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Possible induced earthquake activity along the Dead Sea transform fault system

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ABSTRACT

The Dead Sea is a morphotectonic depression that is characterised by strike-slip and normal faults, local and regional uplift and subsidence. Its tectonics are directly related to the opening of the Red Sea which resulted in a major shear that extends along the Dead Sea farther north to the Taurus–Zagros continental collision zone. This opening and the consequent shear are presently active and are responsible for the seismicity of this region.

The problem of induced seismicity associated with the creation of large water reservoirs is caused by the triggering of tectonic stresses affecting the rocks at critical rates close to their strength through (i) increasing the vertical stress caused by the water load (ii) increasing pore pressure due to either diffusion or direct flow of water through fractures (iii) thermal pressure caused by cool water entering hot rocks. Increasing the water level of the Dead Sea by 10 m will increase both vertical stresses and pore pressures by some 1·2 bars which is likely to trigger critically stressed faults. The seismicity of normal faults will therefore increase immediately after water increase, while that of strike-slip faults will start some time later when the pore pressure had risen.

As damaging tectonic earthquakes are expected to occur in the Dead Sea area, this induced phenomenon may affect the time, location, depth and details of failure of these earthquakes.

INTRODUCTION

The idea of constructing a canal to connect the Mediterranean to the Dead Sea dates back to the nineteenth century. It was in 1850 when a British team suggested a route that starts from Haifa via the Plains of Ibn Amer in Palestine–Jordan Valley–Dead Sea–Wadi Araba and south to the Gulf of Aqaba. This project was never fulfilled due to the construction of the Suez canal. In 1980, the Israeli government has approved a programme for the construction of a canal where water will flow from the Mediterranean to the Dead Sea, whose level will be increased by some 10 m above its present height. The main objective is to produce electrical energy (Amireh 1982).

The Dead Sea is a large tectonic depression which lies on the zone between two major crustal plates and forms a part of the so called 'Dead Sea leaky transform' (Garfunkel 1981). Different geological and seismological data strongly suggest that the crustal rocks of this area are under tectonic stresses (Ben-Menahem & Aboodi 1981; Freund *et al.* 1970). These stresses may be in a critical state, i.e. close to rocks failure.

Different man-made constructions on or near the earth's surface have been known for some time to result in increasing earthquake activities in different parts of the world. Major among these is induced seismicity associated with dams and large water reservoirs, caused by disturbing the stress regime of crustal rocks in the area of the reservoir and ultimately causing failure represented by earthquakes, some of which may be destructive, depending on the geology and tectonics of the area.

A possible increase of the seismicity of the Dead Sea as a consequence of increasing the water level is the main subject of this paper.

GEOLOGY AND TECTONICS

The Dead Sea is a morpho-tectonic depression that forms a part of the Jordan rift (leaky transform) which extends over some 1000 km from the Red Sea in the south to the Taurus–Zagros collision zone in the north. This represents the major tectonic zone between the continental plates of Arabia and Sinai/Palestine. It is directly related to the opening of the Red Sea which started some 40–20 m.y. ago (Girdler & Styles 1974, 1978), when the continental breakup of the previously stabilized craton occurred some 20 m.y. ago (Garfunkel 1981). This breakup was preceded by a volcanic basaltic activity some 30 m.y. ago that continued to Recent times (Barberi *et al.* 1979). Extensive local and regional uplift of the new plate margins is strongly evident and is of the order of 1–2 km in the Dead Sea area, where it increases southward reaching 3–5 km close to the Red Sea (Garfunkel 1981).

The major characteristic feature of the Dead Sea plate boundary is the dominance of a left-lateral slip of some 105–110 km (Quennell 1959; Freund *et al.* 1970). The dating of this slip is not certain, but it seems to accommodate most of the spreading in the Red Sea, with the opening of the Gulf of Suez being small. Thus, motions in the Red Sea and along the Dead Sea transform are essentially contemporaneous (Garfunkel & Bartov 1977).

Beside the Dead Sea, other local morpho-tectonic depressions exist along this transform with varying lengths, widths and depths. These are partly filled with sediments and generally delimited by normal faults. The limited size of these depressions and the presence of major strike-slip along their floor are the major features that distinguish them from normal extensional rift valleys.

The Dead Sea depression is located between the Wadi Araba and the Jericho left-lateral and strike-slip faults (see Fig. 1). Its eastern topographical margins are some 400 m higher than those of the western side. Geological sequence of both sides bordering the depression consist of Precambrian metamorphic and plutonic basement overlain by Paleozoic and Mesozoic sediments of terrestrial and marine origin. While basement rocks outcrop at some 200 m above MSL in the southeastern margin, these are always covered by some 4 km or more of marine sediments in the west. Its deepest northern basin is some 730 m below MSL (Neev & Hall 1979). The lateral slopes of this depression are characterised by steep marginal faults with greater throws on its eastern side. Topographically, the depth of this depression is about 2 km, but tectonically is believed to be of the order of 10 km where the lower 8 km of the trough are filled by Neogene-Recent sediments (Zak 1974), thus suggesting strong subsidence to have occurred since the Miocene time which may also be continuing at the present time.

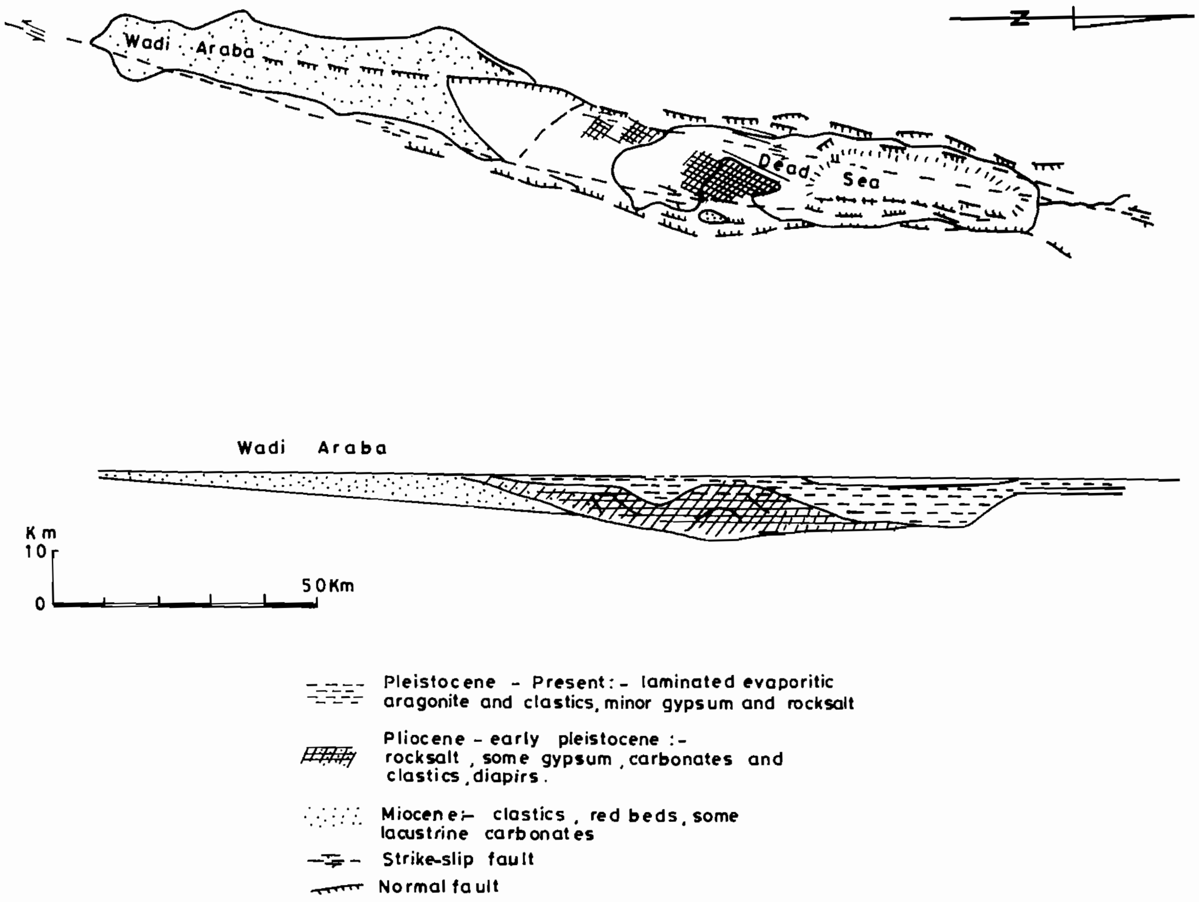

Fig. 1. Geology and tectonics of the Dead Sea transform (after Garfunkel *et al.* 1981).

SEISMICITY

Earthquake occurrences are usually related to tectonic processes and are mostly restricted to zones of weakness of the earth's crust. The Dead Sea transform remains the major tectonic feature that separates the two major continental plates of Arabia and Sinai/Palestine. The shear stresses along this and other related branching zones, together with the internal friction between moving blocks and their physical and mechanical properties are the main causes of earthquakes in this region.

El-Isa (1983) pointed out the existence of an appreciable seismic risk associated with the Jordan shear and other branching zones and demonstrated (El-Isa 1985) that the Dead Sea zone itself remains the major potential source of earthquake activity that caused the destruction of many nearby archeological sites within the last 2000 years. The seismicity of Jordan (Fig. 2) was discussed by El-Isa (1983). It is clear that the activity is higher in the Dead Sea and farther north than in Wadi Araba. This seismic activity, besides other geological observations, strongly suggests that the rocks of this region are under tectonic stresses affecting the whole crust, and perhaps the upper mantle, as the activity seems to be restricted to shallow depths. Whenever these stresses exceed the strength of the rocks, failure occurs, thus producing earthquakes whose characteristics depend on the physical and mechanical properties of the rocks as well as the nature of tectonic stresses, particularly their orientations and values. Fault-plane solutions of some instrumentally recorded earthquakes showed their mechanism to correlate with strike-slip movements along the Jordan transform (Ben-Menahem *et al.* 1976).

INDUCED EARTHQUAKES

The problem of induced earthquakes, i.e. those triggered as a result of man-made activities on, or near, the earth's surface has received much attention within the last 20 years or so. Such earthquakes are known to be associated with the construction of dams and creation of large water reservoirs, large surface quarrying and underground mining, ejection of pressurised water in deep wells, and nuclear explosions. The question of possible induced earthquake activity in the Dead Sea is considered compatible with the first case, i.e. large water reservoirs in active tectonic zones.

A water reservoir is considered 'large' if it either attains a water height of 100 m or more, or if it contains not less than $1000 \times 10^6\ \mathrm{m}^3$ of water, or if both conditions are satisfied (Rothé 1968; Gupta & Rastogi 1976). For such reservoirs it has been noticed, for many years, that following impounding, earthquake activity is initiated, mostly at relatively low levels of both frequency and magnitude, and increasing thereafter up to a point where a main shock occurs followed by a considerable aftershock activity that decays rather slowly. In certain cases, the main shocks have been damaging and destructive, such as the case of Koyna reservoir of India where a magnitude 6 earthquake occurred on December 10, 1967 causing considerable damage and casualties. This major event attracted the attention of earth scientists all over the world. Eversince, many other cases were observed and studied, representing localities of different geological and tectonic settings and reservoirs of different capacities and water heights (Gupta & Rastogi 1976; Leblanc & Anglin 1978; Caloi 1970; Berg 1968; Rothé 1968 and others). Detailed studies of many of these cases revealed the following:

(1) In some cases, induced activity shows good correlation with water level, such

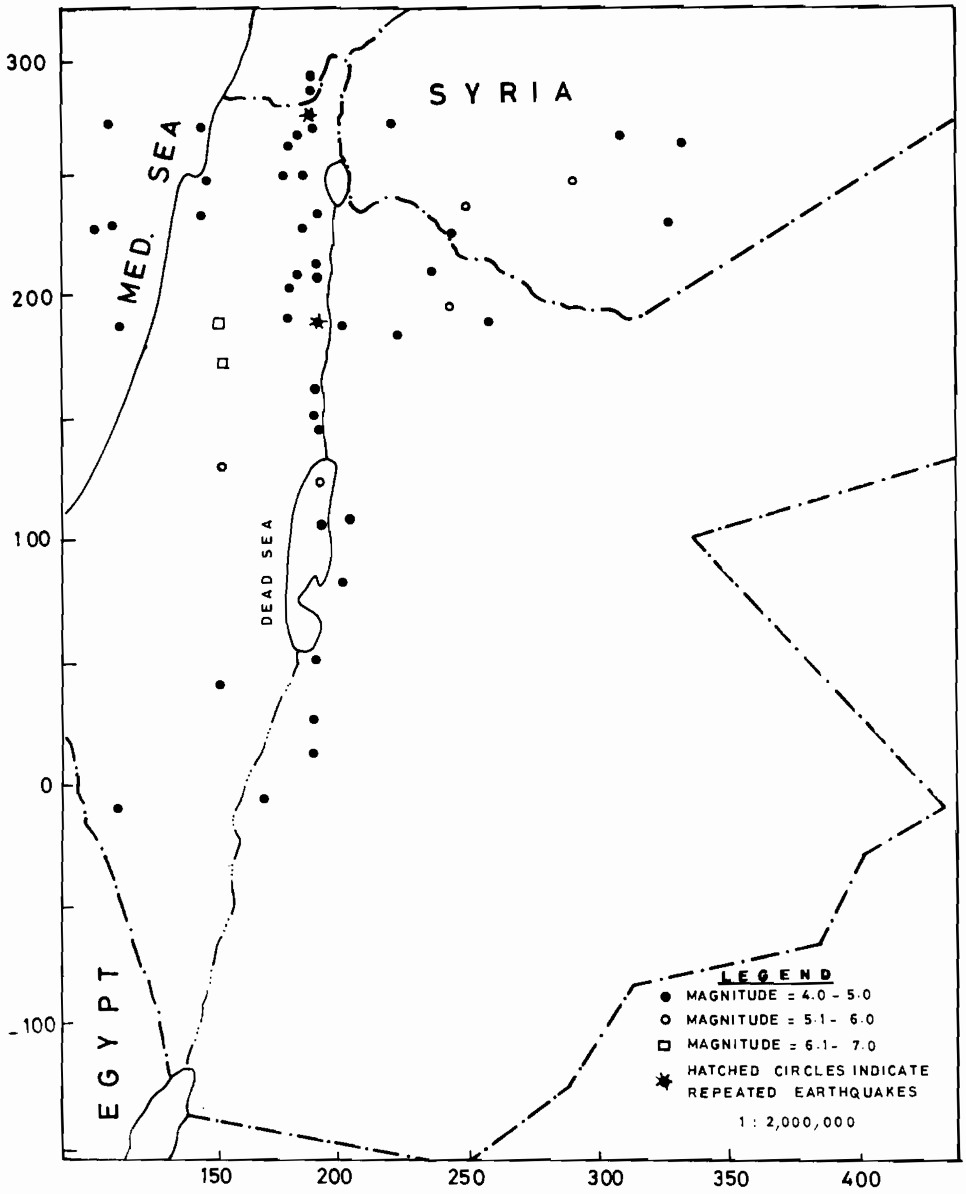

Fig. 2. Seismicity of Jordan (El-Isa 1983).

as the case of Koyna lake (Gupta *et al.* 1969). It was also noticed that seismic activity at this site increased following every rainy season for the years 1963–1967. This criterion was noticed at other places such as Lake Mead and Denver in the United States (Carder 1945; Evans 1966), Lake Kariba, Zambia, Lake Kremasta, Greece and elsewhere (Gupta & Rastogi 1976). This may be taken to indicate that vertical stress caused by the water load is the major factor influencing the induced activity. Contrary to this, however, Leblanc & Anglin (1978) showed that at Manic 3 reservoir, Canada, the main shock as well as the aftershock sequence are most likely due to the triggered release of tectonic stress and not to the direct action of the increased gravity load.

(2) Added stresses due to water load in artificial and limited reservoirs seldom exceed 10 bars. For Lake Kariba ($175{,}000 \times 10^6\ m^3$) the maximum normal and shear stresses were calculated to be 6·68 and 2·12 bars only (Gupta & Rastogi 1976). These stresses are very small when compared with the strength of crystalline rocks which may exceed 1000 bars.

(3) As water percolates in the rocks, this will increase the pore pressure and ultimately decrease their shear strength. Handin & Nelson (1973) calculated a pore pressure of 15 bars beneath Lake Powell, U.S.A. This pressure under artificial lakes may increase by a few tens of bars depending on the type of rock, its porosity and permeability and the presence of cracks, joints and faults, their sizes and orientations.

(4) The level of induced seismicity is not only affected by local and regional stress changes due to water load and increased pore pressure but other related factors are also of some importance. These include (i) the rate of increase and decrease of water level. Rapid emptying of Pieve di Cadore reservoir in Italy resulted in seismicity increase (Caloi 1970) (ii) the period for which high water levels are retained (iii) the water height and the maximum vertical load may be, in certain cases, more important than the areal size of the reservoir (iv) of major importance are other factors that may substantially affect the stress system and ultimately cause the triggering of earthquakes under water reservoirs. Some of these are thermal stresses resulting from cool water entering warm rocks at any depth, as well as the effect of pressure gradients.

(5) In most cases, induced earthquakes seem to concentrate in the vicinity of reservoir, mostly near the dam and farther downstream. In other cases, however, the activity seems to extend some tens of kilometers, e.g. 50 km from Koyna dam (Guha *et al.*1974) and some 80 km from Benmore dam (Adams 1974). Withers & Nyland (1976) suggested an empirical criterion for the definition of the area of influence of a crustal load as that equal to the loaded area plus one load dimension.

(6) For induced earthquakes, it is observed that *b*-values of foreshocks are higher than those of aftershocks, both being $\geqslant 1$. They are greater than the corresponding *b*-values of natural earthquakes (0·3–0·6 for foreshocks and 0·75–1·2 for aftershocks). Berg (1968) concluded that low *b*-values are associated with high stress and strength, whereas high *b*-values are associated with reduced strength and low stress after a major earthquake.

(7) The difference between magnitudes of the main shock and the largest aftershock is found to be small for induced earthquakes (Utsu 1969). As this difference is a function of stress conditions and the heterogeneity of the material, this indicates that artificial lakes probably affect the stress distribution as well as the mechanical properties of the rocks.

POSSIBLE INDUCED SEISMICITY IN THE DEAD SEA REGION

The Dead Sea differs from all studied cases of induced seismicity that the author is aware of, in the sense that it contained water at variable depths of about 300–330 m for the last 10,000–12,000 years and higher depths earlier. In the other cases, water reservoirs are created for the first time in places where there had been only running water in rivers. Prior to the late 1950s, the rates of water evaporation and recharge in the Dead Sea were almost equal and therefore its water level was constant (– 395 m

MSL). Eversince, the Israelis raised the water level of Lake Tiberias and started pumping more than 500 MCM/year in the early 1960s. Local dams were also constructed along the Jordan rift. These, resulted in lowering the water level in the Dead Sea down to (−402 MSL) within a period of 20 years.

The seismicity map (Fig. 2) shows that earthquakes occurred in this region in the past. El-Isa (1985) studied deformation caused to some archaeological sites by nine major destructive earthquakes ($M \geqslant 6{\cdot}2$) that occurred in the last 2000 years. Seven of these seem to have occurred in the Dead Sea or very close to it. This study, and other sources of information indicate that seismic activity in this region dates back to thousands of years, strongly suggesting that the rocks of this region have been, and still are, under high tectonic stresses close enough to the shear strength of crustal rocks. Geological information strongly suggests the existence of such high tectonic stresses, as far back as 20 m.y. or more. These are represented mainly by NW–SE compressive stresses causing the almost N–S shear along the floor of the Dead Sea.

The fact that the Dead Sea lies at a plate boundary implies that faults, as deep as the Moho, exist with other associated smaller and shallower fracture zones and joint systems. These facilitate water percolation down to large depths as well as horizontal areal distances. Ben-Menahem *et al.* (1976) concluded that cracks and pressurised water exist down to a depth of 20 km in the Dead Sea area. It is along these faults and fracture zones that an increase in pore pressure results in the reduction of shear strength and ultimately rock failure at lower stresses, provided these are critically stressed, i.e. close to failure.

Disturbance of the stress regime towards or away from crustal failure can be described utilising Navier–Coulomb failure curve and the Mohr circles (see Fig. 3) where shear stresses (τ) are plotted versus principal effective stresses (σ_e). Hubbert & Rubey (1959) pointed out that the shear stress (τ) of intact rock is given by

$$\tau = \tau_0 + \mu(\sigma_n - P) \quad , \qquad (1)$$

where τ_0 is the cohesive shear strength which approaches zero for fracture rocks on pre-existing faults, P the pore pressure, σ_n the normal stress across the fracture plane, μ the internal friction which usually attains higher values for fractured rocks and $\sigma_n - P = \sigma_e$ the effective stress.

Equation (1) has been utilised for studies of crustal failure under water reservoirs. It clearly demonstrates that failure or stabilisation of rocks depends on changes of normal stresses and pore pressure, thus changing Mohr circles. It is when these circles touch the Navier-Coulomb curve that failure occurs. Utilising this, and the theoretical model calculations of Snow (1972), Jacob *et al.* (1979) discussed quantitatively the vertical stress and pore pressure changes caused by water reservoirs in different tectonic environments, and demonstrated that:

(1) For normal faults, immediately after filling a reservoir, an increase in σ_1 and σ_3 will occur. This increase amounts to ϱhg and $0{\cdot}43\,\varrho hg$ respectively, where ϱ, h and g are water density and height and gravitational acceleration respectively. After some time, pore pressure will increase. Maximum increase will be equal to full reservoir head, i.e. ϱhg. This reduces the effective stresses σ_{e1} and σ_{e3} equally and brings Mohr circle towards failure, thus increasing seismicity (Fig. 3a).

(2) For strike-slip faults the reservoir load increases both σ_1 and σ_3 by $0{\cdot}43\,\varrho hg$, thus moving the system away from failure. Later on, water pore pressure increases by

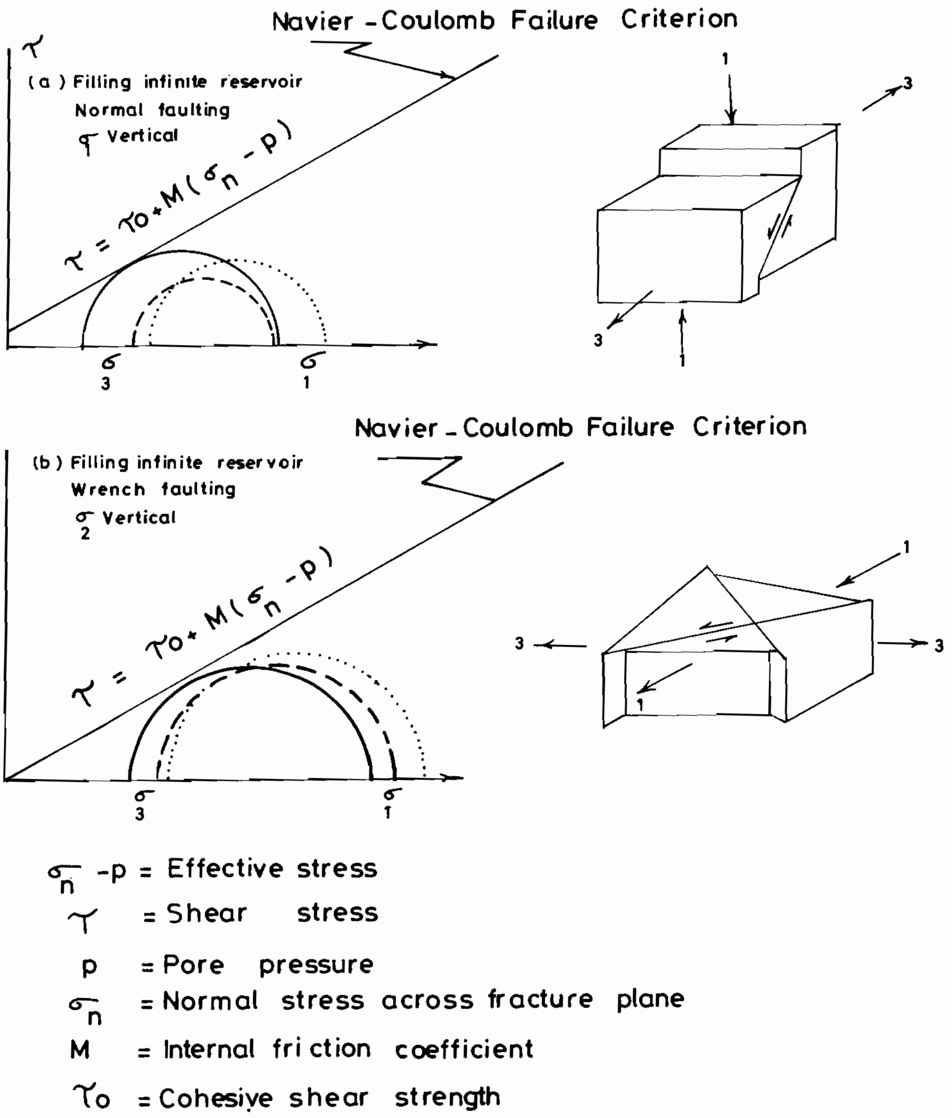

Fig. 3. Mohr diagram of Snow (1972) showing failure due to stress changes in tectonic environments of: (a) normal faulting and (b) strike-slip faulting.

ϱhg, thus decreasing both σ_1 and σ_3 by the same amount and bringing the system closer to failure (Fig. 3b).

The Dead Sea is characterised by both vertical and strike-slip faulting (Fig. 1). It also contained water for thousands of years. Therefore one may expect the effect of both the vertical load and pore pressure to be somehow static and combined with the tectonic stresses. It is the changes in the water level that should be accounted for. An increase of this level of 10 m where the water density is about 1·2 g/cm^3 would result in increasing and decreasing σ_1 and σ_3 (as discussed above) by 1·2 and 0·42 bars respectively. These rather low figures are capable of triggering only critically stressed rocks. At Lake Kariba, Zambia, induced earthquakes were triggered at the Binga fault underneath after increasing the shear stress by only 0·4 bar (Gupta & Rastogi 1976).

As both normal and strike-slip faults are present in the Dead Sea, the seismicity increase is likely to start immediately after increasing water level first at the normal faults and some time later, perhaps a few weeks, it may increase once again at strike-slip faults due to pore pressure increase at depth. A third possibility of an increase of seismic activity in the Dead Sea is anticipated from further pore pressure increase due to the probable existence of hot magmatic bodies within the crust and upper mantle. This is evidenced from different geological and geophysical observations such as the existence of hot springs and basaltic flows east of the Dead Sea as well as the magnetic anomalies of the rift itself (El-Isa & Kharabshe 1983).

As the faulting of the Dead Sea is of regional character (Fig. 1) and since the proposed 10 m increase of water height will increase its surface area, this will result in further increase of the subsurface area affected by high pore pressure. Thus the region of activity is likely to extend horizontally. One should expect more earthquakes farther south in Wadi Araba. It should also be mentioned that fluctuations in the water level will result in continuous disturbance of the stress regime of the region, a process that may result in activating earthquakes.

The level of the expected possible activity may be considerable. In a Jordan transform tectonic type of activity, damaging earthquakes are expected to occur sooner or later. The water level increase of the Dead Sea may strongly affect the timing of occurrence by bringing to failure the critically stressed rocks. Exact location, depth and mechanism of failure may also be influenced.

CONCLUSIONS

The increase of water level in the Dead Sea is compatible with the creation of water reservoirs in tectonically active zones where the associated phenomenon of induced seismicity is believed to be caused by increasing both vertical stresses and pore pressures, as well as causing some thermal pressure due to cool water entering hot media.

As the crustal rocks of the Dead Sea are expected to be under high tectonic stresses, close to their shear strength, the 1·2 bar increase of vertical stresses and pore pressure, due to about 10 m increase in water level, may bring to failure those normal and strike-slip faults successively, thus increasing the earthquake activity that may extend beyond the borders of the Sea. Seismological and tectonic information strongly suggest the expectation of future destructive earthquakes in the area. This induced effect may control earthquakes with regard to their timing, location and rupture details.

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احتمال حدوث نشاط زلزالي تأثيري في البحر الميت

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خلاصة

يمثل البحر الميت منخفضا مورفوتكتونيا يتميز بوجود صدوع رئيسية ذات حركات افقية وعمودية ، وكذلك ارتفاعات وهبوط . هناك علاقة مباشرة بين تكتونية منطقة البحر الميت والانفتاح المستمر للبحر الاحمر الذي بدأ منذ حوالي ٤٠ مليون سنة منتجا صدعا افقيا رئيسيا يمتد عبر خليج العقبة مرورا بالبحر الميت حتى جبال طوروس ـ زاغروس . ان الحركة الافقية على هذا الصدع هي المسبب الرئيسي للنشاط الزلزالي في هذه المنطقة .

تحدث الزلازل التأثيرية في مناطق البحيرات الصناعية بسبب افلات الاجهادات التكتونية الواقعة على صخور المنطقة بحيث تكون قريبة من مدى تحمل الصخور وذلك نتيجة لما يلي : (١) زيادة الاجهادات العمودية الناتجة عن ثقل الجسم المائي . (٢) زيادة اجهادات المسامات الناتجة عن تسرب المياه عبر الشقوق والتصدعات . (٣) الاجهادات الناتجة عن تسرب المياه الباردة نسبيا بالقرب من اجسام ساخنة تحت سطح الأرض .

ان زيادة ارتفاع منسوب مياه البحر الميت بمقدار ١٠م سينتج عنه زيادة اجهادات المسامات والاجهادات العمودية بمقدار ١,٢ بار مما قد يتسبب في افلات وتحريك الصدوع المتأثرة باجهادات عالية ، أما الصدوع العمودية فسيزداد النشاط الزلزالي عليها رأسا بعد ارتفاع منسوب المياه يتبعها زيادة النشاط الزلزالي للصدوع ذات الحركات الافقية ، وبعد أن ترتفع اجهادات المسامات . وحيث أن امكانية حدوث زلازل مدمرة في البحر الميت محتملة دائما فان ظاهرة النشاط الزلزالي التأثيري هنا ستؤثر على المكان والوقت والعمق وكذلك على تفاصيل هذه الزلازل .