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Article in *Arabian Journal of Geosciences* · May 2014

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Historical seismicity of the Jordan Dead Sea Transform region and seismotectonic implications

Zuhair H. El-Isa · Sarah McKnight · David Eaton

Received: 20 March 2014 / Accepted: 19 May 2014
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Abstract Based on all available files, catalogs, and previous compilations, it is found that 96 historical earthquakes ($M \geq 6.0$) were felt along the Jordan Dead Sea Transform region during the last 2,000 years. More than 50 % of these occurred in the form of sequences and swarms that lasted for different periods, some of which were volcanic related. The largest assigned magnitude is 7.6 with 667 years recurrence period, while the maximum possible future magnitude is 7.8 ± 0.2 with $1,000 \pm 80$ years recurrence period. Quiescent periods, with a duration of up to 200 and 400 years and characterized by reduced levels of seismicity, are punctuated by active periods of tens of years when a few large earthquakes occurred. The historical seismicity indicates that all tectonic elements of the study region are presently active. Our results indicate that previous studies overestimate the level of seismicity in this region. Not less than 25 earthquakes, most of which had $M \geq 7.0$, are erroneously related to the transform. It is probable that most of these are located within the East Mediterranean region and/or along intraplate faults, rather than the Jordan Dead Sea Transform. This is evidenced by (i) frequency–magnitude results, (ii) moderate–large East Mediterranean tsunamis, (iii) an apparent higher seismicity of the northernmost three segments compared with the southern three, (iv) relatively high annual seismic slip rate as calculated from the compiled historical seismicity, and (v) overdependence of some previous compilations on secondary

rather than primary sources. The revised historical seismicity implies an annual seismic slip rate of about 0.68 cm/year, which indicates that not less than 30 % of the tectonic movements along the regional structures of the study region are aseismic. This is in agreement with results obtained from pre-historic and instrumental data.

Keywords Historical seismicity · Dead Sea · Seismotectonics · Jordan

Introduction

The Jordan Dead Sea transform is a major continental plate boundary that separates the Arabian and the Sinai Palestine plates. With a NNE general trend and 1,100-km total length, it links the Red Sea seafloor—spreading in the south to complex plate convergence within the Anatolian domain in the north. The transform is divisible into segments that include the Gulf of Aqaba segment in the south, followed by Wadi Araba, the Dead Sea–Jericho, Beqa’a, Al-Ghab, and Karasia segments in successive order. Geological and geophysical evidence indicates cumulative multi-stage left-lateral shear of about 107 ± 1 km along this transform, but with a poorly constrained age of initiation. Nonetheless, an average annual slip rate of 1 cm/year is well established (Quennell 1958, 1959, 1984; Girdler 1990).

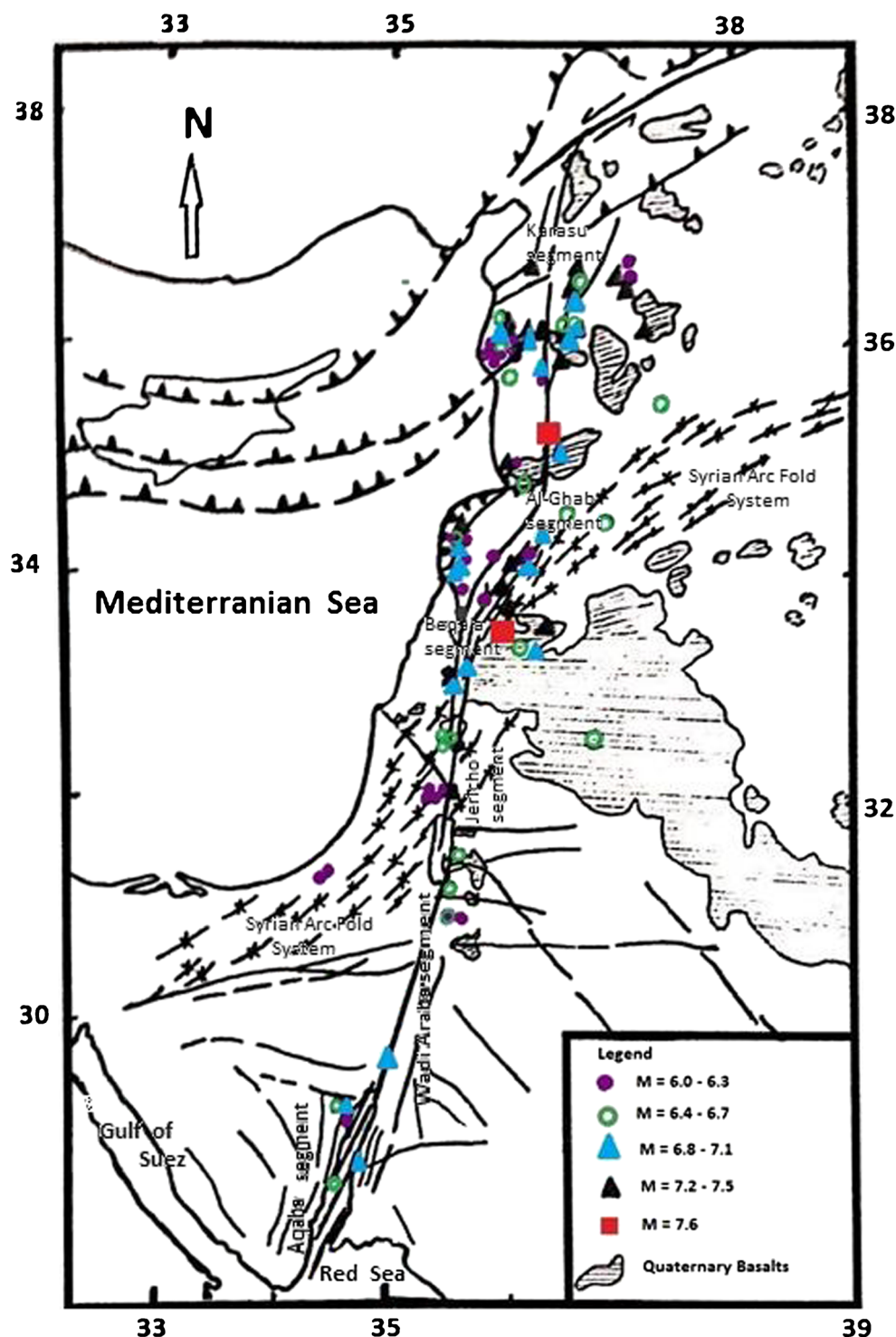
Three major deformational phases have affected the transform region during the Mesozoic and Cenozoic era. The oldest is represented by the Syrian arc fold system, which runs from central Syria to northern Sinai forming an S-shaped fold belt that crosses the transform (Fig. 1). It consists of regional folds that are faulted locally. Deformation in this belt is driven by anti-clockwise rotation of the Arabian plate, which is presently moving in a NNE direction. Timing of deformation is bracketed

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Fig. 1 The regional tectonics of the Jordan Dead Sea Transform region and epicentral distribution of 96 historical earthquakes of Table 1



to a range from Pre-Jurassic to Oligocene–Miocene (Quennell 1958, 1959). The Erythrean fault system represents the second deformational phase, which is dated at Late Miocene–Early Pliocene age. It consists of E–W and NW–SE trending faults, i.e., parallel to the Red Sea. These regional faults cross the transform and are of both strike-slip and normal types. They are

characterized by the presence of Quaternary basaltic flows that, in some cases, cover large areas. During the Middle Cenozoic, the third deformational phase resulted in the formation of the Jordan Dead Sea transform. The N and NNE trending strike-slip faults of this transform appear to accommodate much of the relative plate movements, which are directly related to the

geodynamic processes acting in the Red Sea. Some of these faults are arranged en-echelon, resulting in the creation of rhomb-shaped, pull-apart basins such as the Dead Sea, see Fig. 1.

Structures associated with these three deformational phases are active in the present, as documented by a variety of geological, geophysical, and seismological evidence (e.g., El-Isa 1988, 1992). Three sources of information on the seismicity of the study region are available. These include pre-historic data obtained from earthquake deformations preserved in the Pleistocene–Recent deposits of the Dead Sea and antecedent features (e.g., El-Isa and Mustafa 1986). The second source comprises historical seismicity data, of which the most reliable are those that date back only to about 2,000 years (El-Isa 1985; Abou Karaki 1987). Instrumental seismicity data represent the third source. The quality of this set of data is quite variable, however; the highest quality is represented by data for the period 1981–present, as these data are recorded on local seismological stations. Prior to 1981, the instrumental record of seismicity is based primarily on global network stations.

A number of destructive earthquakes are known to have occurred in this region during the last twenty centuries. Considerable destruction in many archeological sites located along the transform have long been reported by many workers, with noticeably greater deformation at sites located within the transform or close to it (e.g., El-Isa 1985; El-Isa and Mustafa 1986). Many studies and compilations of historical seismicity in this region have been made during the last few decades (Willis 1928, 1933; Saadani 1974; Poirier and Taher 1980; Abou Karaki 1987; Ambraseys 1997, 2004, 2005, 2008; Ambraseys and Barazangi 1989; Ambraseys and Melville 1988; Ambraseys and White 1997; Khair et al. 2000; Meghraoui et al. 2003; Sbeinati et al. 2005). Here, these compilations, supplemented by the National Earthquake Information Center (NEIC) and the Utsu (1990) files, are recompiled and checked against each other in an attempt to produce a new catalog that is suited for the quantitative evaluation of the earthquake hazard in this region. The seismotectonic implications of the revised seismicity are also discussed.

Historical seismicity data

All available historical seismicity sources, publications, catalogs, and compilations have been collected and revised to compile an up-to-date catalog for the historical seismicity of the Jordan Dead Sea Transform region during the last 2,000 years. Sources include catalogs and seismicity maps made by different authors (Willis 1928, 1933; Saadani 1974; Poirier and Taher 1980; El-Isa 1985, 1988, 1990, 1992, 2012; El-Isa and Mustafa 1986; El-Isa and Al Shanti 1989; Abou Karaki 1987; Salamon et al. 1996, 2006; Ambraseys 1997,

2004, 2005, 2008; Ambraseys and Barazangi 1989; Ambraseys and Melville 1988; Guidoboni et al. 1994; Ambraseys et al. 1994; Ambraseys and Jackson 1998; Khair et al. 2000; Harajli et al. 2002; Meghraoui et al. 2003; Marco et al. 2003; Guidoboni et al. 2004a, b; Doeron et al. 2005; Sbeinati et al. 2005; Utsu 1990; Marzouk 2008; Salamon 2010) and the catalogs of other international organizations including the National Earthquake Information Center of the USGS (NEIC), the International Seismological Center (ISC), and the National Geophysical Data Center/World Data Service (NGDC/WDS) files. In compiling the historical seismicity data, the following criteria and considerations were taken into account:

1. Our primary interest was all strong historical earthquakes that were felt with relatively large intensities, not less than VI, magnitudes $M \geq 6.0$, within the Jordan Dead Sea Transform region. All earthquakes associated with the transform will affect some or all cities and towns located within it or nearby, namely, from south to north, Aqaba, Karak, Al-Khalil (Hebron), Al-Salt, Al-Quds (Jerusalem), Nablus, Areha (Jericho), Tabareya, Safad, Haifa, Dera'a, Demasheq (Damascus), Beirut, Ba'alabak, Hems, Hama, Lathekeya, Antakia (Antioch), Halab (Aleppo), and many other smaller villages. Depending on the epicenter and magnitude, felt intensities will vary from one city to the other. Large earthquakes will be strongly felt along all coastal cities of Palestine, Lebanon, and Syria with variable intensities. At the same time, such coastal cities will be affected similarly by unrelated earthquakes of comparable magnitude originating within the Eastern Mediterranean, which will also affect other cities within the transform or close to it. In particular, this implies that not every felt earthquake in some of the above mentioned cities is associated with seismic activity along the transform.
2. Tsunamis are normally associated with marine earthquakes, although nearby large continental earthquakes ($M \geq 6.0$) may trigger submarine slumps that could produce local tsunamis (Geist 2000; Tappin et al. 2001; Clouard & Bonneville 2003; Papadopoulos and Kortekaas 2003; Piper et al. 2003; Wynn and Masson 2003). The tsunamigenic potential of an earthquake depends upon its magnitude, the epicentral distance, structure of the continent–ocean transition and the local submarine topographic, sedimentological, and geological conditions. For the Jordan Dead Sea Transform region, it is likely that some of the large earthquakes may produce local-to-moderate tsunami within the East Mediterranean. We consider it more likely, however, that at least some of the historical earthquakes reported with moderate-to-large tsunami along the Palestine, Lebanon, and Syrian coasts originated from within the Mediterranean. Along the transform itself, some large earthquakes may produce

seiches in the Dead Sea and/or Lake Tiberias if the epicenters of these events are close to them.

3. The historical seismicity of Arabia and the Middle East is well documented through the writings of many old Arab writers, chroniclers, and travelers. Reliable historical records date back to a few centuries before the start of Islam, some 1,440 years ago, as some writers have collected good information on the seismicity of the Islamic regions for the period prior to Islam (e.g., Al-Fryoua 1984). It is unfortunate that evidence exists for the loss of some important old Arab references, one way or another. Nevertheless, available old Arab literature is of great importance in the study of the historical seismicity of this region if investigated carefully. Therefore, concentration and special attention is given to catalogs that depends on such references (e.g., Sbeinati et al. 2005).
4. The seismicity of the Jordan Dead Sea Transform region is characterized by a relatively high proportion of seismic sequences and swarms, some of which are related to subsurface volcanic activities (El-Isa et al. 1984; El-Isa 1988, 1992, 2012; Al-Qaryouti 1990; Salamon 2010). Here, our approach is to pinpoint the occurrence of these sequences and swarms, including their location and period length. The magnitude of only the largest event for each swarm or sequence is reported in our catalog. As discussed below, the magnitude distribution within the swarms is such that this approach has negligible effect on quantitative estimates of cumulative seismic moment.
5. Though the time of occurrence of some of historical earthquakes is documented to the nearest hour and minute, our analyses do not require such precise origin times.
6. There are differences between the Arabic Hijri and the Western Dating Calendars. This has resulted in questionable seismicity data wherein some earthquakes were reported more than once. Careful attention to original Arabic sources and all used references is applied in order to avoid event duplication.
7. Preliminary calculations were made to assess the overall average recurrence periods of earthquakes for some recent compilations. It is found that for earthquakes with magnitudes ≥ 7.0 , the recurrence periods are 105 years for the catalog of Khair et al. 2000, 111 years for Sbeinati et al. 2005, only 73 years for Utsu (1990) files, and 100 years for medium-large earthquakes as compiled by Salamon 2010. The highest assigned magnitudes are in the range ($M=7.7-8.0$). Their years of occurrence are also different from one catalog to the other. Such values imply a relatively high level of seismic hazard. These recurrence periods are much smaller than those deduced from other instrumental, historic, and pre-historic data (e.g., El-Isa 1985, 1992, 2012; El-Isa and Mustafa 1986).
8. Depending on the reported damage at the main cities in Syria, Palestine, Lebanon, and occasionally other nearby

cities, intensities were assigned to each earthquake taking into consideration the assigned intensities of other catalogs and compilations as well as recent lessons from the Aqaba instrumental seismicity (e.g., El-Isa et al. 1984; El-Isa 2012) and the 1927 Palestine earthquake. The assigned intensities were utilized to estimate magnitudes, utilizing the empirical equations of Gutenberg and Richter (1956) together with Maro and Tertulliani (1990). The assigned magnitudes of the other sources were also carefully considered. In general, only small differences are noticed between most of these and our assigned magnitudes. Careful attention was paid to some clear and unjustified exaggeration in destruction reports, such as “a spring was moved 6 miles,” “mountains moved like sheep,” “Jericho and Nablus were swallowed,”..., etc. All such comments were ignored.

9. When two or more events are mentioned by different sources in two or three successive years with different intensities and some date and/or location differences, it was generally considered as one sequence and the largest intensity was used to calculate the magnitude of a single earthquake. For some sequences, however, more than one large earthquake were considered, e.g., the activity of the period 525–528 is represented in this study by three large earthquakes, see Table 1, though some workers (e.g., Sbeinati et al. 2005) have mentioned a large event that occurred in May 526 with intensities up to IX or more in Antioch and casualties not less than 250,000 and another large event that occurred in November 528 with intensity VIII in the same city. Poirier and Taher 1980 quote two events in 526 and 528 with higher intensities, while Khair et al. 2000 quote three events for the years 525, 526, and 528, the latter two with magnitudes $M=6.8$ and 6.9 respectively.

Keeping the above criteria and considerations in mind, all available sources were evaluated and cross-referenced to produce a final historical event catalog (Table 1). This catalog contains some 96 historical single earthquakes and sequences that were felt all along the Jordan Dead Sea Transform region during the last 2,000 years.

Data analysis and interpretation

The assigned epicenters of all earthquakes and the largest of each sequence of Table 1 are plotted on Fig. 1. This set of events includes 96 felt earthquakes with $M \geq 6.0$, with an average recurrence period of about 21 years. Thirty two of these had magnitudes of $M \geq 7.0$, with an average recurrence period of about 63 years. Nine and four earthquakes had magnitudes of $M \geq 7.4$ and 7.5 , with average recurrence periods of 222 and 500 years, respectively. The highest assigned

Table 1 Historical earthquakes with assigned magnitudes $M \geq 6.0$ that were felt in the Jordan Dead Sea Transform region during the last 2,000 years, including all recent instrumentally recorded earthquakes with similar magnitudes

Date (AD)	Epicentral Intensity (I_0)	M	Lat. North	Long. East	Transform segment	Remarks
37	VII–VIII	7.0	36.0	36.5	K	Approximate coordinates
47	$\geq$ VII	6.6	36.1	36.6	K	Possible NE Mediterranean
48	VI	6.1	31.0	35.5	A	Approximate coordinates
53	VII–VIII	7.2	36.1	36.6	K	Possible NE Mediterranean
82–94	VI–VII	6.3	36.0	36.0	K	Approximate coordinates
13.12.115	VI–VII	6.4	36.1	36.1	K	Local Mediterranean tsunami, short period sequence
130	V–VI	6.0	34.4	35.5	B	Small sequence
233	VII	6.2	34.4	35.5	B	Approximate coordinates
245	$\geq$ VII	7.2	36.3	36.5	K?	Possible E Mediterranean epicenter
272	VI	6.0	34.2	35.6	B	Approximate coordinates
303–4–306	VII–VIII	7.2	34.2	35.6	B	Tsunami, multiple long-period sequences
341	VI–VII	6.2	36.1	36.1	K	Sequences, approximate coordinates
348	VI–VII	6.2	33.9	35.5	B	Moderate tsunami along Syrian and Lebanese coasts possible E Mediterranean short period sequences
18–19.5.363	$\geq$ VII	6.6	31.4	35.6	J	Short-period sequence seiches in the Dead Sea
394	V–VI	6.0	36.1	36.1	K	Approximate coordinates
419	VI	6.0	31.2	34.2	A	Short-period sequence
450–458	VI–VIII	6.8	34.0	35.6	B	Strong long-period multiple sequences
500	VI	6.0	35.0	36.0	G	Approximate coordinates
22.8.502	VII–VIII	7.3	35.0	36.0	G	2-Year long sequence, possible volcanic activity
522	VII–VIII	7.3	36.1	37.1	K	Possible NE Mediterranean
May 525	VII–VIII	7.3	34.5	35.5	B	Possible E Mediterranean
May 526	VI–VII	6.8	36.2	36.1	K	Possible NE Mediterranean
29.11. 528	VII–VIII	7.2	36.2	36.1	K	Long period strong sequence, possible E Mediterranean location
531–534	VI–VII	6.4	35.5	37.2	G	3-Year long, possible volcanic sequence
9.7.551	IX–X	7.4	33.9	35.9	B?	2–3-Year strong sequence, moderate tsunami along Lebanese and N Palestinian coasts. Possible E Mediterranean epicenter
565–571	VI–VII	6.6	36.2	36.1	K	Multiple-moderate sequences
588	VI–VII	6.0	36.1	36.1	K	Short-period sequence
634	$\geq$ VII	6.8	34.0	35.5	K	Short-period sequence
15.6.658	VII	6.4	32.5	35.5	J	Approximate coordinates
659–660	VII	6.3	32.5	35.5	J	1-Year long, possible volcanic swarm
28 February–10 March, 713	VI–VII	6.2	36.0	36.0	K	1-Month long swarm
18.1.746–747	VII–VIII	7.4	32.0	35.5	J	2-Years strong sequence severe tsunami along Syrian, Lebanese, Palestinian, and Egyptian coasts. Possible E Mediterranean epicenter
748–749	VII–VIII	7.2	33.0	35.5	J	2-Years possible volcanic sequences, seiches in the Dead Sea in the year 749
758	VI	6.0	31.2	34.2	A	Approximate coordinates
3.5.765	V–VI	6.0	32.0	35.5	J	Approximate coordinates
5.1–25.12.835	VI–VII	6.2	36.0	36.0	K	1-Year long swarm/sequence
28.8.846–16.8.847	VII–VIII	7.2	36.3	36.5	K	1-Year long sequence, possible E Mediterranean epicenter
24.11.847	VII–VIII	7.2	33.5	36.3	B	A short, strong swarm, possible E Mediterranean epicenter
12.6.853	VI–VII	6.5	32.5	35.5	J	Relatively strong swarm in Tiberias area
1.6.854	VIII–IX	7.4	36.0	36.2	K	Strong swarm in N Syria
30.12.859–29.1.860	VII–VIII	7.2	36.6	36.6	K ?	2 months strong swarm, moderate tsunami along Syrian and Lebanese coasts possible E. Mediterranean location
July 963	VI–VII	6.1	36.0	36.2	K	Approximate coordinates
972	VI–VII	6.1	36.0	36.5	K	Approximate coordinates

Table 1 (continued)

Date (AD)	Epicentral Intensity (I_0)	M	Lat. North	Long. East	Transform segment	Remarks
5.4.991	VIII–IX	7.5	34.0	36.0	B	Strong 1-month sequence
10.11.1002– 29.10.1003	VII–VIII	7.1	34.0	36.2	B	1-Year strong sequence, possible E Mediterranean location
1032–1033	$\geq$ VII	6.6	32.5	35.5	J	2-Year long sequence, moderate tsunami along Palestinian and Lebanese coasts on December 5, 1033
21.8.1042– 9.8.1043	V–VII	6.3	33.8	35.8	B	1-Year long sequence
8.7.1046– 27.6.1047	VI–VII	6.3	36.0	36.0	K	1-Year long sequence
30.7.–27.8.1063	$\geq$ VII	6.8	34.3	36.3	G	1-Month long relatively strong sequence
20.4.1067	VI–VII	6.5	29.3	34.6	AQ	Approximate coordinates
18.3–30.8.1068	$\geq$ VII	7.0	29.8	35	A	6-Month long sequence, local tsunami on south. Palestinian coasts
26.9.1091	VI–VII	6.3	36.1	36.2	K	Approximate coordinates
24.12.1105	V–VI	6.0	34.0	36.0	B	Approximate coordinates
18.7.1113– August 1113	VI	6.0	32.5	35.5	J	A possible 1-month swarm
August 1114– December 1115	VII–VIII	7.2	36.1	36.1	K	A 1 year relatively strong sequence, local tsunami in NE Mediterranean on November 29, 1115
October 1138– June 1139	VI–VII	6.6	36.1	36.5	K ?	Possible intraplate 1-year long seq. in NE Syria
28.9.1156–30.5 1159	IX–X	7.6	35.14	36.3	G	3-Year long successive swarms and sequences. In Shaizar-Hama region, Syria, possibly volcanic related. Moderate tsunami along Syrian coasts
1160	VI	6.0	32.0	35.3	J	Approximate coordinates
29.6.1170	VII–VIII	7.2	35.9	36.4	K	4-Months sequences, possible E. Mediterranean location
1182	VI–VII	6.5	32.6	36.7	J ?	Possible intraplate volcanic source
1183	VI–VII	6.5	34.5	36.5	B	Syrian Arc Fold System
6.6.1201	VI–VII	6.4	34.4	36.8	B	Approximate coordinates
20.5.1202	VIII–IX	7.6	33.5	36.0	B?	Felt throughout Mediterranean and Middle East, severe tsunami, gigantic sea waves, and many sunk ships. Mostly E Mediterranean epicenter
2.5.1212	VII–VIII	6.8	29.3	34.6	AQ	1-year long sequence
1236	VI–VII	6.2	36.0	36.0	K	Approximate coordinates
1284	VII–VIII	7.0	33.3	36.2	J/B	“““
11.3.1287	VII–VIII	7.0	35.1	36.4	G	2-Months long relatively strong sequence
11.1–8.2.1293	$\geq$ VII	6.7	31.0	35.5	A	1-Month long swarm/sequence
13.1.–11.2.1339	VII	6.4	34.3	35.5	B	1-Month swarm/sequence
2.2.1344	$\geq$ VII	6.6	33.3	36.2	B	1-Month possible volcanic swarm with 2 large semi equal shocks
20.2.1404	VII–VIII	7.0	35.9	36.3	K ?	5-Month long sequence, moderate tsunami along Syrian and Lebanese coasts possible E Mediterranean epicenter
29.4.1407	$\geq$ VI	6.0	35.7	36.3	K	1-Month long sequence
29.12.1408	VIII–IX	7.4	36.5	36.2	K	Local tsunami on Syrian coast, short-period strong sequence
12.11.1458	$\geq$ VII	6.5	31.2	35.5	A	Approximate coordinates
January–March 1537	VI–VII	6.2	36.0	36.0	K	Relatively moderate 3 months swarm/sequence
January– April 1546	VI–VII	6.2	32.0	35.3	J	4 Months swarm that affected Al-Aqsa mosque and the Jordan River. Seiches in the Dead Sea. Local tsunami in Mediterranean
1577	VI–VII	6.2	36.0	36.0	K	Short-period sequence
4.1.1588	$\geq$ VII	6.5	28.5	34.6	AQ	Moderate swarm
22.7.1616	$\geq$ VI	6.0	36.8	37.0	K	Approximate coordinates
21.1.1626	VIII–IX	7.5	36.5	37.0	K	1-Year strong sequence
1640	$\geq$ VI	6.0	34.0	35.8	B	Approximate coordinates
February 1656	$\geq$ VII	6.6	34.9	36.2	G	Moderate volcanic sequences

Table 1 (continued)

Date (AD)	Epicentral Intensity (I_0)	M	Lat. North	Long. East	Transform segment	Remarks
1719–1723	VI–VII	6.2	36.5	37.0	K	Multiple moderate sequences
25.9.1738	$\geq$ VII	6.4	36.5	36.5	K	Approximate coordinates
30.10.1759	$\geq$ VIII	7.0	33.1	35.6	J	Local tsunami on N Palestinian and Lebanese coasts and seiches in lake Tiberias
25.11.1759	$\geq$ VIII	7.2	33.74	36.0	J?	Felt at 1,100 km, large tsunami affected Lebanese, Palestinian, and Egyptian coasts. Possible E Mediterranean sequences
26.4.1796	$\geq$ VII	6.5	35.7	36.0	G	Liquefaction; 1,500 casualties
1802	VI	6.0	34.0	36.2	B	Approximate coordinates
13.8.1822	VIII–IX	7.4	36.7	36.9	K?	Tsunami; 20,000 casualties; possible E Mediterranean epicenter
26.5.1834	$\geq$ VII	6.3	31.0	35.5	A	A few weeks swarm
1.1.1837	VII–VIII	6.8	33.0	35.5	J	A seiche in Tiberias, 5–6 months swarm with 2 large comparable shocks
3.4.1872	VII–VIII	7.0	36.0	36.2	K	Local tsunami in NE Mediterranean, a 10-month long sequence, possible NE Mediterranean location
6.3.1900	VI–VII	6.2	29.3	34.6	AQ	Aqaba
11.7.1927	VI–VII	6.25	32.0	35.4	J	Instrumentally recorded, seiches in the Dead Sea
16.3.1956	$\geq$ VI	6.0	33.6	35.5	B	Instrumentally recorded
22.11.1995	VII–VIII	7.1	28.81	34.8	AQ	2-Year long sequence. Local tsunami in Gulf of Aqaba <1 m

Segments of the transform are: *AQ* Aqaba, *A* Wadi Araba, *J* Jericho–Jordan Valley, *B* Beqa'a, *G* Al-Ghab, and *K* Karasu

magnitude is 7.6 with an average recurrence period of 1,000 years. These values imply a higher-than-expected seismic hazard compared with estimates based on instrumental data, which show recurrence periods in the range from 260–340 years for the magnitudes of $M \geq 7.0$ (El-Isa 1988, 1992, 2012). About 57 % of historical seismicity occurred in the form of sequences and swarms that lasted for variable periods of time, ranging from a few hours to a few days, weeks, months, and a few years. From a study of the instrumental seismicity of the Gulf of Aqaba region, El-Isa (2012) deduced that not less than 98 % of the local seismicity occurred in the form of sequences and swarms. The most recent swarms accounted for about 32 % of the total released seismic energy and were related to possible subsurface volcanic activities. Some of the Aqaba sequences have lasted for a few years, e.g., the 1995–1998 and the 1999–2003 (El-Isa 2012). Similar characteristics are observed in the compiled historical data of Table 1. For example, the 1156–1159 period of activity lasted for more than three years. This activity and other historic epicenters are located close to outcropping Quaternary basalts along the transform, which may indicate a volcanic origin to such seismic activities, e.g., the sequences of the years 500–502, 531–534, 551, and 659–660. Other shorter period volcanic-related swarms and sequences are also noted, e.g., the activities of the years 1113, 1344, and 1656.

The plotted epicenters show a good correlation with various tectonic elements of the Jordan Dead Sea Transform region. Most epicenters appear to correlate with the regional strike-slip faults of the transform, including the two largest earthquakes ($M=7.6$). At least eight earthquakes appear to

correlate with the Syrian Arc Fold System (SAFS) including one with $M=7.1$. Other earthquakes, not less than six, appear to correlate with the Erythrean Fault System (EFS). The assigned epicenter of one of the two largest earthquakes ($M=7.6$) is located at the junction between a major N–S trending strike slip fault with the major NW–SE trending Serhan fault, see Fig. 1. The historical seismicity data of Table 1 and Fig. 1 may be taken to indicate that the three major tectonic elements of this region are active in the present. This is in agreement with previous conclusions obtained from instrumental data (El-Isa 1988, 1992).

Five of the historical earthquakes, namely those of the years 363, 749, 1546, 1759, and 1927 are reported to have resulted in the occurrence of seiches in either the Dead Sea, Lake Tiberias, or both. The instrumentally recorded earthquake of 1995 caused a small (<1 m) high tsunami in the Gulf of Aqaba, based on unpublished field data collected by the first author from locals and the civil defense of Aqaba soon after the earthquake occurrence, see Table 2. The occurrence of seiches in these bodies of water is taken to confirm that these five earthquakes occurred along segments of the transform. The 1546 and the October 1759 earthquakes are also reported to have generated local tsunamis along the southern and northern Palestinian coasts.

Table 3 also includes 15 other historical earthquakes that have caused tsunamis in the East Mediterranean, see Ambraseys and Synolakis (2010) and Salamon et al. 2007. These have ranged from local tsunamis, i.e., affecting only local areas along the Mediterranean coasts,

Table 2 Seiches and one tsunami that occurred in the Dead Sea, Lake Tiberias, and the Gulf of Aqaba based on historical and recent $M \geq 6.0$ earthquakes that were unambiguously located along the Jordan–Dead Sea Transform during the last 2,000 years

Date	Assigned magnitude	Assigned epicenter		Comments
		North	East	
May 19, 363	6.6	31.4	35.6	Seiche in the Dead Sea
January 18, 749	7.2	33.0	35.5	Seiches in the Dead Sea and in Lake Tiberias
January 14, 1546	6.2	32.0	35.3	Seiche in the Dead Sea
October 30, 1759	7.0	33.1	35.6	Seiche in lake Tiberias
July 11, 1927	6.25	32.0	35.4	Seiche in the Dead Sea
November 22, 1995	7.1	28.81	34.8	<1 m Tsunami in the Gulf of Aqaba

to moderate tsunamis, i.e., affecting larger areas, to large or severe tsunamis affecting the whole East Mediterranean region including the coasts of Egypt, Palestine, Lebanon, Syria, and Cyprus, and causing the sinking and destruction of many ships. Six local tsunamis are reported including two that are known to have been caused by the 1546 ($M=6.2$) and the October 1759 ($M=7.0$) continental earthquakes that have also caused seiches in the Dead Sea and Lake Tiberias. These

events were thus unambiguously located along the transform; the assigned epicenter of the first is about 100 km east of the Mediterranean coast while the second is less than 50 km distant. The magnitudes of the other four earthquakes that caused local tsunamis are in the range from 6.4–7.4 and their inferred distances from the coast vary in the range from 35–175 km. Eight earthquakes are reported with moderate tsunamis including one of the largest historical earthquakes in the year 1156 ($M=$

Table 3 Historical tsunamis that have occurred in the Mediterranean and their causative earthquakes with magnitudes $M \geq 6.0$ that have been felt along the Jordan Dead Sea Transform region during the last 2,000 years

Date	Assigned magnitude	Assigned epicenter		Details of the Mediterranean tsunami
		North	East	
December 13, 115	6.4	36.1	36.1	Local tsunami in NE Mediterranean
348	6.2	33.9	35.5	Moderate tsunami along Syrian and Lebanese coasts
July 9, 551	7.4	33.9	35.5	Moderate tsunami along Lebanese and N Palestinian coasts, sea retreated 1 mile, many ships sank
January 18, 746	7.4	32.0	35.5	Severe tsunami along Syrian, Lebanese, Palestinian, and Egyptian coasts. Many ships sank
November 859	7.2	36.6	36.6	Moderate tsunami along Syrian coasts that extended to N. Palestinian coasts
December 5, 1033	6.6	32.5	35.5	Moderate tsunami along Palestinian and Lebanese coasts
March 18, 1068	7.0	29.8	35.0	Local tsunami along southern Palestinian coasts
November 29, 1115	7.2	36.1	36.1	Local tsunami in NE Mediterranean
September 28, 1156	7.6	35.14	36.3	Moderate tsunami along Syrian coasts
June 29, 1170	7.2	35.9	36.4	Moderate tsunami in NE Mediterranean
May 20, 1202	7.6	33.5	36.0	Severe tsunami that affected Syrian, Lebanese, Palestinian, Cyprus, and Egypt coasts
1404	7.0	35.9	36.3	Moderate tsunami along Syrian coasts
December 29, 1408	7.4	36.5	36.2	Moderate tsunami along N. Syrian coasts
January 14, 1546	6.2	32.0	35.5	Local tsunami along southern Palestinian coasts
October 30, 1759	7.0	33.1	35.6	Local tsunami along N. Palestinian and Lebanese coasts and sieches in Lake Tiberias
November 25, 1759	7.2	33.0?	35.6?	Large tsunami that affected the coasts of Palestine, Lebanon and Egypt
August 13, 1822	7.4	36.7	36.9	Local–moderate tsunami in NE Mediterranean

7.6). Seven of these have assigned locations within the northern half of the transform, within 15–70 km of the Mediterranean coast. Three earthquakes are reported with large and/or severe tsunamis. Their estimated magnitudes are 7.2, 7.4, and 7.6, and assigned locations are 50, 80, and 85 km east of the coast.

The time distribution, assigned magnitudes, and calculated seismic moments of all historical earthquakes are shown in Fig. 2. These graphs show that the historical seismicity of this region has fluctuated with time. Quiescent periods that last about 100–150 years are apparent, e.g., no earthquakes happened during the periods 130–233 and 860–963, and only four earthquakes with magnitudes 6.2–6.8 occurred during the period of 590–745. The seismic moment data, Fig. 2b, also show a few quiescent periods with a time duration of about 200 years each. Contrary to this, other active periods are observed, e.g., four large sequences with magnitudes as large as 7.3 have occurred during a 50-year long period (500–551). Four other large swarms and sequences with magnitudes as

large as 7.4 have occurred during a shorter time period in the years 835–860. Nine large earthquakes and sequences including the largest two ($M=7.6$) are reported to have occurred during the period 1138–1212. The seismic moment data show a gradual seismicity increase during the first eleven centuries to a peak of activity during the period 1138–1212 and a gradual decrease thereafter, see Fig. 2b. When the 25 possible East Mediterranean earthquakes are removed, the time distribution shows a more noticeable fluctuation with longer quiescent periods with a duration of about 400 years, e.g., the periods 50–450, 1202–1625, and 1627–1995, see Fig. 3b.

The spatial distribution of the assigned epicenters of the earthquakes plotted in Fig. 1 is summarized in Table 4. Each of the inferred fault segments has distinctive seismogenic characteristics. The Karasu segment is associated with the largest number of earthquakes (38) and the shortest recurrence period (53 years). This is followed by the Beqa'a segment, with 21 earthquakes and a 95-year recurrence period. The Jericho segment follows with 17 earthquakes and a 118-year

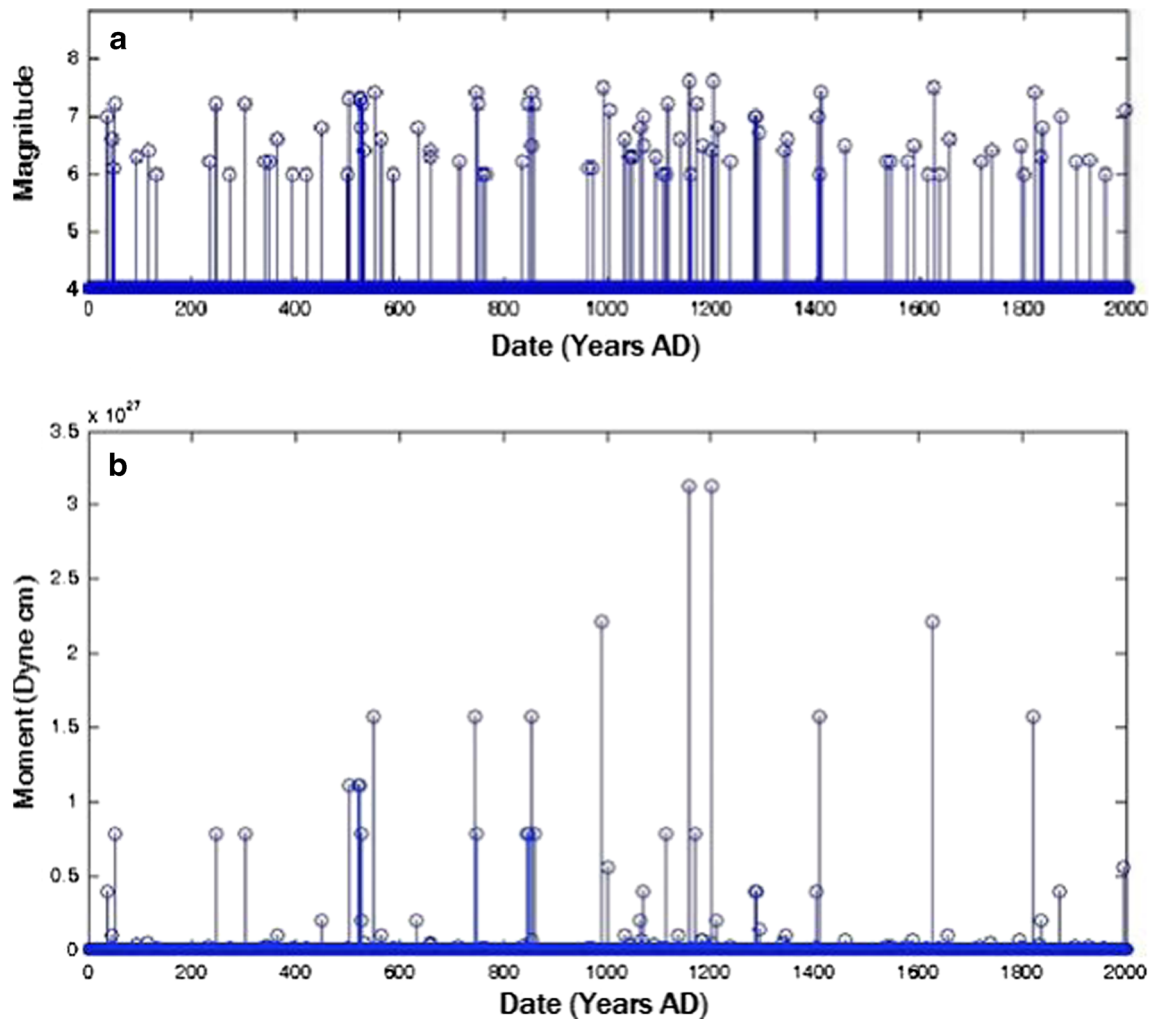


Fig. 2 **a** The time distribution of all historical earthquakes ($M \geq 6.0$) that were felt along the Jordan Dead Sea transform region during the last 2,000 years. **b** The seismic moment time distribution of the same seismicity

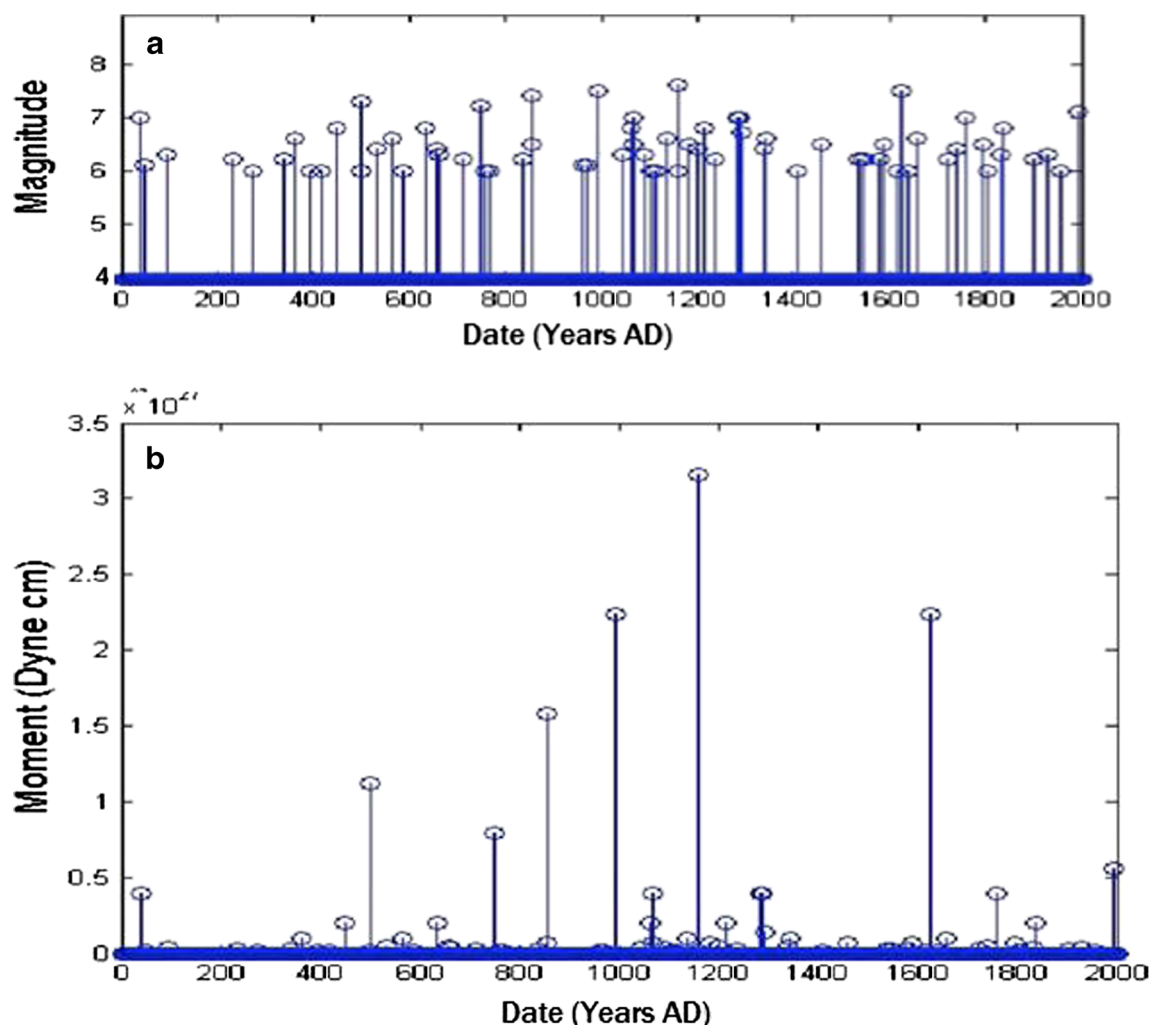


Fig. 3 **a** The time distribution of all historical earthquakes ($M \geq 6.0$) that occurred unambiguously along the Jordan Dead Sea Transform region during the last 2,000 years, i.e., 96–25 possible E Mediterranean epicenters. **b** The seismic moment time distribution of the same seismicity

recurrence period. This is followed by the Al-Ghab, Araba, and Aqaba segments, whose earthquake numbers are 8, 7, and 5, and 250, 286, and 400 years recurrence periods in successive order. The two largest magnitude earthquakes (7.6) are associated with Beqa'a and Al-Ghab segments. It is evident that the seismicity and seismic hazard of the northern part (Beqa'a, Al-Ghab, and Karasu) of the transform is higher than that of its southern part (Aqaba, Araba, and Jericho). The average recurrence period for earthquakes with $M \geq 6.0$ in the northern part is 30 years and the highest magnitude is 7.6, while for the southern part the recurrence period is 69 years and the maximum magnitude is 7.4. For the whole Jordan Dead Sea Transform region, the overall average recurrence period for $M \geq 6.0$ earthquakes is 21 years only.

Table 4 includes an estimate of the maximum plausible earthquake magnitude ($M_{\max}$), calculated using a formula proposed by Wells and Coppersmith (1994),

$$M_{\max} = 5.16 \pm 0.13 + (1.12 \pm 0.08) \log L, \quad (1)$$

where L is the length of the fault in kilometers. An alternative formula to estimate $M_{\max}$ was proposed by Wyss (1979),

$$M_{\max} = \log A + 4.15, M > 5.6, \quad (2)$$

where A is the fault area in square kilometers. Utilizing both Eqs. (1 and 2), $M_{\max}$ varies in the range from $7.6-7.8 \pm 0.2$ based on the fault lengths of Table 4 and assuming the width to be 20 km. When the width is considered to be 10 km, calculated $M_{\max}$ from Eq. 2 is reduced to 7.3–7.5. As the Araba segment is associated with the largest length, it is associated with the largest $M_{\max}$, which varies in the range from $7.6 \pm 0.2-7.8 \pm 0.25$ for all segments.

Table 5 summarizes the total number of felt earthquakes (N1), a subset of historical earthquakes interpreted as unambiguously associated with the Jordan Dead Sea Transform (N2), and a hypothetical model that is discussed below (N3). Frequency-magnitude analysis was applied to the 96 historical

Table 4 The tectonic segments that form the Jordan Dead Sea Transform (JDST), their locations, lengths, directions, historical seismicity, the largest felt historical earthquakes that occurred during the last 2,000 years and the maximum plausible earthquake

Tectonic segment	Coordinates latitude (N), longitude (E)	General strike	Length (km)	Number of historical earthquakes $M \geq 6$ /2,000 years	Average recurrence period (years)	Largest historical earthquakes	Maximum plausible magnitude ($M_{\max}$)
Aqaba (AQ)	28.0°–29.5° 34.2°–35.0°	N 15° E	190	5	400	7.1	7.7±0.2
Araba	29.5°–31.4° 35.0°–35.60	N 10° E	220	7	286	7.0	7.8±0.25
Jericho	31.4°–33.25° 35.4°–35.6°	N 5° E	200	17	118	7.4	7.7±0.2
Southern JDST	28°–33.25° 34.2°–35.6°	N 5°– 15° E	610	29	69	7.4	7.8±0.25
Beqa'a	33.25°–34.5° 35.6°–36.3°	N 30° E	160	21	95	7.6	7.6±0.2
Al-Ghab	34.5°–35.75° 36.25°–36.3°	N–S	140	8	250	7.6	7.6±0.15
Karasu	35.75°–37.5° 36.3°–36.9°	N 12° E	195	38	53	7.5	7.7±0.2
Northern JDST	34.5°–37.5° 35.6°–36.9°	N 0°– 12° E	495	67	30	7.6	7.7±0.2
Entire JDST	28.0°–37.5° 34.2°–36.9°	NNE	1,105	89	21	7.6	7.8±0.3

earthquakes that were felt along the Jordan Dead Sea transform region, listed in Table 1, and N1 of Table 5. Results are presented on Fig. 4a. Application of the Gutenberg–Richter formula using a linear regression approach yields a and b values of 7.4 and 0.876, respectively. The relatively low correlation coefficient ($R^2=0.83$) and unusually low b value compared to the global average of 1.0 ± 0.1 (El-Isa 2013; El-Isa and Eaton 2013) are suggestive of possible inaccuracies in the catalog. In particular, the number of earthquakes with magnitudes in the range from 6.0 to 6.4 falls below the line of best fit, whereas the number of earthquakes with magnitude great than 7.0 falls above the line.

For comparison, Fig. 4b displays the frequency–magnitude results of 71 earthquakes that are interpreted to be unambiguously located along the transform, N2 of Table 5. This set of earthquakes represents the seismicity data of Table 1, with the omission of 25 earthquakes suspected to be located in the East Mediterranean. The revised a and b values are 7.60 and 0.948 and the correlation coefficient increased to 0.99. These data still show a relative deficiency of earthquakes magnitudes in the range from 6.0 to 6.4 and a larger than expected number of events in the magnitude range from 7.0 to 7.4.

Given the inherent uncertainties in the compiled catalog of historical earthquakes, it is useful to consider a hypothetical

Table 5 Analysis of felt earthquakes in the Jordan Dead Sea Transform region with $M \geq 6.0$ –7.6 during the last 2,000 years

Magnitude	Felt earthquakes along JDST (N1)	Subset of earthquakes unambiguously linked to the JDST (N2)	Expected earthquakes, based on the Gutenberg–Richter relation (N3)	Inferred surplus/deficiency (N1–N3)
6.0	18	18	45	–27
6.2	19	18	27	–8
6.4	13	12	16	–3
6.6	8	6	12	–4
6.8	6	5	9	–3
7.0	9	5	5	+4
7.2	14	2	3	+11
7.4	7	2	2	+5
7.6	2	2	3	–1

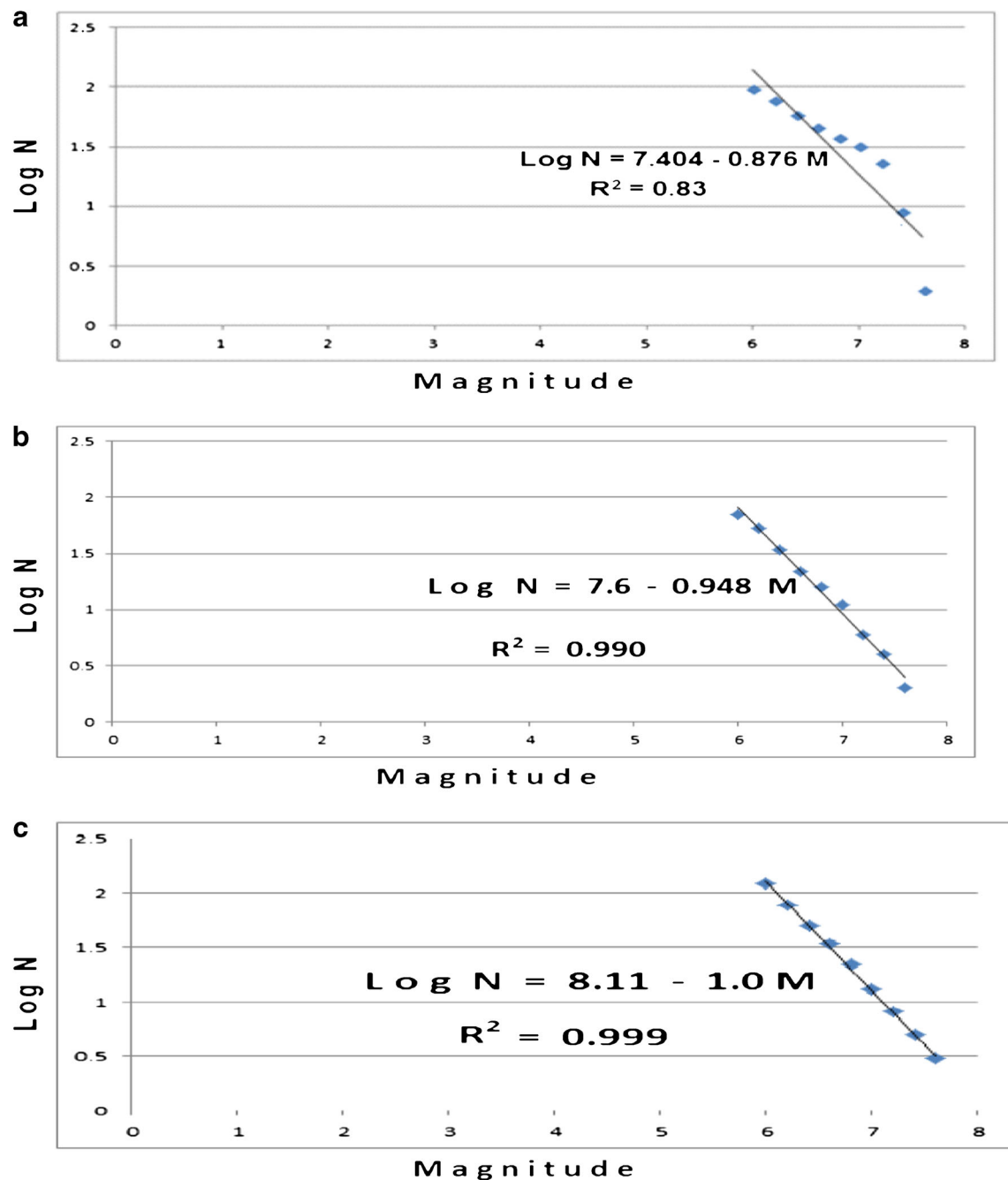


Fig. 4 Frequency-magnitude results of **a** The 96 historical earthquakes felt along the JDST region during the last 2,000 years (N1 of Table 5), **b** The same data excluding 25 earthquakes of possible East Mediterranean epicenter (N2 of Table 5), **c** The expected seismicity data (N3 of Table 5)

distribution. Assuming that three 7.6-magnitude earthquakes have occurred along the Jordan Dead Sea Transform region during the last 2,000 years, i.e., average recurrence period=667 years, and modifying the numbers of all other magnitudes through increasing those with magnitudes in the range from 6.0 to 6.8 and decreasing the numbers of those with magnitudes of 7.0 to 7.4, N3 of Table 5, the frequency magnitude results are shown on Fig. 4c. These gave a , b , and R^2 values as 8.11, 1.0, and 0.999, in respective order. Based on global average seismicity statistics (El-Isa 2013; El-Isa and Eaton

2013), such values appear to be plausible for the long-term seismicity of the Jordan Dead Sea Transform region.

The last column in Table 5 shows N1–N3. Assuming an expected earthquake distribution that follows the Gutenberg-Richter relation, this difference suggests that 27 earthquakes with $M=6.0$ and one 7.6 magnitude are “missing” from these historical data. Moreover, this analysis suggests that some 4, 11, and 5 more earthquakes appear to be erroneously added to the historical data of Table 1. Such results may therefore be taken to indicate that some of the 7.0–7.4 historical

earthquakes of Table 1 have been assigned erroneously high magnitudes or, more likely, are related to the regional structures of the Eastern Mediterranean region rather than the Jordan Dead Sea Transform region. The potential for mis-assignment of earthquakes is particularly acute for the northern part of the transform, where the assigned epicenters generally lie within 15–70 km east of the Mediterranean shores, i.e., within the uncertainty of epicentral determination.

Next, the seismic moments were calculated for all historical earthquakes using the relation of Kanamori and Anderson (1975) and Hanks and Kanamori (1979),

$$M = \frac{2}{3} \{ \log Mo - 16.1 \}, \quad (3)$$

where M is the magnitude and Mo is the seismic moment in dyne per centimeter. Calculated seismic moments were then used to estimate annual seismic slip rate along the Jordan Dead Sea Transform based on the relation

$$Mo = \mu AU, \quad (4)$$

where Mo is seismic moment in dyne per centimeter, A is the sliding area in square centimeters, and U is the slip in centimeters (Aki 1966; Hanks and Boore 1984). Our calculations assume a total length of the transform to be 1,100 km, a variable fault width of 5, 7, and 10 km and the rigidity (μ) of crustal rocks of 3×10^{11} dyn/cm² (Hanks and Kanamori 1979). Results are presented in Table 6. The compiled 96 earthquakes of Table 1 gave annual slip rates of 0.6, 0.852, and 1.193 cm/year for fault–zone depth extents of 10, 7, and 5 km, respectively.

Discussion

Our revised compilation of historical earthquakes in the Jordan Dead Sea Transform includes some 96 earthquakes ($M \geq 6.0$) that were felt during the last 2,000 years. The highest assigned magnitude is 7.6 and the calculated maximum plausible magnitude for the different segments of the transform

varies in the range from $7.6\text{--}7.8 \pm 0.2$. Temporal fluctuation of seismic activity is evident from the time distribution of both magnitudes and seismic moments, Figs. 2 and 3. The historical data show that not less than 50 % of the seismicity of this region occurs in the form of sequences and swarms. The location of many historical epicenters close to outcropping basalts, Fig. 1, strongly suggests a volcanic origin for some of these sequences and swarms. Similar results have been obtained from instrumental data (Al-Qaryooti 1990; El-Isa et al. 1984; El-Isa 2012). Taking this into consideration, together with the assigned magnitudes of Table 1 and the geologically and geophysically deduced slip rate of 1 cm/year (Qunnell 1958, 1959; Girdler 1990; El-Isa 2012; El-Isa and Mustafa 1986) and comparing with similar tectonic environments such as the San Andreas Fault system in California, where the slip rate is about three times or more, with frequent larger magnitude earthquakes, e.g., Bennet et al. 1996; DeMets and Dixon 1999, it is noted that the seismic hazard along the Jordan Dead Sea Transform system can be considered to be moderate.

The historical seismicity information of the Jordan Dead Sea Transform has confirmed that some continental earthquakes with magnitudes $M \geq 6.2$ have produced seiches in the Dead Sea and in Lake Tiberias; furthermore, some events may have produced local-to-moderate tsunamis in the Mediterranean Sea some 100–175 km to the west, see Tables 2 and 3. Such tsunamis are normally caused by large landslides and slumps that are triggered by earthquakes along the continental slope. The slumps size and effect are mainly controlled by the earthquake magnitude, epicentral distance, and other submarine geological, environmental, and sedimentological conditions. Other historical earthquakes are also reported to have caused medium–large Mediterranean tsunamis without seiches in the Dead Sea or Lake Tiberias, see Table 3.

Though the location accuracy of many historical epicenters is not better than ± 50 km, the epicentral distribution of Fig. 1 shows a reasonable correlation with the general tectonics of the study region. Most earthquakes with magnitudes of $M \geq 7.1$, including the largest two correlate with the regional NNE trending strike-slip faults. Some eight and six earthquakes can be associated with the Syrian Arc Fold System (SAFS) and the Erythrean Fault System (EFS), respectively, i.e., the historical

Table 6 Calculated seismic moments and seismic slip rates (cm/year) as deduced from the three sets of historical seismicity data in Table 5, assuming the total length of the transform is 1,100 km and $\mu = 3.0 \times$

10^{11} dyn/cm². An estimated moment value of 0.06×10^{28} dyn/cm is added to the values of column 1 to account for earthquakes with $M < 6.0$

Historical seismicity data	Seismic moment $\times 10^{28}$ dyn/cm	Slip rates (cm/year)		
		Width 5 km	Width 7 km	Width 10 km
96 Felt earthquakes along JDST (N1 of Table 5)	3.935	1.193	0.852	0.60
71 JDST epicentered earthquakes (N2 of Table 5)	2.226	0.68	0.482	0.34
122 expected earthquakes (N3 of Table 5)	2.268	0.69	0.49	0.345

data supports the conclusion of El-Isa (1992) from instrumental data that all major tectonic elements of this study region are active in the present. The apparent higher activity of the northern three segments as compared to the southern three is difficult to justify for such long period of observation (2,000 years), particularly, when it is known that the whole transform region is floored by typical continental type of crust with similar characteristics (El-Isa et al. 1987; Khair et al. 1997). We therefore interpret the higher apparent activity to be a result of mislocation of epicenters of historical earthquakes in previous compilations in this region. In particular, some epicenters might belong to the Eastern Mediterranean region, whereas others might belong to nearby intraplate faults. The distance between the northern part of the transform and the Mediterranean coast is roughly equal to the accuracy of epicentral locations.

Other indirect evidence supports the omission of some events from the catalog. The rather low b value and correlation coefficient of the frequency–magnitude analysis, Fig. 4a–c, suggests that some of the felt earthquakes of Table 1 do not belong to the regional structures of the transform. Smaller correlation values were obtained from the same analysis applied to the data of Sbeinati et al. (2005) and Utsu (1990). The potential for earthquake mislocation is particularly acute for earthquakes with $M=7.0$ – 7.4 . The larger-than-expected number of earthquake in large magnitude bins may be the result of: (i) mislocating some East Mediterranean and/or other intraplate earthquakes, (ii) exaggeration in reported intensities and assigned magnitudes, or (iii) both causes. These factors may also contribute to an apparent deficiency of events observed in the range $6.0 < M < 6.4$. Given the reliability of historical records and the sustained population density of this region, we consider it to be unlikely that events in this magnitude range were not reported.

The generation of tsunamis through submarine slumping caused by continental earthquakes and/or other mechanisms is a well-known phenomenon that has received much attention during the last few decades (e.g., Kawata et al. 1999; Geist 2000; Tappin et al. 2001; Piper et al. 2003; Papadopoulos and Kortekaas 2003). In many cases, slump-related tsunamis remain local and of limited effect on the coastal zone that extends only to about 10–15 km from both sides of the slump. They have wavelengths of a few kilometers with wave heights that attenuate rapidly due to frequency dispersion. The wavelengths, heights, and length of affected areas are mainly controlled by the slump volume (Papadopoulos and Kortekaas 2003). Contrary to this, tsunamis generated by co-seismic displacement of the seabed associated with submarine earthquakes are more widely distributed and their wave heights are magnitude controlled. The wavelength of this class of tsunamis is generally hundreds of kilometers and their amplitude decay is slow because of weak dispersion effects (Geist 2000; Papadopoulos and Kortekaas 2003). Thus, if the affected

coastal zone is larger than 15 km, the tsunami is most likely induced by a slump associated with co-seismic fault displacement component as is the case of Izmit, Turkey, and Papua New Guinea tsunamis (Kawata et al. 1999; Geist 2000; Tappin et al. 2001; Papadopoulos and Kortekaas 2003). This suggests that some of the moderate and all large tsunamis of Table 3 were caused by marine earthquakes, whereas some of the moderate tsunamis might be at least of co-seismic effect associated with slumping. Combining this inference with the aforementioned frequency–magnitude analysis suggests that some of the reported large earthquakes ($M \geq 7.0$) of Table 1 were located within the East Mediterranean rather than along the Jordan Dead Sea Transform.

Based on the complete set of 96 earthquakes, the 1.193 cm/year deduced annual slip rate of Table 6 is considered the best representative estimate from this data, for the following reasons. First, the seismicity of this transform is known to be concentrated in the upper part of the upper crust (El-Isa 1992, 2012; Mechie and El-Isa 1988). Secondly, it is implausible for the whole 1,100 km length of the transform to rupture to a depth greater than 5 km at once. Considering the maximum possible earthquake magnitude to be 7.8, Table 4, the maximum width, as calculated from Eq. (2), is no more than 4 km. Thirdly, it is known that for strike–slip faults in continental regions, the fault's depth extent is smaller and its length is larger than those for normal faults (Papazachos et al. 2004). This deduced slip rate is only slightly higher than the geologically deduced slip rate (1 cm/year) (Quennell 1958, 1959, 1984; Girdler 1990). Furthermore, previous seismicity studies indicate that not less than 30 % of the tectonic slip along the regional strike–slip faults of the study region is aseismic (e.g., El-Isa and Mustafa 1986; El-Isa 2012).

The foregoing discussion leads to the conclusion that the 96 compiled felt earthquakes of Table 1 include some earthquakes that do not belong to the Jordan Dead Sea Transform. Combining frequency–magnitude analysis and tsunami results, it is concluded that some of the large earthquakes ($M \geq 7.0$) of Table 1 have magnitudes that are overestimated or, in our preferred interpretation, some reported large historical earthquakes are from the East Mediterranean region and are thus unrelated to deformation along the Jordan Dead Sea Transform. This conclusion is supported by the deduced slip rates of columns 2 and 3 of Table 6. The 0.68–0.69 cm/year is in agreement with deduced slip rates from pre-historic data (El-Isa and Mustafa 1986).

Finally, the area where the Syrian Arc Fold System crosses the transform approximates the border between the northern and southern parts. This crude partitioning of the fault system into northern and southern regions raises a number of fundamental questions. It is not clear, for example, to what extent this partitioning of the fault

system may affect the geodynamic situation, in which tectonic stresses are evidently higher in the north than in the south. More work is needed to elucidate these relationships.

Conclusions

Detailed studies to the historical seismicity of the Jordan Dead Sea Transform region that occurred during the last 2,000 years have revealed the following:

1. Ninety-six earthquakes have been felt along the study region with magnitudes in the range of $M \geq 6.0$. Most of these occurred in the form of sequences and swarms that lasted for variable periods ranging from a few hours to a few days, weeks, months, and up to a few years. Some of these sequences are located close to outcropping Quaternary volcanic regions and thus are possibly volcanic related. Revised seismicity data Table 5 indicate that recurrence periods for earthquakes with magnitudes of $M \geq 7.0$, 7.2, and 7.4 are 154, 250, and 400 years, respectively. Theoretical calculations indicate that the maximum plausible earthquake magnitudes along the different segments of this transform are in the range from $7.6-7.8 \pm 0.3$ with a recurrence period of about $1,000 \pm 80$ years for the 7.8 magnitude.
2. The historical seismicity shows good correlation with the general tectonics of the study region. Many assigned epicenters, including the largest earthquakes, correlate with the regional NNE trending strike-slip faults. Others appear to correlate with both the regional Syrian Arc Fold and the Erythrean Fault Systems. This indicates that the three major tectonic elements of the study region are active in the present, in agreement with a similar conclusion derived from instrumental seismicity data (El-Isa 1992). An apparent higher seismic hazard is evident for the northern three segments of the transform compared with the southern three, as the average recurrence periods for $M \geq 6.0$ is 30 years for the first and 69 years for the second and the highest assigned magnitudes are 7.6 and 7.4, respectively.
3. The historical seismicity shows obvious fluctuations with time where the time distribution of both magnitudes and seismic moments show quiescent periods that extend 150 to 200 to 400 years interchanged with periods of higher activities, some of which extend for a few tens of years.
4. Frequency-magnitude analysis indicates higher numbers of reported earthquakes with magnitudes $M = 7.0-7.4$ and a relative deficiency of earthquakes with magnitudes 6.0–6.4. This is interpreted to be caused by either overestimation of magnitudes or mislocation of some East Mediterranean earthquakes, particularly, those associated with moderate and large tsunamis.
5. This study illustrates the importance of compiling historical seismicity from original sources, particularly historical Arab literature. In contrast, some other compilations rely on secondary sources, which leads to overestimation of the seismicity of this region, brought about by either (1) repeating some earthquakes and sequences, in some cases, as a result of differences in calendar systems (Lunar Arab versus Western); (2) assigning magnitudes higher than the actual magnitude; and (3) aforementioned mislocations of epicenters, particularly those associated with moderate-to-large tsunamis. Additional evidence for overestimation of seismicity in this region comes from calculated seismic slip rate from the 96 felt earthquakes (1.193 cm/year), which is higher than the long-term geologically deduced slip rate, and apparent higher seismicity of the northern part of the transform, which is most probably caused by mislocating the earthquakes and magnitude exaggeration.
6. The revised historical seismicity data indicate a seismic slip rate of about 0.68 cm/year, similar to calculated slip rates from instrumental data (El-Isa 2012) and pre-historic seismicity data (El-Isa and Mustafa 1986). This indicates that about 30 % of the lithospheric movements along the Jordan Dead Sea Transform are aseismic in nature.

Acknowledgments This work was completed during a sabbatical year the first author spent at the University of Calgary, Canada, with financial support from the University of Jordan, Amman, Jordan.

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