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Earthquake Studies of some Archaeological Sites in Jordan

Introduction

El-Isa (1983a) pointed out the existence of an appreciable seismic risk in Jordan, that cannot be ignored in planning and civil constructions, and recommended a multidisciplinary approach in order to delineate all active zones and determine their levels of risk. This included detailed studies to be carried out on instrumental and historical seismicity of this region.

As instrumental data cover only a short period of time and are limited due to lack of seismological stations, historical data become more and more important. These are luckily available and cover a long period of time, but require different means of investigation. One of the main approaches towards the study and understanding of historical seismicity is to search for deformation and destruction in the debris of ancient sites and check against geological and other sources of information.

Jordan is a country that hosted different civilizations through its long history and thus many archaeological sites are present all over, covering a long period of history. Detailed studies of earthquake deformations of these sites are needed and may reveal interesting results with regard to major zones of seismic activity and their maximum expected earthquakes. A brief study of the damage to four selected sites, in the northern Dead Sea rift, caused by the major earthquakes of the last 2,000 years will be discussed.

Seismicity of Jordan

Seismic risk evaluation requires detailed studies of both instrumental and historical earthquakes for as long a period as possible. Earthquake recurrence periods have been estimated from such data utilising the empirical relationship of Gutenberg and Richter (1965) that relates, for a region, the number of earthquakes 'N' to the maximum magnitude 'M' over a specified period of time, in the form

$$\log_{10}N = a - bM \qquad (1)$$

where 'a' and 'b' are constants that characterise the region, and upon which return periods of earthquakes are dependent. As geological events and subsurface processes affecting the earth are of regional character and cover a long time (thousands and millions of years), it is clear that to obtain reliable quantitative measures of a and b, one should search for more data in the dimensions of time, space and magnitude, keeping in mind that the length of time covered by these data is very short when compared to the geological time scale.

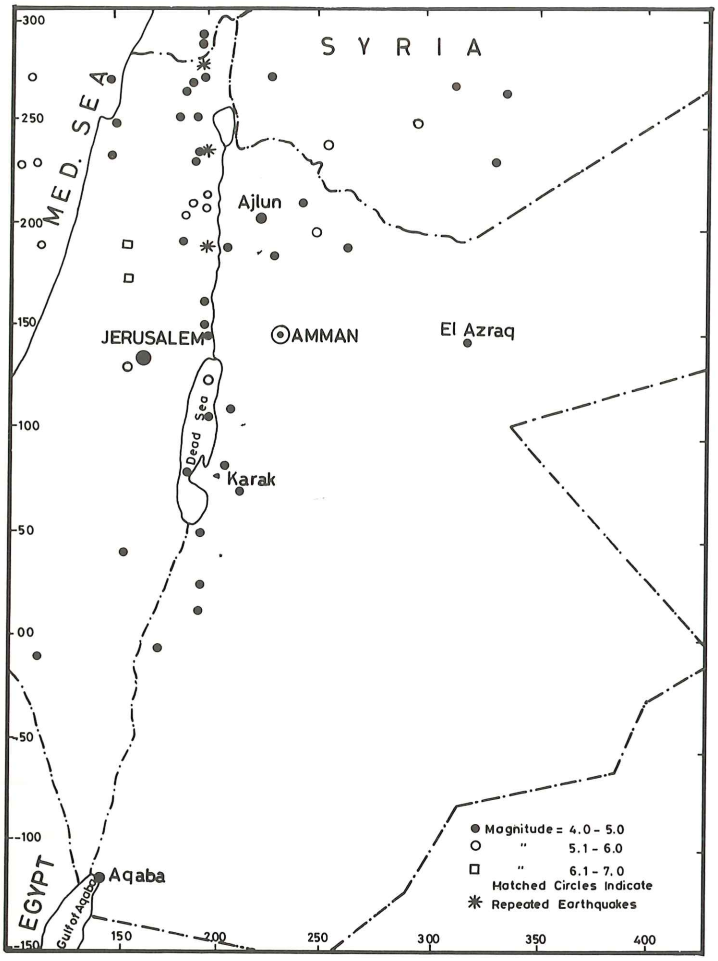
Instrumental earthquake data

These data are unfortunately incomplete. Earthquake monitoring has never been undertaken prior to the establishment of the Jordan University Seismological Station (UNJ) in June 1981 (El-Isa, 1983). The nearest station of Jerusalem was put into operation in 1953 (Ben-Menahem, 1981, p. 199). Before that instrumental data of this region were recorded only partially at the distant stations of Helwan, Ksara and Istanbul which were established in the years 1899, 1910 and 1934 respectively, as well as on more distant stations. This implies that all Jordan earthquakes of magnitudes <4.0 were not instrumentally recorded up to the year 1953, and then these were and still are recorded only partially. Recent experience at UNJ shows that all those quakes with $M \leq 2$ are not recorded if they occur at distances greater than 300 km.

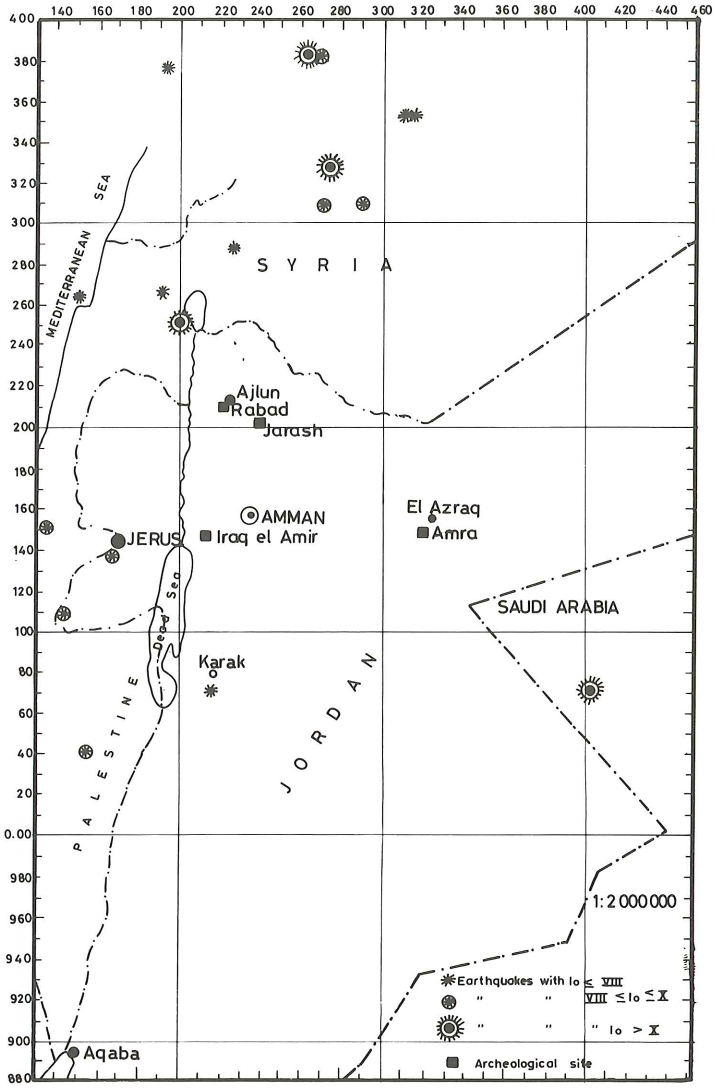
Figure 1 shows locations of instrumental earthquakes that occurred in the Jordan/Palestine region within this century, all of which are of $M \geq 4.0$. Smaller earthquakes have been and are being recorded (see El-Isa (1983b), Wu *et al.* (1973) and Ben-Menahem and Aboodi (1981)). These data show that damaging earthquakes ($M > 5$) have occurred in the region within the last 80 years and most of these are restricted to a major zone that extends along the Jordan rift and other branching zones. But as these data are incomplete, then statistical analysis of the type of equation (1) would not give reliable results.

Historical earthquake data

The shortage of instrumental data may be balanced by well-documented historical data going back as far as possible. Fortunately the Middle East has a good record of many earthquakes that extend back to centuries BC. These were reported and documented in various ways, through religious books and in the writings of many historians, chronologists



1. Instrumental earthquakes with M≥4 of Jordan as reported in IGS files up to 1976.



2. Historical earthquakes of Jordan as compiled from old Arab manuscripts by Poirer and Taher (1980) for 7th to 18th centuries.

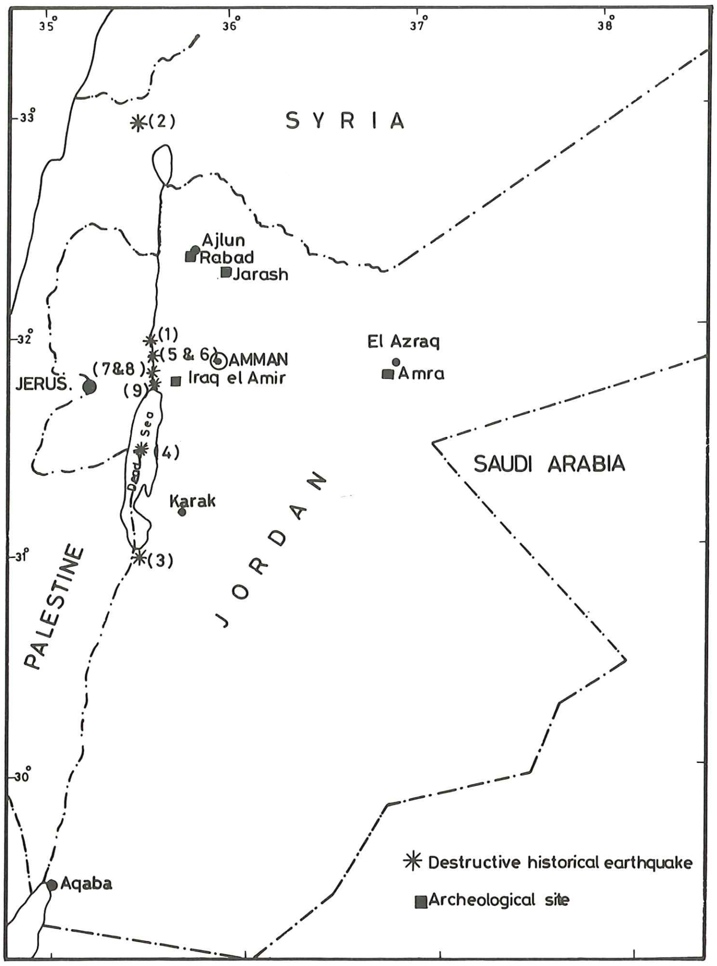
and travellers, as well as through the damage and deformation caused to many archaeological sites in different places and of different ages.

The work of many Arab and Muslim scientists contained valuable and, sometimes, detailed information of the Near and Middle East earthquakes for the period from the 7th to the 18th century. Poirier and Taher (1980) revised these data and assigned localities and intensities of many earthquakes for the said period. Other revisions and compilations were made in the last few decades (Sieberg, 1932; Amiran, 1950; Karnik, 1969, 1971; Arieh, 1967; Ambraseys, 1978 and Ben-Menahem, 1979, 1981), thus producing different catalogues. Searching in these and checking any two against each other, it is noticed that discrepancies exist as to dates and places of some earthquakes. Some mistakes must have been made and sometimes repeated from one catalogue to the other.

Studying the data of Poirier and Taher (1980) for the area between latitudes 29° and 30° and longitudes 35° and 37°, it is found that only two destructive earthquakes are listed to have occurred in the Jordan area within the period 7th to 18th century (see FIG. 2). Other sources, however, do confirm the occurrence of three more, two of which were of magnitudes 7.0 and 7.3 (Ambraseys, 1971, 1978 and Ben-Menahem, 1981) (see also TABLE 1 and FIG. 3). This therefore calls for further work on these catalogues and other sources of information for revision and checking wherever possible on archaeological, historical and geological evidence.

At least nine major destructive earthquakes (M≥6.2) have occurred along the Jordan rift valley since 30 BC as reported in the work of different Arab and Muslim Chronologists and in the different compilations and catalogues of this century (Poirier and Taher, 1980; Ambraseys, 1971, 1978; Ben-Menahem, 1981 and others). Many other earthquakes M≤6.2 were also reported, some of which reports are not very reliable and certainly need revision before being included in any statistical analysis or quantitative calculation. Deformations caused by minor earthquakes are always small and

3. Major destructive earthquakes of Jordan (M ≥ 6.2) that occurred in the last 2,000 years.



local. Therefore a regional archaeological earthquake deformation study should start with those reliable and large earthquakes. The list of TABLE 1 has been checked against different sources: their size and location seem to be fairly reliable.

The discrepancies of present catalogues of historical earthquake data call for a revision to be carried out as early as possible. This can be done through a multidisciplinary study of historical, archaeological and geological aspects. Earthquake deformation caused to archaeological sites may give valuable information as to dates, locations and intensities of historical earthquakes.

Comparing both historical and instrumental data of FIGS 1, 2 and 3 the following points are made:

1) Both data suggest that earthquake activity seems to be concentrated along the Jordan rift zone, being higher from the Dead Sea northward. This is where geological and geophysical observations indicate a left-lateral shear between two major crustal blocks (McKensie *et al.*, 1970, 1972; Girdler and Styles, 1974; Freund, 1965; Freund *et al.*, 1968; Ben-Menahem *et al.*, 1976). The stresses caused by this shear, friction between these blocks and their physical and mechanical properties are the main causes of earthquakes.
2) Other branching zones of considerable earthquake activity may be inferred. Figure 2 shows 48 historical earthquakes to have occurred some 100 km. southeast of Azraq. It is more likely that these occurred in different places along the inferred active zone of Tiberias-Azraq (El-Isa, 1983b) where huge amounts of Quaternary volcanics exist. A few small tremors ($M_L \leq 3.5$) were recorded on UNJ, within the last 12 months, that epicentred along this zone.
3) Historical data of FIGS 2 and 3 are all of intensities ≥ VI. It is clear that all smaller earthquakes were not reported in the past or simply ignored as their damage and effect on humans were not considerable. Much of the seismic activity is also missing from FIG. 1 as many small quakes are not recorded on distant stations due to attenuation of seismic energy.

Effects of earthquakes on archaeological sites in Jordan

Earthquake deformations on archaeological sites are generally represented by one or more of the following: cracks and joints, falling pillars, walls and roofs, and tilting and warping. These may range from minor to major and thus may cause little damage to total collapse. Such deformations are distinguished from other man-made destructions by the following criteria:

1) earthquake deformations at one site show a systematic character i.e. pillars will mostly fall in the same direction, cracks and joints will mostly show a preferable direction, so will the tilt . . . etc. Exceptions to these may occur as a result of, for example, a non-homogeneous structural site. In such a case tensional cracks and joints may take different random directions.
2) earthquakes will shake the whole structure thus affecting its foundations and, leaving some deep effect, while man-made deformations are not very likely to do so.
3) earthquake deformation of any site is not necessarily a function of its age, as other factors are more important such as its structural material and design, subsurface geology, distance from tectonic active faults and the number and size of earthquakes affecting this site.
4) As earthquakes are of regional effect then systematic deformations of a destructive earthquake are likely to affect more than one site at the same time, but most probably with different degrees of damage and orientations according to directions and distances.

A case study

Keeping the above in mind, a field study was carried out on four archaeological sites namely Jarash, Ras el Abd (Iraq el Amir), Rabad castle (near Ajlun) and Amra castle (near Azraq) in an attempt to study earthquake deformations.

These were selected according to the following:

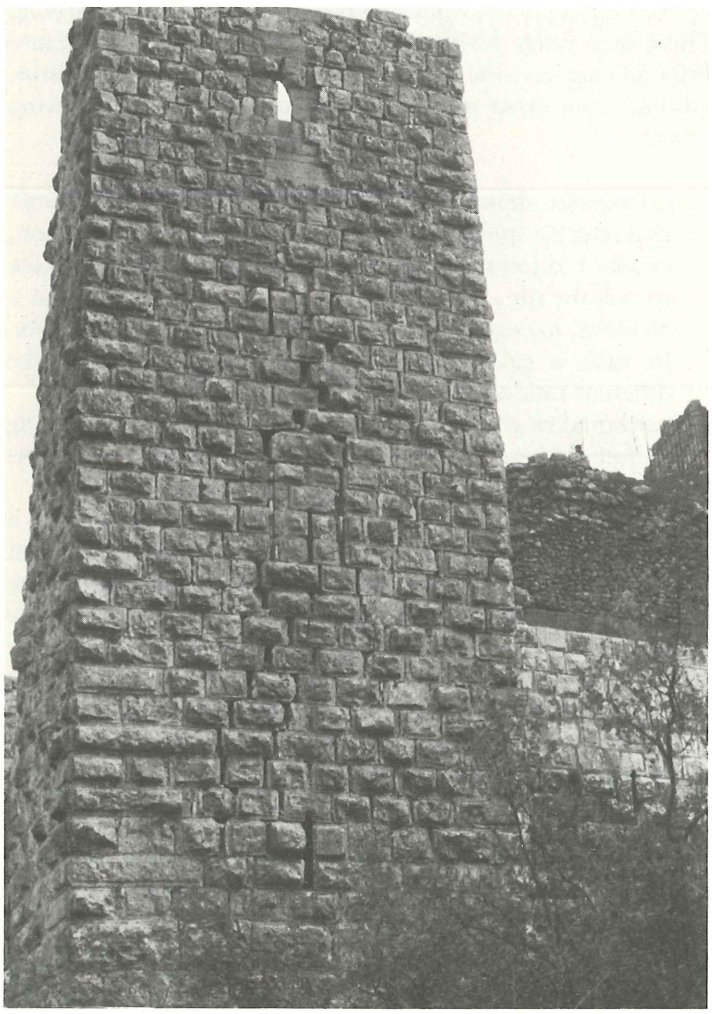
i) Rabad and Amra are younger than Ras el Abd and Jarash by not less than 1,000 years.
ii) Amra and Rabad are about 1,200 and 800 years old and some 100 and 12 km. east of the eastern margin of the Jordan rift valley respectively. Both are of different geological setting.
iii) Ras el Abd and Jarash are almost of the same age but some 10 and 27 km. east of the rift respectively and are of different geological setting.

The following observations are made:

Rabad and Amra

The heavy damage caused to Rabad, represented by the collapse of its upper part, the presence of major and minor tensional cracks and joints (see FIG. 4), as well as slight warping, best seen on the eastern wall, strongly suggest earthquake deformation that resulted from horizontal shaking at a considerable acceleration (over 0.2 g.) caused by a relatively large and near earthquake. The foundations seem to have only been affected very slightly and that has prevented a complete collapse. Tensional cracks seem to be larger in both number and size on northwestern and southeastern sides of the castle.

4. Tensional cracks on the NW wall of Rabad caused by the shaking of 1927 earthquake of Jericho.



The design, structure and building material, with thick walls and being built on the relatively hard massive limestone of the Upper Cretaceous make it a relatively sound structure with a considerable earthquake-resistance and may be classified as Masonary B to C (Richter, 1958). Thus for considerable damage to occur at this castle, earthquake intensities of not less than VIII–IX must be experienced at the site. It is also observed that the castle is sited on top of a hill. When such a site is subjected to oscillations, these may be accentuated, and in this case a very high acceleration is not necessary for considerable damage to occur. The slight tilt on its eastern wall and the system of tensional cracks may be taken to suggest that the destroying earthquake is epicentred in the west-southwest direction or a perpendicular direction, i.e. west-northwest.

Contrary to expectations, the 400 years older Amra castle shows very little evidence of earthquake deformation despite the fact that it is built on the less firm Quaternary sediments, which would indicate more damage if both Amra and Rabad were subjected to the same oscillatory shaking.

Jarash and Ras el Abd (Iraq el Amir)

Effects of earthquakes on Jarash are clear and intensive everywhere. This is seen in cracking and falling pillars, beams and walls, tilting of walls, deformation of paved streets, etc. Current excavations (March 1983) revealing buried buildings may indicate major subsidence of some ground blocks in the region brought about by earth faulting; at this stage, however, such phenomena cannot be confirmed and need more investigation.

For the surface structures, it is noticed that because of construction repair and continuous work at the site it is not easy to extract quantitative information, particularly with regard to sense of motion. Most falling pillars have been removed and many cracks and joints have been cemented. Nevertheless, standing pillars are sheared and slightly tilted. The indications of motion along surface-shears seem to have a preferred direction of northwest and a secondary direction of south–west. This may be taken to suggest that damaging earthquakes originated either from the southwest or northwest respectively.

The Omayad mosque, built in old Jarash some 1,200 years ago, seems to have been demolished and removed. To the author, the only indications of its existence were the relics of its Mehrab and the map of old Jarash by Harding (1959). As the relics of this mosque were removed, it is not possible to suggest any direction of the damaging earthquake. Observation, however, strongly suggests that Jarash was struck by a very strong earthquake sometime between 1,200 and 800 years ago, the period of the establishment of the Omayad mosque of Jarash and the nearby Rabad.

At Ras el Abd (Iraq el Amir) earthquake deformations are very clear and intensive, so that the palace has collapsed almost completely. Overthrown large blocks (some weigh over 20 tons) and large tensional cracking must have been caused by severe shaking at very high acceleration. A major falling direction is northward. Other blocks seem to have fallen westwards, thus indicating two possible directions (S and W) of perhaps two major earthquakes. A major crack seems to cross the building in an ESE–WNW direction that badly damaged the foundations (see FIG. 5). It is noticed that the crack crossed the blocks themselves rather than at their point of contact. This may indicate a ground deformation (rupture). Destruction at this site seems to have been caused by either large earthquakes causing very high acceleration (over 0.3 g.) due to their being close to the site, or the foundations of the palaces being on loose soil, or both causes together.

Maximum expected acceleration

Given the magnitude of an earthquake, its focal depth and distance and the attenuation characteristics of any region, the maximum expected accleration (a) can be calculated at any site utilising an equation of the form

$$a = \frac{2{,}000}{r^2}\,{}_e\; 0.8M \ \mathrm{Cm/S^2 (gal)} \qquad \text{(Cornell, 1968)}$$

where r and M are distance from earthquake and its magnitude. The accelerations caused by the nine earthquakes of TABLE 1 at the above archaeological sites were calculated accordingly and results appear in the table.

5. Major cracking of Ras el Abd palace (Iraq el Amir) that cuts into the foundations.

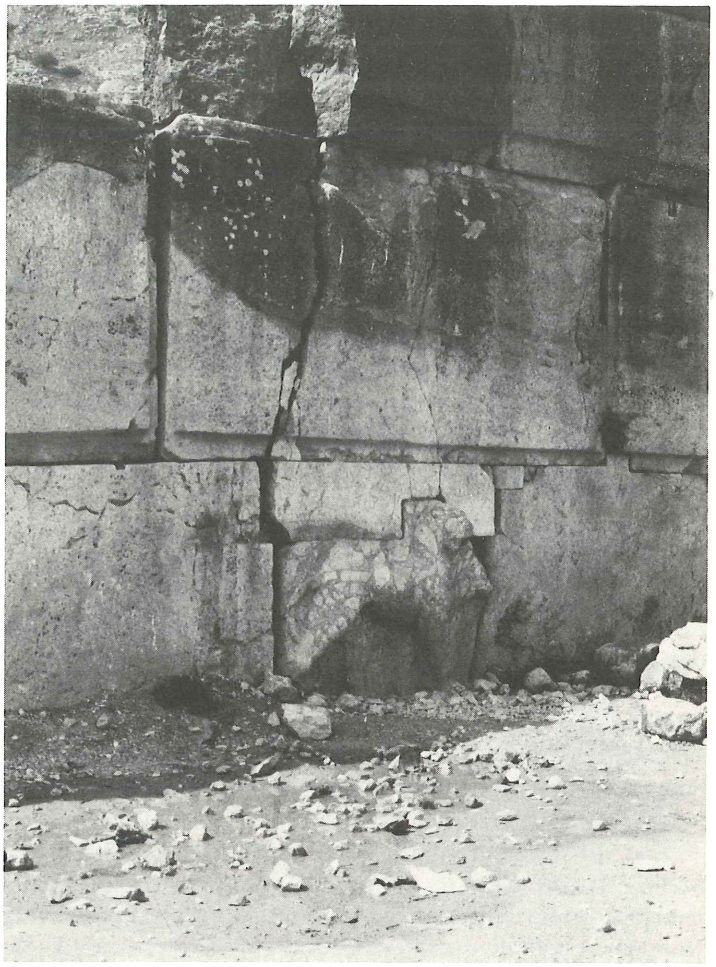


Table 1 Major destructive earthquakes (M≥6.2) of Jordan since 31 BC and the maximum acceleration caused by these at the study sites

No.	Date and origin time	Epicentre	Magnitude (M)	Rabad Δ(km)	Rabad a(cm/s²)	Jarash Δ(km)	Jarash a(cm/s²)	Amra Δ(km)	Amra a(cm/s²)	I. Amir Δ(km)	I. Amir a(cm/s²)
1.	July 11, 1927 13.04.07	32.0/35.5	6.25	38	**205**	43	160	100	30	30	330
2.	Jan. 01, 1837	33.0/35.5	6.4	80	52	90	41	160	13	125	21
3.	May 23, 1834 May 26, 1834	S. Dead Sea (Karak)	6.2	125?	18	120?	20	130?	17	75?	51
4.	Jan. 14, 1546	Central Dead Sea	7.0	80	85	77	91	100	54	25	**864**
5.	, 1034	32.48/35.32	6.6	—	—	70	80	150	18	110	33
6.	853/854?	32.48/35.23	6.6?	—	—	70	80	150	18	110	33
7.	Jan. 18, 746	N. Jericho?	7.3	—	—	40?	**430**	105?	62	35?	**561**
8.	June, 658, 659?	N. Jericho?	6.1–6.6?	—	—	40?	165–245	105?	24–36	35?	215–320
9.	30/31? BC	Jericho	7.0	—	—	40	**338**	105	49	35	**440**

For Rabad, it is shown that the 1546 and 1837 earthquakes have caused maximum accelerations of some 85 and 52 gal. respectively. Such accelerations are not large enough to cause serious damage to Rabad, but may have caused some cracks that weakened its structure and made its upper part ready to collapse when it received an acceleration of about 200 gal. caused by the 1927 earthquake.

The Amra castle has never experienced any acceleration greater than about 55 gal. This is not enough to cause any serious damage. Jarash received the first shock of 30/31 BC that caused accelerations well above 300 gal. This was enough to cause serious damage, but its major destruction, according to these calculations, must have been on Jan. 18, 746 when it received some 430 gal. acceleration. Destruction of Jarash and its Omayad mosque must have occurred on that day and nothing much of its structure was left to be seriously damaged by later earthquakes. This quake was epicentered near Jericho i.e. SW of Jarash. The 1927 earthquake may have caused about 160 gal. acceleration that slightly damaged the ruins.

Ras el Abd must have had a different experience where five of these earthquakes caused it to shake at accelerations in the range of 215–864 gal., the first of which was the 30/31 BC earthquake (440 gals). It is very likely that this palace was destroyed as early as this date.

Discussion

Geophysical, geological and tectonic observations strongly suggest that the Jordan rift valley is a major shear zone where a left-lateral movement exists between the faster moving Arabia (including Jordan on its western borders) and the Sinai/Palestine plate to the west. Such shear stresses should develop further zones of tension and compression on either side and at definite directions of NW, NE and possibly E–W. It is along these zones where stress–strain accumulation and release cause earthquakes and occasionally allow volcanic eruptions, thus suggesting the Jordan rift to be the major stress zone that may be associated with the highest seismic activity. Assuming the seismic slip along this zone is 10–25% of the total slip, Vered (1978) calculated the probable maximum magnitude of earthquake to be 7.5–8. This certainly implies a very high risk to be accounted for in planning and construction, particularly if the recurrence period as calculated from equation (1) is low.

From this limited study of earthquake deformation to archaeological sites, it is established that large destructive earthquakes have occurred in the last twenty centuries which caused the destruction of many sites, some of which indicate large magnitudes well above 6.5. It is clear that the destruction is heavier for those sites close to the rift. A further comparison may be made between Amra and Hisham palace (near Jericho) both of which were built at almost the same time, the second being younger by some 25 years, and yet it was heavily damaged by the 746 earthquake (see Reches and Hoexter (1981)). This strongly suggests that historical destructive earthquakes were limited to the Jordan rift valley, as expected from geological and geophysical observations. As the distance of any site from the rift remains a major factor that controls the expected damage, other factors must also be considered such as (i) the number and size of earthquakes and the maximum ground acceleration experienced at the site. This is a function of magnitude as well as the regional geological characteristics of the area between the site and the earthquake's epicentre, and the physical properties of the subsurface rocks that control the propagation and attenuation of seismic waves. This implies that one should not expect the same damage at two sites in different directions of the epicentre even if both were at the same distance; (ii) local geological conditions immediately under the site, particularly the presence of local faults, the hardness of the foundation rock and underground water conditions. It is likely that Rabad received more damage due to its location on the summit of a hill. Ras el Abd is also likely to have been destroyed at an early stage due to local geological conditions; and (iii) structural material and design of the site itself. A comparison between the Hisham palace and the Omayad mosque of Jarash may indicate that the second has been of a poor quality of structural material and design.

Other seismological aspects may be utilised to check on the amount and type of damage to be expected at any site. Calculations of maximum horizontal accelerations in TABLE 1 showed that Rabad had received its major destruction in 1927 and not earlier. On the other hand, the area of damage and its degree at any site may be utilised, if studied carefully, to deduce the epicentre and magnitude of the damaging earthquake.

As this study is limited to the largest destructive earthquakes of the last 2,000 years and to four archaeological sites, it serves as the start of a detailed joint study that should be extended to cover all archaeological sites in Jordan, their history, geology and earthquake deformations. Thus more information may be obtained on other seismic active zones and perhaps all damaging and destructive earthquakes of Jordan. Then one may be able to carry out reliable statistical analysis of the type of equation (1). Such studies are of help and use to archaeologists as well as seismologists.

Conclusions

1) Archaeological sites of Jordan hide valuable seismological information, which when studied in detail should supply interesting results on the historical seismicity of this region.
2) From a study of earthquake deformations caused to some selected archaeological sites along the eastern side of the Jordan rift between the Dead Sea and Ajlun, it is shown that:

   i) Minor-to-major earthquake deformations on archaeological sites are clear and represented by certain systematic phenomena such as cracks, falling pillars, walls and roofs, warping and tilting, and partial to total collapse. Such deformations, particularly those of Jarash, Iraq el Amir and elsewhere indicate the occurrence of large earthquakes ($M \geq 7$) along the Jordan rift. This agrees with theoretical calculations of maximum expected magnitude of 7.5 to 8 (Vered, 1978).

ii) Major destructive earthquakes that occurred within the last 2,000 years, were restricted to the rift zone which borders Jordan from the west. This and other geotechnical aspects strongly suggest that the Jordan rift zone remains the major potential active source for possible future destructive earthquakes.

iii) Other smaller earthquakes have occurred and are likely to occur at other branching zones. These may be potentially destructive if ignored in planning and construction.

iv) Rabad castle of Ajlun was slightly affected and structurally weakened by two major, relatively distant (more than 80 km.) earthquakes before it received the major destruction caused by the 1927 earthquake. The older Amra castle has experienced less earthquake deformation mainly due to its greater distance from epicentres of those quakes (mostly over 100 km.).

v) Iraq el Amir experienced an early earthquake deformation that destroyed it in the year 30–31 BC. Its major deformation is mainly due to its presence close to the major active zone of the Jordan rift. Four major earthquakes must have added to its deformation in the years 658/9, 746, 1546 and 1927.

vi) Jarash was first destroyed by the 30–31 BC earthquake of Jericho. It is more likely that its largest deformation occurred in the year 746 AD and nothing much was left to be considerably affected by later strong earthquakes.

3) This study of earthquake deformations supplies further evidence that the Jordan rift valley remains the major potential source of seismic risk in this country, though other branching zones must have a lower seismic activity that cannot be ignored.

4) Further detailed studies of all archaeological sites of Jordan are urgently needed. These can supply a good deal of information on seismic risk in this country as they can help to delineate presently active faults and revise historical earthquake data, and ultimately supply more accurate estimates of the expected maximum-magnitude earthquake and its recurrence period—an essential phenomenon for seismic risk evaluation. Such archaeo–seismological studies are of binary benefit for both seismologists and archaeologists.

Bibliography

Ambraseys, N. N. (1978) Middle East—A reappraisal of the seismicity, *Q.J. Eng. Geol.*, V. 11, pp. 19–32.

—— (1971) A note on the seismicity of the Zarqa region (Preliminary note), *Energoprogikt-Beograd*, London.

Amiran, D. H. K. (1950) A revised earthquake-catalogue of Palestine, *Isr. Explor. J.*, pp. 223–246.

Arieh, E. (1967) Seismicity of Israel and adjacent areas, *Surv. Isr. Bull.*, V. 47, pp. 1–14.

Ben-Menahem, A. (1979) A new earthquake catalogue for the Middle East, 92 BC—1979 AD, *Boll. Geofis. Teoret Appl.*, V. 21 pp. 245–310.

—— (1981) Variation of slip and creep along the Levant rift over the past 4,500 years, *Tectonophysics*, V. 80, pp. 183–198.

Ben-Menahem and Aboodi, E. (1981) Micro and macroseismicity of the Dead Sea rift and off-coast eastern Mediterranean, *Tectonophysics*, V. 80, pp. 199–233.

Cornell, C. A. (1968) Engineering seismic risk analysis, *BSSA*, V. 68, pp. 1583–1606.

El-Isa, Z. H. (1983a) Seismic risk in Jordan, *Proceedings of 1st Jordanian Geological Conference, Sept. 1982*, pp. 523–541, Jord. Geol. Assoc., Amman.

—— (1983b) Jordan University Seismological Station (UNJ), *Proceedings of the 1st Jordanian Geological Conference,* Sept, 1982, pp. 542–564, Jord. Geol. Assoc., Amman.

Gutenberg, B. and Richter, C. F. (1965) *Seismicity of the Earth*, Hafner, New York.

Harding, G. L. (1959) *The antiquities of Jordan*, Lutterworth Press, London.

Karnik, V. (1969) *Seismicity of the European area, Part I*, Reided, Dordrecht.

—— (1971) *Seismicity of the European area, Part II*, Reided Dordrecht.

Reches, Z. and Hoexter, D. F. (1981) Holocene seismic and tectonic activity in the Dead Sea area, *Tectonophysics*, V.80, pp. 235–254.

Richter, C. F. (1958) *Elementary seismology*, Freeman, San Francisco.

Sieberg, A. (1932) Untersuchungen über Erdbeben und Bruchschollenbau im Östlichen Mittelmeergebiet. Medizinisch-Naturwiss. Gesellschaft, V. 18, pp. 159–273.

Vered, M. (1978) The probable maximum earthquake magnitude associated with the Jordan rift, *Isr. J. Earth Science*, V. 27, pp. 82–84.

Wu, F. T., Karcz, L., Arieh, E. J., Kafri, U. and Peled, U. (1973) Microearthquakes along the Dead Sea rift, *Geology*, V. 1, pp. 159–162.