.25

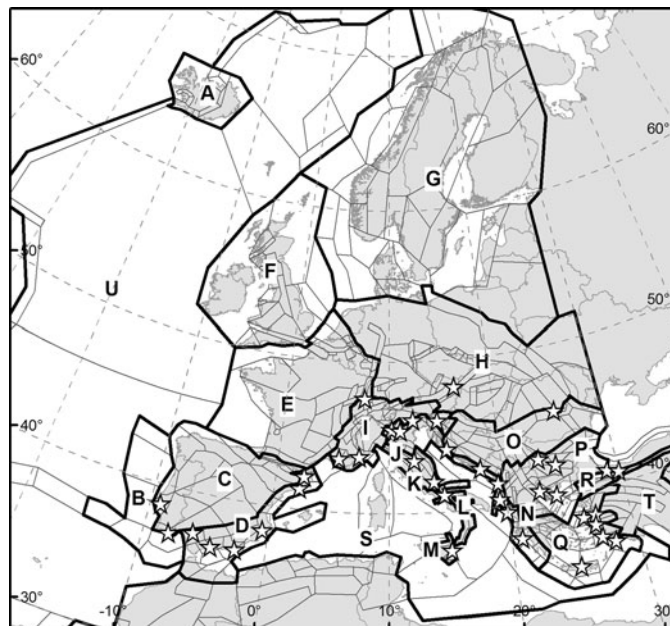
### Appendix 3—SHEEC completeness

SHARE required the catalogue to be delivered together with the assessment of its complete time-intervals for varied  $M_w$  thresholds. In this Appendix, we briefly summarise the procedures used and the obtained assessment.

The assessment of completeness is usually performed according to statistical analyses of the catalogues (e.g. Stepp 1971; Tinti and Mulargia 1985; Musson 1999; Albarello et al. 2001), based on the assumption that the seismogenic process is stationary. An alternative approach is the so-called “historical” one (see for instance Stucchi et al. 2004, 2011). It



**Fig. 12** Earthquake history of Seville, Spain (from AHEAD)



**Fig. 13** The 22 macro-areas used for completeness assessment, together with the localities (*stars*) whose earthquake histories have been considered

starts from the investigation of the “earthquake history” of a place, that is, the chronological series of earthquake effects at a place (see the earthquake history of Seville, Spain, in Fig. 12).

A destructive earthquake, able to produce intensities  $\geq 8$ , usually left traces in the historical accounts: such traces can be preserved or lost, depending on many factors. The approach requires the investigation of the main sources of information to understand whether the gaps in the earthquake histories are due to lack of earthquakes or to lack of sources. Then, using several places as the elements of a network one can assess the completeness starting year for a destructive event ( $M_w \geq 5.8$ ) in that region. In a similar way, one can assess the completeness starting year for  $M_w 6.8$  that is a highly destructive shallow earthquake that may cause intensities  $\geq 10$  in Europe.

For PSHA purposes, the completeness assessment is needed in each seismogenic area source used in the computation. Conversely, it happens that historical considerations apply to areas larger than individual

**Table 5** Completeness starting years for two  $M_w$  thresholds in the macro-areas of Fig. 13

	Macro-area name	5.8	6.8
A	Iceland	(after 1900)	1700
B	Offshore Portugal	(after 1900)	1700
C	Iberia	1800	1300
D	Betic region	1350	1200
E	Central-Western Europe	1450	–
F	British Isles	1500	–
G	Northern Europe	1700	–
H	Central-Eastern Europe	1500	–
I	Alps	1500	1300
J	Northern Italy	1300	1200
K	Central Italy	1500	1200
L	Southern Italy	1650	1450
M	Sicily	1500	1150
N	East Adriatic–Ionian	1800	1600
O	Northern Balkans	1850	1650
P	Southern Balkans	1850	1650
Q	Aegean	(after 1900)	1450
R	Marmara Region	1700	1200
S	Mediterranean background	1800	–
T	Western Turkey	1850	1800
U	Atlantic	(after 1900)	–
V	Vrancea deep	(after 1900)	1750

seismogenic area sources. For this reason, 22 macro-areas, considered to be fairly homogeneous with respect to historical aspects (Fig. 13), were defined grouping together single seismogenic area sources of the SHARE model (Arvidsson and Grünthal 2010).

The earthquake histories of some significant places (Fig. 13), obtained from AHEAD, were considered to determine the completeness starting year for  $M_w 5.8$  and  $6.8$  in the macro-areas where earthquakes of such  $M_w$  values are present. Such analysis was complemented by the analysis of the seismicity time-distribution and by expert judgement of local investigators. The final assessment for  $M_w \geq 5.8$  and  $\geq 6.8$  is presented in Table 5.

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