



An update of Algerian's seismic catalog from historical seismicity, archeoseismological, and paleoseismological studies

Abdelhakim Ayadi¹ · Farida Ousadou¹ · Kahina Roumane² · Assia Harbi¹ · Said Maouche¹ · Mourad Bezzeghoud³ · Mustapha Meghraoui⁴

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Abstract

For any seismic hazard study, a reliable, homogenized, and complete seismic catalog is required. The Algerian seismicity catalog has been recently updated by retrieving and reappraising many historical events. The Algerian seismic network has also been densified up to about 80 seismic stations covering the Tell Atlas which is the most active area of northern Algeria for monitoring of the seismic activity reducing the magnitude threshold. Recently, we have launched archeoseismological studies to retrieve past strong earthquakes that have affected Roman sites located along the Tell Atlas. Here, we proceed with tectonic investigations around selected sites where significant observed damage were identified. On the other hand, paleoseismological investigations were conducted along the El Asnam fault (now Chlef) following the large Ms 7.3 earthquake of 1980. Paleoseismic studies combined with archeoseismological results provide the dating of past earthquakes and contribute to the completeness of the seismicity catalog.

Keywords Historical seismicity · Archeoseismicity · Paleoseismicity · Earthquake catalog · Seismic hazard

Introduction

The Tell Atlas of Algeria experienced strong seismic events which caused heavy damage with significant number of victims. All these events are located around seismogenic zones; most of them are related to the activity of Quaternary basins such that of Cheliff and Mitidja basins. These two basins were struck by the strongest and well-documented events of El Asnam of October 10, 1980, Ms7.3, and Zemmouri of May 21, 2003, Mw6.8 (Fig. 1). Prior to 1900, several

destructive earthquakes were reported by Algerian seismological catalogs (Ayadi and Bezzeghoud 2015; Harbi et al. 2015) such as those of Algiers (1365 and 1716, $I_0 = X$), Oran (1790, $I_0 = X$), and Djidjelli (1856, $I_0 = IX$) (Table 1), cited as almost documented events. These events left thousands of deaths and severe damage in the cities where the earthquakes occurred and in their vicinities. The city of Algiers was completely destroyed during the 1365 earthquake, part of the city was flooded, and many victims were reported. The city was also destroyed during the 1716 earthquake with 20,000 victims and heavy damage. West of Algeria, the city of Oran, was also destroyed during the 1790 seismic event killing 2000 people with heavy damage in the city and its vicinity. During the Djidjelli (now Jijel) 1856 earthquake, the city was heavily destroyed and a tsunami was triggered flooding a large area.

Recently, some historical seismic events were retrieved from documents that were not studied before. There is still a lot of documents and archives waiting for an analysis especially for the Ottoman period and before. Other events have occurred, but no information is available so far except that their effects could be recognized on archeological structures. This is the reason why we focus on the archeological sites to retrieve these effects that are related to past strong earthquakes. The dating will enable us to determine the time when these earthquakes occurred. A recent study on Roman sites in

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✉ Abdelhakim Ayadi
abdelhakim.ayadi@gmail.com

¹ Centre de Recherche en Astronomie Astrophysique et Géophysique, Algiers, Algeria

² Université d'Alger 2 Abou El Kacem Saâdallah, Algiers, Algeria

³ Departamento de Física, Escola de Ciências e Tecnologia (ECT), Instituto de Ciências da Terra (IIFA), Universidade de Évora, Évora, Portugal

⁴ Institut Terre et Environnement de Strasbourg, UMR 7063, France

Table 1. List of significant seismic events in the Tell Atlas of Algeria. The macroseismic intensity I_0 is given in EMS-98 scale

Date	Location	Intensity	Magnitude	Observations
03 01 1365	Algiers	X		Algiers was completely destroyed. Part of the city was flooded. Many victims were reported.
03 02 1716	Algiers	IX		Reports of 20,000 victims. Heavy damage around Algiers. Aftershocks were felt until June 1716.
09 10 1790	Oran	IX–X		Event felt as far away as Malta; 2000 people were killed. Heavy damage in Oran City and its vicinity.
02 03 1825	Blida	X–XI		Blida was completely destroyed, and 7000 people were killed.
22 08 1856	Djijelli	X		A tsunami was reported along the coast a large area was flooded. Djijelli was heavily affected.
02 01 1867	Mouzaia	X–XI		Reports of 100 people killed and 160 injured in Mouzaia. The town was completely destroyed. Surface breaks were reported.
16 11 1869	Biskra	IX		Heavy damage over a large area with 30 people killed.
29 11 1887	Mascara	IX–X		Destructive earthquake with 80 houses destroyed and 20 people killed.
15 01 1891	Gouraya	X		Heavy damage, with 53 buildings destroyed and 38 people killed. Felt about 200 km around Gouraya.
24 06 1910	Sour-el-Ghozlane	X	$M_s 6.4$	Many villages were destroyed and 81 people were killed. Aftershocks were felt until January 1911.
12 02 1946	Béjaia	IX	$M_s 6.0$	Heavy damage with 1000 houses destroyed, 264 people killed, and 112 injured.
10 10 1980	El Asnam	IX	$M_s 7.3$	Destructive earthquake, with 2633 people killed, 8369 injured, 348 wounded, and thousands left homeless. More than 4 m of vertical uplift was measured.
27 10 1985	Constantine	VIII	$M_s 5.9$	Limited damage, with 10 people killed and 300 injured.
29 10 1989	Tipasa-Chenoua	VIII	$M_s 5.9$	Limited damage, with 22 people killed. Strongly felt in Algiers. Numerous aftershocks recorded during 6 months.
18 08 1994	Mascara	VII	$M_s 5.7$	Reports of 171 people killed, 289 wounded, 1328 homeless, and 10,000 dwellings partially or completely destroyed.
22 12 1999	Ain-Temouchent	VII	$M_s 5.7$	Heavy damage, with 26 people killed and 25,000 left homeless.
10 11 2000	Beni-Ourlilane	VII	$M_s 5.7$	Reports of 2 people killed, 50 injured, and 3000 houses damaged.
21 05 2003	Zemmouri	X	$M_w 6.8$	Strong earthquake, with 2278 people killed, 11,450 injured, 45 reported missing, and 44,000 houses damaged. Extensive coastal uplift observed.

the Tell Atlas of Algeria revealed the existence of damage related to strong earthquakes that affected archeological remains (Roumane and Ayadi 2019).

We aim by this study to complete the Algerian seismicity catalog with past strong events retrieved (i) from the analysis of damage on archeological sites and (ii) from paleoseismological investigations. The El Asnam fault zone was explored following the October 10, 1980, Ms7.3 earthquake; no other paleoseismological study was made since that date (Meghraoui 1988).

Historical and archeoseismological investigations

The Algerian territory, particularly its northern part, is one of the most active areas in the Mediterranean basin. This seismicity is concentrated in the Tell Atlas due to the ~4 mm/year African–Eurasian plate convergence (Meghraoui and Pondrelli 2012; Bezzeghoud et al. 2014). The first document relating seismic events in Algeria was written during the fourteenth century, and the studies became more developed during the nineteenth century, and the first seismological station was installed in Algiers in 1910 (Ayadi and Bezzeghoud 2015). The upgrade of the seismological network allowed a better survey and made the earthquake catalog more complete for the instrumental era compared with the historical one. The catalog is considered complete for magnitude $M \geq 5.5$ over the period 1910 to now but has lacked for the historical period prior to 1910. The earthquake catalog contains almost 20,000 seismic events with all magnitude including felt aftershocks. Discarding the events considered as aftershocks and considering only the main shocks, our catalog will contain almost 500 events with $M \geq 4.0$. The magnitudes in our catalog are mostly

in duration magnitude (M_d); other events were assigned surface magnitude (M_s) and moment magnitude (M_w).

Concerning the macroseismic intensity, all the events are homogeneous with intensity assessed or reassessed into European Macroseismic Scale EMS-98 (Harbi et al. 2015). Table 1 summarized the most significant seismic events that occurred in Algeria from 1365 to 2003. The complete catalog is available in the supplementary material of Ayadi and Bezzeghoud (2015) and Harbi et al., (2015). An update of the historical seismicity has been made recently by adding more than 200 new events that occurred in the north central and eastern Algeria to the Algerian catalog (Harbi et al. 2015).

An ongoing project will investigate the historical seismicity in the remaining western parts of the country. It is important to remind that such work takes too much time to investigate very old documents and archives.

Most of the retrieved events were found in archives from newspapers, periodicals, chronicles, unpublished documents and old books, and epigraphic documents. These documents are original and have not been analyzed before. An example of the new seismic events retrieved in (Harbi et al. 2015) are given in Table 2. It is important to notice that more efforts are needed to go back more earlier in time to retrieve strong past earthquakes especially those that occurred during the Roman period. Some events are now available in our database such as those of AD42 that struck the Roman city of *Rusucurru* (now Dellys, Algeria). In his book *De Mundo*, Apulée (AD125–170) reported earthquakes and tsunamis during the first century AD. In *Lambaesis* (now Tazoult in eastern Algeria), a fragment of epigraphic inscription was also found relating an earthquake that occurred in 267. The inscription was found in situ on the arch of the city dated from 268 to 287 and reported reparation and reconstruction of the city damaged by an earthquake. Also in 355, *Thubursicu Numidarum*

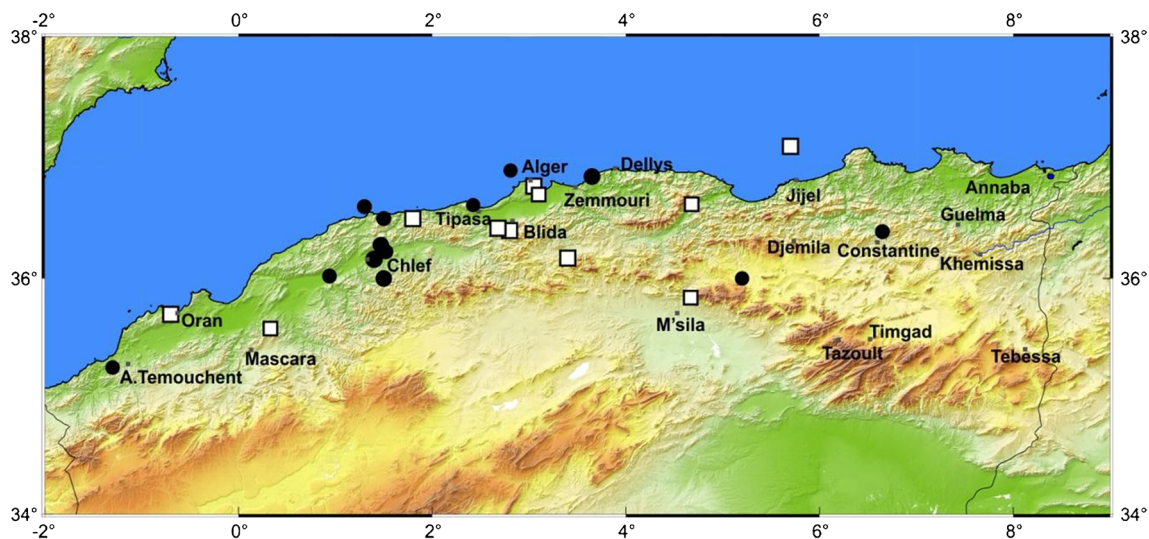


Fig. 1 Map of the strong and destructive earthquakes in northern Algeria. For the instrumental era (1900 to now), we selected events with magnitude $M \geq 6.7$ (black circles), and for the historical era, we plot the available events with intensity $I_0 \geq VIII$ (white rectangle)

Table 2. List of new retrieved events that occurred in the eastern part of the Tell Atlas of Algeria

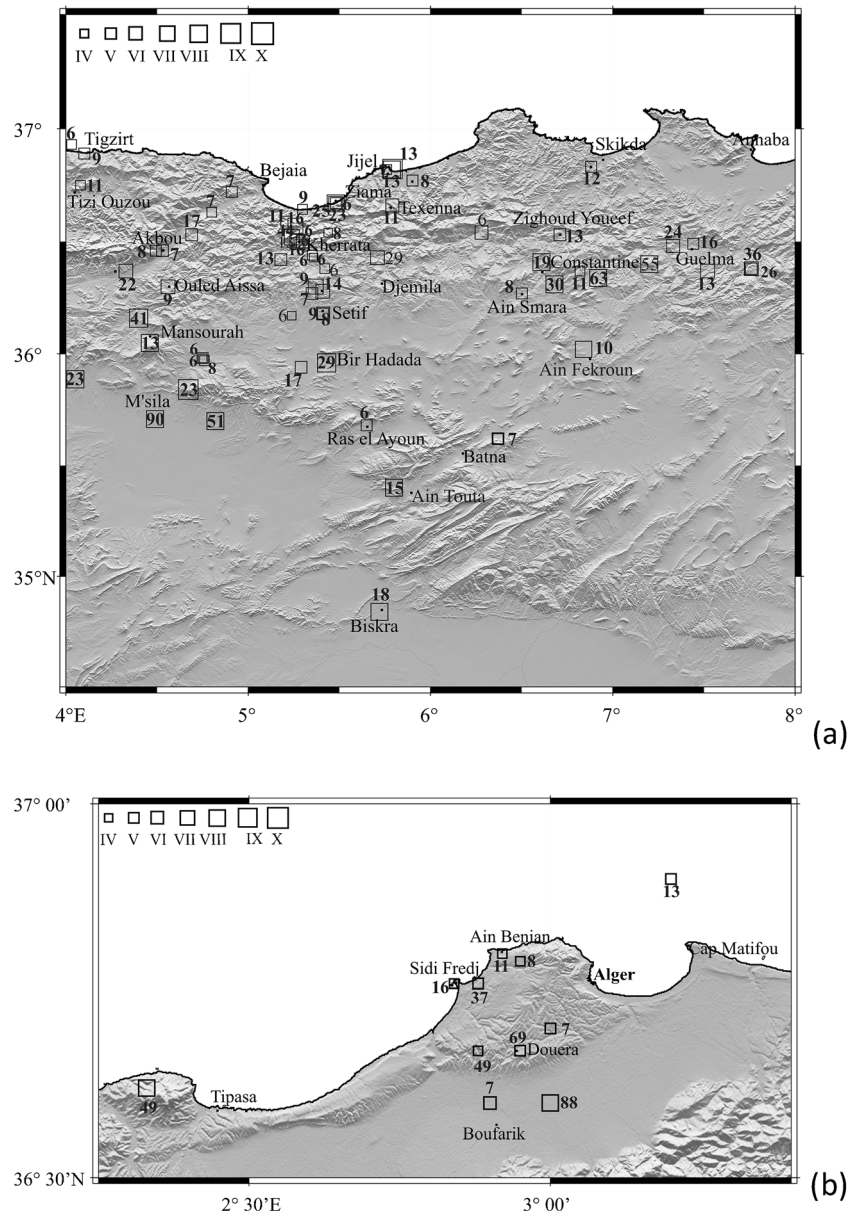
Date	Location	Intensity	Effects
1637	Algiers		Destructive
June 23, 1849	Constantine		Damaging
May 25, 1861	Hammam Debagh (Guelma)		Felt with aftershocks
November 30, 1863	Bougie		Largely observed
January 15, 1870	Philippeville		Strong

(now Khemissa, eastern Algeria) was also suffered from a strong earthquake which caused deteriorations of monuments and statues as reported by another epigraphic inscription. These statues and monuments were moved to another places

(Harbi et al. 2015). More efforts are needed to check and analyze the huge quantity of unread documents.

According to (Harbi et al. 2015), 286 events were retrieved from the analysis of the abovementioned documents

Fig. 2 Distribution of new historical events retrieved from archives and other historical documents. The events are expressed with maximum observed intensity scaled from intensity IV to X. **a** The missed earthquakes for the eastern part of Algeria. The retrieved events are represented with an empty square. **b** The missed earthquakes retrieved from the archives for the central part of Algeria around Algiers Capital city. The numbers in the squares or aside represent the number of the macroseismic data points. On the map, only events with intensity calculated with at least 6 data points are plotted. A data point is an information at a specific location Harbi et al. (2015)



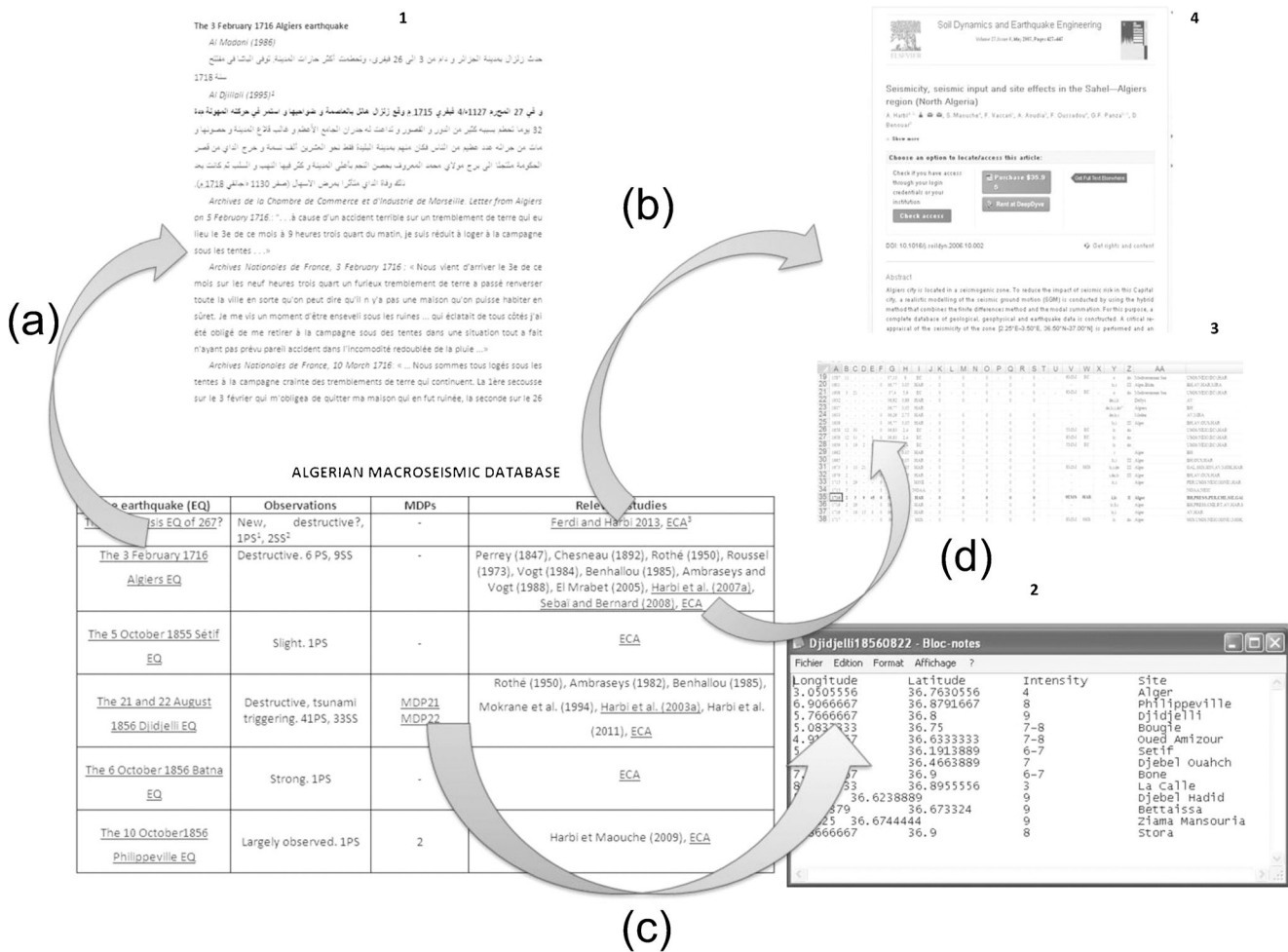


Fig. 3 Example of the historical seismic database of Algeria available on the NAGET website. The database contains a table with different events. Surfing on the table of event will drive the reader to **a** a summary of the event with its characteristics, **b** copy of the original documents or

published papers describing the event, **c** macroseismic data information where one can find the different intensities observed at different locations, and **d** the references that reported the seismic event Harbi et al. (2015)

(periodicals, historical books, unpublished manuscripts, military reports, chronicles and testimonies, and newspapers). Fifty-four were determined with intensity $I_0 \geq VI$ (EMS-98 scale). These unpublished events concern the north central and eastern Algeria (Fig. 2). A seismic database for historical seismicity (Fig. 3) is now available on the website of the North African Group for Earthquake and Tsunami Studies “NAGET” (NAGET webpage n.d.). This database is an update of the existing seismic catalogs. On the other hand, to retrieve missed past events, we now move to archeoseismology. In Algeria, there are several archeological sites with significant observations of damage probably due to earthquakes’ effects.

Damage observed on archeological structures

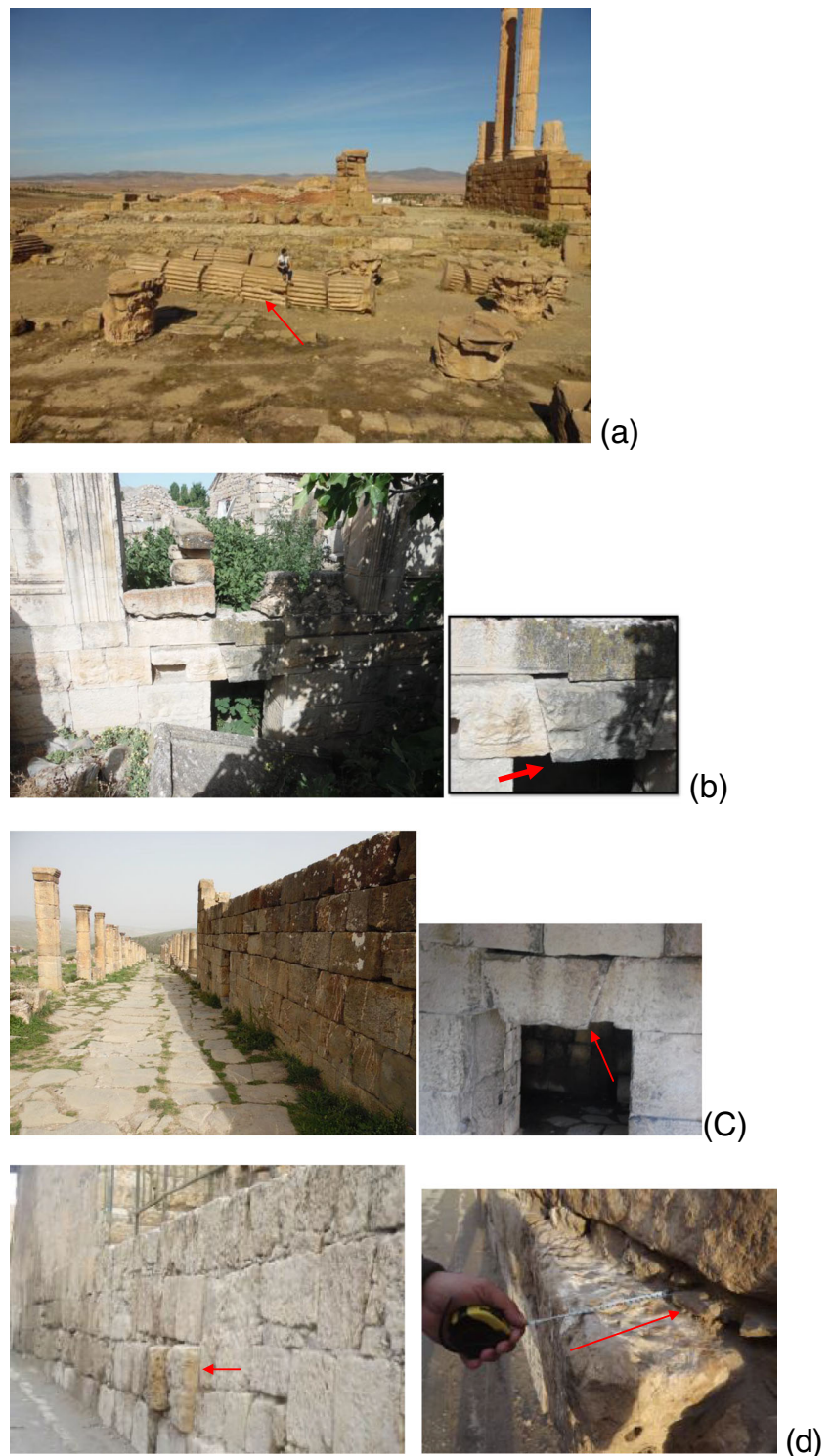
The second part of our study concerns the archeoseismological investigations on selected Roman sites of Timgad, Mopht,

Djemila, and Tebessa (Fig. 4) to show the first-hand observations related to damage on archeological structures. These sites are located in eastern Algeria, and their investigation shows interesting disorders that could be related to the action of strong historical earthquakes.

These damage observed on archeological structures are analyzed regarding whether they could be attributed to earthquakes, human activities, or any other origin (Fig. 4). Comparable damage observed on different sites worldwide have been identified on several Roman sites of northern Algeria. It was suggested that they were caused by earthquakes (Roumane and Ayadi 2019).

In Fig. 4a, we have the drums of columns that collapsed in a domino-type pattern near the Capitol on the site of Timgad (founded AD100 by Emperor Trajan). This Capitol is considered the tallest one in the Roman Empire. These tall columns with their related drums, made of high-quality limestone, were found laying on the ground by the traveler Bruce in 1765. Two

Fig. 4 Damage observed on Algerian Roman sites in eastern Algeria: **a** toppled columns in the Capitol on the Roman site of Timgad. The drums made of limestone collapsed in a domino-type pattern. Two other columns were reassembled on the Capitol place as seen on the right in the back of the picture; **(b)** displaced blocks in lintel in a temple on the Roman site of Mopht south of the Djemila Roman site, the 4 cm vertical downward sliding of the block is an evidence of an earthquake effect; **(c)** displaced block in lintel observed on the site of Djemila in the Curia, a Roman Town Hall. The 5 cm vertical displacement observed is also an indicator of an earthquake shaking; **(d)** displaced block observed on the Byzantine rampart near the arch of Caracalla in Tebessa. About 15 cm displacement was found. The blocks were extruded during the shaking from the wall (Roumane and Ayadi (2019))



other toppled-down columns were reassembled in 1897 and exhibit about 44 m high on bases as we can see on the right side in the back of Fig. 4a (Ballu 1897). The observation of Bruce was reported by (Ballu 1897) who claim that the damage are attributed to the action of an earthquake. These columns are comparable to those of Zeus temple in Greece. (Stiros 2020) reported that the columns of Zeus temple were

toppled down by a storm in 1852. Unfortunately, in the Capitol of Timgad, we have no reference on a storm or any other anthropogenic origin to have toppled down the columns. Thus, we retain that the columns could be damaged and toppled down with their bases by a strong earthquake. Figure 3b shows displacement of blocks of lintel observed in the Temple, on the site of Mopht (founded in AD157). In the

Fig. 5 Trench exposure (view to east) across the El Asnam fault trace near the dammed Chelif River (Meghraoui et al. 1988a, b)



Temple, a vertical sliding of blocks of 4 cm in vault key downward was observed which is a good indicator of seismic origin (Roumane and Ayadi 2019). On the Roman site of Djemila, we have also observed displacement in lintels. Figure 4c shows 5 cm vertical sliding downward of block in lintel observed in the Curia, the Roman Town Hall of Djemila city (founded AD96–98). Figure 4c shows displacement of heavy blocks in the basal part of the Byzantine rampart, a great wall surrounding the city. The wall has 230 m length and 280 m width, with 7–8 m height and 1.2–2.2 m thickness. Such displacement especially in the bottom part of the structures is a good indicator of a seismic origin regarding the dimensions of the structure made with heavy and thick blocks (Sintubin and Stewart 2008; Hinzen et al. 2011). There is no other reason except earthquake that could generate such disorders. There are no trees close to the wall to attribute the deformation to their roots as shown in Fig. 4c. Almost 15 cm displacement was measured in the wall of Caracalla Arc. Such disorders have also been observed on several other structures on other sites.

Paleoseismological observations

The third part of our study concerns the paleoseismological investigations which give indications about strong past events by dating samples from a specified trench.

The application of paleoseismological method is an important tool using trenches dug across a fault zone for the identification of successive large earthquakes over time that affected a selected area. Dating would be useful to determine the earthquake occurrence chronology. The best example that was conducted in Algeria is the one done following the El Asnam earthquake of October 10, 1980, Ms 7.3 (Meghraoui et al. 1988a, b). An example of such investigation is given in Fig.

5. The El Asnam fault, which generated the strongest earthquake known during the recent time, is a well-documented area from paleoseismological point of view; its investigation has shown the existence of several strong events. According to (Meghraoui et al. 1988a, b), based on trench exposures, the El Asnam faulted area underwent several coseismic displacements during late Holocene. Other sedimentary analysis provided that successive uplifted alluvial terraces and flood deposits were associated with earthquakes with magnitude of $M > 7$. We aim to continue paleoseismic investigations near the fault zones close to our investigated Roman sites (Meghraoui 1988).

In our study, paleoseismological investigations will give us answers on the dates of past strong earthquakes that may have generated the damage observed on the Roman sites we investigated.

Conclusion

The completeness of seismic catalog is necessary for seismic hazard assessment. This is possible only if the catalog does not miss significant seismic events especially those considered destructive of having caused significant damage. The Algeria catalog is considered complete for strong and moderate events since 1910 due to the installation of seismological stations (Bezzeghoud et al. 1994). The study of historical seismicity helped to complete several gaps in the catalog for the period between 1365 and 1910; 286 new events that occurred in the central and eastern parts of the country were retrieved from historical documents and archives. These new events were found when analyzing historical documents for the central and eastern Algeria. The western part of Algeria is still under study. Archeoseismological and paleoseismological studies will help to assure more completeness to the seismic

database. Archeoseismological investigations have recently been launched on Roman sites. Several sites were found with archeological structures exhibiting damage probably induced by strong earthquakes such as those of Timgad (*Thamugadi* during the Roman period), Djemila (*Cuicul*), Mopht, and Tebessa (*Thevest*). We expect following these observations of damage to retrieve the date of the event that caused the damage by going back to the epigraphic documents when available, dating and this should be followed by paleoseismological studies to precisely locate and date the damaging seismic events.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

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