Chapter

A Tool for Archiving and Updating Knowledge about Past Earthquakes in Central America

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Abstract

In 2019, we released a prototype version of an online tool called MARCA-GEHN that combines an earthquake catalog and a macroseismic archive for a Central American (CA) sector, which was realized as part of an international project between Italy and four CA countries (Guatemala, El Salvador, Honduras, and Nicaragua). The aim was to build a transnational, common, quality-controlled archive of macroseismic observations capable of documenting and updating the parameters of the main earthquakes recorded in the international historical and instrumental catalogs. Collecting the original documents, critically revising them, and organizing them in a public, open data format is a long, potentially endless process. Thanks to past experience in Europe and the additional efforts of the local CA scientific communities, MARCA-GEHN was updated in 2023. The current database contains about 70 earthquakes with intensities observed at the sites, about 2200 intensity points related to more than 1100 locations. This archive can help improve information on past and current earthquakes, and it is a powerful tool for constraining the seismic sources, a key element of hazard and risk analyses. We briefly present the structure of the archive, the shortcuts for the queries, some results obtained so far, and potentialities for the future.

Keywords: MARCA-GEHN, macroseismic intensities, El Salvador, Guatemala, Honduras, Nicaragua, earthquake catalog, Central America

1. Introduction

Central America is one of the most prone and vulnerable areas in the world to earthquakes, which have caused casualties and high economic and social damage since ancient times. The culture of "risk" necessarily occupies an important place for Central American governments, along with the attempt to regionalize protection and mitigation, especially due to the pressure of events that are often difficult to manage due to their intensity and territorial dimensions.

Knowledge of previous earthquakes in an area is the starting point for any seismic hazard and seismic risk assessment. Both methodological approaches, estimating seismic hazard by probabilistic methods and models or by deterministic earthquake scenarios, are mainly based on parametric earthquake catalogs; they derive from quantitative measurements of instrumental seismology and qualitative assessment of macroscopic impacts or damages caused by earthquakes, a research area of macroseismology. The short time span covered by instrumental seismic data (about a century) may not be sufficient to adequately reconstruct the seismic behavior of a country, and to fill this gap it is necessary to obtain non-instrumental information from historical sources. On the other hand, macroseismology is concerned with the parameterization of earthquakes-that is, the definition of time of occurrence, location, depth, and magnitude-through the collection and mapping of witness reports of felt earthquakes, a fundamental discipline for extending earthquake catalogs back to the time of instrumental seismology. In many countries, there is no or insufficient information from before instrumentation; in some others (e.g., Italy, Greece, Japan), the earthquake catalog useful for hazard analysis is obtained mainly from macroseismic data.

The historical seismicity of Central America is based on regional and national catalogs and on documents, reports, and monographs on individual seismic events, which often do not include estimates of epi/hypocentral parameters, intensity values, or isoseismal drawings. Since the 1960s, only a dozen scientific papers (or seismic catalogs) have been found that rely on new historical sources, some of which provide partial seismological interpretations, in terms of macroseismic analyses with the definition of focal parameters (e.g. [1–5]). In 1999, Peraldo and Montero [1] published, with great compilatory and interpretive effort, an earthquake catalog containing seismic information obtained directly from archives and/or other referenced sources, according to modern practices. They also provided new seismological interpretations as well as the definition of focal parameters of the most destructive earthquakes recorded in Central America. Regarding the parametric catalogs, the main catalog in [2] includes about 17,000 earthquakes; it merges at least 30 different earthquake catalogs that include both macroseismic and instrumental observations, without additional information on macroseismic records or historical sources.

As part of an international collaborative project, we pursued the realization of the first cross-national prototypical archive of macroseismic data points for the four participating countries in Central America. The database MARCA-GEHN (Macroseismic ARchive for Central America countries—Guatemala, El Salvador, Honduras, and Nicaragua) was realized by adopting best practices and lessons learned in Europe in the field of macroseismology, involving local scientific communities and government institutions. The prototype online platform has been publicly available on the Internet since 2019 and seeks to address the different data availability and problems encountered at the borders of neighboring countries. The database takes into account the many specificities of Central American countries exposed to a variety of seismogenic processes, at different levels of ground shaking, and the availability of non-uniform instrumental and historical seismic data. The prototypical archive of macroseismic data represents a dynamic seismic catalog since it can be continuously updated depending on the progress of historical research; it is also designed for the integration of new descriptive data that can better contribute to define the seismic scenario of individual events, such as the main social and economic elements: fatalities, injuries, elements of historical structures related to seismic impacts, temporary and permanent earthquake-related geological effects on the environment, and damage effects due to anomalous sea waves. The coexistence of different tectonic regimens (cortical, interphase, and intraplate subduction) can lead to the differentiation of earthquake impacts on the population, building stock, and natural environment, which are the subject of the documentation searched by macroseismology.

In this work, an attempt was made to verify the quality of the information on the selected seismic events in terms of their geographical location and the reliability of the bibliographic sources. Efforts were also made to verify or assign missing parameter values for each earthquake. As mentioned above, this work should be considered as a first attempt to standardize the available information and its bibliographic references for a limited number of seismic events and to organize them in a publicly available macroseismic database that can be enriched, maintained, and regularly updated through local and international efforts.

2. The online MARCA-GEHN archive

Within the RIESCA project ("Proyecto de formación aplicada a los Escenarios de Riesgo con la vigilancia y monitoreo de los fenómenos volcánicos, sismicos e hidrogeológicos en América Central"), funded by the Italian Agency for Development Cooperation (AICS) for the period 2017–2021 and coordinated by the University of Palermo, we developed the first prototype online archive of macroseismic data points for four Central American countries.

The project was scheduled to end with the onset of the pandemic COVID-19, and the very last stages were diluted in remote work sessions. Nonetheless, the online archive (version 1.6) has been publicly available since September 2020, and a monographic, bilingual open-access issue was published in 2021 [6]. In 2022–2023, we updated some content of the archive and published it on a new domain (version 2.0, https://marca-gehn.info). This book chapter summarizes the main features and capabilities of the data collection. For a more detailed and complete description, readers may refer to the monograph already cited.

To archive the data, we resorted to a programming tool that easily converts tables of macroseismic intensity data into interactive maps. It is called MIDOP (Macroseismic Intensity Data Online Publisher, [7]) and is also used for other macroseismic archives worldwide.

The online database MARCA-GEHN is mainly based on:

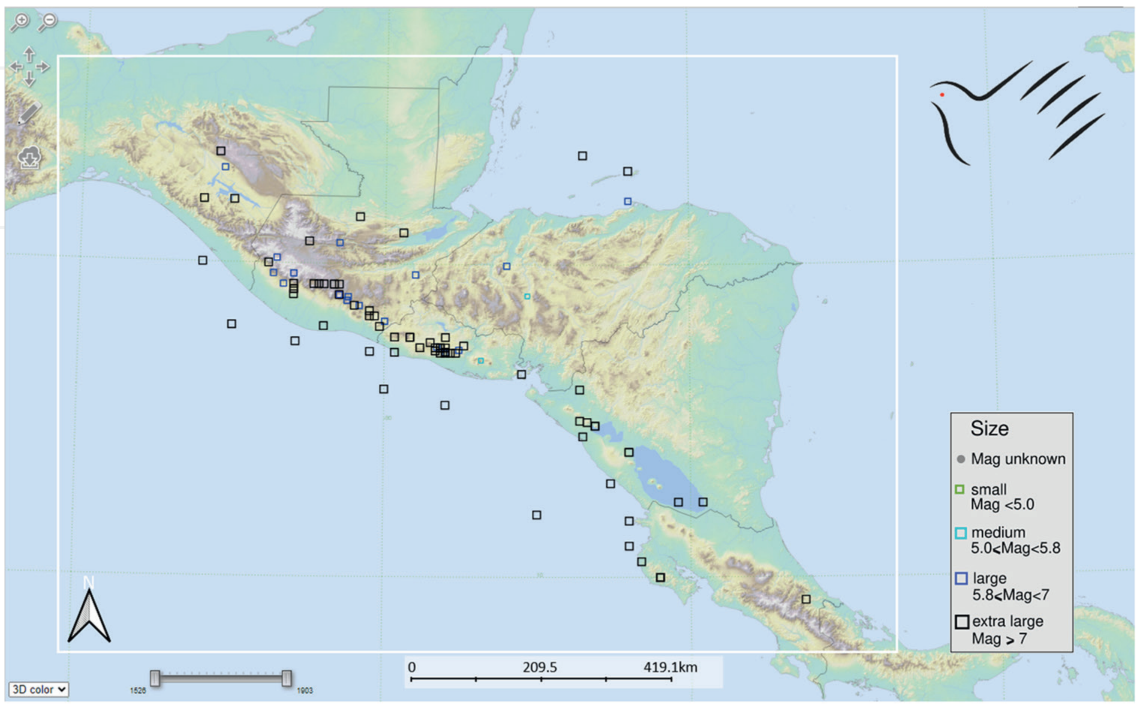
1. an earthquake catalog table: it contains the basic parametric information for selected earthquakes, given in accordance with the reference source;
2. the set of collected macroseismic data point sets (MDP set, sometimes referred to as a set of intensity points or, in the past, as a macroseismic field): an MDP set represents the "picture" in terms of impact and damage on the built and natural environment for a given earthquake listed in the catalog, given according to a categorization made by using appropriate intensity scales.

2.1 The reference parametric catalogs

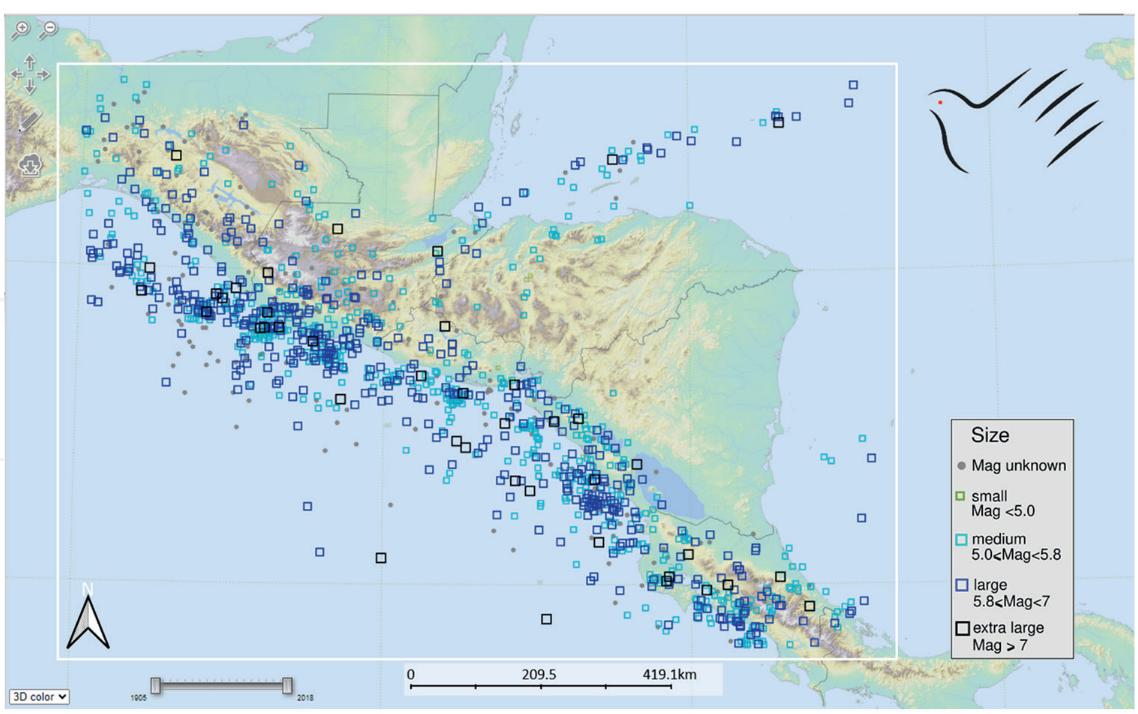
We have relied on internationally published catalogs as the primary source of parametric datasets for unique earthquake identification. This choice is motivated by traceability, consistency, and sometimes more structured access to the original data; however, regional and national earthquake catalogs also exist, and a brief inventory for Central America can be found in [6].

Most of the records related to the pre-instrumentation period, namely the 1500–1903 time window, are derived from the Global Historical Earthquake catalog

GHEC v.1 [8, 9]. They were selected if the epicentral solution adopted by the GHEC compilers is within the geographic area of interest to us (a rectangular area with coordinates [95°W, 9°N; 82°W, 18°N], white frame in **Figure 1**); some records below



(a)



(b)

Figure 1.
Epicentral map representing the MARCA-GEHN reference earthquake catalog; a) historical time frame, namely from 1500 to 1903, mainly based on GHEC v.1 [8, 9]; b) events from 1904 to 2018, mainly based on the solutions proposed by the ISC-GEM Global Instrumental Earthquake catalog, v9.1 [10]. The geographic boundaries include the four Central American countries involved in data collection in the RIESCA project, i.e., Guatemala, El Salvador, Honduras, and Nicaragua.

the magnitude threshold M7+ assumed by GHEC were taken from the catalog [1]. From 1526 to 1903, 92 events are listed in the catalog table, ⅓ of them provided by a MDP set.

For the so-called "instrumental" period, i.e., 1904 onward, the parametric reference list of earthquakes comes from the ISC international catalogs and bulletins. The ISC-GEM Global Instrumental Earthquake catalog, v.9.1 [10] and its supplement, which lists events with poorly defined parameters, have been available since June 2022 and have been adopted by Marca-GEHN v.2.0. The time window now includes 2018 with a magnitude cutoff of M5–5.5+, for continental events and about M5.5+ elsewhere. We selected events in the same geographic area as before (**Figure 1b**), resulting in 1253 records; the catalog table is thus incremented by about 260 events from the ISC catalog v.6.0 used in the previous publication MARCA-GEHN in [6], with almost all new events related to the last three years. In the instrumental part of the catalog, the percentage of events provided by an MDP set decreases to about 3%, but it increases to about 25% if we assume the same magnitude threshold used in the pre-1904 period.

The global features of seismicity in Central America shown in **Figure 1** are primarily due to the tectonic setting characterized by the convergence of the North American Plate, the Caribbean Plate, and the Cocos Plate. Their interaction creates a complex tectonic environment in which transcurrent margins, subduction zones, and volcanic arc seismicity coexist. It is worth noting that until recent decades, earthquake distribution has been severely affected by uncertainties in spatial localization and incompleteness in magnitude, due to population distribution and discontinuous and inadequate instrumental monitoring (especially in offshore areas).

Similar to previous versions, the Marca-GEHN 2.0 catalog allows searching in space (circular or polygonal areas, using the interactive pencil tool) and in time (time cursor tool), different layouts for topography, and exporting the resulting maps in Google Earth format (.kml). A promising new feature was also added in the latest release to link directly to the referenced source of the earthquake record; when an earthquake is selected from the main list (upper left panel), a link appears near the origin time in the lower left panel, leading to an external page of the parent catalog where additional information is immediately available. We intend to propose a similar reverse link in the cited international catalog in the future, directed to the event page MARCA-GEHN.

Some other minor adjustments have also been made to MIDOP, such as the display of epicenters for records without an assigned magnitude or the display of the lowest intensity levels.

2.2 The macroseismic data point (MDP) sets

Assigning intensity to an earthquake means checking the correspondence between the macroscopic effects for as many sites as possible and the description categorized (formally in degrees) by the macroseismic scale; if the formulation of the macroseismic scale does not take into account a statistical distribution of effects, it is essential to summarize the information contained in the various available sources and then compare it with the scenarios represented in the degrees of the macroseismic scale.

The available observations reflect the temporal and cultural environment of the sites studied (building types, materials, but also societal organization, and lexis used in documentary accounts). Although the macroseismic scales aim to establish objective evaluation criteria, it is often not easy to assign a precise degree of intensity.

Frequently, the macroseismic observations provide ambiguous or even contradictory information: When some indicators point to a certain degree, but others are typical of lower or higher degrees, it is a common practice to formalize this uncertainty by intensity intervals (e.g., VI-VII), a solution that is sometimes transformed into an intermediate value (6.5); this is an incorrect use that must be abandoned in order to respect the discrete and ordinal, but not numerical, definition of intensity degrees. In the last 30 years, great progress has been made in the study of historical earthquakes, especially in the search and selection of authoritative sources, in the definition of procedures that allow tracing the paths followed in the analysis, and in the method of data synthesis, which is crucial for evaluating the reliability of historical data. These results have been possible thanks to the stimulating cooperation between historians and seismologists, especially in European countries (see, for example, [11]).

In the Americas, the first written documents on earthquakes date from the XVI century, although rare pre-Hispanic sources have been discovered. Today's knowledge of the historical seismicity of Central America is based on some valuable regional and national data collections, as well as on papers, reports, and monographic volumes that also describe research results for individual seismic events. These are mostly descriptive seismological compilations that often do not include estimates of focal parameters, intensity values, or isoseismal drawings. For a more complete inventory of data collections for CA and their linkage, we refer the reader to [6]. The macroseismic scale most commonly used in Central and South America is the Modified Mercalli intensity scale (MM), which is composed of 12 increasing intensity levels with a hierarchical classification of observed effects that include human perceptibility in the lower levels, low to moderate damage to objects and buildings in the middle levels, and extensive destruction of buildings and also permanent environmental impacts in the highest levels. In our case study, but also more generally in the global application of macroseismic scales, the recovery of basic contemporary key information, e.g., on masonry typology, vulnerability, and population density at the time of the earthquake, is of great importance.

The compilation of the MDP set for a given earthquake begins with the identification of data sources and reference studies from which macroseismic intensities can be obtained and geographically referenced. In our case of the RIESCA project, since we are working remotely and irregularly, we have resorted to an online Google®TM form set up for data entry by users belonging to different institutions and located in different countries. The compiler uses an event code (EVENTID) to select the unique identifier of the earthquake to which each individual Intensity Data Point (IDP) must refer. It then establishes a unique correlation between some parameters of the earthquake (e.g., time of occurrence, location, and magnitude) and the information related to a single location for that event. In a second section of the form, the location of the individual site must be entered with administrative and geographic identifiers that can be customized according to the administrative levels of each country. The site code (SITEID), rather than the geographic coordinates, is the linking element for site searches and for creating a seismic history at the site, i.e., the temporal list of effects related to a site, described later. In a third section of the form, the site-specific macroseismic value must be entered: This is done by selecting from drop-down menus to force the compiler to uniquely identify the intensity scale used and to avoid mismatches or unconventional intensity assignments (e.g., values spanning multiple degrees, 6–8, as sometimes found in the sources). Intensity values are always given in Roman numerals, in accordance with the original definition of the macroseismic scale; other commonly used annotations (e.g., not felt -NF-, heavy damage -HD-)

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are also allowed. Finally, additional information such as the type and reference of the data source, quality identifiers for both the source and the intensity assignment, the annotation, and the name of the compiler are recorded.

The Google®TM form was used for initial data collection after training was provided in San Salvador in November 2017. The form remains available for input of new data, and potential data providers can express interest in contributing to the next version of MARCA-GEHN, also to fill the gap in cross-border data gathering. For given collection deadlines, the final revision post-processing, conducted by a small pool of experienced staff, has made it possible to address errors such as inconsistent geographic locations, control anomalous intensity values, integrate the MDP set with additional sources not previously included, and close the data gap in neighboring countries.

An MDP set is accessible online by querying the earthquake, scrolling, and selecting the appropriate record in the catalog window (see **Figure 2**, top left panel): then a map of all georeferenced points appears in the main panel (right panel), and the list of all locations related to the earthquake is also interoperable in the bottom left panel. Here, in the header, additional information is given. They concern the main reference for the MDP set (click on the event code of the MDP set), the main parameters assigned in the original cat (Epicenter OrCat, represented in the map by a red star), the modified location or magnitude finally proposed by this work (Preferred, green open square). In the map, the intensity data points are shown scaled according to the legend: The map can be zoomed, adjusted, printed, or exported in .kml format. The IDP list can be downloaded in three different formats, and an external link to the MDP is also available. As mentioned above, a new direct link to the event page in the origin catalog has also been added.

Figure 2 shows the macroseismic data set for the 1976 Guatemala earthquake, the deadliest event documented at MARCA-GEHN with an estimated 23,000 fatalities. The MDP set was derived from the USGS Atlas Shakemap compilation, which in turn

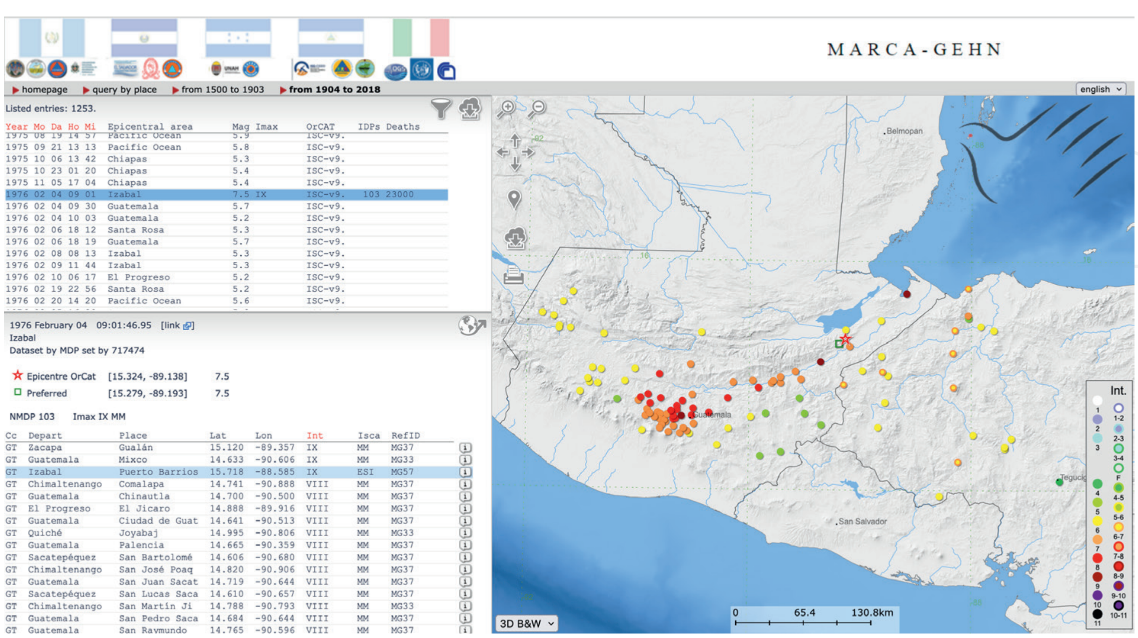

Figure 2.

Macroseismic data point set (MDP) for the Guatemala earthquake of February 4, 1976. Intensities in the Guatemala area are from the study of [12], and in Honduras, they were taken ad hoc from the press. An intensity point based on the ESI scale was also added.

uses the contemporary technical report of [12]. Original sources from the press were used for some localities in Honduras (see Appendix 1 of [6] for the complete list of reference codes).

This earthquake represents a turning point for seismological knowledge of the area, not only because of the extensive damage surveys, the collection of macroseismic questionnaires sent to the most remote areas [12], the geological fieldwork to map surface faults, landslides, and liquefaction, but also because of the pioneering analyses of the instrumental recordings. The location of the surface ruptures and the instrumental data indicate that the February 4, 1976 earthquake was a shallow-depth tectonic earthquake triggered primarily by a slip on the Motagua fault [13, 14].

The main fault was identified in a discontinuous line about 240 km long in the Motagua Valley and west of the valley; [15] assign a sinistral strike-slip rate of 14–22 mm/year; a subparallel segment is mapped for about 110 km east of the 1976 epicenter. Some authors [16, 17] suggest a complex source with an asymmetric bilateral fault extending east and west along the Motagua fault, with the largest moment release occurring ~90 km west of the epicenter near a striking change of the surface fault. Several northward to NE trending secondary fault ruptures, called the Mixco system, were identified in the Mixco area. Among these, reactivation of a segment at least 21 km long was observed [13, 18]. The macroseismic data are crucial in this case both to identify the complexity of the earthquake ruptures and to determine possible similarities or differences in the damage patterns of previous events.

2.2.1 Georeferencing and searching the localities

As mentioned earlier, the location of the individual site must be entered with some administrative and geographic identification data. The MIDOP software can be adapted to the administrative levels of each country: The modified version we used allows five levels of identifiers (string variable) and three numerical values (for the geographic coordinates -latitude, longitude- and the site identification code -SITEID-). In Central America, we adopted the ranking of the country code (CC), geographic regions (if defined by the country), regional administrative areas (Departamentos), municipalities (Municipios), and finally the specific site (Locality) to which the intensity point refers. The geographic coordinates and a unique identification code for the locality are taken, when possible, from the general inventory of localities (Free Gazetteer data, available at http://www.geonames.org/). If they are not inserted correctly, this datum can be adjusted/unified in the post-processing phase. This structure is flexible and powerful and is the core of the query by places, the query of the database, which is the alternative to the query by earthquakes.

A place can be identified by a string search (drop-down menu), in the alphabetical list, or by area selection. The list of localities briefly displays the name of the site, the country code (a field that is generally omitted because macroseismic archives are usually national archives), the maximum intensity observed at that site, and the number of observations related to that location. On the specific web page for each location, all other information uploaded to the archive is then structured, and external references to the geographic database are also linked (see the example for Ahuachapán in the region of the same name with SITEID 3587426, direct link to https://marca-gehn.info/v2.0/query_place/call_place.htm?place=3587426).

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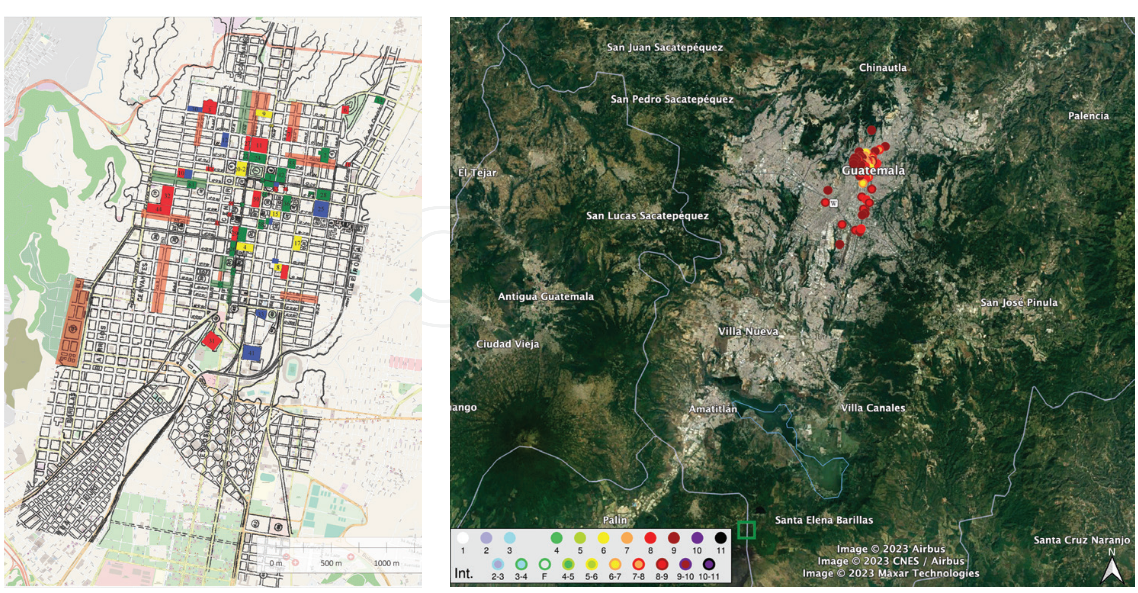
Correct site identification is anything but a trivial matter. Some problems encountered in compiling MARCA-GEHN, most of which have been resolved, are:

- The identification of the inhabited/potentially affected site in relation to the barycentric coordinates of the actual administrative area. Several cases were manually relocated after being verified with Google tools;
- The location of the site at the time of the earthquake; several urban centers were relocated after disasters (Guatemala City, for example, is the best known and most traceable case);
- The identification of sub-areas within the largest metropolitan communities that deserve to be called a "locality" and for which a differential intensity assessment is useful. See, for example, the case study of the December 26, 1917 earthquake, with about 70 intensity points within Guatemala City (**Figure 3**), obtained by damage estimates based on photographs [19].
- Georeferencing of sites for the use of "unconventional" intensity scales that relate to geologic or environmental, rather than inhabited, locations, as discussed below.

2.2.2 The use of multiple intensity scales

One of the distinguishing features of MARCA-GEHN is the collection of macroseismic information that cannot be uniform because it comes from different documentary sources, and the use of multiple intensity scales to preserve the integrity of the original study or the nature of the multiple observations collected. The reason for this



(a) (b)

Figure 3.
The Guatemala City for the 1917–1918 earthquakes: a) distribution of damaged buildings and b) inferred intensity points. The degree of damage is assigned to individual buildings by photo comparison [19], and the intensities are indicative of the local seismic response in urban areas, as they help identify "quadras" susceptible to amplification. More details in [6].

decision is mainly due to the time constraints of the RIESCA project that supported the realization of the archive, as it was not compatible with conducting a full revision study for each earthquake to reinterpret and homogenize the original sources. We discarded the possibility of using simplifying conversion relationships between different intensity scales, as they proved to be critical (see [20]). Finally, by archiving the standard macroseismic intensities, which are usually related to the building stock, we collected additional information on the geologic and environmental consequences of earthquakes that can now be classified by nontraditional intensity scales and that can provide additional clues for knowing the causative source of the earthquake.

Thus, we tolerate the coexistence of non-uniform but original intensity values, as this will allow more reliable harmonization of the intensity dataset and integration of different expertise in the future.

Only in a few cases did we reevaluate intensities assigned using a different scale, relying on available documentary sources, since the original values were on a 10° scale that is incompatible with the graphical representation (e.g., the 1915 September 7 earthquake [21]).

The latest MARCA-GEHN 2.0 archive uses these scales:

- the Modified Mercalli intensity scale (MM) in the 1956 formulation given by Richter in 1958 (for a review of intensity scales see [22];
- the Mercalli-Cancani-Sieberg (MCS) scale as formulated by Sieberg in 1923 [23];
- the Medvedev-Sponheur-Karnik scale (MSK, [24]);
- the DidYouFeelIt (DYFI) proxy scale [25];
- the Environmental Intensity scale (ESI) [26, 27] for geological intensities;
- the Tsunami Intensity scale (TSU) [28].

Even though all scales are in a 12° range, their values cannot be treated together, and users must be strict when merging data from different macroseismic scales.

The collection of ESI and TSU data points began coincidentally to document the effects of one of the largest magnitude earthquakes of the last century, the so-called slow-quake near the coast of Nicaragua in 1992. No relevant seismic shaking effects on buildings were reported, but enormous and diffuse tsunami effects were reported, exceeding those expected given the assumed size of the rupture. A more detailed description can be found in ([6], p. 136 ff).

During the last update, some ESI data points on Guatemala earthquakes of the XVIII and XIX centuries were added to map the geologic seismo-induced effects. They seem to be a promising tool to distinguish between surface and deep causes of past earthquakes.

3. First results

Measuring the outcome of an open-access database usually involves evaluating its impact, use, and added value for users and, more generally, for the reference community. Most of the key metrics and methods that can be used to quantify the outcomes of an open-access database are not applicable to MARCA-GEHN because the platform has not yet been configured for such purposes, e.g., tracking user participation, downloads, and page views. Previous citations are also limited because the first version of the archive was launched during the difficult times of the COVID-19 pandemic. Last but not least, the database is explicitly described as "prototypical" and incomplete. Nevertheless, some numbers are indicative of the amount of data collected so far.

MARCA-GEHN V.2.0 contains an earthquake catalog with 1345 parametric records obtained from international public sources. Sixty-seven earthquakes were provided by MDP sets, i.e., a list of intensity data points representing quality-checked and georeferenced observations collected during our studies. The total number of IDPs is 2167; most of the observations are related to Guatemala, which also experienced the deadliest earthquake in 1976. Most IDPs are given in the Modified Mercalli intensity scale (MM), followed by DYFI proxy intensities representing recent earthquakes; other intensity scales have been used depending on data availability.

The MDP sets vary in number from datasets with only a few points (6 earthquakes with less than 4 localities) to well-documented events (14 earthquakes with more than 50 IDPs). It is worth noting that the events studied were not selected a priori, e.g., using rules based on date or magnitude: They were collected to meet the diverse needs and interests of participating countries and researchers from CA. The magnitudes represented in the MDP sets range from M4.3–4.5 for some earthquakes in Honduras to M8.1 (1862 El Salvador earthquake). It must be clearly stated that magnitudes are not uniform, as they are determined by a variety of methods and instruments. Some parametric records of the studied events were modified with respect to the time of origin (date, time), the name of the epicentral area, or the preferred coordinates with respect to the catalog from which they originated. In addition, 20 events were given a number of fatalities, although sometimes this information can only be indicative. Even if the percentage of earthquakes coming from macroseismic data is low, it should be taken into account that the earthquake catalog is not declustered, as can be the case in other macroseismic databases (e.g., AHEAD, [29]).

Efforts to compile MDPs at the international scale (and thus integrate information across boundaries) and collect intensity values assigned by various scale metrics (e.g., MM, MSK, DYFI, including geologic and tsunami data) are specific choices introduced in MARCA-GEHN. They may represent improvements for enhancing data collection, but may also be viewed as limitations for users who are not sufficiently aware of the different origins and purposes of the data.

We provide some additional considerations here about the potential feedback of this data collection in nearby fields, such as seismotectonics, seismic hazard assessment, and site response studies.

3.1 The identification of the causative sources of earthquakes

The damage distribution resulting from an earthquake can provide valuable information for deciphering its causative source, i.e., the fault responsible for the seismic event. The basic assumption of uniform, isotropic propagation of seismic waves, with energy decreasing from a point source, is firmly established in the seismological literature. According to this view, the extent of the damage/perception areas is in some sense indicative of the energy and depth of the source, while asymmetric patterns in the distribution of the strongest intensities can be attributed to the orientation/finiteness of the causative fault. In the real world, such simplistic assumptions are often violated because of the characteristics of the rupture, the propagation and local amplification properties, the complexity of earthquake sequences, and last but not least, the availability of "observers." From the pioneering representations of damage distribution based on the isoseismal drawings to more recent formalizations of epicenter, magnitude, and propagation properties through mathematical constraints on the distribution of intensity data points (e.g., [30–32]), macroseismic data remain fundamental ingredients for addressing seismic sources in the pre-instrumental era.

At MARCA-GEHN, preliminary analysis of the macroseismic data sets collected to date has in some cases allowed different interpretations of the causative source than those adopted in the original catalog, in terms of earthquake location, proposed depth, and representative magnitude. For example, these changes are proposed to date:

- For the two earthquakes of 1859 and 1862, which occurred in western El Salvador and eastern Guatemala, offshore displacement with a decrease in magnitude is proposed (see [6], from page s41). The December 20, 1862 earthquake is the strongest event reported in the historical subsection of the catalog: an origin time is added with respect to the parent catalog [8]. The changes are motivated by critical reading of several accounts of the events, analogy of tsunami effects with recent events, and some consideration of cumulative damage.

- For the 1719, 1747, 1765, and 1874 events, reinterpretations as shallower magnitude events are preferred; we favor attributing them to the cortical volcanic-tectonic regime, in some cases the changes are also supported by the mapped geologic effects.

- For some events, relocations for mislocation in the origin catalogs are given (e.g., 1733 on the border of El Salvador, Honduras, and Guatemala; 1898 in Nicaragua; 1915 in El Salvador; 1917 Guatemala City; 1931 in Nicaragua).

- Finally, for one of the deadliest events in the historical part of the catalog, the 1773 earthquake, a relocation far away from the mapped sites to the interior of Guatemala is preferred, which now follows the proposal of activation of the Polochic-Motagua fault from the literature (**Figure 4**) [1].

A note is necessary. The modifications proposed for some events are preliminary, and the alternative parameters are given as "preferred" and do not replace the original solution. An exhaustive study for an earthquake could take a long time, which was outside the time span of the RIESCA project. Also, the impact of the proposed changes on a conventional seismic hazard analysis is now likely to be very limited. However rapid access to the maps, data points, referenced sources, and direct linkage to the repositories of the origin catalog have unprecedented potential to accelerate the collaborative growth of a transdisciplinary community that refines and uses these data.

3.2 Maximum observed shaking

One of the products of a macroseismic intensity database is a map of maximum observed intensities, a very basic representation of seismic hazard. In

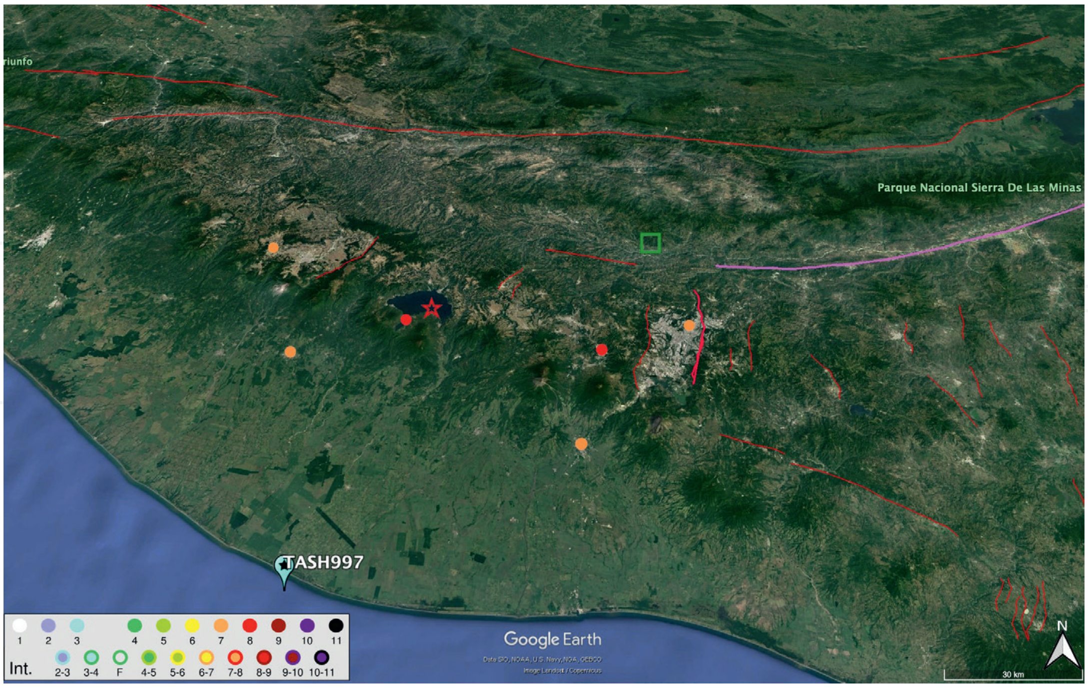


Figure 4.
MDP set for the July 29, 1773 earthquake. The red star shows the epicenter adopted in GHEC [8] and taken from [33]; the light blue pin is the epicenter proposed by [34]; the green square is our preferred earthquake location given by [1]; the assign the event to the Polochic-Motagua fault (in purple). Redrawn from [6].

MARCA-GEHN, such a map appears on the entry page of the "Query by place" option, with the highest value at each locality represented by a color-coded dot. In **Figure 5**, the spatial distribution of the maximum intensity (Imax) is related to the municipalities, with their administrative areas filled in in color and, in addition, all the other sites studied are shown. Note that all MM /MSK/MCS/DYFI intensity data points are plotted together, while the geological and tsunami intensities (ESI/TSU data points) are not. This is still not a rigorous presentation, but it is an acceptable compromise to convey the effects of past earthquakes to a broad audience.

The maximum intensities follow the major fault systems and run in an almost continuous reddish band (intensities VIII and above) along the Pacific Coast volcanic belt from the Guatemalan-Mexican border to Managua in Nicaragua. A similar but less uniform stripe with intensities of VI and above follows the transform fault system from Lake Izabal in Guatemala to the Atlantic coast of Honduras.

Note the extent of the municipalities, which range from a few square kilometers in the most populated areas to huge chunks of territory in the wildest regions of Guatemala, Honduras, and Nicaragua. It should also be noted that some communities are not represented by intensity data points, even if they are located near highly damaged areas. For example, this is the case for some localities on the Pacific coast of Guatemala (SW of the capital): We suspect that this is mainly due to uneven population density and/or economic and cultural importance at the time of the major earthquakes, as reports, especially for historical earthquakes, usually refer to the main cities.

Future studies could also help inform research efforts to fill the knowledge gap on some seismic sources (e.g., the depression zone in Honduras) or in areas where there is little documentary evidence of past earthquakes (e.g., southern Nicaragua and the Pacific coastal strip of Guatemala).

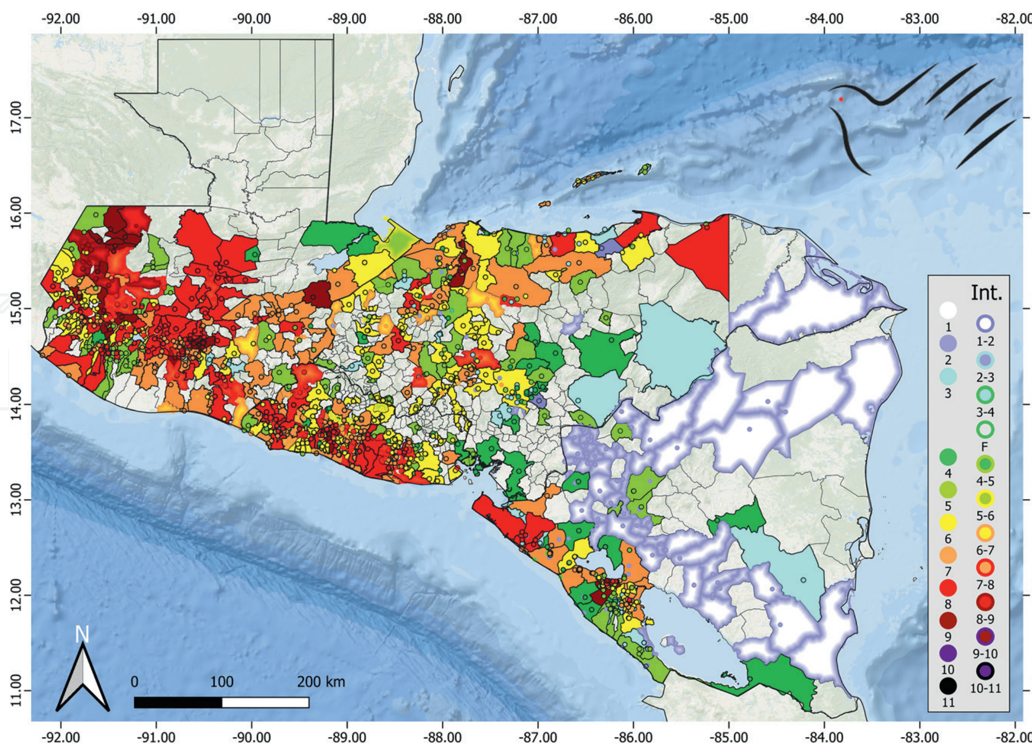


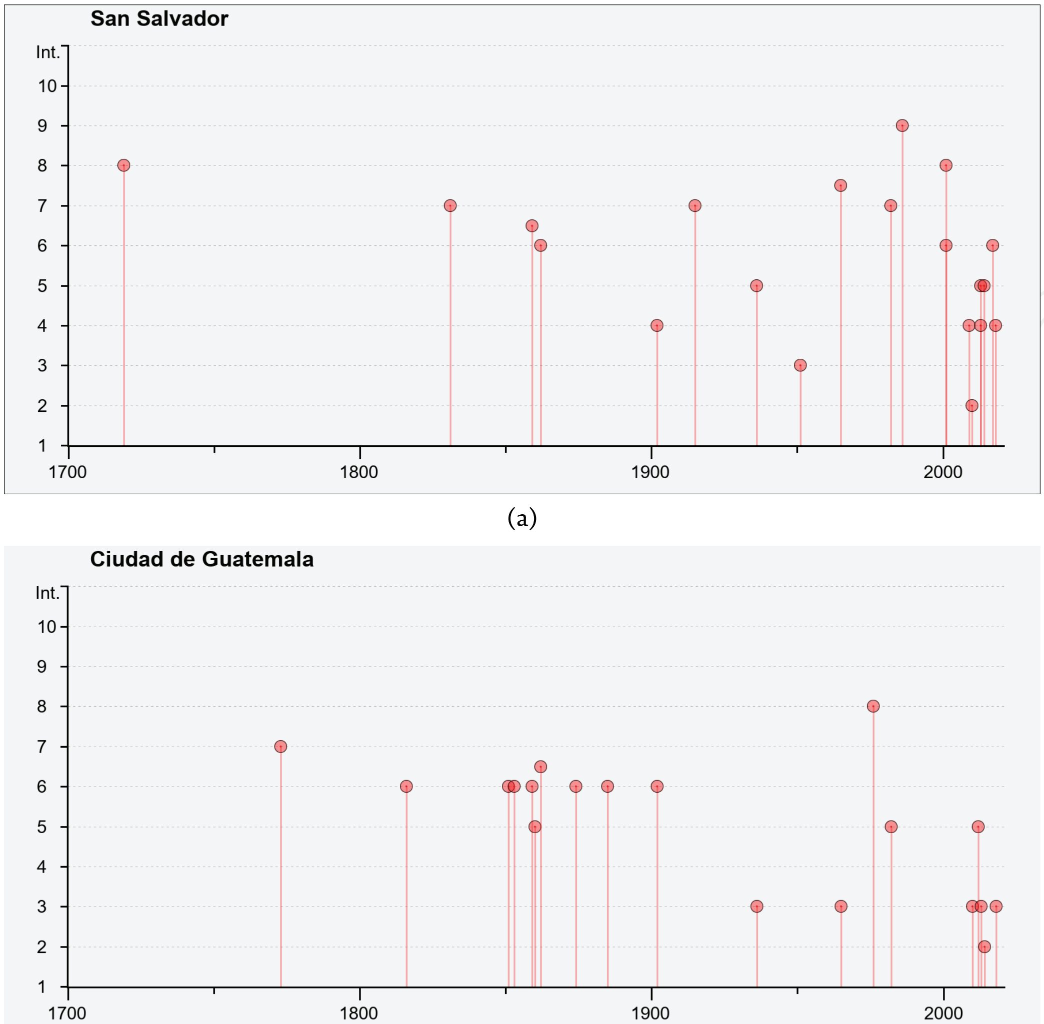
Figure 5.
Maximum observed intensities as given in MARCA-GEHN (V.2.0) for the four countries involved in the RIESCA project. The area of the municipality is indicated with the maximum value according to the color code of the legend on the right. In gray, the municipalities are without data.

3.3 Seismic histories at a site

Similar to the Imax map, the seismic history of a site is an interesting way to present and communicate the relevance of earthquakes to professionals and also to the general public. The collection of long and rich seismic site histories also allows alternative approaches to seismic hazard assessment that are not based on any assumptions about the seismogenic sources (e.g., the site intensity approach, [35]). The data stored to date in MARCA-GEHN are a first attempt at such data-driven studies, although they are not sufficient for reliable application to Central American sites. **Figure 6** shows the seismic histories of Guatemala City and San Salvador, two capitals of the four countries involved in the RIESCA project.

With 20 observations (**Figure 6a**), San Salvador is the most populated seismic site history in the current database (version 2.0). The collected data, which are still very incomplete, range from the beginning of the Spanish invasion (1719, San Vicente earthquake) to a moderate offshore earthquake in 2018. The highest observed intensity is attributed to the 1986 San Salvador earthquake (IX), followed by the January 2001 earthquake and the 1719 one (VIII). Note that the effects above the first damage condition (intensity > = VI) are presented 11 times. We acknowledge that the intensities obtained by the DYFI survey should be considered with great caution since the damage conditions are sometimes supported by very few questionnaire compilations.

Guatemala is known to have had its capital moved from its original location at least three times due to earthquake damage, and the country's seismic history includes many devastating earthquakes. Currently, Guatemala City covers 228 square kilometers and is the most populous city in Central America, with about three million inhabitants. It is therefore very difficult to consider it as a single place, as the MIDOP engine



(a)

(b)

Figure 6.
Seismic site history for: a) San Salvador (SV), available at https://marca-gehn.info/v2.0/query_place/places/../call_place.htm?place=3583361; (b) Guatemala City (GT), available at https://marca-gehn.info/v2.0/query_place/places/../call_place.htm?place=3598132.

has technically done. In this version, the seismic history of the Guatemala City site includes 19 earthquakes (**Figure 6b**), from the Santa Maria de Santiago earthquake of 1773 to the moderate offshore event in El Salvador on January 3, 2018. Note that after the 1773 earthquake, the capital city of Antigua Guatemala (https://marca-gehn.info/v2.0/query_place/places/../call_place.htm?place=3599699) was moved to its current location in 1776, which explains why there are no earthquakes before that date; also note that the 1917–1918 seismic sequence represented by the December 26, 1917, MDP record with 71 IDPs all located in the broad area of the city is not shown on the graph in **Figure 6b**. This is a typical case where assessing intensity at a more detailed scale than the administrative level of the municipality causes some problems. If we assume that the intensity of the 1917 event in Guatemala City can be estimated "globally" at VIII–IX, this results in the highest value observed so far, exceeding the value given for the devastating 1976 earthquake.

For more details, we invite readers to also surf to the list of nearest localities (within 15 km) that appears below the time graph, at the link provided in the caption of **Figure 6**.

Similar conditions with very strong lateral variability of damage due to local site responses (amplification and permanent surface deformation or liquefaction) are reported for Managua (NI) during the December 23, 1972 earthquake, where IDPs were assigned to subsectors of the city. Finally, in Tegucigalpa (HN), initial damage conditions were reached only once, in 1774, while more or less distant earthquakes are felt quite frequently (degrees III and IV): consider that most data for Honduras come from DYFI questionnaires, with all their advantages and disadvantages.

These examples underscore the need for additional basic research efforts on historical and contemporary documentary sources for all countries from CA to increase the reliability of macroseismic intensity assessments.

4. What next?

The macroseismic archive for the countries of Central America-Guatemala, El Salvador, Honduras, and Nicaragua (MARCA-GEHN) was developed in 2017–2020 under the RIESCA project funded by the Italian Agency for Development Cooperation (AICS). The database was updated in 2022–2023 based on the voluntary efforts of some authors.

Guatemala, El Salvador, Honduras, and Nicaragua are exposed to a variety of seismogenic processes, ground shaking of different relevance, and non-uniform instrumental and historical seismic data availability. In addition, local reference institutions sometimes face limited human and material resources, and in general, macroseismology research is not considered as important as instrumental seismology. The RIESCA project has attempted to adapt European best practices in macroseismology research to publish a publicly available online prototype database of macroseismic observations for some countries in CA. The working group has adopted some simplified solutions to solve the problems related to data collection, sharing and verification, and remote working, a problem exacerbated by the COVID-19 pandemics in the final phase of the project. Another special aspect is that MARCA-GEHN has tried to solve problems occurring at the borders of neighboring countries, whereas studies usually focus on the national level.

We have resorted to international earthquake catalogs (GHEC and ISC) to relate the table of IDPs to a specific parametric record. This choice is mainly motivated by the need to clearly identify the data sources (e.g., original seismic phase readings and location for instrumental earthquakes, documentary source studies for historical events); we also pursue the hope of contributing to the improvement of the next versions of these international databases or other publicly available repositories of metadata needed for other applications (e.g., seismic hazard assessment). Viewed in this light, the online database has great potential to serve a large community of researchers and stakeholders, experts, and the general public, but it needs a strategy to ensure continued maintenance and regular updates over the long term.

A major limitation of MARCA-GEHN is the incomplete inventory of primary sources; on the other hand, the most devastating earthquakes of the last two centuries have been studied in some detail. Geologic deformation in the area is often so rapid that many seismic sources have been active during this limited period, and recent earthquakes can be used to make some analogies with the oldest and less documented earthquakes. Some technical issues with the presentation of macroseismic data with different objectives (e.g., geologic or tsunami effects versus intensity data points based on building stock effects) also need to be addressed to allow the easiest use of the database contents.

We hope that this tool will increase the interest of local institutions in using macroseismic data, as interdisciplinary studies that consider the historical, socioeconomic, geological, and seismological aspects of earthquakes together are paramount to safer and better-prepared communities.

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Conflict of interest

The authors declare no conflict of interest.

Notes/thanks/other declarations

The archive MARCA-GEHN is available without user registration.

The first public version V.1.6 (September 2020) and the current version V.2.0 are published on the website http://marca-gehn.info hosted in Honduras; for security and redundancy reasons, the latest version is also accessible at http://marca-riesca.inogs.it managed in Italy.

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