J Seismol (2016) 20:971–985
DOI 10.1007/s10950-016-9575-7

ORIGINAL ARTICLE

Reappraised list of historical earthquakes that affected Israel and its close surroundings

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Received: 10 January 2015 / Accepted: 6 April 2016 / Published online: 16 April 2016

Abstract Numerous historical reports of damaging earthquakes in the Levant have accumulated over the last 3000 years. Here, we screen that information and focus on the damaging earthquakes that affected Israel from the second millennia BCE to the 1927 CE Jericho earthquake and list the earthquakes by date, of major damage, type of sequence, and degree of size. The compilation results in three different lists: (i) 71 reliable earthquakes that in our opinion were most probably associated with the Dead Sea Transform (DST) and affected Israel and its close surroundings; (ii) 41 questionable earthquakes that should be re-evaluated or ignored; and (iii) 46 earthquakes that probably occurred but were erroneously associated with damage in Israel. What emerges from the list of the reliable earthquakes is that (i) Israel and its close surroundings suffered damage about 32 times during the last two millennia, that is, once in about 60 years, although not regularly; (ii) 21 of the earthquakes occurred during the last millennia, i.e., an event every ~45 years; and (iii) three intervals of increased reporting are noticed: between the fourth and the mid-eighth century, from the beginning of the eleventh to the end of the thirteenth century, and from the end of the eighteenth century up to the last entry in 1927, though this period may be extended until today. In-depth evaluation of the changing regimes over time within the study area, the historical reports of earthquake damage outside of Israel, and comparison with physical paleo- and archaeo-seismology evidence, such as the "137–206" and "165–236" paleoseismic earthquakes for which there is no historical match, indicates that the historical list is far from being complete. Thus, we argue that the apparent cycles of historical reporting do not necessarily reflect the actual rate of seismic activity and further investigation is needed to establish a compiled, multi-sourced list to decipher the true nature of cycles of strong earthquakes in this region during historical times.

Keywords Dead Sea Transform · Earthquake damage · Historical earthquakes · Israel · Seismic cycles

1 Introduction

Numerous accounts of past earthquakes, tsunamis, and the damage they caused in the Levant have been accumulating during the last three millennia. They include historical contemporary reports, chronicles, manuscripts, newspapers, drawings, maps, and in recent times even modern photographs. The majority of the historical share was already collected, translated, and organized within several catalogues and lists. However, up to the last three decades, many of these studies were not

Electronic supplementary material The online version of this article (doi:10.1007/s10950-016-9575-7) contains supplementary material, which is available to authorized users.

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critical enough and, consequently, there are a considerable number of questionable, false, or duplicated entries in these lists. Moreover, several errors were copied from one catalogue to another, causing distortion of the information or even fabrication of new earthquakes (Ambraseys 2005a; Karcz 2004; Karcz and Lom 1987). The implications of this shortcoming are too important to ignore. For example, the ground acceleration maps of the current Israeli anti-seismic building code (IC 413) are based upon such a list (Geophysical Institute of Israel, unpublished dataset). Thus, it is essential to screen and construct a reliable list of historical earthquakes that hit or were felt in and around Israel during historical times.

The compilation suggested in this paper is based primarily on a systematical review of the historical share. As the historical archive is partial and inhomogeneous along time (Stucchi et al. 2004), we examine the extent to which it may have influenced the completeness of this archive. We thus compare the temporal spread of the earthquakes in light of their historical context as well as with the archaeoseismic (e.g., Marco 2008) and paleoseismic (e.g., Agnon 2014; Marco and Klinger 2014) inventories available nowadays and conclude with an updated list of historical earthquakes that affected Israel and discuss how complete it might be.

2 The available information of the historical earthquakes

The first attempt to systematically collect and organize the historical reports of earthquakes and construct a Mediterranean inventory was probably in the mid-fifteenth century by (Manetti 1457). Following, Ligorio (1574-77) organized the Mediterranean earthquakes and expanded the time frame, beginning with the first millennium BCE up to his times. During the nineteenth century, a few important catalogues were also published (Hoff 1840; Mallet 1852; Perrey 1850; Schmidt 1881). Although these works were more accurate than the pre-nineteenth century lists, they were still incomplete and contained several inaccuracies and confused items. Unfortunately, the early twentieth century lists of Arvanitakis (1903), de Ballore (1906), Willis (1928), and Sieberg (1932) partially adopted these catalogues along with the inaccuracies already existing, and thus, these ambiguities became rooted in the scientific literature in several of the following compilations (e.g., Karcz and Lom 1987). In the mid-twentieth century, Shalem (1951) made a pioneering attempt to assess the historical earthquakes and their damage consistently. The following compilations (e.g., Amiran 1952; Amiran et al. 1994; Ben-Menahem 1979; Turcotte and Arieh 1988) were more detailed and also listed damaged localities but still preserved several of the significant inaccuracies. For instance, the alleged 92 BCE earthquake in Jerusalem appears in Amiran (1952), Amiran et al. (1994), Ben-Menahem (1979), and elsewhere but was later strongly rejected by Karcz (2004). A second example is the amalgamation made by Amiran (1952) of the local 363 CE and the 365 CE Crete earthquakes, but this was subsequently corrected by the same author (Amiran et al. 1994). Recently, however, the importance of critical interpretation of the historical sources was strongly raised (e.g., Ambraseys 2005a; Guidoboni and Ebel 2009; Karcz 2004; Karcz and Lom 1987) and consequently more critical screenings were conducted. Perhaps, the first harbingers were the review made by Karcz (1987) and the catalogues of Ambraseys et al. (1994) and Guidoboni et al. (1994). Following, their critical approach was adopted in modern catalogues (e.g., Ambraseys 2009; Guidoboni and Comastri 2005), reappraisals (e.g., Ambraseys and White 1997; Salamon et al. 2011; Salamon et al. 2007), and reviews (e.g., Ambraseys 2004; Ambraseys and Finkel 1995; Salamon 2009). Additional sources of historical information can be found in focused investigations of specific earthquakes (e.g., Ambraseys 1997; Ambraseys 2005b; Ambraseys and Barazangi 1989; Ambraseys and Karcz 1992; Ambraseys and Melville 1988; Austin et al. 2000; Avni 1999; Hough and Avni 2010; Russell 1980).

Archaeoseismic and paleoseismic findings constitute evidence complementary to the historical reports. While the historical portion provides information only from the last 3000–4000 years, archaeological remains (e.g., Ambraseys 2006; Bikai 2002; Hayens et al. 2006; Karcz et al. 1977; Korjenkov and Mazor 1999; Marco 2008; Rucker and Niemi 2010; Russell 1985; Thomas et al. 2007; Tsafrir and Foester 1992) and paleoseismic findings (e.g., Agnon et al. 2006; Alsop and Marco 2011; Enzel et al. 2000; Kagan et al. 2005; Kagan et al. 2011; Ken-Tor et al. 2001; Ken-Tor et al. 2002; Marco et al. 1996; Migowski et al. 2004; Wechsler et al. 2014; Zilberman et al. 2005) provide evidence of several thousand years much earlier and up to the Pleistocene, respectively. Thus, they may support and even augment the scope of the historical share. The recent archaeoseismic and paleoseismic reviews of Marco (2008), Agnon (2014), and Marco and Klinger (2014) reflect that modern tendency. In the last few decades, scientists become aware of the benefits in collaboration and a sharp increase in multidisciplinary efforts is evident (e.g., Ellenblum et al. 1998; Ferry et al. 2011; Marco et al. 1997; Marco et al. 2003; Meghraoui et al. 2003; Niemi 2011; Panza et al. 1997; Reinhardt et al. 2006; Shaked et al. 2004; Wechsler et al. 2009; Yagoda-Biran and Hatzor 2010).

3 Methodology—the compilation of the historical reports

3.1 General settings

Our investigation begins at the biblical event of Sodom and Gomorrah (Genesis 19: Bible 1989) which dates back approximately to the second millennium BCE (Ambraseys 2009) and ends with the first recording of the damaging event in 1927 (Avni 1999), which practically ends the pre-instrumental period. Within this time frame, we focused mainly on the earthquakes that caused damage or were felt in at least one locality in Israel and/or its close vicinity. Accordingly, and in light of the existing tectonic settings and the population distribution, we limited our search for damage to an area extending between the geographic latitude coordinates 28.5° and 33.5° and from the Mediterranean coast in the west to about 50 km east of the Jordan and the Arava valleys (Fig. 1). The most southern, northern, and eastern localities within this area are the St. Catherine monastery in Sinai, Egypt and the cities of Tyre (Lebanon) and Zarka (Jordan), respectively.

The main seismogenic unit that crosses the region is the Dead Sea Transform (DST), left lateral fault system extending from the Red Sea in the south to southeastern Turkey in the north, and borders the tectonic plate of Arabia on the east side and the Sinai sub-plate on the west (Freund et al. 1968; Garfunkel and Ben-Avraham 1996; Garfunkel et al. 1981).

For the purpose of review and compilation of the historical reports, we based our evaluation mainly on the critical catalogues, reappraisals, reviews, and focused investigations listed in the previous section. In general, we used the English translations of the raw materials, but in cases of unclear reports or disagreements between the interpretations of some of the scholars, we checked the original document. In addition, in order to substantiate some of the historical reports, we also consulted several paleoseismic (Agnon 2014) and archaeoseismic (Marco 2008) reviews and studies relevant to our work but refrained from circular reasoning (Ambraseys 2005a; Karcz and Kafri 1978) in cases which the historical studies rely on the archaeo- or paleoseismic information or vice versa.

3.2 Compilation of the data

An accurate compilation process depends on the completeness and reliability of the historical reports. Furthermore, the attempt to systematically review and characterize reports that span more than 2000 years encounters difficulties originating from the different languages, authors, places, and historical contexts. Nevertheless, as most of the sources can be evaluated and characterized in light of their contemporaneous settings, we thus classified the inspected reports into contemporary (or near contemporary) and secondary sources. Then, we tracked the "chain of transmitters" (e.g., Elad 1982; Elad 2002), i.e., "who transmitted the report to whom," and inquired whether the transmitter is considered reliable. In cases in which the credibility of a given transmitter was controversial, we referred to discussions concerning his reliability (e.g., Broshi 1982; Mazar 1982) so as to assess possible inaccuracies or exaggerations. Finally, we developed a five-level scale of reliability based upon the number and contemporaneousness of the reports of each event entry (see Table 1). It was then possible to formulate a unified method to determine and grade the degree of reliability of each of the historical earthquakes. Accordingly, an event reported by at least two independent contemporary sources that describe the same phenomena was attributed a "very high" reliability degree. On the other hand, an event reported by a single secondary source that draws its account from unknown sources was attributed a "poor" reliability degree. In cases of historical reports supported also by independent archaeoseismic or paleoseismic evidence, the reliability degree of the reported event was strengthened (see Fig. 2 for the flow diagram of the process). Whenever we were unable to determine the reliability of an event, we used critical, conservative judgment based on the analysis of the underlying historical reports.

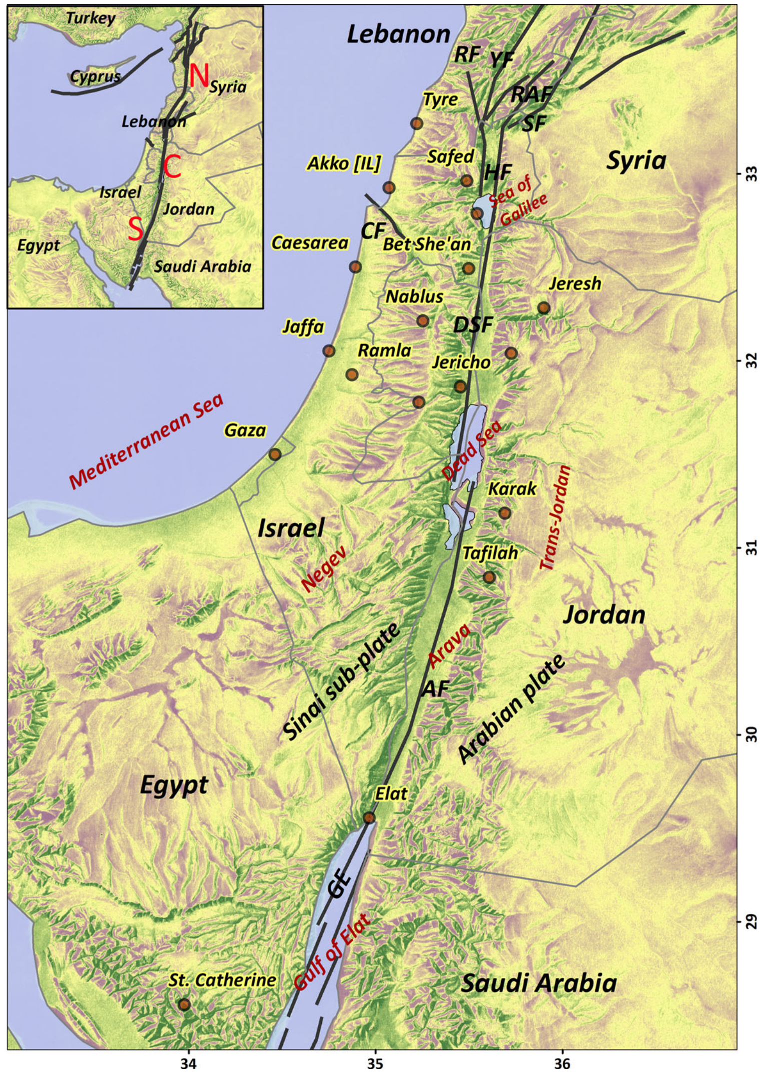

Fig. 1 Map of the study area which includes the central and southern parts of the Dead Sea Transform (DST) and its associated segments: *GE* the pull-apart structures in the Gulf of Elat and Aqaba, *AF* Arava fault, *DSF* Dead Sea fault, *HF* Hula fault, *RF* Roum splay, *YF* Yammouneh fault, *RAF* Rachaya splay, *SF* Serghaya splay, *CF* Carmel fault. A general overview of the DST is presented in the inset map; note the division of the transform into three geographic parts: South (*S*), Center (*C*), and North (*N*). Major ancient localities are marked and labeled

Date, degree of reliability, type (pre-, main, or aftershock) following (Salamon 2009), and zone of maximal damage were attributed to each of the compiled earthquakes. We also added a short description and noted the historical and scientific references we used for each of the entries. The reports of casualties required special attention as in many of the earthquakes the number of casualties seems to be extremely exaggerated. Furthermore, in several occasions, there are hardly any reports of damage but relatively large numbers of casualties. For instance, apart from the general term "Judea," there is no authenticated report of damage from the 31 BCE event, but Josephus (Josephus.AN. 15.121-4) still reports 30,000 casualties. This figure is strongly questioned by Ambraseys (2009). Broshi (1982) also claims that although the circumstances Josephus reports about probably did occur, the figures he notes in many cases are exaggerated.

In addition, we also determined the average of the magnitude values given by early researchers for the damaging earthquakes (e.g., Ambraseys 1997; Ambraseys and Barazangi 1989; Ambraseys and Jackson 1998; Ben-Menahem 1979; Ben-Menahem 1981; Ellenblum et al. 1998; Hough and Avni 2010; Marco et al. 1997; Marco et al. 2003). Although some of these scholars were not aware of the limitations of the historical data, they are all professional geologists and seismologists, well experienced in earthquake studies from all around the world. We therefore think that the earthquake magnitudes, as an opinion given by those

Table 1 Degrees of reliability that characterize a report of an event

Symbol	Reliability	Transmitters
V_R	Very high	Based upon at least 2 contemporary or near contemporary independent sources with no confusion or contradiction regarding date, location, and details of event
H_R	High	Based on at least one contemporary or near contemporary source with no confusion or contradiction regarding date, location, and details of occurrence
M_R	Moderate	Based on at least one secondary source that draws from at least one reliable contemporary or near contemporary source that is not available to us today
P_R	Poor	Based on secondary sources that rely upon other secondary or unknown sources
D_R	Doubtful	False, duplicated, or misinterpreted sources

In case of supporting, independent (dating not relying on historical information) archaeoseismic, or paleoseismic evidence, the reliability of the given event is raised by a degree. For example, an event based on secondary sources that rely upon other secondary or unknown sources but is recorded in supporting archaeoseismic or paleoseismic evidence is graded "moderate" degree instead of "poor"

researchers as an expert group (e.g., Dalkey 1969; Linstone and Turoff 2011), are well worth consulting. Accordingly, we also assigned each of the damaging earthquakes a size degree (see definitions in Table 2).

The compilation described above resulted in three separate lists: (i) reliable earthquakes that in our opinion were most probably associated with the DST and affected Israel and its close surroundings; (ii) questionable earthquakes that should be re-evaluated or ignored; and (iii) earthquakes that probably occurred elsewhere but were erroneously associated with damage in Israel. The complete compilation process is presented in Fig. 3, and the resulting lists appear in Appendices 1–3.

4 Classifying the earthquakes

The compiled list of reliable earthquakes we refer to as "probably occurred" contains 71 earthquakes (electronic supplement, Appendix 1) that were attributed to moderate degree of reliability (symbol M_R) or higher (see definitions in Table 1 and Fig. 2). This threshold reflects the significance we ascribe to the use of contemporary or near contemporary sources in determining the reliability of a report. Of the 71 earthquakes, 32 caused damage to at least one locality within the inspected area (Table 3). The other 39 are all mainshocks that were only felt within the study area, although some of them did cause destruction beyond it.

Although the books of Genesis and Joshua give several descriptions of environmental effects that might be associated with earthquakes (Bentor 1989), the first reliable description that seems to cite a specific earthquake appears at the beginning of the book of Amos (Amos 1.1). It does not specify any destruction or damage but clearly refers to the prophecy of Amos in relation to the rule of kings Uziah of Judea and Yerova'm of Israel, a time frame that we are able nowadays to reconstruct reliably as c. 760 BCE (Ambraseys 2009; Guidoboni et al. 1994). After this event and up to the 31 BCE event, no meaningful quakes are mentioned although further questionable reports do appear (e.g., Zechariah, 14.4-5; Isaiah, 2.19, 21), but to date, we are unable to authenticate any of them. This means nearly 700 years of "silence," although it is reasonable to assume that earthquakes did occur but somehow were not documented. Thus, in order to better assess the recurrence interval of the damaging earthquakes, we focus on the time frame between the 31 BCE and the 1927 AC earthquakes. This leaves us with 31 reliable damaging earthquakes in about 1960 years, that is, one event per ~60 years on average, but not regularly with time. This figure well coincides with Agnon (2014) estimating an event every 65–70 years. Considering only the 20 earthquakes reported also causing casualties (Table 3), indicates a single event per century, again irregularly. Inspecting the last millennium only, we count 21 damaging earthquakes and 14 earthquakes with casualties, i.e., one event per ~45 and ~70 years, respectively. Being aware of the possible incompleteness of the reports, these intervals might be even shorter.

We also identify 41 questionable entries (electronic supplement, Appendix 2) that appear in the existing literature. These are classified into (1) doubtful earthquakes, most probably originating from duplicated records, amalgamations, and erroneous entries, and (2) earthquakes that appear in the literature without indication of their historical sources or that are reported by doubtful sources. Finally, we recognize 46 earthquakes that, in our opinion, are reliable and did occur but were interpreted erroneously as causing damage in Israel (electronic supplement, Appendix 3). This list contains earthquakes that originated along the DST away from

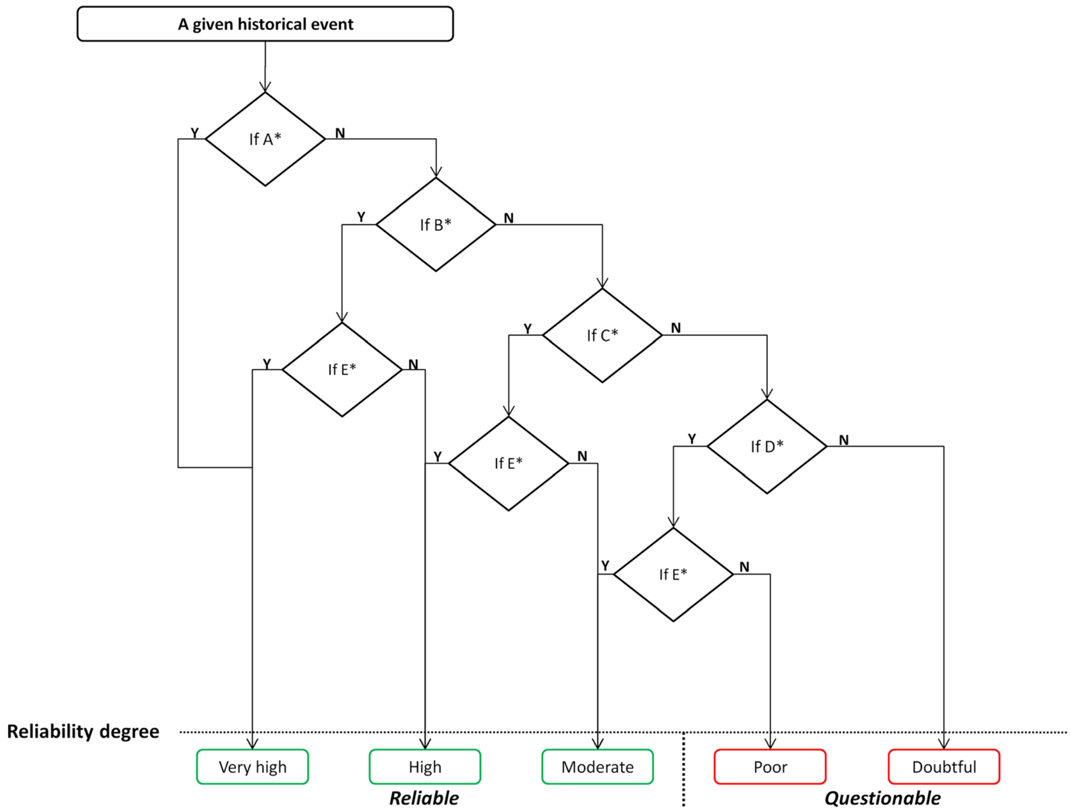

Fig. 2 Decision flow chart for determining the reliability of a given earthquake according to the following criteria: (*A*) At least two contemporary or near contemporary independent sources; (*B*) at least one contemporary or near contemporary source; (*C*) at least one secondary source that draws from at least one reliable contemporary or near contemporary source; (*D*) secondary sources that rely upon other secondary or unknown sources; (*E*) supporting independent (dating not relying on historical information) archaeoseismic or paleoseismic evidence. For full description of the reliability degrees, see Table 1

Israel as well as earthquakes associated with neighboring tectonic sources off the DST system.

Although much effort has been made in screening the historical data, the compiled lists are far from being complete. In case other original historical, archaeological, or paleoseismological evidence is discovered or new interpretations of existing sources are raised, earthquakes should accordingly be added, removed, or shifted between the three lists.

5 Temporal distribution of the earthquakes

Inspecting the documentation of the earthquakes over the past history, we should bear in mind that the Levant is located at the crossroads of Asia, Europe, and Africa, and as such, it has been under several political regimes during the last two millennia. Figure 4 presents the number of reported earthquakes per 100 years along these periods, classified into reliable and doubtful

Table 2 Size of earthquakes classified by degrees, from light (Lht) to great (Grt)

Degree	Size	Symbol	Description	Estimated magnitude
1	Light	Lht	Felt only	$4 \leq M < 4.9$
2	Moderate	Mod	Slight damage to buildings and other structures	$5 \leq M < 5.9$
3	Strong	Str	May cause a lot of damage in very populated areas	$6 \leq M < 6.9$
4	Major	Maj	Major earthquake. Serious damage	$7 \leq M < 7.9$
5	Great	Grt	Great earthquake. Can totally destroy communities near the epicenter	$M \geq 8$

Each degree represents a possible range of magnitudes (adapted from Ambraseys and Jackson 1998)

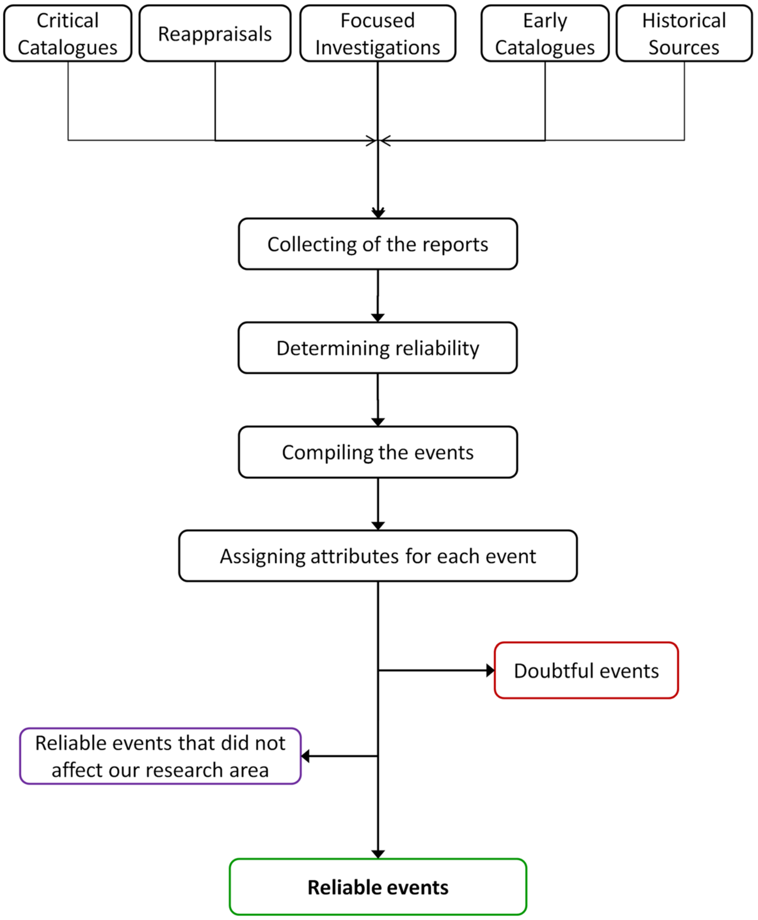

Fig. 3 The complete compilation process. Note the separation of the results into three lists: (1) reliable earthquakes (see also Appendix 1); (2) doubtful earthquakes (Appendix 2); and (3) reliable earthquakes that occur but did not damage any locality within the research area (Appendix 3)

entries. Accordingly, up to the Roman period, the number of doubtful earthquakes is greater than that of the reliable ones. Starting from the Byzantine period, from the fourth century and onwards, the reliable earthquakes constitute ~60 to 80 % of the total reported number. Exceptional is the Mamluk period in which the number of the reliable and the doubtful earthquakes is equal. This period also breaks the expected trend in growth in the total number of reports as we get closer to our present times—it has much fewer reports relative to the preceding Crusader or the following Ottoman periods.

Considering the temporal distribution of the damaging earthquakes (Table 3), we detected three intervals of increased reporting along with a rise in the strength of the earthquakes (Fig. 5): (1) between the fourth and mid-eighth centuries; (2) between the beginning of the eleventh and the end of the thirteenth centuries; and (3) from mid-eighteenth century up to our last inspected historical earthquake of 1927 CE, but this period may not have faded out yet. The first interval includes the earthquakes of 363 and 749 that affected Palestine and the 303, 502, and 551 quakes that affected mainly the southern Lebanese coast. The second period includes the destructive earthquakes of 1033, 1063, 1068, 1157, 1170, 1202, 1212, and 1293, while the third phase that consists of five destructive earthquakes (1759 October and November, 1834, 1837, and 1927) and many other felt ones begins approximately at the first half of the eighteenth century.

5.1 Were there strong earthquakes missed by historians?

We witness cycles of reporting and it raises the question whether these periods reflect the actual seismic activity or they are just an artifact due to incomplete reporting. Figure 6 demonstrates the cumulative number of the reliable felt and damaging earthquakes against the changing regimes in Palestine at the time, and they seem to be in accord, more or less, with each other. This is not

Table 3 List of reliable damaging earthquakes that occurred between c. 760 BCE and 1927 CE and hit Israel and its close surroundings in at least one locality (see Fig. 1)

Date	Reported damaged localities	Estimated magnitude in previous studies	Average magnitude	Size degree	Casualties
c. 760–750 BCE	Jerusalem, Judea	7.8–8.2 (AUS); 8.2 (BM5); 7.3 (BM)	–	–	–
31 early spring BCE	Judea	6–6.5 (KA2); 6.7 (MIG); 6.7 (BM); 7 (BM5); 7 (TUAR)	6.7	Str	M
303 April 2	Tyre	7.1 (BM); 7.1 (MIG after BM)	7.1	Maj	M
363 May 18–19 (night)	Antipatris, Caesarea, Gophna, Hada (unknown), Areopolis, Ashdod, Zippori, A-Salt, Haifa, Jaffa, Baniyas [Israel], Palestine, Tiberias, Bet-Guvrin, Petra, Sebastia, Samaria, Zoar, Bet-She'an, Jerusalem, Nicopolis [Israel], Ashqelon, Lod	6.7 (BM); 6.4 (BM5); 7 (TUAR); 6.7 (MIG after BM)	6.7	Str	M
418	Palestine	6.2 (TUAR); 6.9 (MIG)	6.5	Str	–
502 August 22 night	Akko, Tyre	7 (TUAR); 7 (MIG after BM); 7 (BM)	7.0	Maj	–
551 July 9	Sarafand, Tyre	7.8 (TUAR); Ms 7.2 (DAR); 7.5 (MIG); 7.5 (BM)	7.5	Maj	M
634 September	Jerusalem, Palestine	5.5 (light damage, personal judgment)	5.5	Mod	–
659 June 7	Jericho, St. John, Palestine	6.6 and 6.6 (BM; BM5)	6.6	Str	M
749/Early 750	Jordan River, Palestine, Tabor Mt., Tiberias, Bet-She'an, Khirbet al Karak	$M > 7$ (MAR); 7–7.5 (MIG); 7.3 (BM); 7.3, 7.3 (BM5, BM3); less than 7 (KA2, BEG)	7.2	Maj	M
756 March 9	Jerusalem, Palestine	6 (moderate damage, personal judgment)	6.0	Str	–
1033 December 05 (night)	Jericho, Ramla, Palestine, Baniyas [Israel], Ashqelon, Jerusalem, Akko, Gaza, Nablus, Hebron, el-Badan	7.1 (MIG); 6.7 (BM); 6.7 (BM5)	6.8	Str	M
1063 August	Akko, Tyre	6.5–7 (MIG);	6.7	Str	F
1068 March 18	Palestine, Elat	6.9 (MIG); 6.6–7 (ZIL); $7.0 \le MS \le 7.8$ (AMJA); 7 (BM); Me = 8.1 (GC)	7.3	Maj	M
1068 May 29	Ramla	6 (GC)	6.0	Str	M
1117 June 26	Jerusalem	5.5 (Light damage, personal judgment)	5.5	Mod	–
1157 August 12 (night)	Jerusalem	7–7.5 (MIG); $M > 7$ (AMBR); 7.3 (BM)	7.2	Maj	M
1170 June 29 (0345)	Baniyas [Israel]	7 (MIG); $M > 7$ (AMBR); 6.6 (HOAV); 7.9 (TUAR); $7.0 \le MS \ge 7.8$ (AMJA); 7.5 (BM)	7.3	Maj	M
1202 May 20 (0240)	Akko, Samaria, Tebnine, Vadum-Jakub, Baniyas [Israel], Hunin Castle, Nablus, Tyre, Jerusalem	7.5 (MIG); 7.5 (AMME); 7.6 (HOAV); 6.8 (BM); 6.8 (BM4); $M > 7$ (EMARB); $7.0 \le MS \ge 7.8$ (AMJA)	7.2	Maj	M
1212 May 01	Karak, Elat, St. Catherine, el-Shaubak	6.7 (MIG)	6.7	Str	F
1293 January 11–February 08	Karak, Ramla, Lod, Gaza, Tafilah, Qaqun	6.6 (MIG)	6.6	Str	–
1458 November 16	Ramla, Lod, Hebron, Jerusalem, Karak	6.5 (MIG)	6.5	Str	M
1546 January 14 (afternoon)	Hebron, Maa'yan Elisha, Jericho, St. John, Bethany, Jerusalem, Jordan River, Nablus, Beit-Jala, Bet-Lehem, Batir	$M \sim 6$ (KA2); 7 (TUAR); 6.1 (MIG); 7 (BM); 7.7 (BM5, BM3)	6.6	Str	M
1588 January 04 (13:00)	Elat, St. Catherine	6.7 (MIG)	6.7	Str	–
1643 March 23	Jerusalem	5.5 (light damage, personal judgment)	5.5	Mod	–
1759 October 30 (03:45)	Akko, Quneitra, Benot Ya'aqov Bridge, Sassa, Nazareth, Safed, Tiberias, Nablus	Ms ~ 6.6 (AMBR); 6.5 (BM)	6.5	Str	M

Table 3 (continued)

Date	Reported damaged localities	Estimated magnitude in previous studies	Average magnitude	Size degree	Casualties
1759 November 25 (19:23)	Hula, Deir Hanna, Safed, Nabatiya, Nablus, Sassa, Hermon Mt., Akko, Beit-Jann, Hasbaya, Deir Hanna, Quneitra, Caesarea, Marjuyun, Tiberias, Haifa, el-Rama	7.4 (MIG); MS ~ 7.4 (AMBR, 1989); Ms = 7.4 (AMJA; WECO); 7 ≤ M ≤ 7.2 (GOM); 7.4 (BM)	7.3	Maj	M
1817 March	Jerusalem	5.5 (light damage, personal judgment)	5.5	Mod	–
1834 May 26 (13:00)	Dead Sea Southwest, Caesarea, Jerusalem, Jaffa, Umm al-Rassas, Deir Mar-Saba, Bet-Lehem, Medaba	6.4 (MIG); 6.3 (BM)	6.3	Str	–
1837 January 01 (16:35)	Nabatiya, Qana, el-Fara, el-Salha, Jish, Marun Al-Ras, Bint-Jbeil, Malkiyya, Qadas, Ya'tar, Tebnine, Hunin Castle, Baniyas [Israel], Metula, Zeqqieh, Deir Mimas, el-Khiam, el-Tahta, Deir Mar-Elias, Qaddita, Jibshit, Gaza, Arraba, Attil, Qaqun, Tubas, Ajloon, Nablus, Zeita, Harithiya, Jerusalem, Kfar Bir'im, Lake Tiberias, Hasbaya, Kafr Aqab, Jeresh., Areopolis, Hula, Tarshiha, Dallata, Jaffa, Mrar, Ein-Zeitun, Tyre, Atlit, Meron, Eilabun, Akko, Migdal, Irbid, Reina, Safed, Tiberias, Hadatha, Haifa, Zemah, Kafr Kanna, Kafr, Sabt, Lubiya, Nazereth	7.4 (MIG); *M* > 7 (AM3); MS = 7.4 (WECO); Ms 7.1 (NEM after AM3); 6.7 (BM)	7.1	Maj	M
1839	St. Catherine	5.5 (light damage, personal judgment)	5.5	Mod	–
1927 July 11 (15:04)	Salfit, Soreq River, Nabi-Musa, Abadia, Ajloon, Gaza, Atara,, Meslovia, Lod, Ein-el-Qilt, Ein-Dok, Azraa', Deir, Mar-Saba, Merhavya, Masada, Mrar, Maa'yan Elisha, Moza, Medaba, Migdal, Karak, Kafaringi, En, Harod, Ramat Yishai, Migdal Yava, Qiryat Anavim, Dead, Sea North 1, Tel Aviv, Nablus, Shunam, Refidie, Ramat, Rahel, Dara'a, Ramla, Shiloah Village, Rehovot, Amman, Reina, Rammala, *En-Kerem*, Qalqilya, Kabab, Zora, Safed, Zemah, Petah Tiqwa, Eqron, Afula, Akko, Ein-Fara', Ein Qinya, Ein-Musa, Rosh ha-'Ayin, Be'er-Sheva, Jiftlik, Gimzoo, Gedera, Batir, Beit-Surik, Bet-She'an, Beit-Liqya, Bet-Lehem, Bet-haKerem, Beit-Jimal, Bet-Guvrin, Toov, Mt., Bira, Jisr Magmi, a-Ram, Irbid, A-Salt, el-Hama, Abu Tlul, Nazereth, Jaffa, Yarmouk Fall, Jordan River, Abu-Dis, Abu-Ghosh, Beit-Jala, Zarka Maein, Amman-Jordan Road, Jerusalem-Jericho Road 2, Jerusalem-Jericho Road, Jericho, Holly Mt., Armon ha-Naziv (Jerusalem), Jerusalem, Yalo, Tulkarm, Tiberias, Tabgha, Jaljulya, Hebron, Jenin, Zikhron Yaa'qov, Zarka, Wadi al-Shueib, Mt. Scopus, Olives, Mt., Deir A-Sheikh, Daharia, Bnot-Ya'akov Bridge, Allenby Bridge, Gesher, Jeresh, Michmach Village, Haifa	6.25 (AVN; AVN2); 6.2 (BM2); 6.3 (MIG) = 6.25	6.25	Str	M

Date year of occurrence and whenever possible—also month, day, and hour; *Reported damaged localities* localities damaged within the research area (Fig. 1) that we consider as of moderate (M_R) or higher degree reliability (Table 1; localities that were affected by the listed earthquakes outside our study area are not mentioned); *Estimated magnitude in previous studies* list of studies that estimated the magnitude of the given event. See Appendix 4 for abbreviation reference; *Average magnitude* averaged value of previous magnitude estimations; *Size degree* following categorization made by Ambraseys and Jackson (1998); *Casualties* estimated according to historical reports: *F* few (ten or less), *M* many (more than ten)

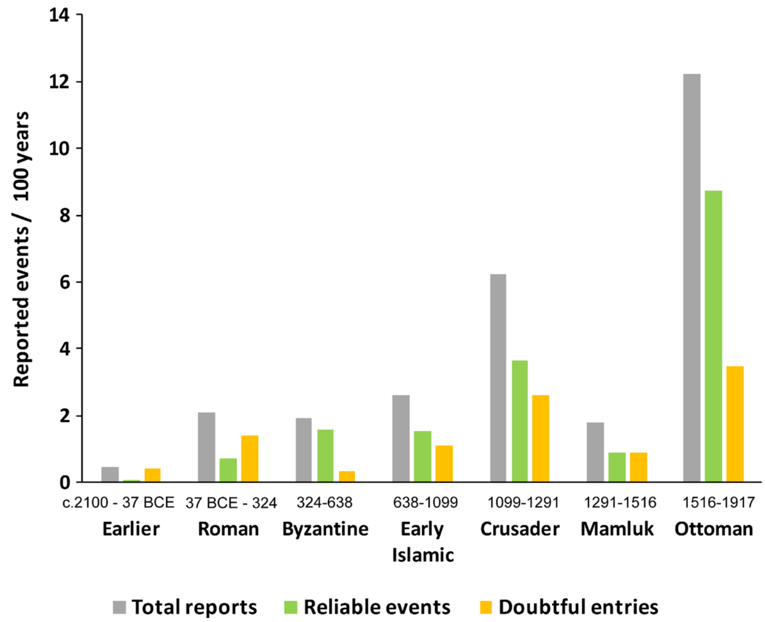

Fig. 4 Average number of reports of felt and damaging earthquakes normalized per 100 years and classified into historical periods and regimes. Note the division into the total number of reports, the reliable (Appendix 1) and the doubtful (Appendix 2) earthquakes

surprising since each of the ruling regimes paid different attention to the land of Palestine.

Prior to the second poorly documented period in the mid-eighteenth century, the Byzantines and their successors, the Umayyads, had a lot of interest in Palestine. However, after the Abassid conquest (750 CE), the political, cultural, and economic center moved eastward to Bagdad (Iraq) and the focus on Palestine significantly decreased (Elad 1978). Towards the end of the eleventh century, the Crusaders defeated the Abbasids and the attention to Palestine rapidly increased again (Praver 1984). The tendency of rising interests again alternated during the Mamluk and the first half of the Ottoman periods. At that time, the land of Palestine was mostly abandoned and thus fewer reports exist. From the mid-eighteenth century, European attention towards the Levant increased, in particular after the journey of Napoleon in 1799 (Ben-Arieh 1970). Then and with greater intensity from the nineteenth century onward with the expansion of media and modernization, the

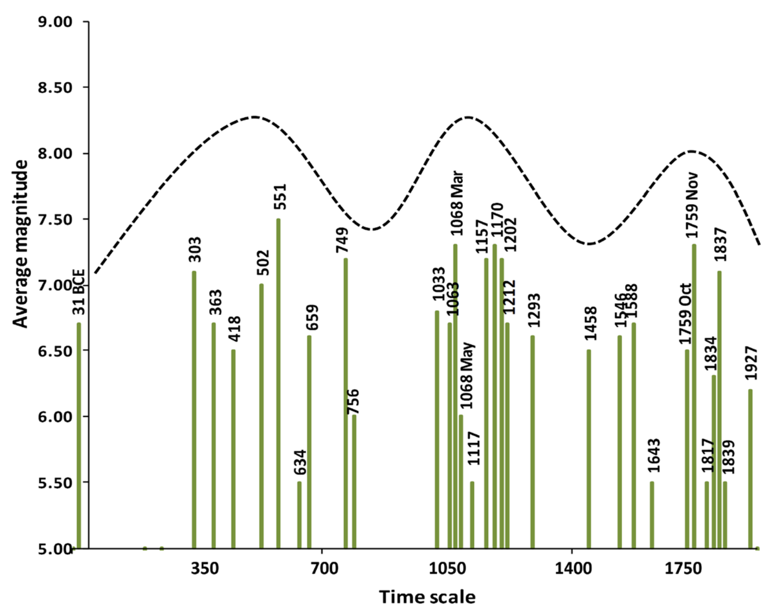

Fig. 5 Temporal distribution of the reliable damaging earthquakes along with the average value of the magnitudes attributed to it in previous studies (Table 3). Note the three alleged cycles of earthquakes in time and size (*dashed line*). The *labels above the bars* denote the year the earthquake occurred

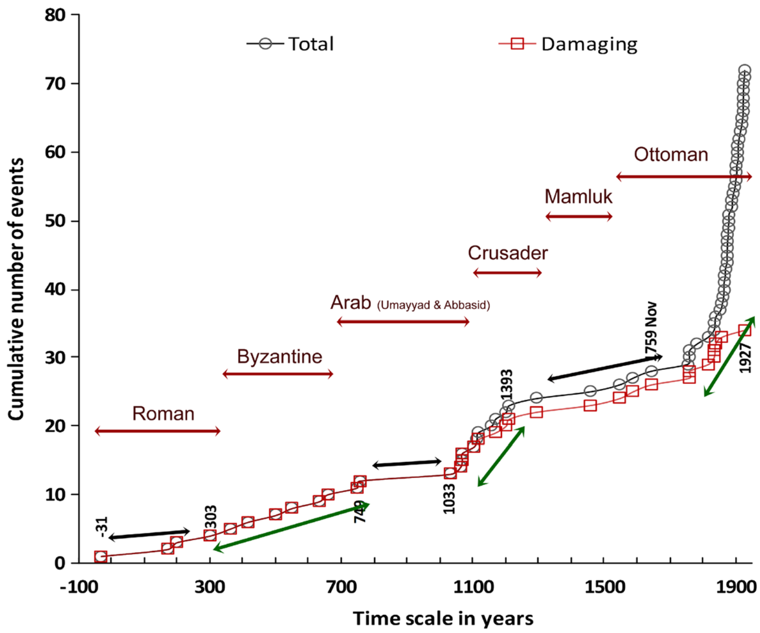

Fig. 6 Cumulative number of the reliable earthquakes that hit Israel and its close surroundings in the last two millennia (foreshocks and aftershocks are excluded). *Red squares and black circles* mark the damaging earthquakes (Table 3) and the cumulative number of damaging and felt earthquakes (Appendix 1) together, respectively. Destructive earthquakes that initiate or end sequences of reporting are labeled. The three cycles of low and increased reporting are demarcated by *black and blue arrows*, respectively, whereas the changing regimes are noted by *brown labels and arrows*

number and quality of the reports rise steeply (Fig. 6). Thus, it is reasonable to assume that when Palestine attracted less attention, the number of reports decreased as well.

Indeed, the modern historical catalogues (Ambraseys 2009; Ambraseys et al. 1994; Guidoboni and Comastri 2005; Guidoboni et al. 1994) do contain reports of considerable seismic activity during the three poorly documented periods. However, the reported damage was not in Palestine but rather in its bordering neighboring countries at the time and thus is not considered in our analysis. During the first period for example, earthquakes occurred in c. 20 BCE in Egypt, 17–15 BCE and 76 CE in Cyprus, and 37 CE, c. 41–54 CE, and 115 CE in northern Syria. The second period, between mid-eighth and mid-eleventh century, includes earthquakes that affected mainly southern Syria (e.g., 813–820 CE, 847 CE, 973 CE, and 991 CE in Syria, 835 CE, 850 CE, and 860 CE in Antioch, and 956 CE in the eastern Mediterranean). The third period, during the Mamluk and the first half of the Ottoman periods, includes earthquakes that damaged Tripoli (1339 CE and c. 1706 CE), Damascus (1399 CE, 1563 CE, 1565 CE, 1618 CE, 1627 CE, and 1712 CE), Baa'lbek (1604 CE, 1606 CE, and 1715 CE), Hama (Syria) in 1626, and Yabrud (Lebanon) in 1705. Since several strong remote earthquakes such as in 1157 and 1170 CE caused damage also in Israel, it is possible that at least some of the earthquakes mentioned above did cause some damage in Palestine but was not documented.

Yet the hiatus or lack of reporting we attribute to the historical share may also, at the same time, support the assertion that there were no damaging earthquakes in Israel during these periods and thus there was nothing to write about. To cope further with this issue, we resort to physical evidence coming from alternative disciplines outside the historical archive, namely, paleo- and archaeo-seismology in our case.

5.2 Complementary sources of information: paleo- and archaeo-seismology

Concentrating on the physical evidence for strong earthquakes that may have affected our research area during the historical period and in particular the "silent" time windows, we find a wealth of evidence. Ken-Tor et al. (2001) examined and correlated eight disturbed sediment layers in the fan deposits of the Ze'elim terrace along the Dead Sea shorelines with historically documented earthquakes (Fig. 1). Migowski et al. (2004) extended the research and inspected the disturbances in the lacustrine sediments of the En-Gedi core and found records of seismic activity, some dated to the poorly documented historical periods. Agnon et al. (2006) followed their study and identified the 1202 CE event. Kagan et al. (2011) compared the former studies with two additional sites in Ze'elim and Ein-Feshkha and pointed towards a quiescent period between the end of the second century and the beginning of the fourth century CE, as well as a high rate of activity in between the ninth and the eleventh centuries. Nonperiodic behavior between the first and seventh centuries CE was also suggested by Wechsler et al. (2014), who trenched the Jordan gorge fault in northern Israel. Outside of Israel and along the northern segments of the DST, Gomez et al. (2001) elaborated on the 1705 CE event, whereas Akyuz et al. (2006) inspected the 859 CE and 1408 CE earthquakes.

The archeoseismic studies of Russell (1985) concluded damage to Avedat and Shivta in the Negev in c. 110–114 CE, whereas Bikai (2002) pointed to a mid-eighth century event and Hayens et al. (2006) concluded damage to Qasr Tilah, south of the Dead Sea, during the earthquake of 873 CE.

5.3 Filling the "historical hiatus?"

Integrating the evidence coming from paleo- and archaeo-seismology as well as historical reports of Palestine does show significant seismic activity during the poorly documented periods in our research area (Table 4). The case of the "137–206" and "165–236" paleoseismic earthquakes suggested by Wechsler et al. (2014) is a good example of the lack of historical reports that could be matched to this physical evidence. Having ruptured the surface, these earthquakes could have been of M6 at least and therefore comparable in size to other historical earthquakes. Thus, these earthquakes do exemplify the incompleteness of the historical share in Palestine during the historically poorly documented periods. We do not reject the possibility of seismic cycles during the last 2000 years, for there still appears to be a quiescent period between the second and fourth centuries and some implications of cycles afterwards. The target of future historically based studies is to further elaborate on these "holes" of reporting, construct an integrated, multi-sourced list of earthquakes, and figure out the form of seismic cycles in Israel during the historical period.

6 Summary and conclusions

This study presents a critical compilation of historical accounts with the aim of constructing a dependable and accurate list of historical earthquakes that damaged or were felt in Israel and its close vicinity. Much effort was made in the systematic collection and organization of the data as well as scrutinizing the authenticity and credibility of each of the historical earthquakes. Overall, we were able to construct a list of 71 reliable earthquakes that caused damage or were felt in Israel

Table 4 Possible seismic activity in Palestine not documented during the "historical hiatus" periods, as well as seismic activity reported outside Israel during these periods

Hiatus during historical periods	Paleoseismic/archaeoseismic evidence for activity during the "historical hiatus"	Historical documentation of earthquakes outside the study area during the "historical hiatus"
31 BCE–303 CE	**KEN**, 33 (5–50) **MIG**, 33; 76; 90; 112; 115; 175 **KAG**, 33; 115 **WEC2**, 33 (392 BCE–91 CE), 130? (137–206), undocumented (165–236) **RUS**, c. 110–114 CE	**AM; GC; GCC:** 20 BCE (Egypt); 19 BCE (Syria); 17–15 BCE and 76 (Cyprus); 37, c. 41–54, 115 (northern Syria)
756 CE–1033 CE	**MIG**, 859; 991; 1032 (?) **KAG**, 847; 859; 873; 956; 991 **HNA**, 873 **AAK**, 859 **BIK**, mid-eighth century	**AM; GC; GCC:** 813–820, 847, 973, and 991 (Syria); 835 and 850, 860 (Antioch); and 956 (eastern Mediterranean)
1293 CE–1759 CE	**MIG**, 1408 (?); 1656; 1712 **KAG**, 1312 **GMD**, 1705 **AAK**, 1408	**AM; GC; GCC:** 1339 and c. 1706 (Tripoli); 1399, 1563, 1565; 1618, 1627, and 1712 (Damascus); 1604, 1606, and 1715 (Baa'lbek); 1626 (Hama); 1705 (Yabrud)

Abbreviations of the data presented in bold: KEN Ken-Tor et al. (2001), *MIG* Migowski et al. (2004), *KAG* Kagan et al. (2011), *WEC2* Wechsler et al. (2014), *HNA* Hayens et al. (2006), *RUS* Russell (1985), *GMD* Gomez et al. (2001), *AAK* Akyuz et al. (2006), *BIK* Bikai (2002), *AM* Ambraseys (2009), *GCC* Guidoboni et al. (1994), *GC* Guidoboni and Comastri (2005) and its close surroundings (Appendix 1). Parallely, we compiled lists of 41 doubtful earthquakes (Appendix 2) as well as 46 earthquakes that did occur elsewhere but were erroneously associated with damage in Israel (Appendix 3). We are aware that these lists might be incomplete and should more original evidence be discovered or a new interpretation of existing sources be raised, earthquakes should be added, removed, or shifted between the lists accordingly.

Of the 71 reliable earthquakes, 31 are considered to have caused damage to at least one locality in Israel between 31 BCE and 1927 CE, that is, a damaging event every ~60 years on average, but not regular with time. An earthquake causing casualties is reported to occur every ~100 years, although not evenly in time. Examining only the last millennium, we count 21 damaging and 14 deadly earthquakes, i.e., one event per ~45 and ~70 years, respectively.

Since the first century CE, we identify three periods of increased reporting: (1) between the fourth and the mid-eighth century; (2) from the beginning of the eleventh to the end of the thirteenth century; and (3) from the end of the eighteenth century to the last entry in 1927, though this period might be extended until today. We find that these peak and low sequences alternate, more or less, in accordance with the changing regimes in Palestine at the time. Nevertheless, paleo- and archaeo-seismological evidence of strong earthquakes, such as the paleoseismic findings of the "137–206" and "165–236" earthquakes for which there is no match during the periods of low historical reporting ("historical hiatus"), suggest the incompleteness of the historical share. Thus, we argue that the apparent cycles of historical reporting do not necessarily reflect the actual pattern of seismicity and further investigation is needed to establish the true nature of the cyclicity of strong earthquakes in this region.

Acknowledgments We highly appreciate the assistance of Alon Moshe and Eliyahu Shara'bi from the Geological Survey of Israel for digitizing and archiving the data. Thanks are also due to Prof. Amikam Elad, Dr. Kate Raphael, and Dr. Katia Cytryn-Silverman from the Hebrew University of Jerusalem, Prof. Shmuel Marco from Tel Aviv University, Dr. Ezra Zilberman and Dr. Tzafrir Levi from the Geological Survey of Israel, and Prof. Thomas Rockwell from the San Diego State University for their useful advice. We also thank Beverly Katz for editing the text. The research was funded by the Ministry of National Infrastructures (Grant no. 210-17-006, no. 29-17-043), the "Amiran" grant of the Hebrew University, the "Rachel Yanait Ben-Zvi" grant from Yad Ben-Zvi, and the Ministry of Science, Technology and Space (Grant no. 10241). We wish to thank also the anonymous reviewers for their highly insightful comments.

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