Repeated historical earthquakes in Sousse, Monastir and El-Jem (Tunisia)—an archaeoseismological study

Miklós Kázmér

Received: 19 May 2020 / Accepted: 16 December 2020 © The Author(s) 2021

Abstract

Tunisia is known of sparse and moderate earthquakes. However, there are seismically damaged historical buildings in the eastern Sahel region. The Roman amphitheatre of Thysdrus (modern El-Jem), various Islamic religious and secular buildings in Sousse and Monastir testify to seismic events with intensity up to IX (EMS98 scale). We raise the hypothesis that their destruction was caused by the nearby east-west Cherichira-Abaieh Fault and the north-south Monastir Fault. Simultaneity of the 859 AD Kairouan earthquake and extensive restoration works in Sousse 50 km to the east allow assessing magnitude up to 7.2 based on segment length. The city was hit both by the 859 AD and a post-1575 earthquake. Being nearby two active faults, seismic hazard in Sousse is higher than either in Kairouan or in Monastir.

Keywords Archaeoseismology · Earthquake · Seismic Hazard · Tunisia

Introduction

The diffuse plate boundary along the northern margin of Africa had earthquakes up to M 7.3 during the past six decades. Tectonic activity is concentrated along transpressional folds and strike-slip faults within the coastal Atlas region, both onshore and offshore (Meghraoui and Pondrelli 2012). There is foreland deformation south of the range. The Tunisian sector is the best studied (Bahrouni et al. 2019, 2020a) of earthquakes larger than M 7 are possible (Fig. 1). Utilizing the information hidden in archaeological objects has started in archaeological circles (Kamoun et al. 1980), followed by exact seismological studies recently. Bahrouni et al. (2019, 2020a) offered a glimpse on archaeological evidence of the AD 859 earthquake in Kairouan.

Recently, the author carried out pilot studies in three sites in the less seismic eastern Sahel region of Tunisia: Roman Thysdrus (modern El-Jem) and in the Islamic medina (old town) of Sousse and Monastir (Fig. 1) (Kázmér 2019). Earthquake archaeological effects are illustrated below, discussed in the framework of active tectonics.

Methods

“Archaeoseismology is… a subdiscipline of paleoseismology with a particular focus on man-made constructions as a potential source of paleoseismological information covering the last few millennia” (Sintubin 2015). Various deformations in the construction fabric are recorded, surveyed and dated within the framework of the individual history of the building. Intensity values are assigned to damage features following the scheme of Rodríguez-Pascua et al. (2013). Sites were studied by visual observation and documented by photography and hand drawings. Measurements were taken by Laser Disto 8 and TriPulse 360B range finders, allowing quick measurement of horizontal and vertical distances.
Results

Thysdrus (El-Jem) amphitheatre

Thysdrus (modern El-Jem or El-Djem) was the rich centre of olive growing in Tunisia in Antiquity, briefly rising to the rank of imperial capital in the AD 230s. Huge public works constructed during its heyday include an impressive, free-standing amphitheatre, which remained the largest and best preserved one in the whole Roman empire except those in Rome and Capua. Construction probably started by Emperor Gordian III in 238 AD. It was repeatedly used for defence purposes in the 5th century against the Vandals and in the 7th century against the Arab conquest. It was a fortress during the revolutions in Tunis in 1695, when cannons were used to break a hole in the wall. It hosted a saltpetre factory in the 18–19th century. Major restoration works were carried out between 1975 and 1980. The amphitheatre is UNESCO World Heritage site since 1979 (Slim 1986, 1996; Slim and Rebourg 1995).

The oval building is 148 m long and 122 m wide. The preserved perimeter wall is 31 m high. Walls are made of sandstone masonry, hiding Roman concrete within. The southern half of the amphitheatre seems more or less intact at first glance. The external wall is missing in the east, while most sectors of the northern half disappeared (Fig. 2). Serious structural damage is visible upon close inspection. Majority of arches are damaged: keystones and entire segments dropped (Fig. 2b). Vousoirs (blocks of masonry arches) bear penetrating fractures (Fig. 2c). More of the radial arches seem to be damaged than the tangential arches, although this needs further field studies to confirm. Arches on the upper floors tend to be more damaged than on lower floors. Second- and third-tier arches are often missing (collapsed). There are no arches preserved in the topmost level (Fig. 2d).

Sousse

Ribat

Modern Sousse, underlain by Roman Hadrumetum, boasts quite a few monuments listed as UNESCO World Heritage. The old town, the medina, its walls and the enclosed fortress, the ribat guarding the coast, the Grand Mosque, the hilltop fortress: the kasbah, seat of the local governor and many other buildings are some of Tunisia’s oldest Islamic constructions.

A ribat is principally a religious institution, dedicated to propagating the good word of Islam. In exchange for privileges, the ascetic inhabitants were entrusted with the surveillance of the coastline to prevent landing of attacking Byzantine fleets. Ribats were members of a chain of watchtowers along the shore of Northern Africa, keeping guard and giving fire or smoke signals from the tower. The ribat of Sousse is the oldest Islamic monument in the city (Fig. 3a). It was founded between 775 and 788 AD. The watchtower was added in 812 (Laporte 2015:24). It underwent several repairs; finally, it was turned into a madrasa (religious college) in 1721. Much of the material used in the building was reclaimed from older buildings of Antiquity (2nd to 6th century): marble columns and capitals were taken from Roman temples. All of the surviving columns are of this provenance. Walls rest on the foundations of a Christian basilica (Djelloul 2007a).

The entrance gate, in the middle of the southern facade, is covered by a porch (Fig. 3b). There are two spolia columns...
flanking the gate: the left one is well-preserved, white marble, the right one is heavily weathered and light brown granite. Two isometric capitals of different Corinthian decoration top the columns, testifying that these were also removed from Roman buildings. The building was used for various purposes during the centuries, involving major architectural modifications. However, the structural organisation as seen today is essentially the same as it was in the late 8th century. Contemporary restoration made the building look like new. However, upon careful observation, one can find evidence for seismic damage: these items are briefly described below.

The marble column on the left of the main gate bears a special broken surface (Pollard and Aydin 1988: his Fig 10B): conchoidal rib marks with rounded profile indicate progress of jointing parallel with column axis, from bottom to top. This fracture was caused by repeated collision between column and plinth during vertical shaking (Fig. 3f). We are studying the exact mechanism of these axis-parallel fractures in columns (Besharatinezhad et al. 2020) to reveal whether static or shaking-induced dynamic loading is the cause.

Further, damaged constructional elements are the broken lintel above the gate (Fig. 3d), and a sunken arch segment above the stairs leading from the second floor to the observation tower (Fig. 3c). Two marble columns on the ground floor entrance hall are damaged: a conspicuous fracture, parallel with oriented texture, cuts through across a marble column obliquely (Fig. 3e). This is a structural weakness, which did not visibly affect the integrity of the column at the time of construction. This damage is probably but not certainly due to seismic attack.

The ribat is now dated to the late eighth century on archaeological grounds. It is generally assumed that it was built by the Muhallabid governor (ruled 772–788) (Fenwick 2018:213).

Great mosque

The great mosque, the largest religious building in Sousse, was built in 851 AD (Fig. 4a). The prayer hall and courtyard might be a bit later, but still from the 9th century. Subsequently, an arcaded portico was added, probably in 1575 (Terrasse 2014). The only suspicious deformations found are on the columns of the arcade. There are vertical penetrative fractures parallel with column axis: up to 25 cm wide, up to 70-cm-high splinters of the stone columns are missing, replaced by concrete (Fig. 4b). Seven out of 12 columns are fractured, displaying preferred orientation, facing
either northwest or southeast (Fig. 4c). The origin of longitudinal and oblique fractures is interpreted as hammering by adjacent architectural elements, in this case by the plinth below. Longitudinal fracture is caused by axial shock, acting parallel with the column axis. Oblique fracture is caused by oblique shock, when the column deviates from the vertical during seismic shaking (Kázmér 2013; Besharatinezhad et al. 2020).

Kasbah

In Sousse, the first kasbah, the city fort, seat of the governor, was built in 844–845 (Fenwick 2018:213). It was increased to a much larger one, as seen today, in 859 AD (Laporte 2015:4–25) (Fig. 5a). Bahrouni et al. (2020a, their Fig. 7e) reported that the southwestern tower bears a conspicuous vertical fracture extending from the top almost down to the foundation (Fig. 5d). There are four marble towers at the entrance to the museum. These have been displaced off their respective plinths (Fig. 5b). The northwestern column “walked off” its foundation almost halfway in northwestern direction (Fig. 5c). The tower and all the kasbah—built of smaller-sized masonry—were rebuilt after the destruction, but the columns—the most expensive, hard-to-obtain elements of the building—were left in place, as they still served their supporting role well.

City wall

City walls are usually built less carefully than religious buildings and fortresses. These were rebuilt repeatedly, both after natural calamities and after every attack and destruction.
Therefore, each sector has a different age, which is often impossible to date.

The medina of Sousse is surrounded by an intact wall. Gates provide access to the old town within. It was probably completed in 859 (Fenwick 2018: 13). Fortunately, it has at least one portion which is well dated by an inscription. This is a memorial to the person who rebuilt the wall in AD 859–860) (Bahrouni et al. 2020a: their Fig. 7a).

Here, we provide data on actual damage of undated portions of the city wall: the southern gate is tilted outwards (Fig. 6a). A collapsed and rebuilt portion of the wall is illustrated by Bahrouni et al. (2020a, their Fig. 7b). An inward tilted portion and the adjacent, reconstructed part is illustrated on Fig. 6c. There is a deformed arch in an undated portion of the wall (Fig. 6b): voussoirs on the left are sunken relative to the right.

Fig. 4 Evidence for damaging earthquake affecting the Great Mosque in Sousse. a Great mosque as seen from the observation tower of the ribat. b5848. b 50 cm high longitudinal fracture, repaired (encircled), in the slender sandstone columns in the 17th century portico of the Great Mosque. #5889. c Preferred orientation of axis-parallel fractures on columns is facing NW or SE. Each petal represents one fracture. EMS98 intensity is assigned after Rodriguez-Pascua et al. (2013). 35° 49’ 37” N, 10° 38’ 23” E

Fig. 4 Evidence for damaging earthquake affecting the Great Mosque in Sousse. a Great mosque as seen from the observation tower of the ribat. b 50 cm high longitudinal fracture, repaired (encircled), in the slender sandstone columns in the 17th century portico of the Great Mosque. #5889. c Preferred orientation of axis-parallel fractures on columns is facing NW or SE. Each petal represents one fracture. EMS98 intensity is assigned after Rodriguez-Pascua et al. (2013). 35° 49’ 37” N, 10° 38’ 23” E
Monastir

Ribat

The fortress of Monastir had similar, military and religious purposes than the ribat of Sousse. It is much bigger, bearing evidence for several construction and reconstruction phases (Djelloul 2007b) (Fig. 7a). The core was built during the Abbasid dynasty in AD 796 (Fenwick 2018: 2016). The western wing with columnar gate is Hafside period (13–16th century). Modifications to military and religious functions followed each other from the 16th century onwards. Repeated consolidation and repair works were carried out in the 20th century. Detailed knowledge of construction history is needed before interpretation can be given.

The western tower has a second gate, flanked by two marble columns, and an arched portico above (Fig. 7b). The western column within the gate displays a fracture, about 90 cm high, parallel with column axis. The broken-off splinter is missing; its place is left unrepaird (Fig. 7c). This fracture is very similar to that seen on the column of the ribat gate in Sousse (Fig. 3f) and to several, repaired fractures in the Great Mosque of Sousse (Fig. 4b). After fracturing, the column was displaced, “walking off” the plinth. There are some more displaced columns within the fortress, e.g. the one on the first floor (Fig. 7d). Detailed knowledge of construction history is needed before interpretation can be given.

City walls

When the ribat was built in 795, Monastir was a town of importance, with strong connections to other ports by sea. This certainly necessitated surrounding the settlement with a protective wall. No data on its construction was found, however. Possibly, it is more or less the same age as the wall around the medina of Sousse: 9th century. The southern gate (Fig. 8a) seems to be intact. However, on close examination, one finds a conspicuous fracture dissecting the arch from top to bottom, displacing nicely carved, adjacent blocks by maybe 2–3 cm or less (Fig 8b).

Discussion

Seismic origin of damage

Ambraseys (2006) warned us to examine all possible ways of destruction before resorting to seismic origin. Here, we discuss alternative mechanisms.

Keystone drop in arches is the most reliable evidence of earthquake excitation. Computer modelling by Kamai and Hatzor (2008) revealed that a single element or a set of elements (a segment) of an arch can drop only under repeated compression and extension, i.e. transient horizontal ground motion (Hinzen et al. 2016). In each extensional step, the
voussoir (one of the set of blocks constituting the arch) drops down a fraction of a millimetre. If the earthquake lasts long enough, the voussoir gets free, detached from its neighbours, drops and the arch collapses. If seismic excitation stops before the loss of a voussoir, the arch survives. Additionally, arch deformation can happen only if there is no excess load on top of the arch, i.e. high walls already collapsed. This is the case in the amphitheatre: damaged arches usually bear the load of less than one floor.

Whenever horizontal loading of the arch exceeds the crushing strength of the stone, throughgoing, penetrative fractures (cracks) or lateral spalling develops. These fractures are directed parallel to the direction of lateral loading (Fig. 2c).

**Vertical penetrative fractures** in standing columns are indicators of extreme vertical loads (Kázmér 2013). Under normal static loading, columns do not break, especially marble columns not. The presence of large-size vertical penetrative fractures in marble columns of the Sousse ribat (Fig. 3f) and Monastir ribat (Fig. 7c) is evidence of repeated, sudden loading, caused by upward push of seismic waves. Computer modelling of these fractures is in progress (Besharatinezhad et al. 2020).

**Lateral shift of columns**—or the lateral shift of anything—can be caused by lateral loading only: agents are warfare and seismic action. Direct blasting from explosives and projectiles (either from trebuchet or firearm) leaves behind easily recognizable, small-scale damage on the surface. Lacking these traces, one can safely assume that seismic action was responsible for displacement (Figs. 5b, e and 7c, d).

**Dating**

There are no direct historical or archaeological records in the region to date past earthquakes. Architectural history of each site is discussed to provide a time frame for destructive events as precisely as possible. Dating results are summarized in Fig. 9 and in Table 1.

**Thysdrus (El-Jem)**

We do not have any documentary evidence referring to the construction and damage history of the Thysdrus amphitheatre. How can one set a date, at least an interval to the earthquake which damaged the building? In theory, it
could be damaged any time after its construction, which started in AD 238. There is ample amount of structural damage; however, there is no evidence of any major reconstruction to the original function. As there is no visible evidence of repair beyond the modern restoration in 1975–1980, we can put that there were neither financial means nor social need to rebuild the amphitheatre after the earthquake. Thysdrus ceased to be an imperial centre after the death of Gordian III in 244 AD. We know that circus games (certainly in amphitheatres) were arranged—even during Christianity—as late as in the fifth century, during the time of Augustine of Hippo (354–430 AD) (Augustine lived in Hippo, i.e. modern Annaba in Algeria). Circus shows set in amphitheatres were still the ways of public entertainment in his times of which he condemned (Brown 2000: 194). The economy behind the richness of Thysdrus probably disappeared a few centuries later when Kahina, a Romano-Berber queen, destroyed most of the olive trees around the city in 695 AD, but probably much earlier. The remaining building was still used for defense purposes repeatedly. Troops of the Bey of Tunis attacked it with artillery in 1695 and in the middle of the 19th century. Material of collapsed parts was re-used in constructing nearby buildings.

Was the Thysdrus amphitheatre damaged by the AD 859 Kairouan earthquake or by another one? An important source to be considered is Kitāb al-Masālik wa-al-Mamālik ("Book..."
of Highways and of Kingdoms”) of Al-Bakri, the greatest geographer of the Muslim West. He reported it as follows: “Ledjem fortress... about a mile in circumference ... built of stones, many of which are about twenty-five spans long. Its height is twenty-four toises; the entire interior is arranged in tiers, from bottom to top; the doors are semicircular and placed one above the other with perfect craftsmanship” (Al-Bakri 1859: 52, translated from the French version of Slane).

Al-Bakri spent his entire life in Al-Andalus (AD 1040–1094), without ever having travelled to the locations of which he wrote. He used various manuscripts in compiling his treatise, some more recent than others. However, it is less probable that he would use two-centuries-old sources describing El-Jem. His description (his unnamed source’s description) is so precise, so vivid: we can easily believe that there was no major damage to the amphitheatre in the 11th century. All or most walls were still standing and the cavea was not yet robbed of the rows of seats. Any major damage to the building potentially occurred later than the AD 859 Kairouan earthquake, and possibly later than the 11th century.

Collapse of the now missing perimeter walls and missing sectors in the north could be caused by either the 1695 or the mid-19th century siege, or by seismic shaking any other time after Al-Bakri’s 11th century description. Collapse of vaults and arches is certainly due to earthquake(s).

**Sousse**

There is a debate, started by Di Vita (1980, 1982) and Foucher (1982) on a supposed earthquake affecting Hadrumetum (modern Sousse) 306-31 AD; the problem is still unsolved (Vogt 1993).

None of the buildings studied are suitable for direct archaeological dating. The most certain archaeological datum comes from an inscription on the Sousse city wall, marking its reconstruction in AD 859–860 (Bahrouni et al. 2020a: their Fig. 7a). It is known that there was a major earthquake which destroyed

| Site                                   | Earthquake name     | Construction/completion time of buildings | Earthquake date |
|----------------------------------------|---------------------|------------------------------------------|-----------------|
| Monastir-Sousse EQ                      | 1575?               |                                         | < 1575          |
| Sousse, Great Mosque, portico          |                     | 13–16th century                          |                 |
| Monastir, ribat, western wing          | Kairouan-Sousse EQ  |                                         | 859             |
| Sousse, kasbah and city wall completed |                     |                                         | < 859           |
| Sousse, Great Mosque, prayer halls     |                     | 9th century                              |                 |
| Sousse, Great Mosque                   | 851                 |                                         |                 |
| Monastir, ribat                        | 8ct                 |                                         |                 |
| Sousse, ribat                          | 775–788             |                                         |                 |
| Thysdrus (El-Jem) amphitheatre         | < 238               |                                         |                 |
| Monastir, Roman mosaic                 | 1–2nd century       |                                         |                 |
much of Kairouan and 13 villages around in that year. Therefore, this monumental inscription most certainly marks completion of rebuilding the city wall after that calamity. All other dating attempts yielded a wide interval for the destruction event at most (Table 1).

The columns in the Sousse ribat were certainly damaged by an earthquake. It could happen any time after construction was completed in AD 788. The first candidate is the 859 AD Kairouan earthquake. The post-1575 earthquake also probably affected the kasbah.

The kasbah was completed right before the 859 AD Kairouan earthquake. This—or another—seismic event certainly severely damaged the fortress, shifting columns of the entrance almost off their foundation. The 859 earthquake is a likely candidate here, so is the post-1575 event.

Fractured columns of the portico arcade in the great mosque indicate an earthquake after the construction date of 1575. Its date is unknown yet. We are not aware of any other destruction which certainly happened at this time.

Monastir

Tunisia is famous for floor mosaics from Roman times. One of these, nearby Monastir, was laid down in the first or second century AD. It suffered deformation subsequently: both folding and faulting affected the floor. It was first interpreted in tectonic terms by Kamoun et al. (1980), Kamoun (1981), and Sorel et al. (1983). A left-lateral strand of the N-S Monastir Fault displaced it by 15 cm (Bahrouni et al. 2014:245 and their Fig. 4c; Ghribi et al. 2018, their Fig. 7).

The ribat of Monastir was built in the 8th century. There is various, obviously earthquake-induced damage in the building. Lacking access to detailed construction history, one can refer to the dated western wing. Built in the 13–16th century, the entrance column suffered damage subsequently, certainly after the 16th century, possibly as early as the 13th century. The damage (fractured column) is severe, but did not hinder usage of the building.

The modern earthquake, which damaged the west wing of the Monastir ribat and the 1575 portico of the great mosque in Sousse, probably occurred before colonial administration started by the establishment of the French protectorate in 1881; therefore, no historical account was found yet.

Intensity

An EMS98 intensity value is assigned to each and every documented earthquake damage feature. Assignment is based on the study of Rodriguez-Pascua et al. (2011) describing Earthquake Archaeological Effects (EAE), and correlating with the MMS98 intensity scale (Rodriguez-Pascua et al. 2013). Maximum estimated intensity for Thysdrus amphitheatre is IX (collapsed arches), for Sousse IX (shifted column) and for Monastir also IX (shifted columns).

The current instrumental records of seismic activity nearby Sousse contain up to M 4.5 earthquakes (Table 2, Fig. 10) (Bahrouni et al. 2014). Historical M 6-7 earthquakes are known in Tunisia elsewhere (Ksentini and Romdhane 2014; Kharrat et al. 2019). Bahrouni et al. (2014) indicate two faults in close proximity to Sousse: the west-east trending Cherichira-Abaied Fault (F5) and the north-south trending Monastir Fault (F6).

Along the Monastir Fault (Skanes-Khnis Fault; Ghribi et al. 2018), the maximum measured earthquake had magnitude M 4.7. There was no surface rupture during this event in 2013. However, displacement of Tyrrenian terraces allows to hypothesize $M_w$ 6.3 earthquakes every 263 years (Ghribi et al. 2018).

Surface rupture of a historical earthquake caused a 15-cm left-lateral displacement in a 2nd century Roman mosaic (Bahrouni et al. 2014:245; Ghribi et al. 2018: their Fig. 7). Such a displacement is in accordance with the damage observed on the marble columns of the ribat there.

Magnitude

The 859 AD earthquake

Historical documents recorded a major earthquake in Kairouan on 9 October 859 AD. An inscription in Sousse marks reconstruction of a portion of the city wall dated 859–860 AD (Bahrouni et al. 2020a). If really the same seismic event hit both cities, it means major damage in places 50 km apart. If we consider the destroyed Cherichira aqueduct 20 km to the west of Kairouan (Bahrouni et al. 2020a), then the total distance is 70 km. It is very possible that displacement along an at least 70 km long segment of the east-west

| Date      | Time  | Lat.   | Long.  | Strike | Dip | Slip | Magnitude | Depth |
|-----------|-------|--------|--------|--------|-----|------|-----------|-------|
| A         | 30 Jan | 21 h 17 | 35°51' | 10°20' | 165 | 90  | -143 | 4.5    | 6     |
| B         | 4 Feb  | 11 h 38 | 35°52' | 10°29' | 085 | 70  | 141 | 4.0    | 6     |
| C         | 1 Feb  | 17 h 11 | 35°53' | 10°32' | 010 | 55  | -137 | 4.1    | 4     |

Table 2: Focal mechanism parameters of three earthquakes along the Cherichira-Abaied Fault, indicating right-lateral strike-slip displacement (after Bahrouni et al. 2014, modified). For locations on a tectonic map, see Fig. 11.
Cherichira-Abaied Fault caused simultaneous destruction in both cities. Using the correlation between segment length and magnitude of Wells and Coppersmith (1994), it can be an earthquake of M 7.2 magnitude.

The post-1575 AD earthquake

There are seismically damaged buildings both in Sousse and Monastir, erected well after 859 AD: the Great Mosque and the west wing of the Monastir ribat, respectively. If the same earthquake damaged both cities, 20 km apart, then a minimum 20-km-long segment of the Monastir fault caused the earthquake, yielding a minimum magnitude M 6.3. These are realistic assessments, not worst-case scenarios.

It is possible that both the E-W and the N-S fault slipped in different time. Both affected Sousse, making the site seismically more hazardous than either Kairouan or Monastir.

Conclusions

There are high number of seismically damaged buildings in the eastern Sahel region of Tunisia. The Roman amphitheatre of Thysdrus (modern El-Jem), various Islamic religious, and secular buildings in Sousse and Monastir testify to past earthquakes of intensity IX, caused by the nearby east-west Cherichira-Abaieh Fault and the north-south Monastir Fault. The 859 AD Kairouan earthquake probably affected Sousse 50 km to the east (but not El-Jem amphitheatre), allowing to assess magnitude up to 7.2. Sousse was hit by both the 859 AD and a post-1575 earthquake. Being nearby two active faults, seismic hazard in Sousse is higher than either in Kairouan or Monastir.

Acknowledgements Sincere thanks are due to Abderrahim Smari (Sousse) for assistance in the field. International Geological Correlation Programme IGCP-659 (Seismic Hazard and Risk in Africa) supported the presentation of results at the 2nd Conference of Arabian Journal of Geosciences in Sousse, Tunisia, on 24–29 November 2019. Two anonymous reviewers and special issue editor Mustapha Meghraoui are thanked for their supporting comments.

Authors’ contributions 100% by single author.

Funding Open Access funding provided by Eötvös Loránd University. Private funding of the author.

Data availability Data are included in the manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Code availability Not applicable.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Al-Bakri (1859) Description de l’Afrique septentrionale par El-Bekri. Traduite par Mac Guckin de Slane. Imprimerie Imperiale, Paris
Ambraseys N (1962) The seismicity of Tunis. Annali di Geofisica 15: 233–244
Ambraseys NN (2006) Earthquakes and archaeology. Journal of Archaeological Science 33:1008–1016
Bahrouni N, Bouaziz S, Soumaya A, Ben Ayef N, Attafi K, Houla Y, El Ghali A, Rebai N (2014) Neotectonic and seismotectonic investigation of seismically active regions in Tunisia: a multidisciplinary approach. Journal of Seismology 18:235–256
Bahrouni N, Meghraoui M, Hinzen K, Arfaoui M, Maamri R, Mahfoud F (2019) Historical and archaeoseismic investigations in Kairouan region (central Tunisia): evidence for the 9 October 859 AD large earthquake. 2nd Conference of the Arabian Journal of Geosciences, 25–28 November 2019, Sousse, Tunisia (in press)
Bahrouni N, Meghraoui M, Hinzen K, Arfaoui M, Mahfoud F (2020a) The damaging earthquake of 9 October 859 in Kairouan (Tunisia):
evidence from historical and archeoseismological investigations. Seismological Research Letters 91:1890–1900. https://doi.org/10.1785/0201902528
Bahrouni N, Masson F, Meghraoui M, Saleh M, Maamri M, Dhafa F, Arafati M (2020b) Active tectonics and GPS data analysis of the Maghrebian thrust belt and Africa-Eurasia plate convergence in Tunisia. Tectonophysics 785:228–240
Besharatinezhad A, Török Á, Al-Tawalbeh M, Kázmér M (2020) Modelling of seismicity-induced cracking of stone columns using discrete-element-method (DEM), a case study of Eufrasius cathedral, Porec, Croatia. European Geosciences Union, General Assembly, 3–8 May 2020, Vienna, Austria. Abstract EGU2020-10462. 10.5194/egusphere-egu2020-10462
Brown P (2000) Augustine of Hippo. A Biography. University of California Press, Berkeley
Di Vita A (1980) Evidenza dei terremoti del 306-310 e del 365 d. C. in Tunisia. Antiquités Africaines 15:303–307
Di Vita A (1982) Evidenza dei terremoti del 306-310 e del 365 in monumenti e scavi di Tunisia, Sicilia, Roma e Cirenaica. Africa 7–8:127–139
Djloul N (2007a) The Sousse ribat. Éditions de l’Agence et mise en valeur du patrimoine et de Promotion Culturelle, Tunis
Djloul N (2007b) The Monastir ribat. Éditions de l’Agence e mise en valeur du patrimoine et de Promotion Culture, Tunis
Fenwick C (2018) Early medieval urbanism in Iriqiyah and the emergence of the Islamic city. In: Panzram, S., Callegarin, L. (eds): Entre civitas et Grombalia fault systems in the north-eastern Tunisia (seismotectonic implication). Geotectonics 52:100–113
Greenhalgh M (2011) Spolia: A definition in ruins. In: Brilliant, R., Kinney, D. (eds): Reuse Value. Spolia and Appropriation of Art and Architecture from Constantine to Sherrie Levine. Routledge, London, pp. 75–96.
Hinzen K-G, Schwellenbach L, Schwepp G, Marco S (2016) Quantifying earthquake effects on ancient arches, example: the Kalat Nimrod fortress, Dead Sea Fault Zone. Seismological Research Letters 87: 751–764
Kamai R, Hatzor VH (2008) Numerical analysis of block stone displacements in ancient masonry structures: a new method to estimate historical ground motions. International Journal for Numerical and Analytical Methods in Geomechanics 32:1321–1340
Kamoun Y (1981) Etude néotectonique dans la région de Monastir-Mahdia (Tunisie orientale). Thèse Doc. 3éme cycle, Univ. Paris XI, Centre d’Orsay
Kamoun Y, Sorel Y, Viguer C, Ben Ayed N (1980) Un grand accident submérien d’âge post-Tyrrhénien en Tunisie orientale: le décrochement sénestre de Skanès (Monastir)-Hammamet. Comptes Rendus de l’Académie des Sciences Paris Series D 290: 647–649
Kázmér M (2013) The rocking columns of Poreč – archeoseismology in the Istria Peninsula, Croatia. In: Grützner, C., Rudersdorf, A., Pérez-López, R., Reichert, K. (eds): Seismic Hazard, Critical facilities and Slow Active Faults. PATA Days. Proceedings of the 4th International INQUA Meeting on Paleoseismology, Active Tectonics and Archeoseismology (PATA), 9-14 October 2013, Aachen, Germany, pp. 117–120
Kázmér M (2019) Why seismic hazard is underestimated in Tunisia. An archeoseismological study. 2nd Conference of the Arabian Journal of Geosciences (CAJG) 25–28 November 2019, Sousse, Tunisia (in press)
Kharrat S, Harbi A, Meghraoui M, Bouaziz S (2019) The Tunisia homogenized macroseismic database (second century – 1981): first investigations. Seismological Research Letters 90:347–357
Ksentini A, Romdhane NB (2014) Updated seismic hazard assessment of Tunisia. Bulletin of Earthquake Engineering. 12:647–670
Laporte J-P (2015) D’Hadrumente a Sousse, des années 350 a 859. RM2E Revue de la Méditerranéenne, édition électronique Tome II. 1:3–34
Meghraoui M, Pondrelli S (2012) Active faulting and transpression tectonics along the plate boundary in North Africa. Annals of Geophysics 55:955–967
Moro E, Kázmér M (2020) Damage in ancient buildings – towards an archeoseismological database. Annals of Geophysics (In preparation)
Pollard DD, Aydin A (1988) Progress in understanding jointing over the past century. Geological Society of America Bulletin 100:1181–1204
Rodriguez-Pascua MA, Pérez-Lópeh R, Giner-Robles JL, Garduño-Monroy VH (2011) A comprehensive classification of Earthquake Archaeological Effects (EAE) in archaeoseismology; application to ancient remains of Roman and Mesoamerican cultures. Quaternary International 242:20–30
Rodriguez-Pascua MA, Silva PG, Pérez-López R, Giner-Robles J-L, Martín-González F, Perucha MA (2013) Preliminary intensity correlation between macroseismic scales (ESI07 and EMS98) and Earthquake Archaeological Effects (EAEs). In: Proceedings of the 4th International INQUA Meeting on Paleoseismology, Aachen, 221–224
Sintubin M (2015): Archeoseismology. In: Beer M, Patelli E, Kougioumtzoglou I, Au I S-K (eds): Encyclopedia of Earthquake Engineering, Springer, Berlin, 133-146
Slim H (1986) Les amphithéâtres d’El-Djem. Comptes Rendus des Séances de l’Académie des Inscriptions et Belles Lettres, 130:440–469
Slim H (1996) El Djem. L’antica Thysdrus. ALIF, Les Éditions de la Méditerranée, Agence Nationale du Patrimoine, Tunis
Slim H, Rebourq A (1995) El Jem. Site archéologique et musée. Les guides Cérès. Cérès Editions, Tunis
Sorel D, Kamoun Y, Sayadi MS, Viguer C, Ben Ayed N (1983) Décrochement d’âge historique et risque sismique dans la région de Monastir (Tunisie orientale). Note de Service Géologique de Tunisie 47:35–41
Terrasse M (2014) Lieux de Priere a Sousse au haut Moyen Age: modeles ou énigmes. RM2E Revue de la Méditerranée édition electronique. Tome I 1:3–10
Vogt J (1993) Further research on the historical seismicity of Tunisia. Terra Nova 5:475–476
Wells DL, Coppersmith KJ (1994) New empirical relationships among magnitude rupture length, rupture width, rupture area, and surface displacement. Bulletin of the Seismological Society of America 84: 974–1002