Geophys. J. R. astr. Soc. (1986) **86**, 413–424

Earthquake deformations in the Lisan deposits and seismotectonic implications

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Accepted 1986 January 29. Received 1986 January 3; in original form 1985 July 22

Summary. Earthquake deformations and induced sedimentary structures preserved in Quaternary sediments include faults, folds, fissures, slumps, sand boils and other effects of liquefaction. Such deformations and structures are well preserved in the Lisan deposits of the Dead Sea. Of most importance are the fold-type deformations known as décollement structures which are present all along the eastern side of the Lisan and seem to decrease gradually westwards to disappear in the middle of the Lisan. These may indicate that palaeoearthquakes originating along the Araba fault have triggered such structures due to shaking of elastoplastic unconsolidated sediments over gentle slopes dipping to the west.

Preliminary results from studies on décollement structures preserved in a section representing some 1733 years of continuous deposition in the uppermost? Pleistocene, in the vicinity of Wadi Araba, indicate that: (1) seismic activity has fluctuated with time. Average recurrence period is about 340 ∓ 20 yr for earthquakes with magnitudes greater than or equal to 6.5. Earthquakes with magnitude greater than 7 seem to have occurred along the Araba fault. (2) Deduced earthquake magnitudes conform to the frequency–magnitude relationship: $\log N = 5.24 - 0.68M$. (3) The deduced seismic slip rate along the Araba fault seems to be not less than 0.64 ∓ 0.04 cm yr^{-1}.

Key words: Dead Sea transform, Earthquake deformations, Jordan, Lisan, seismic slip, seismotectonics

Introduction

The evaluation of earthquake activity and associated hazard for any region requires detailed systematic studies in different disciplines. Of most importance is the delineation of all, presently active, Quaternary regional faults. This also requires statistical analyses of both instrumental and historical earthquakes that have occurred along a particular fault and the estimation of recurrence periods of destructive earthquakes. It has become clear in recent years that neither historical nor instrumental earthquakes are sufficient for reliable estimates, mainly due to: (1) the relatively short record of historical earthquakes (the longest being 2000–4000 yr for the Middle East, Japan and China), (2) the intermittent reporting of historical earthquakes due to wars, sparse population, cultural decline, . . . etc., and (3) the relatively short time of instrumental seismology and the uneven distribution of seismic stations over the world.

The search for earthquake deformations in sedimentary rocks and sediments (seismites, Seilacher 1984), mainly Quaternary, has become an increasingly important tool in the recent past that may aid reliable estimates of average recurrence periods for destructive earthquakes for certain regions. Such deformations are wide-ranging, depending mainly on topographical, hydrological, geological and tectonic environments. These deformations include faults, scarps, drag folds, fissures, slumps and décollement sedimentary structures, sandboils and other effects of liquefaction in soft sediments (see Clark, Grantz & Rubin 1972; Sims 1979; Sieh 1978a, b; Reches & Hoexter 1981; Field *et al.* 1982).

The Upper Pleistocene marl deposits of the Lisan lake, the ancestor of the present Dead Sea, outcrop in most parts of the region. These were given an age of 80 000–15 000 yr BP (Kaufman 1971; Begin, Ehrlich & Nathan 1974; Horowitz 1971; Neev & Emery 1967; Vogel & Waterbolk 1972). The fine lamination of these deposits is a characteristic feature. Successive dark and white laminae (varves) are believed to represent clayey winter and gypseous/aragonitic summer deposition respectively (Bentor & Vroman 1957, 1960). This characteristic annual deposition makes age determination of any section possible. Earthquake deformations in these sediments are presented and discussed in terms of seismicity and seismic slip along the major Araba fault that extends over a length of some 200 km (Ben-Menahem 1981) between the Gulf of Aqaba and the southern Dead Sea region.

Tectonics and seismicity of the Dead Sea

Stratigraphic and structural evidence for some 107 km left-lateral shear along the Jordan–Dead Sea transform (Dubertret 1932; Quennell 1959; Freund 1965) has been widely accepted by earth scientists. This shear resulted in the creation of local depressions of different sizes along the whole transform. These depressions are normally delimited by normal faulting and are mainly characterized by the presence of *en échelon* major strike-slip faults (Quennell 1956; Garfunkel 1981; Garfunkel, Zak & Freund 1981). The Dead Sea occupies one of the largest and deepest of these depressions which is bordered from the west and east by the Jericho and Araba strike-slip faults [about 250 and 200 km long respectively (Ben-Menahem 1981; Ben-Menahem, Vered & Brooke 1982), see also Fig. 1]. Regional and local uplifting is evident all along the Jordan transform. Salt diapirs are widespread in the Dead Sea depression. These are believed to have started in the Pliocene (Zak 1974; Neev & Emery 1967; Bender 1968) and continued during and after Lisan deposition (Garfunkel 1981).

Studies of historical earthquakes for the last few thousand years (Willis 1928; Shalem 1949, 1956; Amiran 1951; Ben-Menahem 1979, 1981; Garfunkel *et al.* 1981; Ben-Menahem *et al.* 1982; El-Isa 1984), as well as instrumental earthquake studies of this century (Arieh 1967; Wu *et al.* 1973; Ben-Menahem, Nur & Vered 1976; Ben-Menahem *et al.* 1977; Arieh *et al.* 1985) clearly demonstrate that damaging earthquakes were located along the major Jordan–Dead Sea transform fault system. The strike-slip faults are most probably the major cause of these damaging earthquakes as they seem to accommodate most of the relative motion between crustal blocks on either side. The only, instrumentally recorded, large historical earthquake of Jericho 1927 ($M = 6.25$) was pure left-slip (Ben-Menahem *et al.* 1976). The deformation of the Omayad Hesham Palace, near Jericho caused by the 7.3 mag earthquake of AD 746, one of the largest historical earthquakes of this region (Ben-Menahem 1979) may suggest a strike-slip motion along the Jericho fault (Reches & Hoexter 1981).

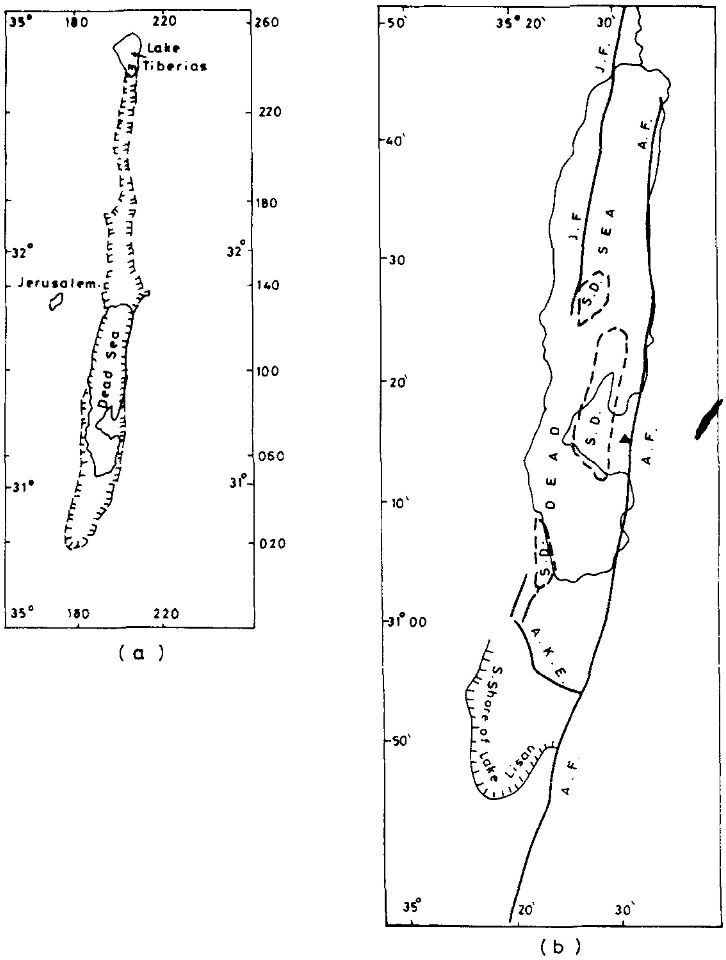

Figure 1. (a) The catchment area of Lake Lisan (after Bentor 1961). (b) The main tectonic features of the Dead Sea. A.F. = Araba Fault, J.F. = Jericho Fault, A.K.E. = Ain Khneizeera Escarpment, S.D. = salt dome, ▲ = Location of cross-section of Table 2.

Seismicity studies clearly show that the activity of Wadi Araba is lower than the Dead Sea and regions further north and the seismic slip is lower than the long-term slip rate. Table 1 summarizes the most relevant of these studies, and also includes recalculated slip rates for the assigned fault lengths assuming a depth of 15 and 20 km in each case (see Ben-Menahem *et al.* 1976). Based on these data the seismic slip along Wadi Araba is of the order 0.02–0.20 cm yr^{-1} and that of the Dead Sea–Tiberias–Beka's regions ranges between 0.13 and 1.08 cm yr^{-1}.

Earthquake deformations in the Lisan deposits

Search for earthquake deformations in the Lisan deposits of the Dead Sea region revealed that these are present and well preserved in many localities and are of different types:

(1) Local faulting, cracking and slumping

Normal and horizontal faults of variable sizes and ages can be seen almost everywhere in

Table 1. A summary of the most relevant published frequency–magnitude relationships for the Jordan–Dead Sea transform. The last two columns show recalculated total expected seismic moment (Wyss & Brune 1968) and seismic slip rates assuming fault lengths of column 2 as quoted by references of column 6 and fault depths of (★) 20 km and (★★) 15 km (see Ben-Menahem *et al.* 1976).

Region	Fault length (km)	Period (yr)	Type of data	Magnitudes	Reference and frequency-magnitude relationship	Period (yr)	Magnitude	Recurrence interval (yr)	Number of expected earthquakes	Total expected seismic moment ($M_0 \times 10^{27}$ dyne cm)	Seismic slip (cm y^{-1})
Jordan Valley–Beka'a	400	1919–1963	Instr.	⩾4.5	(Arieh 1967) log $N = 4.9 - 0.8M$	1700	6.0	36	47.0	33.05	0.81★
							6.5	90	19.0		1.08★★
							7.0	225	7.5		
							7.3	392	4.3		
Wadi Araba	200	2000 BC to AD 1979	Instr. and histor.	⩾1.5	(Ben-Menahem 1981) log $N = 2.56 - 0.86M$	4000	6.0	398	10.0	7.214	0.15★
							6.5	1 070	4.0		0.20★★
							7.0	2 884	1.4		
							7.5	4 285	1.0		
Wadi Araba	186	2000 BC to AD 1979	Instr. and histor.	⩾1.5	(Ben-Menahem *et al.* 1982) log $N = 2.77 - 0.91M$	4000	6.0	1 549	2.6	0.856	0.02★
							6.5	4 416	1.0		0.03★★
							7.0	12 590	–		
							7.3	23 604	–		
Dead Sea Fault	256	2000 BC to AD 1979	Instr. and histor.	⩾1.5	(Ben-Menahem *et al.* 1982) log $N = 3.1 - 0.86M$	4000	6.0	115	35.0	22.257	0.36★
							6.5	309	13.0		0.48★★
							7.0	831	4.8		
							7.3	1 506	2.7		
Dead Sea–Tiberias	190	2000 BC to AD 1979	Instr. and histor.	⩾1.5	(Ben-Menahem 1981) log $N = 2.91 - 0.86M$	4000	6.0	178	22.5	14.228	0.312★
							6.5	478	8.4		0.416★★
							7.0	1 288	3.1		
							7.3	2 333	1.7		
Dead Sea rift excluding Wadi Araba	400	Last 1300 yr	Histor. and one instr.	⩾7.0	(Garfunkel et al. 1981) three earthquakes ($M \geqslant 7.0$) per 1000 yr		–	–	–	3.0	0.125★
											0.167★★

Lisan. Some of these are very young as they cut into the Holocene sediments. Slumping and cracks of variable sizes are also common.

(2) Liquefaction effects

These take different forms:

(a) *Sandboils* are best seen north of the Dead Sea and take different shapes, sizes and ages. Circular-shaped boils of a few centimetres diameter, and sand domes and lenses many tens of centimetres thick are also present. These seem to disappear in the middle of Lisan, possibly due to either the non-existence of sandy deposits or the thick marl dominant layers (a few tens of metres thickness).

(b) *Lamination destruction:* The Lisan deposits have lost their characteristic lamination in some localities. The shaking of such water-saturated layers, caused by earthquakes, may have resulted in destroying their cohesion and ultimate mixing of the particles.

(3) Micro-folding, thrusting and associated sedimentary structures

The most interesting deformations present in Lisan deposits are those sedimentary décollement structures brought about by local micro-folding, faulting and thrusting. Deformed layers are overlain and underlain by undeformed, rather horizontal layers (see Fig. 2). These were studied in some detail with the following findings:

(a) All along the eastern shore of Lisan, i.e. in the vicinity of Araba fault and parallel to it, these structures are present and well preserved throughout any section, i.e. in both horizontal and vertical directions. But they seem to decrease gradually westwards to disappear in the middle of Lake Lisan, though some discontinuous and uncorrelatable similar deformations appear locally and at very small sizes. The presence of these deformations in the vicinity of the Jericho fault, in the west, is confirmed through limited field studies a few kilometres east of the fault zone. The photograph (plate 108A) of Pettijohn & Potter (1964) represents further evidence of the presence of comparable deformations along the Jericho fault.

(b) The amplitudes of these décollements vary from a few millimetres up to some 15 cm. Wavelengths also vary in the range 1–17 cm. Both amplitudes and wavelengths are almost constant for the same deformation in the same locality.

(c) The number of deformed layers vary from three pairs of successive dark and white layers, i.e. three years of deposition (Bentor & Vroman 1957, 1960) to more than 45 pairs (years).

(d) For the eastern side of Lisan, the inclination of décollements is mostly, if not always, westwards.

(e) There is no evidence of substantial mineralogical differences between deformed and undeformed layers.

(f) A few sections in the area were studied some of which were close to the anticipated Araba fault line. Correlation between these sections was not easy as the area is highly faulted and in some parts, bisected by many wadis. The fluctuations of the level of Lake Lisan resulted in the deposition of sandwiched layers of sand, clay and conglomerates. This also complicates the correlation between sections at this stage.

(g) Details of some 1733 continuous years of Lisan deposition in a section that was dug close to the Araba fault (31°14′24″N and 35°30′05″E) (see also Fig. 1b), are given in Table 2 from top to bottom of the section at a depth of about 3.8 m, but not the bottom of the Lisan Formation.

Table 2. Décollement deformations of the Lisan deposits in the cross-section of Fig. 1(b) near the Araba fault. From top to bottom: number of years of deposition, amplitudes of deformations and assigned magnitudes of possible causative earthquakes. Last column gives seismic moments calculated according to Wyss & Brune (1968).

No. of pairs of layers (yr)	Deformed (D) undeformed (U) zones	Deformation amplitudes (cm)	Assigned magnitudes (*M*)	Seismic moment (M_0) $\times 10^{27}$ dyne cm
90	U	–	–	–
10	D1	3	6.0	0.020
18	U	–	–	–
23	D2	2	5.8	0.009
78	U	–	–	–
29	D3	5	6.4	0.096
15	D4	4	6.2	0.044
20	D5	5	6.4	0.096
20	D6	5	6.4	0.096
40	U	–	–	–
08	D7	1.5	5.7	0.006
11	D8	2	5.8	0.009
109	U	–	–	–
04	D9	1	5.6	0.004
67	U	–	–	–
42	D10	6.5	6.7	0.310 ∓ 0.05
23	U	–	–	–
16	D11	4.0	6.2	0.044
28	U	–	–	–
05	D12	1	5.6	0.004
08	U	–	–	–
16	D13	3.5	6.1	0.030
20	U	–	–	–
10	D14	1.5	5.7	0.006
12	D15	3	6.0	0.020
35	U	–	–	–
46	D16	7.5	6.9	0.676 ∓ 0.07
27	U	–	–	–
35	D17	3	6.0	0.020
22	D18	4	6.2	0.044
30	D19	4.2	6.25	0.044 ∓ 0.001
95	U	–	–	–
05	D20	1	5.6	0.004
20	D21	1.5	5.7	0.006
10	U	–	–	–
30	D22	8.5	7.1	1.480 ∓ 0.08
06	U	–	–	–
05	D23	2.5	5.9	0.014 ∓ 0.001
54	D24	13	7.3⁺	3.240 ∓ 0.20
05	D25	1	5.6	0.004
45	U	–	–	–
13	D26	2	5.8	0.009
35	U	–	–	–
21	D27	3	6.0	0.020
258	U	–	–	–
16	D28	5	6.4	0.096
74	U	–	–	–
54	D29	15	7.3⁺	3.240 ∓ 0.20
63	U	–	–	–
06	D30	4	6.2	0.044
Total = 1733 yr				Total M_0 = (9.735 ∓ 0.6) $\times 10^{27}$ dyne cm

Discussion and possible explanation

Earthquake deformations in Quaternary sediments, particularly shallow marine and lake sediments, is well known and has received much attention recently with the hope of gaining a better understanding of the seismicity and seismotectonics of a particular region. Seilacher (1984) has attributed the above mentioned décollements of the Lisan to earthquakes, and by comparing them with others elsewhere he argued that their location in the active Jordan rift zone makes a seismic origin very probable. We present the following arguments to support this idea:

(1) The systematic westward inclination of the micro-anticlines of all deformation zones along the region of the Araba fault may be taken to indicate the slippage of all semi-consolidated or consolidated elasto-plastic layers due to shaking, caused by earthquakes. This requires very gentle slopes (of the order of a fraction of a degree or a few degrees at most). In the case of larger slopes, however, slumping is more likely to occur. Field *et al.* (1982) have presented linear fold deformations in soft marine sediments due to failure on a slope of less than 0.25° that was caused by an earthquake of magnitude 6.5–7.2. Associated uplifting of the eastern side of Lisan is also possible. This would cause similar deformations even on the previously flat-lying sediments.

(2) These décollements are present all along the eastern side of Lisan, as far south as the Ein Khnazeerah escarpment (see Fig. 1b). The fact that they disappear in the middle of Lisan is in agreement with the idea that, in this region, earthquake deformations were restricted to the water layer which was of the order of tens of metres, or more in some localities. On the other hand the Lisan deposits were flat-lying and more probably were not affected by any uplifting which may have accompanied the earthquake. The very small-scale deformations that appear very locally in this region, may be explained by local uplifting caused by active diapirs which are known to exist in the Dead Sea region (Neev & Hall 1979; Garfunkel *et al.* 1981).

(3) The cyclic repetition of such zones of deformation (see Table 2 and Fig. 2) conforms to the cyclic repetition of earthquake activity in any tectonically active region. This does not necessarily imply a symmetrical repetition, which is the case for these deformations.

(4) The variations in thicknesses, amplitudes, wavelengths and number of deformed layers are indications of variable earthquake intensities and/or epicentral distances and amounts of possible associated uplifting. Generally as the number of deformed layers increases, their consolidation increases and therefore they require more energy to be deformed. At the same time, as their thicknesses increase, which could be due to the annual rate of deposition, and not necessarily an increase of the number of layers, the anticipated earthquake magnitude should increase.

(5) Comparing the deformed zones with the overlying and underlying undeformed layers, there seem no sedimentological or mineralogical differences. It is clearly evident that undeformed layers got consolidated in a period of quiescence before the next earthquake which has affected only the top unconsolidated layers.

(6) The presence of secondary local faults and cracks that seem to cut the Lisan deposits at different levels, i.e. are of different ages. Some cracks are seen to cut through the recent sediments at a width of some 10 cm and wedge downwards. Similar cracks were described by Reches & Hoexter (1981) in the vicinity of the Jericho fault, NW of the Dead Sea and were attributed to the 7.3 mag earthquake of AD 746.

(7) Other earthquake effects, mainly liquefaction, are observed in many localities. Such phenomena are well known to accompany destructive earthquakes of magnitudes greater than or equal to 5.5 (see Sieh 1978b and references therein, p. 3914).

(8) Pleated laminated deposits are known to occur due to the expansion of anhydrite as a result of partial or complete alteration to gypsum (Pettijohn & Potter 1964, plate 111A). The asymmetric character of the Lisan décollements together with the fact that pleated layers are overlain and underlain by undeformed layers are taken to eliminate such a possibility.

From the above discussion it is evident that décollement structures of the Lisan deposits are more likely to have been caused by earthquakes. It is therefore proposed, that shaking caused by earthquakes has triggered the uppermost semi-consolidated layers (number and thickness of these are functions of earthquake intensity), to failure through sliding on very gentle slopes (with a westward general dip in the vicinity of the Araba fault). The elasto-plastic character of these sediments resulted in the systematic synclinal–anticlinal character. This could happen in the case of the presence of a thin water cover or more likely the absence of water. Sudden uplifting that may accompany the earthquake will facilitate the process even if layers were flat-lying.

Theoretical considerations of mechanics of displacement of stones, caused by earthquake shaking, were discussed by Clark (1972). Consider a block of height h, mass m, density ρ, basal area A, resting on an inclined surface with an angle θ, due to friction and adhesion, the block will slide during shaking when the downslope components of both weight (w) and horizontal (F_H) and vertical (F_V) inertial reactions to shaking equal or exceed the combined frictional (F_F) and adhesive (F_a) resistance to sliding, where $w = m \times g$, g = gravity; $F_H = m \times a_H$, a_H = horizontal acceleration; $F_V = m \times a_V$, a_V = vertical acceleration; $F_F = \mu [(w - F_V) \cos\theta - F_H \sin\theta)$, μ = coefficient of friction and $F_A = cA$, c is the adhesive strength between the block and the surface (see Clark 1972, fig. 135), i.e.

$$w \sin\theta - F_V \sin\theta + F_H \cos\theta \geqslant F_F + F_a \tag{1}$$

substituting for the defined forces, the critical horizontal acceleration, a_{HC}, necessary for sliding was derived by Clark (1972) as follows:

$$a_{HC} \geqslant \frac{(g - a_V)(\mu - \tan\theta) + c/\rho h \cos\theta}{1 + \mu \tan\theta} \tag{2}$$

which shows that the necessary horizontal acceleration for sliding depends on g, μ, θ, a_V, h, ρ and c. For the Lisan décollements, θ is small and h represents the thicknesses of deformed zones, hence $\sin\theta$ and $\tan\theta \approx 0.0$ and $\cos\theta \approx 1.0$. Therefore, equation (2) reduces to

$$a_{HC} \geqslant \mu(g - a_V) + c/\rho h, \tag{3}$$

i.e. necessary horizontal accelerations depend mainly on μ, g, a_V, ρ, c and h. Equation (3) implies that as h increases, a_{HC} decreases, but in fact as h increases, both μ and c should increase, particularly for the soft, fine-grained, chemical sediments of the Lisan marls. Their density variations, however, remain relatively low. Substituting for $h = 0.03$ m, $\rho = 2 \times 10^3$ kg m^{-3}, $c = 200$ N m^{-2}, $\mu = 0.3$ and $a_V = 0.2$ g (roughly $\frac{1}{3}$ a_H (Housner 1970) that may be caused by an intensity of X), a_{HC} of equation (3) is about 560 cm s^{-2} (i.e. earthquake intensity IX–X). Note that large variations in a_V will slightly affect the calculated a_{HC}. Assuming that if the thickness h is doubled to 0.06 m, both c and μ are doubled, and allowing for a slight increase of density to 2.1×10^3 kg m^{-3}, a_{HC} attains a value of 780 cm s^{-2} (i.e. on earthquake intensity of not less than X).

Sims (1979) attributed similar deformations within the upper 4 cm of lacustrine sediments (silts and clays) to an intensity of VIII–IX, i.e. 6.2–6.9 mag range. Though water saturated clays behave plastically under stresses, the chemical gypseous Lisan deposits should have some higher shear strength, particularly if these were on the shore and uncovered with water.

Figure 2. A photograph of a décollement structure present in the Lisan deposits. Notice the undisturbed laminae above and below the deformed zone. Anticlines point westwards. Diameter of coin is 2.4 cm. See also Table 2 and Fig. 1(b).

Nevertheless, utilizing the above calculations and the results of Sims (1979), we assume that a 4 cm amplitude of deformation has resulted from an earthquake with an intensity of not more than VIII ($M = 6.2$), regardless of epicentral distance, i.e. the earthquake which produced the VIII intensity at the site could have had an epicentre somewhere on the 200 km long Araba fault and yet at a higher magnitude than 6.2. It also seems quite acceptable to assign a 0.2 mag increment for every 1 cm increment in the deformation amplitudes. This implies that a 10 cm amplitude of deformation would require a 7.4 mag of an earthquake. But since the largest historical earthquake in the region was assigned a 7.3 mag, all deformations with amplitudes of 10 cm or more were assigned a maximum magnitude of 7.3. It should be mentioned that theoretical considerations imply the probability of occurrence of earthquakes, along the Jordan transform, with magnitudes as high as 8.0 (Vered 1978). Table 2 includes the amplitudes and assigned magnitudes of all deformations of the study section of Fig. 1(b).

Seismotectonic implications

If the above calculations are valid, then column 4 of Table 2 represents the level of seismic activity ($M \geqslant 5.6$) that was associated with the Araba fault through a period of some 1733 yr during the uppermost? Pleistocene. These data show that:

(1) Through this period, 30 earthquakes occurred with magnitudes in the range 5.6–7.3. Periods of dormancy for all 30 earthquakes range between 5 and 279 yr, and between 54 and 117 and 15 and 125 yr for magnitude ranges 6.5–7.3 and 6.1–6.4 respectively. The three largest shocks ($M \geqslant 7.1$) of the whole period occurred within the start period of 680 yr of the study section, while for the top 1000 yr, or so, the largest two shocks had magnitudes of only 6.9 and 6.7. This indicates that the level of seismicity has fluctuated much through this period. Garfunkel *et al.* (1981) reported a noticeable fluctuation of the historical seismicity of the Jordan transform. On the other hand, suggestions for a common frequency–magnitude relation for both short and long terms of activity were made (Ben-Menahem *et al.* 1977, 1982; Ben-Menahem 1981).

(2) Fifteen, ten and five of these earthquakes were of magnitude ranges 5.6–6.0, 6.1–6.4 and 6.5–7.3 respectively. This indicates average recurrence periods of 56 ∓ 3; 113 ∓ 7 and 340 ∓ 20 yr for earthquake magnitudes equal or greater than 5.6, 6.1 and 6.5 respectively. These recurrence periods are much lower than those derived for Wadi Araba from instrumental and historical data for the last 4000 yr, e.g. for a 6.5 mag, 1070 yr (Ben-Menahem 1981) and 4416 yr (Ben-Menahem *et al.* 1982). For the Dead Sea–Tiberias segment, in the north, Ben-Menahem *et al.* (1982) derived from the same data a recurrence period of 309 yr for a 6.5 mag, see also Table 1.

(3) Deduced earthquake magnitudes of Table 2 conform to the frequency–magnitude relationship $\log N = a - bM$, where N is the cumulative number of earthquakes with magnitudes equal to or greater than M, and a and b are 5.24 and 0.68 respectively. These values are comparable with the 4.9 and 0.8 values obtained by Arieh (1967) for the Jordan Valley–Beka'a region. Our a value is considerably different from the value of 2.56 of Ben–Menahem (1981) and the value of 2.77 of Ben-Menahem *et al.* (1982) obtained for Wadi Araba.

(4) In the last column of Table 2, seismic moments were calculated (Wyss & Brune 1968) with a total of $9.735 \mp 0.6 \times 10^{27}$ dyne cm. Assuming that 'seismic moment = rigidity (3×10^{11} dyne cm^{-2}) × fault length (200 km, Ben-Menahem 1981) × fault depth (20 km, Ben-Menahem *et al.* 1976) × seismic slip', this amounts to 811.3 ∓ 50 cm 1733 yr^{-1}, i.e. 0.47 ∓ 0.03 cm yr^{-1}. If the depth is assumed to be 15 km (Ben-Menahem 1981; Ben-Menahem *et al.* 1982; Garfunkel *et al.* 1981) the seismic slip increases to 0.64 ∓ 0.04 cm yr^{-1}. This is much

higher than the seismic slip of the same fault as reported by Ben-Menahem (1981) (0.2 cm yr^{-1}) or Ben-Menahem *et al.* (1982) (0.03 cm yr^{-1}). See also the last column of Table 1. Our 0.64 ∓ 0.04 cm yr^{-1} deduced seismic slip of the Araba fault is higher than the 0.48 cm yr^{-1} of the Dead Sea northern segment deduced by Ben-Menahem *et al.* (1982). But both figures are smaller than the 0.7–1.0 cm yr^{-1} slip of the Jordan–Dead Sea transform (Quennell 1959; Freuend, Zak & Garfunkel 1968). Our 0.64 ∓ 0.04 is actually less than expected as (1) our calculations did not include any earthquake with magnitudes less than 5.6, and (2) it was pointed out by El-Isa, Merghelani & Bazari (1984) that the Jordan–Dead Sea transform is characterized by both mainshock–aftershock as well as earthquake swarm types of activity. Both categories (1 and 2) of earthquakes that could have happened through the period of our calculations were not incorporated. Furthermore, if the fault depth is less than 15 km, a higher slip rate would be obtained.

As these data suggest, the seismic activity seems to have fluctuated, at least in the 1733 years covered by our calculations. If this is a characteristic of the seismicity of the Jordan–Dead Sea transform, then it becomes more urgent to extend such studies to longer periods of time, i.e. larger depths of the Lisan Formation.

Conclusions

(1) The Lisan deposits of the Dead Sea are characterized by the presence of earthquake deformational features that were well preserved through the last 60 000 yr or so. Of most importance are those décollement structures that are well preserved all along the eastern side of the southern Dead Sea basin, i.e. in the vicinity of the Araba fault. In this region, these décollements can be seen across any section in both horizontal and vertical directions, but decrease gradually westwards to almost disappear in the middle of Lisan. Décollements across any section attain different sizes, amplitudes, wavelengths and number of deformed layers. It is proposed that these have been formed by sliding of semi-consolidated sediments on very gentle slopes dipping to the west due to earthquake shaking with amplitudes being proportional to earthquake magnitude.

(2) Preliminary studies on the décollements of a section, close to the Araba fault, representing some 1733 yr of the uppermost? Pleistocene indicate that:

(a) The seismic activity of the Araba fault has fluctuated, at least within the study period.

(b) Average recurrence periods seem to be of 56 ∓ 3, 113 ∓ 7 and 340 ∓ 20 yr for earthquakes of magnitudes equal or greater than 5.6, 6.1 and 6.5 respectively. The highest anticipated earthquake magnitude seems to be larger than 7.

(c) Deduced earthquake magnitudes conform to the frequency–magnitude relationship: $\log N = 5.24 - 0.68M$.

(d) The deduced seismic slip rate along the Araba fault is of the order of 0.64 ∓ 0.04 cm yr^{-1}, but may be higher due to the fact that seismicity seems to have fluctuated, and also earthquakes with magnitudes less than 5.6 were not incorporated in our calculations, particularly if the assumed depths of 15 and 20 km for the Araba fault were larger than the actual depth.

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