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Seismicity, seismic input and site effects in the Sahel—Algiers region (North Algeria)

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Seismicity, seismic input and site effects in the Sahel—Algiers region (North Algeria)

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Abstract

Algiers city is located in a seismogenic zone. To reduce the impact of seismic risk in this Capital city, a realistic modelling of the seismic ground motion (SGM) is conducted by using the hybrid method that combines the finite differences method and the modal summation. For this purpose, a complete database of geological, geophysical and earthquake data is constructed. A critical re-appraisal of the seismicity of the zone [2.25°E–3.50°E, 36.50°N–37.00°N] is performed and an earthquake list, for the period 1359–2002, is compiled. The analysis of existing and newly retrieved macroseismic information allowed the definition of earthquake parameters of macroseismic events for which a degree of reliability is assigned. Geological cross sections have been built up to model the SGM in the city, caused by the 1989 Mont-Chenoua and the 1924 Douéra earthquakes. Synthetic seismograms and response spectral ratio is produced for Algiers, and they show that the soft sediments in Algiers centre are responsible of the noticed amplification of the SGM.

Keywords: Algiers; Earthquakes; Local geology; Site effects; Synthetic seismograms

1. Introduction

Algiers, the Capital of Algeria, stands up as a vast amphitheatre of hills and plateaus, the *Sahel Massif* where houses rise in tiers (Fig. 1), and is enclosed by the *Mitidja Plain*. It is the intellectual, social, political and economic centre of Algeria. Greater Algiers (the district, Fig. 2) which has a population of approximately four million, represents the most important concentration of investment, government institutions and population in the whole country. The population growth as well as its specific topography and the characteristics of its subsoil increase the vulnerability of this capital city. Algiers has always had to face up to seismic risk being located in a seismogenic zone and closely surrounded by important districts (Fig. 2) also seismogenic [1,2] and which experienced destructive earthquakes during recent times. After the strongest earthquake which occurred in 1716 causing the loss of 20,000 lives (the number of inhabitants was estimated at 100,000 at that time), Algiers was completely rebuilt. Many history books recount for the seismic risk in the city. Baraudon [3] described the dwellings of Algiers

> as houses constructed with stones and whitewashed bricks; most of them are single-storeyed with a salient part sustained by flying buttress in wood. Many houses are shored up in order to preserve them from earthquakes which are quite frequent.

In recent years, disaster risks have increased due to overcrowding, faulty use of land planning and construction, inadequate infrastructure and services, and environmental degradation. The high population density, the

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waterfront location, the acropolis (Casbah, the old city), the topography and the nature of the subsoil make it difficult to affect radical solutions to most of its problems. For all these reasons, it is of crucial interest to build-up a data bank blending information from historical seismicity, local geology along with geotechnical and tectonic data leading to a realistic modelling of the expected strong ground motion (SGM) in the Algiers area.

Algiers in the XVIII century

Algiers now a days

Fig. 1. Algiers city, the arrow indicates the ancient city.

In order to carry out modelling of seismic ground motion (SGM) for such a vulnerable site as Algiers, we used the deterministic method developed by Fäh et al. [4] and Panza et al. [5] and whose mathematics are presented in [6]. The main advantage of this method of simulation, which has been widely used throughout the world [7], lies in the possibility of computing synthetic seismograms with no need to wait for a strong earthquake to occur and then to measure the SGM with an extremely dense set of accelerograms. The SGM can be computed from theoretical considerations which take into account the physical process generating the earthquakes and wave propagation in a realistic media. As a preliminary investigation, we reviewed the tectonics and seismicity of Algiers and surroundings [2°E–4°E, 36°N–37.75°N] and provided the state of the art at the scale of the plate-boundary zone within the Central part of Algeria covering a number of active Plio-Quaternary basins namely: Mitidja, Chellif, Soummam and Hodna (Fig. 3) [2]. In this study, we investigate a single basin, the Mitidja [2.25°E–3.50°E, 36.50°N–37.00°N], for which we re-assess the historical seismicity as far back in time as possible and focus on a single active structure, the Sahel anticline (Fig. 3). At the scale of the Sahel, extending over 80 km from Tipasa to Algiers [8], we construct the most valuable databank that would stand behind the most representative seismic input. In this paper, we proceed as follows: (1) a thorough and critical re-appraisal of past seismicity is performed, each seismic event is meticulously examined by confronting all available sources and the collecting of any available macroseismic information is carried out in order to characterize, at least, the most significant ones; (2) the collection of all available data concerning the shallow geology in terms of lithology, thickness and velocity, and the construction of cross-sections along which the ground motion is modelled; (3) using the developed databank, we compute a set of synthetic seismograms and provide therefore an example of seismic input; (4) we calculate

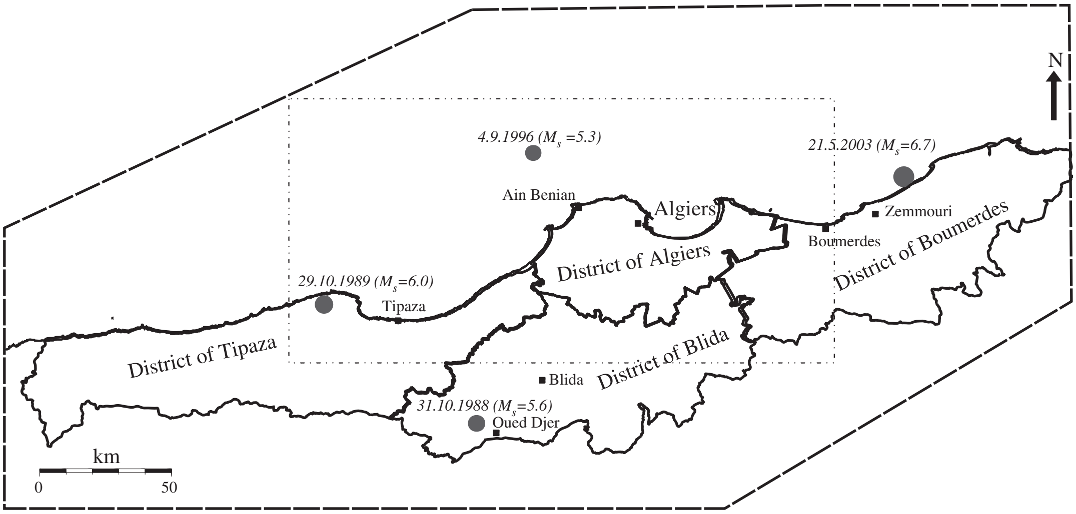

Fig. 2. The largest seismic events which occurred in recent times in the districts of Central Algeria.

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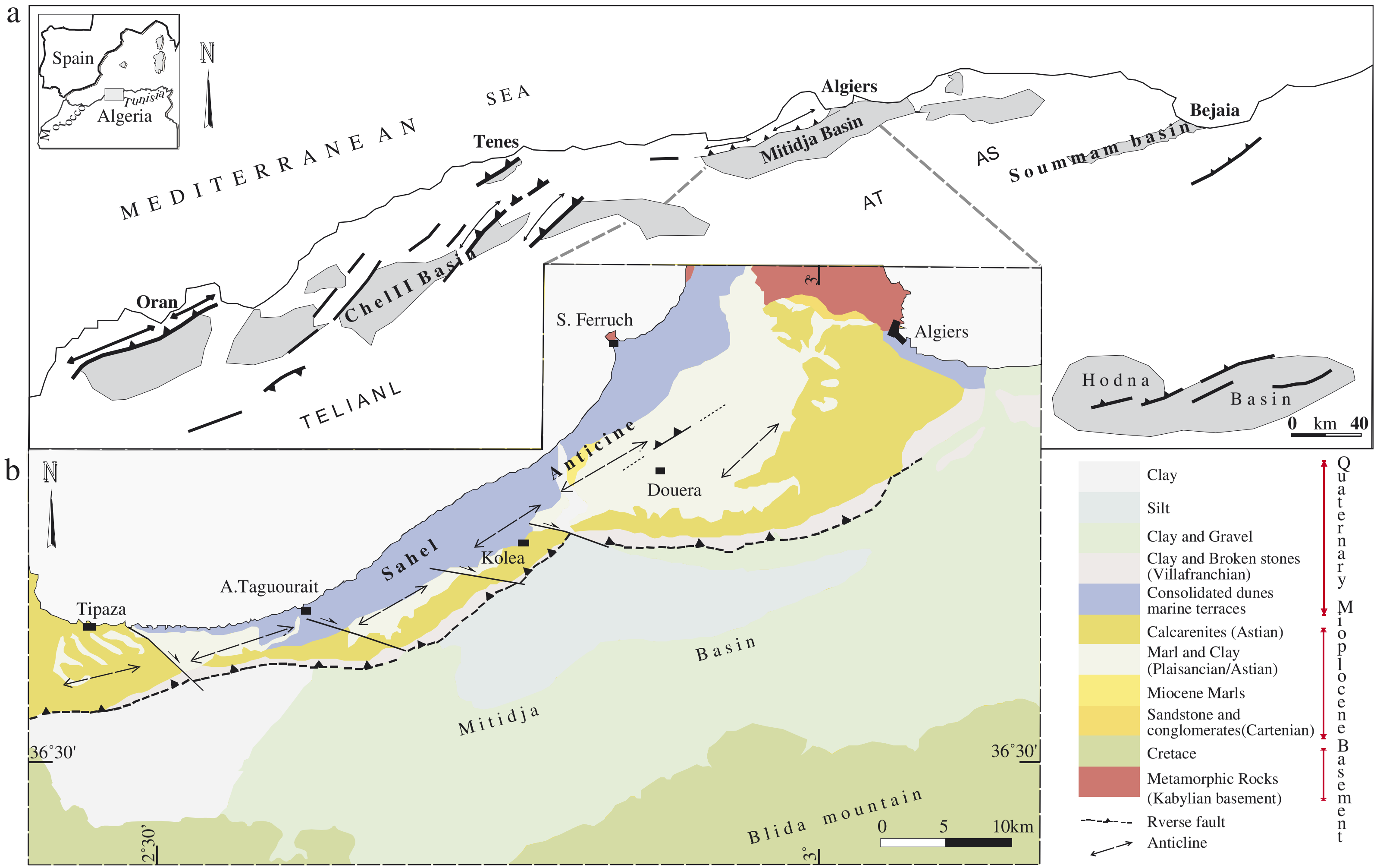

Fig. 3. (a) Schematic distribution of the plio-quaternary tectonic structures in the basins of the Tellian Atlas [8]; and (b) synthetic geological map showing the plioquaternary deposits of the Algiers Sahel [56].

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the response spectra ratio to assess site effects for the first time in the Algiers area.

2. Seismic history of Algiers area

A number of moderate to strong earthquakes that took place in the Algiers province during the last century have been subject to detailed studies. These earthquakes are: The Douéra-Ben Chaabane, 5 November 1924 ($M_s = 4.8 - I_0 = \text{VIII}$ MSK; [9]) revised by Benouar [10]); the Chenoua-Mount, 29 October 1989 ($M_s = 6.0 - I_0 = \text{VIII}$ MSK; [10–12]) and the Ain Benian, 4 September 1996 ($M_s = 5.3 - I_0 = \text{VII}$ MSK; [13,14]).

For historical seismicity, Ambraseys and Vogt [15] were the first to compile a starting catalogue for the Algiers province. Their compilation (Appendix A) is based on original documentary sources that allowed allocating a macroseismic epicentre for some of the events but without assigning any intensity damage. Oussadou [16] confirmed some known seismic events and found out others through Arabic history documents (Appendix A).

Here we provide a more elaborate research based on previous works and extend to additional documentary sources (history books and newspapers) that allow us to compile the most exhaustive possible list of the seismic events that struck Algiers city and its close surroundings. Practical reasons connected to the availability and type of sources led us to subdivide this list into two time windows: before and after 1900 (the number of sources increases from this date).

2.1. Pre-1900 period

For this period, the most recent Algerian catalogue [17], based essentially on [18,19] reported 16 seismic events. Taking into account all the available sources, we increased the number of compiled seismic events to 149. These data have been the subject of painstaking critic using the same method duly described in [20]. The used references are previous works, parametric catalogues and listings [15,17–19,21–24]. Additionally we use documentary sources to find out and crosscheck the seismic events of this period. These sources consist of: (1) historical documents reporting written accounts on some earthquakes [25–29]; (2) scientific reports (Reports of Academy of Sciences, Paris and the Annual Register of Earth Physics of Strasbourg); (3) press reports which significantly contributed to survival of macroseismic information during the French colonization (*Le Moniteur Universel*, *Le Moniteur de l'Algérie*, *L'Atlas*, *Akhbar*, *Le Courrier de l'Algérie*, *La Vigie Algérienne*, *L'Algérie française*, *La Solidarité*). It is worthwhile to note that, with the exception of the catalogue of Hée [22], that compiles seismic events in a continuous way from 1850 to 1899, all the other works report earthquakes sporadically. Besides, the structure of the existing catalogues and listings are different. Throughout the critical review of the compiled events, we encountered some problems related to the determination of the parameters characterizing each seismic event. We think that it is quite hazardous to take into account the parameters reported in classical catalogues without a systematic appraisal of the reliability of the information. This would mislead any subsequent interpretation. The parameterization of historical seismic events, with a certain degree of reliability, is possible only on the basis of a wealth of macroseismic information and this is often rare. The deletion of the related earthquakes is neither suitable because of the importance of these data from the seismic hazard point of view. Thus, each event of our listing is classified according to the significance of macroseismic information. It is important to differentiate well-estimated from poorly estimated parameters of historical events since different users have to be aware of their accuracy. Earthquakes with abundant and fairly sufficient macroseismic information were classified as having quality I and quality II, respectively, quality III is attributed to earthquakes with very poor information or single observation; events with no information are quoted as doubtful events.

The comparison of the available sources enables us to correct some errors of localization (as that of Algiers earthquake of 1839) and to eliminate duplicates and mislocated events (occurred events located outside the study area). Even though the retrieved macroseismic information was not quite profuse to construct retrospectively the earthquakes of Algiers area, it allowed intensity assessment (following EMS-98 scale) for 10 earthquakes, epicentre estimation and re-estimation for 63 and 24 events, respectively, and drawing up of the intensity distribution map of one earthquake (Appendix B). Accordingly, we present in the section *case histories* the most significant events of Algiers area (most of them were not studied before) and some interesting remarks concerning particular cases. All the compiled and checked seismic events are listed in Appendix A.

2.2. Post 1900 period

This period was investigated by Benouar [10] who reported 139 seismic events within the studied region from 1902 to 1990 and by Mokrane et al. [17] who mentioned 48 earthquakes from 1911 to 1989. The compilation of data from all the existing catalogues, listings and previous works [9,10,13,17–19,22,30–39] as well as those provided by national and international centres and agencies allowed us to get 142 additional seismic events from 1901 to 1990 and to produce in all an earthquake list of 352 events from 1901 to 2002. In this work, we are interested in three aspects: (1) verification of seismic events reported only by one source and not taken into account in the most recent Algerian catalogues [10,17]; (2) use of the available macroseismic information, in form of questionnaires and press reports, in order to verify the reliability of (a) the parameters (location and magnitude) previously attributed to non-instrumental earthquakes; (b) the intensity and

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related maps of events with intensity equal or above IV and to reconstruct the related events retrospectively or at least to assign the adequate grade of reliability; (3) verification of the validity of intensity equal or above than V MSK given in previous works for some events without indication attesting the damage caused by these earthquakes.

The destructive earthquakes of this period were studied by the authors cited above and summarized in [2]. However, the experience from the Algerian instrumental seismicity urges us to extend the earthquake catalogue to low-size magnitudes that seem to cluster in time and space before the occurrence of a larger event. As a result of the research performed on the retrieval of macroseismic information based on unpublished works, press reports (*Dépêche Algérienne*, *Journal d'Alger*, *Dépêche Quotidienne*, *Echo d'Alger*, *Echo d'Oran*, *Dépêche de l'Est*, *Dépêche de Constantine*, *Dernière Heure*, *Alger Républicain*, *El Moudjahid*) and questionnaires, we estimate the macroseismic epicentre of 116 earthquakes and re-assess the epicentral intensity, using EMS scale, for 15 seismic events. Whenever possible, we draw up maps (14) in terms of isoseismals, intensity or area of perceptibility (Appendix B). From some of these maps, we re-estimate the macroseismic epicentre of 6 events. It is noteworthy that often with the available questionnaires, one can only estimate an interval of intensities since there is no differentiation between the weak effect and the strong one in these questionnaires.

In the compiled catalogue (pre and post 1900 periods), we differentiate the macroseismic epicentres (*M* in the column of remarks) from the instrumental ones. The code *lc*, which we adopt whenever the macroseismic information is lacking or insufficient, corresponds to the coordinates of the locality where the earthquake was felt or caused the most significant effects. Regarding the non-instrumental seismic events, the catalogue gives an idea on the shaken places whatever the size of the earthquake: Algiers (usually strongly felt at Bab El Oued and Mustapha), Bouzaréah, Boufarik, Alma (now Boudouaou, very close to Boumerdes) and Castiglione (now Bousmail, in the vicinity of Tipasa). Until now, no large earthquake took place in these localities and a strong one has to be expected.

The catalogue we obtained for the Algiers area encompasses 17 earthquakes which induced effects greater or equal to V EMS; we consider here only the seismic events for which the intensity was estimated on the basis of reliable macroseismic information. All the seismic events contained in the catalogue are plotted in Fig. 4 which emphasizes the seismic potential of the Algiers area particularly its offshore part.

2.3. Case histories

2.3.1. 3 March 1359, Algiers

The first ever known historical earthquake that affected Northern Algeria, is dated January 3, 1365 [15]. We found out in the book "General history of Algeria" by Al Djillali [27] evidences of a strong earthquake which occurred on

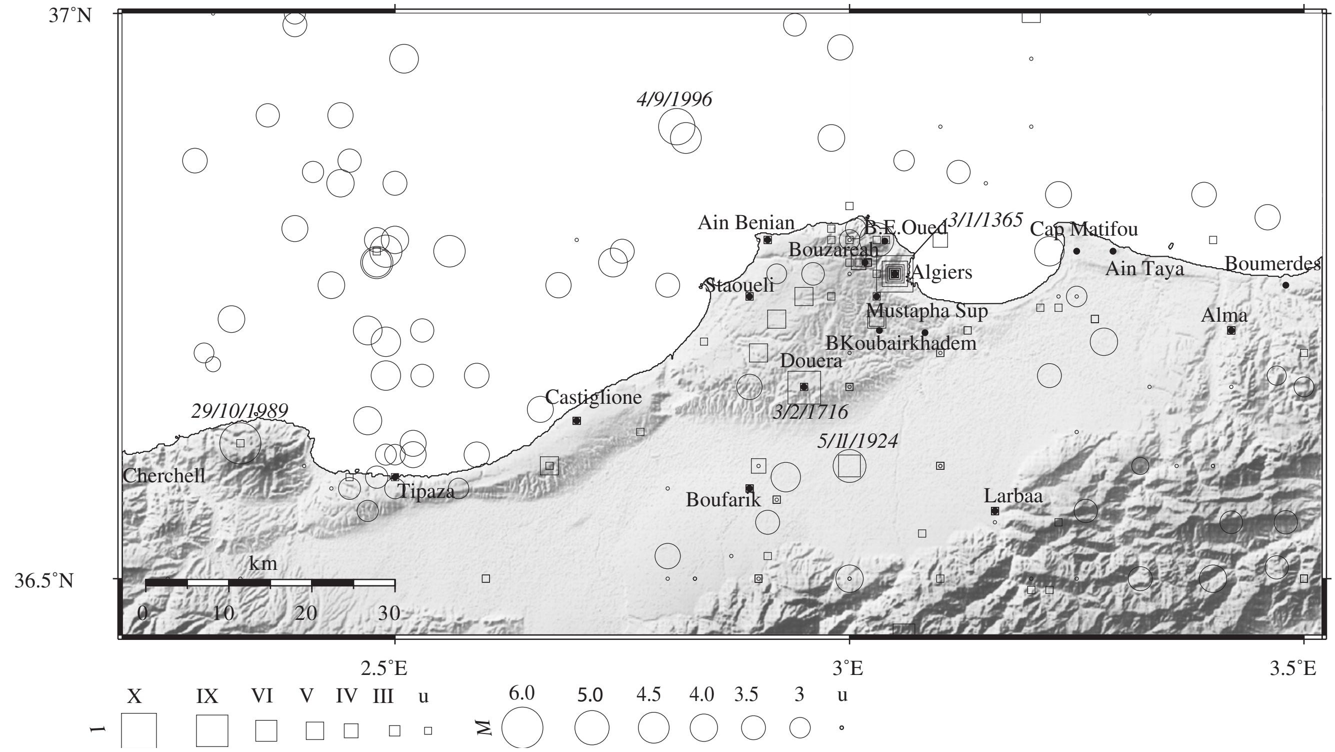

Fig. 4. The spatial distribution of earthquakes (only main seismic events, doubtful events are not plotted) from 1359 to 2002 (square: macroseismic location, circle: instrumental location, u for unknown magnitude or intensity). The most studied earthquakes are pointed up.

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March 3, 1359. Al Djillali [27] in his book (p. 181, vol. 2) reported the following:

> a very strong earthquake destroyed the city of Algiers on 3 Rabie Al Tani 760 AH (Hegira)/3 March 1359 AD.

2.3.2. 3 January 1365, Algiers

The macroseismic information of this earthquake is summarized in [15]. However, it is important to report some additional details cited in the history books we consulted. Al Djillali [27] reported

> the collapse of houses and Palaces of the city, desolation and destruction, and a large number of people killed under the ruins. In Delphin [26] who translated the chronicle of Abdallah Mohammed Ben El Hadj Youssef Echouihat reported that

> Algiers was devastated once by the ants and another time by the plague. El Brechki relates that it was destroyed by an earthquake in 766 (inc. 23 September 1364). It was felt in the night of 10 Rebia El Tani 766 (4 January 1365) after the prayer of sunset. […] El Brechki reports: "In the night of the occurrence of this earthquake, I was in a house located in Haret El Djenane, near Bab El Oued. I was a witness to terrifying things nobody related before me. I heard a woman questioned on the danger she incurred and she replied: I was with my sister bearing my daughter and I run in the house from place to place when a part of it collapsed". […] I (El Brechki) also remembered the woman who escaped with her child during the deluge. The water still rose. Both were submerged by the flood. I was reported that an educated man, trustworthy counted 496 shocks occurring this night.

The time origin of this seismic event is still surrounded by controversy. The 23 September 1364 cited above by El Brechki corresponds (according to available programs of calendars conversion) to 25 Dhu El Hijja 1364 while 10 Rabia Al Tani corresponds to 3 January 1365 and not to 4 January 1365 as stated by Delphin [26]. The contemporary accounts mentioned that the event occurred after the prayer of sunset (called *Maghrib*) then before the last prayer (called *Ishaa*) and at that time maghrib time was at about 17 h and ishaa time at about 18 h 10 min (local time) therefore the time given in [15] (19 h) may be just approximate.

The available information [15,26,27] suggests an intensity damage of X (EMS) for this seismic event which seems to have occurred either on the coast or off Algiers.

2.3.3. 23 December 1585, Algiers

This seismic event, not cited in previous works, is mentioned in [26] as an earthquake occurring in Algiers in 994 H (23 December 1585).

2.3.4. 3 February 1716, Algiers

This is the most cited historical earthquake in previous works and catalogues [15,17–19,23,24,40–43] and it is important to remind its effects since it was known as the strongest one which occurred in Algiers during historical times. This earthquake is also mentioned in: (1) press reports of *Le Moniteur de l'Algérie*, which accounted for the most destructive earthquakes of Algeria after the seismic event of Mouzaïa (to the south of the studied region) of 2 January 1867; (2) in historical documents (the copyist of *Histoire des Premiers Rois de Tlemcen* of Ibn Khaldoun, witness of this event [44]; [25–29]. According to the contemporary witness the copyist cited above,

> a large number of buildings were cracked, the great Mosque and particularly the gardens buildings were strongly damaged, all these buildings were more or less shattered and half-destroyed.

Subsequent historical studies, which related this event, agree with this statement:

> a frightening earthquake caused the destruction of several houses and palaces, the walls of the Mosque and those of the majority of forts of the city [27], the earthquake overturned 2/3 of Algiers houses and damaged the remaining ones [25].

However the collected information does not allow the delineation of the area of maximum damage nor that of perceptibility. Very few details report that the old city

> Casbah was shattered and part of it had to be rebuilt [15].

The earthquake also caused the collapse of several districts of Algiers [29]. Damage spread out in the

> suburbs of Algiers and for a distance of about 2 km of the city; roofs caved in the lower part of Algiers [15]; a large number of country houses in the vicinity of Algiers collapsed (Le Moniteur de l'Algérie).

In fact we do not know with enough precision which zone surrounding Algiers suffered the most. According to Al Djillali [27], *the earthquake caused 20,000 victims at Blida*[1] (there were no major towns apart from Blida and Algiers at that time). For [18] which referred to [42]

> *the event was also destructive at Blida.*

Reporting some geological and hydrological effects observed after the earthquake, Ambraseys and Vogt [15] circumscribe the affected zone between the upper reaches of the Chellif River and Algiers. The 3 February earthquake of 1716 was followed by a long sequence of continuous aftershocks until July. It is generally reported in previous studies and documentary sources that shocks, more or less strong, occurred during the first 24 days and the aftershock of 26 February (the night of 3 Rabia Al

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[1] The other sources mention 20,000 victims at Algiers.

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Aouel 1128H/27 February 1365AD in [26]; at midnight on the 25 in [15]), also felt on board ships, was strong enough to dismay the population and add damage and destruction to the city. Anonymous [44] and Ambraseys and Vogt [15] cited also the shock of 16 July (at 15 h) causing damage and

> collapse of three houses, killing nine people.

According to Grammont (De) [25],

> …the shocks stopped at the beginning of December" (footnote on p. 131) and "…the shocks lasted during nine successive month followed by 10 years of drought (p. 133).

One also noticed that pillage, fires and the wet weather prevailing at that time added to the sinister [27].

This earthquake raises several questions. First on its *origin time*. According to Rothé [18] and Grammont (De) [25] this earthquake occurred at 2 h while [15] report 9 h 45 min and this is almost confirmed by the information given in Anonymous [44] who mentioned: "*in the morning of*…" and Delphin [26] who related "*in the middle of the morning*…" Moreover, out of all the cited sources, historical documents of Al Djillali [27], Saidani [28] and Al Madani [29] date this event on 2 and 3 February 1715 as reported in [16]; this confusion is certainly due to the conversion of the Hegira calendar to the Gregorian one. Delphin [26] who referred to a native chronicle (see above) reported "Monday 9 Safar 1128H" which corresponds to 3 February 1716. Second *on the maximum intensity*. The intensity given in [43] and SSIS data files is X MM while Rothé [18] assigned an intensity of IX MM. However the careful analysis of the collected information suggests instead an intensity of IX (EMS) to Algiers city and its vicinity where maximum damage such large cracks to walls, collapse of structures (half or totally shattered), as well as loss of life (20,000) were observed. Some interesting information attests that intensity X MM could not have been reached since

> non public or religious buildings were seriously affected,…there is no evidence that the fortifications and harbour towers, including the 35 metre high lighthouse and tall minarets in the city sustained any damages [15].

The last point which raises a question is the *epicentral location*. For Rothé [18] and Benhallou [19], the epicentre could be situated in the Mitidjian Atlas; Roussel [43] located the event to the south in the Blidean Atlas probably because the contemporary accounts reported damages and ground deformation in Blida. Ambraseys and Vogt [15] lean rather towards a location near Ouamri (73 km south-west of Algiers) where landslides and landslips were observed. But as these authors [15] stated, these geological effects could be caused by the wet weather prevailing at that time. The same phenomena were observed during the most recent earthquake which occurred on the 21 May 2003 at Zemmouri 50 km east of Algiers and which triggered landslides as far as Benchicao, 93 km south-west Algiers (Heddar, private communication). It is clearly difficult to allocate a reliable epicentre to this important event because of the lack of an appreciable amount of intensity observation points for drawing, with a certain degree of reliability, the isoseismal map or at least an intensity map. Nevertheless, this does not prevent to define tentatively the macroseismic epicentre at Douéra (36.67°N, 2.95°E).[2] This epicentre is located in the vicinity of Algiers, precisely along the line Douéra–Birkhadem–Algiers where

> twelve to fifteen thousand of country houses beautify the surroundings of Algiers at three leagues distance, they are constructed in the middle of vines and gardens planted with olive, fig, pomegranate, orange trees [45]

and corresponds to the place where maximum damage was observed as cited above and confirmed by the native chronicle [26],

> Most of Algiers dwellings collapsed, the great Mosque cracked, but the damage was very important in the surroundings villas" and the contemporary witness [44] "…Villas in the vicinity and the buildings of gardens…

The most significant earthquakes which occurred in the region during the instrumental era: the Douéra earthquake of 5 November 1924 (36.60°N, 3.00°E, $M_s = 4.8$, $I_0 =$ VIII MSK [10]); the Oued Djer earthquake of 31 October 1988 (36.42°N, 2.57°E in the Blidean Atlas, $M_s = 5.6$, $I_0 =$ VII MSK [13]); the Chenoua-Mount earthquake of 29 October 1989 (36.62°N, 2.33°E, $M_s = 6.0$, $I_0 =$ VIII MSK [10]); the earthquake of Ain Benian of 4 September 1996 (36.90°N, 2.81°E, $M_s = 5.3$, $I_0 =$ VII MSK [14]) and very recently the Zemmouri earthquake of 21 May 2003 (36.91°N, 3.58°E, $M_s = 6.7$, $I_0 =$ X EMS [46]), had no similar macroseismic effects and triggered to Algiers city the respective intensity of V, IV, V, V and VII on EMS scale. This is to bring into focus the most documented historical earthquake of Algiers area.

2.3.5. *The earthquakes of 1724*

Referring to Shaw a contemporary account, Ambraseys and Vogt [15] and the newspaper *Le Moniteur de l'Algérie* of 9 January 1867 cited a strong earthquake causing large damages at Algiers. Dr. Shaw, who felt three successive shocks at sea, reported that the seismic event extended from Miliana to Bône, i.e. (about 600 km distant). This earthquake seems to be an offshore event.

2.3.6. *The earthquake of 1755*

It is worth to draw attention to this event reported for the first time in [16], which refers to historical documents. According to Al Djillali [27]

> a frightful earthquake struck Algiers causing the destruction of the majority of buildings of the city, but we do not know its effects on the population.

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[2] SSIS data file adopt an epicentre in Algiers bay at 3.10°E, 36.70°N.

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For Saidani [28] this event, which caused damage to Algiers dwellings and drying up of springs, could be which occurred in Lisbon in November 1755. However, even if the earthquake of Lisbon was felt in Northwest Africa [47], it could not cause such effects and induce aftershocks during 2 months (November and December) as cited by the contemporary witness Ez-Zahar [29].

2.3.7. 17 March 1756, Tipasa

This earthquake is cited by Ambraseys and Vogt [15] who referred to unpublished archives and Playfair [48] and Grammont (De) [49]. According to these authors [15], this event felt at Algiers lasted about 45 s, and caused the collapse of old houses built on the sloping part of the city destroying all houses about 50 km to the west of Algiers with casualties. The authors suggest an epicentral area near Hadjout in the region of Tipasa where the Lake of Halloula was damaged. On 29 October 1989, this area experienced a destructive event and the earthquake of 1756 could have its source near Tipasa.

2.3.8. 6 May 1773

In the Annual Register, vol. XVI, p. 105, one can read the following passage:

> Algiers, Tangiers and the north coast of Africa. About twenty shocks. The tremulous motion between the shocks lasted from six to seven seconds to half minute. At Algiers the sea rose 5 feet 10 inches in every 14minutes, and then fell so low as to leave the boats aground. This decreased from noon until for the next morning. At Tangiers the sea rose 30 feet perpendicularly. The earthquake consisted of succession of trembling and violent shocks. At Tangiers the fountains stopped.

No other consulted source quotes this seismic event. Probably the similarity between the names of both cities induced mistakes concerning this earthquake. Tangiers, a Morrocan city, is about 800 km west to Algiers.

2.3.9. 14 April 1839, Algiers

Mokrane et al. [17] place this event in Constantine 400 km east to Algiers without assigning coordinates. According to Rothé [18], this earthquake was strongly felt in Constantine and Algiers where ramshackle buildings collapsed; and its epicentre could be located at half-way between both cities in Babor or Biban region (at 150 km of both cities). An analysis of the new retrieved information from *Le Moniteur Universel* (of 30 April and 1 May 1839) and Guyon [50] rather suggests a macroseismic epicentre at Algiers. Preceded by a slight foreshock, the main shock lasting 12 s and accompanied by an underground rumbling, hit the town of Algiers and surroundings 5 min later at 14 h 5 m dismaying the population. Serious cracks to several houses were observed and one of them at Bab El Oued threatened to collapse; its inhabitants fled by doors and windows. The main shock was also slightly felt on ships at sea. There is no indication on the macroseismic effects in Constantine where the earthquake was strongly felt, particularly downtown [50] but one reported a storm on 11 April which lasted 3 days and caused disaster to ships in Bône, 120 km east of Constantine. On the basis of this sole information, the maximum intensity we may attribute is $I_0 =$ VII EMS and we locate the macroseismic epicentre at 36.77°N, 3.05°E.

2.3.10. 18 June 1847, Douéra

This earthquake is clearly described in [15,18,21,41] and reported in *Moniteur de l'Algérie* (of 9 January 1867), [17,24]. From the information collected, on some significant damage observed and on the localities where the shock was felt, a schematic intensity map showing the area of perceptibility was drawn and intensities have been re-estimated (Appendix B). Besides, we had to decide which epicentre we should attribute Rothé [18]), repeated later by Mokrane et al. [17], located it near Douéra while Ambraseys and Vogt [15] placed the epicentre at 36.53°N, 2.44°E near Cherchell which was struck by a long sequence of shocks 1 year earlier (3 November 1846). It is worthwhile to remind a stronger event which occurred later on 5 November 1924 known as the Douéra earthquake (or Ben Chaabane according to Benouar [10]. Thus we believe that this event has a similar epicentre in the Douéra area.

2.3.11. 30 August 1850, Algiers

This earthquake, which was mentioned only in [22], has been the subject of several reports by the contemporary press particularly by *L'Atlas* which gave, every 2 days, from the 2 September to September 14, a detailed report of the event and its aftershocks. According to these reports and those of *Akhbar*, the main shock accompanied by an underground rumbling occurred at Algiers on 30 August 1850 at 19 h 42 min. The shaking was so strong that the people of Bouzaréah frightened and fled their homes but no casualties were reported in the city. The oscillations were in SE–NW and the shock was not felt at Douéra, Blida and all the localities surrounding Algiers city. What characterizes this seismic event is less its strength than the aftershocks that followed the main shock (Appendix A). All these aftershocks were felt at Algiers except that of 10 September felt at Douéra 15 km south of Algiers. On the basis of the retrieved information, we think that the macroseismic epicentre is located at Bouzaréah where the earthquake was more strongly felt than anywhere else. Maximum intensity of IV^{+} (EMS) is assigned mainly on felt effects and on the evidence of lack of damage to poor-quality constructions.

2.3.12. 20 July 1851, Algiers

This earthquake which occurred on 2 July at 18 h 10 min, almost 1 year after the previous one, was more violent and also strongly felt at Bouzaréah according to the contemporary press (*Akhbar of 22 July*). No damage or casualties

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among the population nor premonitory and aftershocks were communicated. The macroseismic epicentre is re-estimated from 36.7°N, 3.1°E given in USGS/NEIC data files to 36.78°N, 3.01°E (at Bouzaréah) and an epicentral intensity of IV EMS is assigned.

2.3.13. 16 April 1857, Algiers

On 17 April 1857 at 15 h 17 min, an earthquake lasting 5 s was felt at Algiers and particularly at the bay, according to a fishermen, but not in Blida nor Medea (*Akhbar* of 17 and 19 April). It is maybe an offshore seismic event and this is not unusual in this zone.

2.3.14. 16 January 1865, Arba

This earthquake cited only in [22] occurred at 3 h 57 min after the press reports (*Akhbar*, *Courrier de l'Algérie*, *Le Moniteur de l'Algérie*). The main shock was slightly felt, only by people awake, in Algiers but not at Bouzaréah. Three successive shocks have been felt in El Harrach, Rovigo, Arba and more slightly in Boufarik and Blida. In the locality of Arba 25 km south of Algiers, it caused fine cracks only to one house but no reports of damage in the surroundings farms were found.

2.3.15. 16 October 1873

The catalogue [17] referring to SSIS locates this earthquake at 36.6°N, 2.9°E in Boufarik near Blida with an intensity VI (Rossi Forel). The macroseismic information retrieved from newspapers (*Le Moniteur de l'Algérie*, *La Vigie Algérienne*, *Le Tell, Akhbar*, *L'Algérie française*) do not justify this intensity since they mention only one shock lasting 2–3 s accompanied by an underground rumbling felt at Blida without any casualty, moving of furniture nor broken glasses. The oscillations recorded by the seismograph of Algiers were in the NNE–SSW direction. The earthquake felt at Algiers Médéa, Boufarik, Oued El Alleug, Mouzaia and Cherchell area, did not cause any significant damage or fear among the population. The intensity is re-estimated at IV EMS.

2.3.16. 11 July 1911

This shock was largely observed and rather slightly felt in Algiers and its surroundings. According to *La Dépêche Algérienne*, it caused more frightening than hurt among the population without casualty or important damage. According to this newspaper, the earthquake was felt in several localities (Appendix B) within an area of 80 km radius. The previous catalogues referring to SSI assigned to this event an intensity of 6 MM which seems to be exaggerated.

2.3.17. 18 October 1916, Algiers

This earthquake is cited in Rothé [18], who referring to press report without quoting any information, assign an intensity of VI (MM) at many places (Appendix B). According to the newspaper *l'Echo d'Algérie* of Tuesday 19 October:

> Yesterday in the morning at 3 h 15 min, a strong earthquake accompanied by an underground rumbling awoke most of the inhabitants of Algiers city. Glasses and beds were violently shaken and stacks of plates collapsed with crash. The shaking was so strong that most of the inhabitants fled their homes and took refuge in open spaces and along the seaside, particularly in the suburbs. No damage or casualties, among the population were reported only at Bab El Oued where walls of one house were cracked.

Epicental intensity V is assigned with a rigid interpretation of the EMS scale.

2.3.18. 25 October 1949, Ain Taya

The newspapers of Algiers Le Journal d'Alger and Dernière Heure report:

> on 25 October at about 8 h 30 min, Algiers was shaken for 6 min by an earthquake which awoke people still sleeping. No damage or casualties among the population were reported even if the shock was widely felt along the coastal localities, from Cherchell in the west to Port-Gueydon in the east, where it caused a certain emotion and insignificant damage.

This seismic event was strong, but we do not think that the intensity really reached VI (MM) [35], we rather lean to V (EMS). On the basis of the retrieved information from press reports, we draw a figure showing the localities where this offshore seismic event was felt (Appendix B).

2.3.19. 13 March 1960, Cap Matifou

This earthquake accompanied, by an underground rumbling, which occurred in the morning awakening most of the inhabitants of Algiers, is also an offshore event. According to press reports (*Dernière Heure*), it was followed by five aftershocks with two quite strong. No damages were reported in the Greater Algiers nor in the surrounding cities and villages within a radius of 100 km. From the analysis of the macroseismic information retrieved, intensities have been re-estimated in some sites. Intensity V EMS (Intensity V MM is estimated in previous catalogues)was assigned on the effects of awakening, intensity IV has been confined to Dellys where the shock was less strong than in Courbet (now Zemmouri) and intensity III is allocated on slight effects (Appendix B).

2.3.20. 14 August 1960, Boufarik

This earthquake, located in previous catalogues at Boufarik, with intensity VI–VII MM has been the subject of a detailed report in the newspaper *La Dernière Heure* of the following day.

> Two successive strong shocks accompanied by a violent but brief underground rumbling and lasting 8 s were so

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> seriously felt in the city of Algiers and its surroundings that most of the inhabitants fled their homes. The earthquake was stronger in the upper part of Algiers where houses are less shored up. At Boufarik, significant damage like broken glasses, falling of frames and cracking of walls of buildings even in the recent ones, are reported. Also in Blida in the old part of the city. Both shocks were felt at Birkhadem, Douéra, Guyotville and slightly at Tizi Ouzou.

The epicentral intensity is re-estimated from VI–VII MM given in the previous catalogue to VI EMS (Appendix B).

3. Local geology and geological cross-sections

Algiers is situated in the Sahel which constitutes the northern part of the Mitidja basin (Fig. 3). The geological and tectonic setting of this morphological unit was presented and discussed at length in a previous paper [2]. The lack of a geotechnical map of the city of Algiers constituted an obstacle at the beginning of the study. Therefore, on the basis of previous works [51–55] and field observations controlled by borehole data-set as described in [56], we compiled a geological map (Fig. 3) showing the distribution of the Quaternary deposits in the Mitidja basin as well as their thicknesses. The local geology shows that, beside the islets of basement that outcrops in Bouzaréah and Chenoua Mount, the whole Algiers Area is covered by Plioquaternary deposits. The recent Quaternary includes the alluvial deposits: clay, silt and gravel within the basin area, marine terraces on the northern side of the Sahel fold and alluvial terraces within and nearby river beds. The recent tectonics is highlighted by the structural geology of the different units and the morphology of the most recent deposits, as revealed by the tilted marine terraces and the deformed alluvial deposits. Additionally, the analysis of the aerial photos and satellite images supported by direct field investigations enabled us to map newly recognized lineaments almost perpendicular to the Sahel active fold (Fig. 3).

The availability of an appreciable amount of seismic refraction, boreholes, drilling well data and geological maps allowed the construction of a number of cross-sections within the study area [56]. The cross-sections along with the physical parameters reveal the geometry of the shallow deposits and the soil conditions. In the western part of the Algiers city (Fig. 5a), the local geology is principally constituted of: *bedrock* formed by schist, micaschist, gneiss outcropping at Bouzaréah, Astian molasses at Ben Aknoun and Plaisancian marls from Sidi Fredj and beyond Mahelma. While in the eastern part (from Algiers to Ain Taya, Fig. 5a), much of the local geology consists in incompetent material such as marsh deposits, sandy dunes, alluvial and marine deposits. The geotechnical units of this part consist of: the *Recent dunes* spreading out in an east–west direction from Hussein-Dey to Le Lido; the *Holocene alluvial deposits* are present along the Algiers bay as well as in the river beds; the *Pleistocene dunes and alluvial deposits* consisting of a mixture of sandstone and clay, the marshy deposits extending all over the most recent suburbs such as Bab Ezzouar (BEZ)—Dar El Beida (DEB, airport district) and Alger Plage. Two other units are common to all the zone under study, in both the western and eastern parts: the *Villafranchian-recent alluvial deposit* consisting of solely sand or sand with other components (silt, clay, gravel, sandstone) and the *recent landfill* represented by sandy, greyish, silty or argillous deposits.

4. Seismic input modelling and site effects

The detailed prediction of SGM with the knowledge of accurate, three-dimensional (3D) structures and complex source mechanisms is performed by using the hybrid method (numerical–analytical simulation). This method allows to take into consideration the realistic source, path and local soil effect whatever the complexity and size of the structural model. This hybrid approach, which combines the finite-differences method and the modal summation, allows to calculate the local wavefield from a seismic event, both for small (a few kilometers) and large (a few hundreds of kilometres) epicentral distance.

The most important task in performing the simulation is the construction of the structural model which is essential for seismic hazard computations based on a deterministic approach using complete synthetic seismograms [5]. The role of the upper crustal layers is especially important. For that purpose velocity models obtained from body wave give rather poor results; seismological stations are as a rule situated on rock sites with high velocities and density, and seismic waves (longitudinal and transversal) sample only faster layers. Slower structures in the upper crust are only poorly sampled or not sampled at all. As a consequence, the velocity models resulting from body wave data inversions are faster than the average structure and in waveform modelling usually result in unrealistically small amplitudes. For this reason, we construct the structural model of Algiers area by carefully analysing the geotechnical data collected in order to select the most appropriate ones. The density values of the different geotechnical units are obtained from local geophysical surveys. The P-wave velocities assigned to the soil within the Algiers area are based on seismic refraction surveys carried out in several sites of the region (Fig. 5a). The shear-wave velocities are calculated using the formula: $V_s^2 = V_p^2/3$.

The correlation of all the available geological, boreholes and seismic refraction data, added to a 10-km deep geological cross-section of the sedimentary basin of Algiers (Fig. 5d) adapted to the velocity model available for the Maghreb countries [1], enabled us to define a structural model for Algiers area. Each part of the hybrid method is applied in that part of the structural model where it works most efficiently: (1) The analytical method (mode summation) which allows the treatment of several layers, is

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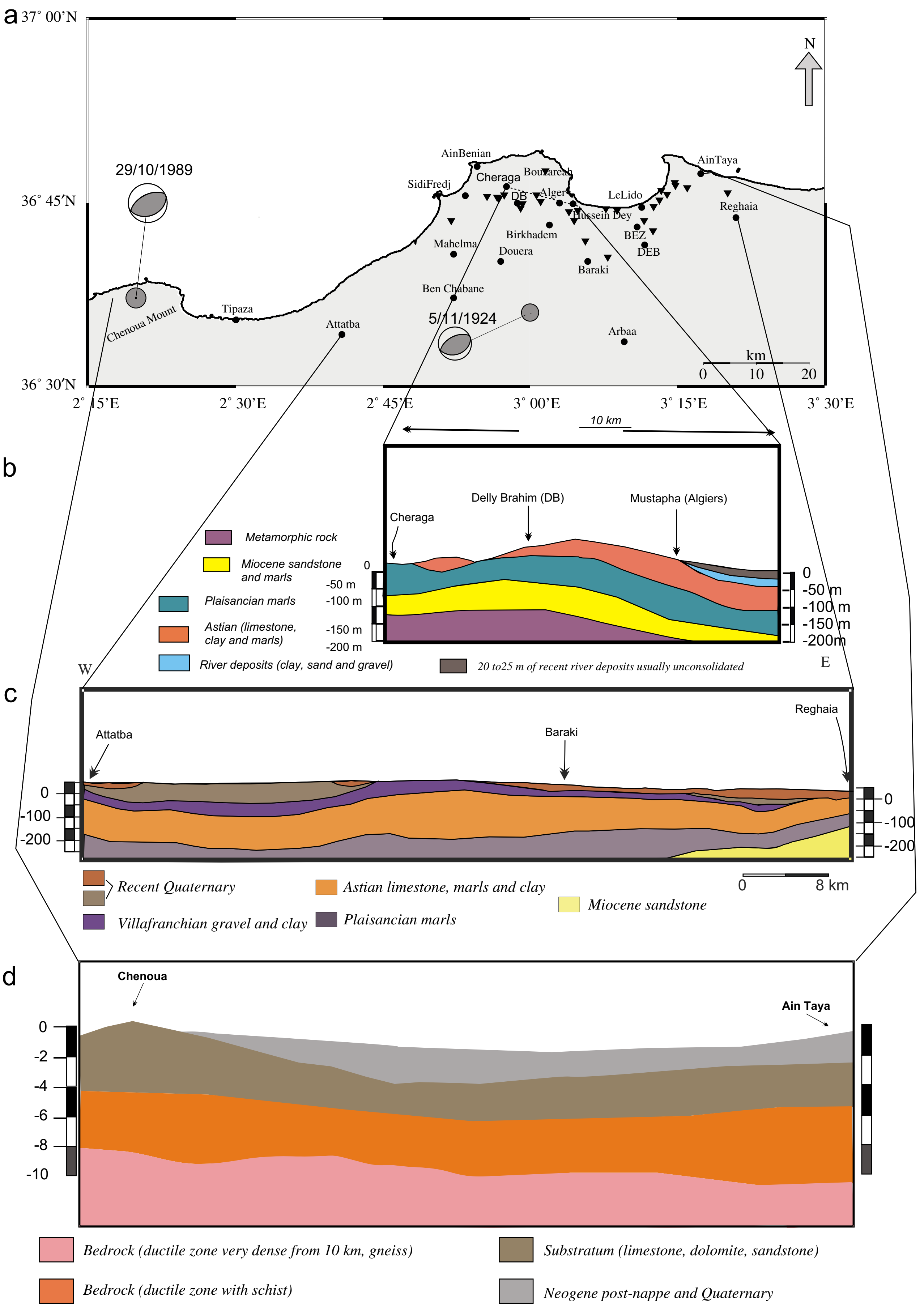

Fig. 5. (a) Map representing the sites where seismic refraction surveys were carried out (triangle), three geological cross sections and the two seismic sources used in the simulation; (b) a 10 km length, 200 m deep cross-section representing the local geological information of the soil of Algiers; (c) a 400 m deep geological cross section; (d) a 10-km deep geological cross section of the sedimentary basin of Algiers.

applied to simulate the wave propagation from the seismic source at Chenoua Mount to Algiers, along a 400 m deep geological cross section (Fig. 5c) (64 km distant). In order to allow the simulation of a realistic rupture process on the fault, the extended source is modelled by a sum of point sources. The path from source position to the sedimentary basin is approximated by a structure of flat homogeneous layers used for the construction of the 1-D model. (2) The numerical method (finite differences) is applied along a 10 km length, 200 m deep cross-section representing the local geological information of the soil of Algiers and pointing up the lateral heterogeneities (Fig. 5b). The structural model proposed in this study is shown in Fig. 6 and the geophysical properties of the sediments are summarized in Table 1.

The SGM in Algiers was simulated, at first, for the Mont-Chenoua earthquake of the 29 October 1989 with the following parameters: Longitude: 2.33°E, Latitude: 36.62°N, magnitude $m_b = 5.7$, $M_s = 6.0$, seismic moment: 3.15×10^{24} dyn cm, depth: 6 km, strike 1: 242, dip1: 55,

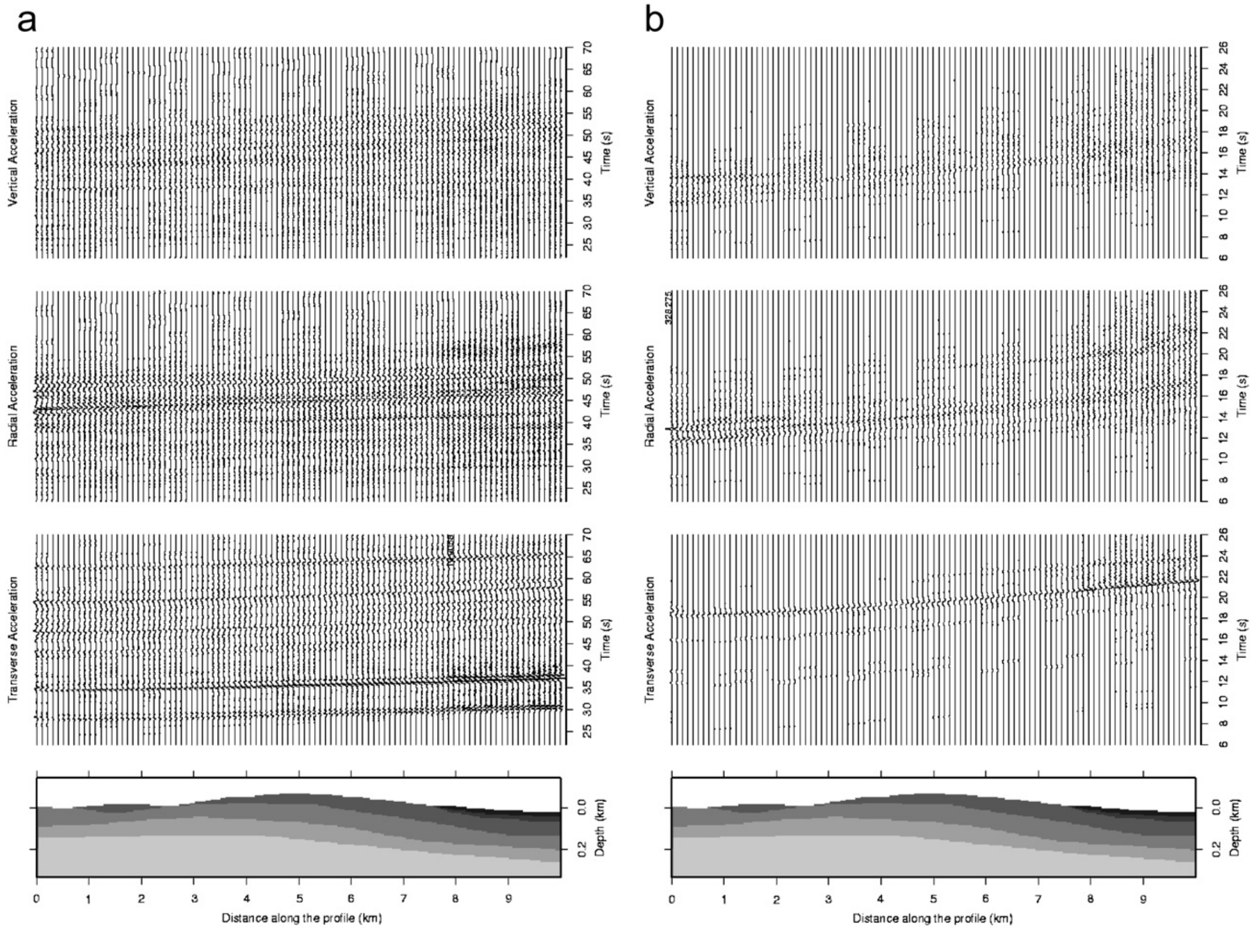

Fig. 6. The structural model and the synthetic seismograms along the Cheraga–Algiers cross-section simulated for the far source, October 29, 1989 (a) and the near source, November 5, 1924 (b).

Table 1
Geophysical properties of the lithological units

Lithological unit	Geophysical parameters				
	Density (g/cm^3)	V_p (km/s)	V_s (km/s)	Q_p	Q_s
Quaternary recent deposits	1.75	2.10	1.21	220	100
River deposits made of clay, sand and gravel	1.80	2.24	1.29	220	100
Astian limestone, clay and marls	1.83	3.00	1.70	220	100
Plaisancian marls	1.90	3.50	2.00	220	100
Miocene sandstone and marls	2.67	5.85	3.40	660	300
Metamorphic bedrock	2.89	6.71	3.90	660	300

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slip1: 87, strike2: 71, dip2: 34, slip2: 94 (Fig. 5a). The coupling of the respective analytical and numerical methods is carried out by introducing the resulting time series obtained with modal summation into the finite-differences computations. The three-component synthetic seismograms have been originally computed for a seismic source of 1 dyn. cm. The amplitudes were then scaled according to the seismic moment of the source considered using the "wide-band spectrum scaling" proposed by Gusev [57]. The corner frequency considered in the numerical simulation for Algiers city is of 5 Hz; the grid spacing used in the finite-differences is of 6 m. Since we noticed an amplification of the signal on the synthetic seismograms (Fig. 6a), we simulate the SGM for another source 20-km distant from the centre of Algiers city. This source, for which we assume a similar focal mechanism, corresponds to the Ben Chaabane earthquake of 5 November 1924 with latitude: 36.64°N, longitude: 2.91°E, depth: 3 km, magnitude: $m_b = 5.2$, $M_s = 4.8$, $I_0 =$ VIII MSK. The same amplification, certainly due to the presence of soft sediments near the city centre, is evident from the computations (Fig. 6b). Fig. 7 shows the relative response spectra, as a function of frequency along the structural model obtained, respectively, for the 64 km distant source (a) and for the 20 km distant source (b).

5. Discussion and conclusions

This work is of paramount importance since it enabled us to produce an important and invaluable data bank to be used in future research works, for multiple purposes, regarding the Algerian Capital city.

5.1. Concerning the compiled catalogue

This study significantly improves our knowledge on the seismicity of Algiers. The revision of the seismicity presented here is part of the upgrading of the Earthquake Catalogue of Algeria. Among the 475 events studied, 48 are quoted as doubtful. These events, reported in [24] which referred to IGNE and EC data files, are sometimes mislocated (located offshore) and surprisingly of high intensity as already noticed for the seismicity of Eastern Algeria [20]. Some of them could sometimes be confirmed from history books such as the Algiers earthquake of October 1541 mentioned in USGS/NEIC catalogue [24]. In [58], one can read:

> In 1541, during the pontificate of Paul III, Charles V resolved with his council to restore the Algiers matters. […] Algiers city still had only a simple wall, without any

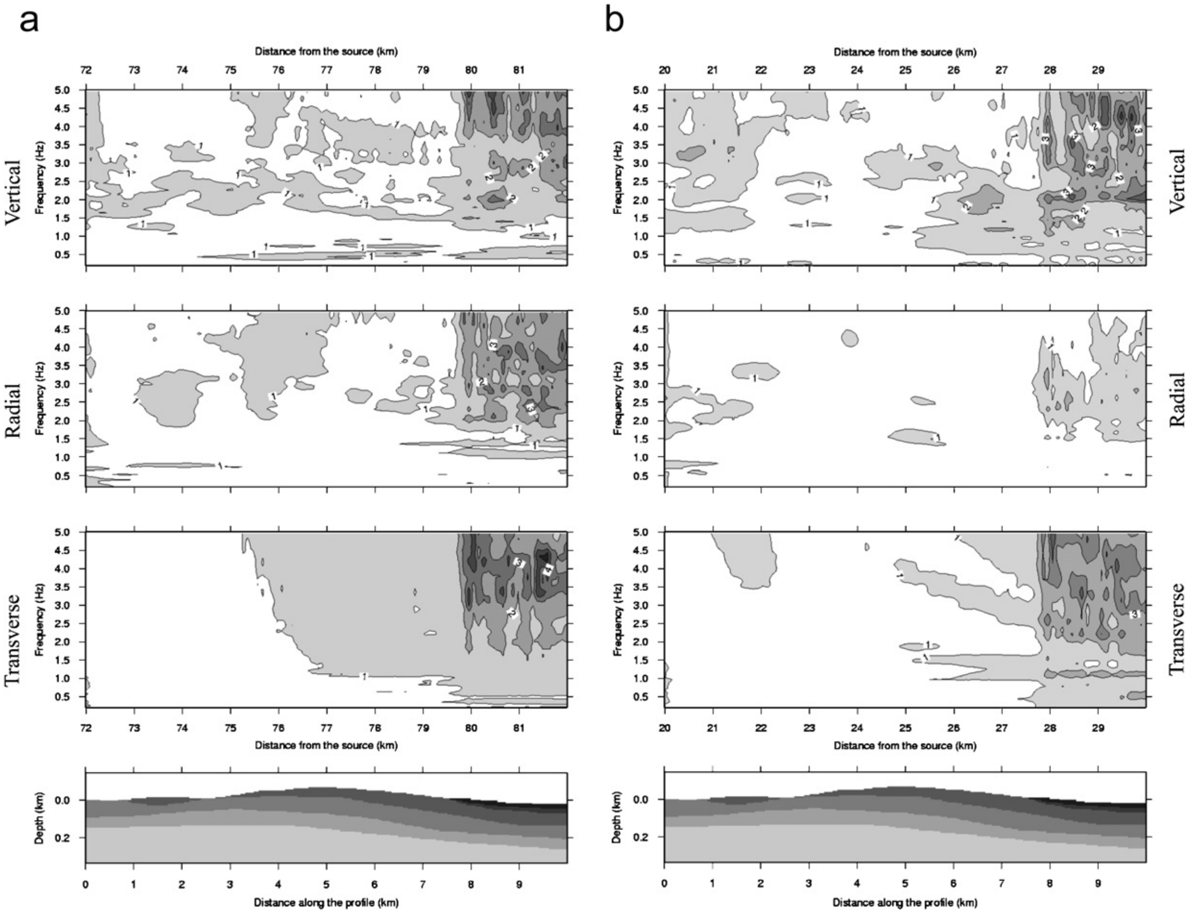

Fig. 7. The response spectral ratio along the Cheraga–Algiers cross-sections simulated for the October 29, 1989 (a) and November 5, 1924 (b) events.

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> advanced workmanship. On the 28th October, a North wind got up; it was accompanied with a howling hailstorm and earthquakes, likely that nature was going to overturn. During the following night, 90 vessels and 15 galleys perished with their crew and all the provisions of the army.

The retrieval of macroseismic information related to these events should be pursued by a thorough research in Ottoman, Spanish and French archives. The earthquakes mentioned by Hée for both periods as well as those cited in [35] and unreported in subsequent studies and/or compilations, are integrated in the Algerian earthquake catalogue since, despite the weakness of their impact, they inform on the permanent seismic activity of the Algiers area.

5.2. *Concerning the produced macroseismic data bank*

The availability of an amount of macroseismic data allowed us to re-appraise some earthquakes in terms of estimated intensity or at least delineating the area of perceptibility. The re-assessment of the related intensities according to the EMS 98 scale adopted in Algeria since the last destructive earthquake of 21 May 2003, will permit to set up a relationship of the intensity ranges between the Modified Mercalli scale (used before) and EMS and then to homogenise the Algerian catalogue. The drawn maps (Appendix B) show that (a) Algiers experienced local events at Cheraga, Staouéli, Douéra and Boufarik; (b) the occurrence of widely felt seismic events on the south boundary of the Mitidja basin at Boufarik, Larbaa and Hamam Melouane and (c) the occurrence of coastal and offshore seismic events along the Algiers area at Bousmail (Castiglione), Tipasa, Ain Benian and Algiers bay (in the vicinity of Cap Matifou). Concerning this last point, we must bring to mind that, before 1900, Algiers experienced five offshore earthquakes one of which was followed by a small tsunami. The sea-wave triggered by the earthquake of 3 January 1365 (X EMS), which caused the "*deluge submerging the inhabitants of Bab El Oued*", could reach more than 2 m high.

5.3. *Concerning the seismic input modelling*

The method used here for the seismic input modelling has given good results in Rome, Naples, Zagreb, Debrecen, Bucharest, Thessaloniki, Sofia and Russe in Europe; Delhi and Beijing in Asia; Cairo in Africa and Santiago de Cuba in South America [7]. Algiers also gives it an appropriate domain of application. As mentioned above, the hybrid method is convenient for the estimation of SGM in sedimentary basins whatever the geological complexity, and the geology of Algiers Sahel is very complex. The hybrid method takes into account the realistic source, site effects and path whatever the distance source-basin and we applied it by considering two sources (64 and 20 km). This method is more suitable than the probabilistic approach which does not take, with enough precision, the important aspects characterising the motion as rupture process, directivity and site effects. The results obtained in terms of synthetic seismograms (Fig. 6) show that the maximum acceleration reached a value of 20 cm/s^2 near the city centre triggered by the Mont-Chenoua seismic source. The amplification noticed in Fig. 7 for both sources (64 and 20 km), from Mustapha to Hussein Dey, is certainly due to the presence of soft sediments in this part of the city. This may explain why the small earthquakes were often more strongly felt at Bab El Oued and Mustapha and the effects of the damaging seismic events were more spectacular in these places. One should also keep in mind that Bab El Oued is built on a marine terrace.

The lack of reliable recordings did not enable us to compare the results obtained with the real values but it is worthwhile to note that the last destructive Zemmouri earthquake of 21 May 2003 (Fig. 2) generated 27 cm/s^2 maximum acceleration recorded at Hussein Dey [59], about 52 km from the epicentre. Besides the magnitude of the respective earthquakes (Mont Chenoua, $M_s = 6.0$; Zemmouri earthquake, $M_s = 6.7$), the characteristics of the soil of Algiers are different from west to east as cited in the section *local geology*. To the east of Algiers centre, from Mustapha onwards, the soil is mainly constituted by thick marine deposits while to the west it is formed by bedrock. Thus, it is important to perform a simulation with a seismic source to the east of Algiers and to compare the results with the strong motions recorded (and calibrated) after the Zemmouri earthquake of 21 May 2003.

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Appendix A

See Table A1.

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Table A1
Earthquakes of Algiers area [2.25°E–3.50°E, 36.50°N–37.00°N] for the period 1359–1895

Year	Mon	D	H	M	S	Lat°N	Lon°E	INT	Au	QG	RMK	Site	References
1359[a]	Mar	4	—	—	—	36.77	3.05			III	lc, de, *i*	Alger	BH
1365[a]	Jan	3	18	0	0	36.77	3.05	XEMS	HAR	II	lc, de, *I*, o ?	Alger	BH, AV, MOK, OUS
1522	Sep	22	—	—	—	36.91	2.5	IXMM	EC	do	lc, o	N. Tipasa	IGNE, USGS/NEIC
1541	Oct	28	—	—	—	36.7	3.1			III	lc,*i*	Alger	BH, EC, USGS/NEIC
1550	Apr	19	—	—	—	36.83	2.4	VIIMM	EC	do	lc, o	N. Mt. Chenoua	EC, USGS/NEIC
1585[a]	Dec	23	—	—	—	36.77	3.05			III	lc, *i*	Alger	BH
1601[a]	—	—	—	—	—	36.77	3.05			III	lc	Alger	BH, AV
1639[a]	—	—	—	—	—	36.77	3.05			do	lc	Alger	BH, OUS*i*, AV
1658	Dec	30	0	0	0	36.83	2.4	VMM	EC	do	lc, o	N. Mt. Chenoua	EC, USGS/NEIC
1658	Dec	31	7	0	0	36.83	2.4	VIIIMM	EC	do	lc, A? o	N. Mt. Chenoua	EC, USGS/NEIC
1659	Jan	19	2	0	0	36.83	2.4	VMM	EC	do	lc, o	N. Mt. Chenoua	EC, USGS/NEIC
1665[a]	—	—	—	—	—	36.77	3.05			III		Alger	BH,OUS*i*
1673[a]	Mar	10	21	0	0	36.77	3.05	VIIIMM	SSIS	III	lc, de	Alger	SSIS, IGNE, MOK, Av*i*
1676[a]	Feb	—	—	—	—	36.77	3.05			III	lc, da,	Alger	BH,AV,OUS*i*
1715	Jan	29	—	—	—	36.7	3.1			do	lc	Alger	IGNE, USGS/NEIC BH, Press, PER, CHE, RT, RS
1716[a]	Feb	3	9	45	0	36.67	2.95	IXEMS	HAR	II	lc, *i*	Alger	SSIS,USGS/NEIC, AV, HB,MOK,OUS
1716[a]	Feb	26	—	—	—	36.67	2.95			II	lc, S, A, *i*	Alger	Press, BH, RT, AV
1716	May	—	—	—	—	36.7	3.1	VIIIMM	SSIS	do	A	Alger	SSIS,BAAS,MOK
1716[a]	Jul	16	15	0	0	36.67	2.95			II	A, lc	Alger	Av*i*
1717	—	—	—	—	—	36.7	3.1	VIIIMM	SSIS	do	lc	Alger	IGNE, SSIS, MOK, USGS/NEIC SSIS, IGNE, PER*i*, USGS/NEIC, RT*i*
1717	Aug	5	23	30	0	36.7	3.1	VIIMM	SSIS	do	lc	Alger	MOK
1722[a]	Nov	29	3	0	0	36.77	3.05	VIIMM	SSIS	III	lc	Alger	SSIS, IGNE, PER*i*, RT*i*, AV*i*, MOK
1724[a]	—	—	—	—	—	36.77	3.05			III	o, *i*	Alger	BH, Press, AV
1755[a]	—	—	—	—	—	36.77	3.05			do?	lc, de, *i*	Alger	BH,OUS
1756[a]	Mar	17	9	30	0	36.62	2.33			III	M, o, de, *i*	Tipasa	AV
1763[a]	10	10	12	12	—	36.77	3.05			III	lc	Alger	PRESS,AV
1770[a]	Jun	20	—	—	—	36.77	3.05			do	S, lc	Alger or Blida?	Av*i*
1772[a]	Apr	18	14	30		36.77	3.05			III	S, lc	Alger	Press*i*, USGS/NEIC, IGNE, AV
1772[a]	Apr	18	16	45		36.77	3.05			III	lc, A	Alger	Press
1772[a]	Apr	18	17	0		36.77	3.05			III	A, lc	Alger	Press
1780[a]	Jun	8	4	30		36.77	3.05			III	lc	Alger	AV
1780[a]	Jun	30	13	57		36.77	3.05			III	S, lc	Alger	AV
1782[a]	May	11	23	48		36.77	3.05			III	lc	Alger	AV
1786[a]	Nov	21				36.77	3.05			III	S, lc	Alger	AV
1792	Mar	7	0	0	0	36.78	3			III	S, lc	Bab El Oued	BH, AV, IGNE, USGS/NEIC
1801[a]	May	28	23			36.77	3.05			III	lc	Alger	Av*i*
1801[a]	Jul	25	1			36.77	3.05			do	lc	Alger	AV
1801[a]	Aug	11	5	45		36.77	3.05			do	lc	Alger	AV
1803[a]	Jan	20	20			36.77	3.05			do	lc	Alger	AV
1803[a]	Jan	22	0	0		36.77	3.05			III	S, lc	Alger	AV
1803[a]	Apr	19	2	45		36.77	3.05			III	S, lc	Alger	AV
1803[a]	May	7	18	30		36.77	3.05			III	S, lc	Alger	AV
1804	Jan	13	17	45	0	36.83	2.8			do	M,o	N. Sidi Fredj	EC, USGS/NEIC
1804	Jan	21	4	30	0	36.7	3	VIIIMM	EC	do	M	Alger	EC, USGS/NEIC
1804[a]	Feb	26	20	0		36.77	3.05			do	lc	Alger	AV
1804	Aug	23	15	30	0	36.8	2.5	VIMM	EC	do	M,o	N. Tipasa	EC, USGS/NEIC
1804	Aug	25	8	30	0	36.8	2.8	IXMM	EC	do	M,o	N. Sidi Fredj	EC, USGS/NEIC

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Table A1 (*continued*)

Year	Mon	D	H	M	S	Lat°N	Lon°E	INT	Au	QG	RMK	Site	References
1806[a]	Jul	12	12	10	24	36.77	3.05			do	lc	Alger	AV
1806[a]	Jul	13	3	30		36.77	3.05			do	lc	Alger	AV
1807[a]	Nov	13	17	0	—	36.77	3.05			III	lc, de	Alger	BAAS, AV*i*
1807[a]	Nov	18	—	—	—	36.77	3.05	VIIMM	SSIS	III	lc, de	Alger	PER*i*, RT*i*, BAAS, EC, USGS/NEIC, MOK
1810[a]	Dec	3	0	0	0	36.77	3.05			do?	S, i, lc	Alger	Av*i*
1810[a]	Dec	16	23	30		36.77	3.05			do?	lc	Alger	AV
1811[a]	Jul	11	14	30		36.77	3.05			III	lc	Alger	BH,AV
1830[a]	—	—	—	—	—	36.77	3.05			do	lc	Alger	BH,OUS
1833	Apr	6	—	—	—	36.7	3.1			do	lc	Alger	IGNE, USGS/NEIC CHE, RT, IGNE, USGS/NEIC, Press, Rt*i*
1839[a]	Apr	14	14	5	0	36.77	3.05	VIIEMS	HAR	II	lc, *i*	Alger	MOK, HAR
1841	Jan	15	12	0	0	36.7	3.1			do	lc	Alger	IGNE, USGS/NEIC
1842	Apr	9	0	0	0	36.7	3.1			do	lc	Alger	IGNE, USGS/NEIC
1842	Oct	24	8	5	0	36.7	3.1			III	lc, S	Alger	IGNE,USGS/NEIC, Press*i*
1842	Nov	1	19	15	0	36.7	3.1			III	A?, lc	Alger	IGNE, USGS/NEIC, Press
1842[a]	Dec	4	3	0	0	36.77	3.05	VIIIMM	SSIS	III	lc	Alger	BAAS, Press, SSIS, MOK
1843	Jan	13	0	0	0	36.7	3.1			do	lc	Alger	IGNE, USGS/NEIC
1843	Jan	18	—	—	—	36.7	3.1			do	lc	Alger	IGNE, USGS/NEIC
1843	Jun	28	23	30	0	36.7	3.1			do	lc	Alger	IGNE, USGS/NEIC
1845	Apr	27	0	0	0	36.7	3.1			do	lc	Alger	IGNE, USGS/NEIC
1845	Aug	21	0	30	0	36.7	3.1			do	lc	Alger	IGNE, USGS/NEIC PER*i*, IGNE, BAAS, RT*i*, HB, Av*i*
1847[a]	Jun	18	5	40	0	36.67	2.95	VIEMS	HAR	II	M, *i*	Douéra	MOK, Press
1850[a]	Aug	30	19	42	0	36.78	3.01	IV + EMS	HAR	II	lc, *i*	Bouzaréah	HEE, Press
1850[a]	Sep	5	15	50	0	36.78	3.01			II	lc, A	Bouzaréah	IGNE, USGS/NEIC, HEE,
1850[a]	Sep	8	3	50	0	36.78	3.01			III	lc, A	Bouzaréah	HEE
1850[a]	Sep	10	22	25	0	36.78	3.01			II	lc, A, S	Bouzaréah	IGNE, USGS/NEIC, HEE, Press
1851[a]	Jul	20	18	10	0	36.78	3.01	IVEMS	HAR	II	lc, *i*	Bouzaréah	IGNE, USGS/NEIC, HEE, Press
1851[a]	Aug	8	—	—	—	36.77	3.05			III	lc	Alger	HEE
1852[a]	Jun	29	18	0	0	36.77	3.05			II	S, lc	Alger	IGNE, USGS/NEIC, HEE, Press*i*
1854[a]	Feb	9	—	—	—	36.77	3.05			III	lc	Alger	IGNE, USGS/NEIC, HEE
1855[a]	Feb	1	3	0	0	36.77	3.05			III	S, lc	Alger	IGNE, USGS/NEIC, HEE
1855[a]	Mar	29	1	30	0	36.77	3.05			II	S, lc	Alger	IGNE, USGS/NEIC, HEE, Press*i*
1856[a]	Oct	3	12	0	0	36.77	3.05			III	lc	Alger	HEE
1856[a]	Oct	3	15	0	0	36.77	3.05		A,lc	III	lc	Alger	HEE
1857[a]	Apr	16	15	17	0	36.77	3.05			II	S, o?	Alger	HEE, Press*i*
1858[a]	Mar	10	5	30	0	36.77	3.05	—		III	lc	Alger	HEE
1859	Mar	28	6	30	0	36.7	3.1			do	lc	Alger	IGNE, USGS/NEIC
1859	Jun	23	12	30	0	36.6	2.89	VIMM	IGNE	III	lc, da	N. Boufarik	IGNE, USGS/NEIC, HEE*i*
1859	Oct	3	9	0	0	—	—			III		Alger	HEE
1860	Sep	22	0	0	0	36.8	2.5	VIIIMM	EC	do	M, o	N. Tipasa	EC, USGS/NEIC
1860	Oct	7	12	50	0	36.83	2.4			do	M, o	N. Mt. Chenoua	EC, USGS/NEIC
1860[a]	Oct	20	0	35	0	36.77	3.05			III	lc	Alger	IGNE, USGS/NEIC, HEE

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1860	Oct	22	—	—	—	36.7	3.1			do	M	Alger	IGNE, USGS/NEIC
1862^{a}	Oct	6	21	0	0	36.77	3.05			III	lc, o	N. Alger	IGNE, USGS/NEIC, HEE*i*
1863	Jan	16	0	0	0	36.7	3.1			do	lc	Alger	IGNE, USGS/NEIC
1863^{a}	Mar	1	7	30	0	36.77	3.05			III		Alger	HEE
1863	Aug	8	3	0	0	36.7	3.2	IVMM	EC	do	M	Dar El Beida	EC, USGS/NEIC
1865^{a}	Jan	16	3	57	0	36.56	3.16	VEMS	HAR	II	lc, *i*	Arba	HEE, Press, USGS/NEIC, IGNE
1865^{a}	Sep	10	3	30	0	36.75	2.89			III	lc	Staouéli	HEE*i*, IGNE, USGS/NEIC
1866^{a}	Jul	7	1	5	0	36.77	3.05			II	lc	Alger	HEE, Press*i*
1870^{a}	Mar	25	0	0	0	36.77	3.05			III	lc	Alger	USGS/NEIC IGNE, HEE
1870^{a}	Oct	29	0	10	0	36.77	3.05			III	lc	Alger	HEE
1872^{a}	Feb	25	21	0	0	36.77	3.05			III	lc	Alger	HEE*i*
1873	Oct	16	22	42	0	36.6	2.9	IVEMS	HAR	II	*i*	Boufarik	Press, USGS/NEIC, IGNE, SSIS, MOK
1874^{a}	Jan	7	23	25	0	36.77	3.05	IIIEMS	HAR	II	lc	Alger	HEE, Press*i*
1874^{a}	Apr	11	—	—	—	36.8	3.04			III	lc	B.E.O. (Alger)	HEE
1874^{a}	Apr	13	11	0	0	36.77	3.05			III	lc, i	Alger	IGNE, USGS/NEIC, HEE*i*
1874^{a}	Dec	17	13	0	0	36.58	2.89			III	lc, i	Boufarik	HEE
1875^{a}	Jan	24	17	30	0	36.77	3.05			III	lc	Alger	HEE
1875^{a}	Jan	27	17	30	0	36.77	3.05			III	lc	Alger	HEE
1875^{a}	Jun	22	16	30	0	36.75	3.05			II	S, lc	Alger	HEE, Press*i*
1878^{a}	Apr	13	1	40	0	36.81	2.96			III	lc	Caxine	HEE
1880^{a}	Oct	14	19	5	0	36.77	3.05			III	lc	Alger	HEE
1880^{a}	Oct	14	19	5	0	36.77	3.05			III	lc	Alger	HEE
1880^{a}	Oct	21	17	0	0	36.77	3.05			III	lc	Alger	HEE
1880^{a}	Nov	19	19	10	0	36.75	2.89			III	lc	Staouéli	HEE
1883^{a}	Jun	20	16	0	0	36.77	3.05	IIIEMS	HAR	II	lc	Alger	HEE, Press*i*
1883^{a}	Sep	22				36.77	3.05			III	lc	Alger	HEE
1883^{a}	Nov	1				36.77	3.05			III	lc, i	Alger	HEE
1884	Feb	18	0	0	0	36.8	3.05			do	lc, o	N. Alger	IGNE, USGS/NEIC
1885^{a}	Jan	21	2	15	0	36.64	2.7			III	lc	Castiglione	HEE
1885	May	25	2	0	0	36.8	2.5	VMM	EC	do	M, o	N. Tipasa	EC, USGS/NEIC
1888	Jan	25	4	30	0	36.77	3.05			III	lc	Alger	HEE
1889	Nov	8	22	11	0	36.7	3.1			do		Alger	IGNE, USGS/NEIC
1893^{a}	May	8	16	30	0	36.77	3.05	IVEMS	HAR	II	lc	Alger	HEE, Press*i*
1893^{a}	Jun	20	0	20	0	36.77	3.05			III	lc	Alger	HEE
1893	Jun	29	0	20	0	36.7	3.1			do	lc	Alger	IGNE, USGS/NEIC
1895	May	21	12	50	0	36.5	3.2			do			USGS/NEIC, IGNE
1895^{a}	Jul	18	23	0	0	36.77	3.05	IV^{+}EMS	HAR	II	lc	Alger	IGNE, USGS/NEIC, RT*i*, HEE, MOK

Au: author; QG: quality grade; RMK = remarks, M: macroseismic location, lc: locality coordinates, S: strong earthquake, de: destructive, da: damaging, o: offshore event, *i*: availability of macroseismic information on the event in this study, do: doubtful. In the column of references the character *i* indicate the availability of information on the event in this reference (even note of very few lines).

References: AV: Ambraseys and Vogt [15]; BAAS: British Association for Advanced Sciences; BH: Book of History (see the text); EC: European Catalogue; CHE: Chesneau [41]; IGNE: Spanish catalogue; HAR: Harbi [20 and this study], HB: Benhallou [19]; HEE [22]; MOK: Mokrane et al. [17], OUS: Oussadou [16]; PER: Perrey [40]; RT: [18]; RS: Roussel [43]; SSIS: Seccion de Sismologia e Ingeniera Sismica (Spanish catalogue).

[a] Epicentre estimated in this study.

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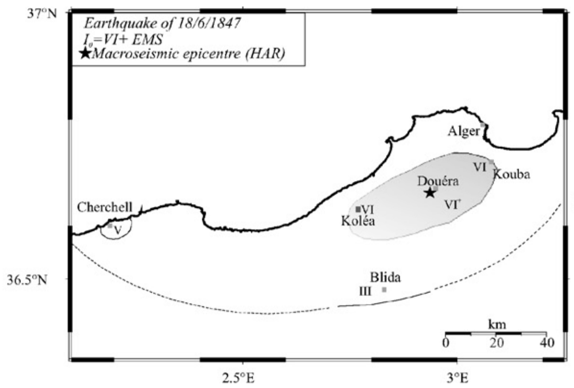
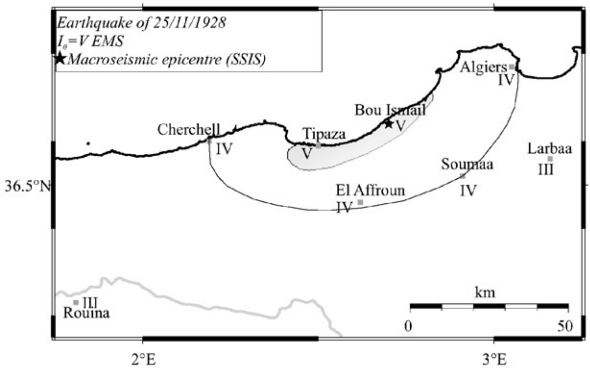
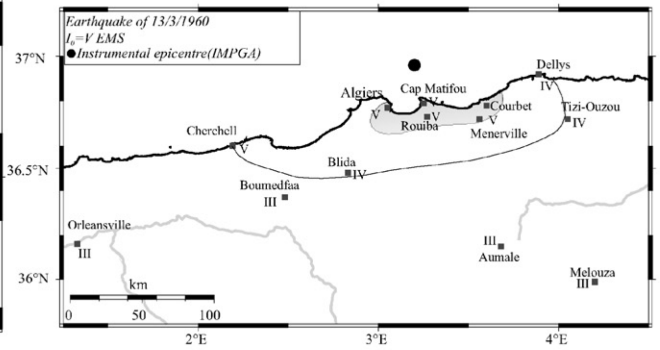
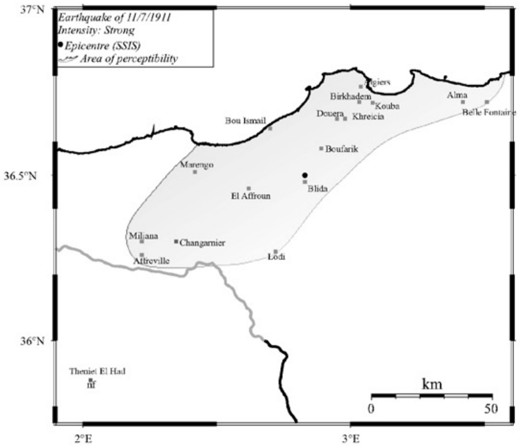
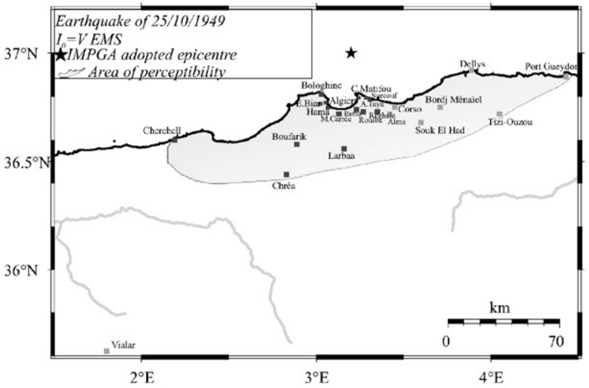
Appendix B

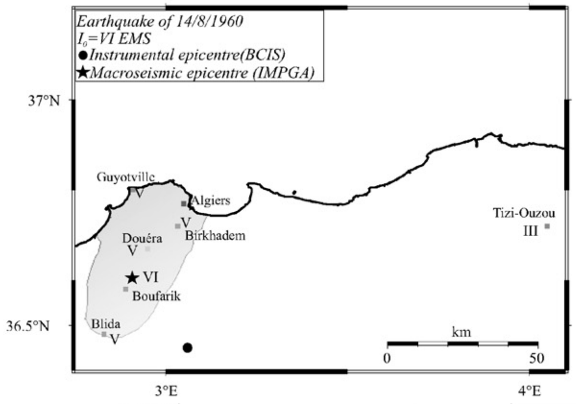


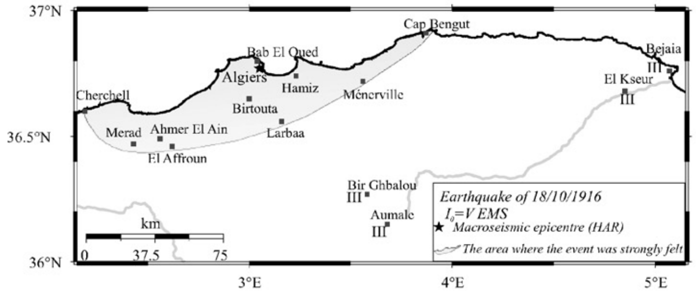


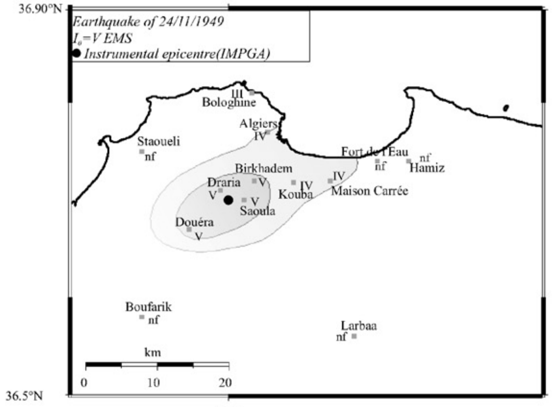


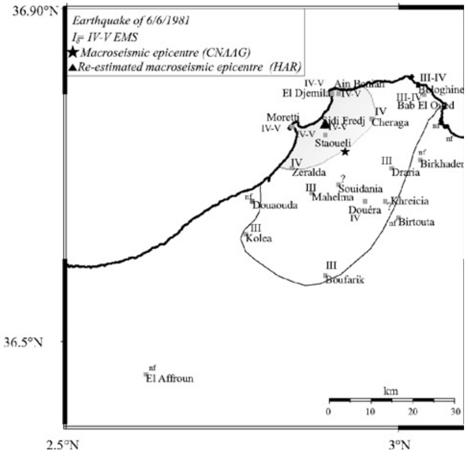












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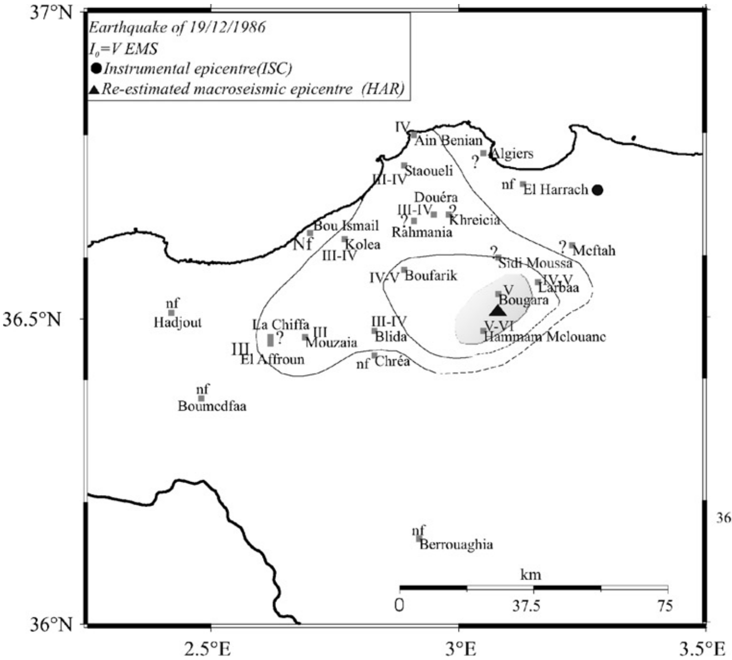

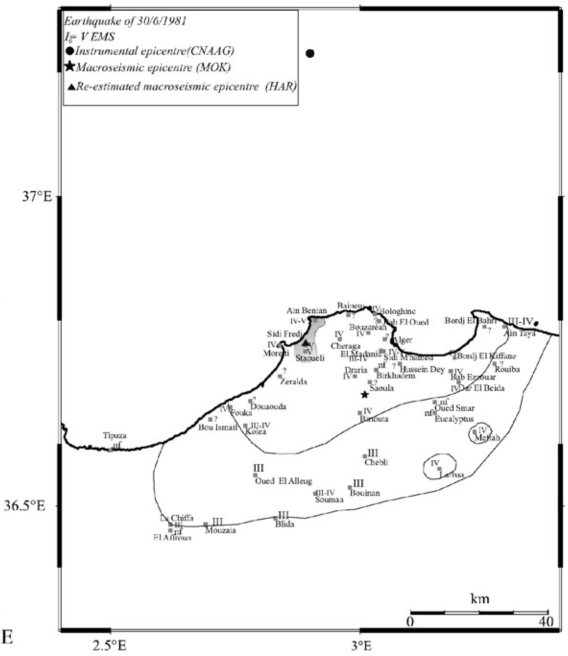

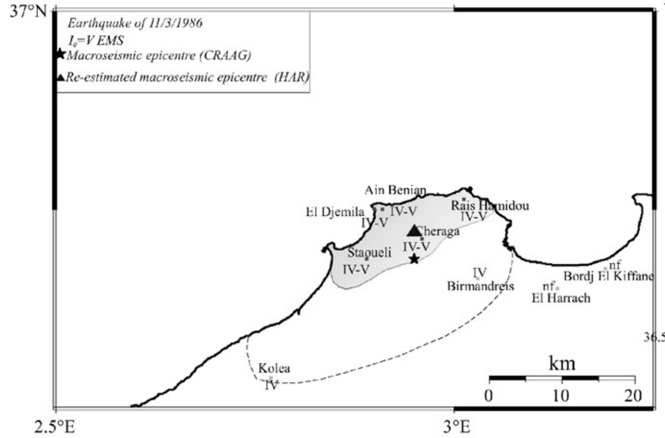

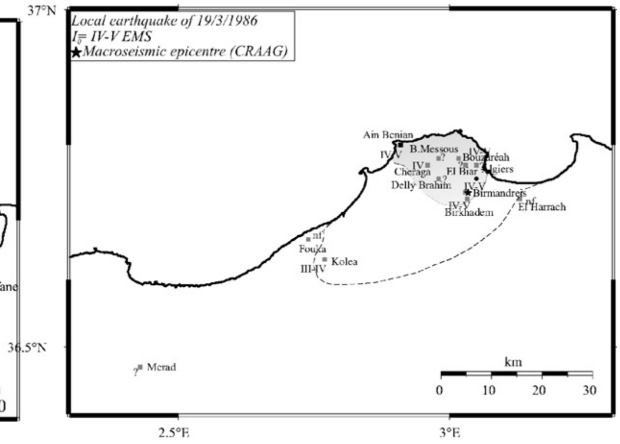

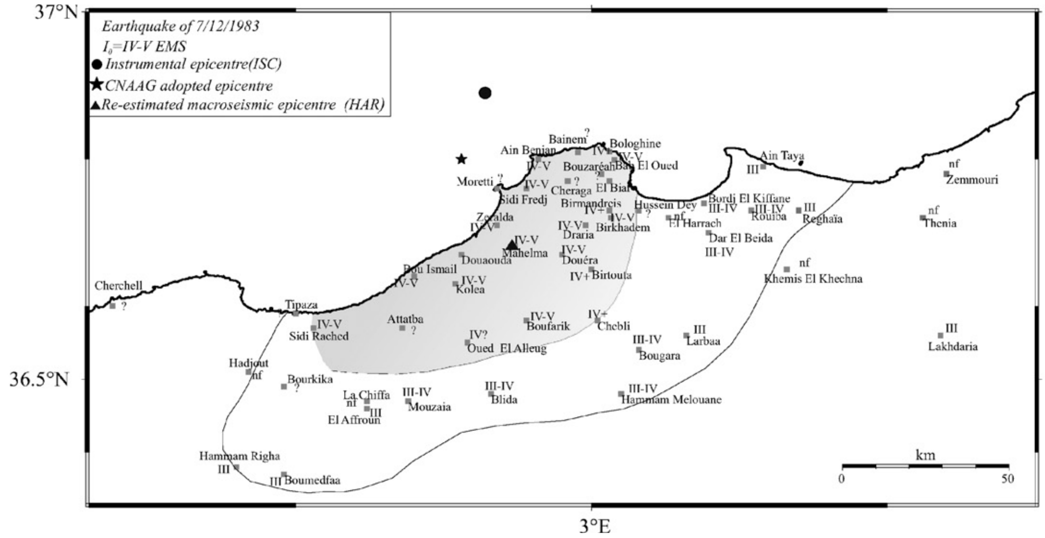

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