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An Earthquake Catalog for the Lebanese Region

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ABSTRACT

The present work aims at establishing an earthquake catalog for seismic hazard assessment in Lebanon. This catalog includes two different parts: historical earthquakes and instrumental earthquakes. The first part of the article describes the work done on the period 31 B.C.E. to the end of the nineteenth century. Numerous studies published in the last 30 yr, devoted to preinstrumental earthquakes in Lebanon, had not been included in any parametric earthquake catalog. A thorough and critical review of these studies was devised to check their respective interpretations of available earthquake records in terms of seismic parameters (date, location, and size) and to select for each earthquake the most reliable interpretation. The second part provides the details on the selection of instrumental solutions for the period 1900–2015 and for magnitudes ≥ 4. From global instrumental earthquake catalogs, we build a unified earthquake catalog for Lebanon and bordering regions. A selection scheme is applied for the choice of the best location and the best magnitude among solutions available. The number of events in the catalog is relatively small, and all earthquakes can be checked one by one. The earthquake catalog is homogenized in moment magnitude. For 89% of the events, an M_w proxy was calculated from the original magnitude, applying conversion equations. The merging of the historical and instrumental periods highlights a specificity of this zone: the instrumental seismicity (1900–2015) corresponds to a relatively quiet period for Lebanon. The historical part, covering 2000 yr, includes similar periods of quiescence, as well as much more active periods with destructive earthquakes.

Supplemental Content: List of considered studies for preinstrumental earthquakes, table of the 31 preinstrumental earthquakes considered with the studies for each of them, preinstrumental and instrumental catalog, details on the International Seismological Centre (ISC) event catalog and solutions from regional agencies, and details on the Geophysical Research Arrays of Lebanon (GRAL) catalog.

INTRODUCTION

When assessing seismic hazard in a region, an earthquake catalog covering the longest possible time window is required. The catalog should include historical earthquakes characterized by macroseismic data and instrumental earthquakes with solutions determined by available seismological networks. This study focuses on Lebanon and its bordering regions, with the aim of building a sound earthquake catalog that is representative of long-term seismicity in this zone and is the first step toward estimating probabilistic seismic hazard assessment (PSHA) for Lebanon. Existing literature available for the eastern Mediterranean region either on specific large past events or on earthquake catalogs states that the area is prone to earthquakes. Several recent projects covering a large-scale region have built earthquake catalogs with the purpose of assessing PSHA (e.g., the Earthquake Model of the Middle East [EMME] project covering the whole Middle East region, Danciu *et al.*, 2018; the Dead Sea Research Venue [DESERVE] project extending over the whole Dead Sea region; Haase *et al.*, 2016). A new earthquake catalog for Lebanon is needed because (1) the exact methodology for compiling these large-scale catalogs is not described in detail in any currently published study; (2) the selection criteria of the most reliable parameters made available by published studies is not defined until this study; (3) we handle far fewer events than large-scale projects, meaning that this selection can be performed with more care and precision; (4) given the large uncertainty on historical earthquake parameters, when available, alternative and similarly credible interpretations are retained.

The first part of this article describes the work done in the period 31 B.C.E. to the end of the nineteenth century. The method proposed in Albini *et al.* (2014) was adopted, which implies collecting and thoroughly revising all available studies of each earthquake to understand on which information sources the current data and background of each earthquake are based (i.e., mostly written historical accounts). The few earthquakes in the area of the study that are dated between the third and the first millennium B.C.E. were not analyzed because the related studies are mostly based on paleoseismological and archeological data. The association of historical earthquakes with specific fault segments is extremely important for hazard assessment (e.g., Daëron *et al.*, 2005; Lefevre *et al.*, 2018); however, this requires another level of interpretation and evaluation of uncertainties that must be addressed in the future. The second part of this article provides details on the selection of instrumental solutions for the period 1900–2015.

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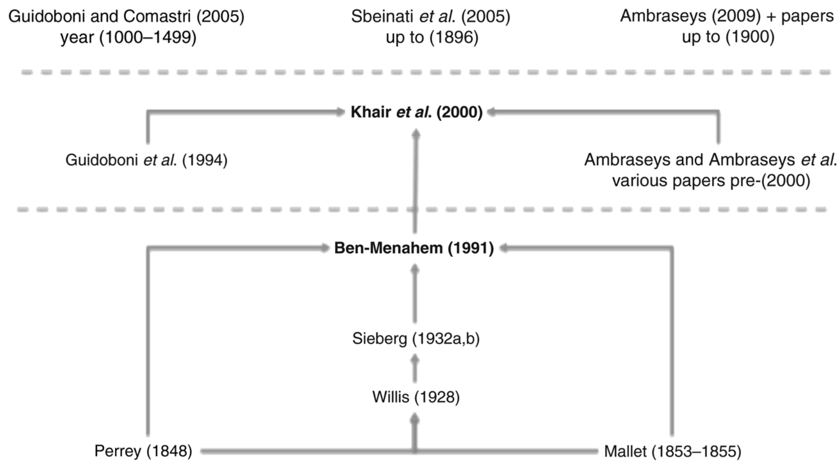


▲ **Figure 1.** Simplified scheme of relationships among the parametric catalogs of Ben-Menahem (1991) and Khair *et al.* (2000) (bold) and their sources of information for preinstrumental earthquakes in Lebanon. Three important studies published after 2000 are shown too, spanning some centuries and a vast geographical area, namely those of Guidoboni and Comastri (2005), Sbeinati *et al.* (2005), and Ambraseys (2009), with the covered time span.

Merging historical and instrumental periods reveals a major specificity of this zone: the relatively quiet instrumental period is not representative of the seismic potential of the zone. Many authors underlined this issue (e.g., Ambraseys, 2006), and its implications in terms of seismic hazard assessment are discussed in the Instrumental Part of the Catalog section.

A REVIEW OF THE PREINSTRUMENTAL EARTHQUAKE DATA

State-of-the-Art

In the last 30 yr, a large number of studies have been devoted to preinstrumental earthquakes in Lebanon (e.g., Guidoboni *et al.*, 1994, 2004; Darawcheh *et al.*, 2000; Marco *et al.*, 2003; Ambraseys, 2004, 2005, 2006, 2009; Karcz, 2004; Sbeinati *et al.*, 2005; Agnon, 2014). Because the results of these studies have not yet been fully included in any comprehensively revised catalog for Lebanon, an *ad hoc* strategy was devised to derive the preinstrumental catalog in the time window from 31 B.C.E. to the end of the nineteenth century (with the last earthquake in 1837). The area of study extends approximately from 31° to 35.5° in latitude and from 34° to 37° in longitude.

Following the method adopted in the Global Earthquake Model (GEM) project "Global Earthquake History" to compile the "Global Historical Earthquake Archive" (Albini *et al.*, 2014), a thorough collection of the studies published in the last years was made, especially those issued after the publication of the catalog by Ben-Menahem (1991). The next-in-line parametric catalogs turned out to be primarily based on the same catalog (Ben-Menahem, 1991), as it is the case of Khair *et al.* (2000) (Fig. 1). The approach they adopted, similarly to that chosen in the compilation of other regional catalogs in the same period, was to enrich the reference catalog by including the earthquake data made available by late twentieth century studies such as Ambraseys *et al.* (1994), Ambraseys (1997), Ambraseys and Jackson (1998), Ambraseys and Karcz (1992), and Guidoboni *et al.* (1994).

From 2000 onward, many other studies on preinstrumental earthquakes were published, among them three studies spanning several centuries and a vast geographical area (Guidoboni and Comastri, 2005; Sbeinati *et al.*, 2005; Ambraseys, 2009). Parameters for individual earthquakes have been proposed in *ad hoc* articles such as Marco *et al.* (2003), Karcz (2004), Ambraseys (2004, 2005), Guidoboni *et al.* (2004), and Hough and Avni (2009). Although a properly compiled catalog has not yet been published for Lebanon, updated lists of earthquake dates, sometimes complemented by epicentral coordinates and magnitude values, can also be found in theses or articles discussing the area of study or a larger area from different points of view (seismotectonics, seismic hazard, etc.) (e.g., Daeron, 2005; Hamiel *et al.*, 2009; Huijer, 2010; Huijer *et al.* 2016; Salamon, 2010; Kagan *et al.*, 2011; Agnon, 2014; Wechsler *et al.*, 2014; Zohar *et al.*, 2016).

In preparing the state-of-the-art catalog, it was reckoned that the reference catalog for the preinstrumental period remains that of Ben-Menahem (1991) (Fig. 1). This newly achieved awareness suggested identifying the sources of earthquake records used by Ben-Menahem to be able to compare his set of sources to those used by later studies. The referenced sources have been comprehensively identified in a set of mid-nineteenth to mid-twentieth century essays that collected short descriptions of earthquake effects and associated them with a specific date. The most used and well known of these earthquake data collections or second-hand studies (Fig. 1) are Perrey (1848), Mallet (1853–1855), Willis (1928, 1933), and Sieberg (1932a,b) (for a discussion of Sieberg, 1932a, see Albini *et al.*, 2019). The contents of these earthquake-data collections and their use by Ben-Menahem (1991) are not further discussed here.

Although late twentieth and early twenty-first century studies mostly used, in a direct and critical way, the records supplied by primary historical sources, differently from the mostly second-hand information used so far, the catalog compilers such as Khair *et al.* (2000) simply added the newly discovered data to those already listed in the previous catalogs. The uncritical aggregation of data from first- and second-hand sources has inevitably resulted in duplication of events, yielding catalogs apparently more complete than the previous ones.

Survey and Analysis

A total of 45 studies dealing with the preinstrumental seismicity of the area of study have been identified, collected, and carefully considered (see Ⓔ ES1, available in the supplemental content to this article). The two types of items that effectively contributed to this review are (1) monographic studies of individual earthquakes, often including parameters (e.g., Ambraseys and Barazangi, 1989); and (2) studies including tens of earthquakes (e.g., Guidoboni *et al.*, 1994). Some of these studies mostly restrained themselves to a descriptive summary of the earthquake effects (e.g., Ambraseys, 2009). Such a wealth of published studies needed a thorough and critical survey to be carried out to serve as the basis for a rigorous analysis of the parameters; such studies had derived from historical earthquake records in terms of date, location, and size for each event. In other words, no new study was performed going back to the primary sources contemporary to each earthquake, nor were any additional reliable earthquake records searched for. The results of any individual study were analyzed and compared with the purpose of appraising the state of knowledge and the reliability of the interpretation supplied for each single earthquake and not with the intent of assessing the overall quality of a particular study.

As the Ⓔ ES2_Table_S1 clearly illustrates, there exist the well-documented earthquakes, such as the 746 earthquakes (see the Case Histories section) for which at least eight different and recent studies are available, and the less-covered ones, such as the 1339 event that is mentioned in two studies only.

The comprehensive survey of these 45 studies has also revealed that many authors relied on previously published studies, with interpretative errors propagating from one study to another, and that along the years some authors added new material and revised their interpretation, sometimes contradicting their own earlier conclusions.

As already noted, the scope of this review was not to investigate types, quality, or reliability of the historical sources that are characterized by significant differences in their original language, scope, and availability, but was to analyze and compare the different interpretations of the same earthquake. In some cases, such a comparison has cast light on some inconsistencies. This was all the more surprising when such interpretations stem from the same historical sources of earthquake records, as illustrated also by the events discussed in the Case Histories section.

In extreme synthesis, the analysis consisted in estimating the reliability level of the interpretation of each earthquake, taking into careful consideration which sources of information were used, and consequently attributing a preference to those interpretations supported by primary sources (1) contemporary to the earthquake, and (2) appropriately used with respect to their historical context and language.

Case Histories

The following examples were selected as representative of the variety of situations, to illustrate the approach followed and explain the peculiarities of the state of knowledge for preinstrumental earthquakes in Lebanon.

746 (or 747 or 749) 18 January, Palestine

How much assumptions and uncertainties inherent in each and every interpretation (Karcz, 2004) may affect the analysis of historical sources of past earthquakes is clearly shown by this case history. A damaging earthquake in Palestine is described in many contemporary or quasi-contemporary sources, variously referenced and used in eight studies published between 1994 and 2009 (Ⓔ ES2_Table_S1). However, the interpretation of this event is far from being satisfactory. A first element of confusion is the dating system that varies from source to source, according to the country and language of origin (Karcz, 2004; Ambraseys, 2005).

According to Karcz (2004, p. 778), "all multiple year dates given in ancient texts were attributed to inconsistent use of different calendars and eras in dating the same event of 18th January 749 A.D. This reduction of all felt reports to the same denominator implies destruction that extended from the Egyptian littoral (Damietta) to NE Syria (Maboug/Manbij) with Ml estimates in the range of 7.3 to 8 [...]. Byzantine and Arab chronicles and traditions clearly report at least two discrete events up to three years apart and hundreds of kilometers apart. "

Ambraseys (2005, 2009) expressed a similar opinion, to the point of identifying three earthquakes when reading sequentially the chronicle of Theophanes (A.D. 760–818):

- 18 January A.D. 746 in Palestine, Jordan, and Syria (Ambraseys, 2005) (dated 749 by Karcz, 2004);
- 749/750, in Mabug/Manbej/Manbij (northeast Syria) and Mesopotamia (Ambraseys, 2005); and
- 9 March A.D. 757 in Palestine and Syria (Ambraseys, 2009).

Consequently, Karcz (2004) and Ambraseys (2005, 2009) cast serious doubts on magnitude values supplied by current catalogs and especially on the reliability of the studies accumulating all the effects and relating them to just one very large earthquake.

As of today, the contrasting interpretations available for this earthquake (see Ⓔ ES2_Table_S1) mostly depend on the following two issues:

- the confusion created by the use of different dating systems in the historical sources has induced some authors to relate all the records to the same earthquake, and
- sources contemporary to the earthquakes, as well as those written centuries later, were given the same level of importance and reliability.

Among the eight studies analyzed, Ambraseys (2006) is the only one providing earthquake parameters for the 18 January A.D. 746 earthquake, alternatively dated 749 by Karcz. The 749/750 and 757 earthquakes are not discussed because they are out of the studied area.

29 June 1170

This is one of the most highly documented events for Lebanon in the middle ages, because several contemporary and detailed accounts have survived. According to the historical sources, the area between present-day northern Lebanon and northwestern Syria was seriously damaged by a series of earthquakes. Modern authors agree on the date of the mainshock but disagree on the intensities attributed to the affected places. In particular, two authors give contrasting interpretations of this complex earthquake sequence, preceded by a similarly large earthquake in

Table 1
Comparing Three Records for the February 1656 Event

Sieberg (1932a, p. 802) and Sieberg (1932b, p. 200)	Hoff KEA von (1840, p. 305)	Dresdnische gelehrte Anzeigen (1756, p. 122)
(a) *1656, im Februar.* ***Tripolis [in Syrien]*** *zur Hälfte zerstört. Auch in Palästina gefühlt.* (b) *1656, im Februar. Ein* ***syrisches Beben****, das auch in Palästina gefühlt wurde, zerstörte Tarablus zur Hälfte. Wiederholung im November.*	*1656 Ein in diesem Jahre erfolgtes Erdbeben zu* ***Tripoli (Tarablus) in Syrien*** *wird von Einigen in den Februar, von Anderen an das Ende des Jahres gesetzt (Dresdn. gel. Anzeigen)*	*Anno Christi 1656 Gegen Ende dieses Jahres, wurde die Stadt* ***Tripoli in der Barbaren****, durch eine ausserordentlich Erderschütterung, fast bis auf die Helfte, übern Hauffen geworfen.*
[(a) 1656 February Tripoli [in Syria] half destroyed. Felt also in Palestine. (b) 1656 February *A Syrian earthquake, which was also felt in Palestine, destroyed half of Tarablus. Repetition in November.]*	[1656 The earthquake of this year in Tripoli (Tarablus) in Syria is dated by some in February, by others at the end of the year.]	[A.D. 1656 Toward the end of this year, the city of Tripoli among the Barbarians/of Barbary was thrown off almost to the half by an extraordinary earthquake.]

Original information in the Dresdnische gelehrte Anzeigen (1756) was misinterpreted by Hoff KEA von (1840), and the error was propagated by Sieberg (1932a,b). Original information is indicated in italic and the locations of the earthquake are indicated in bold

1157: on the one hand, (1) Guidoboni *et al.* (2004) and Guidoboni and Comastri (2005) and on the other hand, (2) Ambraseys (2004, 2009). Overall, Ambraseys (2004, 2009) revised downward the intensity values, with respect to Guidoboni *et al.* (2004) (see intensities in fig. 3.12 of Ambraseys, 2009, with respect to intensities in fig. 7 of Guidoboni *et al.*, 2004). Besides, the most recent parameters' assessment can be found in Hough and Avni (2009), who applied the Bakun and Wentworth (1997) method and explicitly stated to have used the intensity data supplied by Ambraseys himself.

The four epicentral locations provided by just as many studies out of the nine studies here considered are very close, that is within 10–20 km. Guidoboni *et al.* (2004), Sbeinati *et al.* (2005), and Ambraseys (2009) provide quite close magnitude estimates, respectively M_w 7.7, M_s 7.7, and M_s 7.3, with an associated 0.3 uncertainty. However, the magnitude estimated by Hough and Avni (2009) is much lower, M_w 6.6. Because there is no regional attenuation relation, in their application of the Bakun and Wentworth (1997) technique, Hough and Avni used an attenuation equation relying mostly on the 1927 Jericho event intensity dataset.

February 1656 (Wrongly Located in Lebanon)

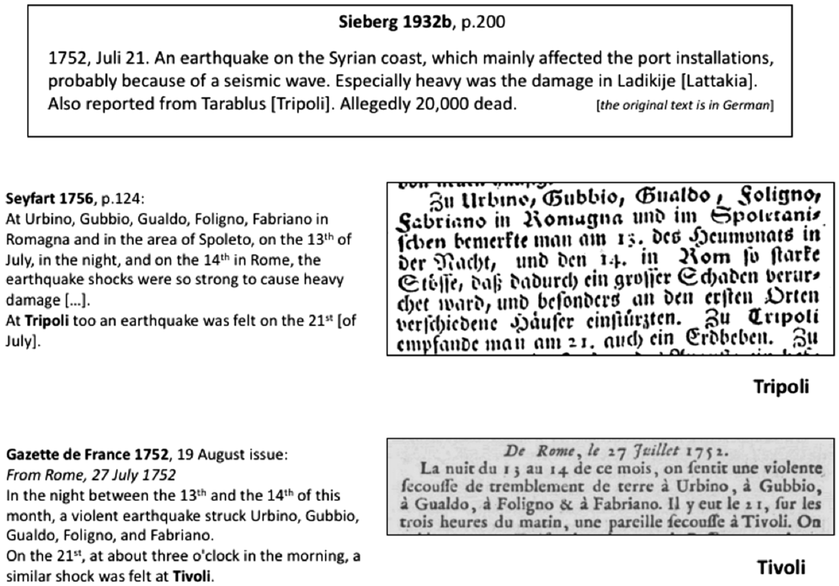
As clearly explained by Ambraseys (2009), this earthquake was incorrectly located by Sieberg (1932a,b) at Tripoli of Syria, today Lebanon, instead of Tripoli of Barbary, today Lybia. In the seventeenth century, eastern and western Tripoli, or Tarablus, was the cities at the center of two provinces of the Ottoman Empire. Although Sieberg did not specifically quote his source, it is very likely that he took the record from Hoff KEA von (1840, p. 305) (see Albini *et al.*, 2019). The reference in von Hoff was retrieved in the original, and it is an eighteenth-century German collection of essays, including a long report on past earthquakes, commonly cited in historical earthquake studies, such as Dresdnische gelehrte Anzeigen (1756, p. 122). The comparison between the three texts (Table 1) shows that the incorrect reading of the record has to be ascribed to von Hoff. Consequently, this record does not refer to an earthquake heavily affecting Tripoli in Lebanon in February 1656, and as the result of a clear misinterpretation, it should be deleted from the catalog for Lebanon.

21 July 1752 (Wrongly Located in Lebanon)

Ben-Menahem (1991, his table 5d) did not mention his sources but described the 21 July 1752 earthquake as located off coast Laodicea, with an epicentral intensity Io = 10 and a magnitude M_L 7.0. The Gazette de France (1752), a French weekly newspaper published in Paris, is the source of information closest in time to the earthquake (Fig. 2). In the 19 August issue, there is a correspondence from Rome dated 27 July about an earthquake felt on 21 July 1752 at Tivoli, a small settlement close to Rome. Quoted by Ambraseys (2009) is also the compilation of earthquake data of Seyfart (1756). Comparing the two eighteenth-century records (Fig. 2) shows that Seyfart had misspelled the name of the affected place, transforming Tivoli into Tripoli in Lebanon. A strong shock, with no consequences, in the process of passing from one secondary source to another, became an earthquake so large as to cause thousands of victims on the Syria and Palestine littorals (Sieberg, 1932b; Sbeinati *et al.*, 2005). This earthquake should be deleted from the catalog for Lebanon, too.

Results

The critical analysis resulted in the selection of studies supplying the most credible and reliable sets of parameters for each earthquake, according to the criteria previously mentioned. It may be observed that the selected interpretations are not necessarily the most recently published ones and finally that the selection was either relatively easy in the case of overall



▲ **Figure 2.** Sources on the presumed 1752 Lebanon earthquake. The source closest in time to the event is Gazette de France (1752). A later source (Seyfart, 1756) clearly misinterpreted and misspelled the place name, turning it from Tivoli (near Rome, Italy) to Tripoli in Lebanon. Ben-Menahem (1979), Willis (1928), and recently Sbeinati *et al.* (2005) all relied upon a unique source of information, Sieberg (1932b), who is at the origin of this fake M 7 event located in Lebanon.

consensus among the studies or difficult to very difficult in the case of substantial disagreement among several studies.

Ⓔ ES2_Table_S1 lists all the 31 earthquakes for which the 45 considered studies supply data. Out of the 31 studied events between 31 B.C.E. and 1837, only 17 entered the revised catalog, that is, those for which at least epicentral location and magnitude are available (Fig. 3). For these 17 earthquakes, the amount of information is indisputably uneven. Whenever the selected study provided an estimate of the uncertainty on the magnitude, it has been indicated in Ⓔ ES2_Table_S1. This uncertainty value is considered as a minimum bound for most earthquakes (especially the earliest ones). Given the large uncertainty on those magnitudes, M_s magnitudes should not be converted to M_w magnitudes and rather should be considered as surrogate.

The different studies selected for their reliable interpretation have, in their turn, applied different methods to locate and estimate the earthquake magnitude from intensity data and isoseismals. This means that the obtained catalog cannot be considered homogeneous in a strict sense. In addition, for some of these earthquakes (e.g., the 363 event), some authors suspect that more than one shock occurred, but due to the difficulty in separating effects, the magnitude estimated corresponds to cumulative earthquake effects.

For the remaining 14 earthquakes (see Ⓔ ES2_Table_S1), the survey and the analysis of the available studies and their data did not allow us to select or propose any reliable interpretation. The occurrence of most of them is confirmed, but the information is so scarce that not even the most reliable studies have assessed a complete set of earthquake parameters. Succinct comments have been included in the last column of Ⓔ ES2_Table_S1 to explain their exclusion from the revised catalog.

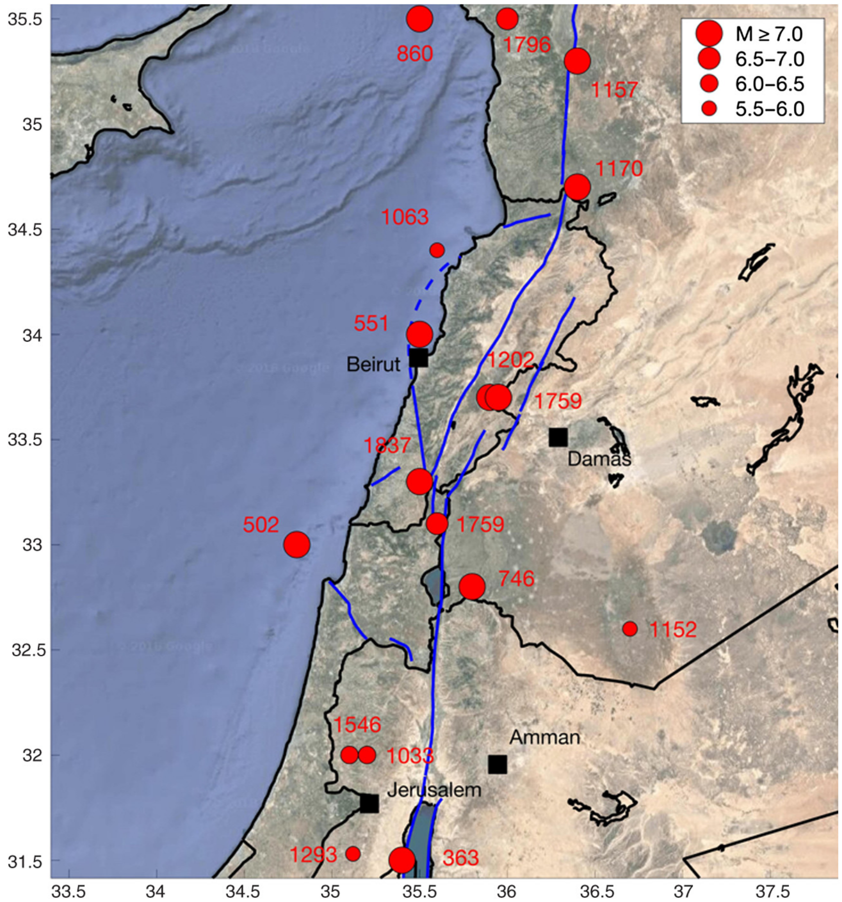
Scaling relationships, such as Leonard (2010), estimate a rupture length of 50–130 km for strike-slip events with magnitudes M_w 7–7.7. When such large events rely on a wealth of data, the macroseismic epicenter is expected to be somewhere along the fault. For events with only a handful of data, the macroseismic epicenter is often the barycenter of intensity data points, which might be off the causative fault. Various studies have related most of the 17 parameterized earthquakes in Ⓔ ES2_Table_S1 with specific faults (e.g., Daëron *et al.*, 2005; Megrahoui, 2015; Lefevre *et al.*, 2018), sometimes contradicting each other. The next step toward building the earthquake model for seismic hazard assessment will be to understand available results in terms of paleoseismicity and archeoseismicity and evaluate the association of earthquakes with causative faults, highlighting in a transparent way the underlying uncertainties.

INSTRUMENTAL PART OF THE CATALOG

The instrumental part of the catalog is built from existing earthquake catalogs and bulletins. A geographical window is defined, extending from 30° to 37° N latitude and from 32° to 39° E longitude to include all earthquakes up to 300 km from the Lebanese border. Considering earthquakes with magnitudes ≥ 4.0, the final catalog includes 420 events from 1900 to 2015. The events were reviewed one by one, and the catalog is built with a degree of precision that is not possible in seismically more active countries, like Ecuador, where catalogs down to magnitude 4.0 contain thousands of earthquakes (Beauval *et al.*, 2013).

The Bulk of the Data: Global Catalogs

The International Seismological Centre-Global Earthquake Model (ISC-GEM) catalog version 6.0 (v.6.0) provides the most authoritative solutions for locations and magnitudes (Di Giacomo *et al.*, 2015; Storchak *et al.*, 2015; Table 2). Hypocenters were computed using a combination of the EHB technique (Engdahl *et al.*, 1998) and the latest International Seismological Centre (ISC) location algorithm and the same velocity model. Earthquakes are described by moment magnitude based on available estimates of seismic moment (Global Centroid Moment Tensor [CMT], Ekström *et al.* 2012; among others) or proxy values obtained from newly calculated M_s and m_b magnitudes. Thirty-four events with M_w 5.1–6.8 are in the spatial window considered. Twenty-three of these events (M_w 5.2–6.4) occur during the early instrumental period (before 1964). A seismograph installed by the Jesuits



▲ **Figure 3.** Earthquakes included in the historical catalog for Lebanon (see Ⓔ ES3_Lebanese_catalog). Epicentral locations and magnitudes rely on macroseismic data (solutions determined by different authors, see Ⓔ ES2_Table_S1). For information, identified active fault segments are indicated (Y. Klinger, personal comm., 2017). The color version of this figure is available only in the electronic edition.

in 1910 in Ksara Observatory, Lebanon, played an important role in this period, because there was a lack of stations in the Middle East (Udias and Stauder, 1996). Following Ambraseys (2001), we did not include the solutions provided by Plassard and Kogoj (1981), dealing with 12 events of magnitude 4–4.9 between 1907 and 1972, located within Lebanon or close to the border (four events offshore), because it is unclear how the locations and magnitudes of these events have been determined. A thorough analysis of the historical archives available in Lebanon would be needed to re-evaluate the intensities associated to these low-magnitude earthquakes.

In addition to the ISC-GEM catalog, four global catalogs and one regional catalog provide most of the information for earthquakes starting with the 1960s:

- The ISC bulletin is the most complete source of earthquake locations and magnitudes on a global scale. Starting in 1964, the ISC reports its own hypocentral locations and teleseismic magnitudes m_b and M_s (1964–1984 has been rebuilt recently; see Data and Resources). The ISC also provides the locations and magnitudes computed by contributing institutions. Here, we use the ISC event catalog over its reviewed period.
- The ISC-EHB bulletin provides improved hypocenter locations for a subset of teleseismically well-constrained earthquakes in the ISC catalog (International Seismological Centre-EHB [ISC-EHB], 2018). The period 2000–2015 has been rebuilt, with respect to the original EHB catalog. This catalog contributes to approximately one-fourth of the hypocentral solutions in our final catalog (Table 3).
- The Global CMT agency has routinely calculated M_w since 1976 and is considered the most authoritative agency to provide M_w (Ekström *et al.*, 2012). In the spatial region considered (30°–37° N latitude and 32°–39° E longitude), Global CMT provides M_w for 17 events with M_w 4.7–5.5, in addition to those already included in the ISC-GEM catalog.
- The National Earthquake Information Center (NEIC) catalog uses fewer stations than the ISC; NEIC solutions are used only if there is not an ISC solution (only two entries in the final catalog, Table 4).
- The Regional Centroid Moment Tensor (RCMT) regional catalog (Pondrelli *et al.*, 2006, 2011) provides RCMTs routinely since 1997 for intermediate-magnitude earthquakes (about $4.5 < M_w < 5.5$) occurring in the Euro-Mediterranean region. When the station distribution is particularly favorable, the catalog also lists some events with magnitudes as low as 4.0

The European-Mediterranean Seismological Centre (EMSC) catalog for the period 1998–2012 was analyzed but not included in the selection. The EMSC currently provides all the data collected to the ISC, and their solutions have no added value with respect to ISC solutions (R. Bossu, personal comm., 2017).

Following is the selection scheme applied to select the best location (Table 2), in decreasing order of priority: ISC-GEM (34 events), ISC-EHB (108 events), and ISC solutions (276 events). ISC solutions constitute 66% of the hypocenter locations in our final catalog (Table 3).

The following scheme is applied to select the best available magnitude in decreasing order of priority: M_w ISC-GEM (34 events), M_w Global CMT/Harvard (17 events), M_w RCMT (24 events), M_s ISC (31 events), m_b ISC (255 events), m_b NEIC (two events), or a magnitude from a regional network reported by the ISC. ISC solutions constitute 68% of the event magnitudes in our final catalog (Table 4; Fig. 4). Surface-wave magnitudes (M_s) are favored over m_b magnitudes to get a proxy M_w, whenever M_s is estimated using at least five stations. Magnitudes m_b tend to saturate and strongly underestimate

Table 2
Priority Schemes for the Selection of the Best Location and for The Selection of the Best Magnitude (Post-1963)

Location	Magnitude
ISC-GEM	ISC-GEM (M_w)
ISC-EHB	Global CMT (M_w)
ISC*	RCMT (M_w)
NEIC	ISC (M_s) if N_stations ≥ 5
	ISC (m_b)
	NEIC (m_b)
	IPRG/GII/NIC/GRAL†

CMT, centroid moment tensor; GII, Geophysical Institute of Israel; GEM, Global Earthquake Model; GRAL, Geophysical Research Arrays of Lebanon; IPRG, Institute for Petroleum Research and Geophysics; ISC-EHB, International Seismological Centre-EHB (Engdahl *et al.*, 1998); NEIC, National Earthquake Information Center; NIC, Seismic network of the Cyprus Geological Survey Department; RCMT, Regional Centroid Moment Tensor.
*ISC own solution.
†Selection of the regional network based on the geographical location of the event.

Table 3
Events in the Final Catalog (Proxy $M_w \geq 4.0$)

Author Location	Start Year	End Year	Total
ISC-GEM	1915	2004	34
ISC-EHB	1967	2015	108
ISC	1964	2015	274
Plassard	1956	1956	2
GUTE	1928	1928	1
ISS	1963	1963	1
Total			420

GUTE, Gutenberg and Richter; ISS, International Seismological Summary.

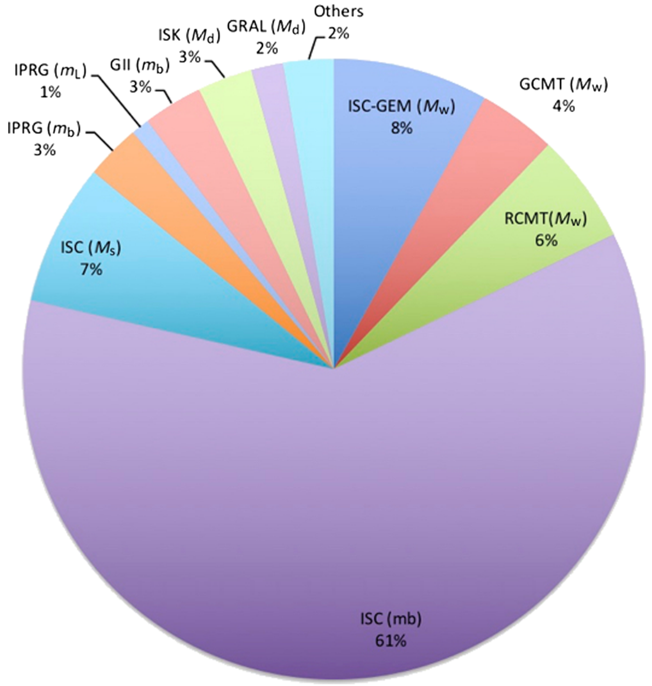
earthquake magnitudes above M_w 5.5–6.0. Moreover, with respect to M_w magnitudes, m_b magnitudes have a much larger data scatter than M_s magnitudes (Lolli *et al.*, 2014; Di Giacomo *et al.*, 2015).

For four early instrumental events, the locations and/or the magnitudes have not been re-evaluated recently but are kept in the dataset: the 1928 event, location and magnitude Seismic network of California Institute of Technology, Pasadena (PAS) determined by Gutenberg and Richter

Table 4
Events in the Final Homogenized Catalog

Author	Type of Magnitudes	Start Year	End Year	Minimum Magnitude	Maximum Magnitude	Total
ISC-GEM	M_w	1915	2004	5.12	6.78	34
Global CMT	M_w	1984	2015	4.7	5.5	17
RCMT	M_w	1997	2015	4.1	5.1	24
ISC	M_s	1984	2015	3.1	5.2	31
ISC	m_b	1964	2015	4	5.6	255
NEIC/NEIS	m_b	1972	1996	4.3	4.6	2
IPRG*	M_L	1984	1988	4.1	4.3	4
IPRG†	m_b	1987	1999	4.2	4.3	12
GII‡	m_b	2001	2011	4.1	4.4	13
ISK§	M_d	1996	2003	4	4.2	12
GRAL	M_d	2008	2014	4.1	4.3	7
PAS	M_s	1928	1940	5.6	5.8	2
MAT	M	1959	1959	5.5	5.5	1
CGS	M	1963	1963	5	5	1
USCGS	m_b	1964	1970	4.3	4.5	5
Total						420

CGS, Central Geological Survey; ISK, Kandilli Observatory and Research Institute; MAT, Seismic Network of The Matsushiro Seismological Observatory; NEIC, National Earthquake Information Center; NEIS, National Earthquake Information Service; PAS, Seismic network of California Institute of Technology, Pasadena; RCMT, Regional Centroid Moment Tensor; USCGS, U.S. Coast and Geodetic Survey.
*Equation based on 298 events with $3 \leq M_{L_{IPRG}} \leq 6.1$: $m_b = 0.221(m_{L_{IPRG}})^2 - 1.2735\ M_{L_{IPRG}} + 5.5757$, $\sigma = 0.28$.
†Equation based on 195 events with $4 \leq m_{b_{IPRG}} \leq 5.8$: $m_b = 0.1693(m_{b_{IPRG}})^2 - 0.5371\ m_{b_{IPRG}} + 3.2675$, $\sigma = 0.28$.
‡Equation based on 55 events with $4 \leq m_{b_{GII}} \leq 5.1$: $m_b = 0.0795(m_{b_{GII}})^2 + 0.2371\ m_{b_{GII}} + 1.6885$, $\sigma = 0.30$.
§Equation based on 293 events with $3.2 \leq m_{d_{ISK}} \leq 6.3$: $m_b = 0.1605(m_{d_{ISK}})^2 - 0.5006 m_{d_{ISK}} + 3.4406$, $\sigma = 0.26$.



▲ **Figure 4.** Unified instrumental catalog: original magnitude type and supplying institutions (420 earthquakes). GII, Geophysical Institute of Israel; GCMT, Global Centroid Moment Tensor; GRAL, Geophysical Research Arrays of Lebanon; IPRG, Institute for Petroleum Research and Geophysics; ISC-GEM, International Seismological Centre-Global Earthquake Model; ISK, Kandilli Observatory and Research Institute; RCMT, Regional Centroid Moment Tensor. The color version of this figure is available only in the electronic edition.

(1944); the 1940 event, magnitude PAS determined by Gutenberg and Richter (1944); the 1959 Cyprus event, magnitude determined by Seismic Network of The Matsushiro Seismological Observatory (MAT), International Seismological Summary (ISS); and the 1963 event, location provided by the ISS.

It is straightforward to apply the scheme for magnitudes larger than 5.0. Events are reviewed one by one, but no specific issues are detected. However, some issues are identified for events with lower magnitudes, and care must be taken to identify doubtful events. We have found events appearing twice in the ISC catalog (e.g., 4 July 1998 m_b 4.2) and in the NEIC catalog (e.g., 24 December 1996 M 5.5 or 26 March 1997 m_b 5.0). Moreover, we have reviewed events carefully for which there were strong discrepancies between the magnitude estimates of different institutions, as well as events with a magnitude higher than 4.5 detected by only one or two networks. Such events were mostly in the seismically active Cyprus region. As an example, we detail the reasons for excluding the m_b 4.8 event reported by the NEIC, 9 November 1987 6 hr 02 min: (1) there is no estimation of the magnitude by the ISC, which is usually the case for an m_b 4.8 in the late 80s; (2) we have found no trace of the event on the Lebanese BHL seismological station, although earthquakes in Cyprus are usually detected starting from M_w 3; (3) the NEIC bulletin reports seven stations only (among them, two are very far away: Nepal and Brazil), which is very low for an earthquake of this magnitude level, (4) the only other magnitude estimate reported by the ISC is an M_L 3.0 from the Israeli network Institute for Petroleum Research and Geophysics (IPRG). Another example is the 20 March 2008 event, with an m_b 5 determined by the ISC. In this case, all other institutions, namely International Data Centre (M_L), Kandilli Observatory and Research Institute (ISK) (M_D), EMSC (M_w), Seismic network of the Cyprus Geological Survey Department (NIC) (M_L), and the Geophysical Institute of Israel (GII; M_D), provide a magnitude in the range 3.5–3.7, so we consider the m_b magnitude provided by the ISC using five stations as very doubtful.

The Ⓔ ES4_ISC_details_catalog provides more details on information extracted from the ISC event catalog and the issues encountered.

For events with magnitudes that were only evaluated by regional agencies, we select the magnitude that was evaluated by the closest network. For events north of Lebanon (12 events in the final catalog), the magnitude M_d estimated by the Turkish network is selected, whereas for events south of Lebanon (29 events), the magnitude estimated by the Israeli network is selected (M_L or m_b). The final catalog includes magnitudes from the Turkish network (ISK) during 1996–2003 and from the Israeli network during 1984–1999 (IPRG) and 2001–2011 (GII). For seven events within Lebanon (2008–2014), the magnitude m_D estimated by the Lebanese Geophysical Research Arrays of Lebanon (GRAL) network was selected (see Ⓔ ES5_GRAL for a short description of the GRAL network).

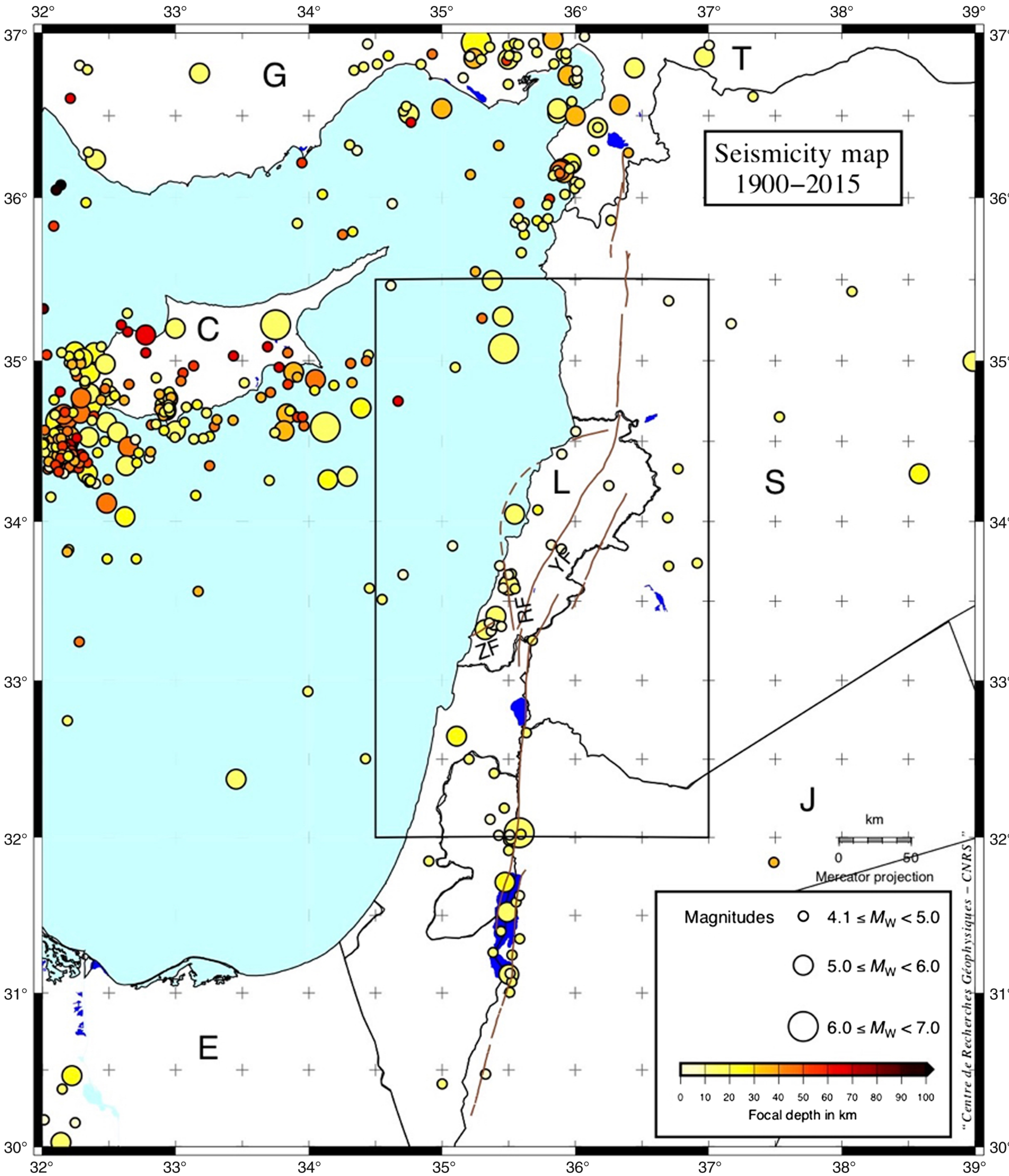
Specific Issues

Two damaging events occurred on 16 March 1956 in Lebanon. The first was M_s 4.81 (proxy M_w 5.3) at 7:32 p.m., and the second was M_s 5.11 (proxy M_w 5.5) at 7:43 p.m. (magnitudes are from the ISC-GEM catalog; Di Giacomo *et al.*, 2015). According to Plassard and Kogoj (1981), 136 people died. Based on the distribution of damage and estimated intensities, Plassard and Kogoj (1981) proposed a unique epicentral location for this double shock, which is located ~25 km south of the ISC-GEM locations. The Plassard and Kogoj (1981) epicentral location is preferred over the instrumental location for this version of the catalog. Given the azimuthal gap in the stations' coverage, the uncertainty on the instrumental location is large (D. Di Giacomo, personal comm., 2017). A reappraisal of the data and intensities would be necessary to reduce the uncertainty on this epicentral location.

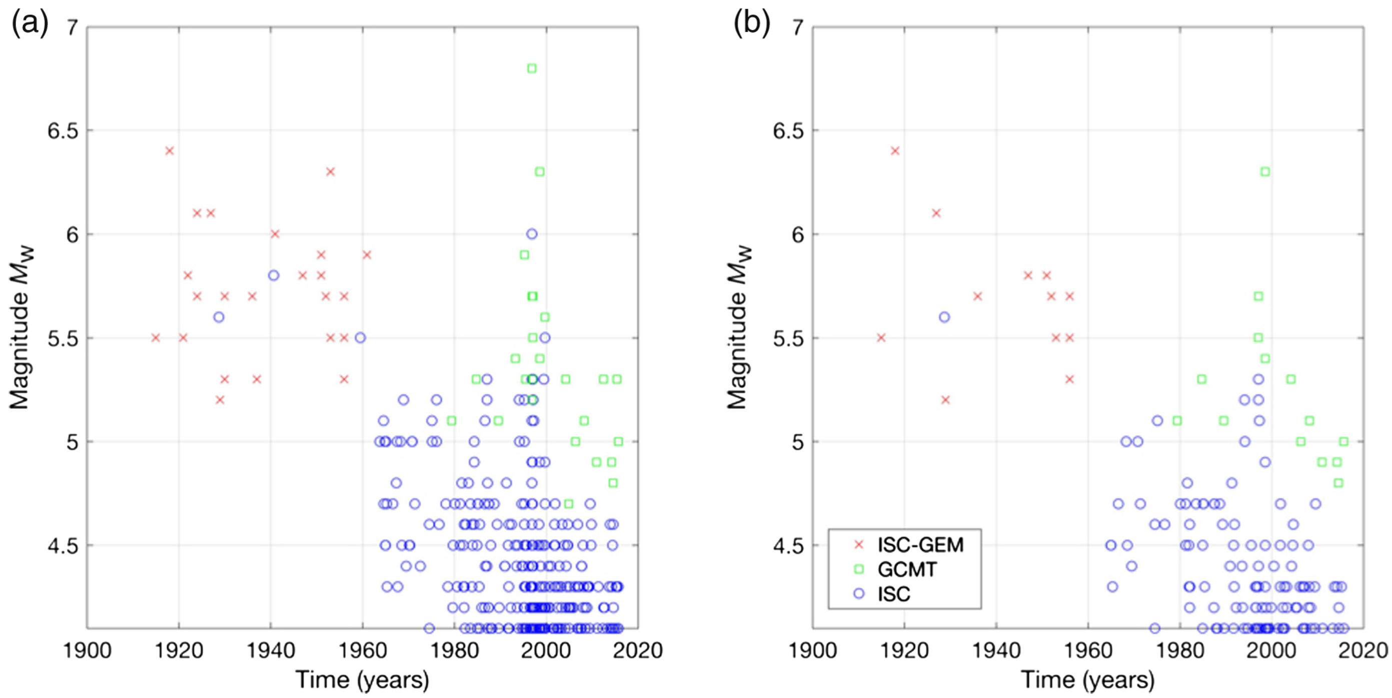
Magnitude Conversions Required for M_w Proxies

Choice of the Conversion Equations for M_s and m_b Magnitudes

The earthquake catalog must be homogenized in moment magnitude. We used the Lolli *et al.* (2014) equations instead of the equations used for the ISC-GEM catalog (Di Giacomo



▲ **Figure 5.** Instrumental catalog (1900–2015), homogenized $M_w \geq 4.1$, with an overlap of the main faults. E, Egypt; G, Greece; J, Jordan; L, Lebanon; RF, Roum fault; S, Syria; T, Turkey; YF, Yammouneh fault; ZF, Zraryeh fault. The rectangle indicates the spatial window considered in the Final Catalog and Implications for Seismic Hazard Assessment Studies section and Figure 7. The color version of this figure is available only in the electronic edition.



▲ **Figure 6.** Instrumental catalog (1900–2015), homogenized M_w. (a) All earthquakes in the instrumental catalog and (b) events with longitude ≥ 34.5° (excluding most of the Cyprian arc). The color version of this figure is available only in the electronic edition.

et al., 2015) to convert magnitudes into M_w proxies. These equations differ significantly for the conversion of m_b into an M_w proxy. Taking advantage of the available recomputed M_s and m_b, Di Giacomo *et al.* (2015) derived new empirical relationships using exponential nonlinear models to obtain an M_w proxy from M_s and m_b and applied a nonlinear least-squares regression. They used global data, extending the ISC-GEM dataset (cutoff magnitude 5.5) down to lower magnitudes, but they did not include M_w estimates from agencies other than the Global CMT, so their dataset is still rather incomplete at low magnitudes (Lolli *et al.*, 2014). They warn users that both the exponential models for M_s and for m_b should be used with caution for magnitudes below 5.0 (Di Giacomo *et al.*, 2015).

Lolli *et al.* (2014) derived conversion equations between teleseismic magnitudes provided by the ISC and M_w magnitudes provided by the Global CMT and NEIC catalogs using the chi-square general orthogonal regression method (Chi-square regression [CSQ], Stromeyer *et al.*, 2004) that accounts for the uncertainties of regressed magnitudes. For M_s, they show that the exponential regression curves are biased by the incompleteness of the global moment tensor catalog for $M_w < 5.0$–5.5. For such magnitudes, their global regression curve overestimates M_w proxies. Lolli *et al.* (2014) concluded that for $M_s \leq 5.5$, M_w proxies should be calculated using the regression curve established from a Euro-Mediterranean data set that includes more events with $M_w < 5.0$–5.5 (integrating moment tensor catalogs of Eldgenössische Technische Hochschule Zürich [ETHZ] and Istituto Nazionale di Geofisica e Vulcanologia [INGV]). Incompleteness of the global catalogs below M_w 5.0–5.5 also leads to a biased dataset for m_b. However, in this case, Lolli *et al.* (2014) showed that using the CSQ method mitigates this problem. They also showed that the exponential regression curve obtained from the more complete Euro-Mediterranean dataset almost coincides with the curve inferred from the global dataset (Lolli *et al.*, 2014).

Therefore, because our catalog includes earthquakes down to M_w 4.1, we apply the Lolli *et al.* (2014) global conversion equations for ISC M_s and m_b magnitudes from 1963 on.

Conversion Equations for Regional Magnitudes (9% of the Final Catalog)

An m_b proxy is determined for earthquakes described only by regional magnitudes (9% of the final catalog, see the The Bulk of the Data: Global Catalogs section); the Lolli *et al.* (2014) conversion equations are then applied to obtain an M_w proxy. To obtain m_b proxies, conversion equations are established from all events in the ISC bulletin described by an ISC m_b and a local magnitude (Table 4). The m_b proxies are determined from magnitudes IPRG (m_b, M_L), GII (m_b), and ISK (m_D). These conversions are necessary, but they carry large uncertainties, because the dispersion in the datasets is significant. For each conversion equation, we calculated an uncertainty on the proxy magnitude and included this uncertainty in the final earthquake catalog. There are only six events with an ISC m_b and a GRAL m_D, and a conversion equation cannot be established. No m_b proxy can be estimated for the seven events with a GRAL m_D magnitude ($4.1 \leq m_D \leq 4.3$) that are thus considered as surrogates for the M_w. Until a proper equation to convert duration magnitudes into m_b or M_w proxy can be established, integration of the full GRAL solutions to the final homogenized earthquake catalog for Lebanon is not possible.

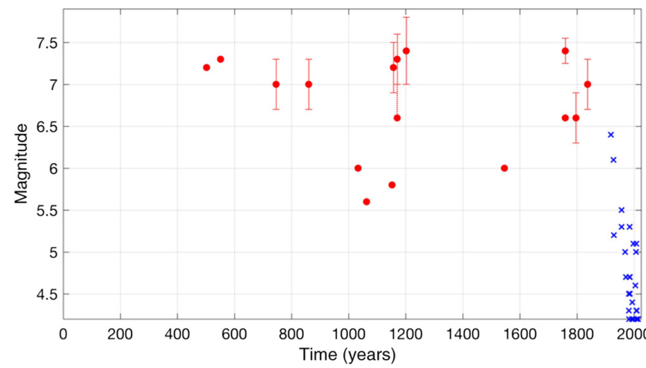
Uncertainties of M_w Magnitudes in the Final Catalog

Except for a handful of early instrumental events, all moment magnitudes in the final catalog come with an estimate of the uncertainty. The ISC-GEM catalog provides M_w magnitudes with an estimation of the uncertainty, which we report. The Global CMT catalog does not provide an estimate of the uncertainty for each event. However, according to several previous works (e.g., Helffrich, 1997; Kagan, 2002, 2003; Gasperini *et al.*, 2012), the uncertainty on M_w is in the range 0.05–0.15; thus we attributed a 0.1 uncertainty to all M_w magnitudes provided by Global CMT and RCMT. The RCMT catalog provides quality flags for M_w magnitudes (A/B/C/D, Pondrelli *et al.*, 2011), which we also reported (23 out of 24 events with A and one with B). For events with a proxy M_w relying on an M_s or an m_b, the uncertainty on the proxy is calculated combining the uncertainty on the original magnitude with the uncertainty on the conversion equation. Only part of the magnitudes m_b and M_s determined by the ISC comes with an estimate of the uncertainty. When no uncertainty was provided, we used the average uncertainty on m_b ($\sigma = 0.24$) and M_s ($\sigma = 0.16$), as estimated by Lolli *et al.* (2014) on a global dataset (table 6 in their publication). In the case of magnitudes from regional networks, the uncertainty on the original magnitude is not provided; the uncertainty on the M_w proxy corresponds to the combination of the uncertainties on the two successive conversion equations. There is no unique way of propagating uncertainties: we provide all intermediary values in our catalog, and we encourage the users to test different methods, from simple ones to more elaborated ones (e.g., Lolli *et al.*, 2014, 2018).

Homogeneous Instrumental Catalog 1900–2015

All earthquakes in the time window 1900–2015 with proxy $M_w \geq 4.1$ are displayed in Figure 5. Seismic activity has been low in Lebanon since 1900. Most earthquakes with proxy $M_w \geq 5.5$ occurred in the first half of the twentieth century (Fig. 6a,b). Within Lebanon, the link between known fault segments and seismicity is tenuous, except for the seismic activity on the Roum and Zrariyeh faults (Fig. 5). South of Lebanon, part of the seismicity is aligned on the Levant strike-slip fault system, on the border between Palestine and Jordan, and along the Dead Sea. Denser seismicity can be found in the Cyprian arc northwest of Lebanon and in Turkey (e.g., northern segments of the Levant fault) at distances >100 km from the Lebanese border.

Plots of the cumulative number of events versus time show that the catalog can be considered complete for earthquakes with magnitudes larger or equal to proxy M_w 4.1 since 1985, $M_w \geq 4.5$ since 1965, and $M_w \geq 5.5$ since ~1910; however, given the uncertainties inherent to the determination of completeness time windows, these numbers must be handled with caution.



▲ **Figure 7.** Instrumental catalog (crosses), appended to the historical catalog (circles), magnitude versus time, spatial window 34.5°–37° in longitude and 32°–35.5° in latitude. Note that the historical catalog is not strictly homogeneous, because the methods applied to estimate earthquake parameters vary among authors. Uncertainty estimates are available only for some events. For the 1170 event, two alternative magnitude estimates are displayed (see the 29 June 1170 section). The color version of this figure is available only in the electronic edition.

FINAL CATALOG AND IMPLICATIONS FOR SEISMIC HAZARD ASSESSMENT STUDIES

We now focus on earthquakes posing a threat to Lebanon that fall in a spatial window extending over 100 km from the Lebanon border to the south and to the north (34.5°–37° longitude, 32°–35.5° latitude; see rectangle in Fig. 5). Figure 7 displays earthquake magnitude versus time over the last 2000 yr. The largest recorded instrumental earthquakes are the 1918 M_w 6.4 event in the Iskenderun basin and the 1927 M_w 6.1 event in Jericho (Fig. 5). The relatively quiet instrumental period contrasts with the historical period, in which ~11 earthquakes occurred with magnitude estimates ranging from 6.5 to 7.7. Two clusters of destructive events occurred in the time windows 1157–1202 and 1759–1837.

Fifteen earthquakes with proxy $M_w \geq 4.5$ and six earthquakes with proxy $M_w \geq 5.0$ occurred over the period 1965–2015, corresponding to mean annual rates 0.29 and 0.12, respectively. Assuming the number of earthquakes decreases exponentially with a magnitude (Gutenberg and Richter, 1944) b-value of 1.0, these rates predict a mean recurrence time of ~340 and ~270 yr, respectively, for events with $M_w \geq 6.5$. Considering 11 historical events with $M_w \geq 6.5$ over a time window of 2000 yr yields a mean recurrence time around 180 yr. The historical record might not be complete for magnitudes ≥ 6.5 (see Ⓔ ES2_Table_S1), and 180 yr is a maximum bound. These numbers must be manipulated with great caution, because the instrumental and historical data contain important uncertainties. However, within the spatial window 34.5°–37° in longitude and 32°–35.5° in latitude, the seismicity rates in the instrumental period predict fewer large events than those observed in the historical period.

With active faults being well identified across Lebanon, a seismic hazard study must include a model that integrates the fault segments. The earthquake catalog (see Ⓔ ES3_Lebanese_catalog) cannot be used to establish magnitude–frequency distributions for these faults because seismicity has been relatively quiet in the instrumental period. Both the preinstrumental earthquakes and the slip-rate estimates (geodetic and geologic) can be used to build earthquake recurrence models. Based on the level of information available, we will have to build on the different published methods to predict how segments will break and evaluate the associated probabilities (i.e., from simple to more complex models; e.g., Andrews and Schwerer, 2000; Field *et al.*, 2014; Valentini *et al.*, 2017). The earthquake catalog can be used to establish gridded seismicity models that rely mostly on small-to-moderate magnitudes in the instrumental period (e.g., Danciu *et al.*, 2018; Petersen *et al.*, 2018). Smoothed seismicity implicitly assumes that future earthquakes will occur where past earthquakes occurred; therefore, off-fault seismicity can be accounted for in particular earthquakes on unknown or blind faults.

CONCLUSIONS

This article works to establish a reliable earthquake catalog for seismic hazard assessment in Lebanon. For the historical part of the catalog, similar to Albini *et al.* (2014), we thoroughly reviewed the literature to select the most robust estimates of location and magnitude. Uncertainty regarding these earthquake parameters varies greatly from one event to another; however, the final list reflects the state-of-the-art in the field of macroseismic studies for our region of interest. Several earthquakes are not included, because there was no study providing reliable parameters according to the criteria adopted in our critical assessment.

We built a unified instrumental earthquake catalog for Lebanon and bordering regions from global instrumental earthquake catalogs. A selection scheme was applied to choose the best location and the best magnitude among available solutions. The magnitude of reference is the moment magnitude M_w. For 80% of the events, an M_w proxy was calculated from the original magnitude applying conversion equations.

Our catalog shows that the instrumental seismicity (i.e., 1900–2015) corresponds to a particularly quiet period for Lebanon and surrounding areas. The historical catalog covering 2000 yr includes similar quiescence periods and more active periods with destructive earthquakes (e.g., sequences in the twelfth to thirteenth centuries and eighteenth to nineteenth centuries). The quietness of the twentieth century is not representative of these destructive events. Building an earthquake model for seismic hazard assessment in Lebanon and surrounding areas appears to be more challenging than in other parts of the world. Geodetic and geologic data should be used to compensate for this lack of instrumental data, and models that are able to account for large clustered events should be looked for. We expect a large variability of the hazard estimates, depending on the assumptions made regarding the source model.

DATA AND RESOURCES

The International Seismological Centre (ISC) online bulletin can be accessed at http://www.isc.ac.uk/iscbulletin/search/bulletin/ (last accessed May 2019). The International Seismological Centre-Global Earthquake Model (ISC-GEM) catalog is available at http://www.isc.ac.uk/iscgem/download.php (last accessed June 2019). The ISC-EHB bulletin is available at http://www.isc.ac.uk/isc-ehb/search/bulletin/ (last accessed June 2019). The Global Centroid Moment Tensor (Global CMT) earthquake catalog can be accessed at http://www.globalcmt.org/CMTsearch.html (last accessed June 2018). The Preliminary Determination of Epicenters (PDE)-National Earthquake Information Center (NEIC) earthquake catalog is available at https://earthquake.usgs.gov/earthquakes/search/ (last accessed October 2014). The European-Mediterranean Regional Centroid Moment Tensor (RCMT) catalog is available at http://rcmt2.bo.ingv.it (last accessed January 2019). The Lebanese seismological bulletins used in this study were provided by the Geophysical Research Center (CNRS-L). Some plots were made using the Generic Mapping Tools v.5.4.2 (www.soest.hawaii.edu/gmt, last accessed January 2019; Wessel and Smith 1998).

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