

The instrumental seismicity of the Jordan Dead Sea transform

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Abstract The instrumental seismicity that occurred in the Jordan Dead Sea transform region during the period 1900–2014 is compiled from all available sources. Some 492 phosphate mining explosions ($M \leq 3.9$) are recognized and filtered from the data. Excluding these, it is found that 4448 earthquakes have occurred with magnitudes $M \geq 3.0$. Only 572, 18 and 2 of these had magnitudes $M \geq 4, 5$, and 6 in respective order. Average recurrence periods for the 5 and 6 magnitudes are 6.3 and 57 years. Much of these have occurred in sequences and swarms. The epicentral distribution of the compiled instrumental seismicity data shows very good correlation with the general tectonics of the study region. All tectonic elements are active in the present with a noticeable hazard. The regional strike-slip faults of the transform proper remain the major sources of this hazard. They account for not less than 99% of the seismic energy released from all instrumental data. The calculated a -parameter of the whole transform is 6.6. It varies for all its strike-slip faults mostly in the range 6.0–6.6. The b -value of the whole transform and some of its major segments is 1.0. Others show b -variations in the range of 1.1–1.3. Such a - and b -values imply recurrence periods of 38 years and 395 years for the 6 and 7 magnitude earthquakes. Such values, their variations and the seismic moment calculations clearly indicate an appreciable level of seismic hazard associated with all segments. This hazard appears to be highest for Al Ghab segment, followed by Beqa'a and Wadi Araba segments, respectively. The other three segments appear to be of lower hazard. The seismicity of this region is

very shallow. More than 99% of the seismic energy has been released from the brittle granitic upper crust whose thickness is about 21 km and its Poisson's ratio is 0.25. More than 93.6% of the energy was released from its upper 10 km. Very little energy is released from the underlying ductile basaltic crust whose Poisson's ratio is 0.29. The calculated seismic slip rate along the Whole Jordan Dead Sea transform is 0.54 cm/year if the fault depth is assumed 10 km. It increases to 0.77 and 1.07 cm/year if the fault depth is reduced to 7 and 5 km, respectively. These slip rates are comparable with the long-term geologically deduced rate of 1 cm/year.

Keywords Seismicity · Seismotectonics · Dead Sea · Jordan Dead Sea Transform

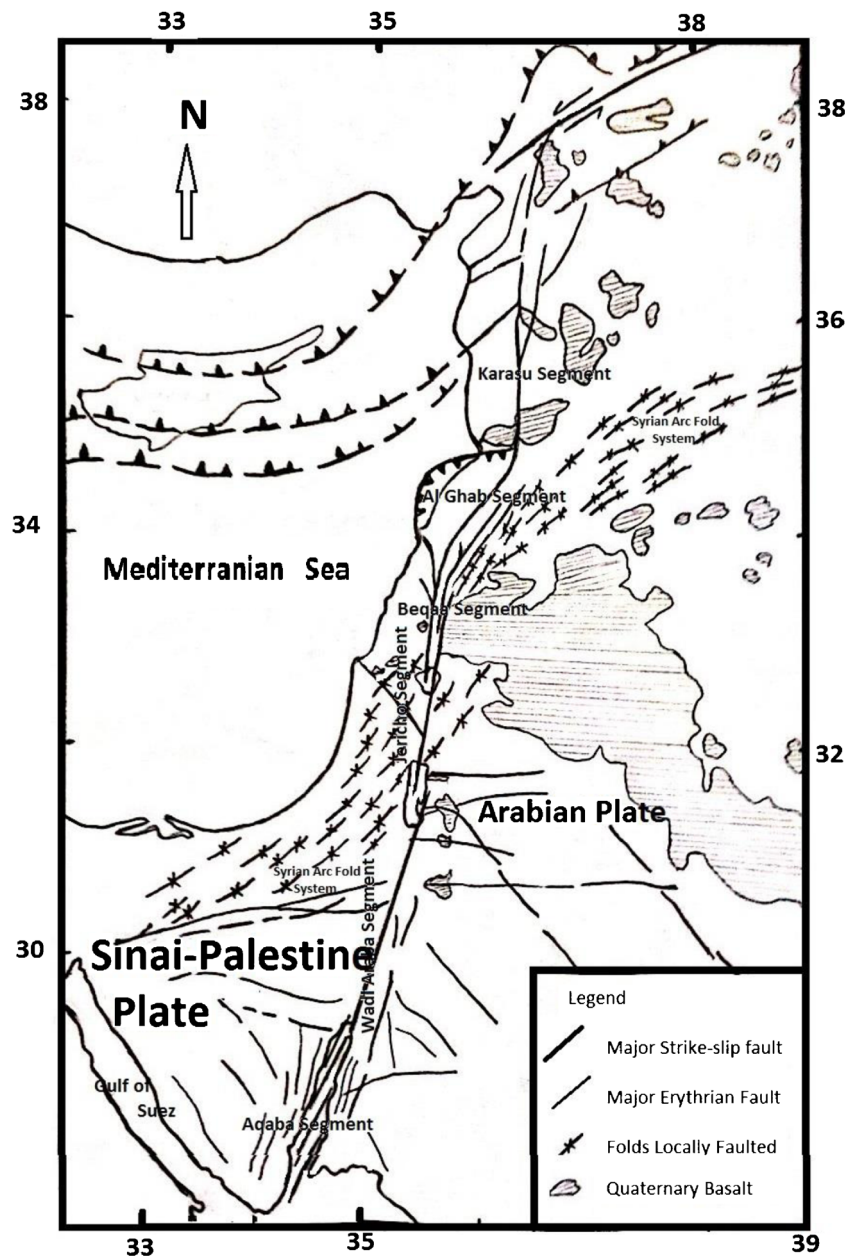
Introduction

The Jordan Dead Sea transform is a major tectonic structure that forms a plate boundary between the Arabian and the Sinai-Palestine plates. With its 1100 km total length and N-NE general trend, it links the Red Sea seafloor-spreading in the south to complex plate convergence within the Anatolian domain in the north. Three major deformational phases have affected the transform region throughout the Cenozoic. The oldest is dated at Pre-Jurassic age. It is represented by the NNE movement and anti-clockwise rotation of the Arabian plate which resulted in the formation of the S-shaped Syrian arc fold belt; see Fig. 1. 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. During the Middle Cenozoic, the third deformational phase resulted in the formation of the Jordan-Dead Sea transform itself. The NNE trending strike-slip faults of this transform appear to accommodate much of the relative plate movements

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Fig. 1 Regional tectonics of the Jordan Dead Sea Transform System



which are directly related to the geodynamic processes acting in the Red Sea. 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 Karasu segments in successive order; see Fig. 1. 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 along this transform (Quennell 1958, 1959, 1984; Girdler 1990).

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 (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 2000 years (El-Isa 1985, 1992). Instrumental seismicity data represent the third source but with variable quality. Prior to the 1950s, the nearest seismological station was the Helwan observatory, Egypt. Thus, the instrumental seismicity of this transform during the first half of this century was mostly limited to earthquakes with magnitudes $M \geq 3$, or more. The highest quality is represented by data for the period 1982–present, as these data are recorded on local seismological stations.

Many studies, compilations, and publications have been made on the instrumental seismicity of this region during the last decades, e.g., El-Isa (1983, 1988, 1992, 2013), El-Isa and Al Shanti (1989), Ambraseys and Melville (1989),

Ambraseys et al. (1994), Khair et al. (2000), Klinger et al. (2000), Salamon et al. (1996); Harajli et al. (2002), Shapira et al. (2007), Hofstetter et al. (2007), and Ambraseys (2009). The results of these studies clearly indicate an appreciable level of seismic hazard associated with the regional faults of the Jordan Dead Sea transform. Maximum expected magnitude as large as $M = 7.5$ was evaluated by different investigators (e.g., Shapira et al. 2007 and references therein).

An up-to-date compilation and filtering is made to the instrumental seismicity of the study region that occurred during the period 1900–2014 utilizing all available seismological sources. The data are analyzed and evaluated in terms of regional tectonics, seismic moment, frequency-magnitude distribution, and seismic slip rate. Results are discussed and presented in this article.

The instrumental seismicity data of the period 1900–2014

All available local and international seismological catalogues and bulletins have been searched for the instrumental seismicity of the study region from the start of the previous century. These include catalogues from the Jordan University Seismological Station (UNJ), the Jordan Seismological Observatory (JSO), the International Seismological Center (ISC), and the National Earthquake Information Center (NEIC) of the USGS and the American Incorporated Research Institutions for Seismology (IRIS). It is found that the JSO and the ISC catalogues appear to have the most complete seismicity data of the study region. In the case of differences, the ISC data were considered. It was carefully meant to compile only the seismicity of the transform and its tectonic elements, i.e., not to include any seismicity that belongs to the Red Sea in the south, or the Gulf of Suez in the southwest or the Mediterranean in the west or any of the Turkish seismicity in the north. Therefore, the search was limited to the area bound by latitudes 28° N– 37.5° N but variable longitudes 34.0° E– 35.5° E in the Gulf of Aqaba segment in the south to a range 36.0° E– 37.5° E in the northernmost Karasu segment; see Table 2. Special attention was given to the reported seismicity ($M \geq 1.0$) epicentered within the region bound by latitudes 29° and 30° and longitudes 36.0° and 36.7° where the Jordan Phosphate Mining company does continuous large explosion activities related to their phosphate exploitation ever since the year 1979. It is found that some 492 reported earthquakes are epicentered within this region with the following characteristics: 1. Their magnitudes varied in the range $M = 1$ – 3.9 ; some 41% of these had $M = 3$ – 3.9 and 51% with $M = 2$ – 2.9 ; 2. All events have occurred during the working hours of the day, some 72% of these in the time range 11 a.m.–14 a.m.; 3. Some 341 events representing 69.3% of the total are reported with zero focal depth, 19.7% with depths

1–10 km and 11% with depths 11–45 km. Such events are quite distant from all seismological stations of the study region which makes their calculated focal depths questionable. Seismic records of a number of these events as recorded on the Jordan University seismological station were examined and correlated with each other and the seismograms of other natural local earthquakes. It is concluded that all the 492 mentioned events are very shallow phosphate explosions. Therefore, all these were removed from the seismicity data.

Excluding the above mentioned phosphate explosions, it is found that during the period 1900–2014, some 7726 earthquakes are reported to have occurred along the study region with surface wave magnitudes ($M \geq 2.0$). Only 4448, 572, 18, and 2 earthquakes are reported with magnitudes $M \geq 3, 4, 5,$ and 6 in respective order. The time distribution of this seismicity is presented in Fig. 2a, b. The noticeable increase of seismicity in the 1980s correlates with the start of earthquake monitoring in Jordan in the year 1981 for the first time (El-Isa 1983). The well-known Gulf of Aqaba earthquake of the year 1995 had the highest magnitude $M = 7.1$. The second largest ($M = 6.25$) is the well-known 1927 Jericho earthquake of Palestine; see Table 1. Out of the 4448 earthquakes ($M \geq 3$) that occurred all along the transform region during the period 1982–2014, some 3451 were epicentered along the tectonic segments of its southern half representing 77.6% of the total number. The percentages of the 1982–2014 activity of the southern half with magnitudes $\geq 4, 5,$ and 6 are 92.5, 90.9, and 100%. Considering the seismicity data of the period 1900–2014, some 89.9, 72.2, and 100% of the activity with $M \geq 4, 5,$ and 6 have occurred within the southern half. These results clearly show that the seismicity of the southern half of the Jordan Dead Sea transform region was much higher than that of its northern half during the last eleven decades; see Table 1 for more details.

Analysis and evaluation of the instrumental seismicity data

The epicentral distribution of the compiled seismicity with magnitudes $M \geq 3.5$ as presented on Fig. 3 shows very good correlation with the regional tectonics. Most large earthquakes including the largest nine ($M = 5.4$ – 7.1) are epicentered along the regional strike-slip faults of the transform proper. Some earthquakes with magnitudes $M \leq 5.0$ are seen to correlate with the Syrian Arc Fold System, and others are epicentered along the faults of the Erythrean system. Other earthquakes are also observed to be epicentered along the outcropping Quaternary basalts. It is well-known that the largest earthquakes, particularly the 1927 and 1995 earthquakes, are mainly of strike-slip mechanism, with secondary vertical components (Abdel-Fattah et al. 1997, 2006; Pinar and Turkelli 1997; El-Isa et al. 1984). This therefore clearly indicates that the regional strike-slip

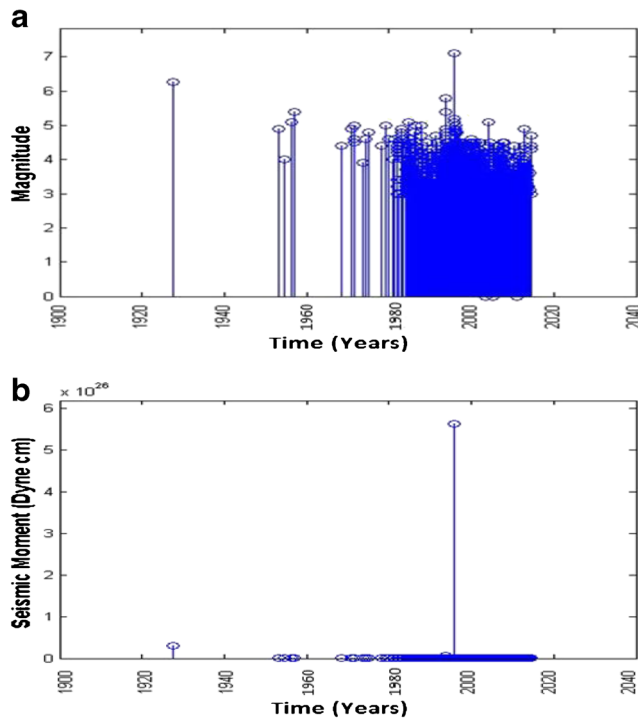


Fig. 2 The time distribution of the instrumental seismicity of the Jordan Dead Sea transform region displays **a** time versus magnitude and **b** time versus seismic moment

faults of the transform proper remain the major sources of seismic hazard in the study region.

The spatial distribution of the instrumental seismicity ($M \geq 3.0$) of the period 1900–2014 is presented in Fig. 4a, b. Thirteen earthquakes are observed to have occurred within the southern half of the transform with magnitudes in the range of $M = 5–7.1$. The largest two are seen at latitudes 28.81° and 31.932° . Only five earthquakes with magnitudes $M = 5–5.1$ have occurred within the northern half; see Fig. 4a. The calculated seismic moment is plotted versus latitude on Fig. 4b. It

clearly shows that the seismicity of the southern half was much higher than that of the northern half during the last eleven decades; see also Table 2.

Much of the seismicity of this region has occurred in the form of sequences and swarms. The Gulf of Aqaba seismicity shows that about 98% of the released seismic energy was from earthquakes of this type and is mostly volcanic-related. The importance of this characteristic stems from the fact that it leads to a reduction in the seismic hazard.

The focal depth distribution (Fig. 5) shows that the seismicity of this region is very shallow. Most of it including all the largest have occurred within the upper part of the crust. More than 99% of the seismic energy was released from earthquakes with depths ≤ 22 km. More than 93.6% of the energy was released from depths ≤ 10 km, i.e., from within the upper part of the upper granitic crust.

Very little energy is released from the lower basaltic crust and uppermost mantle. It is concluded therefore that the Jordan Dead Sea transform region is characterized by a brittle upper granitic crust and a ductile lower basaltic crust and upper mantle. Tectonic movements at depths ≥ 22 km appear to be mostly, if not totally, aseismic.

Frequency-magnitude, seismic moment, and slip-rate calculations

Detailed frequency magnitude analysis was carried out to the instrumental seismicity data for the whole transform region, its southern and northern parts and its individual tectonic segments. Results are presented in Table 2 and Figs. 6 and 7. The *b*-results clearly indicate that the threshold magnitude of the available instrumental seismicity of the Jordan transform including all its components is 3.0. The *a*-value is 6.60 for the

Table 1 Total number of earthquakes (*N*) that occurred along the Jordan Dead Sea transform and its two northern and southern halves during the periods 1900–2014 and 1982–2014 tabulated with their magnitude ranges

$M \geq$	Whole Transform Region				Southern Half				Northern Half				
	Date		Date		Date		Date		Date		Date		
	1900–2014	1982–2014	1900–2014	1982–2014	1900–2014	1982–2014	1900–2014	1982–2014	1900–2014	1982–2014	1900–2014	1982–2014	
<i>N</i>	<i>T</i> (years)	<i>N</i>	<i>T</i> (years)	<i>N</i>	<i>T</i> (years)	<i>N</i>	<i>T</i> (years)	<i>N</i>	<i>T</i> (years)	<i>N</i>	<i>T</i> (years)	<i>N</i>	<i>T</i> (years)
3	4448	0.0256	4422	0.0075	3451	0.033	3443	0.0096	997	0.114	979	0.033	
4	572	0.199	550	0.062	514	0.222	509	0.067	58	1.97	40	0.80	
5	18	6.33	11	3.0	13	8.77	10	3.3	5	22.8	1	33	
6	2	57.0	1	33	2	57	1	33?	0	?	0	?	
7	1	>114?	1	>>33	1	>114?	1	>>33?	0	?	0	?	

T average recurrence period

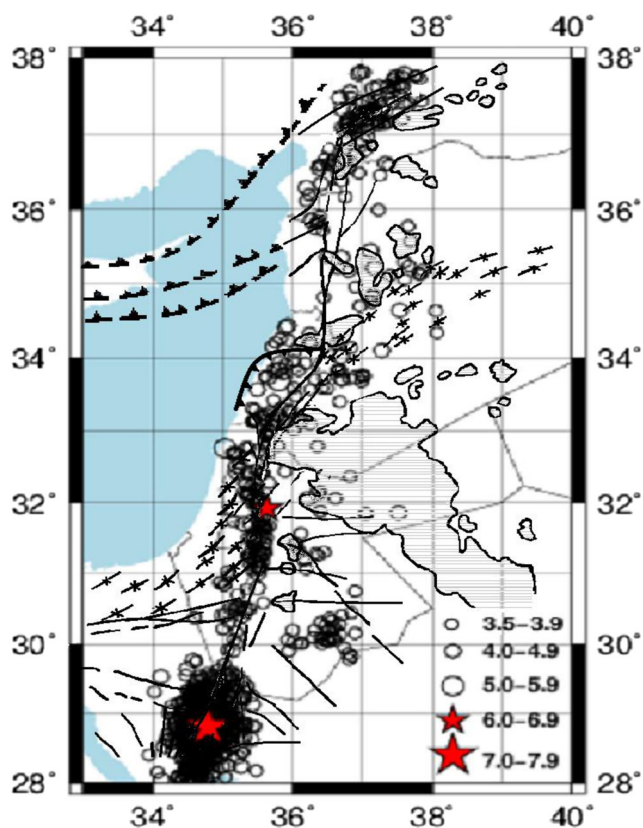


Fig. 3 Epicentral distribution of the instrumental seismicity ($M \geq 3.5$) of the Jordan Dead Sea transform that occurred during the period 1900–2014

whole transform region. It is 6.43 and 6.34 for its southern and northern halves, respectively. It is 6.24 for the Aqaba segment, 6.22 for the Wadi Araba segment, and 5.15 for the Dead Sea-Jericho segment. The a -values of the three northern segments of Beqa'a, Al Ghab, and Karasu are 6.38, 5.86, and 5.73 in respective order. Such relatively high a -values indicate a noticeable seismic hazard all along the length of the Jordan Dead Sea transform including its six tectonic segments.

The calculated b -value for the whole transform is 1.02, typical for such 1100-km long continental transform as the background b -value of the whole Earth (El-Isa 2013; El-Isa and Eaton 2013). For the southern half and its southernmost Gulf of Aqaba segment, it is 0.98–0.99, very close to 1.0. It increases to 1.18 for the Wadi Araba segment and decreases to 0.9 for the Dead Sea-Jericho segment; see Table 2. The b -value of the northern half is 1.13. It increases to 1.27 and 1.3 in Beqa'a and Al Ghab segments and decreases to normal (1.02) in the northernmost Karasu segment. It is largely agreed amongst seismologists that b -variations are caused by a number of factors, of most importance is the level of tectonic stresses. The higher the b -value, the higher is the tectonic stress (Fiedler 1974; Robinson 1979; Smith 1981, 1986; Wyss et al. 1990; Sahie and Saikia 1994; El-Isa 2013; El-Isa and Eaton 2013). On the occurrence of large

earthquakes, the b -value is always reduced to a minimum (El-Isa 2013). This may be taken to indicate that up to the end of the year 2014, three segments, namely, Gulf of Aqaba, Dead Sea-Jericho, and Karasu, appear to be of normal tectonic stresses, while the other three segments, namely, Wadi Araba, Beqa'a, and Al Ghab, appear to be of higher tectonic stresses.

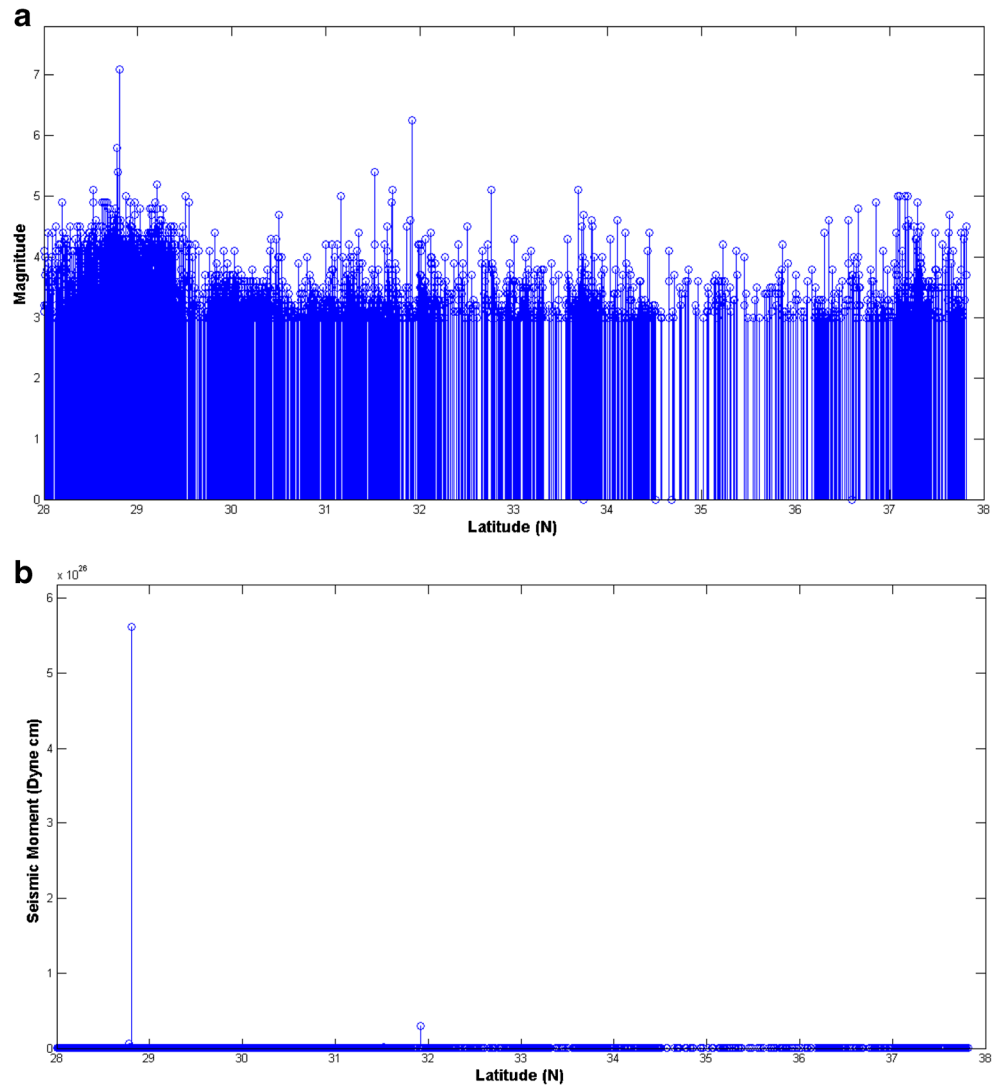
The total seismic moment as calculated from the whole instrumental seismicity (1900–2014) amounts to 6.3523×10^{26} dyne.cm. The seismicity of the three southern segments accounts for 6.2886×10^{26} dyne.cm, which represents about 99% of the total. The Gulf of Aqaba seismicity accounts for about 93.2%, while those of Wadi Araba and Dead Sea-Jericho segments account for only 0.003 and 5.37%, respectively. This is another evidence that the Wadi Araba segment appears to be of higher hazard than the other two southern segments. The seismicity of the three northern segments accounts for only 1% of the total seismic moment. This may indicate that the whole northern half of the transform is of a high seismic hazard. The lowest share (0.029%) is that of Al Ghab segment, followed by the Beqa'a segment whose share represents 0.28% of the total, while that of the Karasu segment represents about 0.698%. This may be taken to indicate that the Beqa'a and Al Ghab segments remain of a relatively higher seismic hazard than that of Karasu.

The calculated total seismic moment from the seismicity of the period 1982–2014 is 6.0067×10^{26} dyne.cm. Considering the 1100 km total length of the transform and utilizing the Wyss and Brune (1968) relationship, it is found that the seismic slip rate along the Whole Jordan Dead Sea transform is 0.54 cm/year when the fault depth is assumed to be 10 km. If the fault depth is reduced to 7 and 5 km, the slip rate increases to 0.77 and 1.07 cm/year, respectively. These slip rates are comparable with the long-term geologically deduced rate of 1 cm/year (Quennell 1958, 1959, 1984; Girdler 1990) and with those calculated from pre-historic seismicity and the historical seismicity data.

Discussion and conclusions

The compiled instrumental seismicity of the Jordan Dead Sea transform region that occurred during the last eleven decades includes many records of large explosions made by the Jordanian phosphate mining company in its exploration sites, particularly Ashideya mine, SE Jordan. These explosions are reported as earthquakes with $M \leq 3.9$ and focal depths, mostly 0–few kilometers, though a few are reported with depths as large as 30–40 km or slightly more. As these explosions are distant from seismological stations, their focal depths remain questionable. Examining the records of many of these at the Jordan University seismological station revealed that these

Fig. 4 The spatial distribution of the instrumental seismicity 1900–2014. Panel **a** displays latitude versus magnitude. Panel **b** displays latitude versus seismic moment



belong to the explosions of Ashideya mine. All events have occurred during the working hours of the day. It is concluded therefore that 492 events belong to the Ashideya phosphate explosions. Filtering these from the seismicity data, it is found that some 4448 earthquakes have occurred with magnitudes $M = 3\text{--}7.1$. Average recurrence periods for the $M = 5.0$ and 6.0 earthquakes are 6.3 and 57 years, respectively. Much of the compiled instrumental seismicity has occurred in the form of sequences and swarms that lasted for variable time periods. El-Isa (2013) reported that about 98% of the instrumental seismicity of the Gulf of Aqaba region was released in this form. More than 57% of both instrumental and historical types of seismicity all along the transform are also reported to consist of sequences and swarms. Many of these sequences are located close to outcropping Quaternary volcanic regions and thus are possibly volcanic related (Al-Qaryouti 1990; El-Isa 2013). This characteristic implies a noticeable reduction in the seismic hazard.

The epicentral distribution of the compiled instrumental seismicity data shows very good correlation with the general tectonics of the study region. All structures of the three mentioned deformational phases are seismically active in the present. The largest instrumental earthquake that occurred along both Syrian arc fold belt and the Erythrean fault system had a limited magnitude $M \leq 5.0$. All large earthquakes with magnitudes $M = 5.3\text{--}7.1$ have occurred along the regional strike-slip faults of the transform proper. The seismicity of the transform proper accounts for about 99% of the total seismic moment; see Fig. 4b. Most of the largest earthquakes including the 1927 and 1995 earthquakes are known to be mainly of strike-slip mechanism, with secondary vertical components (Abdel-Fattah et al. 1997, 2006; Pinar and Turkelli 1997; El-Isa et al. 1984). The pre-historic seismicity data indicate a noticeable activity of the southern major strike-slip faults of the transform (El-Isa and Mustafa 1986). The historical seismicity indicates that most of that activity,

Table 2 The calculated seismic coefficients *a* and *b* and the seismic moment of the instrumental seismicity (1900–2014) of the Jordan Dead Sea transform region and its tectonic segments and their percentages

Tectonic segment	No. of Earthquakes $M \geq 4.0$	Largest mag. (M)	<i>A</i>	<i>b</i>	Seismic moment ($M_0 \times 10^{25}$ dyne.cm)	%
Whole Transform	572	7.1	6.60	1.02	63.523	100
Southern Half	514	7.1	6.43	0.99	62.886	99.0
Gulf of Aqaba 28° N–29.5° N 34.0° E–35.5° E	459	7.1	6.24	0.98	59.2	93.19
Wadi Araba 29.51° N–31.3° N 34.3° E–36.0° E	29	5.0	6.22	1.18	0.18682	0.29
Dead Sea-Jericho 31.31° N–33.0° N 34.3° E–36.0° E	26	6.25	5.15	0.90	3.4138	5.37
Northern Half	58	5.1	6.34	1.13	0.63972	1.0
Beqaa 33.01° N–34.5° N 35.0° E–37.0° E	17	5.1	6.38	1.27	0.17843	0.28
Al-Ghab 34.51° N–35.8° N 36.0° E–37.5° E	4	4.5	5.86	1.30	0.018233	0.029
Karasu 35.81° N–37.5° N 36.0° E–37.5° E	38	5.0	5.73	1.02	0.44305	0.698

including the largest ($M \geq 6.5$), occurred within the transform proper, i.e., along its major strike-slip faults. Other historical earthquakes, mostly with lower magnitudes, appear to correlate with the Syrian Arc Fold and the Erythrean fault systems. It is concluded therefore that all tectonic elements of the study region are active in the present and are of a noticeable seismic hazard, but the regional strike-slip faults of the transform proper remain the major source of this hazard. Seismic moment calculations indicate that the southern half has been almost 100 times more active than the northern half during the last eleven decades. The largest activity was from the Gulf of

Aqaba segment whose seismicity includes the largest earthquake of the year 1995 ($M = 7.1$) and accounts for 93.6% of the released seismic energy. The second active segment is the Dead Sea-Jericho which includes the second largest earthquake of 1927 ($M = 6.25$). It accounts for about 5.37% of the released energy. The third active segment is the northernmost segment, namely Karasu whose released energy represents only about 0.7% of the total. The calculated *b*-values for these three segments are 0.98, 0.90, and 1.02, respectively. Such moment and *b*-values may be taken to indicate that these three segments are of lower hazard than the other three. The released energy

Fig. 5 The focal depth distribution of the instrumental seismicity of the Jordan Dead Sea transform region that occurred during the period 1900–2014

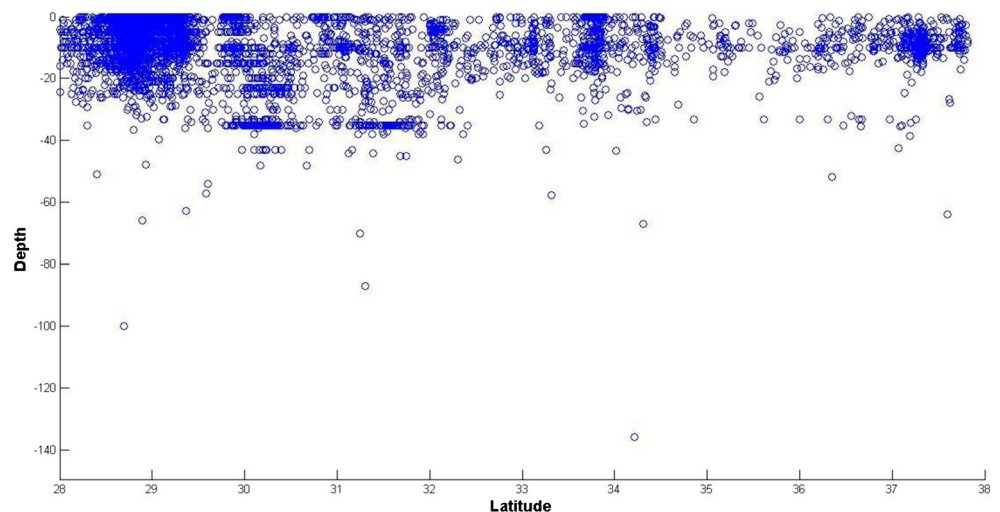
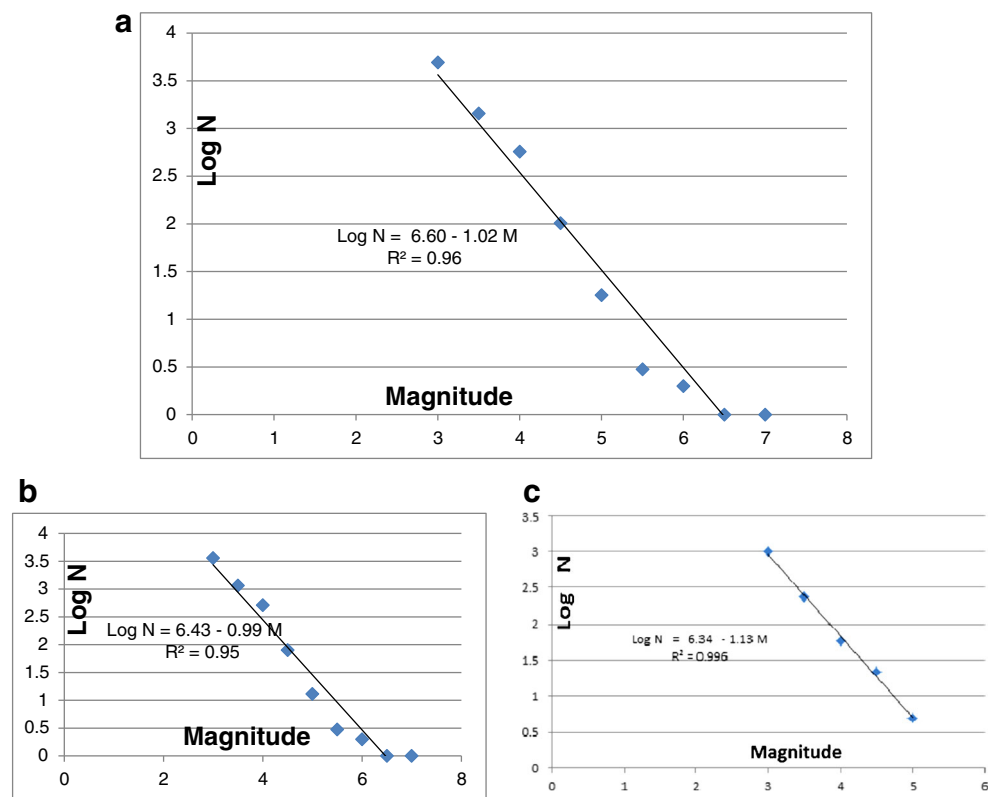


Fig. 6 Frequency-magnitude results of the instrumental seismicity (1900–2014) of **a** the whole transform region, **b** its southern half, and **c** its northern half



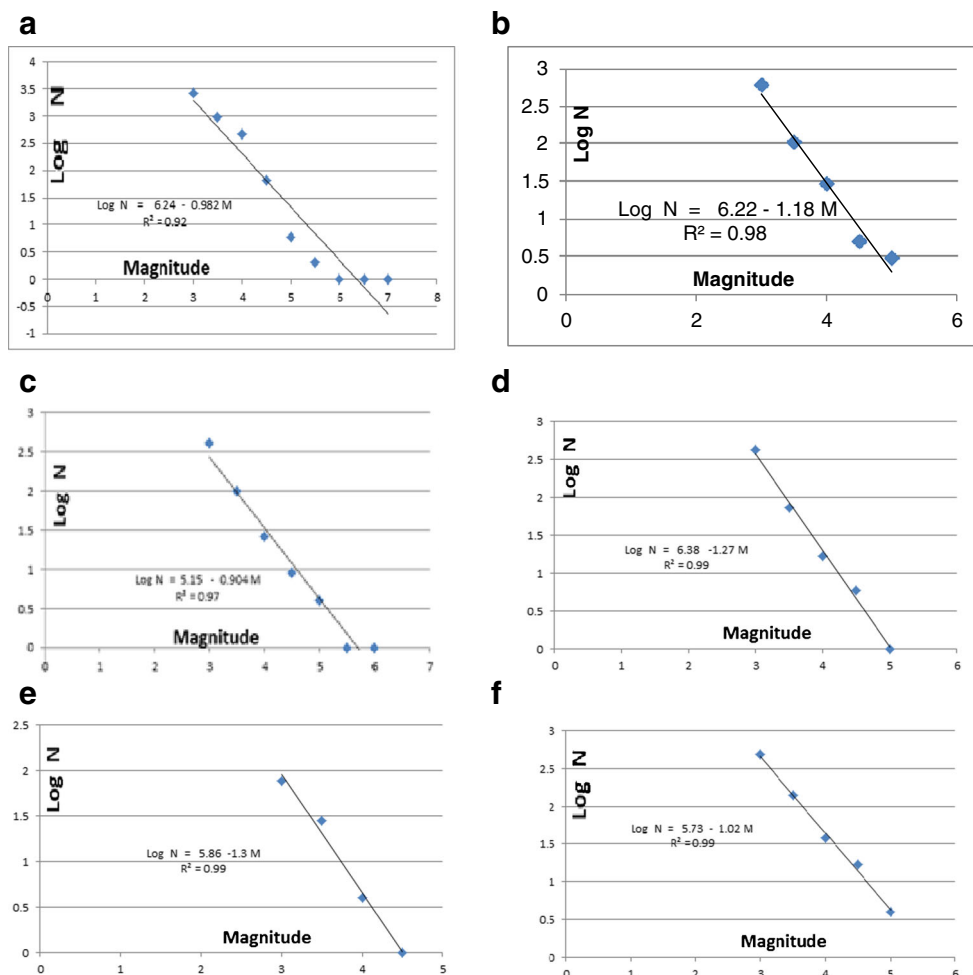
from each of the other three segments, namely Wadi Araba, Beqa'a, and Al Ghab, represents only 0.29, 0.28, and 0.029% of the total in respective order. Their calculated b -values are 1.18, 1.27, and 1.3, respectively. Considering these results, it may be concluded that in the present, Al Ghab segment remains of the highest hazard as its released energy during the last 11 decades are very limited and its b -value indicates possible high tectonic stresses acting in its region. This is followed by the Beqa'a segment and Wadi Araba segments in respective order.

The focal depth distribution (Fig. 5) shows that the seismicity of this region is very shallow. The fact that more than 99% of the seismic energy has been released from depths ≤ 22 km and some 93.6% of it has been released from depths ≤ 10 km is correlated with deep seismic sounding results (El-Isa et al. 1986, 1987; El-Isa 1990). At a depth of about 21 km, the Conrad discontinuity occurs that separates between an upper granitic crust with a normal value of Poisson's ratio (0.25) and a lower basaltic crust with a high Poisson's ratio (0.29). At a depth of about 9–10 km, a discontinuity appears to separate an upper granitic part with variable velocity with depth from a higher constant velocity layer underneath (El-Isa et al. 1987a, b; El-Isa 1990). Very little energy is released from the lower basaltic crust and uppermost mantle. In agreement with previous results (e.g., El-Isa 1990, 1992), it is concluded once again that the Jordan Dead Sea transform region is characterized by a

brittle granitic upper crust and a ductile basaltic lower crust and uppermost mantle. Tectonic movements at depths ≥ 22 km appear to be mostly, if not totally, aseismic.

The frequency magnitude results of the instrumental seismicity of the whole study region indicate that the a -value is 6.6 and the b -value is 1.02. Such values indicate recurrence periods 38 and 395 years for earthquakes with magnitudes $M = 6.0$ and 7.0 , respectively. The 1.02 calculated b -value is typical for such 1100 km long continental transform, similar to the background b -value of the whole Earth (El-Isa 2013; El-Isa and Eaton 2013). Both a - and b -values for the different tectonic segments show variations in the ranges of 5.15–6.6 and 0.9–1.3, respectively. Such values and their variations indicate relatively high seismic hazard anticipated from all tectonic segments. Those segments with higher b -value and low calculated seismic moment (Table 2) are considered of higher hazard. It is largely agreed amongst seismologists that b -variations are caused by a number of factors, of most importance is the level of tectonic stresses. The higher the b -value, the higher is the tectonic stress (e.g., Fiedler 1974; Robinson 1979; Smith 1981, 1986; Wyss et al. 1990; Sahie and Saikia 1994; El-Isa 2013; El-Isa and Eaton 2013). On the occurrence of large earthquakes, the b -value is always reduced to a minimum (El-Isa 2013). Based on this and considering the calculated seismic moments of Table 2, it may be concluded that in the present, the Gulf of Aqaba, Dead Sea-Jericho, and

Fig. 7 Frequency-magnitude results of the instrumental seismicity (1900–2014) for the six tectonic segments. **a** Aqaba. **b** Wadi Araba. **c** Jericho. **d** Beqa'a. **e** Al Ghab. **f** Karasu



Karasu segments appear to be of lower seismic hazard than the other three segments of Wadi Araba, Beqa'a, and Al Ghab.

Considering the calculated seismic moment from the highest quality of seismicity data that belongs to the period 1982–2014, the seismic slip rate along the whole length of the transform (1100 km) is calculated to be in the range of 0.54–1.07 cm/year assuming depths in the range 5–10 km. Firstly, it is very unlikely to expect such tectonic movement to occur all along such huge length. Secondly, the focal depth distribution of Fig. 5 shows that more than 99 and 93.6% of the seismic energy were released from earthquakes with depths ≤ 22 and 10 km, respectively. Deep seismic sounding results revealed that the Jordan Dead Sea transform region is floored by typical continental crust 32–35 km thick. At a depth of about 21 km, the Conrad discontinuity separates a granitic upper crust with a normal Poisson's value (0.25) from a lower basaltic crust with a high Poisson's ratio (0.29). The upper 9 km of the granitic crust shows a gradual velocity gradient followed by a higher constant P-velocity (El-Isa et al. 1987a, b). The concentration of earthquake activity within the upper 22 km and mostly the upper 10 km has a seismic justification. If the movement occurs along the whole length of the transform, one should expect lower depth than

10 km, possibly 5–7 km. Therefore, the instrumental seismicity data support the geologically deduced slip rate of 1 cm/year (Quennell 1958, 1959, 1984; Girdler 1990). Similar results were obtained from both historical and pre-historic seismicity (El-Isa and Mustafa 1986).

Conclusions

1. The compiled instrumental seismicity data that occurred during the last eleven decades include a few hundred explosions made in Ashidya phosphate mine in southeast Jordan. Excluding these, it is found that during the period 1900–2014, some 4448 and 572 earthquakes have occurred in the study region with magnitudes $M \geq 3$ and 4.0, respectively. The largest two earthquakes are of $M = 6.25$ and 7.1. Average recurrence periods for the $M \geq 5.0$ and 6.0 earthquakes are about 6.3 and 57 years. Much of this seismicity has occurred in the form of sequences and swarms. Some are located close to outcropping Quaternary volcanic outcrops and are possibly volcanic related.

2. The epicentral distribution of the compiled instrumental seismicity data shows very good correlation with the general tectonics of the study region. All tectonic elements of the study region are active in the present and of considerable seismic hazard. The regional strike-slip faults of the transform proper remain the major sources of this hazard. These account for about 99% of the seismic energy released from all instrumental activity during the period 1900–2014.
3. The seismicity of this region is very shallow. More than 99% of the seismic energy has been released from depths ≤ 22 km and some 93.6% of it from depths ≤ 10 km. Very little energy is released from the lower basaltic crust and uppermost mantle. At a depth of about 21 km, the Conrad discontinuity separates between a normal brittle upper crust with Poisson's ratio = 0.25 and an up normal ductile lower basaltic crust with a high Poisson's ratio = 0.29.
4. The frequency magnitude results of the whole transform proper and its tectonic segments indicate relatively high a -values, mostly in the range of 6.0–6.6. The b -value for the whole region and some of its segments is about 1.0. Other segments show b -variations in the range of 1.18–1.3. Such a - and b -values and their variations clearly indicate low return periods and an appreciable level of seismic hazard associated with all tectonic segments. These indicate 38 and 395 years recurrence periods for earthquakes with magnitudes $M = 6.0$ and 7.0 , respectively.
5. Seismic moment calculations indicate that during the last eleven decades, the seismicity of the southern half of this transform released seismic energy 100 times more than that of the northern half. Some 93.6, 5.37, and 0.698% of the total energy were released from the Gulf of Aqaba, Dead Sea-Jericho, and Karasu segments, respectively. The b -values of the Aqaba, Dead Sea-Jericho, and Karasu segments are in the range of 0.9–1.02, i.e., normal. Such results may indicate that the seismic hazard of these three segments is lower than the other three. The calculated moment and b -values of Table 2 and Fig. 7 indicate that Al Ghab segment appears to be of the highest hazard of the region, followed by Beqa'a and Wadi Araba segments in respective order.
6. Considering the seismicity data of the period 1982–2014, it is found that the seismic slip rate along the Whole Jordan Dead Sea transform is 0.54 cm/year if the fault depth is assumed to be 10 km. It increases to 0.77 and 1.07 cm/year if the fault depth is reduced to 7 and 5 km, respectively. These slip rates are comparable with the long-term geologically deduced rate of 1 cm/year.

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