The Italian earthquake catalogue CPTI15

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Abstract:	The Parametric Catalogue of Italian Earthquakes CPTI15 (Catalogo Parametrico dei Terremoti Italiani) represents the latest of a 45-years-long tradition of earthquake catalogues for Italy, and a significant innovation with respect to its predecessors. CPTI15 combines all the information on significant Italian earthquakes of the period 1000-2017, balancing instrumental and macroseismic data. Although the compilation criteria are the same as in the previous CPTI11 version, released in 2012, the catalogue has been revised as concerns: the time coverage, extended to 2017; the associated macroseismic data, improved in quantity and quality; the considered instrumental data, new and/or updated; the energy thresholds, lowered to intensity 5 or magnitude 4.0 (instead of 5-6 and 4.5, respectively); the determination of parameters from macroseismic data, based on a new calibration; the instrumental magnitudes, resulting from new sets of data and new conversion relationships to Mw. The catalogue considers and harmonizes data of different types and origins, both macroseismic and instrumental. For all earthquakes, the magnitude is given in terms of true or proxy moment magnitude (Mw), with the related uncertainty. The compilation procedure rigorously implements data and methods published in peer-reviewed

	journals. All data and methods considered are clearly indicated in the catalogue, in order to guarantee the maximum transparency of the compilation procedures. Differently from previous CPTI releases, the final catalogue shows a frequency-magnitude distribution coherent with current instrumental catalogues, making CPTI15 suitable for statistical analysis of the time-space property of the Italian seismicity.
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Abstract

The Parametric Catalogue of Italian Earthquakes CPTI15 (Catalogo Parametrico dei Terremoti Italiani) represents the latest of a 45-years-long tradition of earthquake catalogues for Italy, and a significant innovation with respect to its predecessors. CPTI15 combines all known information on significant Italian earthquakes of the period 1000-2017, balancing instrumental and macroseismic data. Although the compilation criteria are the same as in the previous CPTI11 version, released in 2012, the catalogue has been revised as concerns:

- the time coverage, extended to 2017;
- the associated macroseismic data, improved in quantity and quality;
- the considered instrumental data, new and/or updated;
- the energy thresholds, lowered to maximum or epicentral intensity 5 or magnitude 4.0 (instead of 5-6 and 4.5, respectively);
- the determination of parameters from macroseismic data, based on a new calibration;
- the instrumental magnitudes, resulting from new sets of data and new conversion relationships to Mw.

The catalogue considers and harmonizes data of different types and origins, both macroseismic and instrumental. For all earthquakes, the magnitude is given in terms of true or proxy moment magnitude (Mw), with the related uncertainty. The compilation procedure rigorously implements data and methods published in peer-reviewed journals. All data and methods are clearly indicated in the catalogue, in order to guarantee the maximum transparency of the compilation procedures.

As compared to previous CPTI releases, the final CPTI15 catalogue shows a frequency-magnitude distribution coherent with current Italian instrumental catalogues, making it suitable for statistical analysis of the time-space property of the Italian seismicity.

Keywords

Seismicity, earthquake parameters, macroseismic magnitude, parameters harmonization, seismic hazard

Declarations

Funding: The compilation and maintenance of CPTI15 is funded by the Italian Presidenza del Consiglio dei Ministri - Dipartimento della Protezione Civile (DPC), and by Istituto Nazionale di Geofisica e Vulcanologia (INGV)

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The Italian earthquake catalogue CPTI15

1. Introduction

This new version of the Parametric Catalogue of Italian Earthquakes (Catalogo Parametrico dei Terremoti Italiani, hereafter CPTI15) represents a significant evolution with respect to the previous ones, as far as input data, both macroseismic and instrumental, and parameter determinations are concerned. Besides the extension to the end of 2017, innovations involve the basic macroseismic data, which have been significantly improved as concerns the number of earthquakes supported by intensity distributions and the update of the related macroseismic studies. As for the latter, a number of studies published between 2008 and 2019 were taken into account, together with some older ones not considered in the previous version of the catalogue, released in 2012 (hereafter CPTI11). The criteria for the selection and the harmonization of different types of instrumental magnitudes are completely revised and improved, according to recently published datasets and procedures, as described below. Macroseismic parameters were determined with the same approach as in CPTI11 but the new macroseismic and instrumental datasets provided an updated and more robust calibration of the macroseismic magnitudes. As a specific choice, the catalogue adopts as much as possible peer-reviewed, and publicly-accessible data and procedures, all documented in detail and reproducible.

Another feature of CPTI15, refined with respect to that already experimented in CPTI11, is the presentation and combination of both instrumental and macroseismic parameters. Indeed, when both a macroseismic and instrumental dataset exist for the same earthquake, the two sets of parameters derived from each of them are combined in a "preferred" set. Such a choice aims at maximizing the harmonization of the parameters, especially magnitude, of recent and ancient earthquakes.

The criteria used for the selection of the preferred dataset, for determining earthquake parameters are detailed in the following Sections, together with an overview of the considered datasets.

After a first release of the catalogue in July 2016 (CPTI15 version 1.5), the new CPTI15 version 2.0 has been recently compiled and published, in order to extend the coverage to the end of 2017, including data on the 2016-2017 central Italy seismic sequence. This latest release is the subject of this paper.

Overall, CPTI15 contains 4760 earthquakes occurred in the entire Italian territory and in neighboring areas and seas (Figure 1) in the time period 1000-2017, with a minimum macroseismic intensity of 5 or a minimum magnitude of 4.0. Some earthquakes with magnitude lower than 4.0 are also included in the catalogue, such as i) earthquakes in the Mt. Etna and Neapolitan volcanic areas, and ii) earthquakes in CPTI11 for which the new parametrization reduced the value to Mw < 4.0.

For all the earthquakes, the magnitude is given in terms of true or proxy moment magnitude (Mw) and the related uncertainty is provided. All the data considered and methods used are clearly indicated in the catalogue, in order to guarantee the maximum transparency of the compilation procedures. As CPTI11,

CPTI15 is not declustered, and thus contains known foreshocks and aftershocks within the considered intensity and magnitude thresholds.
The catalogue file (https://doi.org/10.13127/CPTI/CPTI15.2) is available for download at https://emidius.mi.ingv.it/CPTI15-DBMI15/index_en.htm, and it is accessible through the dedicated web interface described in Section 7.

2. Background: 45 years of earthquake catalogues in Italy

The need to catalogue all available information on Italian seismicity in the most complete and homogeneous form has been clearly recognized since the dawn of modern seismological science at the beginning of the 20th century. In Italy, this need is matched by the extraordinary effort of compiling made by Baratta (1901), the point of arrival of a long tradition of national and regional seismological compilations, based mainly on local historiography. Baratta's compilation was the starting point for the realization of the first Italian parametric earthquake catalogues in the 1970s.
The first of such catalogues was compiled by the National Committee for Nuclear Power CNEN (Comitato Nazionale Energia Nucleare; Carrozzo et al. 1973) as part of the studies for the program for the construction of nuclear power plants. The CNEN catalogue contains 10,604 entries and covers the time interval from the year 0 to 1971. Among other parameters, it gives date and time, maximum intensity in the Medvedev-Sponheur-Karnik (MSK) scale (Medvedev et al. 1964), the coordinates of the epicentre, the depth, and the magnitude.
In 1975 a more extensive catalogue was prepared by Geotecneco, a private firm, for the National Electric Company ENEL (Ente Nazionale Energia Elettrica). The catalogue contains 20,670 earthquakes, covers the years 1000 to 1975, and is available as a computer file (ENEL 1977). The provided parameters are more or less the same as in the CNEN catalogue, with the exception of the intensity expressed in the Mercalli-Cancani-Sieberg (MCS) scale (Sieberg 1923).
In 1977, within a major research project of the National Research Council, called "Project on Geodynamics" (Progetto Finalizzato Geodinamica - PFG) a dedicated Working Group acquired the ENEL catalogue with the specific goal of revising and extending it to 1980. The result of this work was the PFG catalogue (Postpischl 1985a), compiled by carefully collating the ENEL (1977) catalogue with several other national, and local parametric catalogues (Table 1) and some dozens of historical-seismological ad hoc studies on the 68 strongest earthquakes of the Italian seismic history (Postpischl 1985b). The PFG catalogue contains 37,211 events (most of them derived from the ENEL catalogue), and covers the period from the year 1000 to 1980. The PFG catalogue was actually published, making available for general use more than 37,000 earthquake records, whereas the previous catalogs were all meant for restricted use only, or available only to scientific institutions. Unfortunately, the PFG catalogue was essentially a patchwork of inhomogeneous components.

It is important to stress that the PFG catalogue, as all the parametric catalogues of its generation merged within it, is largely derived from the parameterization of 19th century seismological compilations, primarily that of Baratta (1901), while the parameters of the 20th century earthquakes are directly derived from seismological bulletins (macroseismic and/or instrumental). Overall, only a negligible percentage of events is based on historical-seismological studies (Camassi 2004).

After the compilation of the PFG catalogue, historical investigations were carried on with the involvement of historians (Stucchi and Guidoboni 1993). Between 1983 and 1988 ENEL promoted a massive historical-seismological research for the nuclear power plants siting project, involving dozens of historians.

After the abandonment of the nuclear power plant projects in 1987, these studies continued in the framework of a project, supported by the National Institute for Geophysics (Istituto Nazionale di Geofisica, ING), aimed at the revision of the knowledge on all the “strong earthquakes”, i.e. those with an epicentral intensity ≥ 8-9 included in the PFG catalogue. This project, implemented by SGA (a private company), between 1995 and 2006, produced four different editions of the “Catalogue of Strong Italian Earthquakes (Catalogo dei Forti Terremoti in Italia, CFTI; Boschi et al. 1995, 1997, 2000; Guidoboni et al. 2007), now available in a new online version (CFTI5med; Guidoboni et al. 2018, 2019).

In the same years, the National Group for Protection against Earthquakes (GNDT - Gruppo Nazionale per la Difesa dai Terremoti) started the “seismic hazard project”, a five-years research program aimed at realizing a new national seismic hazard map based on a completely revised and homogeneous earthquake catalogue (Slejko et al, 1998). The effort resulted in the NT4.1 Catalogue (Camassi and Stucchi 1997), the first in Italy to be accompanied by an online database (DOM, Monachesi and Stucchi 1997) providing intensity data for more than one third of the earthquakes.

The two groups of researchers merged when joining the National Institute for Geophysics and Volcanology (INGV - Istituto Nazionale di Geofisica e Vulcanologia) in 1999, and since then continuously revised and improved the knowledge on Italian earthquakes, starting from historical-seismological investigations, with important contributions of professional historians.

The result of over thirty years of research is the enormous wealth of macroseismic and historical-seismological data on Italian earthquakes, well represented by the dedicated databases managed and maintained by INGV, i.e. CPTI15 itself and the associated Database of Italian Macroseismic Data (DBMI15 - Database Macrosismico Italiano; Locati et al. 2019), the mentioned CFTI5med, and the Archive of Italian Historical Earthquake Data (ASMI - Archivio Storico Macrosismico Italiano; Rovida et al. 2017).

However, it is worth noting that the current knowledge still heavily depends on Baratta’s (1901) compilation. The newly discovered earthquakes are a limited percentage of those we know today, a detail to be carefully considered for the evaluation of catalogue completeness (Camassi et al. 2011).

As noted above, the PFG and previous catalogues were mainly based on macroseismic information because a dense network of seismometric stations was not available in Italy until about the end of the 1970s. The first attempt to revise and harmonize the Italian instrumental database dates back to the Italian Instrumental Catalogue (Catalogo Strumentale dei Terremoti Italiani – CSTI; CSTI Working Group 2003, 2005) and concerns the period from 1981 to 1996. In such a work, the arrival times of the INGV Seismic Bulletin have been merged with those of some local networks operating in Italy at the time (OGS, University of Genoa, Macerata Observatory, etc.) and used to relocate all the events with homogeneous methods. The duration and amplitude magnitudes were recalibrated and integrated, according to Gasperini (2002), with a set of ML magnitudes calculated from real Wood-Anderson (WA) instruments (Anderson and Wood 1925) or WA synthetic waveforms from Very Broad Band stations of the INGV Mednet network (Boschi et al. 1991). Afterwards, a similar effort was performed for the period from 1997 to 2002, by Castello et al. (2006, 2007), who produced the Catalogue of Italian Seismicity (CSI - Catalogo della Sismicità Italiana). In the meantime, INGV started releasing online (today at http://terremoti.ingv.it/) real-time locations and local magnitudes of the earthquakes detected by the Italian National Seismic Network. Such data are periodically revised and published on a three-months basis in the Italian Seismicity Bulletins (BSI - Bollettino Sismico Italiano; Margheriti et al. 2016, 2016a, 2016b, 2017, Nardi et al. 2016, Rossi et al. 2017, Battelli et al. 2018, Cantucci et al. 2019, Lombardi et al. 2019).

3. Macroseismic data and parameters

The quality and reliability of a parametric earthquake catalogue strongly depend on i) the quality and accuracy of the basic data from which earthquake parameters are derived, and ii) the reliability of the methodology used for deriving such parameters.

Usually, macroseismic data used for the compilation of earthquake catalogues consist of earthquake studies, intensity data points, previous catalogues, etc. Such a material is often unpublished and available only to the catalogue compiler(s), and the procedures applied to the assessment of the parameters are poorly documented, or not documented at all. Following the tradition summarized in the previous Section, the criteria adopted for the compilation of CPTI15 aimed at providing the best possible results in terms of reliability and transparency of the compilation procedures. Since most of the content of any catalogue covering a time span of more than 1000 years is necessarily macroseismic, the first step in the compilation of CPTI15 consisted in selecting the best available macroseismic data.

Since the compilation of the NT4.1 catalogue (Camassi and Stucchi 1997), a comprehensive archive has been built and continuously implemented, with the scope of collecting and qualifying the necessary macroseismic datasets. Because different datasets may refer to the same earthquake and provide coinciding, conflicting, or complementary information, such an inventory was used to compare them and to identify the best available dataset for each earthquake. In addition, the inventory includes instrumental data of recent earthquakes, in order to select also the most robust instrumental parameters, whenever available. As shown in Stucchi et al. (2013), the described procedure ensures the control and transparency of the flow of information from the earthquake descriptions provided by historical sources to the earthquake parameters, via the assessment of macroseismic intensity data points (or macroseismic data points, hereafter MDPs). In addition, problems related to both duplicate and fake events are easily dealt with. Through time, the archive content has been digitized as much as possible, and it has been organized by means of a relational database structure similar to that adopted by its European counterpart, the European Archive of Historical Earthquake Data (AHEAD; https://www.emidius.eu/AHEAD/), described in Locati et al. (2014), and Rovida and Locati (2015). The Italian archive has been recently made accessible on the web with the name of ASMI "Archivio Storico Macrosismico Italiano" (Italian Historical Macroseismic Archive, https://emidius.mi.ingv.it/ASMI/index_en.htm; Rovida et al. 2017), making available all the background knowledge upon which CPTI15 is built. Figure 2 illustrates the scheme used in the compilation of the catalogue and the relationships among input data, ASMI, DBMI15, and CPTI15.

3.1 Macroseismic data: DBMI15

The collection and systematic archiving of the most recent and significant studies facilitated the creation and update of the list of earthquakes to be included in the catalogue, and the selection of the study that represents the most complete knowledge and provides the most robust data upon which to build the catalogue entry.

The MDPs supplied by the studies selected for each earthquake constitute DBMI15, the 2015 version of the Italian Macroseismic Database (Locati et al. 2019). The main goal of DBMI15 is to both collect and harmonize the sets of MDPs upon which CPTI15 is built, and to provide reliable seismic histories of Italian populated places, i.e. the list of earthquake effects, in term of macroseismic intensity, that were recorded at a given place.

Studies providing data to DBMI are selected, as much as possible, according to the criteria described in the following. 1) The study must provide a set of MDPs for one or more earthquakes, defined in terms of place name, possibly its geographical coordinates, and a value of macroseismic intensity expressed according to a published macroseismic scale. 2) The study should be published, either in a scientific journal or in a technical report. 3) The study should possibly describe the process that ended in the assessment of the provided intensities, mentioning the considered sources of information and how they were interpreted. In case multiple studies are providing alternative sets of MDPs, the selection takes into account many aspects, such as the historical sources used by the authors of the study, the number of MDPs provided and their geographical coverage. The date of publication is mostly irrelevant in the selection process as the most reliable study is not necessarily the most recent.

The selection process resulted in 189 studies (listed in Table ES1 in Online Resource 1) providing MDPs related to 3219 earthquakes, with a total of 123,756 MDPs.

The number of considered data sources and provided data represent a wide heterogeneity of approaches and ways of presenting intensity data. For compiling a homogenous set of MDPs to be used in CPTI15, original

MDPs are re-compiled, although preserving as much as possible the original information as provided from the study. For this purpose, all the three components of a MDP, i.e. intensity, place coordinates, and place name, are re-processed and harmonized.

All intensity values are re-compiled using Arabic numerals, with uncertain intensities expressed using a hyphen (e.g. 6-7). Reported unconventional, descriptive intensities such as “felt” or “damage” are reduced to a list of standardized codes (Table 2). To be used as input for the assessment of earthquake location and magnitude, intensity values have to be expressed also as numerical values. Uncertain intensities are treated as half values, e.g. 6.5 for 6-7, and alphanumerical codes are associated to the numeric values in Table 2.

The uncertainty reported by a study is sometimes expressed as a wide range of degrees, and intensities such as 5-7 or 3-5 might appear in the original data. Such values, besides being not consistent with the practice of intensity assessment provided in Grünthal (1998), cannot be directly used in the calculation of earthquake parameters, and an average value cannot be adopted. In such cases, one of the defined non-conventional descriptive values (e.g. “HD”, “D”, or “F”) is assigned, selecting the code that better matches the indications provided by the EMS-98 scale (Table 3).

A first step in the homogenization of the original intensities with the abovementioned criteria resulted in the recompilation of 59283 observations as reported in Table 4.

A second aspect in the homogenization of intensities deals with those intensities referred to localities that do not comply with the requirements of the macroseismic scale, such as settlements made up of very few or sparse buildings. Such cases are marked in DBMI15 as “Special cases”, according to the codes described in Table 5, and the intensity value attributed by the study is retained. In the cases of single isolated buildings (“IB”) and wide geographical areas (“TE”), the provided values are converted into descriptive codes, for the latter no coordinates are associated to the MDP.

The intensity data contained in DBMI15 are referred to a Gazetteer of geographical coordinates and place names that was created and managed in-house since the first release of DBMI, called DOM (Monachesi and Stucchi 1997). The Gazetteer contains data related to about 87,000 Italian localities, each associated with a unique identifier, a pair of coordinates and the modern, official place name, and census information periodically published by the Italian National Institute of Statistics (ISTAT).

3.2 Macroseismic parameters

The selected MDPs distributions were used to derive location and magnitude for earthquakes in both the “pre-instrumental” and “instrumental” periods. The procedure selected for such a purpose is the Boxer method (Gasperini et al. 1999, 2010). The main reason for choosing Boxer is the continuity with the previous CPTI04 and CPTI11 versions, and with the “SHARE European Earthquake Catalogue (SHEEC) 1000-1899 (Stucchi et al. 2013). For the same reason, among the location methods implemented in the latest version of the code (Boxer 4.0; Gasperini et al. 2010), we mostly relied on the so-called “method 0”, which determines the epicentre as the barycentre of the data points with the highest intensities. Such a method guarantees the stability of the solution even with few or irregularly distributed data. As a drawback, Boxer solutions are not reliable when MDPs are absent in the epicentral area, and it does not assess the hypocentral depth. The latter, however, is rather unreliable even when instrumentally determined for crustal earthquakes occurred before the last decades.

For the computation of magnitude, Boxer relies on a calibration against earthquakes with both reliable macroseismic intensity data and known instrumental magnitude and location. The empirical method used by Boxer to relate macroseismic data with magnitudes is based on the formula by Sibol et al. (1987):

$$\boldsymbol{M_i = a_i + b_i log^2_{10}(A_i) + c_i I_0^2} \quad (1)$$

where *M* is magnitude, A_i is the area of a circle with a radius equal to the average epicentral distance of places whose observed intensity belongs to the *i-th* intensity class (see below), *Io* is the epicentral intensity, and a_i, b_i, c_i are empirical coefficients to be calibrated for each *i-th* intensity class by means of a procedure described in Appendix 1 of Gasperini et al. (2010). Following Gasperini and Ferrari (1995, 2000), the Boxer method computes the earthquake magnitude as the weighted average of the values independently obtained from each *i-th* intensity class through Equation (1), with a weight that is inversely proportional to the number of intensity data and to the square of the standard deviation of the regression for the corresponding intensity class.

For CPTI15 the calibration of the coefficients was updated with respect to that used for CPTI11 that dated back to the compilation of the 1980-2002 portion of CPTI04 (Gasperini 2004). The new calibration derives from a dataset related to 354 earthquakes homogeneously spread throughout Italy, and with both instrumental magnitudes, either Mw or Mw proxy, between 2.8 and 7.1 (Figure 3A) and macroseismic data (30138 data points, with intensity between 2 and 11 MCS; Figure 3B). Only earthquakes shallower than 30 km and with more than 10 intensity data were included in the calibration dataset, and those earthquakes with partial or incomplete intensity distributions (e.g. earthquakes at sea) were discarded.

Instrumental magnitudes of the calibration earthquakes include both true Mw derived from moment tensor inversions as well as proxy Mw computed from other types of magnitudes as described in the following section, in order to ensure magnitude (or intensity) and temporal coverages as wide as possible. Sixteen intensity classes, ranging from 2 to 9 with intermediate uncertain values and "felt" as an independent class, were calibrated. Intensities classified as "felt" are assigned to a separate class because of their significant number in the macroseismic database, and the very wide range of epicentral distances at which such intensity is classified. According to Stucchi et al. (2007), and Locati et al. (2019) a conventional numerical value of 3.9 has been assigned to Felt.

The coefficients are shown in Table 6, together with the three additional parameters needed for defining the weight of each intensity class in the magnitude calculation: the standard deviation of the regression *s*, the weight normalization factor *K*, and the number of degrees of freedom of the regression (see for details Gasperini et al. 2010, Appendix 1).

Figure 4 shows the results of the calibration procedure as the comparison between the observed instrumental Mw magnitudes (Mobs), and the corresponding values calculated from intensity data (Mcalc), using the coefficients in Table 6, for the 354 calibrating events. The agreement is reasonably good for Mobs≥4.0, whereas for lower magnitudes Mcalc significantly overestimates Mobs (Figure 4a). The residuals Mobs-Mcalc show a fairly Normal distribution (skewness=-0.17, kurtosis=0.29) with average -0.08 and standard deviation 0.40 (Figure 4b).

Boxer calculates magnitude with the described procedure only if at least two intensity class contains at least two MDPs or if a single intensity class contains at least four of them. In case the available MDPs are insufficient to apply such method, the magnitude is calculated by an empirical linear relationship between epicentral intensity Io and moment magnitude Mw. The calibration dataset was also used for deriving the coefficients of such a relationship, as follows:

$$Mw = (0.4667 \pm 0.0191)\ Io + (1.8267 \pm 0.1571) \qquad (2)$$

$$std = 0.11;\ R^2 = 0.99$$

The parameters cards with the newly calibrated coefficients to be used as input ("inpparm.dat" file) for the Boxer code are reported in Online Resource 2.

The macroseismic magnitudes in CPTI15 are determined for 3005 earthquakes, 54% of them is calculated using MDPs distributions as described above, and 36%, related to poor intensity distributions, with the new Io-to-Mw relation. The remaining 10% of magnitudes concerns earthquakes in the Mt. Etna volcanic area for which macroseismic magnitude was calculated using the empirical relationship between Io and ML by Azzaro et al. (2011), then converted to Mw with the relationships by Tuvè et al. (2015), both specifically calibrated for the Etnean area. In the lack of any specific relationship, the Io-to-Md relationship by Tuvè et al. (2015) was applied in the Phlegrean volcanic area and at Ischia Island, with the obtained Md values converted to Mw using the relationship by Petrosino et al. (2008), specific for the area.

In a few cases, the epicentre estimated by Boxer as the barycentre of the highest intensity points ("method 0") conflicts with the likely location offshore or in coastal areas of the earthquake. In such cases, the epicentre was assessed using "method 4", which derives the hypocentral location (latitude, longitude, and depth) and the expected epicentral intensity through the attenuation relation proposed by Pasolini et al. (2008), as described in Gasperini et al. (2010). New coefficients (*a*, *b*), and a new reference depth (*h*) of the relationship by Pasolini et al (2008), were also derived from the same calibration dataset described above: $a = 0.00289 \pm 0.00021$, $b = 1.248 \pm 0.019$ and $h = 7.45 \pm 0.28$, as well as a new relationship between the expected intensity at the epicenter (I_E) and *Mw*:

$$I_E = (0.650 \pm 0.021)\ Mw + (0.799 \pm 0.123) \qquad (3)$$

$$std = 0.395$$

CPTI15 provides macroseismic locations for 3009 earthquakes, calculated with Boxer “method 0” for the 94% of the cases. Boxer “method 4” solutions proved to be stable only with more than 10 MDPs, and for this reason it was used only as an alternative to “method 0” for only 63 earthquakes. For 33 earthquakes, labelled in the catalogue file, usually with few MDPs, the solution by Boxer resulted inconsistent with the intensity distributions, and the epicentre was modified either assuming it as coinciding with the point of maximum intensity or excluding one or more high-intensity data points (assumed to be outliers) from the processing. Finally, for 79 earthquakes in the Mt. Etna area the location proposed by the reference macroseismic study, determined by taking into account also the observed coseismic surface faulting (see Azzaro et al. 2000), was preferred to that derived from the available MDPs.

The uncertainty associated with the epicentral coordinates, as calculated by Boxer by both “method 0” and “method 4” is available for 2033 earthquakes, i.e. with enough intensity data. The uncertainty associated to the macroseismic magnitude computed through the intensity distributions, with 0.10 as a minimum value, is always reported in the catalogue. The uncertainty associated with magnitudes derived from epicentral intensity through Equation 2 was assumed equal to 0.46, corresponding to the standard deviation of the distribution of the individual earthquakes in the calibration dataset.

4. Instrumental data and parameters

As already mentioned in the introduction, the instrumental catalogues CSTI and CSI report revised locations and magnitudes of Italian earthquakes from 1981 to 2002. Although in the following years some research projects aimed at the continuation of such work, no official releases have been published until now and then for the years following 2002 one has to refer to the Italian Seismic Bulletin (Bollettino Sismico Italiano - BSI) and the Italian Seismological Instrumental and Parametric Database (ISIDe; ISIDe Working Group 2007) of INGV. Over time, this latter was subject to several changes in both the format and the methods of parameter determinations. From 2003 to 30 April 2012 the official BSI source is the website http://bollettinosismico.rm.ingv.it, which provides fortnightly summary files of hypocentral locations and magnitudes. However, starting from 16 April 2005 the most comprehensive and complete source of preliminary and revised location and magnitudes of INGV became the Italian Seismic Instrumental and parametric Database (ISIDe). Actually, since the beginning of May 2012 the location software that feeds ISIDe with real-time locations and magnitudes was updated to Earthworm (Johnson et al. 1995). This change implied that the duration magnitude Md was not provided anymore for most earthquakes. The ISIDe website was dismissed at the beginning of 2017 and replaced by a new data portal (http://terremoti.ingv.it/) and web services (http://webservices.ingv.it), which include and provide also the revised data of BSI for the period 1 May 2012 - 31 August 2018 (Margheriti et al. 2016; 2016a; 2016b; 2017; Nardi et al. 2016; Rossi et al 2017; Battelli et al. 2018; Cantucci et al. 2019; Lombardi et al. 2019; Melorio et al 2019; Bono et al. 2019).

The heterogeneity of the procedure used in the course of time to compute magnitudes prevents the simple direct use of such data to compile a harmonized catalogue of Italian seismicity. Hence, Gasperini et al. (2013) recalibrated the local and duration magnitudes of CSTI, CSI, and BSI from 2003 to 2010 through the comparison with a harmonized dataset of Mw magnitudes from various MT databases (Gasperini et al. 2012), using general orthogonal regression (GOR) methods (Fuller 1987; Stromeyer et al. 2004; Castellaro et al. 2006; Lolli and Gasperini 2012). The same regression equations obtained by Gasperini et al. (2013) for the period from 16 April 2005 to 2010 have been used for converting to Mw even the Md and ML of ISIDe from 2011 to the present. Recently, Lolli et al. (2018) extended the harmonization in terms of Mw to local magnitudes of Italian earthquakes from 1960 to 1980, using similar methods. As such work was not yet published at the time of the compilation of the first version CPTI15, only few magnitudes from a preliminary version of the paper were actually used in case no other magnitude were available for a given earthquake.
Instrumental locations and magnitudes for the Italian region are also provided by the Bulletin of the International Seismological Centre (ISC 2019) starting from 1964. ISC Bulletin reports MS and mb computed according to international standards (Bormann et al. 2013) using the amplitude and period data provided by contributing institutions. Lolli et al (2014, 2015) computed conversion equations from MS and mb from ISC to Mw at the Global, European and Italian scale by GOR methods. Another compilation of Italian magnitudes is provided by Margottini et al. (1993), who collected ML, MS and mb of Italian earthquakes from 1903 to 1986 by rereading seismograms and original bulletins. As MS and mb from Margottini et al. (1993) also conforms to international standards, their conversion to Mw is made using the same equations used for ISC. Conversely, the conversion of ML from Margottini et al. (1993) does not require any computation because, according to Gasperini et al. (2013), it coincides with Mw within the error bounds.
All this patrimony of instrumental information has been considered to compile CPTI15. We proceeded by integrating the list of earthquakes having known macroseismic effects with locations of instrumental earthquakes (with Mw≥4.0) not matching any of the previous ones. Even if we should expect that a Mw≥4.0 should have been felt by the population, the reasons for the possible omission of macroseismic information might be manifold.

4.1. Instrumental locations

Given the different characteristics and time coverages of the mentioned data sources, the selection of the "preferred" instrumental location was performed according to a temporal priority scheme, as follows:

1. CSTI1.1: 1981 - 1996
2. CSI1.1: 1981 - 2002
3. BSI: 2003 – 2017 (April)
4. ISIDe: 2017 (May-December)

Even if both CSTI and CSI cover the interval 1981-1996 the preference was generally given to CSTI because CSI discarded many magnitudes, and does not adopt any criteria to discard unreliable locations outside the coverage of the Italian seismic network.

To ensure the best solution among the available ones, the adopted priority scheme was integrated with other data sources for particular areas of the Italian territory. Locations provided by the Bulletin of the ISC (International Seismological Centre), available for earthquakes up to June 2016 at the time when CPTI15 was compiled (beginning of 2019), were selected for deep events in the Tyrrhenian Sea and for many other earthquakes outside the coverage of the Italian seismic network (e.g. Central Adriatic Sea, Ionian Sea, Sicily Channel, Western Tyrrhenian Sea).

In some 30 cases, the priority scheme described above was not applied because the “preferred” determination proved to be inconsistent either with the other existing instrumental solutions or with the reported intensity distributions. For some other earthquakes, the “preferred ” dataset does not provide any epicentre, contrary to other “unpreferred” ones. In all such cases, the choices also took into account the quality of the data, verifying the number of phases, the azimuthal gap, the distance from the closest station etc.

Data from local catalogues and bulletins, such as the Bulletin of the OGS (Istituto Nazionale di Oceanografia e Geofisica Sperimentale) for Northeastern Italy or different instrumental catalogues for the Mt. Etna volcanic area (Patané et al. 2004; Distefano and Di Grazia 2005; Barberi et al. 2016) have been preferred in their respective areas and time windows. The instrumental catalogues of France (SI-Hex; Cara et al. 2015) and Slovenia (Živcic 2009, for events after 1973) were also considered.

The lack of any reliable instrumental catalogue for the Italian territory before 1981 forced the search for instrumental epicentres in alternative European and global datasets. The only published Italian instrumental locations are contained in the predecessor of the abovementioned BSI, the “Bollettino Sismico Mensile”, published on a monthly basis by Istituto Nazionale di Geofisica (now INGV) since its foundation. Such a bulletin contained mixed data about earthquakes in the Italian territory (and abroad) consisting mainly in phase arrivals, in a few cases complemented by hypocentral coordinates, most of which are not calculated but rather reported from international agencies or assessed from macroseismic data (also reported in some cases). In this situation, the main source of epicentral locations was again the ISC reviewed bulletin, which provided 274 determinations from 1957 to 1981. These were selected as the preferred instrumental solution all over this period. An alternative source of data for the same period is the list of “Preliminary Determinations of Epicenters” of the United States National Earthquake Information Center – the so-called NEIC-PDE catalogue. For the period before 1963, also the International Seismological Summary (ISS), and the monthly bulletins of the Bureau Central International de Séismologie in Strasbourg (France) were considered. Important contributions for Northeastern Italy came from Sandron et al. (2014) and Slejko et al. (1999), who provide revised locations for 374 earthquakes from 1901 to 1976 in the Eastern Alps and for the 1976 Friuli sequence, respectively. Seven more published papers on the (re)assessment of the epicentres of significant earthquakes were also taken into account, although not systematically. The full list of catalogues and databases contributing instrumental locations is presented in Table ES2 of Online Resource 1.

4.2. Selection and harmonization of instrumental magnitudes

Following the criteria described in Gasperini et al. (2012), a total of 953 moment magnitude estimates provided by the catalogues of moment tensors listed in Table 7 were considered, related to earthquakes between 1976 and 2017. When different catalogues provide alternative Mw estimates for the same earthquake, the different Mw values were combined and harmonized according to Gasperini et al. (2012). As a result, Mw estimates from moment tensor inversions, ranging from 3.9 to 6.8, are available for 614 earthquakes, representing 13% of the catalogue (see also Figure 7). The uncertainty associated to Mw estimates was determined according to Gasperini et al. (2012), as well. The complete list of catalogues providing magnitude estimates is given in Table ES3 of Online Resource 1.

Lacking moment magnitude determinations from moment tensor inversions, other types of instrumental magnitude of different origins were considered, and converted to Mw, for a total of 1754 magnitude estimates. For the main portion of the catalogue, in the time period from 1981 to 2017 different types of local magnitude provided by the CSTI1.1 (CSTI Working Group 2005), and CSI1.1 (Castello et al. 2006) catalogues, and by the Seismic Bulletin and ISIDe database of INGV were considered. Magnitudes from such catalogues were selected, converted to Mw, and combined according to Gasperini et al. (2013), as shown in Table 7.

For the period between 1964 and 1980, MS and mb values from the ISC Bulletin were mainly selected, and they were complemented with estimates from the catalogue by Margottini et al. (1993). MS and mb values were treated and converted to Mw according to Lolli et al. (2014; 2015). Mw proxies derived from mb and MS estimated by ISC were considered also in the period from 1981 to 30 June 2016 and combined, through the average weighted with the inverse of the square of the uncertainty, with values derived from ML. For deep earthquakes (mainly in the Southern Tyrrhenian sea area) or those located out of the coverage of the Italian seismic network, Mw proxies from ML are discarded. In the period 1972-1980, Wood-Anderson (WA) ML determined either by Monte Porzio observatory in Rome and contained in the ING Bulletin, or by the Trieste station and published in Sandron et al. (2015) were also considered. The first ML WA values were converted to Mw by adding a fixed offset of 0.22 magnitude units (Lolli et al. 2018), for the latter the conversion proposed by Sandron et al. (2015) was adopted. Proxy Mw derived from ML WA were combined with those derived from ISC, when both available (see Table 7). Lacking any other determination, ML values from the PFG catalogue (Postpischl 1985a) were used considering them as equivalent to Mw, as deduced from the comparison with ISC data (Lolli et al. 2018). A few mb and MS estimates from Margottini et al. (1993) were considered also for earthquakes occurred before 1963.

As a conclusion, the overall priority scheme for the selection of instrumental magnitudes is shown in Table 7.

In addition, moment magnitudes derived by Bernardi et al. (2005) for 12 earthquakes with epicentres in Switzerland and by Pino et al. (2000) for the 28 December 1908 earthquake (Messina straits) were taken into account.

As for earthquakes in the Etna volcanic areas, apart from Mw from moment tensor solutions, instrumental magnitudes were selected from the available local catalogues and specific conversion relations were used as shown in Table ES4 of Online Resource 1.

5. Results of compilation

As shown in Figure 5, out of the total 4760 earthquakes in CPTI15, macroseismic parameters were computed for 3009 events and instrumental hypocentres and/or magnitudes for 1901. Both macroseismic and instrumental parameters are available for 721 earthquakes dating as back as 1904 with frequency progressively increasing with time. In addition, because of the absence of either intensity datasets or instrumental data, the parameters of 459 earthquakes, mainly in bordering countries, derived from five parametric catalogues (Postipischl 1985a; ECOS-09, Fäh et al. 2011; Herak 1995; Zivcic 2009; ZAMG 2010) of prevailing macroseismic origin.

The macroseismic determination of the epicentre was preferred for earthquakes up to 1984, and the instrumental one for later earthquakes (Figure 6). Several exceptions relate, for example, to earthquakes located at sea or close to the coast, for which the instrumental location is generally selected. The macroseismic location was conversely preferred in areas where the coverage of the seismic network was poor even in the recent past. The choices were made by taking as much as possible into account the reliability of the available data.Macroseismic data of 86 earthquakes in DBMI15 were not considered reliable enough to be parametrized (e.g. those related to aftershocks); additional 26 records correspond to earthquakes for which neither macroseismic nor instrumental data are available, although they are well attested by the reference study.

As a whole, the default magnitude is assessed from macroseismic data for 2449 earthquakes (Figure 7). Macroseismic and instrumental magnitude estimates are both available for the same event in 837 cases. Unless the instrumental magnitude strictly derives from a moment tensor inversion, for 571 earthquakes the preferred magnitude is taken as the average of the two values, weighted with the inverse of the square of the associated uncertainties. In such cases, the uncertainty is estimated as the square root of the inverse of the sum of the weights. The default Mw is derived from moment tensor solutions for 619 earthquakes and as a proxy Mw from 869 ones. Figure 8 shows the 1900-2017 timeline for the different magnitude determinations.

For records derived from catalogues of bordering countries, the magnitude is obtained from epicentral intensity through the empirical relation described in eq. (2), except for the Swiss catalogue ECOS-09 (Fäh et al. 2011), from which Mw values and related uncertainties provided by the catalogue were adopted. For 45 earthquakes an epicentral location was available either from instrumental data or from a catalogue, but no magnitude estimates were found in the literature.

The extension of the catalogue from 2006 to the end of 2017, implied the addition to CPTI11 of 452 earthquakes, 39 of which are also supported by intensity data from macroseismic field surveys.

In the common time-period (1000-2006) CPTI11 and CPTI15 contain 3182 and 4298 earthquakes, respectively.

Fifty earthquakes in CPTI11, listed in Online Resource 3, are not anymore in CPTI15 either because they turned out to be fake (32), not supported by reliable data (8), or because of errors in the original data or in the compilation of CPTI11. As a result, CPTI15 contains 1192 more earthquakes than CPTI11. Most of such a difference is due to the lowering of the energy thresholds from intensity 5-6 to 5 and from Mw 4.5 to 4.0, which accounts for the addition of 757 events with respect to CPTI11. The remaining 435 earthquakes, with higher intensity and/or magnitude mostly derive from new historical macroseismic studies (e.g. Camassi et al. 2011; Molin et al. 2008, Castelli et al. 2016; Azzaro and Castelli 2015; Guidoboni and Ciuccarelli 2011), and parametric catalogues (Živcic 2009; Fäh et al. 2011). In addition, 50 deep earthquakes in the Southern Tyrrhenian Sea area, not considered by CPTI11, were added.

The 3129 common earthquakes between CPTI11 and CPTI15 may show considerable differences in both location and magnitude.

As macroseismic epicentres are computed with the same method used for CPTI11, the differences in epicentral location (Figure 9) are mainly related to the updated macroseismic input data. An exception is represented by 21 earthquakes, for which the macroseismic epicentre in CPTI11 was determined with the method by Bakun and Wentworth (1997), and in CPTI15 is substituted by an instrumental determination (4 cases), or a Boxer "method 0" (6) or "method 4" (11) determinations. Other significant differences are due to new instrumental solutions and, to a lesser extent, to the substitution of macroseismic epicentres with instrumental ones.

Apart from the differences in input data, variations in magnitude may be due to the different parameterization of macroseismic magnitudes, to the different conversions of instrumental magnitudes or to a combination of the two.

Figure 10 shows the Mw differences between CPTI15 and CPTI11, according to the Mw determination in CPTI15 (left panel: mean, from the method of circles, from epicentral intensity; right: observed true or proxy Mw).

As a general trend, Mw values in CPTI15 are lower than those in CPTI11, especially for small earthquakes. As for macroseismic magnitudes, the effect of the many (882) values now derived from MDPs is evident in their distribution over wide magnitude ranges instead of their clustering around values obtained from the linear Io-Mw relationship. Macroseismic determinations also account for the variations observed for high magnitudes. Such differences are due to the substitution of some solutions from the method by Bakun and Wentworth (1997) for large offshore earthquakes with determinations by Boxer (homogeneous with the rest of the catalogue), or to the new intensity distributions, sometimes remarkably different from previous ones. Significant variations, again mainly towards low values, derive also from the adoption of the solutions proposed by the new Swiss catalogue ECOS-09 (Fäh et al. 2011), which is updated with respect to the version ECOS-02 considered by CPTI11.

Instrumental magnitudes higher than 5.5 are substantially equivalent in the two catalogues, probably as a result of the few changes in the considered magnitude type for large earthquakes. For low magnitude values, some differences are present, especially as far as proxy Mw are concerned. This probably results from the new harmonization and combination criteria adopted. Differences in low values of Mw from moment tensor solutions are due to the corresponding datasets, previously not considered.

6. Frequency magnitude distribution and completeness

It is well known that the number *N* of earthquakes occurring in a given area within a given interval of time follows the power law as a function of magnitude *M* first proposed by Gutenberg and Richter (1944) (hereafter GR)

$$log_{10}N = a - bM \qquad (4)$$

in which *a* is related to the seismic productivity of the considered area and depends on spatial and temporal coverage of the earthquake catalogue, and *b* (b-value) is an index of the relative proportion between large and small earthquakes. The general validity of the GR law has been tested by a number of studies concerning different regions of the world, although small deviations of b-value from the average value 1 have been observed and related to the state of stress of the region (e.g. Schorlemmer et al. 2005; Scholz 2015, Petruccelli et al. 2018). Significant deviations from the linear behaviour of eq. (4) are usually observed at large and small magnitudes and are explained by physical spatial limits of the dimension of the seismogenic fault and by the incompleteness of small earthquakes recording due to the limited sensitivity of the seismometric network, respectively.

The assessment of the magnitude threshold of completeness of an earthquake catalogue is of fundamental importance for any statistical analysis of seismicity, and for seismic hazard assessment. The completeness of a catalogue for which the sensitivity of the network detection is constant with time is usually evaluated just observing the point below which the frequency-magnitude distribution of earthquakes deviates from the linear law (see Woessner and Wiemer 2005, for a thorough overview). If instead the sensitivity of the detection network changes (usually increases) with time a combined analysis of the GR and of the cumulative plot of the number of earthquakes with time has to be made (see e. g. Mulargia et al. 1987).

In the case of CPTI15, which spans in time more than 10 centuries, the concept of detection network has to be intended in a broader sense than a modern seismometric network, available only since the end of XIX century. In this context, the detection network concerns the presence (or absence) over the territory of cultural centres where the information on earthquake effects was recorded and preserved over time (see Stucchi et al. 2004).

To assess the overall completeness of CPTI15, we analyze the cumulative plots of the numbers of earthquakes above different magnitude thresholds at 0.5 intervals, from the nominal minimum magnitude of the catalogue (Mw≥4.0) to the maximum possible threshold (Mw≥7.0). The visual analysis of the cumulative plot for Mw≥4.0 (Fig. ES1 of Online Resource 4) indicates that the present rate of about 30 earthquakes per year was reached only in 1975. This date actually represents a milestone in the evolution of the Italian seismometric network because at about that time ING (today INGV) started to locate earthquakes using computer codes minimizing the sum of squares of arrival times residuals and to compute magnitudes using standard Wood-Anderson seismometers. For Mw≥4.5 (Fig. ES2 of Online Resource 4) the cumulative plot indicates that the present rate of about 8 shocks per year was reached around 1880. Even in this case, we can relate the date with a significant improvement of the detection capability because at about that time a dense network of observatories and meteorological stations, in some cases also equipped with the first mechanical seismometers, became operational over the entire Italian territory. With the establishment, in 1887, of the Geodynamic Service within the Central Office of Meteorology, the practice of collecting news on the effects of earthquakes through questionnaires ("macroseismic cards") became systematic, a practice further developed with the birth, in 1895, of the Italian Seismological Society (see Camassi 1991; Ferrari 1992; Molin et al. 2008). Even for Mw≥5.0 (Fig. ES3 of Online Resource 4) the present rate of about 2.5 earthquakes per year seems to be reached around 1880. The present rate (Fig. ES4 of Online Resource 4) of about one Mw≥5.5 shock every two years can be observed from 1780 on. Such an improvement should refer to the ability to record information on the macroseismic effects of earthquakes. The occurrence, in the second half of the 18th century, of a series of large earthquakes (the great 1783 Calabrian earthquakes, together with the long seismic sequences that shook central Italy in the second half of the 18th century) resulted in a strong increase in sensitivity to earthquakes, also linked to a scientific interest related to the development of new theories about their origin. This growth of attention stimulates the proliferation of collections of news about earthquakes, also favoured by the development of the European journalistic networks (Camassi and Castelli 2004; 2005). For Mw≥6.0 (Fig. ES5 of Online Resource 4) a clear change in the slope of the cumulative plot toward the present rate of about one earthquake every 6 years can be observed around 1620. The explanation of this abrupt improvement of the information available on earthquakes might refer in general to the increase of interest on scientific phenomena starting from the beginning of the 17th century. This was accompanied by the growth of the Italian and European journalistic network (handwritten "avvisi" and printed gazettes), which allowed an efficient circulation of news, later collected in the 19th century seismological compilations (Camassi and Castelli, 2004; 2005). Even for the other thresholds Mw≥6.5 and Mw≥7.0 (Fig. ES6 and ES7 of Online Resource 4, respectively) the slope change to the present rates of about one earthquake every 13 and 50 years respectively appears to have occurred around 1620.

Assuming the above-mentioned completeness intervals (since 1975 for Mw≥4.0, since 1880 for Mw≥4.5, since 1780 for Mw≥5.5, and since 1620 for Mw≥6.0), we computed the b-value in each of them with the method by Aki (1965), obtaining 1.01±0.03, 1.05±0.03, 1.06±0.09 and 0.94±0.11 respectively. These values indicate a rather good consistency of the frequency magnitude distribution with the global average b-value (H1) and among the different time intervals. Even the productivity coefficient (*a*-value) is rather consistent among different completeness intervals, as demonstrated in Figure 11 where the frequency magnitude distributions, normalized for the duration of each completeness interval, are superimposed. The only notable discrepancy concerns magnitudes around 5.5, for which the shorter time interval shows slightly larger rates than longer intervals. The abrupt decrease of all the rates for Mw≥7.1 indicates that such magnitude probably represents an upper limit in most of the seismogenic areas of Italy. The only earthquake with larger magnitude (Mw=7.3) is that one occurred in Eastern Sicily on 11 January 1693.

7. Website

CPTI15 and the related macroseismic database DBMI15 are publicly available on a dedicated and specifically developed website, as all their previous versions and predecessors back to the NT4.1 catalogue (Camassi and Stucchi 1997) and DOM macroseismic database (Monachesi and Stucchi 1997).

The CPTI15-DBMI15 website (https://emidius.mi.ingv.it/CPTI15-DBMI15/), available in English and Italian, allows querying CPTI15 by earthquake, and retrieving all the events in a table with the earthquake date, the epicentral area, the number of macroseismic intensity data points (if any), the epicentral intensity, and the moment magnitude. Earthquakes' epicentres are also plotted on a map that can be panned and zoomed, and the symbol representing the epicentre can be clicked to obtain more details on the selected event. Once an earthquake is selected, the user is presented with a series of additional information, such as the macroseismic and/or instrumental parameters, the source of the macroseismic intensity data, and the list of macroseismic intensities (with place name, coordinates and intensity), depending on their availability. In addition, a permalink directly points to the downloadable Microsoft Excel (.xlsx) and Comma Separated Value (.csv) catalogue files. Another link gives access to all the additional data related to the earthquake archived in the Italian Archive of Historical Earthquake Data ASMI (see Section 3), such as earthquake parameters provided in other parametric catalogues, the information contained in the selected study, and the list of alternative studies related to the same earthquake.

Users may apply a filter to the list of earthquakes based on one or more parameters of their choice, either year, number of macroseismic intensity data points, epicentral intensity or magnitude. A circular or polygonal geographical selection is also possible by either drawing the area of interest directly on the map, or by entering the coordinates of the vertices for a more precise selection. To simplify the reproduction of the same geographical selection later on, the user can copy and paste the entered parameters, i.e the list of coordinates representing the vertices of the polygon, and then paste it for re-creating the same selection polygon.

Macroseismic intensity data can be queried by searching a place name, in alphabetical order, by geographical selection on the map, or by an administrative subdivision, either region, province or municipality. Once the user selects a place, the list of all the earthquakes that were recorded as a macroseismic effect at the place itself is provided.

The table of CPTI15 can be downloaded in two formats, for Microsoft Excel (.xls), and as an Open Document Format for Office Applications (.odf). The spreadsheet contains three sheets presenting: a) the content and few other useful information, such as the list of the authors, the terms of use and the bibliographical citation, b) the description of each field, and c) the catalogue table itself.

The website is created using an updated version of the open-source web application called MIDOP (Locati and Cassera 2010), developed in-house. MIDOP, the Macroseismic Intensity Data Online Publisher, was originally meant for publishing Italian intensity data that are periodically updated at each new release of DBMI. Since 2012, in the framework of AHEAD, the European Archive of Historical Earthquake Data (Locati et al. 2014; Rovida and Locati 2015), MIDOP has been extended to allow the publication of intensity data in other European, then worldwide geographical areas. MIDOP is presently in use at the British Geological Survey (BGS), the Institut Cartogràfic i Geològic de Catalunya (ICGC), the University of Athens (UoA), the Instituto Geográfico Nacional (IGN), and is currently being tested at the Earth Observatory of Singapore (EOS) and the University of Bergen (UiB).

In addition to the user-friendly website and the downloadable spreadsheet, CPTI15 can be accessed using two distinct types of web services. The first type is a FDSN-event web service, a standard proposed by the Federation of Digital Seismograph Networks for exchanging earthquake parameters using a simple RESTful interface, which provides users with the possibility of sending a complex query based on a series of parameters that can be freely combined together. Examples of available query parameters are the minimum or maximum magnitude, a time-range, a circular or rectangular geographical area, and the desired output format. The standard FDSN-event service should support at least two output formats: a compact and simple plain text (.csv) with the most relevant parameters, such as epicentral location and magnitude, and the more complex QuakeML (Schorlemmer et al. 2011), an XML based format which is able to associate multiple epicentral and magnitude estimations to an earthquake.

The second type of web services are compliant with OGC (Open Geospatial Consortium), a general-purpose standard meant to transfer geographical information across the web using platform-independent calls. The WFS (Web Feature Services) are able to output the original geographical features together with the associated parameters, and the WMS (Web Map Service) is able to output georeferenced map images where the features are represented with a pre-configured set of symbols. In the case of CPTI15 the output features are points representing the epicentres, to which the list of CPTI15 parameters is associated. The general-purpose nature and the widespread use of the OGC standard web services enable the user to directly load CPTI15 in any OGC compliant software, most notably the Open Source QGIS and ESRI GIS products, such as the ArcGIS in both the desktop and online versions.

8. Conclusions

The most recent version (2.0) the Parametric Catalogue of Italian Earthquakes CPTI15 represents the latest step in the evolution of the Italian tradition and experience in earthquake cataloguing. Such a tradition began 45 years ago, as far as modern parametric catalogues are concerned, but it may date back to the long history of compiling earthquake data and information started in Italy in the late 19th century.

Even with respect to the previous version CPTI11, released in 2011, the changes and improvements of CPTI15 are many. Changes mainly deal with the update of the input macroseismic data, deriving from the great improvement in terms of both the number and the quality of the historical macroseismic investigations that have been performed in Italy in the last few years, as well as with the refinement in the procedures related to magnitude acquisition, conversion and harmonization. The latter particularly affected the low magnitudes, the assessment of which is now much more robust than before. In general, a great effort aimed at harmonizing magnitude estimates of various origin and periods. This concerned, on the one hand, the harmonization of instrumental and macroseismic magnitudes, and on the other hand the conversion of magnitudes from different origins, methods and scales to modern moment magnitude from the inversion of moment tensors. In the compilation, published and peer-reviewed data and procedures are used as much as possible and are fully coded in the catalogue file. In addition to the website specifically developed to consult and access the catalogue, the input macroseismic data and the studies they derive from are collected and fully accessible through dedicated databases and web portals, namely the Italian Macroseismic Database DBMI15, and the Archive of Italian Historical Earthquake Data ASMI.

The analysis of the cumulative number of earthquakes above different magnitude thresholds indicates that CPTI15 is complete since 1975 for Mw≥4.0, since 1880 for Mw≥4.5, since 1780 for Mw≥5.5, and since 1620 for Mw≥6.0. Unlike previous catalogues of Italian seismicity, the frequency magnitude distribution obtained from CPTI15 for this different completeness time intervals presents a b-value ≈ 1, consistent with the global average and current instrumental catalogues. For this reasons CPTI15 is suitable for robust statistical analyses of the time-space property of Italian seismicity.

In spite of the mentioned features and the considerable step forward it represents, CPTI15 cannot be taken as a point of arrival, since many enhancements are possible and some issues are still to be faced. The legacy of the late 19th-century seismological compilations is still important, resulting in the possibility of finding data on unknown earthquakes in historical sources and archives that have not been fully exploited so far.

This possibly results also in a spatial and/or temporal inhomogeneity of the catalogue, depending on the areas and/or periods that have been the object of subsequent specific research, none of which has ever been aimed at a homogeneous revision of the earthquake catalogue at the national scale. In addition, historical investigations of the past mostly focused on the strongest earthquakes, sometimes neglecting the definition of minor seismicity, equally important in many applications. Another possible inhomogeneity concerns the representation of seismic sequences, which is particularly important in most of the areas of the Italian Apennines. This is a consequence of both the objective difficulty (or impossibility) of discriminating single shocks in a sequence from the point of view of their macroseismic effects, and, again, of the legacy of past studies that sometimes did not dedicate sufficient attention to such a problem.

The procedure established and followed in the compilation of the catalogues of the CPTI family ensures the easy and rapid incorporation of new and fresh data. Future releases will take into account all the wealth of data that hopefully will become available in the future, for a more and more robust and thorough knowledge of the past Italian seismicity.

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Tables

***Tab. 1** List of the national and regional parametric catalogues contributing to the PFG catalogue (Postpischl 1985a), together with their spatial coverages, number of entries, and reference code*

Reference	Code	Region	Entries
ENEL (1977)	000	Italy	16,117
Iaccarino and Molin (1978)	501	North-Eastern Italy	1,725
Dell'Olio and Molin (1980)	502	Lazio	5,511
Magri and Molin (1979)	503	Basilicata	553
Bernardis et al. (1977)	504	Friuli	1,664
Bernardis et al. (1978)	505	Friuli	134
Eva et al. (1978)	506	Liguria	778
Carrozzo et al. (1975)	507	Calabria and Sicily	7,633
ING Seismic Bulletin (1976-1980)	226	Italy	2,735

***Tab. 2** List of non-conventional descriptive codes, their meaning, associated numerical value, and the corresponding number of MDPs reported in DBMI15*

Code	Description	Ass. value	MDPs
HD	Heavy Damage	8.6	189
D	Damage	6.4	707
SD	Slight Damage	5.6	31
HF	Highly Felt	5.1	112
F	Felt	3.9	5400
SF	Slightly Felt	2.9	49
NC	Not Classified	1.8	131
NF	Not Felt	1	24028
G	Generic damage information	0.2	5

***Tab. 3** List of the large uncertain intensities and their corresponding translation in the best-matching non-conventional intensities*

Greatly uncertain intensity	Non-conventional descriptive codes	MDPs
8-10	HD	1
≥ 7	HD	18
7-9	HD	7
6-8	D	55
5-7	D	7
3-5	HF	44
2-5	F	47
2-4	SF	34

***Tab. 4** Recompilation criteria adopted for the homogenization of the original intensities*

Recompilation criteria	MDPs
Unchanged	64473
Roman to Arab numbers (e.g. "V-VI" to "5-6")	30270
Decimal to Text (e.g. "5.5" to "5-6")	25537
Code conversion (e.g. "S" used in CFTI to "HF")	1814
Translation to English (e.g. *"sentito"* to "F")	763
Divided by 10 (e.g. "50" to "5")	423
Slash to minus (e.g. "5/6" to "5-6")	237
Large uncertainty (e.g. "6-8")	213
Word to code (e.g. "felt" to "F")	26

Tab. 5 *Intensity recompilation criteria in relation to localities not fulfilling the macroseismic scale requirements. In brackets, the corresponding decimal value, used for calculations is given. The code "SC" stands for a "Special Case" locality: Absorbed locality (AL), City Quarter (CQ), Deserted Locality (DL), Small settlement (SS), Multiple settlement (MS), Unidentified locality (UL), Isolated Building (IB), Territory (TE)*

<table>
<tr><th colspan="2"></th><th colspan="18">Original intensity</th><th></th></tr>
<tr><th colspan="2"></th><th>1</th><th>1-2</th><th>2</th><th>2-3</th><th>3</th><th>3-4</th><th>4</th><th>4-5</th><th>5</th><th>5-6</th><th>6</th><th>6-7</th><th>7</th><th>7-8</th><th>8</th><th>8-9</th><th>9</th><th>9-10</th><th>10</th><th>10-11</th><th>MDPs</th></tr>
<tr><th rowspan="9">Special Cases</th><th>no SC</th><td rowspan="7">NF (1)</td><td rowspan="7">1-2 (1.5)</td><td rowspan="7">2 (2)</td><td rowspan="7">2-3 (2.5)</td><td rowspan="7">3 (3)</td><td rowspan="7">3-4 (3.5)</td><td rowspan="7">4 (4)</td><td rowspan="7">4-5 (4.5)</td><td rowspan="7">5 (5)</td><td rowspan="7">5-6 (5.5)</td><td rowspan="7">6 (6)</td><td rowspan="7">6-7 (6.5)</td><td rowspan="7">7 (7)</td><td rowspan="7">7-8 (7.5)</td><td rowspan="7">8 (8)</td><td rowspan="7">8-9 (8.5)</td><td rowspan="7">9 (9)</td><td rowspan="7">9-10 (9.5)</td><td rowspan="7">10 (10)</td><td rowspan="7">10-11 (10.5)</td><td>111975</td></tr>
<tr><th>AL</th><td>148</td></tr>
<tr><th>CQ</th><td>44</td></tr>
<tr><th>DL</th><td>206</td></tr>
<tr><th>SS</th><td>449</td></tr>
<tr><th>MS</th><td>4143</td></tr>
<tr><th>UL</th><td>76</td></tr>
<tr><th>IB</th><td colspan="2" rowspan="2">NF (1)</td><td colspan="3" rowspan="2">SF (2.9)</td><td colspan="2" rowspan="2">F (3.9)</td><td colspan="2" rowspan="2">HF (5.1)</td><td rowspan="2">SD (5.6)</td><td colspan="4" rowspan="2">D (6.4)</td><td colspan="6" rowspan="2">HD (8.6)</td><td>166</td></tr>
<tr><th>TE</th><td>53</td></tr>
</table>

Tab. 6 *Recalibrated coefficients (a,b,c), standard deviations of regressions (s), weight normalization factors (K) and degrees of freedom (df) for computation of macroseismic magnitude with the Boxer program.*

Intensity	a	b	c	s	K	df
2	3.12202	0.04414	0.02241	0.2611	10.4	82
2-3	3.01875	0.04769	0.02309	0.1805	10.7	43
3	2.94284	0.05239	0.02345	0.2482	17.9	211
3-4	2.89718	0.05662	0.02400	0.2194	16.4	139
F (3.9)	3.60901	0.02733	0.02374	0.2017	14.0	22
4	3.20351	0.05107	0.02218	0.2413	23.0	224
4-5	3.16818	0.04417	0.02667	0.2390	20.1	134
5	3.69208	0.02425	0.02462	0.2433	27.1	118
5-6	3.97257	0.01983	0.02254	0.2337	21.4	48
6	3.83759	0.03590	0.02196	0.2244	33.8	50
6-7	3.96044	0.03437	0.02104	0.2112	29.5	32
7	4.00027	0.06045	0.01794	0.1942	49.3	27
7-8	4.29349	0.03671	0.01825	0.1265	30.7	15
8	4.45795	0.05282	0.01579	0.1410	41.9	14
8-9	4.70681	0.04980	0.01462	0.0619	29.0	4
9	5.60472	0.14657	-	0.1350	23.1	5

Tab. 7 *Priority and conversion scheme for the instrumental magnitude adopted in the catalogue*

Catalogue	Validity	Mag.	Considered data	Conversion to Mw	Priority	Notes
RCMT – INGV	1976-2017	Mw	508	-	1	Combined with other Mw according to Gasperini et al. (2012)
TDMT – INGV	2004-2017	Mw	241	-	1	Combined with other Mw according to Gasperini et al. (2012)
SEDMT – ETHZ	1999-2005	Mw	104	-	1	Combined with other Mw according to Gasperini et al. (2012)
Global CMT	1976-2017	Mw	83	-	1	Combined with other Mw according to Gasperini et al. (2012)
NEIC	1980-2009	Mw	17	-	1	Combined with other Mw according to Gasperini et al. (2012)
CSTI1.1	1981-1996	Ml/Md	330	Gasperini et al. (2013)	2	Combined with ISC Proxy
CSI1.1	1997-2002	Ml/Md	166	Gasperini et al. (2013)	2	Combined with ISC Proxy
INGV Bulletin/ISIDE	2003-2017	Ml/Md	116	Gasperini et al. (2013)	2	Combined with ISC Proxy
ISC Reviewed bulletin	1964-2015	MS/mb	575	Lolli et al. (2018)	3	Combined with Ml Proxy
Bollettino ING	1972-1980	ML (WA)	91	Lolli et al. (2018)	4	Combined with Proxy ISC
Sandron et al. (2015)	1977-1978	ML (WA)	4	Sandron et al. (2015)	4	Combined with ISC
Margottini et al. (1993)	1964-1975	mb	296	Lolli et al. (2014; 2015)	5	If it is the only solution
PFG	1962-1978	ML	8	Lolli et al. (2018)	6	If it is the only solution

Figure captions

Fig. 1 Map of the earthquakes in CPTI15. The solid blue line indicates the boundary of the area covered by the catalogue. Earthquakes of CPTI11 relocated outside the area are maintained in CPTI15

Fig. 2 Scheme used in the compilation of the catalogue and the relationships among input data, ASMI, DBMI15, and CPTI15

Fig. 3 a) Magnitude and b) intensity distributions in the dataset used for calibrating Boxer

Fig. 4 Comparison between the observed (instrumental) Mobs and calculated (macroseismic) magnitude values Mcalc for the 354 calibrating events. a) The grey line indicates the equality between the two estimates. b) The black line indicates the frequencies of a Normal distribution with average -0.08 and standard deviation 0.40

Fig. 5 Type of default epicentral location in CPTI15. MI = macroseismic (alternative to instrumental); IM = instrumental (alternative to macroseismic); II = instrumental (only option); MM = macroseismic (only option); PC = from parametric catalogue; NP = not determined

Fig. 6 Data availability and selected locations in four different time-windows in the 20th century. II = exclusively instrumental; MI = macroseismic alternative to instrumental; IM = instrumental alternative to macroseismic; MM = exclusively macroseismic.

Fig. 7 Types of default magnitude in CPTI15 (InsO = instrumental "genuine" Mw; InsC = proxy instrumental Mw; Mdm = macroseismic, from intensity data; MIo = macroseismic, from epicentral intensity; Mpc = from another parametric catalogue; Wmim = mean of macroseismic and instrumental values; NP = not parametrized)

Fig. 8 Timeline (1900 - 2017) for the different magnitude determinations

Fig. 9 Main differences between the epicentral locations (≥ 30 km) in CPTI15 (coloured squares) and in CPTI11 (black dots)

Fig. 10 Comparison between CPTI15 and CPTI11 magnitudes. Magnitudes are shown according to their type in CPTI15. Left: Wmim = mean of instrumental and macroseismic determinations; Mdm = macroseismic, from intensity data; MIo = macroseismic, from epicentral intensity; Mpc = from parametric catalogue. Right: InsO = instrumental, Mw from moment tensor solutions; InsC = instrumental proxy Mw

Fig. 11 Frequency-magnitude distribution (cumulative) of earthquakes in the catalogue for different time intervals and magnitude thresholds.

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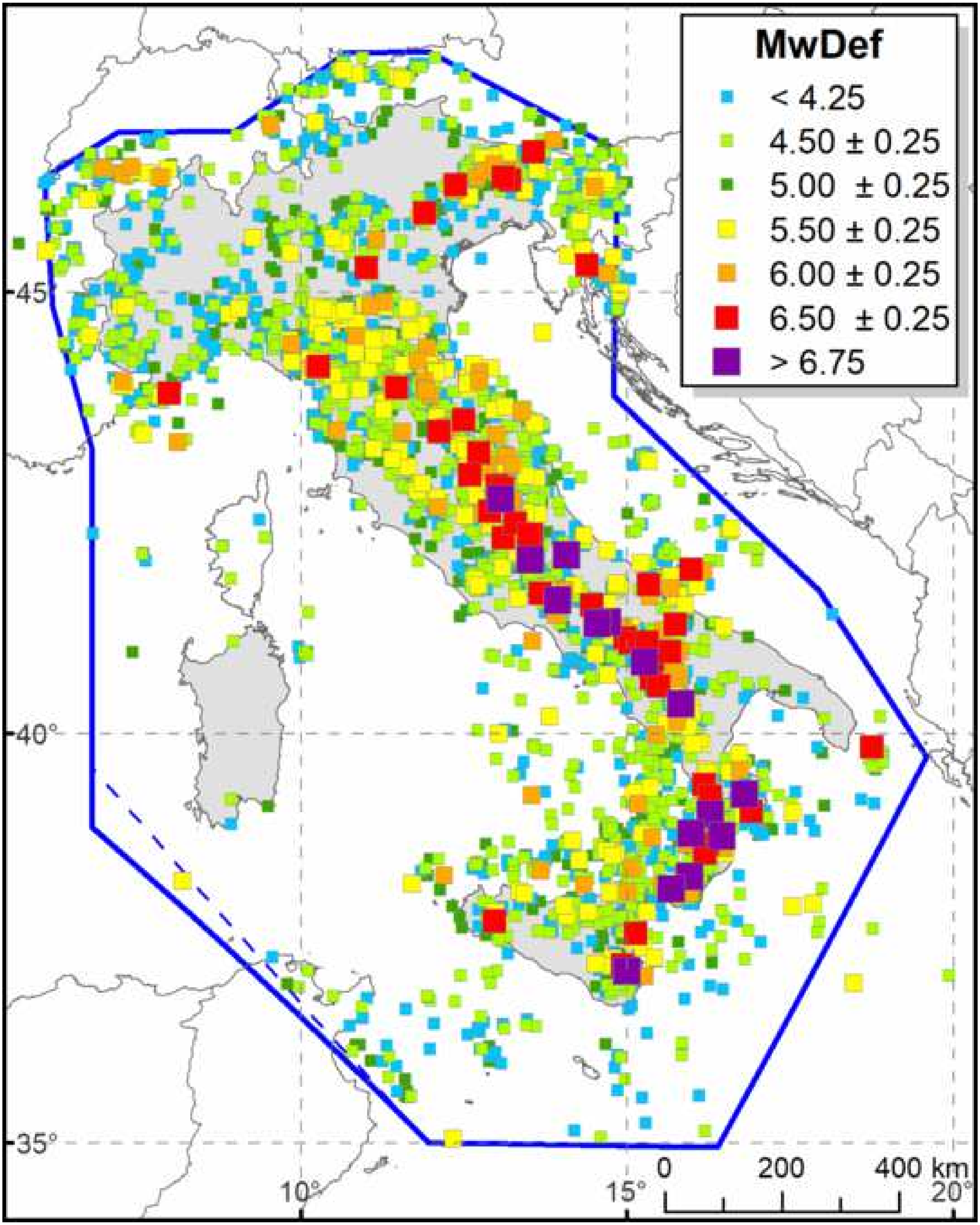

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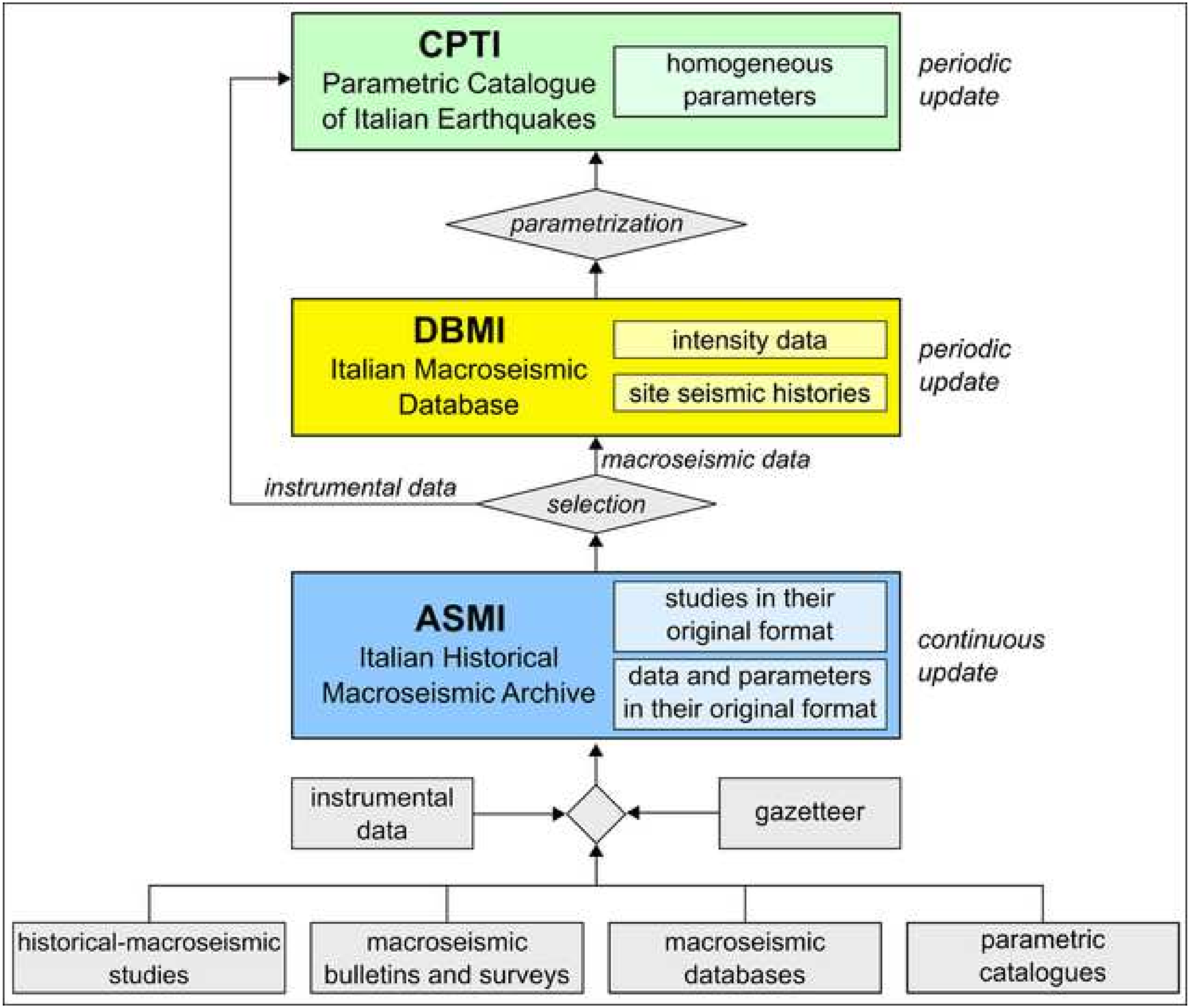

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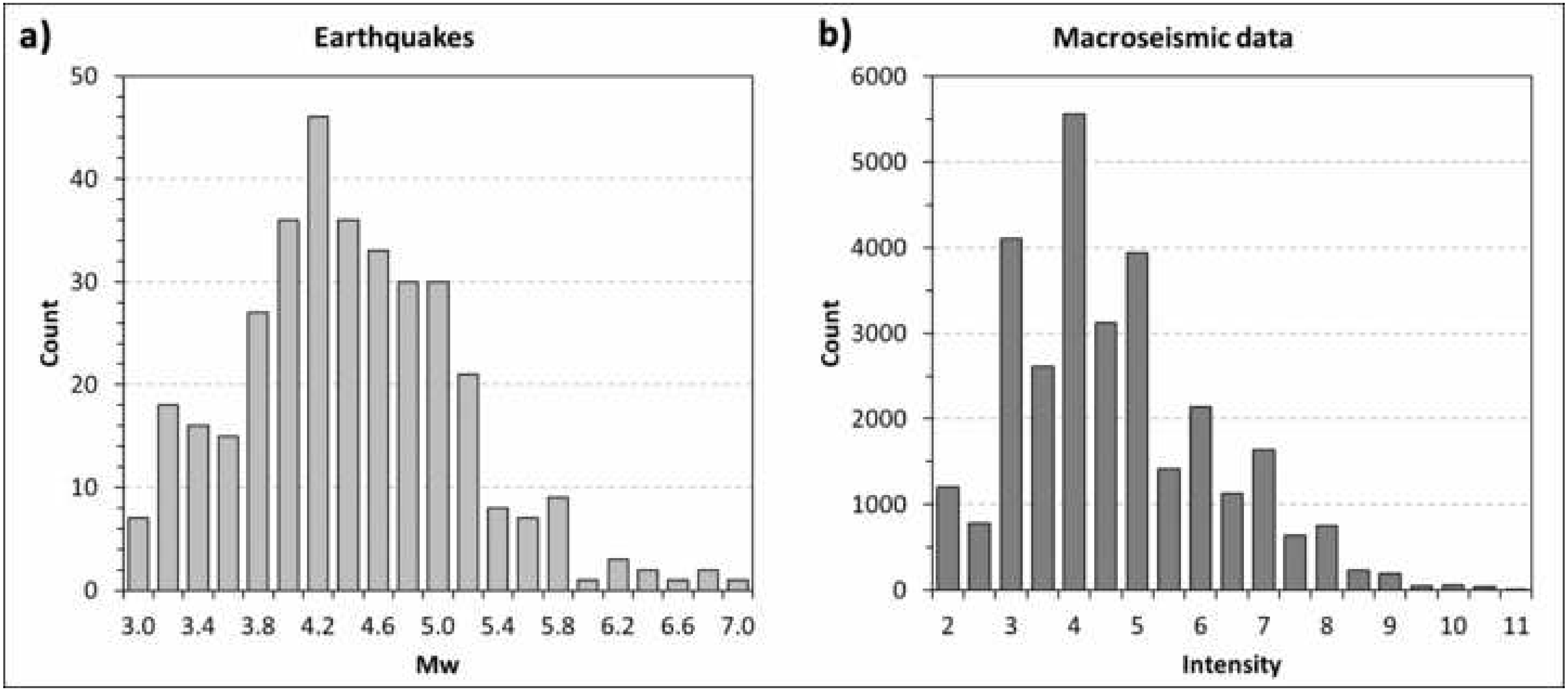

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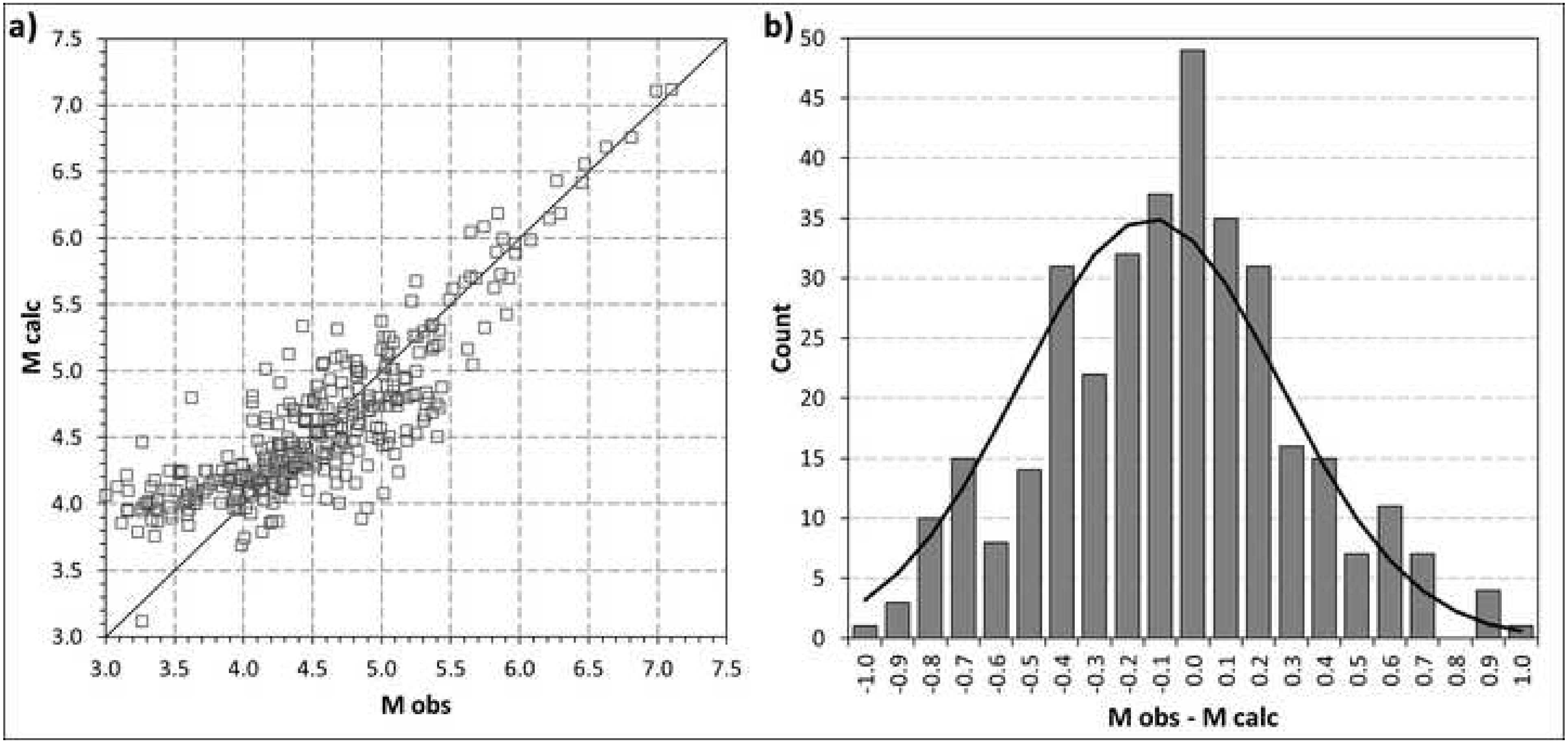

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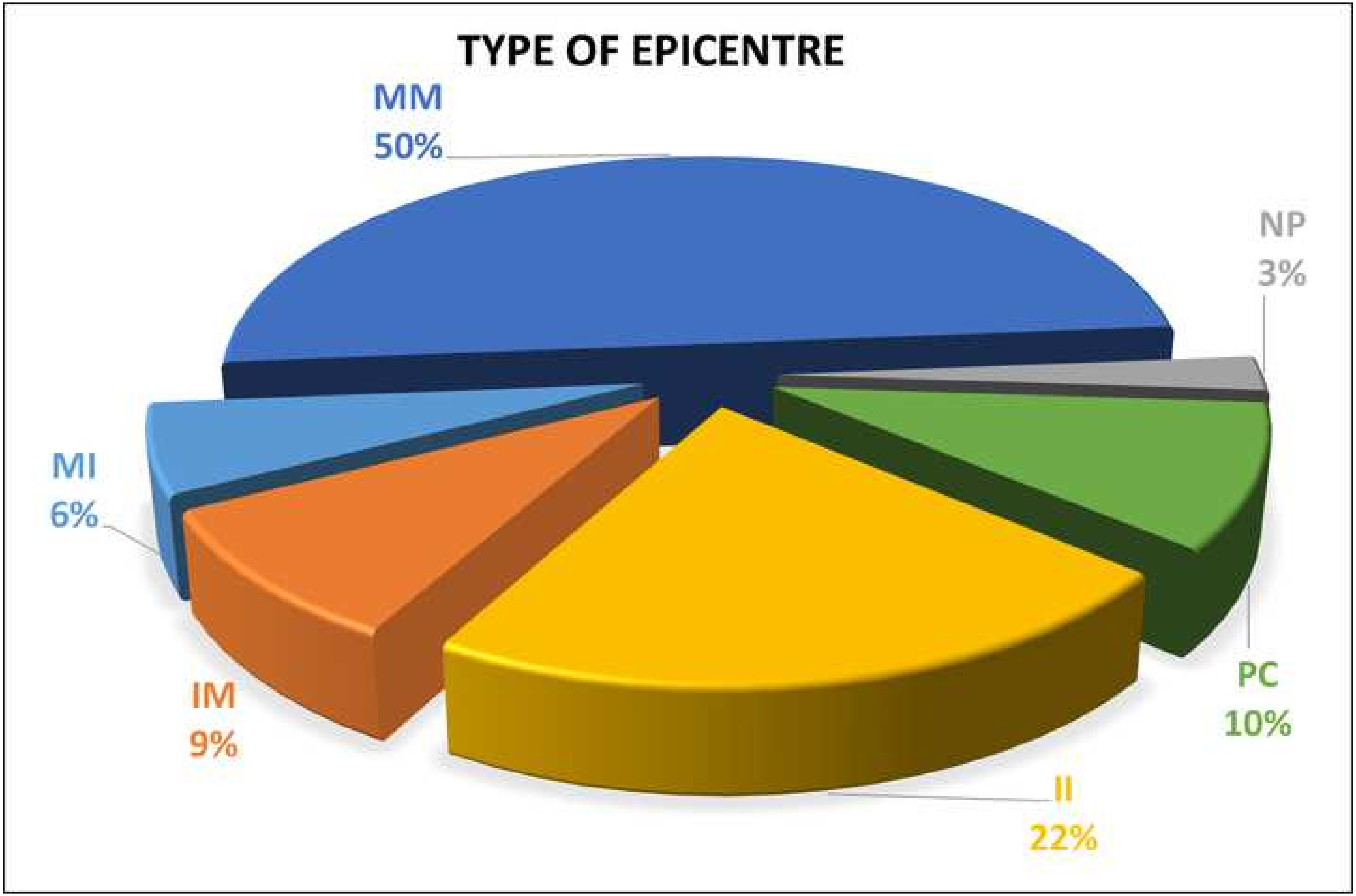

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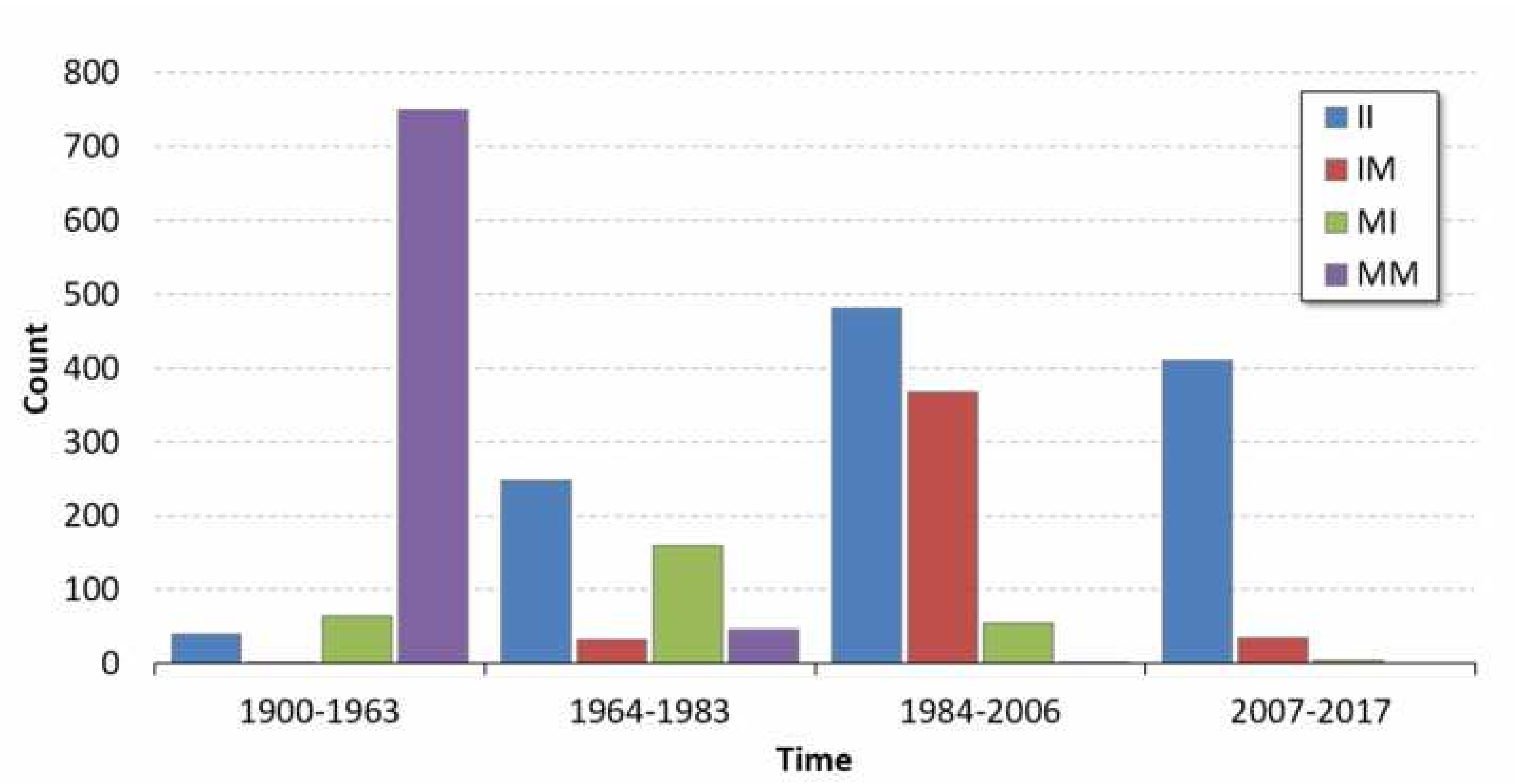

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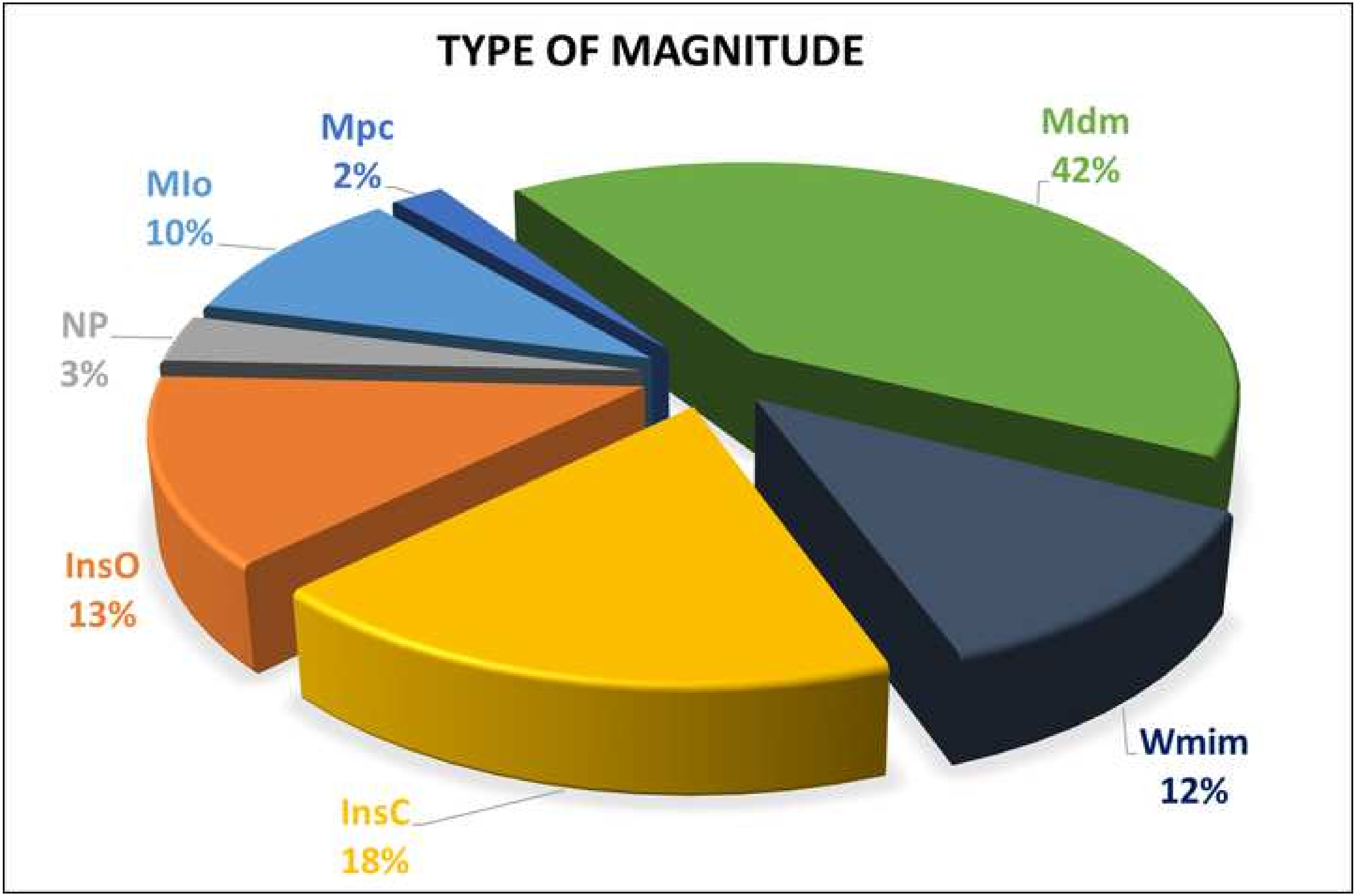

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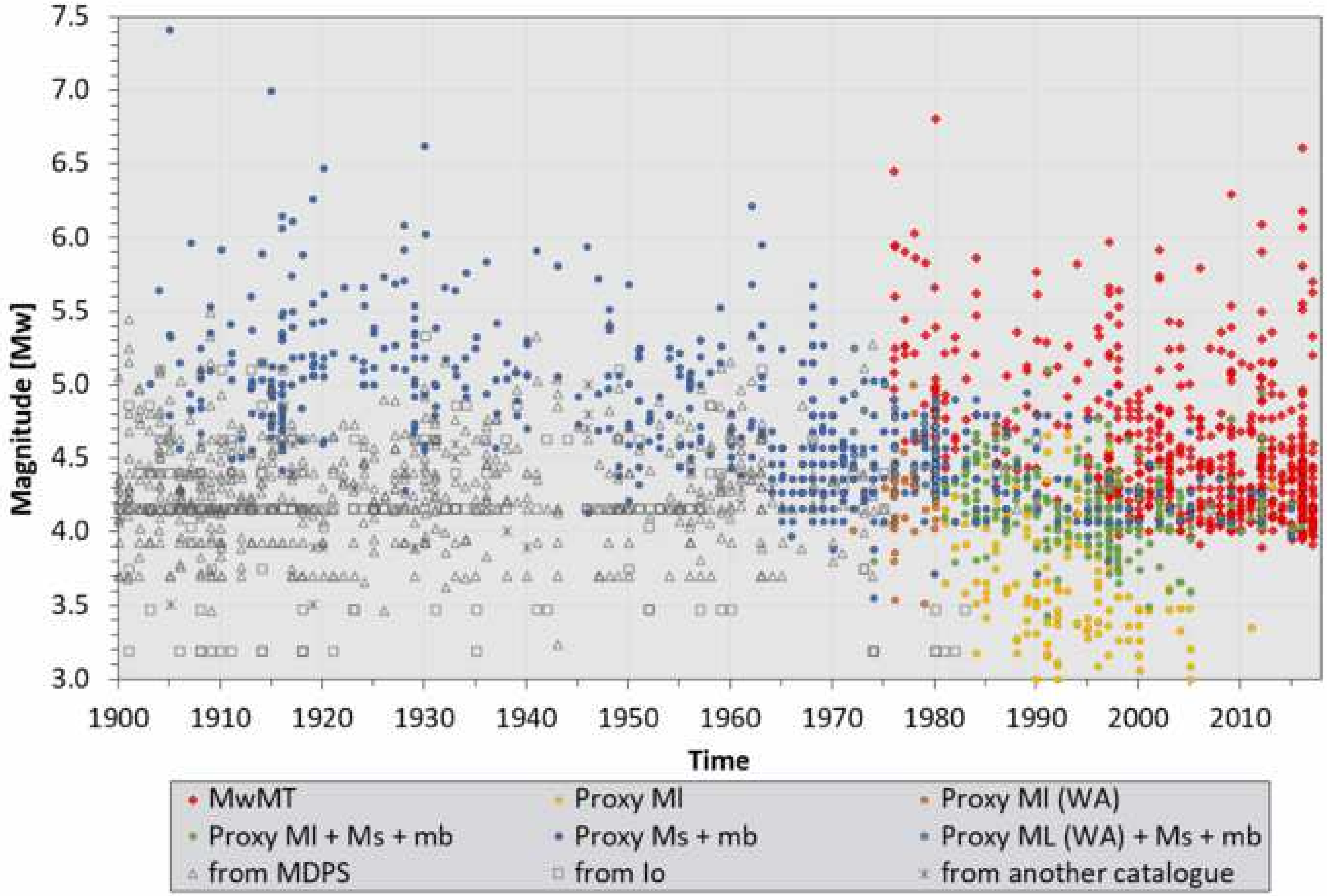

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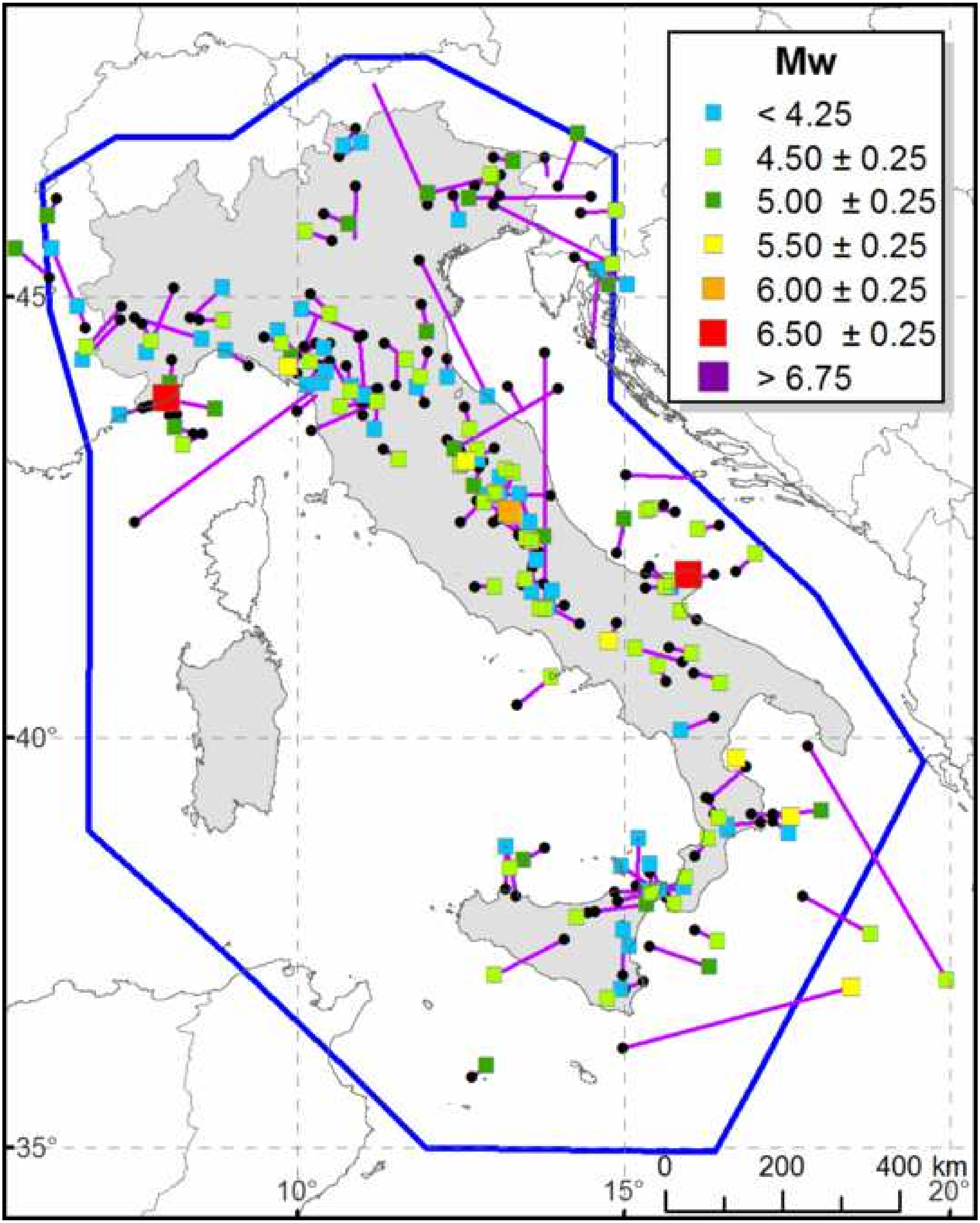

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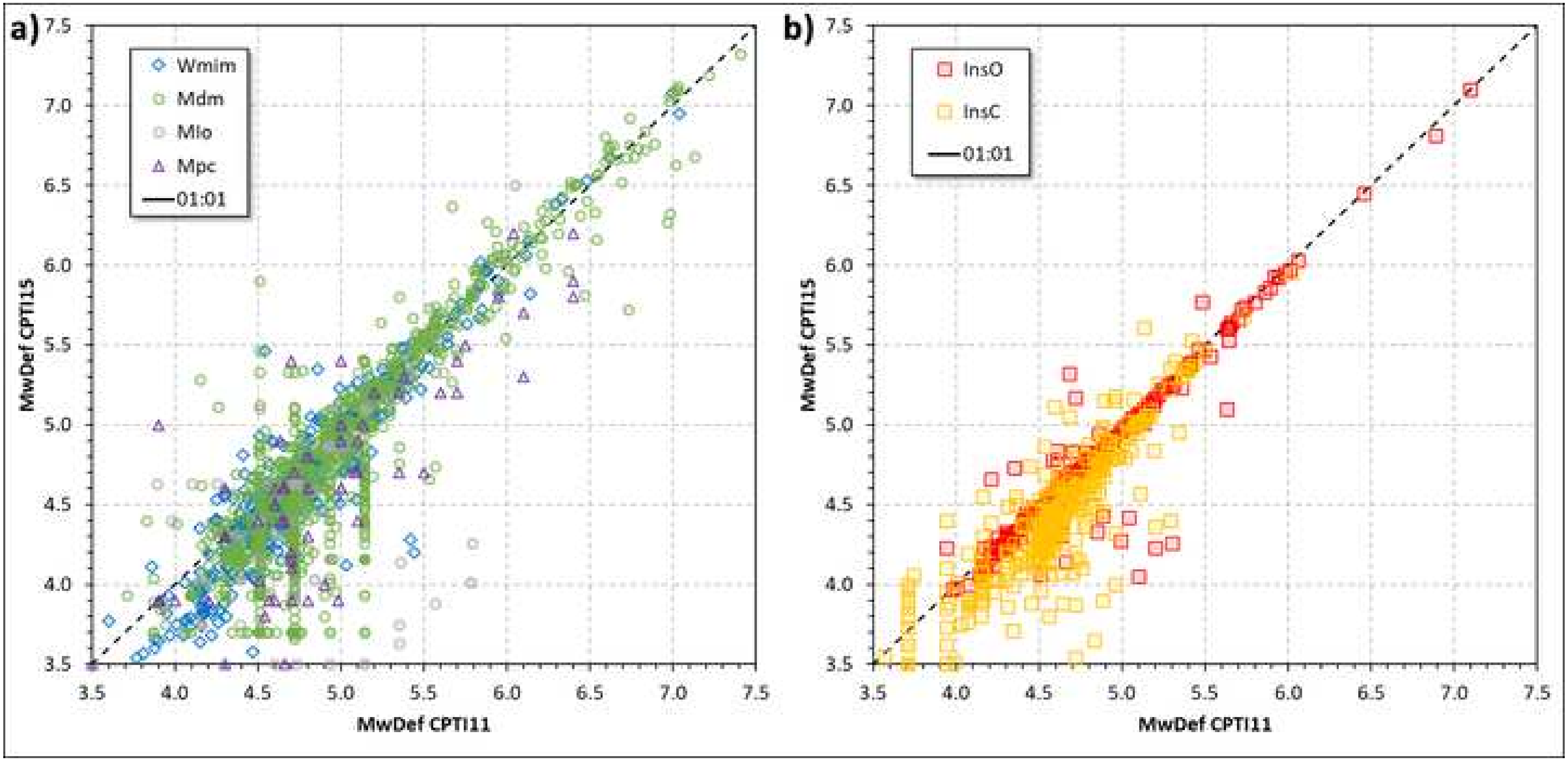

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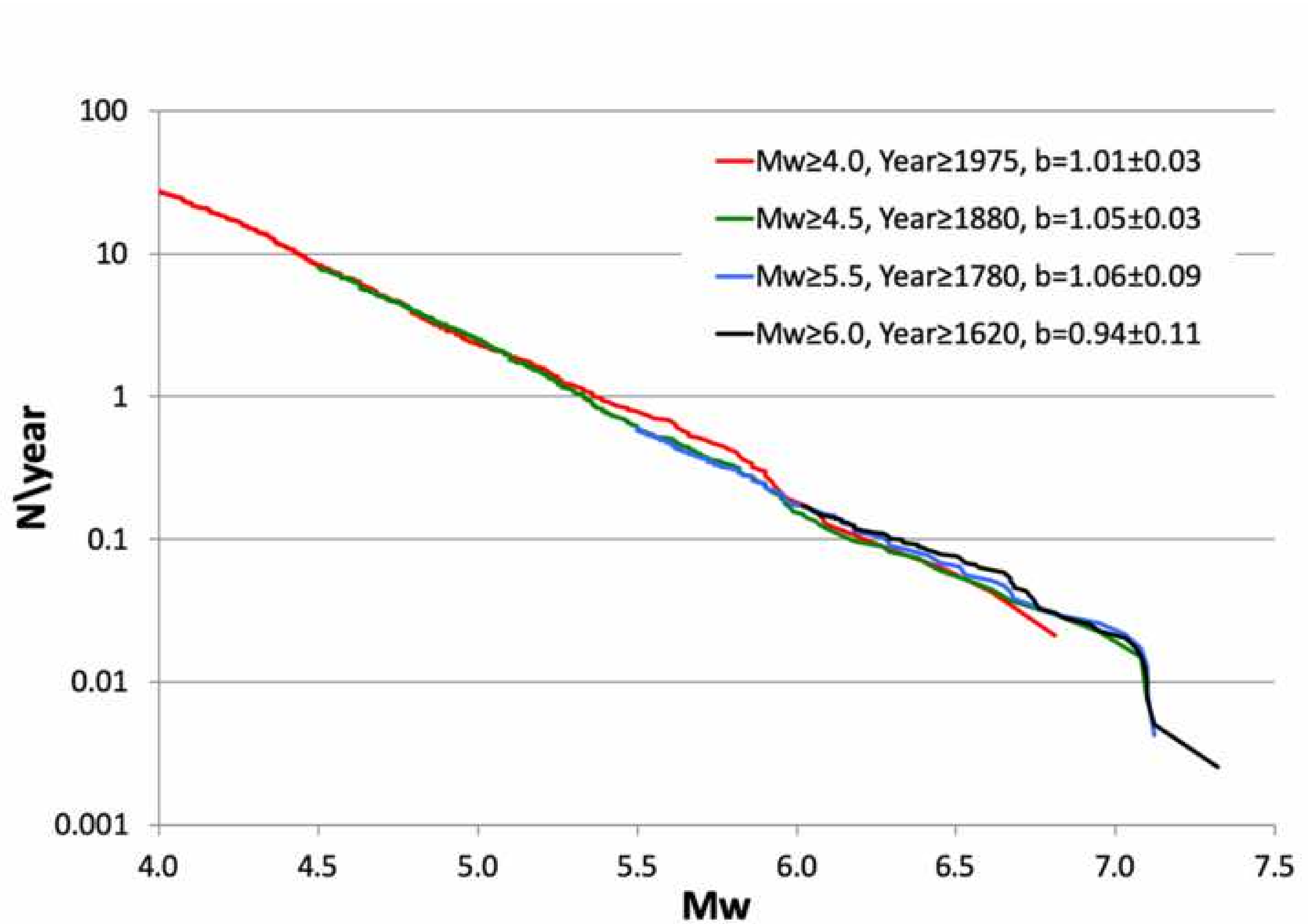

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