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Patterns of seismic sequences in the Levant—interpretation of historical seismicity

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Abstract There are historical accounts of about a hundred damaging earthquakes that occurred during the last two millennia in the Levant, in and around the Dead Sea fault system, and about half of which were associated with additional felt shocks. Several modes of earthquake sequences can be distinguished in them: (a) In 46 accounts, only one single event is noted. These are not known from tectonic settings similar to that of the Levant, and may just be a result of incomplete reporting. (b) In four cases, quakes preceded the mainshock by minutes, hours, and up to several weeks—possibly foreshocks. (c) Thirty-five mainshock–aftershock sequences were noted, lasting hours, days, weeks, months, and even more than a year; four of these also have foreshocks. No typical delay time was recognized for the largest or most significant aftershocks: they appeared up to several months later. (d) Six of the reported mainshock–aftershock sequences appeared in a "storm." Another 13 sequences are insufficient to specify further.

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1 Introduction

How strong aftershocks are and how long they last are big concerns after the mainshock. Strong events are infrequent in the Levant, but reports accumulated for more than two millennia do describe them, although not necessarily in modern terms. Earthquakes appear in various temporal and spatial distributions, mostly in dense clusters consisting of one large event, the mainshock, which is usually followed by many smaller ones, the aftershocks. Occasionally, the mainshock is preceded by a single or several foreshocks (preshocks). A sequence in which there is no predominant single earthquake is a swarm, and a successive occurrence of several mainshock–aftershock sequences is a second kind of a swarm or a seismic storm (e.g., Kisslinger 1996; Utsu 1961, 2002, and references therein). There is no universal definition or procedure for classifying seismic sequences or determining the exact nature of any single earthquake in a cluster. Most researchers refer to aftershocks as events immediately following a large earthquake within a distance of one to two rupture lengths from it and at a rate of occurrence that is higher than the

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background seismicity of that area prior to the mainshock. Practically, however, aftershocks are defined ad-hoc, according to the scope of the given study (Utsu 1961, 2002).

In general, the stronger the mainshock, the larger and more numerous the aftershocks are and the longer their period of occurrence is, even up to several years. These short-term relations have traditionally been expressed by three empirical scaling laws, namely: (1) the frequency–magnitude power law relation (Gutenberg and Richter 1954); (2) the average size of the largest aftershock is ~1.2 magnitude units smaller than the mainshock (Båth 1965), but this may vary widely from 0.3 to three units or more and cannot be predicted; and (3) the frequency of aftershock occurrence decays at a rate proportional to t^{-p}, where t is the time after the mainshock and $p \sim 1$ (Omori 1894). The generalized Omori law attempts to incorporate all three relations into one (Shcherbakov et al. 2004). The timing of the largest aftershocks, delaying days, weeks, and even months, cannot be predicted (e.g., Hough and Jones 1997). Moreover, often, an earthquake sequence triggers a new sequence nearby in which the mainshock is sometimes even stronger than the previous one. This might be explained by a stress-triggering effect, but so far, its timing is not predictable either. The area affected by an aftershock occurrence is relative to the size of the mainshock (e.g., Utsu 2002), in accordance with the notion that the length of the seismogenic rupture scales with the magnitude of the mainshock.

Much reliable historical data of seismic sequences in the Levant has been gathered in recent times. All this information, which extends over a period paralleled only in a few other areas worldwide, has not yet been analyzed. Although limited and partial, evaluation of these data could be more productive than waiting for future events, and may give us greater insight into the seismogenic nature of the Dead Sea fault system (DSFS), the major seismotectonic element in the Levant. Therefore, this study focuses on typifying the sequence of events that preceded and followed strong historical earthquakes in and around the DSFS. How the list of damaging earthquakes was compiled is explained and the patterns of seismicity that were possible to identify are discussed.

2 Historical seismicity

There are several sources that report or indicate past earthquakes; each has advantages and limitations, and none lack uncertainties. Most common are historical documentations, paleoseismic evidence, and archaeoseismic findings; the former constitute the main body of information that details patterns of the past seismicity. Although written in various languages from many places and cultures, described in many different ways and points of view, and expressing political and religious views, these are the most credible sources available. Bringing all the events together to a common denominator in one language and in seismological terms is essential in order to build as unified and complete a catalogue as possible, but this is not a trivial matter. This aim has already been targeted by several modern investigators (e.g., Ambraseys, Guidoboni, Karcz), and this work is based on their studies.

2.1 Limitations of the historical data

The notion that many catalogues of historical earthquakes contain erroneous entries has already been raised by several researchers (e.g., Ambraseys et al. 2002; Guidoboni and Comastri 2005; Karcz 2004) and that of the Levant is of no exception. They demonstrated that several of the events noted in the published literature originated from misprinting, misinterpretation, duplication, etc., and, in fact, are false. Their critical studies were able to filter out many of the questionable events and verify the record of many significant earthquakes. Overall, it seems that sufficient reliable information has already been accumulated, enabling the reconstruction of a dependable and comprehensive list of earthquakes that originated in the Levant area. The evaluation made here is based upon these works.

The main limitation of the historical reports is the subjective description, which does not detail the source parameters. Moreover, parameterization of the past accounts is also an unavoidable subjective process involving considerable uncertainties. In contrast to modern instrumental recording, where the threshold of detection is more or less known and completeness of the list can be defined, it is not possible to know which category or type of event is missing from the historical record. Hence, the reported earthquakes are probably a partial accounting of the actual occurrences. It is therefore important to mark out a clear line between the original story and the evaluated parameters. It is not even possible to quantify the uncertainty associated with the evaluation because it is a result of personal judgment rather than of a measuring procedure. Therefore, one should be aware of the unknowns typical to the historical material, and realize how far an interpretation can go. The uncertainties associated with each of the source parameters are discussed below.

2.2 Sources of data

In general, the studies that relied directly on contemporary and primary sources and extracted an accurate description of an event with minimal necessary interpretation (e.g., translation, historical perspective, etc.) are the more reliable. Studies that provide detailed and accurate referencing to the primary sources are also dependable. On the other hand, the authenticity of events that appear in lists with no reference to the original accounts should be doubted. Several in-depth investigations (e.g., Ambraseys et al. 2002; Guidoboni et al. 1994; Karcz 1987, 2004; Karcz and Lom 1987) examined most of the existing catalogues, pointed out their advantages and shortcomings, and stressed the caution needed in studying their information. Following these works, it was possible to prioritize the available catalogues, compile lists of events whose authenticity could be well verified, and point to the doubtful events. There was no attempt here to reexamine the original sources, and so, the present work relies on comparing and evaluating different studies that rely on primary accounts, while not escaping their uncertainties. Nevertheless, as new data are discovered and better interpretation offered, there will be a need to reexamine the original sources and to reevaluate the reliability of the present listings.

Most of the information regarding events around the Mediterranean up to the fifteenth century A.D. has already been collected, compiled, analyzed, and presented in the catalogues of Ambraseys et al. (1994), Guidoboni et al. (1994), and Guidoboni and Comastri (2005). Later events, however, have not yet been analyzed in a similarly systematic approach. Other invaluable reviews were published by Ambraseys (1989, 2004), Ambraseys and Finkel (1995), Poirier and Taher (1980), and others. Reappraisals by Ambraseys (2005a, b), Ambraseys and White (1997), and Karcz (2004), as well as focused investigation on specific events (e.g., Ambraseys and Barazangi 1989; Ambraseys and Karcz 1992; Ambraseys and Melville 1988; Darawcheh et al. 2000; Guidoboni et al. 2004a, b), are also available. Many other lists draw from both primary and secondary sources (e.g., Amiran et al. 1994; Ben-Menahem 1991; Khair et al. 2000; Plassard and Kogoj 1968; Sbeinati et al. 2004), and they are referred to after cross correlating their data with the primary sources.

There have been far fewer direct field investigations of past earthquakes, and these may provide a better estimate of the rupture zone, magnitude, and mechanism (e.g., Akyuz et al. 2006; Amit et al. 1999; Daëron et al. 2005, 2007; Elias et al. 2007; Ellenblum et al. 1998; Gomez et al. 2001, 2003; Klinger et al. 2000; Marco et al. 1997, 2003, 2005; Meghraoui et al. 2003; Neimi et al. 2001; Nemer and Meghraoui 2006; Reches and Hoexter 1981; Zilberman et al. 2004, 2005). Attributing source parameters to historical events, however, is not a straightforward process. In most cases, field evidence is associated with the candidate from a known list of historical earthquakes that best fits it. Taking the paleoseismic data back to prove and support the existence of the selected historical event should be done with care because, for example, this event may not have been reported at all.

Other seismogenic effects, such as lacustrine seismites and deformed layers from the Dead Sea basin (Marco et al. 1996; Enzel et al. 2000; Ken-Tor et al. 2001; Migowski et al. 2004), may attest to the strength of shaking or to the distance from the source of many of the historical events. These natural features may also record strong earthquakes that were possibly missed, ignored, lost, or not reported in the course of history. Similarly, archaeoseismological evidence also contains useful information. These sources are limited in pointing to the exact date, source area, and strength of the event, yet they provide invaluable information that certainly should be addressed in future studies (Ambraseys 2006a; Karcz et al. 1977).

3 List of events

On the whole, all the events reported by historical sources to have occurred in the Levant and to have damaged at least one site were considered (Appendix A). Events inferred from seismites or archaeoseismic findings were not considered in this study. The collected data were correlated with the existing literature in order to validate or question each of the events. In most cases, studies that relied on primary sources and extracted the original description more accurately enabled distinguishing real events from questionable ones. In cases still unresolved, personal judgment was counted on. This resulted in a compact, yet more reliable list of earthquakes than if every possible event were listed. Clearly, this is not an error-free evaluation, and the list will need to be updated if new sources are discovered and better interpretations are offered.

As the nature of the DSFS was focused on, and given the limited resolution of the historical data, all the events that affected the Levant and that seemed to originate from this source were listed. For example, Elias et al. (2007) suggested that the damage in the coastal cities of Lebanon caused by the earthquake of 551 A.D. was due to the rupture of the offshore Mount Lebanon thrust, and that this thrust belongs to the DSFS system. This implies that, in addition to shear events that originated from the Dead Sea Transform and its parallel and branching faults, thrusts and normal faults were related to as well. On the other hand, events reported to affect nearby regions that belong to another seismotectonic regime were excluded, such as, for example, the event of 1222 from Cyprus (Guidoboni and Comastri 2005), that of 1568 from the Mediterranean west of the Syrian coast (Ambraseys and Finkel 1995), and the 1269 earthquake in Cilicia (Guidoboni and Comastri 2005), which may have all originated from the Cypriot Arc. Similarly, the 1114 sequence may have come from the East Anatolian Fault zone (Ambraseys 2004); the 749 event in Mesopotamia (Karcz 2004) seems to be closer to the Arabia–Anatolia collision zone; and earthquakes in Egypt, which are clearly west of the DSFS, resulted from structures such as the Suez Rift and others.

There is no consistent or systematic way to determine the location and strength of historical earthquakes, and they are mainly based on felt shocks and damage reports. Several quantitative methods were developed in cases where a good set of data is available (e.g., Shebalin 1973; Bakun and Wentworth 1997; Gasperini et al. 1999; Sirovich and Pettenati 2001), as well as empirical intensity–magnitude relations (e.g., felt area–magnitude, by Frankel 1994). In addition, evaluation of paleo- and archaeoseismological data, in the context of the areal neotectonics, can help in constraining the source parameters. Running these procedures, however, requires special attention and is beyond the scope of this work. Nonetheless, the preliminary estimates already available in the existing literature suit the purpose of this study. The present list (Appendix A) shows the date of occurrence of each of the events, locality of the most severely affected areas, estimated size class, sources of information, and the pattern of seismicity, as explained herein.

3.1 Origin time

As trivial as this parameter may be, determining it is not at all simple. For example, the exceptionally intense seismic sequences along the northern Dead Sea transform during the twelfth century were extensively studied by Ambraseys (2004) and Guidoboni et al. (2004a, b). Basically, the two researchers drew from more or less the same original contemporaneous sources, but each arrived at different origin times (by days) of what seems to be the same sequence of events.

In general, origin times were taken from studies that carefully examined the given event and addressed errors in the published literature, because misinterpretation may simply have resulted in duplicating that event and inflating the actual list. In cases that were hard to resolve, the best estimate, in our opinion, was adopted. Still, some uncertainties remained, thus making the present interpretation only preliminary to future resolution of uncertainties. The selected events are cited by their time of occurrence and, to the extent known, by the year, month, day, part of the day, hour, and minute.

3.2 Location of the historical earthquakes

Ideally, the center of the most severely damaged area should coincide with the rupture zone of the given earthquake. However, this was proved to be too simplistic an assumption, and in fact, the relationship is much more complicated. The populated area is not homogeneously scattered around the earthquake epicenter or in the area of interest, the spread of the seismic waves is not symmetric (e.g., velocity structure, focal mechanism, directivity), site effects dramatically vary from place to place, and historical reports in most cases are biased and incomplete. Locating a historical event is, therefore, a dependent procedure and, if not carefully done, may result in duplicating an event, moving it to a different area, or borrowing it from elsewhere (e.g., Karcz 2004).

The original reports vary from referring generally to the affected area, pointing to one site only, and listing (all?) the affected localities and structures. Single sites might have been mentioned for being the most severely affected; those only known to be affected; most important or of special interest for the reporter; and, in some cases, the site where the earthquake was felt by the reporter. In some cases, it is possible to delineate the most severely affected area (I_0), while in others, where only a partial coverage of the affected zone was available, only the site of maximal damage (Imax) can be identified. The last is possibly the closest to the epicenter, but the seismogenic source could well be far away. Some localities, such as Antioch or Jerusalem, were mentioned to have been hit again and again, possibly due to being important cultural, political, and religious centers. For the very same reason, we may assume that other less important sites might have just been neglected.

Given the above constraints, the simplest and least biased preliminary interpretation would be to assume that the center of the most severely damaged zone represents the seismic epicenter. The estimates given here regarding the center of the affected area are adopted mainly from previous studies and presented in Appendix A. Future work is needed to determine more accurately the intensities of all damaged localities and calculate the macrocenter (intensity center or barycenter) or the epicenter.

3.3 Size of the historical earthquakes

Obviously, the original reports do not contain full coverage of the damage and effects and there is no simple calibrated damage–intensity relationship available. With the present understanding, where a magnitude of historical seismicity is mainly based on macroseismic data rather than on measurable parameters, it is impossible to assign a clear magnitude.

The descriptions, both full and partial, vary from place to place, time to time, and event to event. Therefore, some large events may be under-reported and listed as moderate. Similarly, inflated reports of moderate earthquakes, some closely timed moderate events, a mainshock followed by an intensive aftershock sequence, an earthquake swarm with several strong events, and a sequence of strong events may all be described as one large earthquake. Moreover, factors such as site effects and directivity that increase damage are not considered either.

Given such large uncertainties, it was possible only to estimate the size of the historical event rather than assign definite or discrete magnitude grades of modern scales. The present estimations were adopted from historical, geological, and paleoseismological studies and, if not available, made by personal judgment. They are more or less correlated with the broad categories suggested by Ambraseys and Jackson (1998) as follows: V, very large event ($Ms \geq 7.8$); L, large ($7.8 > Ms \geq 7.0$); M, moderate ($7.0 > Ms \geq 6.0$); and S, small ($6.0 \geq Ms$).

Minimal magnitudes of historical earthquakes are also important, mainly for the study of small events such as fore- and aftershocks. Experience shows that the lowest magnitude of felt earthquakes is on the order of M3.5–4, given that the observer is near to the source. As distance from the epicenter increases, the threshold of felt earthquakes increases as well.

3.4 Is the historical list reliable?

The shortcomings presented here are inherent properties of the historical data and may strongly affect the quantification of aftershock activity. Future studies may reveal new historical sources and narrow uncertainties, but nevertheless are not expected to parameterize descriptive information. Thus, in our opinion, it is important to extract the most out of the historical data cautiously and limit the conclusions accordingly, rather than to ignore their potential.

Regarding the type of sequence activity, it all depends on whether the reporter intuitively grouped several events together and conveyed the impression that this was a seismic sequence. The information is given in terms of relative spatial and temporal relations between each of the events in the given sequence, rather than the exact source parameters. In this sense, the accuracy of the origin time is not essential as long as the event is not duplicated; the exact location is not critical either because the simultaneous occurrence of strong seismic sequences in nearby regions is rare or it would be reasonable to assume that all the felt events should be related to the same area. The magnitude, however, is a significant parameter for it determines whether a selected event is a fore-, main-, or aftershock and, thus, typifies the nature of the seismic sequence. Of course, even though detailed parameters are much preferred, that it is generally possible to interpret the historical data in terms of modern seismology means that there is still a realistic core. Perhaps the most important deficiency is that the historical data available are only a part of what really happened.

4 Synthesis—the historical sequences

Altogether, there were close to a hundred damaging earthquakes in and around the DSFS area that were identified since about the second century B.C. up to the end of the nineteenth century A.D. (Appendix A). Modern, twentieth century felt fore- and aftershock activities were added for comparison. References to all the events and quotations mentioned hereafter are listed in the following tables and appendices.

Looking at the spatial and temporal appearance of the earthquakes listed, in most cases, a single earthquake is mentioned, but interestingly enough, there are reports of sequences of several events, as well as of lighter shocks that followed the strongest one. Yet, so far, the cumulative behavior of these sequences has been overlooked. Here, these sequences are arranged firstly in a table that presents the duration they lasted (Table 1). A noted event, possibly the largest fore- or aftershock, is also listed by the time it preceded or followed the mainshock. Secondly, the various sequences are classified in order to identify characteristic patterns (Appendix A) and compare them with modern sequences (Appendix B). The total number of sequences per duration and the number of noted aftershocks per time delay after the mainshock are presented in the summary of Table 1 and in histograms in Figs. 1 and 3. Historical patterns with no modern parallels are also discussed. Interestingly, people related to the strength and length of the shaking of the main event, and these patterns are classified as well.

4.1 Single events

Many reports describe single earthquakes with no mention of any other shocks (Table 2). Present-day single events in the DSFS area are mostly of small magnitude, and as seismic networks improve, aftershocks are detected for even smaller events. On the other hand, almost all modern large earthquakes that occurred in tectonic settings similar to that of the DSFS were associated with aftershocks. It is therefore reasonable to assume that large historical earthquakes were also associated with aftershocks, but the reports skipped these. Therefore, in our opinion, the recounting of large (damaging) historical earthquakes as single events is due to incomplete reporting. All together, 46 single events were counted, five of which occurred in the years B.C. and 41 in those A.D.

Table 1 Duration of inferred foreshock and aftershock sequences

Foreshocks				Main event		Aftershocks																								
Wks	Days	Hours	Min	Size	Date	Hours	Days						Weeks			Months														Unk
							1	2	3	4	5	6	1	2	3	1	40d	2	3	4	5	6	7	8	9	10	11	12	>12	
				M	341				+																			⊗		
				M–L	363	•, 6, ⊗																								
				S–M	458																									?
				M	526							?																⊗	18?	
				M	528	1,⊗																								
				S	587–8																									?
				S–M	634											⊗														
				M	713												⊗													
				M–L	746												⊗													
				M	991											⊗														
				M–L	1033	•, ∼6	•	•					⊗																	
				L	1068 03	•,2.5,⊗																								
				M	1091																									?
				M–L	1138–9	•			•					•										•,⊗						
				S	1156 09	+	+							⊗																
				S–M	1156 10	+				+	+		+	+	+	+		⊗												
				S–M	1156 12	⊗																								
				S–M	1157 04		+	⊗																						
				M	1157 07	⊗																								
				L	1157 08	+				+			+		+			+	+	+	+				+			+	21, ⊗	
				L	1170															⊗										
				L	1202	+				⊗																				
		•		M	1212																							⊗		
				S	1259																									?
				M–L	1344											⊗														
9, •				M–L	1404									+							⊗									
				M	1546													•		•,⊗										
		•		M	1705	+										⊗														
				M	1759 10											⊗, ?														
				L	1759 11	•							•		•	•									⊗					

Table 1 (continued)

Foreshocks				Main event		Aftershocks																								
Wks	Days	Hours	Min	Size	Date	Hours	Days						Weeks			Months														Unk
							1	2	3	4	5	6	1	2	3	1	40d	2	3	4	5	6	7	8	9	10	11	12	>12	
				L	1796													⊗												
+	+		30,•	L	1822	+																							30, ⊗	
				S–M	1834								⊗																	
				M–L	1837									•	•						•,⊗									
				L	1872											+		+								⊗				
Modern events																														
				M	1927		+					+	+	+	+	+				+	+	•		+				+	38? ⊗	
				S	1956																				⊗					
+	+			M	1969																	•							21, ⊗	
+	+	+		S	1983								•												⊗					
				S	1984									⊗																
		+	12,•	S	1993																⊗									
				L	1995														•										24, ⊗	
				S	2004			•														•⊗								
Summary of the duration of historical sequences (⊗)																														
2	–	2	–	36 sequences		5	–	1	–	1	–	–	2	1	–	5	2	2	–	2	2	–	–	1	1	1	–	3	2	4
Summary of the time delay of the noted aftershocks in historical sequences (•)																														
1	–	2	1	4 foreshock and 7 aftershock		5	1	1	1	–	–	–	1	2	2	1	–	1	–	1	1	–	–	1	–	–	–	–	–	–

Information on the historical and modern events relate to felt events ($M > 3.5$–4), except 1956, where the minimal threshold is not known, and 1984, for which the recorded events were possibly of $2 < M < 3$; see details in Appendices A and B.

+ Reported activity; • noted event, possibly the largest fore- or aftershock; ⊗ reported or inferred end of sequence; *Wks* weeks; *Min* minutes; *Size* estimated magnitude, see Appendix A for explanation; *Unk* unknown; 40*d* 40 days

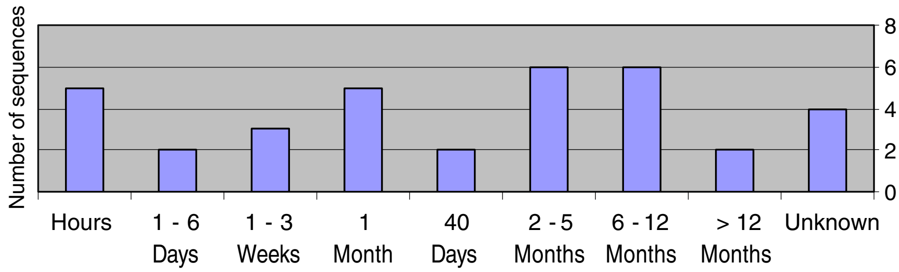

Fig. 1 Duration of historical aftershock sequences in the Levant, in and around the DSFS (simplified from Table 1)

4.2 Mainshocks

Many descriptions relate to the strength and length of the shaking of the main event, whether reported as a single event or as part of a sequence.

4.2.1 Duration of the mainshock

Nine descriptions tell how long the shaking lasted and, in a few cases, even distinguish phases within the given event, and it was possible to arrange these by seconds, minutes, and even hours (Table 3). Modern earthquakes that "lasted for two and a half hours," such as those reported for March 18, 1068, are not known. Strong motion of earthquakes on the order of M7 may last several tens of seconds, and even the 2004, M9.2 Sumatra earthquake lasted no more than about 10 min. Presumably, the immediate strong aftershocks were thought of as part of the mainshock and gave the people at the time the impression that the earthquake lasted for hours.

Some reports describe a very close sequence of shocks, such as on January 3, 1344: "Two shocks in close sequence." It is not possible to further classify these as a large, shortly delayed aftershock, or even speculate these as subevents. Nevertheless, this is invaluable information since it tells us that some destructive earthquakes may have started "low" and intensified in later stages (e.g., 1872), thus giving the people short but precious time to evacuate into the open.

4.2.2 Strength of shaking

Ten reports described earthquakes "such as has not occurred before" (e.g., 31 B.C.) and the great impact of the shaking (Table 4). No tools are available to quantify terms such as "tremendous shaking" or "mighty earthquake"; these just tell us that this was the impression people got at the time. Even today, in places where a great earthquake is inevitable, the timing and shaking will most probably be a complete surprise. Yet, when the reports tell that "everything had been tossed," it is reasonable to assume that the motion was considerably strong. This, of course, may also result from being at or near the seismogenic source or even from a significant site effect.

The strongest shake may arrive right at the start of an event (e.g., 1796 A.D.) or in later phases (e.g., 1872). Whenever the strong shaking appears,

Table 2 Historical events reported as a single earthquake

Origin time of single historical events	
B.C.:	760–750, mid-second century, February 21, 148 (or 130), c. (69–) 65, 31.
A.D.:	March 23, 37; c. 47; December 13, 115; c. 127–130; 303 or 304; 348 or 349; 450–457; August 22,502; July 9, 551; c. 570; 580 or 581; 601–602; 634; June 659; September 659–August 660; June 12, 853–June 1, 854; 972; November 10, 1002–October 29, 1003; August 21, 1042–August 9, 1043; May 29, 1068; June 26, 1117; August 17 1140–August 6, 1141; c. 1150; August 1163; October 13, 1284; March 8, 1287; March 22, 1287; January 11–February 8, 1293; January 13–February 11, 1339; April 9–May 8, 1407; December 29, 1408; November 8 or 16, 1458; March 9, 1537; February 1557; September 13, 1563; January 4, 1588; January 21, 1626; March 1719; 1722–1723; April 15, 1726; September 25, 1738

Details and references in Appendix A

Table 3 Durations of the mainshock

Duration	Descriptions	Comments
Seconds to a minute	January 4, 1588 (AMA): A strong shock of earthquake was felt in Cairo, where it was of long duration	Duration can be correlative to magnitude
	April 26, 1796 (AF2): Lasted with intermissions for about 1 min	
	August 13, 1822 (Am3): The main shock happened in three phases lasting altogether 40 s	
	January 1, 1837 (Am4): The main shock lasted between 10 and 30 s	
Minutes to hours	November 29, 528 (GCT): The earthquake... lasted for 1 h	Can be a succession of strong aftershocks immediately after the mainshock
	November 24, 847 (GCT, one of the events): Dreadful earthquake, lasted for 3 h	
	March 18, 1068 (GC): An earthquake... lasted for two and a half hours	
	August 13, 1822 (Am3): ...the main shock was followed for about 8 min by successive shocks, about 30 in all, each of short duration but of damaging intensity	
Number of shocks	January 3, 1344 (GC): Two shocks in close sequence	Can be subevents, triggered events or immediate strong aftershocks
	January 1, 1837 (Am4): The earthquake consisted of two distinct shocks about 5 min apart	
	April 3, 1872 (Am3): Between the first shock and the latter part of destructive shaking, many people managed to run out of their houses into the open	

References abbreviations in Appendix D

and as trivial as it can be in our eyes, the historical reports clearly tell that the destruction was associated with the strong shakings, and this, in fact, is the essence of antiseismic engineering.

4.3 Foreshocks

Only four accounts report on earthquakes that preceded the main event by several minutes to a few months (Table 5), all of which also contained aftershocks. There could also have been foreshocks that occurred a few minutes or seconds before the mainshock, but the historical data do not distinguish them from what happened during the main event.

The reports do not tell if people did perceive in real time that a strong earthquake was to come, but clearly say that they felt worried: "... a strong shock was felt in the region: this caused considerable concern and warned the people of

Table 4 Strength of main shaking

The shaking	Descriptions
Strength of shaking	31 B.C. (GCT): Such as has not occurred before
	December 13, 115 (GCT): Unusually powerful, tremendous quaking
	341 (GCT): Most violent earthquake
	April 3, 1872 (Am3): Between the first shock and the latter part of destructive shaking, many people managed to run out of their houses into the open
Effects	May 18–19, 363 (GCT): A mighty earthquake tore up the stones of the old foundation of the temple
	July 9, 551 (GCT): Mountains were uprooted and violently split open
	December 5, 1033 (GCT): "We have seen the mountains shake, leap like stags, their stones broken into pieces, the hillocks swaying to and fro, and the trees bending down... In some places the waters in the cisterns reached the brim..."
Strong motion?	September 13–14, 458 (GCT): Everything had been tossed and terribly shaken
	May 20/29, 526 (GCT): Foundations of buildings were struck by thunderbolts, thrown up, lifted, and collapsed
	April 26, 1796 (Am3): In Latakia so violent that almost everything collapsed with the first shock

References abbreviations in Appendix D

Table 5 Possible historical foreshocks

Time before the main event	Descriptions
Minutes	August 13, 1822, 20:40 (Am3): . . . At 8 h 10 m pm on August 13, a strong shock was felt in the region: this caused considerable concern and warned the people of what was to follow. The main shock happened 30 min later
Hours	749 (or 750, or March 9, 757) (GCT): There was a tremor at night. . . and everyone had gone out of the city to pray at the temple. . . there was a sudden tremor and the temple collapsed on top of them. . . [a]
	May 1, 1212 (GC): Foreshock at sunset 30.4, mainshock at dawn 1.5
	November 24, 1705 (AF1, SDM): Three main different sized shocks happened on Tuesday night: The first caused general panic, the second was the strongest, causing the damage
	Modern example: August 3, 1993, 12:43 (a swarm or a sequence) (Ho, GII): The largest event ($M_L = 5.8$) appeared third, 2.5 h after the first one ($M_L = 3.5$), and 12 min after the second one ($M_L = 4.8$). The second largest event ($M_L = 5.6$) was recorded 4.5 h after the sequence started
Days, a few weeks	August 13, 1822, 20:40 (Am3): Slight shocks, began on August 5 and continued intermittently until August 12. . .
	Modern example: March 31, 1969, 7:16 (Suez Rift) (BMA, Sa1, Ke): Preceded 2 weeks before by 35 large foreshocks, including 3 $M_L \geq 4$
	February 3, 1983, 23:30 (Gulf of Aqaba): Preceded 2 weeks before the strongest event in the swarm
Months	February 20, 1404 (GC): Before that, there had been an earthquake (December 18, 1403), at midday

References abbreviations in Appendix D

[a]This event occurred in Mesopotamia, outside the present study area, but is mentioned here as an example

what was to follow. The main shock happened 30 min later. . . ” (in 1822) or “The first caused general panic, the second was the strongest, causing the damage” (1705). In the case of 198–199 B.C., although there is no explicit mention of a preceding event, people realized the worst was to come and reacted: “. . . but the number of victims was limited, because it did not happen in a single shock.” Different instincts, unfortunately, were not so seismic-proof: “There was a tremor at night. . . and everyone had gone out of the city to pray at the temple. . . there was a sudden tremor and the temple collapsed on top of them. . . ” (749, in Mesopotamia, Guidoboni and Comastri 2005).

Identifying foreshocks in real time is extremely important because this is a true alarm, and it seems that, somehow (fear, intuition, cumulative experience?), people realized that, although they did not always react right. Omitting the 46 reports of single events that are believed to be incomplete and the 13 unresolved clusters, about a ninth (four out of 35) of the sequences were preceded by foreshocks! Obviously, this is of great importance in early warning evaluation and needs further examination.

4.4 Aftershocks

The appearance of secondary shocks that closely followed the main shock is common in historical reports, mostly from the second millennium A.D., and refers to about a third (35 of 94, six of which appeared in a storm, see Section 4.5) of the listed events. Former reports are indirect, and the occurrence of aftershocks is inferred from the reaction of the people at the time: “Danger for three days” (341 A.D.) or “the inhabitants forced to take refuge in the desert, where they stayed for forty days” (746 A.D.).

4.4.1 Duration of aftershock sequences

The reported aftershocks are classified by the time they lasted after the main shock, in hours, days, months, etc. (Table 6). Large earthquakes ($M > \sim 6$) are known to produce intensive aftershock sequences, which may last

Table 6 Duration of sequences that followed historical earthquakes

Duration	Descriptions
Several hours	363 (GCT): Event took place on the third hour, and partly on the ninth hour of the night
	March 18, 1068, 8:30 (GC): The earthquake was followed by two more shocks within the same period (two and a half hours?)
Several days	December 5, 1033 (GC): For 8 days, the mind has not been satisfied and the soul is not at rest. On that night (the earth) shook again (December 5–6, 1033); on Friday (December 6, 1033), as well as on the following night (December 6–7, 1033), the shocks recurred
	May 20, 1202 (AM1): The major earthquake was followed by brief shocks towards noon on the same day, which were slightly felt in Cairo... earthquake at Hamat on May 21 was followed by another shock in the afternoon. Altogether, the shocks lasted for 4 days
	May 26, 1834 (AAT): Strong, many aftershocks during 10 days
A month	September 634 (GCT): An earthquake with a series of tremors lasted for a month
	April 5, 991 (GCT): The shocks went on repeatedly till... (May 5) in the same year
	January 3, 1344 (GC): Two shocks in close sequence. In relation to the worst affected area, it is recorded that the places concerned were abandoned by their inhabitants for more than a month
	November 24, 1705 (AF1, SDM): Light shocks continued to be felt till Ramadan (1 month)
	October 30, 1759 (AB): Series of strong aftershocks (time not specified), some of which were felt as far as Aleppo, that added to the damage. Note that, after a month, this event was followed by the November 25, 1759, strong earthquake
40 days	February 28/March 10, 713 (GCT): Earthquakes began throughout the world and lasted for 40 days
	January 18, 746 (GCT): A strong earthquake in Syria... the inhabitants forced to take refuge in the desert, where they stayed for 40 days...
Several months to a year	341 (GCT): Danger for 3 days, shocks for a whole year
	May 20 or 29, 526 (GCT): Lasted for 6 days (possibly the fire)... the earth shook for a year... The earthquake continued every day and night for a year and a half without ceasing
	October 11, 1138, until June 1139 (Am5, GBC): Destructive seismic sequence until June, 1139. The main event was followed by three large events on the first day. A total of 80 shocks were felt during the whole seismic sequence
	June 29, 1170, 3:45 (GBCB): The earthquake lasted for 3 or 4 months, or perhaps longer. There were times when three or four or even more shocks were felt by day or night
	May 1, 1212 (GC): Aftershocks for a year
	February 20, 1404 (GC): The most violent earthquake at Aleppo was followed by a sequence of less powerful shocks, which lasted until early July 1404
	January 14, 1546 (AK): Then, on March 13, 1546, there was another alarm, the noise of which was greater before it died out. Then, on May 13, there occurred another shock felt by some people more than others, apart from the continuous shocks of previous days, some of which occurred at night and some during the day
	November 25, 1759 (AB): Aftershock sequence until August 1760. Damaging shocks on November 26, December 5, December 12, December 30
	April 26, 1796 (Am3): Aftershocks continued to be felt for 2 months
	January 1, 1837 (Am4): Aftershocks continued to be felt for almost four (five?) months. Important are: January 16 widely felt and caused considerable damage in the south, January 22 and 25 reported from the north and caused panic in Damascus. May 20 was reported from the north and caused considerable damage at Hashbeya
	April 3, 1872 (Am3): Aftershocks continued to be felt with decreasing severity throughout April and May, but did not cease altogether until February 1873
	Modern seismicity: July 11, 1927, 13:04 (Av): Twelve $3.5 < M < 5$ aftershocks until February 1928, and two such more until September 1930. Most powerful were on July 17 and February 22, 1928
	March 16, 1956, 19:32, and March 16, 1956, 19:43 (ISC, PK): Thirty weak aftershocks until November 1956
	March 31, 1969, 07:16 (in the Suez Rift) (BMA, Sa1, Ke): Mainshock with more than 2,000 events. Preceded 2 weeks before by 35 large foreshocks including 3 $M_L \geq 4$, followed by 19 $M_L \geq 4$ in half a year and four more in the next 15 months until December 1970

Table 6 (continued)

Duration	Descriptions
	February 3, 1983, 23:30 (Ho, Sa1): A swarm, lasted 8 months, largest event $M_L = 5.3$ after 2 weeks, 28 events $M_L \geq 4$; 94 events $M_L > 3$
	August 3, 1993, 12:43 (Ho, GII): A swarm or a sequence? The two largest are M_L 5.8 and 5.6, in the first hours. Strongest event preceded by a foreshock. Overall, 420 events of $M_L > 3$
	November 22, 1995, 4:15 (Ho, AT): Mainshock followed by >5,000 aftershocks, largest aftershock after 3 months on February 26, 1996, Mw = 5.6, most $M_L > 4$ occurred in the first 100 days, a few $M_L > 4$ continued for 2 years
	February 11, 2004, 8:15 (Sa2, GII): Mainshock with a few tens of aftershocks over half a year, the largest, M_L3.7, occurred 2 days later
Several years	August 13, 1822 (Am3): It was followed by an aftershock sequence that lasted almost 2.5 years
Unknown period of time	September 13–14, 458 (GCT): When the earthquake ceased, everyone of those who fled regained his confidence
	November 29, 528 (GCT): The earthquake that now occurred lasted for 1 h and was accompanied by a terrible sound. Then He appeared to a pious man, who told the survivors to write at the top of their doors 'Christ is with us. Stop'. When this was done, the wrath of God abated
	587 or 588 (GCT): Later shocks…
	September 26, 1091 (GC): There was an earthquake and 86 towers in the walls of Antioch collapsed… there were numerous earthquakes in the Syrian territory
	March 22, 1259 (GC): There were numerous shocks in Syria at the time when the Tartars arrived

References abbreviations in Appendix D

several months and longer, including M3.5–4 events, which are considered as the lowest limit for felt quakes (Appendix B). Obviously, the threshold of historical records is also of felt events, and it is therefore reasonable to accept historical sequences of similar length.

About a half (17 of 35) of the sequences lasted a month or less, a sixth lasted 2–5 months, and a quarter lasted almost a year or longer. In four reports, it was possible to infer the occurrence of intensive activity after the main destructive event, but the time each lasted was not specified. Short durations are not known in modern times from in and around the DSFS, and it is reasonable to assume that the historical record is incomplete for such sequences. Possibly, these reports may have related to the immediate strong aftershocks, neglecting the later and weaker stages of the sequence. Only when the observer is far away from the epicenter does the aftershock sequence seemingly "become" shorter, simply because shaking decreases with distance. The notion of 1 month or 40 days could be a metaphoric sign of a significant period of time derived from religious or cultural views, rather than what actually happened. For example, many Biblical events lasted "40" days, nights, years, etc. It therefore should be taken as a symbolic time frame rather than as a nominal figure.

Correlating the duration of the aftershock sequences with the estimated magnitude of the historical mainshocks (diamonds in Fig. 2), many short sequences (< 40 days) appear in all the range of magnitudes. Long durations, however, appear with moderate (M > ∼6) and large (M > ∼7) earthquakes where the historical sequences lasted up to about 500 and 1,000 days,

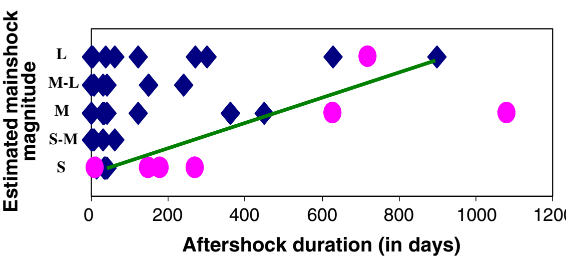

Fig. 2 Aftershock duration–estimated mainshock magnitude relations. *Diamonds* denote historic events and *ellipses* signify modern events. The *line* delineates the envelope of maximal duration of the historical aftershock sequences

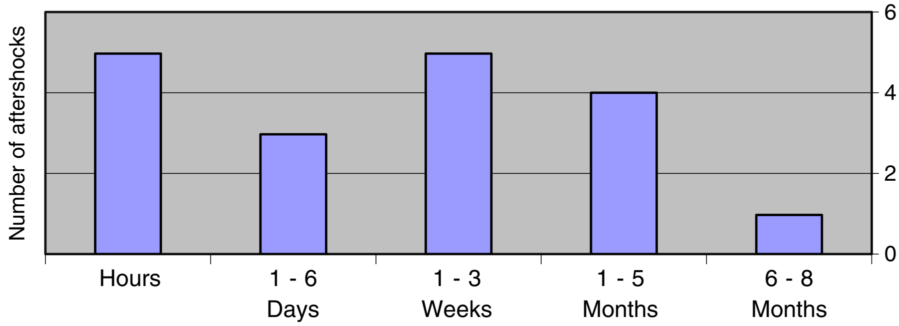

Fig. 3 Time delay of the noted (largest?) historical aftershocks (simplified from Table 1)

respectively. These maximal durations seem to correlate, more or less, with the lower bound of duration of modern aftershock sequences (ellipses in Fig. 2) and, therefore, can be considered to be more realistic.

4.4.2 Time delay of the noted (strongest?) aftershocks

Of special interest after the mainshock is over is the timing of the strongest aftershock because it may add to the damage. Indeed, the historical accounts mention several aftershocks increasing the damage or panic or being exceptionally strong, and these can sometimes be suspected to have been the strongest in the sequence and possibly even to have been the mainshock. All together, there were 18 notable aftershocks mentioned in seven sequences. Some sequences thus include several aftershocks, but it was not possible to determine which one was the strongest. Therefore, all the "noted aftershocks" were included in the evaluation. This, of course, biases the examination but eventually seems not to have affected the main conclusion much. Table 1 and Appendix A, and Figs. 3 and 4, present the time delay of the most significant aftershocks of the historical events.

Most of the noted aftershocks appeared just after the mainshock and in the following days and weeks, but several others were delayed a few months, or even as much as 8 months. There is no simple correlation between the time delay and the mainshock magnitude (Fig. 4), even for aftershocks in modern times, and no simple explanation either. The lack of correlation may result from the incompleteness and bias of the database; nevertheless, that strong aftershocks were delayed days, weeks, and months after the mainshock is a significant conclusion.

4.5 Earthquake storms

Between September 1156 and May 1159, there was an intensive sequence of six destructive earthquakes in northwestern Syria, each followed by many smaller events, some of which were strongly felt (Ambraseys 2004; Guidoboni et al. 2004a). This series, which was termed "paroxysm" by Ambraseys (2004) and "destructive seismic crises" by Guidoboni et al. (2004a), can also be called a seismic storm according to Utsu's (2002) terminology. The mainshocks of the major sequences occurred on September 27, 1156; October 13, 1156; December 9, 1156; April 2, 1157; July 5 1157; and August 9–September 7, 1157, the last being the largest one. Close sequences also occurred

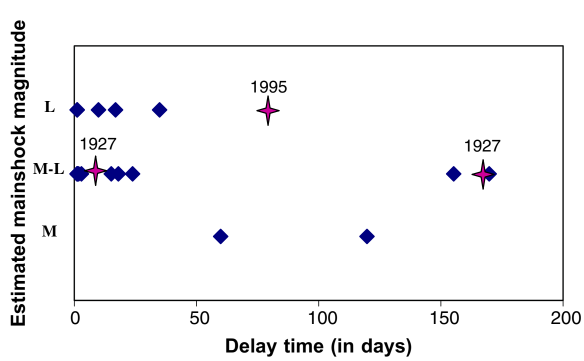

Fig. 4 Delay time–estimated mainshock magnitude relations. *Diamonds* denote historic events and *stars* denote modern ones

Table 7 Unspecified clusters of historical earthquakes

Unspecified sequences	
199–198 BC (GCT)	"but the number of victims was limited, because it did not happen in a single shock."
419 (GCT)	Great earthquakes in the East
March 9, 757 (Am6)	Four events, or a single one followed by three significant aftershocks
January 5–December 25 835 (GCT)	The earth shook for 40 days. Possibly a duplication of 713?
November 24, 847 (GCT)	A dreadful earthquake at Damascus... The earthquake reached Antioch... Then it reached Mawsil...
December 30, 859–January 29, 860 (GCT)	Earthquakes which...
January 9, 951–May 28, 952 (GCT)	"... there were many earthquakes tremors in Aleppo and other cities. They lasted for forty days,... "
July 30–August 27, 1063 (GC)	There were earthquakes.
May 19–June 18, 1094 (GC)	In that month, there was a series of many earthquakes in the Syrian territories lasting for a long time
September 28, 1151 (GC)	Earth shook three times
February 1, 1152 (GC)	Earth shook three times
February 1287, 2nd half (GC)	A series of earthquakes
December 1795 (AF2, SDM)	Two shocks

References abbreviations in Appendix D

between 526 and 528 around Antioch and in 1759 in southern Lebanon and northern Israel, but these were not as notable as the 1156–1159 storms.

4.6 Unspecified clusters

There are 13 reports such as "numerous earthquakes," "great earthquakes," "earth shook three times," or just "there were earthquakes," with no mention of a specific event (Table 7). This is insufficient to distinguish the various categories used here, and they could be any type of a sequence, including a regular mainshock–aftershock sequence, a swarm, or a storm. Moreover, they could also be a compilation of several different earthquakes from remote locations into a single cosmic event, such as the "circum-Mediterranean" 881 A.D. earthquake: "there was a strong earthquake in Syria, Egypt, some parts of Mesopotamia, North Africa and Andalusia," and this is why it was not included in this study.

4.7 Missing sequences

A swarm-like sequence, in which the magnitude slowly increases to a maximum that is not much stronger than the preceding or following events, was not identified. This is not to say that swarms have not occurred, but only that the resolution and magnitude determination of historical data is insufficient to recognize such clusters.

5 Conclusions

Historical and modern accounts report about a hundred damaging earthquakes in the Levant during the last 22 centuries (Appendices A and B). Obviously, the complex nature of the historical data may bias the classification of earthquake sequences, and therefore, reinspection of the original data is desired in order to improve the reliability of the present listings (tables and Appendices A and B). This is an extremely large task, certainly beyond the scope of the present work. Yet, although subjective, interpretative, and incomplete, past descriptions enable considerable expansion of the seismic experience, almost 20-fold the limited and short time span of the instrumental period. Of course, as new information arises and better understanding develops, reevaluation of the original sources will be well worth doing. Overall, comparing the pattern of seismic sequences as it appears in the now existing historical record with that of today, it is possible to distinguish several modes:

(a) Single events: Forty six accounts (about a half) reported single strong earthquakes with no additional shocks mentioned (Table 2). Such events are not known in modern seismology and may just be the result of incomplete reports.
(b) Mainshocks: Thirty five accounts reported a "multievent" sequence that included one predominant earthquake, the mainshock, which caused most of the damage (Table 1). Some shakings, mostly in recent centuries, were reported to last for several tens of seconds, which is reasonable. Other past events were said to last a few hours, a duration that is unexplainable, unless the mainshock was merged with its immediate strong aftershocks (Table 3). Commonly, the earthquake surprised the inhabitants "such as has not occurred before," sometimes with a violent onset, "everything collapsed with the first shock" (e.g., 1796), and occasionally with the later phase being the destructive one, allowing invaluable spare time for evacuation (in 1822) (Table 4).
(c) Foreshocks: Earthquakes that preceded the major shock were reported in four sequences only (11%), ranging from minutes to several weeks (Table 5). In some cases, people reacted on time, evacuated, and saved their lives. This may indicate a true fear, a good instinct, and even an educated experience, rather than a clear understanding of this natural phenomenon.
(d) Aftershocks: Thirty five mainshocks were followed by additional earthquakes, lasting for hours, days, weeks, months, and sometimes more than a year (Table 6). Several sequences included tens of felt tremors, some of which added to the damage. Since, in a given seismotectonic area, larger events, supposedly, produce more numerous and stronger aftershocks (Bath and Omori lows), it is reasonable to assume that longer historical sequences followed larger mainshocks (Fig. 2). Hence, historical events associated with a long sequence of aftershocks (e.g., A.D. 341, 526, 1212) could have been stronger than previously assumed.
(e) Largest aftershocks: Close to half (eight of 18 events) of the notable aftershocks appeared within a week after the mainshock, but some were delayed by as much as a month (5/18 events), half a year (4/18 events), and even more (Figs. 3 and 4).
(f) Seismic storms: A series of six successive mainshock–aftershock sequences appeared between September 1156 and May 1159 in northwestern Syria. Smaller series may have occurred there also in 526–528, and in 1759 in southern Lebanon and northern Israel.
(g) Unspecified clusters: The data regarding 13 sequences is insufficient to further classify them (Table 7).
(h) Swarms: This was identified only in the modern activity; however, though they were unidentifiable because of the lack of data and details, they cannot be excluded from the historical record.

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Appendix A

Table 8

Appendix B

Table 9

Table 8 Seismic sequences associated with historical damaging earthquakes in the Levant

Date	Affected area	Size	Ref.	Type of sequence	Pattern of seismicity: Foreshocks	Main	Aftershocks	Noted after
760–750 B.C.	Jerusalem	?	Am6, GCT, ZAB	S		1		
199–198 B.C.	Sidon	M	AW, GCT, Ka2	C		Several		
Mid 2nd cent. B.C.?	Nearby Sidon	M	AW, GCT, GMDH, Ka2	S		1		
February 21, 148, afternoon B.C. (or 130 B.C.)	Antioch	M	AW, GCT, Ka2	S		1		
c. (69–) 65 B.C.	Syria and Antioch	M	AW, GCT, Ka2	S		1		
31 B.C. early spring	Judea	M	Ka1, Ka2, GCT, RH	S		1		
A.D. March 23, 37 early in the morning	Antioch	S (–M)	GCT	S		1		
c. 47	Antioch	S (–M)	GCT	S		1		
December 13, 115, morning	Antioch	M (–L)	AJ, GCT, Ka1, MGS	S		1		
c. 127–130	Nicopolis, Caesarea	M	Ka1, GCT	S		1		
303 or 304	Tyre and Sidon	M	GCT	S		1		
341	Antioch	(S–) M	GCT	A		1	1 year	3 days?
348 or 349	Berytus (Beirut)	S (–M)	GCT	S		1		
May 18–19, 363, night	Judea and Samaria (and possibly Petra)	M–L	Am8, GCT	A		1	Tremors	1, after 6 h
419	Palestine, Jerusalem	M	GCT, Ka1	C		Several		
450–457 night	Tripolis	S (–M)	GCT	S		1		
September 13–14, 458, night	Antioch	S – M	GCT	A		1	Unknown length	
August 22, 502, night	Ptolomais, Tyre, Sidon	M	GCT	S		1		
May 20 or 29, 526, midday	Antioch and Seleucia	M	GCT	A		1	1–1.5 year	6 days
November 29, 528	Antioch and Laodicea	M	GCT	A		1 (lasted 1 h?)	Unknown length	Lasted 1 h?
July 9, 551, day	Beirut, off coast Lebanon	M–L	AJ, Am2, Am8, AMA, GCT, DEK, ETSK, DSM	S		1 (or 2)		
c. 570	Around Antioch	M	GCT	S		1		
580 or 581 noon	Daphne and Antioch	S (–M)	GCT	S		1	Tremors?	
587 or 588 late October, night	Antioch	S (–M)	GCT	A		1	Unknown length	

Table 8 (continued)

Date	Affected area	Size	Ref.	Type of sequence	Pattern of seismicity			
					Foreshocks	Main	Aftershocks	Noted after
601–602 day	Syria, Rum (Cilicia)	M	GCT	S		1		
September 634	Palestine, Jerusalem	S–M	GCT	A		1	1 month	
634	Aleppo	S	GCT	S		1		
June 659	Jerusalem	M	GCT	S		1		
September 659–August 660	Jericho	S–M	GCT	S		1		
February 28 or March 10, 713, middle of the night	Antioch, Allepo, Qenneshrin	M	GCT	A		1	40 days	
January 18, 746, morning	Between Jerusalem and Tiberias	M–L	AAT, Am7, Am8, GCT, Ka2, MHH, RH	A		1	40 days	
March 9, 757, midnight (or 749, or 750)	Jerusalem	S–M	AAT, Am6, GCT	C		1	3 events?	3 events?
January 5–December 25, 835	Antioch	S	GCT	C			40 days	
November 24, 847 morning	a. Damascus b. Antioch c. Mawsil	a, b, c.: S–M	GCT	C		Several events, a: lasted 3 h		
June 12, 853–June 1, 854, night	Tiberias	S	GCT	S		1		
December 30, 859–January 29, 860	Laodicea–Antioch	M–L	AAKY, Am8, AMA, An, GCT	C		1 (several?)		
June 9, 951–May 28, 952	Aleppo	M	GCT	A			40 days	
972	Around Antioch	S–M	GCT	S		1		
April 5, 991, night	Damascus and Ba'albek	M	GCT	A		1	1 month	
November 10, 1002–October 29, 1003	Syria at the time	M	AJ, AMA, GC	S		1		
December 5, 1033, before sunset	Jericho–Nablus–Akko	M–L	GC	A		1	8 days	December 5–6; December 6, December 6–7, all 8 days?
August 21, 1042–August 9, 1043	Tudmur, Palmyra	S–M	GC	S		1		
July 30–August 27, 1063	Tripoli	M	GC	C		Several		
March 18–August 30, 1068	Ayla, or Hejaz	L	AJ, AZP, GC, ZAP	A		1 lasted 2.5 h		2 events in 2.5 h?
May 29, 1068	Ramla?	M	GC	S		1		
September 26, 1091, night	Antioch	M	GC	A		1	Numerous	

May 19–June 18, 1094	Syrian territories	S	GC	C	Many in 1 month		
June 26, 1117, night	Tyre (Scandelion)	S	GC	S	1		
Sequence from: October 11, 1138, afternoon, to June 1139	Around Azrab, south of Triple Junction of east Anatolian fault	M–L	Am5, GBC, GC	A	1 (3 subevents?)	80 events in 8 months	October 11: 3 events, October 14, 3 in October 27, several on October 29 and October 31, terrifying June 21
August 17, 1140–August 6, 1141	Sheizar	S	SDM	S	1		
c. 1150 (1160?)	Jerusalem and Jericho	S–M	GC	S	1		
September 28, 1151, night	Busra	S	Am5, GC	C	3 shakes		
February 1, 1152, shortly before dawn	Busra	S	Am5, GC	C	3 shakes		
September 27, 1156	Damascus?	S	Am5, GBC, GC	A, St	1	Several	
October 13, 1156, night	Afamiyah (between Allepo and Hamat)	S–M	Am5, GBC, GC		1	Many	
December 9, 1156, night	Allepo	S–M	GBC, GC		1	Many	
April 2, 1157, night towards dawn	Afamiyah	S–M	GBC, GC		1	Several	
July 5, 1157, morning	Hamat	M	Am5, GBC, GC		1	Several	
August 9–September 7, 1157	Aleppo, Hamat, Hims	L	Am5, GBC, GC		1	Many	
August 1163	Antioch	M	GC	S	1		
June 29, 1170, 3:45 UT	Antioch, Tripoli Bakaa Valley, Allepo	L	Am5, GBCB, GC, MGS	A	1–2	>3–4 months	
May 20, 1202, 2:40 UT	Lebanon, Syria, Israel: Akko, Tyre, Baniyas, Safad…	L	AB, AJ, AMA, AM1, AM2, Am8, DKT1, DKT2, EMA, GC, MAE	A	2 shock or 2 subevents	4 days	4 days?

Table 8 (continued)

Date	Affected area	Size	Ref.	Type of sequence	Pattern of seismicity			
					Foreshocks	Main	Aftershocks	Noted after
May 1, 1212, night/dawn	Ayla, Shubak–Karak	M (–L)	AMA, Am8, GC, KAD	F + A	1, ~12 h before	1	1 year	
March 22, 1259, night	Damascus	S	GC	A		1	Numerous	
October 13, 1284	Damascus	S	GC	S		1		
February 1287, 2nd half	a, between Zafad and Hims; or b, near Hims; or c, near Zafad	S	GC	C		Series		
March 8, 1287	Near Hims	S	GC	S		1		
March 22, 1287	Near Laodicea	S	GC	S		1		
January 11–February 8, 1293	Karak, Tafila	M (–L)	GC	S		1		
January 13–February 11, 1339	Tripoli	S	GC	S		1		
January 3, 1344	Aleppo	M–L	GC	A		2 closed	> 1 month	
February 20, 1404	Aleppo and Tripoli	M–L	AB, GC	F + A	1, on 1403 12 18	1	5 months	10 days?
April 9–May 8, 1407	Antioch	S	GC	S		1		
December 29, 1408	Shughr Bakas and Balatunus	M	AAKY, AB, GC	S		1		
November 8 or 16, 1458	Karak	M	Am8, AMA, GC, KAD	S		1		
March 9, 1537	Antioch	S	AK	S		1		
January 14, 1546, afternoon	Jordan Valley, Jerusalem to Nablus	M	AK	A		1	> 4 months	March 13, May 13
February 1557	Jerusalem	S	AK	S		1		
September 13, 1563, dawn	Damascus	S	AK, SDM	S		1		
January 4, 1588, 13:00	Aila and Tabuk	M	AMA	S		1		
January 21, 1626	Gaziantep, Aleppo, Hama	M	AF2, SDM	S		1		
November 24, 1705, night	Yabrud, Al-Qastal, Damascus	M	AF1, GMDS, SDM	F + A	1	1	1 month	
March 1719	Aleppo	S	AF2	S		1		
1722–1723	Aleppo	S	AF2	S		1		
April 15, 1726	Jum, NW of Aleppo	S–M	AF2	S		1		
September 25, 1738	Amanus	M	AF2, SDM	S		1		

October 30, 1759, 03:45 LT	Zafad and Qunaitra	M	AB, DKT1, Ka1, MRH	A		1	Series	
November 25, 1759, 19:23 LT	Litani and Bakaa	L	AB, AJ, Am8, DKT1, GMDS, Ka1	A		1	> 9 months	November 26, December 5, December 12, December 30
December ??, 1795, 14:10	Aleppo	S	AF2, SDM	C		2		
April 26, 1796, 9:05	Latakia	L	AB, AF1, AF2, AJ, Am3, SDM	A		1, for 1 min	2 months	
August 13, 1822, 20:40	Gaziantep, Aleppo, Han Shekhum	L	AB, AJ, Am3, SDM	F + A	8 days slight shocks, 1 strong half hour before	1 in 3 phases in 40 s	2.5 years	30 in 8 min
May 26, 1834, 4:00	Jerusalem and Bethlehem	S–M	AAT, BM, Shal	A		1	10 days	
January 1, 1837, 14:34	Southern Lebanon	M–L	AJ, Am4, Am8	A		2 in 5 min, 10–30 s ea.	4–5 months	January 16, January 22, January 25, May 20
April 3, 1872, 7:40	Antakya	L	AAKY, AB, AJ, Am3, Am8	A		1 in 2 phases	10 months	2 months

This table shows a list of historical earthquakes that caused damage in the Levant, most of which possibly originated from the DSFS and nearby structures. See detailed explanation in the text, Section 3. Under the "date" column, events are marked by time of occurrence, as detailed as known, by the year, month, day, and part of the day or night. The "affected area" column shows locality of the most severely affected area. This is not necessarily the epicenter zone. Under the "size" column, estimated size of the earthquake is given in the broad categories as suggested by Ambraseys and Jackson (1998). Estimations were taken from historical, geological, and paleoseismic studies and, if not available, were made by personal judgment. The "ref." (references) column shows studies used for that event. Most of these works are based on primary sources; some others rely on secondary sources or paleoseismic studies. See abbreviations in Appendix D. The "pattern of seismicity" column shows the sequence of events. Foreshocks are noted by number of events and period of time they preceded the main event; main(shocks) are given by number of events and the time lasted; aftershocks are described by number and length of time they lasted; and noted after(shocks) are mentioned by number, date of occurrence, and the time delayed.

L large ($7.8 > Ms \geq 7.0$), *M* moderate ($7.0 > Ms \geq 6.0$), *S* small ($Ms < 6.0$), *A* aftershock(s), *C* cluster, *F* foreshock(s), *S* single, *St* storm

Table 9 Pattern of seismicity associated with significant modern earthquakes in the Levant

Date	Affected area	Size, Mag.	Ref.	Type of sequence	Pattern of seismicity			
					Foreshocks	Main	Aftershocks	Noted after
July 11, 1927, 13:04	Northern Dead Sea	M, $M_L = 6.2$	Av, ABSN, SAN	1A		1	12 in 7 months, 2 more in next 29 months?	M_L4.5 on July 17, M_L 5.5 on February 22, 1928
March 16, 1956, 19:32 and March 16, 1956, 19:43	Southern Lebanon	S $M_L = 5.2, 5.5$	ISC, PK	A		2	30 weak events, lasted until November	
March 31, 1969, 7:16 (Gulf of Suez)	Shadwan, Gulf of Suez	M, $M_L = 6.6$	BMA, Ke, Sa1	P + A	35 in 2 weeks, 3 $M_L \geq 4$	1	$>$2,000; 19 $M_L \geq 4$ in half a year; 4 in next 15 months	$M_L \geq 5$ on April 8 and September 26
February 3, 1983, 23:30	Gulf of Elat (Aqaba)	S, $M_L = 5.3$	Ho, ISC, Sa1	P + A	2 weeks	1 in swarm	8 months, 28 events $M_L \geq 4$; 94 events $M_L > 3$	
August 24, 1984, 6:02	Haifa	S $M_L = 5.3$	GII, HvES	A		1	Five $2 < M_L < 3$ aftershock within 10 days	
August 3, 1993, 12:43	Gulf of Elat (Aqaba)	S, $M_L = 5.8, 5.6$	Ho, GII, ISC	P + A	$M_L = 3.5$, 2.5 h before the mainshock	2, in a swarm?	420 of $M_L > 35$ in 5 months	
November 22, 1995, 4:15	Gulf of Elat (Aqaba)	L, $M_L = 6.2$ Mw = 7.2	AT, Ho	A		1	$>$5,000, most in 100 days, a few $M_L > 4$ continued for 2 years	February 26, 1996, Mw = 5.6
February 11, 2004, 8:15	Northern Dead Sea	S, $M_L = 5.2$	GII, Sa2	A		1	A few tens in half a year	M_L3.7 on February 13 and July 9

This table shows a list of significant modern (twentieth century) earthquakes that occurred in the Levant and were associated with fore- and aftershocks. Origin time, affected area, magnitude, and pattern of seismicity were taken from the references mentioned (see abbreviations in Appendix D). Sizes of the events are in terms suggested by Ambraseys and Jackson (1998)

Appendix C

Comments regarding some selected events that were considered in this study

In general, only historical events that were reported to damage at least one site or cause significant effects were included. Earthquakes that were reported to have caused no damage, based only on archaeological data, found dubious and in need of further investigation, or seen only in deformed layers (KAE, MAB), were not included. The area of interest is the Levant, in and around the DSFS. See the text, Section 3, for explanation. The list is partly based on Salamon et al. (2007, electronic supplementary) and should be considered as preliminary.

760–750 B.C. Also known as Amos's, Zechariah's or Uzziah's earthquake. It was possibly associated with notable effects. Am6: "…an event the date, location and magnitude of which cannot be assessed…" relating, for example, to AFF and BM (October 11, 759 B.C., evening, $M_L = 7.3$).

525 B.C. This was listed by Am2 and BM as $M_L = 7.5$ that destroyed Sur and Sidon. However, we could not trace back the ancient sources that reported this event.

Second century B.C. Following AW, GCT and Ka2, the following interpretation is suggested:

1. 199–198 B.C., AW, GCT: Earthquake in Sidon, Phoenicia and Syria. Ka2: "famed emergence of the island of Hiera in 198 B.C."
2. Mid-second century B.C., We follow Ka2, although AW and GCT suggested the 199–198 B.C earthquake in Phoenicia and Syria.
3. February 21, 148 or 130 B.C., AW, GCT: Earthquake in Antioch. Ka2: possibly 146 B.C. or 140 B.C.
4. February 28, 92 B.C., Ka2: False earthquake, "imported into the Israeli catalogues from elsewhere in Eastern Mediterranean" (e.g., by Shal, BM, AAT). It was probably taken from the mid-second century B.C. earthquake.
5. Ca. 90 B.C., AW, Ka2: Earthquake in Apamea Kibotos (Phrygia, Asia Minor). GCT: The Apamea Kibotos (Turkey) occurred before 88 B.C.

69–64 B.C Ka2: Occurred in Antioch and later "…imported into the Israeli catalogues…" and placed at 64 B.C. in Jerusalem (e.g., by AAT, BM). GCT date this event to 65 B.C. and AW to 69 B.C.

31 B.C. Ka2: This was a moderate event rather than a strong one, as was previously suggested by others (e.g., AAT, BM: for September 2, 31).

27–20 B.C. GCT, Ka1: Affected eastern Mediterranean, possibly Lydia, Phrygia, and the Aegean.

A.D. 19 Listed by several authors (e.g., AAT, BM, Si, Wi) to affect Sidon and the Lebanese coast. However, the earliest reference we could find for this event is Ar, who does not refer back to any specific source. It is possible that Ar mixes up the earthquake of 17 A.D., which hit several cities in present-day western Turkey (and not of Bithinia), with another earthquake that occurred in Bithinia in 29 A.D. (or perhaps in 32 A.D.) and was also suggested by Ar to affect Judea and Jerusalem (see also GCT).

33 AAT: Slight damage, local effect, and apparently small. Wi discusses it in light of the Crucifixion event. We follow Am6: "…the earthquake at the Crucifixion is a spurious physical event."

90 This is one of the several events that are seen only in deformed layers (e.g., MAB). Principally, a remote and large earthquake could have produced the same deformed layer like a close and small ($M < 6$) one. Such events were not included in the list.

112 AMA: "Archaeological evidence suggests early second century destruction at…," however, we did not find written sources for this event.

303–306 AAT and BM report an earthquake in 306. We follow GCT, who mention an earthquake in 303/304 in Sidon, Tyre, and Syria.

348/9 GCT: Probably between September 1, 348, and August 31, 349.

362–363 Several events are mentioned in this time span. Following GCT, only the May 18–19, 363, event is introduced.

447 Based only on archaeological evidence from Hammat Gader (AAT). GCT: Earthquake on the night of January 26, 447, in Constantinople, Turkey, and other places.

475 GCT: Gabala, Syria, no mention of damage.

Ca. 500 Ka1: "Verification of time and spread across Palestine should be attempted."

532 GCT: Antioch, no damage.

565 Mentioned by BM, who relies on Si and Ws1. Ws1 made a systematic error as regards the chronology and did not convert the dates of the Egira into the Julian calendar, so 30 entries of his catalogue are brought forward by about six centuries. Willis himself (Ws2) and, subsequently, Am1 had pointed out this error, but these corrections were evidently not assimilated by the subsequent catalogue makers. In this case, the year 565 of the Egira corresponds to the period September 25, 1169–September 13, 1170; thus, it is the large earthquake of June 29, 1170.

634 GCT: "Although the tremors which struck Jerusalem and Aleppo presumably occurred in the same year (634 A.D.), there may have been two separate earthquakes, since the two cities are a great distance apart."

717 GCT: in Mesopotamia.

746–750 For this period: BM and Shal, an earthquake on January 18, 746; AMA, an earthquake on January 18, 747; and AAT, an earthquake on January 18, 749. We follow Ka2 and Am7, who suggest the occurrence of two earthquakes (at least) of which "The second earthquake, which occurred in 749 or early in 750, affected only Mesopotamia and presumably the adjacent part of northern Syria."

May 3, 765 (756/758–775) Ka1: Needs further investigation.

808 (775–780) Ka1: Needs further investigation.

January 5–December 25, 835 GCT: "The earth shook for forty days…"; however, there is no mention of a single notable event, and it is therefore defined as a cluster.

June 12, 853–June 1, 854 AAT: 853+

May 16, 881 The affected area is too large to conclude of a specific event.

1016 Ka1: Needs further investigation.

March 6, 1032 GC: confused with March 6, 1033, which occurred in Constantinople.

January 4, 1034 GC: Arabic sources gave the date of December 5, 1033, as January 4, 1034. AAT: One of the main shocks during 1033/4 winter earthquake swarm.

March 12, 1036–March 11, 1037 GC: The earthquake occurred in Cilicia, southern Turkey, west of the Iskendrun Bay.

1060 Ka1: "It is possible that felt reports for years 1060–1063 and possibly even later events were fused together" regarding damage in Jerusalem. Needs further investigation.

1063+ AAT mention epicenter in Antioch and destruction in Elat and may have confused reports from the event of 1063 in Tripoli, Lebanon, with reports from 1068 in Elat.

1067–1070 Several earthquakes are mentioned during this time period (e.g., AAT, BM), and they are mostly attributed to the event that occurred on March 18, 1068, in southern Israel. AMA, GC: The dates of April 20, 1067; November 11, 1067; April 20, 1068; February 25, 1070; March 18, 1168; and 1169 are duplications and misreports of the earthquakes that actually occurred on March 18 and May 29, 1068.

April 18, 1086–April 7, 1087 Eastern Syria, Iraq, Mesopotamia, probably outside the region of this study.

May 19–June 18 1094 GC: "there were earthquakes night and day…"; however, there is no mention of a single notable event, and it is therefore defined as a cluster.

December 30, 1097 GC: No explicit mention of damage.

December 24, 1105 GC: Jerusalem, no damage.

1113–1117 Several events are mentioned to have occurred in southern Turkey and northern Syria and around Jerusalem in this time period (e.g., Am5, AAT, BM, GC):

1. The two events of July 18, 1113, and August 9, 1113, as mentioned by AAT, are below the damage threshold considered for this work and were not included.
2. According to Am5, the strongest earthquake occurred on November 29, 1114;

it was preceded by foreshocks on August 10, 1114, and November 13, 1114, and they "...are clearly associated with the East Anatolian fault zone..." Therefore, they were not included.

3. GC (as well as AAT) suggest that the August 10, 1114, earthquake may have occurred in the region of Jerusalem causing no damage and the other two in southern Turkey (GC event of November 29, 1115, is November 29, 1114, of Am5, and possibly of December 25, 1115, of AAT).
4. GC: On June 26, 1117, an earthquake occurred in southern Lebanon, causing limited damage only. AAT considered this event to have happened in Jerusalem. We follow GC, who refer to original sources.

1156–1159 Detailed discussion in Am5, GBC, and GC.

1201+ Is excluded since it "... may be identical to the following one," i.e., 1202 (AAT).

October 1, 1261–September 30, 1262 GC: Earthquake in Syria, no mention of damage.

April 17, 1269 GC: Occurred in Cilicia, central and southern Turkey, probably northwest of the Iskendrun Bay, not included here.

May 1, 1312 AMA: This event was taken by BM from May 1, 1212.

January 20, 1322 GC: in Damascus, no damage.

September 7, 1366–August 27, 1367 GC: Safad, Israel, no damage.

September 20, 1399 GC: Damascus, slight earthquake, no damage.

November 16, 1402/3 AM2: erroneous location in Syria. It actually occurred in the Gulf of Corinth, Greece.

December 18, 1403 GC: In Aleppo, northwestern Syria, but did not cause any damage.

November 5–December 4, 1404 GC: In Aleppo, northwestern Syria, but did not cause any damage.

1456–59 Between one and three events. We follow GC and include only the event of November 8 or 16, 1458.

May 1481 AAT: An earthquake in Syria and Palestine. We follow GC, who mention a large earthquake in the southern Aegean on May 3, 1481.

March 29–April 28, 1484 GC: In Aleppo, no mention of damage.

1534 This is very probably a duplication of the earthquake of January 14, 1546. AK: "Arvanitakis (1904), on the authority of Dositheos (1715), dates the event to 1534, and Willis (1928) copies the earthquakes of 1534 and 1546 from Arvanitakis (1904) and Perrey (1850), respectively, thus duplicating the event. Sieberg (1932) and later authors [...] add nothing but confusion."

January 7, 1537 AMA, SDM: Eastern Mediterranean (Damietta in Egypt, and Antioch in Syria), possibly an association of two events, needs further investigation.

October 10, 1568 AF2, SDM: Damage in Latakia, Syria, also felt in Cyprus. A possible location between Syria and Cyprus. It therefore seems to be too small and outside the region of interest.

February 1656 AMA: "...strong earthquake in Tripoli in Libya destroyed almost half its houses..." Later authors (BM, AAT) place this event in Tripoli in Syria.

1712 AAT: Limited damage in Jerusalem only, needs further investigation.

July 21, 1752 Earthquake is mentioned by many writers, probably starting from Si; however, as noted by Am2, "no authority is quoted." This event should be further studied.

1801–1802 Ka1: Needs further investigation.

1896 SDM, AAT: Several earthquakes in Syria (February 20, May 12, May 14, June 29), no damage.

Appendix D

Reference abbreviations

AAKY	Akyuz et al. (2006)
AAT	Amiran et al. (1994)
AB	Ambraseys and Barazangi (1989)
ABSN	Avni et al. (2002)
AF1	Ambraseys and Finkel (1993)
AF2	Ambraseys and Finkel (1995)
AJ	Ambraseys and Jackson (1998)

AK	Ambraseys and Karcz (1992)
AM1	Ambraseys and Melville (1988)
AM2	Ambraseys and Melville (1995)
AMA	Ambraseys et al. (1994)
Am1	Ambraseys (1962a)
Am2	Ambraseys (1962b)
Am3	Ambraseys (1989)
Am4	Ambraseys (1997)
Am5	Ambraseys (2004)
Am6	Ambraseys (2005a)
Am7	Ambraseys (2005b)
Am8	Ambraseys (2006b)
An	Antonopoulos (1980)
Ar	Arvanitakis (1904)
AT	Al-Tarazi (2000)
Av	Avni (1999)
AW	Ambraseys and White (1997)
AZP	Amit et al. (1999)
BM	Ben-Menahem (1991)
BMA	Ben-Menahem and Aboodi (1971)
DEK	Daëron et al. (2004)
DKT1	Daëron et al. (2005)
DKT2	Daëron et al. (2007)
DSMP	Darawcheh et al. (2000)
EM	El Mrabat (2005)
EMA	Ellenblum et al. (1998)
ETSK	Elias et al. (2007)
GBC	Guidoboni et al. (2004a)
GBCB	Guidoboni et al. (2004b)
GC	Guidoboni and Comastri (2005)
GCT	Guidoboni et al. (1994)
GII	Geophysical Institute of Israel (2007)
GMDH	Gomez et al. (2003)
GMDS	Gomez et al. (2001)
Ho	Hofstetter (2003)
HvES	Hofstetter et al. (1996)
ISC	International Seismological Centre (2001)
Ka1	Karcz (1987)
Ka2	Karcz (2004)
KAD	Klinger et al. (2000)
KAE	Ken-Tor et al. (2001)
Ke	Kebeasy (1990)
MAB	Migowski et al. (2004)
MAE	Marco et al. (1997)
MGS	Meghraoui et al. (2003)
MHH	Marco et al. (2003)
MRH	Marco et al. (2005)
PK	Plassard and Kogoj (1968)
RH	Reches and Hoexter (1981)
Sal	Salamon (1993)
Sa2	Salamon (2005)
SAN	Shapira et al. (1993)
Shal	Shalem (1956)
Si	Sieberg (1932)
SDM	Sbeinati et al. (2004)
Wi	Williams (2004)
Ws1	Willis (1928)
Ws2	Willis (1933)
ZAB	Zilberman et al. (2004)
ZAP	Zilberman et al. (2005)

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