Temporal and Spatial Patterns of Seismic Activity Associated with the Dead Sea Transform (DST) during the Past 3000 Yr

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Abstract

Historical reports of earthquakes occurring before the twentieth century along the Dead Sea Transform (DST) are available for the past 3000 yr. Most of them are organized in various catalogs, reappraisals, and lists. Using a comprehensive and consistent compilation of these reports, the historical seismicity associated with the DST as a complete tectonic unit was examined. The compilation, supported by paleoseismic and archeoseismic evidence, resulted in 174 reliable historical earthquakes and 112 doubtful ones. The reliable earthquakes, along with 42 post-nineteenth century instrumental earthquakes, are an up-to-date evaluation of the DST seismicity starting from the mid-eighth century B.C.E. until 2015 C.E. Additionally, the scenario of historical earthquakes such as the 363 C.E. and 1033 C.E. events was resolved. The characterization of temporal and spatial patterns of DST seismicity, classifying them into four geographical zones, raised that most of the northern destructive earthquakes are clustered while clustering at the central and southern zones is less abundant.

Cite this article as Zohar, M. (2019). Temporal and Spatial Patterns of Seismic Activity Associated with the Dead Sea Transform (DST) during the Past 3000 Yr, *Seismol. Res. Lett.* 0, doi: 10.1785/0220190124.

Supplemental Material

Introduction

Historical records of seismic activity associated with the Dead Sea Transform (DST) are available for the past 3000 yr, from biblical times (Bentor, 1989; Nur and Ron, 1996) until the beginning of the twentieth century. They vary and are comprised of chronicles, accounts, documents, letters, theological writing, maps, drawings, photographs, and more. Although occasionally incomplete, exaggerated, and inaccurate (Stucchi *et al.*, 2004; Woessner and Wiemer, 2005), the historical share is too important to be ignored. Consequently, since the fifteenth century C.E., many historical records documenting earthquakes were collected in various global and regional catalogs, lists, and reappraisals. The first known earthquake list with relevance to the Mediterranean region was probably compiled by the Italian Giannozzo Manetti during the mid-fifteenth century (Manetti, 1457). This was followed by compendiums made by the Muslim scholar al-Suyuti (Razani, 1972) at the beginning of the sixteenth century and of the Italian artist Pirro Ligorio in the late sixteenth century (Ligorio, 1574–1577). In the seventeenth and eighteenth centuries, additional compilations, primarily for European earthquakes, were composed (e.g., Bonito, 1691; Coronelli, 1693; Seyfart, 1756; Berryat, 1761). In the nineteenth century, detailed earthquake compilations evolved, transforming gradually from simple lists to structured catalogs (e.g., von Hoff, 1840; Perrey, 1850; Mallet, 1852; Schmidt, 1879, 1880; Fuchs, 1886), which became the base for the early and second half-twentieth century catalogs that include the Dead Sea region (e.g., Arvanitakis, 1903; de Ballore, 1906; Willis, 1928, 1929; Sieberg, 1932; Amiran, 1952; Plassard and Kogoj, 1968; Ben-Menahem, 1979; Poirier and Taher, 1980). Although being descriptive and detailed, until the late twentieth century, many of the catalogs paid little attention to the complexity involved in interpreting historical sources and consequently, potentially erroneous entries made by their predecessors were accepted. Furthermore, some of the catalogs do not cite nor mention the references that the earthquake entries are based on. Therefore, errors, duplications, and misinterpretations of historical sources have been entered as true earthquakes into several of these catalogs (Karcz, 2004; Ambraseys, 2005; Albini, 2011).

The inclusion of problematic earthquake entries into the literature was raised and intensely discussed toward the end of the twentieth century (e.g., Ambraseys and Melville, 1982; Guidoboni, 1985; Karcz and Lom, 1987; Guidoboni and Ferrari, 1989; Alexandre, 1991; Vogt, 1991) and marked the transition of historical seismology into the phase of critical approach in interpreting historical sources. Consequently, since late twentieth century, significant efforts were expended on the region encompassing the Dead Sea to clarify and filter out erroneous readings, arrayed in catalogs (e.g., Karcz, 1987;

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Ambraseys *et al.*, 1994; Amiran *et al.*, 1994; Guidoboni *et al.*, 1994; Papazachos *et al.*, 2000; Guidoboni and Comastri, 2005; Sbeinati *et al.*, 2005; Salamon, 2009), reappraisals (Ambraseys, 1992; Salamon *et al.*, 2007, 2011; Salamon, 2009; Zohar *et al.*, 2016), and focused investigations (Ambraseys and Melville, 1988; Ambraseys and Barazangi, 1989; Ambraseys and Karcz, 1992; Ambraseys, 1997, 2004; Guidoboni, Bernardini, and Comastri, 2004; Guidoboni, Bernardini, Comastri, *et al.*, 2004). Also, the era of digital data and the expansion of Internet resources enabled online compilations of the historical data and facilitated the ability to interactively present the data using web browsers and smart phones. Examples may be found in Grünthal and Wahlström (2012a) after Grünthal and Wahlström (2012b), who compiled 107 European events until 1903, namely the unified catalogue of earthquakes in central, northern, and northwestern Europe (CENEC, see Data and Resources); the SHARE European Earthquake Catalogue (SHEEC, see Data and Resources) listing historical earthquakes between 1000 and 1899 C.E., and instrumental earthquakes between 1900 and 2006 C.E., for the western Mediterranean region (Stucchi *et al.*, 2012); and the European Archive of Historical EArthquake Data (AHEAD, see Data and Resources) as a pan-European platform supporting the research of historical earthquakes (Locati *et al.*, 2014). Nevertheless, these online databases mostly span the Europe and western Mediterranean region with little attention given to the Middle East. To the large amount of historical reports of earthquakes occurring before the twentieth century, one can add geological and archeological evidence, which date back between several thousands and up to tens of thousands of years, alongside seismograph-based monitoring recorded since the beginning of the twentieth century. Altogether, these comprise the major sources of information for the analysis of historical earthquakes.

Most of the seismic activity in the Levant is associated with the DST (Garfunkel and Ben-Avraham, 1996; Salamon *et al.*, 1996, 2003; Garfunkel, 2010), which is the main source of many destructive historical earthquakes (Hamiel *et al.*, 2009). It is a sinistrally lateral, leaky transform system extending over 1000 km from the Red Sea to southeastern Turkey (Fig. 1). It borders the Arabian plate and the Sinai subplate with an overall sinistral displacement since the Miocene of ~105 km (Quennel, 1959; Freund *et al.*, 1968; Garfunkel *et al.*, 1981). Recent Global Positioning System measurements indicate that the DST slip rate is about 4–5 mm/yr (Gomez, Karam, *et al.*, 2007), 4.9 ± 1.4 mm/yr (Le Beon *et al.*, 2008), 4.7 ± 0.7 mm/yr (Masson *et al.*, 2015), and ~4.1 mm/yr (Hamiel *et al.*, 2016), which represent an accumulated potential strain of ~4–5 m per millennium.

In general, historical reports of Levant earthquakes are organized chronologically in the various catalogs and reappraisals alongside their resulting damage. Sometimes, a given earthquake entry is tied to the triggering tectonic unit, in particular when there is supportive on-fault archeoseismic or paleoseismic evidence precisely indicating the ruptured tectonic segment (e.g., Ellenblum *et al.*, 1998; Altunel *et al.*, 2009; Klinger *et al.*, 2015). Classifying historical earthquakes into their potential tectonic origin is of great importance and attempts to characterize the long-term seismic activity should rely on earthquake entries associated as accurately as possible to a given tectonic unit. Recently, a spatial distinction of the historical earthquakes associated solely with preinstrumental DST activity was implemented (Zohar *et al.*, 2017). However, although proved to be more accurate than the already-in-use earthquake list of the Geophysical Institute of Israel (GII; Meirova *et al.*, 2017), their study was confined only to Israel and its close surroundings while neglecting other parts of the DST. Therefore, it is of great importance to widen the study to the rest of the DST using historical seismology approaches (Guidoboni and Ebel, 2009).

In this study, the historical seismicity associated with the DST is examined through a comprehensive and consistent compilation of the historical share, archeological remains, paleoseismic evidence, and instrumental data. This study attempts to distinguish between earthquakes associated with the DST and those originated by other tectonic units while paying careful attention the reliability of the relevant historical reports. Once a reliable list is compiled and sorted, the DST seismicity is evaluated using temporal and spatial patterns of the earthquake distribution.

Data

The sources of information used for the compilation include primarily modern catalogs and reappraisals (Guidoboni *et al.*, 1994; Guidoboni and Comastri, 2005; Sbeinati *et al.*, 2005; Ambraseys, 2009; Salamon, 2009; Salamon *et al.*, 2011), and to a lesser extent also early catalogs and lists (Willis, 1928, 1929; Shalem, 1951; Russell, 1985; Amiran *et al.*, 1994). In specific cases, when the interpretations of the historical sources in the literature were not decisive or were contradictory, the historical sources themselves were inspected. The process also consulted archeological evidence (Klinger *et al.*, 2000; Meghraoui *et al.*, 2003; Marco, 2008; Niemi, 2011), paleoseismic findings such as lake seismites, speleoseismites, rock falls, and landslides (Ken-Tor *et al.*, 2001; Migowski *et al.*, 2004; Kagan *et al.*, 2005; Agnon, 2014; Wechsler *et al.*, 2014) and focused, interdisciplinary studies (e.g., Karcz *et al.*, 1977; Marco *et al.*, 1997, 2003; Shaked *et al.*, 2004; Sbeinati *et al.*, 2010; Ferry *et al.*, 2011). Because of the poor documentation before the first millennia B.C.E., the compilation starts with the report of the earthquake occurring in mid-eighth century B.C.E. as appears in the book of Amos ("The Bible: New international version," 1989, Amos 1.1; Zechariah 14:3-5), thus excluding Bronze and Iron age earthquakes deduced in archeological sites (Marco *et al.*, 2006; Raphael and Agnon, 2018). The compilation ends at the beginning of the twenty-first century with added $M \geq 5$ instrumental earthquakes occurred

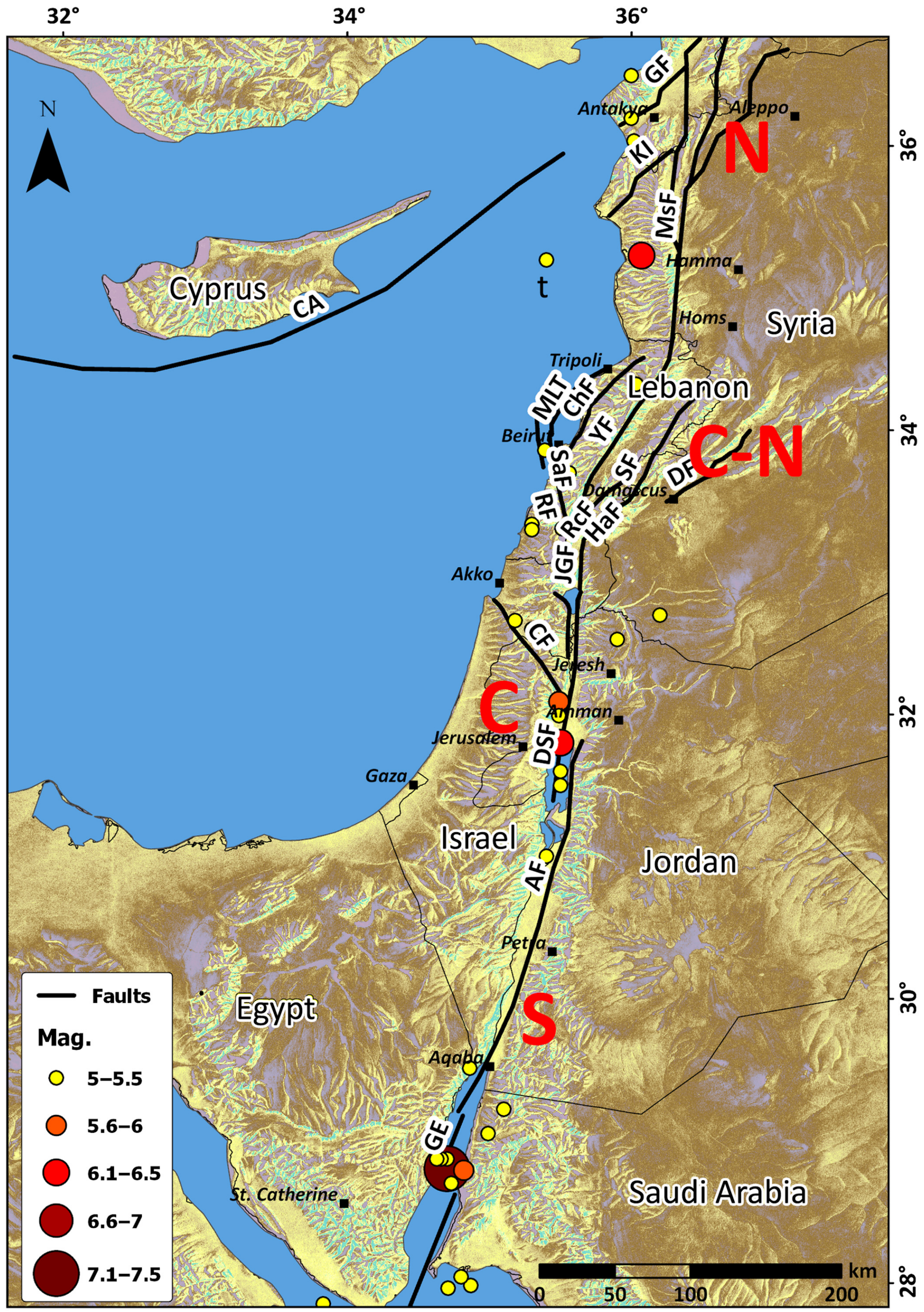


Figure 1. Map of the study area and instrumental earthquakes of magnitude M ≥ 5 between 1903 and 2017. The major tectonic element is the Dead Sea Transform (DST) system divided into four geographic zones (Zohar *et al.*, 2017): south (S), center (C), center-north (C-N), and north (N). The associated DST tectonic segments, from south to north, are: AF, Arava fault (Amit *et al.*, 1999; Porat *et al.*, 2009; Zilberman *et al.*, 2005); CF, Carmel fault; DSF, Dead Sea fault (Garfunkel *et al.*, 1981); GE, the pull-apart structures in the Gulf of Eilat and Aqaba (Garfunkel and Ben-Avraham, 1996); GF, Al-Ghab fault (Meghraoui, 2014); MsF, Missayf fault (Meghraoui *et al.*, 2003); RcF, Rachaya splay fault (Nemer *et al.*, 2008); RF, Roum splay fault (Khair, 2001; Nemer and Meghraoui, 2006); SF, Sergaya splay fault (Nemer *et al.*, 2008); YF, Yammouneh fault (Daëron *et al.*, 2007). Other tectonic segments are: CA, Cyprus Arc; ChF, Coastal flexure; DF, Damascus fault; HaF, Hasbaya fault; JGF, Jordan George fault (Nemer *et al.*, 2006); Kl, Killis fault (Gomez, Nemer, *et al.*, 2007); MLT, Mt. Lebanon thrust (Elias *et al.*, 2007); and SaF, Saida fault. The color version of this figure is available only in the electronic edition.

between ~1900 and 2015 C.E., extracted from previous studies (Salamon *et al.*, 1996; Salamon, 2004) and the U. S. Geological Survey and the GII archives (see Data and Resources).

Compilation of the Historical Accounts

One of the most important contributions of such compilations is the level of confidence given to each earthquake occurrence. Zohar *et al.* (2016) adopted the technique referred to as chains of transmission developed by Elad (1982), and defined a five-degree scale of confidence levels in which the authentication of a given occurrence is determined in relation to the historical context and the contemporary reporting sources. Accordingly, an earthquake documented by at least two contemporary (or near-contemporary) independent sources is accounted as highly reliable ("Very high" in Table 1), while an earthquake documented by unverified sources is considered to be questionable ("Doubtful" in Table 1). When an occurrence is also supported by archeoseismic remains or paleoseismic findings (or both), the confidence level rises by a degree. In cases of "Doubtful" or "Poor" events, the confidence level rises by 2 degrees and the earthquake occurrence becomes reliable ("Moderate" or "High" in Table 1). Additionally, to determine which of the earthquakes is part of a sequence of events, the compilation included classification into single (main), cluster, foreshock, and aftershocks (following Salamon, 2009).

For twentieth century C.E. earthquakes, the source parameters of size and epicenter are

TABLE 1
Level of Confidence in Verifying the Occurrence of a Given Earthquake

Confidence Level	Transmitters
Very high	At least two contemporary or near-contemporary independent sources with no confusion or contradiction regarding date, location, and details of the event
High	At least one contemporary or near-contemporary source with no confusion or contradiction regarding date, location, and details of occurrence
Moderate	At least one secondary source that draws from at least one reliable contemporary or near-contemporary source
Poor	Only secondary sources relying upon other secondary or unknown sources
Doubtful	False, duplicated, or misinterpreted sources

The scale was developed by Zohar *et al.* (2016) following the "chain of transmitters" suggested by Elad (1982).

TABLE 2
Size Degree of Earthquakes, Starting from Light to Great

Degree	Size	Description	Estimated Magnitude
1	Light	Felt only	$4 \le M < 4.9$
2	Moderate	Slight damage to buildings and other structures; few casualties	$5 \le M < 5.9$
3	Strong	A lot of damage and casualties in populated areas	$6 \le M < 6.9$
4	Major	Serious damage; many casualties	$7 \le M < 7.9$
5	Great	Total destruction of structures and communities near the epicenter	$M \ge 8$

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

monitored and available. This is also true for preinstrumental earthquakes resolved by on-fault archeoseismic and paleoseismic evidence which tie an earthquake occurrence to the originating tectonic fault. On the other hand, when interpreting historical sources, the veracity and incompleteness of the sources significantly limit the ability to resolve the size and location (Musson, 1998). Nevertheless, in cases of full coverage of the resulting damage, one can use the most severely affected zone (I_0) as a close approximation of the focus area, relatively close to the actual rupture (Cecic and Musson, 2004). Being aware that reports from the most severely affected zone may be inaccurate, the most reported damage zone (MRDZ) was used instead as a substitute for the earthquake origin. Each resulting MRDZ was applied to one of the four DST zones as follows (Fig. 1): (1) a southern zone (S)—extending south of the Dead Sea until the Red Sea and comprising the tectonic segments of the pull-apart structures in the Gulf of Eilat and Aqaba (Ben-Avraham *et al.*, 1979; Garfunkel and Ben-Avraham, 1996) and the Arava fault (Amit *et al.*, 1999; Zilberman *et al.*, 2005; Porat *et al.*, 2009); (2) a central zone (C)—extending from the Dead Sea to the Hula basin and comprising the pull-apart basin of the Dead Sea, the Dead Sea fault, the graben structure of Kinnarot, and the Sea of Galilee and the Jordan Gorge fault (Garfunkel *et al.*, 1981); (3) a central-northern zone (C-N)—spanning the Hula pull-apart basin and the fault system that splays into several branches, namely the Lebanon Bend-related Rachaya-Serghaia (LBR, see Marco and Klinger, 2014). That is, the Rachaya and Sergaya splays, the Yammouneh fault, and the Roum splay (Khair, 2001; Gomez *et al.*, 2003; Daëron *et al.*, 2005, 2007; Nemer and Meghraoui, 2006; Nemer *et al.*, 2008); and (4) a northern zone (N)—spanning northern Syria and southern Turkey and comprised of the Myssayf and al-Ghab faults (Meghraoui *et al.*, 2003; Akyuz *et al.*, 2006; Meghraoui, 2014). Similar to earthquake origin, uncertainty also surrounds the estimated magnitude of many of the historical earthquakes. The process of seismic intensity evaluation may not be accurately accomplished for many of the Levantine structures and materials in the various historical periods were yet to be characterized. Therefore, assessing each of the historical earthquakes made use of size degrees rather than inferred magnitude values (Table 2, following Ambraseys and Jackson, 1998). The process included consulting previous magnitude estimations (e.g., Ambraseys and Barazangi, 1989; Ambraseys, 1997; Ellenblum *et al.*, 1998; Meghraoui *et al.*, 2003; Akyuz *et al.*, 2006; Nemer *et al.*, 2008; Hough and Avni, 2010), as well as personal judgment of the resulted damage, casualties and severity as appearing in historical sources.

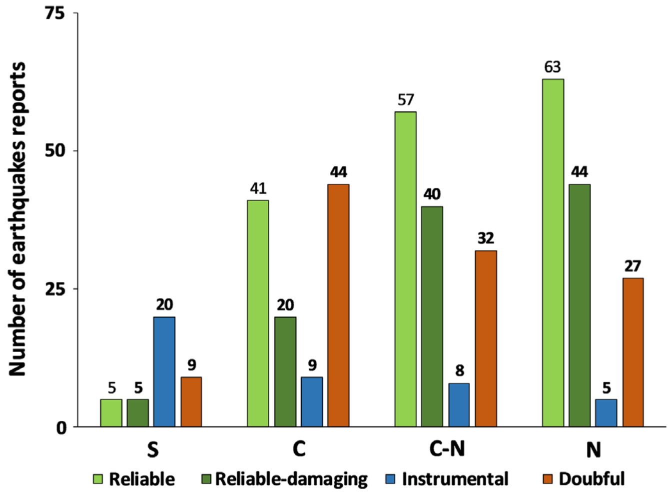


Figure 2. Classification of earthquakes (excluding foreshocks and aftershocks) into DST zones (S, C, C-N, and N): (1) reliable earthquakes; (2) reliable damaging earthquakes (size degree greater than "Light," see Table 2); (3) instrumental earthquakes (1903–2015 C.E.); and (4) doubtful earthquakes. Detailed information of each of the earthquakes appears in Tables S1 and S2. The color version of this figure is available only in the electronic edition.

Naturally, the documented earthquakes we are familiar with, are only part of the actual past seismicity. This is evident in several archeoseismic and paleoseismic findings, which record activity not reported by historical sources. Thus, when inspecting an earthquake dated by archeological and geological evidence, much attention was made to accurately decipher individual events for the dating accuracy occasionally span periods of several dozens or several hundreds of years. In case of unsuccessful deciphering or suspicion that an event is masked by successive events, a range of dates was used with the proper notation of the uncertainty.

The compilation resulted in three lists of historical earthquakes: (1) 166 reliable earthquakes associated with DST activity excluding foreshocks and aftershocks. That is, earthquakes credited by confidence level from moderate to very high. The list includes two new entries of earthquakes that were not interpreted until now in the existing literature (see Table 3 for interpretation and notes). Out of the reliable earthquakes, 109 are considered as damaging events; that is, damage in at least one location within one or more of the DST zones. Together with the 42 $M \geq 5$ instrumental earthquakes (between 1903 and 2015), the combined list of reliable earthquakes contains 208 entries (Table S1). (2) 112 doubtful events; that is, duplications, conflicting interpretations of the historical records, fake events or questionable earthquakes that to date remain unauthenticated (Table S2). It is to be stressed, however, that this list is not final and upon future discoveries, some of these events may be shifted to the reliable list. (3) 71 reliable events that affected or damaged regions close to the DST but their MRDZ is far away from any DST zone, thus most likely implying an off-DST seismic events (Table S3).

Results

The first reliable earthquake in the compiled list is the 750–760 B.C.E. biblical event, while the last occurred in 27 June 2015 at 15:33. The strongest evaluated earthquakes characterized with major size degree occurred during the Common Era: 13 December 115; 18 March 1068; 12 August 1157; 29 June 1170; 20 May 1202; 25 November 1759, as well as the 22 November 1995 M 7.2 instrumental earthquake (Shamir, 1996). Figure 2 presents the number of earthquake reports (excluding fore- and aftershocks) classified into plausible origin in the DST zones. The lowest number of pre-instrumental reports is

TABLE 3
New Entries of Earthquakes and Damage Not Mentioned Hitherto in the Existing Earthquake Catalogs and Literature

Number	Date	Notes
1	1785	George Browne reports of an earthquake occurred in Latakia in 1796 but adds that: "but not so violently as that which happened in the year 1785 in which many persons perished and which was succeeded by a plague that almost depopulated the place" (Browne, 1806, pp. 429–430). Browne, contemporary, cites dates and details precisely thus is considered as accurate. Furthermore, no other earthquake report at that year is known so far. Sbeinati *et al.* (2005), base on Plassard and Kogoj (1968) and Sieberg (1932), place two events in 4 December 1783 in Aleppo and 14 December in Aleppo and Tripoli. The latter event is also cited in Ambraseys (2009). Papazachos *et al.* (2000) cite an earthquake in Patara, Greece, in 1785. Yet, the distance between Latakia and Patara implies that these are two separate earthquakes
2	13 February 1874	A report on nineteenth century Palestine Exploration Fund (PEF) documents produced by the Royal Commission of Historical Manuscripts, lists occurring events in Palestine and cites an earthquake in Jerusalem: "a small earthquake tremor in J." [Jerusalem, my interpretation] (HMC-WS/CON/86, 1975, p. 10). In general, PEF documents and maps are considered contemporary and reliable (e.g., Gavish, 2005; Levin, 2006) thus implying this earthquake, although felt only, probably occurred

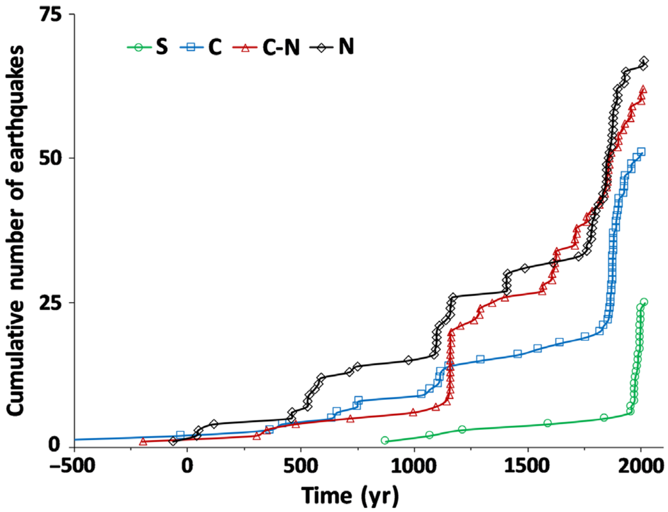


Figure 3. Cumulative reports of reliable earthquakes (Table S1) occurred between 198 B.C.E. and 2015 C.E. classified into the S, C, C-N, and N zones of the DST (Fig. 1). The color version of this figure is available only in the electronic edition.

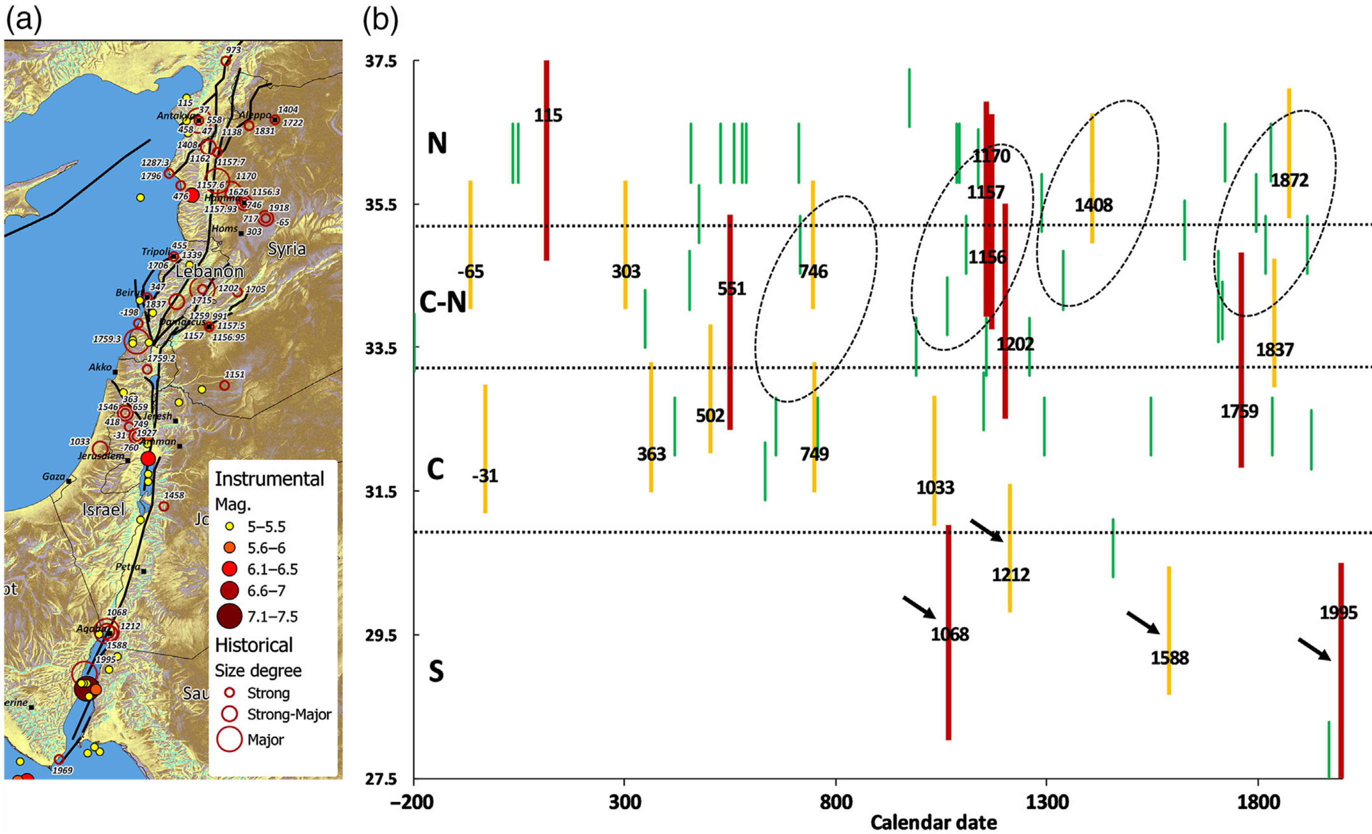
associated with the southern zone (S) while the largest is associated with the northern zone (N). This is also the case for damaging earthquakes (events with size degree greater than "Light"). It seems that the number of the reliable preinstrumental earthquakes increases from south to north. On the other hand, aside from the S zone, the number of doubtful reports is decreasing toward the north. Accordingly, the ratio between the reliable and doubtful earthquakes of the S, C, C-N, and N zones is 0.5, 0.9, 1.7, and 2.3, respectively, indicating an increasing reporting trend from south to north. The latter is important for comparing the completeness of reports between the zones as well as assessing the global reliability of reporting of a given zone. The instrumental earthquakes ($M \geq 5$) present the opposite trend; the largest number of earthquakes (20) was in the S zone, while only five events occurred in the northernmost N zone.

The cumulative reliable earthquakes (without foreshocks and aftershocks) are presented in Figure 3. The earliest reliable report (750–760 B.C.E.) affected zone C while the first report associated with zone S appears only in 873 C.E. The latter is characterized with moderate reporting separated by hiatuses lasting approximately 100–300 yr until the mid- twentieth century when a sharp increase is detected due to quantitative monitoring installed in southern Israel. The C zone is characterized with a slight increase in reporting in the fourth and sixth–seventh centuries C.E., and significant growth during the eleventh–twelfth and eighteen–twentieth centuries C.E. The C-N zone is characterized by a slight increase during the third–fourth centuries, a prominent leap in the eleventh–twelfth centuries, and then a gradual rise (with another leap in the seventeenth century) toward the twentieth century. The N zone is probably the most structured in terms of gaps or leaps in reporting, with distinguished leaps in the first–second, fifth–sixth, eleventh–twelfth (similar to the C-N zone), and thirteenth–fourteenth centuries C.E., with a sharp rise from the eighteenth century onward. This rise probably reflects the expansion of media and press reports and is first observed at the C-N zone during the seventeenth century, and only afterward in the N, C, and S zones during the eighteenth, nineteenth, and twentieth centuries, respectively.

Figure 4 presents the temporal and inferred south–north spatial distribution of the reported earthquakes categorized into Strong, Strong-major, and Major size degrees (Table 2). The inferred south–north length of the lines denoting the earthquakes, accords with the center of the MRDZ and scales with the evaluated size degree. Obviously, it may not necessarily reflect the actual I_{max} zone or the full damage distribution. Yet, it may serve as a rough estimate for classifying the damage and the potential seismic activity in each of the DST zones, thereby allowing the examination of temporal and spatial patterns. Accordingly, for the Strong-major and Major earthquakes, from the eighth century C.E. onward a postulated activity seems to alternate between the DST northern (C-N and N) and southern (S) zones: (1) a northern cluster at the mid-eighth century (including the 746 and 749 C.E. earthquakes) followed by central 1033 C.E. earthquake and the southern 1068 C.E. earthquake; (2) a second cluster of northern strong events in 1157, 1170, and 1202 C.E., followed by the successive 1212 C.E. earthquake; (3) a third instance starting with the 1408 and ending with the 1588 C.E. earthquakes; and (4) a final instance starting at mid-eighteenth–nineteenth centuries (1759, 1837, and 1872 C.E. earthquakes), while ending, at least for now, in 1995. When inspecting also the strong earthquakes, the northern activity (C-N and N zones) seems to be more clustered and intense than the southern activity (S and C zones). Naturally, the difference may result artificially from differences in the rate of reporting (Fig. 2) but may also yield from a change in the tectonic settings (Fig. 1). Before the eighth century C.E., postulated activity alternations are also observed but they skip the S zone, probably due to poor documentation. This is apparent in the northern 65 B.C.E. earthquake with a successive central earthquake in 31 B.C.E.; the northern 115 C.E. that is followed by an event in 363 C.E., and in the case of the 501 and 552 C.E. earthquakes followed by the mid-eighth century C.E. clustered events.

Discussion

When inspecting the number of reliable earthquakes (damaging and none-damaging), a south to north increasing trend of reporting is observed while a reversed trend is noted for the number of doubtful reports (Fig. 2). This is not surprising, because authenticating reports originated from deserted and remote regions such as the S zone tend to be challenging due to fewer reports that one can cross-correlate. The number of instrumental earthquakes ($M \geq 5$) reinforces this claim; in



which, the largest is in the S zone with a decreasing trend toward the north. That is, the lack of preinstrumental earthquakes associated with the S zone indicates poor reporting, most likely of weak events, rather than of reduced seismic activity. Giving high credibility to the reporting associated with the C-N and N zones (Fig. 2), the low and high rates of reporting periods may be indicative of actual fluctuations in seismicity. This refers mainly to significant growth between the eleventh–twelfth and sixteenth–seventeenth centuries C.E. in the C-N zone and the eleventh–twelfth, thirteenth–fourteenth centuries C.E. in the N zone (Fig. 3). Quiescent periods of northern seismic activity is also supported by paleoseismic and archeoseismic studies investigating the activity of the Missay fault and the LBR system (e.g.,Meghraoui *et al.*, 2003; Nemer and Meghraoui, 2006; Sbeinati *et al.*, 2010; Ellenblum *et al.*, 2015).

Potential seismicity shifts of earthquake series moving successively from north to south along the east Anatolian and Dead Sea fault systems were previously suggested by Ambraseys (2004). According to Figure 4, alleged south–north alternations of DST activity are also apparent. Although the reporting is probably incomplete (Van-Eck and Hofstetter, 1989; Begin, 2005), it is reasonable to assume that most of the destructive earthquakes ($M \geq \sim 6$) that occurred in the second millennia C.E., were indeed documented (Haas *et al.*, 2016). Thus, the question raised is whether the temporal patterns portrayed in Figure 4 may be a close approximation of the actual

Figure 4. (a) Inferred most reported damage zone (MRDZ) locations of historical earthquakes classified with size degree greater than "Strong" (Table 2). The diameter of the red circles scales with the degree size of the earthquakes. The epicenter of instrumental earthquakes (post-nineteenth century) is positioned together with adjacent magnitude. (b) Spatial and temporal distribution of earthquakes during the last three millennia. Strong, Strong-major, and Major earthquakes are scaled in length and noted by green, orange, and red vertical lines, respectively, with center points aligned with map location to the left. Postulated south–north trends of strong activity reporting (events with size degree of "Strong-major" and "Major") as reflected by the historical share is outlined by dashed ovals and arrows. The color version of this figure is available only in the electronic edition.

strong activity during and before the second millennium C.E. To better characterize the temporal and spatial patterns before the second millennium C.E., a contribution of additional sources is required. Cross-correlating the historical share with pertinent archeological and geological evidence (Agnon, 2014; Marco and Klinger, 2014; Meghraoui, 2014) is likely to enlarge the inspected period and indicate events that probably occurred but were not documented. However, a prominent shortcoming of using this evidence is the inability to accurately date events; as the available techniques (e.g., radiocarbon and optically stimulated luminescence) resolve the dating within a range of only decades. Furthermore, occasionally upon the discovery of some

TABLE 4
Earthquakes Derived from Archeological and Geological Data Which Are Not Supported by Historical Sources

Date	Zone	Notes
980–830 B.C.E. (Iron age IIA)	C-N	An earthquake that ruptured Tell-Ateret causing a slip of ~2 m (Ellenblum *et al.*, 2015)
525 B.C.E.	C-N	Karcz and Lom (1987) pointed out that the entry citations by Sieberg (1932), Plassard and Kogoj (1968), and Ben-Menahem (1979) are not supported by specific reference of occurrence. However, Migowski *et al.* (2004) and Kagan *et al.* (2011) correlated seismites found in Ein Gedi cores and at Ein Feshkha with this event. This earthquake is listed also by Sbeinati *et al.* (2005), with damage to the southern Lebanese towns Tyre and Sidon, and a local sea wave
338–213 B.C.E.	S	Klinger *et al.* (2015) implies a ruptured Arava fault between 338–213 B.C.E. No supporting historical sources. May be associated with two successive down-faulting events buried by a coral-reef in the Gulf of Aqaba (Shaked *et al.*, 2011)
142 B.C.E.	C-N	Ellenblum *et al.* (2015) found a slip of ~2.5 m at Tell-Ateret and date an earthquake to post 142/143 using minted coins. Wechsler *et al.* (2014) found evidence of an event between 392 B.C.E.–91 C.E. and perhaps these are two indications of the same event. Note that historical sources imply an earthquake that destroyed Antioch in 21 February 148 (130?) B.C.E.*
137–206 C.E.	C-N	Paleoseismic evidence. Wechsler *et al.* (2014) associate this event with an ~130 event. However, the latter probably occurred in Asia Minor (Karcz, 1987; Ambraseys, 2009) and thus, this event may be an undocumented event
165–236 C.E.	C-N	Paleoseismic evidence (Wechsler *et al.*, 2014) undocumented in the historical share
18–19 May 363 (night)	S	Kagan *et al.* (2011) suggest that two events of M ~ 6.5; one from 363 north of the Dead Sea and one from a close date south of the Dead Sea, had been erroneously amalgamated to a single M > 7 event. Agnon (2014) summarizes the findings from the Dead Sea region noting the absence of matching from Zee'lim Creek and Ein Gedi core by Ken-Tor *et al.* (2001), Migowski *et al.* (2004), and Kagan *et al.* (2005) but is suggestive two consecutive earthquakes although notes that this event needs further research. Zohar *et al.* (2017) analyzing the north–south damage extent of the 363 event, observed relatively large extent in comparison to other central earthquakes, suggesting that the source of the earthquake was probably two events instead of one
873 C.E.	S	Hayens *et al.* (2006) correlated evidence in Qasr Tilah. Vague identification of the event by Kagan *et al.* (2011)

Zones: C, central; C-N, central-northern; N, northern; S, southern.

*A third earthquake was dated by Ellenblum *et al.* (2015) to the post-Hellenic period which may indicate of an already known earthquake and thus, was not included in the analyses.

evidence, an attempt is made to tie the evidence with one of the known earthquakes, which may in turn lead to circular reasoning due to incorrect association (Rucker and Niemi, 2010). On the other hand, when no relevant, close-in-time earthquake is known, deciphering an earthquake occurrence using archeological or geological evidence becomes less complicated and can indicate an earthquake missed by the historical sources. Following these principles, paleoseismic and archeoseismic evidence were examined with a goal to enrich the temporal distribution based solely on historical sources (Fig. 4). The outcome was an addition of three events that occurred in the S zone and five in the C-N zone (Table 4 and references therein). Four of these events occurred during the first millennium B.C.E.: during Iron age IIA (980–830); ~525; between 338 and 213; and ~142 B.C.E. The other four occurred during the first millennium C.E. in 137–206, 165–236, 18–19 May 363 (a second event on that date), and 873. No additional entries to the ones reported by the historical share were detected during the second millennia C.E.

Altogether, the strong DST activity, as reflected by the historical share and complemented by paleoseismic and archeoseismic findings, comprises of 84 reliable earthquakes presented in Figure 5a,b. Accordingly, the alternated activity between the DST northern (C-N and N) and southern (S) zones appear also prior to the second millennium C.E. whereas the 338–213 B.C.E., 363 C.E., and 873 C.E. precede the 142 and 65 B.C.E., 502 and 551 C.E., and 1033 C.E., respectively. Among the four zones, the C zone seems to experience the weakest earthquakes. Zohar *et al.* (2017) demonstrated that the damage from earthquakes in this zone tend to be confined approximately between the north of the Dead Sea and the Lake of Galilee with a single exception of extensive damage in 363 C.E., which raises the question whether there might be a second masked event. Indeed, in the letter by Cyril, the Bishop of Jerusalem (Brock, 1977), two successive events occurred on Sunday, 18 May 363, at the third and ninth hours after sunset (i.e., Sunday, 18 May at ~21 : 00 and Monday, 19 May, at about 03:00).

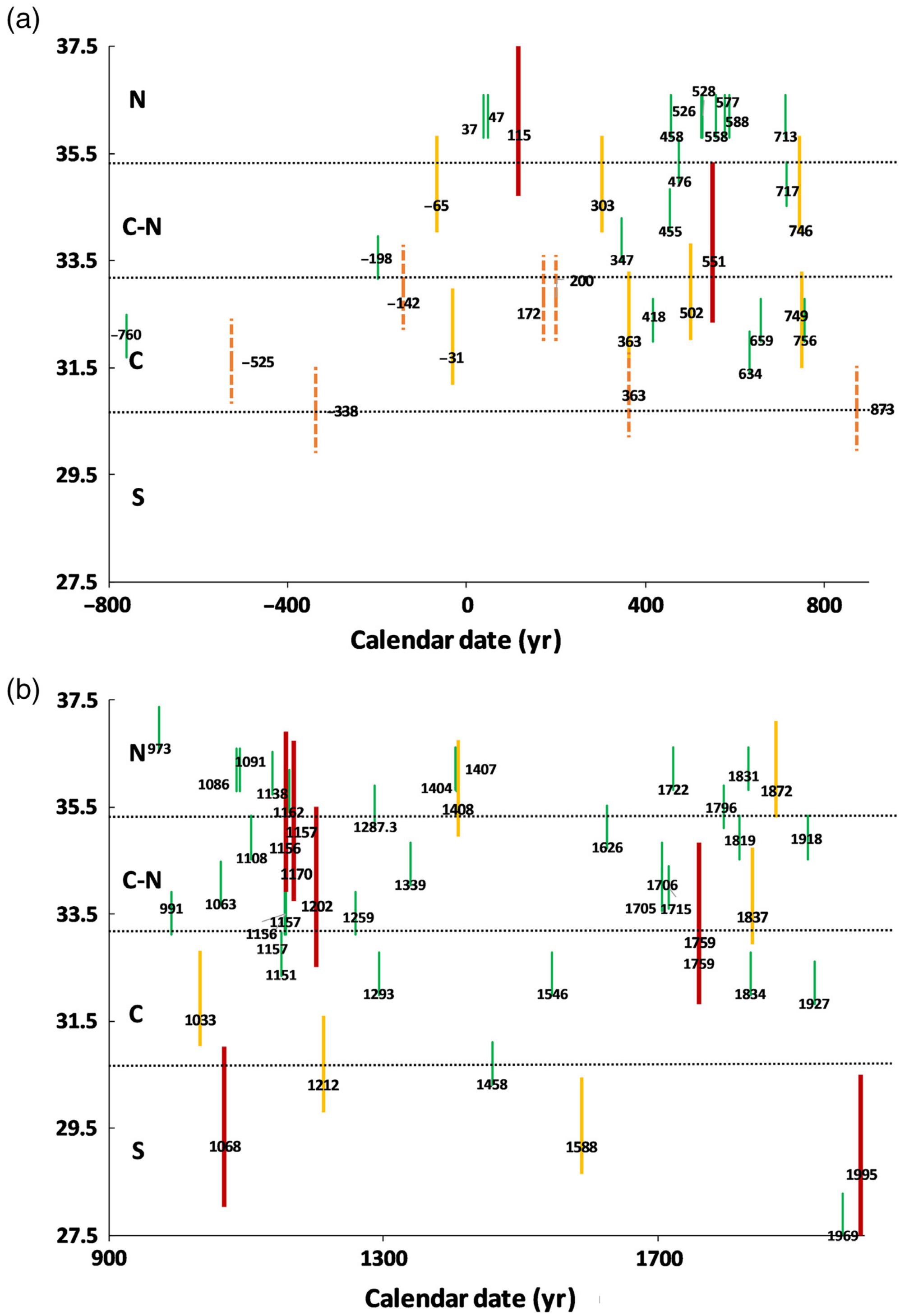


Figure 5. Spatial and temporal distribution of DST earthquakes during the last three millennia. Strong, Strong-major, and Major earthquakes are scaled in length and noted by green, orange, and red vertical lines, respectively, with center points of vertical lines denoting latitude of the earthquake. The dashed vertical lines represent earthquakes deciphered only in archeoseismic or paleoseismic evidence. South–north alternations of strong activity (events with size degree of Strong-major and Major) reflected by historical, archeoseismic, or paleoseismic evidence are outlined by dashed black line: (a) between eighth century B.C.E. and the ninth century C.E.; (b) between ninth century C.E. to the present. The color version of this figure is available only in the electronic edition.

The letter also describes 22 damaged locations throughout Palestine including the remote city of Petra. Records of southern activity were also found in Zoar (Meimaris and Kritikakou, 2005), in paleoseismic findings at the Dead Sea (Ken-Tor *et al.*, 2002) and by Klinger *et al.* (2015) dating a rupture of the Arava fault between 9 B.C.E. and 492 C.E. associated with the 363 C.E. earthquakes. Other studies imply, however, also of a northern activity. Kagan *et al.* (2011) suggested that two events of $M \sim 6.5$, the first in 363 C.E. extending north of the Dead Sea while the second, dated close to 363 C.E. and extending south of the Dead Sea, had been erroneously amalgamated into a single $M > 7$ event. Kanari *et al.* (2019) have correlated rock falls at northern Galilee with the earthquake of 363. Altogether, these findings imply of two successive events erroneously amalgamated rather than a single event. The second case worth discussion is the 1033 C.E. earthquake that was associated with a central activity in previous studies, primarily due to the destruction of Ramla (Zohar *et al.*, 2017). However, the damage distribution of the 1033 C.E. earthquake is questioned; whereas, it damaged Banyas in northern Palestine and other sites in Syria but also Hebron and Jerusalem. Ambraseys (2009) contradicts Guidoboni and Comastri (2005), suggesting a destructive earthquake with an epicenter in Syria rather than in Palestine. Kanari *et al.* (2019) support this claim and suggest a northern activity by dating rock falls resulted from the 1033

TABLE 5
Sequences Length of Strong, Strong-Major, and Major Earthquakes Categorized into S, C, C-N, and N Zones

DST Zone	Number and Percentage	Sequence Length 1	2	3	4	Total
N	*n*	10	3	3	1	17
	%	59	18	18	6	100
C-N	*n*	14	4	1	2	21
	%	67	19	5	10	100
C	*n*	10	2	0	0	12
	%	83	17	0	0	100
S	*n*	7	1	0	0	8
	%	88	12	0	0	100

Chi-square statistic; degrees of freedom (DF) = 3; value = 3.3363; and the probability (Prob) = 0.3426. DST, Dead Sea Transform.

TABLE 7
Proportions of Successive Strong, Strong-Major, and Major Earthquakes Categorized into S, C, C-N, and N Zones

DST Zone	Number and Percentage	DST Zone of the Successive Earthquake N	C-N	C	S	Total
N	*n*	12	12	4	1	29
	%	41	41	14	3	100
C-N	*n*	12	12	6	3	33
	%	36	36	18	9	100
C	*n*	3	5	2	4	14
	%	21	36	14	29	100
S	*n*	2	3	2	1	8
	%	25	38	25	13	100

Chi-square statistic; DF = 3; value = 4.8658; and Prob = 0.1819.

earthquake at the north of Galilee. In other words, if the damage resulted by central events does not extend north of the Hula basin (Zohar *et al.*, 2017), then the 1033 C.E. event is most likely associated with a C-N activity rather than originating in the C zone.

With the additional entries based on the paleoseismic and archeoseismic findings, as well as the separation of the 363 C.E. event into two successive earthquakes, characterization of the earthquake's sequences was examined. Table 5 presents the length of earthquakes sequences categorized into the four zones. Accordingly, a single earthquake sequence, that is followed by chronological successive earthquake in a different zone, appears 88%, 83%, 67%, and 59% of the total sequences of the S, C, C-N, and N zones, respectively. Furthermore, in S and C zones there are no sequences greater than two successive earthquakes. These results are not significant statistically (Prob = 0.3426). However, consolidating the earthquakes into two groups of northern and southern activity (Table 6) indicates 79% of clustered activity in the north and only 36% in the south (significant, Prob = 0.0219). Limiting the activity to strong-major and major events only, 83% of the northern activity is clustered while only 17% in the south, although not significant

TABLE 6
Sequences Length of Earthquakes Consolidated into Two Groups: Southern and Central Earthquakes (S and C); and Central-Northern and Northern Earthquakes (C-N and N)

Size Degree of Events	Region	Number and Percentage	Sequence Length 1	2+	Total
Strong, Strong-major, and Major	C-N and N	*n*	3	11	14
		%	21	79	100
	S and C	*n*	9	5	14
		%	64	36	100
	Chi-square statistic		DF = 1	Value = 5.25	Prob = 0.0219
Strong-major and Major	C-N and N	*n*	1	5	6
		%	17	83	100
	S and C	*n*	5	1	6
		%	83	17	100
	Fisher's Exact test			Two-sided Pr ≤ P = 0.0801	

TABLE 8

Proportions of Successive Earthquakes Consolidated into Two Groups: Southern and Central Earthquakes (S and C); and Central-Northern and Northern Earthquakes (C-N and N)

Size Degree of Events	Region	Number and Percentage	DST Zone of the Successive Earthquake		
			C-N and N	S and C	Total
Strong, Strong-major, and Major	C-N and N	*n*	48	14	62
		%	77	23	100
	S and C	*n*	13	9	22
		%	59	41	100
	Chi-square statistic		DF = 1	Value = 9.9240	Prob = 0.0016
Strong-major and Major	C-N and N	*n*	9	6	15
		%	60	40	100
	S and C	*n*	5	2	7
		%	71	29	100
	Fisher's Exact test		Two-sided Pr ≤ P = 0.3615		

(Prob = 0.0801). Table 7 presents the proportions of successive earthquakes. Accordingly, 41%, 36%, 14%, and 13% of the successive earthquakes at the same zone occur in the N, C-N, C, and S zones, respectively, although not significant (Prob = 0.1819). Consolidating the earthquakes into northern and southern activity (Table 8) yields 77% and 41%, respectively, for Strong, Strong-major, and Major earthquakes (significant, Prob = 0.0016) whereas 60% and 29% for Strong-major and Major earthquakes only (Prob = 0.3615). That is, the northern seismic activity in the C-N and N zones is more clustered than in the S and C zones. In other words, upon a strong earthquake occurrence in the S or C zones, it is likely to be followed by a longer quiescent period than after an occurrence in the C-N or N zones. The observed south–north shifts of activity (Figs. 4, 5) implying of a postulated alternation pattern of strong seismicity, cannot be verified statistically to this point. In order to do so, the spread of the damage of each earthquake should be evaluated accurately and then tied to a potential triggering tectonic segment (Fig. 1). However, this task is beyond the scope of this study.

Summary and Conclusions

This study continues earlier historical seismology studies but focuses on the DST itself as a complete tectonic unit. Although much of the information is already collected and interpreted, it is of great importance for every generation to review and criticize former compilations in order to add, improve, and provide new perspectives and insights. The synthesis of the historical reports, archeoseismic remains, paleoseismic findings, and instrumental earthquakes constitutes an up-to-date reliable compilation and contributes to the characterization of past seismicity of the DST. The compilation resulted in 166 reliable earthquakes, 109 of them are regarded as damaging. Classifying the DST into four zones indicates 5, 41, 57, and 63 earthquakes (excluding foreshocks and aftershocks) in the S, C, C-N, and N zones (Fig. 1), respectively. Combined with 42 instrumental earthquakes, the list of reliable earthquakes represents continuous activity from mid-eighth century B.C.E. until 2015 C.E. The process also resulted in 112 doubtful earthquakes entries and 71 reliable earthquakes that affected small areas around the DST, but most of their damage extends further away.

Two earthquake cases under debate were interpreted and re-evaluated. The first is the occurrence of two successive earthquakes in 363 C.E. rather than a single event and the second is the association of the 1033 C.E. earthquake to tectonic origin in the northern C-N zone instead of an epicenter at the central C zone. Examination of the temporal and spatial patterns during the last 3000 yr implies that most of the earthquake occurrences in the S and C zones are single while the activity in the C-N and N zones is mostly clustered.

The study conducted and the database established may serve as a base for future studies of the DST as a complete tectonic unit. To do so, further interdisciplinary efforts should be made particularly in resolving the full scope and severity of the resulted damage, which may assist substantially in refining the presented results.

Data and Resources

The CENEC website can be accessed at http://www-app1.gfz-potsdam.de/pb53/cenec/. The SHARE European Earthquake Catalogue (SHEEC) website can be accessed at https://www.emidius.eu/SHEEC/. European Archive of Historical EArthquake Data (AHEAD) can be accessed at http://www.emidius.eu/AHEAD/. For U.S. Geological Survey (USGS) data, see https://earthquake.usgs.gov/earthquakes/search/, while for the GII records see http://seis.gii.co.il/3heb/earthquake/searchEQS.php. Most of the magnitude values are of body-wave magnitude (M_b) but also moment magnitude (M_w) and duration magnitude (M_d). For more information see https://earthquake.usgs.gov/learn/topics/magintensity/magnitude-types.php. All websites were last accessed in January 2019. Supplemental material for this article includes Tables S1, S2. and S3.

Acknowledgments

The author wishes to acknowledge Emanuella Guidoboni and Thomas Rockwell for their wise insights and suggestions. The author also would like to acknowledge Ruth Kark and Aviv Openheim from the Hebrew University of Jerusalem for their assistance in acquiring relevant historical sources; Efrat Yaskil from the Statistical Consulting Unit, University of Haifa; and Moshe Devere for language editing. Finally, the author would like to thank the two anonymous reviewers for their constructive comments and remarks. The research was funded by the Ministry of Energy, State of Israel, Grant Number 3-14604.

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Manuscript received 21 May 2019
Published online 23 October 2019