



Effects of large historical earthquakes on archeological structures in Jordan

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Abstract

This study tackles a set of conclusions and involves an evaluation of presumptive historical earthquakes in the Eastern Mediterranean Region, which hit the region and strongly affected the archeological sites in Jordan. Actually, the core of the study was the ancient cities of Umm Qais (Gadara), Umm Al-Jimal, Deir Al-Kahf, Al-Azraq, and Pella in the North and Dhahil water reservoir and Humaima in the South. The archeological excavations made during the past 20 years helped a lot of the region's seismicity re-evaluation and relocation of historical earthquakes, about which the researchers argued on determining their epicenters and magnitudes. The recent excavations at Umm Qais (Gadara) indicated that earthquake-impacted ruins have been buried under nearly 2 m of dust deposits for centuries. So, such important indicators that can be relied upon to determine the epicenter and magnitude evaluation of these historical earthquakes were unveiled. Based on the recent available excavations, it is obvious that Umm Qais was affected by two seismic events within a time interval of not less than 100 years. In the light of the results found in Umm Qais and the remote archeological sites of Umm Al-Jimal and Deir Al-Kahf, there was no azimuthal projection of neither collapsed nor tilted columns indicating that there was a major earthquake with the epicenter located in the Carmel rupture zone in the North of Palestine, and not in the rift zone as reported earlier. But, the second earthquake was at the northwest of Umm Qais. The earthquake reported here seems to coincide with the reported major earthquake in 748 AD while the second one that occurred earlier corresponds to the 551 AD. The eastward collapsed towers in the South with respect to the southern archeological site of Humaima and a seismic swarm in Sep. 20, 2003, suggested that the Wadi Araba fault may not be continuous but segmented, subject to confirmation by detailed sub-surface structural information.

Keywords Earthquake · Eastern Mediterranean Region · Archeological sites

Introduction

The Eastern Mediterranean Region (EMR) is located in the immediate vicinity of the historically seismic active Dead Sea Transform (DST) zone which is also the boundary between the Arabian plate and the Palestine–Sinai sub-plate. The recorded evidence of seismic events is preserved in the widespread remains of man-made archeological structures: sedimentary covers that date back to thousands of years and in the written regional history. However, the observed macro

evidence reveals that seismic events can reach a magnitude of more than 7.5.

The region is known by the variety of archeological sites; according to Jordan Department of Antiquity, there are more than 28,000 sites in Jordan. It is clear that the region has always been a place that attracted habitation due to the moderate climate and favorable environment. Geologic–tectonic factors contributed to a large extent in the source for attractive climatic conditions for human migration since the last ice age, 20,000 years ago. Thereafter, these conditions contributed to the development of human agriculture and trade to establish the first communities in the world. Jericho, which is the oldest city in the world, is located at the northern tip of the Dead Sea.

In times of wetter climate conditions throughout the Quaternary, even the present areas of arid conditions in South Jordan became habitable; a huge number of archeological sites are scattered all over the region; many of

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them are found even in areas where presently arid conditions prevail, indicating that the climate was certainly wetter than it is now. Dry lakes, Dead Sea terraces, and rivers (presently dry Albatin River in Saudi Arabia) are found in the desert.

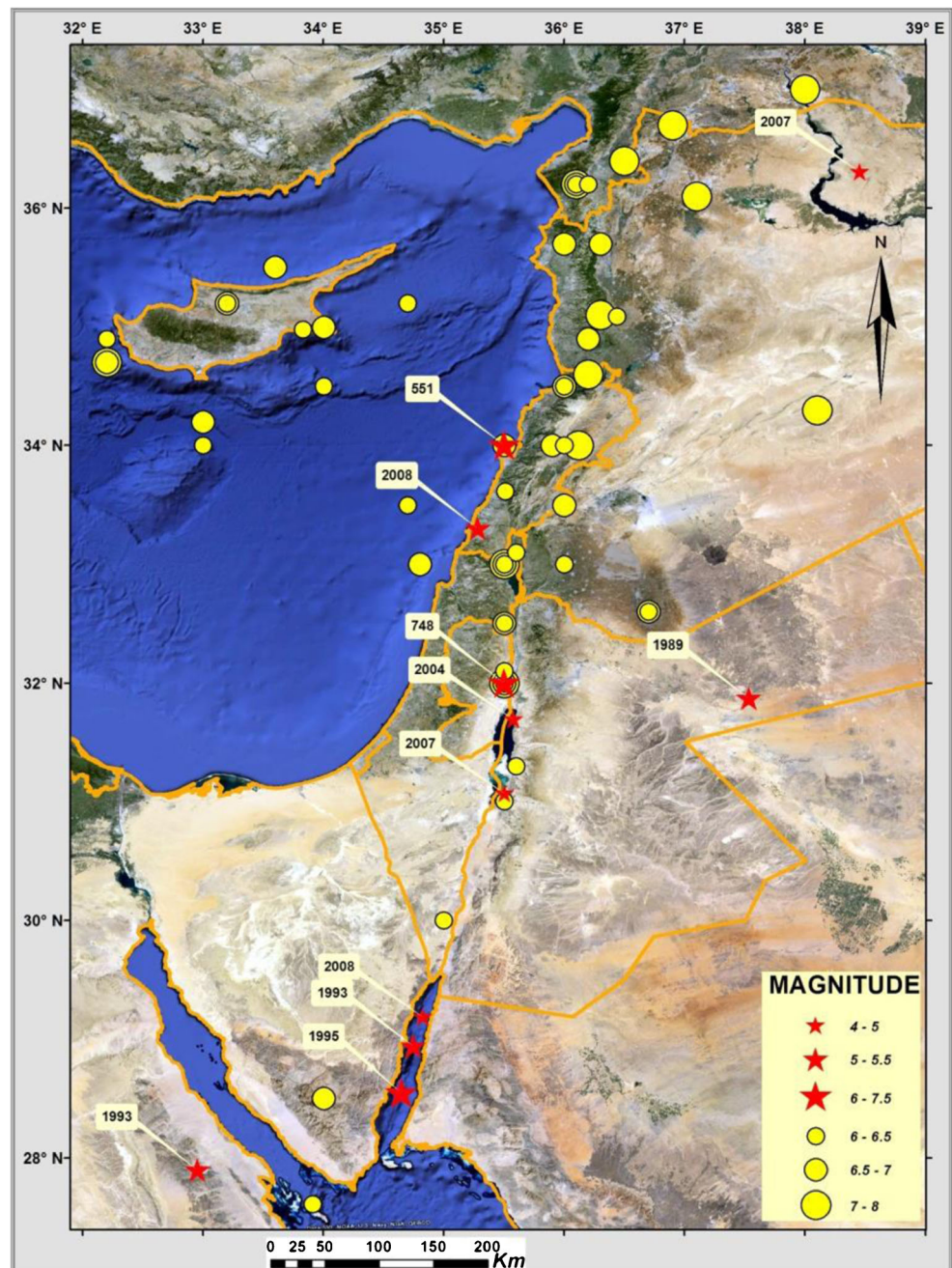
Furthermore, there is the perceived visual evidence of earthquakes that hit the region as many narrators give similar narratives of the seismic activity they witnessed. The city of El-Ramla in Palestine suffered a tsunami caused by an earthquake. Scientists have disagreed in determining the source of this event; some of them attribute it to the earthquake in 1034 AD, while others attribute it to the 1068 AD earthquake

(Samir et al. 2004; Ambraseys et al. 1994). In this study, the facts on the ground proven by archeological excavations and their relationship to major earthquakes that hit the region are discussed.

Tectonic setting and the seismicity of the region

Geological evidence reveals that the structural weakness along the Dead Sea Transform extends over more than

Fig. 1 Eastern Mediterranean Region earthquake distribution from 19 to 2008 AD; red stars are earthquakes hitting the region during the past 20 years including the 551 AD and the 748 AD (Jordan Seismological Observatory Catalogue)



1000 km, linking a region of extension in the Red Sea to the Zagros–Taurus convergence zone, and was in existence since the Precambrian period, while the structural movements started in the Oligocene period some 20–25 Ma (Bender 1975). Recent studies (Klinger 1999; Klinger et al. 2000; Le Béon et al. 2012) give an estimate of 12–18 Ma since the beginning of the structural movements. Geological and geophysical studies reveal a significant longitudinal slip totaling about 105 km of earth offsets which takes place along a zone of strike-slip faults of the Dead Sea rift, ascribed as left lateral movement with annual slip rate of 1 mm to 2 cm. The Wadi Araba Fault segment within the Araba Valley forms the major branch of the DST between the Dead Sea and the Gulf of Aqaba. Scientists consider it a continuous segment although there are signs of segmentation referred to in this study. The DST is characterized by the presence of numerous pull-apart features, but by far, the largest is the deep rhomb-graben of the Dead Sea itself. Tectonically, the Dead Sea area is the most active part of the rift. A recent study indicated that the point is at 420 m below sea level while the surface is decreasing annually by 0.7 m (Shahrazad and Stephan 2009). Earlier space radar techniques revealed that the Dead Sea bottom is at 731 m below sea level (Hall 1996).

Although a large number of damaging earthquakes with magnitudes ranging from 4 to 8 occurred along the DST since 19 AD (Fig. 1), there are still disagreements in the literature of studies about the exact date of the large earthquakes in the region, for example, the earthquake which is the subject of this study that occurred in 748 AD. Some suggested it was in 749 AD while others said it was in 748 AD. This study supports the year 748 AD and argues that the earthquake was centered on the Carmel (fault) rupture zone, not on the DST, as in previous publications and historical earthquake catalogs of the region.

Calculated seismic parameters for the region are presented in Table 1. The data in the table indicates that the largest expected earthquake magnitude in the region is from the Cyprus seismic source, based on the results revealed in this

Table 1 Seismic parameters of the Eastern Mediterranean Region for the period 1900–2000 AD based on local magnitude

Seismic source	Parameter (a)	Parameter (b)	Max. expected earthquake
Dead Sea	3.633392525	-0.617000718	5.89
Wade Araba	4.194305301	-0.827759470	5.07
Gulf of Aqaba	5.967783692	-0.933203299	6.39
Gulf of Sues	4.457676321	-0.732933815	6.08
Cyprus	4.786226723	-0.676167380	7.08



Fig. 2 Southwestward collapsed columns in Umm Qais (Gadara)

study. Note that the large-sized earthquakes could occur on geological structures that were thought to be marginal due to inaccurate historical data, like the 748 AD earthquake which source turned out to be the Carmel (fault) rupture zone, but not the Dead Sea Transform fault.

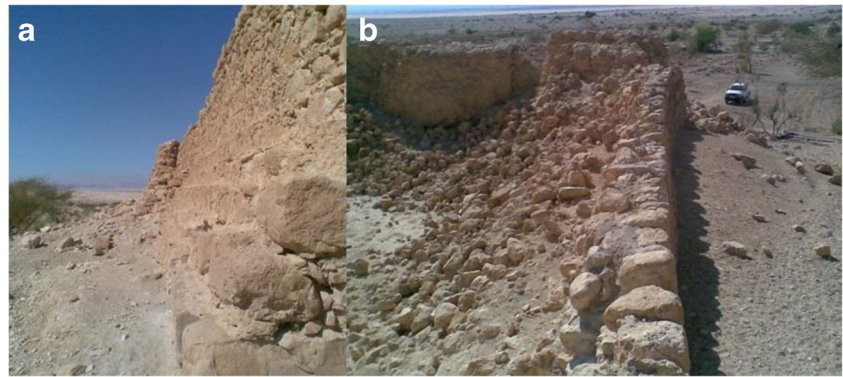
Well-preserved historical seismicity

The destructive effects of historical earthquakes are evident on the majority of archeological sites in Jordan. Based on the remaining macro evidence, a small number of these sites (Gadara and Pella) located in northwestern Jordan clearly show the multiple effects of different earthquakes from different directions relative to the site. Gadara, locally known as Umm Qais, is considered as one of the Byzantine Decapolis built during the Byzantine period. This historic city is located in the northwestern corner of Jordan. The city was prosperous and densely populated prior to the effects of a major devastating ancient earthquake with its epicenter at the northwest of



Fig. 3 Evidence of liquefaction in Umm Qais (Gadara)

Fig. 4 **a** Sudden displacement of the southeastern part of the water reservoir at about 2.2 m in the nearly northeast direction. **b** clearly indicates a clockwise rotation of the northern reservoir wall



Umm Qais at an azimuth somewhere between 350° and 354° relative to the city. The city seems to have been abandoned after this earlier earthquake based on accumulated dust deposits exposed through excavations.

The direction of the epicenter relative to the site is identified according to the direction of the collapsed archeological columns. Based on the direction of the collapsed columns mentioned above, this ancient earthquake which strongly affected Gadara was most likely the July 9 551 AD earthquake of magnitude 6.4 (Guidoboni et al. 1994). We were unable to find any trace of this (551 AD) earthquake on the remote sites. Lack of data on other remote ancient sites hampers an accurate determination of this particular earthquake. It seems to us that the location identified by Darawsheh et al. (2000) seems more reliable than the site named by others.

Latest excavations at the site strongly proved that the city of Gadara was heavily affected by two different earthquakes, separated by a period of not less than 100 years, as seen through the accumulation of dust deposits beneath a number of columns. In this case, the other collapsed columns refer to another earthquake south to westward of the site (at an azimuth of 260°). The time interval between these two events can be determined by calculating the thickness of the dust deposits beneath the collapsed columns as it appears in the image, compared with the annual rate of dust deposition, taking into account the dust thinning caused by soil compaction caused by the collapsed columns (Fig. 2).

Excavations on the paved western corridor of the city showed evidence of soil liquefaction, the result of occurrence of a nearby major earthquake (Fig. 3).

Well-preserved archeological water reservoir in the area of Dhahil located in the Araba valley that was built across the Wadi Araba fault is actually part of the remains of the Tilah Castle. Large quantities of shards were found at this site, suggesting that the castle was built during the Roman or early Byzantine period (Homes Fredericq and Hennessy 1989; Raikes 1985). The water reservoir is cut and clearly indicates the sliding side of the southern part of this reservoir in the northeastern direction for 2.2 m relative to the northwestern corner. This movement caused a clockwise rotation of the

western part of the northern wall of the reservoir in the direction of the offset, as seen in Fig. 4. Such rotation patterns usually occur when the direction of the seismic motions is oblique to the wall trend. *Most likely, this shift was created as a result of a sudden offset caused by a historical earthquake with the epicenter definitely to the south of the reservoir site in Wadi Araba, not by a continuous slow creeping.*

Determination of epicenters and discussion

Earlier earthquake epicenter that seriously affected the city of Umm Qais cannot be determined due to the lack of clear and strong indications on other archeological sites, such as in Umm Al-Jimal and Deir Al-Kahf which are located southeastward of Umm Qais. The lack of strong indications at these remote archeological sites relative to Umm Qais suggests that the earthquake was either less powerful than the subsequent one, that these historical sites have been rebuilt later, or that it was a distant earthquake located northwest of the city of Umm Qais at an azimuth of 350° – 354° .



Fig. 5 Arch of underground water reservoir curved in the direction of 285° found excavated in Umm Al-Jimal

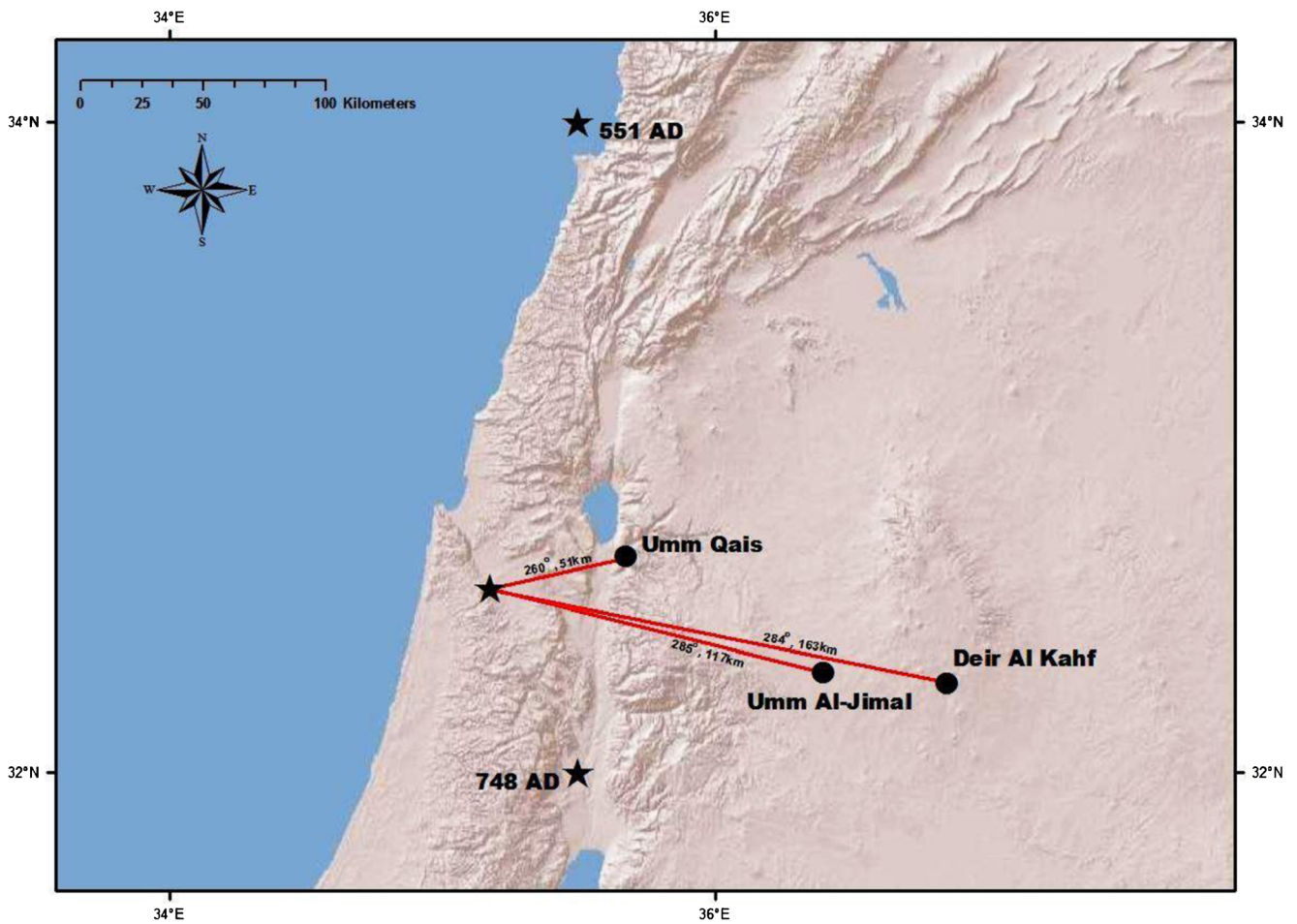


Fig. 6 New relocation of 748 AD historical earthquake that left heavy damages on Gadara, Umm Al-Jimal, and Deir Al-Kahf

Exploring the ruins of Umm Al-Jimal, Deir Al-Kahf, and Pella had not provided any sign of seismic activity at an azimuth which may coincide with the obvious macro evidence found in Umm Qais (Gadara). On the other hand, numerous

signs were found in both Umm Al-Jimal and Deir Al-Kahf that they have been strongly affected by an earthquake source at an azimuth of 285° with respect to Umm Al-Jimal (Fig. 5) and at an azimuth of 284° with respect to Deir Al-Kahf. It was also discovered that Umm Al-Jimal city was reconstructed after being hit by a devastating earthquake.



Fig. 7 Recently excavated underground water reservoir pushed towards northeastward along an axial azimuth of 60°

In light of the observations obtained, the directions to the inferred epicenter from Umm Qais, Umm Al-Jimal, and Deir-Al-Kahf sites (i.e., the azimuths) were projected on the arc-GIS map. The three projections intersect at a point of latitude at 32.57° N and longitude at 35.15° E, on the Carmel fault zone system, at the North of Palestine. The intersection point is concluded as the epicenter of this historical earthquake which is 51 km from Umm Qais, 117 km from Umm Al-Jimal, and 163 km from Deir Al-Kahf (Fig. 6).

The strong effect at Deir Al-Kahf at a distance of 163 km as well as at Umm Qais (Gadara) and Umm Al-Jimal undoubtedly indicates that this earthquake was strong enough to cause destruction at a long distance of 163 km. This result suggests that the magnitude of the earthquake must be more than 7 on the Richter scale. Therefore, seismic potential and regime of the Carmel fault system should be

Fig. 8 Eastward collapsed cylindrical and hexagonal stone towers in Humaima at an azimuth angle of 103°



reevaluated and upgraded to reflect recent studies and approach with new technologies using archeological excavations.

In addition, the reevaluation of historical earthquakes that affected the region by using excavated destructive macro evidence leads to a better assessment of the seismicity of the Eastern Mediterranean Region. We should also reconsider reliance on written descriptions by historians as definite evidences to determine historical earthquake epicenters.

Not far from Umm Qais (Gadara), a number of the collapsed columns in Pella, 24 km southwest of Gadara, pointed to the downfall of the columns in the direction of azimuth angle 298° (south of northwest); its inferred projection to the epicenter would approximately coincide with the intersection obtained by the other three azimuths.

All historical catalogs discussed about more than a seismic event hitting the area and also provided occurrence times that are relatively consistent with the thickness of the accumulated dust deposits on the fallen columns excavated recently, but presented different locations (Al-Fryouai 1984; Ibn Tagri Birdi 1932; Michael the Syrian 1899; Menahem 1979; Guidoboni et al. 1994; Sbeinati et al. 2005). Referring to the latest methodology depending on recent excavations, we

assume in this study that the time of this major historical earthquake that hit the region with widespread damages up to Deir Al-Kahf at 163 km from the epicenter is the 748 AD earthquake.

Accordingly, it is a must to reevaluate historical earthquakes in regard to their location, time, and magnitude and also to deeply examine the Carmel seismic regime in the light of this approach.

Away from Umm Qais (Gadara) to the south of Jordan lies the Nabatean city of Humaima (more than 300 km southward), approximately 55 km northeast of Aqaba city and 46 km southwest of Ma'an city. Numerous macro evidences of historical earthquakes during the past two millennia have been found. Most recent excavated ancient structures in Humaima were found to be affected by seismic activities in Wadi Araba, while recent masonry structures of local nomads have been seriously affected by the 1995 Gulf of Aqaba earthquake. A latest excavated underground water reservoir (Fig. 7) clearly shows that the ceiling arches were pushed northeastward along an axial azimuth of 60° . Thus, two interpretations could be possible: either that the city was affected by northeastwardly released compression acting at an azimuth of 60° or southwestwardly dilatation acting at 240° relative to the city. Not far from Humaima,

Fig. 9 Archeological evidence of water channel offsets caused by historical activity that affected Humaima



numerous archeological stone towers of unknown functions, nearly 2 km west of the city (Fig. 8), all collapsed towards the East. Are these cylindrical and hexagonal stone towers affected by westward dilatational or westward compression as a result of the initial shock? If they are affected by compression released in Wadi Araba, then all of them, or at least some, should have collapsed towards the West, but all of them collapsed nearly in an eastward direction. If they were affected by a dilatational act in Wadi Araba, then the hypothesis fits with the towers collapsing eastward at an azimuth angle of 103° . Another possibility is that this city was affected by a sudden compression shock as a result of an earthquake located at the east of Humaima at an azimuth angle of 103° .

This anomaly remained unexplained until Sep. 20, 2003, when the Jordan Seismological Observatory (JSO) network recorded four earthquakes in Wadi Araba at 24.5 km southwest of Humaima with epicenters at Lat. 29.8180° N and Lon. 35.1410° E, azimuth angle 233° . The epicenter locations of all four events fit approximately with the direction of the macro evidence finding mentioned earlier at the underground water reservoir. Moreover, all southern stations of the Jordan Seismological Network distributed in the region have dilatational negative arrivals. Hence, this definitely means that a dilatational act should characterize the earthquake mechanism in the relevant location and therefore reveals that the Wadi Araba main fault with a length of more than 160 km is probably intersected by an active fault in an eastwestern direction or the presence of normal fault located next to the village of Qatar. This means that Wadi Araba fault could not be explained as one unit. The regional tectonic setting map of Wadi Araba modified by Daëron and Elias, provided by Maryline Le Béon (Le Béon et al. 2012), clearly refers to normal faulting in the area of Qatar village.

In an attempt to provide further evidence of this idea showing a westward and northwestward dilatational action, a field study was conducted later for the purpose of (a) tracing the ancient city water supply channel that goes northeastward of the city for more than 14 km and (b) proving if there are any of lateral offsets along the water channel. As a result of that field study, six lateral channel offsets were found. Some of them were buried but can be recognized from the surface, while others are clearly visible on the surface. The largest dislocation was on the water channel at Lat. 29.95937° N and Lon. 35.35272° E and is around 3 m. The channel was dislocated along an azimuth of 330° , supported by several nearby discontinuities along the same azimuth (Fig. 9).

Based on an active strike-slip, a fault of nearly westward motion or a normal fault system next to the village of Qatar could exist.

Conclusions

The general conclusion is that many studies still need to be done to understand seismic activity in the Eastern Mediterranean Region. Archeological sites in the region can provide valuable data for the sake of reevaluating the overall seismic regime of the region.

The 748 AD earthquake was determined to be centered at more than 70 km at northwest of the location by Ben Menahim (1979) and nearly 40 km west of the location by Sbeinati et al. (2005), and its magnitude must be more than 7.

The tectonic map as well as the regional seismicity of the Eastern Mediterranean Region is incomplete. Therefore, all related studies in structural geology, geophysics, regional geology, environment, archeology, and GPS technology must be used.

The relocation of the 748 AD earthquake source seems logical based on the regional tectonic setting.

Concluding, we dare say that it is imperative to reconsider and upgrade new seismic sources and regimes that were deemed marginal with respect to the DST but are found to be significant.

New results lead to assumption that Humaima was affected by four historical earthquakes of magnitude 6 or greater, at azimuth angles of 240° , 257° , 283° , and 330° during the past two millenniums.

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