Tectonophysics 696–697 (2017) 1–13

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Earthquake damage history in Israel and its close surrounding - evaluation of spatial and temporal patterns

Motti Zohar [a,*], Amos Salamon [a], Rehav Rubin [b]

[a] Geological Survey of Israel, 30 Malkhe Israel Street, Jerusalem 95501, Israel
[b] Department of Geography, the Hebrew University of Jerusalem, Mount Scopus, Jerusalem 91905, Israel

ARTICLE INFO

Article history:
Received 14 June 2016
Received in revised form 5 December 2016
Accepted 14 December 2016
Available online 15 December 2016

Keywords:
Historical earthquakes
Damage patterns
Severity
Dead Sea Transform
Israel

ABSTRACT

Israel was hit by destructive earthquakes many times in the course of history. To properly understand the hazard and support effective preparedness towards future earthquakes, we examined the spatial and temporal distribution of the resulted damage. We described in detail our systematic approach to searching the available literature, collecting the data and screening the authenticity of that information. We used GIS (Geographic Information System) to map and evaluate the distribution of the damage and to search for recurring patterns. Overall, it is found that 186 localities were hit, 54 of them at least twice. We also found that Israel was affected by 4, 17, 8 and 2 damaging earthquakes that originated, respectively, from the southern, central, central-northern and northern parts of the Dead Sea Transform (DST). The temporal appearance of the northern earthquakes is clustered; the central earthquakes are more regular in time, whereas no damage from the north-central and the central quakes, with the exception of the year 363 earthquake, seems to have occurred south of the Dead Sea region. Analyzing the distribution of the damage, we realized that the number of the damage reports reflects only half of the incidents that actually happened, attesting to incompleteness of the historical catalogue. Jerusalem is the most reported city with 14 entries, followed by Akko (Acre), Tiberias, Nablus and Tyre with 8, 7, 7 and 6 reports, respectively. In general, localities in the Galilee and north of it suffered more severely than localities in central Israel with the exception of Nablus and the localities along the coastal plain of Israel, most probably due to local site effects. For the sake of hazard management, these observations should be considered for future planning and risk mitigation.

1. Introduction

Instrumental earthquake records for Israel have been available since the beginning of the 20th century, during which this area was affected by the destructive M = 6.2, 1927 Jericho earthquake (e.g., Ben-Menahem et al., 1976; Vered and Striem, 1977; Avni, 1999) and the nearby M = 7.1, 1995 Nuweiba earthquake (Baer et al., 2008; Shamir, 1996). Obviously, these two instrumentally recorded earthquakes are neither sufficient to characterize the long-term impact of strong earthquakes nor to define typical spatial and temporal patterns of damage, if there are any. Thus, the historical records as well as archaeological and paleo-seismological evidence of pre-instrumental earthquakes may assist greatly in filling that gap.

Written in various languages from many places, historical damage reports include accounts, chronicles, drawings, manuscripts and, from the second half of the 19th century, also photographs (Zohar et al., 2014). Most of the reports were already collected, translated and organized within modern catalogues (e.g., Guidoboni et al., 1994; Guidoboni and Comastri, 2005; Sbeinati et al., 2005; Ambraseys, 2009), reappraisals (Karcz, 1987; Ambraseys and Finkel, 1995; Ambraseys and White, 1997; Ambraseys, 2004; Salamon et al., 2007, 2011; Salamon, 2009; Agnon, 2014; Marco and Klinger, 2014) and focused investigations (e.g., Ambraseys and Melville, 1988; Ambraseys and Barazangi, 1989; Ambraseys and Karcz, 1992; Ambraseys, 1997). Although some of these records contain inaccuracies and exaggerations (Karcz and Lom, 1987), they are still the richest sources available for resolving source parameters of earthquakes such as size and location, comparing earthquakes from different places and times and relating the past to modern earthquakes (e.g., Sirovich and Pettenati, 2001; Bakun et al., 2002, 2003; Sirovich and Pattenati, 2003, 2009; Bakun, 2006; Gasperini et al., 2010; Hough and Avni, 2010; Zohar and Marco, 2012).

Given the wealth of the existing data and the essential need of Israel to establish a reliable and up-to-date database of earthquake-related damage, we first reappraised the list of historical earthquakes that affected Israel and its close surroundings (Zohar et al., 2016). This task is now complemented with the construction of a focused, dedicated archive of the damage caused by these earthquakes, targeting first on compiling the inventory of reliable reports of damage and then analyzing the spatial and temporal spread of the damage in order to identify typical patterns if exist.

* Corresponding author at: Department of Geography, the Hebrew University of Jerusalem, Mount Scopus, Jerusalem 91905, Israel.
E-mail address: motti.zohar@mail.huji.ac.il (M. Zohar).

http://dx.doi.org/10.1016/j.tecto.2016.12.015
0040-1951/

2. The area of interest

We focused on the area of Israel and its close surroundings (Fig. 1) in attempt to delineate the typical scope of damage that may hit Israel, regardless of its tectonic origin. The main seismogenic fault in the study area is the Dead Sea Transform (DST) system (Fig. 1), that appears to cause the majority of the strong and damaging earthquakes in Israel (Ben-Menahem, 1991; Begin, 2005; Hamiel et al., 2009; Agnon et al., 2010). It is a left lateral fault system extending from the Red Sea in the south to southeastern Turkey in the north, and bordering the eastern side of the Arabian tectonic plate and the western side of the Sinai sub-plate. The overall sinistral displacement along the DST since its origin in the Miocene is estimated to ca. 105 km (e.g., Quennel, 1959; Freund et al., 1968; Garfunkel et al., 1981). That is, an average slip rate

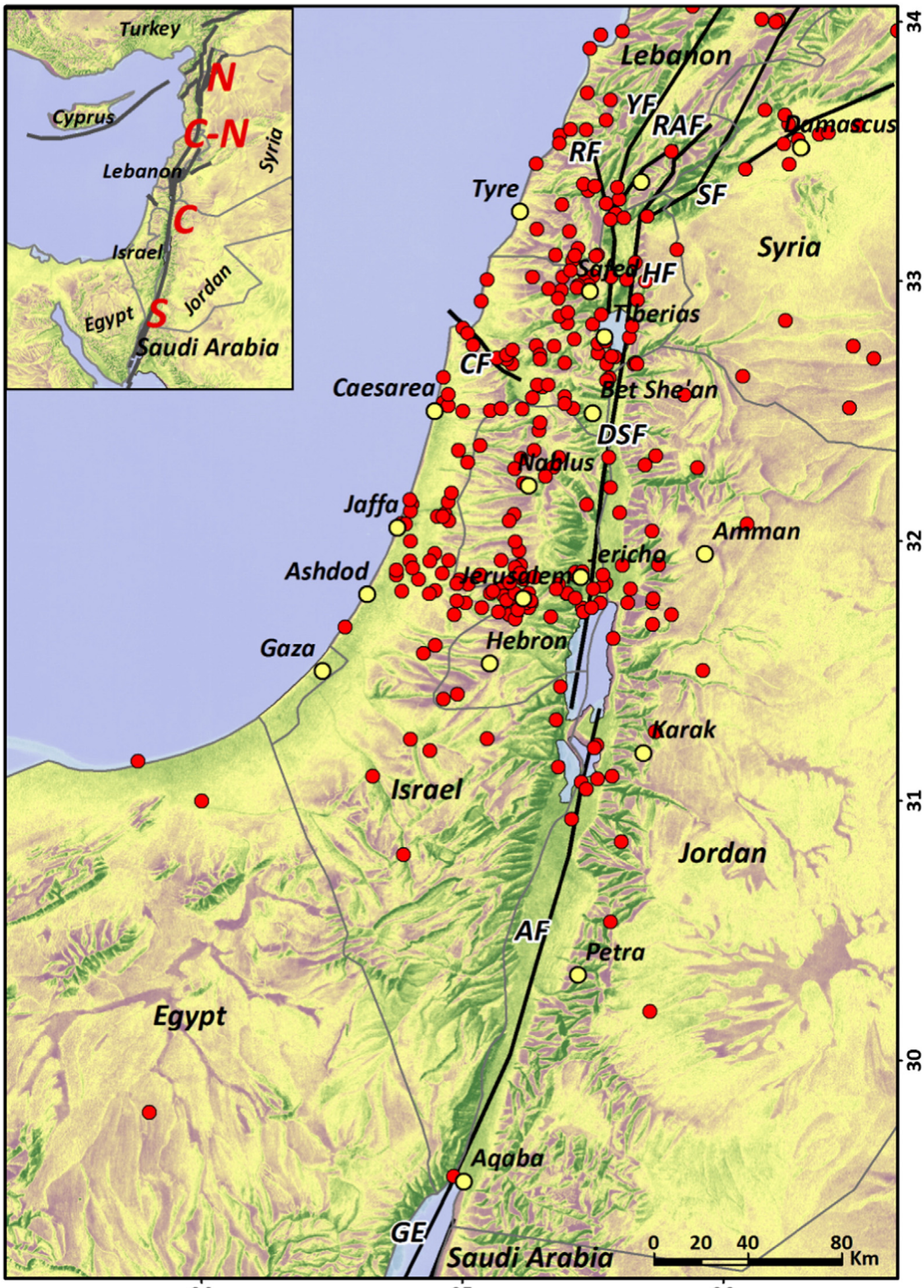

Fig. 1. Map of the study area and the localities that were hit during the last 2000 years (red circles). Yellow circles symbolize localities under focus in this study for being repeatedly hit. The main active tectonic element in that area is the Dead Sea Transform (DST) system. It is divided herein to three geographic parts (inset map): South (S), Center (C) and North (N), and the transition zone Center-North (C-N). The associated DST elements, from south to north, are: GE - the pull-apart structures in the Gulf of Eilat and Aqaba (Garfunkel and Ben-Avraham, 1996); AF – Arava Fault (Amit et al., 1999; Zilberman et al., 2005; Porat et al., 2009); DSF – Dead Sea Fault (Garfunkel et al., 1981); CF – Carmel Fault; HF – Hula Fault; RF – Roum Fault (Khair, 2001; Nemer and Meghraoui, 2006); YF – Yammouneh Fault (Daëron et al., 2007); RAF – Rachaya Fault (Nemer et al., 2008); SF – Sergaya Fault (Nemer et al., 2008). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of ca. 5 mm per year, although this seems to have varied throughout the Miocene and the Plio-Pleistocene (e.g., Garfunkel, 2010). Apart from the DST, other faults exist in Israel along the coastal plain and inland. These faults, much smaller than the DST, are also responsible for a regional seismic activity, although less frequent and much weaker than that of the DST. In historical times such activity, resulting in little damage, was occasionally ignored and hardly documented. In any case, its influence on the cumulative damage is negligible and thus, in order to simplify our analysis we ignored this activity and focused mainly on the DST activity.

3. Materials and methods

Following our inventory of reliable earthquakes (Zohar et al., 2016) and in light of the shortcomings of the historical information (e.g., Karcz and Lom, 1987; Karcz, 2004; Guidoboni and Ebel, 2009), we based our evaluation of the damage primarily on critical reviews of the historical sources. For each of the dependable earthquakes (Table 1) we further authenticated the related damage reports. We used the methodology suggested by Elad (1982, 2002) which relies on the contemporaneousness and context of the given historical document and was already described in detail and adopted by Zohar et al. (2016). Now we utilized the method to consistently grade the reliability of the damage reports (see definitions in Table 2). In addition to the historical accounts, we examined also archaeological evidence (e.g., Ambraseys, 1971; Russell, 1980, 1985; Tsafrir and Foester, 1992; Stiros and Jones, 1996; Ambraseys, 2005, 2006; Marco, 2008; Ellenblum et al., 2015) and paleo-seismic studies (e.g., Marco et al., 1996; Klinger et al., 2000; Ken-Tor et al., 2001, 2002; Migowski et al., 2004; Daëron et al., 2005; Kagan et al., 2011, 2005; Zilberman et al., 2005; Hayens et al., 2006; Wechsler et al., 2014), but avoided circular reasoning if the dating of these studies relied on the historical record (Rucker and Niemi, 2010). Using the reliability grade, we compiled the list of the affected localities and the extent of the resulted damage (Table 1).

In modern days, damage reports are converted into a scale of macroseismic intensity which grades the earthquake effects from "not felt" to "total destruction". Commonly used scales are the Modified Mercalli Intensity (MMI, Wood and Neumann, 1931; Richter, 1958), the Mercalli-Cancani-Sieberg (MCS, Sieberg, 1930), the MSK (Medvedev et al., 1965), and the recently developed European Macroseismic Scale (EMS-98, Grünthal, 1998). In our case, the conversion of the described damage into a degree of intensity is not straightforward as the type of construction, materials and their quality (e.g., Ferrari and Guidoboni, 2000) along the various historical periods have not yet been fully defined and characterized. Thus, we characterized the descriptions of the damage typical to our research area and construct an ad-hoc severity scale that grades the scope of the damage (Table 3). Finally, we stored the compiled records within a geographic relational database built using the Microsoft ACCESS™ platform and the ESRI ArcGIS™ software. The database design (Fig. 2), which follows the concepts of the Entity Relational Diagram (ERD) suggested by Howe (1983), enables flexible queries and analyses of the data.

4. Results – Spatial and temporal frame of the earthquakes

For the earliest earthquake dated to c.760 BCE there are no reliable damage reports beyond the mention of its mere occurrence. The second earthquake occurred in 31 BCE, nearly 700 years later. Although it is reasonable to assume that earthquakes did occur during this time gap, the absence of documentation from that period does not enable further evaluation. Thus, we concentrated on the damage reported only from the mid-1st century BCE to the first instrumentally recorded damaging earthquake of 1927 CE. The following damaging earthquakes in the region, on March 1956 (Salamon et al., 1996) and November 1995 (Baer et al., 2008; Shamir, 1996), affected mainly Lebanon and Egypt, respectively. This leaves us with 31 reliable earthquakes over a period of nearly 2000 years (Table 1). In general, the reports are not spread in time evenly, and as it get closer to our time, the number of the reports as well as their reliability increases significantly (Zohar et al., 2016).

Overall, we counted 420 reliable damage reports that are attributed by reliability degree of moderate or higher (Table 2) and refer to 186 localities (Fig. 1). 54 of these localities are reported to have been hit at least twice. The areal spread of the damage reports around the most probable seismogenic source - the DST, is not homogenous. The Mediterranean Sea in the west, the sparsely populated Arabian Desert and Transjordan in the east and the Negev Desert in the south, limit the spatial extent for these records. Accordingly, most of the damage is concentrated within the regions, mainly in northern and central Israel. We therefore modified our spatial perspective and examined the extent of damage in the north-south (N-S) direction only (Fig. 3). Considering that the most likely mechanism of strong earthquakes along the DST is a sinistral strike slip (Garfunkel et al., 1981) and that its geographic orientation along our study area is N-S, result in a reasonable approximation.

We classified the earthquakes according to their projected damage location along the DST (Fig. 3). Overall we identified 4, 17, 8 and 2 damaging earthquakes along the southern (S in Fig. 1), central (C), central-northern (C-N) and northern (N) parts of the DST, respectively. Obviously, the damage zones do not necessarily reflect the actual tectonic origin of these earthquakes but it is reasonable to assume that they correspond with the nearby segment of the DST. Apart from the geographic origin, the damage may also reflect the magnitudes of the earthquakes. Accordingly, we measured the N-S damage extent of each earthquake and projected the outcomes on a comparative chart (Fig. 4). It appears that the March 1068, 1837, 1588 and Nov 1759 earthquakes show the greatest extent of damage - >500 km, while the 634 and 1458 are the smallest ones - <100 km. The group of earthquakes of intermediate extent of damage, between 300 and 400 km, contains the 363, 551, 1063, 1157, 1170, 1202, 1212 and Oct 1759 earthquakes, although 1202 was interpreted as largest on record (Sieberg, 1932; Ambraseys and Melville, 1988). Interestingly, the damage extent of the instrumentally recorded earthquake of 1927 was approximately 200 km. It means that at least 12 historical earthquakes sharing greater extents of damage were most probably stronger in magnitude. The earthquakes of 31 BCE, 418, May 1068, 1117, 1643, 1817 and 1839 with only a single reported locality, seemingly implying a minimal extent of damage, but this also might be the result of an incomplete record of the history.

5. Discussion

5.1. Damage extent and size of the historical earthquakes

From previous studies we learn that there is a strong correlation between the size of a given historical earthquake and the affected area (e.g., Topozada, 1975; Bakun and Wentworth, 1997; Ambraseys and Jackson, 1998), and also between the magnitude and the length of the surface rupture (Wells and Coppersmith, 1994). Since the extent of reporting west of the DST is limited by the Mediterranean Sea and eastwards by the Arabian Desert (Trans-Jordan), the N-S extent is left as the only indicator for the stretch of the damage. Thus, we examined the relation between the local N-S damage extents of the historical earthquakes that occurred in our area of interest with the average of the magnitudes assigned to these earthquakes in previous studies (Fig. 5, solid line).

Until an independent, reliable method of determining source parameters of historical earthquakes in our study area is developed, we regarded the previous studies that have already appeared in the scientific literature as the best expert judgment available. To better cope with incompleteness and reliability of the data we examined only the earthquakes of the last Millennium. Then we compared this relation with the global 'magnitude-length of surface rupture' empirical

Table 1
List of reliable historical earthquakes (Zohar et al., 2016) from ca. 760 BCE until 1927 CE that damaged at least one locality in Israel and its close surroundings (see Fig. 1). Date – time of occurrence in year and whenever possible - also the month, day and hour; Reported damaged localities – localities reported to have been damaged within the research area (Fig. 1) that we consider of moderate (M_R) or higher degree of reliability (Table 2). Asterisk denotes earthquakes that caused damage also beyond our area of interest; estimated magnitude in previous studies – list of studies and the magnitudes they estimated for that earthquake. Abbreviations: AMARB – Ellenblum et al. (1998); AMBR - Ambraseys and Barazangi (1989); AMJA - Ambraseys and Jackson (1998); AM3 - Ambraseys (1997); AMME - Ambraseys and Melville (1988); AUS - Austin et al. (2000); AVN - Avni (1999); AVN2 – Avni et al. (2002); BEG - Begin (2005); BM - Ben-Menahem (1991); BM2 - Ben-Menahem et al. (1976); BM3 - Ben-Menahem and Aboodi (1981); BM4 - Ben-Menahem (1981); BM5 - Ben-Menahem (1979); DAR – Darawcheh et al. (2000); GC - Guidoboni and Comastri (2005); GOM - Gomez et al. (2003); HOAV - Hough and Avni (2010); KA2 - Karcz (2004); MAR - Marco et al. (2003); MIG - Migowski et al. (2004); NEM - Nemer and Meghraoui (2006); TUAR - Turcotte and Arieh (1988); WECO - Wells and Coppersmith (1994); ZIL - Zilberman et al. (2005); Avg. mag. – the average value of the estimated magnitudes (see Zohar et al., 2016); Size deg. – In terms suggested by Ambraseys and Jackson (1998). See explanation in Table 4; N-S extent (km) – the distance between the northernmost and southernmost damaged localities, in km; and Casu. – estimated scope of casualties according to the historical reports: '-' – no casualties or not mentioned or not known, F - few (10 or less), M - many (>10).

Date	Reported damaged localities	Estimated magnitude in previous studies	Avg. mag.	Size deg.	N-S damage extent (km)	Casu.
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 Apr 2*	Tyre	7.1 (BM); 7.1 (MIG after BM)	7.1	Maj	153	M
363 May 18–19 (night)	Antipatris, Caesarea, Gophna, Hada (Unknown location), Areopolis, Ashdod, Zippori, A-Salt, Haifa, Jaffa, Banyas, Tiberias, Bet-Govrin, 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	453	M
418	Palestine	6.2 (TUAR); 6.9 (MIG)	6.5	Str	?	-
502 Aug 22 night*	Acre (Akko), Tyre	7 (TUAR); 7 (MIG after BM); 7 (BM)	7.0	Maj	113	-
551 Jul 9*	Sarafand [Lebanon], Tyre	7.8 (TUAR); MS 7.2 (DAR); 7.5 (MIG); 7.5 (BM)	7.5	Maj	284	M
634 Sep	Jerusalem, Palestine	5.5 (light damage, personal judgment, Zohar et al., 2016)	5.5	Mod	47	-
659 Jun 7	Jericho, St. John, Palestine	6.6 and 6.6 (BM; BM5)	6.6	Str	154	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); <7 (KA2, BEG)	7.2	Maj	160	M
756 Mar 9	Jerusalem, Palestine	6 (Moderate damage, personal judgment, Zohar et al., 2016)	6.0	Str	70	-
1033 Dec 05 (night)	Jericho, Ramla, Banyas [Israel], Ashqelon, Jerusalem, Akko, Gaza, Nablus, Hebron, el-Badan	7.1 (MIG); 6.7 (BM); 6.7 (BM5); Me = 6 (GC)	6.6	Str	190	M
1063 Aug*	Acre (Akko), Tyre	6.5–7 (MIG); Me = 5.6 (GC)	6.1	Str	357	F
1068 Mar 18*	Palestine, Elat	6.9 (MIG); 6.6–7 (ZIL); 7.0 ≤ MS ≤ 7.8 (AMJA); 7 (BM); Me = 8.1 (GC)	7.3	Maj	780	M
1068 May 29	Ramla	Me = 6 (GC)	6.0	Str	?	M
1117 Jun 26	Jerusalem	5.5 (light damage, personal judgment, Zohar et al., 2016)	5.5	Mod	?	-
1157 Aug 12 (night)*	Jerusalem	7–7.5 (MIG); M > 7 (AMBR); 7.3 (BM)	7.2	Maj	515	M
1170 Jun 29 (0345)*	Banyas [Israel]	7 (MIG); M > 7 (AMBR); 6.6 (HOAV); 7.9 (TUAR); 7.0 ≤ MS ≥ 7.8 (AMJA); 7.5 (BM); Me = 7.7 (GC)	7.3	Maj	497	M
1202 May 20 (0240)	Akko, Samaria, Tebnine, Vadum-Iacob, Banyas [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 ≤ MS ≥ 7.8 (AMJA); Me = 7.6 (GC)	7.3	Maj	380	M
1212 May 01	Karak, Elat, St. Catherine, el-Shaubak	6.7 (MIG); Me = 5.8 (GC)	6.2	Str	330	F
1293 Jan 11–Feb 08	Lod, Ramla, Gaza, Qaqun, Tafilah, Karak	6.6 (MIG); Me = 5.8 (GC)	6.2	Str	185	-
1458 Nov 16	Ramla, Lod, Hebron, Jerusalem, Karak	6.5 (MIG); Me = 5.6 (GC)	6.1	Str	70	M
1546 Jan 14 (afternoon)	Hebron, Ma'ayan Elisha, Jericho, St. John, Bethany, Jerusalem, Jordan River, Nablus, Beit-Jala, Bet-Lehem, Batir	M ~ 6 (KA2); 7 (TUAR); 6.1 (MIG); 7 (BM,BM5, BM3);	6.5	Str	140	M
1588 Jan 04 (13:00)*	Eilat, St. Catherine	6.7 (MIG)	6.7	Str	600	-
1643 Mar 23	Jerusalem	5.5 (light damage, personal judgment, Zohar et al., 2016)	5.5	Mod	?	-
1759 Oct 30 (03:45)*	Akko, Quneitra, Benot-Ya'aqov Bridge, Sasa, Nazareth, Safed, Tiberias, Nablus	MS ~ 6.6 (AMBR); 6.5 (BM)	6.5	Str	350	M
1759 Nov 25 (19:23)*	Hula, Deir Hanna, Safed, Nabatiya, Nablus, Sassa, Mt. Hermon, Akko, Beit-Jann, Hasbaya, Deir Hanna, Quneitra, Caesarea, Marjuyun, Tiberias, Haifa, el-Rama	7.4 (MIG); MS ~ 7.4 (AMBR); MS = 7.4 (AMJA; WECO); 7 ≤ M ≤ 7.2 (GOM); 7.4 (BM)	7.3	Maj	580	M
1817 Mar	Jerusalem	5.5 (light damage, personal judgment, Zohar et al., 2016)	5.5	Mod	25	-
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	170	-
1837 Jan 01 (16:35)*	Nabatiya, Qana, el-Fara, el-Salha, Jish, Marun Al-Ras, Bint-Jbeil, Malkiyya, Qadas, Ya'tar, Tebnine, Hunin Castle, Banyas [Israel], Metulla, Zeqqieh, Deir Mimas, el-Khiam, el-Tahta, Deir Mar-Elias, Qaddita, Jibshit, Gaza, Arraba, Attil, Qaqun, Tubas, Ajloon, Nablus, Zeita, Harithiya, Jerusalem, Kefar-Bir'im, Sea of Galilee, Hasbaya, Kafr-Aqab, Jerash, 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, Nazareth	7.4 (MIG); M > 7 (AM3); MS = 7.4 (WECO); MS 7.1 (NEM after AM3); 6.7 (BM)	7.1	Maj	635	M

Table 1 (*continued*)

Date	Reported damaged localities	Estimated magnitude in previous studies	Avg. mag.	Size deg.	N-S damage extent (km)	Casu.
1839	St. Catherine	5.5 (light damage, personal judgment, Zohar et al., 2016)	5.5	Mod	25	-
1927 Jul 11 (15:04)	Salfit, Soreq River, Nabi-Musa, Abadia, Ajloon, Gaza, Atara, Meslovia, Lod, Ein-el-Kelt, Ein-Dok, Azraa', Deir Mar-Saba, Merhavya, Massada, Mrar, Maa'yan Elisha, Moza, Medaba, Migdal, Karak, Kafaringi, Ein-Harod, Ramat Yishai, Migdal Yava, Qiryat Anavim, Tel Aviv, Nablus, Shunam, Refidie, Ramat, Rachel, Dara'a, Ramla, Shiloach Village, Rehovot, Amman, Reina, Ramallah, Ein-Karem, Qalqilya, Kabab, Zora, Safed, Zemah, Petah Tiqwa, Eqron, Afula, Akko, Ein-Fara', Ein-Qinya, Ein-Musa, Rosh Ha-ha'Ayin, Be'er-Sheva, Jiftlik, Gimzoo, Gedera, Batir, Bet-Sorik, Bet-She'an, Bet-Liqya, Bet-Lehem, Bet-HaKerem, Bet-Jimal, Bet-Govrin, Toov, Mt., Bira, Jisr-Magmi, a-Ram, Irbid, A-Salt, el-Hama, Abu-Tlul, Nazareth, Jaffa, Yarmouk Fall, Jordan River, Abu-Dis, Abu-Ghosh, Beit-Jala, Zarka-Ma'in, Jericho, Holly Mt., Armon Ha-Naziv, Jerusalem, Yalo, Tulkarm, Tiberias, Tabgha, Jaljulya, Hebron, Jenin, Zikhron Ya'aqov, Zarka, Wadi al-Shueib, Mt. Scopus, Olives Mt., Deir A-Shech, Daharia, Benot-Ya'akov Bridge, Allenby Bridge, Gesher, Jerash, Michmash village, Haifa	6.25 (AVN; AVN2); 6.2 (BM2); 6.3 (MIG) = 6.25	6.25	Str	220	M

correlation (Fig. 5, dashed line, adapted from Wells and Coppersmith, 1994, Table 1). Although our local 'magnitude-damage extent' correlation is weaker ($R^2 = 0.72$) than the global 'magnitude-surface rupture' one ($R^2 = 0.81$), the N-S damage extent still appears to be a reasonable indicator for the size of the earthquakes.

5.2. Seismic moment and slip rate

Further on we examined whether the average magnitude of the damaging earthquakes (Table 1) may serve as a proxy of the total coseismic displacement of each of these earthquakes. Accordingly, we used the standard relations representing the magnitude of a given earthquake, the contributed slip and the seismic moment (Hanks and Kanamori, 1979; Wells and Coppersmith, 1994) as follows:

$$M_0 = \mu DA \quad (1)$$

$$Mw = 2/3 * \log M_0 - 10.7 \quad (2)$$

where M_0 is the seismic moment, μ is the shear modulus, D is the average slip across the fault surface, A is the area of the fault surface that ruptured (depth * length of the rupture plane) and Mw is the moment magnitude. Developing Eqs. (1) and (2) leads to the following relation aimed for extracting the slip (offset) for a given earthquake:

$$D = \frac{10^{\frac{3(M_W+10.7)}{2}}}{\mu A} \quad (3)$$

Dividing the slip by the return period will yield the average slip rate for that time window.

Of great interest to Israel is the damage zones that have been generated by the earthquakes concentrated between the Dead Sea and the Sea of Galilee (Fig. 3), i.e. along part C of the DST (Fig. 1), about ~160 km long. Thus, we examined the slip rate and seismic moment contributed by the 17 central earthquakes. The values used in relation [3] are the average magnitude (Table 1); 3.1×10^{11} dyne/cm^2 for μ that accords with crustal faults (Wells and Coppersmith, 1994); an average seismogenic depth of 15 km (Braeuer et al., 2014); and the rupture length (see Fig. 5, following Wells and Coppersmith, 1994). The results appear in Table 5.

The total slip contributed by the 17 central (C) earthquakes is ~193 cm i.e., an annual average slip rate of 0.09 cm/y. For the first (7 earthquakes) and second millennium (10 earthquakes) CE, the rate is 0.15 cm/y and 0.03 cm/y, respectively. These rates are not compatible with the annual slip rate, ranging between ca. 0.45 ca. 0.5 cm/y and based upon GPS measurements (Garfunkel, 2010). A plausible explanation for such a gap may be the probable incompleteness of the data (Zohar et al., 2016) in which additional, undocumented earthquakes contributed the missing amount of slip. We assumed that most the earthquakes graded as major or great (M > 7, Table 4) were probably documented; their enormous damage spread and resulted casualties most likely did not escape reporting (Ambraseys, 2009; Guidoboni and Ebel, 2009). We also assumed that many of the strong earthquakes (M > 6) were documented as well (Begin, 2005). That is, the majority of the missing earthquakes was of light and moderate degree (M < 6) and contributed only minor slip. Therefore, incompleteness cannot explain

Table 2
Degrees of reliability (Zohar et al., 2016) characterizing a report of damage. Supportive archaeological or paleo-seismological evidence raises the reliability of a given report by a single grade.

Symbol	Reliability	Transmitters
V_R	Very high	Based upon at least 2 contemporary or near contemporary independent sources with no confusion or contradiction regarding the date, location and details of the earthquake.
H_R	High	Based on one contemporary or near contemporary source
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 reporting, duplicated documentation or misinterpreted sources

Table 3
The severity of damage in typical terms used in the historical reports, from the lowest (Felt-FD) to the highest (Severe-SD). Suggested correlation with the EMS-98 Scale (Grünthal, 1998) appears in the rightmost column. In our opinion, up to the 20th century construction quality was poor and there were almost no such structures to withstand the high range (X–XII) of EMS-98 intensity degrees. Thus, our ad-hoc severity scale tops at about intensity IX.

Symbol	Severity	Typical description of the reported effects	Possible correlation with degrees of the EMS-98 Scale
F_D	Felt	Felt without damage	II–III/V
L_D	Light	Cracks, plaster failure	V–VI
M_D	Moderate	Collapse of a few walls or weak houses	VI–VII
H_D	Heavy	Collapse of many houses and buildings	VII–VIII
S_D	Severe	Nearly total destruction	VIII–IX

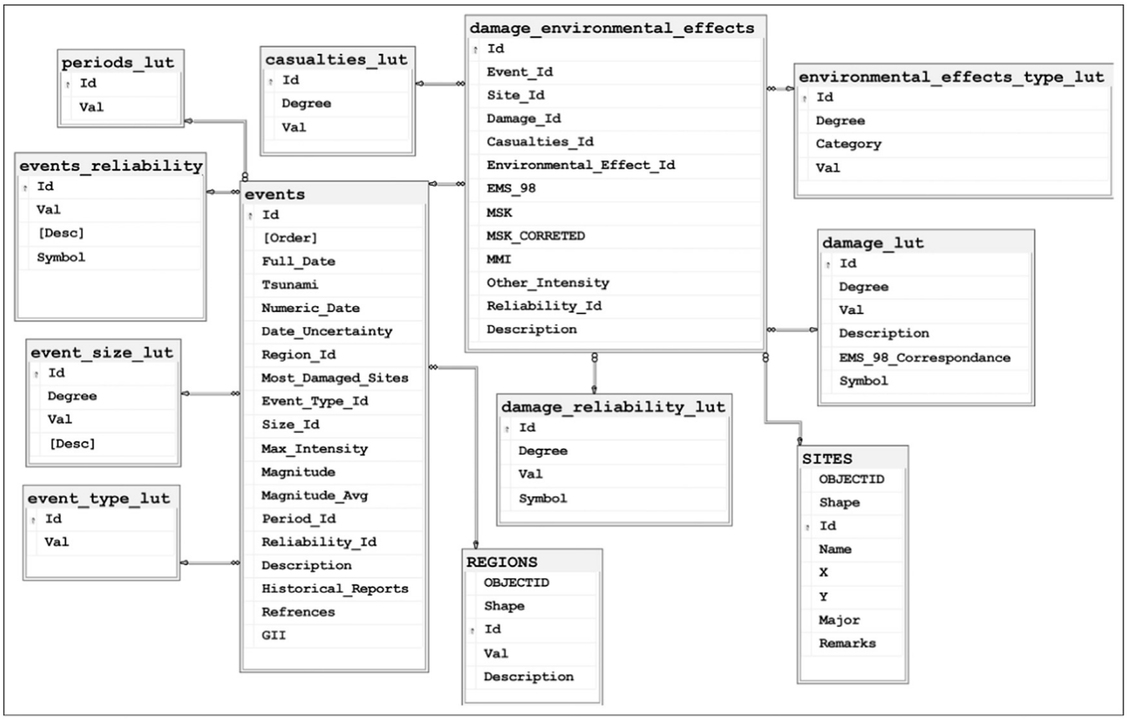

Fig. 2. The schema of the database that was constructed to store and manipulate the compiled damage reports. The major entities are the alpha-numeric tables of the earthquakes, damage and environmental effects, as well as the geographic layers of the sites and the regions.

entirely the missing amount of slip and there ought to be other explanations.

The second possible explanation might stem from the inaccurate estimation of the magnitudes. The low slip rate of 0.09 cm/y possibly implies that the magnitudes we used may have been underestimated and consequently resulted in insufficient slip. To test this hypothesis, we added half a degree to each of these magnitudes (Table 5). This time the resulted total slip reached 1066 cm which reflects an annual slip rate of 0.54 cm/y. That is, increasing the magnitude by half a degree appears to be consistent with the calculated annual slip rate of ca. 0.5 cm/y. For the first (7 earthquakes) and second millennium (10 earthquakes) the annual slip rate was 0.85 and 0.21 cm/y, respectively. Although the former value seems to be ‘too’ high while the second one is ‘too’ low, it can still be concluded that in general the average magnitudes we used, based on previous studies (Table 1), tend to be underestimated.

This is also apparent when inspecting the total seismic moment (M_0). Using relation [1] with an average slip rate of 0.5 cm/y yields an expected total seismic moment of 7.02E + 27 dyne/cm^2 for the last two Millennia. However, the total accumulated seismic moment of the 17 central earthquakes is only 1.39106E + 27 dyne/cm^2 (Table 5). Similar increase of the magnitude by half degree results in a total seismic moment of 7.67288E + 27 dyne/cm^2, which almost equals the expected value. This means that an increase of ~0.5 degree magnitude to each of the historical earthquakes may potentially explain the observed deficit of seismic moment. Whether the magnitudes of the historical earthquakes are indeed underestimated is yet to be investigated, together with the incorporation of other components of the tectonic slip such as possible creep, postseismic deformation and off-fault deformation (e.g., Baer et al., 2008; Ellenblum et al., 2015; Hamiel et al., 2016). This way or the other, determining the magnitude of the historical earthquakes is of crucial importance.

5.3. Repeating damage patterns

The damaged area resulting from the historical earthquakes (Fig. 3) seems to cluster in distinct groups that hint at typical patterns recurring throughout history. The most prominent is the central pattern, which is discussed first, and then the northern one. Characterization of the southern pattern, however, is much more complex as relevant information is scarce.

5.3.1. The central pattern

The damages from the central (C) earthquakes such as the 659, 749, 1033, 1293, 1458, 1546 and 1834, do not extend north of the Hula Basin (latitude of ~33.2°N) or south of the Dead Sea (latitude of ~31°N) (Fig. 3). In general their extent (749, 1033, 1293 and 1834 earthquakes) equals or is slightly less (659, 1458 and 1546 earthquakes) than that of the M = 6.2 1927 earthquake (Figs. 4, 5). The similarity of the extents, however, does not enable us to determine magnitude values for those earthquakes. Instead, we cautiously suggest that their sizes may have been roughly similar or less than that of the 1927 earthquake. This claim is in accordance also with Ambraseys and Karcz (1992) regarding the 1546 earthquake. On the other hand, we might be underestimating the size of the 749 earthquake, for the details of this earthquake are not clear and there is disagreement among the scholars (Karcz, 2004; Ambraseys, 2005).

The central earthquake of 363 CE deserves further attention. Cyril (c. 313–386 CE), the Bishop of Jerusalem, reported off two consecutive earthquakes occurred on the night between the 18th and 19th of May 363 CE. In his letter, he listed 22 affected localities with various degrees of destruction. Noted among the damaged localities is ‘RQM’, identified by Brock as Petra (Brock, 1977). Apart from Cyril, who in our opinion is reliable, no other contemporary or near contemporary source mentions damage to Petra. The others, potentially relevant reports, were determined as questionable and suspected of having theological biases (Russell, 1980).

Resolving the question of damage to Petra is of great importance whereas it is located 80 km south of any other reported locality. With Petra included, the noted spread of the damage extends enormously, which means that the 363 earthquake should be considered as of a much larger magnitude (Ambraseys and Jackson, 1998). Seemingly, the unclear identification of Petra, the problematic sources and the

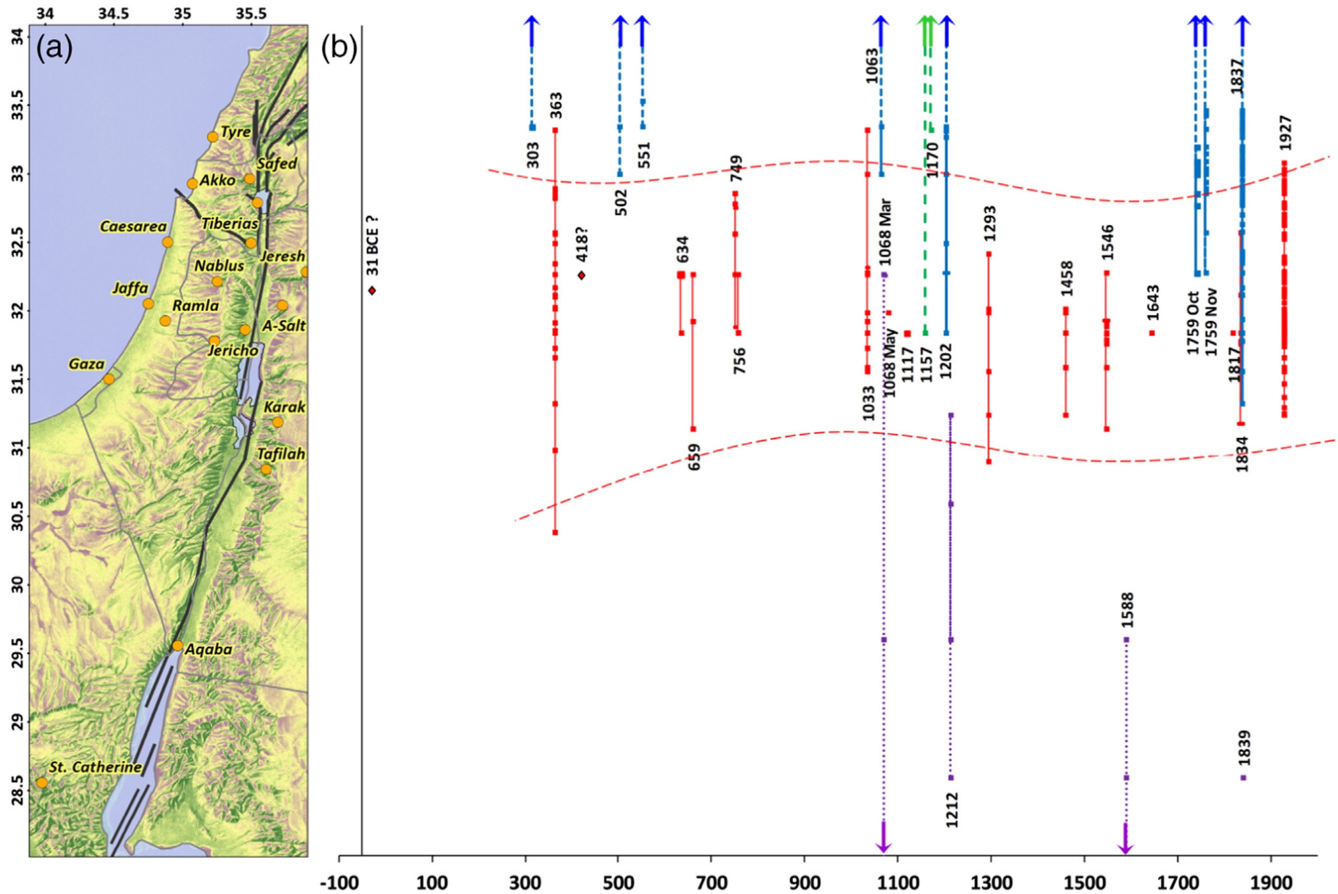

Fig. 3. Distribution of historical records on earthquake damage along the DST since the 1st century BCE: (a) Location map; (b) Time history of the spread of damage per each of the earthquakes. The square dots denote the damaged localities and the vertical lines represent the total N-S extent of the damage caused by the noted earthquake (arrows denote damage extended beyond the limits of the present map): round points line - Southern region; solid line - Central; short dashes line - Central-Northern; and long dashes line - Northern (see the geographic division of the DST in Fig. 1). The regions of Judea and Palestine that were reported to have been damaged in 31 BCE and 418 CE with no mention of specific locations are represented by question marks. The horizontal wavy dashed lines delineate the extent of damage caused by the Central earthquakes.

extreme distance of Petra from the other affected sites casts doubt on the actual damage to Petra specifically from the 363 earthquake. However, inscriptions found lately in the excavation of ancient Zoar, southeast of the Dead Sea (Meimaris and Kritikakou, 2005), strengthen the claim of damage to Petra. They document the death of four people during the 363 earthquake and consequently imply of damage extending southwards, at least to the south of the Dead Sea area. This means the damage extent is similar to that of the 1927 Jericho earthquake in case we exclude Petra, or greater than that of 1927 in case Petra is included. Still, the size estimation of the 363 earthquake cannot be fully concluded for Cyril reports of two consecutive quakes. These may reflect two separate earthquakes or it is a sequence of a main earthquake followed by an aftershock or a pre-shock that precedes the main earthquake. Either way the data so far available to us does not enable resolving this issue unless we assume that all the damage described by Cyril refers to the main earthquake only.

The 363 earthquake presents further complications since, in general, the damages from the C earthquakes and also from several of the C-N and N earthquakes, do not extend south of the Dead Sea area (Fig. 3, geographic latitude 31.5°N). This raises the question as to whether the apparent diminished damage reports southwards result from a true change in the tectonic style of activity south of the Dead Sea, or rather from the lack of reporting due to the sparse population in these arid regions. We thus suggest delineating a border (Fig. 3, southern dashed line) south of which the damage seems to weaken. Whether this is an artifact of poor reporting or true tectonic behavior of the DST south of the Dead Sea basin remains for future investigations. The case of 363 also demonstrates an interesting 'what-if' scenario: had the detailed letter of Cyril not been discovered, the spread of the damage and the magnitude assessments would have been considered much less than we reckon today. This is true for all historical earthquakes whereby those reported by fewer reports attract less attention and thus might be underestimated while those having impressive descriptions might end up as stronger than they actually were. More on missing data is discussed in the next section.

5.3.2. The northern pattern

The damage extent of the N and C-N earthquakes is much greater than that of the C earthquakes (Fig. 4). Apart from the 303 and 502 earthquakes, the N and C-N earthquakes share damage extents of >300 km, in particular the well-documented November 1759 and 1837 earthquakes with damage extents of nearly 600 km. Moreover, the temporal distribution of C-N and N earthquakes is significantly different than that of the C earthquakes. While the central damaging earthquakes form a recurrence pattern more regular in time, the northern ones are stronger and temporally clustered in three major sequences separated by a few hundred years of weak activity: between 303–551, 1063–1202 and 1759–1837. Although reports of damage in Syria and Lebanon during the mid-13th and mid-18th centuries do exist (Ambraseys, 2009), no damage is reported in our area of interest. Had a large earthquake occurred, the resulting damage would probably have been documented, particularly from the 16th century onward when information from western travelers in Palestine gradually became known (Röhricht, 1890; Ish-Shalom, 1965). Thus, we assume that the clustering of the C-N and N earthquakes does reflect the actual seismic activity.

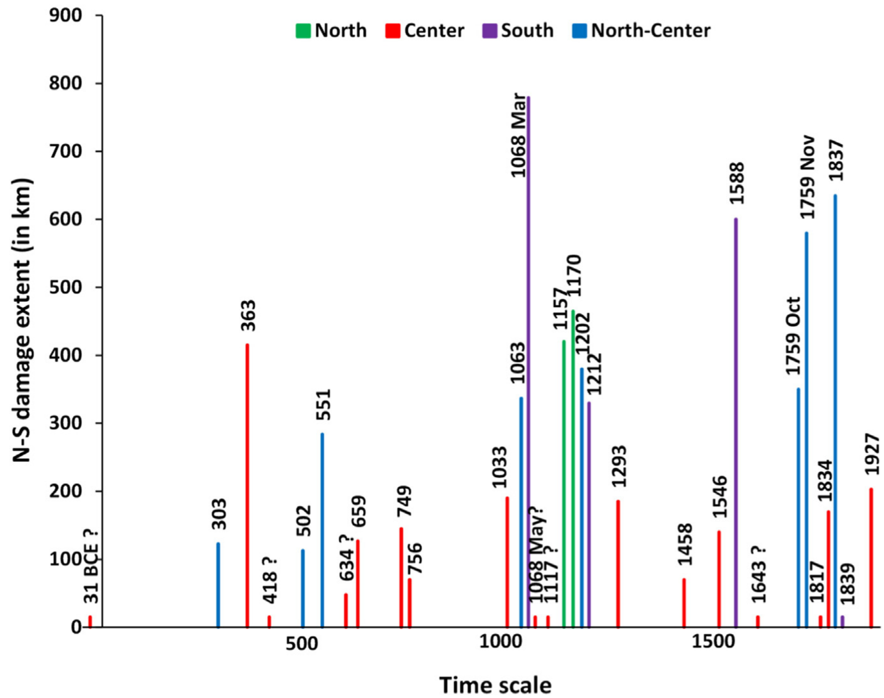

Fig. 4. Temporal history of the earthquakes that affected the area of interest (Fig. 1) in relation to their N-S damage extent (in km, based on Table 1). The earthquakes are classified by their assumed origin along the DST, whether along the Southern, Central, Central-Northern or Northern region (see the geographic division of the DST in Fig. 1). The 31 BCE, 418, May 1068, 1117 and 1643 earthquakes affected a single damaged locality or area only and thus were question-marked as possible incomplete record.

The intervals of low and high activity in the northern DST may reflect accumulation of stresses along several hundred years followed by a sudden release within short periods of 100–200 years. Earthquakes in the central DST, however, occur more often and regularly: the 10 earthquakes in the second millennia occur about every 100–150 years. This may explain the higher magnitudes of the C-N and N earthquakes compared to the C ones. Interestingly, the DST system along the N and C-N geographic parts splays into several branches and undergoes transpression while the C part is a simple transtensional leaky transform (Garfunkel et al., 1981; Garfunkel, 2010). It seems that the style of release of the stress accumulated along the DST (Garfunkel, 2010) changes along its various segments. Certainly, these findings require further analysis of the mechanism.

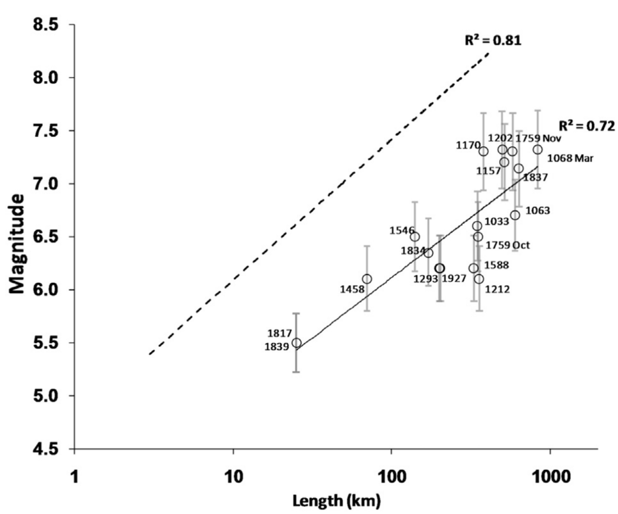

Fig. 5. The correlation between the N-S damage extents of the last millennium earthquakes that occurred in our study area with the average of the magnitudes assigned to these earthquakes in previous studies (noted by solid line). For comparison, a global empirical correlation between the length of surface rupture (either left or right lateral slip) and the magnitude is presented (dashed line, after Wells and Coppersmith, 1994, Table 1).

5.3.3. The southern pattern

Reports of damage from the southern (S) earthquakes are much fewer than in the other inspected parts of the DST (Fig. 3). Only four earthquakes, in March 1068, 1212, 1588 and 1839 caused damage in the southern part of the DST. Evidence of additional possible earthquakes appears in Niemi (2011), describing seismic activity along the Arava Valley and Gulf of Aqaba in the 4^{th}, 7^{th}–8^{th}, 11^{th}–13^{th} and 15^{th}–16^{th} centuries, and thus suggesting a three- to five- century recurrence rate of intense seismic activity. Unfortunately, the few reports and information limit our ability to identify or conclude temporal patterns.

5.4. Severity of the damage

During historical times, many localities were reported to have been hit repeatedly (Table 6), with Jerusalem leading the list (14 times). This is probably not only due to its proximity to the DST but also to its being a continuous political and cultural center throughout time. The cities following are Akko (Acre), Tiberias, Nablus and Tyre with 8, 7, 7

Table 4
The size of earthquakes classified by degrees, starting from light (Lht) to great (Grt). Each degree represents a possible range of magnitudes adapted from Ambraseys and Jackson (1998).

Size	Symbol	Description	Estimated magnitude
Light	Lht	Felt only	4 ≤ M < 4.9
Moderate	Mod	Slight damage to buildings and other structures	5 ≤ M < 5.9
Strong	Str	May cause a lot of damage in very populated areas	6 ≤ M < 6.9
Major	Maj	Major earthquake. Serious damage	7 ≤ M < 7.9
Great	Grt	Great earthquake. Can totally destroy communities along the entire rupture length and beyond	M ≥ 8

Table 5
Seismic moments and slip rates of damaging earthquakes along the central part (C, Fig. 1) of the DST: Earthquake – the date of the earthquake; M – average magnitude (Table 1); R.L. – rupture length (Fig. 5, after Wells and Coppersmith, 1994); M_0 – seismic moment in dyne/cm^2; D – slip rate (cm/y) corresponding to the length of central part (~160 km) and D_R – slip rate corresponding to the length of the rupture (R.L. / 160 ∗ 100). For sensitivity tests, similar calculations were carried out for the average magnitude (M) minus and plus half (0.5) a magnitude degree.

	Average magnitude					Average magnitude − 0.5					Average magnitude + 0.5				
Earthquake	M	R.L.	M_0	D	D_R	M	R.L	M_0	D	D_R	M	R.L	M_0	D	D_R
31 early spring BCE	6.7	29	1.258E + 26	97	17	6.2	12	2.238E + 25	41	3	7.2	69	7.079E + 26	228	98
363 May 18–19	6.7	29	1.258E + 26	97	17	6.2	12	2.238E + 25	41	3	7.2	69	7.079E + 26	228	98
418	6.5	20	6.309E + 25	68	9	6.0	9	1.122E + 25	29	2	7.0	49	3.548E + 26	162	49
634 Sep	5.5	4	1.995E + 24	12	0	5.0	2	3.548E + 23	5	0	6.0	9	1.122E + 25	29	2
659 Jun 7	6.6	24	8.912E + 25	81	12	6.1	10	1.584E + 25	34	2	7.1	58	5.011E + 26	192	70
749/Early 750	7.2	69	7.079E + 26	228	98	6.7	29	1.258E + 26	97	17	7.7	164	3.981E + 27	538	553
756 Mar 9	6.0	9	1.122E + 25	29	2	5.5	4	1.995E + 24	12	0	6.5	20	6.309E + 25	68	9
1033 Dec 05	6.6	24	8.912E + 25	81	12	6.1	10	1.584E + 25	34	2	7.1	58	5.011E + 26	192	70
1068 May 29	6.0	9	1.122E + 25	29	2	5.5	4	1.995E + 24	12	0	6.5	20	6.309E + 25	68	9
1117 Jun 26	5.5	4	1.995E + 24	12	0	5.0	2	3.548E + 23	5	0	6.0	9	1.122E + 25	29	2
1293 Jan 11–Feb 08	6.2	12	2.238E + 25	41	3	5.7	5	3.981E + 24	17	1	6.7	29	1.258E + 26	97	17
1458 Nov 16	6.1	10	1.584E + 25	34	2	5.6	4	2.818E + 24	15	0	6.6	24	8.912E + 25	81	12
1546 Jan 14	6.5	20	6.309E + 25	68	9	6.0	9	1.122E + 25	29	2	7.0	49	3.548E + 26	162	49
1643 Mar 23	5.5	4	1.995E + 24	12	0	5.0	2	3.548E + 23	5	0	6.0	9	1.122E + 25	29	2
1817 Mar	5.5	4	1.995E + 24	12	0	5.0	2	3.548E + 23	5	0	6.0	9	1.122E + 25	29	2
1834 May 26	6.3	14	3.162E + 25	49	4	5.8	6	5.623E + 24	21	1	6.8	34	1.778E + 26	115	25
1927 Jul 11	6.2	13	2.660E + 25	45	4	5.7	6	4.731E + 24	19	1	6.7	32	1.496E + 26	105	21
Total			1.391E + 27		193			2.473E + 26		34			7.672E + 27		1066
Average (cm/y)					0.09					0.01					0.54
Average (1st Mill.) (cm/y)					0.15					0.02					0.85
Average (2nd Mill.) (cm/y)					0.03					0.007					0.21

and 6 reports, respectively. However, these figures represent only the reported damage; we suspect that other instances of damage, particularly in remote or peripheral sites, may have occurred but were not documented or the documents haven't been found yet. Close examination of the N-S extent of damage of the various earthquakes (Fig. 3) may support this claim because there are localities within the damage zones that were not reported to be hit. It is likely that localities between two damaged sites might have been hit as well, or at least might have experienced severe shaking (e.g., Guidoboni and Ebel, 2009). Accordingly, we list not only the sites that were explicitly reported to have been damaged, but also the localities that might have been hit as well but not reported (Table 6).

It appears that the total number of the reports almost equals the number of the 'missed' accounts (Table 6) i.e., the incompleteness of the damage catalogue up to the 18th century is at least close to 50% and might be even larger. We also achieve some balance between several pairs of neighboring cities that should have undergone, more or less, a similar history of severe shaking. For example: Lod and Ramla; Akko (Acre) and Tyre; Tiberias and Bet-She'an; and Caesarea and Haifa. Yet, in several cases such as Jerusalem and Jericho or Jerusalem and Bet-Lehem, such a balance is not apparent. It is not necessarily because Jerusalem is more susceptible to damage but rather due to the preferred attention it has attracted throughout history in comparison with the other two cities. Altogether, we attempt to compensate for at

Table 6
Localities reported to have been damaged at least three times between 31 BCE and 1927 CE in the study area, arranged in decreasing number of times. Ascribed to each locality are also its geographic longitude (Lon)-latitude (Lat) coordinates; the maximal degree of severity (see also Figs. 4, 5); number of reports that mention damage at the given site; number of times a strong-damaging shaking may have affected that site but no reports are known from it (see text for explanation); the total number of times this site may have had a damaging shaking; and a rough estimate of the recurrence interval of damage according to the total assumed hits.

Locality	Lon	Lat	Max severity	Number of times reported to be hit	Possible hits that were not reported	Assumed damaging shaking	Recurrence interval (years)
Jerusalem	35.23	31.78	Heavy	14	2	16	121
Akko	35.07	32.93	Severe	8	1	9	217
Tiberias	35.54	32.79	Severe	7	4	11	177
Nablus	35.25	32.21	Heavy	7	6	13	150
Tyre	35.22	33.27	Severe	6	4	10	195
Ramla	34.87	31.92	Heavy	5	4	9	217
Banyas [IL]	35.62	33.24	Heavy	5	4–5	9–10	195–217
Haifa	35.00	32.82	Heavy	4	3–4	7–8	244–279
Jaffa	34.75	32.05	Severe	4	4	8	244
Hebron	35.10	31.53	Heavy	4	5	9	217
Gaza	34.46	31.50	Heavy	3	6	9	217
Safed	35.49	32.96	Severe	4	7	12	162
Jericho	35.45	31.86	Heavy	4	6	10	195
Lod	34.89	31.95	Heavy	4	8–9	12–13	150–163
Karak	35.69	31.18	Heavy	4	5	9	217
Bet-She'an	35.50	32.49	Heavy	3	7	10	195
Caesarea	34.89	32.50	Heavy	3	2	5	390
St. Catherine	33.98	28.56	Moderate	3	1	4	488
Aqaba	35.00	29.50	Severe	3	–	3	650
Bet-Lehem	35.20	31.70	Heavy	3	8–9	11–12	163–177
Nazareth	35.30	32.70	Heavy	3	5–6	8–9	217–244
Hasbaya	35.68	33.38	Severe	3	6	9	217
Total				104	98–103	202–207	

least some of the missing information and thus better estimate the actual number of times a given locality was affected, as well as the average recurrence interval. For the sake of hazard assessment, it is important to realize that such localities had undergone destructive shaking, whether populated or not and thus to be aware of the actual hazard there.

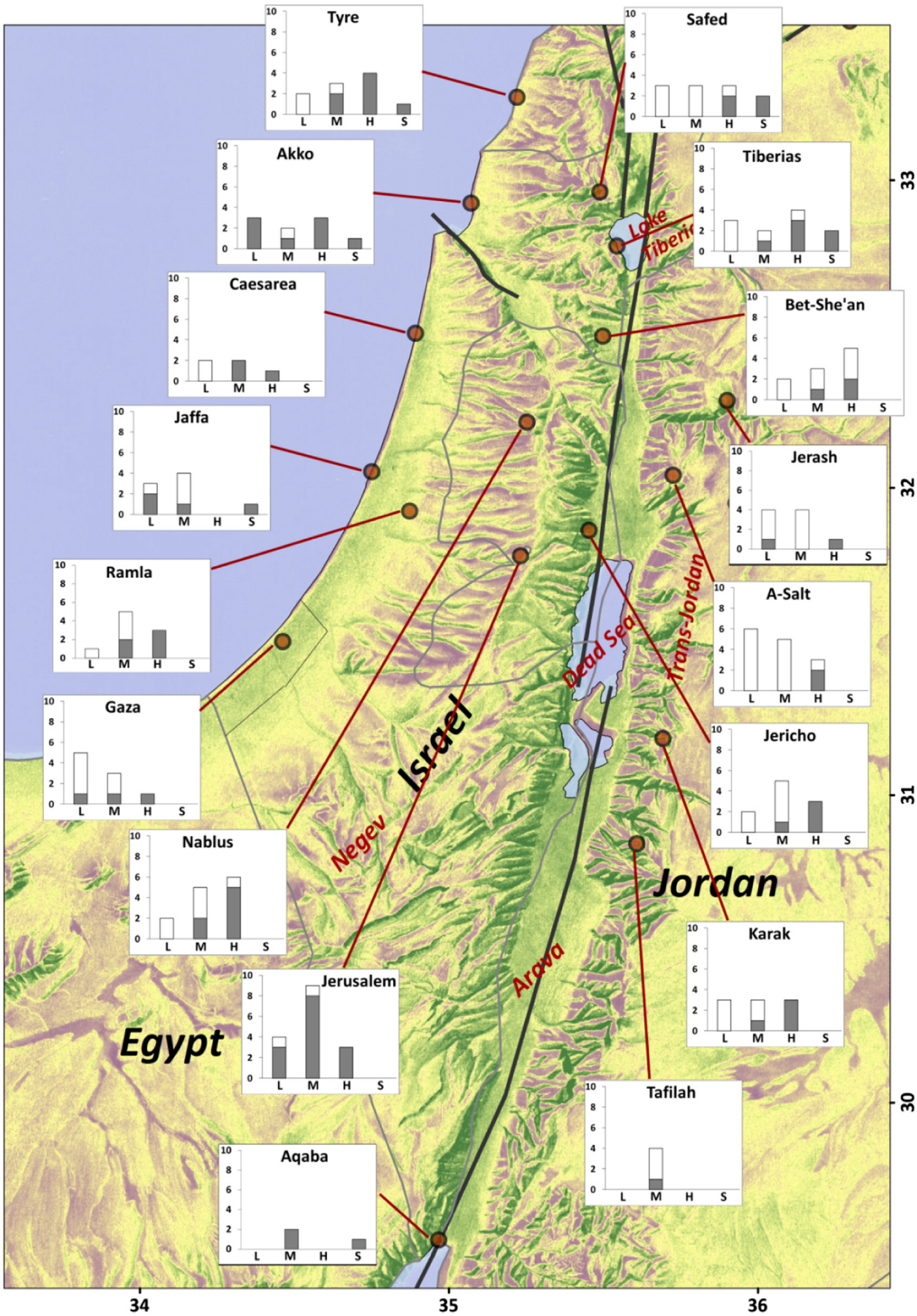

Fig. 6. Recurrence of damage in major localities in Israel and its close surroundings between 31 BCE and 1927 CE (based on Table 6). Insets represent the number of times the given locality was hit, classified into severity of damage: L – light, M – moderate, H – heavy and S – severe (see definitions in Table 3). The gray portion of the bars denote the number of reports of damage in that locality while the hollow part of the bars represent the assumed number of 'missing' reports, i.e., cases where strong shaking most likely affected that site but there were no reports from there.

5.5. Damage in ancient cities

Fig. 6 presents histograms of the cumulative damage (reported and unreported) along with severity estimations (Table 3) for the major ancient cities in our study area. Accordingly, Tyre, Akko (Acre), Safed and Tiberias were reported to be heavily or severely hit at least four times. South of the Galilee, most of the cities suffered much less; the only exceptions are Nablus and Bet She'an with six and five hits of heavy damage, respectively. Thus, although the northern cities were affected by fewer damaging earthquakes (mainly the C-N and N earthquakes), the historical experience shows they suffered more severely than the central or southern cities. This conforms to our previous observation of the N and N-C earthquakes tending to be more destructive (stronger) than the C earthquakes. It should be stressed, however, that other reasons may affect the damage severity as well, such as the proximity of a given site to the epicenter, construction quality and local site-effects (e.g., Zaslavsky et al., 2003). Nevertheless, in terms of preparedness towards and mitigation of future earthquakes, these severity observations ought to be taken into consideration.

Cities closer to the Jordan Valley are less reported than expected. This is not surprising as the Jordan Valley and Transjordan were much less populated than the coastal plain and inland Israel during the last two millennia. Thus, their proximity to the DST suggests they might have experienced more damage than reported. Indeed, Bet She'an, Jerash, A-Salt, Jericho, Karak and Tafilah seem to have been damaged more than twice the times known to us from the number of reports (Table 6). We back up this claim using the damage distribution of the $M = 6.2$ 1927 Jericho earthquake (Avni, 1999) originating at the northern Dead Sea (Shapira et al., 1993; Zohar and Marco, 2012). The earthquake damaged not only central Israel but also A-Salt, Jerash, Karak and Tafilah in Jordan. Its N-S damage spread is similar to that of several type C earthquakes, e.g., the 363, 1033, 1293, 1458 and 1834 earthquakes (Fig. 3). Therefore, these historical earthquakes, just like the 1927 earthquake, might have damaged cities in or close to the Jordan Valley as well. For instance, the 1546 earthquake (Ambraseys and Karcz, 1992) caused damage in Karak and Jerash but might affected Jericho and A-Salt as well.

Most of the damage reports ascribed to Jerusalem are of a moderate degree and the city was heavily damaged only three times. However, although well documented and <30 km from the DST, there is not a single report of severe damage. Nablus on the other hand, with similar proximity to the DST, suffered much more, probably due to the influence of local site-effects (Katz and Crouvi, 2007). In comparison once again to the 1927 Jericho earthquake, Nablus was severely damaged with dozens of casualties while Jerusalem suffered less with only a single death (Avni, 1999).

Along the coastal plain of Israel, Caesarea and Gaza were reported to be heavily damaged only once while Jaffa, located in between, suffered severe maximal damage. The region of Jaffa, part of the coastal and inner plain of Israel, which also contains the cities of Antipatris, Nicopolis (Emmaus), Lod and Ramla, was affected more severely than other localities in their surroundings. Similarly, during the 1927 earthquake Lod and Ramla were damaged much more than cities closer to the epicenter (Shapira et al., 1993) such as Jerusalem and Jericho. As in Nablus, the dominance of local site-effect amplification might be the reason (Gvirtzman and Zaslavsky, 2009).

6. Conclusions

This paper presents a comprehensive examination of damage from historical earthquakes that affected Israel and its close vicinity. The data were systematically collected, screened, authenticated and stored within a GIS-based relational database. Overall, in 31 damaging earthquakes we counted 420 damage reports in 186 localities, 54 of them reported to be hit at least twice. The most reported site is Jerusalem with 14 hits, probably due to its close proximity to the DST and to its being a continuous political and cultural center throughout history. Following are Akko (Acre), Tiberias, Nablus and Tyre with 8, 7, 7 and 6 reports, respectively. We also found that the total number of damage reports almost equals the number of estimated missing reports, which supports the obvious working hypothesis that the historical share covers only part of what had really happened.

We classified the earthquakes by their north-south damage extent and associated each with a geographic part of the DST. Altogether we detected 4, 17, 8 and 2 earthquakes that struck the southern, central, central-northern and northern parts of the DST, respectively. We found that although the previously assessed magnitudes might have been underestimated, the extent of the N-S damage serves as a good indicator of the size of the earthquakes. Accordingly, we graded the earthquakes for which the information was sufficient. The damage extent and the size of the northern earthquakes seem to be greater than that of the central earthquakes. In addition, apart from the southern earthquakes, the damage seems (with the exception of the 363 earthquake) not to extend south of the Dead Sea region (geographic latitude of 31.5°N). This may imply a possible change in the style of tectonic activity in the southern part of the DST, but could also be explained by the lack of reports from the desert regions in southern Israel and Jordan. The temporal distribution of the northern earthquakes is clustered in short periods of 100–200 years with low activity intervals of several hundred years in between, while the central earthquakes occur more regularly, about every 100–150 years.

Localities in the Galilee and north of it suffered maximal damage more than localities in central and southern Israel with a few exceptions: Nablus and its close surroundings and also the coastal plain delineated roughly by Jaffa, Antipatris and Nicopolis (Emmaus). In these cities site effects were probably more dominant than in other regions. For the sake of hazard management, these severity observations ought to be taken into consideration for future planning and risk mitigation.

Acknowledgments

We highly appreciate and thank Alon Moshe and Eliyahu Shara'bi from the Geological Survey of Israel for their assistance in collecting and digitizing the data. Thanks are also due to Dr. Milka Levy-Rubin from the National Library of Israel, Prof. Amikam Elad, Dr. Kate Raphael and Dr. Katia Cytryn-Silverman from the Hebrew University of Jerusalem, Prof. Shmuel Marco and Prof. Gideon Biger from Tel Aviv University, Dr. Ezra Zilberman and Dr. Tsafrir 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 (Grants #210-17-006, #29-17-043), the Ministry of Science, Technology and Space (Grant #10241), and the Amiran and Rachel Yanai't Ben-Tzvi fellowships.

References

Agnon, A., 2014. Pre-instrumental earthquakes along the Dead Sea Rift. In: Garfunkel, Z., Ben-Avraham, Z., Kagan, E. (Eds.), Dead Sea Transform Fault System: ReviewsModern Approaches in Solid Earth Sciences vol. 6. Springer, Dordrecht, pp. 207–261.
Agnon, A., Amit, R., Hough, S.E., Michetti, A.M., 2010. Introduction: the Dead Sea Rift as a natural laboratory for neotectonics and paleoseismology. Isr. J. Earth Sci. 58:139–145. http://dx.doi.org/10.1560/IJES.58.3-4.139.
Ambraseys, N.N., 1971. Value of historical records of earthquakes. Nature 232, 375–379.
Ambraseys, N.N., 1997. The earthquake of 1 January 1837 in Southern Lebanon and Northern Israel. Ann. Geophys. 11 (4), 923–935.
Ambraseys, N.N., 2004. The 12th century seismic paroxysm in the Middle East: a historical perspective. Ann. Geophys. 47, 733–758.
Ambraseys, N.N., 2005. Historical earthquakes in Jerusalem - a methodological discussion. J. Seismol. 9, 329–340.
Ambraseys, N.N., 2006. Earthquakes and archaeology. J. Archaeol. Sci. 33, 1008–1016.
Ambraseys, N.N., 2009. Earthquakes in the Mediterranean and Middle East. A Multidisciplinary Study of Seismicity up to 1900. Cambridge University Press, New York.
Ambraseys, N.N., Barazangi, M., 1989. The 1759 earthquake in the Bekaa Valley - implications for earthquake hazard assessment in the eastern Mediterranean region. J. Geophys. Res. Solid Earth Planets 94 (B4), 4007–4013.

Ambraseys, N.N., Finkel, C., 1995. The Seismicity of Turkey and Adjacent Areas, a Historical Review, 1500–1800. Eren Yayincilik, Istanbul.

Ambraseys, N.N., Jackson, J.A., 1998. Faulting associated with historical and recent earthquakes in the Eastern Mediterranean region. Geophys. J. Int. 133, 390–406.

Ambraseys, N.N., Karcz, I., 1992. The earthquake of 1546 in the Holy Land. Terra Nova 4 (2), 253–262.

Ambraseys, N.N., Melville, C.P., 1988. An analysis of the Eastern Mediterranean earthquake of 20 May 1202. In: Lee, W.K.H., Meyers, H., Shimazaki, K. (Eds.), Historical Seismograms and Earthquakes of the World vol. 1. Academic Press, San Diego, pp. 181–200.

Ambraseys, N.N., White, D., 1997. The seismicity of the eastern Mediterranean region 550–1 BC: a reappraisal. J. Earthq. Eng. 1, 603–632.

Amit, R., Zilberman, E., Porat, N., Enzel, Y., 1999. Relief inversion in the Avrona playa as evidence of large-magnitude historical earthquakes, southern Arava valley, Dead Sea Rift. Quat. Res. 52 (1), 76–91.

Austin, A.S., Franzb, G.W., Frostc, E.G., 2000. Amos's earthquake: an extraordinary Middle East seismic event of 750 B.C. Int. Geol. Rev. 42 (7), 657–671.

Avni, R., 1999. The 1927 Jericho Earthquake, Comprehensive Macroseismic Analysis Based on Contemporary Sources. (PhD.). Ben Gurion University, Beer-Sheva.

Avni, R., Bowman, D., Shapira, A., Nur, A., 2002. Erroneous interpretation of historical documents related to the epicenter of the 1927 Jericho earthquake in the Holy Land. J. Seismol. 6, 469–476.

Baer, G., Funning, G.J., Shamir, G., Wright, T.J., 2008. The 1995 November 22, MW 7.2 Gulf of Eilat earthquake cycle revisited. Geophys. J. Int. 175 (3):1040–1054. http://dx.doi.org/10.1111/j.1365-246X.2008.03901.x.

Bakun, W.H., 2006. Estimating locations and magnitudes of earthquakes in Southern California from Modified Mercalli Intensities. Bull. Seismol. Soc. Am. 96 (4A), 1278–1295.

Bakun, W.H., Wentworth, C.M., 1997. Estimating earthquake location and magnitude from seismic intensity data. Bull. Seismol. Soc. Am. 87 (6), 1502–1521.

Bakun, W.H., Haugerud, A.R., Hopper, G.M., Ludwin, S.R., 2002. The December 1872 Washington state earthquake. Bull. Seismol. Soc. Am. 92 (8), 3239–3325.

Bakun, W.H., Johnston, A.C., Hopper, M.G., 2003. Estimating locations and magnitudes of earthquakes in eastern North America from Modified Mercalli Intensities. Bull. Seismol. Soc. Am. 93 (1), 190–202.

Begin, B.Z., 2005. Destructive Earthquakes in the Jordan Valley and the Dead Sea - their Recurrence Intervals and the Probability of their Occurence. Geological Survey of Israel, Jerusalem, p. 51.

Ben-Menahem, A., 1979. Earthquake catalog for the Middle East (92 B.C.–1980 A.D.). Boll. Geofis. Teor. Appl. 21, 245–310.

Ben-Menahem, A., 1981. Variation of sleep and creep along the Levant Rift over the past 4500 years. Tectonophysics 80, 183–197.

Ben-Menahem, A., 1991. Four thousand years of seismicity along the Dead Sea rift. J. Geophys. Res. 96 (B12), 195–216.

Ben-Menahem, A., Aboodi, E., 1981. Micro-and macroseismicity of the Dead Sea rift and off-coast eastern Mediterranean. Tectonophysics 80, 199–233.

Ben-Menahem, A., Nur, A., Vered, M., 1976. Tectonics, seismicity and structure of the afro-Eurasian junction-the breaking of the incoherent plate. Phys. Earth Planet. Inter. 12 (1), 1–50.

Braeuer, B., Asch, G., Hofstetter, R., Haberland, C., Jaser, D., El-Kelani, R., Weber, M., 2014. Detailed seismicity analysis revealing the dynamics of the southern Dead Sea area. J. Seismol. 18 (4):731–748. http://dx.doi.org/10.1007/s10950-014-9441-4.

Brock, S.P., 1977. A Letter Attributed to Cyril of Jerusalem on the Rebuilding of the Temple. Bulletin of the School of Oriental and African Studies vol. 40. University of London: Cambridge University Press, pp. 267–286.

Daëron, M., Klinger, Y., Tapponnier, P., Elias, A., Jacques, E., Sursock, A., 2005. Sources of the large A.D. 1202 and 1759 Near East earthquakes. Geology 33:529–532. http://dx.doi.org/10.1130/G21352.1.

Daëron, M., Klinger, Y., Tapponnier, P., Elias, A., Jacques, E., Sursock, A., 2007. Long record of 10 to 13 paleoearthquakes on the Yammouneh fault, Levant system, Lebanon. Bull. Seismol. Soc. Am. 97, 749–771.

Darawcheh, R., Margottini, C., Paolini, S., 2000. The 9 July 551 AD Beirut Earthquake, Eastern Mediterranean region. J. Earthq. Eng. 4, 403–414.

Elad, A., 1982. An early Arabic source concerning the markets of Jerusalem. Cathedra 24, 31–40.

Elad, A., 2002. Community of believers of 'Holy Men' and 'Saints' or community of Muslims? The rise and development of early Muslim historiography. J. Semit. Stud. XLVII (1), 241–308.

Ellenblum, R., Marco, S., Agnon, A., Rockwell, T., Boas, A., 1998. Crusader castle torn apart by earthquake at dawn, 20 May 1202. Geology 26 (4), 303–306.

Ellenblum, R., Marco, S., Kool, R., Davidovitch, U., Porat, R., Agnon, A., 2015. Archaeological record of earthquake ruptures in Tell Ateret, the Dead Sea. Tectonics http://dx.doi.org/10.1002/2014TC003815.

Ferrari, G., Guidoboni, E., 2000. Seismic scenarios and assessment of intensity: some criteria for the use of the MCS scale. Ann. Geofis. 43 (4), 707–720.

Freund, R., Zak, I., Garfunkel, Z., 1968. Age and rate of sinistral movement along the Dead Sea rift. Nature 220, 253–255.

Garfunkel, Z., 2010. The long- and short-term lateral slip and seismicity along the Dead Sea Transform: an interim evaluation. Isr. J. Earth Sci. 58, 217–235.

Garfunkel, Z., Ben-Avraham, Z., 1996. The structure of the Dead Sea basin. Tectonophysics 266 (1–4), 155–176.

Garfunkel, Z., Zak, I., Freund, R., 1981. Active faulting in the Dead Sea rift. Tectonophysics 80, 1–26.

Gasperini, P., Vannucci, G., Tripone, D., Boschi, E., 2010. The location and sizing of historical earthquakes using the attenuation of macroseismic intensity with distance. Bull. Seismol. Soc. Am. 100 (5A), 2035–2066.

Gomez, F., Meghraoui, M., Darkal, A.N., Hijazi, F., Mouty, M., Sbeinati, M.R., ... Barazangi, M., 2003. Holocene faulting and earthquake recurrence along the Sergahya branch of the Dead Sea fault system in Syria and Lebanon. Geophys. J. Int. 153, 658–674.

Grünthal, G., 1998. European Macroseismic Scale 1998 EMS-98. Paper presented at the European Seismological Commission, Luxembourg.

Guidoboni, E., Comastri, A., 2005. Catalogue of Earthquakes and Tsunamis in the Mediterranean Area from the 11th to the 15th Century. INGV-SGA, Bologna.

Guidoboni, E., Ebel, J.E., 2009. Earthquakes and Tsunamis in the Past: A Guide to Techniques in Historical Seismology. Cambridge University Press, New York.

Guidoboni, E., Comastri, A., Traina, G., 1994. Catalogue of Ancient Earthquakes in the Mediterranean Area up to the 10th Century. ING-SGA, Bologna.

Gvirtzman, Z., Zaslavsky, Y., 2009. Map of Zones with Potentially High Ground Motion Amplification: Explanatory Notes. Geological Survey of Israel and Geophysical Institute of Israel, Jerusalem, p. 4.

Hamiel, Y., Amit, R., Begin, B.Z., Marco, S., Katz, O., Salamon, A., ... Porat, N., 2009. The seismicity along the Dead Sea fault during the last 60000 years. Bull. Seismol. Soc. Am. 99 (3), 2020–2026.

Hamiel, Y., Piatibratova, O., Mizrahi, Y., 2016. Creep along the northern Jordan Valley section of the Dead Sea fault. Geophys. Res. Lett. 43. http://dx.doi.org/10.1002/2016GL067913.

Hanks, T.C., Kanamori, H., 1979. A moment-magnitude scale. J. Geophys. Res. 84, 2348–2350.

Hayens, J.M., Niemi, T.M., Attalah, M., 2006. Evidence for ground-rupturing earthquakes on the northern Wadi Araba fault at the archaeological site of Qasr Tilah, Dead Sea Transform fault system, Jordan. J. Seismol. 10:415–430. http://dx.doi.org/10.1007/s10950-006-9028-9.

Hough, S.E., Avni, R., 2010. The 1170 and 1202 CE Dead Sea rift earthquakes and long-term magnitude distribution of the Dead Sea fault zone. Isr. J. Earth Sci. 58, 295–308.

Howe, D.R., 1983. Data Analysis for Data Base Design. Edward Arnold, London.

Ish-Shalom, M., 1965. Christian Travels in the Holy Land. Description and Sources on the History of the Jews in Palestine. Am Oved Publishers, Tel Aviv.

Kagan, E.J., Agnon, A., Bar-Matthews, M., Ayalon, A., 2005. Dating large infrequent earthquakes by damaged cave deposits. Geology 33 (4), 261–264.

Kagan, E.J., Stein, M., Agnon, A., Neumann, F., 2011. Intrabasin paleoearthquake and quiescence correlation of the late Holocene Dead Sea. J. Geophys. Res. Solid Earth 116 (B4). http://dx.doi.org/10.1029/2010JB007452.

Karcz, I., 1987. Bibliographic Reliability of Catalogues of Historic Earthquakes in and around Israel. Catalogue of Turcott and Arieh (1986)Geological Survey of Israel, Jerusalem, p. 92.

Karcz, I., 2004. Implications of some early Jewish sources for estimates of earthquake hazard in the Holy Land. Ann. Geophys. 47 (2/3), 759–792.

Karcz, I., Lom, P., 1987. Bibliographic Reliability of Catalogues of Historic Earthquakes in and Around Israel: Methodology and Background. Geological Survey of Israel, Jerusalem, p. 89.

Katz, O., Crouvi, O., 2007. The geotechnical effects of long human habitation (2000 < years): earthquake induced landslide hazard in the city of Zefat, northern Israel. Eng. Geol. 95 (3–4), 57–78.

Ken-Tor, R., Agnon, A., Enzel, Y., Stein, M., Marco, S., Negendank, J.F.W., 2001. High-resolutiongeological record of historic earthquakes in the Dead Sea basin. J. Geophys. Res. 106, 2221–2234.

Ken-Tor, R., Stein, M., Enzel, Y., Agnon, A., Marco, S., Negendank, J.F.W., 2002. Precision of calibrated radiocarbon ages of historic earthquakes in the Dead Sea basin. Radiocarbon 44 (1), 396–397.

Khair, K., 2001. Geomorphology and seismicity of the Toum fault as one of the active branches of the Dead Sea fault system in Lebanon. J. Geophys. Res. 106 (B3), 4233–4245.

Klinger, Y., Avouac, J.P., Kraraki, N., Dorbath, L., Bourles, D., Reyss, J.L., 2000. Slip rate on the Dead Sea Transform fault in northern Arava valley (Jordan). Geophys. J. Int. 142, 755–768.

Marco, S., 2008. Recognition of earthquake-related damage in archaeological sites: examples from the Dead Sea fault zone. Tectonophysics 453, 148–156.

Marco, S., Klinger, Y., 2014. Review of on-fault paleoseismic studies along the Dead Sea fault. In: Garfunkel, Z., Ben-Avraham, Z. (Eds.), Dead Sea Transform Fault System: ReviewsModern Approaches in Solid Earth Sciences vol. 6. Springer, Dordrecht, pp. 183–205.

Marco, S., Stein, M., Agnon, A., Ron, H., 1996. Long-term earthquake clustering: a 50,000-year paleoseismic record in the Dead Sea graben. J. Geophys. Res. 101 (B3), 6179–6191.

Marco, S., Hartal, M., Hazan, N., Lev, L., Stein, M., 2003. Archaeology, history, and geology of the A.D. 749 earthquake, Dead Sea Transform. Geology 31, 665–668.

Medvedev, S.W., Sponheuer, W., Karnik, V., 1965. Seismic Intensity Scale Version MSK 1964. United Nation Educational, Scientific and Cultural Organization, Paris, p. 7.

Meimaris, E.Y., Kritikakou, I.K., 2005. Inscriptions from Palaestina Tertia vol. 1. National Hellenic Research Foundation, Athens.

Migowski, C., Agnon, A., Bookman, R., Negendank, J.F.W., Stein, M., 2004. Recurrence pattern of Holocene earthquakes along the Dead Sea transform revealed by varve-counting and radiocarbon dating of lacustrinesediments. Earth Planet. Sci. Lett. 222 (1), 301–314.

Nemer, T., Meghraoui, M., 2006. Evidence of coseismic ruptures along the Roum fault (Lebanon): a possible source for the AD 1837 earthquake. J. Struct. Geol. 28 (8), 1483–1495.

Nemer, T., Meghraoui, M., Khair, K., 2008. The Rachaya-Sergahaya fault system (Lebanon): evidence of coseismic ruptures, and the AD 1759 earthquake sequence. J. Geophys. Res. 113 (B5).

Niemi, T.M., 2011. Earthquakes in Aqaba, Jordan over the past 2,000 years: evidence from historical, geological and archaeological data. 2nd INQUA-IGCP-567 International

Workshop on Active Tectonics, Earthquake Geology, Archaeology and Engineering. Corinth, Greece.

Porat, N., Duller, G.A.T., Amit, R., Zilberman, E., Enzel, Y., 2009. Recent faulting in the southern Arava, Dead Sea transform: evidence from single grain luminescence dating. Quat. Int. 199 (1–2), 34–44.

Quennel, A.M., 1959. Tectonics of the Dead Sea Rift. Paper Presented at the 20th International Geological Congress, Mexico.

Richter, C.F., 1958. Elementary Seismology. W. H. Freeman and Company, San Francisco, pp. 135–149.

Röhricht, R., 1890. Bibliotheca Geographica Palaestinae: Chronologisches Verzeichnis der von 333 bis 1878 Verfassten Literatur über das Heilige Land. John Trotter Publishers, London.

Rucker, J.D., Niemi, T.M., 2010. Historical earthquake catalogues and archaeological data: achieving synthesis without circular reasoning. Geol. Soc. Am. 471, 97–106.

Russell, K.W., 1980. The earthquake of May 19, A.D. 363. Bull. Am. Sch. Orient. Res. 238, 47–64.

Russell, K.W., 1985. The earthquake chronology of Palestine and northwest Arabia from the 2nd through the mid-8th century A.D. Bull. Am. Sch. Orient. Res. 260, 37–59.

Salamon, A., 2009. Patterns of seismic sequences in the Levant-interpretation of historical seismicity. J. Seismol. 14 (2), 339–367.

Salamon, A., Hofstetter, A., Garfunkel, Z., Ron, H., 1996. Seismicity of the eastern Mediterranean region: perspective from the Sinai subplate. Tectonophysics 263, 293–305.

Salamon, A., Rockwell, T., Ward, N.S., Guidoboni, E., Comastri, A., 2007. Tsunami hazardevaluation of the eastern Mediterranean: historical analysis and selected modeling. Bull. Seismol. Soc. Am. 97 (3), 705–724.

Salamon, A., Rockwell, T., Guidoboni, E., Comastri, A., 2011. A critical evaluation of tsunami records reported for the Levant coast from the second millennium BCE to the present. Isr. J. Earth Sci. 58, 327–354.

Sbeinati, M.R., Darawcheh, R., Mouty, M., 2005. The historical earthquakes of Syria: an analysis oflarge and moderate earthquakes from 1365 B.C. to 1900 A.D. Ann. Geophys. 48 (3), 347–435.

Shamir, G., 1996. The November 22, 1995, Nuweiba Earthquake, Gulf of Elat (Aqaba): Mechanical Analysis. the Geological Survey of Israel, Jerusalem.

Shapira, A., Avni, R., Nur, A., 1993. A new estimate for the epicenter of the Jericho earthquake of 11 July 1927. Isr. J. Earth Sci. 42, 93–96.

Sieberg, A., 1930. Geologie der Erdbeben. Handbuch Geophys. 2 (4), 552–555.

Sieberg, A., 1932. Untersuchungen Uber Erbeben und Bruchschollenbau im ostlichen Mittelmeergebiet Denkfchriften der Medizinisch Natur-wissenschaftlichen Gesellschaft. Jena 18, 159–273.

Sirovich, L., Pattenati, F., 2003. Tests of source-parameter inversion of the U.S. Geological Survey intensities of the Whittier Narrows 1987 earthquake. Bull. Seismol. Soc. Am. 93, 47–60.

Sirovich, L., Pattenati, F., 2009. Validation of a kinematic and parametric approach to calculating intensity scenarios. Soil Dyn. Earthq. Eng. 29, 1113–1122.

Sirovich, L., Pettenati, F., 2001. Test of source-parameter inversion of the intensities of a 54,000-death shock of the seventeenth century in southeast Sicily. Bull. Seismol. Soc. Am. 91 (4), 792–811.

Stiros, S., Jones, R.E. (Eds.), 1996. Archaeoseismology. Institute of Geology and Mineral Exploration, Athens.

Topozada, T.R., 1975. Earthquake magnitude as a function of intensity data in California and western Nevada. Bull. Seismol. Soc. Am. 65, 1223–1238.

Tsafrir, Y., Foester, G., 1992. The dating of the earthquake of the sabbatical-year of 749 CE in Palestine. Bull. Sch. Orient. Afr. Stud. Univ. Lond. 55, 231–235.

Turcotte, T., Arieh, E., 1988. Catalog of Earthquakes in and around Israel. Israel Electric Corporation, Haifa.

Vered, M., Striem, H.L., 1977. A macroseismic study and the implications of structural damage of two recent major earthquakes in the Jordan rift. Bull. Seismol. Soc. Am. 67 (6), 1607–1613.

Wechsler, N., Rockwell, T., Klinger, Y., Stepacikova, P., Kanari, M., Marco, S., Agnon, A., 2014. A paleoseismic record of earthquakes for the Dead Sea transform fault between the first and seventh centuries C.E.: Nonperiodic behavior of a plate boundary fault. Bull. Seismol. Soc. Am. 1 (3). http://dx.doi.org/10.1785/0120130304.

Wells, D.L., Coppersmith, K.J., 1994. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. Bull. Seismol. Soc. Am. 84 (4), 974–1002.

Wood, H.O., Neumann, F., 1931. Modified Mercalli Intensity scale of 1931. Bull. Seismol. Soc. Am. 21, 277–283.

Zaslavsky, Y., Shapira, A., Leonov, J., 2003. Empirical evaluation of site effects by means of H/V spectral ratios at the locations of strong motion accelerometers in Israel. J. Earthq. Eng. 7 (4), 655–677.

Zilberman, E., Amit, R., Porat, N., Enzel, Y., Avner, U., 2005. Surface ruptures induced by the devastating 1068 AD earthquake in the southern Arava valley, Dead Sea rift, Israel. Tectonophysics 408, 79–99.

Zohar, M., Marco, S., 2012. Re-estimating the epicenter of the 1927 Jericho earthquake using spatial distribution of intensity data. J. Appl. Geophys. 82:19–29. http://dx.doi.org/10.1016/j.jappgeo.2012.03.004.

Zohar, M., Rubin, R., Salamon, A., 2014. Earthquake damage and repair: new evidence from Jerusalem on the 1927 Jericho earthquake. Seismol. Res. Lett. 85 (4):912–922. http://dx.doi.org/10.1785/0220140009.

Zohar, M., Salamon, A., Rubin, R., 2016. Reappraised list of historical earthquakes in Israel and its close surroundings. J. Seismol. http://dx.doi.org/10.1007/s10950-016-9575-7.